OKLAHOMA GEOLOGY notes

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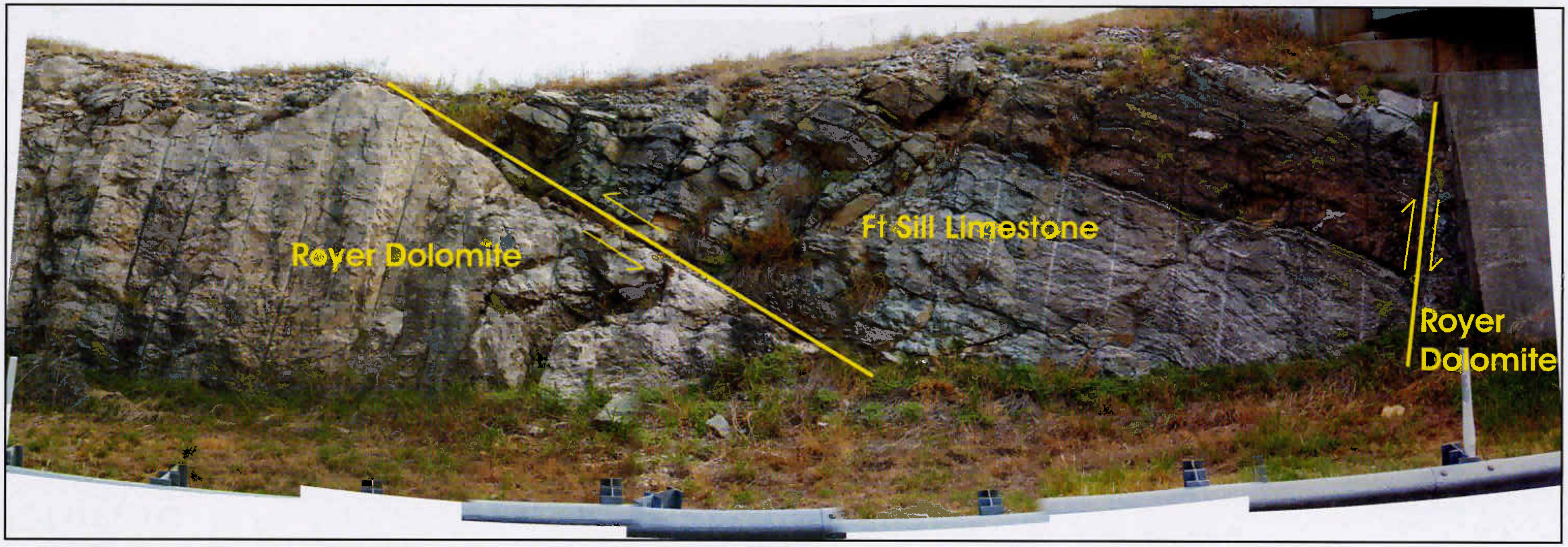
Featuring:

- Pre-Pennsylvanian Paleocanyon in a Portion of McClain County, Oklahoma: Implications for Deese Oil and Gas Production
- Influx of Advanced Drilling Technologies Maximizing Productivity of Mature Region

—On the Cover

Interesting Outcrop in Southern Murray County, Oklahoma



The outcrop seen in the photographic mosaic shows a high angle reverse fault (to the right and not shown on the front cover), and a lower angle thrust fault (center-left). The two faults juxtapose a section of the Upper Cambrian basal unit of the Fort Sill Limestone of the Arbuclke Group up to the slightly younger (yet still) Upper Cambrian Royer Dolomite also of the Arbuckle Group. In the Arbuckle Mountains, the Arbuckle Group (Cambrian-Ordovician) reaches a total thickness of 6,000 to 7,000 feet. Deposition of the Arbuckle Group progressed as the Southern Oklahoma Aulacogen (failed arm of an ancient rift system) slowly subsided and subsequently filled with shallow marine carbonates. The view of the photographic mosaic is to the north. The roadcut is located between the north and south Interstate 35 overpasses at Exit 47 in southern Murray County. Permian infill and collapse breccia indicate that karsting occurred in the Royer Dolomite and is seen to the right (east) of the concrete abutment of the north-bound lane of Interstate 35. At this location the Royer Dolomite is a white sucrosic to coarsely crystalline dolomite with some glauconite. The Fort Sill Limestone is thin-bedded and dominated by carbonate mudstones, and lacks a typical peritidal facies. The roadcut is an excellent field trip stop for fans on their way to the Cotton Bowl in Dallas for the OU-Texas game. Travelers on a casual geological excursion can directly observe the faults and the karst features in detail without interference of the dangerous Interstate 35 traffic.

—Galen W. Miller

Cover photo montage by Galen W. Miller

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OKLAHOMA GEOLOGY notes

Vol. 66, No. 1 Spring 2006

Pre-Pennsylvanian Paleocanyon in a Portion of McClain County, Oklahoma: Implications for Deese Oil and Gas Production

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ABSTRACT

The Payne and Golden Trend oil fields in south-central Oklahoma are prolific producers of oil and gas. The Golden Trend Field produced 84 million bbls of oil and 1 TCF of gas since 1979. During that time the Pennsylvanian (Desmoinesian) Deese interval produced 34 million bbls of oil and 119 bcf of gas.

The study area is in T. 5 N., R. 3 W., in McClain County, Oklahoma, and produced more than 1.3 million bbls of oil and 14 bcf of gas from the Deese interval. The Payne Field produced more than 160,000 bbls of oil and 0.7 bcf of gas from the Deese in the study area.

The study examined well logs, mud logs, completion reports, LASSER® production data, and available seismic and previously published work in the area. The Deese interval contains interbedded limestones, shales, and sandstones. Most oil production comes from the Hart (4th Deese) sandstone. The dominant feature in the study area is a paleocanyon trending approximately north-south. The canyon was identified by the absence of Tulip Creek to Caney strata as indicated by well logs, and confirmed by an east-west seismic line. The vertical extent of the paleocanyon erosional feature is on the order of 2,000 feet. The upper Hart sandstone appears most productive updip from the canyon with good production in thicker channel sandstones, but also in some thinner sandstones on the eastern edge of the channels that drained into the canyon.

INTRODUCTION

The Golden Trend oil field in McClain and Garvin Counties in south-central Oklahoma is a giant field that has been extensively studied since the first successful well was drilled in the 1940s. Swesnick (1950) described the development of the Golden Trend oil field in its early production history. According to our estimates from LASSER® production data, the Golden Trend Field produced 84 million bbls of oil and 1 TCF of gas since 1979. A good portion of the production came from the Pennsylvanian (Desmoinesian) Deese interval that produced 34 million bbls of oil and 119 bcf of gas since 1979. Similar estimates for the Payne Field, northeast of the Golden Trend Field, show that 160,000 bbls of oil and 0.7 bcf of gas were produced from the Deese interval.

The Payne and Golden Trend oil fields are on the northern flank of the Arbuckle Mountains, the eastern flank of the Anadarko Basin, south of the Nemaha Ridge (Nemaha Fault Zone), and just west of the Pauls Valley Uplift (Fig. 1). The study area is in the western portion of T. 5 N, R. 3 W., McClain County, Oklahoma (Fig. 1). The area is the northern portion of the Golden Trend oil field and the southwestern end of the Payne oil field. We estimate that 1.3 million bbls of oil and 14 bcf of gas were produced from the Deese interval in this area.

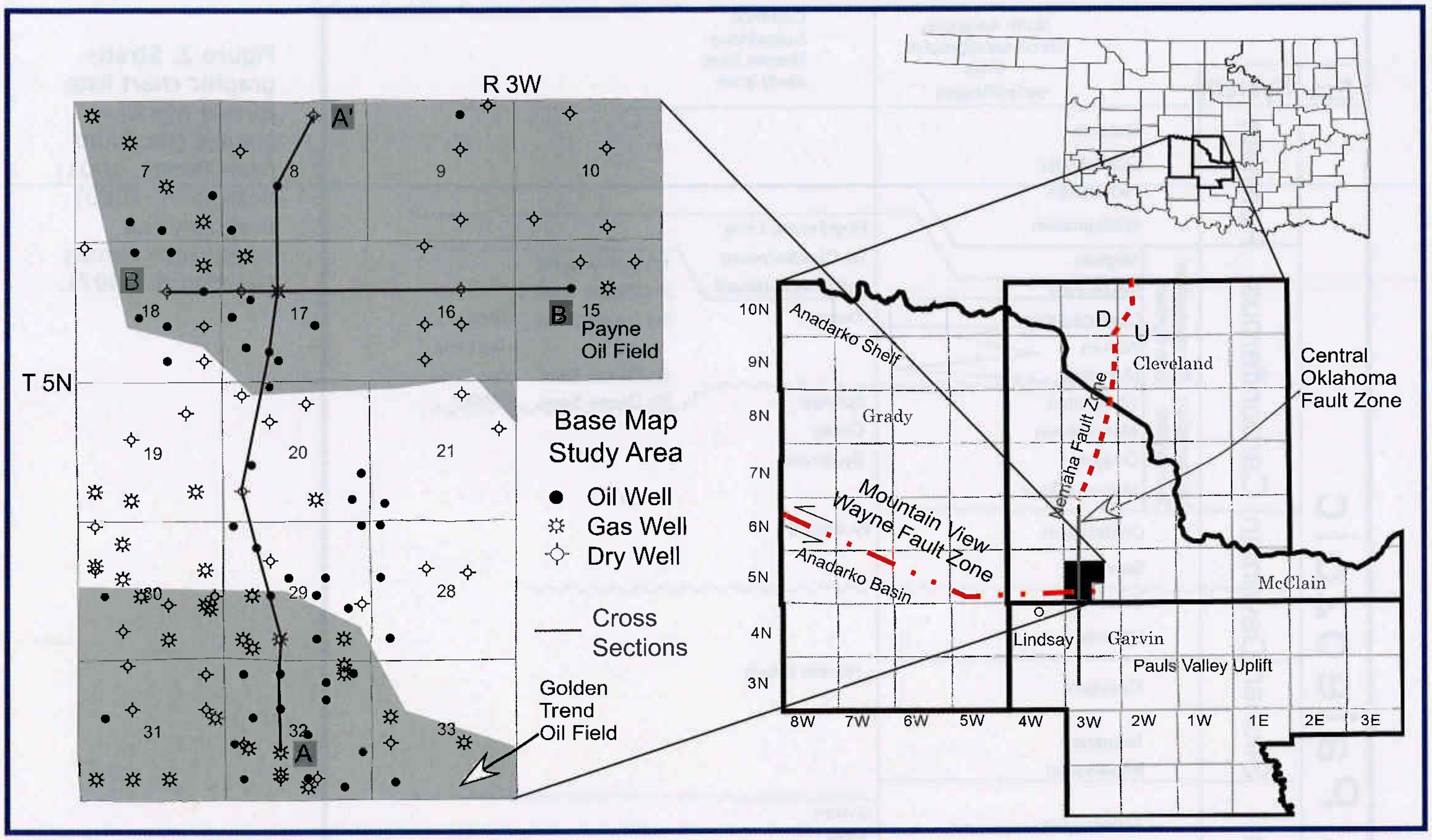


Figure 1. Map of the study area shows cross sections A-A′ and B-B′, well locations, and regional features of interest.

Stratigraphy

In the Anadarko Basin, Deese (lower Desmoinesian) sediments were deposited northward and unconformably upon Atokan and older rocks during a major transgression (Huffman, 1959; Rascoe and Adler, 1983). A stratigraphic column in Figure 2 shows the formations encountered in wells drilled in the area. Atokan and Morrowan sediments have not been recognized in the study area, but may be present in the paleocanyon. Swesnick's (1950, fig. 5) paleogeographic map of the pre-Pennsylvanian subcrop shows Springer rocks to the east, Woodford and Hunton to the west, with a very narrow strip of Caney and Mayes in between.

Deese sandstones are typically 10–35 ft thick, medium-grained, well sorted, permeable, and porous (Thomas, 1962). Facies changes may occur abruptly, however, and the sands become hard, impermeable, and fine-grained, sometimes with interspersed silt and shale. Some offset wells can be nonproductive as a result (Swesnick, 1950).

Deese sands onlap onto the Pauls Valley Uplift, forming the multiple stratigraphic traps of the Golden Trend (Jacobson, 1949). The updip limit of the 4th Deese (Swesnick, 1950), which is also known as the Hart sandstone, is within one quarter mile of the southeastern edge of the study area. But north of the Lindsay area (T. 4 N., R. 4 W. in Fig.1), Deese sandstones are not traceable. The sandstones found in the Deese interval (north of the Lindsay area) are erratic, thin, and fine-grained. Deese thickness and structure correlate reasonably well, with the Deese thickening in the graben in the western portion of T. 5 N., R. 3 W., and thinning on all structurally high areas (Jacobson, 1949).

Structure

The structure in the area is complex because of the effect of the Wichita, Arbuckle, and Ouachita orogenies, which produced displacement of the Mountain View – Wayne Fault, the Central Oklahoma Fault, and the Nemaha Fault Zone (Fig. 1). The Mountain View – Wayne Fault Zone is an east-west trending, left lateral, strike slip fault zone that runs through T. 5 N., R. 3 W. with about 1.0–1.5 miles of

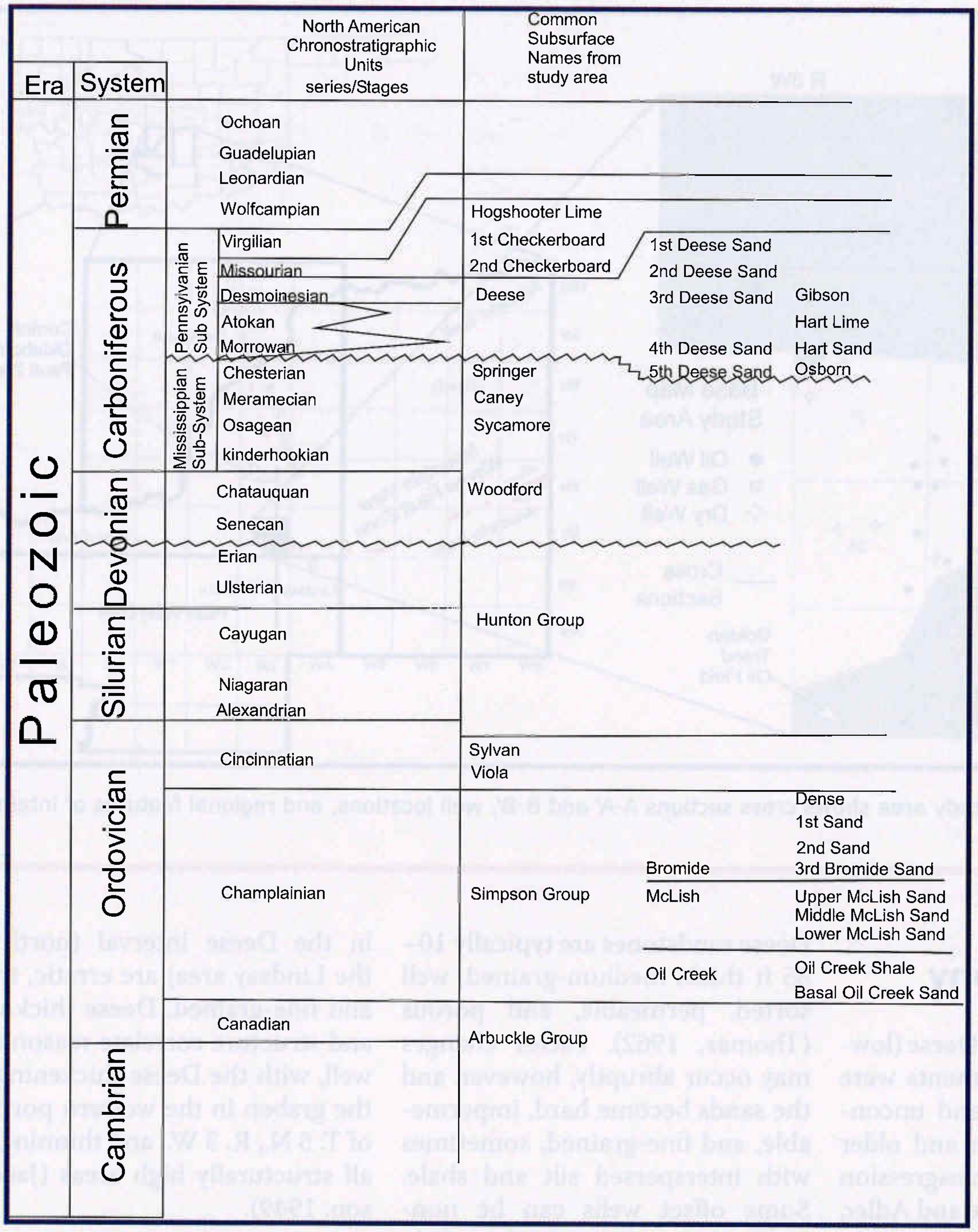
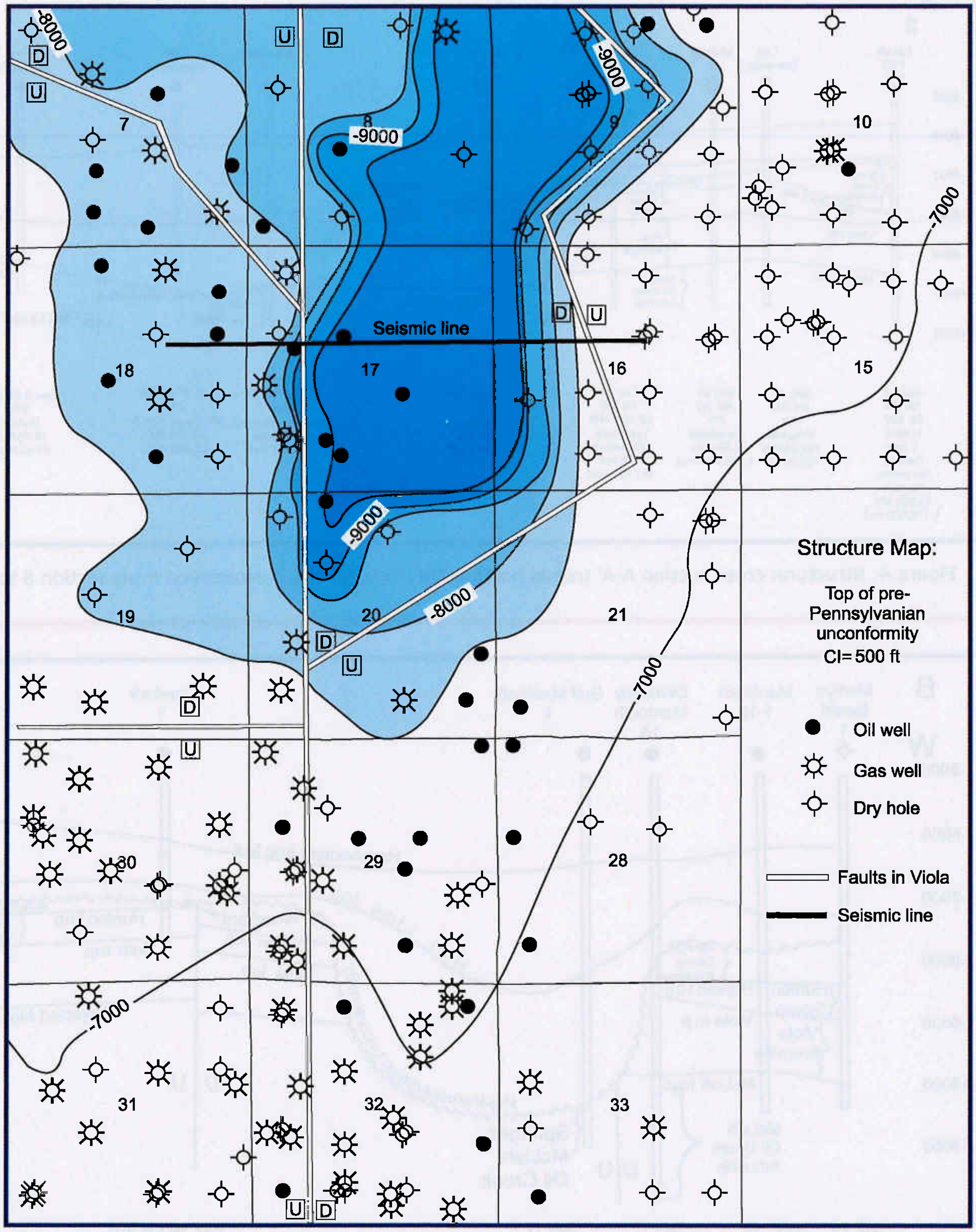


Figure 2. Stratigraphic chart lists formal nomenclature (modified from Boggs, 2001; Rottmann, 2000) and common subsurface names (Northcutt, 1997).

displacement. The Mountain View – Wayne Fault was caused by the Wichita orogeny. During this orogeny, truncation of Morrowan and older rocks occurred as the Pauls Valley Uplift and Hunton Arch rose. At the end of the Wichita orogeny, final uplifting of the Pauls Valley Uplift and Hunton Arch occurred. (Axtmann, 1983)

The McClain County Fault Zone (or Central Oklahoma Fault Zone) is a zone of intense shearing (Jacobson, 1949; Friess, 2005); it is the major fault in the area. The fault zone separates the Anadarko Basin from the Pauls Valley Uplift (Central Oklahoma platform). The fault zone intersects the Mountain View – Wayne Fault Zone in T. 5 N., R. 3 W. (Axtmann, 1983). The Central Oklahoma Fault appears as a narrow graben in subsurface maps, and has variable throw from north to south in the study area (Thomas, 1962). Friess (2005) describes the Central Oklahoma Fault as a small pull-apart graben in the extreme south end of the study area. Faults in the area are not easily discovered because of multiple intersecting shear zones.

Figure 3. Structure map at the top of the pre-Pennsylvanian unconformity shows pre-Deese paleo-surface features. Also shown are locations of a seismic line from section 16 to section 18 (dark line), faults in the Viola (hollow lines), and 500-foot contours highlighting the canyon area (darker shading is deeper).



Generally, strata dip to the west at 200 ft/mi, but they are interrupted by the McClain County Fault with 150–900 ft of displacement (Thomas, 1962).

CURRENT STUDY

Our study is based on 110 well logs, LASSER® production data, an east-west trending seismic line, and completion reports (form 1002A).

From all the data, we constructed a structure map and two cross sections of the pre-Pennsylvanian surface. An east-west seismic line in the area was used to confirm the existence of the paleocanyon.

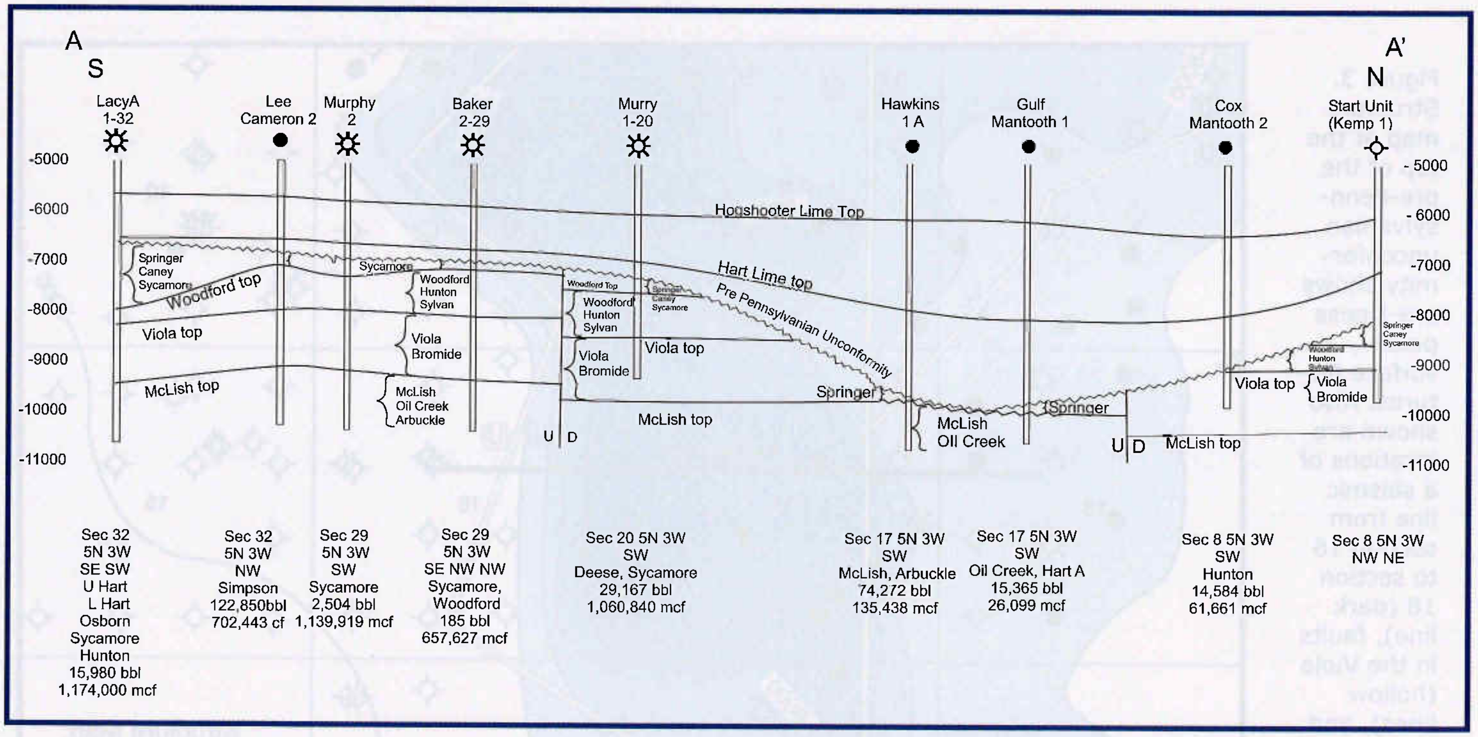


Figure 4. Structural cross section A-A′ trends north-south through the paleocanyon from section 8 to section 32.

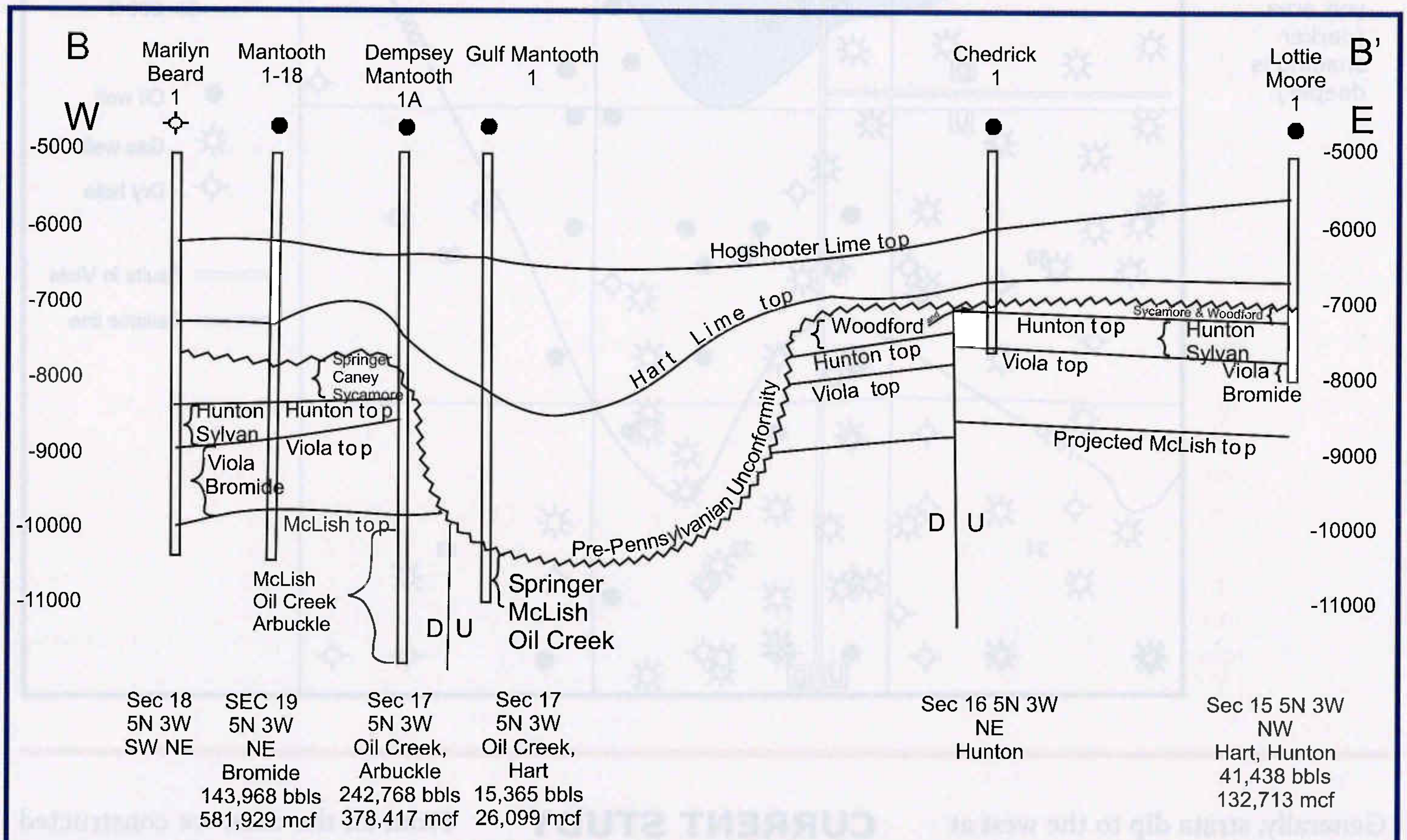


Figure 5. Structural Cross section B-B′ trends east-west across the canyon from section 18 to section 15.

The paleocanyon in sections 8 and 17 is the main subsurface feature in the area, and is shown in the pre-Pennsylvanian surface map (Fig. 3), cross sections A-A' and B-B' (Figs. 4 and 5), and the seismic data (Fig. 6). A pre-Pennsylvanian surface map was generated from well logs using various formations that occur just below the Pennsylvanian strata. In the western portion of the area the Springer is the first pre-Pennsylvanian formation, and in the eastern portion of the area the first pre-Pennsylvanian formation is either the Woodford or Springer. In several wells, missing strata indicate erosion (Figs. 4 and 5). For example, in the Hawkins 1A and Gulf Mantooth 1 wells, directly below the pre-Pennsylvanian unconformity, the Springer rests unconformably on the McLish, with the Oil Creek resting below the McLish.

The vertical extent of erosion in the paleocanyon, as seen in the well logs, is on the order of 2,000 ft (Fig. 5). The paleocanyon is clearly visible in the seismic data (Fig. 6). Based on the seismic interval velocity of 13,000 ft/sec, calculated from stacking velocities above the unconformity, the amount of erosion observed in the seismic section is consistent with the well data.

Faulting was also involved in the formation of the paleocanyon. Our study of the structure shows that east-west trending faults (Mountain View – Wayne Fault Zone) are cut by north-south trending faults (Central Oklahoma Fault Zone) in the Viola (Fig. 3). Fault locations were determined by contouring the top of the Viola. The general trend of the faults matches fairly

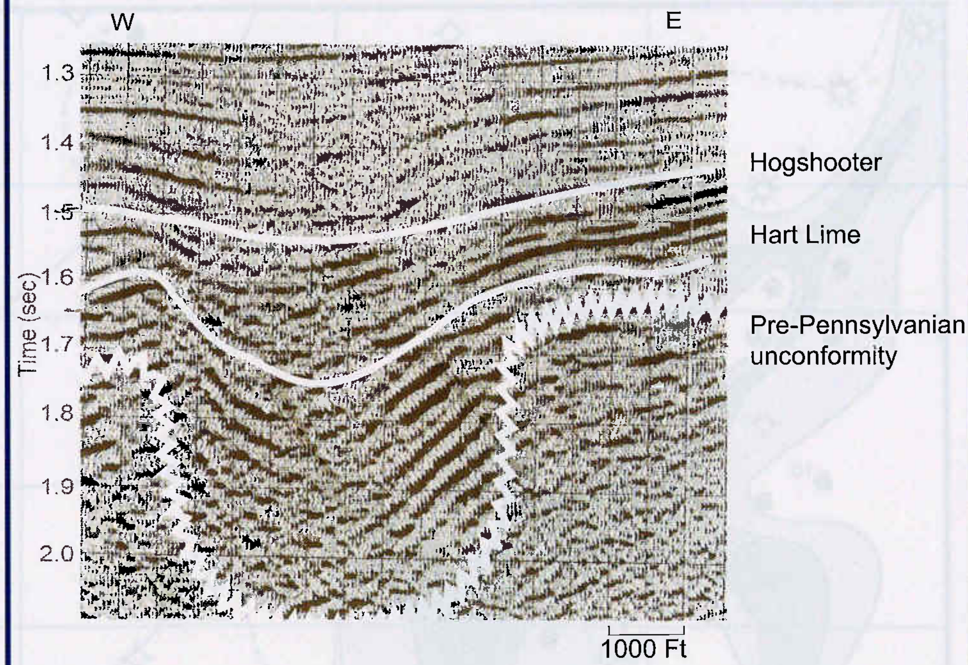


Figure 6. East-west seismic section, roughly paralleling cross section B-B', shows the interpreted paleocanyon and other reflectors of interest (white).

well with the faults described by previous researchers, particularly Swesnick (1950). Moreover, our east-west cross section (from section 18 through section 15) shows total uplift to the east of about 1,100 ft using the Hunton top; the seismic section, however, does not show the faulting that is observed in the well data. The seismic section shows a deep canyon in section 17, in which some pre-Pennsylvanian strata are missing.

The canyon is interpreted as erosional: 1) we observed no significant faulting in the seismic section below the canyon; 2) the seismic section shows features that appear to be channel fill (reflectors dipping towards the center of the canyon); and 3) there is a similarity between our seismic section and seismic sections of canyons in the subsurface of the Gulf of Mexico.

Friess (2005) shows a seismic section in southern McClain County that is interpreted as a pull-apart basin in the Central Oklahoma Fault Zone. This section shows Springer and Hunton dipping to the west, with a dip steeper than those for beds on either side of the pull-apart basin. It appears that the pull-apart basin shown by Friess (2005) is in the southern portion of T. 5 N., R. 3 W., whereas our section is in the west-central portion of T. 5 N., R. 3 W. Apparently the structural character of pre-Pennsylvanian rocks changes dramatically within a short distance, illustrating the need for 3-D seismic data for a detailed structural analysis.

The pre-Pennsylvanian unconformity may be important for oil production in the area. The deep paleocanyon identified in our study influenced drainage in the area during deposition of early Desmoinesian sediments. The

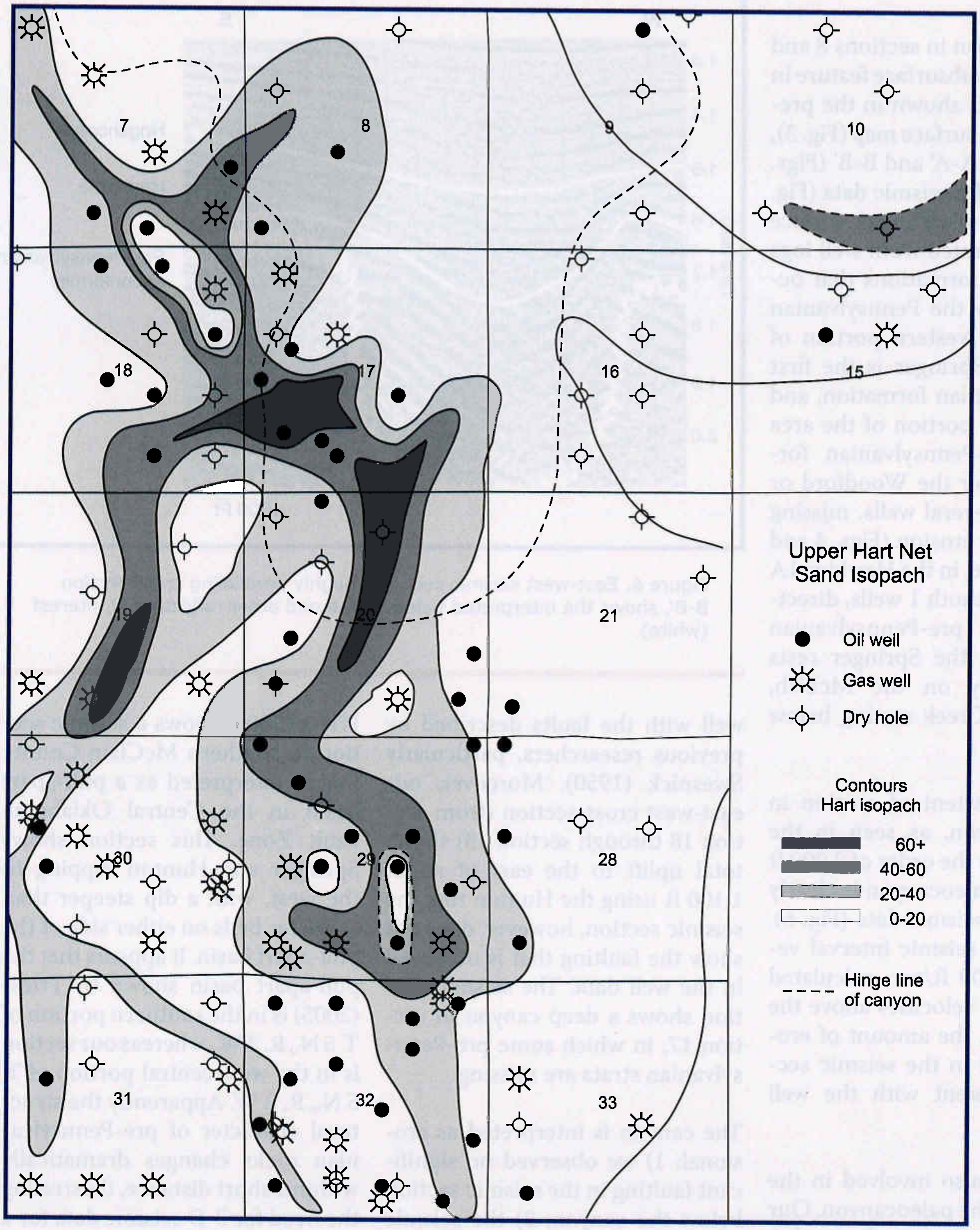
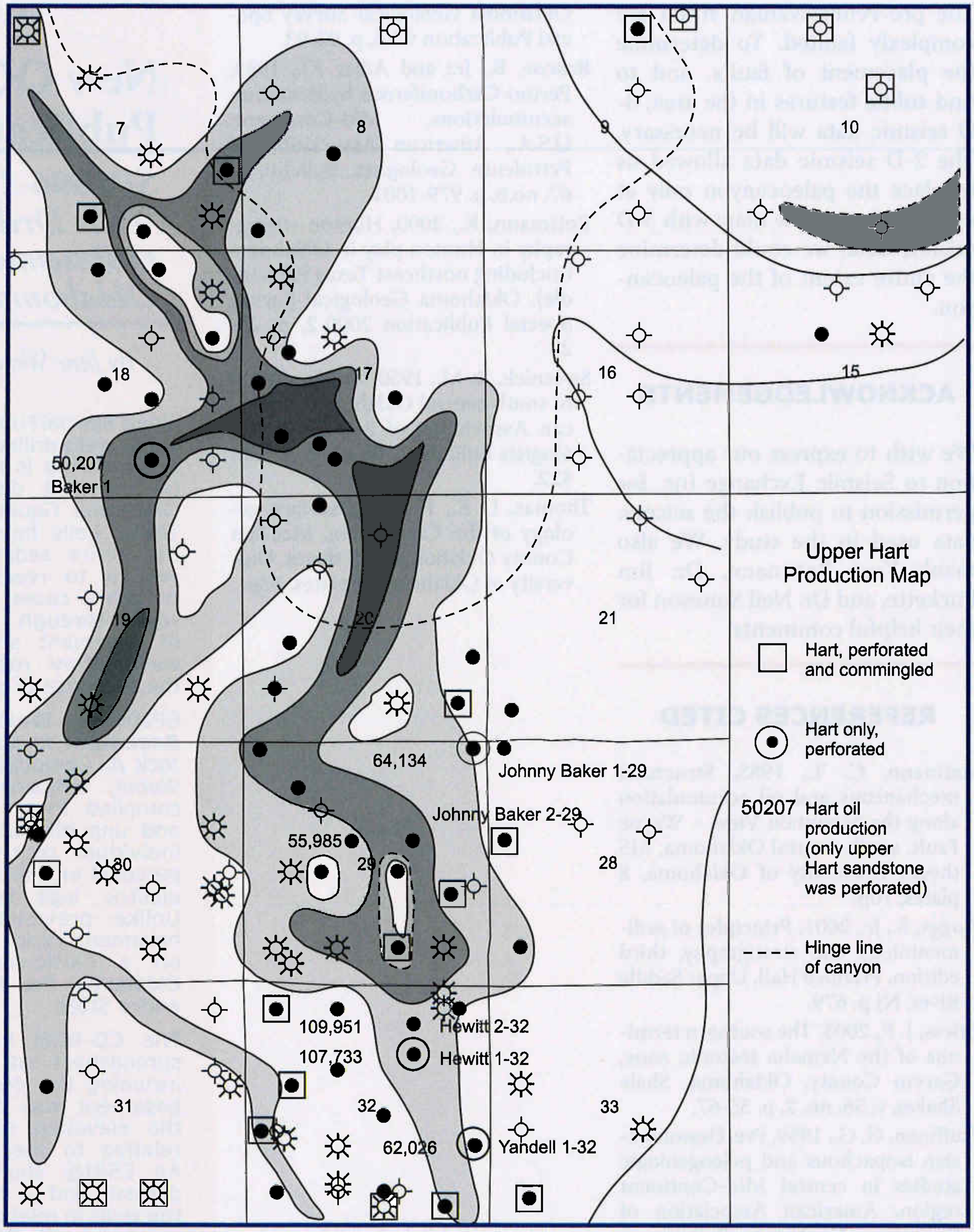


Figure 7. Upper Hart net sand isopach shows the thicker sandstones that occur in the tributary channels draining into the canyon.

net sand isopach map of the upper Hart sandstone shows channels that flowed into the canyon. A large variation of sandstone thickness is evident in the study area (Fig. 7). The Hart sandstone appears to pinch out eastward, as described by Swesnick (1950). The production map (Fig. 8) shows wells that were perforated only in the upper Hart sandstone, or that had no or insignificant production from other zones. It is clear from Figure 8 that production is confined mainly updip from the paleocanyon in thicker sandstones deposited in channels that drained into the canyon; there is production, however, from some wells in thinner sandstones on the eastern edges of the channels.

Figure 8. Upper Hart sandstone production map on the Hart net sand isopach shows wells that were perforated only in the upper Hart sandstone.



CONCLUSIONS

The evidence from well and seismic data shows that a paleocanyon exists in McClain County, Oklahoma. The paleocanyon in the western portion of T. 5 N., R. 3 W. has an erosional component on the order of about 2,000 ft. The paleocanyon is filled with Springer and Deese sediments. Tributary channels that flowed into the canyon had deposited the upper Hart sandstone. The upper Hart sandstones produce oil updip from the canyon, and also within thicker sandstones in the channels, or in thinner sandstones on the eastern edge of the depositional system.

The pre-Pennsylvanian strata are complexly faulted. To determine the placement of faults, and to find subtle features in the area, 3-D seismic data will be necessary. The 2-D seismic data allowed us to place the paleocanyon only at one position on the map; with 3-D seismic data, we could determine the entire extent of the paleocanyon.

ACKNOWLEDGEMENTS

We wish to express our appreciation to Seismic Exchange Inc. for permission to publish the seismic data used in the study. We also thank Kurt Rottmann, Dr. Jim Puckette, and Dr. Neil Suneson for their helpful comments.

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New OGS Publication

SP2006-1, Wells Drilled to Basement in Oklahoma

By Jane Weber, OGS Staff

A new Special Publication listing 1,232 wells drilled to basement in Oklahoma is now available on compact disc from the Oklahoma Geological Survey. These wells have penetrated the entire sedimentary rock section to reach basement. In some cases, the drill bit went through a thickness of basement and back into sedimentary rock, indicating the presence of a fault.

SP2006-1, ***Wells Drilled to Basement in Oklahoma***, by Jock A. Campbell and Jane L. Weber, contains information compiled from 17 published and unpublished sources, 14 individual contributors, and personal examination of some electric logs by Campbell. Unlike previous studies of basement rocks that focused on a particular region of Oklahoma, this list covers the entire State.

The CD-ROM has an Excel spreadsheet list of the wells, including the depth at which basement was reported and the elevation of that depth relative to mean sea level. An ESRI® shapefile of the dataset and a map showing the wells in relation to geologic provinces of Oklahoma are also on the CD.

The cost of SP2006-1 is $3, with an additional $2 for postage if mailed. To obtain a copy, call the OGS sales office at (405) 360-2886, email them at ogssales@ou.edu, or stop by the sales office at 2020 Industrial Blvd., Norman.

Influx of Advanced Drilling Technologies Maximizing Productivity of Mature Region

Steve Simonton, Larry Seigrist, Robert Huizenga Cimarex Energy Co; Sandeep Janwadkar, Baker Hughes INTEQ and Matt Isbell, Hughes Christensen

ABSTRACT

Economical development of oil and gas reserves in Kiowa and Washita counties of Southwestern Oklahoma requires drilling complex structural features with faulted formations and highly dipping beds. To address these challenges, many operators employ packed hole and/or conventional directional motor assemblies to keep inclination to a minimum drilling the production section. While this type of bottom hole assembly has improved directional control, in many cases it still leads to unacceptable angle building tendencies (i.e., bit walk) and high dogleg severity. This type of BHA has also led to poor vertical hole quality resulting in additional directional issues in subsequent hole sections. In addition, the conventional directional assembly increases well costs due to multiple deviation correction runs with different BHA configurations resulting in more flat time, lower cumulative bit penetration rate, and more bits/runs per hole section.

To reduce drilling costs and maximize production in the region, a service company conducted a detailed analysis of drilling performance, mud logs and wireline data from offset wells. The in-depth study helped engineers identify key problems limiting drilling performance. This led the operator to set new objectives for the production hole section of achieving the highest possible rate of penetration while maintaining a near-vertical wellbore. An implementation strategy was outlined that had two main components including a vertical deviation control system and new PDC bit technology.

This strategy has been implemented to drill 17 wells with excellent results (operator had previously drilled over 55 wells in the area with the old BHA). The new BHA combination has minimized directional deviation (inclination) and reduced dogleg severity. It has also reduced torque and drag helping deliver a smooth, high quality wellbore and has totally eliminated costly correction runs and increased efficiency and quality of cementing operations. This has allowed the operator to log and set tubulars without incident.

Introduction

The geology in southwestern Oklahoma presents numerous challenges for the oil and gas industry. The operator faced several problems while drilling in Kiowa and Washita Counties. The general location of the study area is shown in **Figure 1**.

Figure 2 shows the geological provinces of Oklahoma in addition to the major fault systems. The locations of the subject wells can be broadly classified in to three fields, including, Rocky field, Gotebo field and the Mountain View field located in the western, central and the eastern part of the Mountain Front respectively. Several wells were drilled in these areas and each area posed its own problems. This led to high drilling costs, extended number of days to drill, log and complete the wells due to a variety of downhole complications. The conventional drilling techniques and steerable assemblies were cost prohibitive and still not able to successfully meet all the requirements.

Complex Geological Environment

All subject wellbores encounter steeply dipping (40° - 80°) overthrusted and overturned formations. Formation dip is predominantly in a

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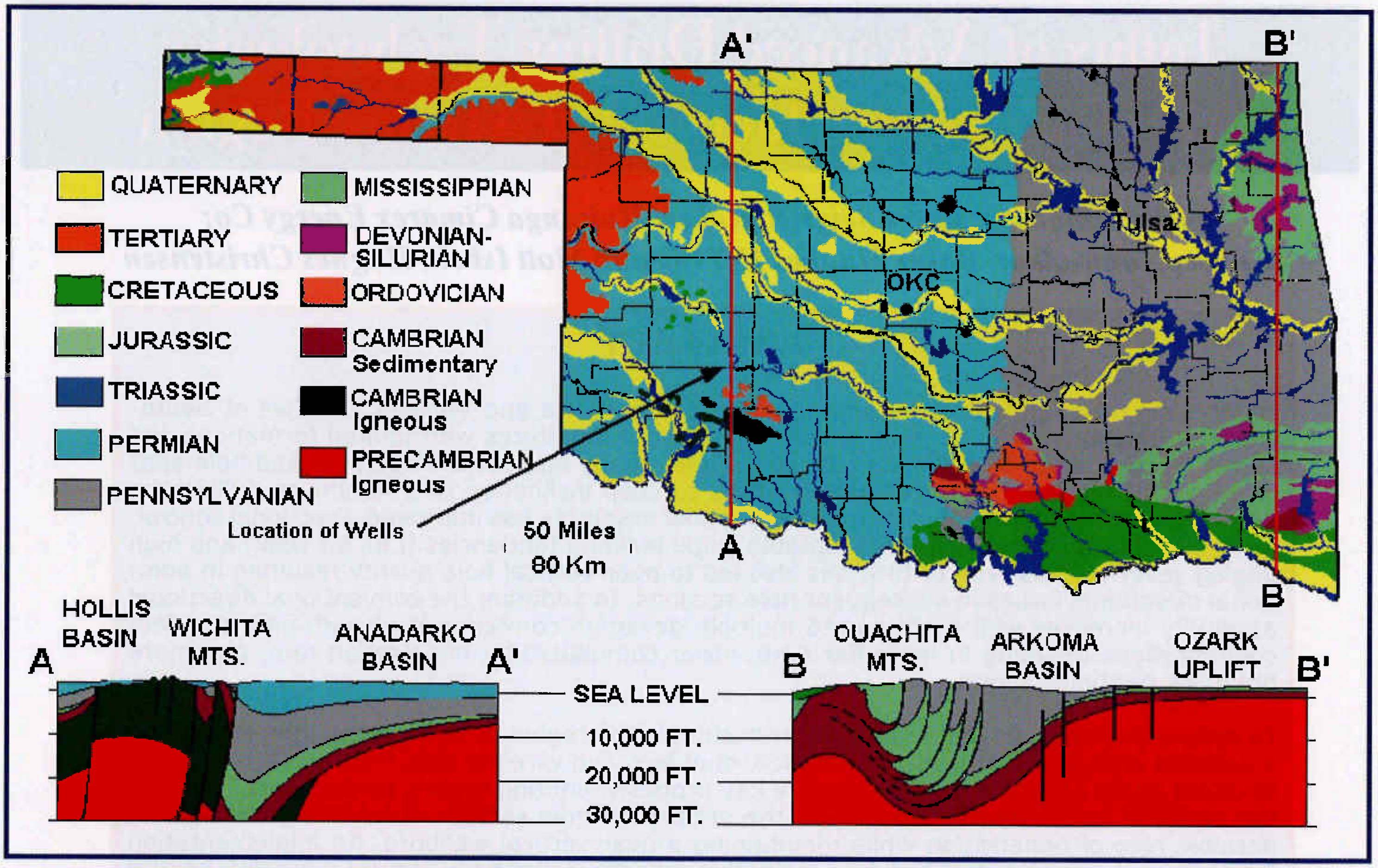


Figure 1. Generalized surface geological map of Oklahoma state showing the location of wells considered in the case study (Map modified by T. Wayne Furr, after Branson and Johnson; WWW version by Jim Anderson, Source: Oklahoma Geological Survey – Seismology, location: http://www.okgeosurvey1.gov/level2/geology/ok.geologymap.html, reproduced with permission)

southerly direction, but other dip directions are also frequently encountered. Additionally, the intense faulting coupled with secondary internal folding of the geological structure makes the drilling environment more challenging.

A structural cross-section of the area (**Figure 3**) shows there are at least three Springer sequences encountered along a vertical wellpath. They are generally known as the shallow overthrusted Springer, the intermediate overturned Springer and the deep basal Springer. The main target is the intermediate overturned Springer formation, which ranges in depth from 10,000-12,000 feet to 6,000-8,000 feet, east to west across the trend. The shallow overthrusted Springer, at 3,000-5,000 feet, is a secondary uphole target in the western portion of the trend.

Drilling in this highly complex geological environment has led to high inclinations and dogleg severity that make subsequent operations (e.g., drilling, tripping, logging, casing to bottom) extremely difficult.

Solutions

The ability to effectively drill vertically for all or parts of the well is a key objective. All subsequent operations performed in the well would be greatly simplified and the related costs both of drilling and subsequent work-over operations would be significantly reduced. To address these challenges, personnel from the operator and the service company developed a strategy that had the following three components:

Offset Well Analysis

A drilling optimization service conducted a detailed analysis of drilling performance, mud logs and wireline data from offset wells. Digitized offset logs (**Figure 4**) were analyzed by the service company's software to estimate the formation lithology, friction angle, abrasivity and unconfined compressive strength (UCS). This helped identify potential problems and led the operator to set objectives for drilling the well

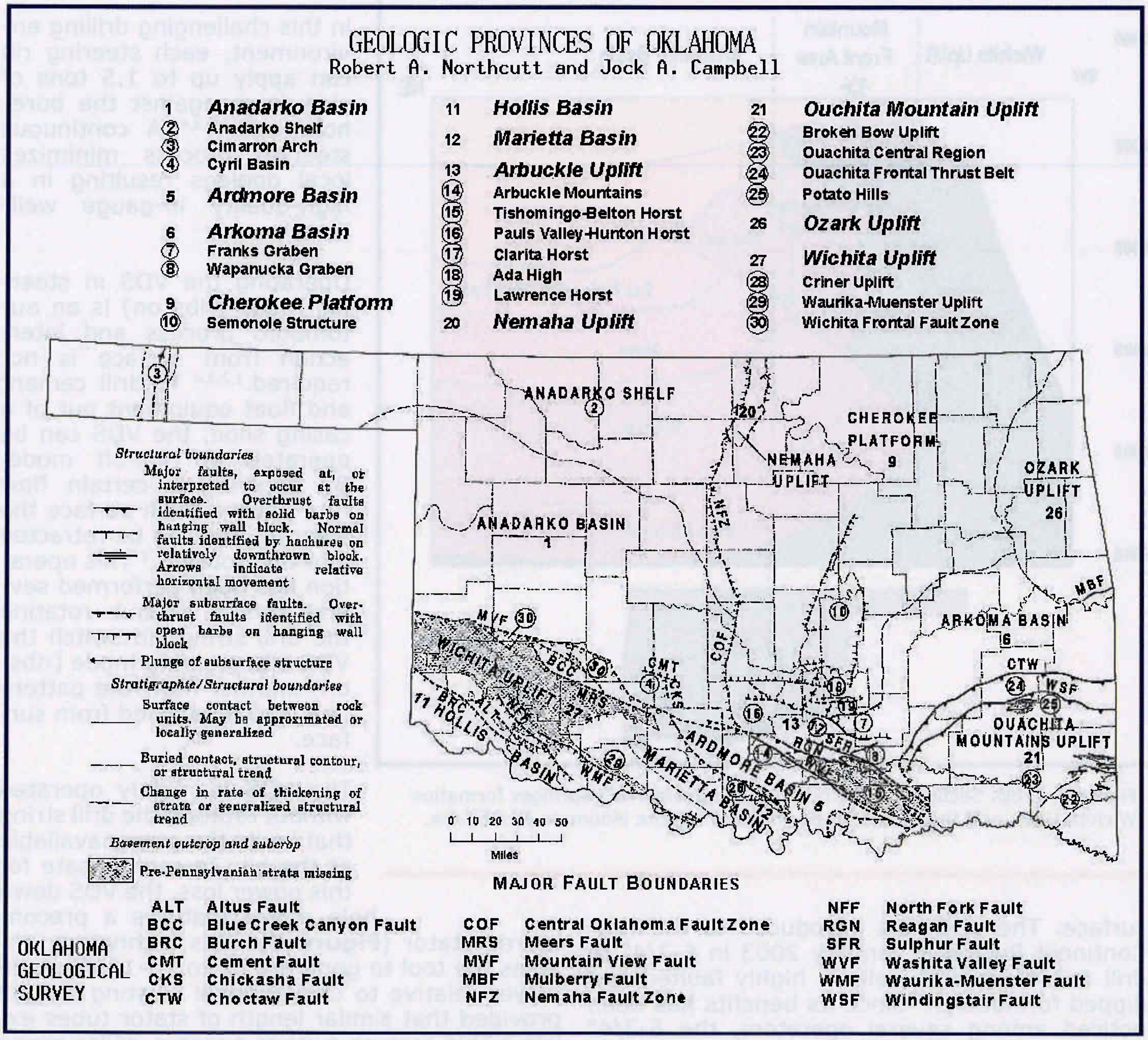


Figure 2. Geological Provinces of Oklahoma showing major fault systems (Map by Robert A. Northcutt and Jock A. Cambell, Source: Oklahoma Geological Survey – Seismology, reproduced with permission, location: http://www.okgeosurvey1.gov/level2/geology/ok.geo.provinces.large.gif

at the highest possible ROP while maintaining a near vertical wellbore.

Vertical Drilling System—Tool functionality and design

The vertical drilling device (VDS) consists of an automated single closed-loop downhole tool. The major components (bottom-top) are the steering unit (including bearing housing with steering ribs), a high torque power section, the control sub (with the electronic module and control unit) and the pulser housing (with turbine, oil pump and pulser). The VDS tool is an individual closed loop system with the option of 2-way communication with the driller at surface.[1,2,3,4] Both the VDS tool and the surface system are furnished with state of the art drilling and evaluation technology.

The surface system requires a standard set up consisting of a pressure transducer and a pulse decoding system.[1,2,3,4] The surface system continuously decodes the positive mud pulses sent from the VDS tool. A repetitive series of pulses provide valuable information (e.g., borehole inclination, high-side tool face orientation, ribs off/on mode and internal hydraulic pressure) to

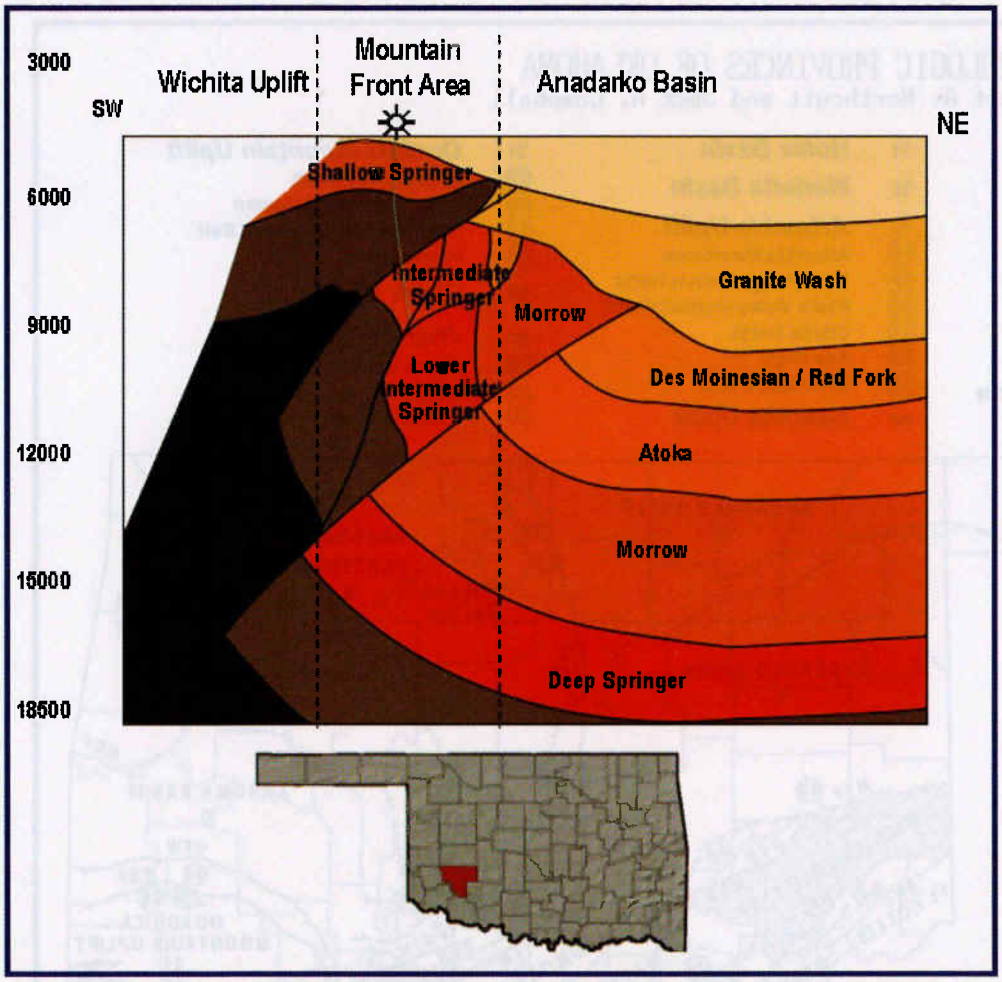


Figure 3. Cross Section of overthrusted and overturned Springer formation Wichita Uplift and the Anadarko Basin adjoining the Mountain Front Area.

in this challenging drilling environment, each steering rib can apply up to 1.5 tons of side force against the borehole wall.[1,2,3,4] A continuous steering process minimizes local doglegs resulting in a high-quality in-gauge wellbore.[5]

Operating the VDS in steering mode (ribs on) is an automated process and interaction from surface is not required.[1,2,3,4] To drill cement and float equipment out of a casing shoe, the VDS can be operated in ribs-off mode. By applying a certain flow rate pattern from surface the steering ribs can be retracted into the housing.[3] This operation has been performed several times without rotating the drill string. To switch the VDS into steering mode (ribs-on) another flow rate pattern needs to be applied from surface.

The VDS is mainly operated without rotating the drill string that limits the power available at the bit. To compensate for this power loss, the VDS down hole motor features a precontoured stator (**Figure 6**). This technology enables the tool to generate up to 50-100% more power relative to conventional existing stators provided that similar length of stator tubes exists.[5] This feature further opens a wider range of drilling applications in regards of higher circulating temperatures.

surface. The VDS was introduced to the Mid-Continent Region in January 2003 in 6-3/4″ to drill 8-3/4″ vertical wells in highly faulted and dipped formations.[4] Since its benefits has been noticed among several operators, the 6-3/4″ VDS has also been operated in a wider range of hole sizes from as small as 8-1/2″ to 9-7/8″.

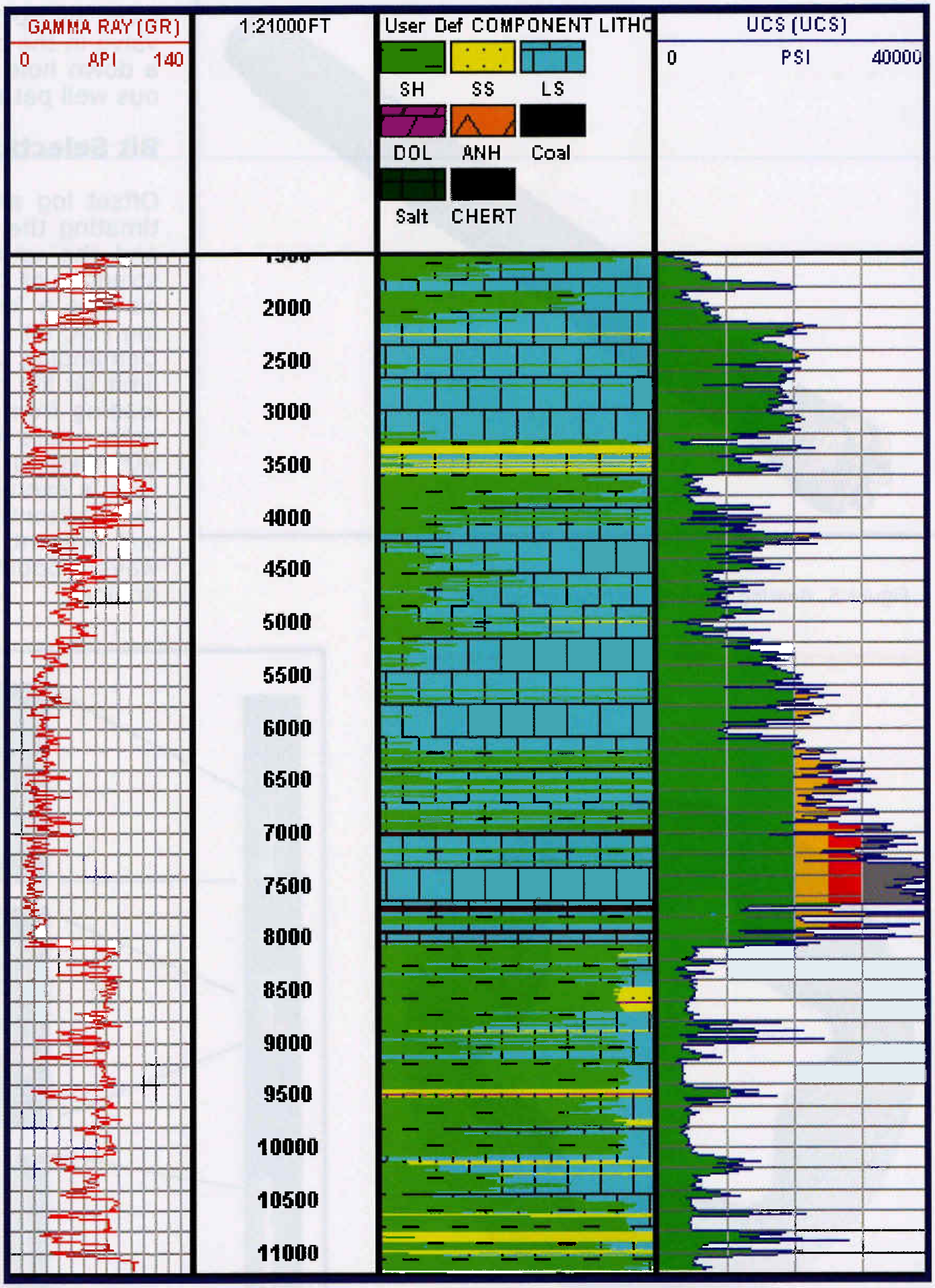
Three hydraulically controlled spring loaded steering ribs are located at the upper bearing housing approximately 2 ft behind the bit[1] (**Figure 5**). The short distance to the bit and the ability to control each rib individually keeps the BHA at its desired vertical path. The steering ribs are connected to the control sub by three hydraulic lines drilled through the mud motor section to energize either one or two steering ribs should the BHA deviate form its near-vertical well path (vertical well path correction).[1,2,3,4]

Highly dipping formations are an ideal application to deploy VDS to minimize expensive corrections runs due to high formation dip angles (40°-60°). To maintain a near-vertical well path

Two different power sections are available; medium speed/high torque and a slow speed/high torque power section enabling the operator to choose the right motor for the application. The slow speed/high torque motor reduces bit RPM leading to longer bit life. It could also be utilized for some PDC bits that perform at reduced RPM. The medium speed/high torque power section has been field tested and successfully proven in several different PDC applications.

The sensors for the measurement of borehole inclination, down hole temperature and the oil pressure for the steering ribs and the valves are located inside the control sub. A turbine in the mud flow of the pulser housing provides the re-

Figure 4. Offset Log Analysis for Lithology and Rock Strength Estimation



quired electric energy to power the system. A mud pulser (internal component of the pulser housing) transmits all measured down hole data and tool status information to surface (**Figure 7**).

Two accelerometers attached to the electronic module measure deflection from a true vertical position (accuracy 0.01°), highside tool face, and automatically correct back to a vertical position. Within the mudflow, a turbine drives the alternator and generates the necessary voltage to power the electronic module. The same drive train also houses a hydraulic oil pump to deliver the necessary pressure to the hydraulic pistons within the spring-loaded steering ribs (**Figure 8**). Within each steering cycle (minimum every 30 seconds) either one or two ribs will be ener-

Figure 5. Bearing Housing with Steering Ribs

Figure 6. Cross Section of High Torque/Medium Speed Stator

gized by opening the appropriate valve in the control unit to deliver a down hole closed loop continuous well path correction.

Bit Selection

Offset log analysis helped in estimating the component lithology and the unconfined compressive strength of the rock. This analysis was a key factor to optimizing PDC bit selection for the VDS. Demanding steerable applications limit bit life due to increased side loading from the bent sub during both rotate and slide operations. VDS extends bit life since the bit face is evenly engaged. However, the horizontal load component is still present since the tool is always producing a side load while drilling.

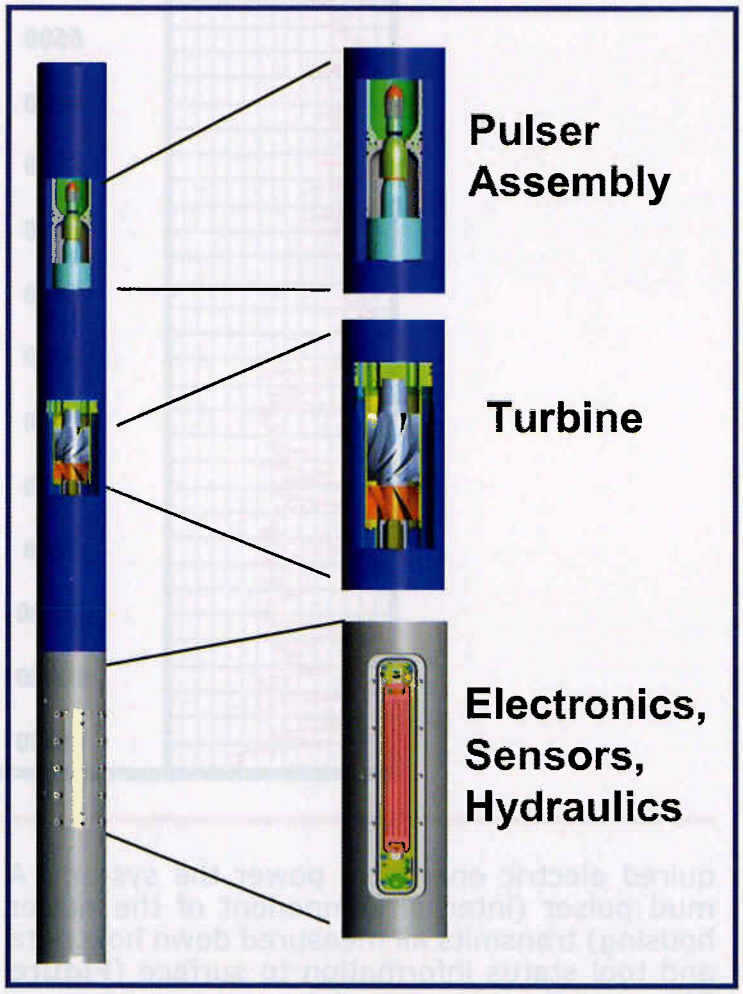
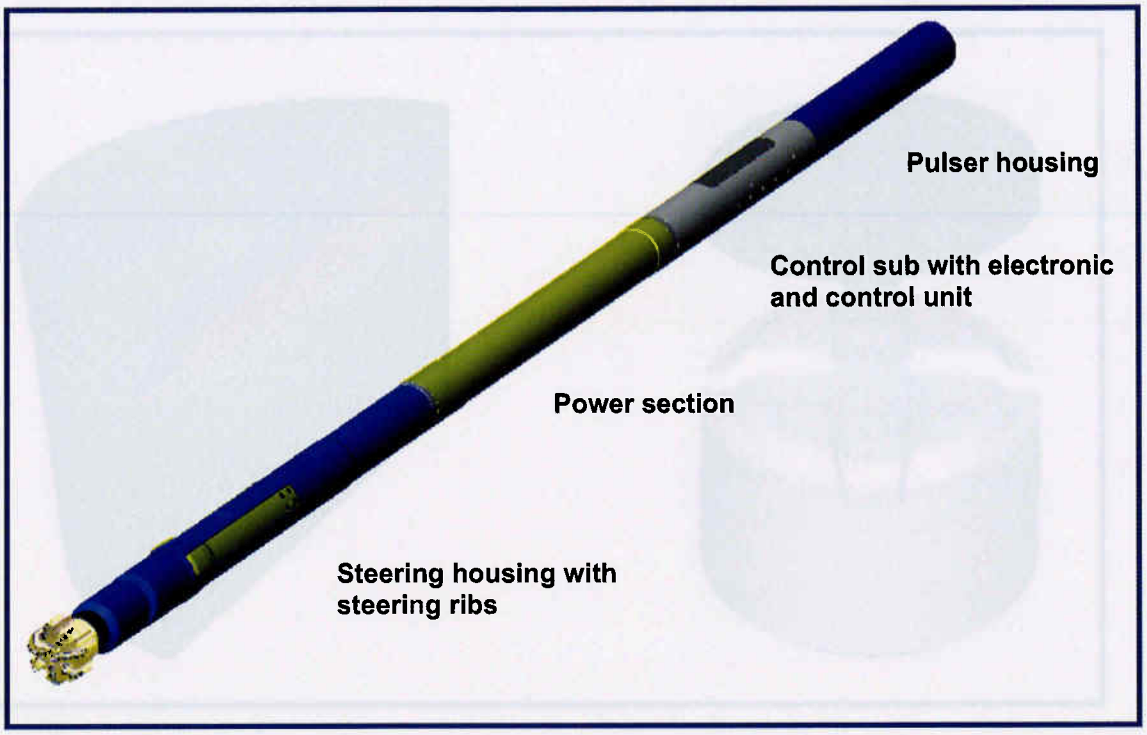


Figure 7. Control Sub and Pulser Housing

Figure 8. Vertical Drilling System (VDS)



Engineers would utilize the best performing bits from VDS offset wells. Roller cone bits were configured to maximize durability with the VDS. A variety of IADC code 527 through IADC code 627 bits were required to drill the hard sandstone and limestone. The outer bit legs were fortified with gauge compacts and hardfacing to maximize resistance to rubbing on the bore hole wall. Diamond gauge and heel compact enhancement were utilized to assure an in-gauge hole diameter, even in the event of cutting structure breakdown.

Opportunities for PDC bits were pursued to improve footage and ROP. Six, eight, and nine bladed bits were selected, depending on the need for abrasion resistance and durability. The latest generation of abrasion resistant 0.5″ and 0.625″ cutters (**Figure 9** & **Figure 10**) extended the use of PDC bits into harder more abrasive formations than previously possible.[6]

Generally, longer gauge bits with engineered side cutting aggressiveness were selected for running with the VDS. Additionally shorter gauge bits were also planned to be used in certain cases. Also, bits with a depth-of-cut control feature[7] to provide a torque limiting function were also used having been found well matched to the steering function of the VDS.[8,9,10,11]

Drilling Background

The operator drilled their first well in the Rocky area in 1995. These wells have a total depth in the range of 5,000 to 8,000 feet and were relatively shallower in comparison to the wells drilled in the Mountain View area that were typically in the 8,000 to 14,000 feet range. The operator faced the following problems:

- High wellbore inclination reaching up to 10°-15° for wells that were intended to be vertical
- Dogleg severity exceeding 10°/100 ft for vertical wells
- Unable to re-run steerable assemblies back to bottom resulting in unintentional sidetrack of wellbores
- Keyseating and difficult tripping of drill string
- Keyseating of open hole logging cable
- Destabilization of time sensitive shales
- Inability to slide with conventional drilling tools
- Drag (overpull above the string weight) in the range of 150,000 – 200,000 lbs
- Difficulty running logs to bottom requiring additional clean out trips to condition the wellbore for rerunning logs

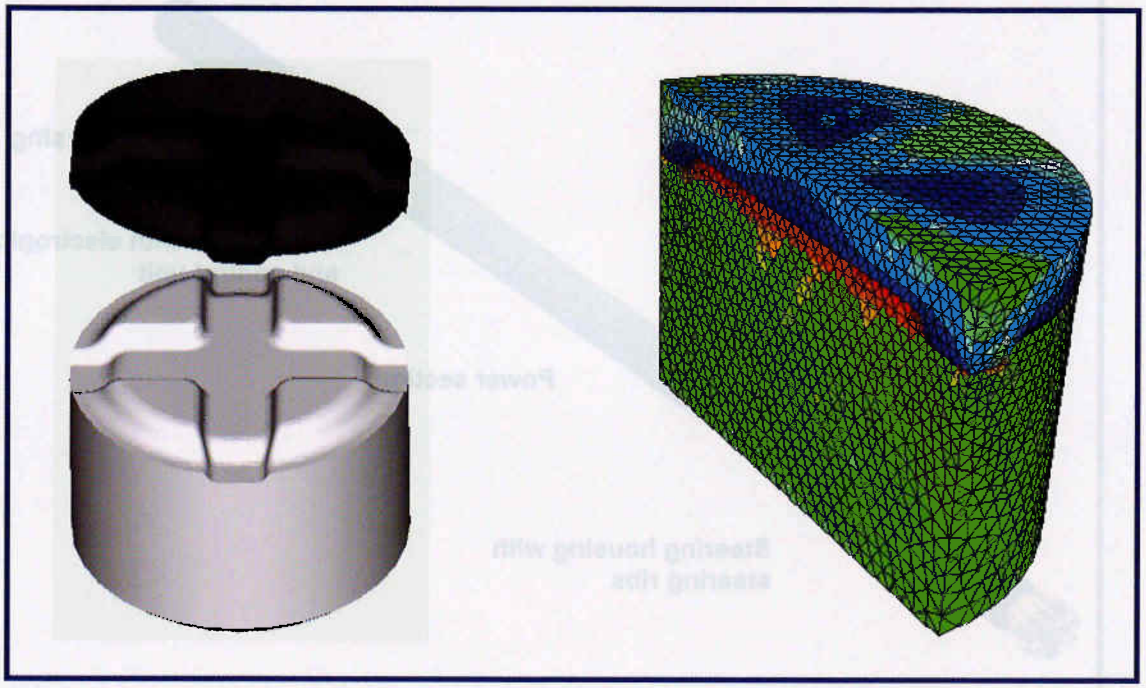


Figure 9. New PDC Cutter Interface with Residual Stress Plot

- Lubricant additives in the mud system partially reduced wellbore friction and drag but substantially augmented the daily operating cost
- Excessive drilling torque and poor transfer of weight to the bit resulting in reduced rates of penetration which in turn resulted in more bits/trips in reaching target depths
- Higher cost per foot
- Poor wellbore quality due to wash-outs and keyseating
- Excessive cement volumes required to ensure zonal isolation over all productive zones
- Excessive wear on drill pipe and BHA components in wells with severe wellbore tortuosity

Some of the solutions tried before the VDS tool include:

- Drilling with a packed hole assembly until the deviation was 5° or greater then pulling this assembly and going with a conventional bent housing motor to directionally drill to TD. With this strategy, the first assembly may drill from ±800 ft to ±3,000 ft before being pulled. If only 800 ft was drilled, significant flat time was encountered picking up and laying down the assembly.
- While attempting to keep the wellbore vertical drilling with a conventional bent housing motor from surface pipe to TD involved excess time sliding to overcome the dipping beds. This in turn slowed the penetration rate and extended the drilling time.
- Spotting the SHL to let the well "walk-out" and then "walk-back" to the correct BHL when crossing the fault. This technique was a major risk because doglegs could be so great the well would require HWDP all the way to target depth making it quite difficult to get WOB. Some wells would have 150 to 200k overpull once the well was down. Logging was difficult due to the complexity of the wellbore.

Case Study 1 – East Mountain Front (Rocky Area)

After drilling over 15 wells in the area (**Figure 11**) the strategy was to drill the 12-1/4" surface casing ±1200 ft with a slick BHA. Then using a packed hole assembly, drill the production interval (+5,300 ft) as described below. For this case study, the Buddy 5-32 & 4-32 are compared to the Buddy 6-32 which employed the VDS sys-

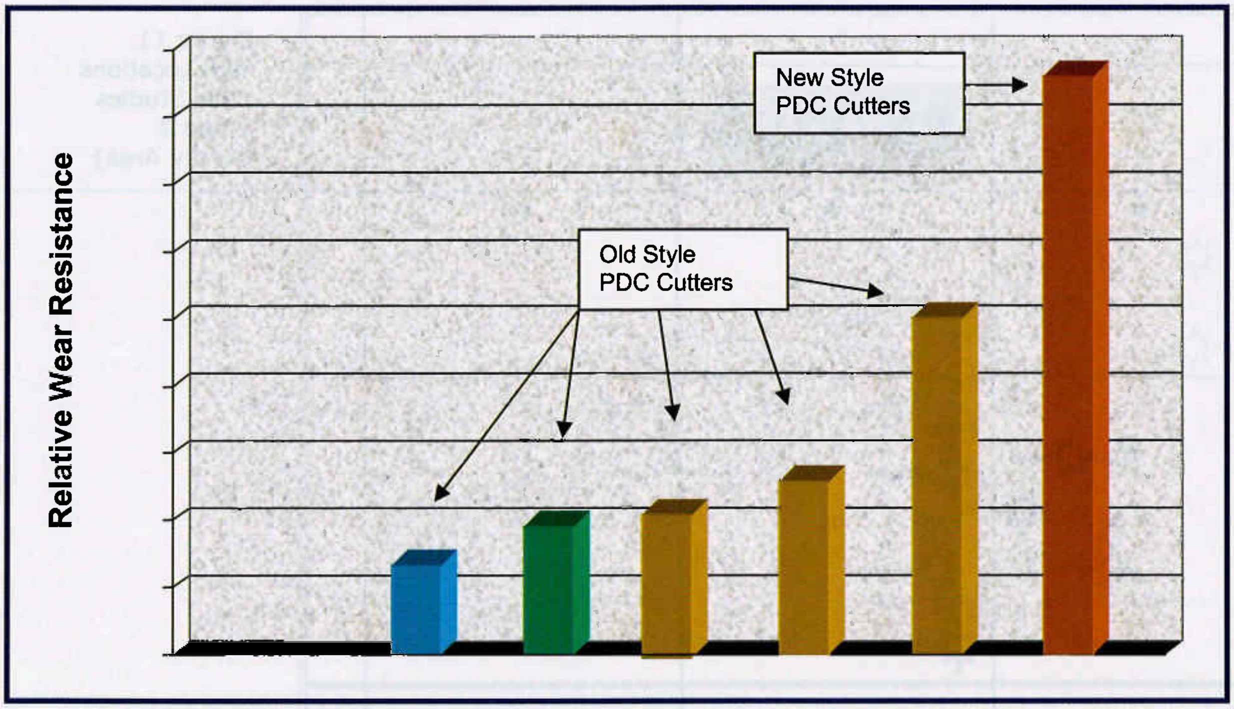


Figure 10. Laboratory Results Document Significant Increase in the New Cutter's Abrasion Resistance

tem. Note 8-1/2" hole section was selected so that additional clearance was achieved to reduce drag on drill pipe. The VDS system used 8-3/4" due to recommendation from the service company that this hole size was the optimal size in this application to achieve all the necessary goals.

Table 1: Packed Hole BHA 1

QTY	BHA ITEM
1	8-1/2" BIT
1	8-1/2" 6 PT REAMER
1	8-1/2"TRI-COLLAR (15 ft)
1	8-1/2" 3 PT REAMER
1	8-1/2 TRI-COLLAR (15 ft)
1	8-1/2" 3 PT REAMER
1	6-1/2" MONEL DC
18	6-1/2" DC's
1	DRILLING JAR
3	6-1/2" DC's
12	4-1/2" HWDP

Despite utilizing a packed hole assembly to drill the Buddy 5-32, the inclination reached 6.5° at a depth of 4,148 ft. It was decided to drill the remaining portion of the hole with a steerable assembly and a bent sub with a setting of 1.83°. On the trip out of hole, four hours were spent jarring on the drill string from 3,598 ft to 3,500 ft due to tight hole and high drag plus from 3,500 ft to 3,400 ft pumping the drill string out of the hole. The well was drilled to a target depth of 4,800 ft with a steerable assembly and a 7-7/8" (reduced from previous bit size of 8-1/2") roller cone bit. Although the steerable assembly managed to reduce the inclination to 3.5°, the dogleg severity reached up to 8.5°/100 ft (**Figure 12**).

The operator had a similar experience drilling the Buddy 4-32 utilizing an identical packed hole BHA (**Table 1**) with the addition of a shock sub below the monel drill collar from 1,204 ft to 4,761 ft. When the inclination reached 4.4°, a steerable assembly (bent sub with a 1.5° setting) and bit size reduced to 7-7/8" was utilized to drill from 4,761 ft to a TD of 5,300 ft. On the trip out of hole to change the BHA, an overpull of 50,000 lbs was observed and several hours spent in clearing the tight spots from 4,073 ft to 3,394 ft. The high inclination and dogleg severity on the wells is shown in **Figure 12**.

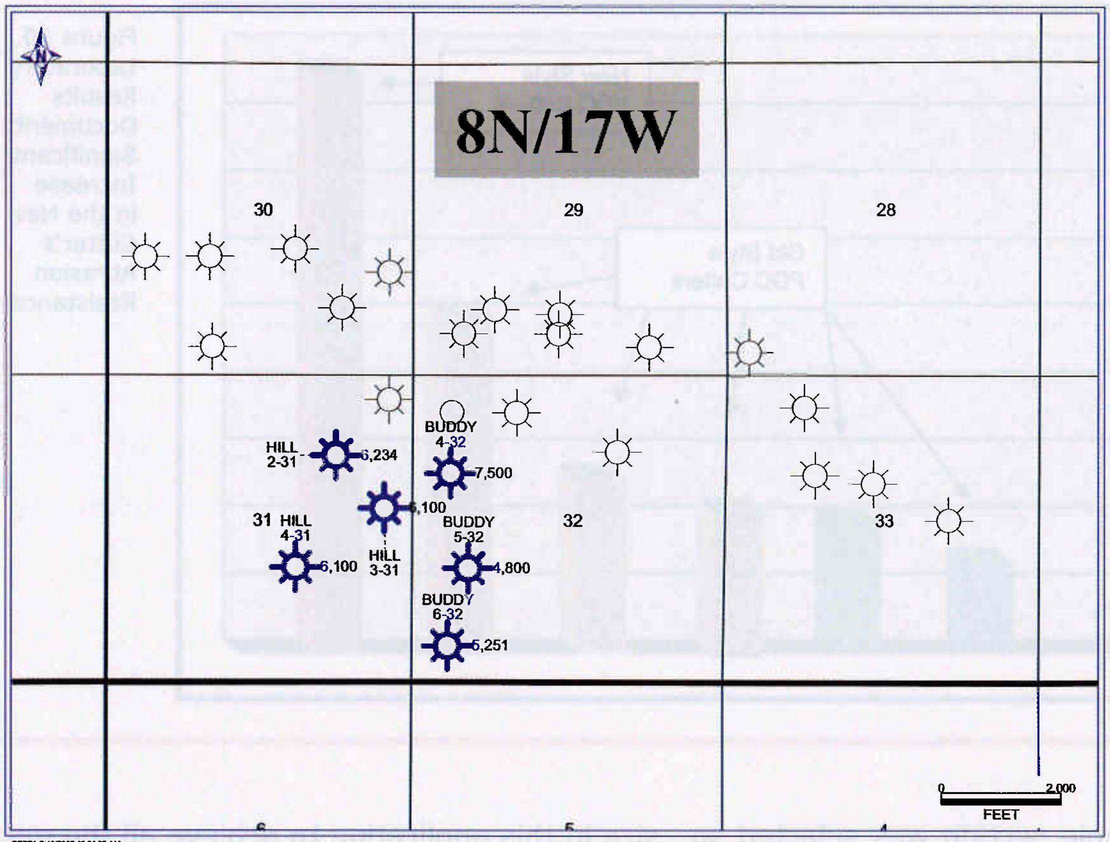


Figure 11.
Well Locations
Case Studies
1 and 2
(Rocky Area)

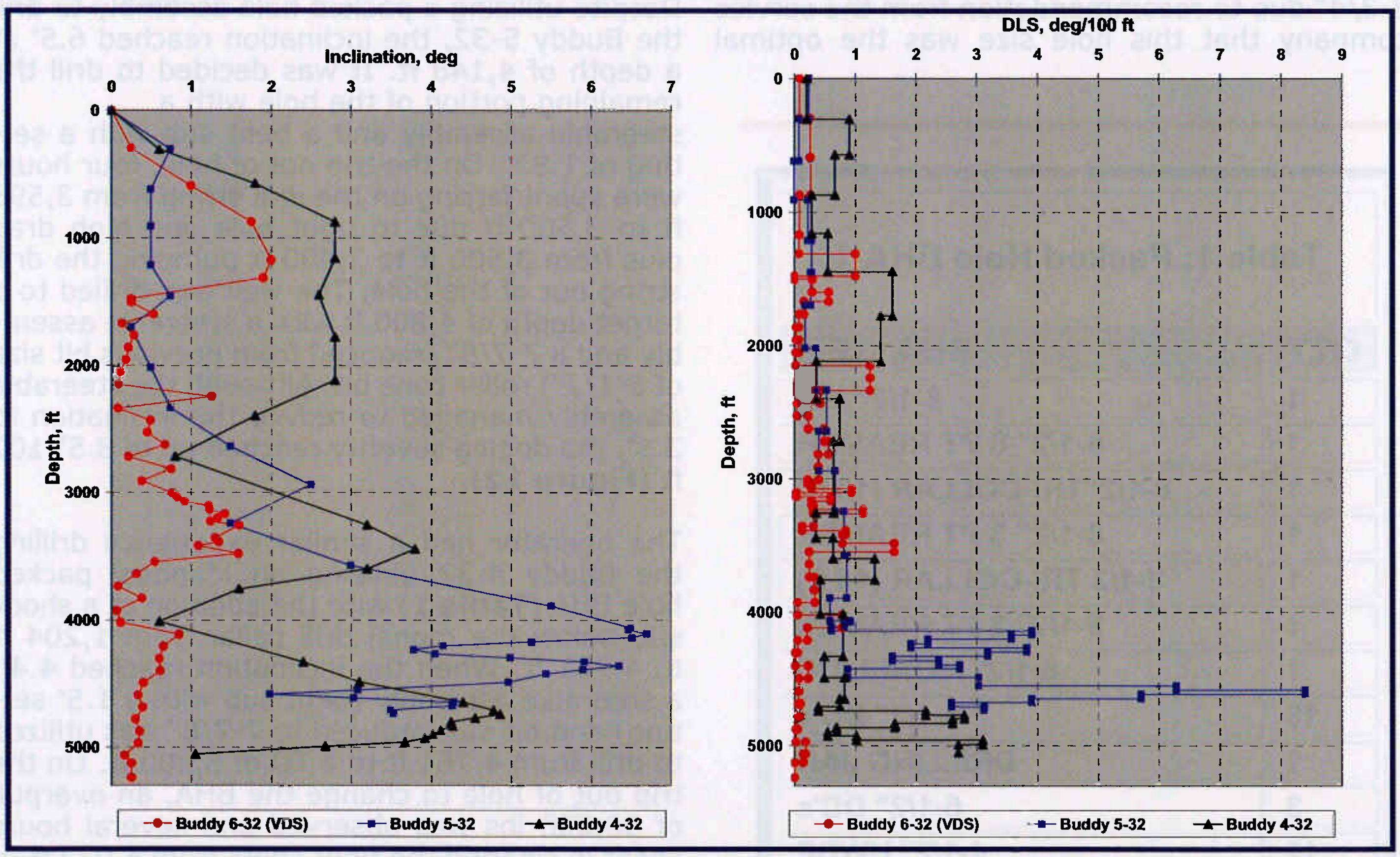


Figure 12. Inclination and Dog Leg Severity Plots (Case Study 1)

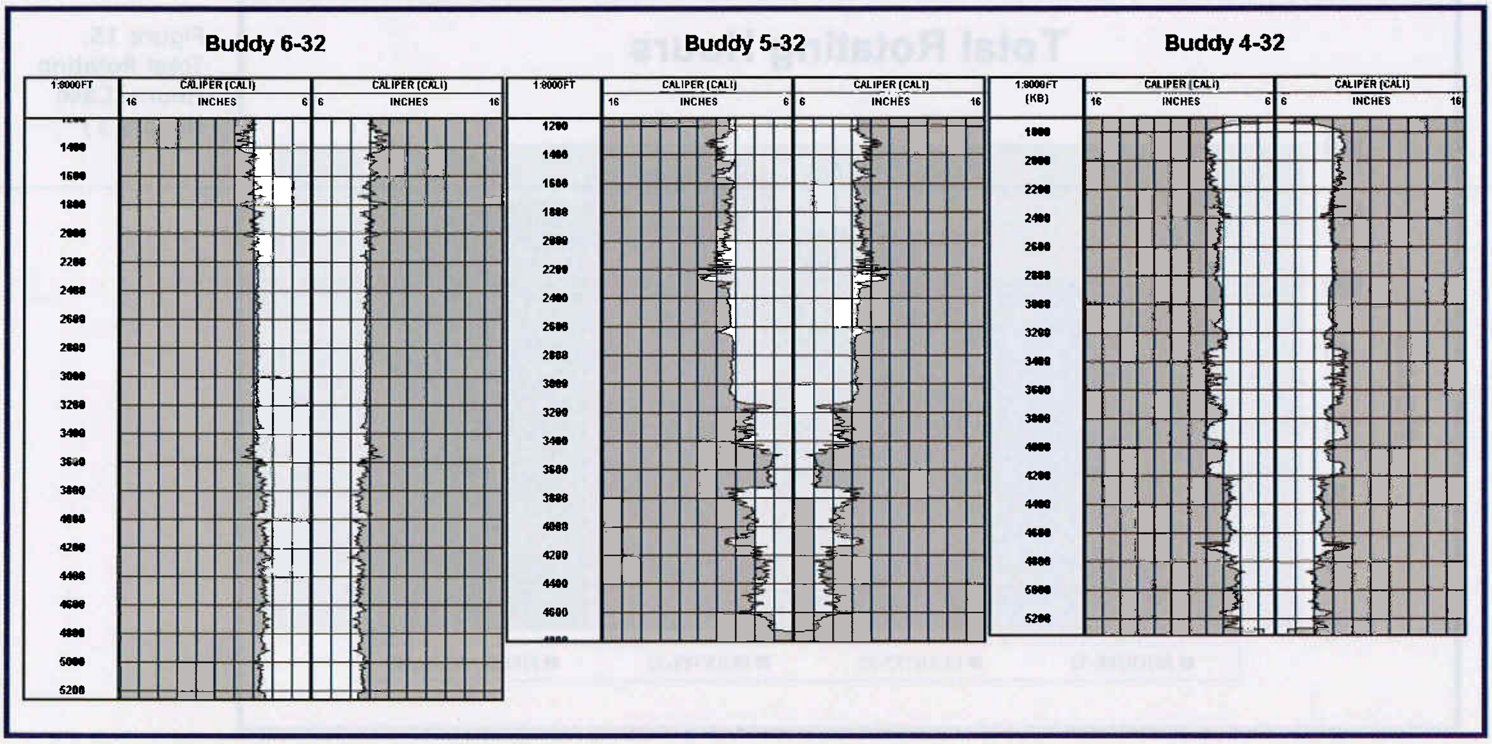


Figure 13. Caliper Logs (Case Study 1)

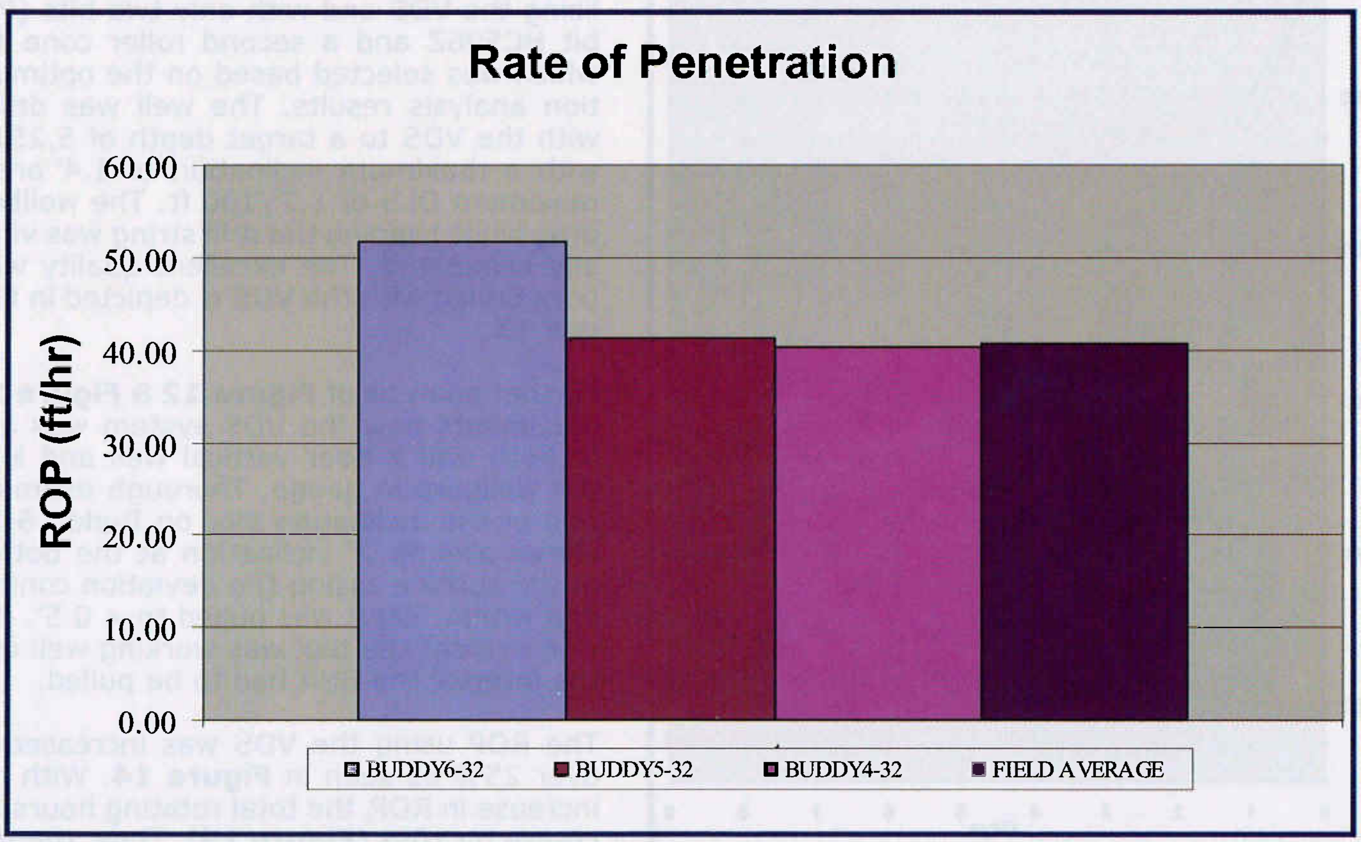


Figure 14. Rate of Penetration (Case History 1)

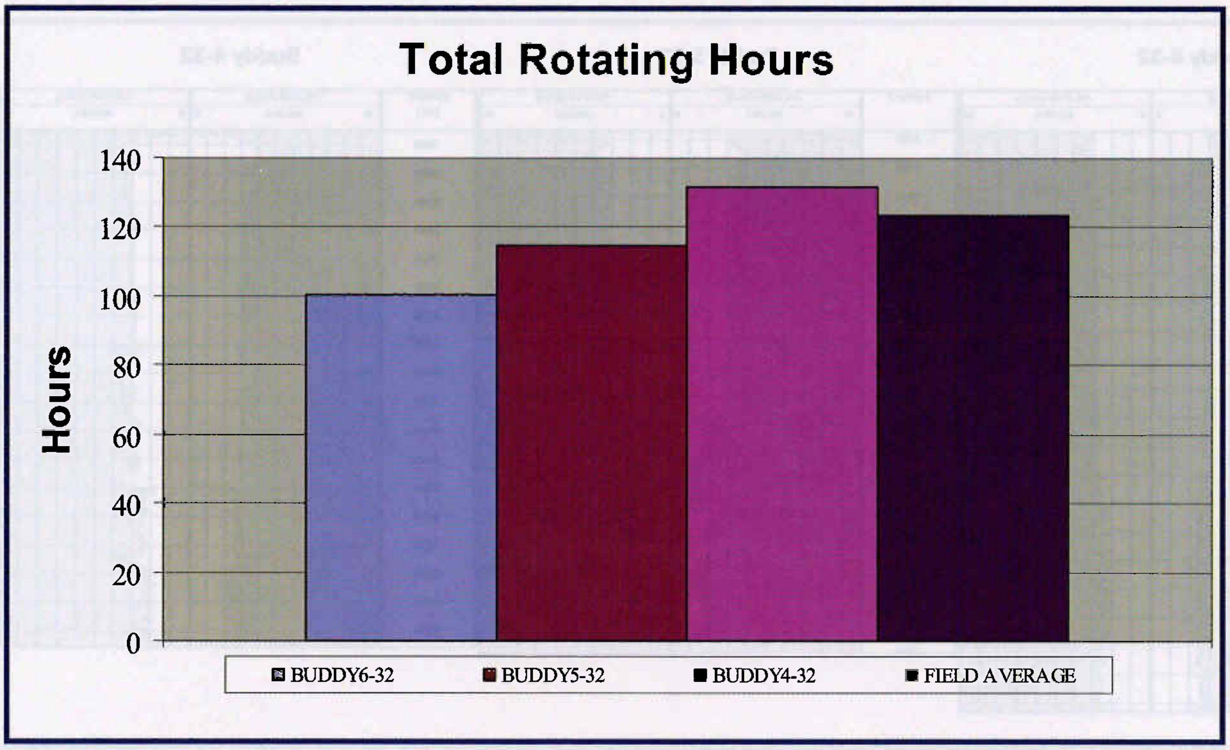


Figure 15. Total Rotating Hours (Case History 1)

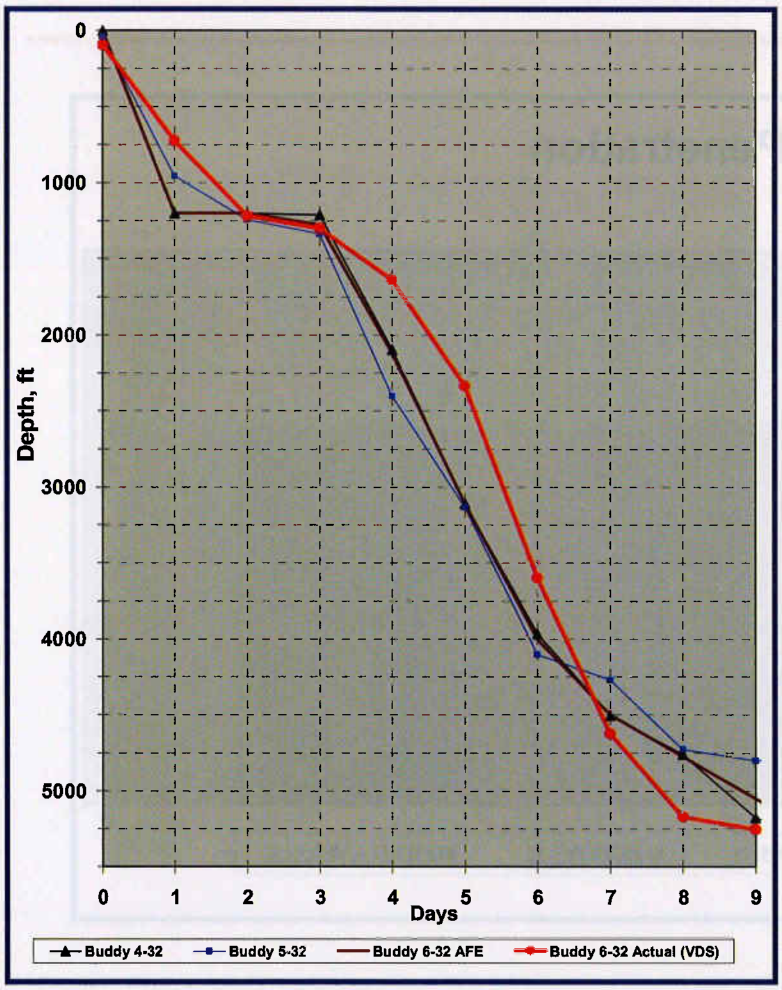


Figure 16. Days vs Depth Plot (Rocky Area)

The Buddy 6-32 well was drilled to TD utilizing the VDS and with only two bits (PDC bit HC506Z and a second roller cone bit) which was selected based on the optimization analysis results. The well was drilled with the VDS to a target depth of 5,251 ft with a maximum inclination of 1.4° and a maximum DLS of 1.7°/100 ft. The wellbore drag while tripping the drill string was virtually eliminated. The excellent quality wellbore drilled with the VDS is depicted in **Figure 13**.

Further analysis of **Figure 12** & **Figure 13**, documents how the VDS system was able to both drill a near vertical well and keep the wellbore in gauge. Thorough examination of the inclination plot on Buddy 6-32, shows around 2° inclination at the bottom of the surface casing (no deviation control) and within 100 ft was pulled to < 0.5°. It is also evident the tool was working well over the interval the BHA had to be pulled.

The ROP using the VDS was increased by over 25% as seen in **Figure 14**. With this increase in ROP, the total rotating hours decrease by 16% (**Figure 15**). Thus, the VDS system was able to achieve the economic goals set forth by the team (**Figure 16**).

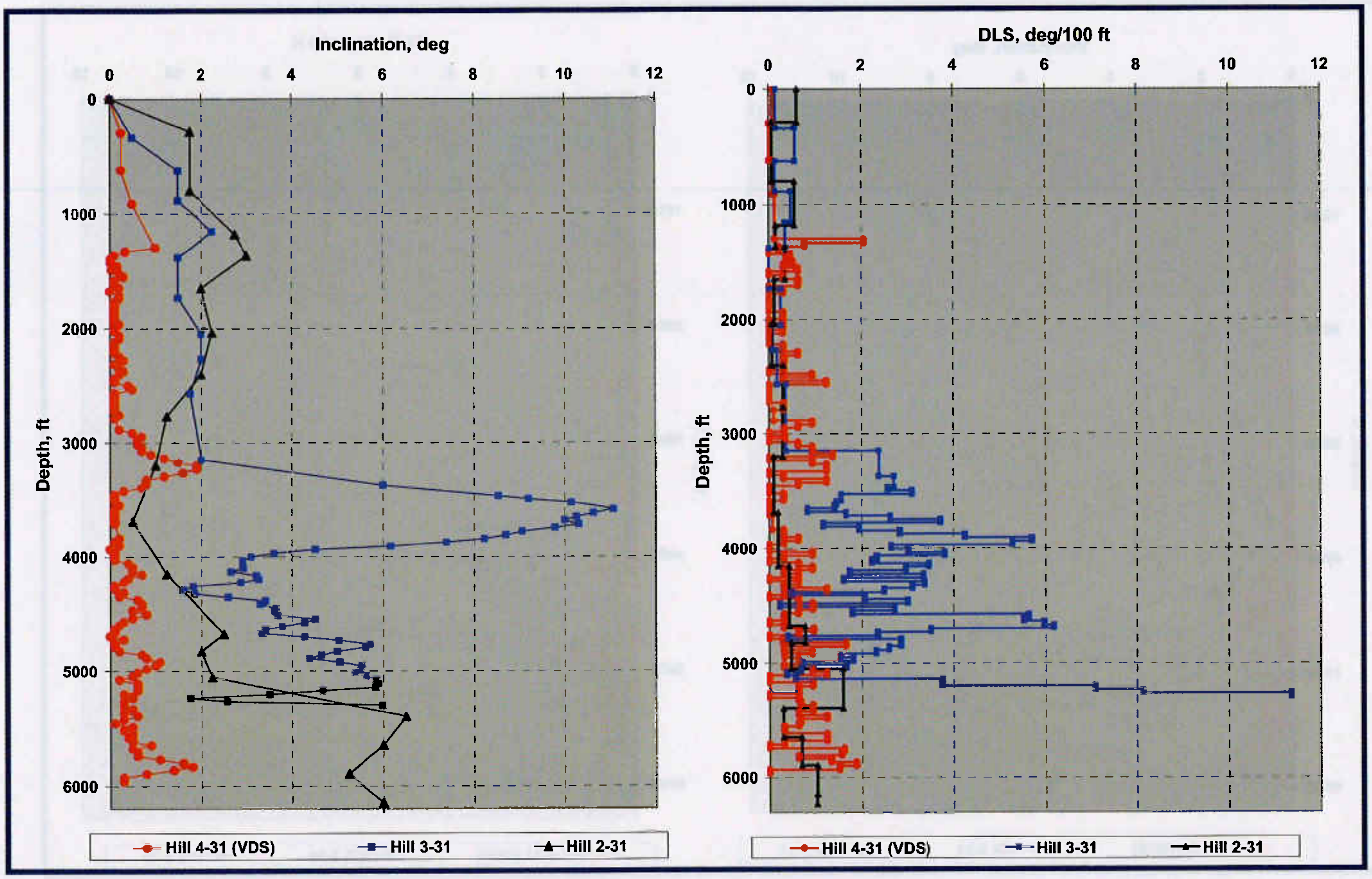


Figure 17. Inclination and Dog Leg Severity Plots (Case Study 2)

Case Study 2 - East Mountain Front (Rocky Area)

The second case study is west of the first case study (**Figure 11**). Wells Hill 2-31 and Hill 3-31 were drilled with a packed hole assembly while the Hill 4-31 used the VDS system.

The entire 8-1/2" hole section (1,210 ft to 6,230 ft) on Hill 2-31 was drilled with four roller cone bits and a packed hole assembly as shown in Table 1 with the addition of the shock sub below the monel drill collar. While drilling the well, inclinations up to 6.5° were reached (**Figure 17**). During the logging of the well, obstructions were encountered at 5,580 ft caused additional cleanout trips to get logs to bottom.

The excellent quality wellbore drilled with the VDS is depicted in Figure 18. On well Hill 2-31 logging tools encountered severe obstruction at a depth of 5,580 ft. An additional clean out trip was required to condition the hole and enable re-running logging tools to bottom.

On the Hill 3-31, the operator utilized an identical packed hole BHA (**Table 1**) with the addition of a shock sub below the monel drill collar from 1,204 ft to 3,520 ft. Inclination peaked to 6° and therefore a steerable assembly (bent sub with a 1.5° setting) and bit size reduced to 7-7/8" was utilized to drill from 3,520 ft to a TD of 6,100 ft. A total of five bits were required to drill the 8-1/2"/7-7/8" hole section. The maximum inclination and DLS were 11° and 11.5°/100 ft (**Figure 17**). This helps illustrate how fragmented and difficult the drilling is in the area because the wells do not always drill exactly alike.

The entire 8-3/4" hole section on the well Hill 4-31 was drilled from to 1,240 ft to the target depth of 6,000 ft utilizing the VDS with only three bits (PDC bit HC506Z and two additional roller cone bits). The well was completed with a maximum inclination and DLS of 1.9° and 1.8°/100 ft respectively. There was no drag or overpull on any of the trips.

The ROP using the VDS was increased by over 27% (**Figure 19**). With this increase in ROP the total rotating hours decreased by 20% (**Figure 20**). Again saving time and money over the original plan of using a packed hole assembly until the angle was greater than 5°.

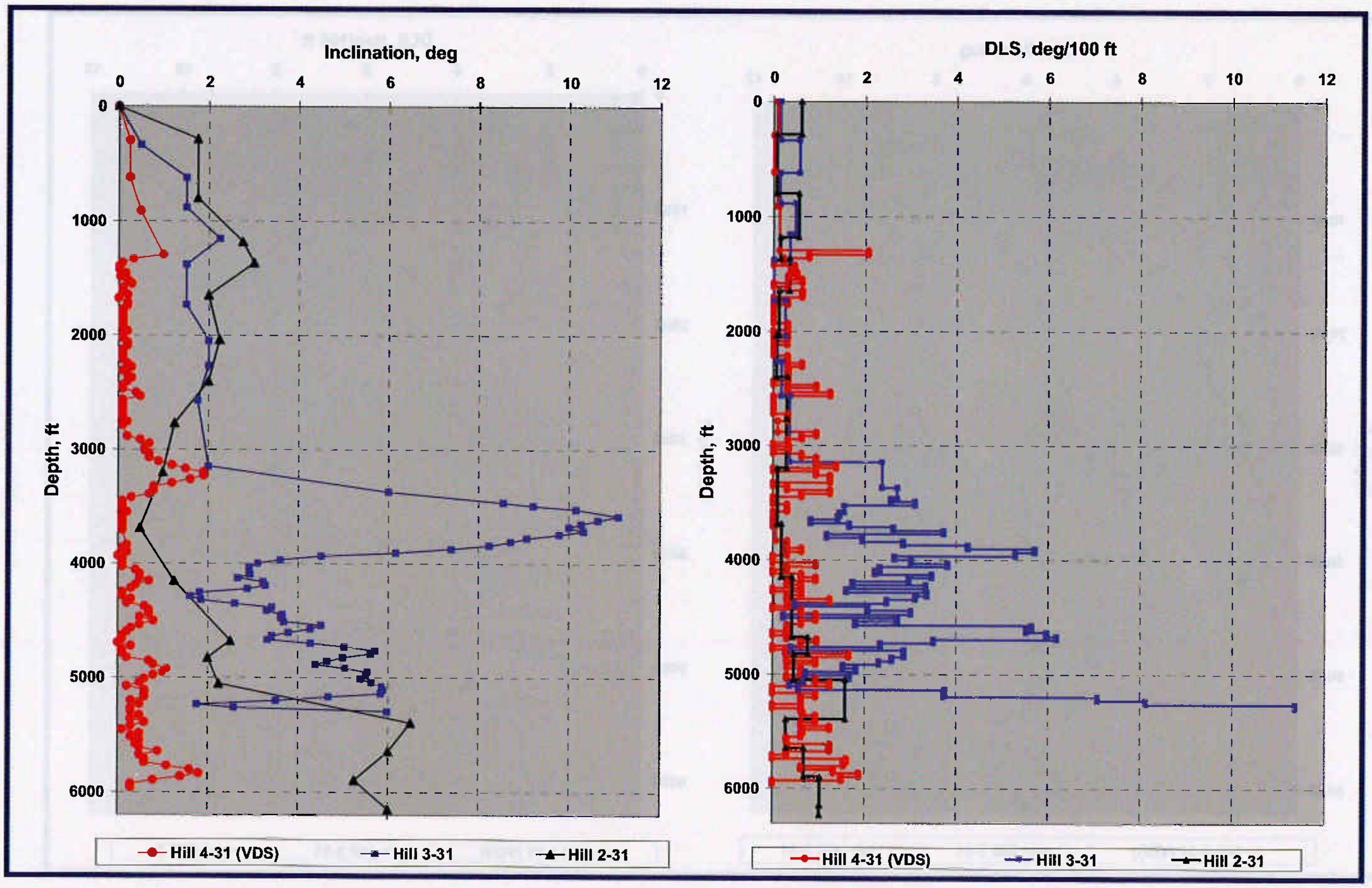


Figure 18. Caliper Logs (Case Study 2)

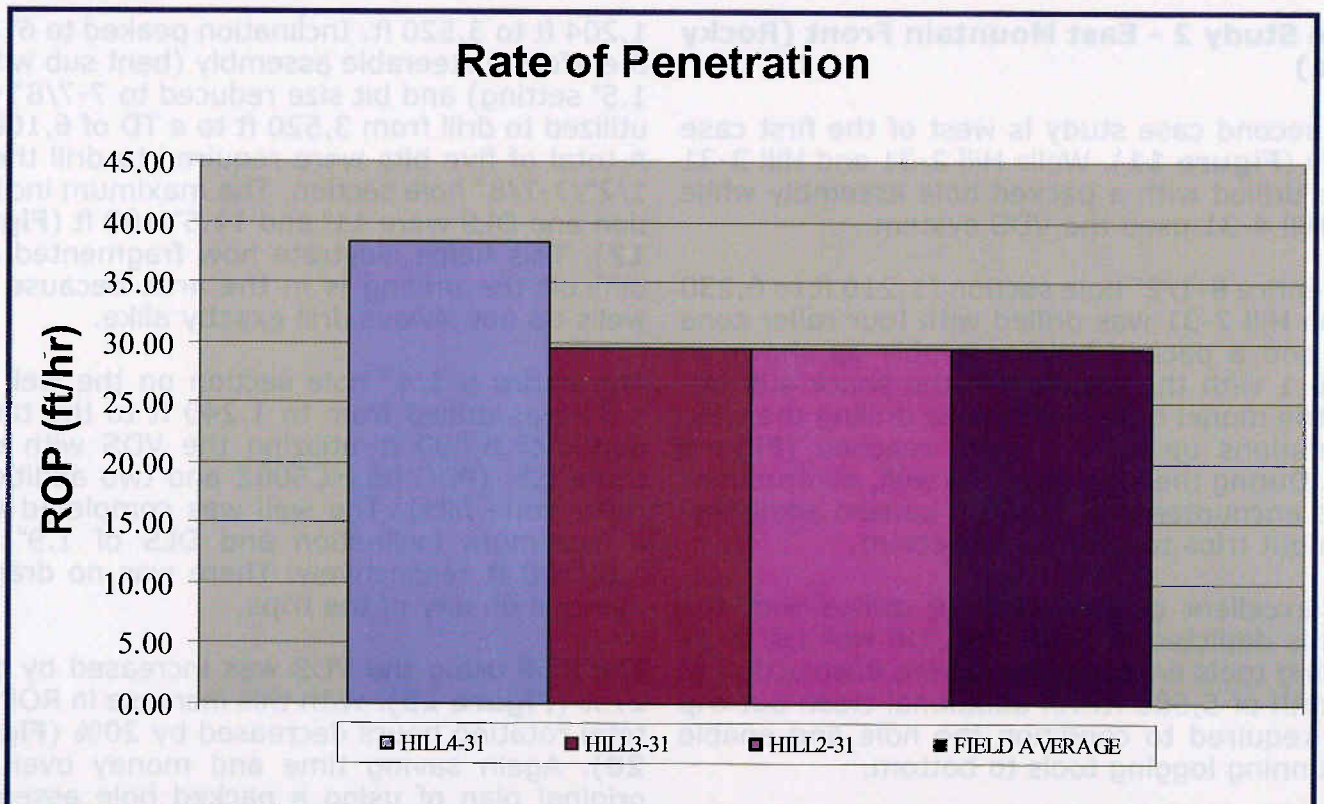


Figure 19. Rate of Penetration (Case History 2)

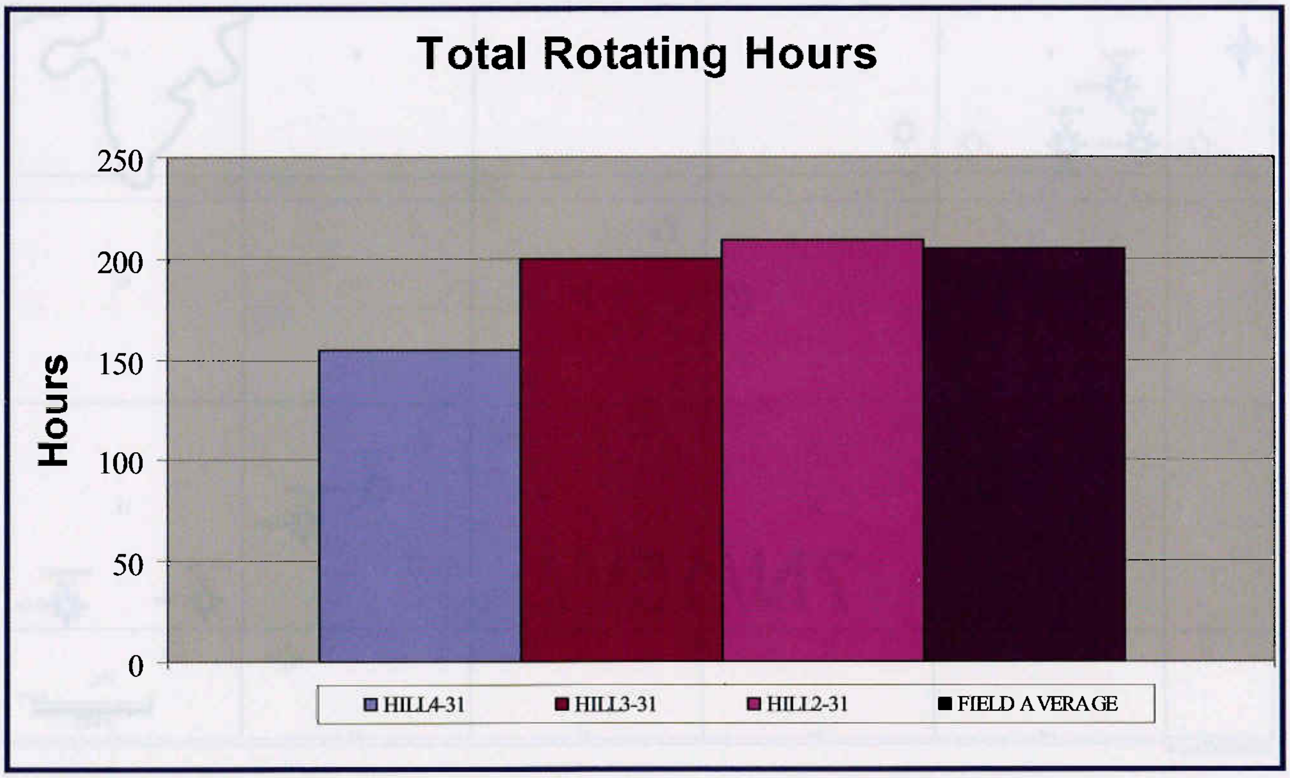


Figure 20. Total Rotating Hours (Case History 2)

From case study 1 and 2 it can be concluded that by offset well analysis, VDS and optimized bit selection, higher rates of penetration, fewer bits, fewer trips, ease of running logs and elimination of drag and tight hole on trips resulted in reaching TD in relatively fewer days and at a much lower cost per foot. Additional savings were achieved due to the elimination of the necessity to add lubricant to the mud system.

Case Study 3 - Mountain View Area

After setting the 9-5/8″ casing on Darla 3-5 (**Figure 21 - map**) at a depth of 2,200 ft and anticipating a complicated geological structure, a steerable assembly with a 1.5° bend was selected to drill the 8-3/4″ hole that was intended to be vertical. The poor wellbore quality of the well Darla 3-5 is shown on the caliper log in **Figure 22**. The 1.5° bent steerable assembly was not able to control the inclination building tendency of the hole which reached 5.72° at a survey depth of 2,833 ft and therefore a trip was made to change the bend to 1.83°. The inclination was steered back to vertical and subsequently stayed under control with the 1.83° bent motor but doglegs with severity of 8°/100 ft per induced in the wellbore as seen in **Figure 23**.

From a depth of 9,100 ft to 9,750 ft, the well was steered directionally to meet reservoir targets that were revised while drilling for geological reasons. The 8-3/4″ hole section was drilled with seven bits. Several hours were spent to clear tight hole while tripping for bit/BHA change and overpull exceeding 100,000 lbs above string weight was encountered.

On the Darla 4-5, 9-5/8″ casing was set at 1,210 ft and a packed hole assembly with a 8-1/2″ bit as was run (**Table 1**). The inclination climbed to 8° at a survey depth of 3,047 ft and therefore a steerable assembly with a 7-7/8″ bit was run.Despite having directional tools in hole, wellbore inclination and dogleg severity reached 15.5° and 6.76°/100 ft at a survey depth of 7,496 ft (**Figure 23**). The well was drilled to a TD of 9,000 ft with total 11 bits (1 x 8-1/2″ and 10 x 7-7/8″). The lower 1,000 ft of the well was steered to meet the targets based on geological reasons. The high dogleg severity in the wellbore lead to overpull on several trips made for bit/BHA change. The overpull peaked up to 170,000 lbs above the string weight on the trip out of hole after drilling to TD.

A conditioning trip was made prior to running logging tools. However, logging tools encountered obstruction and could not be run to bot-

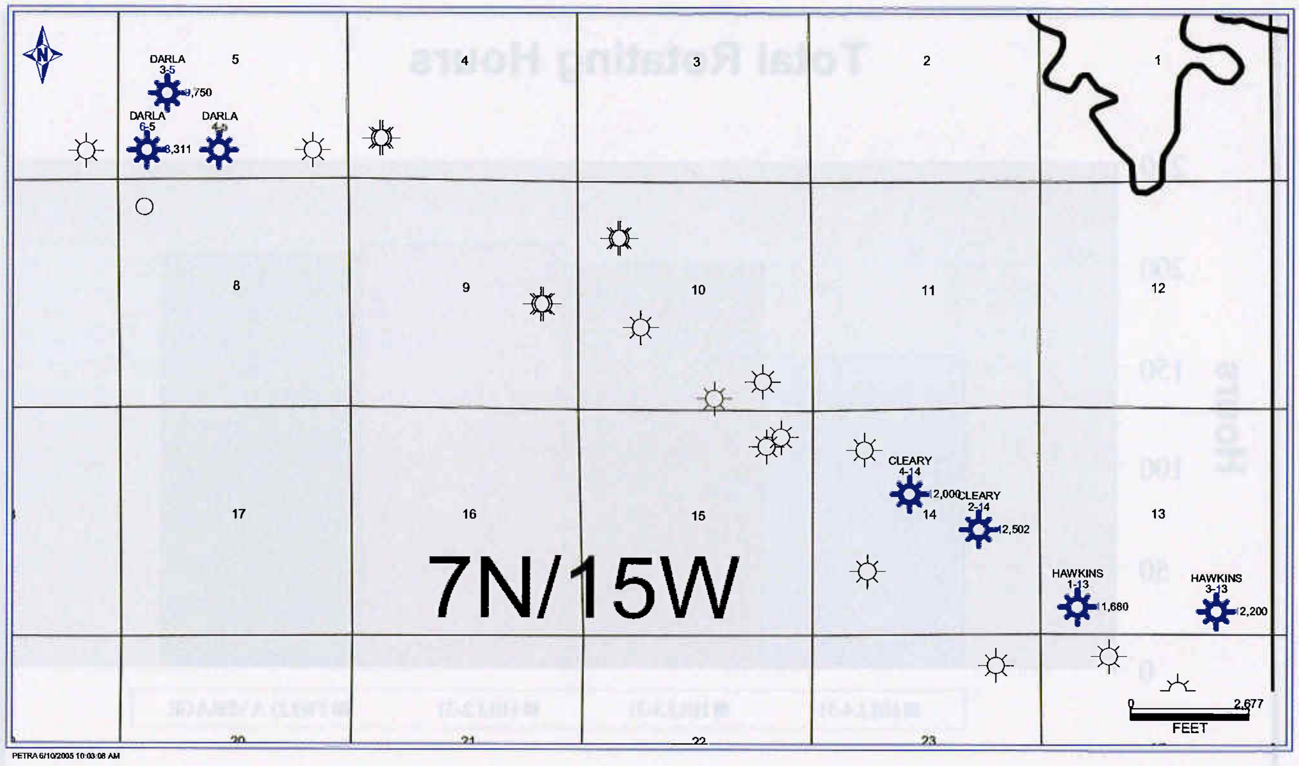


Figure 21. Well Locations of Case Studies 3 and 4 (Mountain View Area)

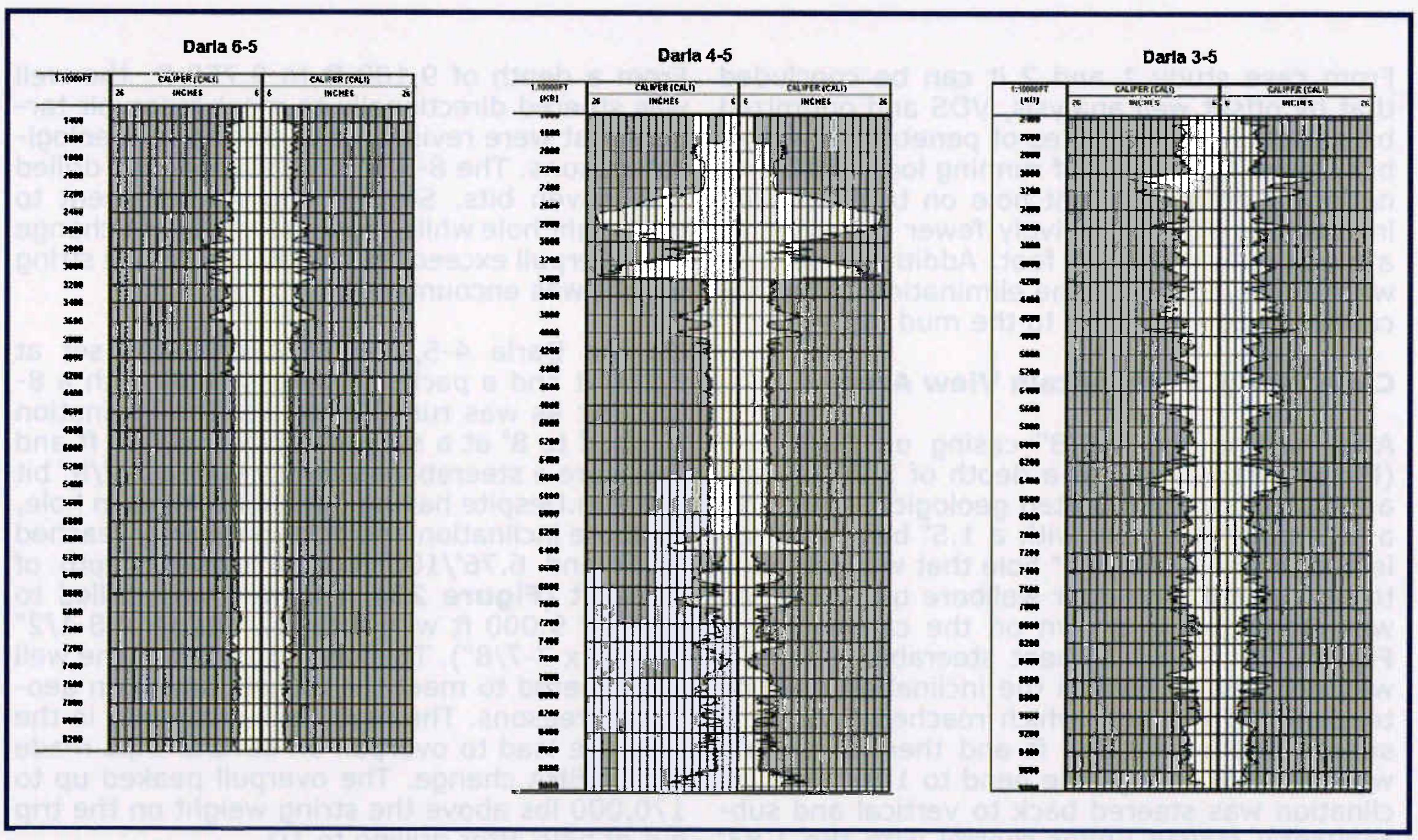


Figure 22. Caliper Logs (Case Study 3)

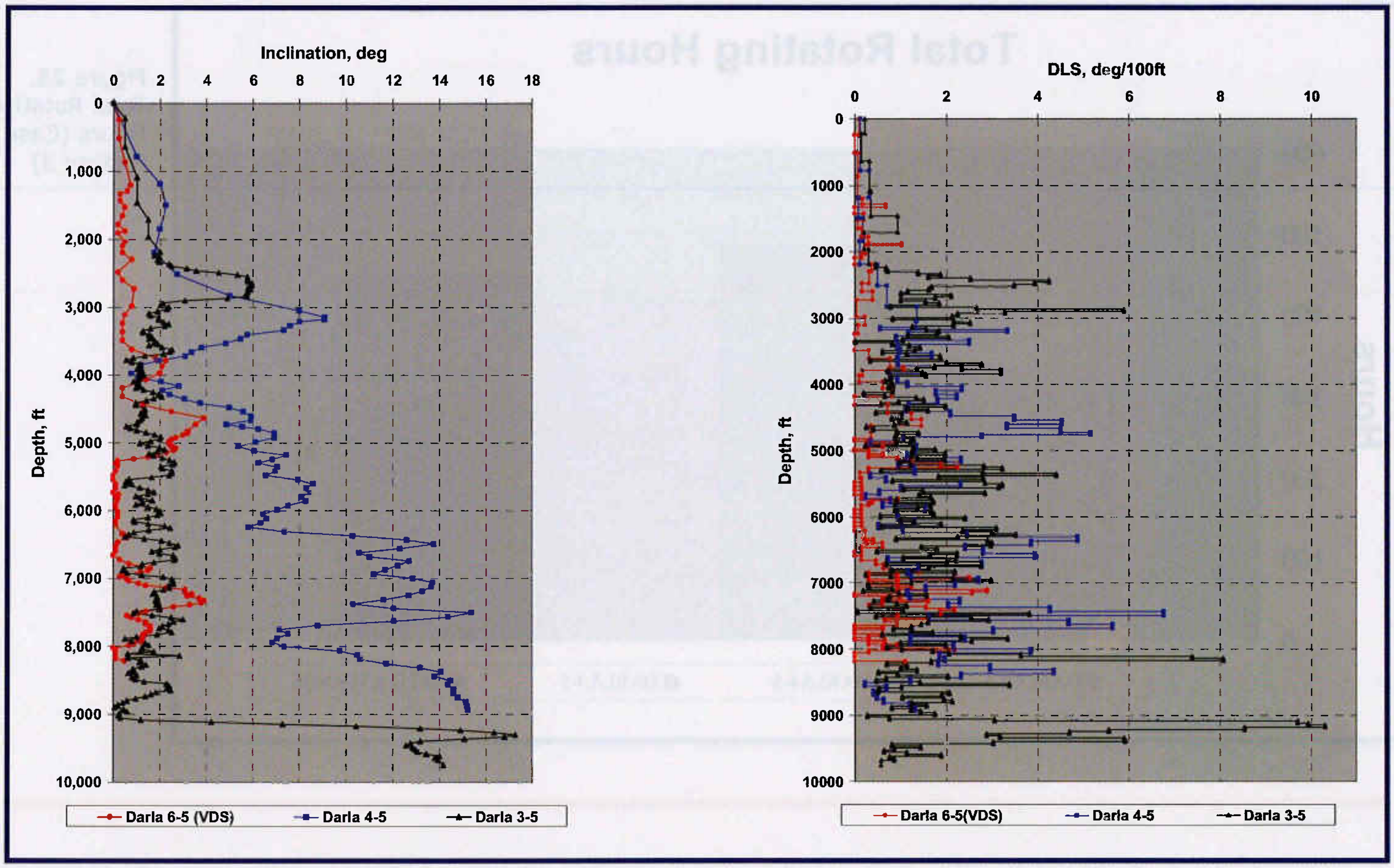


Figure 23. Inclination and Dog Leg Severity Plots (Case Study 3)

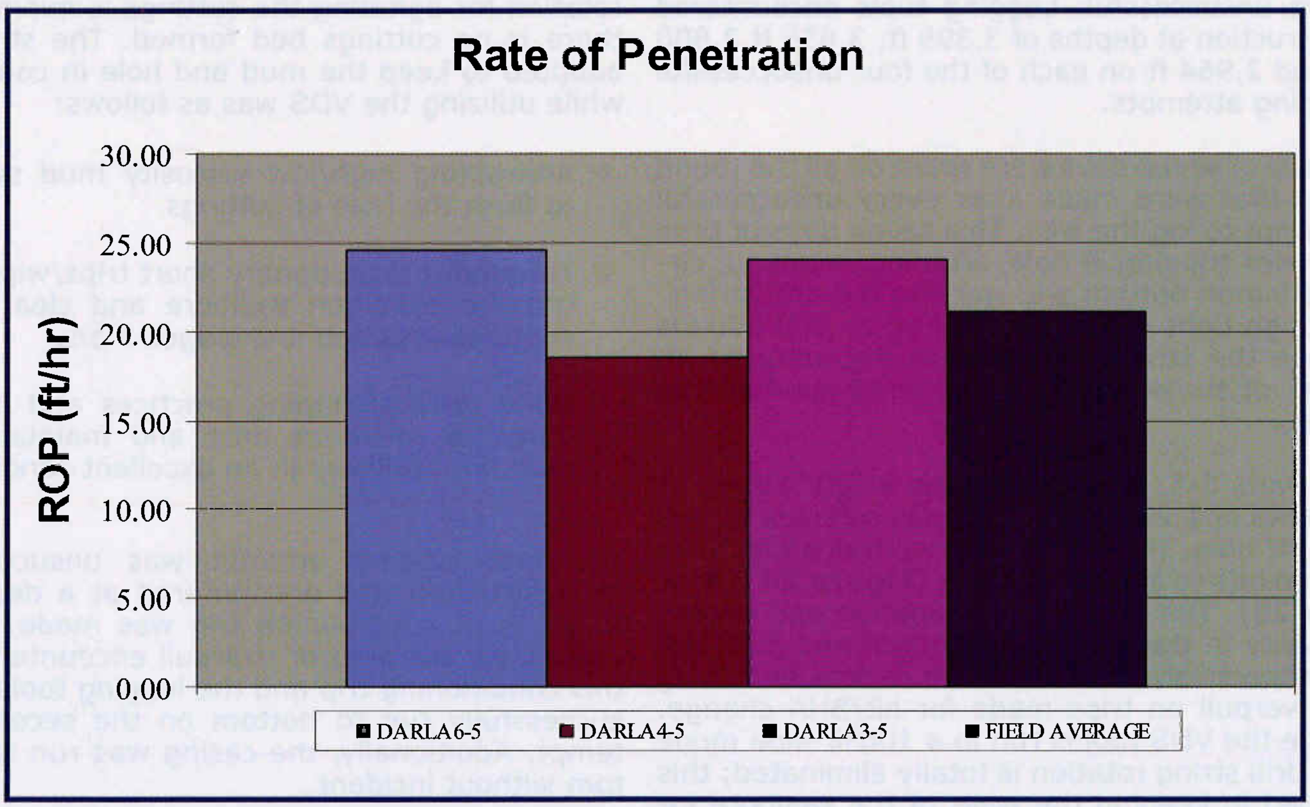


Figure 24. Rate of Penetration (Case History 3)

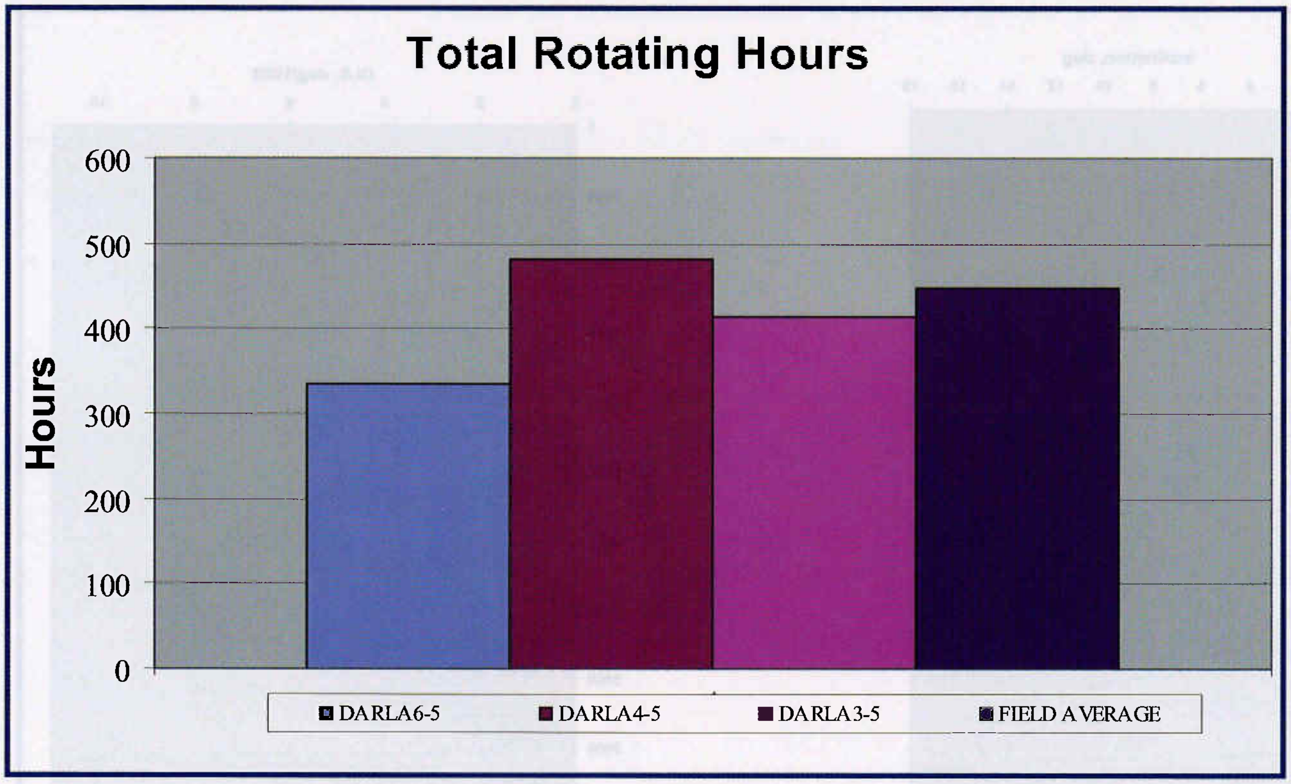


Figure 25. Total Rotating Hours (Case History 3)

tom due to high dogleg severity, poor wellbore quality and a severe obstruction(s) encountered in the wellbore. A total of six attempts were made to run logging tools. The first four were unsuccessful. Logging tools encountered obstruction at depths of 3,395 ft, 3,655 ft 2,800 ft and 2,964 ft on each of the four unsuccessful logging attempts.

A total of seven days were spent on all the round trips that were made after every unsuccessful attempt to log the well. This seven days of time includes tripping in hole, washing, reaming, circulating on bottom and working the drill string through tight spots; overpull up to 200,000 lbs above the string weight were encountered on most of these wellbore and mud conditioning trips.

On Darla 6-5, after setting the 9-5/8" casing at a depth of 1,239 ft the VDS was selected to drill 8-3/4" hole. The 8-3/4" interval was drilled with seven bits to a TD of 8,311 ft (**Figure 24** & **Figure 25**). The maximum inclination and dogleg severity in this interval were 3.9° and 2.9°/100 ft respectively. There was no excess hole drag or overpull on trips made for bit/BHA change. Since the VDS tool is run in a 100% slide mode the drill string rotation is totally eliminated; this helped in keeping the walls of the wellbore intact and eliminated the wear on drillpipe, casing and the rotary rig equipment. In directional or lateral wellbores drillstring rotation aids in keeping the wellbore clean by agitating the cuttings lying on the low-side of the annulus. In case of vertical wellbores, the benefit of drill string rotation for agitating the cuttings is minimal as there is no cuttings bed formed. The strategy adopted to keep the mud and hole in condition while utilizing the VDS was as follows:

- Alternating high/low viscosity mud sweeps to flush the hole of cuttings
- Frequent precautionary short trips/wiper trips to condition wellbore and clear tight spots/obstruction and ledges if any
- Good drilling/tripping practices and procedures to minimize drag and maintain the mud and wellbore in an excellent condition

The first logging attempt was unsuccessful as obstruction was encountered at a depth of 6,120 ft. A conditioning trip was made, there was no excess drag or overpull encountered on this conditioning trip and the logging tools were successfully run to bottom on the second attempt. Additionally, the casing was run to bottom without incident.

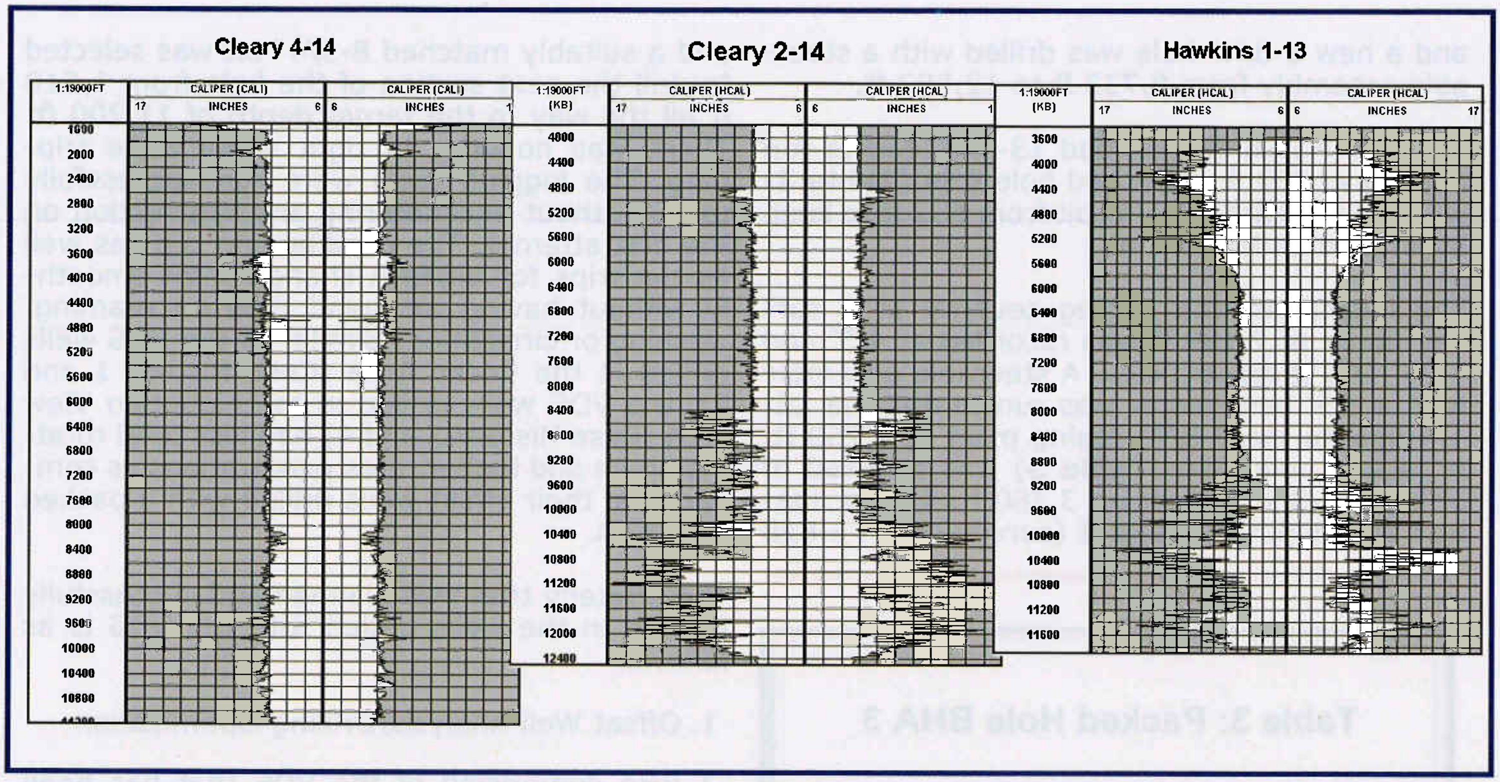


Figure 26. Caliper Logs (Case Study 4)

Case Study 4 - Mountain View Area

Cleary 2-14 and Hawkins 1-13 (**Figure 21 - map**) are the offsets to Cleary 4-14 (VDS well). On Cleary 2-14, a 12-1/4″ hole was drilled from 625 ft to 4,830 ft (9-5/8″ casing point); a steerable assembly with a 1.5° bent sub was utilized from 1,795 ft to 4,830 ft to keep the inclination under control. The caliper logs for the offset wells Cleary 2-14 and Hawkins 1-13 show washouts and very poor wellbore quality as compared to the VDS wells Cleary 4-14 (**Figure 26**). The maximum inclination and dogleg severity recorded in this hole section were 7.7° and 5.86°/100 ft (**Figure 27**).

On the well Cleary 2-14; 9-5/8″ casing was run and set at 4,830 ft; subsequently a steerable assembly with a 1.6° bend was utilized to drill the 8-3/4″ hole section from 4,830 ft. The survey at a depth of 8,703 ft indicated an inclination and dogleg severity of 6° and 10°/100 ft respectively. A trip was made to change the bit and to change the bend from 1.6° to 2°. After drilling to a depth of 10,147 ft, the high inclination was brought under control (1.6° inclination). After making a bit change, the steerable assembly could not be run back to bottom (obstruction encountered at 8,733 ft) due to the high dogleg severity and poor wellbore quality. After several unsuccessful attempts to run the steerable assembly back to bottom, the hole was inadvertently side-tracked

Table 2: Packed Hole BHA 2

QTY	BHA ITEM
1	12-1/4" Bit
1	6 Pt. Reamer
1	9-13/16" Short Drill Collar (10 ft)
1	Full Wrap Stabilizer
1	10" Monel Drill Collar
1	Full Wrap Stabilizer
1	9-1/2" Drill Collar
1	Full Wrap Stabilizer
2	9-1/2" Drill Collars
3	9" Drill Collars
9	7" Drill Collars
8	6-1/4" Drill Collars
1	Jar
3	6-1/4" Drill Collars

and a new 8-3/4″ hole was drilled with a steerable assembly from 8,733 ft to 12,502 ft.

The well Hawkins 1-13 had 13-3/8″ casing run and set at 632 ft. A packed hole BHA (**Table 2**) was run with the 12-1/4″ bit from 632 ft to keep inclination under control.

The inclination and dogleg severity at a survey depth of 2,189 ft was recorded at 4.5° and 1.93°/100 ft respectively. A steerable assembly with a 1.5° bent motor was run to drill the 12-1/4 hole to the 9-5/8″ casing point at 3,760 ft. A packed hole BHA (**Table 3**) was selected to drill the 8-3/4″ hole from 3,760 ft. The inclination at a depth of 5,983 ft (survey depth 5,828 ft) climbed to 6.5°; subsequently a steerable assembly with a bent motor was run to control the inclination. The well was drilled to a depth of 11,926 ft with a steerable assembly. High wellbore drag and tight spots required several hours of washing, reaming and circulation to condition wellbore and mud.

Table 3: Packed Hole BHA 3

QTY	BHA ITEM
1	8-3/4" Bit
1	6 Pt. Reamer
1	6-3/4" Short Drill Collar (8 ft)
1	String Stabilizer
1	6-5/8" Monel Drill Collar
1	String Stabilizer
1	7" Drill Collar
1	String Stabilizer
1	7" Drill Collar
1	String Stabilizer
7	7" Drill Collars
15	6-1/4" Drill Collars
1	Jar
3	6-1/4" Drill Collars

The 9-5/8″ casing was run and cemented at a depth of 1,510 ft on the Cleary 4-14. The VDS and a suitably matched 8-3/4″ bit was selected to drill the next section of the hole from 1,510 ft all the way to the target depth of 11,200 ft. There was no drag or tight spots while tripping. The logging tools were run successfully to TD without encountering any obstruction on the first attempt. The conditioning trips as well as the trips for bit/BHA change went smoothly without having to spend time on reaming, washing or circulation. Similar to the VDS wells drilled in the Rocky Area (Case History 1 and 2), the VDS wells drilled in the Mountain View area (Case History 3 and 4) had less total rotating hours and higher rates penetrations as compared to their offset wells drilled with a packed hole BHA.

The strategy that was planned and successfully applied in the wells drilled with the VDS is as follows:

1. Offset Well Analysis/Drilling Optimization
2. BHA comprising of the VDS that has been selected and carefully fine tuned to meet the specific requirements of the well based on the results of the offset well analysis
3. Bit selection based on the functioning and the requirements of the VDS as well as based on the results of drilling optimization
4. Alternating high and low viscosity mud sweeps to ensure wellbore and mud are in excellent condition
5. Short trips (wiper trips) done frequently to ensure wellbore is free of abnormal drag and tight spots

Cost Analysis

Figure 28 is a histogram of the drilling cost in dollars/foot for the depth intervals drilled with the VDS and the corresponding depths drilled with steerable drilling assembly (directional tools). A total of seven wells are considered in the cost analysis, five wells out of the 12 total were dropped from the cost analysis as they were drilled several years ago and their costs are not comparable with the other seven wells that were drilled recently during a closely spaced time-span. As seen in **Figure 28**, drilling costs for the intervals drilled with the VDS are substantially lower then the corresponding intervals drilled with steerable assemblies. On average, a savings of at least US $150,000 was achieved on each of the wells that were drilled with the VDS.

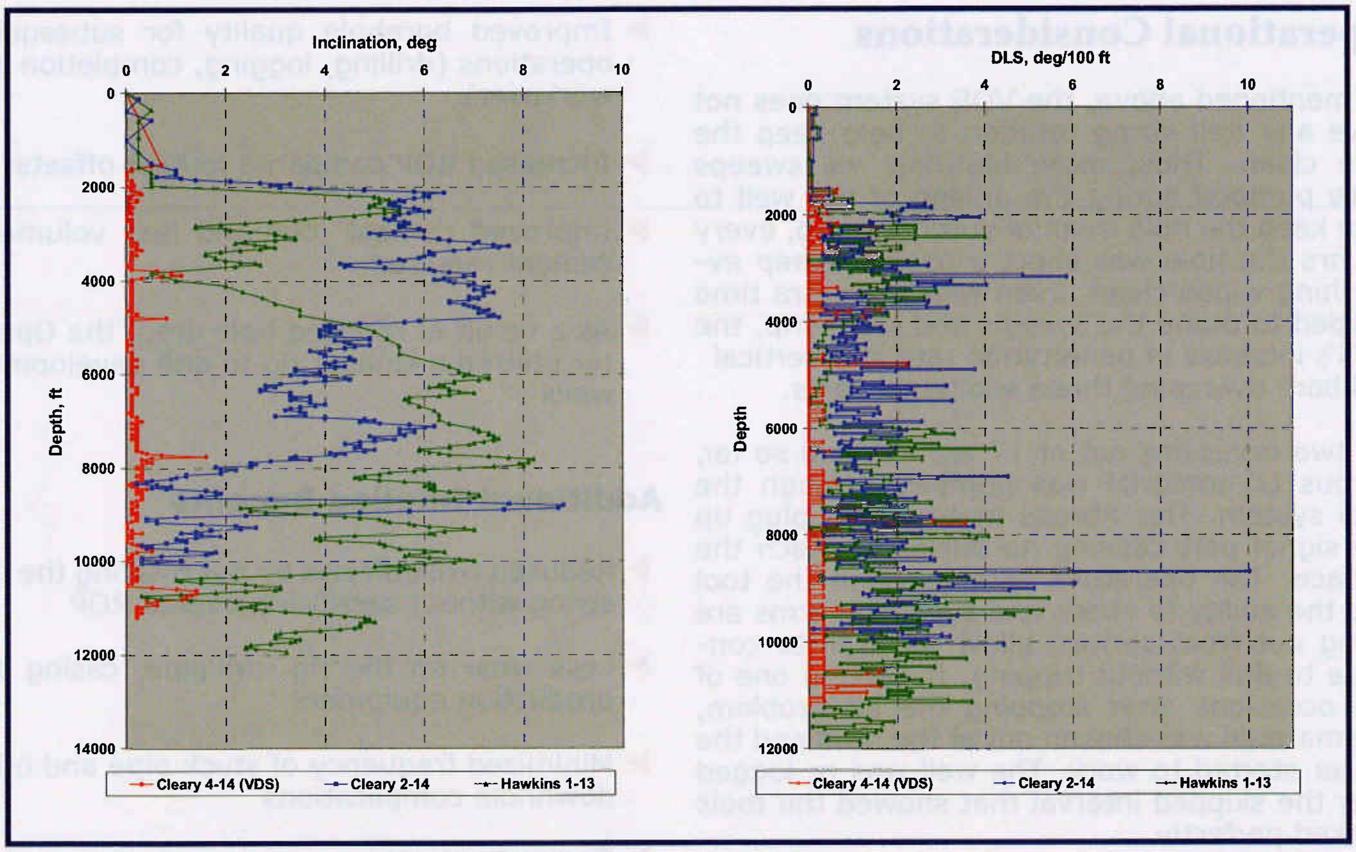


Figure 27. Inclination and Dog Leg Severity Plots (Case Study 4)

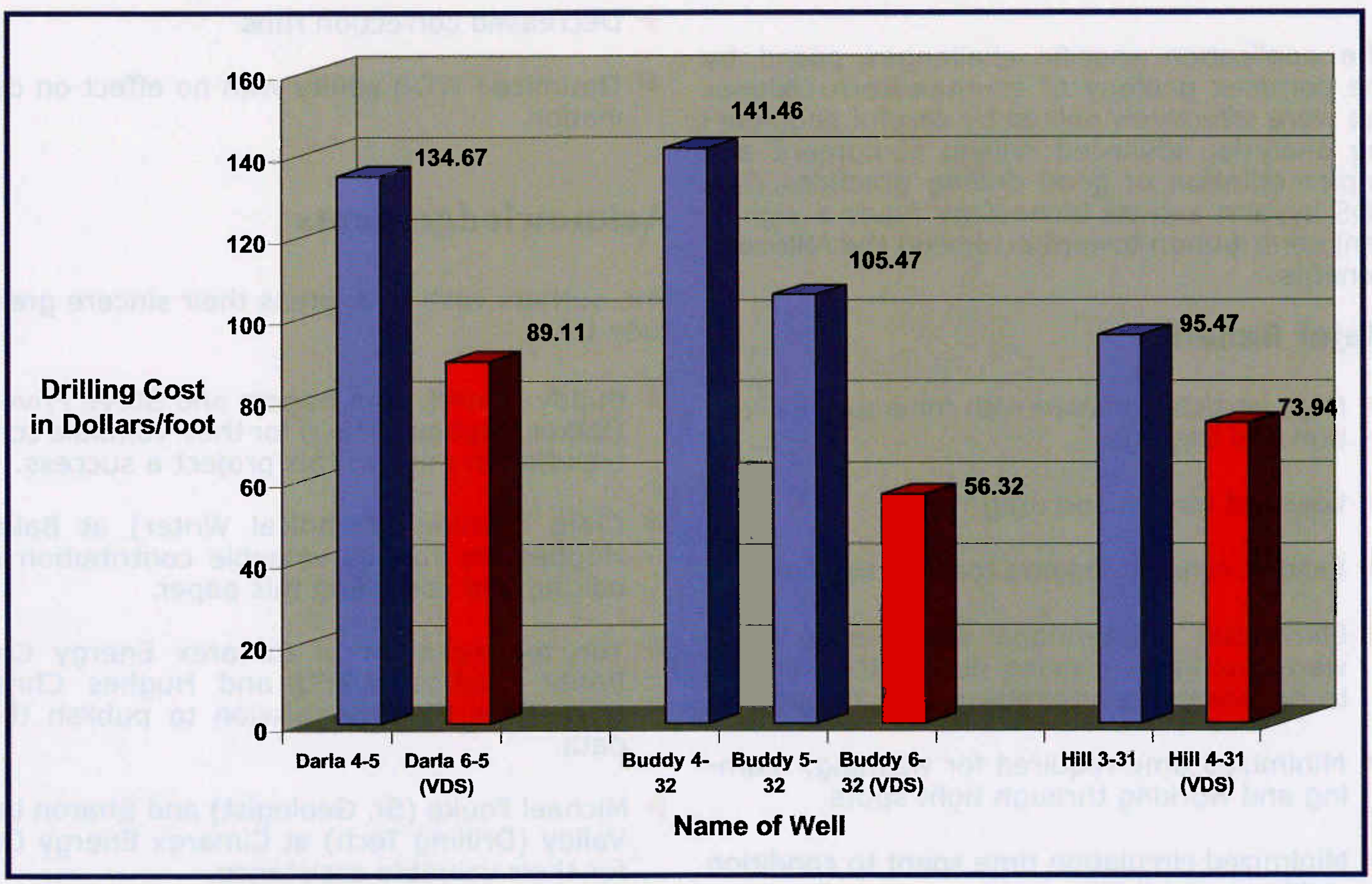


Figure 28. Cost Savings in Dollars/Foot: Case History Wells

Operational Considerations

As mentioned above, the VDS system does not have any drill string rotation to help keep the hole clean. Thus, more high/low vis sweeps were pumped during the drilling of the well to help keep the hole clean of cuttings. Also, every 36 hrs the hole was short tripped to keep everything wiped clean. Even with the extra time needed to pump the sweeps and short trip, the VDS's increase in penetration rate and vertical wellbore overcame these additional costs.

On two occasions out of 17 wells drilled so far, fibrous LC material was pumped through the VDS system. This fibrous material did plug up the signal port causing no pulses to reach the surface. The operator's confidence in the tool and the ability to check and see if the arms are going out from surface allow the well to continue to drill without tripping. In fact, in one of the occasions after stopping the LC problem, the material was shaken out of the mud and the pulser started to work. The well was re-logged over the skipped interval that showed the tools worked perfectly.

Conclusions

The application specific challenges posed by the complex geology of southwestern Oklahoma were effectively solved by careful engineering analysis, advanced drilling equipment and implementation of good drilling practices. The VDS system and bit technology made a significant contribution toward achieving the following benefits:

Major Benefits

- Near vertical wellbore with minimum inclination and doglegs
- Lowered torque and drag
- Ease of running logging tools to bottom
- Eliminated unintentional side-tracks which were previously caused due to the inability to run steerable assemblies back to bottom
- Minimized time required for washing, reaming and working through tight spots
- Minimized circulation time spent to condition wellbore and drilling mud
- Improved borehole quality for subsequent operations (drilling, logging, completion and workover)
- Increased ROP compared to best offsets
- Improved cement jobs and less volume of cement required
- As a result of reduced hole drag, the Operator utilized a smaller rig to drill development wells

Additional Implied Benefits

- Reduced twist off risk by not rotating the drill string without sacrificing overall ROP
- Less wear on the rig, drillpipe, casing and production equipment
- Minimized frequency of stuck pipe and other downhole complications
- Earlier Production
- Leaner casing profiles
- Decreased correction runs
- Optimized WOB ability with no effect on deviation

Acknowledgements

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Clair Cameron Patterson: The Unsung Geologist

Ray Brown
Oklahoma Geological Survey

One of the driving forces behind many scientists, besides their natural curiosity, is the desire to be recognized for their work. Historical recognition, however, is not always achieved because of numerous favorable human factors. This means that no matter what was accomplished during the lifetime of some individuals, their names may not be familiar. One such person is Clair Cameron Patterson. He deserves much more recognition from the scientific community. This article describes how Patterson, a geologist who has not received enough of the credit that belongs to him, changed our thinking about the age of the Earth and even helped people live healthier, longer lives!

Who is Clair Cameron Patterson?

Clair Cameron Patterson never received a Nobel Prize. This can be written off to human forces. Nobel Prize winners are chosen from a very select population. For example, Nobel specifically did not want mathematicians to receive the award because his wife was having an affair with a mathematician. In addition, the Nobel Prize is dominated by sciences other than geology.

Patterson did not gain very much fame from his fellow geologists even though he spent one half century addressing important issues, and developed selflessly many contributions to his science. Bill Bryson (2003) in his book, *A Short History of Nearly Everything,* suggests that Patterson could be considered *"the most influential geologist of the twentieth century."* In fact, most of the material here comes from Bryson's book. His statement stems from Patterson's role in determining the age of the Earth, and an important contribution he made to our environmental health. In the following, I shall examine Patterson's role in changing both his technical world, and the world in which we live.

Age of the Earth

The efforts to estimate the age of the Earth have a long history. Pamela Gore (2004) gives a brief history on the internet of the efforts to estimate the age of the Earth. Surprisingly, the calculated age of the Earth got older progressively through modern times. The problem could not be solved accurately until scientists became aware of radiation and then how to use it in estimating the age of rocks.

Earliest Methods

In 1654 the Anglican Archbishop of Ireland, James Usher, used the genealogy in the Bible to estimate that the Earth was 6,000 years old. Although no specific estimate was made, James Hutton (1726-1797), sometimes referred to as the father of Geology, thought that the Earth was much older than Usher had predicted. Hutton observed that Hadrian's Wall, the wall the Romans constructed to keep the barbaric Scots out of the southern part of the British Isle, suffered little change in 1,500 years; so Hutton argued that the Earth was much older than 6,000 years.

Quantitative Scientific Approaches

The use of scientific methods to measure the age of the Earth was often based upon the estimation of some rate process. These processes often neglected some important aspect of the exercise.

In England in 1897 Lord Kelvin assumed that the Earth was originally molten, and calculated a date of 24 to 40 million years based upon the rate of cooling magma. This really was a great idea, but it neglected the amount of heat due to radioactive decay within the Earth.

In 1899 to 1901 John Jolly, an Irishman, calculated the age of the Earth using his estimation of the rate that salt was added to the ocean. He estimated the age of the Earth to be 90 to 100 million years old. Some problems with this method include: (1) there was no way to account for recycled salt; (2) the amount of salt incorporated into clay minerals was unknown; and (3) the amount of ocean salt lost in the formation of evaporite deposits was not taken into account.

Another method of estimating the age of the Earth involved using the total thickness of sediments determined from the sedimentary record and dividing by an assumed rate of sedimentation of 0.3 meters per 1,000 years. The age of the first fossiliferous rocks is about 500 million years old using this approach; this method, however, does not account for the erosion of sedimentary rocks in the past, or differences in rates of sedimentation. In addition, ancient sedimentary rocks disappeared after they were metamorphosed or melted.

Charles Lyell (1797 – 1875) determined the amount of evolutionary development of mollusks in the Tertiary system that had occurred from the beginning of the Pleistocene. He estimated 80 million years for the age of the Cenozoic Era alone. So there was some evidence that the Earth was a lot older than anyone was willing to suggest; no one, however, stepped forward. The correct measurement of the age of the Earth awaited the development of radioactive dating.

Radioactive Dating and the Age of the Earth Estimated by Clair Cameron Patterson

The discovery of radioactivity in 1896 by Henri Becquerel led to a new method of age dating. Ernest Rutherford estimated the age of some uranium to be around 500 million years; some technical problems, however, prevented the accurate estimation of the age of the Earth.

The Earth is geologically active. Much of the activity is related to plate tectonics, or the movements of the Earth's surface. Through these activities, rocks have been processed and reprocessed so that the atomic clocks in them are reset. In other words, as a result of the processes associated with plate tectonics, when a rock melts into a liquid state and cools again to become a solid rock, the radioactivity clock is reset at the time of the last melting. Using the radioactivity of rocks found on the surface of the Earth to measure its age, represents a lower limit on its age.

Clair Cameron Patterson Measures the Age of the Earth

During the late 1940s, Clair Cameron Patterson was a graduate student at the University of Chicago. He was using a new method of lead isotope measurement developed by Harrison Brown at the University of Chicago to try to get a better estimate of the age of the Earth. Unfortunately most of his samples contained much more lead (a hundred times more) than anyone expected. The reason for the high level of lead was an invention by Thomas Midgley, an inventor from Ohio. More will be said about this later.

Harrison Brown, a professor at the University of Chicago, wanted to measure the age of the Earth. He realized that the work could be tedious, so he gave the project to his graduate student, Clair Cameron Patterson, as a dissertation assignment. Patterson started his work at the University of Chicago in 1948, and finished it while at the California Institute of Technology (Cal Tech) seven years later. During the spring of 1953 he traveled to the Argonne National Observatory at the University of Chicago in Argonne, Illinois, where he was given time on a mass spectrograph with which to measure small quantities of uranium and lead, locked up in ancient crystals in his rock samples. One can imagine Patterson's excitement when he finally completed the measurements. He was so excited that he thought he was having a heart attack, and drove home to his mother's home in Iowa where his mother checked him into the hospital. Luckily his condition was due only to his excitement over the work.

One of the unique aspects of Patterson's measurement was the rock sample he analyzed. He applied the age of the Earth estimate to a meteorite rather than a rock sample from Earth. Patterson had made the assumption that meteorites are building materials left over from the early history of the solar system. Meteorites, therefore, managed to retain a more accurate measure of the age of the Earth in their radioactivity clocks. The idea, way ahead of its time, was that radioactive age dates found for meteorites would better approximate the age of the Earth.

Patterson presented the estimated age of the Earth at a technical meeting in Wisconsin after he settled down a bit. He estimated the age of the Earth to be 4,550 million years (plus or minus 70 million years) old. After two hundred years of age estimating, Patterson set the bar at a new level of understanding that still holds up today. He certainly deserves to be in the geology hall of fame for his accomplishment.

Ethyl, Get the Lead Out!

Besides giving us our modern estimate of the age of the Earth, Clair Cameron Patterson went on to save many lives. When Patterson began his age dating work at the University of Chicago, all the samples he studied had much more lead than expected. The high level of lead was attributed to an invention by Thomas Midgley, Jr., an engineer at the General Motors Research Corporation in Dayton, Ohio.

In 1921 Midgley developed a compound known as tetraethyl lead. When tetraethyl lead was added to fuels for internal combustion engines, the compound would reduce or eliminate engine knock. The lead compound was an immediate success (depending upon how one defines "success"). Three corporate giants (General Motors, Du Pont and Standard Oil of New Jersey) formed a new company that would later be called "the Ethyl Corporation." If a person wanted one's automobile to run better (without knocking), then "ethyl gasoline" was the preferred fuel. With so many automobiles burning leaded gas, it caused the air to become contaminated with lead.

The effects of ingesting lead were not known at the time. Lead was used in water tanks, toothpaste, paints, and other seemingly harmless applications. When Patterson finished his estimate of the age of the Earth in the 1950s, he turned to trying to discover where all the lead came from in the environment that caused the raised level of lead in his rock sample at the University of Chicago. He was astounded to find the amount of misinformation about lead. For the previous 40 years, most of the published studies on lead had been funded exclusively by companies that produced lead fuel additives! Apparently the system was flawed.

Patterson quickly took on the challenge and estimated that there was a lot of lead in the atmosphere (and there still is because it never goes away), and that about 90% of it apparently came from automobile engine exhaust. Unfortunately, he could not prove it beyond a doubt.

To prove that the lead in the environment was modified by the use of lead in gasoline, Patterson needed a way to measure the amount of lead in the atmosphere before the introduction of lead into gasoline in 1923. This would allow him to compare the amount of atmospheric lead in the atmosphere prior to 1923 with the amount of lead in the atmosphere during the time of his research. Patterson had the bright idea of comparing ice in Greenland that was deposited before the 1920s to recently deposited ice to get an estimate of the rate of change in the amount of lead in the Earth's atmosphere. The process might be compared to studying tree rings used to estimate the age of a tree. In this case, the chemistry of an ice layer deposited before the 1920s is compared to the age of a layer of recently deposited ice. Patterson's method became the foundation of modern ice core studies that are used to study the history of the Earth's climate.

When Patterson discovered that there was very little lead in the air before the 1920s, and that the amount of lead steadily increased to the current values that he measured, he made it his mission to eliminate the use of lead in gasoline. Luckily for everyone, he was a very determined man.

The Ethyl Corporation was equally determined. More importantly, the Ethyl Corporation had connections in high places. The Ethyl Corporation exerted influence on Patterson's receipt of research contracts, and even tried to get him fired from Cal Tech; there are some things, however, that money cannot buy. Eventually Patterson was influential himself, claiming part of the responsibility for the Clear Air Act of 1970, and for the removal from sale in 1986 of all leaded gasoline in the United States. The levels of lead in blood samples of Americans fell by almost 80% as a result; but lead is forever. The amount of lead in blood samples of Americans today is 625 times the amount of lead in Americans' blood a century ago. ***Hopefully, the name of Clair Cameron Patterson sticks with those who benefited from his efforts. He literally saved millions from the debilitating effects of ingesting lead from the atmosphere!***

Summary

In the 1950s, Clair Cameron Patterson measured the age of meteorites, which is responsible for the modern estimate of the age of the Earth. He then took on the challenge of saving millions from the harmful effects of ingesting large quantities of lead from the atmosphere. Apparently he did so without much fanfare because his name is not very well-known. Patterson died in 1995, but his accomplishments belong in our memory banks. I agree with Bryson when he says that ***Patterson was "the most influential geologist of the twentieth century."***

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OKLAHOMA GEOLOGICAL SURVEY DIRECTOR NAMED REGENTS' PROFESSOR

L to r, University of Oklahoma Provost Nancy J. Mergler; OGS Director Charles J. Mankin; and College of Earth and Energy Dean Larry R. Grillot. Photo by Margaret Vennochi.

Charles J. Mankin, believed to be the longest-serving director of any state geological survey in the country, was named a Regents' Professor by the University of Oklahoma Board of Regents during its March meeting.

"No one is more deserving of this honor than Charles Mankin," OU President David L. Boren said. ***"His scholarship, teaching and research have left a lasting mark on our state and its economy and energy industry."***

Mankin, director of the Oklahoma Geological Survey and professor of geology at OU, as well as former director of the Sarkeys Energy Center, is known as the **"dean of state geologists"** among his peers. He was hired in 1959 during the presidency of George Lynn Cross, OU's seventh and longest-serving president, and was asked to become the acting director of the university's School of Geology and Geophysics in 1963, while still an assistant professor. He became the school's director in 1964 and served in that capacity for 14 years. He was named director of the Oklahoma Geological Survey in 1967 and as director of the Sarkeys Energy Center in 2000. He served as executive director of the OU Energy Resources Institute from 1978 to 1987.

Mankin has served on numerous professional and scientific boards, committees and panels at state and national levels. Additionally, he is a member of numerous professional, scientific and technical organizations, including the Association of American State Geologists, the American Institute of Professional Geologists and the Geological Society of America, and has served as president of several national organizations. He is a 50-year member of the American Association of Petroleum Geologists and a life member of the Oklahoma City Geological Society, receiving honorary membership in 1994. He also serves on the National Petroleum Council, with a two-year term beginning in 2004.

In recognition of his achievements, Mankin has received the Ian Campbell Memorial Medal from the American Geological Institute; the Public Service Award from the American Association of Petroleum Geologists, serving as secretary of that organization for two years; the Martin van Couvering Memorial Award and the Ben H. Parker Memorial Medal from the American Institute of Professional Geologists; and the Conservation Service Award from the U.S. Department of the Interior, among many others.

Born in Dallas in 1932, Mankin earned his bachelor's, master's and doctoral degrees in geology from the University of Texas at Austin and was a post-doctoral fellow at the California Institute of Technology.

Aside from his posts at OU, he has taught at the University of Texas, served as a special instructor in geology for Shell Oil Co. engineers and as a geologist for the New Mexico Bureau of Mines and Mineral Resources.

To qualify for a Regents' Professorship, a faculty member must have rendered outstanding service to the academic community or to an academic or professional discipline through extraordinary achievement in academic administration or professional service. Nominees for Regents' Professorships are presented to the OU Regents by the president after conferring with the chairman of the Board of Regents, the chair of the appropriate Faculty Senate, and the University Council on Faculty Awards and Honors. The term of a Regents' Professorship is continuous until retirement.

NOTED GEOPHYSICS LEADER NAMED DEAN OF OU'S COLLEGE OF EARTH AND ENERGY

A geophysicist with 30 years of technical and managerial experience in the petroleum industry was named dean of the newly formed College of Earth and Energy at the University of Oklahoma. The appointment, which was effective April 1, was announced at the March meeting of the OU Board of Regents.

"Larry Grillot combines outstanding academic credentials with experience in leading America's energy industry at the highest level," said OU President David L. Boren. *"He is ideally equipped to be the first dean of OU's new college, which has the potential to further enhance OU's reputation as a national leader in the energy field."*

Larry R. Grillot worked for Phillips Petroleum Co. for 30 years, almost half of which were spent in Bartlesville, in a variety of technical and managerial posts in exploration and production. His assignments took him to Canada, Europe, and Africa in successively more responsible roles, the last of which was as manager of E&P Technology and Services, Upstream Technology and Project Development. Before that, he was manager of International Exploration and Worldwide Exploration. Other positions he held at Phillips include president and region manager for Phillips Petroleum Canada Ltd., Calgary (a subsidiary of Phillips Petroleum Co.), and manager of E&P Planning.

He earned his bachelor of science degree in physics from Mississippi State University and his master's and doctoral degrees in geological sciences from Brown University.

The College of Earth and Energy, formally established in January 2006, grew out of talks between OU representatives and alumni in both the oil and gas and the weather industries, who determined that OU should restructure its assets in the areas of energy and meteorological education and research. OU historically has been at the forefront in educating petroleum engineers, who are consistently ranked by *U.S. News and World Report* as one of the top five programs in the nation. The restructuring was designed to educate students for fields of the future and to conduct research that will benefit industry and the nation at large.

The College of Earth and Energy places the Sarkeys Energy Center in a more integrated role. Also under its umbrella are the Oklahoma Geological Survey, Mewbourne School of Petroleum and Geological Engineering, and School of Geology and Geophysics.

In addition to continuing to support the exploration and extraction of hydrocarbons, the new college will be involved in interdisciplinary research and education on alternative sources of energy and in the economic and public policy aspects of all forms of energy. In partnership with the College of Engineering and the Michael F. Price College of Business, the new college, under Grillot's direction, will develop optional minors in business that will enhance the employability of OU's undergraduates and provide opportunities for more interdisciplinary master's degrees.

—Upcoming Meetings

2006

OCTOBER

22—25 Geological Society of America, Annual Convention, Philadelphia, Pennsylvania. Information: Geological Society of America, P.O. Box 9140, Boulder, CO 80301; (303) 447-2020; fax 303-357-1071; e-mail: meetings@ geosociety.org. Web site: http://www.geosociety.org/meetings/2006.

26 Oklahoma Oil and Gas Trade Expo, Oklahoma City, Oklahoma. Information: Oklahoma Marginal Well Commission, 3535 N.W. 58th St., Suite 870, Oklahoma City, OK 73112; (405) 604-0460 or (800) 390-0460; fax 405-604-0461; e-mail: mwc@marginalwells.com. Web site: http://www.marginalwells.com.

NOVEMBER

1 Oklahoma 3-D Seismic Applications Workshop, Norman, Oklahoma. Information: Michelle Summers, Oklahoma Geological Survey, 100 E. Boyd, Room N-131, Norman, OK 73019; (405) 325-3031 *or* (800) 330-3996; fax 405-325-7069; e-mail: mjsummers@ou.edu. Web site: http://ogs.ou.edu.

5—8 American Association of Petroleum Geologists, International Conference and Exhibition, Perth, Australia. Information: AAPG Convention Dept., P.O. Box 979, Tulsa, OK 74101; (918) 560-2617; fax 918-560-2684; e-mail: convene@aapg.org. Web site: http://www.aapg.org/perth/.

14—16 Hard Rock 2006: Sustainable Modern Mining Applications, November, Tucson, Arizona. Information: Alina Martin, Science Applications International Corporation (SAIC), (703)318-4678.

2007

FEBRUARY

25—28 Society for Mining, Metallurgy, and Exploration (SME) Annual Meeting & Exhibit and 109th National Western Mining Conference, February, Denver, Colorado. Information: SME, (303)973-9550 and (800)763-3132; FAX: (303)973-3845; 8307 Shaffer Parkway, Littleton, CO 80127; website: http://www.smenet.org/meetings/annualMeeting2007/index.cfm.

MARCH

12—14 Northeastern GSA Section Meeting, Durham, New Hampshire. Information: Wally Bothner, University of New Hampshire, (603)862-3143, wally.bothner@unh.edu; website: http://www.geosociety.org/sectdiv/northe/07nemtg.htm.

29—30 Southeastern Section GSA Meeting, Savannah, Georgia. Information: website: http://www.geosociety.org/sectdiv/southe/07semtg.htm.

APRIL

1—4 AAPG Annual Convention and Exhibition, *Understanding Earth Systems Pursuing the Checkered Flag*, Long Beach, CA. Information: AAPG Convention Department; P.O. Box 979; Tulsa, OK 74101-0979 USA; 1(888) 945-2274 ext. 617 (U.S. / Canada); 1(918) 560-2617. Web site: http://www.aapg.org/.

11—14 North-Central / South-Central Sections GSA Joint Meeting, Lawrence, Kansas. Information: website: http://www.geosociety.org/sectdiv/Northc/07nc-scmtg.htm.

22—24 AAPG Southwest Section Meeting, *Unconventional Challenges - Innovative Solutions*, Wichita Falls, Texas. Sponsored by North Texas Geological Society. Call for Abstracts information (due March 1): Brian Brister, Gunn Oil Company, PO Box 97508, Wichita Falls, TX 76307; (940)723-5585; bbrister@gunnoil.com.

MAY

4—6 Cordilleran Section, GSA 103rd Annual Meeting, Bellingham, Washington. Information: website: http://www.geosociety.org/sectdiv/cord/07cdmtg.htm.

7—9 Rocky Mountain Section, GSA Annual Meeting, Saint George, Utah. Information: website: http://www.geosociety.org/sectdiv/rockymtn/07rmmtg.htm.

20—25 43rd Forum on the Geology of Industrial Minerals, Boulder, Colorado. Information: Colorado Geological Survey, 1313 Sherman Street, Room 715, Denver, CO 80203; (303)866-2611; web site: http://im-forum2007.crmca.org.

SEPTEMBER

9—11 AAPG Mid-Continent Section Annual Meeting, *New Ideas - More Oil & Gas*, Wichita, Kansas. Sponsored by Kansas Geological Society. Information: Ernie Morrison; EMorrison@MULLDRLG.com; Phone: 316-264-5368. Website: http://www.aapg.org/meetings/midcont07.pdf.

23—28 Society for Exploration Geophysicists (SEG) International Exposition & 77th Annual Meeting, San Antonio, Texas. Sponsored by Kansas Geological Society. Information: 8801 S. Yale, Tulsa, OK 74137, Phone: 918-497-5538, Fax: 918-497-5557; website: http://meeting.seg.org/.

OCTOBER

3—6 2007 Precious Metals Symposium, Tucson, Arizona. Information: website: http://www.smenet.org/meetings/.

6—9 AAPG Rocky Mountain Section 56th Annual Meeting, *Exploration Discovery Success*, October, Snowbird, Utah. Information: website: http://www.aapg.org/meetings/index.cfm#sections.

28—31 Geological Society of America, Annual Convention, *Earth Sciences for Society — Beginning of the International Year of Planet Earth,* Denver, Colorado. Information: Geological Society of America, P.O. Box 9140, Boulder, CO 80301; (303) 447-2020; fax 303-357-1071; e-mail: meetings@ geosociety.org. Web site: http://www.geosociety.org/meetings/2007/.

Oklahoma 3-D Seismic Applications Workshop

November 1, 2006

Norman, Oklahoma

The techniques for seismic applications in Oklahoma are as varied as the basins themselves. Each basin, play type, and reservoir has its own personality. With these unique personalities come unique obstacles to overcome for successful seismic applications.

The workshop is built around specific oil and gas plays in Oklahoma. Each play will be discussed individually by **Jim Puckette *(Oklahoma State University)*** to include the generalized geologic information concerning the plays' depositional and/or tectonic setting and the distribution of reservoirs, with geologic maps and cross sections used to illustrate typical relationships between reservoir and seal rocks in each play. The geologic discussion will be followed by presentations by **Bob Springman *(Dominion E&P)*, Ray Brown *(OGS)*, and Kevin Werth *(Dawson Geophysical)*** with examples of specific geophysical applications for the plays, such as:

- ☐ **Overview of the geophysical tools with 3-D applications;**
- ☐ **Data acquisition options with recommended designs;**
- ☐ **Data processing techniques to image specific objectives;**
- ☐ **Forward modeling to define specific acquisition and processing parameters**
- ☐ **Interpretation techniques;**
- ☐ **Limits of the 3-D seismic data (horizontal and vertical);**
- ☐ **Potential pitfalls.**

Registration will be on an as-received basis; workshop fee is $75.00, which includes coffee breaks, lunch, and a copy of the presentations.

Information: Michelle Summers,
Oklahoma Geological Survey
(405) 325-3031
or (800) 330-3996
Web site: http://ogs.ou.edu

—Oklahoma Abstracts

The Oklahoma Geological Survey thanks the American Association of Petroleum Geologists for permission to reprint the following abstracts of interest to Oklahoma geoscientists.

Potential Gas Shales in Oklahoma, U.S.A

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Black shales, considered important hydrocarbon source rocks and cap rocks, are now being evaluated as gas reservoirs. The current gas-shale activity in Oklahoma is in the Woodford Shale (Upper Devonian—Lower Mississippian; equivalent to the Ohio Shale and other Devonian gas shales in the eastern United States), Caney Shale (Mississippian; equivalent to the Barnett Shale in Texas), and Excello Shale Member (Pennsylvanian). Gas produced from the Excello Shale Member is included with gas reported from the Mulky coal (an impure coal below the Excello Shale Member).

Data gathered on these potential gas shales include depth, thickness, thermal maturity, kerogen type, and kerogen quantity. Thermal maturity is determined by vitrinite reflectance. Kerogen type and quantity are determined by Rock-Eval pyrolysis. An Oklahoma gas-shales database, available on the Oklahoma Geological Survey Web site, contains information on gas wells completed in the Woodford Shale or Caney Shale. To date, initial potential gas rates range from 8 to 2,100 thousand cubic feet of gas per day from 62 wells at vertical depths from 763 to 9,983 ft. Three horizontal wells with lateral lengths from 834 to 3,037 ft have been drilled in the Woodford Shale in Coal and Pittsburg Counties in eastern Oklahoma.

Shale-gas production in Oklahoma is a frontier play. Unresolved factors for successful gas-shale wells include the affect of natural versus induced fractures on gas production, optimum thermal maturity for oil generative organic matter, and best completion practices.

Detailed Fingerprints of Global Sea-level Change Revealed in Upper Devonian / Mississippian Woodford Shale of South-central Oklahoma

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Gamma-ray logging profiles in organic-rich shale commonly contain intervals in which readings exceed 150 API units. These intervals of elevated gamma-ray, or "hot streaks", are considered stratigraphic condensed sections; relatively long periods of continuous geological time amalgamated in and represented by a relatively a thin slice of stratigraphic section.

Inspection of these profiles, however, reveals that "hot streaks" contain much more stratigraphic information than heretofore recognized. We have prepared full-scale displays of gamma-ray profiles from subsurface well logs through the marine Woodford Shale and made comparisons with spectral gamma-ray profiles collected at outcrop with a handheld spectrometer. Most of the Woodford has gamma-ray readings >150 API units. Some intervals of the formation contain up to 110 ppm uranium and approach 1000 API units.

Our analyses indicate that the gamma-ray response in the Woodford is clearly dictated by the uranium in the shale. Noted by past researchers, and verified by our work, the distribution and intimate association of uranium with the shale suggests the source of the uranium was seawater. Therefore, the uranium enrichment was likely caused by diffusion from Devonian/Mississippian seawater into the upper 10—20 cm of the underlying, chemically-reducing seafloor mud. Once in the mud, uranium would have been fixed in the sediments through chemical reduction, thereby establishing a concentration gradient in the porewaters to further drive diffusion. In this sense, the concentration of uranium in the muddy substrate would be linked to sedimentation rate, with extremely slow or starved sedimentation exhibiting the most abundant uranium concentrations.

Bromide Dolomite (Ordovician) Inner Ramp Depositional Cycles, Arkoma Basin, Southeastern Oklahoma

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The Bromide Formation (early Late Ordovician, Mohawkian) is known primarily from normal marine ramp limestone and shale facies that outcrop in the Arbuckle Mountains of southern Oklahoma, and very little subsurface carbonate lithofacies data on the unit are available. In the subsurface

Arkoma Basin of southeastern Oklahoma, Bromide Dolomite gas reservoirs consist of very shallow-water inner ramp facies deposited on the low-angle South Ozark Platform. Cores through the Bromide Dolomite section are composed of repetitive thin (3–10 ft. thick), very shallow subtidal to peritidal shallowing upward cycles. Typically, the basal unit in a cycle consists of a thin quartz sandstone composed of mature well-rounded fine- to medium-grained sands that were transported from the north by wind and water during sealevel lowstands, and then reworked during subsequent marine transgressions and storms.

Quartz sand continues upward throughout most cycles with variable abundance, but dolostones usually dominate the middle and upper parts of the cycles. Subtidal dolostones are most common in the lower to middle cycles. Subtidal facies vary from dolomudstones to coated dolograinstones, and locally contain sparse pelecypod, gatropod, and ostracod bioclasts, but no normal marine fauna (e.g., brachiopods, bryozoans, echinoderms) occur, which indicates predominantly restricted marine paleoenvironments. Peritidal dolostones predominate the upper parts of cycles. Peritidal facies vary from stromatolitic dolobindstones, and dolomudstones to dolopackstone - grainstones with vadose features and dessication cracks. Dolopackstones and dolograinstones are composed mostly of micritic (microbialite) intraclasts, peloidal grains, and sometimes ooids. Fenestral (keystone) fabrics are common, and locally there are solution cavities and breccias. Thin intraclastic tempestites occur. No direct evidence of evaporite deposition has been recognized. Dolostones vary from very finely crystalline dolomite with well-preserved depositional fabrics to more coarsely crystalline dolomite with unrecognizable depositional fabrics. The diagenetic history of the Bromide is complex and contains early to deep-burial diagenetic features.

Naturally Underpressured Compartments and Geologic Sequestration of Carbon Dioxide

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Reservoir-pressure data from multiple sources were used to characterize the compartmentalized nature of the Pennsylvanian and Permian rocks of the Anadarko basin. Integrated pressure, production and wireline log data were used to delineate abnormally high- and low-pressured reservoirs and identify bounding seals. Abnormal overpressure is restricted to the deeper parts of the basin, whereas natural underpressure occurs across the northern shelf. Compartmentalized reservoirs offer a geologically unique opportunity for the subsurface sequestration of fluids. Abnormally underpressured reservoirs, by virtue of their shallow depth, were identified and mapped using available petroleum industry data.

Case study reservoir compartments were selected and analyzed. The results indicate that they contain low pore-fluid pressures and are completely sealed by thick confining units. Pressures in these exemplar reservoirs are further reduced by the production of oil and gas. As a result they have low injection and displacement pressures. Volumetric calculations indicate these depleted oil and gas reservoirs can accept large volumes of injectate without exceeding original pre-production reservoir pressures.

Estimated disposal volumes for these selected reservoirs range from approximately 0.5 million to 21 million stock tank barrels of liquid per well. Compartmentalized reservoirs with abnormally low fluid pressures offer an intriguing alternative for CO2 sequestration. Seal longevity and integrity are evidenced by the intra-stratal isolation of compartments in the Pennsylvanian, which contains underpressured reservoirs in the Oklahoma Panhandle that have not equalized with extreme overpressures in the deep Anadarko basin. These reservoirs, by virtue of their compartmentalized nature, fulfill two critical criteria for CO2 sequestration, (1) non-migration and (2) isolation from the sphere of human activities.

Multiscale Geologic and Petrophysical Modeling of the Giant Hugoton Gas Field (Permian), Kansas and Oklahoma

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Reservoir characterization and modeling from pore to field scale of the Hugoton Field (central U.S.) provides a unique and comprehensive view of a mature giant Permian gas system and has implications for production strategies in similar reservoirs worldwide. Volumetric calculations of the static model for the 16,000 square km field indicate the 963 billion m3 (34 TCF) gas produced in seventy years from the Kansas-Oklahoma portion of the field represents approximately 65–70% of original gas in place. Most remaining gas is in lower permeability pay zones of the 170-meter thick, differentially depleted, layered reservoir system.

Thin-bedded (2–10 meter), marine carbonate mudstones to grainstones and siliciclastics in thirteen fourth-order marine-nonmarine cycles, illustrated in core, are the main pay zones separated by eolian and sabkha redbeds of low reservoir quality. The heterolithic system is a classic example of sedimentary response to rapid glacio-eustatic sea level fluctuations on an extremely gently sloped ramp of an asymmetric foreland basin (Anadarko) on a craton. Petrophysical properties vary between eleven major lithofacies classes. Water saturations cannot be interpreted from logs due to deep filtrate invasion.

Geostatistical methods (neural network and stochastic modeling) and data analysis automation facilitated building a detailed 3D cellular reservoir model using a four step workflow: 1) define lithofacies in core and correlate to electric log curves (training set), 2) train a neural network and predict lithofacies at non-cored wells, 3) populate a 3D cellular model with lithofacies using stochastic methods, and 4) populate model with lithofacies associated petrophysical properties and fluid saturations.

Time, Surfaces, and Rock Volume: A Four-Dimensional Re-Evaluation of Reservoir Development in the Spiro Sandstone and Wapanucka Limestone, Arkoma Basin, Southeast Oklahoma

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The Wapanucka Limestone and Spiro sandstone are mapped as separate formations of late Morrowan and early Atokan age in the subsurface of the Arkoma basin and outcrops of the Ouachita Mountains. Regional stratigraphic correlations identify these rock units as two depositional sequences separated by the basal Atokan unconformity. Detailed correlations demonstrate the importance of identifying unconformities, understanding the stratigraphic relationships of surfaces and correlative rock volumes, and their time-space distributions.

The sub-Spiro shale that separates the Wapanucka Limestone from the overlying Spiro sandstone is time transgressive and correlative with Wapanucka carbonate facies in the Wilburton Field area and "Spiro" siliciclastic deposits in the Kinta Field. These strata are overlain by the basal Atokan unconformity. The down-dip (lowstand) deltas coeval to this erosional surface are observed in well log correlations in the hanging wall of the palinspastically restored Ouachita fold-and-thrust belt.

Younger Spiro sandstone strata crop out along the Choctaw Fault and onlap this surface juxtaposing reservoir-quality sandstones of different ages in the sub-surface. Deciphering the time-stratigraphic relationships interpreted from vertical facies successions of the Wapanucka and Spiro observed in cores explains the spatial relationships of reservoir-quality "Spiro" sandstones. They occur in distinct time-stratigraphic intervals that are correlative with both the Wapanucka and Spiro depositional sequences. These relationships help to predict future exploration potential for deep-water Spiro sandstone reservoirs and to identify undrained compartments in current producing fields.

Artificial Neural Networks May Help Predicting Abnormal Pressures in the Anadarko Basin

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Many sedimentary basins throughout the world exhibit areas with abnormal pore-fluid pressures (higher or lower than normal or hydrostatic pressure). Predicting the presence as well as other parameters (depth, extension, magnitude, etc.) of such areas proves often to be a challenging task. Among other tools used by specialists to meet that challenge, the sonic log (DT) seems to be preferred due to its accuracy and sensitivity to changes in porosity or compaction produced by abnormal pore-fluid pressures. Unfortunately, the sonic log is not commonly recorded in oil and/or gas wells. We propose using artificial neural networks (ANN) to simulate a sonic log by employing more available logs, such as natural gamma (GR), deep resistivity (RD), and caliper logs (CAL) (the last one, only for quality control procedure). The operation of the ANN can be divided into three steps: (1) supervised training of the neural network; (2) verification of the model validity by applying it to additional sets of data that contain the inputs (GR and RD logs) and the target values (DT). During this step, the validity of the model can be evaluated in terms of relative errors and goodness of fitting between the "training well" (step one) and the "confirmation wells" (step two); (3) the model is applied to wells containing only the input curves (GR and RD) and the output is the simulated DT. This procedure was applied to predict the presence of overpressured zones in the Anadarko Basin, Oklahoma. The results are promising and encouraging for the future development of the method.

Mechanical Modeling of Slip Along Regional Faults in the Arbuckle Anticline to Estimate Fracture Orientation and Density Constrained by Geohistory

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The Arbuckle anticline in south central Oklahoma has been interpreted as a fold that formed above the tip of a propagating thrust fault. In outcrop, limestone beds in the fold limbs show fractures confined to individual beds and through-going fracture sets that cut across several layers. The through-going fractures are oriented NE-SW subparallel to a more regional trend on the shallow dipping limb of the fold south of the major bounding Washita Valley Fault (WVF). A second set of regional fractures oriented nearly north south lie north of the WVF and west of the tip of the Reagan fault to the north. To estimate fracture orientations as analogs to similar fractures sets in the subsurface, we modeled shear on the large bounding faults using finite element and boundary element models. Discrete fracture sets can be produced from a boundary element code in which the regional faults slip under the applied load to a zero residual stress state on the fault surface. By assuming a failure criterion in the model material, discrete fracture sets can be predicted. The models show that a single stress boundary condition is insufficient to produce the two regional fracture orientations and a multi-stage stress history is required suggesting independent development of the fractures observed. In this structure the ENE-WSW shortening explains the southern fractures, and NNW-SSE shortening the northern fractures, which suggests a multiphase deformation history for fracture development in the Arbuckles. This geomechanical method demonstrates the importance of structural history and regional fault orientation and shape in prediction of fracture orientation and in turn the limits in fracture productivity.

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