Information Circular 39C
FF-OG-OU 017

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ARKANSAS GEOLOGICAL SURVEY
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INFORMATION CIRCULAR 39C

STRUCTURAL AND STRATIGRAPHIC ANALYSIS OF THE SHELL INTERNATIONAL PAPER NO. 1-21 WELL, SOUTHERN OUACHITA FOLD AND THRUST BELT, HOT SPRING COUNTY, ARKANSAS

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2014

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Acknowledgments

The authors express their gratitude to Shell Exploration & Production Company (SEPCO) for sharing their data, technical advice, and subsurface knowledge of the Ouachita Mountains region in Arkansas for this publication. This is the final of a three part series summarizing the wells that Shell drilled in the southern Arkansas Ouachitas in the 1980s. A special thanks goes to fellow Shell team members who participated in the evaluation and drilling of the International Paper well: Florence Kunze, Frank Kozack, Susan Waters, John Bobbitt, Karol Valek, Don Beaudry, Sam Milner, and Peter Nordstrom. We would also like to thank the geologists of the Arkansas Geological Survey (AGS) for reviewing the technical aspects of the manuscript and providing supplemental geologic information for this report. Finally, we would like to extend our gratitude to Kayla Miller at the AGS for assisting with the editing and layout of this publication and to Brian Kehner and Nathan Taylor for preparing the graphics and plates in this report.

Structural and Stratigraphic Analysis of the Shell International Paper No. 1-21 Well, Southern Ouachita Fold and Thrust Belt, Pike County, Arkansas

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Introduction

A joint research project between the Arkansas Geological Survey (AGS) and Shell Exploration & Production Company (SEPCO) was undertaken to report the findings of three exploration wells drilled by Shell during the 1980s in the Arkansas portion of the Ouachita Mountains. Shell recognized several potential targets in the Ouachita fold and thrust belt of Arkansas and drilled three wildcat wells to test their hydrocarbon potential. The three wells were designed to test the reservoir potential of the Carboniferous sandstones in the Jackfork and Stanley Formations (Rex Timber well, Clark County); the Lower Mississippian-Devonian Arkansas Novaculite and the Ordovician Bigfork Chert (Arivett well, Pike County); and the Ordovician Crystal Mountain Sandstone and Bigfork Chert (International Paper well, Hot Spring County) (Plate 1; Figure 1). The results and conclusions from these wells are published in a three part series of Information Circulars at the AGS. As the final of the three publications, this report focuses on the International Paper No. 1-21 well located in S21-T4S-R20W.

The International Paper (IP) well was spudded on October 12, 1982 and subsequently plugged and abandoned as a dry hole on February 12, 1983 after reaching a depth of 7,868 ft

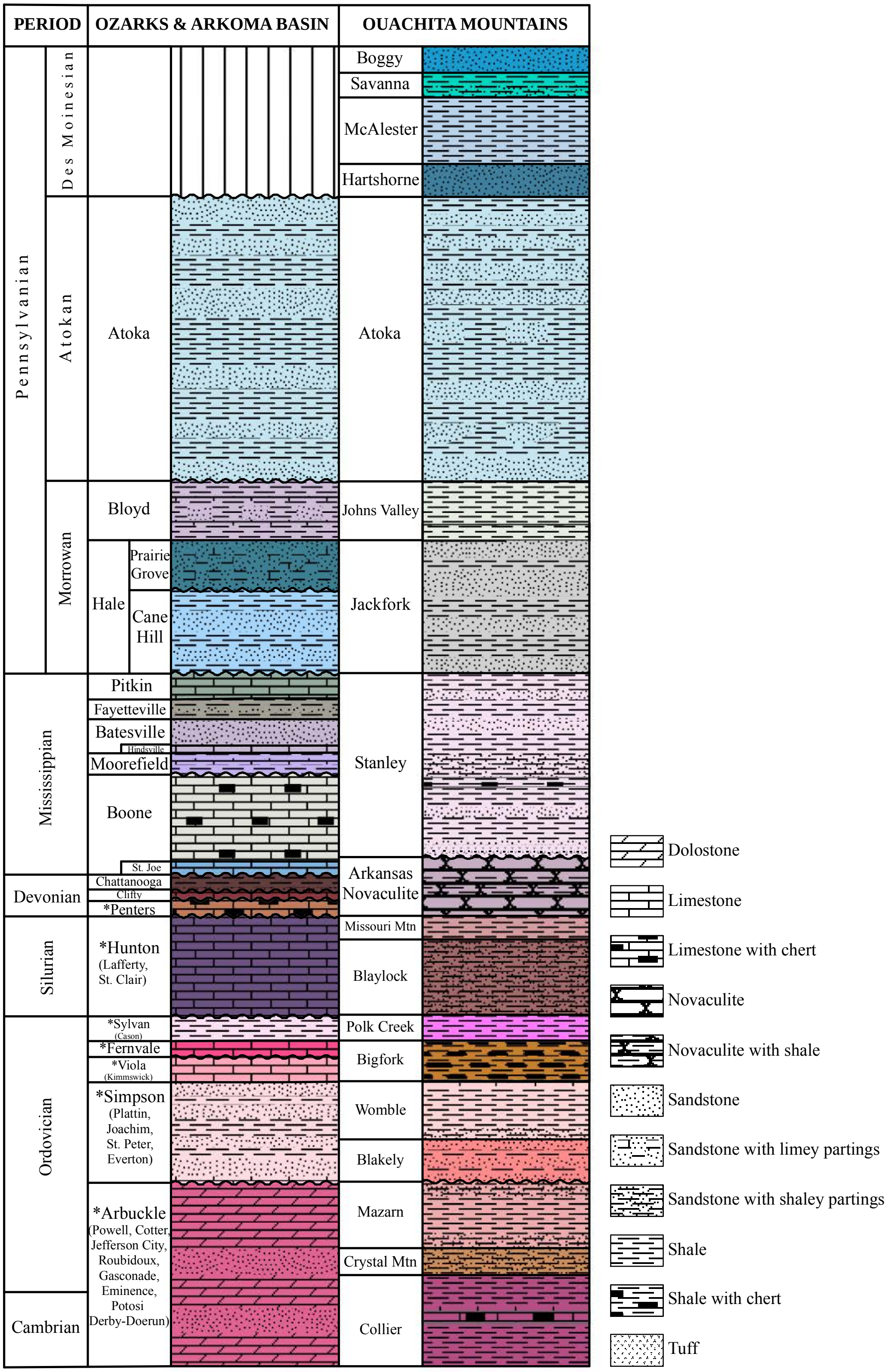


Figure 1. Stratigraphic correlation between the Ozark Plateaus and Arkoma Basin and the Ouachita Mountains regions in Arkansas.

(2,398 m) in the Ordovician Bigfork Chert. The IP well did not have a prospect name because it was drilled primarily as a stratigraphic test of geologic concepts. The lack of significant hydrocarbons was determined through the use of air/mist drilling. This type of drilling technique acts as a continuous flow check for hydrocarbons. In the air-drilled IP well, without the presence of any mudcake which might hinder or mask hydrocarbon evaluations, the well did not detect live hydrocarbon shows. The objectives of this report are to present both the reasons for drilling this stratigraphic test in the Trap Mountains and to present raw data with structural and stratigraphic interpretations.

Regional Geologic Setting

The Ouachita Mountains physiographic province lies between the Arkansas River Valley to the north and the Gulf Coastal Plain to the south and extends from Little Rock, Arkansas westward to Atoka, Oklahoma (Plate 1). The total area of the exposed mountain range is approximately 12,000 mi^2 (31,080 km^2), slightly more than half of which lies within Arkansas. Late Cambrian to Carboniferous deepwater sedimentary rocks comprise the Ouachita Mountains. The stratigraphic section exposed in the Ouachita Mountains represents coeval deepwater deposition of shallow water facies in the Arkoma Basin province (Nicholas and Rozendal, 1975; Bush et al., 1977; Visher and Wickham, 1978; Arbenz, 1989; Lowe, 1989) (Figure 1).

The basement in the Ouachita foreland basin is deeply buried by imbricate thrust-sheets of sedimentary rocks. These imbricate thrusts and basement faults are observed in deep reflection seismic lines acquired by the Consortium for Continental Reflection Profiling (COCORP) (Nelson et al., 1982). Based on COCORP seismic data, the Ouachita frontal thrust zone is composed of approximately 39,000 ft (11,887 m) of both allocthonous and autochthonous sediments (Nelson et al., 1982). South of the frontal thrust zone, the deformation created a large anticlinorium known as the Benton Uplift. The uplift is composed of about 23,000 ft (7,010 m) of thrusted sedimentary rocks that lie above the crystalline basement (Nelson et al., 1982; Arbenz, 1984; Suneson, 2008). South of this uplift, deep-seismic data indicate that as much as 46,000 ft (14,021 m) of deep-water sediments are thrust over the basement complex (Lillie et al., 1983). Blythe (1988) made two balanced regional cross sections using the COCORP data. The three deepest subsurface penetrations south of the Benton Uplift were drilled by Shell. The oldest formations penetrated in each well are the 1) Ordovician Bigfork Chert (International Paper - stratigraphic test; Godo et al., 2014); 2) Mississippian Stanley Shale (Rex Timber/Moccasin Prospect; Godo et al., 2008); and 3) Silurian Blaylock Sandstone (Arivett/Rattler Prospect; Godo et al., 2011A; 2011B).

Stratigraphic and Structural Test Concept

Shell began to evaluate the oil and gas potential of the Arkansas Ouachitas south of the Benton Uplift in the early 1980s. The purpose of the investigation was to evaluate the source rock and petroleum potential of the sedimentary sequences in this region. Discoveries of oil and gas made in the 1970s and 1980s in the Arkansas Novaculite (Oklahoma) and Caballos Novaculite (west Texas) gave incentives to explore chert and novaculite lithologies for their reservoir potential. Small oil fields located in the Ouachita Mountains of Oklahoma producing from the Stanley Formation provided incentive to explore for additional hydrocarbon potential in the Arkansas Ouachitas (Morrison, 1982; Voight and Sullivan, 1983).

Major issues potentially hampering reservoir development include the thermal maturation history associated with burial and uplift and secondary heating by Cretaceous igneous intrusives (Dennison, 1977; Erickson, 1963; Stone et al., 1986; Stone and Haley, 1986; Howard, 2007). Regional heating associated with low grade metamorphism is not confined to the older stratigraphic units; there is a later thermal overprint that crossed stratigraphic boundaries (Figure 2) (Goldstein, 1955; Shell internal studies, 1981-82; Houseknecht et al., 1985; Guthrie et al., 1986; Tottent et al., 1993). The area of rock affected by this secondary heating was referred to internally by Shell geologists as the "heat chimney." South of the Benton Uplift (and heat chimney), the thermal maturities of outcrops are lower. Shell considered this region to have potential for natural gas exploration.

The thermal maturity of all rock samples ranging in age from Pennsylvanian to Ordovician was analyzed during the 1980s, and the reflectance values from all organic macerals were optically measured. Vitrinite reflectance was used as a standard, but rocks older than Devonian required determination of reflectance from other macerals to make vitrinite equivalent reflectance estimations. Although not a primary measurement, Shell used the level of organic metamorphism (LOM) (Hood et al., 1975) as an alternative method to correlate thermal maturity values. This technique uses information such as coal rank, thermal alteration index (TAI), maximum temperature (T_{max}), vitrinite reflectance (R_o), spore carbonization, and other scales that measure the level of organic thermal maturity in rocks (Bertrand and Heroux, 1987; Senftle and Landis, 1991; Cardot, 2012).

Before drilling, an average LOM 15.5 was determined for outcrops in the Trap Mountains through geochemical analysis. The IP well was a stratigraphic test aimed at encountering Ordovician cherts and sandstones to better understand subsurface conditions, including the paleo-thermal gradient. Though later wells were to stop when LOM 18 was reached, the IP well was designed to drill below LOM 18 to further explore the stratigraphy and structure of the Trap Mountains. This exploration floor was based primarily on a geologic depth that corresponds to paleo-geologic temperatures of LOM 18 which correlates to $R_o > 3.32$. These values are consistent with the onset of low-grade greenschist facies metamorphism (Spry, 1969; Keller et al., 1977; Keller et al., 1985; Hoersch, 1981). The prediction of depth at which these high levels of R_o would occur was based on the composite reflectance profiles of nineteen wells drilled in the Ouachita Mountains outside of the heat chimney and distal from the Benton Uplift (Godo et al., 2011A). R_o values in these wells have a linear increase in thermal maturity with depth, regardless of the amount or degree of thrust faulting. This linear trend of R_o values indicates enough time has passed for the rocks to equilibrate to the regional thermal gradient, unlike maturity gradients from thrust belts with more recent faulting (Oxburg and Turcotte, 1974; Angevine and Turcotte, 1983; Senftle and Landis, 1991).

Shell designed and drilled three wildcat wells to test various potential reservoirs and source rocks in the Ouachita Mountains. Based on the results from these wells, a decision would be made whether or not to continue exploration efforts. Preparing for the 1980 to 1982 drilling campaign, geologists measured stratigraphic sections; collected shales for source rock analysis; reviewed surface geologic maps; and investigated subsurface data from shallow water wells and early exploration wells (Godo et al., 2011A; 2011B). Seismic data south of the Benton Uplift was not available for evaluation. Early in 1982, Shell moved geophysical crews to an Arkadelphia, Arkansas headquarters and began to acquire proprietary 2-D seismic data across major surface thrust faults or otherwise structurally high complexes. Due to the very steep dips of bedding on the surface, particularly in the Trap Mountains, the resolution of folded seismic reflectors at depth was poor. Consequently, a decision was made to spud the IP well in October of 1982 before the first seismic line was fully processed.

The overall structure of the Trap Mountains is a large, westward-plunging anticlinorium with rocks as old as the Ordovician Bigfork Chert exposed at the eastern end of the structure. This structural high appears to be isolated from the Benton Uplift, which is believed to be cored by a basement thrust complex. Additional secondary vertical heat flow was thought to have primarily affected the easternmost exposures of the Trap Mountains. The Mazarn synclinorium is a structural low that separates the Trap Mountains structural high from the Zig Zag Mountains fold belt of the Benton Uplift (Plate 1). The Zig Zag Mountains have axial folds that plunge to the southwest; whereas the Trap Mountains exhibit a westward-plunging trend (Purdue, 1909; Haley and Stone, 2006). By spudding the Trap Mountains well in the Silurian Blaylock Formation, there was potential to drill deep enough to encounter the Ordovician sandstones (Blakely and Crystal Mountain). Prior to the IP well, no wells had penetrated the Paleozoic sequence outside of the core uplift of the Ouachita Mountains region (Morrison, 1982).

Pre-Drill Reservoirs (Ordovician Sandstone Objectives)

In the most optimistic structural scenario, the IP well was anticipated to penetrate the Ordovician Blakely and Crystal Mountain Sandstones. Sandstones are considered to be favorable hydrocarbon reservoirs at depth when they are coarse-grained, well-rounded, compositionally mature, and display secondary porosity due to leaching of selected mineral constituents. Many of the sandstone exposures in the Ouachita Mountains exhibit these characteristics.

Originally described by Purdue (1909), the Crystal Mountain Sandstone was named for fine- to medium-grained (with some local coarse-grained intervals) sandstone that crops out in the Crystal Mountains of Montgomery and Garland Counties, Arkansas. Purdue described the weathered Crystal Mountain Sandstone as having a “consistency and color of brown sugar.” Shelf formational equivalents of the Crystal Mountain Sandstone have been correlated to the Ordovician McLish Sandstones (productive oil reservoirs on the shelf) (Mitchell and Hester, 1994) of the Simpson group in Oklahoma due to their similar stratigraphic position (Pitt, 1955). The thickness of the Crystal Mountain Sandstone varies across the Ouachitas. In Oklahoma, it ranges from 5 to 100 ft (1.5 to 30 m), according to Pitt (1955); while Goldstein (1955) determined a thickness between 0 and 500 ft (0 to 152 m). In Arkansas, workers have reported a thickness range for the Crystal Mountain Sandstone between 180 and 450 ft (55 and 137 m) (Pitt et al., 1961; Flores, 1962; Craig et al., 1993).

The Blakely Sandstone, as described by Miser and Purdue (1909), is about 500 ft (152 m) thick, composed of approximately 75% shale, and lies stratigraphically between the overlying Womble Shale and the underlying Mazarn Shale. Pitt (1961), working in Montgomery County, Arkansas, measured a thickness of 450 ft (137 m). Sommer (1971) documented that the Blakely can attain a maximum thickness of 700 ft (213 m) in the Ouachita Mountains of Arkansas. Buthman (1982), working in the area around Lake Ouachita, measured stratigraphic sections of the Blakely Sandstone and reported a thickness range of 250 to 500 ft (76 to 152 m) and a net to gross ratio between 30% and 40% sandstone. Compositionally, the Blakely Sandstone in the Crystal Mountains (Gaudet, 1986) and south of

Lake Ouachita (Bathke, 1984) is described as having both arenites and rudites with a mixed siliciclastic-calciclastic composition. Siliciclastic grains are dominantly quartz with lesser amounts of feldspar, feldspathic rock fragments, and sedimentary rock fragments. Calciclastic grains are wackestone and grainstone intraclasts composed of varying amounts of peloids, oolites, and skeletal material, including brachiopods, trilobites, and crinozoans.

Interpretations of the depositional environments of the Crystal Mountain and Blakely Sandstones range widely from aeolian to deep marine. For the Blakely Sandstone, the depositional environments are interpreted as: (1) the neritic environment of an epicontinental sea (Davies and Williamson, 1976) and (2) a deep-marine environment (Haley and Stone, 1973; Morris, 1974). For the Crystal Mountain Sandstone, the depositional environments are interpreted as: (1) aeolian (Honess, 1923); (2) shallow marine neritic (Flores, 1962); (3) littoral (Goldstein, 1961); (4) sublittoral sheet sandstones (Goldring and Bridges, 1973; Davies, 1976); (5) beach (Miser and Purdue, 1929); and (6) deep marine turbidites (Haley and Stone, 1973; Morris, 1974).

Pre-Drill Reservoirs (Ordovician Bigfork Chert Objective)

Due to the relatively shallow depth of the IP well, a secondary reservoir objective was the Bigfork Chert (Figure 1). A critical exploration component that was sought for the success of this well was a stratigraphic top seal. However, a top seal for the Bigfork reservoir was difficult to project at depth due to present day erosion that locally removed the top seal and exposed the Bigfork chert in outcrops. Subsurface Bigfork Chert needed to have some degree of fault separation in order to isolate any viable trap from the surface exposures. The Polk Creek Shale was deposited directly over the Bigfork Chert and was considered to be the closest stratigraphic top seal for this reservoir. Based on Satterfield's map (1982), the Polk Creek Shale crops out approximately 1 to 2 mi (1.6 to 3.2 km) due east of the IP well location.

A reservoir analogue for oil and gas production from the Bigfork Chert is the Isom Springs Field in Marshall County, Oklahoma which produces hydrocarbons from the Arkansas Novaculite. This field is located along the frontal thrust belt of the Ouachita Mountains. To date, the Bigfork Chert has not been as productive a reservoir as the younger Arkansas Novaculite (Morrison, 1982). Morrison further suggested that completion problems may be a partial reason for its less effective production rates. At the Isom Springs Field, the formation consists of limestone with chert interbeds which are more likely to contain good fracture porosity. Exposures of the Bigfork Chert in Garland County, Arkansas are intensely folded and fractured. The high permeability of the Bigfork Chert makes it the most reliable aquifer in Arkansas and also indicates good hydrocarbon reservoir potential.

The Bigfork Chert is Middle to Late Ordovician and equivalent in parts to the Viola Limestone in Oklahoma (Chenoweth, 1966; Ireland, 1966; Sediqi, 1985). The Bigfork Chert is named for its proximity to the post office in Big Fork, Polk County, Arkansas where it is well exposed on the surface (Purdue, 1909). Purdue and Miser (1923) also described Bigfork outcrops exposed in the core uplift in the Zig Zag Mountains of Hot Springs, Arkansas. This area is referred to as the Zig Zag Mountains due to distinctive tight folding patterns displayed in outcrops. The closest outcrops of the Bigfork Chert to the IP well are located in the eastern portion of the Trap Mountains in two narrow, eastward-trending belts (Purdue and Miser, 1923; Haley et al., 1993).

The true thickness of the Bigfork Chert is difficult to discern due to highly folded and contorted bedding. Across the Oklahoma Ouachitas, the thickness of the Bigfork Chert was estimated at 722 ft (220 m) in McCurtain County, 790 ft (241 m) in the Potato Hills region (Roe, 1955), and 600 ft (183 m) at Black Knob Ridge (Hendricks et al., 1937). In the Hot Springs region of Arkansas, the Bigfork was estimated to be about 700 ft (213 m) by Purdue and Miser (1909). The chert, which is typically black and laminated, is interbedded with siliceous shale, limestone, and sandstone. The shale occurs in intervals ranging from 1 in to 3 ft (3 cm to 1 m) in thickness. The bluish-black limestone is dense and finely crystalline with thicknesses reported between 1 to 12 in (3 to 30 cm). Interbedded sandstone exposures in the Zig Zag Mountains are fine-grained, gray, and thin-bedded. Miser and Purdue (1929) described the sandstone on the northwest slope of Glazypeau Mountain and estimated it to be 50 ft (15 m) in thickness. Bigfork Chert typically weathers to a medium-dark gray color and is locally porous. The average thickness of individual chert beds is between 2 to 8 in (5 to 20 cm) (Craig, 1993). The chert beds are locally disseminated with small quantities of calcite and pyrite.

Differences of opinion occur in the literature regarding whether the chert is a primary or secondary deposit (Miser and Purdue, 1929; Goldstein and Hendricks, 1953; Goldstein, 1959) or perhaps a product of diagenetic or metamorphic processes (Honess, 1923; Harlton, 1938; Sediqi, 1985). Lozano (1963) described sponge spicules and possible radiolarian fauna from Bigfork outcrops. Bellis (1990) concluded that some of the layers of cryptocrystalline chert contain ghosts similar in size and shape to lime peloids. Conglomeratic beds with flattened pebbles and cobbles of chert ranging in thickness from 0.4 to 2 in (1 to 5 cm) are interbedded with dense chert layers. The Bigfork appears to have been silicified during deposition or perhaps by post-depositional alteration before folding because the brittle chert layers are broken along minutely spaced joints (Craig et al., 1993).

Pre-Drill Structural Setting and Analysis

The Trap Mountains of Arkansas consist predominantly of tightly folded Mississippian-Devonian Arkansas Novaculite but also include older rocks such as the Silurian Blaylock Formation. The mountain range is approximately 30 miles (48 km) long by 5 miles (8 km) wide (Plate 1). The eastern terminus of the belt is covered by Gulf Coastal Plain sediments of Cretaceous and younger age formations. In the north, west, and south directions, the Trap Mountains appear to be structurally higher than younger Mississippian outcrops that are located nearby. Based on the deep seismic COCORP interpretation, the Trap Mountains may represent a regional anticlinorium cored by basement rocks that is not a part of the Benton Uplift (Lillie, 1983). The IP well was located on this structural feature and was selected as the first stratigraphic test of Shell's exploration program in the Ouachita region of Arkansas.

The Trap Mountains are physiographically defined by the erosion-resistant ridges of Arkansas Novaculite. The stratigraphic sequence from the Arkansas Novaculite through the Bigfork Chert is comprised of approximately 3,500 ft (1,067 m) of rigid, load-bearing section flanked by the thicker shale units of the overlying Stanley Formation and the underlying Womble Shale. Within this generally rigid sequence, very ductile shale formations (Missouri Mountain and Polk Creek shales) and numerous intraformational shale partings facilitate flexural flow folding. This sequence typically displays tight, asymmetric folds with 0.5 to 2 mi (0.8 to 3 km) spacing and northward vergence. Outcrop exposures of parasitic folds are common on the limbs and hinges of large-scale (mappable) folds. These recapitulate the vergence of the larger structures.

Given that the proposed IP well bore would likely penetrate a folded and duplicated stratigraphic section, it was deemed unlikely that a 10,000 ft (3,048 m) deep well would intersect an overlying stratigraphic seal. Consequently, faults were also investigated as potential structural seals. It is well established that the subsurface identification of the Potato Hills duplex structure in Oklahoma led to the commercial discovery of structurally trapped natural gas in the underlying Jackfork Formation (Miller, 1955; Roe, 1955; Arbenz, 1968; Viele, 1989; Allen, 1991A; 1991B; Petzet, 1996; Miller and Smart, 2003; Denny, 2003; Zeng et al., 2004).

Prior to drilling the IP well, a conceptual regional cross section was constructed for the Trap Mountains area that incorporated surface geological features that were mapped by Shell. Figure 2 illustrates a hypothetical stacked duplex structure of thrust faults and folds that was postulated to exist at depth, creating a shallow, folded fault seal. Geologic features in the Trap Mountains were closely examined to identify fault seals or structural highs that may exist in the subsurface. However, no surface geologic features were found to suggest that a thrust duplex structure might exist at depth in the Trap Mountains region.

Pre-Drill Thermal Maturity

The thermal maturities of the rocks in the IP well were anticipated to be high but still within the present-day gas window for potential hydrocarbons drilled to 3,000 ft (914 m) below the surface. Exploration within high-maturity orogenic belts suggests that the source rocks are presently at the end of their hydrocarbon expulsion window and that the reservoir quality may be significantly reduced due to quartz cementation and other diagenetic processes.

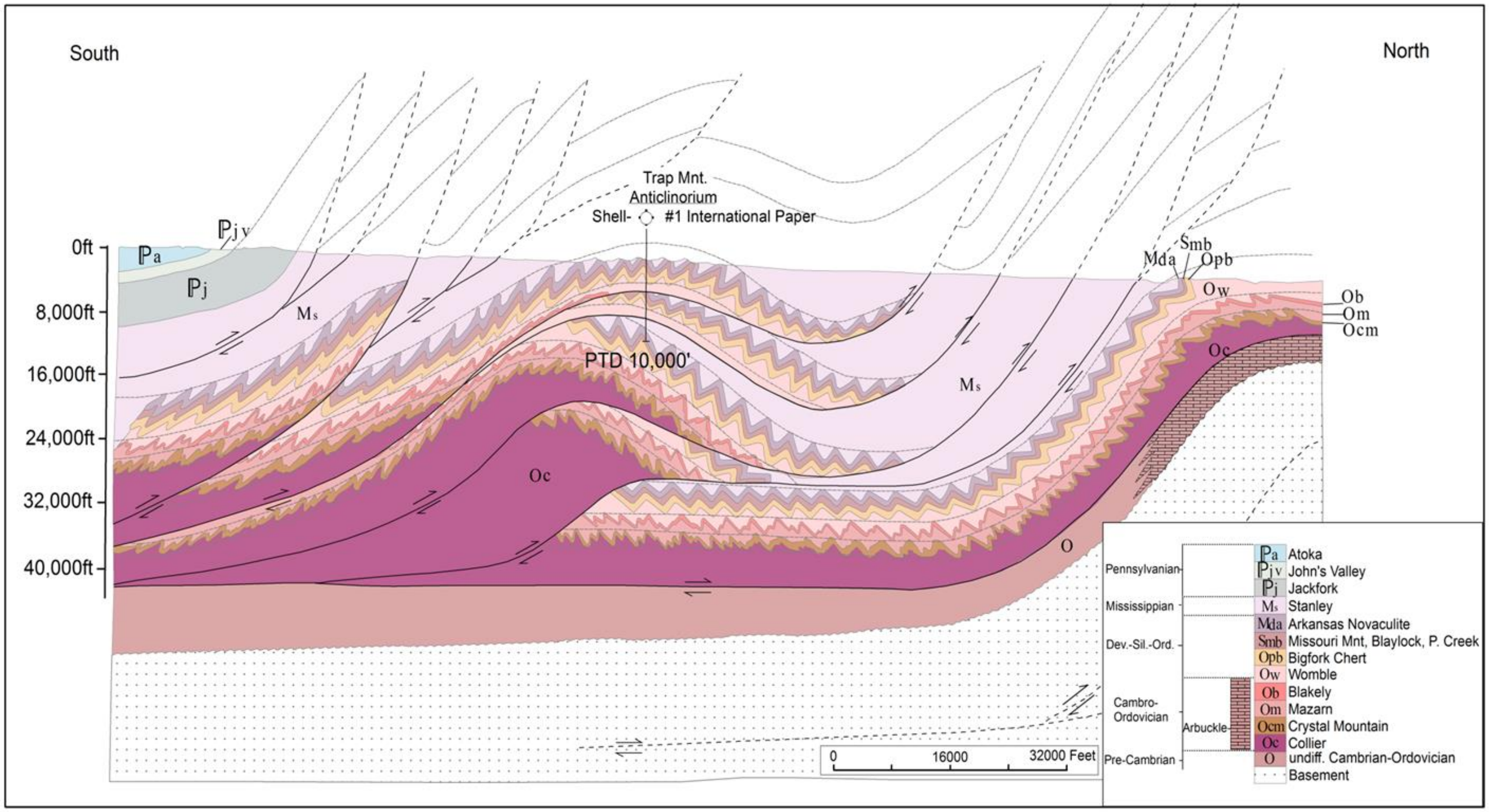


Figure 2. Pre-drill conceptual cross section of the Trap Mountains anticlinorium.

The prospective reservoirs are in a much lower temperature regime today, as significant erosion has occurred since their maximum depth of burial and exposure to higher temperatures. Measurements of the thermal maturities from outcrops surrounding the IP well location indicate that these rocks were not subjected to temperatures that would invalidate exploration for natural gas. The maximum maturity or exploration floor for drilling at that time was based on rocks that attained an R_o of 3.22% (LOM 18), which is considered to be equivalent to the onset of greenschist facies metamorphism.

The Caulksville Field, located in the Arkoma Basin of Arkansas, is a productive gas field with very high thermal maturity. In this field, producing reservoirs exhibit a measured R_o of 3.32%. However, current bottom hole temperatures only reach a temperature of 205 ^oF (96 ^oC), which indicates that the rocks were more deeply buried in the past than at present. Two wells from this field in Logan County, Arkansas were chosen for geochemical analysis: the Arkla #1 Weeks (S4-T7N-R27W; API 03083000080000) and the Gulf #1 Hembree (S13-T8N-R26W; API 03083000410000). The Arkla #1Weeks is the discovery well for the Caulksville Field, and production from this well is from the lower to basal Atokan sandstone with a measured R_o of 3.32%. The porosity in these sandstones ranges between 8% and 19% through the 22 ft (7 m) pay zone. In the Gulf #1 Hembree, the lower Atokan sandstone reservoir has a measured R_o of slightly above 3.32%. Examination of the maturity gradient from both wells indicates a gradual increase of maturity with depth. This maturity gradient displays the same slope as wells drilled in the Ouachitas located outside the vicinity of the Broken Bow-Benton Uplifts. Wells drilled within the core uplifts were subjected to late heat flow which resulted in higher thermal maturity values at the surface (Godo et al., 2011A; 2011B). The late heat flow centered on the Benton Uplift is well documented (Clardy and

Bush, 1975; Stone, 1976; Konig and Stone, 1977; Howard, 1979; Kurris, 1980; Houseknecht and Matthews, 1985; Guthrie et al., 1986).

The emplacement of nearby Cretaceous intrusives potentially degraded the reservoir properties in the sedimentary rocks around the Trap Mountains where the IP well was drilled. Much of the igneous activity in Arkansas results from the reactivation of the aulacogen known as the Reelfoot Rift (100 to 85 Ma). This fault system strikes generally northeast to southwest and is sub-parallel with the boundary and onlap of unconsolidated sediments of the Mississippi Embayment and the Arkoma Basin. Orientation of these intrusives is congruent with this trend, and they intersect the eastern portion of the Trap Mountains (Howard, 2007). It is thought that, as tensional stress increased due to rift subsidence, the rocks along the eastern terminus of the Ouachita fold and thrust belt weakened. This weakened condition allowed magma generated at depths greater than 20 miles (32 km) below the earth's crust to migrate upward through faults and fractures (Howard, 2007).

Magnet Cove, a well-studied alkalic igneous intrusion, is located approximately 17 miles (27 km) northeast of the IP well (Erickson and Blade, 1963; Howard and Chandler, 2007). Intrusions decrease in number and size to the west and southwest away from Magnet Cove (Figure 3). Despite the likelihood that these igneous intrusions increased local heat flow, R_o values measured from nearby shale exposures of the Stanley Shale, Arkansas Novaculite, and Blaylock Sandstone ranged between 2.12 and 2.32% (LOM 14.5 to 15.5). However, subsequent investigation showed that these initial maturity measurements were artificially too low due to surficial weathering.

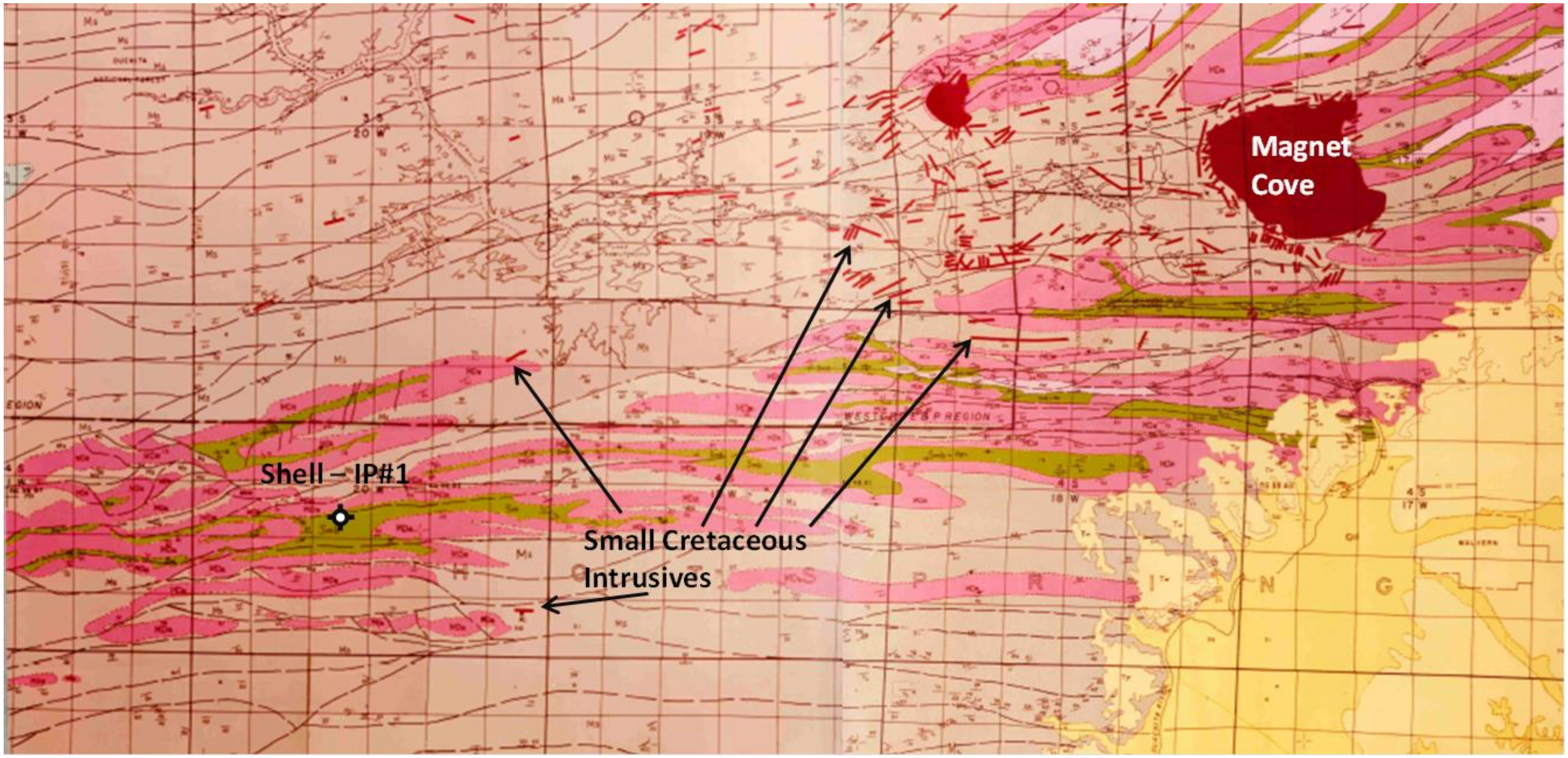


Figure 3. Surface geologic map with Cretaceous intrusives (red). Modified from unpublished geologic mapping by Haley et. al., 1969; Woodward et al., 1968.

Post-Drill Results

Structural Interpretation

A composite regional seismic profile constructed by Shell consists of three separate seismic lines extending from the Moccasin prospect (Shell Rex Timber 1-9) (Godo et al., 2008), northward through Degray Lake, and across the Trap Mountains anticlinorium (Plate 2). The seismic interpretation illustrates the subsurface features that Shell analyzed before drilling the well. No additional seismic surveys were acquired in the Trap Mountains region due to poor resolution of the tightly folded reflectors. Therefore, the IP well represented a stratigraphic test without seismic support in order to gain subsurface information for ongoing exploration efforts in the Ouachita Mountains region of Arkansas. Nearly all of the structural dips in the well bore are to the south with varying inclination ranging from 25^{o} to 65^{o}, with most dipping around 65^{o}. Low dips of approximately 25^{o} occur between 3,100 and 3,700 ft (945 and 1,128 m), which is consistent with tight folds observed in outcrops and a northward vergence of the fold axes. A post-drill conceptual cross section of the Trap Mountains region was constructed by integrating the stratigraphic and structural features encountered in the IP well with surface geological features (Figure 4).

The IP well was the first test of a new proprietary logging tool that Shell developed called the borehole televiewer (BHTV) (Rambow, 1984; Dudley, 1993). The BHTV log acoustically images the borehole using a rotating transducer that scans the formation wall. The transducer rotates at three revolutions per second and fires 1,500 times per second, calculating 500 measurements of the borehole wall in each revolution. The system digitizes the amplitude and time of flight of the reflected pulse and, together with the magnetometer signal, constructs an image of the borehole wall which is oriented with the Earth's magnetic field. A gray scale

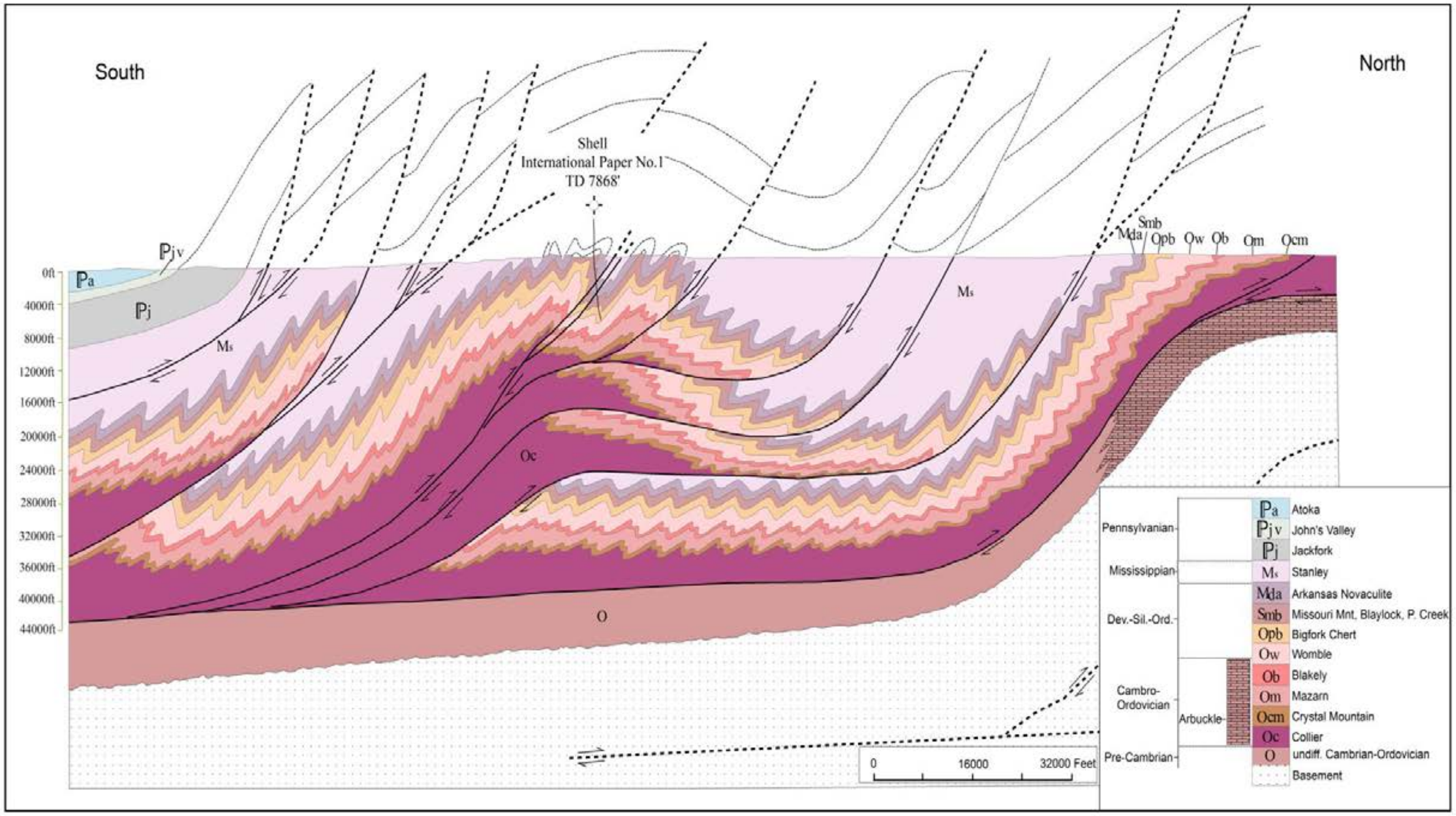


Figure 4. Post-drill conceptual cross section of the Trap Mountains anticlinorium.

image of the borehole wall is generated on both a video monitor and a continuous hardcopy printout. The BHTV image is a 360° view of the borehole presented on a two-dimensional display (Figure 5). The visual image is a slice of the borehole showing a cross sectional view of the bedding and fracture planes. The amplitude of the reflected acoustic pulse is represented in gray scale as white marks representing higher amplitude and dark marks representing lower amplitude. Features such as bedding and fractures can be confidently resolved down to less than 1 inch (2.5 cm). In many respects, the BHTV surpasses the performance of the dipmeter by detecting and differentiating between fractures, bedding, folds, faults, and even smaller borehole features such as vugs or cross bedding (Rambow, 1984).

Stratigraphic Formations Penetrated

Stanley Shale

The Mississippian Stanley Shale was the youngest formation penetrated by the IP well. It totaled less that 200 ft (61 m) in stratigraphic thickness. The faulted top of the Lower Stanley Shale is at 3,065 ft (934 m) in the IP well based on dipmeter results across the structure and microfauna sampled 200 ft (61 m) above the top of the Mississippian-Devonian Arkansas Novaculite Formation at 3,295 ft (1,004 m) (Figure 6). The only supporting fossil information is from a palynology report citing three types of spores from the *Radiizonates* genus generally thought to be of Early Carboniferous age (Appendix 1). Shales in the Stanley Formation are medium to dark gray with rare thin interbeds of silty sand. Satterfield (1982) reported approximately 30 ft (9 m) of limestone beds from outcrops at or near the contact with the Arkansas Novaculite and from the basal Stanley Formation located just southwest of the IP well.

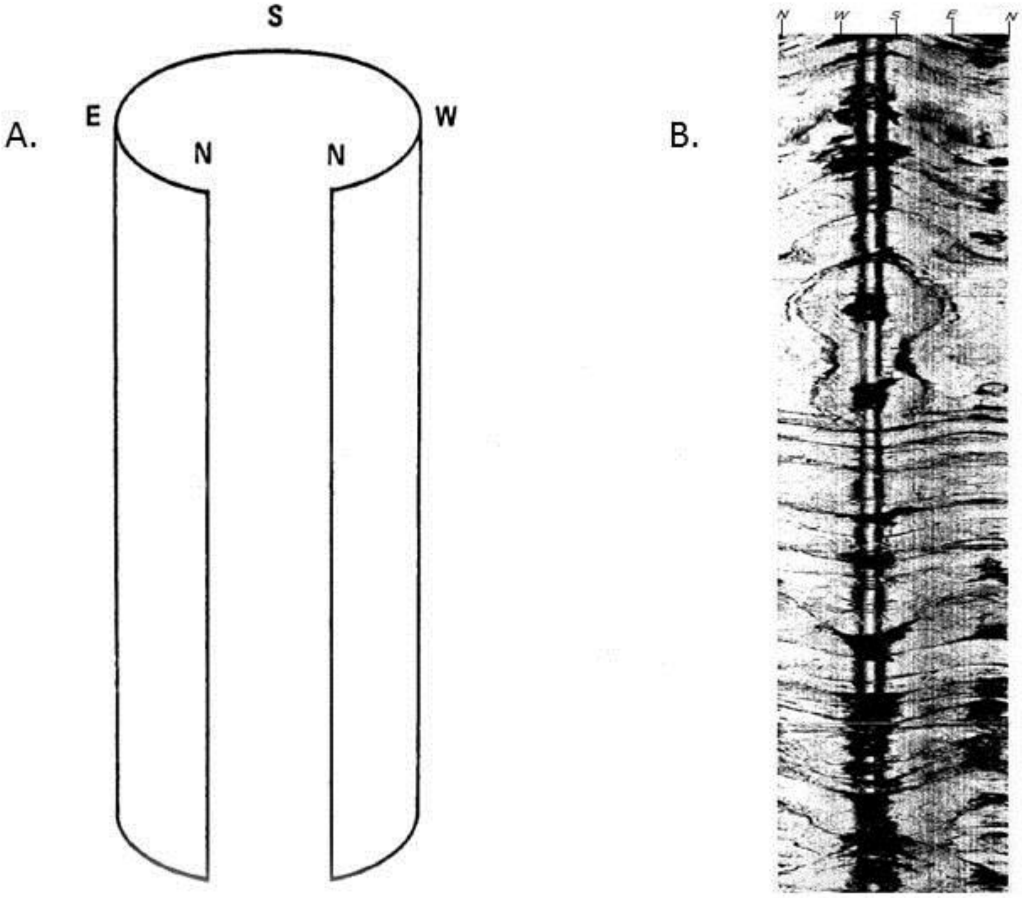


Figure 5. The borehole televiewer (BHTV) portrays a 360° panoramic image of the borehole. The two-dimensional presentation can be thought of as a cylindrical image of the borehole that is laid flat from a vertical slice down the northern side (A). This BHTV log from the IP well (B) shows a tight fold in the Ordovician Bigfork Chert.

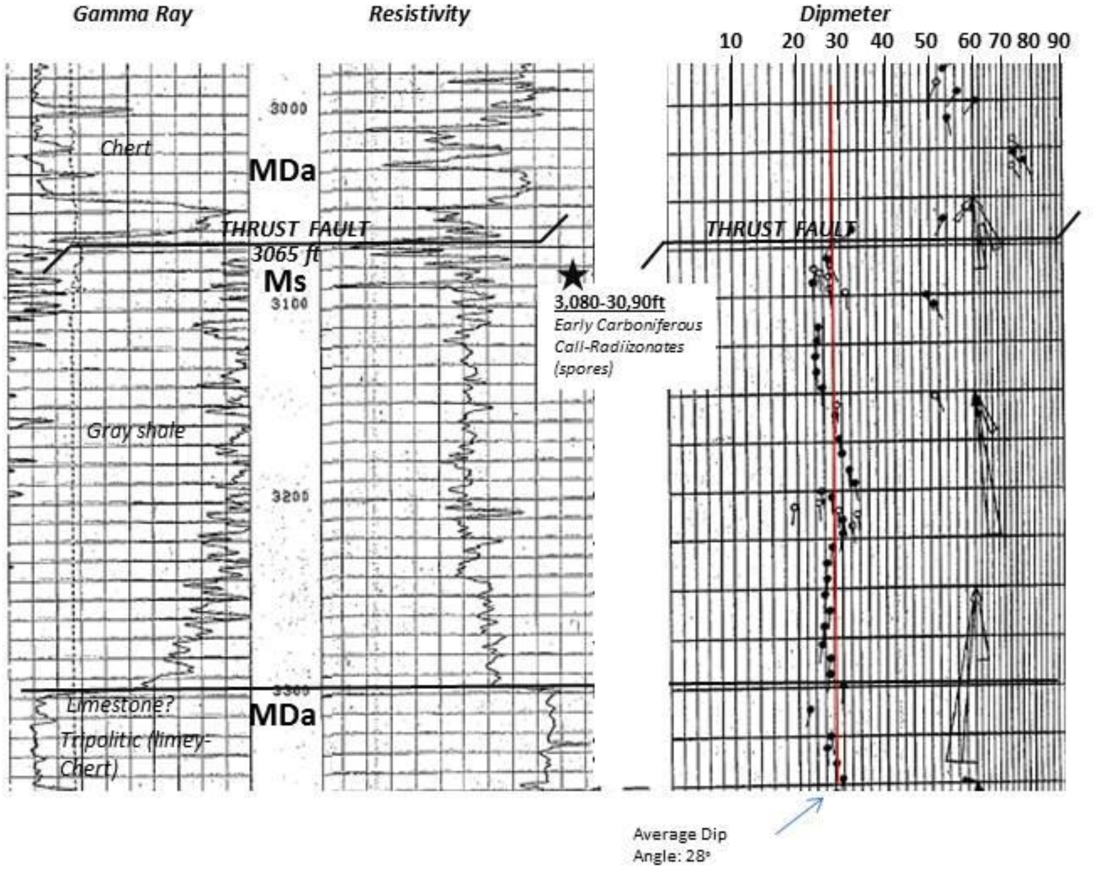


Figure 6. Well logs in the Mississippian Stanley Formation of International Paper No. 1-21 well.

The stratigraphic contact between the Stanley Shale and the tripolitic zone of the upper Arkansas Novaculite (3,295 ft or 1,004 m) was described in the IP mudlog as a contact between shale and limestone. The limestone described in the IP well could be equivalent to the basal Stanley limestone described by Satterfield, or it could be a more calcite-rich interval of the tripolitic upper member of the Arkansas Novaculite. The dipmeter results in the IP well show no inflection of bedding attitudes across the stratigraphic contact of the Stanley and the Arkansas Novaculite (Figure 6).

Arkansas Novaculite

The Arkansas Novaculite crops out about 600 ft (183 m) north of the IP well and is overturned and dipping southward at approximately 60^{o}. The novaculite was penetrated three times in the IP well, as shown in the cross section of Figure 7. The first and second penetrations of this formation occurred at 990 ft (302 m) and 2,670 ft (814 m), respectively. Both penetrations are interpreted as overturned stratigraphic sections as observed in nearby outcrops. This part of the well bore appears to intersect a portion of a fold limb. The two penetrations only intercepted the lower part of the Arkansas Novaculite before a major thrust fault was pierced, and the Stanley Shale was encountered in the footwall of the fault.

The third penetration of the Arkansas Novaculite was at a depth of 3,295 ft (1,004 m). The stratigraphic contact at this depth is interpreted as an upright normal sequence with the Stanley Shale overlying all three parts of the Arkansas Novaculite (Figure 7). There is a relatively small displacement fault interpreted to have repeated part of the lower member at approximately 4,285 ft (1,306 m). The interpretation of this fault is based on abrupt changes of dip at that depth from the dipmeter log.

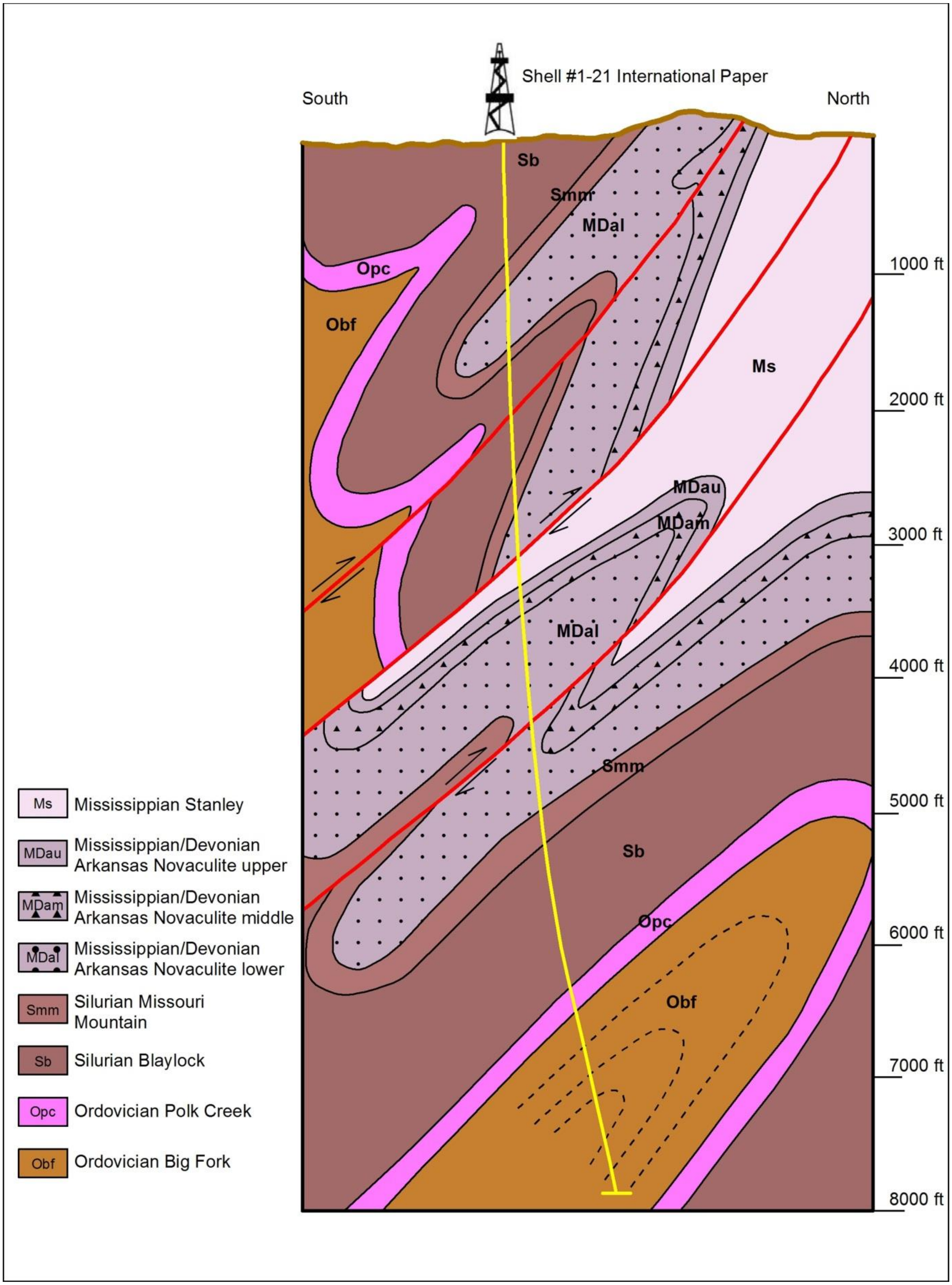
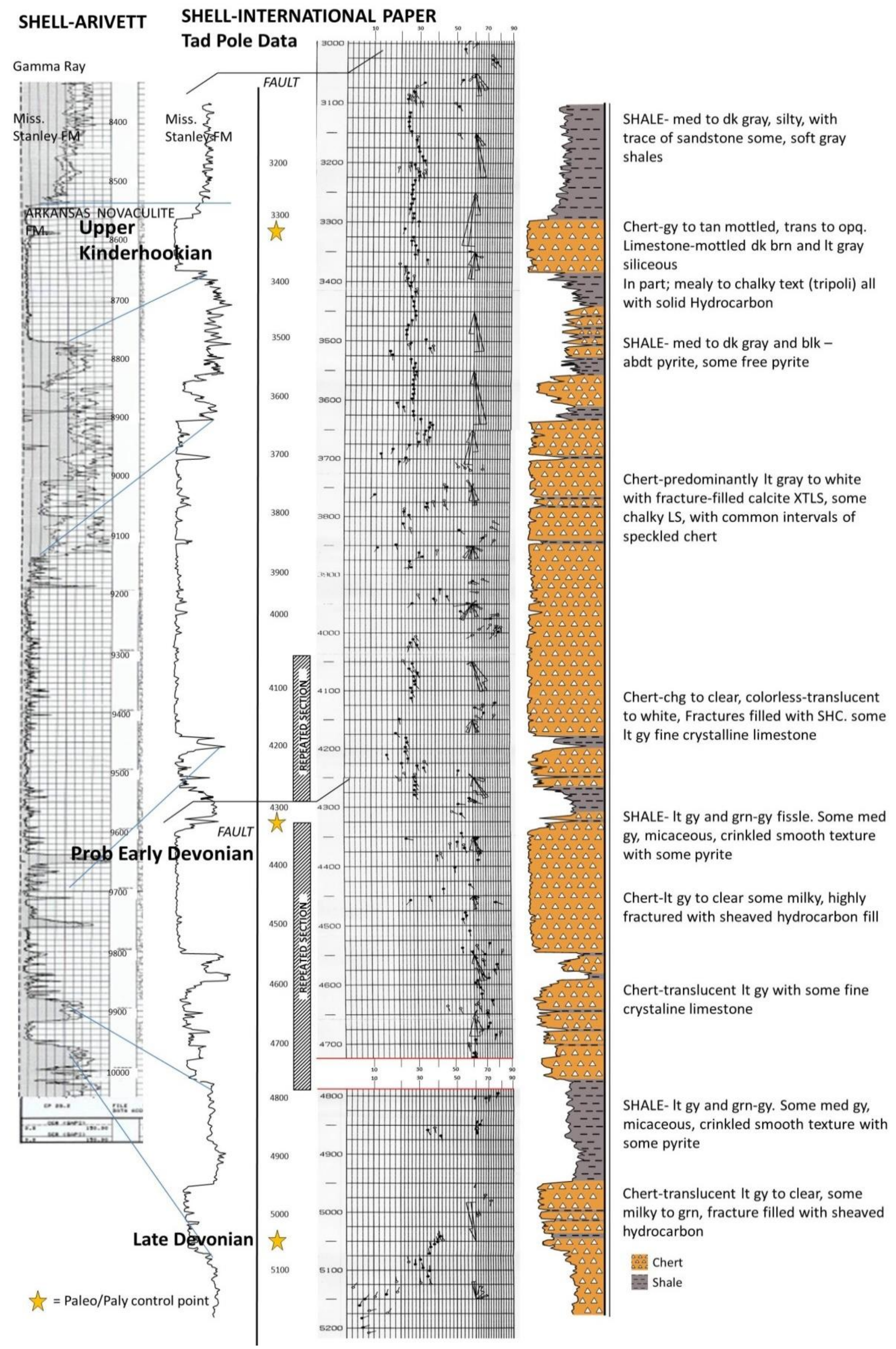


Figure 7. Post-drill cross section and interpretation of International Paper No. 1-21 well.

The Arkansas Novaculite is stratigraphically made up of three informal parts: the upper, middle, and lower (Honess, 1923; Miser and Purdue, 1929, Sholes and McBride, 1975). These three parts were penetrated in a normal complete stratigraphic succession with flat dips in the Shell Arivett well (Figure 7) (Godo et al., 2011A). In the IP well, however, the Arkansas Novaculite was encountered in three partial penetrations of the formation which stratigraphically correlate to the Arivett well succession (Figure 8). Three intervals of micropaleontology and palynological fauna and flora support the identification of the most complete penetration of the Arkansas Novaculite in the IP well between 3,300 and 5,300 ft (1,006 and 1615 m)(Appendix 1). Between 3,300 and 3,350 ft (1,006 and 1,066 m), fauna consisting of conodonts, gastropods, sponge spicules, and fish remnants indicate a Mississippian Kinderhookian age. Overlap of the stratigraphic ranges of these fauna limits the stratigraphic interval in which they can all occur together. These fauna include *Gnathodus antetexanus*, which is known to range from extreme uppermost Kinderhookian into lower Osagian and *Polygnathus inornatus,* which is mostly a Kinderhookian form, although it can range into the Late Devonian. *Polygnathus radinus* and the genus *Siphonodella* are restricted to Kinderhookian age strata. The composite fauna assemblage is latest Kinderhookian and is proximal to the Osagean boundary. The faunal data from the IP well supports the same age call for this interval of the Arkansas Novaculite as that reported by Hass (1951; 1956).

Between 4,300 and 4,310 ft (1,311 and 1,314 m), there are poorly preserved rare to common arcritarchs; however, there is also a spore identified as *Stenozonotriletes sp*. which likely has an age range in the Early Devonian (unpublished Shell in house palynological



SHALE- med to dk gray, silty, with trace of sandstone some, soft gray shales

Chert-gy to tan mottled, trans to opq. Limestone-mottled dk brn and lt gray siliceous
In part; mealy to chalky text (tripoli) all with solid Hydrocarbon

SHALE- med to dk gray and blk – abdt pyrite, some free pyrite

Chert-predominantly lt gray to white with fracture-filled calcite XTLS, some chalky LS, with common intervals of speckled chert

Chert-chg to clear, colorless-translucent to white, Fractures filled with SHC. some lt gy fine crystalline limestone

SHALE- lt gy and grn-gy fissle. Some med gy, micaceous, crinkled smooth texture with some pyrite

Chert-lt gy to clear some milky, highly fractured with sheaved hydrocarbon fill

Chert-translucent lt gy with some fine crystaline limestone

SHALE- lt gy and grn-gy. Some med gy, micaceous, crinkled smooth texture with some pyrite

Chert-translucent lt gy to clear, some milky to grn, fracture filled with sheaved hydrocarbon

Figure 8. Well log correlation of the Arkansas Novaculite Formation between Arivett No. 1-26 and International Paper 1-21 wells.

studies). Between 5,000 and 5,050 ft (1,524 and 1,539 m), spores are identified as *cf. Emphanisporites* with a fair degree of confidence. Two specimens are black and do not transmit light. If the identification of these spores is correct, then the age is probably Late Devonian. Other recognizable spores collected in this interval include *Verrucate, Baculate, Echinate,* and *Scabrate*.

Lithologically, the Arkansas Novaculite interval between 3,300 and 5,300 ft (1,006 and 1,615 m) has the typical sample and log characteristics found at Caddo Gap (Sholes, 1977 and Godo et al. 2011A; 2011B). In the upper part of the formation, there is a mixture of limestone and chert that develops porosity when leached of the limestone component. After leaching, the resultant texture is referred to as tripolitic. The samples in the tripolitic chert and throughout the Arkansas Novaculite contain solid hydrocarbons that were thermally cracked to “dead oil” and interpreted as anthraxolite material (Figure 9). The “dead oil” is thought to represent a potential paleo-oil accumulation that was subsequently cracked to gas at higher temperatures, leaving only the solid carbon residue. The tripolitic upper part of the Arkansas Novaculite was actually the primary reservoir objective that Shell pursued in the Arivett No. 1-26 well drilled in Pike County (Godo, et al., 2014; 2011A; 2011B).

The middle part of the formation encountered in the IP well between 3,400 and 3,650 ft (1,036 and 1,113 m) was determined to have a significant amount of organic matter and is considered to be a viable source rock (Figure 7) (Weber, 1994; Godo, et al., 2011A; 2011B; Craig, et al., 1979; Landis, 1962). Geochemical analyses were conducted on two organic-rich shale samples in this section. The results indicate that thermal maturity is as high as 4.5% $R_{o,}$ and TOC values for the two samples are 6.57% at 3,425 ft (1,044 m) and 4.99% at 3,645 ft (1,111 m), respectively (values uncorrected for thermal maturity).

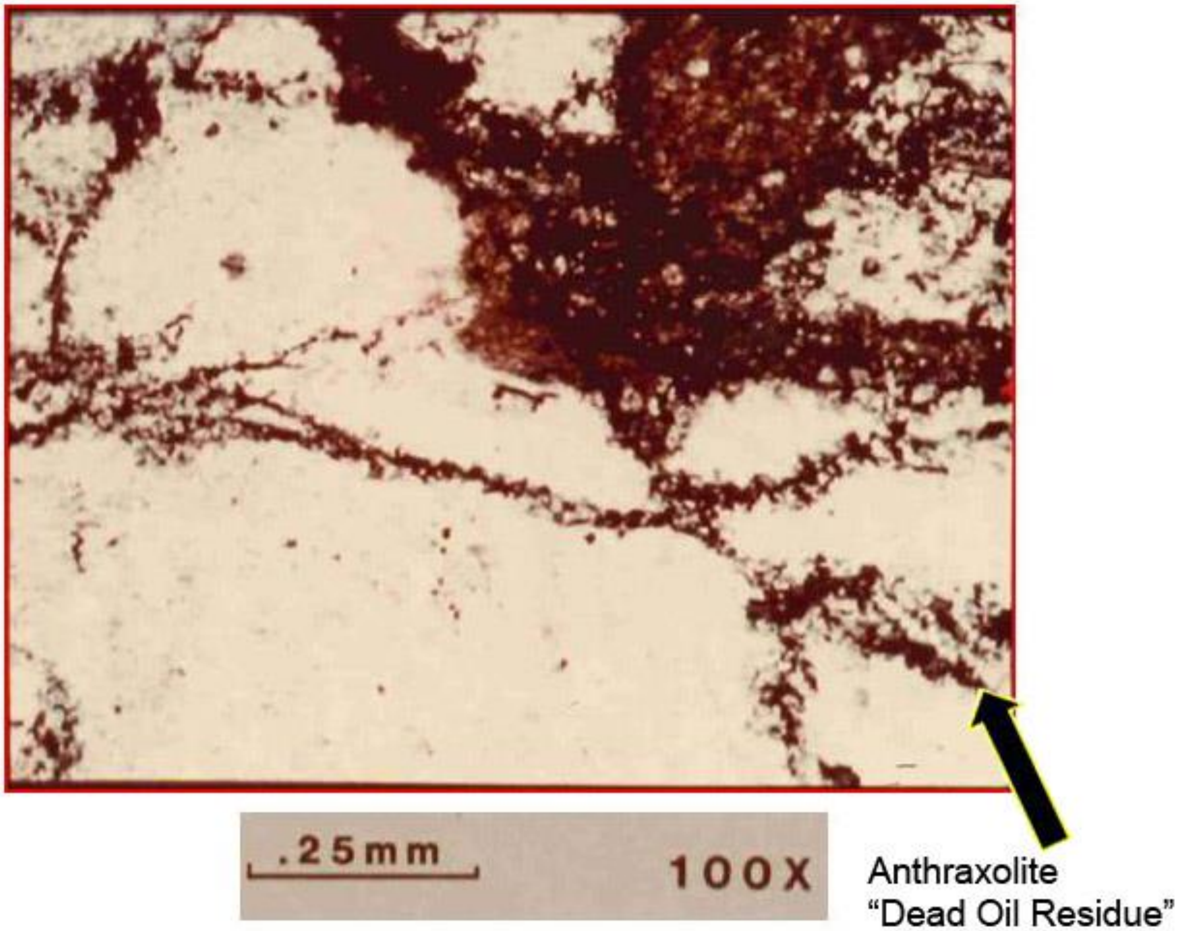


Figure 9. Arkansas Novaculite photomicrograph from ditch cuttings sampled at 3,800-3,810 ft (1,158-1,161 m) in the International Paper No. 1-21 well. Modal estimation of 15% anthraxolite via point counting.

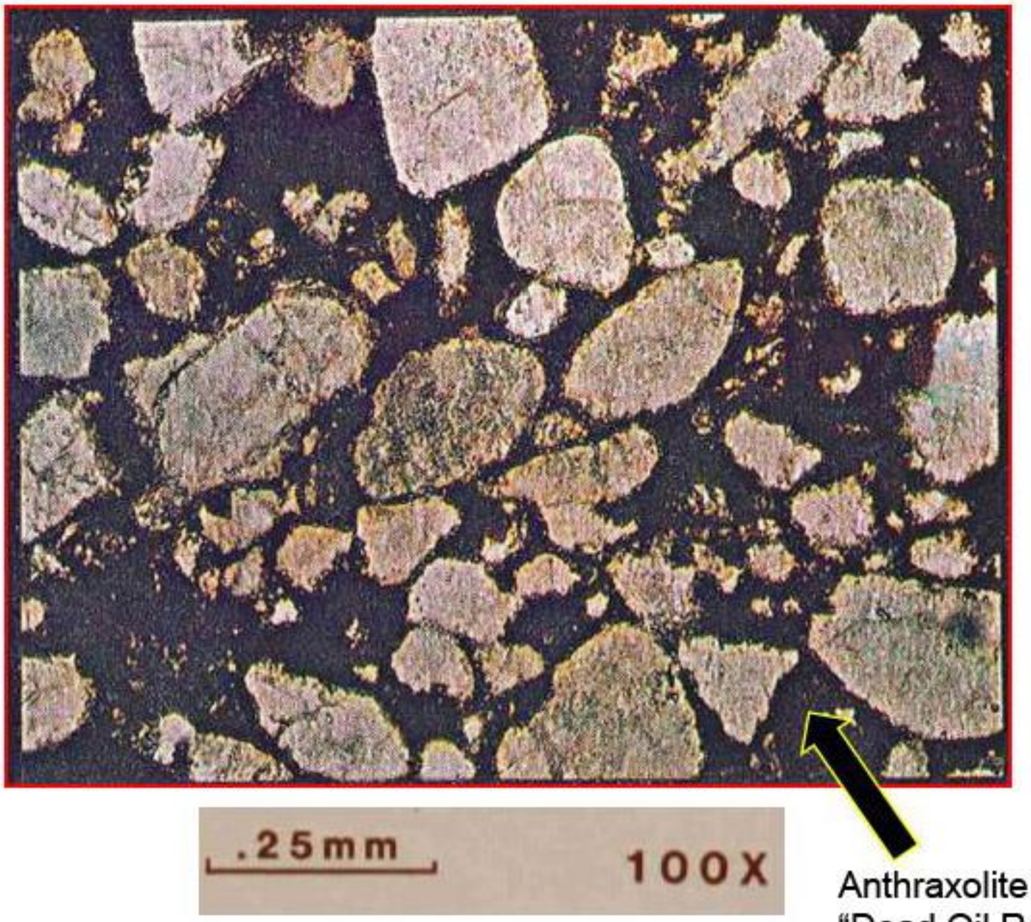
The lower part of the Arkansas Novaculite between 3,650 and 5,300 ft (1,113 and 1,615 m) appears to have some minor fault repetition (Figure 8) and is distinctively white, colorless to translucent, and light gray in color. Fractures filled with anthraxolite are common, especially adjacent to a fault located at approximately 4,300 ft (1,311 m) and at the base of the formation.

Blaylock Sandstone and Missouri Mountain Shale

The Silurian Blaylock Formation is a turbidite sequence with a thickness ranging from 0 to 1,500 ft (0 to 457 m) in the Ouachita Mountains of Arkansas. Satterfield (1984) described the sedimentology and petrography of measured sections and outcrops of the Blaylock in the Trap Mountains and proximal to the IP well site. Although not considered a hydrocarbon objective in the IP well, part of the well plan was to gain subsurface information (porosity, velocities, and densities) for potential reservoir objectives in future wells. Samples of the Blaylock Sandstone contain anthraxolite material or “dead oil” residue (Figure 10).

The Blaylock Sandstone was penetrated three times in the IP well (Figure 7). Well logging began at about 350 ft (107 m) in an overturned section of the Blaylock; the Missouri Mountain Shale was penetrated at approximately 800 ft (244 m). After exiting the Missouri Mountain Shale at 1,720 ft (524 m), an upright stratigraphic section of the Blaylock Sandstone was penetrated again. At a depth of approximately 2,200 ft (671 m), the Blaylock is tightly folded across an axial plane, and the sequence remains overturned through a depth of 2,620 ft (799 m) where the well bore re-entered the Missouri Mountain Shale.

The third and deepest Blaylock penetration in the well began at 5,300 ft (1,616 m) after exiting an upright section of the Missouri Mountain Shale (Figure 7). This third penetration from 5,300 to 6,280 ft (1,616 to 1,915 m) appears to be a complete stratigraphic



Anthraxolite
“Dead Oil Residue”

Figure 10. Blaylock Sandstone photomicrograph from ditch cuttings sampled at 5,300-5,310 ft (1,615-1,618 m) in the International Paper No. 1-21 well. Modal estimation of 20% anthraxolite via point counting.

sequence of the Blaylock, with all beds facing upright and dipping southward between 50° to 65° (Figure 11). The well penetrated approximately 1,000 ft (305 m) of Blaylock in the well bore which, when dip corrected, would represent about 500 to 600 ft (152 to 183 m) of stratigraphic thickness. This stratigraphic thickness determination is similar to estimates by Danilchik and Haley (1964) from the nearby Malvern Quadrangle. Satterfield (1984) reported that bedding in the Blaylock Sandstone exhibited a range of thickness from 4 to 12 in (10 to 30 cm). Thin beds were measured at 1 to 4 in (3 to 10 cm) with the thickest beds measured at 3 to 6 ft (1 to 2 m). An example of bedding thickness in the IP well is observed on the BHTV log where it can be resolved to less than 6 in (15 cm) (Figure 12). The two examples of sandstone bed thicknesses illustrated in Figure 12 (sandstone shown in white; shale in black) are approximately 2.5 ft (76 cm) and 6 in (15 cm), respectively. The dipmeter indicates that bedding is dipping to the southwest and west. A small-scale fault is noted on the dipmeter log but is not resolvable (Figure 11). This same structure is shown on the BHTV log at a depth of 5,620 ft (1,713 m) as a well-defined fault zone that is approximately 3 ft (1 m) thick (Figure 11). The base of the Blaylock Sandstone is interpreted to be at approximately 6,280 ft (1,914 m) and is conformable with the underlying Polk Creek Shale.

Polk Creek Shale

The Polk Creek Shale was named for Polk Creek in the Caddo Gap Quadrangle where exposures are present at its headwaters (Purdue and Miser, 1929). The Polk Creek Formation is not well-exposed in the area surrounding the IP well. A more complete section of the Polk Creek crops out in the Malvern Quadrangle where it is reported to be 125 ft (38 m) thick (Danilchik and Haley, 1964). In the IP well, the top of the Polk Creek is picked at 6,280 ft (1,914 m), and the base of the unit is at 6,510 ft (1,984 m) (top of the Bigfork Chert).

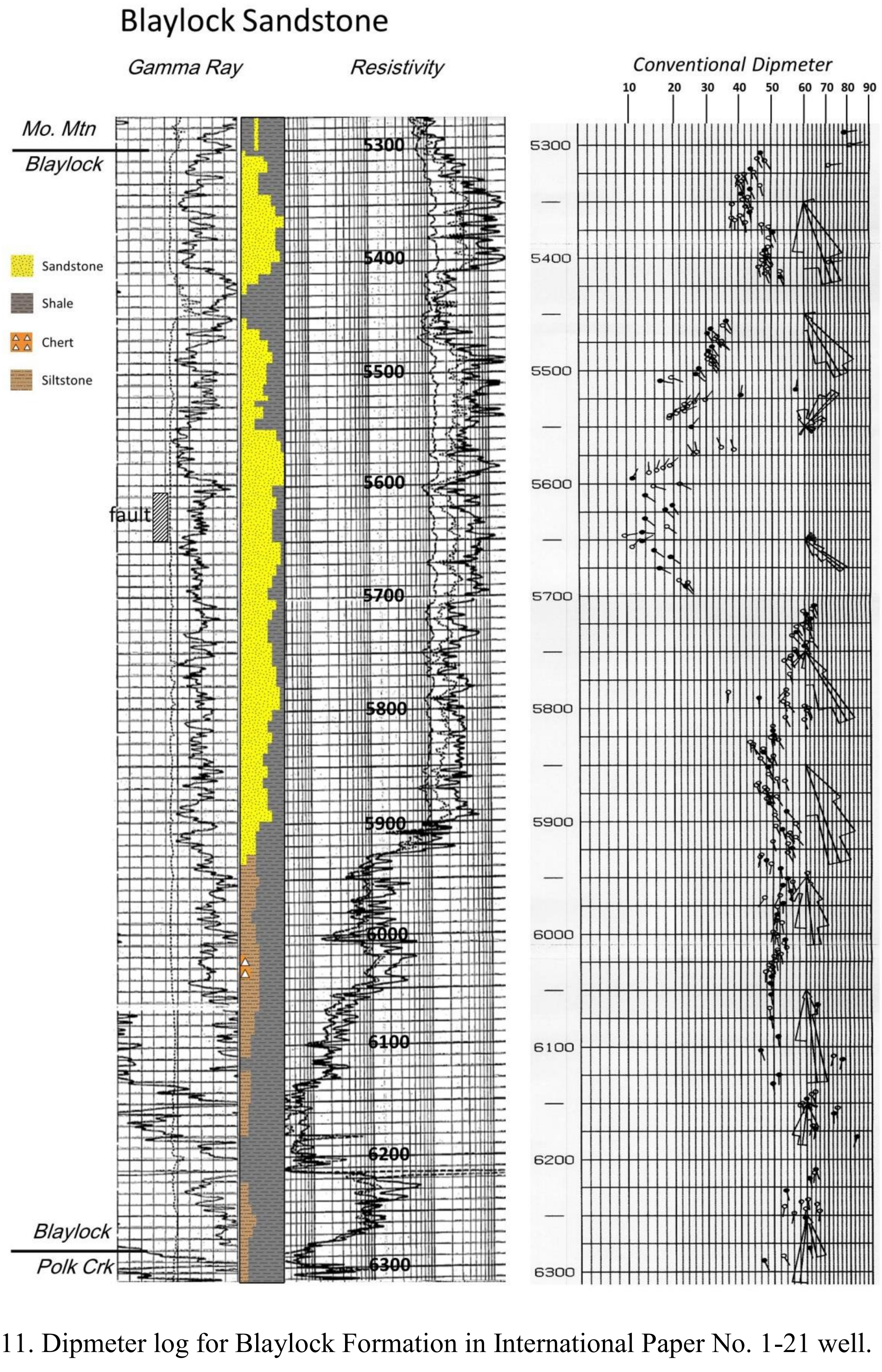
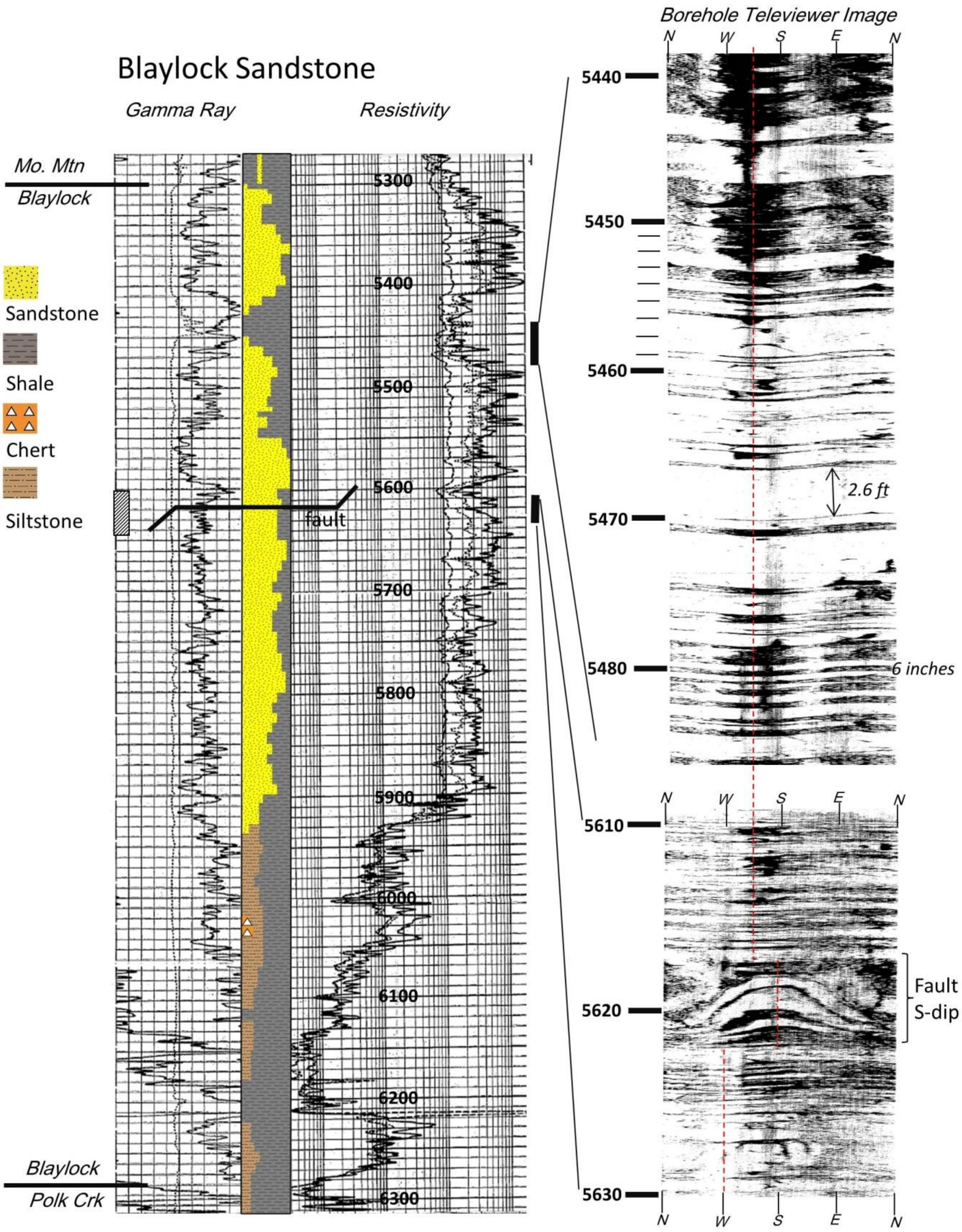


Figure 111. Dipmeter log for Blaylock Formation in International Paper No. 1-21 well.



Red line marks the lowest depth on the bed, hence the downdip direction

Figure 122. Borehole televiewer (BHTV) log of the Blaylock Formation in International Paper No. 1-21 well.

Assuming an average dip angle of 60^o, the stratigraphic thickness of this interval is slightly over 100 ft (30 m) thick, similar to the thickness reported in the Malvern Quadrangle by Danilchik and Haley (1964). Polk Creek lithologies in the IP well consist principally of shale interbedded with very thin beds of chert and sandstone, and the contacts are gradational with both the overlying Blaylock Sandstone and underlying Bigfork Chert. Thin layers of dense, black chert, like that of the Bigfork Formation, and beds of hard quartzitic sandstone are typical components of the Polk Creek formation (Purdue, 1909). A bedding thickness of 1 to 3 in (3 to 8 cm) is shown on the BHTV log (Figure 12). The BHTV's higher resolution measurements of dip and bedding thickness can be observed when compared to the standard dipmeter log as shown in Figure 11.

The Polk Creek and Womble Formations are reported to have the highest TOC (Curiale and Harrison, 1981, Curiale, 1983). Weber (1994) sampled shales from outcrops in eight stratigraphic units within the Ouachitas and indicated that the Caney, Woodford, Arkansas Novaculite, and Polk Creek samples exhibit good to very good hydrocarbon-source potential. In Shell's in-house study, a TOC value of 6.15% was measured from drill cuttings from 6,360 to 6,370 ft (1,939 to 1,942 m) within the Polk Creek Shale (uncorrected for high maturity at R_o of 4.5%) (Figure 13). Previously published regional studies show similar results (Houseknecht and Matthews, 1985; Keller et al., 1985; Guthrie et al., 1986; Arbenz, 1989).

Bigfork Chert

The Bigfork Chert was penetrated at a depth of 6,510 ft (1,984 m), and the wellbore stayed in this formation to the total depth of 7,867 ft (2,398 m) (Figure 14). The Bigfork is conformable with the overlying Polk Creek Shale, and no lithologic evidence of the

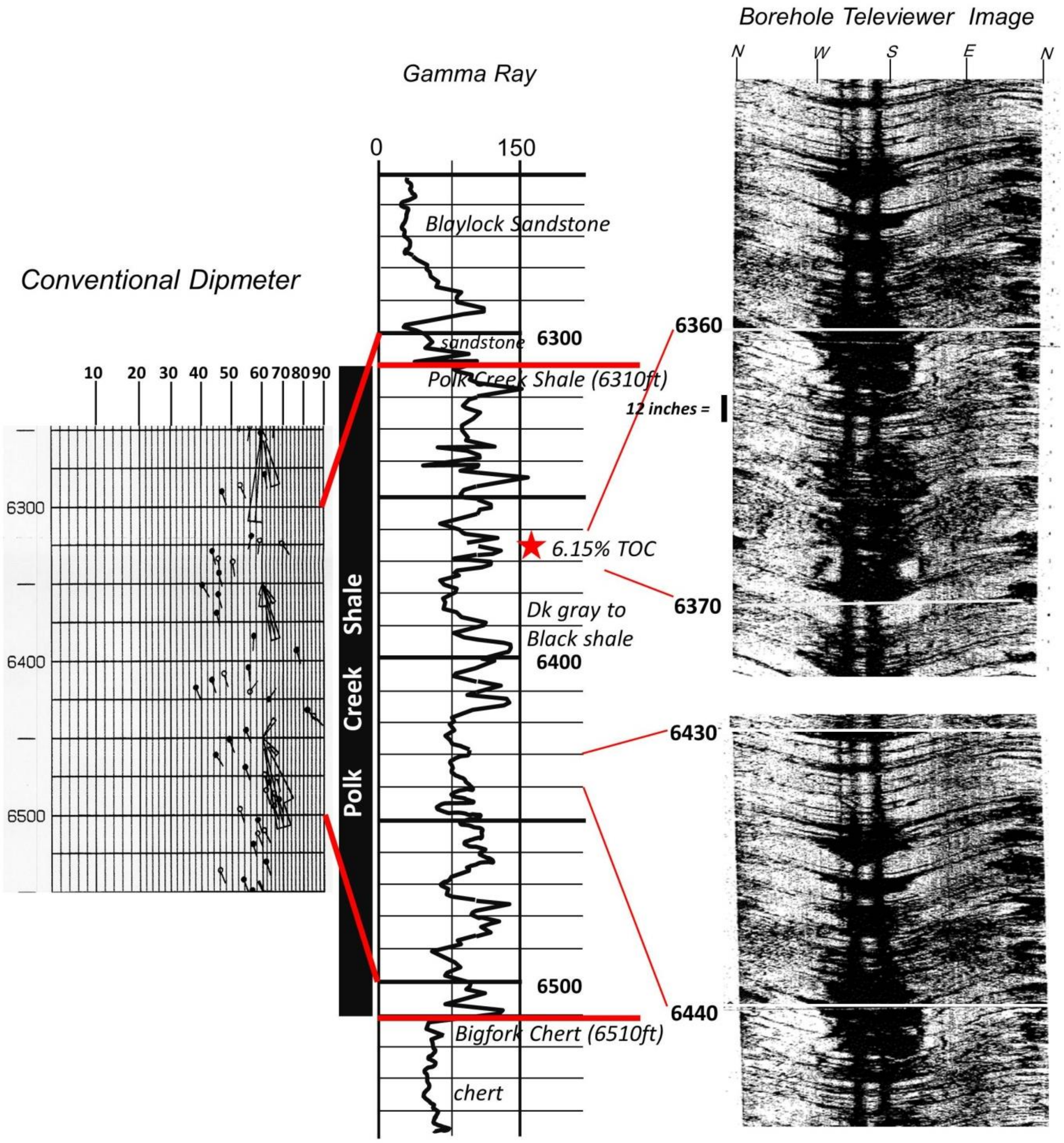
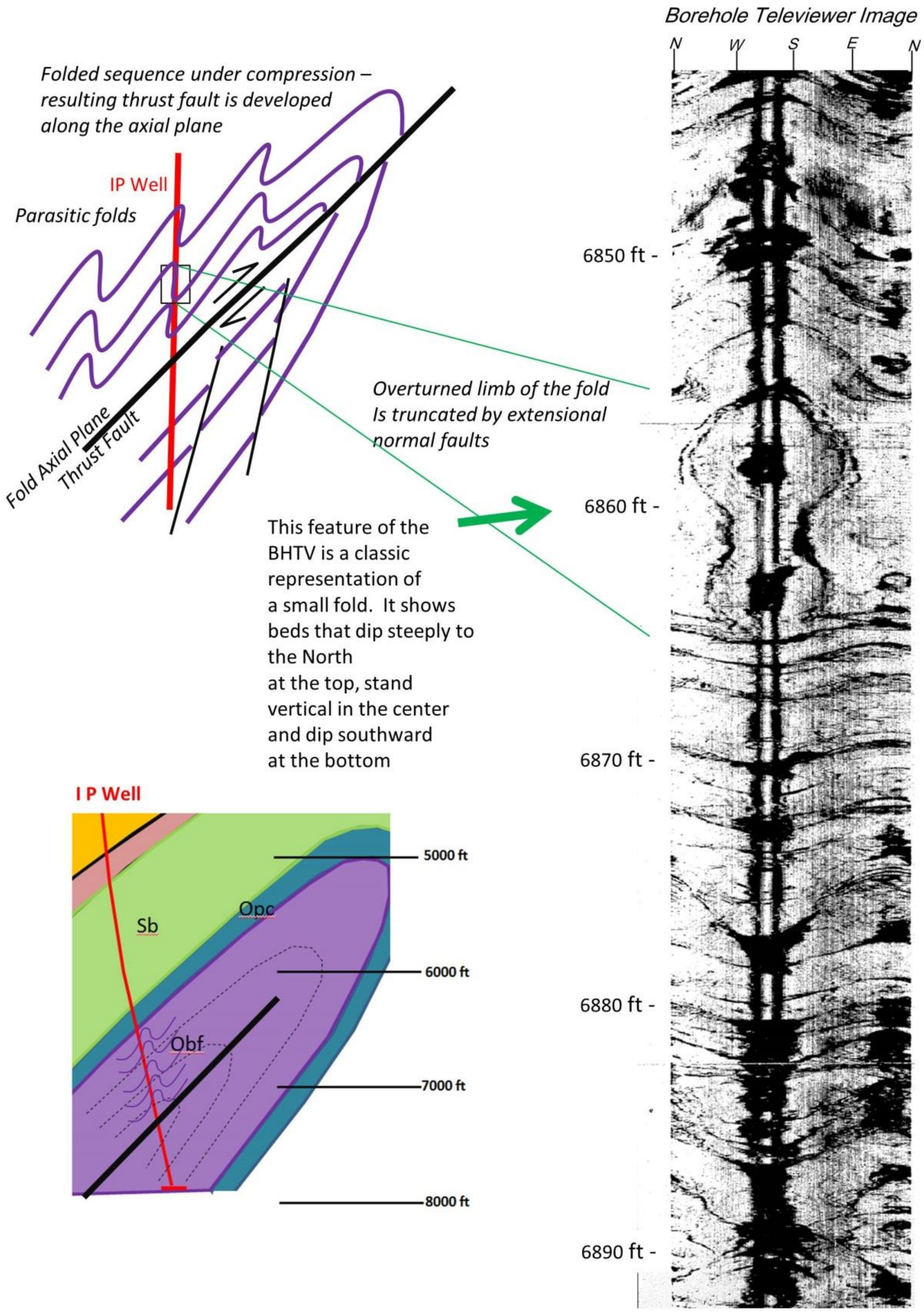


Figure 13. Summary logs of the Polk Creek Formation in International Paper No. 1-21 well.



Borehole Televiewer Image

Overturned limb of the fold Is truncated by extensional normal faults

This feature of the BHTV is a classic representation of a small fold. It shows beds that dip steeply to the North at the top, stand vertical in the center and dip southward at the bottom

Figure 14. Tight fold in the Bigfork Chert of the International Paper No. 1-21 well

underlying Womble Shale was observed. The IP well is interpreted to have penetrated an upright fold limb of the Bigfork Chert, and the well bore intersected the fold axis at approximately 7,300 ft (2,225 m) (Figure 15). Below this depth, the well bore appears to have penetrated the overturned limb of the Bigfork and remained in this structural limb to the total depth of well. If the well had continued another 300 to 400 ft (91 to 122 m), a repeated section of the Polk Creek Shale would likely have been intersected. Based on the fold interpretation of Figure 7 and Figure 14, the thickness of the upright limb on the Bigfork fold is approximately 800 ft (244 m). Correcting for an average structural dip of 60^{o} and taking into account small scale parasitic folds, the estimated true thickness of the Bigfork section is approximately 400 ft (122 m) (Figure 16).

Four intervals of well cuttings were collected at 10 ft (3 m) intervals. A detailed petrographic report incorporating point counting techniques was completed for these samples. Anthraxolite was noted in high concentrations throughout the Bigfork interval. This is delineated in Figure 17. Point count percentages of anthraxolite were reported to be 22% at 6,680 ft (2,036 m); 24% at 6,690 ft (2,039 m); 19% at 6,700 ft (2,042 m); and 15% between 6,800 and 6,810 ft (2,073 and 2,076 m).

Thermal Maturity

Extremely high thermal maturity levels exceeding LOM of 18 or R_o 3.3% were measured on samples taken along the IP well bore. These include samples collected from depths as shallow as 50 ft (15 m) below the surface of the well. Samples collected above 250 ft (76 m) were weathered and gave erroneously low R_o measured values. Prior to drilling

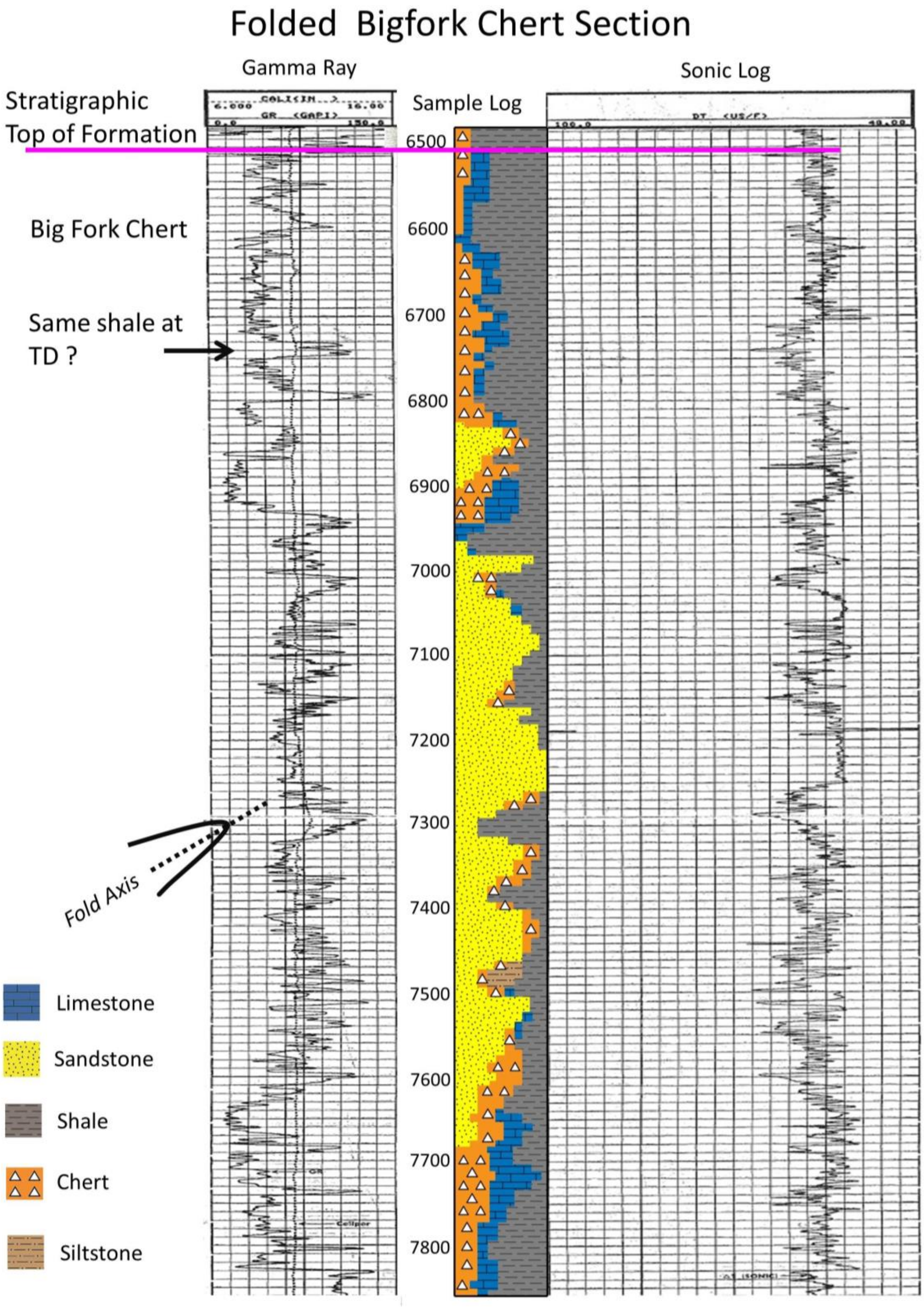


Figure 15. Gamma ray and sonic logs of the Bigfork Formation in International Paper No. 1-21 well.

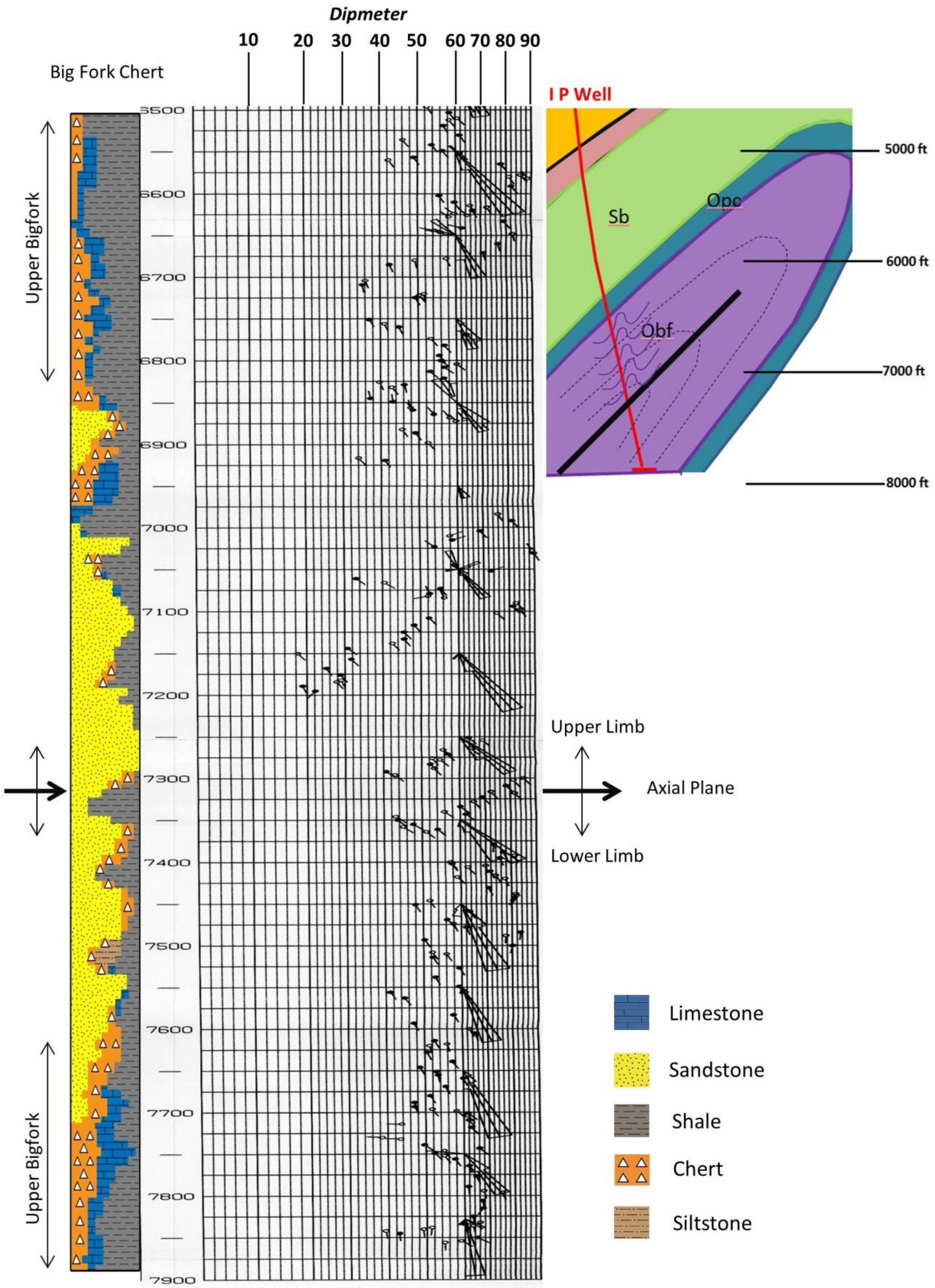


Figure 16. Dipmeter log of the Bigfork Formation in International Paper No. 1-21 well.

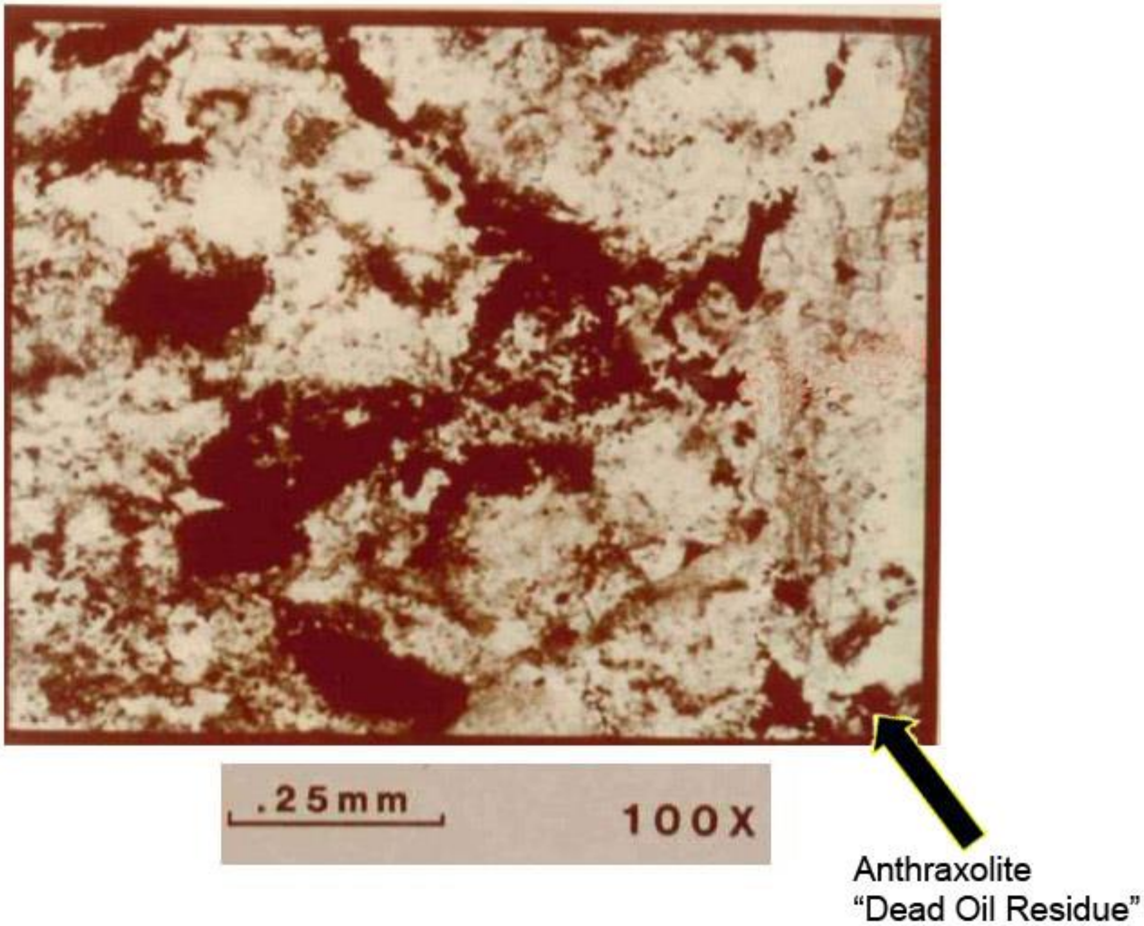


Figure 17. Photomicrograph of the Bigfork Chert ditch cuttings sampled at 6,800-6,810 ft (2,073-2,076 m) in the International Paper No. 1-21 well. Modal estimation of 15% anthraxolite via point counting.

the IP well, Ro measurements from surrounding shale outcrops predicted a starting LOM of 15.5.

After realizing that surface weathering caused the R_o values to be artificially low, a truck-mounted drilling rig was employed to drill five shallow test holes nearly 300 ft (91m) below the surface within a 1 mi (1.6 km) radius to the IP well. Two of the shallow drill holes were drilled directly over the original surface outcrops, and fresh samples taken at 250 ft (76 m) below the surface measured R_o 2.12%. Three other test wells indicated R_o values of 3.48%, 3.58%, and 3.67% at a depth of 250 ft (76 m). More unweathered Stanley Shale cuttings were collected from 250 ft (76 m) below the surface from seismic shot holes drilled along an east-west oriented transect south of the Trap Mountains. The seismic line was acquired through the middle of Township 5 South and between Ranges 18 West through 22 West. Stanley Shale cuttings from these shot holes were collected and analyzed, and the R_o values range from 2.80% to 2.87%. Shell's geochemists suggested that the outcrop samples had been subjected to surficial weathering, which lowered the reflectance values measured from the organic macerals. Some technical reports indicate that weathered samples can give erroneous reflectance values that are either higher or lower than fresh samples (Chandra, 1962; Leythaeuser, 1973; Clayton and Swetland, 1978; Stach, 1982; Barker et al., 1983; Marchioni, 1983).

Clayton and Swetland (1978) stated that thermal alteration via high temperature exposure during burial may result in an increase in the ratio of saturated to aromatic hydrocarbons. This can be achieved either by the thermal generation of saturated hydrocarbons or by the preferential destruction of the aromatic hydrocarbons in a high temperature regime. In cases of extreme weathering, it can be difficult to distinguish the effects of surficial weathering from those of thermal maturation or “incipient metamorphism.”

Leythaeuser (1973) showed that surface weathering in the semi-arid environment of the Cretaceous Mancos Shale of Utah resulted in a decrease of organic richness as well as changes in rock composition. His study also concluded that the depth of alteration by surficial weathering extends downward from 6 to 7 m (20 to 23 ft) with the first 3 m (10 ft) having the most alteration effects. Barker (1983) concluded that unweathered rock samples had higher reflectance measurements related to differences in the near-surface environment. His report attributed the higher reflectance values at the surface to recent microbial alteration of organic matter generated from hydrocarbon seepage above an oil field.

Summary

The IP well was drilled primarily as a stratigraphic test to collect early information for future exploration wells and to characterize the natural gas potential south of the Benton Uplift. One of the well objectives was to explore for in situ hydrocarbons in the form of natural gas. Given the shallow depth of the IP well, it was unlikely that a regional seal would exist before the well reached its projected total depth. The other main risk and uncertainty associated with the IP well was the emplacement of Late Cretaceous intrusives throughout the Ouachita thrust belt that may have adversely affected both the charge timing and reservoir quality.

Shell geologists decided to stop the well at 7,867 ft (2,398 m) due to structural complications, high thermal maturity, and a lack of stratigraphic seals. The high thermal maturity of all sediments encountered in the IP well suggests that the post-structural heating event associated with the Benton Uplift adversely affected the hydrocarbon potential of the rocks within the IP well. Based on the ubiquity of solid hydrocarbon (anthraxolite) in all formations, particularly the Arkansas Novaculite and Blaylock Sandstone, the stratigraphic section penetrated likely represents an exhumed oil field. A viable oil field may have existed in the Late Pennsylvanian, but subsequent thermal anomalies associated with the Benton Uplift and emplacement of Late Cretaceous intrusions likely “overcooked” the oil and destroyed any top seals. Hydrothermal solutions associated with these events likely destroyed remaining porosities due to intergranular cementation.

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APPENDIX A. PALYNOLOGY and MICROFAUNA of INTERNATIONAL PAPER NO. 1-21 WELL

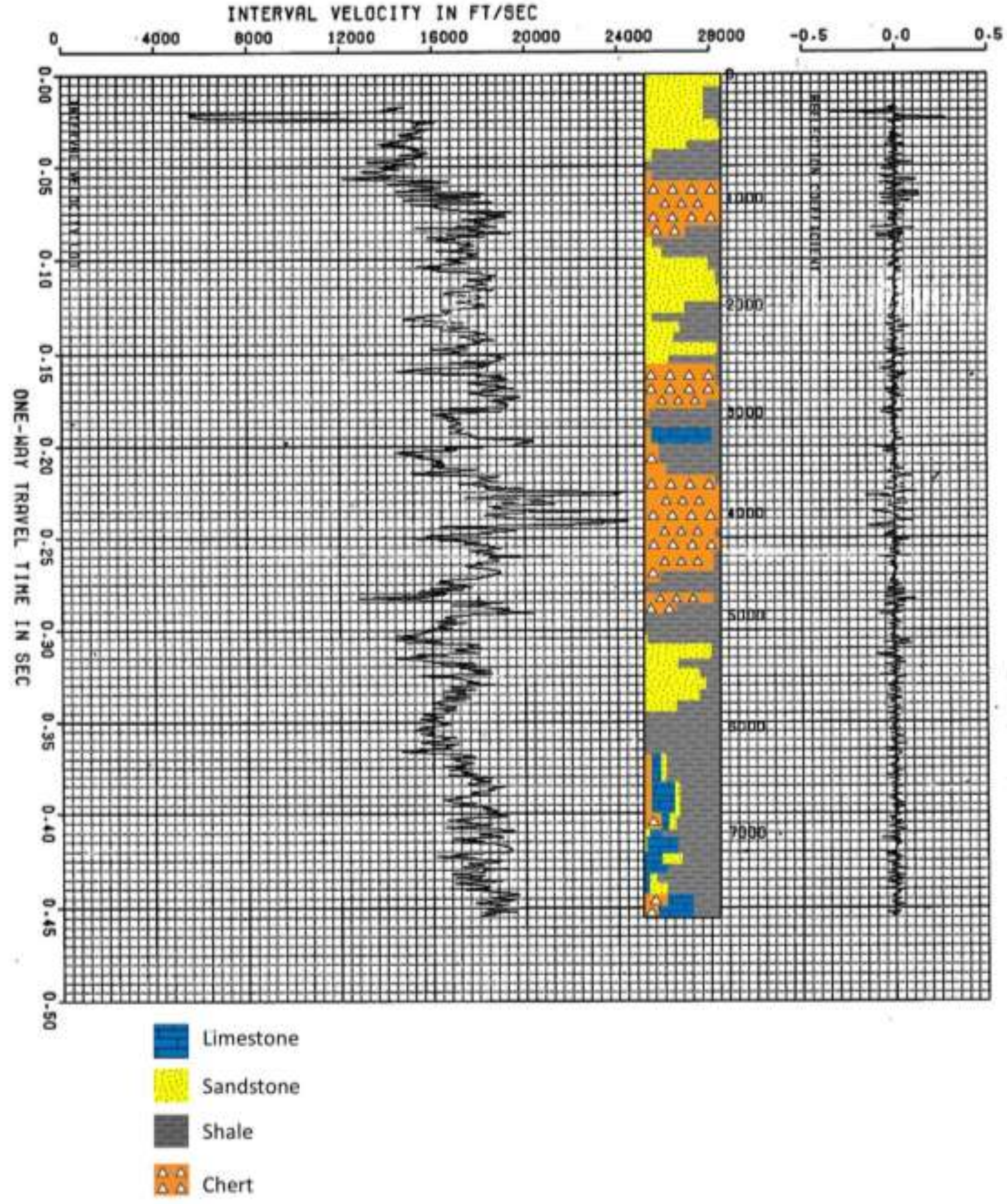
N/I = Not Identified

Interval (feet)	Age	Formation	LOM	Interval lithologies	Comments
90-100	N/I	N/I	N/I	Mostly sandstone	Black, angular charcoal splinters; barren of fossils
190-200	N/I	N/I	N/I	Mostly sandstone w/ asph	Black, angular charcoal splinters; barren of fossils
300-310	Prob. Silurian	Blaylock	13+	50% sand 50% shale med to dk gray	Reliability of this call is very poor owing to few fossils at high LOM
400-410	N/I	N/I	N/I	Mostly sandstone w/ asph; lt gray shale	Black, angular charcoal splinters; barren of fossils
510-520	N/I	N/I	N/I	Poor samples; attempt to blow hole dry	Black, angular charcoal splinters; barren of fossils
600-610	N/I	N/I	N/I	Mostly sandstone	Black, angular charcoal splinters; barren of fossils
620-630	N/I	N/I	N/I	Mostly sandstone w/ asph in fractures	Black, angular charcoal splinters; barren of fossils
700-710	Prob. Silurian	Blaylock	13+	Mostly sandstone w/ asph	Three specimens of Acritarchs in entire sample; poor reliability
800-810	Silurian (prob. early to middle)	Missouri Mtn Shale	13+	Mostly black platly shale; some dk gray	Contains rare, jet black chitinoza and acritarchs; structureless organic matter in low to medium quantities; good to fair age determination
890-900	N/I	N/I	N/I	Shale lt gray, carbonate streaks, and fine mica	Barren of fossils and nearly devoid of organic material
1000-2150	N/I	N/I	N/I	Shale gray and green, chert, sandstone	Barren
2150-60	N/I	N/I	N/I	90% black shale, 10% sandstone	Barren
2190-2200	Prob. late Ordovician to early Silurian	Blaylock	15+	80% gray green shale; 20% dk gray shale	Very few fossil fragments; poor reliability
2230-2240	N/I	N/I	N/I	60% dk gray shale; 10% gray shale; 30% sandstone	Barren
2270-2280	Prob. early Silurian	Blaylock	N/I	60% dk gray shale; 10% gray shale; 30% sandstone	Questionable graptolitic fragment; one chitinozoan VAR-989
2310-2320	N/I	N/I	N/I		Barren
2350-2360	N/I	N/I	N/I		Barren
2390-2400	N/I	N/I	N/I		Barren
2430-2440	Prob. Silurian	Blaylock	15+	45% sandstone w/ asph; 55% dk and lt gray shale	VAR-989 AB; AC-9937; VAR-954; prob. graptolitic fragment
2470-2480	Late Ordovician to early Silurian	Blaylock	15+	50% dk gray and black shale; 30%siltstone; 20% sandstone	Abundant chitinozoans; several species in common with depth 5800'; Good reliability; photos on file
2510-2520	N/I	N/I	N/I		Barren
2550-2560	N/I	N/I	N/I		Barren
2590-2600	N/I	N/I	N/I		Barren

2630-2640	N/I	N/I	N/I		Too few specimens for age determination
2670-2680	Prob. late Devonian to early Carboniferous	Arkansas Novaculite	15+	Shale dk and black	Black spores, poorly preserved, but with recognizable trilete marks and some sculpture; spores like those at 3600' where age was also late Dev. to early Carboniferous
2780-2790	Prob. Devonian	Arkansas Novaculite	15+	85% med gray shale; 15% lt gray chert	One jet black chitinozoan (CHI-5593); rare spores with terrible preservation; poor reliability
2810-2820	Prob. Silurian to Devonian	Arkansas Novaculite	15+	Mostly dk brown chert and med gray shale	Acritarchs: AC-9504; AC-9322; AC-9964; AC-9474; one questionable spore; poor reliability
2870-2880	N/I	N/I	N/I	75% lt gray siliceous calc-chert with asph stain; 25% shale	Barren
2890-2900	N/I	N/I	N/I	25% lt gray siliceous calc-chert with 75%shale	Barren
2900-2950	N/I	N/I	N/I	All chert lt gray some tripolitic	Samples are charcoal with disintegrating fuzzy edges; no identifyable fossils
2950-3000	N/I	N/I	N/I	All chert mottled lt to dk some tripolitic with asph	Samples are charcoal with disintegrating fuzzy edges; no identifyable fossils
3060-3070	N/I	N/I	N/I	Gray chert highly fractured	Too few specimens for age determination
3080-3090	Prob. late Devonian to early Carboniferous	Stanley	15+		Spores: SC-5419; SC-5417; cf. SCZ-5471, *Radiizonates* sp; 4 slides; poor reliability
3100-3500	Kinderhookian/ Osagean?	Arkansas Novaculite (upper member)	N/I	Mostly med gray shale in this interval with intervals of chert, limestone, or calc-chert	Samples from all mist drilled cutting in this interval contain charcoal fragments but no recognizable fossils. See microfaunal report at 3300-3350' for favorable faunal age comparison; Kinderhookian to Osagian
3600	Early Carboniferous	Arkansas Novaculite (upper member?)	14-19	Black chert shale interbedded with dk and lt chert	Fossils at 3600' include spheroidal to subtriangular, jet black spores. High LOM makes even generic identification of spores difficult; it is believed that one specimen retained a trilete mark; further work reveals flanges or encircling sacci. We believe the genus to be *Potonieisporites sp* , a monosaccate probably from the early Carboniferous on poor to fair data
3650-4199	N/I	N/I	N/I	Nearly 100% massive chert mostly lt gray and wt	Interval is devoid of recognizable fossils; organic residues still consist of black, finely dispersed, disintegrating organic detrius and/or splintery, angular, probably fusintic matter; typical organic macerals
4200-4210	N/I	N/I	N/I	80% lt gray shale, 20% chert	Barren. Fragments of jet black, structureless disintigrating patches; organic matter (SOM); splintery fusinite; no recognisable fossils
4300-4310	Prob. Early Devonian	Arkansas Novaculite	15+	100% lt gray some med gray shale	Jet black, rare to common acritarchs having very poor preservation; one black specimen may be *Stenozonotriletes* sp. an early Devonian spore according to Bartlen (1971); jet black outlines of other spores are present; poor reliability
4400-4410	N/I	N/I	N/I	100% chert clear to lt gray with limestone inclusions	Barren, except for two splintery fragments of acritarchs; fusinite maceral
4500-4510	N/I	N/I	N/I	100% chert lt gray with fracturing asph fill	Barren. No recognizable fossils. Finely dispersed, black SOM
4600-4610	N/I	N/I	N/I	100% chert lt gray with fracturing asph fill	Barren. No recognizable fossils. Finely dispersed, black SOM
4700-4710	N/I	N/I	15+	80% brown chert; 20% lt gray shale w/ flecks mica	Four slides examined. Four objects which may have been spores were seen, but age determination is impossible
4800-4810	N/I	N/I	N/I	100% med gray shale	Barren
4900-4910	N/I	N/I	N/I	100% black gray shale	Barren
4930-4940	Prob. Silurian	N/I	15+	90% lt gray chert; frac filled with dead HC (asph)	Trilete spore; spore, psilo-scabrate, shiny black; *Acritarch* cf. AC 9993; *Acritarch* cf. AC 9967. Poor reliability

5000-5050	Prob. late Devonian	Blaylock (basal)/ Arkansas Novaculite	15+	75% lt gray chert abundant frac asph and pyrite; 25% med gray pyritic shale	Two significant spore speciens identified as jet black and transmitting no light; further infared studies will be done; other recognizable microfossils: 4 species of Verrucate spores; 2 species of Baculate; 1 Echinate spore, and 1 Scabrate spore; 1 questionable monolete monosaccate spore and abundant splintery fusinite fragments; SOM is med. to low. Reliability of age call is fair.
5200-5250	N/I	N/I	N/I	100% lt gray with some black shale	Barren
5300-5310	N/I	N/I	N/I	80% vfg sandstone, calc with asph 20% lt gray shale	Barren
5400-5410	N/I	N/I	N/I	100% vfg to fg sandstone silica cement	Barren
5500-5510	N/I	N/I	N/I	80% vfg to fg sandstone silica cement	Barren
5590-5600	N/I	N/I	N/I	90% lt to med gray shale; 10% sandstone as above	Barren
5700-5710	N/I	N/I	N/I	50% lt gray sandstone w/ small streaks of asph; 50% shale	Barren; vial discarded
5800-5810	Probably late Ordovician	Blaylock ?	15+	85% vf to fn grn sandstone with 15% med gray shale	Sample contains several workable species of chitinozoans; shiny back; to be studied in outline only. Good reliability: *Cyathochitina campanulaeformi* cf.; *Cyathochititina dispar* cf.; *Cyathochitina granulata* ; *Conochitina intermedia* ; *Pogonochitinaspinifera intermedia; Conochitina* cf.*; micracantha granulata: brevicollis; Ancyrochitina fragilis; Conochita decipiens; Rhabdochitina* cf. *canna; Conochita decipiens; Rhabdochitina* cf. *canna; Sphaerochitina sphaerocephala; Lagenochitina*
5900-5910	N/I	N/I	N/I	50% sandstone as above; 50% lt to med gray shale	Fine, black fuzzy edged charcoal fragments; no identifiable fossils
5990-6000	N/I	N/I	N/I	80% coal black shale; 20% iron black hard brittle siltstone	Rounded 50-150 micron diameter; black disintegrating patches of SOM only
6000-6600	N/A	N/I	N/I	6000-6300': black micaceous shale interbedded with <20% siltstone w/ mica and quartz veining; 6300-6600': is 85% black mica-rich shale and 15% dk brown chert	Samples not analyzed
6600-7190	N/I	N/I	N/I	6600-6800': 50% blk shale with 50% dk brown chert and lt gray to dk mottle limestone with rhombs (calcite-rich chert?); 6800-7000 - 2 intevals of 50% interbedded sandstone, chert, and blk shale separated by a 30% chert, 30% blk shale, and 30% limestone	No recognizable fossils in this interval
7190-7650	Not analyzed	N/I	N/I	Section dominated by 75% sandstone; 20% black shale and up to 10% dk brown chert	Samples not analyzed
7650	N/I	N/I	N/I	30% chert, 30% black shale and 30% limestone	Barren
7700-7790	Probably late Ordovician	Bigfork Chert	N/I	The mud log describes 3 lithologies over this interval; 40% black, mica-rich shale; 25% dk brown chert; 35% lt to dk brown limestone with slightly fossiliferous intervals	Samples contain abundant patches of disintegrating SOM. Additionally there are a few fragments of "fossil" material which are like those associated with Chitinozoans from the Ordovician Violas Limestone. These organic fragments are long, thin, jet black, echinate, branched at many angles. Two pieces of virgellae from graptolite are seen at 7700' At 7780', one looks like the lower part of a thin prosicula underlain by a tapering virgella in the metasicular portion of a graptolite. Determination is made on these tenuous IDs; poor reliability
42-3200	N/I	N/I	N/I		Barren of microfossils; most of the samples contain pyritized radiolarian-like spheres of unknown origin (may be inorganic)
3300-3350	Upper Kinderhookian	Arkansas Novaculite (upper member)	CAI=5	Interbedded calcareous chert and some shale	Fauna consist of conodonts, gastropods, sponge spicules, fish remnants and other skeletal material; *Gnathodus antetexanus G. s.; Palygnathus* cf.; *P. radinus P.* aff. *P. inornatus inornatus P.* sp.; *Siphonodella* sp.; *Hindeodella* sp.; other conodont fragments

Appendix B. Internal velocity and reflection coefficient from the calibrated curve.



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APPENDIX C. STANDARD WATER ANALYSIS OF INTERNATIONAL PAPER NO. 1-21 WELL

SAM NO. ARK -W-	DEPTH (feet)	FORMATION (age)	pH	R_W (Ω - m)	SPECIFIC GRAVITY	TDS (105°C)	Cl (ppm)	SO_4 (ppm)	HCO_3 (ppm)	CO_3 (ppm)	Na (ppm)	K (ppm)	Ca (ppm)	Mg (ppm)	Fe (ppm)
2	2771	Obf	7.2	25.2	1.0026	300	22	8.6	188	<5	25	9.6	45	7.5	0.6
3	3050	Obf	6.8	14.8	1.0066	1100	28	3.6	274	<5	18	6.0	43	6.5	110
4	3900	MDa	7.4	26.0	1.0063	700	11	2.3	252	<5	30	2.3	39	6.5	34
5	4100	MDa	6.6	25.0	1.0063	800	9.9	3.8	128	<5	28	2.7	35	7.0	11
6	4300	MDa	7.1	20.2	1.0063	800	15	2.9	254	<5	33	12	42	10	39
7	4500	MDa	7.2	23.4	1.0063	500	15	<1	234	<5	28	2.7	42	7.5	14
8	4700	MDa	6.8	24.4	1.0063	1000	11	1.8	178	<5	32	5.5	47	8.0	14
9	4939	MDa	8.6	7.0	1.0067	1400	235	145	290	<5	250	115	10	1.6	<0.1
10	5000	MDa	5.8	16.5	1.0004	1200	11	8.0	350	<10	36	20	22	7.4	1.9
11	5200	Smb	7.7	24.6	1.0005	1100	9.5	1.0	200	<10	45	23	37	11	7.3
12	5327	Smb	7.1	15.7	1.0006	1100	11	<1	280	<10	65	42	22	11	22
14	5600	Smb	6.6	9.8	1.0000	2900	11	220	220	<10	66	29	22	7.2	2.3
15	5734 - 40	Smb	5.8	10.8	1.0006	1800	9.6	200	40	<10	39	18	17	8.3	3.5
16	5800	Smb	6.7	8.6	1.0006	2100	9.5	250	170	<10	56	28	13	8.2	1.0
17	6000	Opb	6.0	8.5	1.0008	2100	21	260	80	<10	50	19	30	1.3	0.6
18	6200	Opb	6.1	11.2	1.0006	1200	21	120	120	<10	44	17	21	8.5	1.9
19	6400	Opb	6.5	9.6	1.0007	1500	15	190	160	<10	25	7.8	70	8.8	2.9
20	6600	Opb	7.0	11.2	1.0008	1200	17	94	160	<10	25	7.7	74	8.5	<0.1
21	6800	Opb	6.9	8.8	1.0008	1300	51	180	180	<10	98	17	67	8.4	0.3
22	7000	Obf	6.7	8.4	1.0008	1700	56	150	260	<10	110	24	78	9.7	1.4
23	7200	Obf	6.7	12.2	1.0007	1000	25	100	150	<10	48	13	55	11	0.1

SHELL OIL CO.,
INTERNATIONAL PAPER #1-21
API #03-059-10004
SEC. 21-T04S-R20W
HOT SPRING CO., ARKANSAS

STANDARD WATER ANALYSIS

	ARK -W- 24	ARK -W- 25	ARK -W- 26
pH	6.1	6.8	6.6
R_W (Ω m)	10.2	5.90	9.50
Specific Gravity at 25°C	1.0007	1.0010	1.0007

PARTS PER MILLION

TDS	1100	1800	1400
Sodium	77	130	59
Potassium	14	15	6.0
Calcium	62	82	79
Magnesium	8.0	9.8	9.0
Iron	10	0.7	0.2
Chloride	34	150	74
Sulfate	130	210	110
Bicarbonate	190	230	180
Carbonate	<10	<10	<10

SAMPLING INFORMATION

Depth interval (feet):	7400	7600	7800
Date of Sample:	2/2/1983	2/4/1983	2/8/1983

Appendix D. Porosity and Diagenesis in the Blaylock Sandstone

Locally, the Blaylock Sandstone displays high porosity values from weathered surface exposures. Porosity values as high as 29% with 12 millidarcies of permeability were measured from these outcrops, and the porosity appears to have developed through the dissolution of carbonate particles. Most outcrops, however, only exhibit trace amounts of porosity. Florence Kunz, Shell Geologist, investigated the diagenetic history of the Blaylock in the International Paper (IP) well.

To determine how diagenesis may have influenced porosity in unweathered subsurface samples, well cuttings from the IP well were analyzed using petrographic methods, scanning electron microscope (SEM), x-ray diffraction (XRD), and cathodoluminescence (CL) evaluation. Samples from the IP well revealed that solid hydrocarbons were present in pore spaces of the sandstone constituting up to 40% of some individual cuttings (Figure 12). Assuming that the solid hydrocarbons were once mobile oil, then this fluid would have filled existing porosity, with an average paleo-porosity of about 15%. The ubiquity of the solid hydrocarbons in these pores is evidence that this was effective porosity prior to an oil charge. Geochemical studies indicate that at least one late, local, short-termed heating event was responsible for the transformation of liquid hydrocarbons into solid hydrocarbons. Bulk x-ray analysis and point counting methods applied to thin sections of Blaylock sandstone and shale shows clay mineralogy is consistently 80-90% illite.

The interpreted paragenetic sequence for the sandstones of the Blaylock is complex. This complexity probably results from the fact that these sands were at times part of an open system. The opening of the system was apparently caused by a number of fracturing events. Multiple sets of fractures were documented with the BHTV log and by observation in well cuttings. These fracturing events probably opened this system to the influx of subsurface fluids of differing composition, resulting in episodes of both cementation and dissolution.

Silica and carbonate cements in fractures, many of which were partially filled with solid hydrocarbon, indicate that formation waters rich in silica and carbonate passed through fracture networks. The interaction of carbonate- and silicate-rich formation waters with sands and shales is indicated by:

1. quartz overgrowth cement.
2. zoned dolomite rhombs.
3. zoned calcite cement.
4. replacive texture of calcite cement.
5. albitization.

The complex diagenetic history of the Blaylock Sandstone was responsible for the creation and preservation of significant pre-charge porosity. Primary intergranular porosity was initially preserved by a phyllosilicate cement (or matrix) which prevented total compaction of the sands. Replacive carbonate cement also aided the preservation of primary porosity. Secondary porosity formed as a result of two carbonate dissolution events which partially removed both carbonate particles and cement. All the elements necessary for a balanced mass transfer were provided by the interaction of interstitial water and sediments.

The cements in these sandstones consist of two end members of a continuum: calcite cement and illite cement. However, we are uncertain whether these end members represent different source areas for the sands, rapidly changing subsea conditions, or just different paragenetic sequences related to the fracturing events. The data strongly suggest that diagenesis was significantly influenced by the anisotropic flow of different formation fluids through the sand via fractures.

An alternative interpretation considers separate diagenetic histories for each end member. No transitional populations were directly observed, but this may have been due to a sampling bias resulting from the small size of the well cuttings, which averaged 1-2 mm in diameter. Early quartz overgrowth cement left an open-packed fabric with the grains in tangential or straight contact with each other. This is interpreted as the first stage in the paragenetic sequence. This widespread secondary quartz overgrowth cement is clearly distinguished from the detrital quartz grains, as the clasts and the overgrowths are separated by a dusty line or faint seam under petrographic examination. Also, when examined with cathodoluminescence, the detrital grain luminesces while the overgrowth does not. This lack of luminescence is considered evidence of authigenic growth. Illite forms the matrix of one end member of these samples. This cement probably formed during compaction and burial of the sediments. This early phyllosilicate cement may have inhibited compaction and thus served to preserve some primary porosity. Illite cemented sandstone has secondary porosity which probably formed as a consequence of full or partial dissolution of rhombic- and amorphous-shaped carbonate particles or cements. This porosity was later filled with hydrocarbons.

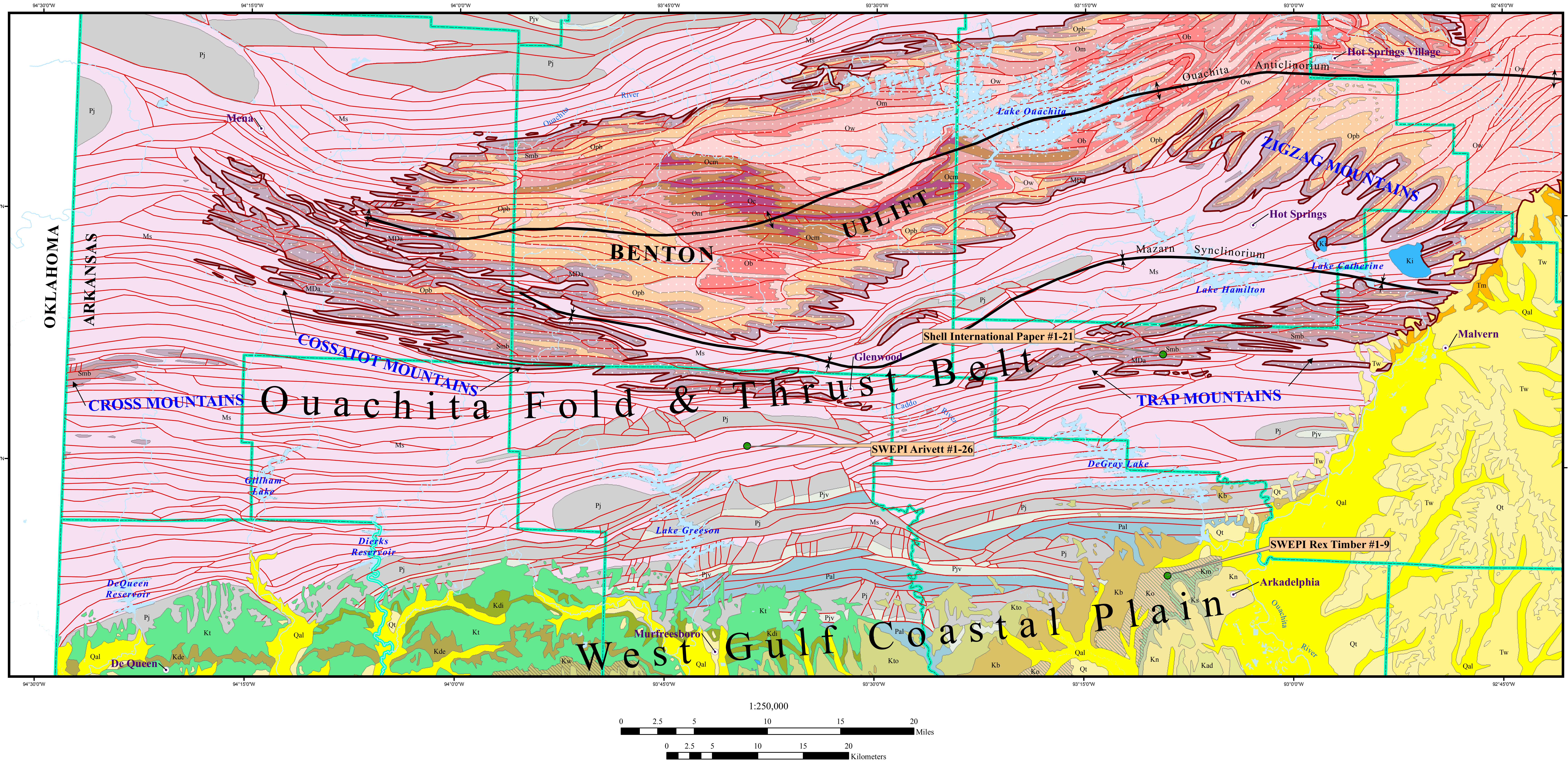
Arkansas Geological Survey
Bekki White, Director and State Geologist

Location Map and Surface Geology of the Southern Ouachita Fold and Thrust Belt, Arkansas

Ted Godo[1], Peng Li[2], and M. Ed Ratchford[2]
1: Shell Exploration and Production Company, Houston, Texas
2: Arkansas Geological Survey, Little Rock, Arkansas

Plate 1

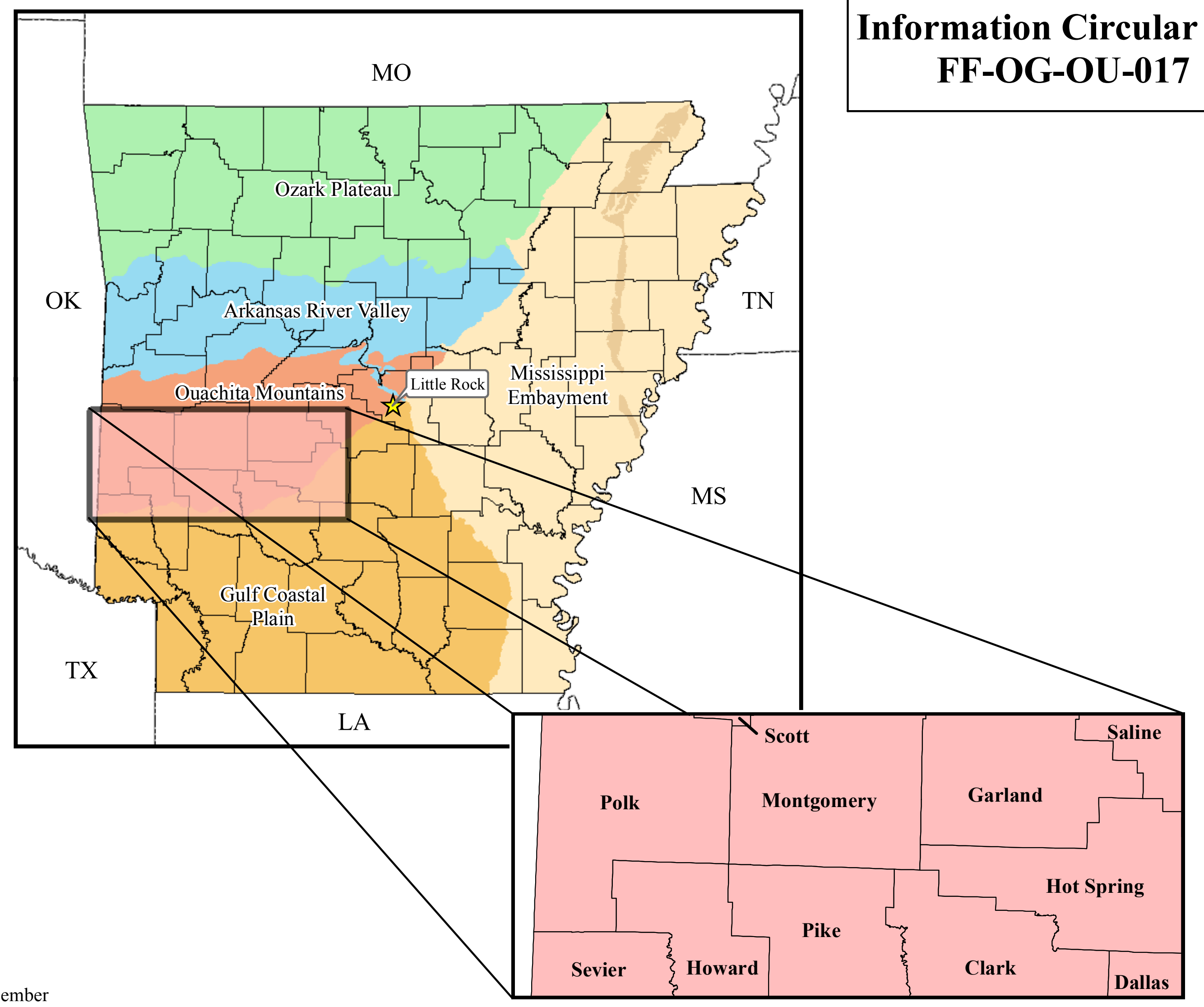
Information Circular 39C
FF-OG-OU-017



Stratigraphic Column

Holocene	
Qal	Alluvium
Late Pleistocene	
Qt	Terrace Deposits
Early Eocene	
Tw	Wilcox Group
Paleocene	
Tm	Midway Group
Late Cretaceous	
Kad	Arkadelphia Marl
Kn	Nacatoch Sand
Ks	Saratoga Chalk
Km	Marlbrook Marl
Ko	Ozan Formation
Kb	Brownstown Marl
Kto	Tokio Formation
Kw	Woodbine Formation
Early Cretaceous	
Kt	Trinity Group
Kde	De Queen Limestone Member
Kdi	Dierks Limestone Member
Cretaceous	
Ki	Acid to Intermediate Igneous Rock
Middle Pennsylvanian	
Pal	Lower Atoka Formation
Early Pennsylvanian	
Pjv	Johns Valley Shale
Pj	Jackfork Sandstone
Early Mississippian	
Ms	Stanley Shale
Late Devonian to Early Mississippian	
MDa	Arkansas Novaculite
Late Silurian	
Smb	Missouri Mountain Shale and Blaylock Sandstone
Middle Ordovician to Late Ordovician	
Opb	Polk Creek Shale and Bigfork Chert
Middle Ordovician	
Ow	Womble Shale
Early Ordovician to Middle Ordovician	
Ob	Blakely Sandstone
Early Ordovician	
Om	Mazarn Shale
Ocm	Crystal Mountain Sandstone
Cambrian to Early Ordovician	
Oc	Collier Shale

Study Area



Symbols

┼	Fold trace of Synclinorium
┼	Fold trace of Anticlinorium
— - - -	Thrust fault - Also tear faults in some areas, Dashed under lakes to show continuity
▨	Benton Uplift
●	Well Locations
⊙	Cities
▭	Water Body
▭	County Boundary

Disclaimer: Although this map was compiled from digital data that was successfully processed on a computer system using ESRI ArcGIS 10.x software at the Arkansas Geological Survey (AGS), no warranty, expressed or implied, is made by the AGS regarding the unity of the data on any other system, nor shall the act of distribution constitute any such warranty. The AGS does not guarantee this map or digital data to be free of errors or assume liability for interpretations from this map or digital data, or decisions based thereon.

Sources: Geologic base map is enlarged and modified from the original 1:500,000 scale Geologic Map of Arkansas, Haley, B. R. et al., 1993, U.S. Geological Survey and the Arkansas Geological Commission.
Fold traces shown on the map are from Croneis, C., 1930, Geology of the Arkansas Paleozoic Area, Arkansas Geological Survey, Bull. 3, Plate 1-B.
Boundary outline for the Benton Uplift is derived from Arbenz, J.K., 1989, The Ouachita system, *in* Bally, A.W. and Palmer, A.R., eds., The Geology of North America - An Overview, Vol. A, p. 387.

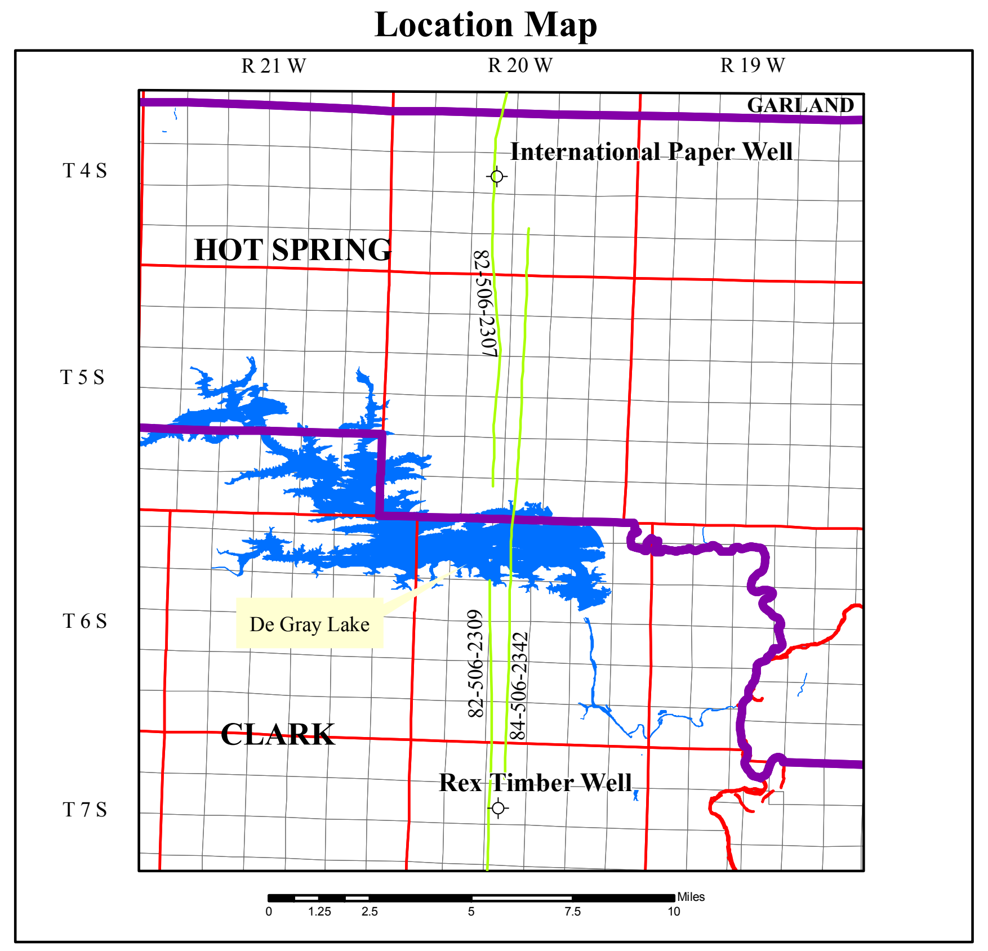
Cartography By: Nathan H. Taylor

Seismic Compilation and Interpretation

Plate 2

Information Circular 39C
FF-OG-OU-017

Location Map



Map Legend

- Wells
- Seismic Lines

Seismic Legend

- Form Lines
- Faults