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TECHNICAL NOTE

# Investigation of a Powerful Tool for the Development of Thinly Bedded Carbonate Reservoirs

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ABSTRACT

In thin-layered reservoirs, drilling engineers face tough challenges—planning their drilling programs to follow the most productive reservoir layers while avoiding nearby water, gas or high-pressure zones. The rewards for a successful drilling strategy are clear—increased oil production and reduced water cut. In an oil field in the Persian Gulf, for example, oil production was increased four- to six fold and water cut reduced by one-third using the latest formation modeling and geosteering techniques. Until recently, drilling thin layers was extremely difficult. Traditional geometrical drilling trajectories were unable to match the subtle variations in layer dip and depth, so many wells left the target zone and encountered watered-out layers. This paper has implemented modern geosteering methods to give drillers much greater control and help change the way operators develop thin-layered oil reservoirs, enabling them to increase hydrocarbon recovery and reduce water cut.

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## 1. INTRODUCTION

As more deviated and horizontal wells are drilled today, geosteering has become a relevant issue. Geosteering is used for correcting the well trajectory based on the measurements performed while drilling, the goal being to achieve the optimal trajectory and thus, to maximize well productivity. When drilling deviated and horizontal wells, it is essential to determine the distances to the top and base of the reservoir, and to its inner boundaries (water- oil and gas-oil contact, clay layers), as early as possible [1, 2]. In this case, the drillstring can be redirected in time to avoid opening the water-bearing bed or the gas cap. The deeper the logging while drilling for the data one may obtain, the more efficient are the solutions which could be available [3].

Horizontal drilling has been increasingly used through recent decades as a way of enhanced oil recovery. However, it requires precise geosteering to avoid abandonment risks if the borehole taps gas- or water-saturated zones of the reservoir. Currently geosteering is provided with the method of high-frequency (0.875 to 14 MHz) induction logging which allows estimating the depth to interfaces to an accuracy defined by measured resistivity errors. The resistivity of a typical oil-saturated formation measured at 0.4 to 1.1 m away from the borehole may bear an error of 24% to 50%, respectively, while errors in the width of the low-resistivity zone may reach 40% [4].

Horizontal wells are now standard practice in many of the world's most prolific oil and gas regions. Across the Middle East, horizontal wells are being used to develop new fields and to get more from existing fields with significant volumes of bypassed oil. Most operators are currently focusing their attention on optimizing the modeling, drilling, completion and stimulation of horizontal wells to ensure that they maximize production rates and recovery [5].

Drilling is perhaps the most demanding aspect of this process. Drilling engineers need to design and drill wells that penetrate the most productive parts of the reservoir and stay within the target layer. This calls for

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for combining an understanding of the reservoir's structure with a detailed plan for the well trajectory. Oil and gas reservoirs are extremely complex environments. Small-scale (sub seismic) faults and fractures, and abrupt face changes all combine to make the drilling engineer's task extremely demanding [6].

Even the most detailed geological models cannot predict exactly what a well will pass through, so the ability to change direction and modify the trajectory while drilling is extremely valuable. Responding to unexpected developments in real time and modifying the drilling trajectory accordingly, can mean the difference between a successful well that drains the reservoir efficiently and one that misses significant hydrocarbon volumes (Figure 1). Using drilling-related, geological and petro-physical data in real time, drilling engineers can geosteer their wells—guiding them through a hydrocarbon reservoir geologically rather than according to a rigid, predefined geometric plan.

When geosteering, the operator's objectives are to maximize pay-zone footage, improve production per foot drilled and lower completion costs [7]. Until now real-time geosteering has been difficult because of the distance between the bit and the measurement device—usually 18 to 30 m, depending on the bottom-hole assembly.

In many instances, wellbores have drilled through the floor or roof of the reservoir because the necessary data were not available at the bit. Today, leading technology from Schlumberger, the VISION475* 4 $^{3}/_{4}$-in. MWD/LWD system has made it possible to take decisions so that the target is not missed, as the distance between the bit and the nearest measurement has been reduced to only 2 m [8].

In recent years, the number of wells with geosteering and rotary steerable drilling has been soaring across the world [9].

Geosteering, integrating drilling, LWD and reservoir engineering organically into one [10], aim to optimize the placement of horizontal well trajectory in reservoir, reduce drilling risk, enhance drilling efficiency and maximize well productivity and investment return. In this technology, geosteering operation is realized by use of rotary steerable tools [10] instead of the previously used slide-drilling by means of bent housing downhole motor, in combination with LWD/MWD to measure geological and engineering parameters, and real-time interpretation and control of drilling track are realized by the surface software system through timely adjustment of the formation/structure models based on parameters from MWD [11].

Geosteering while drilling has been widely used abroad, such as Bakerhuges company's Trak series, which includes AziTrak Deep Azimuthal Resistivity (AZiTrak), LithoTrak Bulk Density and Neutron Porosity (LithoTrak), MagTrak Magnetic Resonance (MagTrak), SoundTrak Acoustic Formation Measurements (SoundTrak), StarTrak High-Definition Resistivity Imaging (StarTrak), TesTrak Formation Pressure Testing (TesTrak), etc. In China, logging while drilling technology (LWD) is just starting to rise while mud logging (including comprehensive logging), MWD (Measurement While Drilling) and so on are mainly used to geosteer while drilling.

However, no matter what techniques are used in geosteering, the core of mud logging is utilizing much more information (lithology, resistivity, petro physical and oil-bearing properties) obtained by logging while drilling to predict or geosteer. Prediction here is stratigraphic correlation and prediction before drilling into horizontal interval and geosteering is geological interpretation and orientation during drilling in the horizontal interval. Hence, the former aims at drilling into oil layer and the latter aims at making sure the horizontal interval in the oil layer to improve the economic benefits. In this paper, two critical techniques—stratigraphic correlation and prediction, and geological interpretation and orientation—for geosteering while drilling horizontal wells are discussed.

Oil layer drilling-encounter ratio after drilling into the horizontal interval is a crucial indicator to judge whether the horizontal well is drilled successfully or not [1]. Advanced geosteering techniques such as LWD imaging logging, azimuthal resistivity logging, NMR logging and remote boundary detection have been used extensively in horizontal wells abroad. Currently, geosteering in horizontal wells has a wide gap from that overseas [12]. For example, both LWD technique and interpretation lag far behind. However, lithology, physical properties and oil bearing data by mud logging while drilling and resistivity information by LWD/MWD, combined with seismic section, can still correct oil layer models at real time during drilling, realizing precise geosteering to increase oil layer drilling-encounter ratio [8]. Although surface logging may be affected by borehole factors and lag behind a little, the information is direct and intuitive, which can reduce the multi-solution of the interpretation results. This is an advantage thatLWD data doesnot have. Furthermore, the lagging parameters in horizontal wells of middle or shallow layers are in real time so that the geological interpretation should combine these two methods [13].

In the past, several wells were examined as part of a PS Platform* new-generation production services platform survey of field production. The production profile indicated that oil production was generally higher in the zone h unit than in the zone c unit. At the reservoir crest, oil production from zone h was around 1700 BOPD. Close to the main fault, this figure dropped significantly and water cut increased to 80%. Wells in the northwest of the reservoir produced more than 2000

BOPD with a water cut of just 4%. This variation in water cut (negligible at the crest, increased dramatically in the southeast where injected water had broken through) made it extremely important that the horizontal wells were drilled in the most appropriate locations. The PS Platform results indicated that Well A would be suitable for production enhancement if the horizontal section of the well was located far enough from the main fault. It also indicated that the well was a good candidate for production in the zone c and h units, with their low water cuts, if it was drilled in a northwest direction, parallel to and away from the main fault.

The reentry of Well A was planned to extend and enhance the production from selected horizons within the upper carbonate sequence. The well was reentered to drill horizontal legs in the thin carbonate layers. Initially this well had been completed to produce oil from a shaly carbonate reservoir unit. Geosteering was implemented during drilling of Well A. PEDCO and DCS monitored all the VISION475 tool measurements while drilling to conduct real-time reservoir modeling. Geosteering was used to increase the penetration length within the target zone (highly permeable and porous) with minimum nonproductive time.

## 2. GEOSTEERING TO THE TARGET

Geosteering technique is usually utilized in the horizontal well drilling to improve the drilling rate. Using resistivity, gamma, neutron and other measures to guide the drilling tool to penetrate in the reservoir, geosteering can normally determine if the drilling tool and borehole trajectory (horizontal well or extended reach well) are in or outside the reservoir. However, these methods cannot occur rately identify the boundaries of the reservoir and the cap rock or measure the distance from the drilling tool to the reservoir boundary.

Hence, the drilling tool sometimes enters into and out of the reservoir and re-entered into it in the horizontal geosteering, forming a wavy well trajectory [14].

The targets are over 5000 m deep, vertically in general, and the total depth is 5500- 600m [15]. When using conventional slide drilling, friction and torque will rise as depth increases, and requirements on MWD signal transmission will be higher too. The targets are two sets of sandstones, in which pay zones are thin, only 1-2 m thick [16]. To get better development, double-step horizontal drilling needs to be applied. The rotary drilling mode used in the rotary geosteering drilling, conducive to cutting removable and hole cleaning, can lower drag, and enhance the capability of horizontal section extension significantly.

An oil field located in the Persian Gulf (Figure 2) with a thin-layered carbonate reservoir was selected for production enhancement using the latest geosteering methods. The field structure is an asymmetrical, salt-induced anticline. It has three main producing zones, two in the Jurassic and a third in the lower Cretaceous. The upper carbonate sequence is mainly crystalline, sucrose or anhydrite dolomite units inter bedded with a few nodular anhydrite layers. This sequence is characterized by secondary porosity and it is overlain by a thick anhydrite formation.

**2. 1. Leading Technology** The tool used for geosteering in this oil field was the VISION475 system (Figure 3). The data returned to surface make it possible to see where the bit is with respect to the reservoir and provide proper bit orientation for subsequent drilling. VISION* down hole imaging services lower well costs by improving drilling efficiency and providing real-time data for quick drilling decisions. The real-time data also mean that production can be improved through geosteering. The new-generation formation evaluation measurements help operators make better completion decisions. An ADN* Azimuthal Density Neutron tool provides focused formation evaluation measurements for improved interpretation of the reservoir. The 16-sector, azimuthal density data provide a 360° petrophysical view of the wellbore. The measurements obtained are oriented and imaged to provide quick and accurate interpretation of complex data.

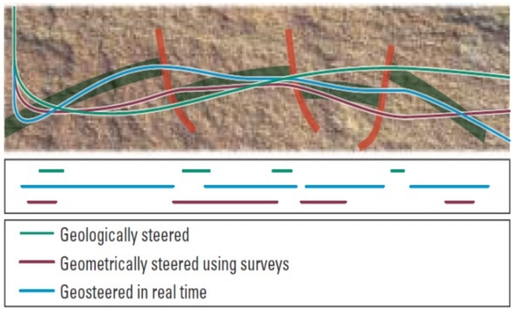


**Figure 1.** Responding to unexpected developments and modifying the drilling trajectory.

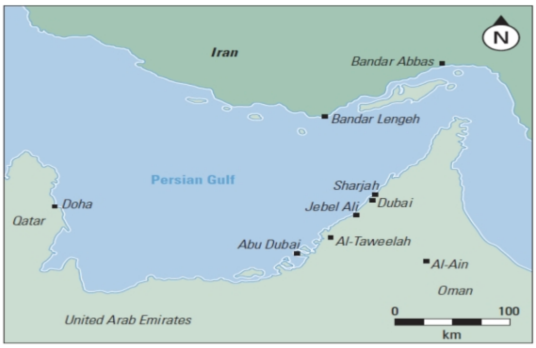


**Figure 2.** The field is located in the Persian Gulf.

The geological and petrophysical structure can be identified in real time to geosteer the wellbore in the optimum reservoir. The VISION service utilizes the ARC* Array Resistivity Compensated tool to provide borehole-compensated resistivity measurements of phase shift and attenuation outputs at five spacing. The system simultaneously measures at two frequencies of 2 and 400 kHz to provide up to 20 depths of investigation. Multiple depths of investigation are critical for identifying and differentiating between borehole effects, shoulder-bed effects, invasion and/or anisotropy.

**2. 2. The Benefits of VISION Technology** VISION downhole imaging services use a breakthrough technology that combines simultaneous drilling and surveying with new-generation, formation evaluation measurements for 43⁄4-in. and 63⁄4-in. bottom hole assemblies (BHA). These systems allow drillers to see where the bit is with respect to the reservoir and identify where they want the bit to go. Well costs are lowered through improved drilling efficiency and real-time data that enable rapid drilling decisions to be made.

Production is improved, as real-time data make geosteering possible and the formation evaluation measurements enable better completion decisions to be made. VISION services provide many benefits for drilling operations. Six-axis stationary surveys and continuous surveys while rotating or sliding are obtained. The VISION systems have an optional AIM* At-Bit Inclination Measurement tool to identify changes in bit inclination for absolute trajectory control. Combining continuous surveys with AIM measurements lowers costs by improving drilling efficiency and saving rig time. Continuous surveys reduce the number of stationary surveys required. The use of the AIM tool reduces borehole tortuosity to produce a smooth build section and minimizes the undulations in a horizontal well. This reduces torque and drag on the drillstring, which results in a greater rate of penetration while reducing the chances of getting stuck.

The VISION services use variable frequency, continuous, mud-pulse telemetry that accommodates the widest range of drilling conditions and provides the fastest telemetry rate in the industry. Flexible data frames can be tailored to meet drilling requirements.
The downlink telemetry can switch among preselected data frames and rates if requirements change during drilling. As with all tools that use radioactivity, the radioactive sources are retrievable if the BHA becomes stuck, allowing the operator to carry out vigorous fishing operations without worrying about the environmental hazards. Recorded data from the density/neutron tools are also retrievable, which ensures log data retrieval in a difficult hole.

APWD* Annular Pressure While Drilling measurements are combined with the VISION services. These measurements are necessary to monitor hole cleaning and optimize mud weight to maintain wellbore stability in deviated boreholes. VISION services measure and transmit real-time downhole shocks and the speed of revolution of the BHA. The tools are powered with a combination of batteries and downhole mud turbine generators that offers extended battery life.

## 3. MODELING

**3. 1. Modeling Thin Layers** Complex, thinly bedded reservoirs can contain large quantities of oil in layers that are intimately inter–bedded with water-filled units. The biggest challenge facing field operators is extracting oil as efficiently as possible, with the smallest water cut [17].

Thinly bedded reservoirs can be characterized using borehole imagery and detailed logs, allowing asset teams to build up an accurate picture of the formation in each well. The next step is to predict dip, thickness and continuity variations in these layers so that an efficient well trajectory can be planned. This formation modeling process provides a drilling road map for the drilling engineer to follow (Figure 4).

In the past, when directional drilling was performed on a strictly geometric basis, drilling engineers were stuck on a single road. The development of geosteering methods allows the drilling team to change direction and drive the bit down the best routes while drilling.

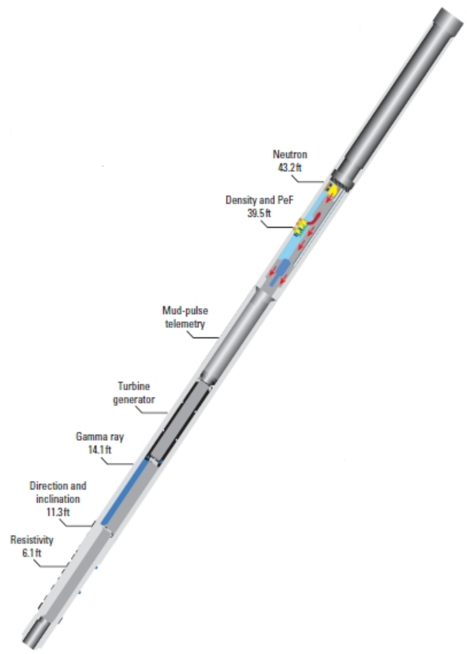


**Figure 3.** The VISION475 tool provides formation resistivity, gamma ray, bit speed and inclination measurements at the drill bit.

**3. 2. Formation Modeling** Formation modeling for this oil field simulated log responses along the well trajectories to guide drillers and help interpreters evaluate the formations through which the bit would pass.

This approach allowed the drilling team to plan their trajectories, select the best fluids, and decide 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 benefited from close cooperation between geologists, log analysts and directional drillers.

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

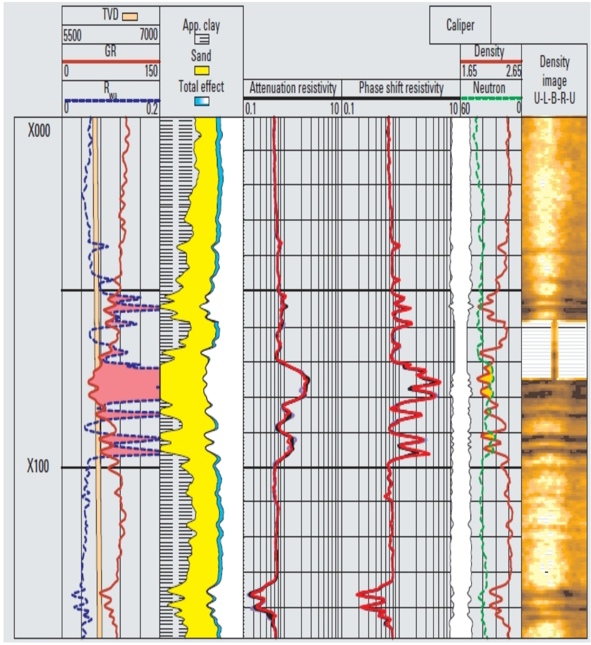


**Figure 4.** Typical output data from the VISION475 tool

**3. 3. Well A** The target sub layers for Well A were zones c and h. Four offset wells were selected to evaluate the thickness and log the property variations of the target units. A detailed earth model was developed for both the legs planned for Well A.

Their trajectories are shown in Figure 5. The path of leg 1 was maintained within the porous upper section of zone h, with neutron porosity and density matching the responses predicted from the earth model. The observed gamma ray trend matched the trend in the earth model, although the values in the model were significantly higher than those in the log (Figure 6).

The presence and location of a major fault were confirmed by neutron porosity variation along the path of leg 1. The path of leg 2 was maintained in the porous upper section of zone c. Almost 50% of the trajectory was in the lower section of zone b. The gamma ray, neutron porosity and density logs matched the earth model responses (Figure 7). In this way, the trajectory was maintained in the uppermost section of zone c to avoid drilling in the water-filled, bottom sub layers of zone c.

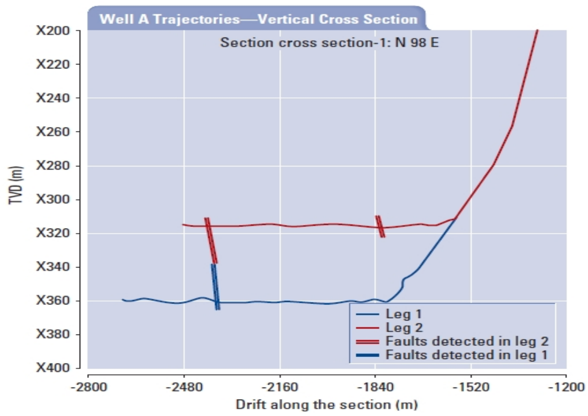


**Figure 5.** The trajectories of the horizontal legs of Well A

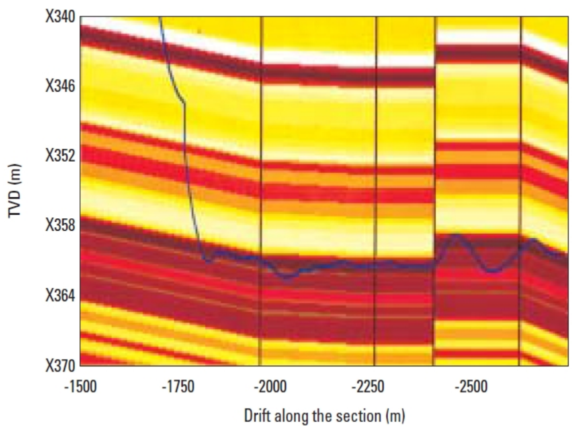


**Figure 6.**The gamma ray trend shown in the log for leg 1 of well A.

## 4. RESULTS AND DISCUSSIONS

**4. 1. Analysis Petrophysical** Analysis was conducted with the ELAN Plus* Elemental Log Analysis module. ELAN Plus software performs elemental volumetric analysis and was developed to provide information on the three major rock components—anhydrite, dolomite and calcite.

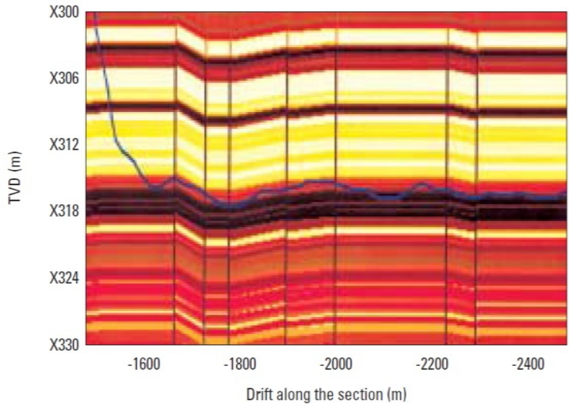


**Figure 7.** The path of leg 2 in Well A was maintained in the porous upper section of zone c.

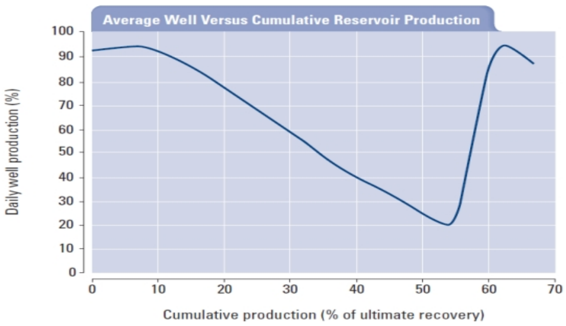


**Figure 8.** The production history of all wells for the same target zones.

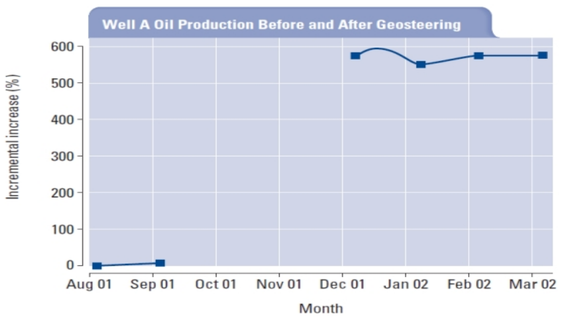


**Figure 9.** Geosteering new legs into zones c and h led to a dramatic increase in production at Well A.

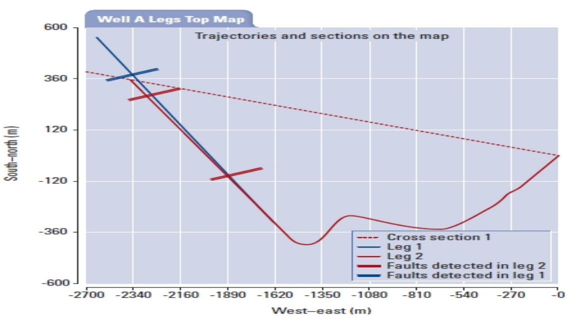


**Figure 10.** The geosteering technique helped the operators to detect faults in Well A.

In Well A, zone h lithology was shown to be mainly dolomite. The path of leg 1 has penetrated zone g anhydrite several times. The zone c lithology is mainly dolomite and the anhydrite sub layers of zone b were penetrated several times by leg 2 to maintain it within zone c. The drilling of horizontal legs in Well A was a major success. The well production has increased to three times the average production of a horizontal well in the same reservoir.

Since the enhancement program, Well A has been producing at significantly higher rates (four- to six fold higher than vertical wells and 50% higher than horizontal reentry wells in this field). In addition, the recorded water-cut values are consistently low (one third that of vertical wells in the field). There are several reasons for this:

The well has two legs in the target formation, giving an average porosity of almost 21% per meter in both legs.

The new branches follow the crest of the fold that defines field structure, minimizing water breakthrough. The new branches are located in the northwest of the field, where water injection is helping to maintain reservoir pressure.

Well A production has boosted the average daily well production for all wells completed in the same target zones (Figure 8). When horizontal drilling commenced, the average production started to improve. However, with geosteering techniques, the efficiency of well placement has dramatically increased, which is reflected on the production profile.

After the completion of the Well A, average well production returned to the previous field rate from the same zone. The low rates at this well had led the operators to shut in. The increased production achieved at the Well A underlines how the latest technology can improve productivity (Figure 9).

**4. 2. 3D Geological Findings** In complex carbonate reservoirs, it is difficult to predict the heterogeneity of the reservoir in locations where high-resolution measurements (borehole logging) are unavailable. Even major geological features, such as faults with low displacement, cannot be detected by seismic measurement.However, with the availability of azimuthal measurements (azimuthal coverage of borehole) and simultaneous modeling (geosteering), the detection of these hidden features has become easier and can be made while drilling.

In Well A, a fault was detected along the path of leg 1. The block beyond this fault has lifted upwards by approximately 2 m with respect to the block before the fault along the path of leg 1. The fault is confirmed by the neutron porosity variation along the path of the leg. Two possible faults were detected along the path of leg 2. These were confirmed by the neutron porosity and bulk density variations along the path of leg 2. By combining these findings in 3D frame (Figures 5 and 10), the fault detected in leg 1 is seen to extend to leg 2. In addition, on the basis of this fault dip, the first fault detected in leg 2 might extend to leg 1. In conclusion, the displacement of the faults detected is about 2 m in zone handalmost no displacement in zone c.

## 5. CONCLUSIONS

While drilling horizontal wells, there are many uncertainties such as lithology and structure. Advanced techniques of logging and mud logging while drilling provide powerful means for horizontal well geosteering. In addition, drilling workers should have rich geologic knowledge and experience. Only the close integration of petroleum geology and petroleum engineering technology can result in accurate stratigraphic correlation and target depth prediction before drilling into target zone, and correct geological interpretation and drilling geosteering also after drilling into the target zone, so that the borehole quality and oil layer drilling-encounter ratio can be improved.

Many oil and gas companies reduced their costs by drilling fewer, but more productive wells. However, accuracy in the placement of horizontal wells has improved significantly. In many regions, drillers have to plan and drill designer wells with extremely complex trajectories. Planning these trajectories often involves identifying a target from careful seismic interpretation, detailed geological mapping and petrophysical analysis. Despite recent technical advances, drilling a horizontal well that will land precisely in the reservoir zone (and stay there) remains a difficult task, requiring a combination of oilfield skills and detailed planning.

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. Geosteering provides a powerful tool for the development of thinly bedded reservoirs. The tools available offer real-time information on boundaries, fluids and lithology, allowing the driller to react to changing circumstances, even in lithologically complex formations such as carbonates. The widespread application of formation modeling and geosteering methods will open up many thinly bedded reservoirs for more efficient development.

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Geometrical Drilling

**چکیده**

در مخازن نازک لایه، مهندسان حفاری با چالش برنامه ریزی سخت برنامه های حفاری خود رو به رو هستند تا به پربهره ترین بخش لایه برسند و در عین حال از لایه‌های آب ، گاز و یا مناطق با فشار بالا در آن نزدیکی پرهیز کنند. ثمره‌ی یک استراتژی موفق حفاری تولید نفت بیشتر و کاهش قطع آب. به عنوان مثال، در یک میدان نفتی در خلیج فارس با استفاده از آخرین مدل سازنده و فنون ژئو استیرینگ (gesteering)، تولید نفت چهار تا شش برابر و میزان آب یک سوم شده است. تا همین اواخر، حفاری لایه‌های نازک بسیار دشوار بود. حفاری‌های مرسوم هندسی قادر به مطابقت با تغییرات دقیق و ظریف در شیب وعمق لایه نبودند، به طوریکه بسیاری از چاه‌ها از منطقه‌ی هدف دور شده و بالایه‌ی پر آب مواجه می شوند. در این مقاله با استفاده از روش جدید geosteering به کنترل بسیار بیشتر حفاری و کمک به اپراتور برای تغییر روش توسعه‌ی مخازن نفت نازک لایه پرداخته است. به این ترتیب، می‌توان موفق به افزایش برداشت هیدروکربن و کاهش میزان آب شد.

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