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ARKANSAS GEOLOGICAL SURVEY
BEKKI WHITE, DIRECTOR AND STATE GEOLOGIST

INFORMATION CIRCULAR 39B

STRUCTURAL AND STRATIGRAPHIC ANALYSIS OF THE SHELL ARIVETT NO. 1-26 WELL, SOUTHERN OUACHITA FOLD AND THRUST BELT, PIKE COUNTY, ARKANSAS

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ARKANSAS GEOLOGICAL SURVEY
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Table of Contents

List of Figures and Table

List of Appendices and Plate

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Structural and Stratigraphic Analysis of the Shell Arivett 1-26 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 in the 1980's in the Arkansas portion of the Ouachita Mountains. Shell recognized three exploration targets in the Ouachita fold and thrust belt of Arkansas and drilled three wildcat wells to test their hydrocarbon potential. These 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 Devonian-Lower Mississippian Arkansas Novaculite and Ordovician Bigfork Chert (Arivett well, Pike County), and the Ordovician Crystal Mountain Sandstone (International Paper well, Hot Spring County) (Plate 1). The results and conclusions from these three wells will be published in a three part series of Information Circulars at the AGS. As the second of the three publications, this report is focused on the Arivett No. 1-26 well located in Section 26-T5S-R25W. The well was spudded in August of 1985 and subsequently plugged and abandoned as a dry hole in November of 1985 after reaching a depth of 10,570 ft (3,223 m) in the Silurian Missouri Mountain

Shale/Blaylock Sandstone. The Arivett No.1-26 well tested the Shell exploration prospect named the Rattler.

The principal objectives of this report are to (1) report the pre- and post-drilling well information, (2) provide a seismic interpretation and structural cross-section of the well, (3) assess the reasons for a lack of movable hydrocarbons in the well and (4) comment on the remaining natural gas potential along the southern flank of the Ouachita fold and thrust belt in Arkansas.

Regional Geologic Setting

The Ouachita Mountains physiographic province lies between the Arkoma Basin to the north and the Gulf Coastal Plain to the south and extends from Little Rock, Arkansas westward to Atoka, Oklahoma. The total area of the exposed mountain range is approximately 12,000 mi^2 (31,080 km^2), of which slightly more than half lies within Arkansas. Late Cambrian to Carboniferous deepwater sedimentary rocks comprise the surface exposures, which define the Ouachita Mountains. The stratigraphic section exposed in the Ouachita Mountains represents coeval deepwater deposition of shallow water facies found in the Arkoma Basin province (Nicholas and Rozendal, 1975; Bush et al., 1977; Visher and Wickham, 1978; Arbenz, 1989; Lowe, 1989). The basement is deeply buried in the Ouachita foreland basin where imbricate-style thrust facies have stacked sedimentary sequences. 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 the COCORP seismic data, the Ouachita frontal thrust zone is composed of approximately 39,000 ft (11,887 m) of both allochthonous and autochthonous sediments (Nelson et al., 1982). Southward from the frontal thrust zone, the Ouachita anticlinorium, also known as the Benton Uplift, has about 23,000 ft (7,010 m) of thrusted sediments that lie above the interpreted crystalline basement (Nelson et al., 1982). South of this uplift where the Rattler Prospect was drilled, as much as 46,000 ft (14,021 m) of deepwater sediments have been thrusted and stacked over the basement complex based on a deep-recorded seismic line (Lillie et al., 1983). Blythe (1988) made two balanced regional cross-sections using the COCORP data. One cross-section was oriented along the seismic line and the other drawn parallel to the first and located nearby Shell's Rattler Prospect.

A stratigraphic correlation, shown in Figure 1, defines the formation names and general lithologies used in this report. Shallow marine carbonates were deposited in the Arkoma Basin during pre-Mississippian time, which is often referred to as the Arbuckle facies (Gardner, 1936; Ham, 1959; Brigg and Roeder, 1975; Walper, 1977; Viele, 1979). Coeval stratigraphic sequences are dark gray to black, organic-rich shales interbedded with siltstone, sandstone, conglomerate, detrital limestone, and chert that make up the exposed rocks of the Ouachita Mountains of Oklahoma and Arkansas. These lithologies are thought to be off-shelf, deepwater (slope to abyssal) sediments deposited by pelagic fallout, turbidity currents and other mass-flow mechanisms (Lowe, 1976; Murgatroyd, 1980; Buthman, 1982; Lowe, 1989; Craig et al., 1993). Age dating of these pre-Mississippian sediments is determined from relatively rare fossil assemblages of graptolites, conodonts, radiolarians, chitinozoans, acritarchs, and deep-water outer shelf trilobites (Hohensee and Stitt, 1989; Krueger and Ethington, 1991; Stitt et al., 1991; and Shell's in house palynology report from the Rattler Prospect).

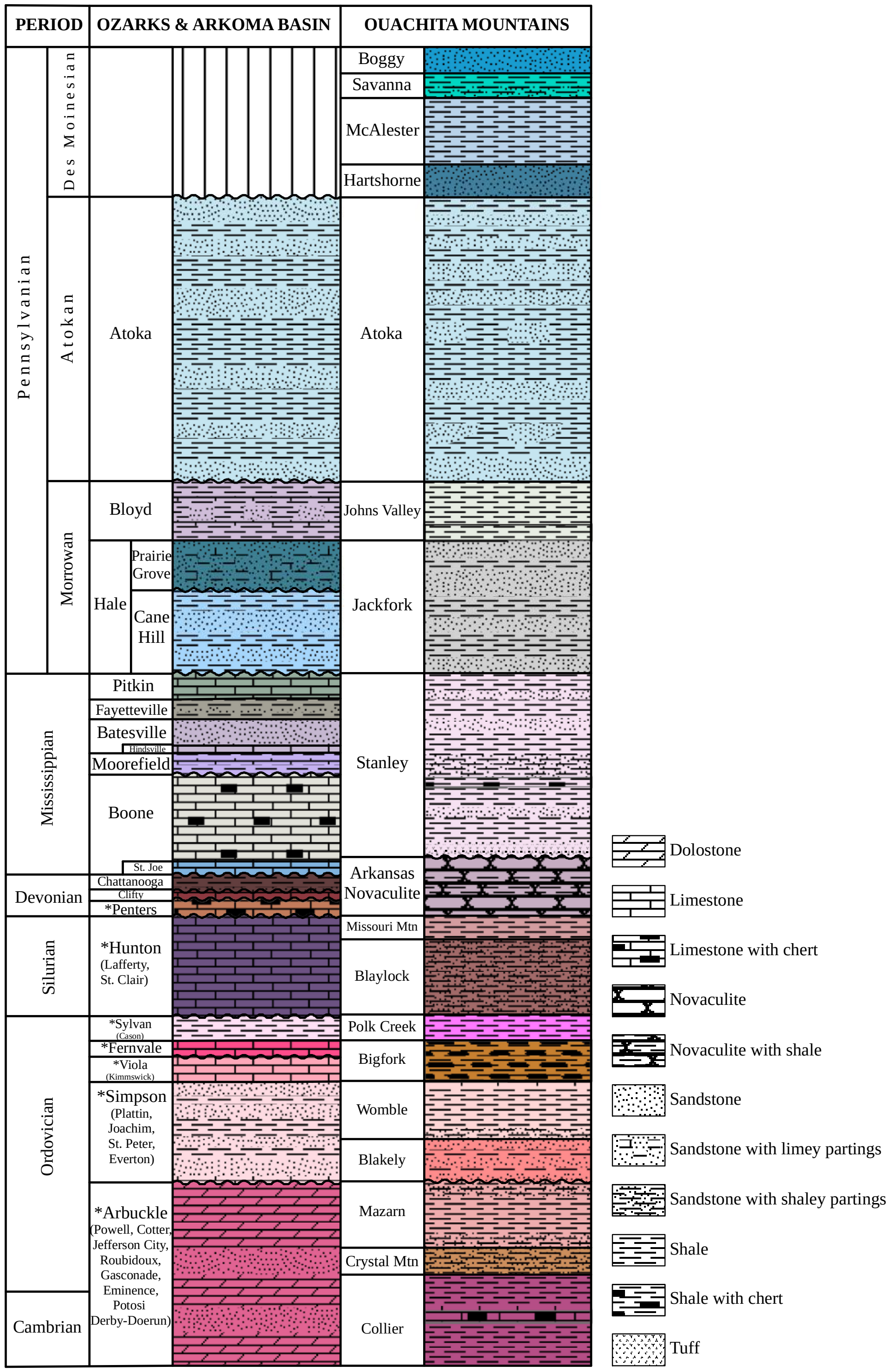


Figure 1. Stratigraphic correlation between the Ozark Uplift/Arkoma Basin and Ouachita Mountains region in Arkansas.

The deepwater Ouachita facies are separated into two periods with drastically different sedimentation rates. The age boundary that divides these two periods is the end of the Meramecian stage in the Mississippian. The Meramecian has been shown to correspond with the top of the Arkansas Novaculite (Hass, 1951; AAPG, 1983-1986). Sediments younger than Meramecian age are characterized by thick, foredeep, syn-orogenic flysch deposits that accumulated at a rate of approximately 7.5 times that of the pre-Meramecian sediments (chert, shale, carbonate and some sandstone). The sediment thicknesses of Cambrian to lowermost Mississippian Ouachita facies are estimated by Shell to be approximately 11,000-13,000 ft (3,653-3,962 m) in Arkansas based on regional outcrop measurements and reconstructed subsurface thickness estimates. For the Carboniferous Ouachita facies, the total thickness is estimated by Shell to be approximately 33,000 ft (10,058 m); however, thickness estimations vary significantly due in large part to uncertainties regarding the thickness of the Atokan section (Gordon and Stone, 1977; Stone and Bush, 1984). The stratigraphic top of the Atoka Formation is not preserved anywhere in the interior of the Ouachitas because of early folding and thrusting that was followed by later erosion and deposition of Mesozoic Gulf coastal sediments. Shell's thickness estimation for the Atoka Formation ranges between 15,000 and 20,000 ft (4,572 and 6,096 m). The thickness of the Pennsylvanian Jackfork Formation is estimated between 5,000 to 8,000 ft (1,524 and 2,438 m) and the estimated thickness of the Mississippian Stanley Shale ranges between 6,000 and 10,000 ft (1,829 and 3,048 m).

Regional Source Rock and Hydrocarbon Charge Potential

In order to better understand the petroleum source rock potential within the Ouachita Mountains, a regional geochemistry study was initiated in 1981 and completed in 1983. A major goal of the study was to analyze both the total organic carbon (TOC) content and thermal maturity of geologic formations across the Ouachita Mountains in Oklahoma and Arkansas. Because vitrinite is not present in rocks that are older than Devonian, the optical reflectance of both graptolite and vitrinite macerals were measured to assess the thermal maturity of shale samples that range in age from Ordovician through Pennsylvanian (Bertrand and Heroux, 1987). In total, geochemical analyses were conducted on 550 outcrop samples and from drill cuttings collected at ten-foot intervals from 23 wells in the Ouachita Mountains of both Oklahoma and Arkansas (Appendix 1). A full geochemical review of all 550 samples is beyond the scope of this paper, but attention will focus on data that is germane to the Rattler Prospect and Arivett well.

Total Organic Carbon

TOC results from this study indicate that source rocks with fair to excellent quality occur throughout the entire stratigraphic sequence of the Ouachitas. A summary of the source rock distribution sorted by geologic formation indicates that the Carboniferous Stanley and Jackfork Formations contain the leanest source rocks with TOC values between 1 and 1.5%. Shales in these formations are characterized as having disseminated humic organic matter, which is prone to generate natural gas. By contrast, the richest source rocks are present in the older strata which include the Arkansas Novaculite through the Cambrian/Ordovician Collier Formation. The shales in all of the pre-Carboniferous formations contain lipid-rich kerogen. The formation with the highest organic content is the Ordovician Polk Creek Formation, which has an average TOC value of 7% and a range from 1 to 24%. The formation that has the second highest concentration of organics is the Ordovician Womble Shale with an average TOC value of over 4% and a range between 1 and 23%. The middle member of the Arkansas Novaculite Formation also contains organic-rich zones with an average TOC value of 4% and as high as 20%. In a similar published study by Curiale (1981, 1983), the Polk Creek and Womble Shales were reported to contain the highest TOC values in lipid-rich source rocks. There have been other previously published regional studies which show similar results with regard to TOC values compared to Shell's geochemical study (Houseknecht and Matthews, 1985; Keller et al., 1985; Guthrie et al., 1986).

Thermal Maturity

The original maturity values reported in this document use a scale developed at Shell called the LOM (Level of Organic Metamorphism) as devised by Hood et al. (1975). Although not a primary measurement, the LOM value may be correlated with coal rank, vitrinite reflectance (R_o), spore carbonization and other scales to measure the level of organic thermal maturation in rocks. For this paper, calculated R_o values are reported with corresponding measured LOM values since the former is more commonly used at present for assessing thermal maturity. Methods of comparative analysis of thermal maturity values such as thermal alteration index (TAI), maximum temperature (T_{max}), and coal rank are discussed by Senftle and Landis (1991).

The maturity profile (or gradient) from nineteen wells drilled distant from the Benton-Broken Bow uplifts all indicate the presence of a uniform and identical thermal gradient that shows no offset of reflectance values across faults (Figure 2). The maturity gradients (or LOM/ R_o gradient) from each well are all parallel and illustrate the same thermal gradient increase with depth. This reflectance gradient has a slope equal to about 1.2 ^{o}F/100 ft (2.2 ^{o}C/100m).

The relations are in sharp contrast to thermal maturity observations from wells drilled in other thrust belts around the world. For example, the maturity plot from a well drilled in the Wyoming overthrust belt shows a considerably different thermal gradient pattern from that of a well in the Ouachita overthrust belt (Figure 3). The vertical thermal gradient from the Wyoming well displays what is referred to as a "saw tooth" pattern of reflectance with depth (Oxburg and Turcotte, 1974; Angevine and Turcotte, 1983; Senftle and Landis, 1991). This pattern is the result of older rocks with a higher thermal maturity which are thrusted above younger rocks with lower thermal maturities. In a paper by Furlong and Edman (1984), they also describe a "saw tooth graphical pattern" of thermal values from a thrust belt where thrusting occurred as recently as 75 Ma. By comparison, compressional deformation ceased in the Ouachita overthrust belt at approximately 300 Ma. Hence, our interpretation for the uniform thermal gradient observations in the Ouachita Mountains (excluding the uplifts) is that thermal equilibrium has occurred for a long period of time on both hanging wall and footwall sides of the thrust faults and that is reflected as a linear increase in reflectance values with depth, typical of a normal geothermal gradient.

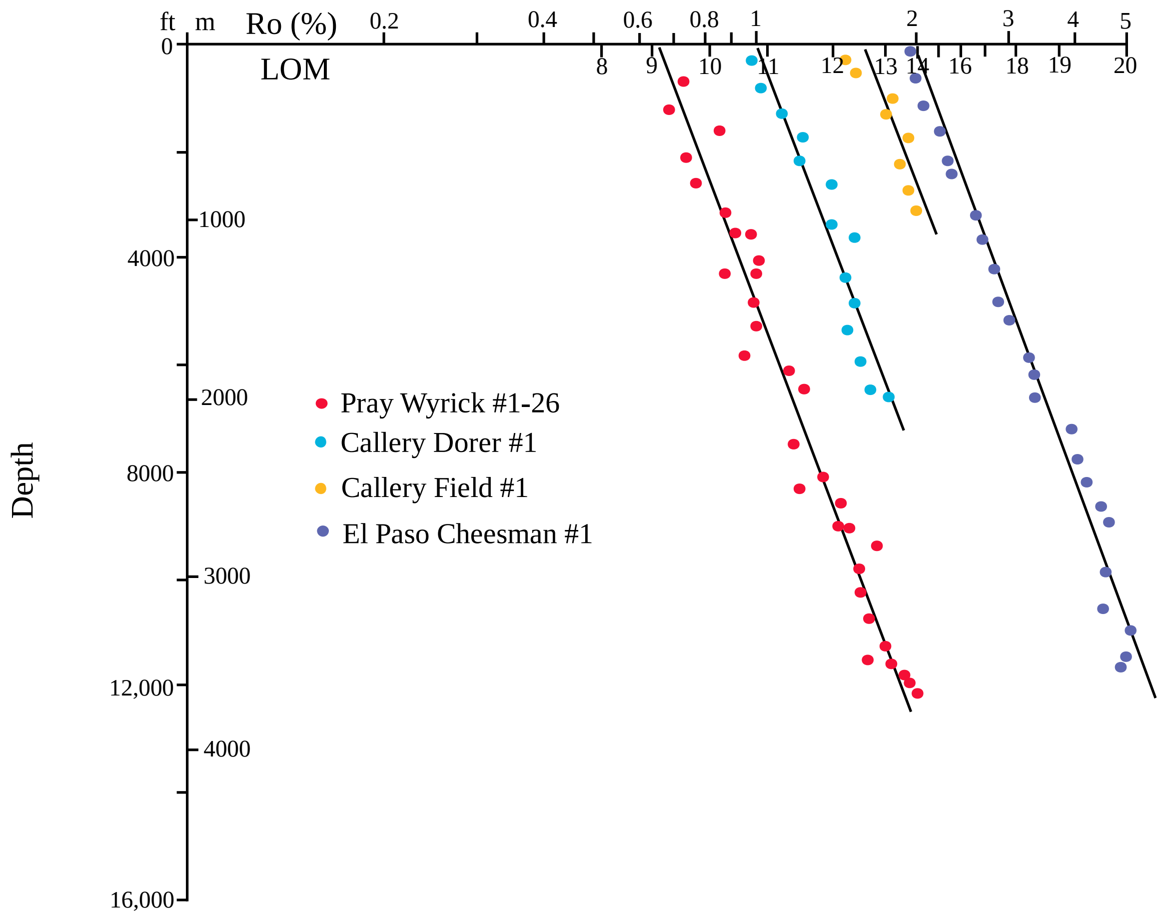


Figure 2. Maturity profiles of four wells drilled outside the Benton-Broken Bow uplifts in the Ouachita Mountains. See Appendix 1 for location information of these four wells and fifteen additional wells in the same region.

Wells drilled in the Benton-Broken Bow uplifts where the surface maturity is high (> R_o 3.0%) typically possess abnormal vertical reflectance gradients compared to the surrounding Ouachita and Arkoma Basin region. Four (4) wells that were examined in this study were drilled into this thermally anomalous area (Figure 4): (1) Shell International Paper # 1-21 (Sec. 21-T4S-R20W, API: 03-059-10004), in Hot Spring

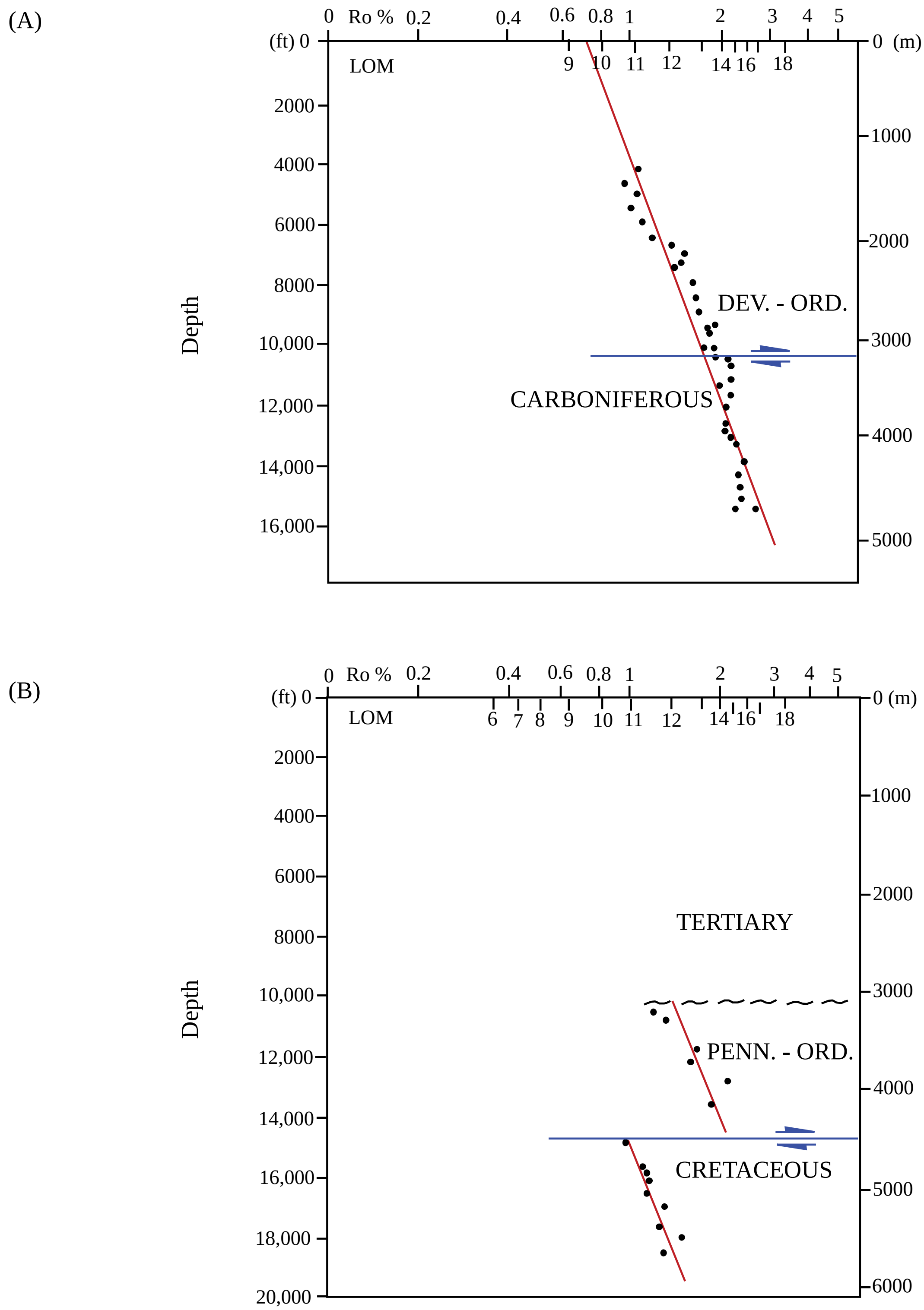


Figure 3. Comparison of the thermal maturity profiles between (A) American Quasar Cabe #1 well (Sec. 11-T2N-R20E), Pushmataha County, OK, and (B) Amoco/Champlin #457 Amoco A#1 well (Sec. 7-T17N-R119W), Uinta County, WY.

County, Arkansas, (2) Viersen-Cochran Weyerhaeuser # 1-25 (Sec. 25-T5S-R23E, API: 35-089-20005), in McCurtain County, Oklahoma (Goldstein, 1975), (3) Ambassador Montgomery # 1-21 (Sec. 21-T2N-R10W, API: 031-190-0003), in Pulaski County, Arkansas and (4) Kitselman Kitselman #2 (Sec. 2-T1S-R13W, API: 031-190-0014), in Pulaski County, Arkansas. All of the four wells were spudded on the surface with R_o values above 3.32% (LOM ≥ 18) which is generally recognized as the onset of

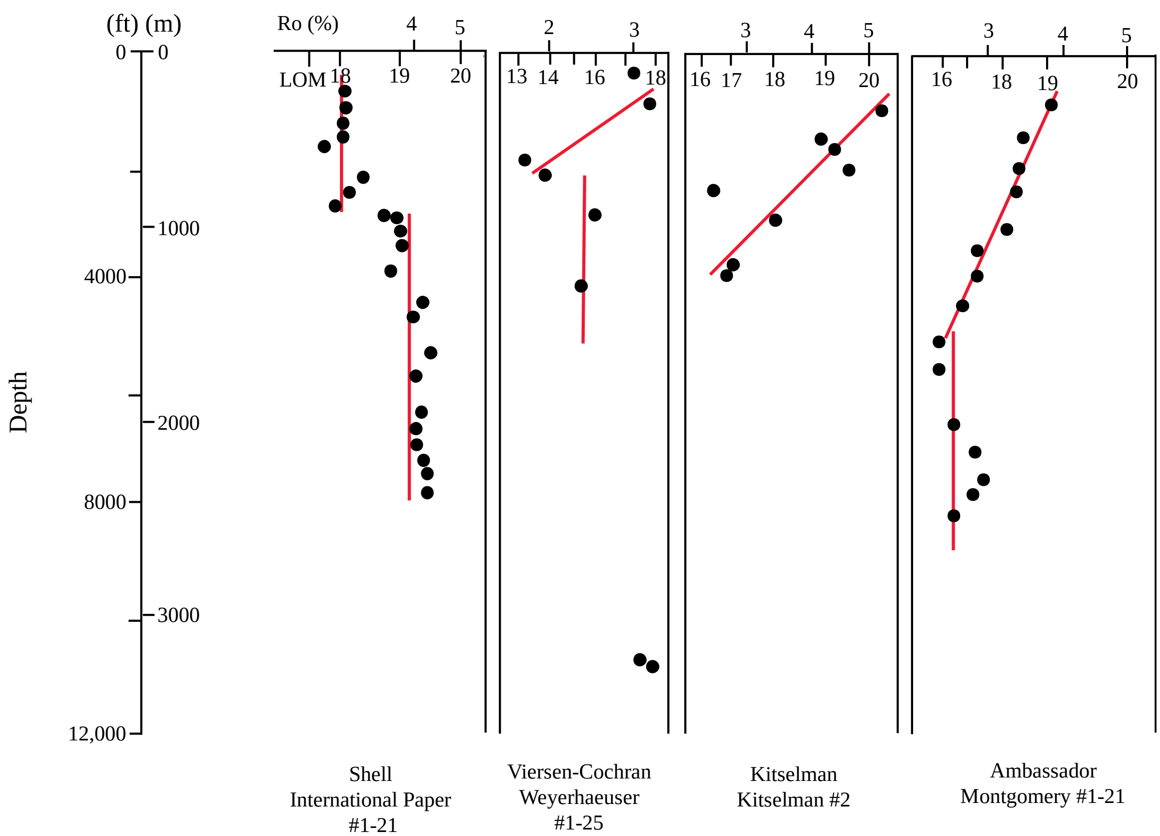


Figure 4. Maturity profiles of four wells drilled within the Benton-Broken Bow uplifts in the Ouachita Mountains. See Appendix 1 for the location information of the wells.

greenschist facies metamorphism. The four wells all have different maturity profiles compared to the 19 wells drilled both north and south of the Benton-Broken Bow uplifts. The profile patterns in the wells from the uplift vary from a near vertical gradient to a gradient that both increases and decreases with depth without a regular pattern or a consistent gradient.

A common feature observed in the rocks of the Benton Uplift is abundant cement-filled fractures. The fracture fill is made up of minerals deposited by hydrothermal fluids that migrated through the fractures and fissures (Clardy and Bush, 1975; Stone, 1976; Konig and Stone, 1977; Howard, 1979; Kurris, 1980). The heating associated with much of these vein filled deposits has been suggested by some to be dated around the Pennsylvania/Permian boundary (Denison et al., 1977).

Additional supporting evidence for rapid heating within the uplift is also evidenced by the “coking” of organic macerals within shale lithologies. A maceral is a common component of organic-rich shale and these constituents are primarily composed of inertinite, vitrinite, and exinite. “Coking” likely occurred during a rapid heating event (possibly the hydrothermal fluids within fractures) after the rocks attained an initial estimated overburden R_o of 1.1 to 1.8% (LOM of 11 to 13).

In summary, normal maturity profiles can be explained by the upward heat convection that would result in uniform heat reduction as rocks become less buried. Conduction of heat via hot hydrothermal fluids seeking permeability pathways could result in uneven heating of the overlying rocks, resulting in vertical and more erratic maturity profiles. Post-structural heating in this region, at least locally, was caused by emplacement of Cretaceous igneous intrusives which may have also elevated the otherwise normal geothermal gradients (Houseknecht and Matthews, 1985; Guthrie et al., 1986).

Key Stratigraphic Units – Devonian/Mississippian Arkansas Novaculite (Reservoir) and Mississippian Stanley (Seal)

Arkansas Novaculite

The organic-rich cherts and shales of the Arkansas Novaculite have long been known to be time-correlative to the source rocks found in the Woodford and Chattanooga Shales (Figure 1). The reservoir potential for hydrocarbons in the Arkansas Novaculite, however, was not recognized in the literature prior to the mid-1970's. After the first oil discoveries were made in the Isom Springs field of Oklahoma in 1977 (Morrison, 1980), the interest in the reservoir potential of the Arkansas Novaculite rose to a much higher level. It is generally accepted that due to the limited matrix porosity found in the chert beds, the well-developed fractures are the necessary conduits to deliver favorable hydrocarbon flow rates for commercially viable reservoirs.

Outcrop studies were undertaken by Shell to assist in the understanding of the reservoir characteristics and fracture distribution of the Arkansas Novaculite. The closest outcrop of Arkansas Novaculite to the Isom Springs field is the Black Knob Ridge area near the town of Atoka, Oklahoma. The Arkansas Novaculite in this outcrop is made up of thin-bedded, green, brown, gray and black chert interbedded with paper-thin shale (Hendricks et al., 1936). It seems to match descriptions of subsurface cuttings from the wells at the Isom Springs field. The structures in the outcrop are highly fractured and folded and the interbedded black shale is very organic-rich with the highest TOC value exceeding 20% and R_o value of 0.75% (just into the oil expulsion window).

Further northeast from Black Knob Ridge is another well-described outcrop of Arkansas Novaculite called Potato Hills that is located in Latimer, Pushmataha and Leflore Counties of Oklahoma. The Arkansas Novaculite in the Potato Hills region is described as black, green, and lighter-colored chert beds of 1 to 18 inches (2 to 46 cm) thick and is separated by black to olive-colored shale partings and beds from less than one inch to several feet (2 cm to ~1-3 m) (Arbenz, 1968). Lithologically, the dark and multicolored chert beds with black organic-rich shales generally characterize the Arkansas Novaculite throughout much of the Ouachita Mountains in Oklahoma both in the subsurface (Bramlett, 1979; Morrison, 1982; Voight and Sullivan, 1983; Allen, 1991b) and in outcrop (Black Knob Ridge, Potato Hills, and Broken Bow Uplift).

Some obvious changes occur in outcrops of Arkansas Novaculite between Oklahoma and Arkansas in terms of bedding thickness, color, texture and composition of the chert. Thinner-bedded, dark chert is characteristic in Oklahoma; whereas, thicker bedded, lighter-colored chert occurs in the lower to middle portions of the Arkansas sequence with a cream to white calcareous chert in the upper part of the formation.

For an excellent historic stratigraphic framework of the Arkansas Novaculite the reader is referred to the report of Sholes (1977). There is no type locality for this formation, but is named for quarries that produced this rock under the trade name of "Arkansas Novaculite" (McFarland, 2004). Probably the most referenced section of Arkansas Novaculite is along a road cut adjacent to the Caddo River near Caddo, Arkansas (Zimmerman, 1984).

The first active novaculite quarry was originally located a few miles from Hot Springs, Arkansas and operations began in 1818. The ability of novaculite to sharpen steel blades is best revealed through examination using a scanning electron microscope (SEM) (Keller et al., 1977). Under the SEM, novaculite exhibits polygonal, triple-point grain boundaries consisting of silica/quartz grains. These inherent properties make novaculite highly effective as a whetstone for sharpening knives, razors, and other steel implements. This polygonal texture is described by Spry (1969) as a thermally metamorphosed silica rock texture (Ro >3.32% or LOM ≥18). The microcrystalline novaculite texture is present in chert with multiple color variations and bed thicknesses. Novaculite that crops out along the southern portion of the Benton Uplift is composed primarily of white to cream chert, which was locally subjected to low-grade metamorphism (especially around Hot Springs and Magnet Cove, Arkansas). The high thermal environment that caused recrystallization in the novaculite rocks of Hot Spring County, Arkansas occurred near the end of the Pennsylvania period. A subsequent thermal event during the Cretaceous period is associated with emplacement of igneous intrusives in the Ouachita Mountains region (Bass and Ferrara, 1969; Denison et al., 1977).

Stanley Formation

Although the Stanley sequence was first designated as a formation by Taff (1902) from exposures near the village of Stanley in Pushmataha County, Oklahoma, Harlton (1938) elevated the Stanley to group rank and subdivided it into three formations in Oklahoma. In ascending order, they are the Tenmile Creek, Moyers and Chickasaw

Creek Formations. The Tenmile Creek is dominated by shale, while the Moyers is more sand prone (Morris, 1989). The Chickasaw Creek is the thinnest formation (only a few hundred feet or ~100-300 m) and is characterized by siliceous shale dated with radiolarian fauna that contains a mixed assortment of sponge spicules, indicating an age of latest Chesterian or approximately the Mississippian/Pennsylvanian boundary (Cline, 1968; Coleman, 1990; Roberts, 1994). The Stanley is conformably overlain by the sand-rich Jackfork Formation.

Miser and Purdue (1929) stated that the Stanley sand is distributed over a large area that includes both Arkansas and Oklahoma. More sand is present toward the top and the bottom of the formation and shale lithologies dominate the middle part. Niem (1976) also described the basal 500 ft (152 m) of the Stanley including the Hatton Tuff beds in eastern Oklahoma and westernmost Arkansas as the dominant sandstone. Sub-regionally, the basal Stanley contains a mappable sandstone unit referred to as the Hot Springs Sandstone by Purdue (1910) with a type section near Hot Springs, Arkansas (Miser and Purdue, 1929). Hamilton (1973) described the extent of the Hot Springs Sandstone but defined a more widespread distribution south of the Benton Uplift from Hot Springs in the east to as far west as Mena, Arkansas. He also described a nearly 300 ft (91 m) sand-rich section above the Hot Springs Sandstone which is currently assigned to the lower Stanley. This overlying sand-rich interval is exposed in an outcrop along a railroad cut in Glenwood, Arkansas, approximately 6 miles (10 km) east-northeast from the Rattler Prospect.

McFarland (2004) compiled and condensed the published descriptions of the Stanley Formation in Arkansas. Overall, the Stanley consists of dark gray shale interbedded with fine-grained sandstone. A thick sandstone member, the Hot Springs Sandstone, is present near the base of the sequence or an equivalent thin conglomerate/breccia occurs at the base of the unit in many other locales. Minor amounts of tuff, chert and conglomerate have also been noted in various parts of the sequence. The tuffs, the Hatton Tuff and others, are mostly restricted to the lower part of the formation; whereas, cherts are locally present in the middle and upper parts of the Stanley sequence.

The Stanley Formation is described below from two key wells drilled relatively close to the Rattler Prospect. The wells were drilled in 1981 and 1982 by Sheraton Oil Corporation and were named the Kyle No. 1-29 (Sec. 29-T4S-R22W, API 03-059-10003) and the Bean No. 1-15 (Sec. 15-T5S-R23W, API 03-019-10002). Both wells are located east of the Rattler Prospect approximately 13 and 16 miles (21 and 26 km) respectively in Hot Spring and Clark Counties of Arkansas.

The Bean No. 1-15 well was mist-drilled entirely in the Stanley Formation to a total depth of 2,900 ft (884 m) and had no electric logs acquired (Figure 5). Geochemical evaluation of the drill-cuttings was conducted to measure the levels of TOC and R_o. This well is interpreted to have spudded in the middle of the Stanley Formation located on the footwall side of a thrust fault. Based on the analysis and petrographic description of the well cuttings from the Bean well, very few sands are present in this portion of the Stanley Formation. The clastics that are present are mainly siltstone and fine-grained sandstone. A considerable amount of thermally dead carbon called anthraxolite remains in some of the sands (Figure 6). Anthraxolite is a term used to describe the metamorphosed bitumen (Hunt, 1978) that is composed mostly of carbon (Landis and Castano, 1995).

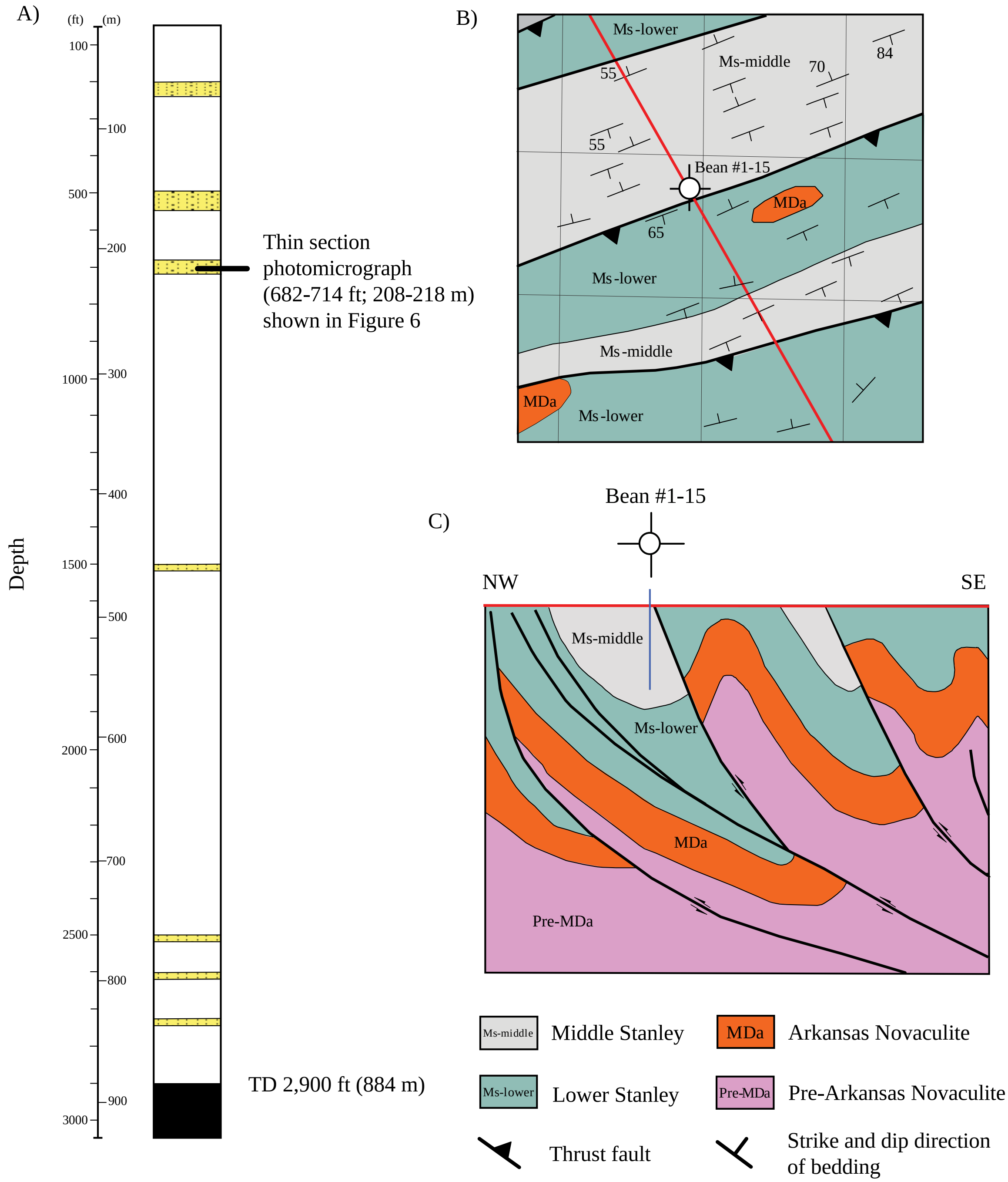


Figure 5. Sheraton Bean No. 1-15 well in Clark County, AR. (A) Simplified lithologic log showing the depths of sandstone units. Note that no electric logs were acquired in this well. (B) Surface geologic map surrounding the well (unpublished mapping by Shell). (C) Cross-section transversing the well. See (B) for the location of the cross section.

Anthraxolite is likely a remnant of oil charges that have been thermally cracked (Rogers et al., 1974).

The Kyle No. 1-29 well was mist-drilled to 3,800 ft (1,158 m) and then mud-drilled to a total depth of 4,546 ft (1,386 m) with a mud weight of 9.4 pounds/gallon (ppg) (Figure 7). This well is interpreted to have been drilled mostly in the lower Stanley based

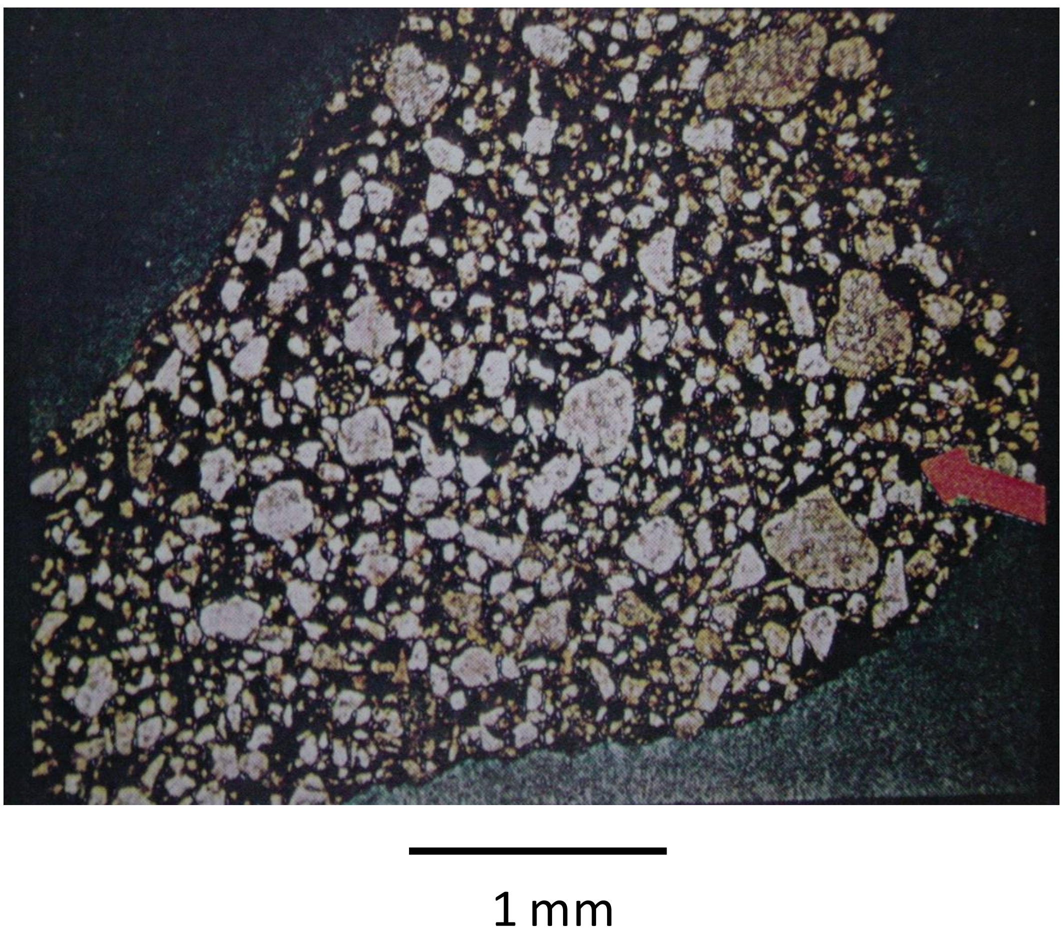


Figure 6. Photomicrograph of well cutting in the Mississippian Stanley sandstone (682-714 ft or 208-218 m) of the Sheraton Bean No. 1-15 well in Clark County, AR. This sample exhibits a poorly sorted, fine-grained sandstone texture with anthraxolite filling the dark matrix areas between grains (shown by red arrow). Anthraxolite accounts for about 40% of interstitial filling by point count methodology.

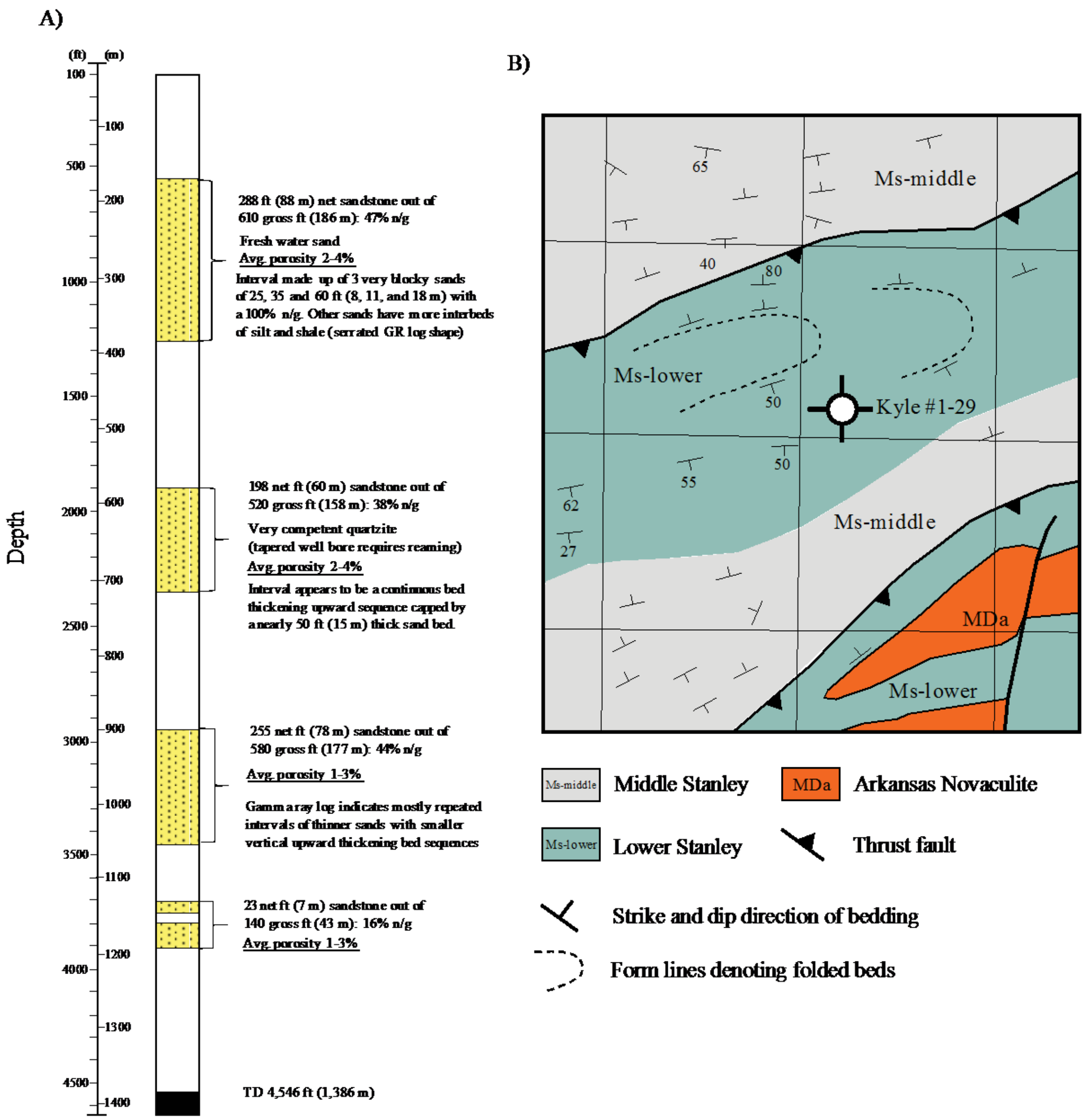


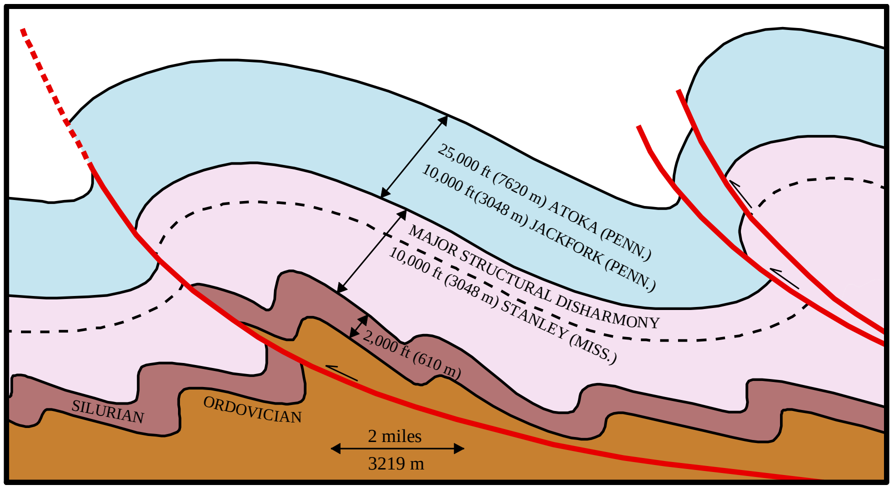
Figure 7. Sheraton Kyle No. 1-29 well in Hot Spring County, AR. (A) Simplified lithologic log showing the depths, thicknesses, average porosity values and net-to-gross ratios of sandstone beds. (B) Photogeologic map interpretation surrounding the Arivett No. 1-26 well (courtesy of Trollinger Marsch Resources).

primarily on the high concentration of sand-rich lithologies. The sandstone in the Kyle well produced fresh water flows at depths of 950 ft (290 m) and 1,100 ft (335 m) which created some difficulty during the mist-drilling. Tighter, less permeable sandstone intervals were also present in the Kyle well. These particular sandstones are abrasive and hard and required additional reaming in the well bore to open the hole to gauge as otherwise the well bore would become tapered due to excessive bit wear. A log suite including a density log for porosity calculations was acquired in the Kyle well. An interpretative summary of average porosity values and net-to-gross ratios for sand and shale are also provided in Figure 7. The interpreted section of sand-rich lower Stanley in the Kyle well is also consistent with the measured section of Hamilton (1973) at Glenwood, Arkansas.

Regional Structural Style

Structural styles of folding and faulting in the Ouachita-Arkoma stratigraphic sequence are strongly affected by the distribution and contrast of relatively ductile and rigid rocks (Figure 8), which some researchers refer to as mechanical stratigraphy (Jamison, 1992). The deformation style of the Ouachita region is distinctly different when compared to the classic ramp and platform deformation in areas such as the Canadian foothills of Alberta, the Wyoming thrust belt, Appalachian Valley and Ridge Province, and the Zagros Mountains of Iran. In these provinces, the fault plane climbs up-section obliquely across thick rigid layers of rock and steps horizontally or at a very low-angle along thin ductile beds. A repeated stratigraphic section is often encountered

A)



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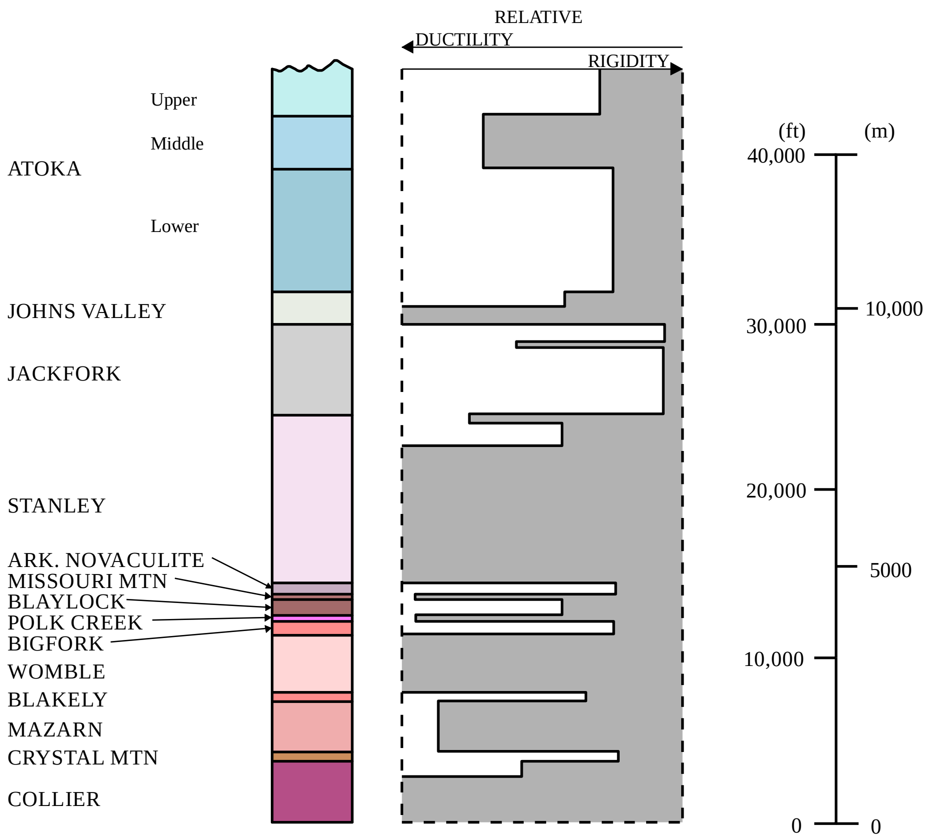


Figure 8. Structural styles in the stratigraphy of the Ouachita Mountains. (A) Diagrammatic section of structural disharmony between the late Paleozoic sandstones and early to middle Paleozoic chert, sandstone, and shale. (B) Mechanical stratigraphic section indicating the distribution of relatively ductile and rigid formations.

when drilling a vertical well through such a fault system as the overthrust block overlays the autochthonous footwall rocks and forms a complete rollover anticline feature (Rich, 1934; Dahlstrom, 1970; Wheeler, 1980; Ramsay and Huber, 1987; Woodward, 1987; Jamison, 1992). Conversely, Ouachita-style deformation commonly consists of an upper competent zone of younger folded and rigid rocks that overlies a deformed zone of thick and ductile beds where complicated faulting and flow take place at depth (Wiltschko and Chappie, 1977).

In the Ouachita Mountains, relatively thick, rigid strata of the upper Stanley and Jackfork overlie thick, pre-Mississippian ductile shale sequences that are interbedded with thin, rigid chert and sandstone beds. The resulting Ouachita fault geometry as viewed in cross-section is characteristically listric in form. Compressional forces generated a master "sole fault" deep in the pre-Mississippian section with a sub-horizontal attitude (Dennis, 1967). The fault geometry climbs up-section with a listric shape through thick ductile shale. This fairly homogeneous, ductile lithology allows a more defined upward curve of the fault plane. The fault plane steepens at about 60-70^{o} toward the overlying Jackfork sandstone and uplifts the fault block to relieve the compressional stress. As a result, the ductile Stanley shale flows into a narrow antiformal structure (Boyer and Elliott, 1982; Stewart, 1996). The boundary between the rigid and ductile strata is located approximately in the upper one-third of the Stanley Formation and can be viewed directly on a surface geologic map (Figure 9).

Both plant and invertebrate fossils are known in the Stanley, but preservation is poor and thus informal division of the formation into its lower, middle, and upper parts with biostratigraphic indicators is difficult. Moreover, it is extremely difficult to map the

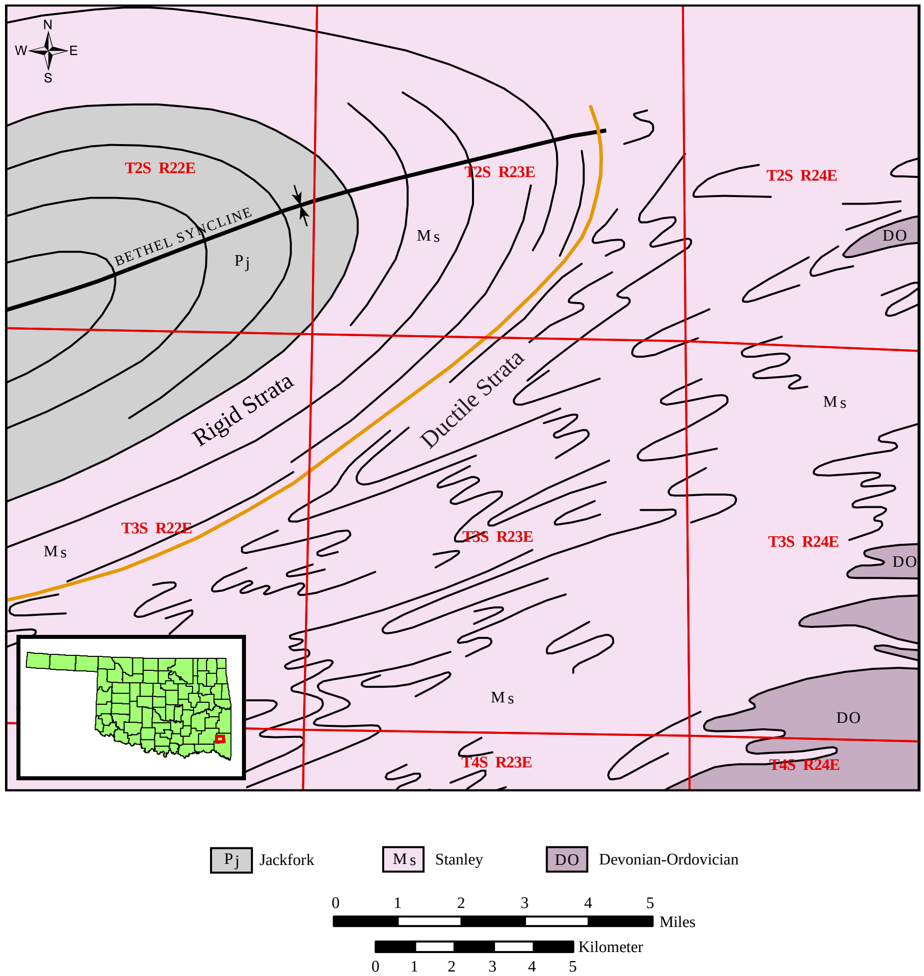


Figure 9. Structural decollement in the Stanley Formation. Note that the decollement surface between the rigid and ductile strata is located approximately in the upper one-third of the Stanley as shown diagrammatically by the orange line.

various members within the Stanley Formation if the Jackfork sand is absent. Presence of the Jackfork sand thus assists geologic field mapping by allowing a determination of the stratigraphic succession for a given sequence. In the Antimony District of southwest Arkansas numerous faults of unknown displacements indicate that tectonic thickening of the Stanley has occurred due to multiple repetitions of fault-bounded stratigraphic slices that juxtapose Stanley on Stanley sequences (Howard, 1979). In this report, the Stanley members are identified by relating the different outcrop patterns to a regional understanding of sand/shale percentages and folding styles in the three informal members. For example, the middle Stanley contains the most shale and displays a very rapid change in dip pattern over a short mappable distance. The lower sandstone-rich Stanley and Arkansas Novaculite display tight folds with similar wavelength and amplitude in outcrop exposures.

Oil and Gas Exploration

Hydrocarbon exploration activity has been conducted primarily in the Carboniferous strata of the Arkoma Basin and the adjacent Ouachita thrust belt by numerous oil and gas companies. In the frontal thrust zone of Oklahoma, the exploration objectives are focused on thrust sheets which often consist of repeated sections of Atokan Spiro and Morrowan Wapanucka Formations. Exploration in the interior zones of the Ouachita Mountains has historically seen much lighter activity and less favorable production rates (Voight and Sullivan, 1983). Exploration in the Ouachita Mountains is typically concentrated on drilling the narrow belts of the Stanley outcrop between large, relatively simple synclines cored by Jackfork and younger formations. The narrow belts of Stanley outcrop define the leading edges of many of the major thrust faults, which translated the synclines upward. Several tar seeps have been identified in the Stanley outcrops near these thrust faults. Earlier exploration ventures simply drilled only a few hundred feet (~100-300 m) below the tar seeps to find more movable oil. Some of the Stanley exploration ventures involved deeper drillings such as the Southwest Moyers Field in Pushmataha County, Oklahoma. Gas was produced from Stanley sandstones at rates of 100 to 500 Mcfgpd over a depth range of 2,100 to 6,100 ft (640 to 1,859 m) (Morrison, 1982). More recent and deeper drilling in the Potato Hills Gas Field of Oklahoma has led to the discovery of natural gas below the Ordovician Womble Shale in the duplex structure originally described by Miser (1929) (Arbenz, 1968; Allen, 1991b). The reservoir section consists of Jackfork sandstone and was discovered by GHK in 1997 (Montgomery, 1996; Petzet, 1996; Denny, 2003; Zeng et al., 2004).

The Arkansas Novaculite became a primary exploration target for Shell in thrust fault traps after announcements of oil discoveries in the Ouachita thrust trend in Oklahoma and west Texas. These discoveries include the Isom Springs Field in Marshall County, Oklahoma in 1977 (Morrison, 1982), the McKay Creek Field in 1979, and the Pinon Field in 1982, both in west Texas (Reed and Strickler, 1990). Shell drilled its first novaculite discovery well in the Thistle Field of west Texas in 1984.

While exploration efforts in the Arkansas Novaculite were underway in west Texas (there called the Caballos Novaculite) in the early 1980's, Shell also studied the exploration potential of the Arkansas Novaculite and other formations in the Ouachita Mountains of Arkansas and Oklahoma. Surface geologic maps of both states were reviewed for regional geology and to identify potential exploration targets. The surface geology of Oklahoma is characterized by large areas of Jackfork-cored synclines and narrow belts of Stanley-cored anticlines located along the leading edges of major thrust sheets. In comparison, large areas of faulted Stanley Formation are exposed south of the Benton Uplift as shown on the Geologic Map of Arkansas (Haley et al., 1993). Based on this observation, the primary exploration objective, Arkansas Novaculite, would likely be drilled at shallower depths in Arkansas compared with Oklahoma. The Rattler Prospect was designed to test the gas-bearing reservoir potential of the Arkansas Novaculite by spudding the well in a large aerial distribution of Stanley rocks along a major thrust sheet.

The second exploration target was the Ordovician sandstones such as the Blakely and Crystal Mountain Formations. This well test was predicated on spudding the well in the Devonian or older sequences, thereby reducing the depth to drill to the target horizon. Based on surface geologic relations, the Trap Mountains of Arkansas are part of a large anticlinorium with Silurian rocks exposed at the surface. The Shell International Paper No. 1-21 well was planned to test the Ordovician section.

The third exploration target is an exposure of a Jackfork-cored plunging anticline, located in Clark County, Arkansas. This structure was drilled by Shell as the Rex Timber No. 1-9 well to test for hydrocarbons in stacked reservoir–seal pairs in the lower Jackfork and upper Stanley sandstones (Godo et al. 2008). These play concepts were the basis for a leasing program concentrated in the southern Arkansas portion of the Ouachita Mountains and drilling plans were made to implement a three-well drilling program between 1983 and 1986.

Rattler Prospect

The Shell Arivett No. 1-26 is a vertical well penetration in the Rattler Prospect reaching a total depth of 10,570 ft (3,222 m). The legal location of the Arivett well is Sec. 26-T5S-R25W. It was spudded on July 23, 1985 and abandoned as a dry hole on November 3, 1985. The well received a complete subsurface evaluation that includes all identified hydrocarbon shows (Table 1). Well cuttings were acquired for lithologic description, paleontologic analysis, and a well log evaluation that includes a complete log

Table 1. Water and gas shows in the Arivett 1-26 well.

Depth ft (m)	Formation	Show Type	Description
6,280 (1,914)	Stanley	water flow	well began misting-salinity measured 18,000 ppm of Nacl
7,523 (2,293)		casing point	
7,810 (2,380)	Stanley	water flow	water salinity measured 77,000 ppm of Nacl
7,958 (2,426)	Stanley	gas flare	2 1/2 foot gas flare lasting 6.5 minutes with a total gas show of 3,190 units; associated water is 77,000 ppm of Nacl
8,280 (2,524)	Stanley	gas flare	3 1/2 foot flare lasting 4.75 minutes with a total gas show of 1,200 units
8,400 (2,560)	Stanley	gas flare	3 foot flare lasting 12 minutes with a total gas show of 1,075 units; associated water is 70,000 ppm of Nacl
9,065 (2,763)	Middle Arkansas Novaculite	gas flare	5 to 6 foot flare lasting 15 minutes with a total gas show of 970 units
9,300 (2,835)	Lower Arkansas Novaculite	gas flare	1 to 3 foot flare lasting 18 minutes with a total gas show of 1,060 units
9,380 (2,859)	Lower Arkansas Novaculite	gas flare	2 to 6 foot flare lasting 25 minutes with a total gas show of 1,100 units; associated water is 78,000 ppm of Nacl
10,240 (3,121)	Missouri Mountain	gas flare	2 to 3 foot flare lasting 15 minutes with a total gas show of 420 units

suite to measure porosity and fluid saturation.

Air/mist drilling methods were used by Shell in the Arkansas portion of the Ouachita Mountains. This method provides the best opportunity to evaluate oil and gas shows with no mud overbalances and to obtain the largest volume of drill cuttings for study. In effect, the air/mist drilling presents a continuous drill stem test (DST) while drilling. Only the last 50 ft (15 m) of the Arivett well was mud-drilled. The well cuttings produced during the air/mist drilling exhibited good quality comparable to those produced by percussion drilling with cable tool methodology. Whole cores were collected near the bottom of the well in the Blaylock Sandstone at depths of 10,511-10,525 ft (3,204-3,208 m). However, during the drilling of the Arkansas Novaculite at depths of 8,565-8,569 ft (2,611-2,612 m), the penetration rate was extremely low as three different core heads were used to cut only 4 ft (1 m) of whole core before the coring operation had to stop due to cost considerations.

Pre-Drill Reservoir Character

The upper member of the Arkansas Novaculite displays good matrix porosity in outcrops within the Cossatot Mountains, south of the Benton Uplift in Arkansas (Figure 10). Large amounts of interstitial calcium carbonate are present in this member as a component of the chert matrix. During surface weathering, the calcium carbonate is leached which results in a porous, tripolitic chert with potentially good reservoir characteristics.

To test porosity and permeability of the upper Arkansas Novaculite the Langley quadrangle map was examined for locations of tripolitic chert quarries (Haley and Stone, 1994). In these quarries, the distribution of calcium carbonate in the chert varies from a fine-grained, disseminated texture to coarser blebs up to approximately 0.4 inches (1 cm) in diameter. When leached of calcium carbonate, the chert has similar physical properties and appearance to that of pumice with irregular open vugs and low density. The porosity and permeability of outcrop samples were measured in various leached chert beds. Porosity values ranging from 15 to 40% are quite common. The corresponding permeability ranges between 1 to 65 millidarcies (md) with an average of 15 to 30 md.

Three tripolitic novaculite exposures were studied in the southeastern Cossatot Mountains, directly north of the Rattler surface anticline. These outcrop exposures are located in (a) Sec. 26-T4S-R29W of Polk County, (b) Sec. 1-T5S-R27W of Pike County, and (c) Sec. 7-T5S-R24W of Pike County. At locality (a), vertical beds of the Stanley

A) “Vuggy” tripolitic novaculite

B) Altered surface of “vuggy” tripolitic novaculite

C) “Powdery-textured” tripolitic novaculite

Figure 10. Typical outcrop samples of decalcified tripolitic novaculite from the upper member of the Arkansas Novaculite in the southeastern Cossatot Mountains.

and Arkansas Novaculite are exposed in the east face of a quarry. The tripolitic novaculite is separated by only 1 to 2 inches (several centimeters) of shale. Thin sections of the tripolitic novaculite show that calcium carbonate is in the form of highly abraded fossil fragments. The identified fossil components are dominantly echinoderms and bryozoans (Figure 11). At locality (b), the upper member of the Arkansas Novaculite is exposed near the nose of a small syncline with beds dipping approximately 12^{o}. This section is 135 ft (41 m) in thickness and all but the uppermost 10 to 25 ft (3 to 8 m) is tripolitic. The porosity values measured from two tripolitic chert samples are 38.5% and 34.6% with corresponding permeabilities of 18 and 63 md, respectively. Caddo Minerals Inc. drilled a core hole into the synclinal axis of the Novaculite which is located about 1,000 ft (305 m) west of the outcrop on the bank of Blocker Creek. The core hole discovered approximately 107 ft (33 m) of tripolitic novaculite out of 115 ft (35 m) drilled section in the upper member of Arkansas Novaculite. Locality (c) is along a road cut on the southeast side of US Highway 70, which exposes the upper and middle members of the Arkansas Novaculite. Porosity measurements were made on three different samples with indicated values of 20.2%, 30.4% and 52.3% and corresponding permeabilities of 1.1, 10.0 and 18.0 md were measured. Tripolitic chert was also identified at a depth of 800 ft (244 m) in the Benedict No. 29-1 Fee well (Sec. 29-T3S-R15W, API 03-125-00003) in Saline County, Arkansas (Figure 12).

In summary, a successful exploration parameter for the Arivett well was identification of tripolitic chert that contains considerable matrix porosity created by leaching of calcium carbonate in the upper member of the Arkansas Novaculite. Although there is no unique way of predicting the distribution of carbonate in the chert,

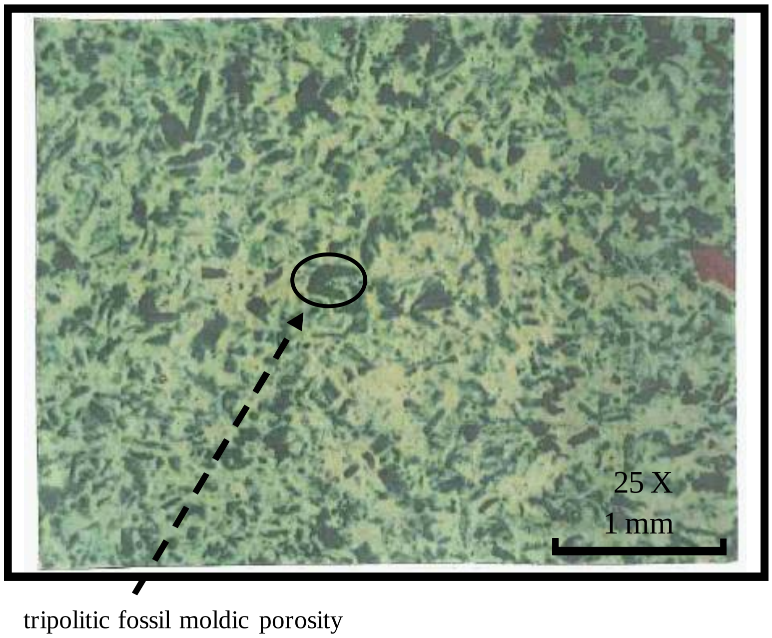


Figure 11. Thin section (25X) of tripolitic chert from the Upper Arkansas Novaculite collected from a quarry in Sec. 26-T4S-R29W, Polk County, Arkansas. Note that the arrow points to a fossil mold. Fossil moldic porosity is 25% in this sample.

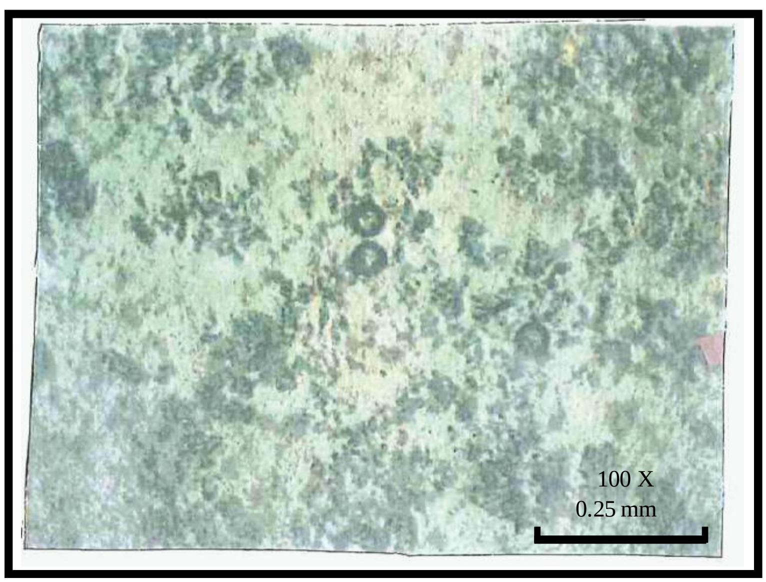


Figure 12. Thin section (100X) of tripolitic chert from well cuttings at a depth of 816 ft (249 m) in the Benedict No. 29-1 Fee well in Saline County, Arkansas. Rhombic moldic porosity is 15% in this sample.

the Rattler Prospect is located just south of east-west-trending, tripolitic chert outcrops and was expected to have similar reservoir characteristics in the subsurface. A fracture system was also anticipated in this highly folded and faulted formation, which could potentially enhance both porosity and permeability.

A secondary reservoir target in the Rattler Prospect is sandstone in the Stanley Formation, provided sufficient porosity could be located in those units. However, further examination of the Sheraton Bean No. 1-15 and Kyle No. 1-29 wells provided little encouragement due to poor subsurface well control and a lack of suitable sandstone units for regional correlation. In fact, there was no specific Stanley sandstone targeted by seismic or outcrop correlation prior to drilling the Arivett well.

Pre-Drill Structural Trap Character

Rattler was the first prospect in Arkansas that was designed to test the Arkansas Novaculite as one of the reservoir objectives in a culmination along a major thrust sheet. This prospect was initially identified using surface geologic maps as no seismic data existed during this time period for the southern Ouachita Mountains of Arkansas. The northern leading edge of the Rattler Prospect is bounded by a major thrust fault named the Caney Fault (Figures 13 and 14). On the upthrown side of the Caney Fault, there are highly deformed lower and middle (?) Stanley Shale sequences adjacent to the fault. These shale sequences form a stratigraphically conformable contact with younger Pennsylvanian strata in a structural monocline containing south dips that extend upward through the Atoka Formation. The east and west boundaries of the Rattler Prospect were also defined using surface geology. The Rattler Prospect is divided by two major

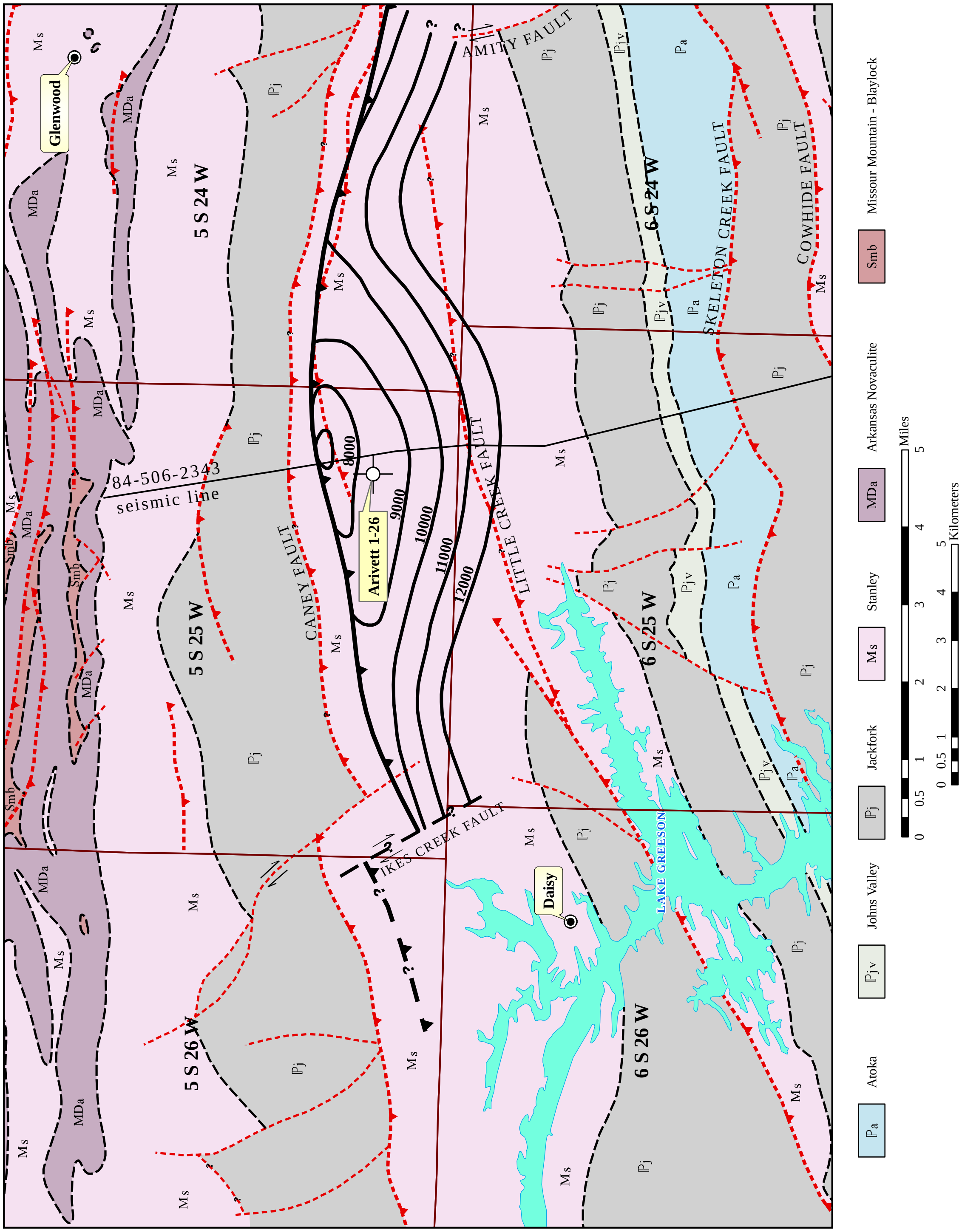


Figure 13. Structural contour map of the Arkansas Novaculite proximal to the Rattler Prospect. Structural contours are based on the deep scenario interpretation of seismic line 84-506-2343. Geologic base map is modified from Haley et al. (1993).

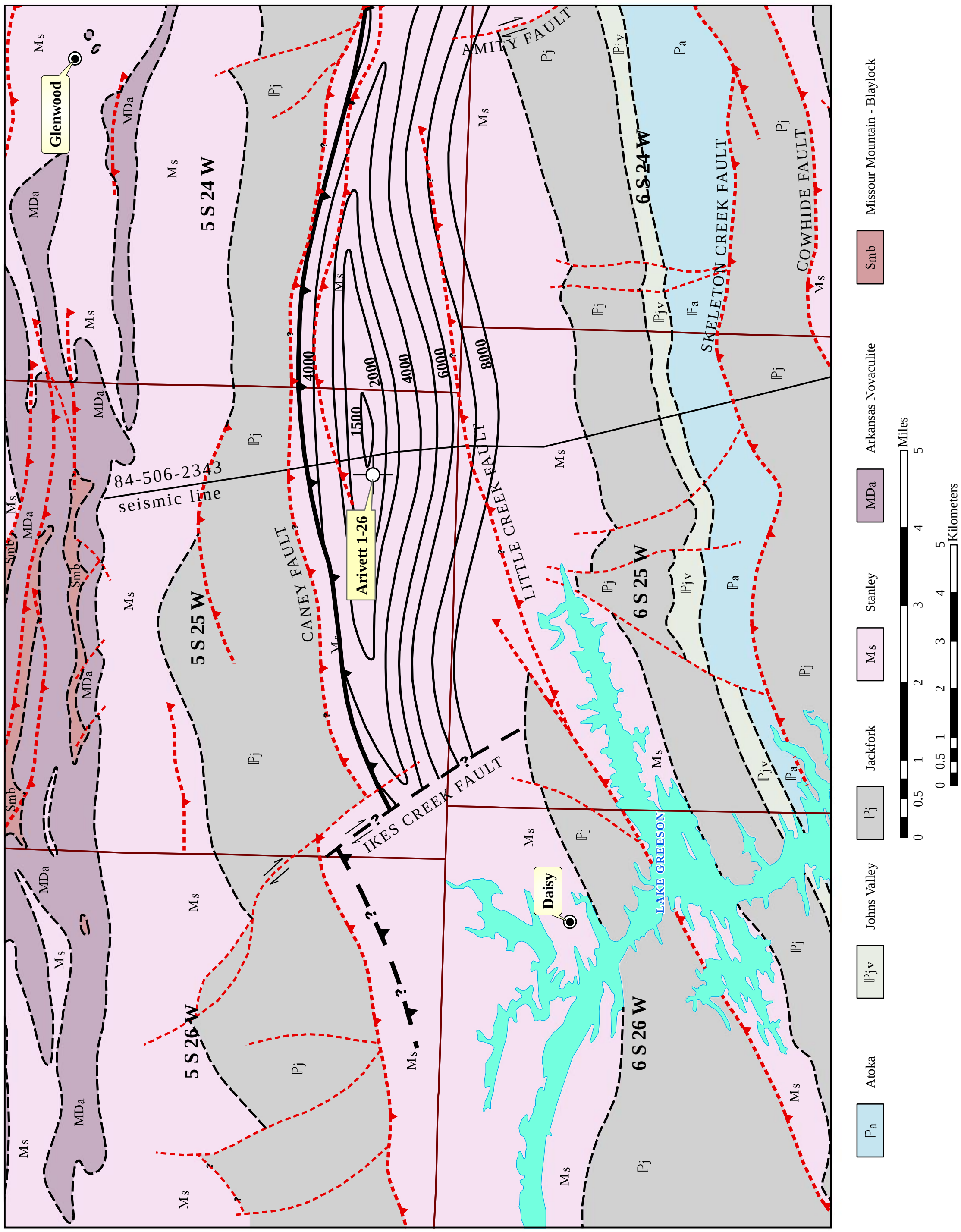


Figure 14. Structural contour map of the Arkansas Novaculite proximal to the Rattler Prospect. Structural contours are based on the shallow scenario interpretation of seismic line 84-506-2343. Geologic base map is modified from Haley et al. (1993).

northwest-southeast-trending tear faults, the Amity Fault located to the east and the Ikes Creek Fault on the west. The two tear faults are roughly parallel and are located approximately 10 miles (16 km) apart. The apparent dextral strike-slip movement on the two faults appears to have isolated the Arkansas Novaculite from the regional east-northeast structural trend.

Rigorous field examination was conducted along the leading edge of the Caney Fault to delineate the extent of the lower Stanley Formation. However, these field observations and measurements proved unsuccessful for estimating the amount of displacement along the fault. An attempt was made by Shell geologists to identify the stratigraphic members of the Stanley Formation based on the net-to-gross sand/shale ratio of outcrop exposures. Identification of the lower Stanley surface exposures helped to delineate any local, structurally high culminations along the thrust sheet. Field work and air photographic interpretation were used to map key beds within the Stanley, which assisted in the design of the 2D seismic program that Shell acquired.

During late 1983 and early 1984, Shell used its own geological crews to acquire 2D seismic lines over the Rattler Prospect (Figure 15). A total of seven (7) seismic lines (6 dip-oriented lines and 1 strike-oriented seismic line) were acquired over the Rattler Prospect. Some of the seismic data are poor quality due to inherent anisotropy associated with faulted and folded reflectors at depth. The best seismic image to resolve possible Arkansas Novaculite reflectors is shown on Line 84-506-2343 (Figure 16). On this seismic line, southward-dipping reflectors beginning at approximately shot point (SP) 480 illustrate a roughly conformable sequence from the Upper Stanley through the Atoka Formation. Resolution of continuous and mappable events in sediments older than upper

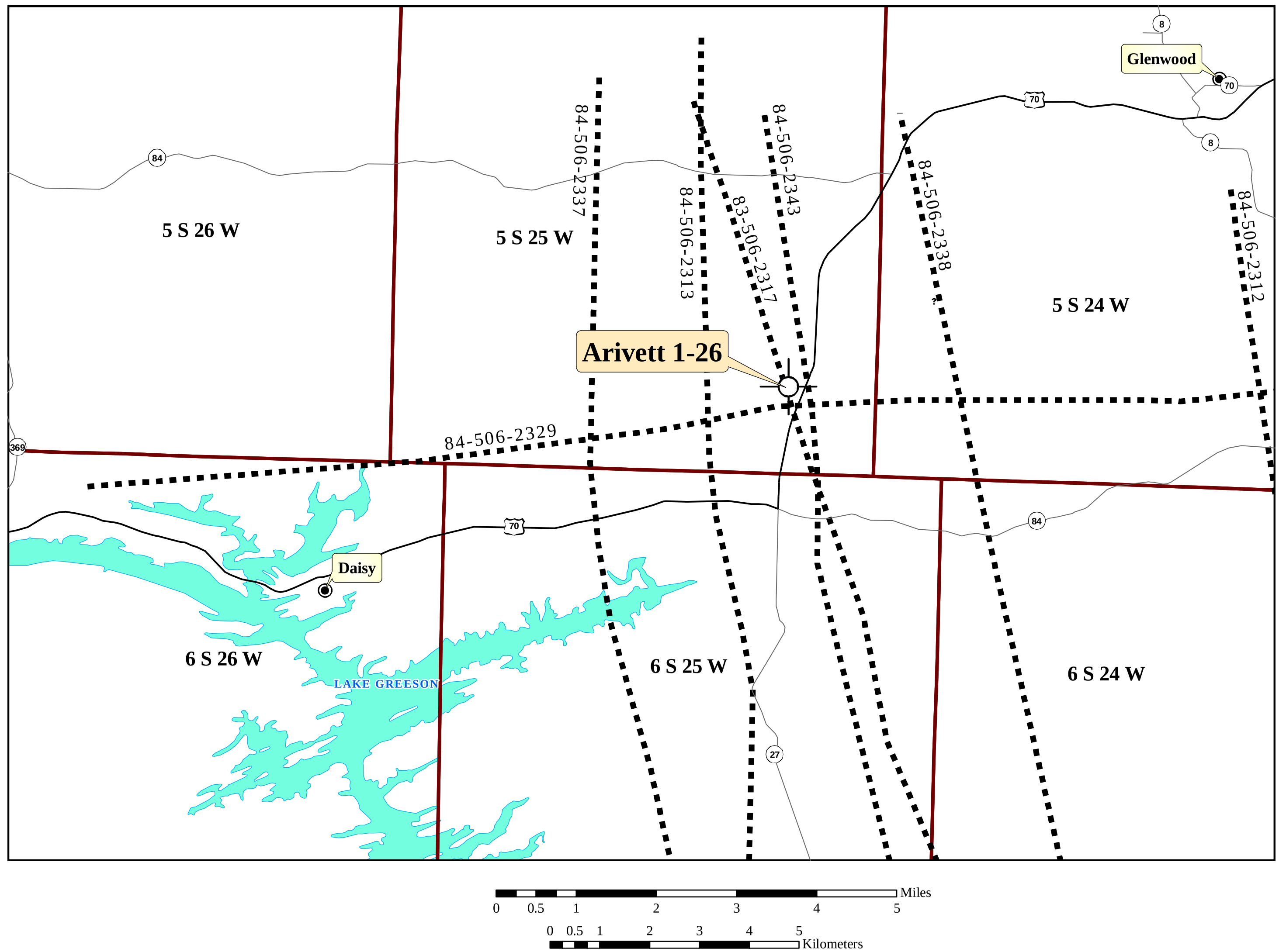
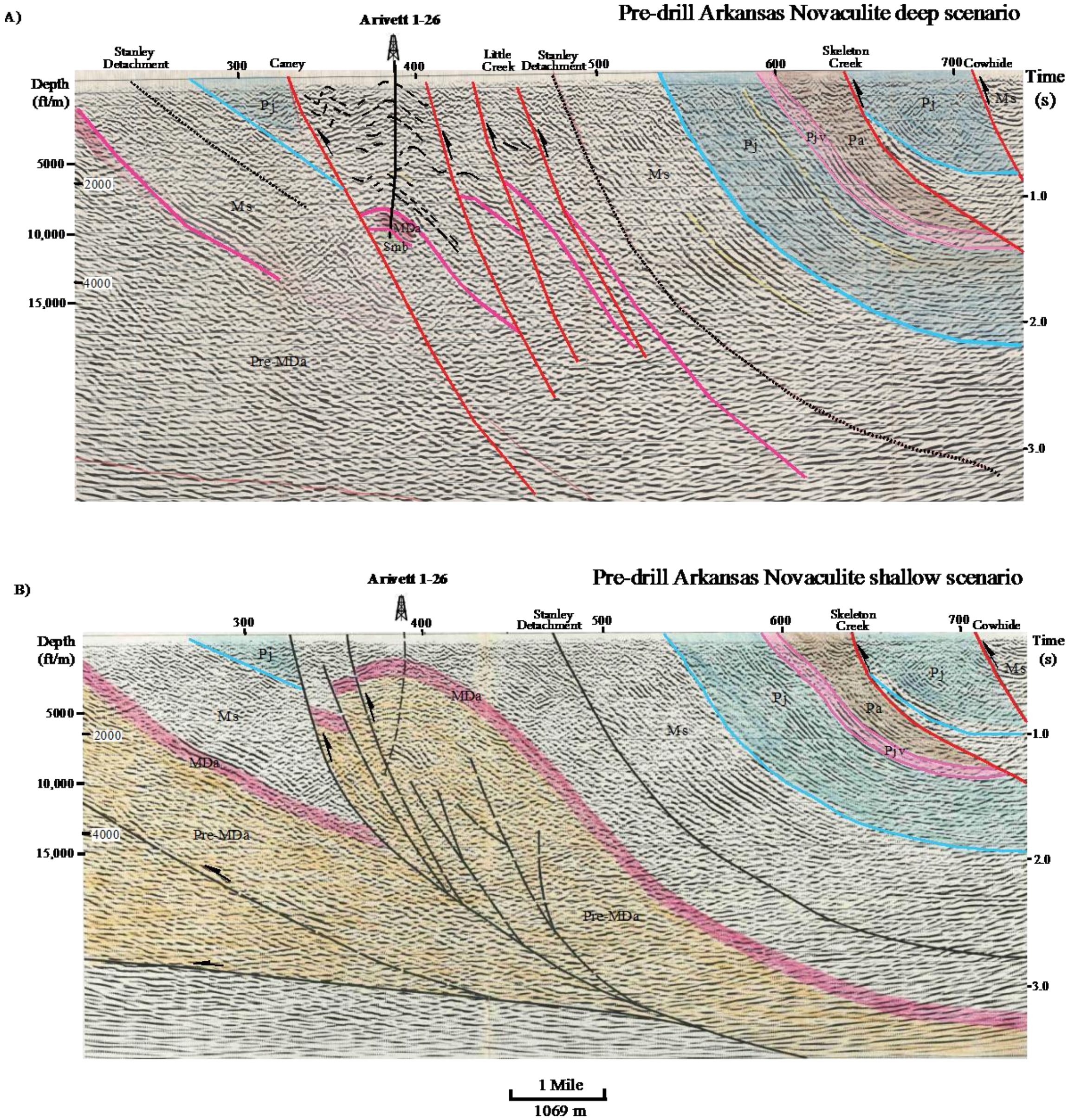


Figure 15. Location map of the seismic lines around the Rattler Prospect.

Stanley (detachment SP 480) is very poor on the 2D seismic profiles. One reason for these relations is the presence of tight folds in the subsurface sequence that contain numerous changes in bedding orientation from near horizontal to vertical. Seismic event correlations in these strata rely on the proper identification of relatively short lengths of a consistent event such as the strong magnitude on Line 84-506-2343 that the Arivett well targeted as the main objective to penetrate. Mapping the Arkansas Novaculite required connecting the few strong seismic reflections across larger areas of extremely poor to nonexistent data while keeping stratigraphic contacts concordant with younger strata in the area. Although it is still questionable what the patchy dip reflectors represent, this is a viable method for correlating stratigraphic sequences in this region of the thrust belt.

Due to the low quality of seismic data and the relative uncertainty of the interpretation for the seismic events, a range of interpretation scenarios was provided for a particular seismic line. Two interpretation scenarios are shown for the seismic line 84-506-2343 across the Rattler Prospect (Figure 16). A shallow interpretive scenario places the crest of the Arkansas Novaculite at approximately 1,800 ft (549 m) which corresponds to a thermal maturity level in the gas window (Figure 17). If the Arkansas Novaculite were found at this shallow level, then the targeted seismic amplitude objective would represent Ordovician Blakely or Crystal Mountain Sandstones. In the deep interpretive scenario, the top of the Arkansas Novaculite is represented by the seismically bright amplitude patch of coherent events at about 8,400 ft (2,560m). It is more difficult to interpret the strike-oriented seismic line (the only one is 84-506-2329) than the dip-oriented ones, because the former one was acquired across the entire surface of the highly folded and faulted Stanley Formation without any well-bedded younger formations



Pa = Atoka; Pjv = Johns Valley; Pj = Jackfork; Ms = Stanley; MDa = Arkansas Novaculite; Pre-MDa = Pre-Arkansas Novaculite; Smb = Missouri Mountain-Blaylock

Figure 16. Pre-drill interpretations for dip-oriented seismic line 84-506-2343. (A) Deep scenario interpretation places the top of the Arkansas Novaculite at the deep amplitude patch that is at about 8,400 ft (2,560 m). (B) Shallow scenario interpretation places the top of the Arkansas Novaculite at approximately 1,800 ft (549 m).

present to better constrain the interpretation (Figure 18). This structural complexity added challenges for making the correct stacking and migration of seismic event fragments. The culmination area was defined by interpreting discontinuous seismic reflections that showed the opposite dips on either side of a structural high. The exploration drill site was located over this seismic dip reversal and targeted the deep amplitude patch of events on the dip-oriented seismic profile (Figure 19).

Pre-Drill Charge Description

Good source rocks are present throughout much of the stratigraphic column in the Ouachita Mountains. The most likely source rock for the Arkansas Novaculite reservoir

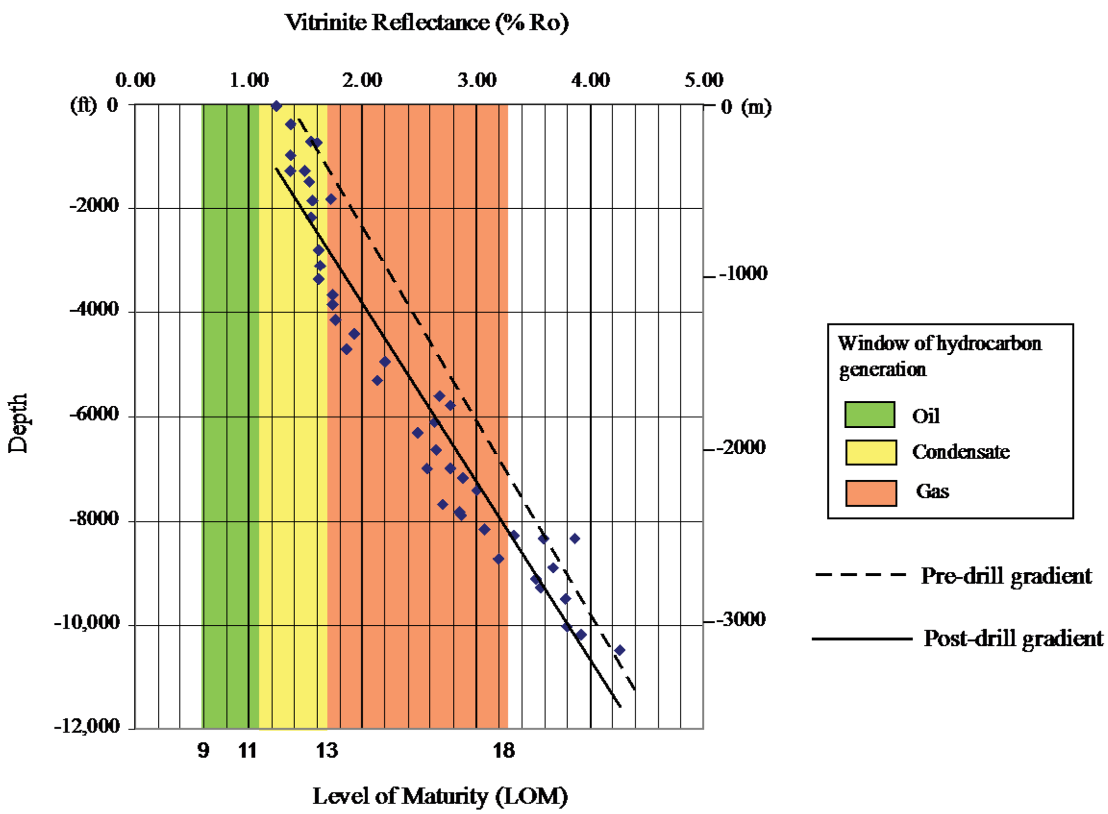


Figure 17. Thermal maturity profile of the Arivett 1-26 well.

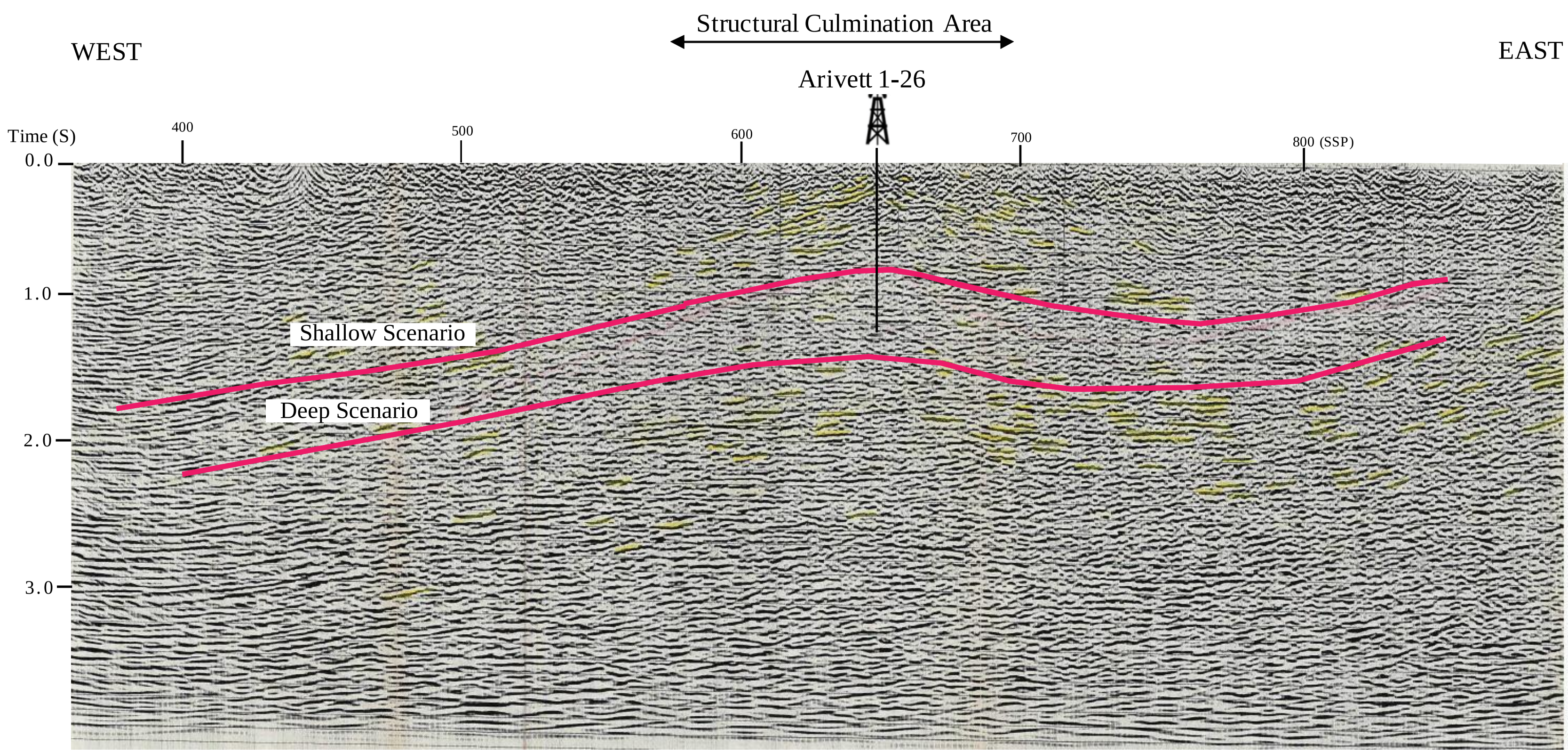
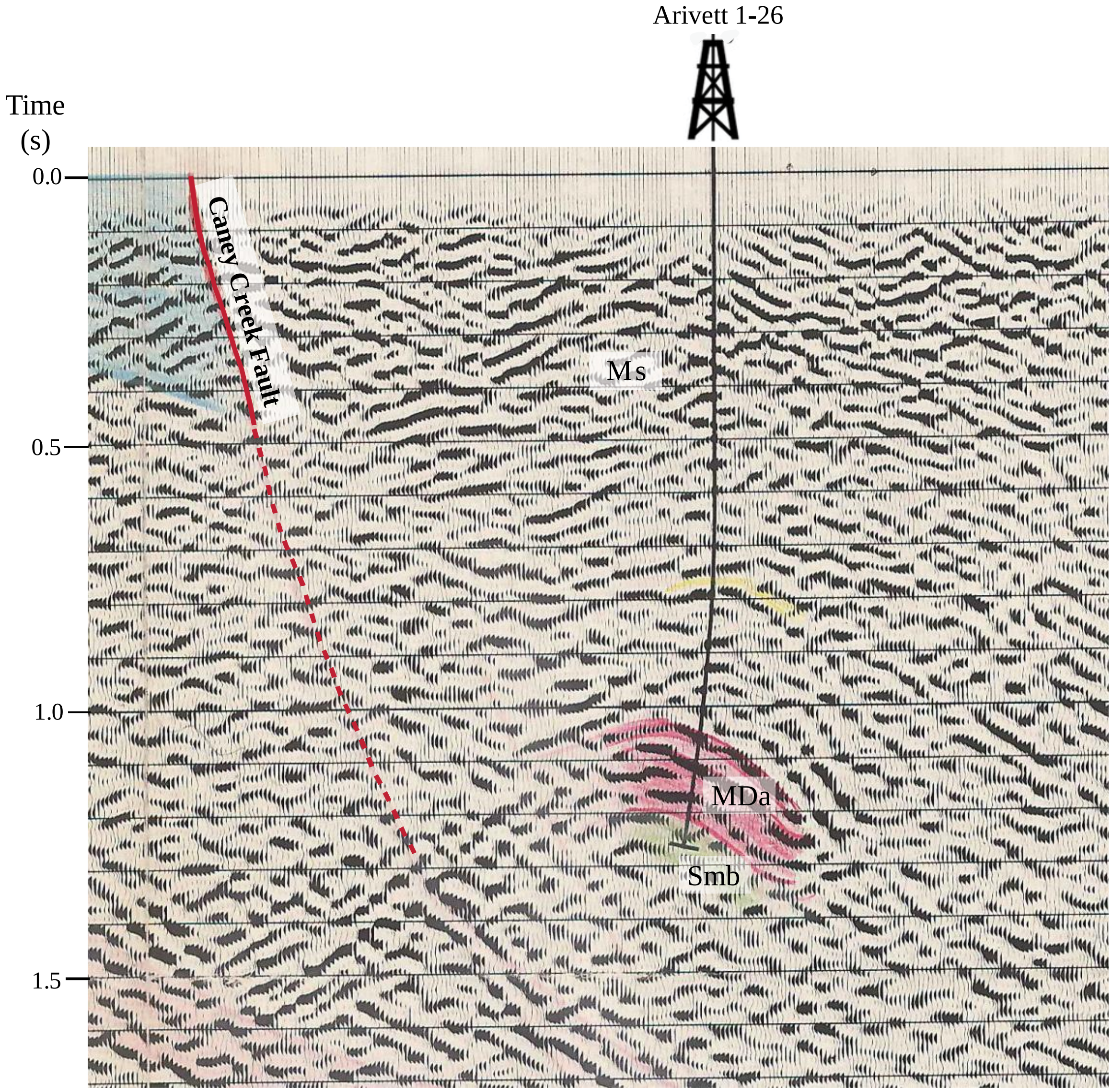


Figure 18. Pre-drill interpretations for strike-oriented seismic line 84-506-2329.



Ms = Stanley; MDa = Arkansas Novaculite; Smb = Missouri Mountain-Blaylock

Figure 19. Close-up of the bright amplitude patch of coherent events between 1 and 1.2 seconds in seismic line 84-506-2343.

was recognized to be the middle member of the same formation. The key uncertainty in exploring south of the Benton Uplift in the Ouachitas of Arkansas is determining the thermal maturity history and the timing of hydrocarbon expulsion with respect to the timing of the formation of structural traps (herein referred to as the charge/timing history).

In the Ouachitas of Oklahoma, the discovery of oil and gas in the Arkansas Novaculite indicates that the charge/timing history is favorable for the Arkansas Novaculite reservoirs. Devonian and older strata in the subsurface as well as in outcrop (e.g. Isom Springs Oil Field, outcrops at Potato Hills and Black Knob Ridge) possess thermal maturity levels in the oil window. However, in the Arkansas Ouachitas south of the Benton Uplift, the thermal maturities measured from outcrop and well cuttings are much higher, placing them in the gas window. A charge/timing model was regionally constructed across the Ouachitas in both states and applied to the Rattler Prospect using observations of present-day thermal maturities in the Ordovician Womble Shale. The maturities of the Womble Shale were measured from outcrops at Black Knob Ridge and Potato Hills in Oklahoma (Figure 20). Present-day R_o values ranging between 0.4 % (LOM of 7) at Black Knob Ridge and 0.5% (LOM of 8) at Potato Hills indicate that the Womble Shale had entered into the oil window before being thrusted toward a structurally higher position which ended further thermal maturation. It was realized prior to the drilling that shales from the Arkansas Novaculite and lower Stanley in Arkansas are at higher thermal maturity levels than the shales at Black Knob Ridge and Potato Hills in Oklahoma. Therefore there was concern that perhaps the charge/timing model based on the analysis of Oklahoma outcrops was overly optimistic for having a similar charge/timing model in Arkansas. Some Shell colleagues argued that since the higher reflectance measurements are present in Devonian and lower Mississippian outcrops that flank the late thermal anomaly associated with the Benton-Broken Bow uplifts, it may mask what might be otherwise a similar charge/timing story as observed in

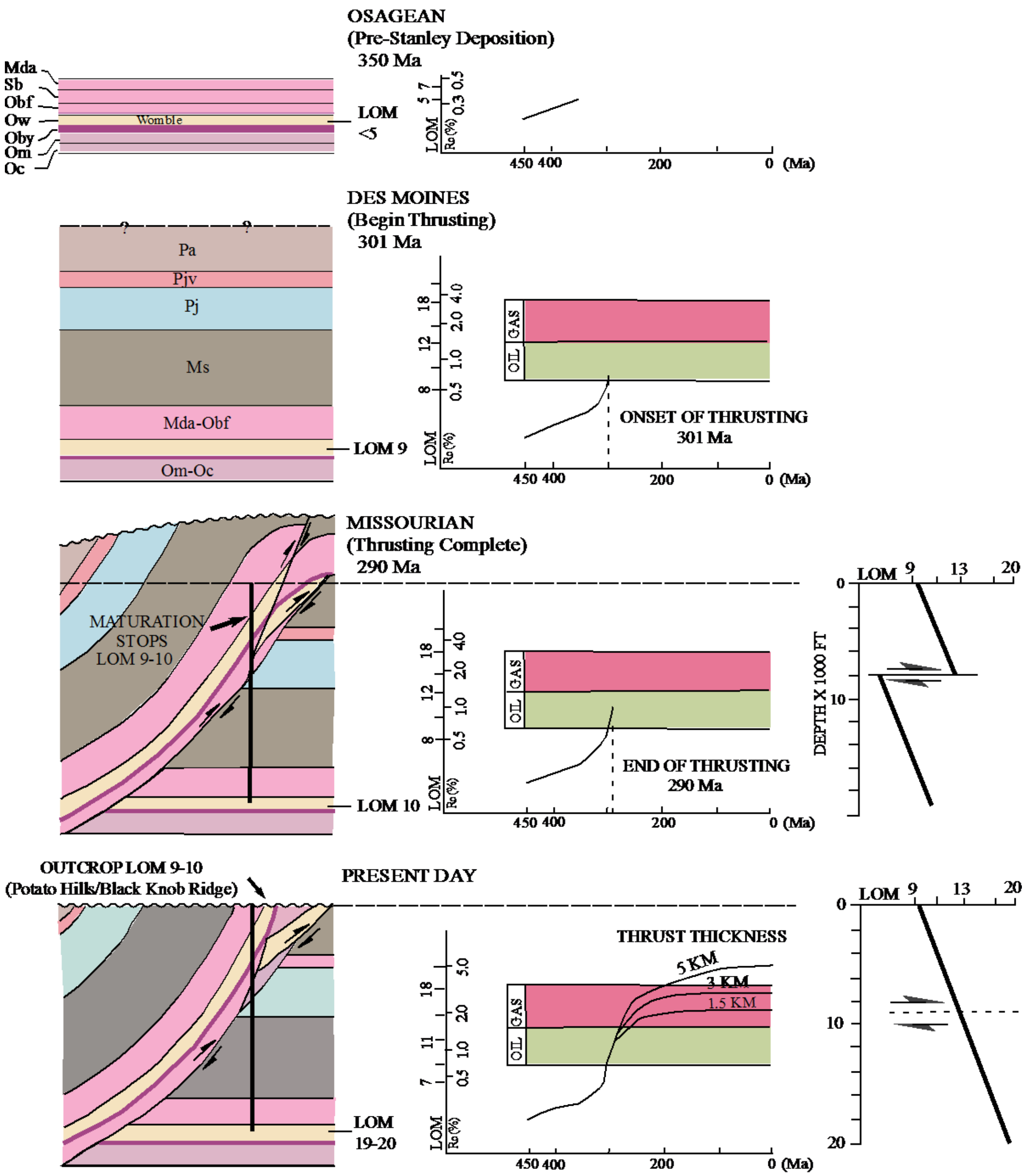


Figure 20. Pre-drill charge/timing model in the Arkansas Ouachitas. The Ordovician Womble Shale serves as a source rock in this model.

Oklahoma. R_o values measured from Mississippian/Devonian shale outcrops just north of the Rattler Prospect around the town of Glenwood, Arkansas range between 1.45 and 1.67% (LOM of 12.1 to 12.7). At the Rattler Prospect, R_o values from the Stanley Shale near the surface were measured in unweathered rock samples, reaching a value of 1.5% (LOM of 12) on average. These samples were obtained by collecting the cuttings from seismic shot holes over the prospect.

Because of the unknown depth to the Arkansas Novaculite at the Rattler Prospect, it was predicted that the rocks would have reached R_o of 3.32% (LOM of 18) at a depth of approximately 7,000 ft (2,133 m) (Figure 17). At shallower depths, such as the shallow scenario model of 3,000 ft (914 m), the thermal maturity of the Arkansas Novaculite could be within the condensate window. It is not uncommon to find gas fields at very high maturity levels, however, the charge/timing in these cases is probably different from the Rattler's. One such analogue is the Waveland Field located in the Arkoma Basin of Arkansas, which produces natural gas in the strata with R_o of 3.32% (LOM of 18) (Ratchford and Li, 2008). The clastic reservoir's porosity in this field is significantly reduced by cementation. Similarly, Shell tested the strong seismic amplitudes near 8,400 ft (2,560 m) at the Rattler Prospect believing that commercial gas might be present in a high thermal maturity regime.

Post-Drill Reservoir Results

The Arkansas Novaculite in the Arivett well comprises the same three members as described in outcrops at Caddo Gap, Arkansas (Zimmerman, 1984) (Figure 21). Reservoirs in the Arkansas Novaculite were less developed than expected in the pre-drill assessment. The upper member of the Arkansas Novaculite was predicted to contain an appreciable amount of calcium carbonate in the subsurface. The carbonate was thought to be leached and filled by the migrating (acidic) oil and subsequently the oil thermally cracked to gas. However, in the Arivett well only one carbonate-rich chert section was identified in this member, which was neither significantly leached nor filled with significant hydrocarbons. These observations are based on cuttings and core analysis in thin section photomicrographs, as well as evidence from the wireline log evaluation including the photoelectric log (Figure 22). Furthermore, analysis of air/mist drilling results is in effect a continuous flow check for hydrocarbons without having mudcake issues (see also Table 1).

In interpretation of the Arivett well, the photoelectric log provides a semi-quantitative estimate of the large amount of calcium carbonate present in the upper member of the Arkansas Novaculite. The photoelectric index (Pe) is a supplementary measurement by a density logging tool and records the absorption of low-energy gamma rays by rocks in units of barns per electron. The logged value is a direct function of the aggregate atomic number (Z) of the elements in the rocks, and therefore is a sensitive indicator of mineralogy. Based on petrographic information from core and cuttings and from analysis of nearby outcrops, the two dominant minerals in the Arkansas Novaculite of the Arivett well are quartz and calcite. The Pe values recorded in the Arivett borehole can be used to semi-quantitatively distinguish calcium carbonate-rich chert from the silica-rich chert. Pe values vary greatly between quartz of 1.81 barns/electron (yellow line) and calcite of 5.08 barns/electron (blue line). If an assumption is made that calcite and silica are the only two mineralogical components of the chert section of the Arkansas

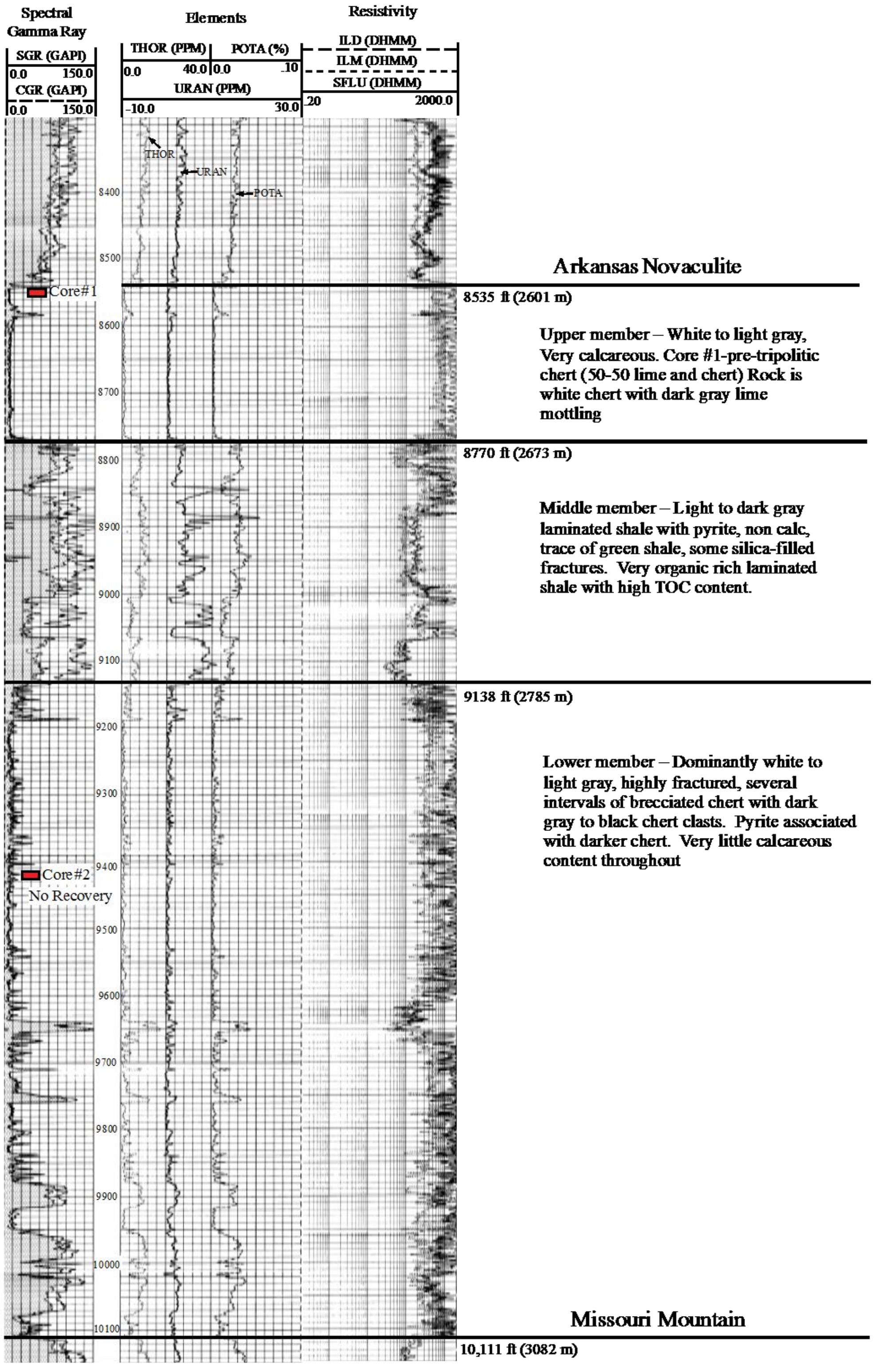


Figure 21. Wireline log suite and lithologic description of the Arkansas Novaculite in the Arivett 1-26 well.

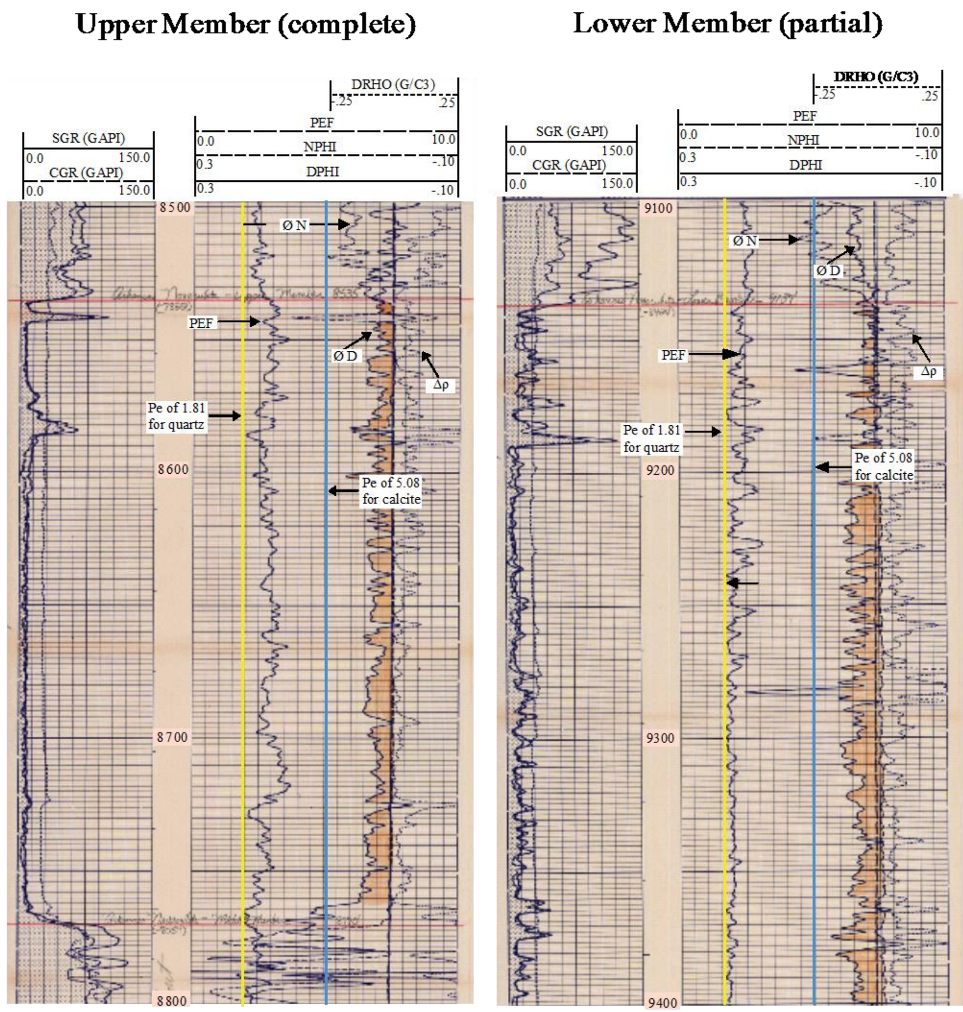


Figure 22. Photoelectric log for the Arkansas Novaculite in the Arivett 1-26 well. Calcium carbonate is present in the upper member indicated by high values and is almost absent in the lower member represented by low values.

Novaculite, then the Pe curve that moves 25-50% from the pure silica value (1.81 barns/electron) toward the pure calcium carbonate value (5.08 barns/electron) might represent a carbonate content of 25-50% in the chert. Indeed, the sub-regional outcrop observations also show that the calcium carbonate content of 25-50 % is common in the Upper Arkansas Novaculite, which are consistent with the qualitative estimate of calcium carbonate content based on the Pe log interpretation. By comparison, the lower member of the Arkansas Novaculite in the Arivett well contains an average carbonate content of less than 10% with some intervals near zero. This is also consistent with petrographic analysis of nearby outcrop samples.

The short four (4)-foot core taken from the upper member of the Arkansas Novaculite in the Arivett well (8,565-8,569 ft or 2,611-2,612 m) was evaluated to examine the type and distribution of calcium carbonate within the novaculite by petrographic point counting techniques in closely spaced thin sections (Figure 23). Calcium carbonate is distributed within the dark chert samples as small spherical blebs up to 4 mm in size. It is unknown what the original source of the carbonate nuclei are in the matrix of the novaculite. Similar distribution of carbonate blebs can be seen in the tripolitic novaculite of the upper member across the southeastern Cossatot Mountains. Outcrop exposures on this trend often show visual signs of carbonate leaching. The leached carbonate blebs leave holes that give the rock texture the appearance of pumice or scoria. Photomicrographs of thin sections taken from the short core interval in the Arivett well are shown in Appendix 2. Small carbonate grains and widely disseminated individual carbonate crystals are commonly present in thin sections. Radiolarians and sponge spicules were identified as part of the chert matrix. Fractures can also be seen in the novaculite filled with calcite, quartz and hydrocarbon (pyrobitumen). A contrasting comparison can be made between an unleached carbonate-rich novaculite in the Arivett core (8,565 ft or 2,611 m) with a carbonate leached tripolitic novaculite sample taken from a roadside outcrop in Section 8, T5S, R24W (Figure 24). Poor reservoir development may have been a factor in failure of significant hydrocarbon

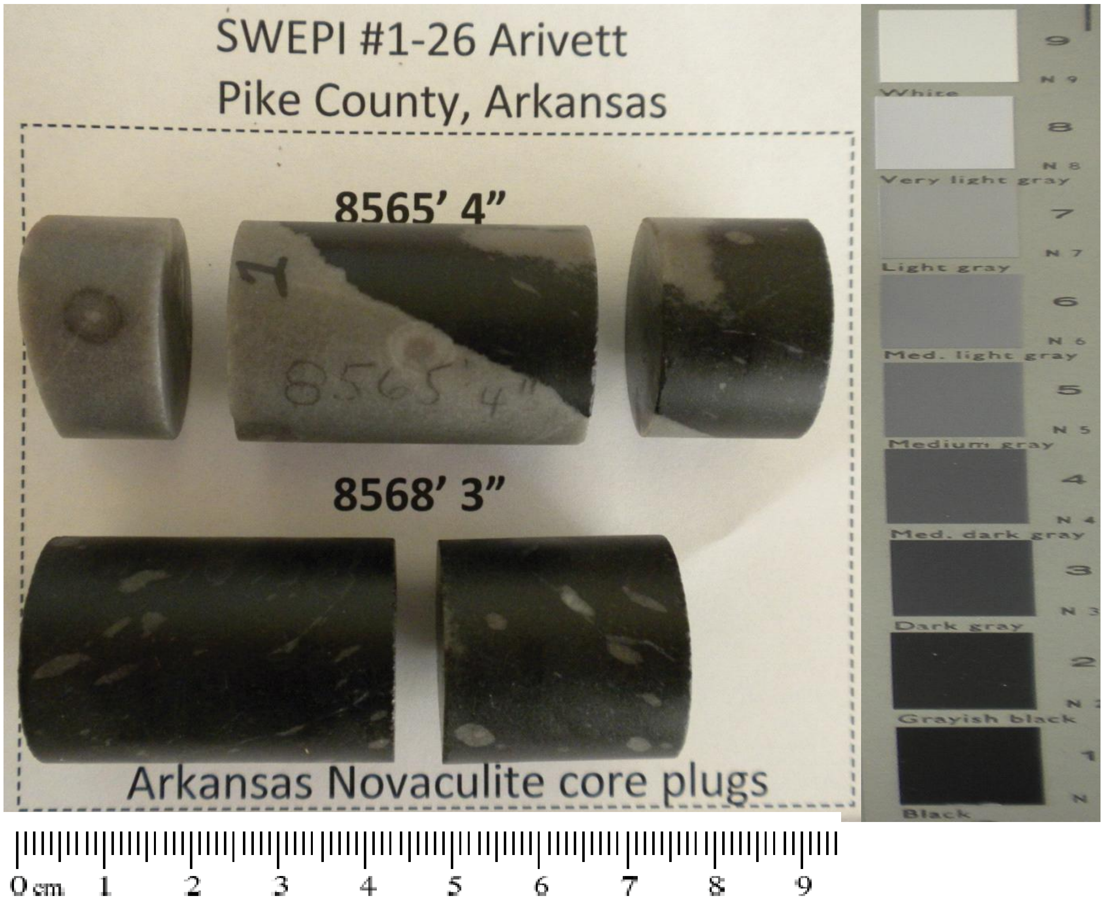
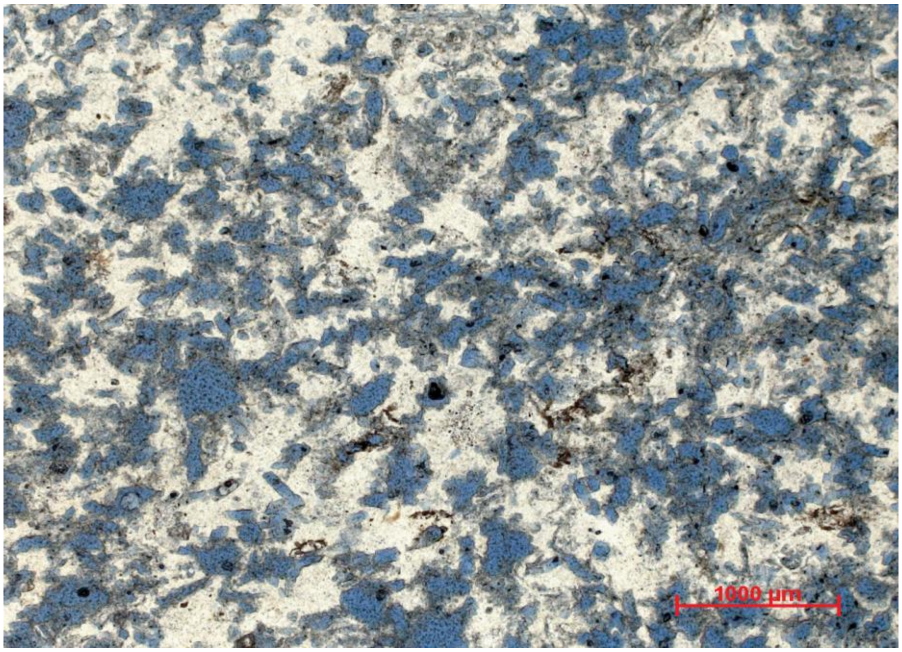


Figure 23. Two core plugs of the Arkansas Novaculite in the Arivett No. 1-26 well.

accumulation in the Rattler structural trap. It is evident from the photoelectric log and thin sections that carbonate is present, but not significantly leached and therefore did not provide much matrix porosity. In addition, fracture porosity is likely more limited overall in the complete Arkansas Novaculite sequence. It is somewhat ironic that given the structurally complex folding and faulting in the Ouachitas, the Arivett wellbore penetrated a complete section of Arkansas Novaculite containing flat or low bedding dips, A)



B)

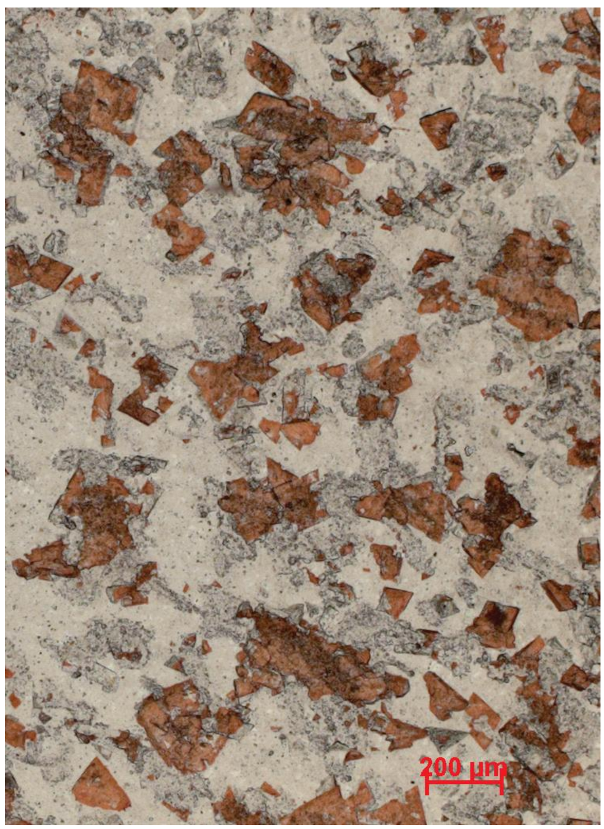


Figure 24. Thin sections of the upper Arkansas Novaculite. (A) A carbonate-leached tripolitic chert sample taken from a road outcrop in Sec. 8-T5S-R24W. (B) An unleached carbonate-rich chert from a core plug at 8,565 ft (2,611 m) in the Arivett No. 1-26 well.

which is relatively unfaulted. These characteristics have not been observed in many well bores where the Arkansas Novaculite was drilled. Most novaculite intervals drilled in Arkansas have significant folding and fracturing which typically enhances reservoir development to form a commercial reservoir (Morrison, 1982; Reed and Strickler, 1990). Stanley sands were encountered in the Arivett well, but relatively little porosity was identified.

Post-Drill Trap and Seal Results

The results of the Arivett well test at the Rattler Prospect reveal that the Arkansas Novaculite was penetrated at a depth that is associated with the strong seismic amplitude (Figures 16 and 19). The pre-drill deep scenario for the Arkansas Novaculite was penetrated in the Arivett well. In fact, the Arivett well penetrated a complete section of the Arkansas Novaculite which is stratigraphically upright, relatively flat- lying and unfaulted (Figure 21). The dipmeter log indicates that the overall average dip of the Arkansas Novaculite is about 1^{o} to the southeast (Figure 25). Consistent dip patterns are common to the upper member while the shaley middle member shows small-scale chaotic folding and wide-ranging dip patterns. Rapid dip changes in the middle member are most likely due to bedding plane slippage along thin beds with small fault propagation and tight folding. Such small-scale folding and faulting can be seen in the outcrops but when viewed at a large-scale, such as in air photographic images, then these small-scale features are difficult to discern (Zimmerman, 1984; Allen, 1991a).

A structural cross-section was made along the dip-oriented seismic line 84-506-2343 over the Rattler Prospect (Figure 26). The data used for constructing the cross-

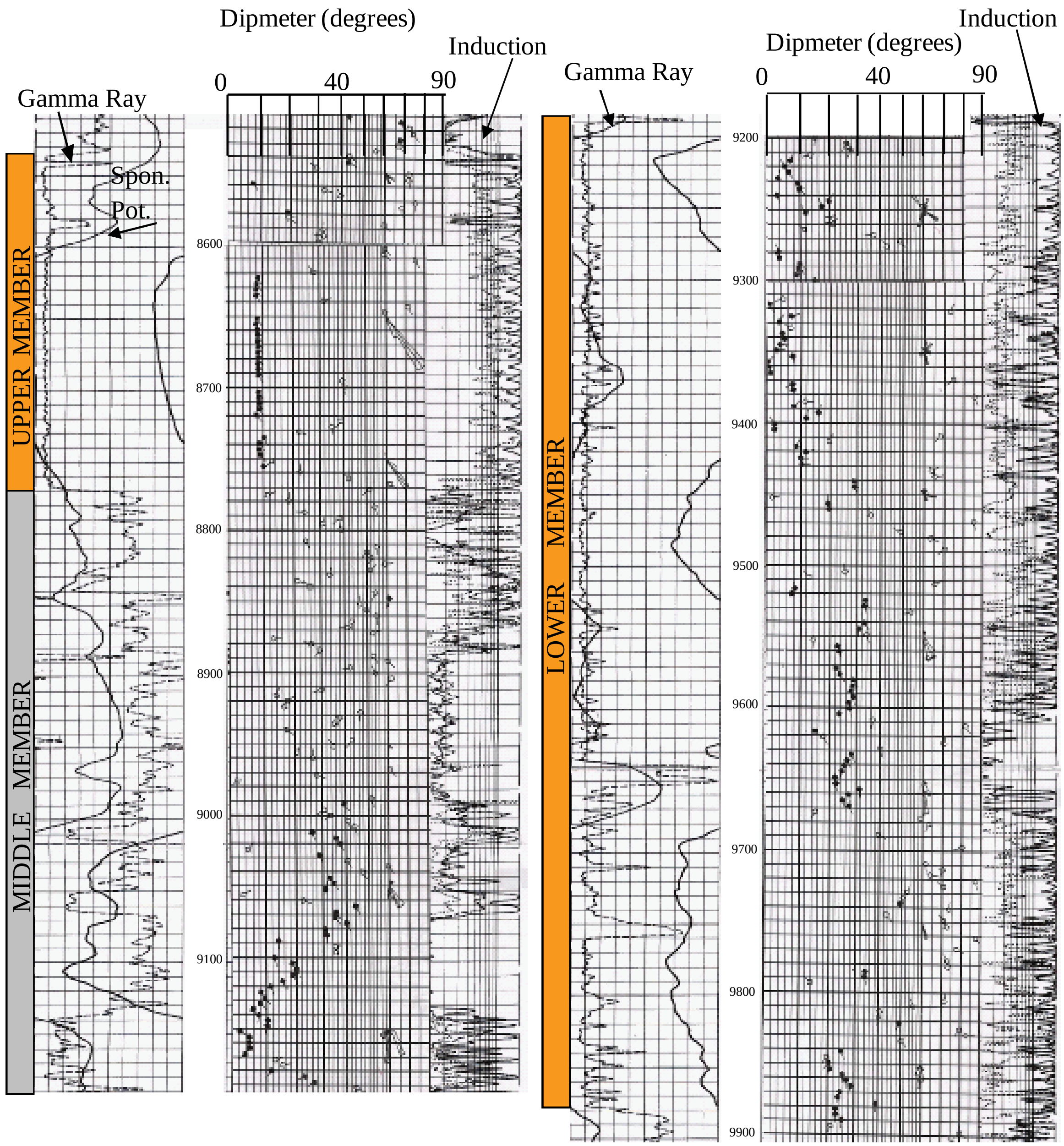


Figure 25. Dipmeter log of the Arkansas Novaculite in the Arivett No. 1-26 well.

section includes the surface geology, seismic data, and borehole data interpreted from the Arivett well. Although various data constrained the interpretation of the cross-section, rapid changes in geology away from the well control and poor seismic reflection profiles allowed for multiple interpretations of the cross-section. The pre-drill interpretation implied that the Arivett well would spud in the sandy section of the Stanley Formation and drill results proved this prediction to be accurate. However, it appeared that the sandy package was identified as the upper Stanley member rather than the lower member. Gross interpretation of the well lithology from the Arivett well in descending order is that of the upper sandy Stanley, middle shaley Stanley, lower Stanley including the Hatton Tuff and Hot Springs Sandstone, all three members of the Arkansas Novaculite, Missouri Mountain Shale and Blaylock Sandstone.

The Arivett well encountered seven zones that produced small methane gas shows (Table 1). Three zones were in the Stanley Formation, three in the Arkansas Novaculite and one gas show in the Missouri Mountain Shale. In the Arkansas Novaculite, small amounts of the thermally dead oil residues or anthraxolite were commonly found in fractures and leached carbonate micropores (Appendix 2). This indicates that some oil has migrated through the Arkansas Novaculite but never accumulated.

Post-Drill Charge Results

The hydrocarbon charge was predicted to be primarily sourced from the shaley middle member of the Arkansas Novaculite that is juxtaposed with the reservoir rock in the upper member as well as potential reservoir rock in the lower novaculite member. The middle member of the Arkansas Novaculite in the Arivett well is approximately 368 ft (112 m) thick and contains low structural dips. It was expected to be a good source rock before drilling and this assertion is supported by organic richness values (up to 4% TOC not corrected for high thermal maturity) measured from cuttings collected every 10

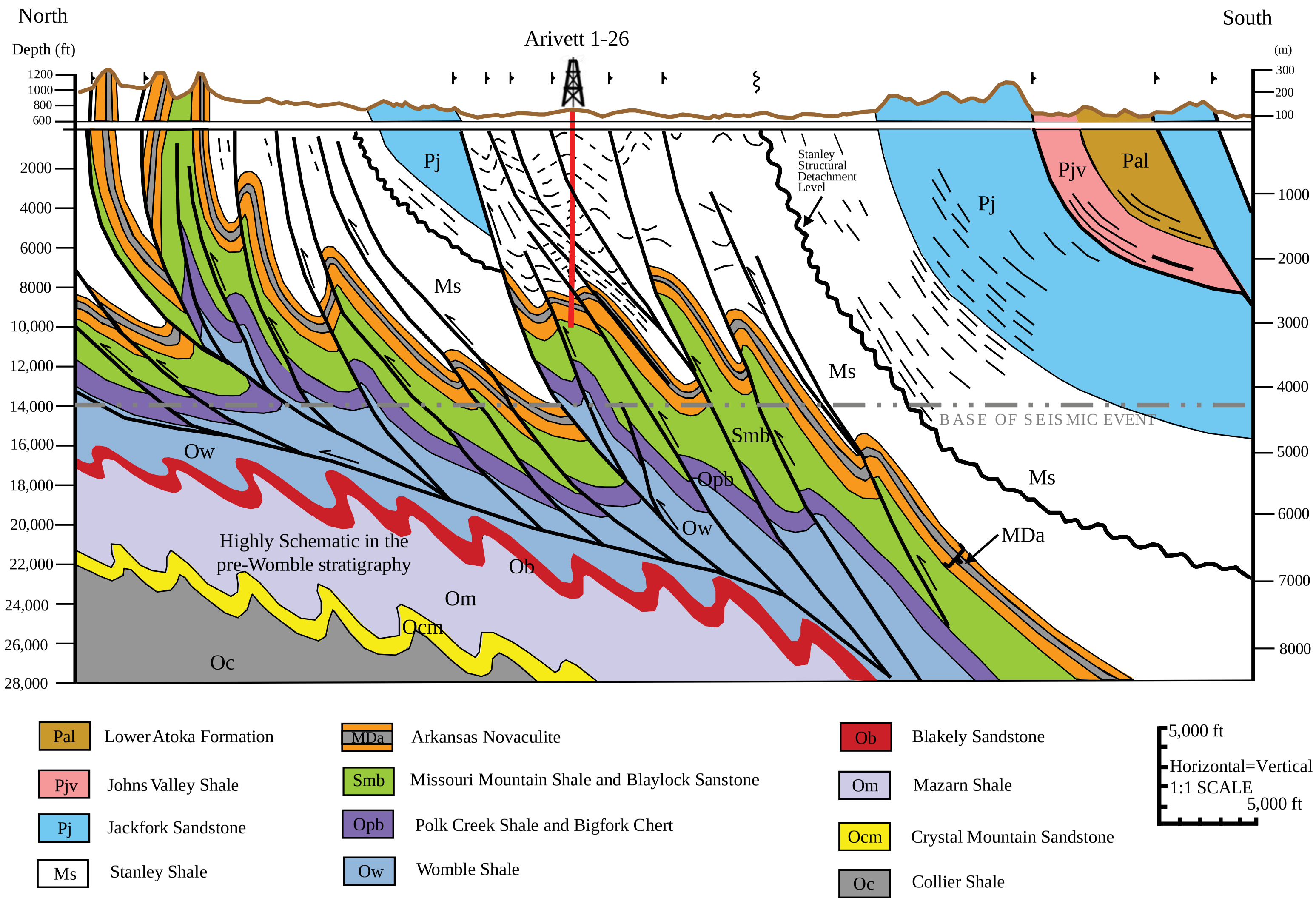


Figure 26. Structural cross section along seismic line 84-506-2343 over the Rattler Prospect.

ft (3 m) in the well (Figure 27).

The organic richness within the middle member can also be calculated from the natural gamma ray log (Figure 28). The measured TOC values are compared with the three element curves of Uranium, Thorium and Potassium on the gamma ray log. Increases in Uranium levels are frequently associated with the presence of organic matter (Adams and Weaver, 1958; Fertl and Rieke, 1980; Lüning and Kolonic, 2003). TOC values from ditch cuttings of the Arivett well correlated well with the Uranium values. Other factors also affect the correlative U/TOC ratios in black shales such as the primary uranium content of the water body, carbonate content and sedimentation rate (Lüning and Kolonic, 2003). With respect to the thermal maturity of the strata, the maturity gradient predicted in the pre-drill estimate closely matches the post-drill results in the Arivett well (Figure 17). The reflectance profile indicates that the Arkansas Novaculite is thermally over mature. If the Arkansas Novaculite would have been penetrated at a shallower depth than 7,000 ft (2,134 m), then the maturity level of the source rock and reservoirs would have likely been in the dry gas window.

Charge/Timing Modeling

Results after drilling three exploration wells in the Arkansas portion of the Ouachita Mountains indicate that the Carboniferous sediments deposited south of the Benton Uplift in Arkansas are thicker and/or more tectonically stacked than those modeled before drilling. This effect of overburden thickness is the major factor that resulted in failure of commercial hydrocarbon discovery in the Arkansas Ouachitas. However, a cooler thermal environment existed in the Oklahoma Ouachitas, which

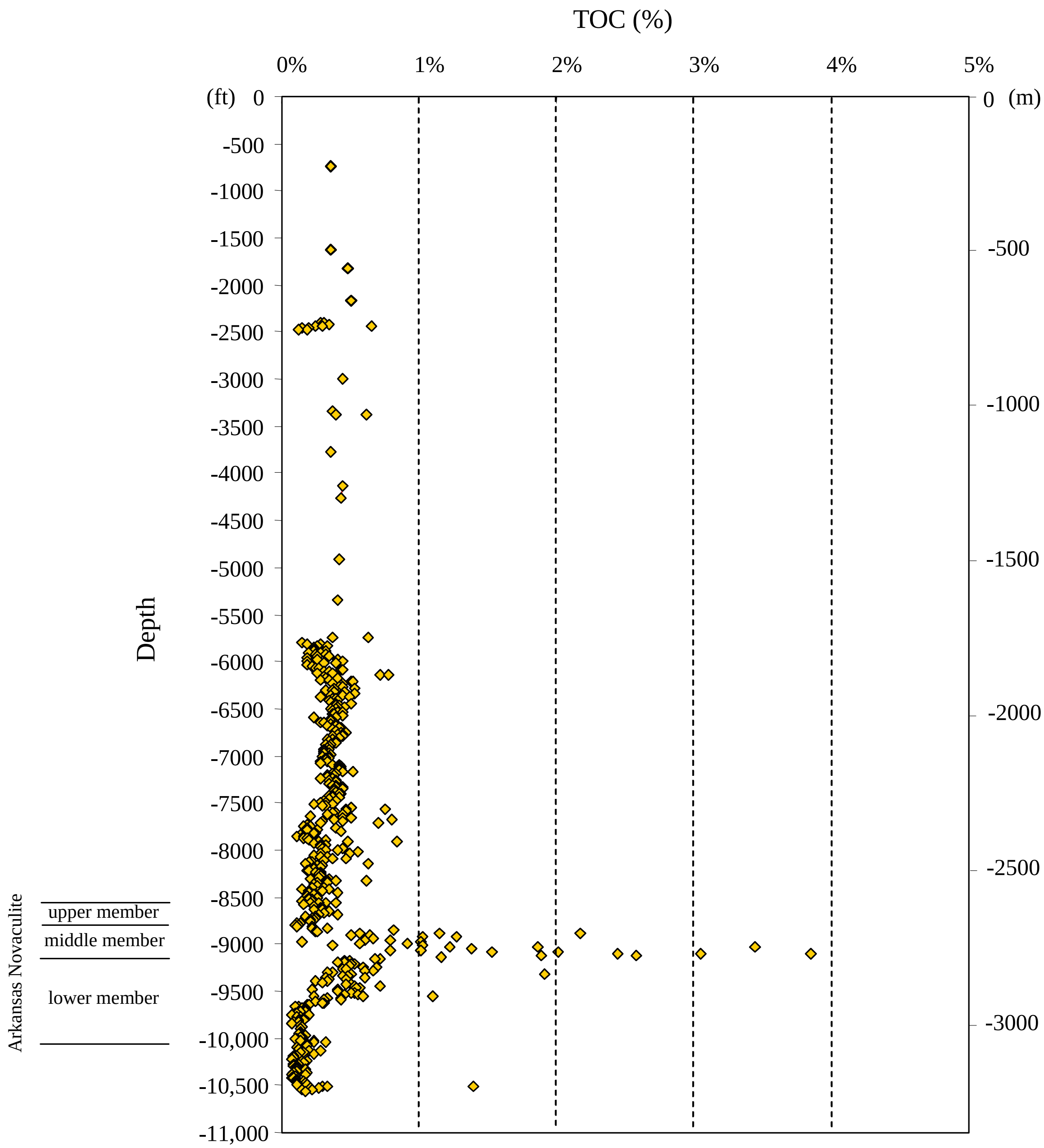


Figure 27. Total organic carbon content in the Arivett No. 1-26 well. Maximum values occur in the middle Arkansas Novaculite shale.

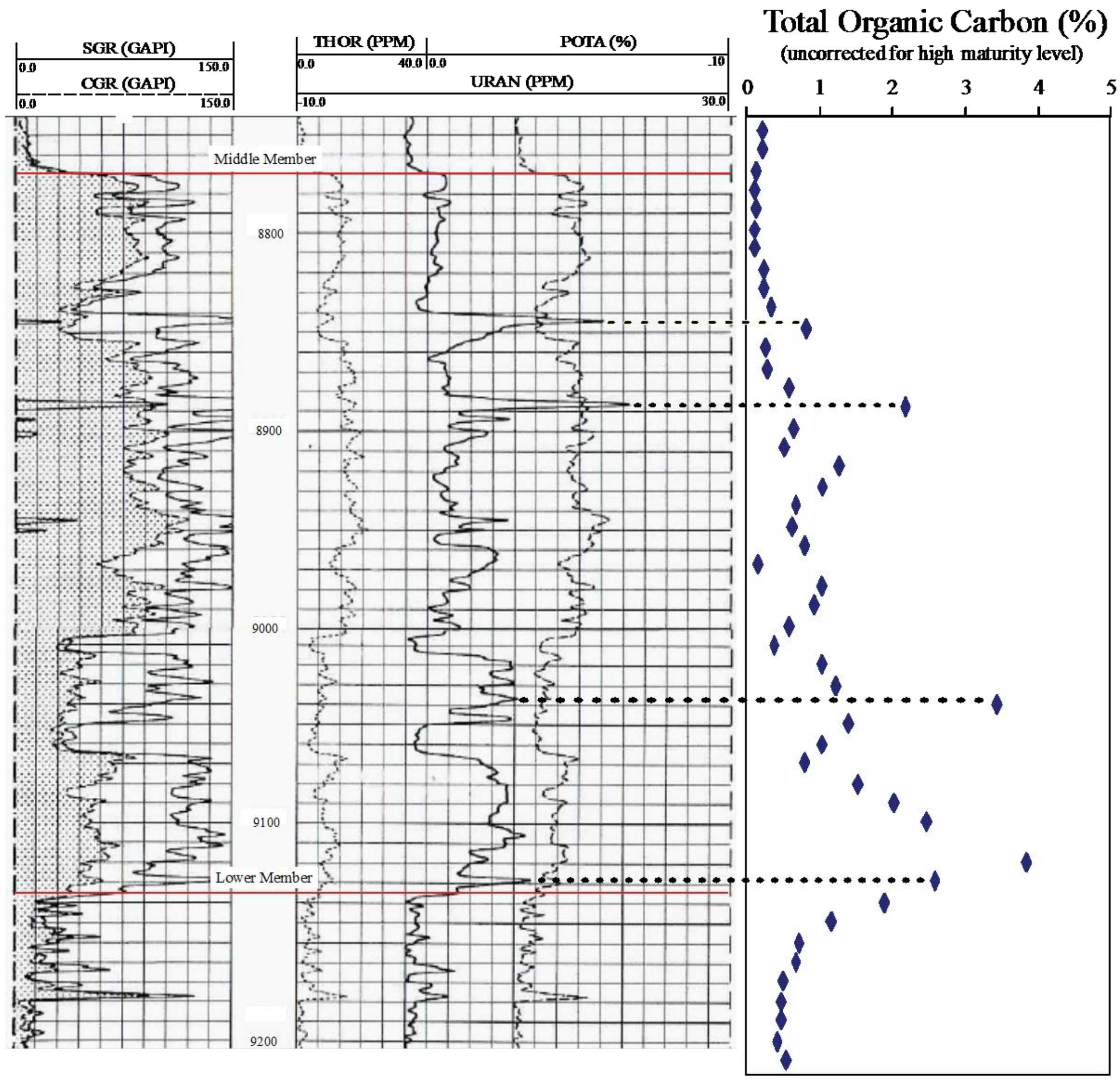


Figure 28. Total organic richness of the Middle Arkansas Novaculite calculated from the spectral gamma ray log of the Arivett No. 1-26 well.

facilitated the source rock of the Arkansas Novaculite to expel and retain hydrocarbons in the structural traps. The thick Carboniferous sequence in Arkansas appears to have buried the Arkansas Novaculite at such great depth that oil generation likely commenced before thrusting occurred. By the time the traps were formed in the present positions, little potential was left for the remaining hydrocarbons to migrate into structural traps.

The charge/timing model was conducted by incorporating the results of all three Shell wells drilled south of the Benton Uplift and has not been updated for this report (Figure 29). The software used for this model was a Shell Internal Temperature, Time Maturation (TTM) program. Four types of input data were required for the TTM modeling program: stratigraphic tops and ages, surface temperature (59^{o}F or 15 ^{o}C), geothermal gradient (1.3^{o}F/100 ft or 2.4 ^{o}C/ 100m), and thermal conductivity of rock units. Erosional events are also considered in the TTM program with high initial rates that appreciably slow down as relief is reduced (Schumm, 1963). The thrust timing used in the model was between 301 to 290 Ma during the Desmoinesian time. Thrusting ceased sometime before the end of the Desmoinesian as evidenced by the deposition of undeformed shallow water clastics and limestones of Desmoinian age just south of outcrop exposures in the Ouachita Mountains of Arkansas. For the purposes of modeling, the amount of thrust-emplaced overburden was distributed evenly over the period of 11 million years.

The model indicates that the middle member of the Arkansas Novaculite at the Rattler Prospect attained a R_o of 2% (LOM of 14.5) before the thrusting event (Figure 29). When correlated with the associated source rock kinetics, it is estimated that less than 5% of the total hydrocarbons still remained in the source rock prior to thrusting. As the thrusting ensued, the thermal maturation process continued until 291 Ma. The present-day R_o of the Rattler model is 3.3% (LOM of 17.7) and less than 2% of hydrocarbons are left in the source rock. As a result, the model predicts that the Arkansas Novaculite

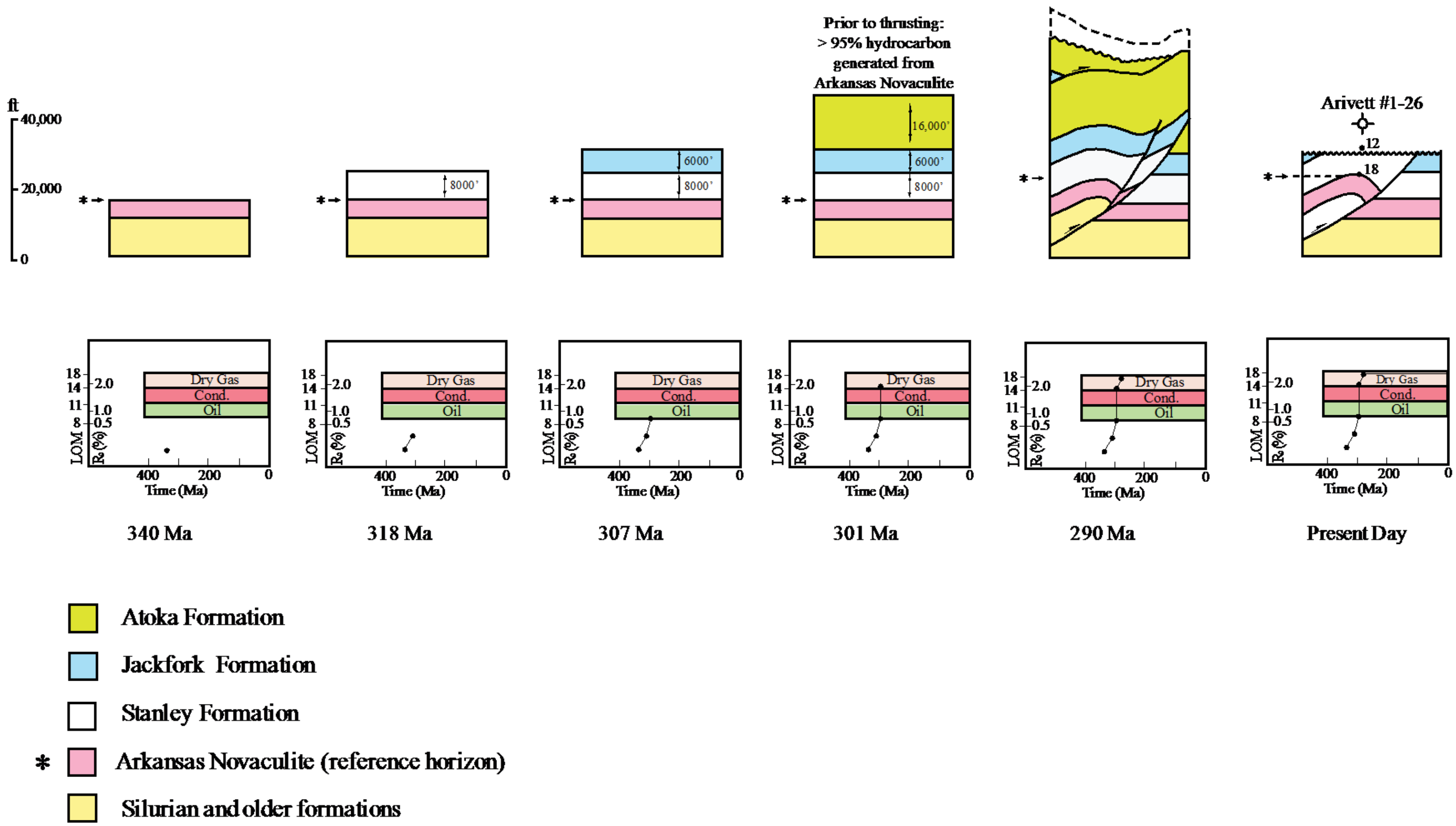


Figure 29. Charge/timing model for the Arkansas Novaculite as a source rock, south of the Benton Uplift.

reservoirs at the Rattler Prospect hold only small chances of being charged by the middle member and the older source rocks are less likely to provide hydrocarbon charge to prospective reservoirs.

Had the Arkansas Novaculite been encountered at a shallower depth in the Rattler Prospect, then there would have been a higher probability for hydrocarbons to fill prospective reservoirs. For example, if the Arkansas Novaculite was present between 2,000 and 3,000 ft (610-914 m), then the hydrocarbon type encountered would have been gas with R_o range between 1.8 and 2.3% (LOM 13 to 15).

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Appendix 1. Location information of the 23 wells that are studied for this report from the Ouachita Mountains of Oklahoma and Arkansas.

Name	API	Section	Township	Range	County	State	TD (ft)
Four (4) wells in the Benton-Broken Bow uplifts							
Viersen-Cochran Weyerhaeuser #1-25	35-089-20005	25	5S	23E	McCurtain	OK	10,019
A. L. Kitsekman #2	03-119-00014	2	1S	13W	Pulaski	AR	4,080
Ambassador Montgomery #1-21	03-119-00003	21	2N	10W	Pulaski	AR	8,005
Shell International Paper #1-21	03-059-10004	21	4S	20W	Hot Spring	AR	7,868
Nineteen (19) wells outside the Benton-Broken Bow uplifts							
Pray Wyrick #1-26	35-005-20050	26	1N	14E	Atoka	OK	12,088
Callery Dorer #1	35-079-30006	26	3N	25E	Leflore	OK	6,543
Callery Fields #1	03-113-00001	28	1S	32W	Polk	AR	4,970
El Paso Cheesman #1	03-127-00015	22	3N	28W	Scott	AR	11,680
American Quasar Cabe #1-11	35-127-20007	11	2N	20E	Pushmataha	OK	15,514
Sheraton Kyle No. 1-29	03-059-10003	29	4S	22W	Hot Spring	AR	4,546
Sheraton Bean No. 1-15	03-019-10002	15	5S	23W	Clark	AR	2,900
Shell Williams #32-27	35-077-20217	27	5N	19E	Latimer	OK	16,172
Shell Arivett #1-26	03-109-10001	26	5S	25W	Pike	AR	10,570
Shell Rex Timber #1-9	03-019-10003	9	7S	20W	Clark	AR	6,765
Shell Retherford #1-24	35-077-20212	24	4N	17E	Latimer	OK	14,164
Mobile Gilley #1	35-127-20001	22	3S	16E	Pushmataha	OK	11,143
Potter Ellis #1	35-023-00002	31	5S	16E	Choctaw	OK	12,088
Sinclair Douglas #1	03-057-10004	27	12S	26W	Hempstead	AR	13,778
Sinclair Reneau #1	35-077-00045	32	3N	20E	Latimer	OK	7,097
Sunray Dierks #1	35-127-00019	16	4S	20E	Pushmataha	OK	6,605
Westheimer & Neustadt Houk #1	35-095-20237	35	7S	5E	Marshall	OK	
Gulf Hembree #1	03-083-00041	13	8N	26W	Logan	AR	8,078
Arkansas-Louisiana Weeks #1	03-083-00008	4	7N	27W	Logan	AR	10,250

Appendix 2. Photomicrographs of thin sections of well cuttings from the Stanley Formation and whole cores of the Arkansas Novaculite in the Arivett 1-26 well.

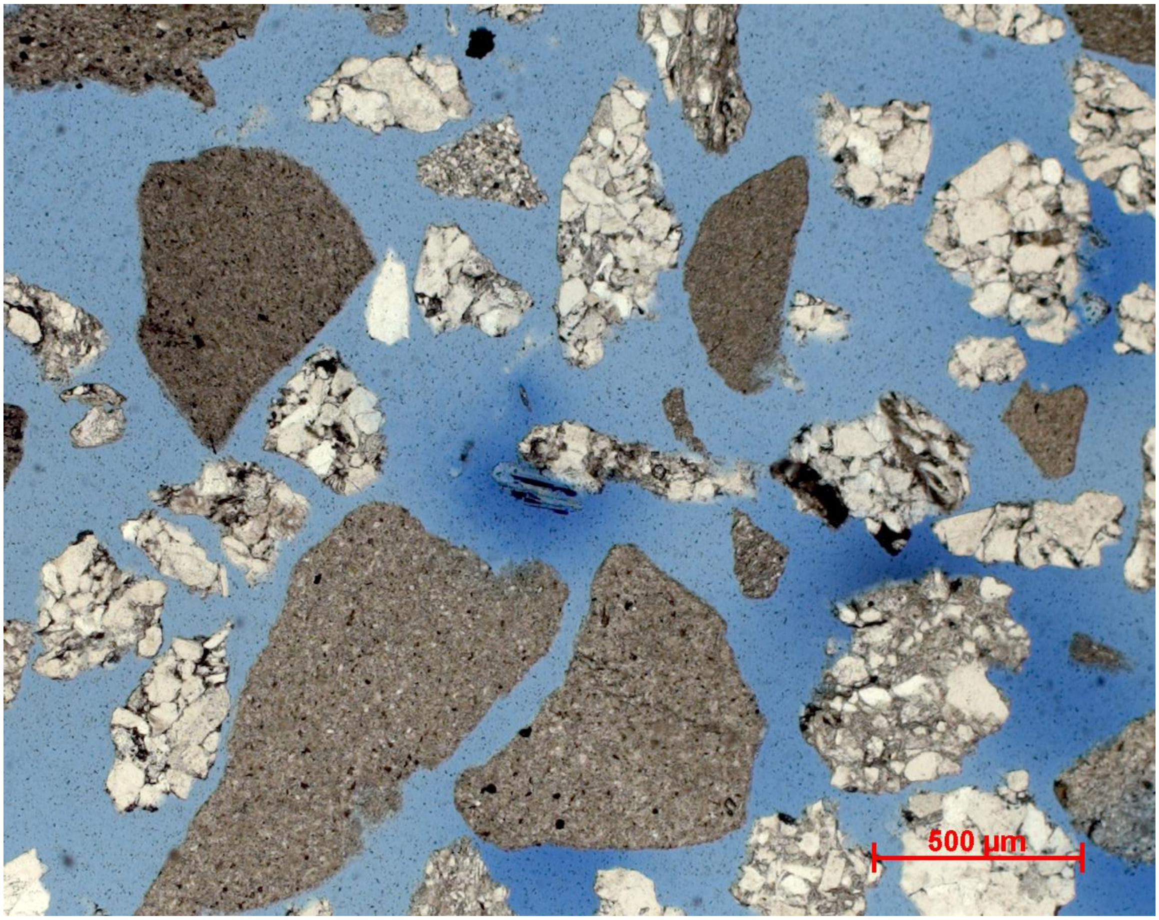


Figure 1. Photomicrograph of thin section of well cuttings in the Mississippian Stanley Formation at 6,650-60 ft (2,027-30 m) (plane polarization). Dark colored cuttings are welded tuff. This may be called the Hatton Tuff in outcrop. Other cuttings are fine- to medium-grained sandstones.

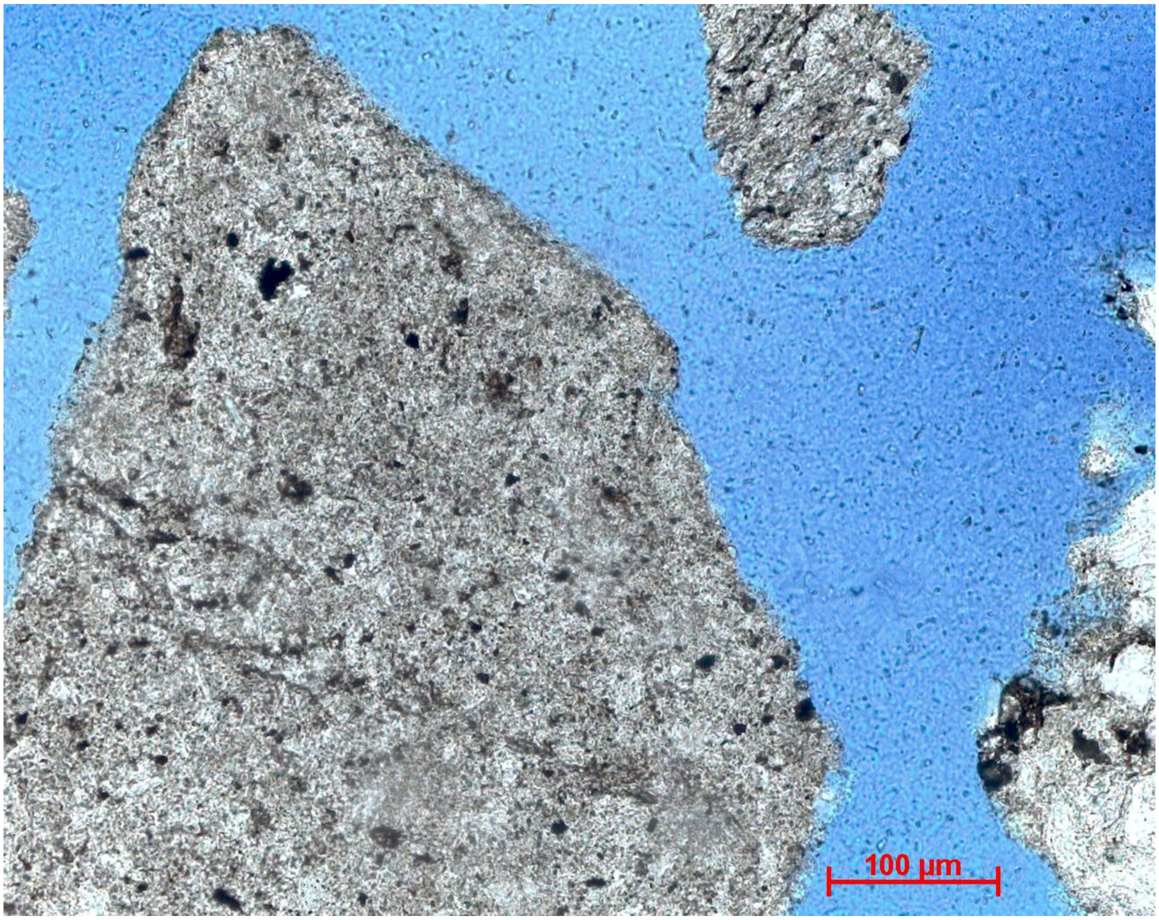


Figure 2. Photomicrograph of thin section of well cuttings in the Mississippian Stanley Formation at 6,650-60 ft (2,027-30 m) (plane polarization). Closeup of the welded tuffs in Figure 1.

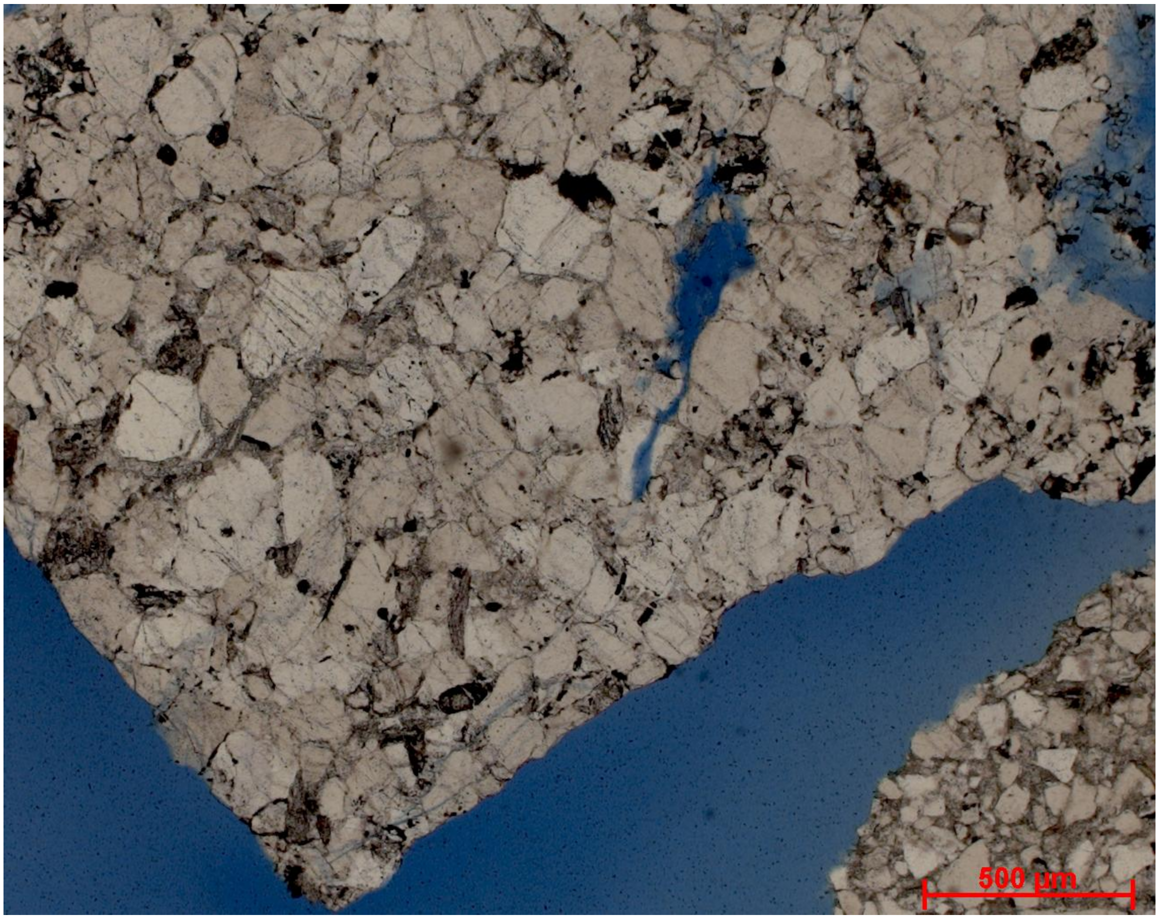


Figure 3. Photomicrograph of thin section of well cuttings in the Mississippian Stanley Formation at 7,240-50 ft (2,207-10 m) (plane polarization). Highly compacted fine- to medium- and medium- to coarse-grained sandstones. Moderate quartz overgrowth and calcite cementation. Mica (?) in the ground mass with high birefringence.

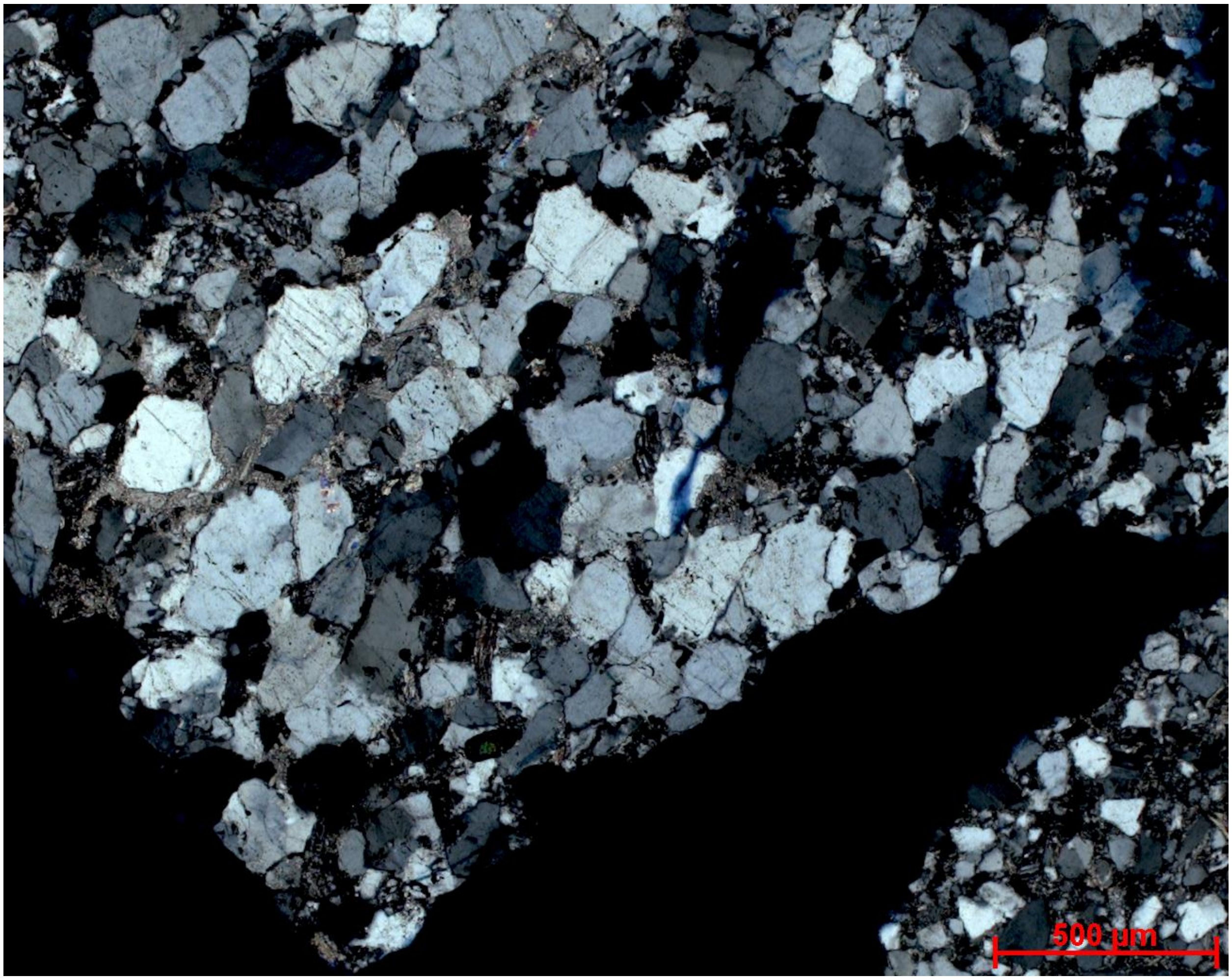


Figure 4. Photomicrograph of thin section of well cuttings in the Mississippian Stanley Formation at 7,240-50 ft (2,207-10 m) (cross polarization).

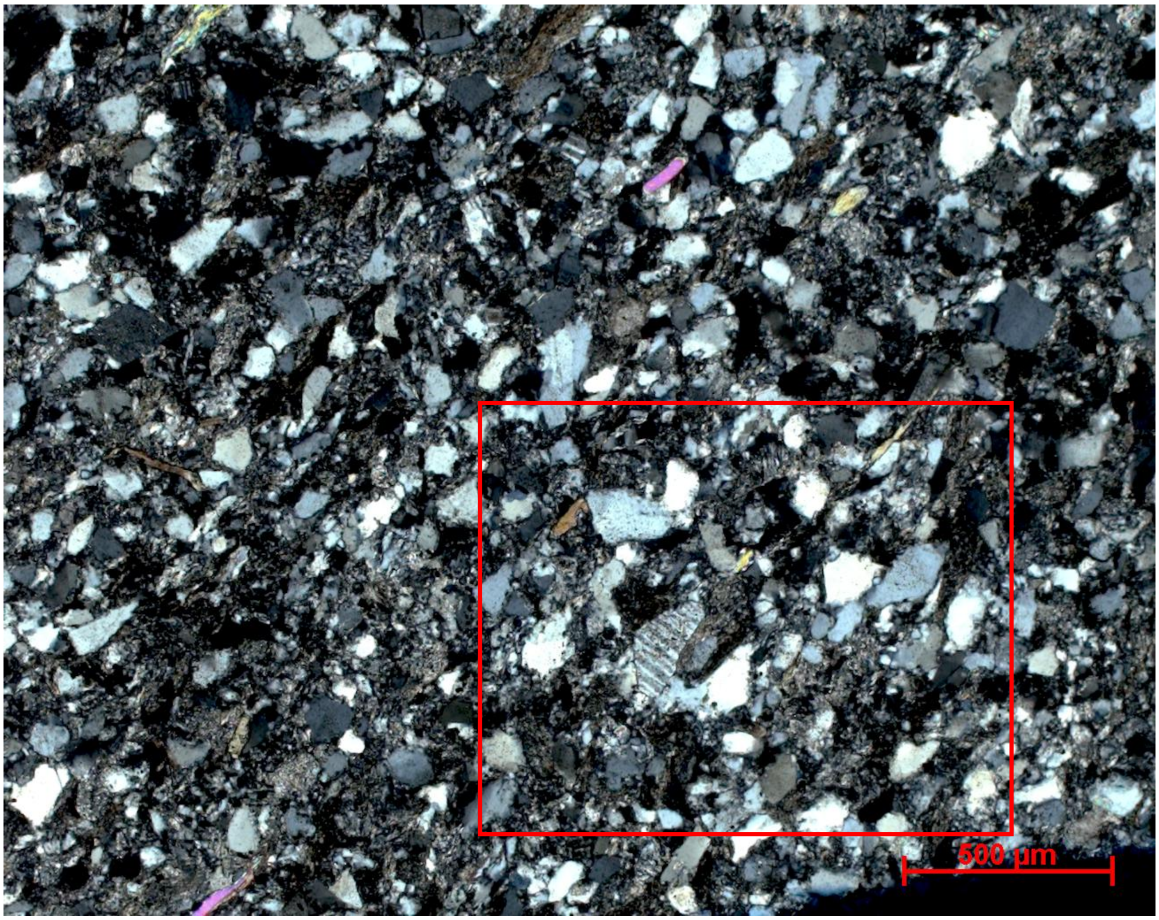


Figure 5. Photomicrograph of thin section of well cuttings in the Mississippian Stanley Formation at 7,950-70 ft (2,423-29 m) (cross polarization). Fine- to medium-grained sandstone with quartz and feldspar and lithic grains is compressed such that a vague lineation appears from lower left to upper right corner of the slide. Abundant ground mass of altered grains and chert cementation. The lineation is not diagenetic but depositional, and is related to burial/compaction.

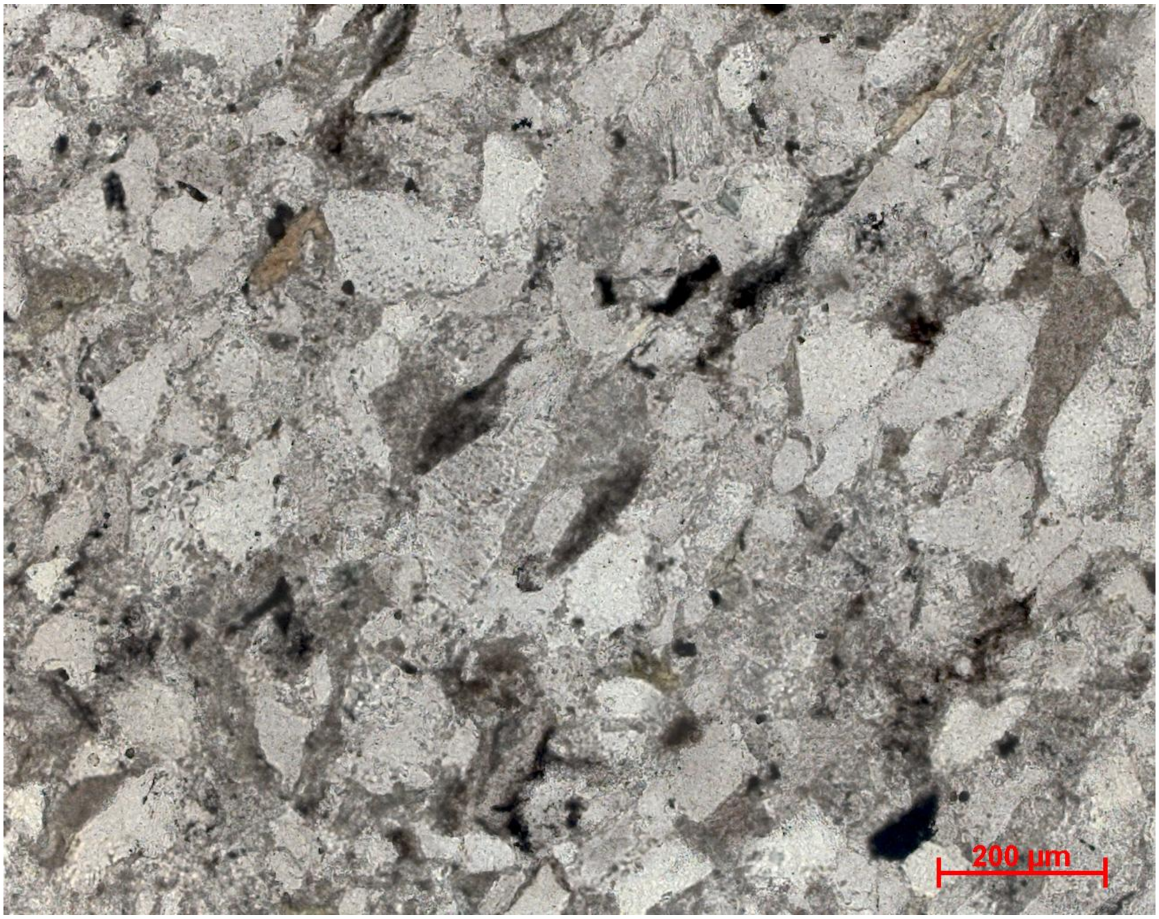


Figure 6. Photomicrograph of thin section of well cuttings in the Mississippian Stanley Formation at 7,950-70 ft (2,423-29 m) (plane polarization). Area denoted by red box in Figure 5.

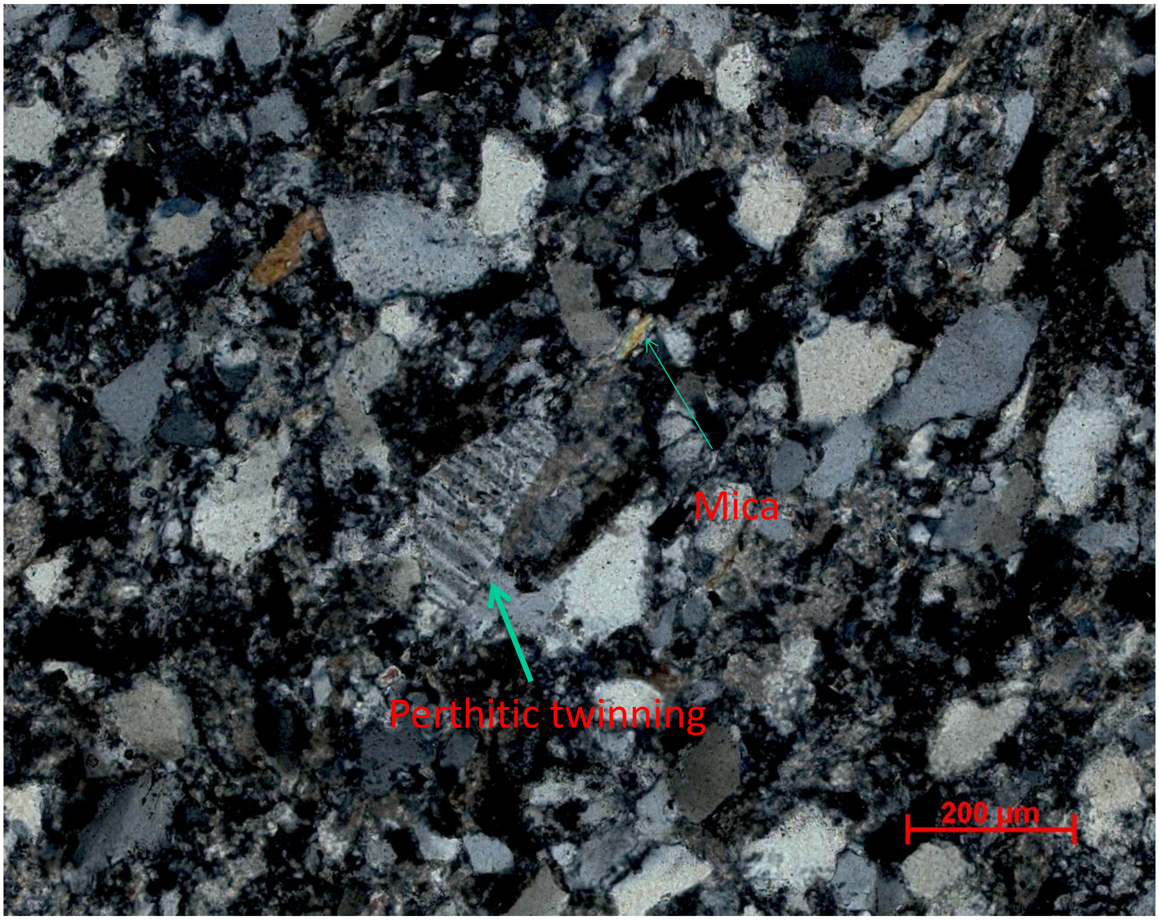


Figure 7. Photomicrograph of thin section of well cuttings in the Mississippian Stanley Formation at 7,950-70 ft (2,423-29 m) (cross polarization). Closeup of the red box area in Figure 5.

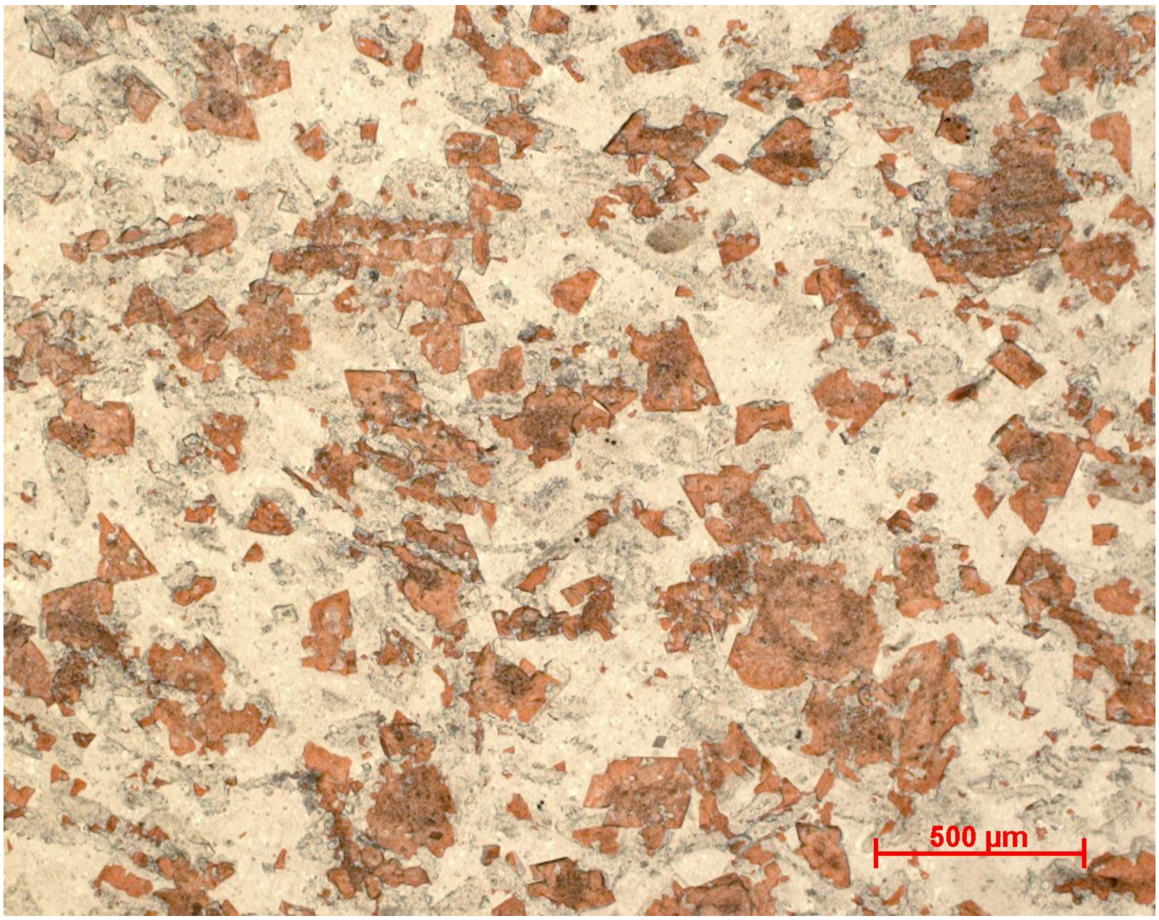


Figure 8. Photomicrograph of thin section of a whole core in the Arkansas Novaculite Formation at 8,565 ft 2 in (2,610.7 m) (plane polarization). Dark colored (reddish) calcite in a groundmass of chert (white).

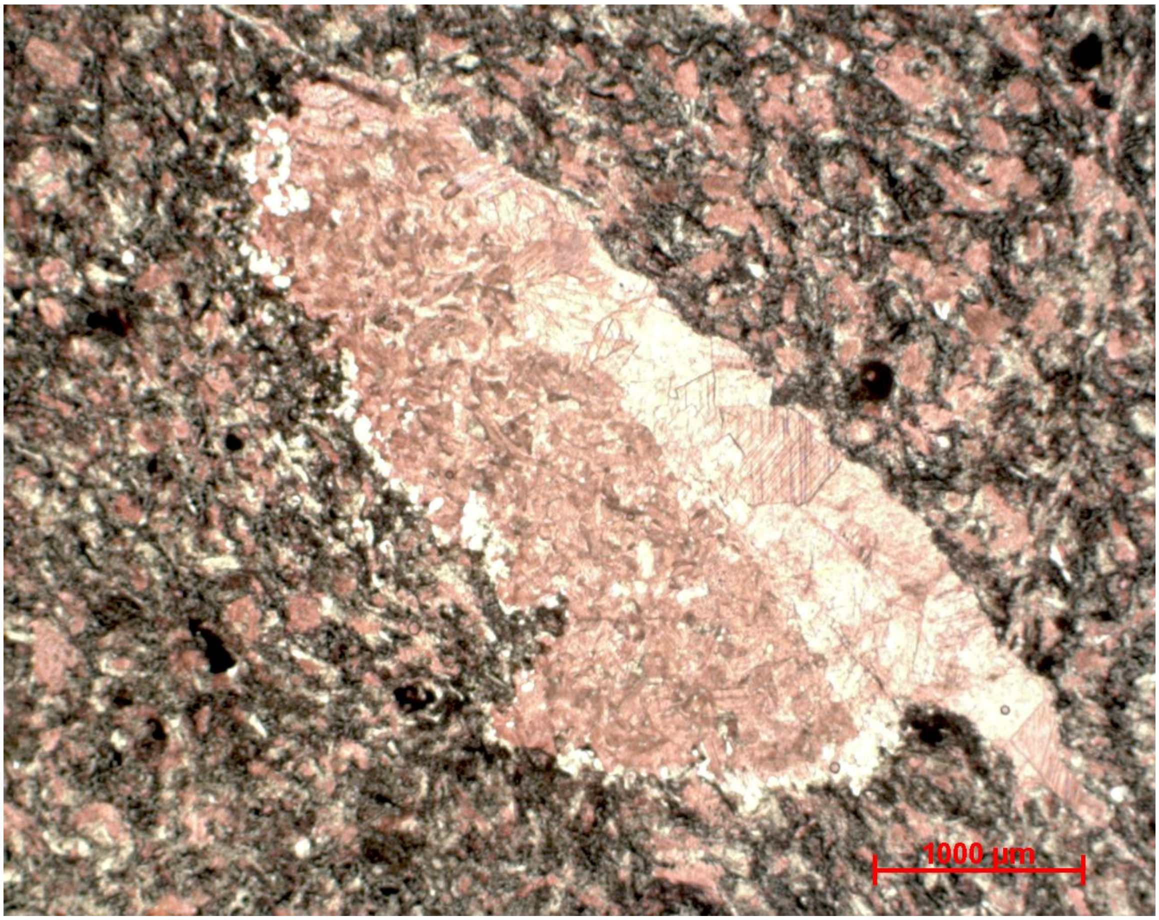


Figure 9. Photomicrograph of thin section of a whole core in the Arkansas Novaculite Formation at 8,568 ft 7 in (2,611.7 m) (plane polarization).

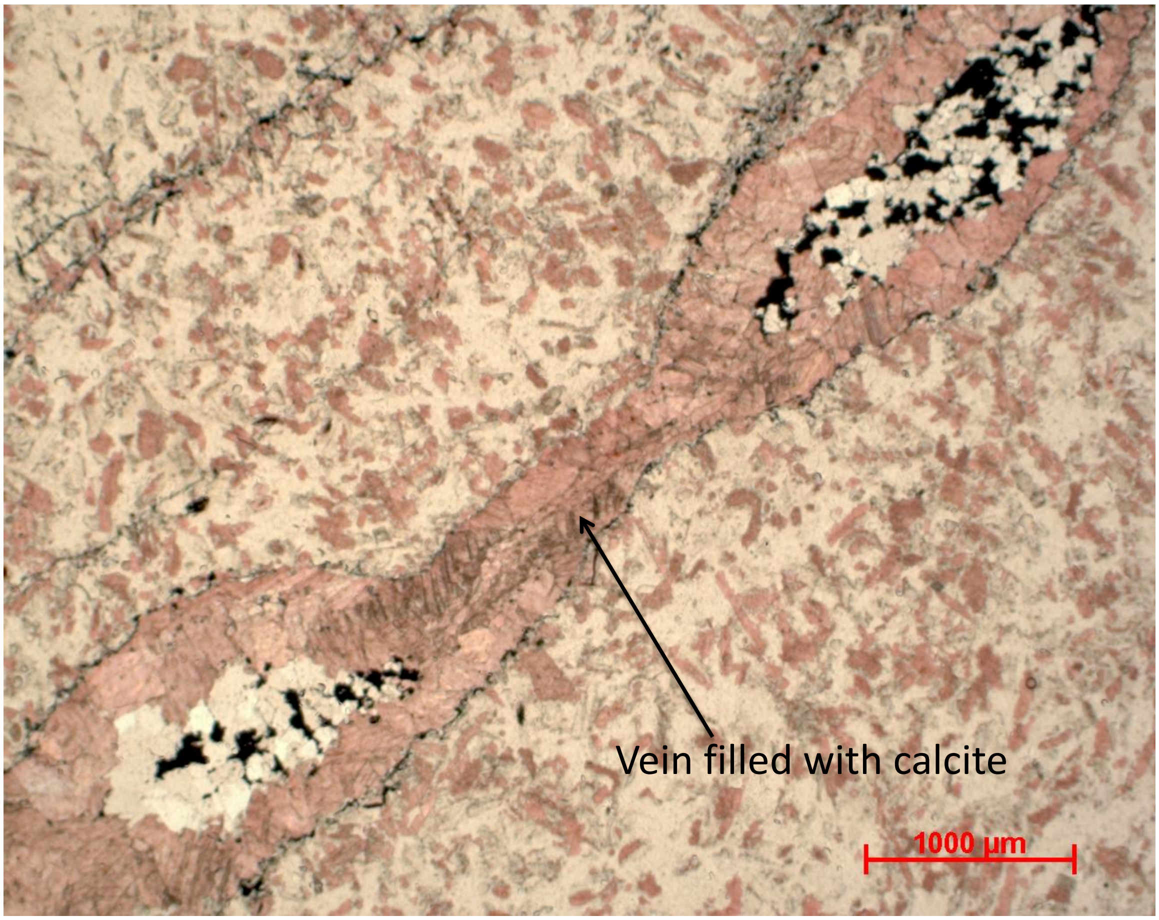


Figure 10. Photomicrograph of thin section of a whole core in the Arkansas Novaculite Formation at 8,566 ft 6 in (2,611.1 m) (plane polarization). Vein is filled with calcite.

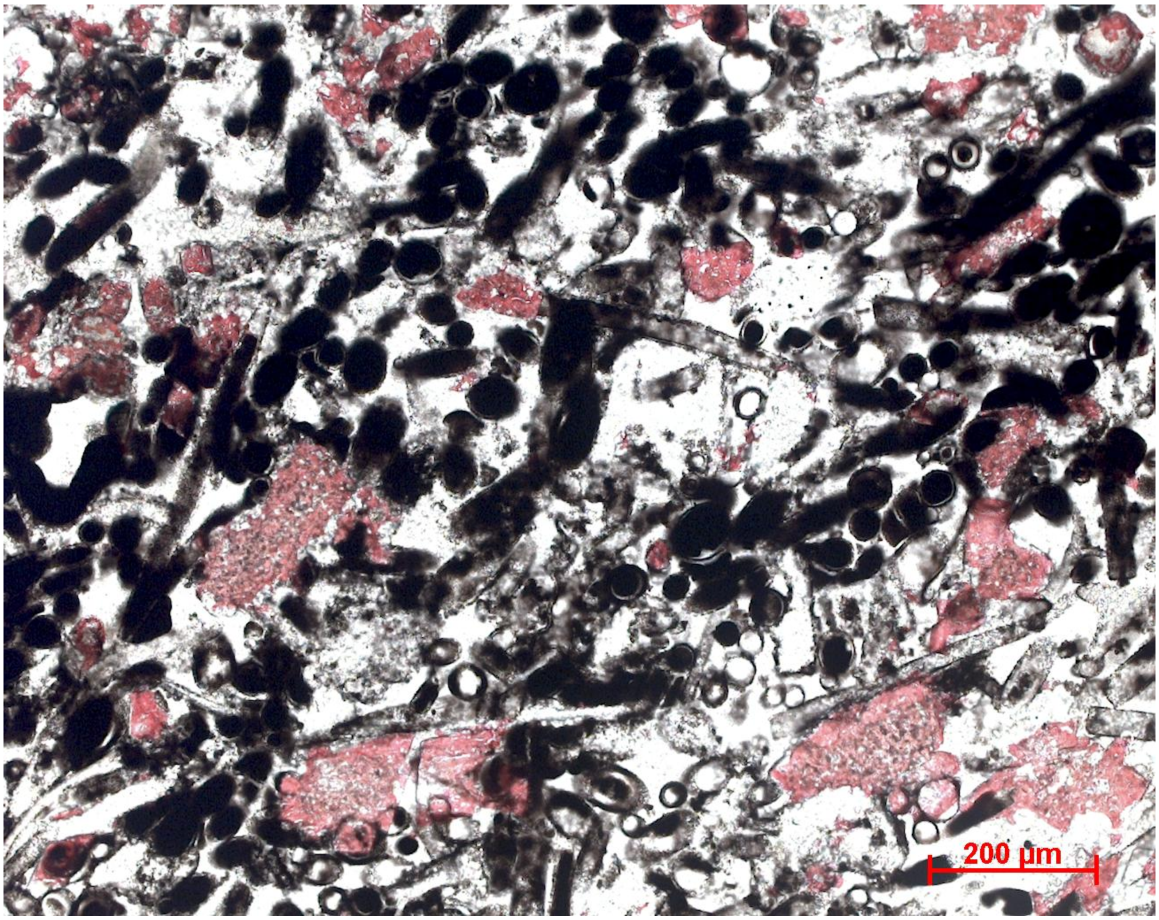


Figure 11. Photomicrograph of thin section of a whole core in the Arkansas Novaculite Formation at 8,565 ft 5 in (2,610.7 m) (plane polarization). Sponge spicules and radiolarian-rich chert with calcite.

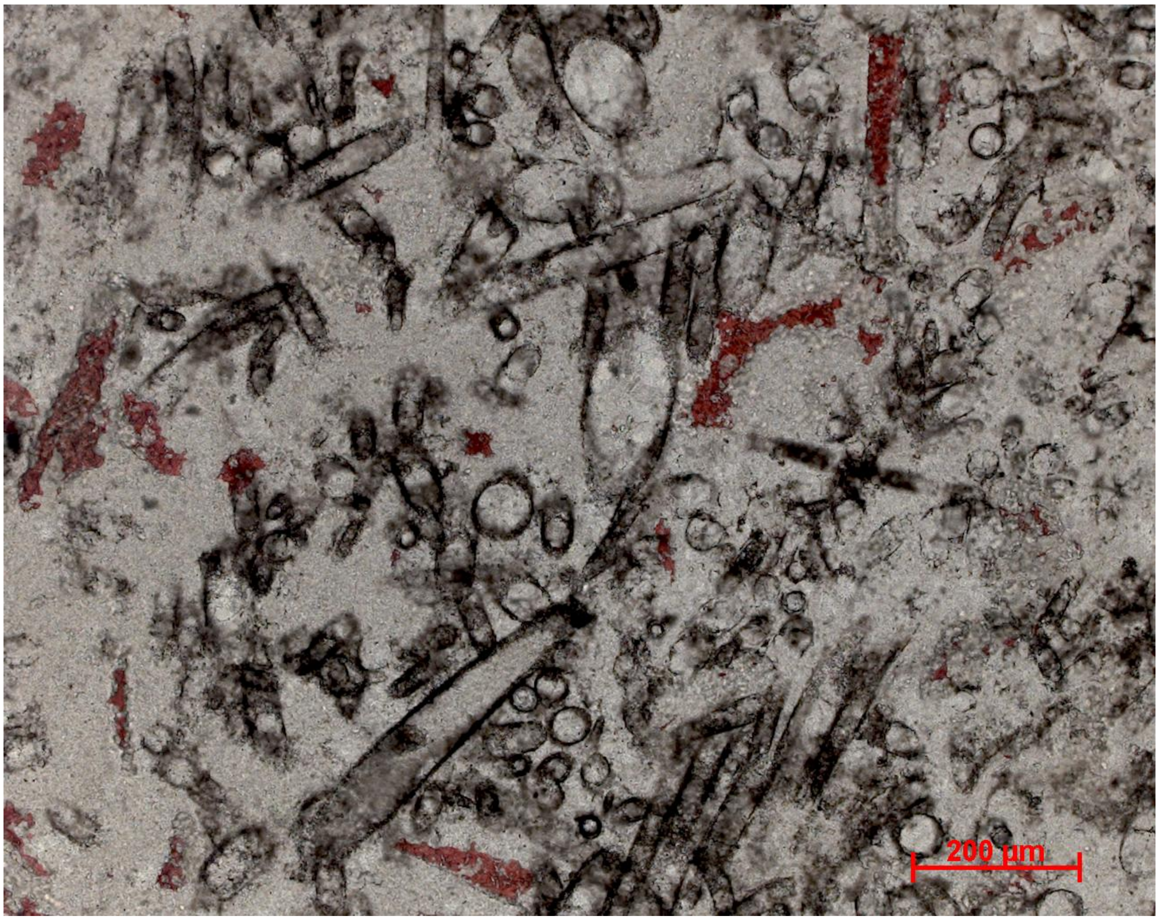


Figure 12. Photomicrograph of thin section of a whole core in the Arkansas Novaculite Formation at 8,565 ft 5 in (2,610.7 m) (plane polarization). Some of the sponge spicules are filled with calcite (red).

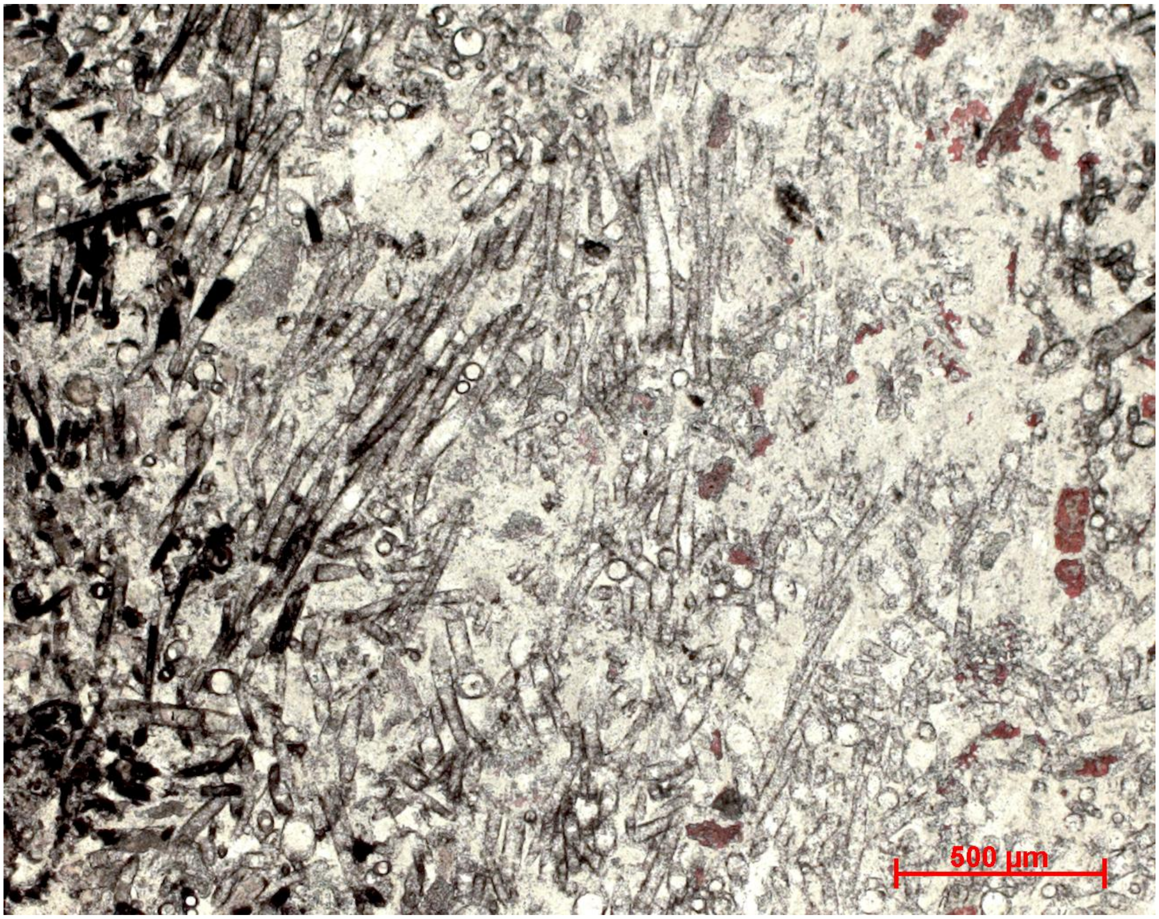


Figure 13. Photomicrograph of thin section of a whole core in the Arkansas Novaculite Formation at 8,565 ft 5 in (2,610.7 m) (plane polarization). The alignment of the sponge spicules probably indicates the depositional flow direction.

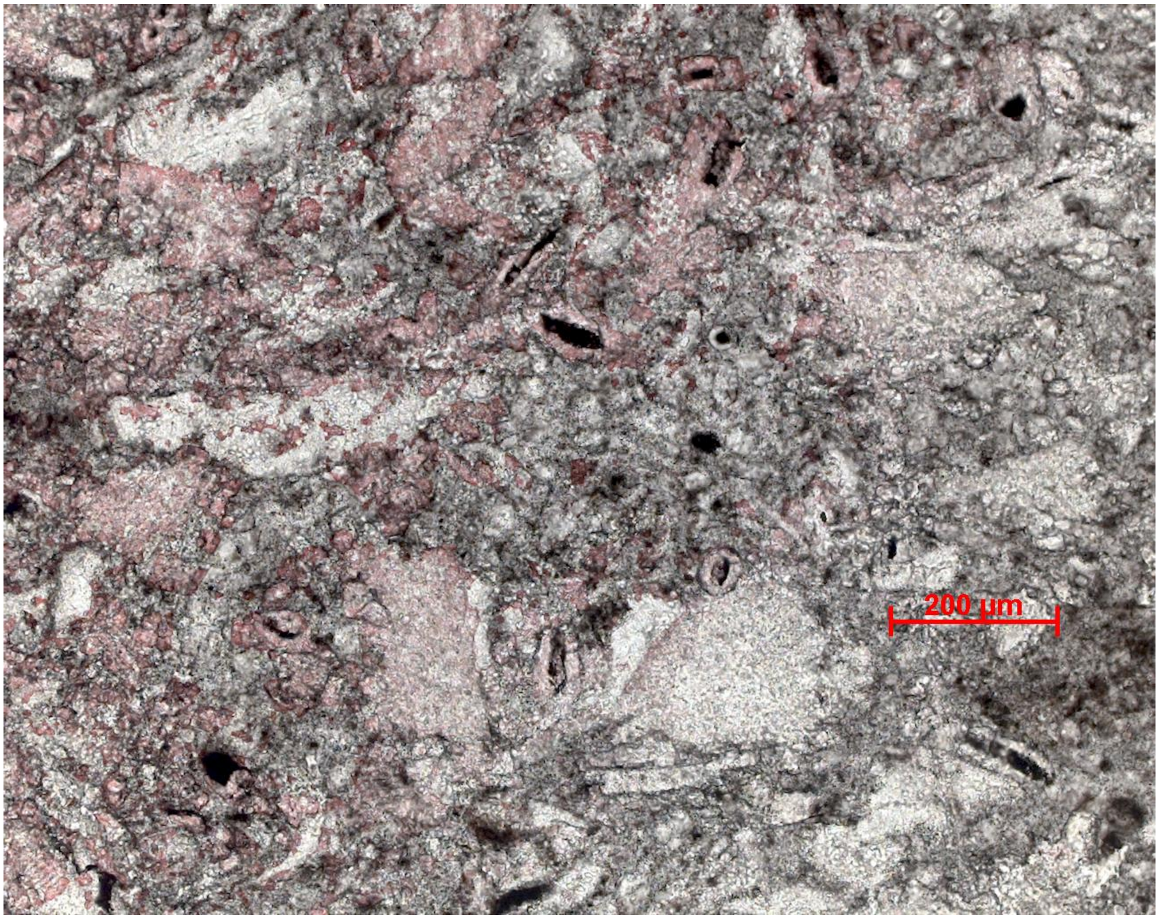


Figure 14. Photomicrograph of thin section of a whole core in the Arkansas Novaculite Formation at 8,567 ft 2 in (2,611.3 m) (plane polarization).

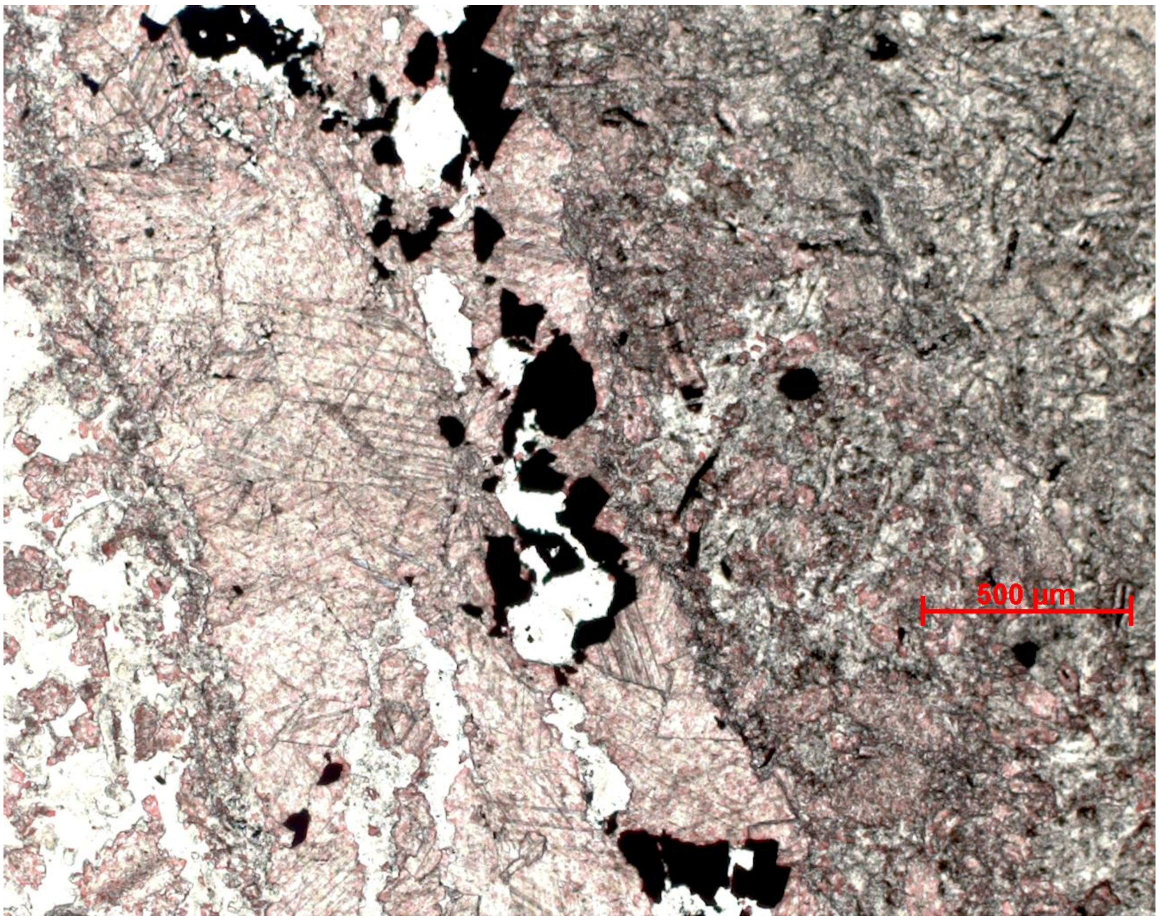


Figure 15. Photomicrograph of thin section of a whole core in the Arkansas Novaculite Formation at 8,567 ft 2 in (2,611.3 m) (plane polarization). Fracture was filled with euhedral calcite, followed by hydrocarbon charge and quartz.

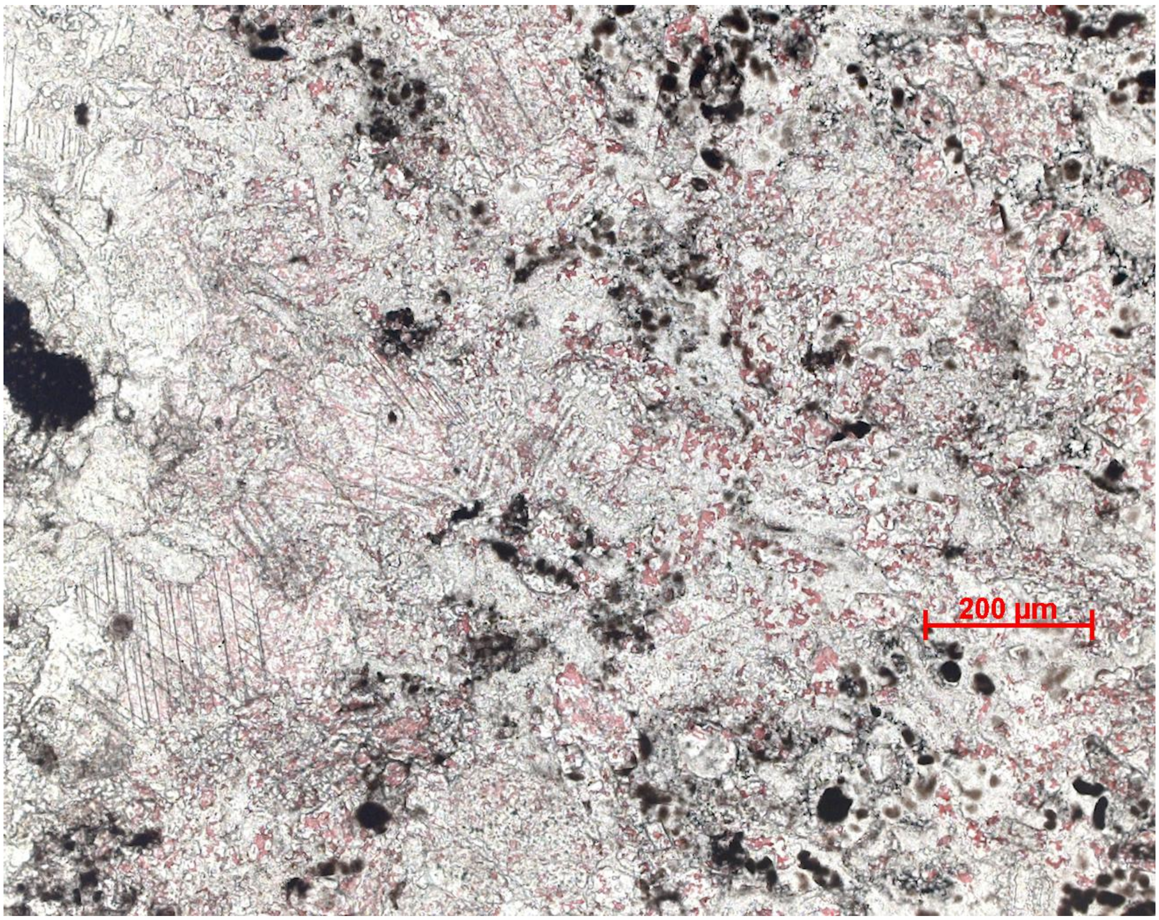


Figure 16. Photomicrograph of thin section of a whole core in the Arkansas Novaculite Formation at 8,568 ft 3 in (2,611.6 m) (plane polarization).

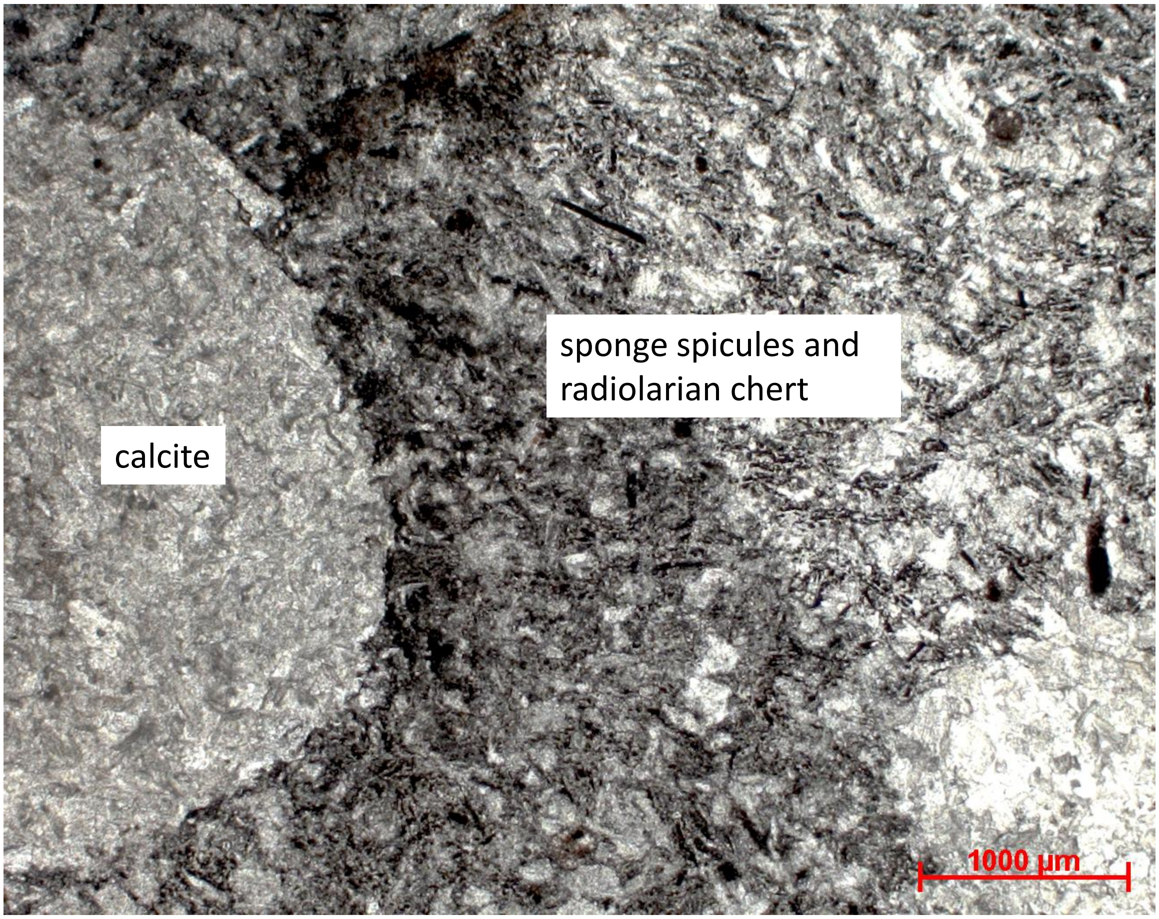


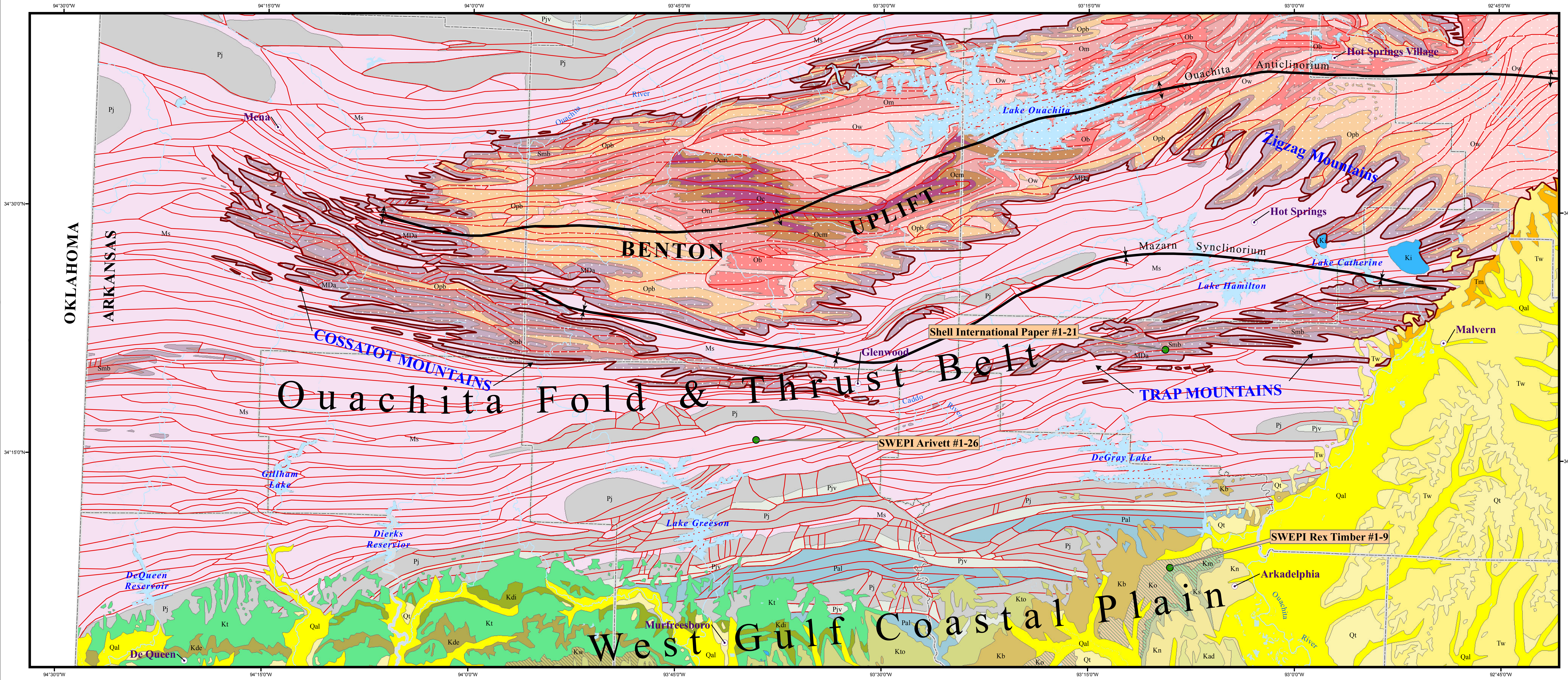
Figure 17. Photomicrograph of thin section of a whole core in the Arkansas Novaculite Formation at 8,568 ft 9 in (2,611.8 m) (plane polarization).

Arkansas Geological Survey
Bekki White, Director and State Geologist

Information Circular 39B
FF-OG-OU-016

Location Map and Surface Geology of the South Central Ouachita Mountain Region, 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



1:250,000

0 2.5 5 10 15 20 Miles

0 2.5 5 10 15 20 Kilometers

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 - Atokan
- Pal — Lower Atoka Formation

Morrowan - 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

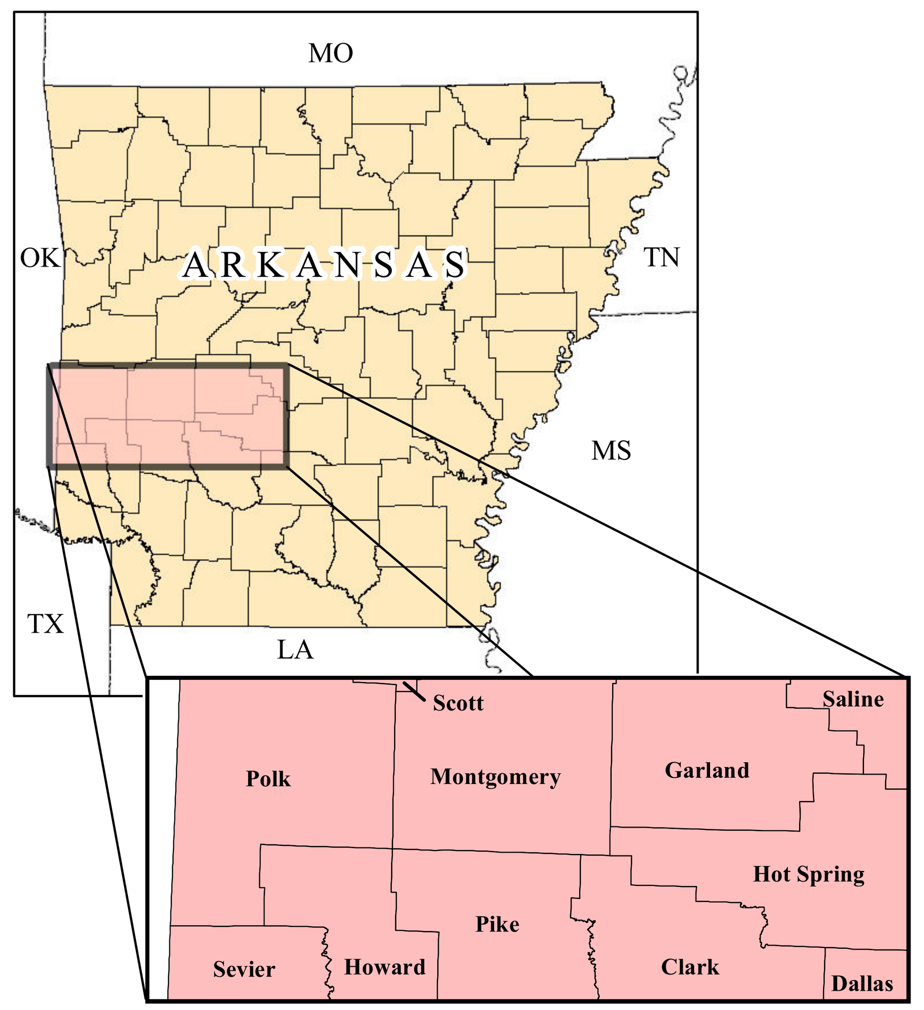
Middle Ordovician
- Ow — Womble Shale

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

N E S W

Disclaimer: This map was prepared using ESRI software on computers at the Arkansas Geological Survey. The Arkansas Geological Survey does not guarantee the accuracy of this map, especially when used in another system or with other software. Surface geology mapped and compiled by Haley, B. R. et al, 1993 and is subject to personal interpretation.

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

Plate 1