IN THE DRIVER'S SEAT WITH LWD AZIMUTHAL DENSITY IMAGES

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ABSTRACT

Historically, formation evaluation has been done "after the fact," using wireline logs run at either an intermediate casing point or when the well was terminated (TDed). While this procedure is clearly inefficient in unexplored areas, there is significant room for improvement, even in relatively developed areas, in measuring and analyzing formation attributes just after drill bit penetration. Tool ruggedization and miniaturization of electronics have yielded devices that can be placed just behind the drill bit; increasingly efficient data transmission protocols permit ever more data to be examined, in real time. Saudi Aramco uses this technology for real time formation evaluation and wellbore trajectory optimization. The basic logged-while-drilling (LWD) service includes gamma ray (GR), density-neutron porosities (Rhob-NPhi) and resistivities at a variety of depths of investigation, transmitted up-hole at sufficient resolution to allow real time formation evaluation. This information makes it possible to quantitatively monitor local reservoir quality and to make recommendations for wellbore trajectory (deflect up or down) and wellbore length (drill ahead, TD early). This procedure does not, however, make it possible to address reservoir geometry questions (bed dip), which have a direct bearing on the "drill ahead question".

Modern LWD services include azimuthal gamma ray, density and resistivity measurements, which "look" up, down and to the side. As the wellbore intersects various reservoir features, well documented sinusoidal patterns visually present themselves in the data. When coupled with real time directional survey measurements these make it possible to deduce local reservoir geometry. Drilling and formation evaluation personnel are literally "in the driver's seat" and can steer the wellbore either through or along (depending on circumstances) the feature of interest. This local geometry can be extrapolated (as opposed to field average) over to the next drilling location and therefore, compound the benefits. These capabilities are illustrated with actual data sets, in a development well environment.

INTRODUCTION

The field was discovered and delineated in the late 60s and early 70s, but due to its remote location, not developed until the late 90s. About 35 vertical wells were drilled and cored during the delineation phase and initial formation evaluation algorithms (porosity, contact identification, fluid saturation and permeability estimates) developed. These statistics provided an overview of what to expect going into the development phase.

Development was in two phases:

1) Drilling of additional vertical wells, which were cored and served to further define the field boundaries and interpretation techniques.
2) Horizontal wells, which were generally located and drilled to allow efficient reservoir depletion. Some wellbores were deliberately steered to both produce a commercial wellbore and to delineate the reservoir by deflecting them upward near the toe of the well to intersect the top formation.

In horizontal wells, gravity is not sufficient to pull the tools into the outer reaches of the well, so pipe-conveyance was used in conjunction with routine wireline logs. Logging-while-drilling (LWD) options were investigated and as favorable experience was gained with this technique, it was relied on more and more. Modern LWD tools provide basic petrophysical measurements and borehole images. These images were repeatedly found to be beneficial in the development well environment.

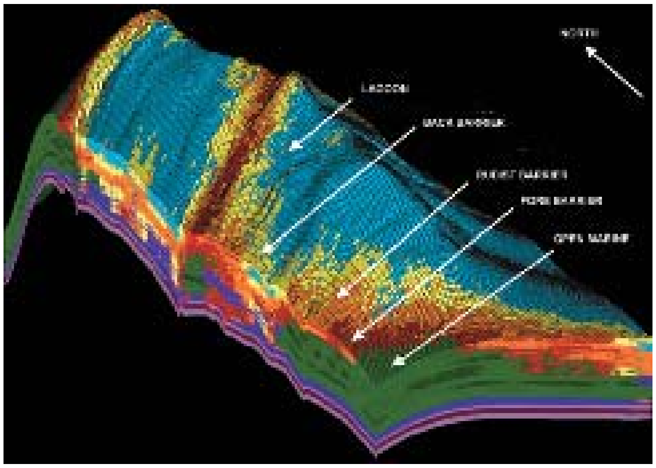


Fig. 1. "In the driver's seat"

GEOLOGICAL SETTING

Approximately 110 million years ago, this early Cretaceous reservoir (fig. 1) was deposited on a gentle carbonate ramp with 16 recognizable cycles and two depositional sequences. A typical upper sequence cycle comprises inner ramp lagoonal facies and back barrier facies transitional into the ramp crest rudist barrier facies, passing down-slope into bioclastics of the fore barrier facies and finally into the outer ramp slope facies. The lower sequence is characterized by a sheet-like development of muddy, high porosity but low permeability algal carbonate platform cycles. A seven-layered reservoir zoneation scheme was established reflecting the reservoir quality variations controlled by facies, diagenetic overprint and structural development.

Reservoir facies can be broken into three basic textural classes that, due to their individual permeability relationships, dramatically impact production performance:

1) muddy, high porosity (26-28 percent) and low permeability (3-10 mD) rocks of the lagoon and slope;

2) the more grain-rich, high porosity (26-28 percent) and moderate permeability (17-30 mD) rocks of the back and fore barrier; and

3) coarse grained, low porosity (10-25 percent) and high permeability (60 mD-1 D+) rocks of the rudist barrier.

Production behavior is dominated by the impact of permeability relationships associated with each facies; the most robust production performance comes from highly permeable rudist, fore and back barrier facies, while the weakest performance comes from lower permeability lagoon and slope facies.

Superimposed upon this generally well developed geological model are sudden, discrete bed boundaries, whose locally specific geometry is best characterized with wellbore images.

Image Analysis

Borehole image analysis is a well-developed topic generally known and routinely used throughout the industry. Of particular interest in the application at hand is the geometrical pattern and reservoir geometry implications resulting from an intersection of the wellbore and reservoir bed boundaries (figs. 2 and 3). The combination of sinusoidal image and borehole trajectory uniquely define the orientation of the reservoir bed and allows extrapolation into adjacent well sites.

This information, historically, was only available by wireline, but continuing LWD tool improvements have advanced the concept from a two point (up-down) measurement to four points (up-down-right-left) in real time with considerably more detail recorded in tool memory and available with a surface download.

Sixteen azimuth bulk density-Pef images are available in both 12 cm (4.8 in) and 17.1 cm (6.8 in) tools, and a 56 azimuth resistivity image may be acquired in a 21.5 cm (8.5 in) hole. Our typical development wellbore is drilled with a 15.5 cm (6.1 in) bit, and so it's the smaller diameter, bulk density image device that is commonly used.

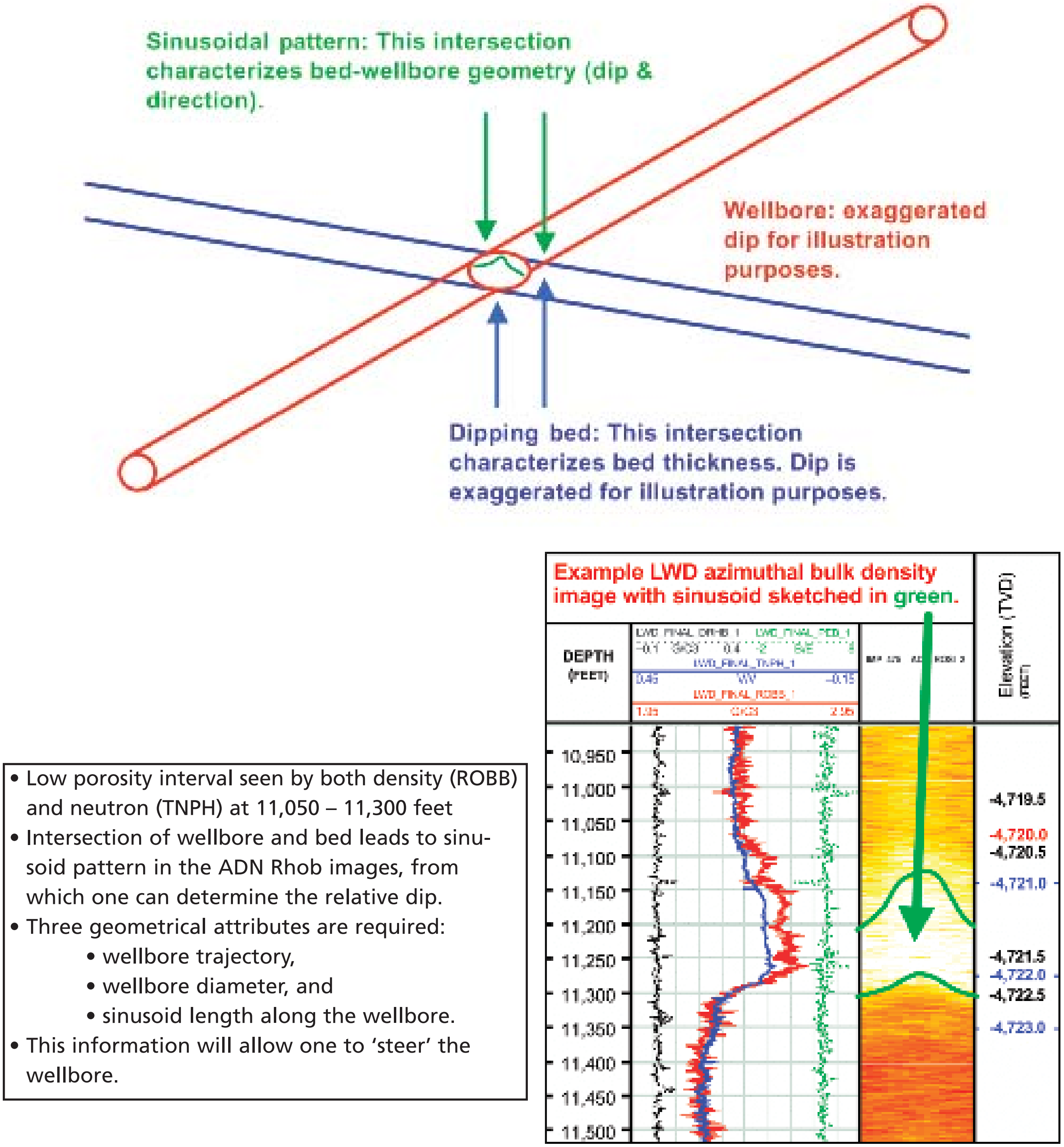
Unexpected Low Quality Reservoir

Even with more than 150 wells in the field and a very good understanding of geology, surprises are still occasionally encountered. The acquisition of bulk density images, simultaneous with the LWD bulk density measurements, allows local geology to be updated in a much more complete, real time manner than would be possible with only the routine bulk density measurements.

Well A (fig. 4) was drilled first and exhibited the expected, relatively uniform reservoir properties. Well B was next, and an unexpected tight zone was discovered near TD (which was not encountered in well A and for which there was no a-priori reason to anticipate). With well C on the drilling schedule, it's clear that the localized geology-geometry deserves review, and that more information with regard to the orientation of the tight zone is a key requirement.

Routine LWD measurements are effective because if an unexpected encounter takes place it is possible to respond quickly (i.e. TD the well early, kick up or down) but the question of local geometry remains unanswered. In this instance, there was no reason to expect this local occurrence and no intuitive orientation with which to extrapolate the tight zone: enter the azimuthal density images (fig. 5).

Because boundaries are often associated with a significant change in average bulk density (reservoir porosity), images are generally displayed as two different shading scales, side-by-side. This gives the analyst an immediately



- Low porosity interval seen by both density (ROBB) and neutron (TNPH) at 11,050 – 11,300 feet
- Intersection of wellbore and bed leads to sinusoid pattern in the ADN Rhob images, from which one can determine the relative dip.
- Three geometrical attributes are required:
    - wellbore trajectory,
    - wellbore diameter, and
    - sinusoid length along the wellbore.
- This information will allow one to 'steer' the wellbore.

Fig. 2. Conceptual illustration

available contrast as decisions are made quickly.

In actual practice, the geometrical analysis can be performed at different levels of complexity, ranging from a comparison of up-down bulk density, Pef responses (fig. 6), to a 16-azimuth image evaluation (fig. 7). Bed dip and azimuth calculations are often done with a simple spreadsheet calculation initially (appropriate for basic reconnaissance and quick-look results), with later work producing a full-fledged (wireline log type) geometrical study. Although spreadsheet results are compromised by simplistic geometry they are quick to develop and provide an important reference with which to compare detailed results.

The combination of well B's image sinusoids and wellbore trajectory allows the establishment of a local tight zone orientation in regard to well C, and to then fine tune the placement of that wellbore.

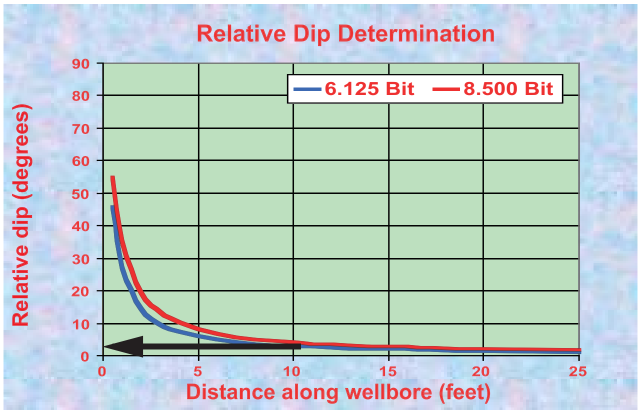
While these images are invaluable in circumstances such as this they are not a substitute for the much more detailed wireline tool results.

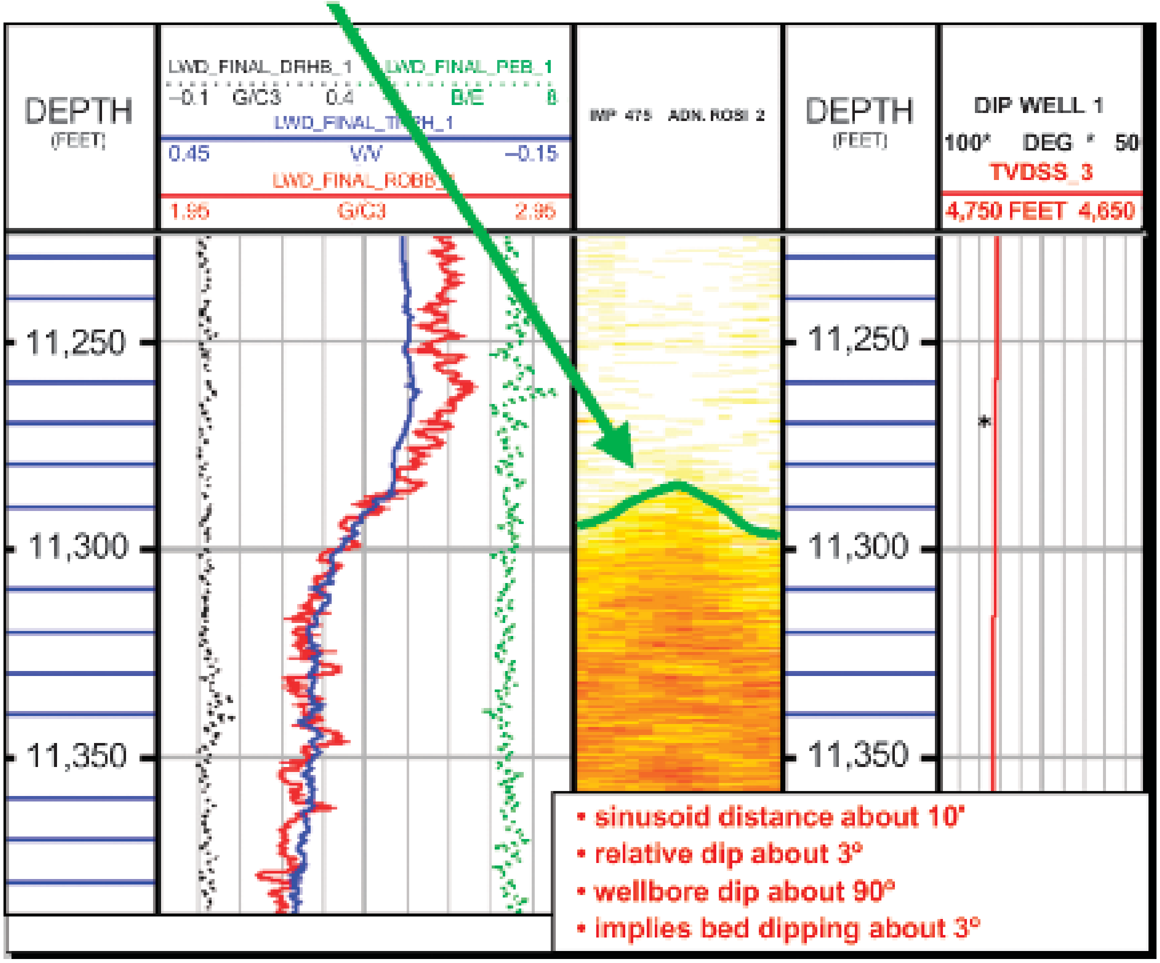
Expected Low Quality Reservoir

During early development drilling, two neighboring wells, D and E (fig. 8), were cored and analyzed, with results suggesting local reservoir compartmentalization. At a specific elevation (fig. 9), water saturation in one well is significantly different than that in its neighbor. Next, every horizontal well drilled from the well D location was observed to cross a boundary, beyond which the Sw - SSTVD relation changed from well D to well E. Finally, well F to the west also exhibited a distinct boundary across which log responses changed dramatically. With this information it was possible to establish both the lateral extent of the horizon and the average geometrical orientation.

When development drilling returned to this location,

- Intersection of wellbore and bed leads to sinusoid pattern in the images, from which one can determine the relative dip and azimuth.
- This information will allow one to 'steer' the wellbore

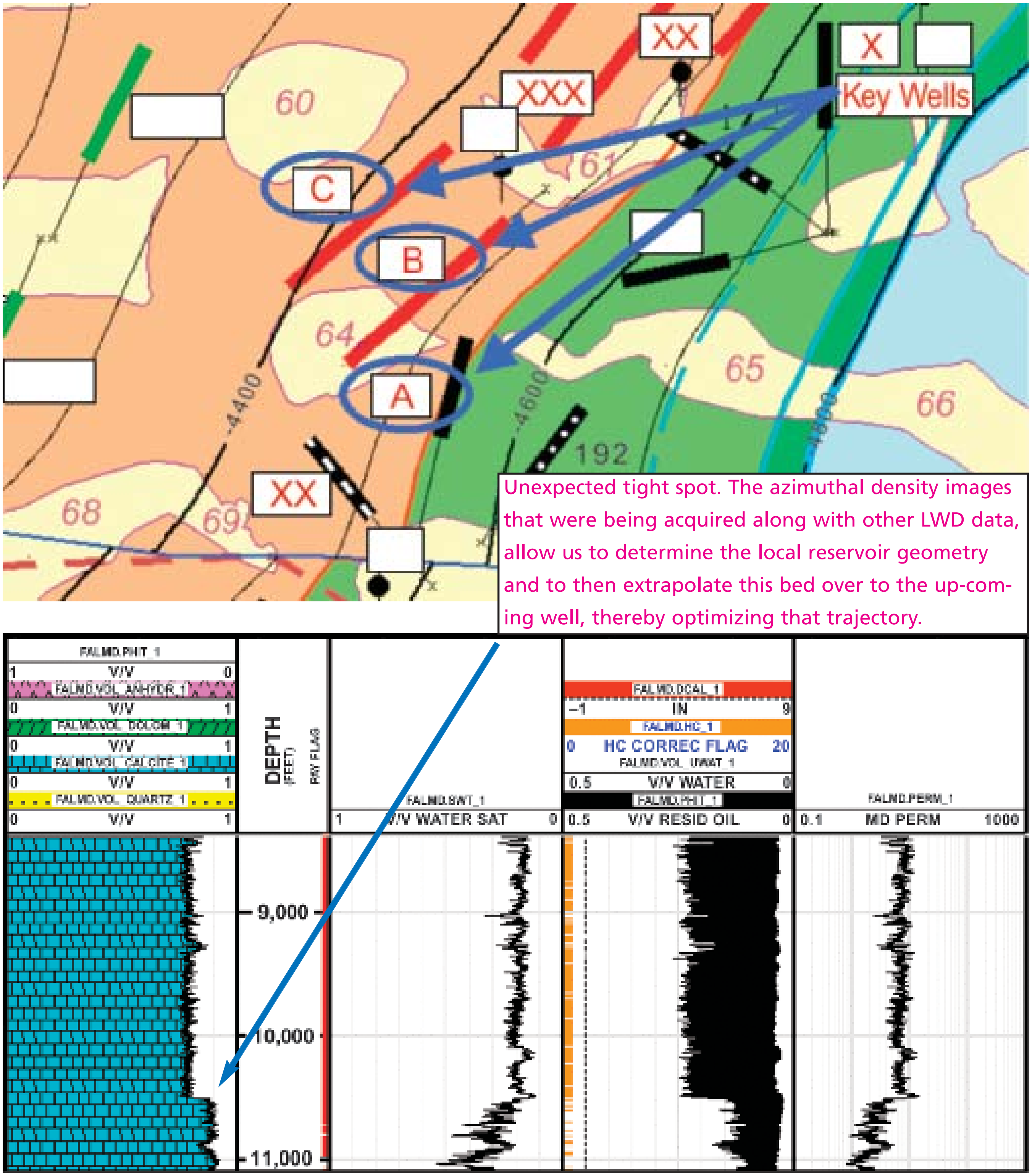




- sinusoid distance about 10'
- relative dip about 3°
- wellbore dip about 90°
- implies bed dipping about 3°

Fig. 3. Conceptual illustration

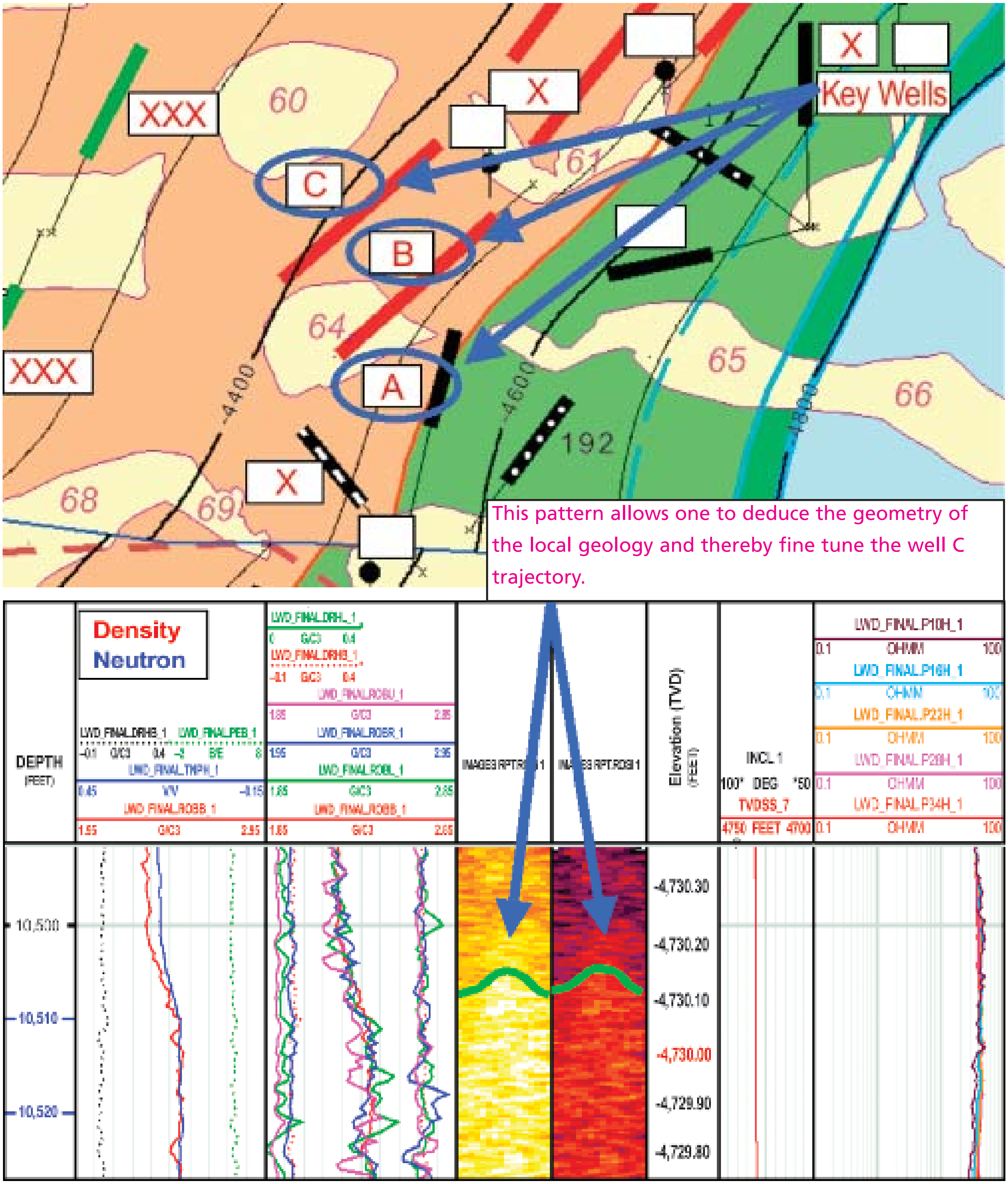
Unexpected tight spot was encountered while drilling well B, that was not seen in well A. Azimuthal density images allow one to calculate the local geometry of that boundary and extrapolate over to the upcoming well C, and thereby fine tune that wellbore trajectory.



Unexpected tight spot. The azimuthal density images that were being acquired along with other LWD data, allow us to determine the local reservoir geometry and to then extrapolate this bed over to the up-coming well, thereby optimizing that trajectory.

Fig. 4. Unexpected low quality reservoir

Unexpected tight spot was encountered while drilling well B, that was not seen in well A. Azimuthal density images allow one to calculate the local geometry of that boundary and extrapolate over to the up-coming well C, and thereby fine tune that wellbore trajectory.



This pattern allows one to deduce the geometry of the local geology and thereby fine tune the well C trajectory.

Fig. 5. Unexpected low quality reservoir

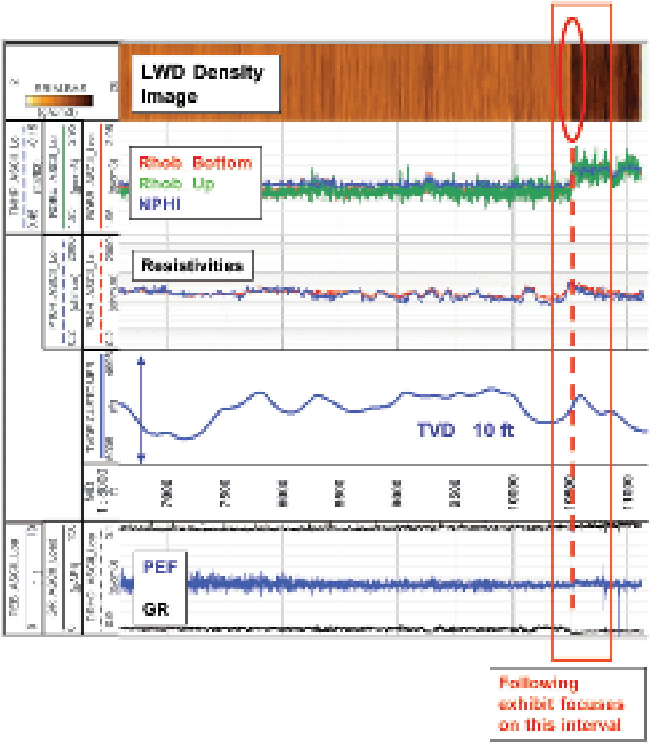


Fig. 6. ***Unexpected low quality reservoir.*** *Basic LWD data that is used to both evaluate formation foot-by-foot and establish local geometry.*

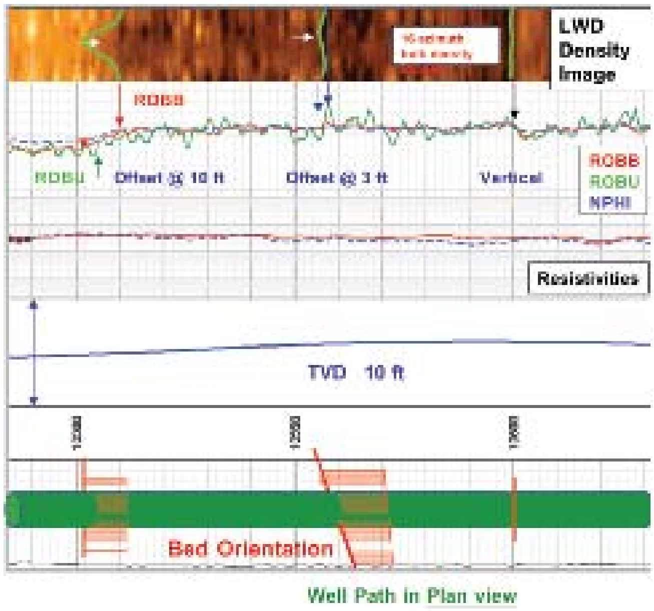
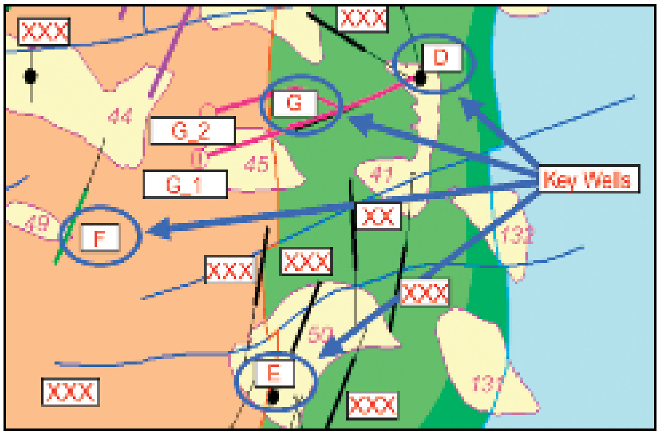


Fig. 7. ***Unexpected low quality reservoir.*** *Quick look image analysis to establish local geometry. Detailed image analysis will utilize enhanced (processed) images and result in the normal 'tadpole' plot.*

there was a clear need to place drilling and formation evaluation personnel "in the driver's seat," prepared to characterize the local geology-geometry in real time.



Two existing wells (D & E) showed significantly different water saturation and elevation relations, suggesting reservoir compartmentalization. Well D penetrated a tight zone that was not present in well E, which was thought to be the barrier. Well F to the west also encountered a barrier, and thereby established the lateral extent of this feature and the 'average' dip of the boundary. LWD azimuthal density images, acquired as well G was drilled, allowed one to estimate the actual, local reservoir geometry and 'steer' the well accordingly.

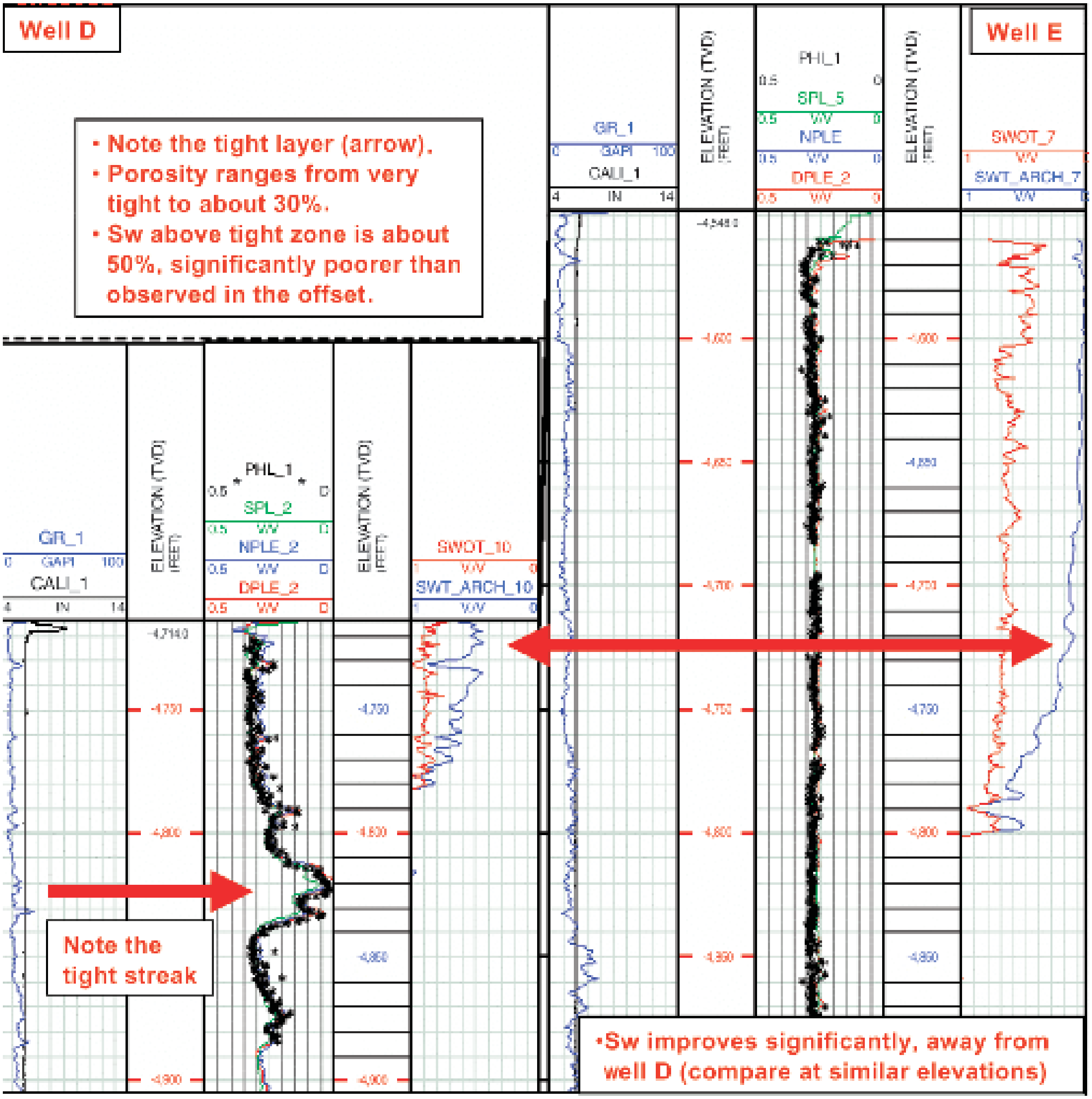
Fig. 8. ***Unexpected low quality reservoir (but local geometry unknown).*** *Original well G plan. Final wellbore trajectories were altered to accommodate actual reservoir geometry per LWD results.*

Additional drilling called for wells G1 and G2 (fig. 8) to be deepened and sidetracked with a multi-lateral completion, to improve productivity and local drainage. Optimum trajectories were planned with information at hand, all the while recognizing that LWD data would guide the actual well paths.

A full suite of LWD data was acquired during drilling, some available in real time (quadrature density) and others that were downloaded from memory when the tool was pulled from the hole (azimuthal Rhob-Pef images). Fig. 10 clearly identifies the boundary in question, as well as other important features and definitively characterizes the local reservoir geometry at both a specific boundary (fig. 11) and within the context of the overall wellbore path (fig. 12). The lateral trajectory was revised (fig. 13 vs. fig. 8), taking into account local geology-geometry and encountered the expected tight zone, after which the "sweet spot" was penetrated.

In the development well environment, with geology generally well known, azimuthal density data provides real time, locally specific information that confirms the

- At a specific elevation, Sw is unusually high in well D.
- Every well originating from the well D location is observed to cross a boundary, beyond which the Sw - SSTVD relation changes from that of the left (well D) to that (improved) on the right (well E).
- Well F, far to the west, establishes the extended nature of this boundary and the average bedding dip, but not the specific local geometry.
- Real time formation evaluation, to include geometrical considerations, are key to success.



- Note the tight layer (arrow).
- Porosity ranges from very tight to about 30%.
- Sw above tight zone is about 50%, significantly poorer than observed in the offset.

Note the tight streak

- Sw improves significantly, away from well D (compare at similar elevations)

Fig. 9. Local reservoir attributes (fig. 8 area)

- Wellbore trajectory dipping slightly.
- Bed boundaries seen on bulk density and images.
- Combination allows calculation of bed thickness, dips and azimuth.
- Vertically oriented hard streaks also seen on azimuthal density.

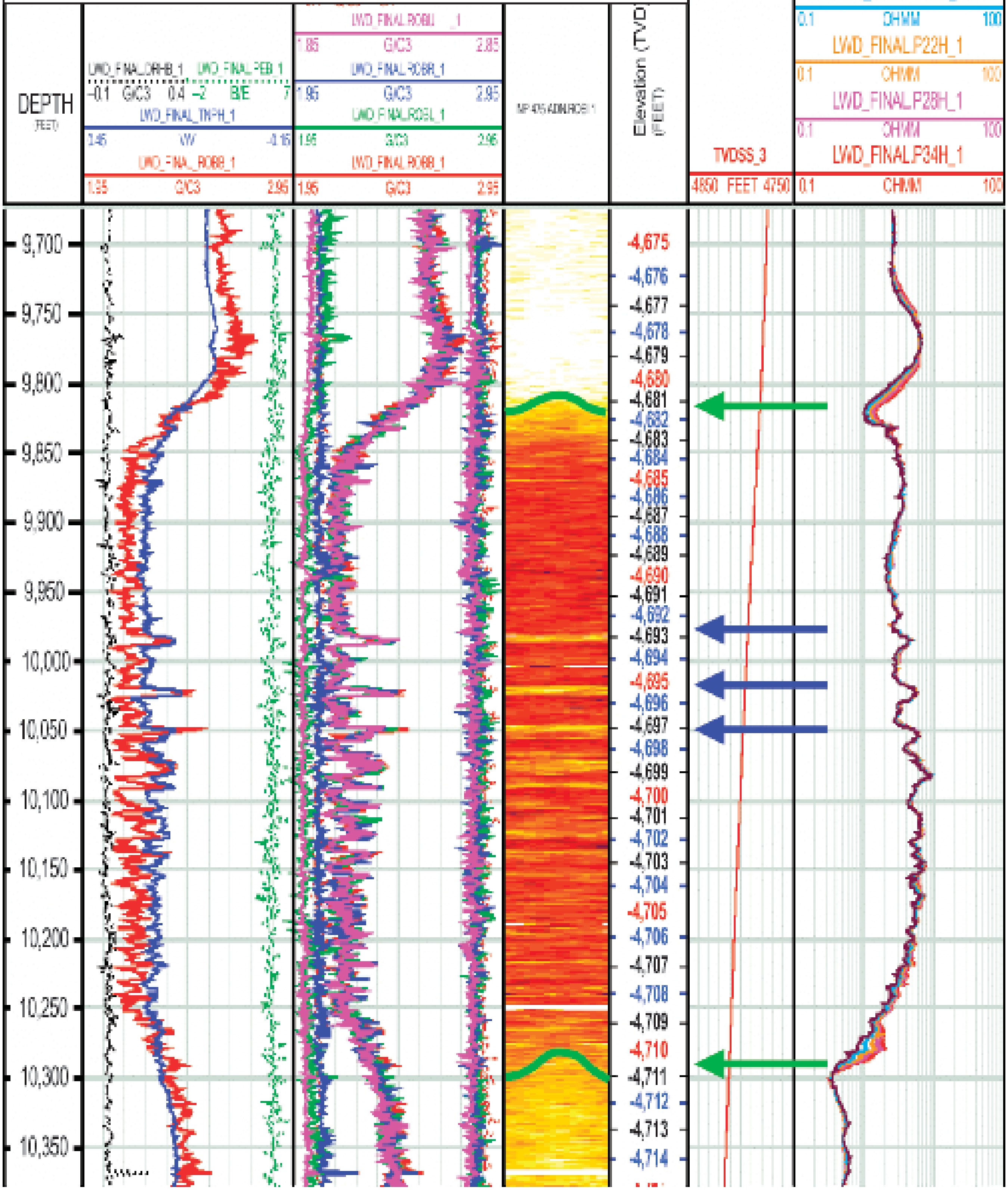
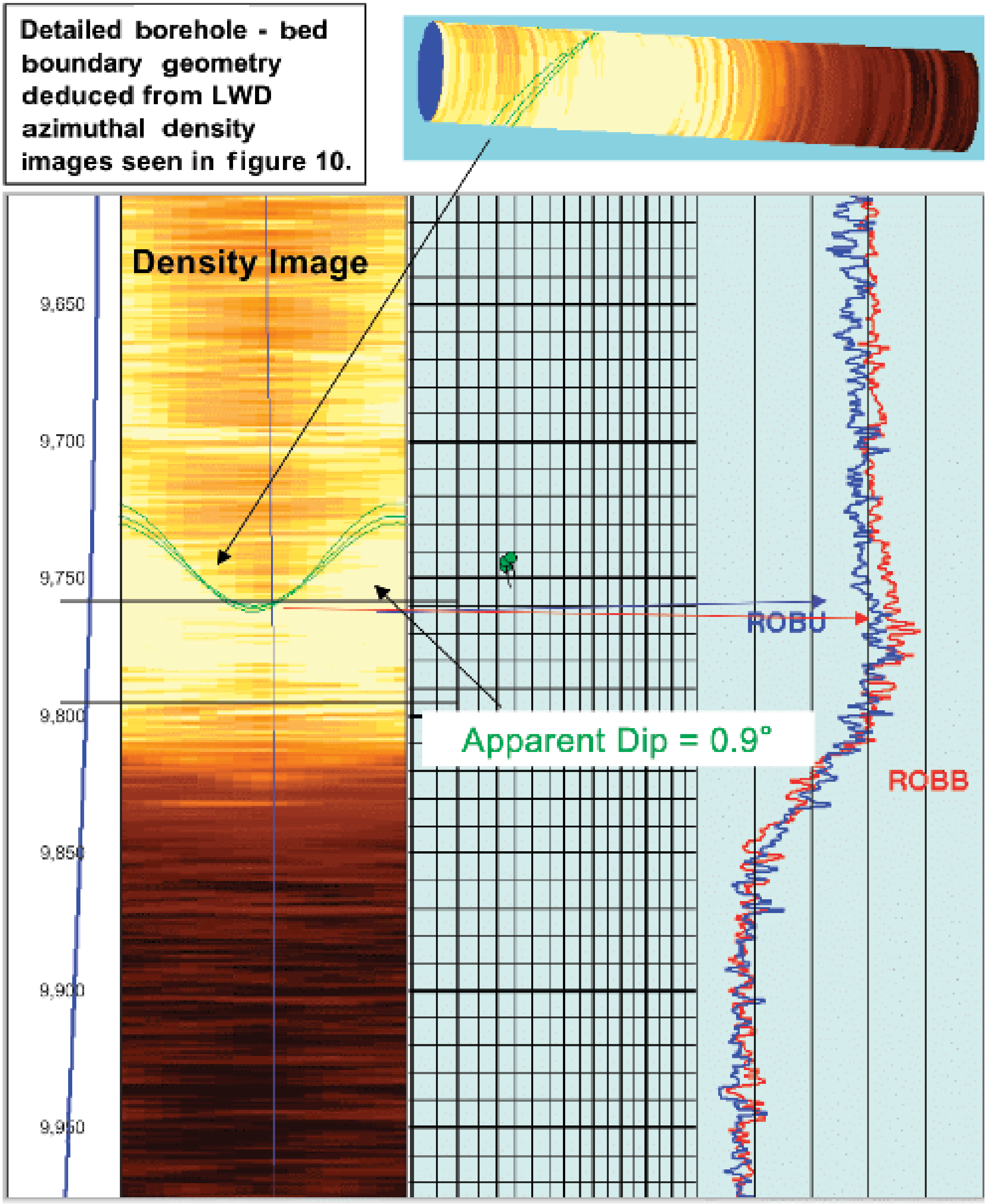
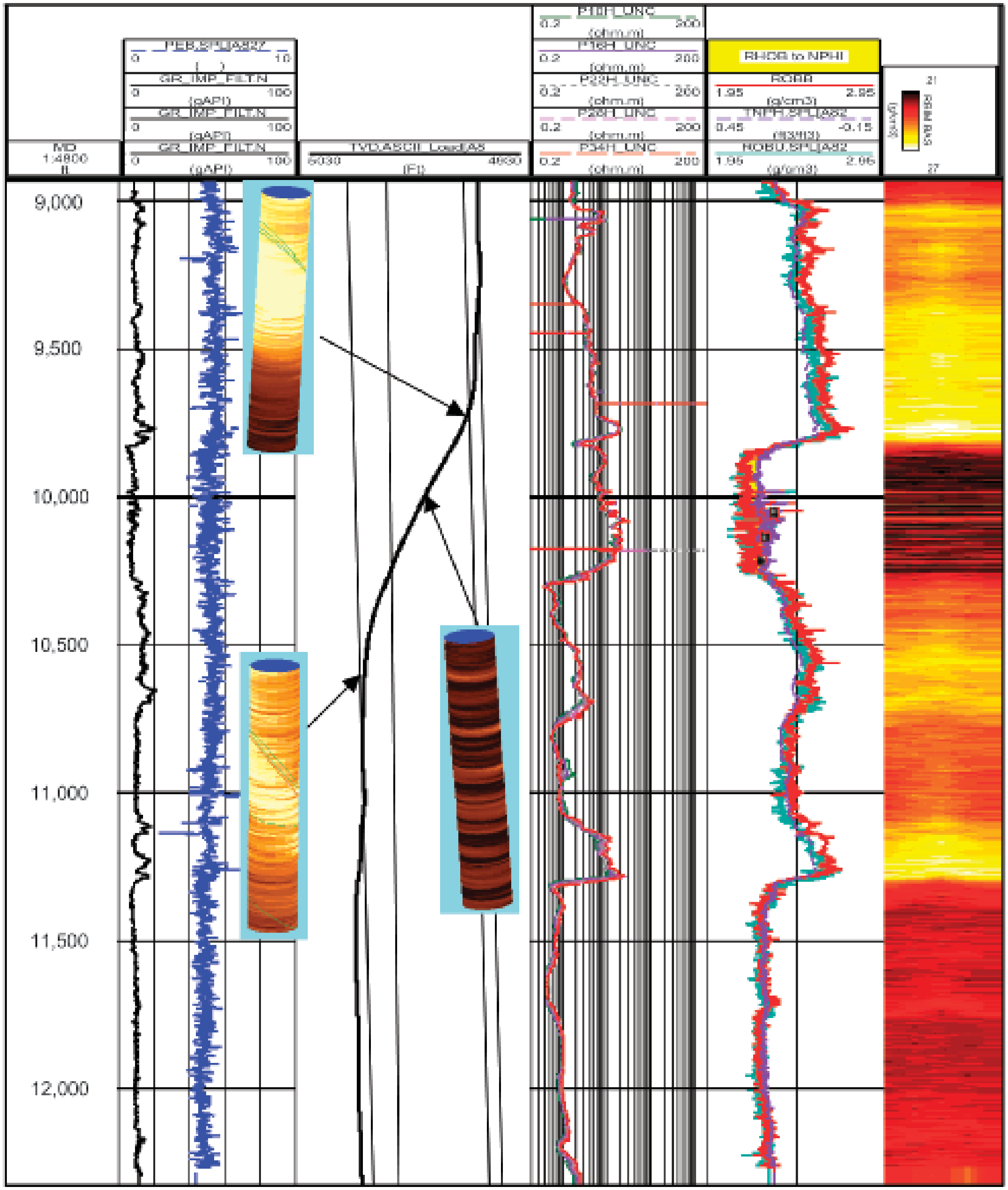


Fig. 10. LWD azimuthal density images in well G



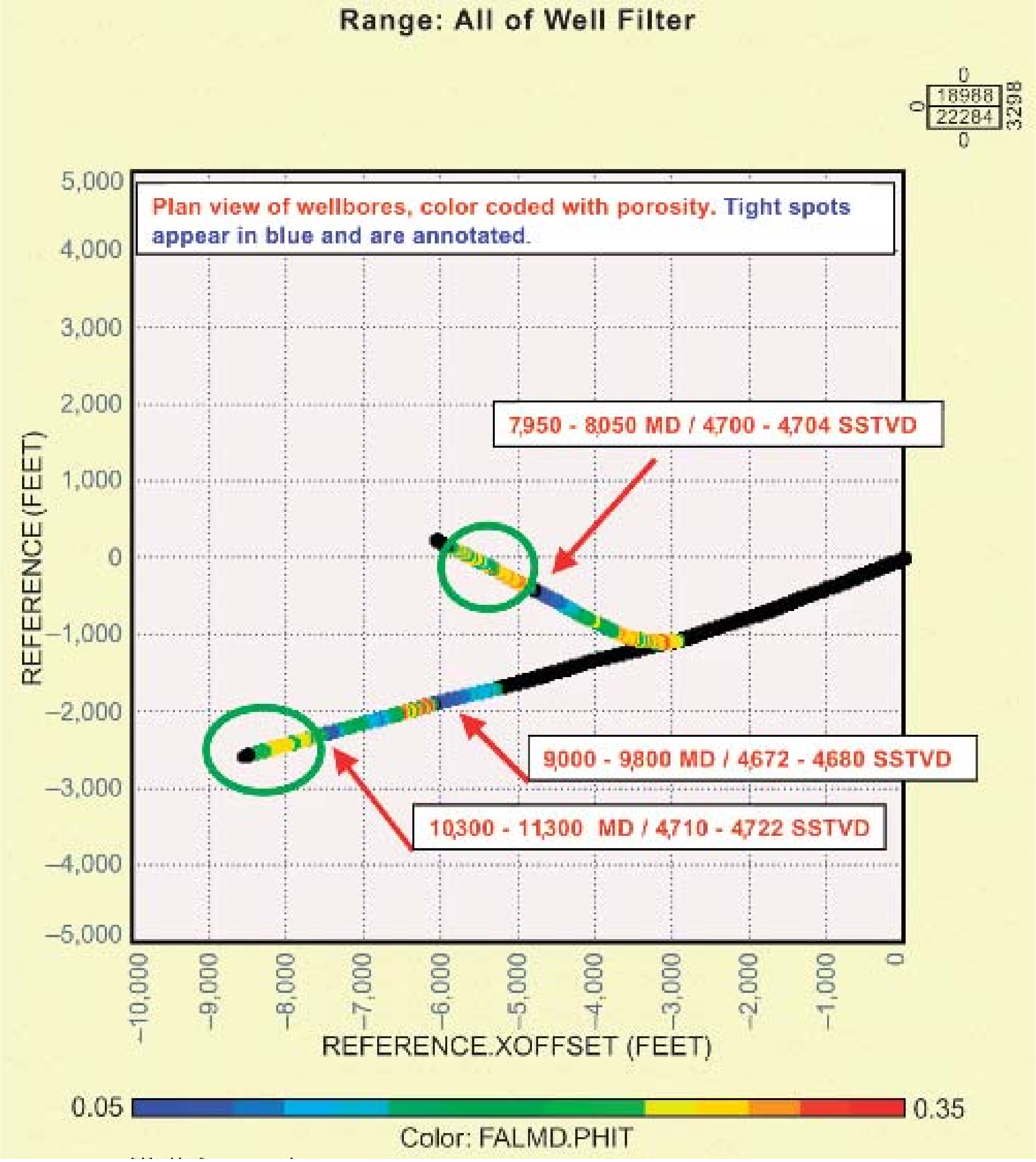
Detailed borehole - bed boundary geometry deduced from LWD azimuthal density images seen in figure 10.

Fig. 11. caption to come



Borehole - reservoir geometry deduced from LWD azimuthal density images.

Fig. 12. Expected low quality reservoir: well G (but local geometry unknown).



Borehole - bed boundary geometry deduced from LWD azimuthal density images allowed us to 'steer' the wellbore into the local 'sweet spot'.

Fig. 13. Expected low quality reservoir (but local geometry unknown).

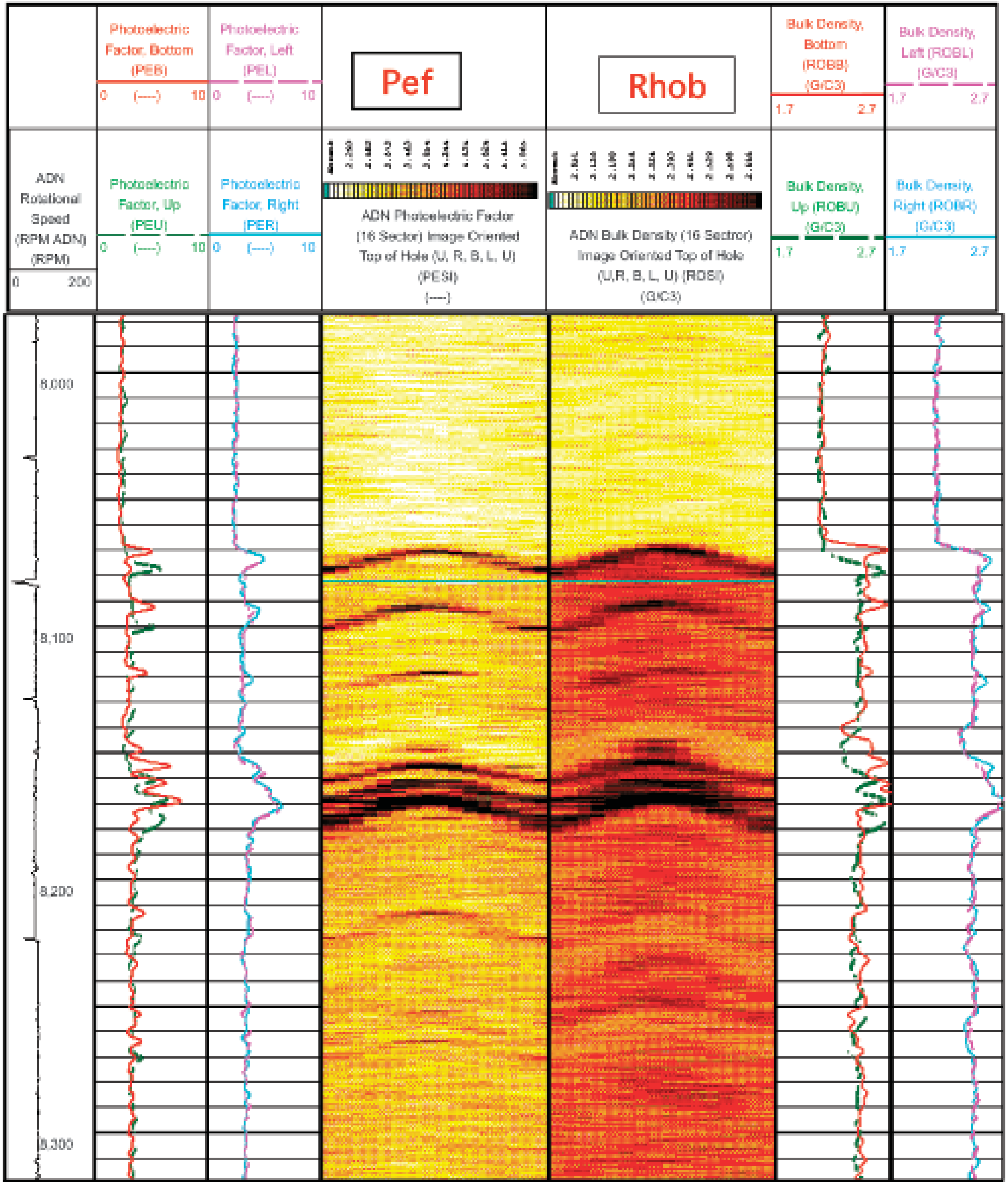


Fig. 14. Example of the 8.5 inch wellbore density and pef images.

presence of the anticipated horizons and specifies their corresponding geometry.

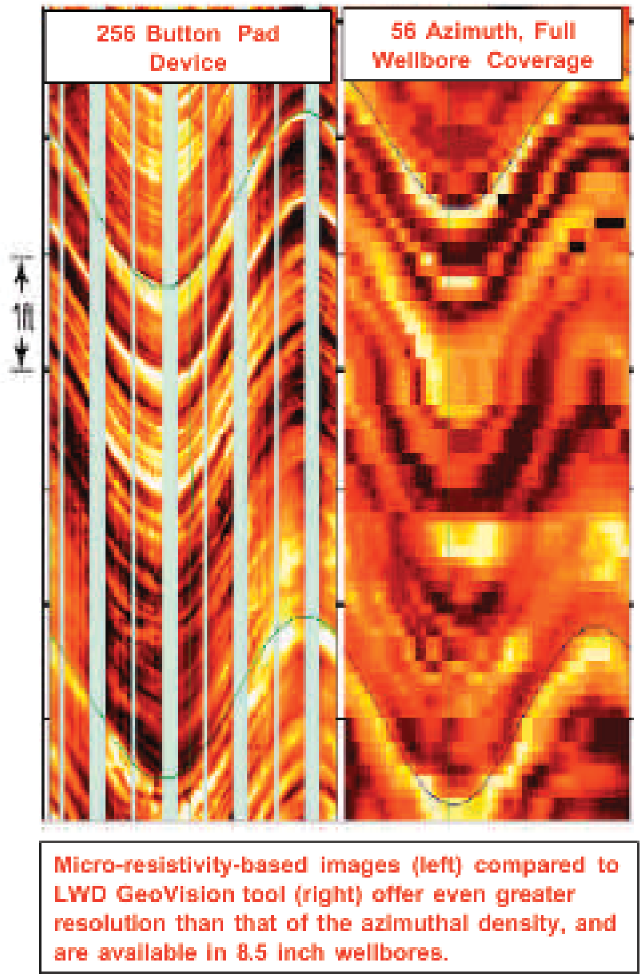
8.5 in Wellbore

Our routine horizontal wellbore is drilled with a 15.4 cm (6.1 in) bit, but on occasion larger holes are drilled. At 21.5 cm (8.5 in) the LWD image options increase, to include not only the 16 sector azimuthal bulk density - Pef results (fig. 14), but also 56 sector azimuthal resistivity images at three depths of investigation: 2.5 cm, 7.6 cm and 12.7 cm (1 in, 3 in and 5 in, respectively) (fig. 15).

These images have a nearly four-fold increase in resolution, approaching the quality of the 256 button wireline device. In fact, these images provide full wellbore coverage in comparison to the partial view, but with higher resolution that is given by a wireline device.

Drilling Considerations

LWD borehole images not only place drilling and formation evaluation personnel "in the driver's seat," but as a part of a systematic LWD program offer additional benefits in drilling performance and formation environment evaluation.



Micro-resistivity-based images (left) compared to LWD GeoVision tool (right) offer even greater resolution than that of the azimuthal density, and are available in 8.5 inch wellbores.

Fig. 15. Example of the 8.5 inch wellbore wireline images versus LWD GeoVision

Wellbore trajectory can be altered or TDed early in real time, as opposed to "after the fact" with pipe-conveyed methods. There is also a reduced risk of differential sticking since no additional trip in the hole is required (which also expedites the drilling schedule). Unexpected lost circulation events have also been experienced, which precluded pipe-conveyed operations due to safety issues, without loss of LWD formation evaluation information. And finally, fluid contact identification may be more obvious with minimal invasion LWD data, as opposed to delayed wireline measurements.

Real time LWD enhancements on the horizon, which will improve the drilling program even more, include transmission of downhole pressure data for calculation of the equivalent circulating density (ECD), leading to better hole cleaning and/or minimization of differential sticking and pack-off problems.

CONCLUSIONS

Borehole image analysis is a well established and appreciated technique now available in the LWD world. While it has obvious applications in exploration, it can also be beneficial in field development. Locales with known problems (such as compartmentalization) can be drilled in a much more efficient manner; unexpected events are characterized as they are encountered. The technology continues to evolve and improve and additional capabilities are expected soon.

ACKNOWLEDGMENTS

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