Horizontal drilling has become a routine procedure in many parts of the world and is particularly popular in the Middle East. Despite increasing familiarity with the techniques, there remain many potential pitfalls for anyone drilling horizontal wells or lateral drainholes.

The array of tools and techniques that can be used to guide a drill bit towards its target indicates the complexity of modern geosteering operations. Formation modeling is an extremely powerful tool for accurate directional drilling and has played a vital role in many of the Middle East’s most successful horizontal wells. Peter Hook explains how formation modeling techniques can be used to guide wells to their intended targets.
The 1990s have seen a huge increase in the number of horizontal wells being drilled in the Middle East. As exploration and development budgets are pared back, oil and gas companies are reducing costs by drilling fewer wells. The wells that are being drilled must be optimized to provide the most cost-effective production performance. Drilling successful horizontal wells is a complex process.

Over the past few years, the demands on accuracy in the placement of horizontal wells, and the margin of error when drilling them, have become much bigger challenges. Drillers are being asked to plan and drill ‘designer’ wells with extremely complex trajectories (Figure 3.1). Once a target has been defined from seismic interpretation, geological mapping and petrophysical analysis, the well trajectory can be planned. Despite recent technical advances, drilling a horizontal well that will land precisely in the reservoir zone remains a difficult task requiring a combination of oilfield skills and attention to detail in the planning stage. Uncertainties in the position of the target, coupled with unpredictable structural and stratigraphic variations, mean that even the most effective drilling plans can run into problems.

Forward modeling is used to simulate log responses along planned or drilled well trajectories to guide drillers and help interpreters to evaluate the formations through which the bit will pass. The drilling team must plan the trajectories in great detail, select the best fluids, work out how to steer the hole accurately to target, evaluate the formation and complete the well. The planning, steering and formation evaluation stages of the process benefit from close cooperation between geologists, log analysts and directional drillers.

Forward modeling helps to make efficient use of logging-while-drilling (LWD) logs in horizontal wells. Using the data from these logs, analysts can help drillers to predict tool response and to use that prediction to guide the drill bit. IN FORM® Integrated Forward Modeling software provides an interface for building a formation model and simulating log response (see box: Informed opinion). This capability allows prediction of what the bit will encounter as it follows the chosen trajectory.

**Modeling first**

In many horizontal wells, ‘chasing’ the reservoir target means drilling close to an impermeable caprock or to a gas-oil contact above and/or close to an oil-water or nonproductive layer below (Figure 3.2). This may mean drilling a well that is parallel and close to a lithological or fluid boundary for hundreds or even thousands of feet. In many cases the driller’s objective is to stay close to the boundary without leaving the target formation.

Most resistivity tools probe several feet into the formation, so they are affected by resistivity variations around the well and even ahead of the drill bit. This early warning feature can be used by directional drillers to steer wells into target layers or away from problem zones before they are encountered by the bit. This ‘proximity effect’ for resistivity tools can be modeled while the drilling plans are being finalized and can be used during drilling as a ‘route map’ for the driller.

![Figure 3.1](image1.png)

*Figure 3.1 Many modern horizontal wells have extremely complex trajectories. These ‘designer’ wells can drain reservoirs much more efficiently than one or more conventional, nonsteered horizontal wells.*

![Figure 3.2](image2.png)

*Figure 3.2 In some reservoirs, geosteering technology may be required to keep the well on a relatively simple track (a) that avoids other formations such as an overlying shale or aquifer unit. Where the reservoir’s structure is more complicated, the well’s trajectory may have to be modified many times during drilling (b).*
Informed opinion

The INFORM system allows analysts to develop a detailed geometrical and petrophysical model of the rock layers that have been or will be penetrated by a well. Having constructed the model, analysts then simulate tool responses along the well trajectory. Establishing the ‘best guess’ 3D structural description of the prospect from seismic interpretation, geological maps, cross sections and offset well logs forms the initial part of the INFORM process.

Logs and petrophysical data from offset or pilot wells provide the foundation for the INFORM model, defining layer thicknesses and properties. In a process known as ‘log squaring’, bed boundaries are determined from inflection points on the logs and the average layer properties are extracted from the log values (Figure 3A.1). The INFORM system offers a range of automatic and interactive tools for log squaring.

As a well deviates with depth there will be, in addition to the variations in formation properties, changes in the distance and angle between the tool and various layer boundaries; these variations will affect logging tool response (Figure 3A.2). Modeling the changes in tool response through the continuous angular variation calls for code that is both fast and accurate. The simplest technique is to approximate the curved well trajectory with a small number of straight line modeling runs. This is quick but inaccurate. Another method involves computing tool response at every point on the trajectory. This is very accurate but too slow for geosteering purposes.

The INFORM software uses a compromise technique that computes tool response to the squared log column expected to be penetrated by the well path. The tool response is calculated for specified angles between the tool and each layer and the results are stored in a matrix. The INFORM software then interpolates between values in this matrix to produce a modeled response for any sampling along the wellbore. The precalculated values can be accessed rapidly, making this technique fast enough for geosteering applications.
Figure 3.3 Gamma ray data from the original vertical well were combined with logging-while-drilling data from the lateral well to develop an accurate picture of formation properties in and around the target along the well's trajectory.

If the structural geology is relatively simple, LWD gamma ray and porosity log data in conjunction with forward modeling can greatly enhance the effectiveness of geosteering as well. The driller can make use of improved directional drilling capabilities to act upon advice from the modeling analyst and make precise adjustments in near real time, during drilling. Drilling technology has also changed dramatically.

Sidetrack to success

In the United Arab Emirates, an oil company wanted to steer a horizontal sidetrack well through a relatively low-porosity target formation. Their reservoir is in the gas-bearing Shuaiba Formation. One of the most important constraints on the task was to avoid the soft overlying Nahr Umr shale unit: penetrating this unit could result in borehole collapse and sidetrack abandonment. To achieve the objectives, the oil company was looking for a forward model-
There is a close correlation between clay mineral content and gamma ray response through much of the shale unit of the vertical well. Below the shale, however, there is considerable gamma ray activity unrelated to the clay content. The precise cause of this non-clay gamma ray response is unclear, but may be due to trace amounts of uranium in the formation. Whatever the cause of this response, it provides a consistent stratigraphic marker across the field.

Advanced INFORM software was used to build a cross-sectional model of the reservoir and assess the location of the well with respect to the target layer and the overlying shale unit. A modeling section was chosen starting at the point where the horizontal well kicks off from the vertical well and with an orientation of average azimuth of the planned well trajectory (Figure 3.4). The discrepancies between the well trajectory and the plane of section are accounted for by the INFORM code to ensure that all information will be handled as accurately as possible. For later integration of all structural and petrophysical properties, it is best to choose a single, straight cross section for INFORM work.

A base INFORM section was constructed using the ‘best guess’ 3D structural description of the prospect and squared (blocked) log responses from the vertical well. For display purposes, a choice of log data types can be used, such as gamma ray or porosity (Figure 3.5).

Once the formation properties had been ‘projected’ away from the vertical well, the next step was to convolve the tool response to the beds for relative angular variation. A simulated gamma ray and porosity log response could then be generated for the horizontal sidetrack (Figure 3.6). These simulated logs show considerable variation in the early part of the well where the borehole is moving down through various underlying formations. As the sidetrack turns to the horizontal and enters the target layer, it will be within a relatively homogeneous reservoir unit, so porosity and gamma ray variations should be reduced to a minimum. The same log data can be
presented in a more conventional log display and printed out to have in hand at the wellsite well in advance of drilling the section of interest (Figure 3.7). It is best also to model in advance the effect of variations within the expected accuracy of the assumed formation structure (for example, ± 0.5° to formation dip). With these plots available at the wellsite, comparison to the LWD log data will quickly evaluate which structural scenario is best fitting actual log responses.

During drilling, the sidetrack turned towards the horizontal at a much shallower depth than had been planned (Figure 3.8). Comparison of modeled gamma ray response (from the vertical well log) with LWD results indicated a serious mismatch starting less than 300 ft from the vertical well (Figure 3.9). Analysis of the model showed that increasing the structural dip of the beds by around half of a degree brought the modeled and actual measurements into much closer agreement (Figure 3.10).

When the section was replotted after this modification, the geoscientists could see that the well was approaching the overlying shale unit much more quickly than had been anticipated by the original structural model. Daily data transfer from the wellsite to expert interpreters, whose modeling results were then emailed to the client’s offices, helped to keep the well out of the shale caprock and on course for 1500 ft of pay. When LWD data are available during drilling, changes in the well’s trajectory can be made quickly and accurately to ensure that it meets its objectives.

In the pay zone the gamma ray response varies quite regularly and the porosity response also shows a cyclic change from fairly high porosity down to almost zero. The regularity of this variation indicates that the wellbore is passing through the same low-porosity layer several times as it moves along the target zone (Figure 3.11). It is interesting to note the excellent agreement between modeled and actual gamma ray log data in the interval of drift 800–1500 ft, yet here recorded log porosity is less than that expected from INFORM modeling. Given that the gamma ray provides a more dependable stratigraphic marker, lateral variations in formation porosity are strongly indicated. Note the gas effect on the NPHI and RHOB response.

Currently the LWD RAB* Resistivity-at-the-Bit Real Time Dip product is under field trial. Had LWD dip information been avail-
When analysts compared their modeled gamma ray response with actual LWD-derived response they found a mismatch between modeled data and actual data starting less than 300 ft from the vertical well.

Modeling last

When a horizontal well has been drilled and logged, making meaningful presentation of the log data and derived structural information can be challenging. An advanced multidisciplinary software platform, such as the GeoFrame® system, is required to present a consistent, integrated display of results.

The INFORM software produces a picture of reservoir structure and property distribution that is much more accurate than anything that can be achieved with seismic or well-to-well correlation, or geological mapping (although the latter information provides a useful starting point for an INFORM analysis). The results of this more detailed modeling can be used to refine seismic interpretations and structural mapping. Information derived about reservoir characteristics, such as lateral porosity variations, allows the geoscientist to take results from the INFORM software and incorporate them in reservoir simulation models.

Modeling resistivity: no easy task

Modeling results in dipping beds and in horizontal wells indicate that resistivity logs in complex formations contain geometrical information. However, extracting that information is challenging. In modeling a resistivity tool, the geoscientist must specify the boundaries of regions with different resistivity properties and the properties within each region. Having done that, the tool must be introduced into the model. This means accounting in detail for interactions between transmitters and formation and between the formation and the tool’s receivers, in an effort to predict overall tool response.

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New software being developed by GeoQuest will provide log analysts with the tools for invasion-based resistivity-modeling formation analysis. The programs are based on forward modeling for layered formations and the interpretation allows for the evaluation of dynamic reservoir properties—early-stage permeability, water cut and fractional fluid flow. The system will help the analyst through the most time-consuming activities associated with modeling. This is achieved through a graphic interface using interactive parameter selection, which promotes a more accurate $R_t$ evaluation from multiple resistivity measurements.

Conclusions

Forward modeling provides vital information for drillers and this is changing the way horizontal wells are drilled. It also addresses the difficult questions about well location and the quality of the formation that could, in the past, only be answered by logging once the well had landed. The INFORM system is playing an increasingly important role, not only in forward modeling of LWD measurements for the geosteering of horizontal wells, but also in the horizontal well planning and evaluation stages.

To meet industry demands of optimizing drilling and production performance, LWD sensors are becoming more and more sophisticated, and offer a greater range of real-time measurements. To ensure that optimal use can be made of the new LWD technology, the GeoFrame software system provides powerful modeling capabilities to interpret, in an integrated multidisciplinary manner, complex structural and petrophysical environments.
Figure 3.12 The accuracy of the cross section model can be assessed using independent methods to measure dips along the borehole. Dip information derived from borehole image interpretation confirmed the validity of the structural modeling.

Figure 3.13 Using powerful data presentation options with an appropriate choice of projections, a composite display of various horizontal and vertical well data can be presented in a consistent, complementary manner. The LWD-derived formation-evaluation results near the bottom of the figure indicate reservoir quality along the trajectory.