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Unique Field Research Facility Designed to Accelerate New Technology Development and Enhance Tool Reliability

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Abstract

A field research drilling facility has been developed near Tulsa, Oklahoma in the city of Beggs. The new facility bridges the gap between laboratory testing and commercial applications by providing real world testing and field conditions. Highlights of the location and equipment include a wide variety of geology within a relatively shallow depth, a carrier based drilling rig for quick moves between surface holes and specialized data collection equipment, both on the surface and downhole. The facility is being used to reduce cycle time between the inception of an idea to the commercialization of a new product.

Introduction

The need to continually improve designs requires the service companies to conceptualize, design, develop and manufacture reliable tools as rapidly as possible. Most product and service suppliers use their customer's wells as testing grounds for their new products. This helps lower their up-front development costs. The downside to this approach is the operator assumes higher risk, which in some cases has caused the loss of the well. This approach also lengthens tool development time since the priorities of the operator (commercial production) are contrasted by tool testing that may require frequent unplanned trips.

Baker Hughes Inc. began groundbreaking operations in 1997 for a unique field research facility south of Tulsa, Oklahoma designed to enhance product reliability and accelerate new technology. The Baker Hughes Experimental Test Area (BETA), is located on a 640 acre lease in northernmost Okmulgee County, 24 miles south of the City of Tulsa, in northeastern Oklahoma (Fig. 1). The legal description is Section 4, Township 15 North, Range 12 East. BETA is unique to the industry as it helps integrate a wide spectrum of the corporation's downhole tools and products division's research efforts. The new facility bridges the gap between laboratory testing and commercial applications by providing real world testing and field conditions. Figure 2 is a photograph of the rig and figure 3 shows the layout of the equipment.

Information access is centerpiece of this facility. A sophisticated real time data acquisition system and a server based intranet website allow real-time and post analysis of data by any employee within the corporate computer firewall. This web based system enables engineers to monitor virtually every variable and allows digital analysis of both time and frequency based data. Real time data being collected includes depth, WOB, hookload, rate of penetration, rotary speed, torque, flow rate, pump pressure, axial vibration and torsional vibration. Additional information is accumulated through a specialized downhole sub that collects detailed vibration data and can measure torsional, axial or lateral acceleration. This sub also utilizes a magnetometer to calculate off-center running or drilling in an angular direction by measuring changes in instantaneous rotation speed.

This paper will review the geology at BETA, detail the specialized data collection and web based archival system and lastly, summarize a handful of tests from across the divisions where BETA has played a vital role in tool development and cycle time reduction.

Geology

The first well drilled at BETA was well BH-1 which was continuously cored (two-inch diameter) from a depth of 66.8 ft to 2955.78 ft, and then conventionally drilled to 3162 ft. A total of 2711.41 ft of core was pulled for a recovery of 94%. Hinch[1] has described the entire core and depositional environment.

The geology in and around the Tulsa, Oklahoma area is quite unique in that it offers a wide array of formation types within a relatively shallow depth. The combination of varied lithology and close proximity to a major city is why the location was picked for drilling research. The geology at the new test site consists of a Pennsylvanian section from surface to 2,250 ft; a Mississippian section from 2,250 - 2,660 ft; and an Ordovician section from 2,660 down to the granite base. These formations include sandstone, limestone, shale, coal, dolomite, and granite. Many of the formations still contain residual amounts of oil and gas. In fact, much of the oil industry's early growth centered around Tulsa after the discovery of oil at nearby sites such as Redfork, Glenpool, and Barnsdall[2].

The presence of oil, gas, coals, permeable sands, and unstable shales provides conditions that closely mimic oil field conditions. The large variation in rock strength provides ideal test conditions for testing downhole tools and systems. The entire section between surface and basement has been cored and extensively logged at the new facility. Petrophysical descriptions (permeability, porosity, compressive strength, etc.) are available for selected formations of interest.

All rocks encountered at the facility are consolidated and cemented sedimentary rocks of both marine and non-marine origin. Shale is the predominant rock type encountered, constituting more than 70% of the rock section above 2400 feet. Sandstone and siltstone comprise most of the remaining rock at shallower depths. Below 2400 feet, limestone, sandstone, shale and dolomite were encountered in approximately equal proportions. Numerous thin coal beds and numerous minor oil shows were encountered.

BETA is located in the Central Plains or Interior Lowlands of the United States. This area is composed of (underlain by) nearly flat-lying sedimentary rocks of Paleozoic age, generally less than 5000 feet thick, overlying granite and metamorphic "basement" rocks of Precambrian age. Locally within the Interior Lowlands, the "basement" has subsided to great depths, allowing the Paleozoic rocks to accumulate thicknesses of twenty to thirty thousand feet. In Oklahoma, the Anadarko and Arkoma Basins contain such thicknesses.

Fringing the North American Continent along its south (Caribbean) and eastern (Atlantic) margins is a thick wedge of sediments and sedimentary rocks of Mesozoic and Cenozoic (Tertiary & Quaternary) ages. In general, these younger sediments are much softer and less consolidated than the older Paleozoic rocks of the central region. Figure 4 is a geologic time scale illustrating these subdivisions of the Earth's history[3]. Figure 5 is a simplified map of North America showing these major subdivisions of strata underlying the continent[4]. Figure 6 is a stratigraphic column for Oklahoma, showing the rock sequence for BETA near the right margin of the illustration[5].

Northeastern Oklahoma is a region of gently rolling hills, partly densely wooded, but largely open prairie land. Topographically the land slopes gently westward from the Ozark Uplands in the eastern part of the state, and slopes gently eastward from the High Plains in the western part of the state. BETA, at an elevation of about 750 feet above sea level, is less than 100 feet above the regional low point at the Arkansas River which flows through and drains the region.

The sedimentary rocks of northeastern Oklahoma represent a thin veneer over the granite and volcanic "basement" rocks. In general, the slope of the "basement" dips south and southwestward towards the Arkoma and Anadarko Basins. However in detail, the surface of the "basement" is highly irregular, with buried "hills" extending up to within 1500 feet of the surface with local relief of greater than 2000 feet as shown in Fig. 7[6]. The thickness of the deepest geologic formations is controlled by the irregular topography on top of the Precambrian.

Above the Precambrian is a sequence of sedimentary rocks that thicken to the south and west following the dip of the "basement". These strata are tilted gently westward and dip at a rate of about 50 feet per mile. Initial deposits are the Reagan Sandstone of the late Cambrian or earliest Ordovician age that formed when the Paleozoic Ocean first inundated the region. Above the Reagan is several thousand feet of marine dolomite termed the Arbuckle Group that formed in a very shallow sea during the latest Cambrian and early Ordovician. The succeeding formations of Ordovician age also record very shallow marine conditions and periodic withdrawals of the sea caused by lowering of sea level and/or tectonic raising of the land surface. Strata of the Silurian and Early and Middle Devonian age (representing 60 million years of Earth's history) are missing from northeastern Oklahoma. They may have been deposited in the area but subsequently removed by weathering and erosion during the great lowering of sea level in the Middle Devonian.

A great flooding of the North American Continent took place in the late Devonian, as recorded by the deposition of the Woodford Formation, a deep-water black shale that is distributed all across the continent. Minor withdrawals of the sea occurred, but the continent mainly remained inundated into the Mississippian Period. The sea gradually regressed as sediments were deposited, largely forming thick banks of limestone north and east of BETA in northern Oklahoma and southern Kansas with thinner shales and shaley limestones in central Oklahoma. A lowering of sea level and subsequent deepening led to deposition of the Moorefield Formation, and the sea again receded. Another deepening brought about the deposition of the Fayetteville shale which regressed upward into the Pitkin Limestone. A final lowering of sea level caused a period of subareal exposure and weathering which is widely recognized in the rock record as the Mississippian\Pennsylvanian unconformity. With the onset of Pennsylvanian time, there was a major change in the type of deposits and sequence of formations in the region. Sea level began to raise and lower in a regular, cyclic fashion, and mountain-building activity in the eastern and western United States caused great amounts of sand and shale to enter the area. In the early Pennsylvanian, in the Morrowan, Atokan, and early Desmoinesian, sediments are derived mainly from the north, west, and east of the region.

During periods of relatively high stands of sea level, shale was deposited, with localized limestone banks forming when water depth and clarity permitted. During relatively lower stands of sea level, rivers flowed across the area, depositing at times great thicknesses of sandstone, such as the Bluejacket (Bartlesville) Sandstone, one of the major petroleum reservoir sands in the region. The alternating sequence of limestone, shale, and sandstone is characteristic of Pennsylvanian sedimentary rocks in the region, and is fundamentally explained by the raising and lowering of sea level.

In late Desmoinesian, yet another major change occurred. In southern Oklahoma, the Ouachita region, which had been in a deep oceanic basin, began to rise in response to the collision of major crustal plates in the Earth. The collision of the African plate into the North American plate caused large-scale mountain building in the Ouachita region. This created, for the first time, a significant southerly source of sediments. The Senora Formation and the succeeding Marmaton Group record this dual source, with a region of deeper water, mainly shale deposition in central Oklahoma, including the BETA Site. Underlying early Desmoinesian sediments include the thick sandstone of the Bluejacket Formation, which is known as the Bartlesville sand in the subsurface and is a prolific oil producer in the Glenn Pool field a few miles to the north.

As mentioned above, the section from 67 ft to 2956 ft was cored and then evaluated to describe the geological sequence. A full logging suite was run in the initial cored well to further characterize the formations. This well was later followed by two separate wells drilled first with rollercone bits and then by PDC bits to characterize drilling performance. Table 1 shows the formation names and tops at BETA. Additional studies performed to characterize the lithology at BETA can be found in the literature.[7,8,9,10,11]

Equipment

Drilling at BETA is accomplished with a carrier based Ideco H35 truck mounted rig with a freestanding mast capable of 350,000 lbs hookload. The mast has a height of 110 ft and can handle doubles, drilling with 60 ft stands of drillpipe. The substructure of the rig is mounted on top of a skid system to minimize downtime between wells. The rig is skidded through the use of two hydraulic rams, which are used to pull the rig from one surface hole to the next.

Rotation of the pipe is with a Tesco 150 ton topdrive using a 550 Hp Caterpillar 3406E engine. The topdrive has a high and a low speed setting and it was configured with two separate gears for optimizing rotary speed and torque. The factory specifications of the top drive show the torque being constant with rotary speed until near full speed. However, actual calibration shows the torque reduces with increasing speed. Figures 8 and 9 show the measured torque and rpm as a function of gear ration and number of stators (one or two). With a 2.19:1 gear and two stators, the top drive is capable of developing a maximum of 16,000 ft-lbs maximum torque near stall speed, reducing down to 10,500 ft-lbs at 125 rpm. With one stator, the top drive develops 8,000 ft-lbs torque at stall reducing to 6,400 ft-lbs torque at 230 rpm. With a 1.64:1 gear and two stators, the top drive is capable of developing a maximum of 10,000 ft-lbs maximum torque near stall speed, reducing down to 8,000 ft-lbs at 150 rpm. With one stator, the top drive develops 5,000 ft-lbs torque at stall reducing to 3,900 ft-lbs torque at 300 rpm. Figures 8 and 9 show the rpm and torque response of the Tesco top drive. The higher speed was designed at special request to allow bottom hole assembly and drillstring dynamics modeling research.

The mud system is set up as a closed loop system capable of processing up to 700 gpm. The 480 bbl mud system is divided into two parts. The active mud system has a volume of 360 bbl, which is divided into six sections. The premix section has a volume of 120 bbl, which is divided into two sections. Each section has an agitator with paddles to keep the mud stirring in the tank.

The mud cleaning consists of two Cagle Linear Screen Adjustable-While-Drilling shale shakers, a Bird centrifuge and a Brandt mud cleaner. A 60 ft conveyor lattice type belt conveyor is used for transporting all solids to a concrete retention pond where they are held for disposal.

Flow is accomplished with a 1300 Hp Skytop Brewster triplex mud pump driven by a 1250 Hp 3512 Caterpillar engine. The mud pump horsepower rating is higher than most in the area, driven by testing needs of LWD, MWD and motor tools.

Data Collection

Traditional rig data collection systems collect data on the order of 1 to several times per second. While this is acceptable for trending and plotting applications, it is not sufficient to perform dynamic analysis of signals as so often required for cutting-edge technologies. For this reason, the BETA system was designed to allow high-speed data collection and real-time frequency domain analysis. Pertinent high frequency data is processed and manipulated, and the results stored alongside slower speed data. The overall scheme provides necessary detail without an overwhelming amount of data being produced.

Because the quality of produced data depends entirely on the accuracy of the measuring device, particular importance is placed upon the type of sensors used at the rig-site. Sensors are used to measure torque, rpm, pump pressure, flowrate, vibration and hook-load. Pump flow rate is measured with both stroke count and magnetic flow-meter systems, giving a theoretical vs. actual situation. A Surface Dynamics Measurement System (SDMS) sub placed directly beneath the top drive is also available to compliment the existing surface sensors. The SDMS, 38" long by 9.5" wide, is capable of sampling four dynamics channels (axial force, axial acceleration, torque and torsional acceleration) and five static channels (hook load, torque, rotary speed and standpipe pressure). All channels are sampled at a 16 bit resolution. SDMS is an evolutionary design and builds on previous surface dynamics measurement devices that were constructed by INTEQ. Its key features are low power consumption, excellent dynamic response and low electronic noise.

The heart of the data collection system is the Data Acquisition (DAQ) hardware manufactured by IOTeq. The DAQ is capable of sampling 16 analog channels and 8 digital signals at a maximum rate of 100 kHz with a resolution of 16 bits. The speed is quite impressive but on the practical side, very few applications actually need sampling in excess of 100 Hz, much less 100 kHz. Two Daq's are used during data collection; the first for primary data collection and the second for a back up for the first and as a secondary data source.

The data collection software was custom written to support the varying test protocols used at BETA. Data is displayed in three depth-base on screen charts as well as two charts which can display either a window of time-based data or a frequency response. Eight numeric displays can b configured to show the current value of any of the 16 measured signals and 25 calculated values derived from the measured parameters. The software stores all 37 channels into a file. Each data line in the file can be either dime based or depth based. This allows for constant data updates regardless of the speed of drilling. A core subset of 18 parameters stored to a separate file and simultaneously printed on a line printer for reference. In addition, short bursts of selected signals at high speed can be stored if needed. These files are stored directly via the local-area-network to the on-site file server where they are indexed by the web/data server.

Downhole vibration monitoring is accomplished through the use of two commercially available tools, VSS and CoPilot.[14,15] The VSS (Vibration Stick Slip) monitoring tool is used as a stand-alone tool to record and transmit downhole vibration and pressure data to the surface. The CoPilot tool also records and processes downhole vibrational data and in addition, provides real-time recommendations to the rig floor. The CoPilot tool measures stresses, pressures and vibrations simultaneously at a high data rate (1000 Hz). A downhole computer processes the information with sophisticated software that determines the occurrence and severity of various downhole drilling dysfunctions. The information on these phenomena (stick-slip, bit bounce, BHA whirl, etc.) is then transmitted to the rig floor where it is displayed alongside surface data, giving the driller immediate feedback on drilling parameter changes.

Drilling bits, downhole tools and other test equipment used in the tests at BETA are photographed in detail before and after they testing using a professional grade digital camera. It is not uncommon to take up to 80 or more high resolution (5 MB uncompressed) photographs during each phase of the test program. The camera differs from most conventional digital cameras in how it acquires and stores color information, which provides higher detail in its photos. The photographs are then converted to a web-safe format and stored for retrieval on the BETA web site. Typical turnaround times between the time photos are taken and the time they are available on the web site is approximately 15 minutes.

The rig is also equipped with two conventional video cameras, one mounted in the derrick and the other showing a view of the rig floor. These cameras are linked to a computer video capture board that updates the BETA web site "real-time" video window every 10 seconds. The video can be viewed as part of the BETA website link or as a standalone view on the computer desktop.

All data, reports, photographs and logs are digitally stored on the local file server running Windows NT. Separately, a web server running Debian Linux is used to allow remote access to all employees within the BHI computer firewall. This means that any employee of BHI, whether located in Oklahoma, Texas, Scotland or any place with an internet connection can view and access current and archived test data from BETA. Figure 10 is a view of the BETA website with multiple windows opened, showing real-time and archived data access.

The web server running Debian Linux contains "front end" to the files on the file server as well as handling the database indexing and real-time display of data. The data archival system is mainly comprised of a MySQL database backend and several Perl scripts, which actual update the database. The scripts periodically access files on the data acquisition computer and the file server across the network, analyze their contents and update the database accordingly. This allows the web site to be updated in near real-time when test parameters, bits, etc. changed during a test. The current data is cross-checked against previous data to allow records for bits, etc. to be reused if the bit has been used once before. A Microsoft Access front-end to the database is used to input mud record information and to update references to photo collections related to a particular test.

Testing

Since coring the first observation well in the fall of 1997, the BETA facility has drilled in excess of 97,000 ft on 42 wells. A total of 101,000+ hours have been worked by the rig crew and onsite engineers without a single lost time accident during the past 3-1/2 years. This record is remarkable considering the number of specialized pieces of downhole and surface equipment being tested in prototype stages, many requiring tripping of the BHA to download memory data after drilling as little as one to five feet.

HS&E Awareness starts the first day before the employee ever start their job. The new employee's orientations are defined by the job he/she is assigned using a team based safety process developed by Hughes Christensen headquartered in The Woodlands, Texas. After the orientation, the employee receives an HS&E Handbook and is given a tour of the entire facility. Once the orientation is completed, an individual HS&E training plan is developed for the employee based upon his/her job functions. Hughes Christensen developed a Computer Based Training CD-ROM, which is used in conjunction with the Baker Hughes KnowIt CD-ROM to complete the orientation process at BETA. The safety record at BETA is the direct result of a behavior based safety training program that was implemented at BETA in 1998.

Most of the projects at BETA have been completed working five days a week, 10 – 12 hour days. However, certain projects require extensive testing or the combination of depth and deviation makes the shorter days less efficient. For these cases, the facility works five to six days per week, 24 hours per day. BETA is currently operates 24 hours per day. Following is a sampling of tests performed at the facility.

- CoreDrill Wireline Coring System
- CoPilot Vibration Measurement Tool
- Autotrak Rotary Steerable System
- e2Tech Expandable Tubulars Hole Quality
- PDC Cutters

CoreDrill System

The first well drilled at BETA was cored from a depth of 64 ft to 2995 ft, just shy of the Arbuckle dolomite. A wireline retrievable core system was selected because of the amount of footage to be cored. The wireline coring was with INTEQ's CoreDrill system which is a rotary drilling system designed to selectively drill full hole or core on demand without the need to trip the drillstring. The CoreDrill concept has been applied successfully on land type operations in hole sizes ranging from 7 7/8" to 8 ¾". Overall core recovery with the 8-1/2" x 2" INTEQ wireline coring system at BETA was 94% as previously mentioned. Anti-Whirl PDC core bit designs were used with the system to improve stability and minimize damage to the 2" core. Although core lengths of 30 ft are typically pulled, a number of world first 60 ft cores were pulled on wireline. An attempt to fill a 120 ft barrel resulted in an impressive 105 ft of core being retrieved on wireline.

More recently, INTEQ developed an improved wireline coring system called CoreDrill Navi-Gamma that was tested at BETA[14]. The tool is instrumented with a battery operated retrievable MWD directional sensor package providing real-time position of the borehole while drilling in full hole mode. In addition, the MWD probe features a nearbit gamma ray sensor to aid in the detection and interpretation of formation tops and the selection of core points. The testing at BETA was initially performed to provide a shakedown of the CoreDrill Navi-Gamma equipment before commercial field runs. Several successful runs in the North Sea followed the successful testing at BETA. However, a problem arose when trying to retrieve the MWD probe in near horizontal directional wells. The tool was sent back to BETA for analysis in a directional well where the overshot latch mechanism was found to prematurely release across sections with high doglegs. The overshot was redesigned and the tool was put back into service without incident.

CoPilot

The CoPilot MWD vibration measurement tool previously mentioned was initially tested at BETA. Complex downhole dynamics are measured by the CoPilot sensors and then processed downhole using algorithms within the tools digital signal processor (DSP) and transformed into simple diagnostic levels. The diagnostic levels are designed to speed uphole transmission and to enable rapid evaluation of complicated downhole dysfunctions at the surface. The purpose of the testing at BETA was to create different downhole drilling dysfunctions to allow refinement of the diagnostic algorithms used inside the tool to distinguish the type of vibration. Drilling dysfunctions were created taking into consideration lithology, BHA design, bit type and drilling parameters. In other words, considerable effort was made to create what can be described as very bad drilling conditions to simulate the variety and destructive nature of drillstring dysfunctions.

Testing of the CoPilot MWD tool was performed at BETA on well BHC-1 in a 12¼" vertical well. Testing was performed over 10 runs with various BHA configurations and bit types and using both modular collar and probe-based MWD platforms. The BETA test facility allowed the collection of data that would have been difficult on a commercial well. Figure 11 is an example of downhole recordings of bit bounce with a 12-1/4" rollercone bit run with 8" drill collars. Average surface WOB was 40,000 lbs at the time bounce was detected. Peak downhole WOB loads of 130,000 lbs and torque loads of 20,000 ft-lbs were measured by the CoPilot tool. Equally surprising was the measurement of negative torque at the bit, up to minus 4,000 ft-lbs. Not surprisingly, the box connection of a new 8" drill collar was cracked during the vibration testing. The variety of drilling dysfunctions and ability to trip out of the hole, inspect tools and modify the diagnostic algorithms inside the CoPilot tools helped decrease the cycle time for commercial testing by a minimum of 12 months.

AutoTrak

The AutoTrak rotary steerable system has been tested extensively at BETA to continually improve tool performance and reliability. The advanced design allows complete and continuous control of both the magnitude and direction of the steering force to the bit through full real-time two-way communication from downhole to surface and from surface to downhole. In addition, sensors built into the downhole tool provide real-time nearbit formation evaluation data plus continuous near bit inclination measurements that contribute to a high degree of accuracy in positioning the wellbore, either within a particular geologic formation or at a particular geometric position[15].

The high demand for these tools and the necessary testing requirements for improvements require efficient use of development resources. Testing at BETA with AutoTrak tools has shown that a six-week test period is nearly equal to a six-month test period in customer wells. BETA allows problems to be thoroughly analyzed to get to the root cause. Small changes can be tested without knowing exactly whether the fix will solve the problem. In other cases, quick fixes can be implemented in order to continue testing other tool components. Surprisingly, testing in customer wells can be quite expensive since the tools must be 100% lab tested and ready prior to each field run. Each customer well requires a full mobilization and demobilization of people and equipment. For testing of two or three tools, you go to the field and hope to get one or possibly two tools run at best before taking everything back to the lab for evaluation. BETA allows the researcher a field trial earlier in the project phase without full mobilization of equipment. Tools can be run knowing full well that hardware or software components are not fully qualified. This process helps speed up the development and debugging significantly.

e2Tech Expandable Tubulars Hole Quality

Expandable tubular technology has the potential to significantly reduce well construction costs. Conventional well construction results in telescoping of the well size from the wellhead down to the reservoir. Apart from resulting in large expensive surface casing, wellhead, trees and operating equipment, the method can result in an unworkable small hole size at the required depth. Expandable tubular technology has created a need for improved understanding of the directional tendencies of eccentric drilling tools run on steerable assemblies and the wellbore geometry and quality that can be achieved. Consistent wellbore diameter is of particular concern for expandable tubulars. If the wellbore diameter is too small, expansion of the pipe with a fixed diameter cone might not proceed properly across sections of firm formation. Worse yet, the expansion cone could become stuck requiring remediation or sidetrack of the well. A wellbore that is too large could affect the sealing effectiveness depending on the sealing system used.

A test program was performed at BETA to evaluate the use of Drill Out Steerable Ream While Drilling (DOSRWD) tools for an expandable tubular application in the North Sea[16]. The testing used 9-7/8" DOSRWD tools in conjunction with 6-1/2" pilot bits (both PDC and roller cone). Motor bent housing settings included 1.0°, 1.5°, 1.75° and 2.0° bends to evaluate directional and stability response. Surface speeds were varied from 0, 35, 50 and 75 rpm at each motor housing setting. Caliper logs including four and six-arm and ultrasonic borehole imaging (UBI) tools were used to characterize the borehole under all conditions. This was the most extensive test program known to have been performed with eccentric tools. Testing and correlation of data using commercial wells would have been feasible but not practical, both from timing and a cost standpoint. Test testing is believed to have reduced the cycle time to get the information by a minimum of one to two years.

One very surprising discovery during the testing and evaluation was the inaccuracy of standard caliper logging tools. Caliper comparison was not the intent of the test program however, after initial review it became apparent certain logging systems delivered more accurate and detailed information. The standard bread-and-butter four-arm caliper produced both inaccurate and inconsistent results and consistently measured hole diameter significantly under true diameter. In addition, wellbore deviation was found to affect both four-arm and 6-arm data

Figure 12 shows different logging tool interpretations for a 12-1/4" hole due to off-center placement of the tool. Surprisingly, each of the three tool orientations show an average size of 11.9" but with completely different interpretations of wellbore geometry (C1, C2 and C3 arm pair readings). The two major logging companies were contacted at the conclusion of this project to initiate algorithm modifications to account for off-center running of 6-arm logging tools.

PDC Cutters

Polycrystalline Diamond Compact (PDC) cutters have continued to expand their application in fixed cutter bits. Understanding the primary causes of wear, both steady-state abrasive wear and dynamic loading have led to significant advances in cutter life[17]. For a PDC cutter under development, it must pass a series of advanced modeling, laboratory testing and commercial field trials before it is placed into a product line. Test correlation is tedious and often the result of dozens of unique tests.

The varied and repeatable formations at BETA make it a unique facility for PDC cutter testing and evaluation. Figure 13 compares cutter wear for a standard cutter and a "next generation" cutter recently placed into commercial service in the Genesis PDC bit product line. The 13mm cutters were run on the same 8-1/2" PDC bit frame, beginning at the same depth and stopping at the same depth. The photographs show negligible wear on the Genesis cutters compared to significant wear flats on the standard cutters. More significant is the effect of cutter wear on performance. Figure 14 shows the Genesis bit averaging nearly twice the rate of penetration of the same bit was standard cutters.

Field testing of the new cutters and bit design recently showed an improved rate of penetration in a 12-1/4" hole section on the Kingfisher Project well, Central North Sea[18]. For this project, a combination of improvements related to stability modeling, cutter design and hydraulic modeling gave the improved performance. Drilling of the abrasive Kimmeridge section resulted in one bit manufacturers bit to be ¾" undergauge after drilling only 50 ft. The genesis bit with improved cutter technology was able to ream the undersize hole and drill ahead 395 ft at triple the rate of penetration. A second bit of the same design drilled 507 ft and again tripled the rate of penetration seen with standard technology. The Genesis bit with the improved PDC cutters is being launched at the writing of this paper.

Conclusions

Development is not an exact science; an enormous amount of iterations are sometimes required for new products. The varied geology at BETA and the unique data collection system and intracompany website are helping transform the way we evaluate tools. More importantly, the facility is helping reduce the cycle time from concept to commercial product, helping to reduce the operators drilling cost while improving the overall understanding of drilling mechanics.

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Table 1

Core Tops & Intervals (ft.)	E-Log Tops & Intervals (ft.)	System	Series	Group	Formation	Member	Marker Bed	Subsurface Name	Comments
Surface	Surface	Pennsylvanian	Desmoinesian	Marmaton	Holdenville Shale				
66.80									Top of core
317.75	317				Wewoka				
638.00 - 640.00	636					Anna Shale		Oologah	From Gamma Log
749.70								Oswego	Fossiliferous sandy shale
772.10	770			Cabaniss	Senora	Excello Shale			Radioactive shale marker
781.50 - 781.70	779					Iron Post Coal	Hot Coal		Radioactive coal
875.10	872					Verdigris Limestone			Fossiliferous limestone marker
877.10	874					Unnamed Black Shale			Dark gray to jet black
1010.00 - 1014.90	1006					Mineral Coal			Coal, clay and shaly coal
1028.20 - 1132.00	1026					Chelsea Sand		Skinner	Very prolific reservoir
1209.50 - 1211.30	1206					Tebo Coal		Pink Lime	Good e-log marker
1211.30 - 1225.00	1207						Red Fork Ss.		Very prolific reservoir
1321.25 - 1321.45	1318					Weir-Pittsburg Coal			Produces gas in certain areas
1321.45	1318			Krebs	Boggy				
1363.10 - 1364.40	1358					Unnamed Coal			Coal, underclay soil and silt
1364.40 - 1422.00	1360					Taft Sand		L. Red Fork	Very prolific reservoir
1536.60 - 1538.00	1539					Unnamed Coal			Shaly coal
1544.30 - 1545.76	1541					Inola Limestone			Good e-log marker
1545.76 - 1546.15	1542					Bluejacket Coal			
1595.60 - 1702.90	1592 - 1699					Bluejacket Sand		Bartlesville	Very prolific reservoir
1702.90					Savanna				
1741.00	1737						Brown Ls.		Radioactive shale marker
1745.65	1742					Donley Limestone			Fossiliferous, brachiopods
1746.35	1743					Rowe Coal			Produces gas in certain areas
1753.50	1750					Sam Creek Limestone			
1773.50 - 1775.85	1770					Spaniard Limestone			Fossiliferous, brachiopods
1775.85					McAlester				
1852.00 - 1863.10	1848							U. Booch	
1878.15 - 1878.60	1874					McAlester Coal		Stigler	Bright, hard
1903.95 - 1904.55	1900					Keefton Coal			Bright, hard
1905.30 - 1916.00	1901					Warner Sand		L. Booch	Productive in certain areas
1975.90					Hartshorne				Very prolific reservoir
2009.00	2005		Atokan		Atoka				Very prolific reservoir
2162.20	2167		Morrowan		Wapanucka				
2209.00	2204				Union Valley				Produces sparsely
2264.50	2262	Mississippian	Chesterian		Pitkin				Good e-log marker
2266.42	2265				Fayetteville				Lost 18.73 feet of core
2363.80	2362				Hindsville				Very fossiliferous
2367.00 - 2402.00	2366		Meramacian		Moorefield	Ordinance Plant			
2402.00	2399							Mayes	
2485.50	2482		Osagian		Keokuk-Reed Sp.				Produces in certain areas
2579.70	2975		Kinderhookian	Choteau	Saint Joe			Kinderhook	
2623.00 - 2653.87	2619	Devonian	U. Devonian		Woodford Shale			Woodford	Major source bed
2653.87						Misener Sand		Misener	Very prolific reservoir, sharp
2655.92	2652	Ordovician	U. Ordovician	Viola	Welling			Fernvale	
2661.95	2659				Viola Springs	Viola Dense Limestone		Viola Dense	Produces in certain areas
2664.30	2662					Viola Dolomite		Trenton	Produces in certain areas
2671.30	2669		M. Ordovician	Simpson	Bromide			2nd Wilcox	Very abrasive and prolific
2768.29	2764				McLish			McLish	Very prolific reservoir, sharp
2832.00	2826				Oil Creek			Oil Creek	Very prolific reservoir, sharp
2993.00	2990		L. Ordovician	Arbuckle	?			Arbuckle	Drilling cuttings examination
			(Ibexian)						
3162.00 T.D.	3146 T.D.								Stopped drilling in Arbuckle

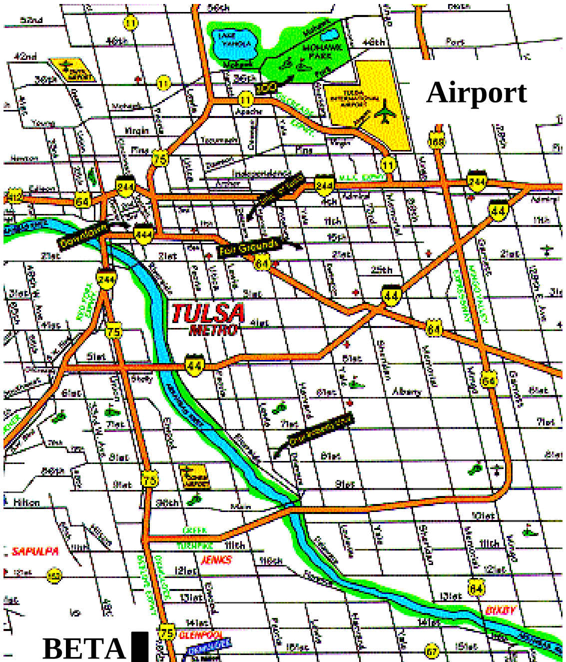

Figure 1: BETA Location from Tulsa, Oklahoma

Figure 2: BETA Rigsite

Figure 3: BETA Site Location

Eras (or Erathems)	Periods (or Systems)		Epochs (or Series)	Length in millions of years	Age estimates of boundaries in millions of years
Cenozoic	Quaternary		Holocene	.01	.01
			Pleistocene	1.6	1.6
	Tertiary	Neogene (subperiod)	Pliocene	3.7	5.3
			Miocene	18.4	23.7
		Paleogene (subperiod)	Oligocene	12.9	36.6
			Eocene	21.2	57.8
			Paleocene	8.6	66.4
Mesozoic	Cretaceous			78	144
	Jurassic			64	208
	Triassic			37	245
Paleozoic	Permian			41	286
	Pennsylvanian			34	320
	Mississippian			40	360
	Devonian			48	408
	Silurian			30	438
	Ordovician			67	505
	Cambrian			65	570
	Precambrian time*				
Proterozoic Eon	Proterozoic Z				800
	Proterozoic Y				1600
	Proterozoic X				2500
Archean Eon					
	Oldest known rocks in the United States				3600

Figure 4: The Geologic Time Scale and Geologic Columns

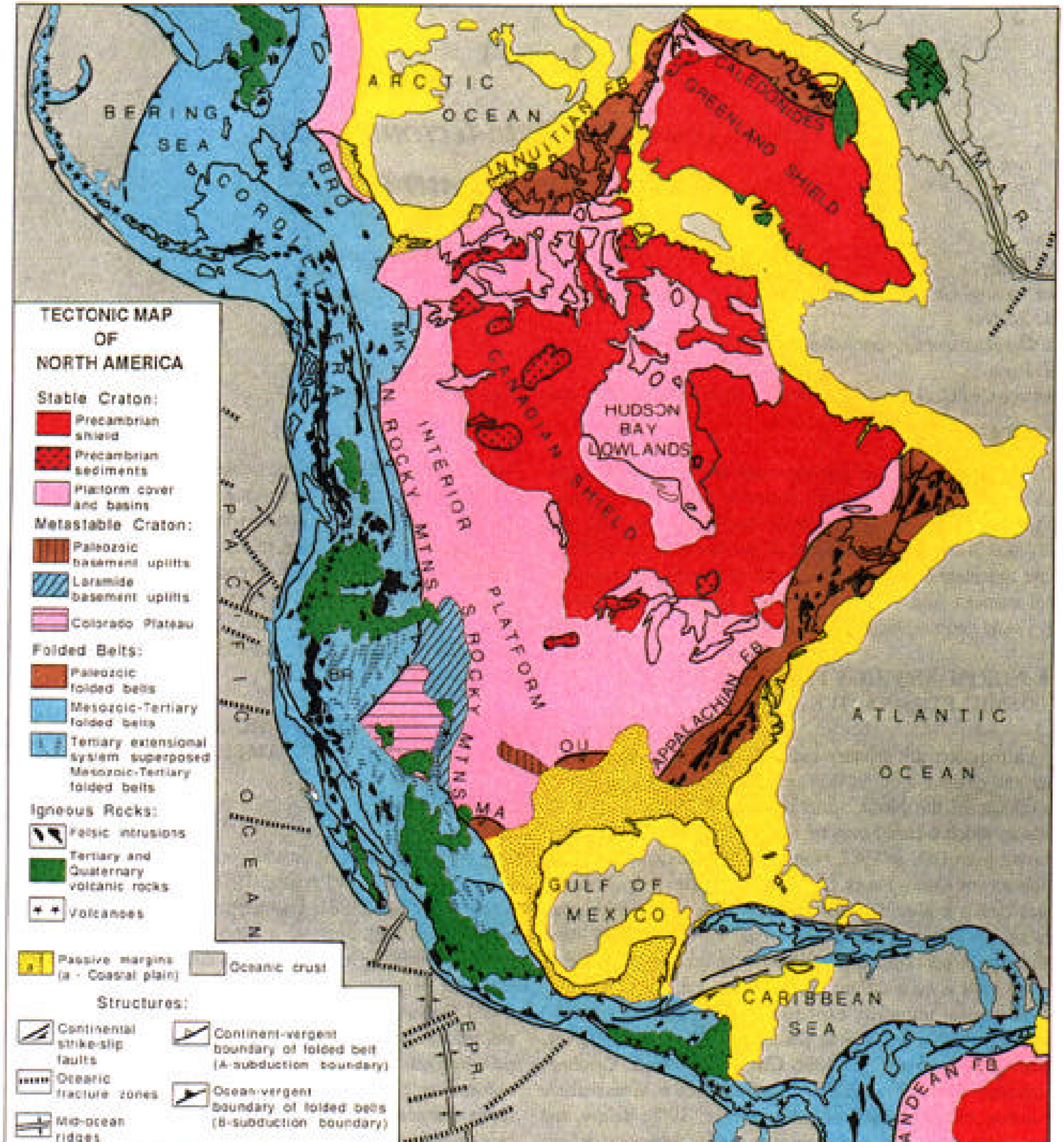

Figure 5: Simplified Tetonic Map of North America

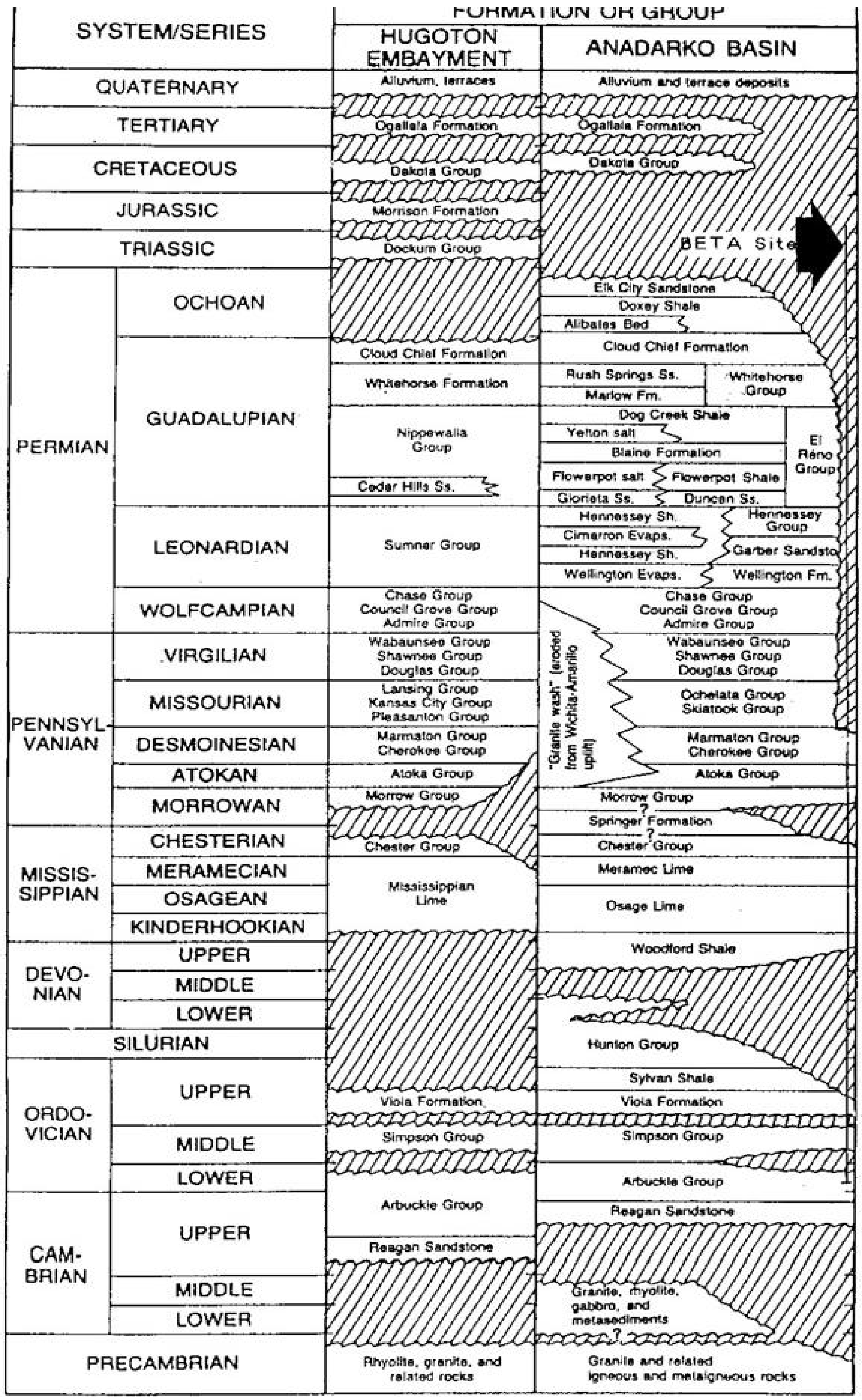

Figure 6: Stratigraphic Column for Oklahoma Showing Rock Sequence for BETA

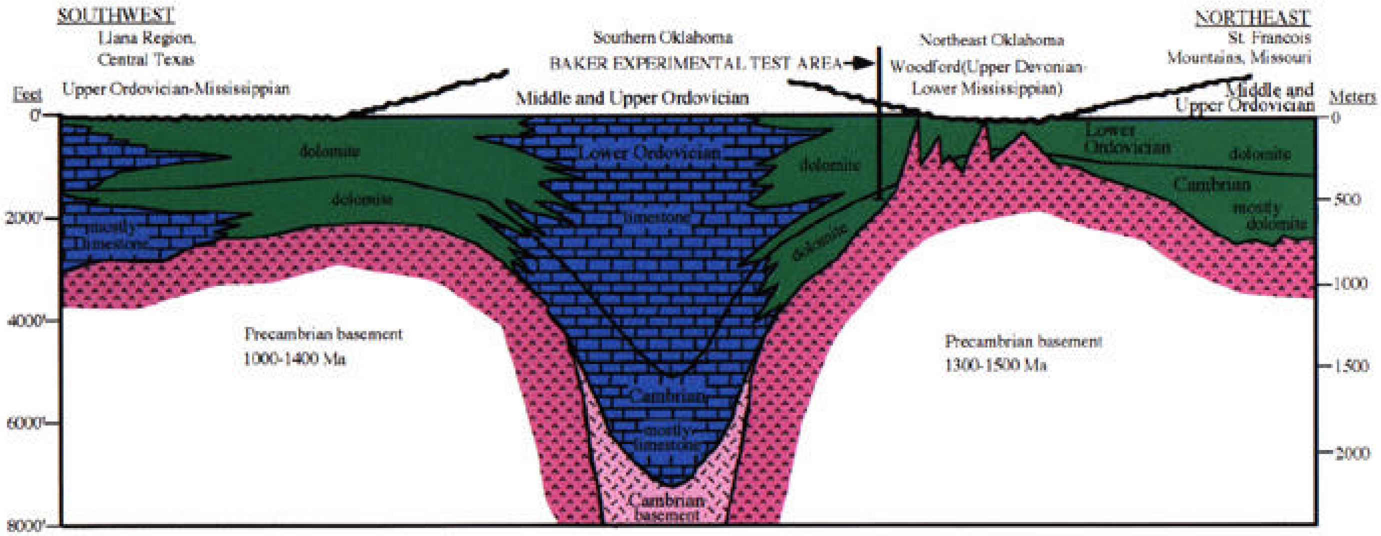

Figure 7: Schematic of Early Paleozoic Cross-Section of Oklahoma

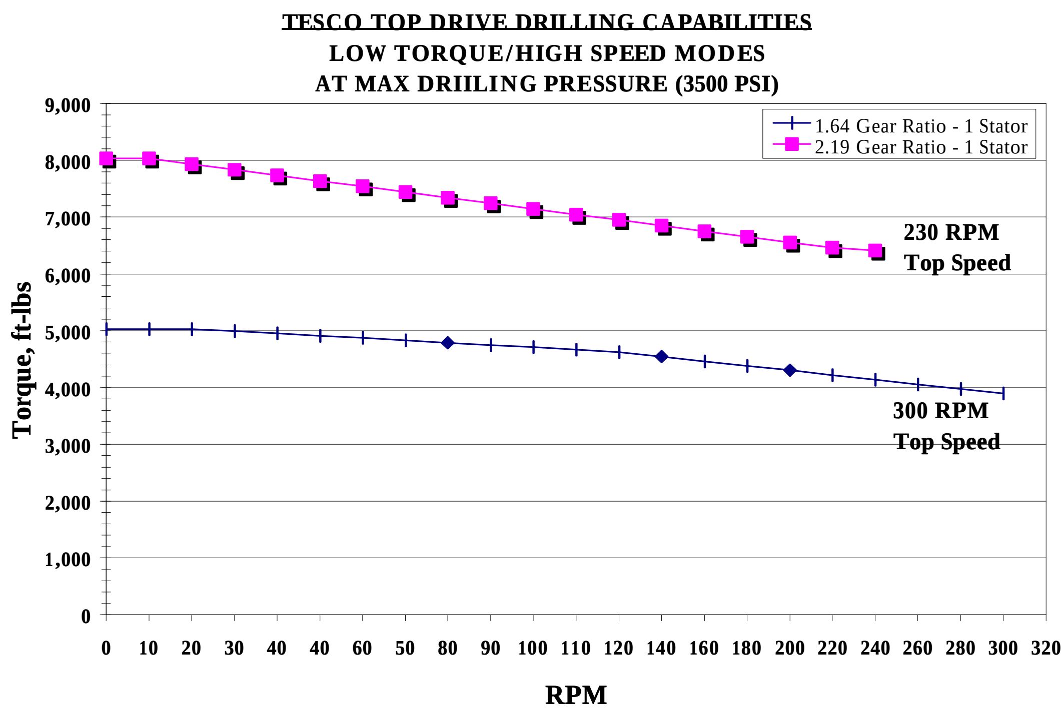

Figure 8: Tesco Top Drive RPM and Torque response with 1 Stator

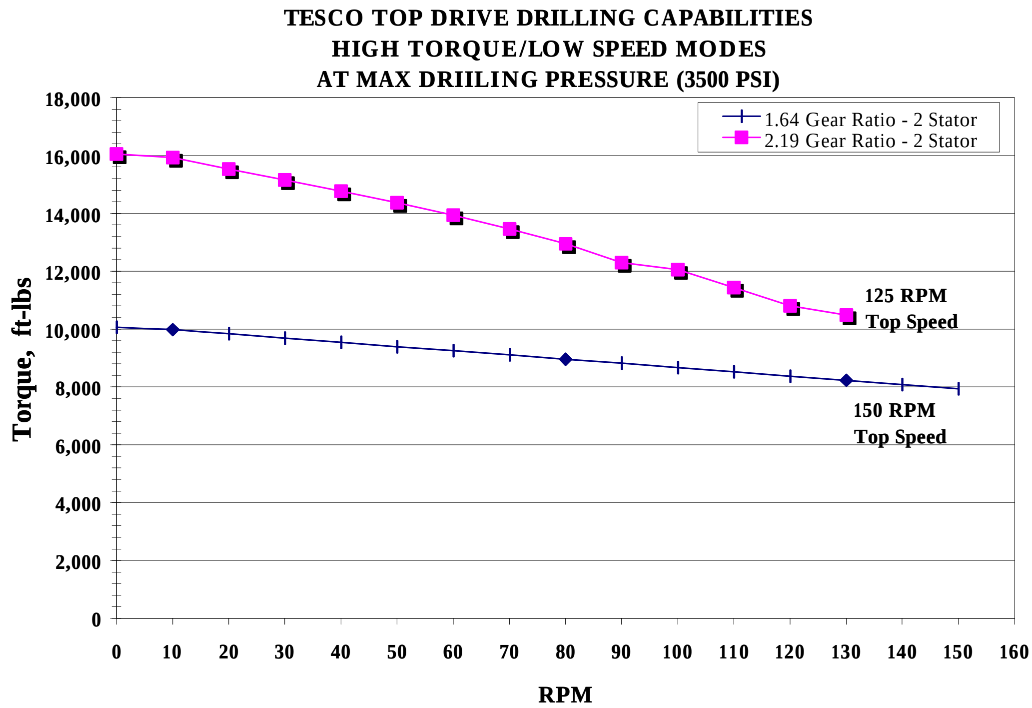

Figure 9: Tesco Top Drive RPM and Torque response with 2 Stators

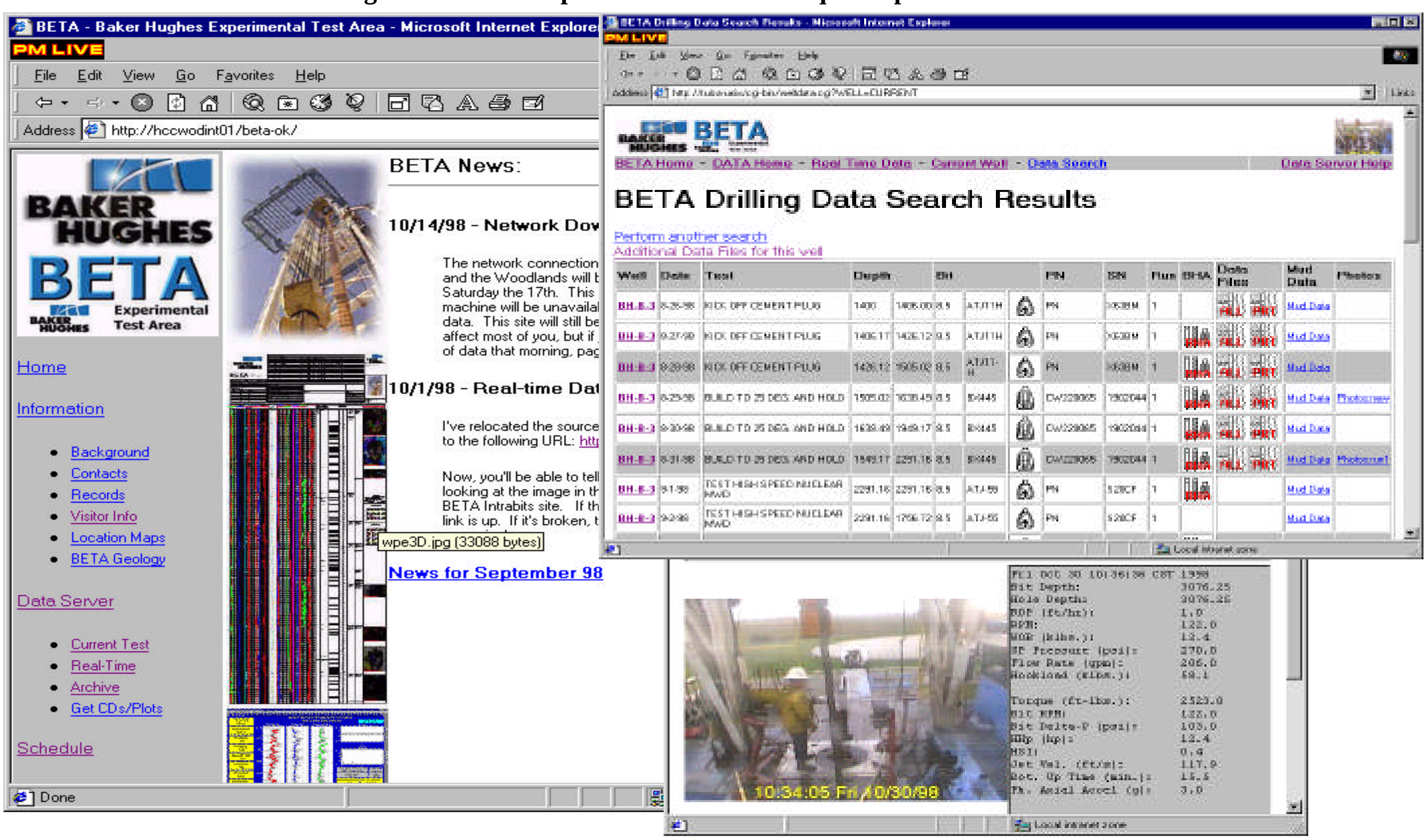

Figure 10: BETA Intracompany Website with Realtime and Archived Data Displayed

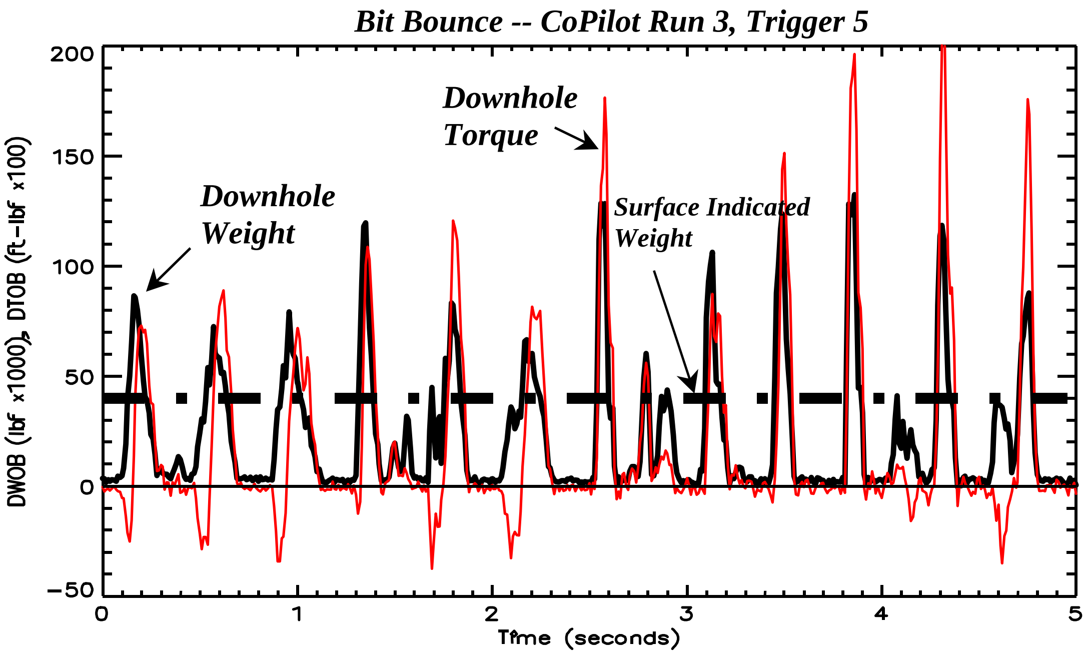

Figure 11: CoPilot Measurement of Bit Bounce with a 12-1/4" Rollercone Bit

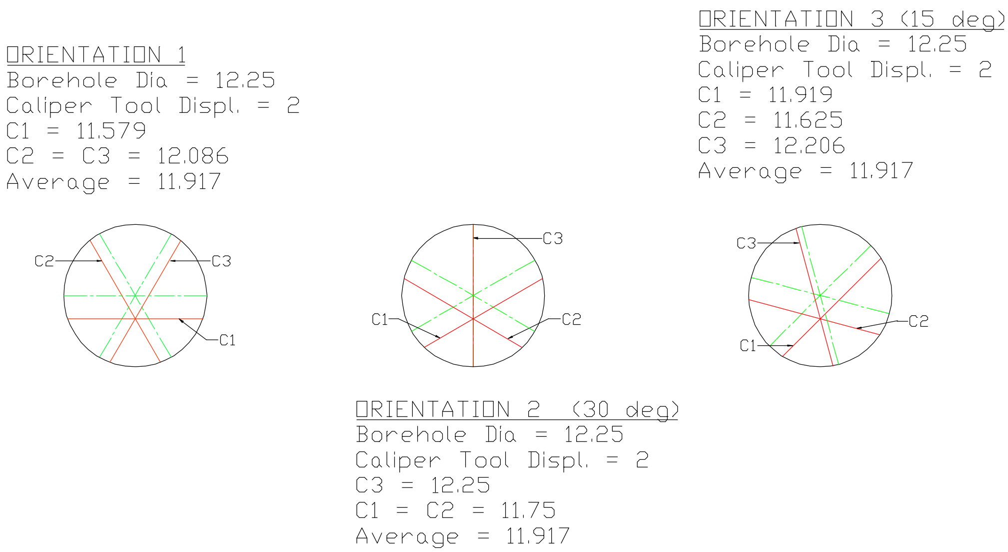

Figure 12: Inherent Inaccuracy with 4-arm and 6-arm Caliper Logs in a 12-1/4" Hole.

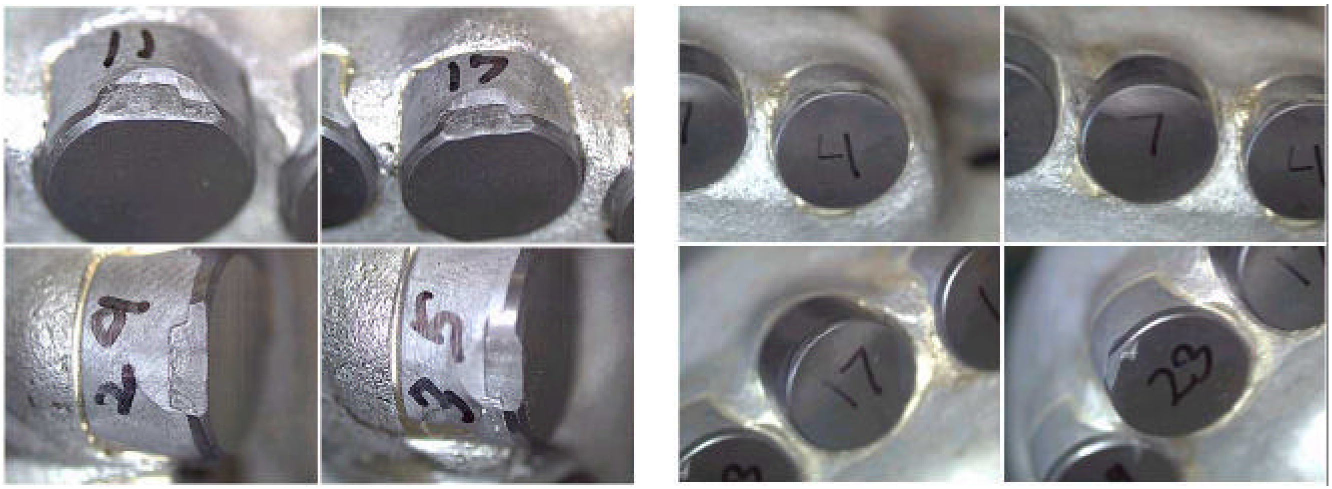

Figure 13: Standard Cutter Wear on Left Compared to "Next Generation" Cutter Wear on the Right.

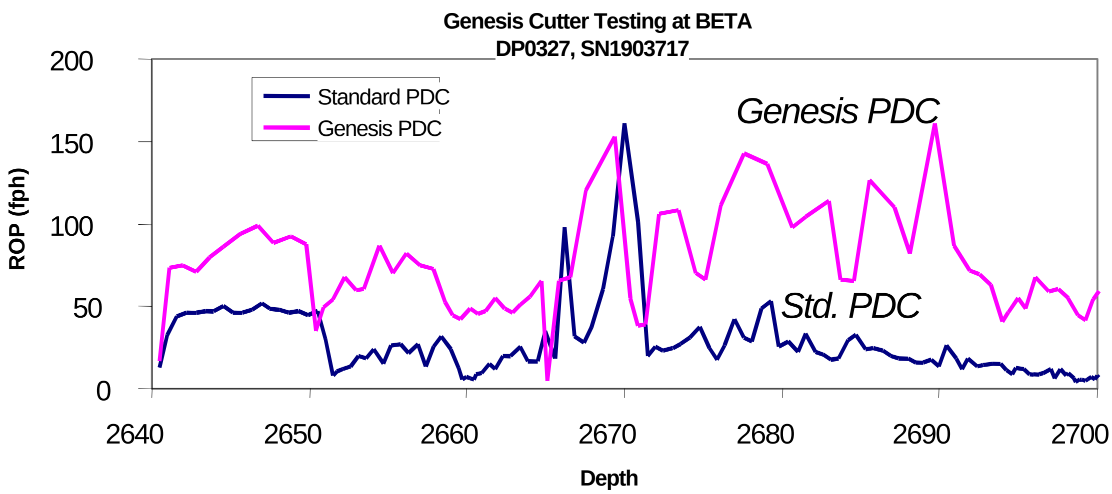

Figure 14: Improved PDC Cutter Rate of Penetration due to Less Cutter Wear Drilling Wilcox Sand.