GOING BEYOND "GEOMETRICAL DRILLING": A REVIEW OF THE CONTRIBUTION OF LWD MEASUREMENTS TO THE IMPROVEMENT OF WELL PLACEMENT.

Jacques R. Tabanou, Jean Michel Denichou, Jack Horkowitz, Dzevat Omeragic, John Rasmus, Jian Yang (Schlumberger)

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ABSTRACT

Over the past 25 years, the oil and gas industry has evolved from drilling wells based on a predefined geometrical pattern, to an interactive, real-time drilling process known as "Geosteering". Since placing the well within reservoir "sweet spots" is akin to navigating inside the reservoir, an accurate map and a means to estimate the position of the well trajectory with respect to specific reservoir features are required. The maps used today and the means to determine the BHA position in space are more refined as a result of the significant improvements in LWD measurements, measurement inversion and interpretation workflow. Optimizing the well path to insure maximum contact with the pay zone also requires improved drilling technology and methodologies. This paper addresses only the navigation aspects of the problem.

One of the by-products this paper is a historical review of the evolution of well placement using LWD technology. In the early days, a "layer cake model" was consistent with available measurements, i.e., such as using "polarization horns" from resistivity propagation measurements. Progress came with the introduction of azimuthal GR and resistivity at-the–bit, by allowing the capability of looking around the well bore in greater detail than by quadrants. LWD images from resistivity and density tools provided the measurements required to stay in the pay zone by delineating more precisely variations in formation bedding properties including thickness, dip and orientation. Non-directional, deep resistivity measurements are currently being utilized to maintain horizontal well trajectories 5 to 10 meters above an OWC. To increase production and recovery factors, directional EM measurements are making it possible to accurately place wells in complex reservoirs to recover by-passed oil such as "attic oil" and to maximize reservoir contact in stacked channel sands.

Each of the LWD technologies described above can be ideally suited to achieve the well placement objectives for a specific reservoir structural configuration and/or petrophysical property distribution. However, it is important to recognize that none of these technologies alone can be considered as the ultimate solution to every well placement challenges.

INTRODUCTION

It has taken over two decades for the accuracy and reliability of measurement while drilling technology (MWD) to compare to the level of quality and maturity of wireline measurements. Used first for correlation purposes, early measurements were designed to help petrophysicists do formation evaluation (FE) [1], [2] in a fashion similar to what they had been providing with wireline technology. Geometrical drilling was the rule and these measurements were used for simple correlation after the fact, not to help place the well in the "sweet spot" of the reservoir.

In subsequent years, the drilling of high angle, horizontal and extended reach wells began to represent a larger segment of the total MWD/LWD activity. The technology to transmit downhole information in real time to the surface also was improving significantly during this time, and Formation Evaluation While Drilling (FEWD) found applications to help steer wells based on geology. This new application quickly learned to take full advantage of the various effects induced by the low angle existing between the tool axis and the formation stratigraphy. A good example of such effects was the observation that the 2 MHz propagation resistivity measurement was strongly affected by the proximity between two layers of different resistivity [4]. At first, the so called "polarization horns" appearing whenever the well trajectory was crossing or was within 5 feet of the boundary found a practical use to help maintain the trajectory inside the reservoir [5].

The same paradigm continued with the development of other FE measurements such as bit resistivity [6], neutron porosity and density. Real-time imaging was originally aimed at improving the characterization of reservoir structure and sedimentology. But the directional drilling engineers quickly adopted the imaging technology as a powerful means to evaluate the relative behavior of the well in regards to the structure of the reservoir (drilling up-sequence, or drilling down sequence). This was of considerable

value in maintaining the well trajectory within the reservoir, especially when the formation was significantly laminated. It also helped to correct the well trajectory as soon as the image showed that one had drilled out of the reservoir. However, these images were shallow and after the fact; even a measurement made directly at the drill bit is detecting the crossing of a boundary only after it has already occurred.

The purpose of this paper is to illustrate the mutual benefits of LWD technologies to both real-time well placement (WP) and Formation evaluation (FE). The two are no longer separate and independent activities. The industry today is facing challenges evaluating the petrophysical properties of the reservoir in horizontal wells as they become the new "standard" type well. Also, one can argue that the rapid adoption of this new standard well type is a direct consequence of the increased success in designing and implementing LWD well placement technology. It is the view of these authors that much of the technology is available today to help solve the issues of formation evaluation in horizontal wells.

WELL PLACEMENT OBJECTIVES

Clearly, tapping smaller and more complex reservoirs has motivated the industry to develop specific technologies to drill and navigate tens of thousands of feet away from drilling platforms. As, the ultimate objective for oil and gas companies is to maximize Net Present value (NPV), maximizing the length of the drain in the pay zone yields better productivity, and tapping bypassed and attic oil contributes to improved recovery factor. The challenge in well placement comes from geological uncertainty as represented on Figure 1: seismic resolution is generally too coarse, and uncertainty on depth is directly related to uncertainty in proper stacking velocities. Stacked channel sands exhibit complex 3D structures resulting in additional geometrical uncertainties.

DRILLING CONSIDERATIONS

The introduction of drilling motors and steerable drilling assemblies have enabled the drilling of complex and extended reach wells, especially offshore, where drilling costs are extremely high. As rotary steerable systems (RSS) were brought into play, it became even easier to control the well trajectory while also providing a significant improvement in data coverage used for formation evaluation. This was the result of the continuous rotation of the BHA, and azimuthal data and formation evaluation was no longer limited only to rotating intervals (as opposed to sliding intervals).

Several considerations must also be taken into account when deciding when to utilize the most sophisticated well placement technologies. Among these we should mention, the cost of drilling a well, the possibility or not to side-track, the risk and associated cost of entering in a water zone, the uncertainties of the target reservoir. One should also consider uncertainties in true vertical depth (TVD), well trajectory, reservoir boundaries and fluid contacts, the possibility of faults, and the overall capability to predict what is ahead of the bit.

WELL PLACEMENT METHODS

There is no single best fit for determining when to employ various well placement methods, as different methods are used today depending on some of the considerations presented above. Uncertainties associated with seismic vertical resolution limitations (Figure 2), well trajectory and the delineation of reservoir target affects the overall performance of the well being drilled.

"Follow the drilling plan" characterizes a geometrical drilling method well adapted to simple homogeneous "layer cake" reservoirs with constant structural dip. But in highly laminated reservoirs encountered often in turbidite channel and deltaic sands, geological drilling methods are aimed at maintaining the well trajectory inside a specific reservoir layer. Optimum well production often requires maintaining the well trajectory at some specific distances from fluid contacts or reservoir structures. Production criteria may dictate the well trajectory and how long the drain should be. Except for "Geometrical drilling", all the other methods involve the use of LWD FE measurement to achieve their objectives.

HISTORY OF LWD TECHNOLOGY FOR WELL PLACEMENT

It is enlightening to briefly review the history of LWD FEWD since it is very much linked with the history of drilling high angle and extended reach horizontal wells. Such a historical perspective may help anticipate how the synergy between WP technology and new LWD FEWD may continue to contribute to both fields.

The following table illustrates the rapid technological response to the specific challenges brought about by MWD and FE on drill pipe. It took slightly more than 20 years since the introduction by NL [2] of the first 2 MHz propagation resistivity on a drill collar. But this is faster than the preceding 50 years for the development of wireline technology!

1980	Resistivity Short Normal and GR
1984	The first 2MHz Propagation Resistivity is introduced.
1988	GR and 2MHz Propagation Resistivity. Geosteering relies on correlations between real time logs and modeling based on offset / pilot well measurements to evaluate the dip of the formation.
1992	Azimuthal GR and Resistivity at the Bit
1994	LWD Sonic measurement
	Resistivity at the Bit Imaging
1999	Real Time Dip from Resistivity Images
	Sonic, compressional velocity.
2001	Real Time Images transmission (resistivity and Density).
2002	Ultra Deep Resistivity (very deep investigation, non azimuthal)
	Collaborative environment for multidisciplinary decision to correct well trajectory in real time.
	NMR
2003	Seismic while drilling ("putting the bit on the seismic map"
	Formation Pressure while drilling
2005	Azimuthal Deep Resistivity (deeper investigation and azimuthal)

DRILLING A WELL IN THE "SWEET SPOT" COSTS AS MUCH AS DRILLING A DRY OR MARGINAL WELL!

When dealing with simple, massive, homogeneous and "flat" reservoirs with known TVD, drilling geometrically makes a lot of sense and is certainly very cost effective. However, for most reservoirs, this is never the case. Figure 3 illustrates several well paths drilled in a specific reservoir. In this example, drilling geometrically without a pilot well would result in 15 feet producing interval. Adding information from a pilot well, simple geometrical drilling would increase this interval to 650 feet. Using FE LWD measurements such as FE imaging, the producing interval can be increased to 1400 feet, resulting in a doubling in overall production when compared to the original productive interval that would have been achieved by simple geometrical drilling with a pilot well. The lesson here is that it costs an oil and gas company as much to drill a marginal well as one that can maximize the productive interval.

ARE WE APPROACHING THE RESERVOIR?

Placing a well in the "sweet spot" is like landing an airplane on the proper runway! Before the wheels can touch the tarmac, the pilot must be approaching the "right" airport. Landing the well in the reservoir is therefore a critical step in achieving optimum well placement.

Starting to drill the horizontal section too early (too shallow, above the top of the reservoir) will increase the borehole drift, requiring the need to drill a longer interval in order to correct for the TVD shift, resulting in a drastic reduction of the net/gross ratio of the reservoir section, as well as increased total drilling time and exposure time.

On the opposite extreme, waiting to recognize the top of the reservoir on the LWD logs before initiating the landing of the well will increase the risk to drill through the sweet spot. Also, the trajectory used to correctly position back the drain in the target interval will likely present a U-shape that will penalize optimal flow when the well is put on production.

Therefore, the landing section of the well is usually done while drilling by correlating with reservoir maps and cross sections obtained from seismic interpretation and well logs. Seismic while drilling technology introduced in the last 5 years is similar to wireline VSP technology and produces similar results in near real-time, while the well is being drilled. As shown on Figure 4, it provides the information required to develop more accurate time-depth relationships, and can also illuminate reflectors associated with targets several hundred feet ahead of the drill bit.

ARE WE DRILLING IN THE RESERVOIR?

Drillers have always relied on FEWD to tell them if they were drilling in the reservoir, at first by simply correlating GR with 2 MHz propagation resistivity measurements in memory mode (this is hard to believe nowadays as we are accustomed to real time decision making while the well is being drilled) and then rapidly in real time as mud pulse technology managed to bring an increasing number of data, including images, to the surface in real time.

GEOSTEERING USING A DETAILED 1D MODEL BASED ON PILOT WELL INFORMATION AND REAL TIME IMAGES

During the mid 80's to mid 90's, the industry recognized also the benefits of predictive modeling, specifically GR and 2 MHz resistivity, as a powerful means to help drill long extended reach horizontal wells. Essentially a 1D model is built as shown in Figures 5a and 5b, using a "layer cake" formation model constructed from log data derived from one or several vertical pilot or offset wells and knowledge of regional structural dip information correlated with seismic cross sections. Real time GR and 2 MHz resistivity information acquired while drilling the well were then continuously compared with model data to help geosteer the well.

ARE WE CROSSING A BOUNDARY? SHOULD WE STEER UP, DOWN, LEFT OR RIGHT?

One of the fundamental questions when drilling through a reservoir bed and crossing a boundary is to know if we are exiting through the roof or the floor of the reservoir. 2 MHz propagation resistivity is not a directional measurement. It cannot distinguish between the four scenarios depicted in Figure 6. The need for azimuthal discrimination was recognized by the drillers and motivated the development of azimuthal measurements. The quadrant GR was the first FEWD allowing checking if the zone above was either a shale or a sand by stopping the drilling and orienting the GR sensor towards the top or the bottom of the borehole.

Consider the four well placement scenarios above using a BHA with a LWD measurement sensor placed at some distance behind the bit, represented by the red BHA element (Figure 6). Using a non-azimuthal measurement, the sensor readings would not distinguish between the four scenarios even though dramatically different steering decisions are required in order to remain in the hydrocarbon bearing reservoir. For scenario A, the inclination must be dropped, for B it must be held constant or dropped, for C it must be increased, and for D it must be held constant or increased. If the trend of the measurement verses depth was examined, one could narrow the choices down to A or C verses B or D. In the first case, you would only have a 50% chance of making the correct steering decision, whereas for the latter, you need to make the decision to hold angle to remain in the sand. It is easily seen that only the azimuthal measurements contain the required information to remain in the sand. The azimuthal measurements allow us to visually determine the relative angle of the BHA to the bedding. By examining the 3D LWD laterolog resistivity image, we can determine that the drilling process represents scenario D. The inclination is being nudged up in order to climb into the higher resistivity portion of the reservoir.

In the late nineties, LWD resistivity imaging and the second generation of neutron and density measurements on drill pipe were introduced (Figure 7 and 8). These new measurements took advantage of the continuous rotation of the sensors to produce first "quadrant" logs, then soon after full fledge images that could be utilized by both the geologists and petrophysicists. Although the resolution of these images was on the order of a few inches, these images were quickly adopted by the geosteering community who could easily recognize when the sensor was crossing fine stratigraphic beddings (Figure 9). It provided the ability to determine in real time when to drill up or down, based on the features seen on the image. When the well path was sub-parallel to bedding surfaces, images would display the characteristic "bull eyes" shapes, now so familiar to the industry.

Additionally, formation dips computed from the images allow us to precisely determine the value of inclination we must build or drop to in order to remain bed parallel and remain in the sand. The azimuthal measurements allow us to navigate through the reservoir very precisely, following the local geological structure as it changes laterally.

HOW FAR ARE WE FROM AN OIL WATER CONTACT OR A GEOLOGICAL MARKER?

If real-time imaging revolutionized well placement, its inherent shallow depth of investigation had limitations, mainly due to a combination of distance between the imaging sensor and how quickly the well trajectory could be modified. There are cases, however in relatively thick reservoirs, when the well must be placed tens of feet above an oil water contact or some geological marker. Figure 10 depicts such a situation where An LWD ultra-long spacing induction measurement with two spacing and several frequencies was field tested. The tool could estimate the distance to the OWC located 5 to 10 meters below and could sense the effect of the roof several tens of meters above the well path.

For GeoSteering at the reservoir and sub-seismic level, a new LWD Ultra Deep Resistivity tool (UDR) has recently been developed. This tool relies on the addition of lower frequencies and longer transmitter to receiver spacing to achieve this capability. One of the primary applications is determining the distance to the OWC while drilling, thus insuring the well will not pre-maturely cone water when put on production. Other uses include the identification of distance to

boundaries while drilling. These boundaries could be either a conductive shale or a resistive caprock. An inversion of the measurements in real time allows for these distances to be calculated while drilling.

An experimental prototype tool has also been successfully tested in a series of field tests in the North Sea for Norsk Hydro, Statoil, and Kerr McGee [8]. Figure 10 illustrates an OWC delineation combined with top and bottom reservoir shale for a 2000m [6562 feet] horizontal producer well. By inverting a formation model that consists of a resistivity profile (with variable slope) combined with a possible top and bottom shale boundary, a consistent estimation of the OWC located 7m [23 feet] below the wellbore was possible. Due to the variation of the resistivity-saturation profile along the path of the wellbore, the saturation-height function technique combined with a traditional resistivity could not be reliably used to determine the OWC.

DISTANCE TO AND ORIENTATION OF A BOUNDARY: AZIMUTHAL RESISTIVITY

The most recent innovations have resulted with the introduction of a dedicated well placement EM technology offering both 360° azimuthal coverage and deeper investigation than the imaging technology.

The antenna layout of this azimuthal resistivity tool is shown in Figure 11. The measurement system includes a set of conventional propagation resistivity measurements, with the antennae aligned with the tool axis; i.e., transmitters T_1–T_5 and receivers R_1 and R_2. At both ends of the tool, there are two tilted receiver antennae R_3 and R_4, inclined 45° with respect to the tool axis, and the transverse transmitter T_6. This symmetric tool configuration enables removal or amplification of sensitivities to dip, anisotropy, and nearby boundaries, resulting in simplified responses and interpretation.

As shown on Figure 12, throughout 360° of coverage around the borehole, this tool determines the direction presenting the highest conductivity contrast. Measurements along this direction are used to determine distance to a nearby boundary or two boundaries oriented 180° apart. During drilling, structural interpretations along the well trajectory are updated and presented in real time to facilitate timely geosteering decisions. An automated inversion program based on 1D models shown in Figure 13, processes all available data for display on a graphical user interface.

The resulting presentations show distance to boundaries and azimuthal orientation, along with formation resistivity. Visual results are displayed in two distinct views. A polar plot (Figure 14) shows the position of boundaries around the wellbore projected into a plane perpendicular to the tool axis. Distance to boundary or boundaries and their orientations are indicated on this plot. A curtain section display (Figure 15), provides a side view showing structure and formation properties along the trajectory.

After drilling, a 3D visualization shown in Figure 16 is made illustrating the contribution of well placement to improved reservoir characterization.

BUILDING MODELS WHILE DRILLING, INVERSION BASED INTERPRETATION AND PRESENT LIMITATIONS

As seen before, the estimation of boundary distance and orientation necessitates the use of an inversion based on a 1D layer model. In this model, one of the parameter is obviously the shoulder-free bed resistivity Rt (possibly anisotropic). This resistivity estimate is by definition not affected by the bed above and/or below. It is therefore the resistivity that should enter in a classical estimation of water saturation and reserves.

In the horizontal well example presented in Figures 18a and 18b [10], such inversion yields a better Rt than can be obtained from a standard FE propagation resistivity measurement that could be affected by reading of multiple layers. This example illustrates the contribution of workflows developed initially for well placement which provides an improved Rt determination in horizontal wells. In other words, well placement technology which has been provided the benefit from many advances in new LWD FE sensors is now returning the favor and starting to help the FE methodology. In our view this is just the beginning of a trend where the full utilization of directional EM measurements will contribute to achieve more accurate FE answers, especially in high angle and horizontal wells.

As in any model-based inversion technique, the model uncertainty is the most important limitation in achieving consistent interpretation. Regardless of real geological complexity of the reservoir, the real-time interpretation algorithm always utilizes a maximum of three-layer model, assuming parallel bed boundaries. The assumed model is adequate most of the time, but it is still an approximation of reality, which is always more complex: boundaries may not be parallel and often they are not be sharp; possible cross-bedding is ignored, potential presence of extreme asymmetric invasion in water-base mud, thin (less than 1-foot thick) conductive streaks.

WHEN SHOULD WE STOP DRILLING?

The previous generation of well placement was dealing primarily with some geometrical attribute of the reservoir. However, in many instances well placement decisions are based on petrophysical properties of the reservoir, such as porosity and/or permeability. LWD FE measurements are playing a crucial role there obviously. In order to minimize the overall drilling cost, it is legitimate to ask "when should we stop drilling this well".

As shown on Figure 18, real time formation evaluation coupled with reservoir simulation, such as ECLIPSE, can help in making such decisions. It is fair to say that even though such methodologies are currently available, they are not yet being routinely used in the field.

Figure 10 illustrates the successful simultaneous application of azimuthal and formation evaluation measurements during a well placement job in W. Africa [9]. Upon drilling out from the shoe, the magnetic resonance measurements indicated low permeability and free fluid volumes, while the azimuthal resistivity measurements indicated the cleaner sand was above the well. After actively steering the well up, the sand count increased from 40% to 90-100%, the grain size increased from fine to medium, the computed permeability from less than 300 md to about 1000 md, and the resistivity increased from 1.5 to 10 ohm.meters. The 15 x marks on the trajectory indicate the decision points made by everyone involved that kept the wellbore within the cleanest, most permeable portion of the sand even as the well drilled up and over the crest of the anticline at the highest ROP ever drilled in this formation. Due to the low permeabilities at the heel of the well, it was determined to extend the well an additional 200 feet for a total of 1400 feet in order to accumulate the necessary permeability-feet for economical production. When the well was put on production, the IP was 1600 BOPD, exceeding the objective of 1200 BOPD.

The upper panel shows the progressive gain in net pay as a function of well placement sophistication. Drilling the planned trajectory before the pilot well, the penetration would have been 15 feet. Adjusting the trajectory with the knowledge gained from the pilot results in 650 feet of net pay. Both are below the economic limit. Only by actively geosteering the well with azimuthal and formation evaluation measurements was the 1400 feet of net pay and economic success achieved.

WHAT IS AHEAD OF THE BIT? PREDICTIVE EXTRAPOLATION VS. LOOK AHEAD.

Despite the impressive list of Well Placement and FE technologies introduced in the past 25 years, two challenges remain illustrated on Figures 21 and 22: looking ahead of the bit and handling the effects of complex 3D reservoir geometry.

All the existing well placement methods in use today are not truly capable to look ahead of the bit at large distances. They are all providing a way to extrapolate ahead of the bit a simple reservoir model (usually 1D) from the observations and inversions made up to that point. For instance, if a roof is approaching the well path, existing technology will be able to anticipate where the trajectory might exit the reservoir assuming that the reservoir roof is continuing to dip at the same angle it has been dipping up to that point. Certainly the industry lacks the technology to detect the presence of a small sub-seismic fault tens of meters ahead of the bit.

Finally, real reservoirs cannot be reduced to simple 1D models. The channel sand shown in Figure 21 illustrates the complexity one has to handle when the well path is moving away from the center of the channel towards the channel edge. To be able to handle such added complexity, new inversion methods as well as new technologies must be developed.

The advent of fast and cheaper computers coupled with parallel processing ability and new powerful visualization techniques will certainly enable the industry to tackle these remaining challenges.

The novel wired drill pipe technologies already emerging in the field will certainly contribute also to this evolution by increasing by several orders of magnitude the amount of data transmitted from the LWD downhole assembly to the surface decision center.

CONCLUSIONS

The last decade has witnessed an explosion in While Drilling technology resulting in increased production and recovery factor for numerous oil and gas reservoirs. The rapid introduction of sophisticated LWD measurements has played a significant role in the evolution of well placement. Each of the above LWD technologies is well suited to placing the well for a specific reservoir geometry and petrophysical property distribution. But it is important also to recognize that none of them can be considered as the ultimate solution to every well placement challenge. Their synergetic use in a collaborative environment (Figure 22) is often what makes the difference.

Some of the remaining challenges reside in providing deep investigation look ahead technologies to

complement borehole seismic while drilling, modeling, interpreting and visualizing increasingly complex (3D) reservoir conditions and developing improved collaborative and multi-disciplinary means to help in planning and real time decision making.

ACKNOWLEDGEMENTS
A lot of people from many operating and service companies have contributed through the years to the development of LWD technologies for improved Well Placement. Although the list of their names would be too long to be cited here, their creativity and innovative spirit has contributed to the significant increases in hydrocarbon production and recovery factor from more complex reservoirs.

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ABOUT THE AUTHORS

Jacques R. Tabanou is Formation Evaluation Engineering Advisor at Schlumberger Product Center in Sugar Land, Texas.

Jean Michel Denichou is the Schlumberger Global Well Placement Domain Champion, based in Sugar Land, Texas.

Jack Horkowitz is the Petrophysics Domain Advisor for Schlumberger Drilling and Measurements in Sugar Land, Texas.

Dzevat Omeragic is currently Program Manager Modeling and Inversion Technologies at Schlumberger-Doll Research, based in Boston where he works in the area of computational electromagnetics, high-angle and horizontal well formation evaluation, high performance computing, low frequency antenna design, optimization and inverse problems.

John C. Rasmus is an Advisor-Reservoir Characterization in the Schlumberger LWD product line based in Sugar Land, Tx. Current duties include LWD interpretation InTouch field and client support, resistivity and nuclear interpretation support and special projects.

Jian Yang is senior physicist in the Formation Evaluation Department at Schlumberger Sugar Land Product Center. He received his PhD in condensed matter physics (1989) from Nanjing University, China. Before joining Schlumberger in 1998, he conducted research at Texas Center for High Temperature Superconductivity at University of Houston, USA. His current interests are electromagnetic modeling, data inversion, and 3D visualization.

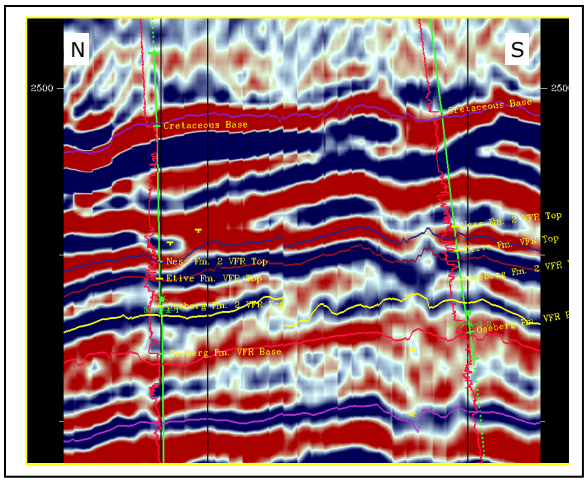


Figure 1: *Typical Seismic cross section used to plan for well placement.*

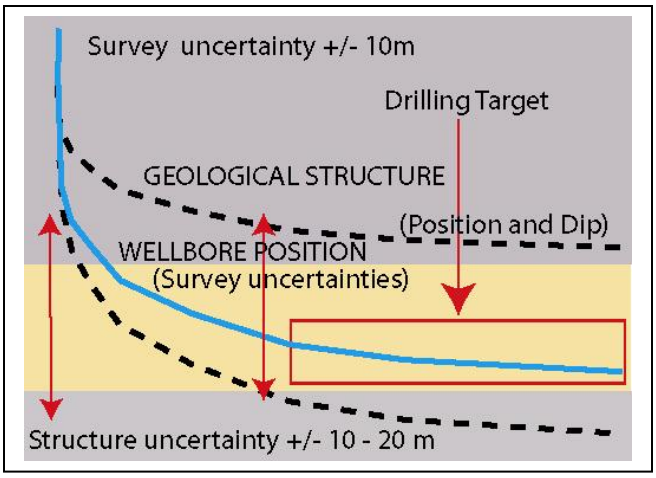


Figure 2*: Typical uncertainties involved in drilling an horizontal well in a simple case*

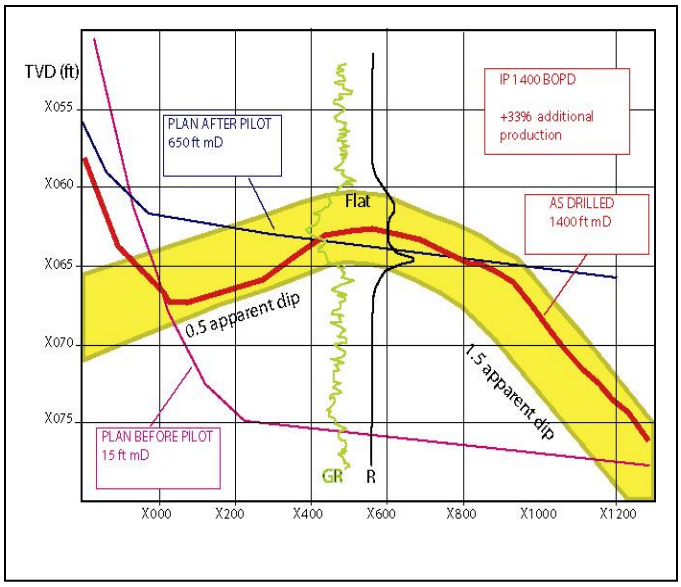


Figure 3*: This figure illustrates the significant increase in productive interval as we go from simple geometrical drilling (magenta) to geometrical drilling using pilot or offset well data (black) and to the optimum drilling procedure using real time well placement technologies*

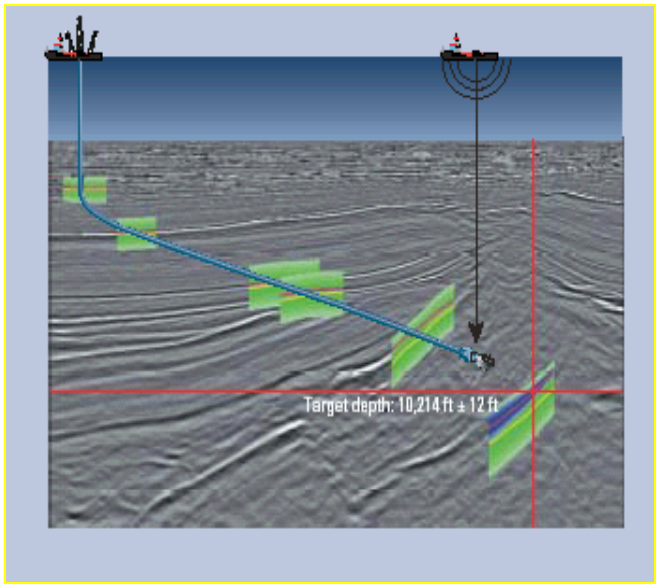
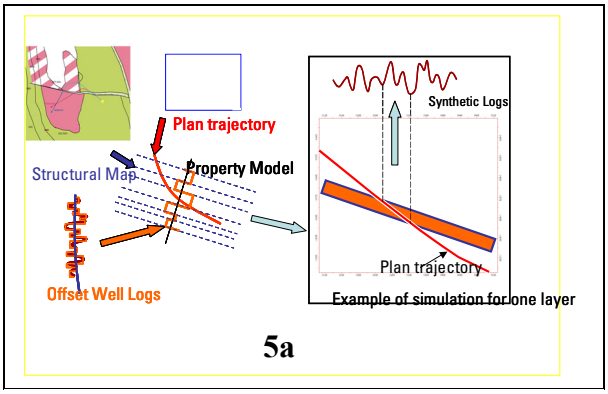


Figure 4: *Illustration of Seismic drilling survey used to improve depth correlation. The yellow band represents the pre-drill depth location of the specific seismic reflector while the green box represents the depth uncertainty of the same seismic reflector. The red band represents the actual depth of the reflector found while drilling. For the last reflector, the red band surrounded by the blue shading represents the current estimate of the reflector and its depth uncertainty.*



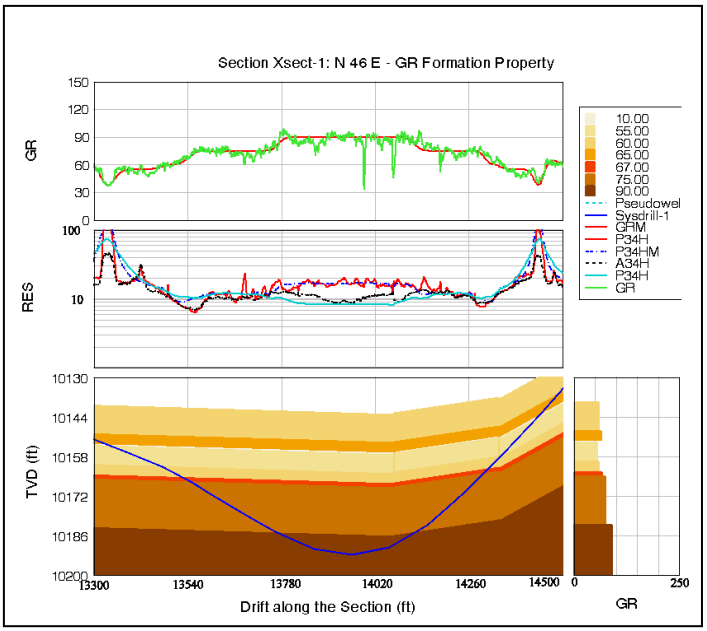


***Figure 5a ,5b**: Methodology used in the mid 80's to mid 90's for well placement based on 1-D modeling of Resistivity and GR from a simple layered cake model constructed on offset well log data and knowledge of reservoir structure. Real time data was compared with model data to decide in RT how to modify well trajectory.*

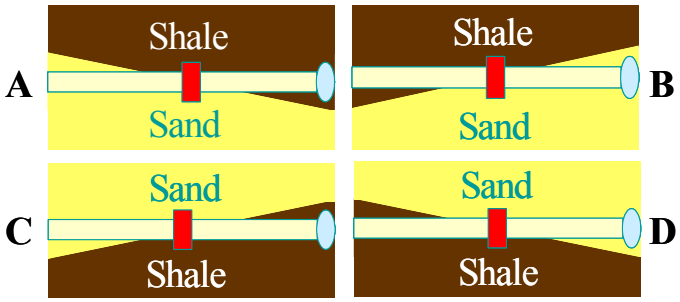
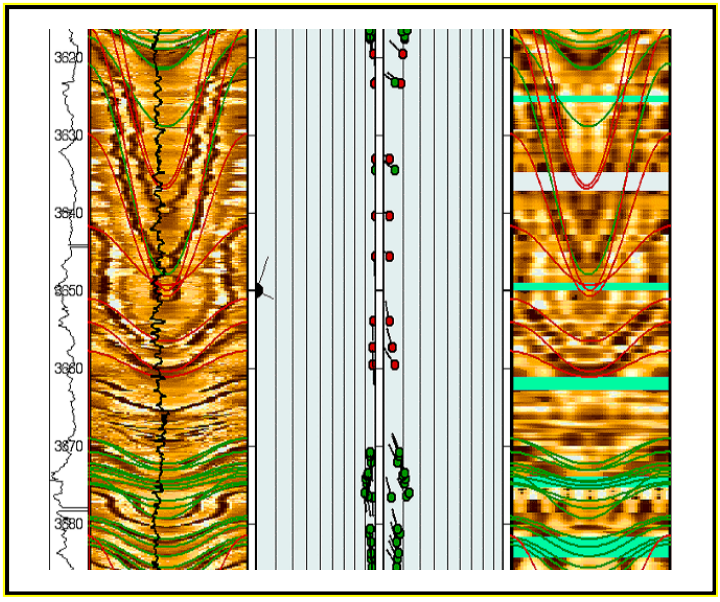


***Figure 6**: For these four different scenarios a non directional FE measurement will give the same ambiguous response. However a true directional measurement such as directional image will distinguish between these four cases.*



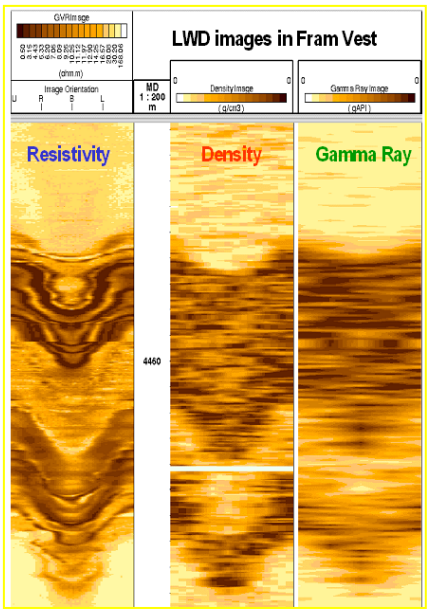


***Figure 7:** Illustration of the various LWD images available today.*

***Figure 8:** Comparison between Memory Mode Resistivity image on the left with real time Resistivity image on the right.*

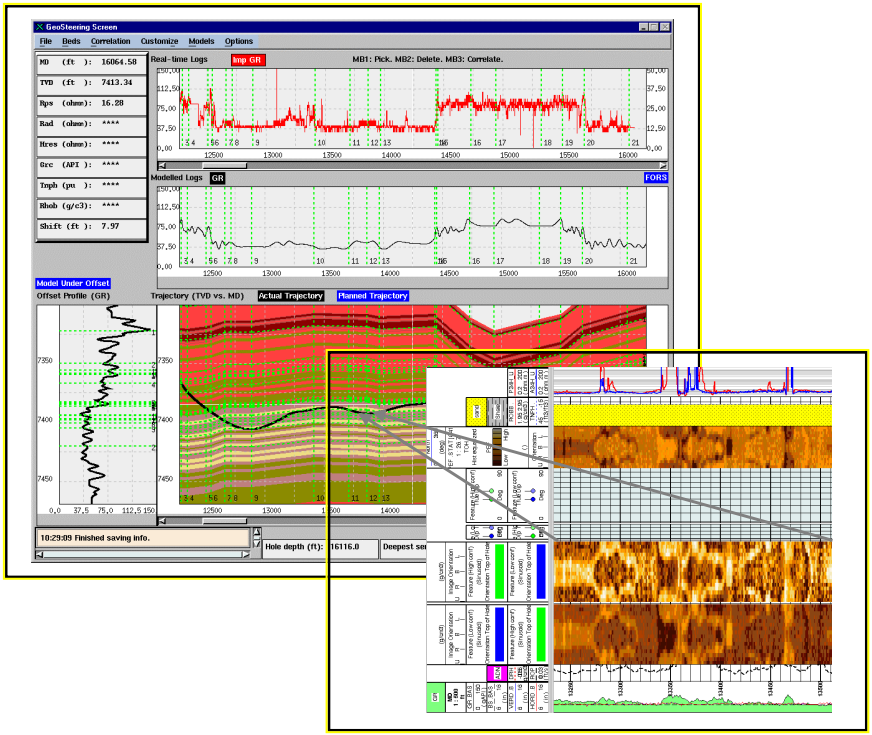


Figure 9: *The panel on the left shows typical geosteering panel display (TVD versus MD). In this particular well the GR was non descriptive and requires the use of the Density image to determine if they were drilling up or down through the layers.*

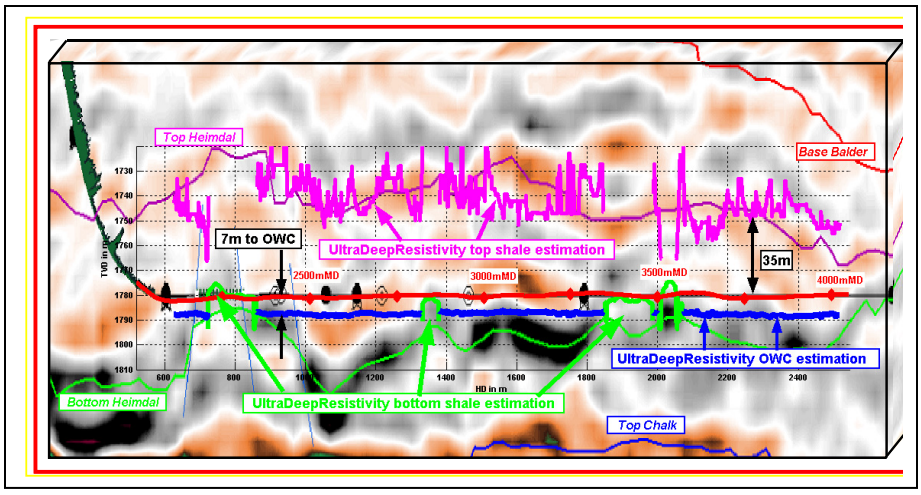


Figure 10: *Result from a field test for a horizontal section of 2000m [6562 ft.] illustrating the reservoir steering capability of the Ultra Deep Resistivity above OWC*

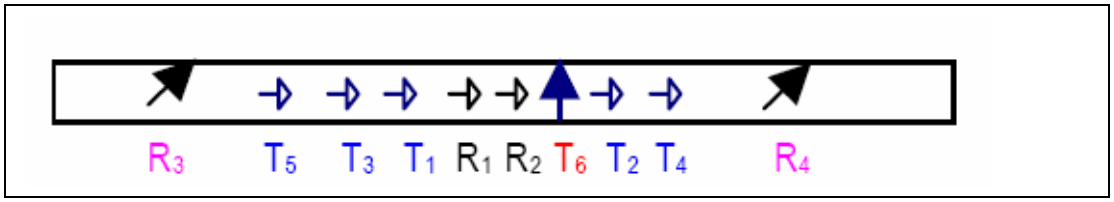


Figure 11: Transmitter Receiver configuration for an azimuthal resistivity tool used to estimate distance and orientation of nearby boundaries.

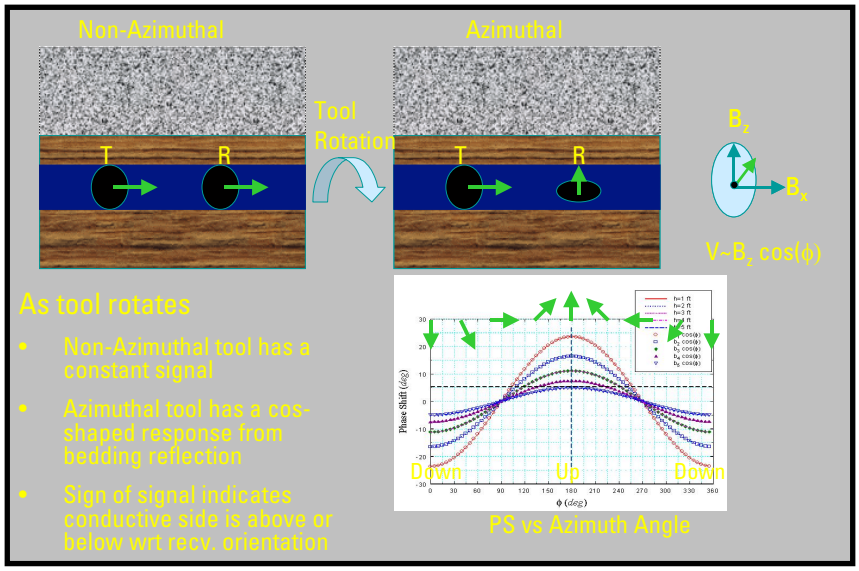


Figure 12: *Illustration of the azimuthal resistivity tool response as it rotates in the presence of a boundary*

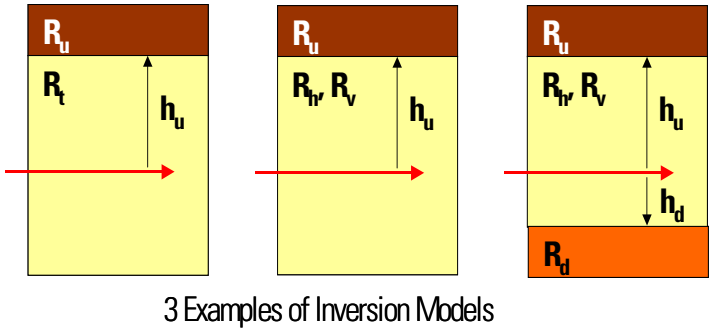


Figure 13: *1-D inversion models used to invert for distance and orientation of one or two nearby boundaries*

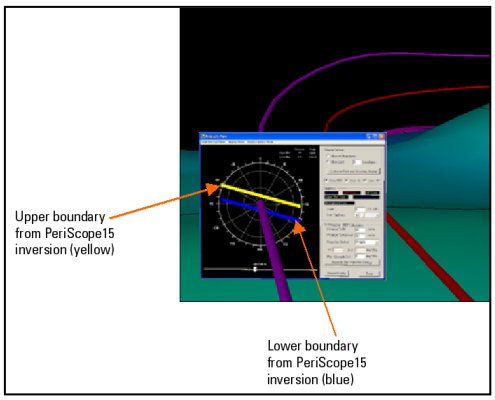


Figure 14: *Typical "cockpit" view of nearby boundary displayed in real time.*

Figure 15*: Corresponding real time "curtain section"*

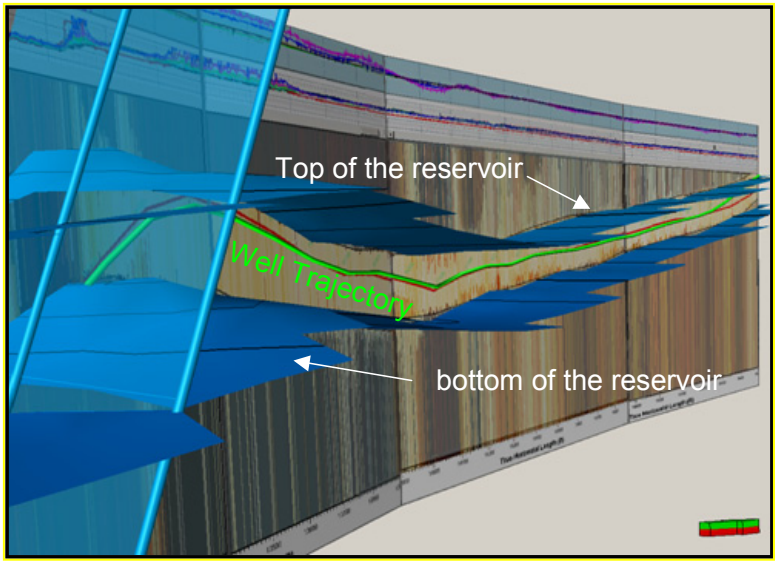


Figure 16: *The results of importing distance and orientation of boundaries into a 3D reservoir model.*

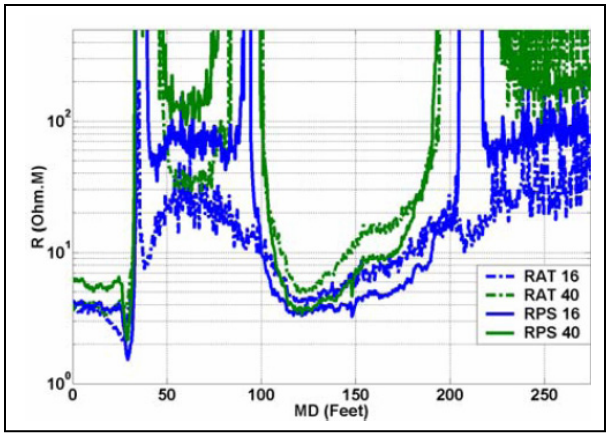


Figure 17 a: *Measured Phase and Attenuation resistivity measured in an horizontal well in the North Sea crossing reservoir boundaries.*

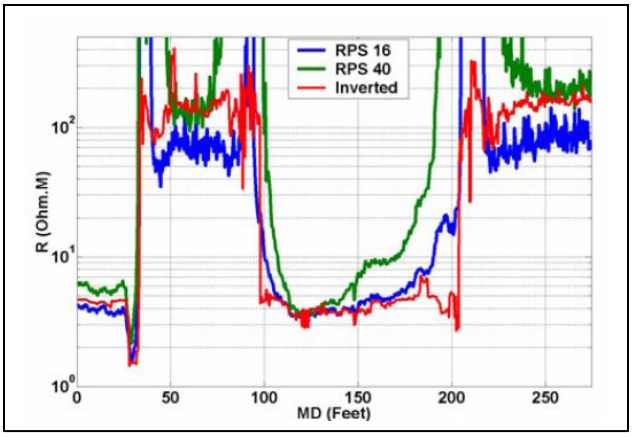


Figure 17 b: *This figure illustrates the improvement in Rt estimation by combining both standard 2 MHz resistivity with azimuthal resistivity information.*

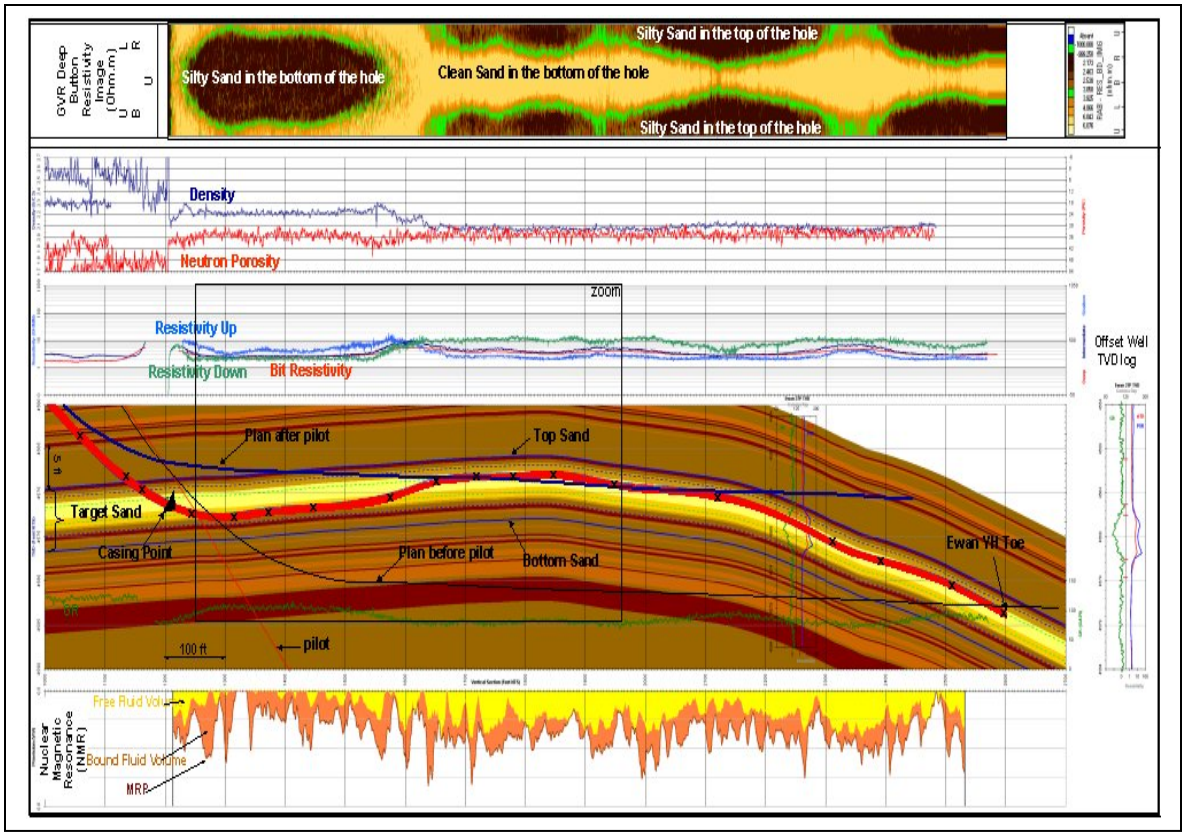


Figure 18: *This example illustrates our ability to place a well in a few feet thick and determining the productivity as the well is being drilled using Resistivity image and NMR*

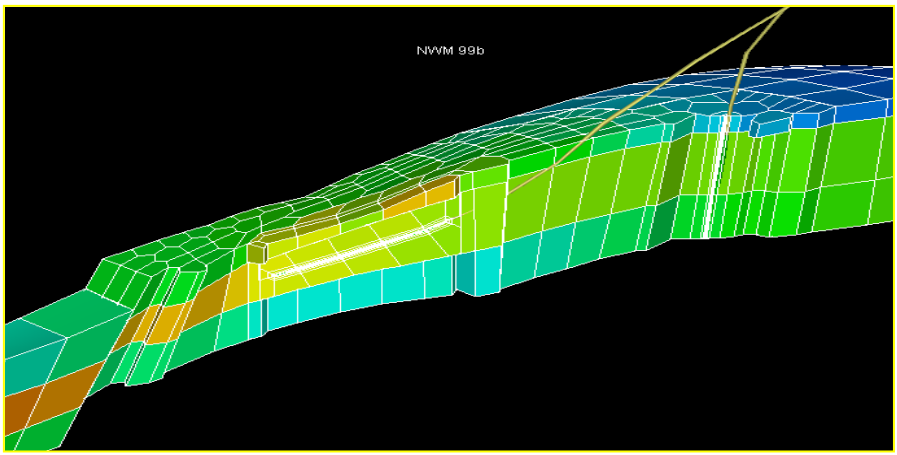


Figure 19: *3D ECLIPSE model used to estimate the production of an horizontal well being drilled, using petrophysical parameters estimated from LWD Formation Evaluation measurements.*

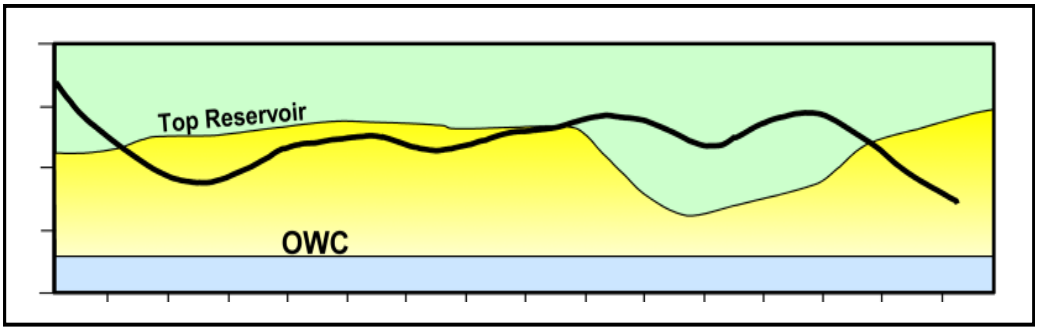


Figure 20: *This figure illustrates the possible lateral variation in reservoir properties that cannot be to day fully anticipated by existing well placement technologies.*

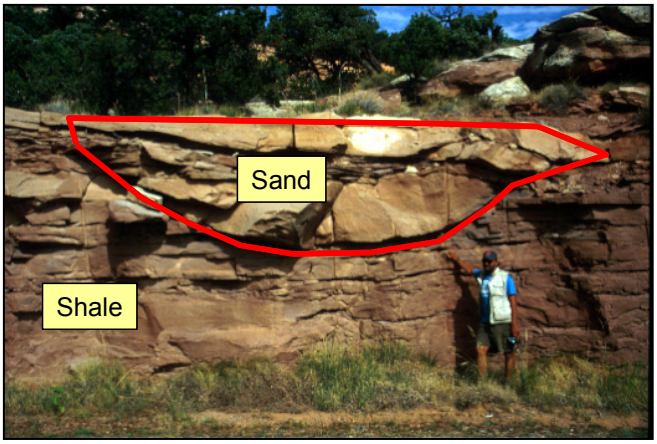


Figure 21: *Real reservoirs such as channel sands exhibit in general some 2-D and possible 3D effects that will require the development of new technologies as well as inversion methods that are not limited by present 1-D models.*

Figure 22: *Typical collaborative environment used today to plan, drill and evaluate high angle and horizontal wells.*