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Structural and Stratigraphic Analysis of the Shell Rex Timber No. 1-9 Well, Southern Ouachita Fold and Thrust Belt, Clark County, Arkansas

Ted Godo[1], Peng Li[2], and M. Ed Ratchford[2]

[1] **Shell Exploration & Production Company, Houston, Texas**

[2] **Arkansas Geological Survey, Little Rock, Arkansas**

Bekki White, Director and State Geologist
Arkansas Geological Survey

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STATE OF ARKANSAS
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ARKANSAS GEOLOGICAL SURVEY
Bekki White, Director and State Geologist

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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 had 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 Ordovician Crystal Mountain Sandstone (International Paper well, Hot Spring County), the Carboniferous sandstones in the Jackfork and Stanley Formations (Rex Timber well, Clark County) and the Devonian Arkansas Novaculite/Bigfork Chert (Arivett well, Pike County) (Plate 1). The results and conclusions of the integrated analysis from these three wells will be published in a three part series of Information Circulars by the AGS. As one of the three publications, this report is focused on the Rex Timber No. 1-9 well located in Section 9-T7S-R20W (Figure 1). The well was spudded in February of 1985 and subsequently was plugged and abandoned as a dry hole in May of 1985 after reaching a total depth of 6765 ft (2062 m). The principal objectives of this

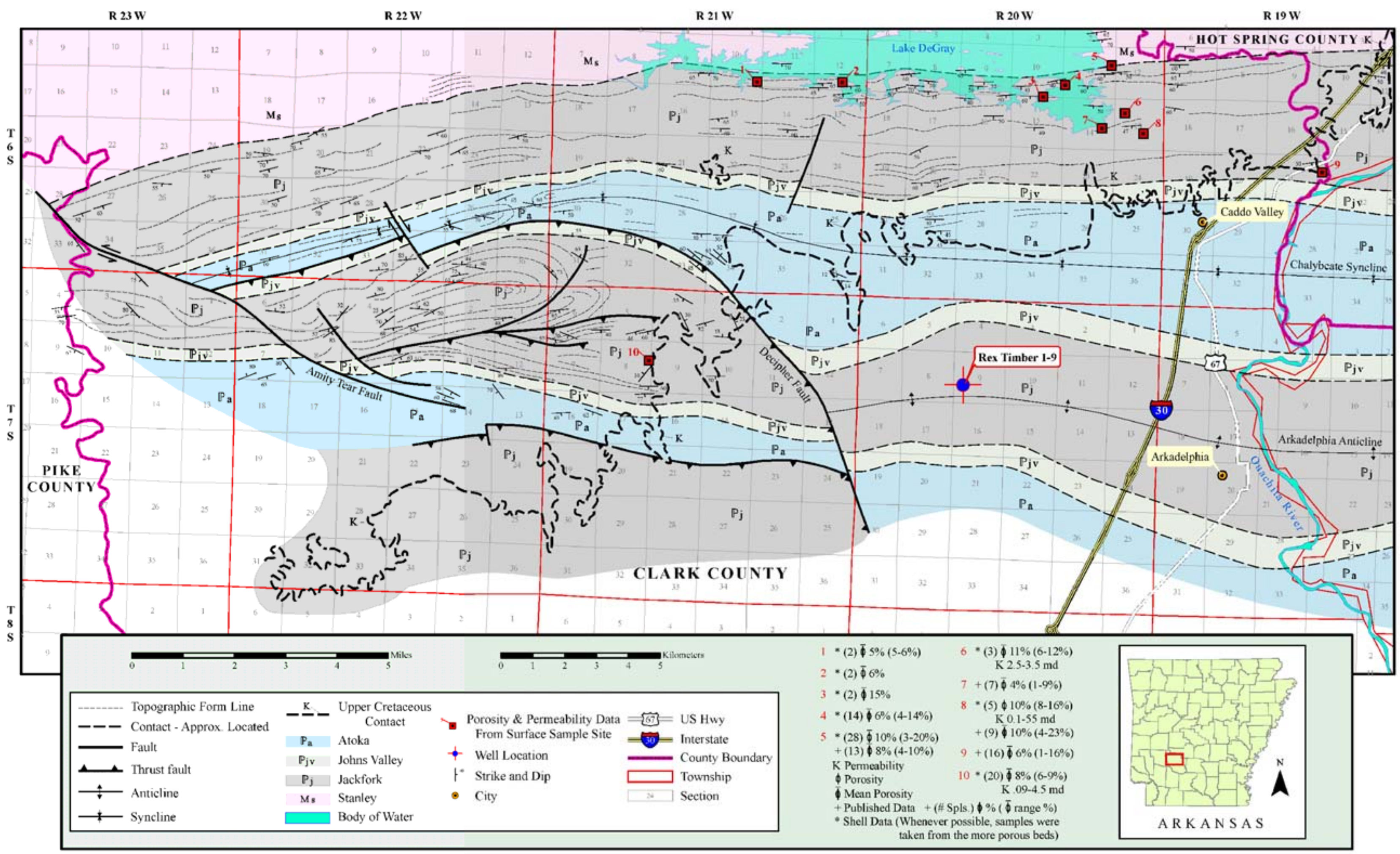

Figure 1. Surface and subcrop geology of the Rex Timber No. 1-9 well, Clark County, Arkansas.
(A larger digital PDF version of this map is on the disk)

report are to (1) evaluate and report the pre- and post-drilling well information, including structural evaluation, depositional environment, sandstone petrology, diagenesis, geochemistry, well log analysis and seismic interpretation, (2) assess the reasons for a lack of movable hydrocarbons in this well, (3) assess the reservoir play potential along the southern flank of the Ouachita fold and thrust belt in Arkansas based on integration of the results from the Rex Timber well with the other two wells studied in the 3-part series of Information Circulars.

Regional Geologic Setting

The Ouachita Mountain geographic 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 (Figure 2). Volumetrically, siliciclastics of the Carboniferous Stanley, Jackfork, Johns Valley and Atoka Formations make up more than 80% of this interval (Roberts, 1982). The Carboniferous stratigraphic succession of the Ouachita Mountains is an approximate 32,808 ft (10,000 m) interval of deepwater siliciclastic and cherty sedimentary rocks deposited during foreland basin subsidence immediately prior to Late Carboniferous (Late Pennsylvanian) folding and thrusting during the Ouachita Orogeny. This thick sequence is highly representative of foreland basin deepwater detrital fill (Coleman, 2000). Coleman suggested the Jackfork

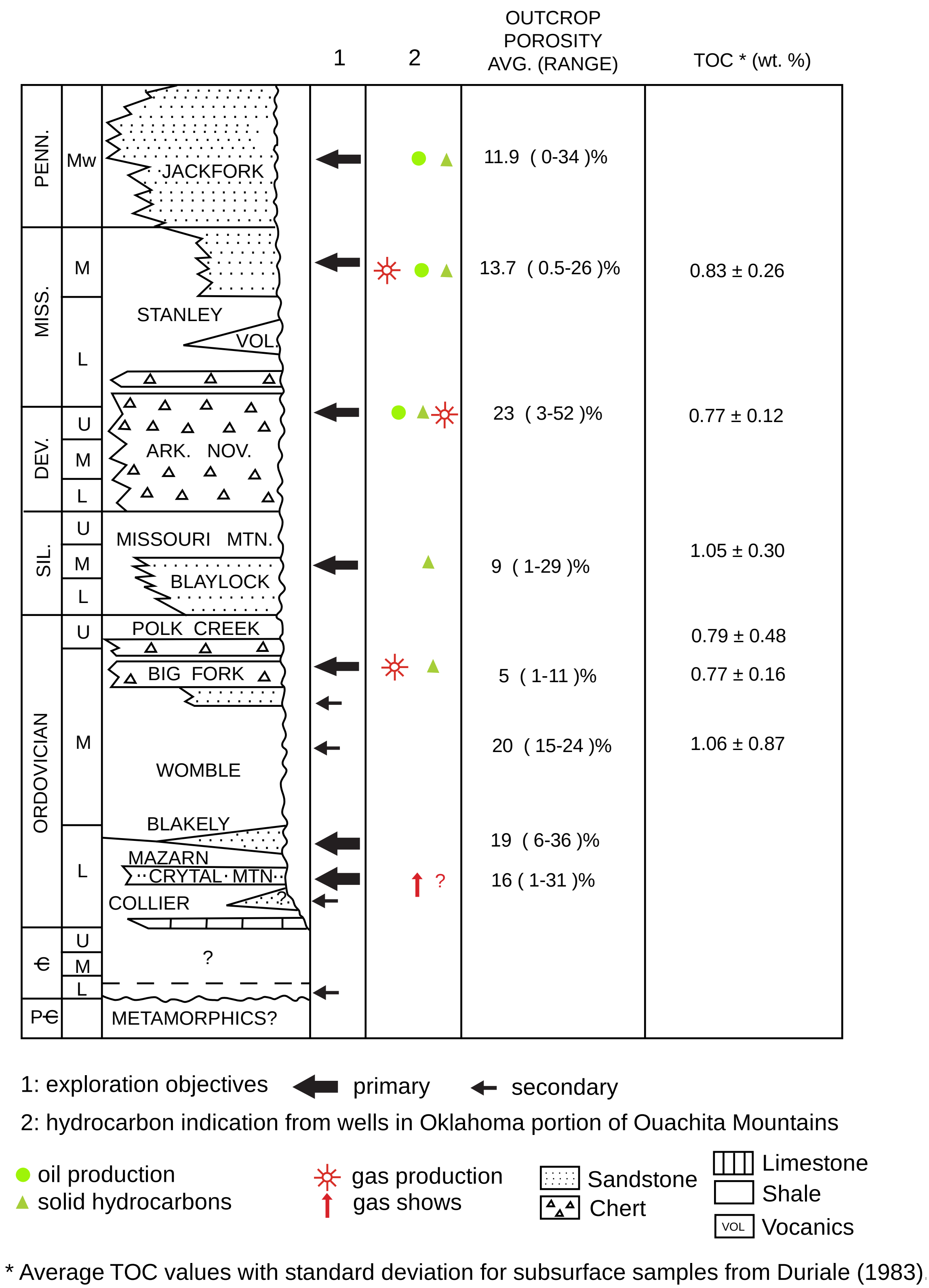

Figure 2. Partial stratigraphic section from the Ouachita Mountains region, Arkansas and Oklahoma (modified from Shell's internal report).

was deposited in water depths of 4,921 to 6,562 ft (1,500 to 2,000 m) and the Stanley and Atoka were also deposited in similar water depths.

The Ouachita Mountains can be subdivided into the following tectonic provinces from north to south primarily on the basis of different structural styles: frontal zone, defined by imbricate faults that bring Carboniferous rocks to outcrop, a core zone uplift which exposes Cambrian through Mississippian pre-flysch sediments (also known as the Benton–Broken Bow uplifts), and a southern zone characterized by a return to Carboniferous rocks, but exposed in broader fold structures. The Rex Timber No. 1-9 well is located in the southern tectonic province of Clark County, and was drilled in the core of a Carboniferous anticline.

The southern Ouachita province forms a narrow strip about 12 mi (20 km) wide and 93 mi (150 km) long consisting of Carboniferous outcrop exposures that reside mostly in Arkansas. Part of this province is known geomorphically as the Athens Plateau. Relatively simple structures characterize the outcrops of Jackfork through Atoka sequences in this province, but an exceedingly complex fault and fold pattern prevails as a disharmonic detachment zone within the underlying Mississippian Stanley Formation (Arbenz, 1989). The stratigraphic column also shows vertical variations in sedimentary facies. The pre-Stanley section is relatively thin and is characterized by cherts and dark graptolitic shales, indicating a period of very slow sedimentation in a starved trough. The Stanley-Jackfork-Johns Valley-Atoka sequence is much thicker and is characterized as a flysch facies that contains abundant sandstone intervals representing periods of rapid sedimentation in a deepwater environment (Cline and Shelburne, 1959).

The Stanley Formation of the southern Ouachitas consists of a thick shale interval (maximum of 10,991 ft or 3,350 m) with upper and lower sandstone sections that were deposited during a sea level highstand (Coleman, 2000). The overlying Jackfork Formation is predominantly a sandstone sequence (maximum of 6,890 ft or 2,100 m), which was deposited during a sea level lowstand with no shelf equivalent (Ross and Ross, 1988). Paleocurrent indicators from the Jackfork suggest that the majority of sediments were derived from the southeast and northeast and additional sediments were contributed from the southern and northern shelves (Coleman, 2000). The Johns Valley Formation overlies the Jackfork Formation and consists predominantly of shale (maximum of 886 ft or 270 m), with intercalated turbidite sandstone and unusually abundant exotic boulders of diverse composition (Morris, 1989). Stratigraphically overlying the Johns Valley is the Atoka Formation, which consists of a thick succession of lower and middle Pennsylvanian sandstone and shale that originally exceeded 29,987 ft (9,140 m) in depositional thickness (Coleman, 2000).

Well Evaluation

The Rex Timber No. 1-9 was drilled as a rank wildcat test of the Shell's Moccasin prospect. The Stanley-Jackfork Formations were the primary exploration objectives and were penetrated to a total depth of 6,765 ft (2,062 m). The original proposed total depth was 10,000 feet (3,048 m), but the well was stopped short as the drilling results came in and the costs rose due to slow penetration rates. The closest well control is the 1938 Witherspoon Love 10-1 located approximately one mile east of the Rex Timber (Figure 3), which penetrated a depth of only 2,655 ft (809 m). The prospect area lies beneath a very thin cover of Upper Cretaceous sediments, but is on trend with a surface anticline which has the Jackfork Formation in its core. In addition to mapping the surface geology and projecting the anticlinal trend beneath the Cretaceous cover, seismic reflection data and refraction velocities were measured along the Cretaceous/Paleozoic unconformity, and were used to help define the structural trap of the Moccasin prospect. The resulting interpretation of the Moccasin prospect is that of a relatively simple anticline cored by the Jackfork and flanked both on the north and south sides by the Johns Valley Shale. A structural culmination along this anticline was inferred, but not positively identified at the prospect location (Figure 3). Only the suggestion of an east plunge is postulated for the anticline that is projected from "trendology" on the surface geologic map (Figure 1).

The Rex Timber well was spudded in the Upper Cretaceous Ozan Formation, which is composed of gumbo clays and calcareous sandstones with a thin, basal chert conglomerate that overlies the Jackfork Formation at 217 ft (66 m) down the well bore. The Jackfork Formation consists primarily of a thick sequence of interbedded sandstones, siltstones and shales, and comprises approximately 5,500 ft (1,676 m) of the Rex Timber well (Figure 4). The Jackfork-Stanley boundary is difficult to determine due to a paucity of reliable paleontologic data and a transitional lithologic change between the two units. Based on the increased percentage of shales (>50%), the stratigraphic top of the Stanley is placed at approximately 5,700 ft (1,737 m) down the well bore. The interval between 5,700 ft (1,737 m) to a total depth of 6,765 ft (2,062 m) consists of shale with a lesser amount of sandstone and is assigned to the upper Stanley.

Four cores were taken in the well, three in the Jackfork and one in the Stanley. The sandstone lithology in the cores is quartz arenite, with little or no porosity. Log

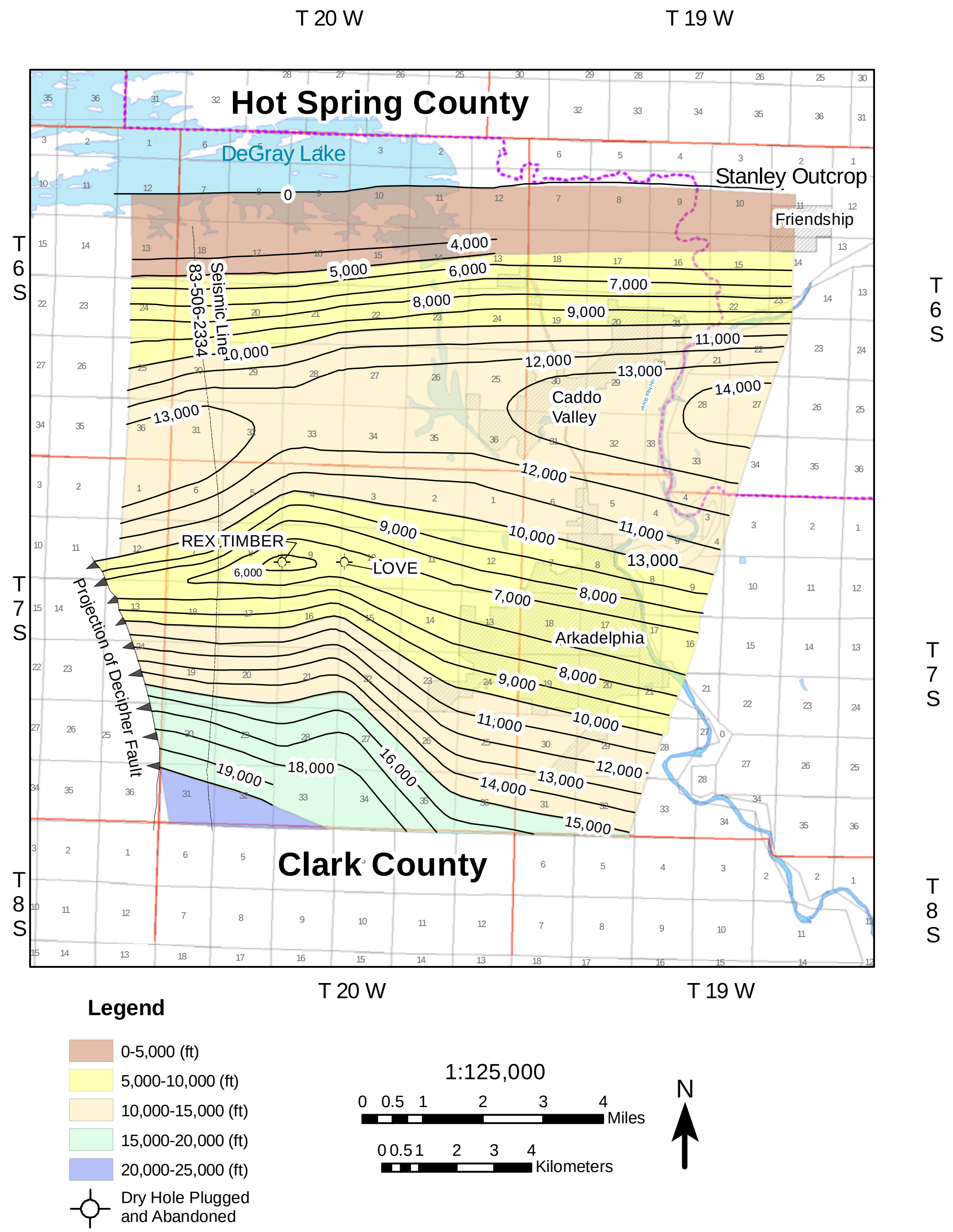

Figure 3. Structural contour map of the top of Stanley Formation near the Rex Timber 1-9 well.

porosities rarely exceed more than 2%. Although background gas was encountered from 700 ft (213 m) to total depth, no significant gas shows occurred. Trace amounts of solid hydrocarbons were evident throughout the well (Figure 4). The solid hydrocarbons may represent a limited paleoporosity within the reservoir present at the time of oil migration.

The shales penetrated in the well had some sealing capabilities as indicated by the saline formation water encountered at depths greater than 3,000 ft (914 m). However, there is some question as to whether the shales that were encountered in the Rex Timber well could have provided an adequate seal for an extensive amount of time after hydrocarbons were emplaced. The tight nature of the fold and the fracture network observed in the Rex Timber well would require a thick overlying shale sequence to preclude leakage through any fractures in the sandy sequence. The thickest shale sequence penetrated in the well is less than 150 ft (46 m) and is stratigraphically in the upper Stanley Formation. As the drilling depth approached 6,800 feet (2,073 m), there was little encouragement for porosity development, adequate seal thickness, or sufficient reservoir quality. Consequently, Shell concluded that they had drilled deep enough to obtain the necessary information and the well stopped short of the original target depth. Based on outcrop analogs, there is a reasonable possibility that thicker shales are present in the middle and lower Stanley but were not penetrated in the well. It is not known if these deeper shales could have provided adequate sealing capability during hydrocarbon development and migration. Furthermore, it is not known if the Arkansas Novaculite (another regional objective) would be in the core of this anticline at depth.

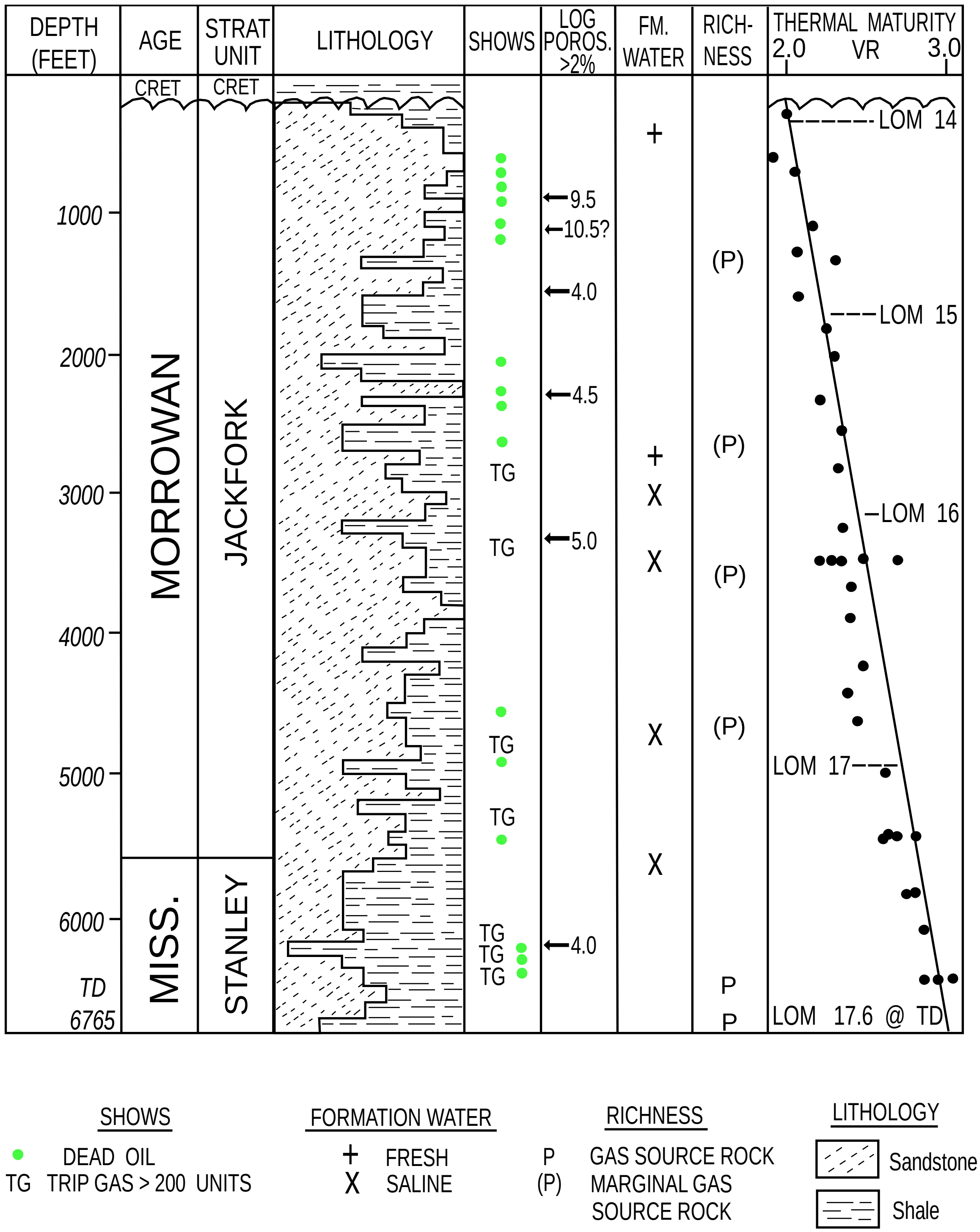

Figure 4. Stratigraphic and thermal maturity evaluation of Rex Timber No. 1-9 well (modified from Shell's internal report).

Geochemistry

Vitrinite and graptolite reflectance studies on Paleozoic outcrops and well samples in the Ouachita region outline an area of low-grade metamorphosed sediments that lie in and adjacent to the older exposed Ordovician to Mississippian rocks. The rocks exposed at the surface are characterized by high level of maturity (LOM) >18 (consistent with the onset of greenschist metamorphism). LOM is a unique thermal maturity level parameter that was developed by Shell geologists while working in the Ouachita Mountain region during the 1980s. LOM values can be converted and correlated to measured vitrinite reflectance values (Ro) as shown in Figure 5. These relations combined with features such as hydrothermal quartz veining throughout the uplifted core region indicate a heating event occurred after or concurrent with the uplift. High thermal maturity trends disregard stratigraphic boundaries and are measured by the distribution of high LOM values in shale outcrops that culminate with highest values closest to the center of the uplift. An example of this later heating event and associated trend can be measured in shale sequences of the Jackfork. Jackfork exposures that are proximal to the core uplift contain high LOM values that are nearing greenschist facies metamorphism. However, the LOM values of Jackfork shale on the north and south flanks of this uplift can be observed as low as 9 to10, which is in the oil window. Analysis of twelve (12) Ouachita and Arkoma Basin wells that were drilled outside the core uplift (high heat flow area) in Arkansas and Oklahoma indicates a reflectance gradient that corresponds to a geothermal gradient of 1.2 ^{o}F/100 ft.

Fair to excellent organic richness values are documented in thick Ordovician through Pennsylvanian shales (Curiale, 1983). Average total organic carbon (TOC)

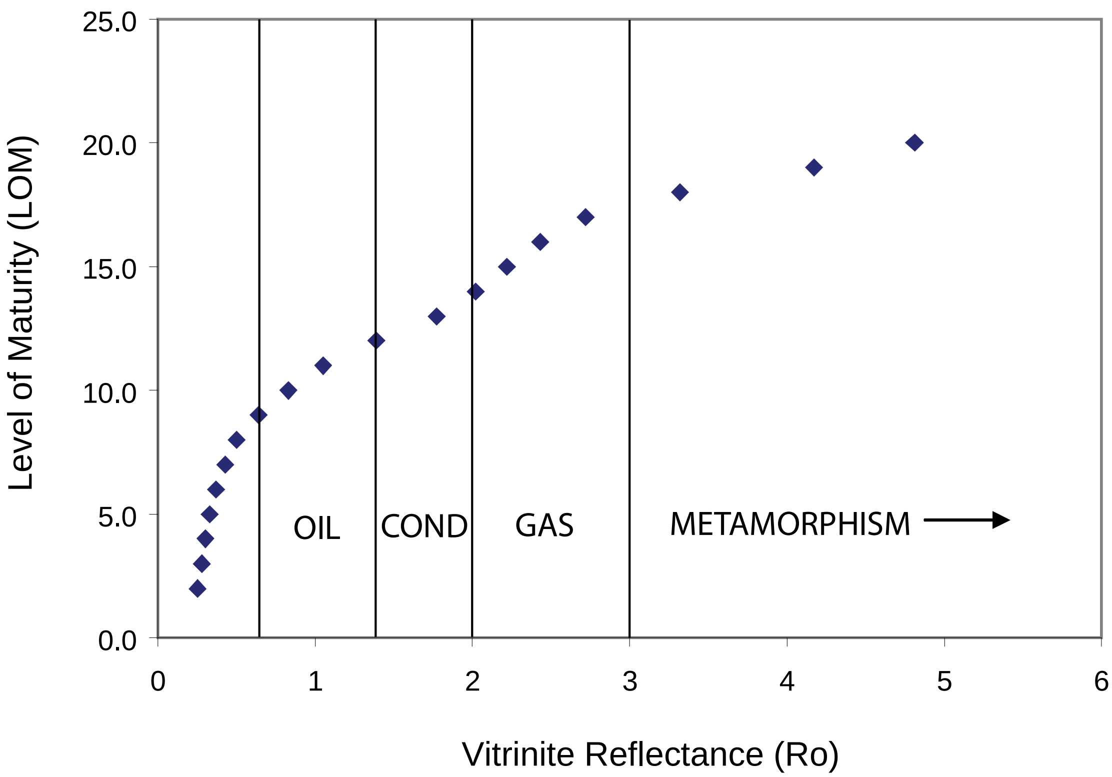

Figure 5. The conversion relationship between level of maturity (LOM) and vitrinite reflectance (Ro).

values in subsurface Lower Paleozoic sequences range from 0.77% to 1.06% (Figure 2). In Arkansas, natural gas is the most likely hydrocarbon that is present in the Paleozoic sequence due to (1) the higher LOM values that are documented in the shales throughout much of the project area and (2) because of the abundance of humic rich kerogen in the Carboniferous section. Paleozoic oil is likely in the western most portions of the Ouachitas which have experienced less heating. Crude oil has been produced from Stanley and Arkansas Novaculite at the Potato Hills region and at Isom Springs field in Atoka County, Oklahoma.

Shell also examined the source rock quality of the shales in the Rex Timber well. TOC analyses were conducted on ten-foot intervals of ditch cuttings (Figure 6 and Appendix 1). The definition of a source rock is herein characterized by a total organic richness of equal to or greater than one percent. As defined, both the Jackfork and Stanley have qualified source rock intervals. The Jackfork had eleven source rock intervals over one percent. The richest value of 1.96% was measured in a core at 1,311 ft (400 m). The Stanley had three source rock intervals with the highest TOC value of 2.96% at 6,730-40 ft (2,051-54 m). A determination could not be made regarding the type of organic material, whether lipid or humic rich, due to the high thermal maturity (LOM) of the kerogen (Table 1). However, Shell had observed that Stanley and Jackfork shales in Oklahoma with corresponding to lower maturity values contained mostly humic organic matter. Because of a similar depositional environment for these Carboniferous sediments, it was assumed that the shales in the Rex Timber are likely to contain humic organic matter as well. Since humic source rocks generate only gas, a question arose pertaining to the source of the solid hydrocarbons (thermally altered oil) that were identified in the Carboniferous section drilled in the Rex Timber well. It is assumed that the source of the solid hydrocarbons must be from lipid source rocks in the lowermost Stanley and in the Arkansas Novaculite.

The thermal maturity of the shales in the Rex Timber well was also determined by analysis of vitrinite reflectance values. Pre-drill predictions of thermal maturity closely matched the measured results. The top of the Jackfork sequence in the Rex Timber well has an LOM value of 14 that is approximately equivalent to a vitrinite reflectance value of Ro = 2.0%; whereas, at a total depth of 6,765 ft (2,062 m) the corresponding LOM

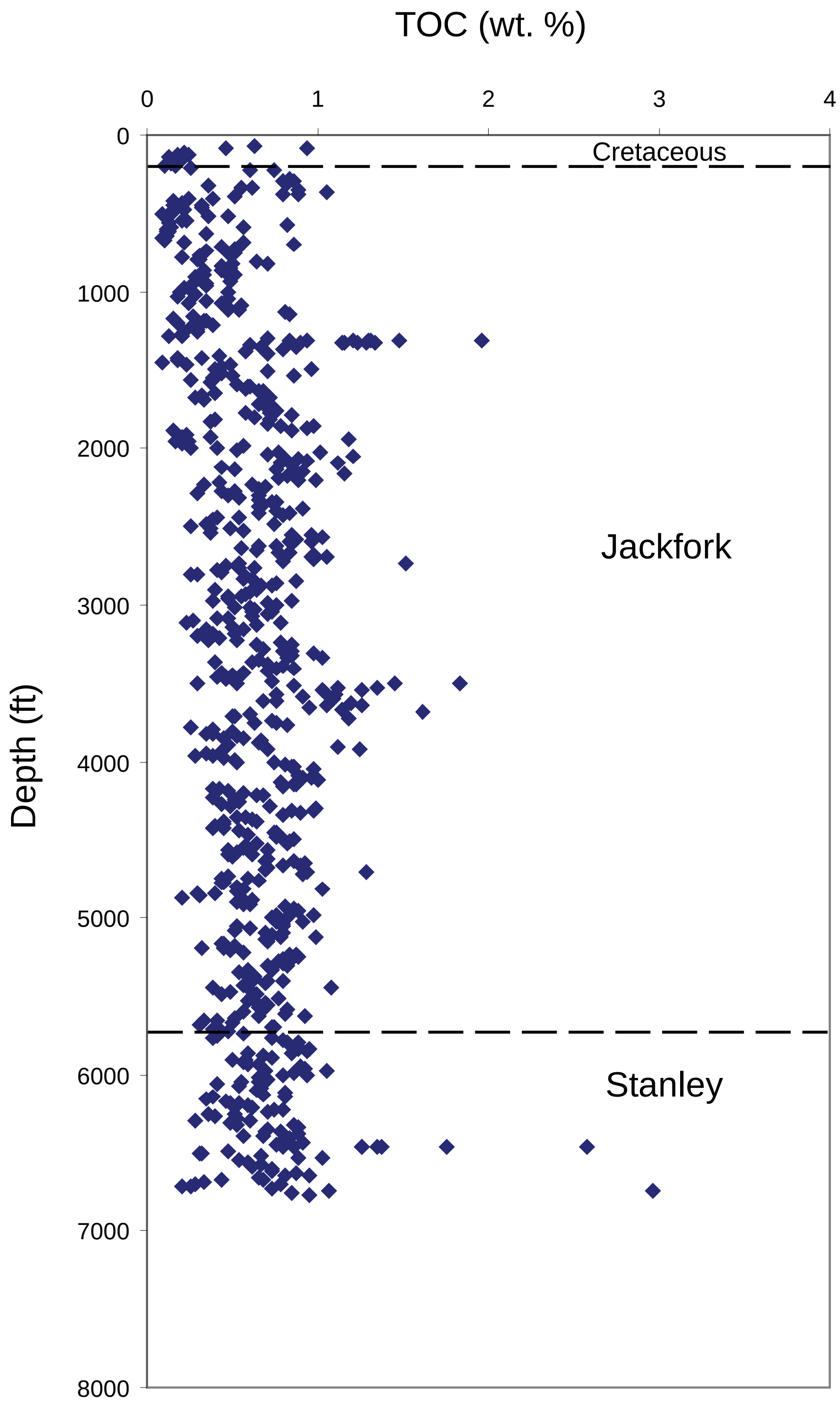

Figure 6. Total organic carbon (TOC) values of samples in the Rex Timber No. 1-9 well.

Table 1. Thermal maturity level and visual kerogen type analyses for Rex Timber No. 1-9 well.

Depth (ft)	Ro (%)	LOM	Visual Kerogen B	KI	V	I
Jackfork						
280-300	2.03±0.04	13.9-14.3		40	35	25
600-610	1.94±0.01	13.7	10		45	45
700-720	2.03±0.03	13.2-14.2	15		70	15
710-730	2.02±0.03	13.9-14.2	<1	30	40	30
1000-1010	2.01±0.03	13.9-14.3		25	50	25
1120-1140	2.17±0.04	14.6-14.9		30	40	30
1311-1312	2.08±0.03	14.2-14.5	5	65	20	10
1600-1630	2.08±0.04	14.2-14.5	<1	35	50	15
1840-1870	2.27±0.03	15.1-15.4	2	35	53	10
2030-2070	2.31±0.04	15.3-15.7	2	43	40	15
2360-2400	2.21±0.04	14.8-15.2	1	34	45	20
2570-2600	2.32±0.05	15.3-15.7	<1	35	50	15
2840-2880	2.29±0.02	15.2-15.5		55	25	20
3280-3330	2.40±0.08	15.5-16.2	<1	60	15	25
3510-3600	2.23±0.01	15.0-15.1	10	35	30	25
3670-3680	2.36±0.02	15.6-15.8	<1	45	43	12
3900-3920	2.38±0.02	15.7-15.8	<1	44	44	12
4290-4330	2.45±0.02	15.0-15.2		43	42	15
4480-4520	2.34±0.02	15.5-15.7	1	20	69	10
4570-4580	2.56±0.47	14.0-16.5	1	98	1	
4650-4700	2.36±0.03	15.6-15.8	<1	10	65	25
5000-5040	2.64±0.05	16.6-16.9	<1	10	82	8
5510-5530	2.57±0.04	16.4-16.7	1	3	86	10
Stanley						
6100-6150	2.85±0.02	17.3-17.4	<1	30	50	20
6459-6460	2.98±0.17	17.1-17.8	<1	30	40	30

B=Solid Hydrocarbon
KI=Micrinized Kerogen
V=Vitrinite
I=Inertinite

value for the upper Stanley is 17.6, equivalent to Ro = 3.0% (Figure 4 and Table 1). This reflectance gradient is equivalent to about 1.2 ^{o}F/100 ft which is the same for wells regionally (Western Ouachitas and Arkoma Basin) that experienced heating by normal burial processes. If the well had been drilled to the proposed depth of 10,000 ft (3,048 m), then the predicted Ro value would have been 4.65% with a corresponding LOM value of 19.7. The level of heating that these rocks would experience is very high and there was concern that compaction and cementation would have reduced the porosity to essentially zero. However, it is noteworthy to consider that there are reservoir analogues in the adjacent Arkoma Basin that possess high LOMs. Shell had identified producing fields in the Arkoma Basin where the production interval has an LOM of just over 18 from Morrowan sandstone (e.g. Gulf-Hombre S13-T8N-R26W). Although these relations were well understood, it was determined before the well was spudded that Shell would stop the well short of the 10,000 ft (3,048 m) proposed total depth if unacceptable porosity was encountered while drilling.

Depositional Environment

Deepwater Elements and Terminology

Deepwater refers to sediments deposited in water depths greater than 1,500 ft (457 m), i.e., those under gravity flow processes that occur below storm wave base (Weimer and Slatt, 2004). In a deepwater turbidite system, clastic sediments are transported beyond the shelf edge into deep water by sediment gravity flow processes and are deposited on the continental slope and in the basin. Bouma (2000) has developed a depositional model for fine-grained turbidites based partially upon his work on the Jackfork Formation. This model is composed of confined channels on the slope, levee channels near the toe of slope, and unconfined sheet sands on the basin floor.

Channels and their associated channel fills develop on the slope, at the toe of slope, and on the basin floor. On the slope, they develop in confined settings such as intraslope basins or submarine canyons. Channel morphology and position within a turbidite system are controlled by depositional processes and are primarily erosional or depositional in origin (Mutti and Normark, 1991). Levee-overbank sediments consist predominantly of mud, but are also composed of thin-bedded sands. Thin-bedded sands are ideal stratigraphic traps owing to their lateral wedging and thin interbedding of sand and mud and sometimes have excellent porosity and permeability (Weimer and Slatt, 2004). Sheet sands are deposited at the termini of channels in an unconfined setting. They tend to have simple reservoir geometries: good lateral continuity, potentially good vertical connectivity, high net:gross (sand/shale) ratios, narrow range in grain size (and thus greater porosity and permeability), and few erosional features (Weimer and Slatt, 2004).

Outcrop Analogs and Well Log Interpretation

Outcrop exposures were used as an analog for pre-drill forecasting of the depositional environments of the targeted sandstone sequence in the Rex Timber well. Shell's interpretations were similar to others published on the Stanley and Jackfork where the overall depositional environment is characteristic of an ancient deepwater submarine fan (turbidite) deposit (Morris, 1977a; Coleman, 2000; Slatt et al., 2000). Core samples from the well provided important downhole information, but were of little help in reconstructing the depositional environment due to a lack of intercepted sandstone or a lack of logs available through the cored interval.

Dual induction logs can be used as a tool to suggest the types of depositional environments. Analysis of resistivity logs in the Rex Timber well demonstrates several common log shapes that have been suggestive of distinct depositional environments. There are five main characteristic log shapes identified in the Jackfork and Stanley Formations which are illustrated in Figures 7A-C. The shaly log signature seems to correlate to either the pelagic or distal (4B) facies of Morris (1977a). The serrate package of thin interbedded sands and shales are similar to Morris' (1971) distal facies or Walker's (1978) lower fan facies. Selly (1978) regarded coarsening upwards successions as distal turbidite fan sequences and placed fining upwards sequences into a proximal turbidite setting. Walker (1978) places coarsening upwards sequences either in the lower fan or on the smooth portion of suprafan lobes (mid-fan). Walker's fining upwards sequence is indicative of the channeled portion of suprafan lobes. The blocky sequences are characteristic of thick channel fill deposits (Selly, 1978). Walker (1978) also shows a model of a submarine fan and some, but not all, of the environments of the observed log shapes could be correlated with the Rex Timber well.

The upper 1,000 ft (305 m) of the Rex Timber well consists predominantly of blocky sandstones defining substantial channel fill characteristic of upper fan or uppermost mid-fan (Figure 7A). From 1,000 to 4,000 ft (305 to 1,219 m), the blocky log shapes (30-150 ft or 9-46 m thick) are interbedded with both fining and coarsening upwards sequences (40-150 ft or 12-46 m and 30-150 ft or 9-46 m thick, respectively). These relations are interpreted as a series of prograding, overlapping suprafans. Lower fan deposits are present on the log from 4,000 to 5,300 ft (1,219 to 1,615 m), and consist of coarsening upwards sequences (50-250 ft or 15-76 m thick) that are interbedded with occasional minor shaly intervals. The lower 1,000 ft (305 m) of the well log (5,300-6,300 ft or 1,615-1,920 m) is characterized by serrate sequences (100-300 ft or 30-91 m thick) and thin shaly intervals (20-40 ft or 6-12 m thick) (Figure 7C). The lower portions of the Rex Timber stratigraphic succession are interpreted as the distal portion of the lower fan.

Structural Evaluation

The Moccasin prospect is interpreted as a potential structural culmination along an elongate anticline referred to as the Arkadelphia Anticline (Figure 1), which has

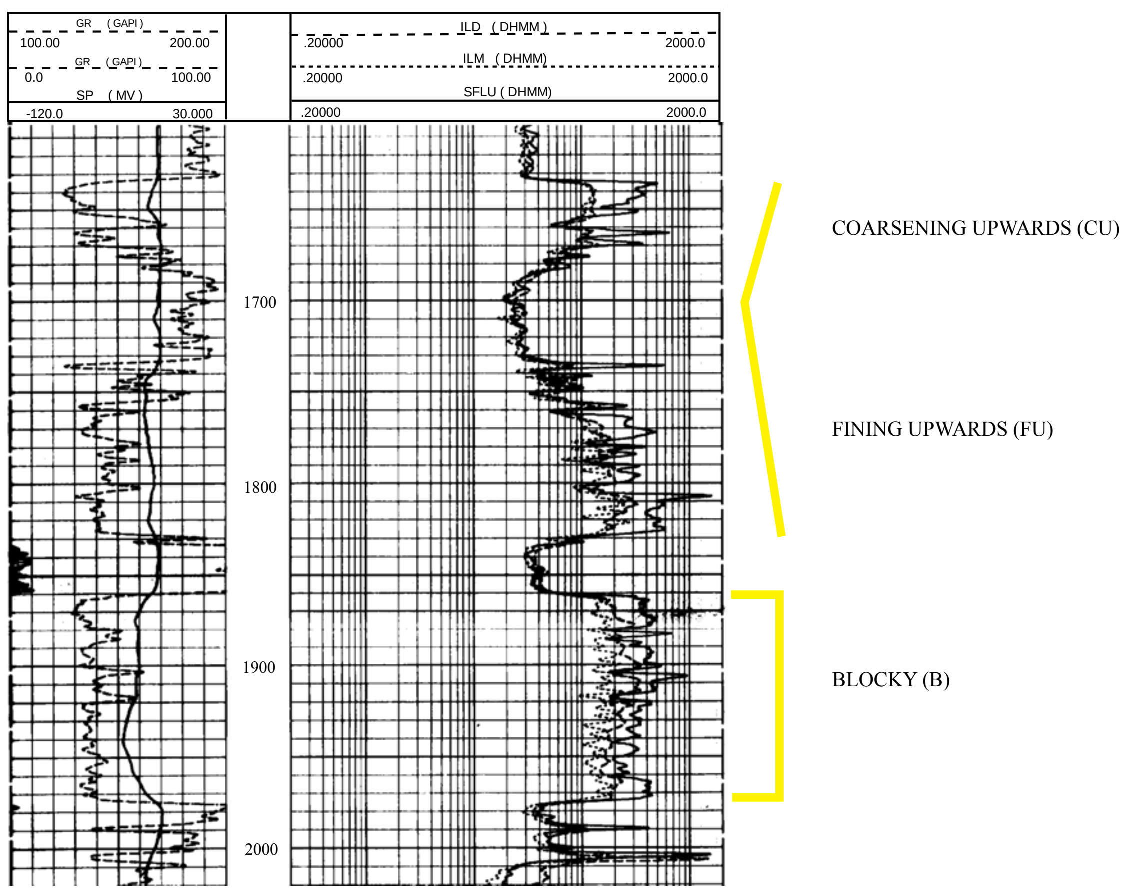

Figure 7A. Interpreted electrical log shapes from the Rex Timber No. 1-9 well (1,700 – 2,000 ft).

steeply dipping flanks of 60-65°. This projected anticline is exposed west of the Moccasin prospect and is thrusted northward over the Chalybeate Syncline. An eastern

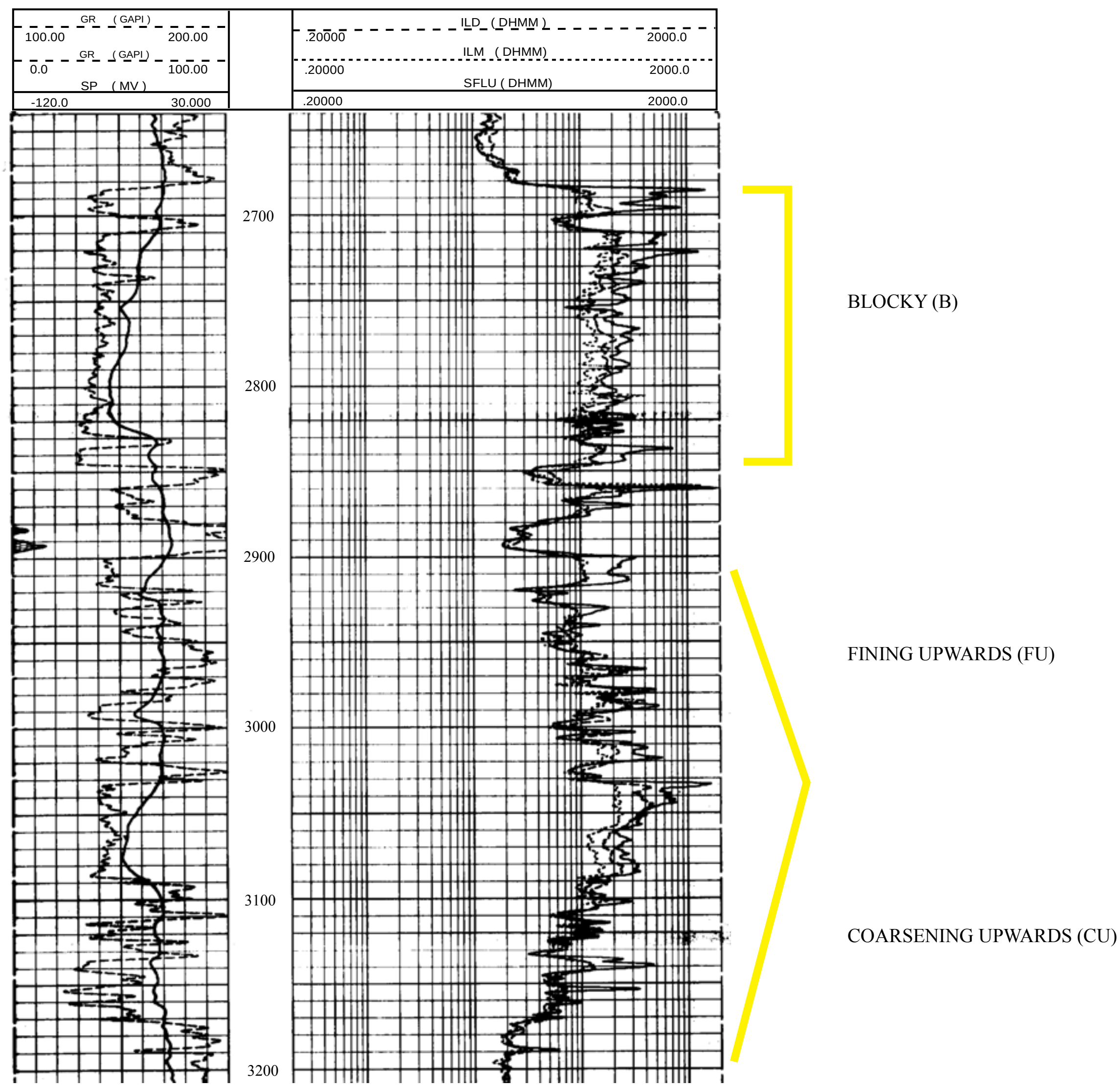

Figure 7B. Interpreted electrical log shapes from the Rex Timber No. 1-9 well (2,640 – 3,200 ft).

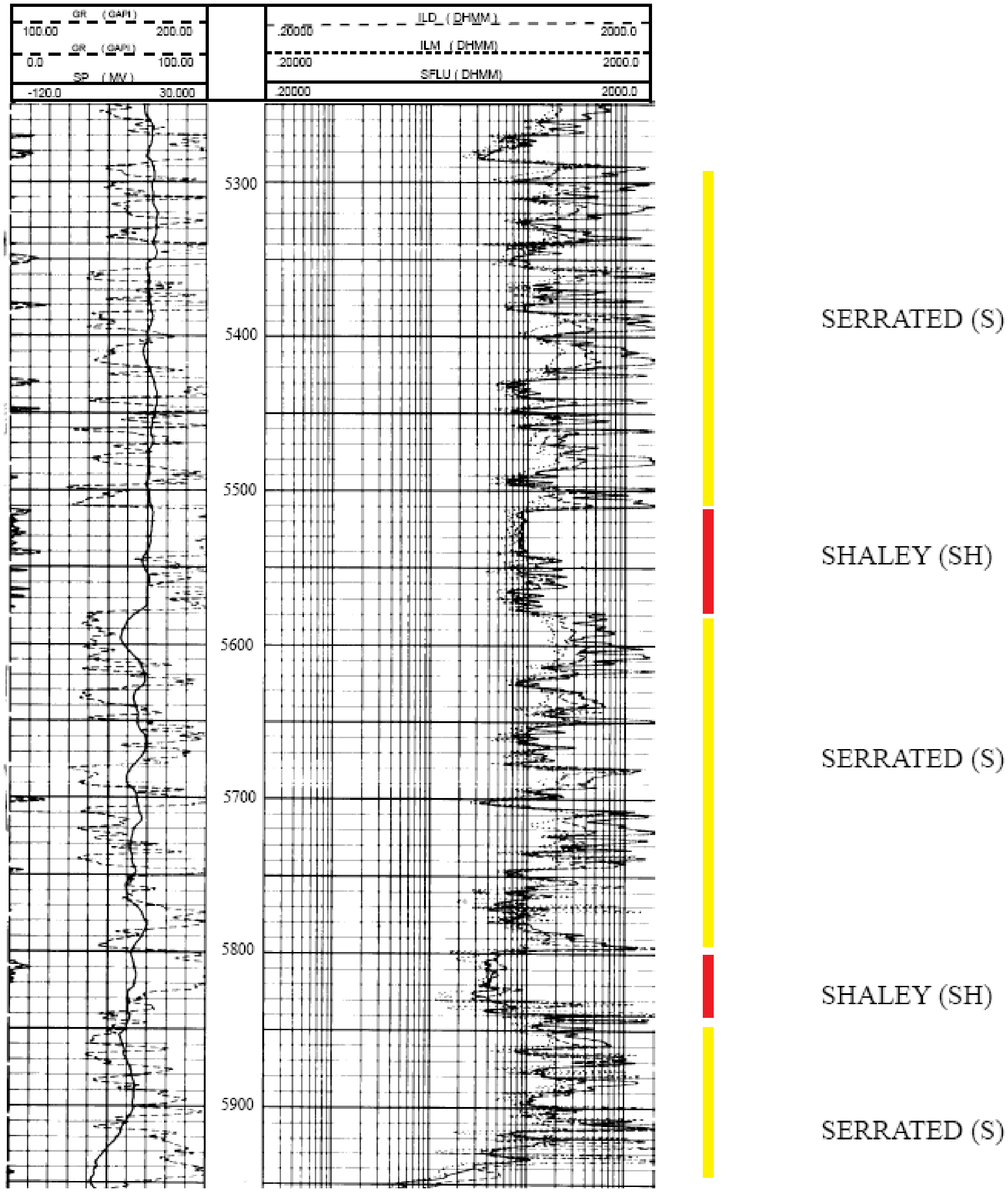

Figure 7C. Interpreted electrical log shapes from the Rex Timber No. 1-9 well (5,250 – 5,950 ft).

plunge may exist for the Arkadelphia anticline in the Moccasin prospect area based on projection of bedding attitudes into the subsurface (Figure 1). This anticline is truncated on its eastern edge by the Decipher fault that turns southward before being covered by a Cretaceous unconformity. The Decipher fault is thought to provide a potential sealing element on the western edge of the Arkadelphia anticline. There is no information from seismic surveys to confirm this directly or to document a plunge in either an east or west direction for the Arkadelphia anticline penetrated by the Rex Timber well. If there were more evidence to suggest a plunge direction, then more support would exist for a structural culmination on the anticline. It is Shell's opinion that there are many more structural complications at depth along the anticline at the Rex Timber well site based on surface geological relations; however, the seismic surveys show only a relatively simple upright fold that is associated with a single thrust fault (Figure 8).

The subsurface evidence generated from the Rex Timber well supports confirmation of the structural interpretation of the Moccasin prospect. Based on dip meter and borehole televiewer data (BHTV), the dominant dip in the borehole is to the north, which at least confirms the critical north dip, an essential component of the trap. A significant amount of information about fracture patterns within the structure was also obtained from the BHTV survey, which is compiled in an internal Shell report. The detailed results of the fracture survey are not presented herein and contain some elements of existing confidentiality.

Borehole Televiewer Analysis

The Borehole Televiewer (BHTV) was a common geophysical tool used during the 1980s when the Rex Timber well was drilled and provided detailed image data such as bed dips, fracture patterns and rock density. The BHTV is an acoustic logging tool conveyed by a logging cable and images the rock in the borehole. Originally developed in the research lab at Mobil in the 1960's, it was used only sparingly before losing company support. In the 1970's Amoco, then later Shell began to redevelop, upgrade, and use this tool more readily. By 1981 the upgraded version of the BHTV viewer was more readily used by Shell for down hole logging applications. As the BHTV detects relative differences in impedance along the borehole, an image is produced on paper in which the sonic variance of the rock is produced in sixteen (16) shades of gray.

The Ouachita Mountains are structurally complex and bedding orientations in well bores cannot be distinguished from fracture orientations with a typical resistivity contrast dipmeter. The dipmeter measures fractures as well as bedding and may show 60-100 ft (18-30 m) gaps between readings. In contrast, the BHTV presents a continuous image of the borehole and allows bedding to be distinguished from fractures. For these reasons, the BHTV log was used to determine fracture orientations, fracture densities and bedding orientations in the Rex Timber well. In addition, small-scale folding (wavelengths <100 ft or 30 m) and small displacement thrust faulting were also documented in the well bore. Eighteen drilling breaks were correlated to major sandstone to shale lithologic boundaries and thin sandstone lenses were observed in shales of the Jackfork Formation. Dense, high velocity sandstones, limestones and dolostones tend to reflect high amplitude signals and appear light-colored on the BHTV log presentation.

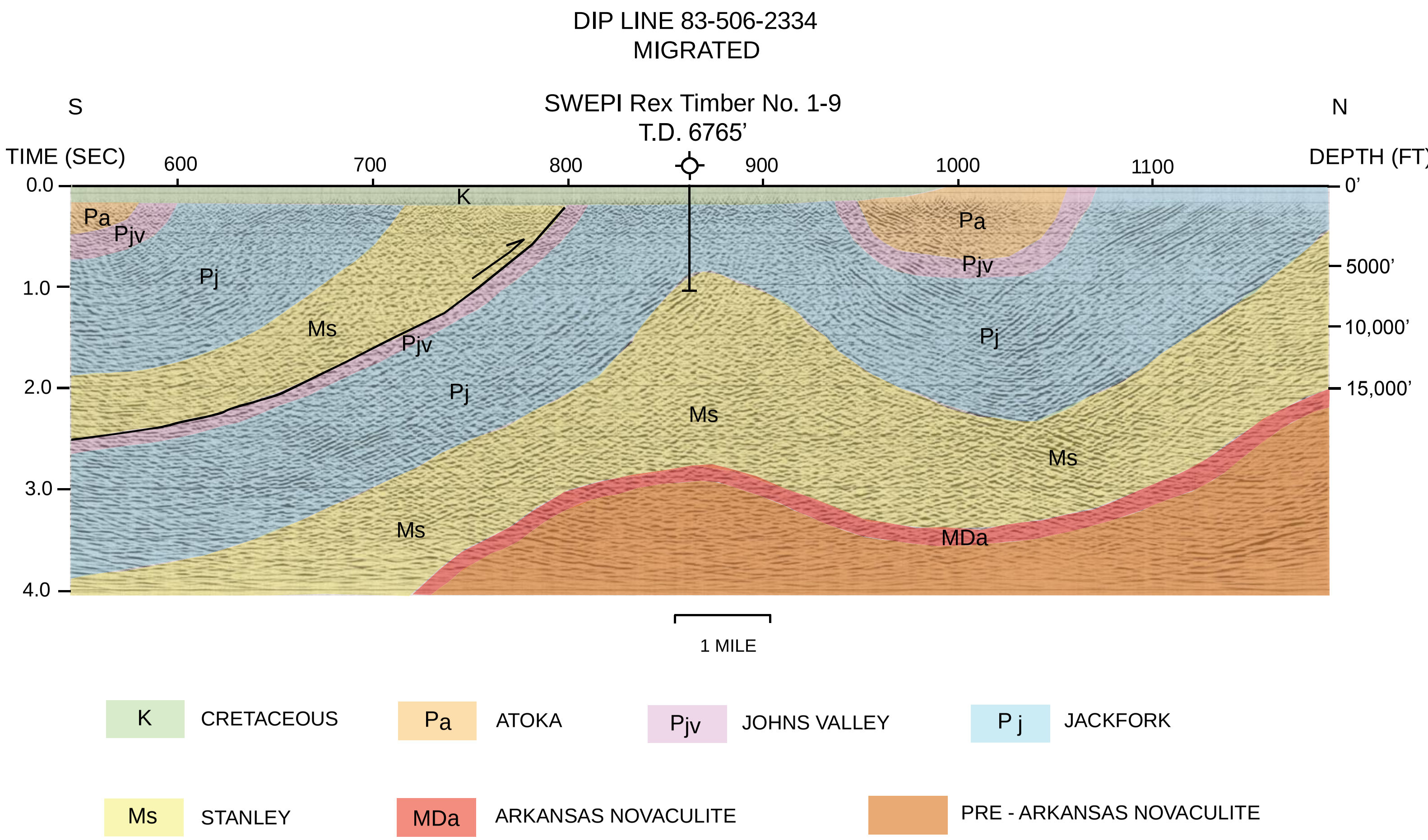

Figure 8. Seismic line 83-506-2334 (migrated stack) displaying a dip section of the Moccasin prospect.

Less dense, lower velocity shales tend to reflect low amplitude signals and appear dark-colored. Areas of borehole caving and open fractures also reflect low amplitude signals and appear dark-colored.

Fractures on the borehole televiewer display have more irregular orientations and spacing than bedding and the fractures cross-cut bedding at high to low-angles (Figure 9A). High-angle fractures are better resolved than low-angle fractures using the BHTV because of the greater trough to crest distance (Figure 9B). Open fractures are most often observed on the BHTV display because calcite or quartz filled fractures reflect high amplitude signals.

Open fractures are observed in the brittle sandstone lithologies throughout the well. Both the upper Stanley and the lower Jackfork contain numerous sandstone beds, with the Jackfork dominated by sandstone successions. Abundant and randomly oriented high-angle (>50^o) extension fractures are observed in the upper Jackfork. Low-angle (20-50^o) shear fractures are localized into clusters in the lower interval of the well. These clusters are separated by zones of undeformed sandstone (Figure 9C).

The change in fracture orientation with depth reflects the changing stress field from extension to compression as the well penetrates deeper into the Arkadelphia anticline. Dieterich and Carter (1969) studied the orientation of the stress field for two dimensional folding of a viscous layer in a less viscous matrix. They determined that the direction of most compressive stress (σ_1) is parallel to bedding prior to folding. As folding is initiated and continues the σ_1 direction rotates to a higher angle relative to the limbs and the outer hinge of the folded layer. The σ_1 direction remains parallel to bedding in the core of the folded layer throughout folding (Figure 9D). This orientation of the

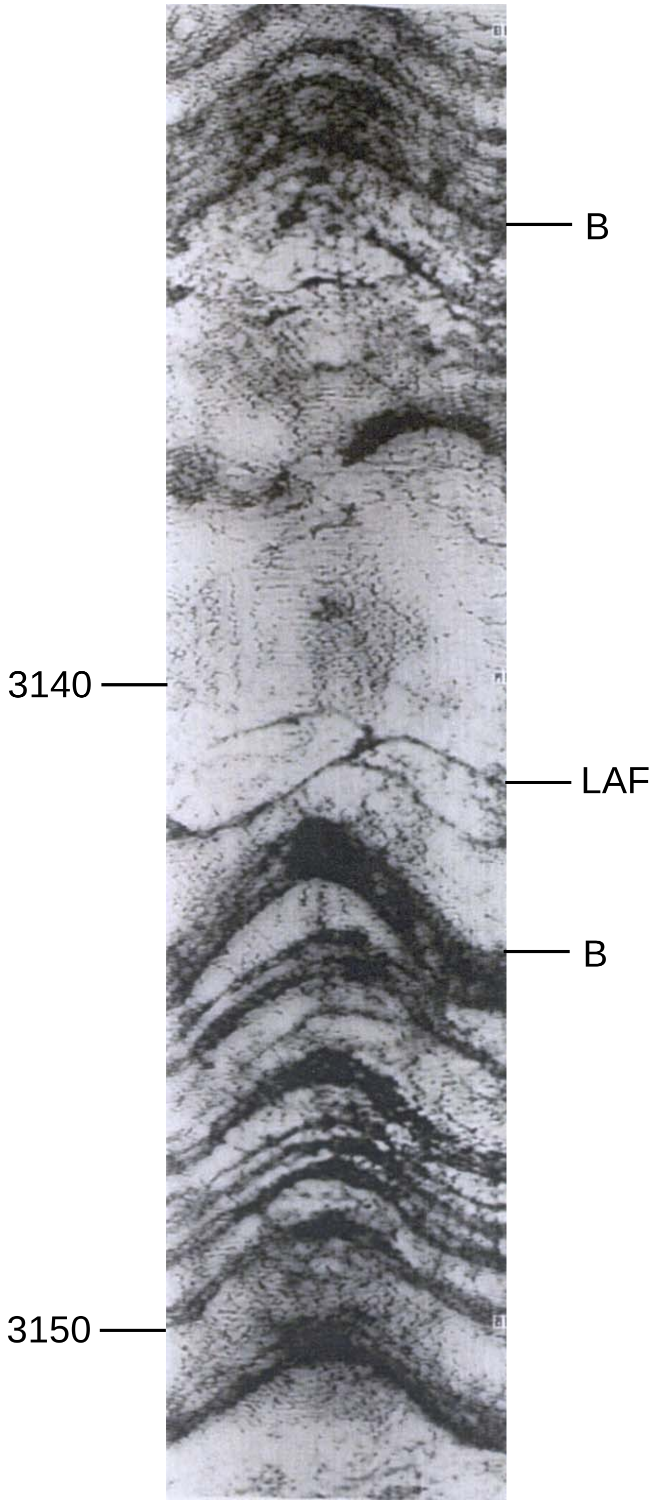

Figure 9A. Low-angle fractures (LAF) and bedding (B).

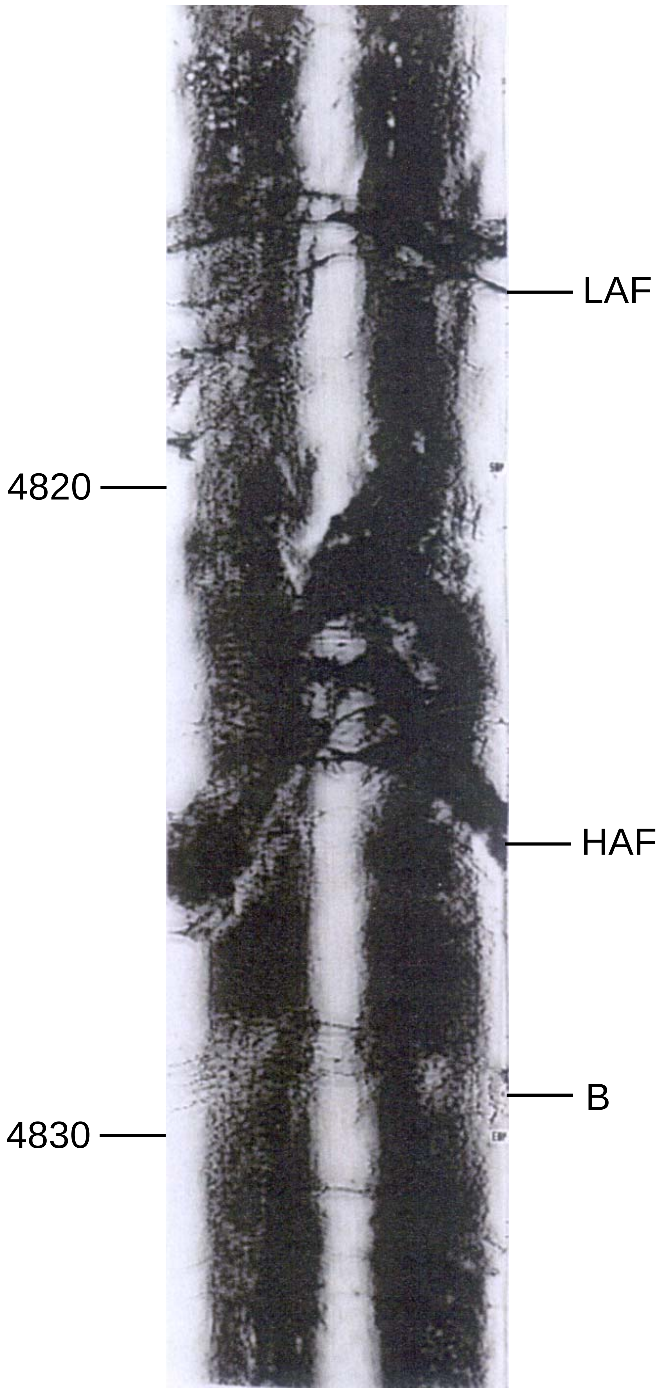

Figure 9B. Low-angle fractures (LAF) and high-angle fractures (HAF).

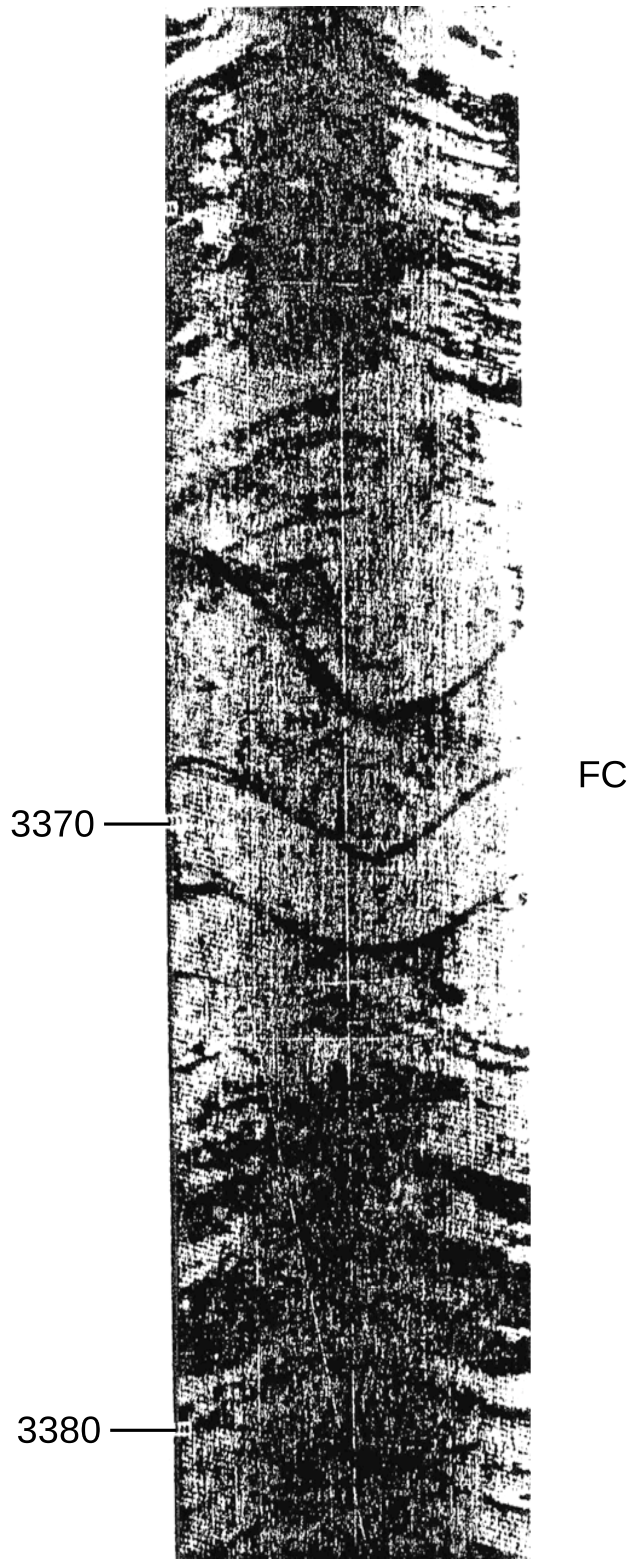

Figure 9C. Fracture cluster (FC) with undeformed sandstone above and below.

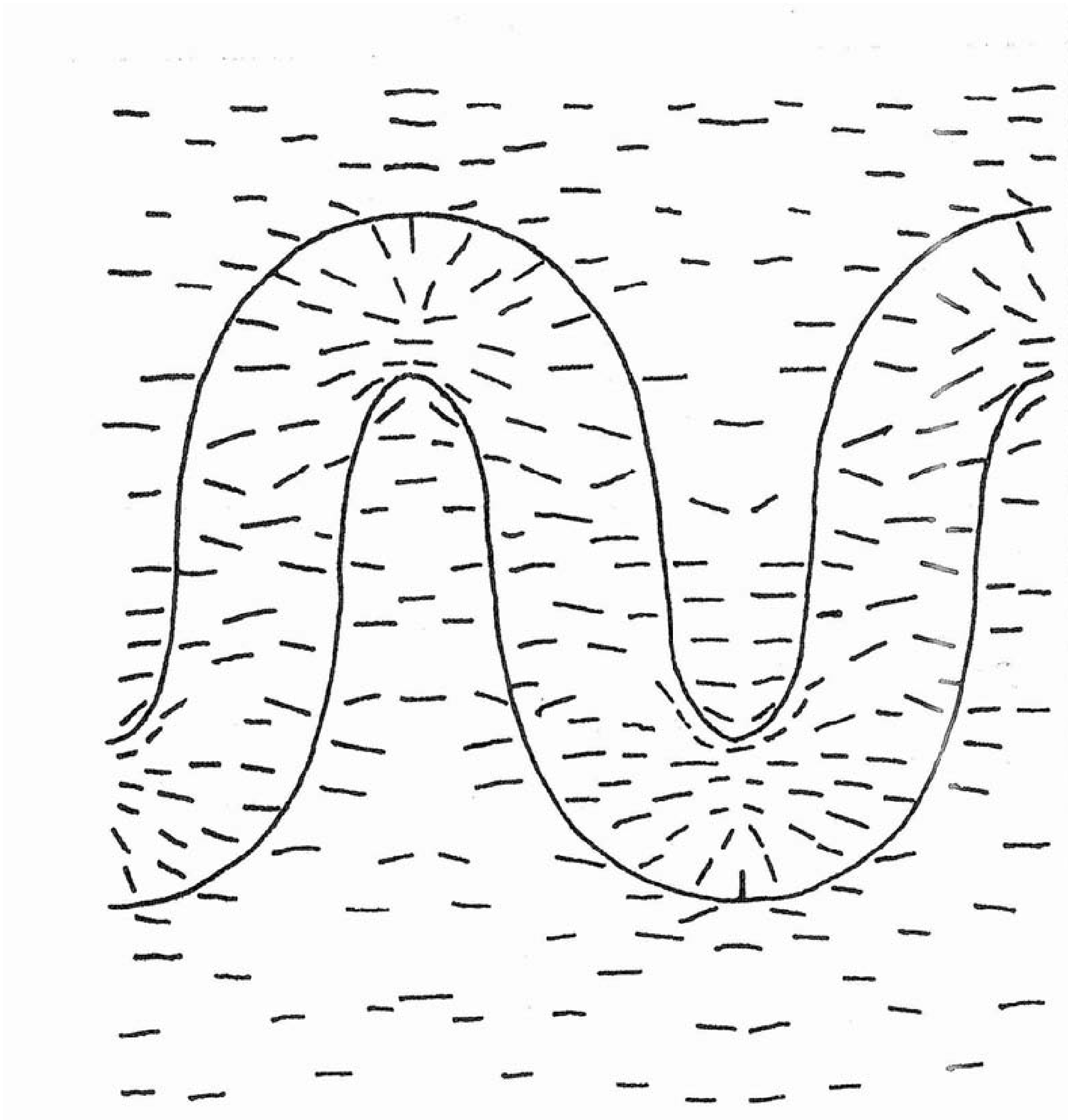

Figure 9D. Lines drawn parallel to the direction of maximum compressive stress (σ1) during folding (modified from Dieterich and Carter, 1969).

stress field produces extension on the outer hinge and limbs and compression in the core of the fold. Hobbs et al. (1976) experimentally deformed a block of Solenhofen Limestone and determined the orientation of fractures relative to the σ_1 direction. Their results showed that conjugate shear fractures and extension fractures form when σ_1 is parallel to bedding and normal to bedding, respectively. These results also confirm the field observations of Stearns (1968) on the orientation of fractures that form by folding.

Using the structural models from the authors cited above, the fracture orientations observed in the Rex Timber well are explained by the orientation of the stress field during folding. High-angle extension fractures are dominantly observed above 2,684 ft (818 m) in the well and low-angle shear fractures are prevalent below 2,684 ft (818 m). These changes in fracture orientation reflect the rotation in the σ_1 orientation from dominantly normal to bedding above 2,684 ft (818 m) to dominantly parallel to bedding below 2,684 ft (818 m) in the well.

Bedding throughout the interval of 1,271-2,229 ft (387-679 m) shows dips of 30 to 50^{o} northwest to northeast. A zone of small-scale folding above a thrust fault was observed within the interval of 2,299-2,397 ft (701-731 m). The beds in this interval showed north, vertical and south dips (Figure 9E). The changes in bedding orientation were gradual throughout the rest of the interval of 2,397-6,324 ft (731-1928 m) and dips ranged from 40-50^{o} northeast to northwest. Lenticular bedding was also observed in the Jackfork Formation (Figure 9F). These thin sandstone lenses suggest small suprafan lobes, which may have been deposited on a mid submarine fan by turbidity currents.

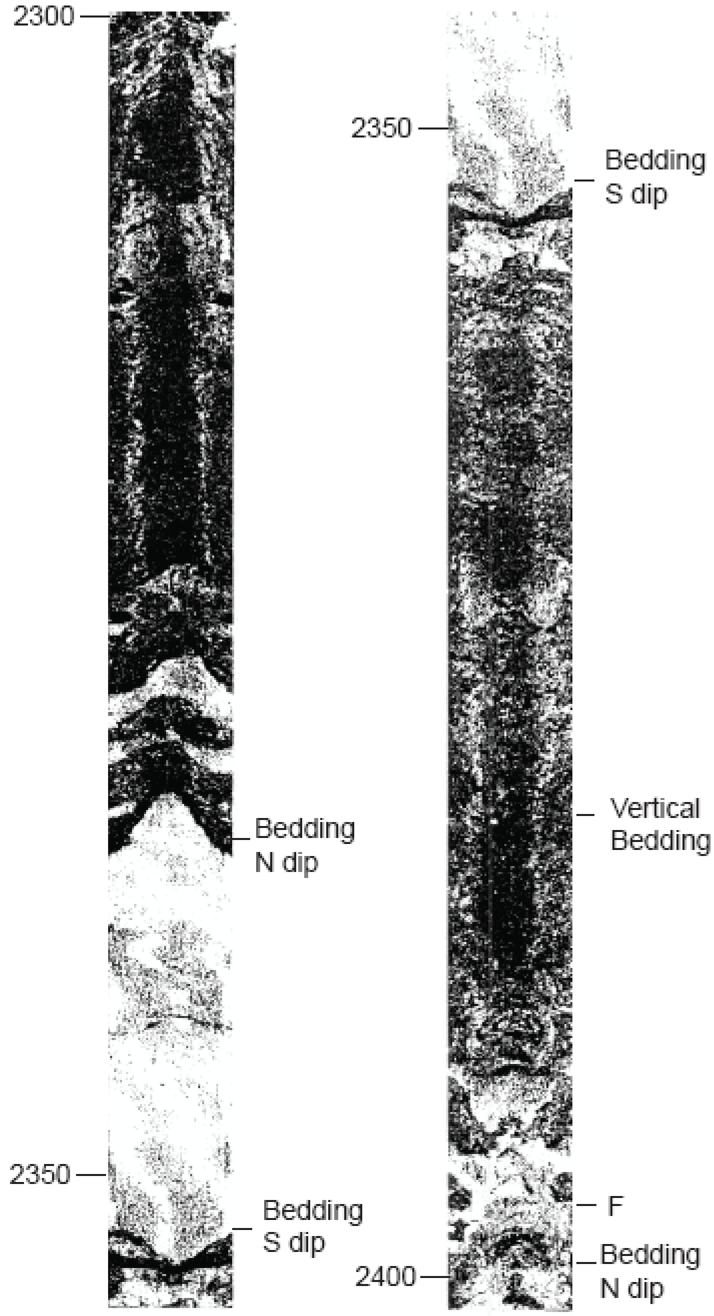

Figure 9E. Interval of 2,299-2,397 ft (701-731 m) showing fold above a thrust fault (F).

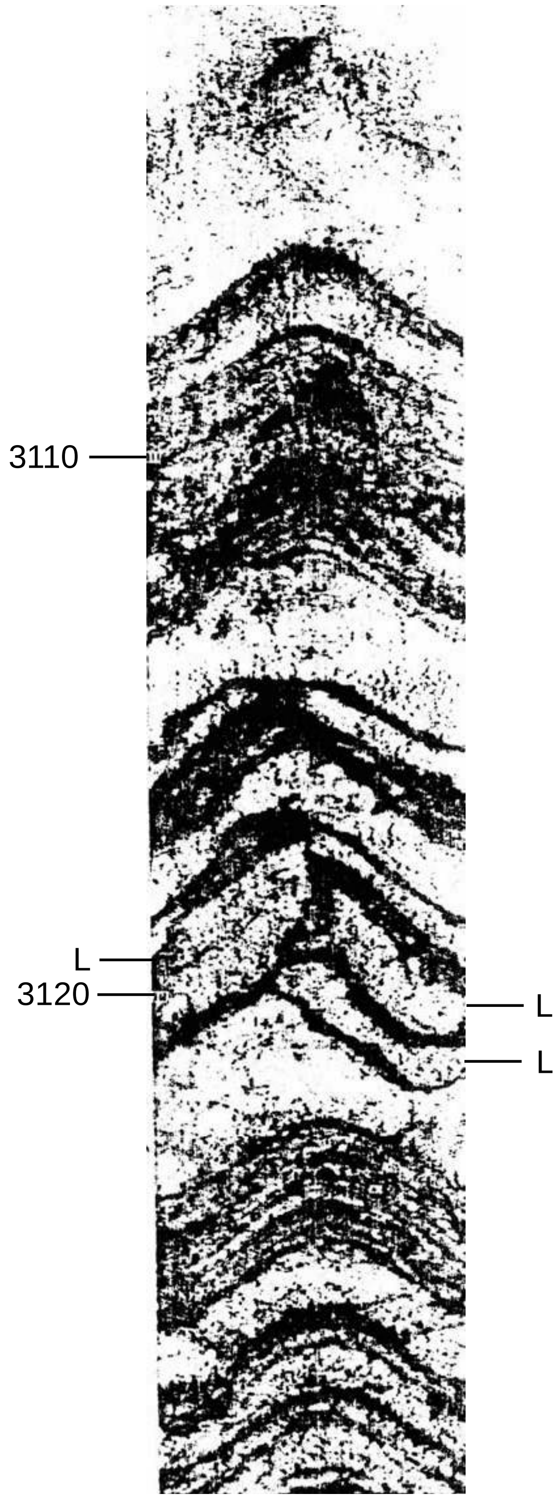

Figure 9F. Lenses (L) of Jackfork sandstone in shale.

Sandstone Petrology

General Discussion

Shear (2006) studied Jackfork outcrops in an inactive gravel quarry located north of Highway 7 near the De Gray Lake spillway in Clark County, Arkansas. The Rex Timber well is approximately 7 mi (11 km) south of Shear's study area.

The Jackfork Formation is subdivided into upper, middle, and lower parts in this area of Arkansas. Based on the work of Slatt et al. (2000), the lower Jackfork is a mixture of amalgamated and layered sheet sandstones and interbedded, lenticular, channel sandstones. The middle Jackfork is interpreted as channel-fill sandstones with associated levee/overbank deposits at its base. The upper Jackfork has two different depositional sequences of lowstand deposits, with two associated sequence boundaries.

The sandstones in the upper Jackfork outcrops contain a high concentration of quartz cement. The middle Jackfork sandstones contain a high concentration of clay in the matrix with few quartz overgrowths. The matrix consists primarily of kaolinite, which is more easily dissolved and eroded than quartz cements and thus is the cause of friability in the middle Jackfork sandstones. On average, the sandstones in the middle Jackfork are 17% more friable than the upper Jackfork, and contain 12% more unconsolidated zones than the upper Jackfork.

Shear (2006) also correlated outcrops from his study area to the Rex Timber well for comparison of petrologic characteristics of the Jackfork. Friability was identified at depths between 2,700 and 5,000 ft (823 and 1,524 m). Within the middle Jackfork, 58% of the total sandstones range from slightly friable to unconsolidated, while 41% of the upper Jackfork sandstones range from slightly friable to unconsolidated according to

Shear (2006). Subsurface friability can also be inferred by noting intervals of increased drilling rates, and increase in grain size and by the evaluation of mud logging notes that describe friability and hardness of cuttings.

Natural gas is generally thought to be held in fractures associated with the cemented sandstones (Garich, 2004). However, the friable middle Jackfork sandstones in Arkansas may be an untapped gas reservoir (Shear, 2006). Garich (2004) and Romero (2004) found that friable sandstones are interpreted to have been deposited in a channelized environment, as opposed to cemented sandstones deposited as sheets. These relations suggest that the identification of channelized environments in well logs can help locate similar friable sands.

Petrographic Analysis of Well Samples

Well samples that contain special characteristics (presence of hydrocarbons, porosity, etc.) were selected for thin section analysis by Shell. Sixty-two (62) thin sections made from ditch cuttings and representative of the well from surface to total depth were compiled. Luminescence petrography was employed primarily to differentiate between the effects of authigenic quartz overgrowths and quartz pressure solution. Shell also used scanning electron microscopy (SEM) to study the types of cements in the sandstones. A number of thin sections were also examined by Energy Dispersive Analysis of X-rays (EDAX).

Twenty-two (22) thin sections were selected for point counting in order to statistically determine the composition of the Jackfork and Stanley sandstones. The down-hole depth of the samples range from 520 to 6,390 ft (158 to 1,948 m). For each thin section, Shell petrographers counted 300 points to tabulate Appendix 2 in the fashion described by Van der Plas and Tobi (1965).

The upper (520-1,440 ft or 158-439 m) Jackfork sandstones are quartz arenites and the remaining sandstones are sublitharenites (Figure 10). The lithic components consist primarily of sedimentary and metamorphic fragments. The sedimentary fragments consist primarily of chert and shale, whereas the metamorphic fragments are mica schist. The feldspars include both K-feldspar and plagioclases. The percentage of rock fragments and feldspars illustrate an overall increase with depth (Figure 11).

Clay concentrations also increase with depth (Figure 11); however, there is no attempt in this project to differentiate between detrital and authigenic clays. Carbonate content shows no linear relationship with depth (Figure 11). The most interesting aspect about the carbonate content is the high concentrations identified in the well in comparison with information in published literature. Carbonate content of only 0 to 3% was reported for Jackfork sandstone from outcrops in southern Arkansas, whereas average carbonate content of 6.29% was documented in the Rex Timber well (Morris, 1977b; Morris et al., 1979; Stone and Lumsden, 1984). These relations suggest that surface leaching of the carbonates has likely occurred. This may be the primary reason that porosities from outcrop samples appear to contain good reservoir potential for the Jackfork and Stanley, which has yet to be encountered in the subsurface. In fact, the average carbonate content of 6.29% observed in the Rex Timber well is very close to the average amount of porosity (8.45%) in Jackfork outcrops surrounding the Moccasin prospect. Additionally, the pore geometries in Jackfork outcrops are very similar to the distribution geometry of carbonate from Rex Timber core samples (Stone and Lumsden, 1984).

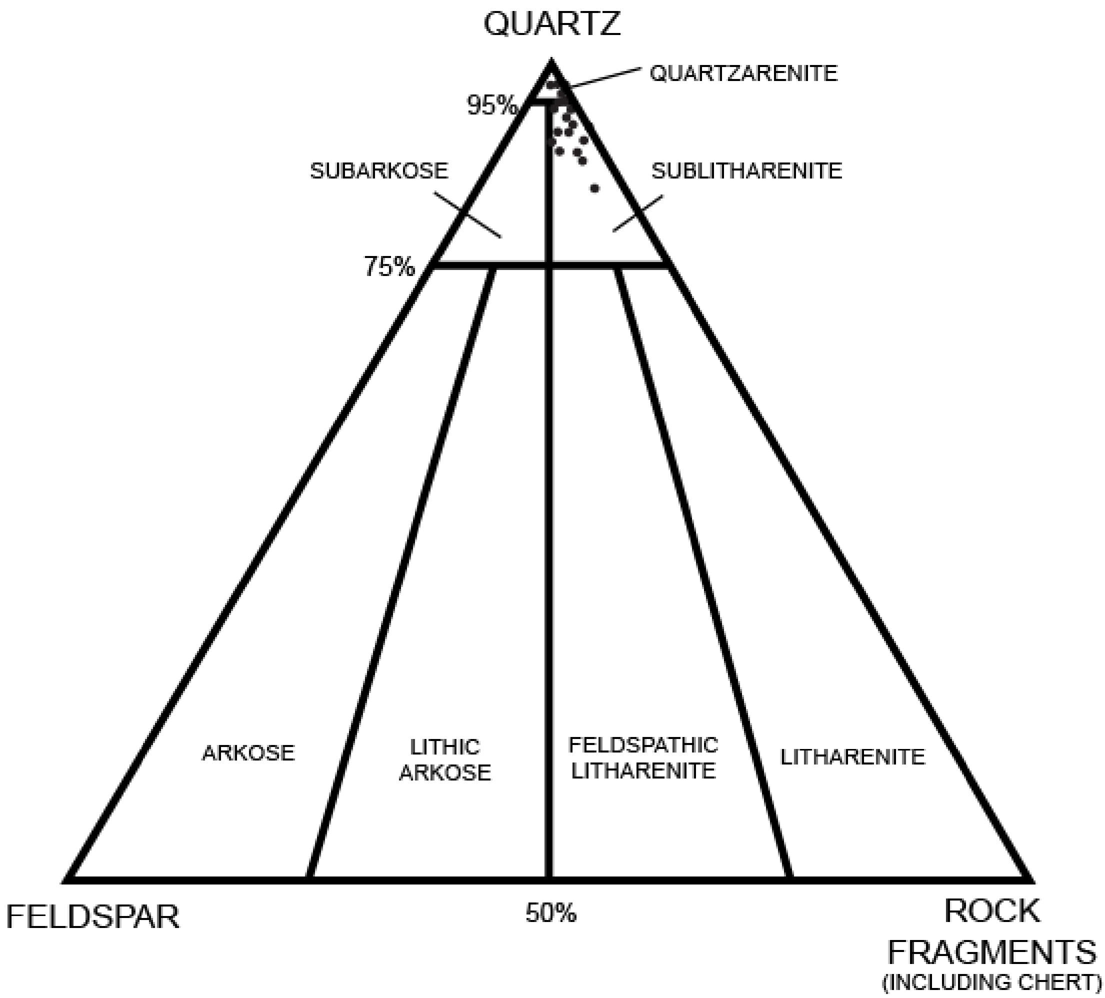

Figure 10. Classification of sandstone examined by point counting methods using twenty-two (22) thin sections from the Rex Timber No. 1-9 well. Classification scheme is from Folk (1968).

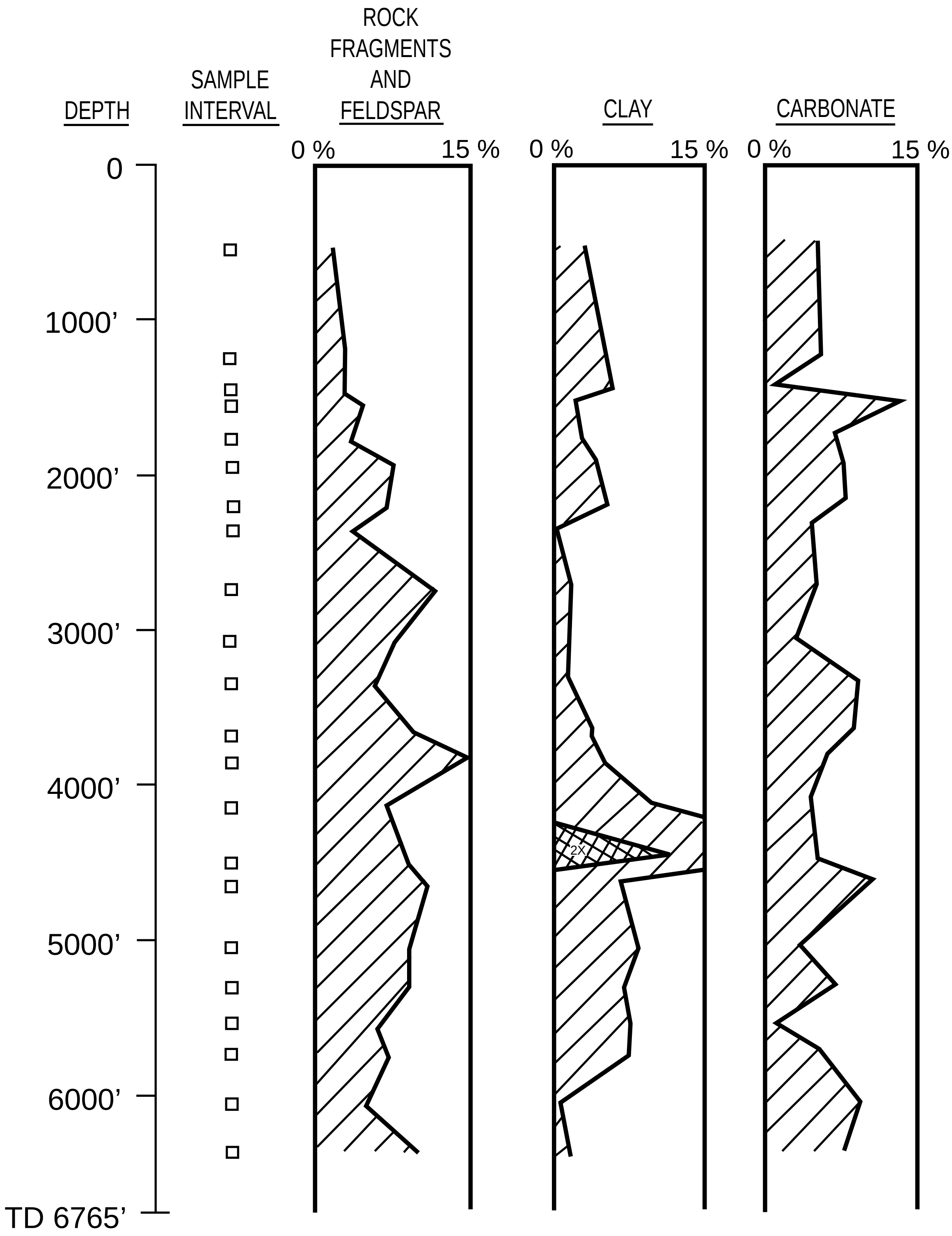

Figure 11. Constituents of sandstones examined in Rex Timber No. 1-9. Results based on point counts of thin sections from ditch cuttings (300 points per thin section).

Diagenesis

The present character of the Jackfork and Stanley sandstones is a consequence of significant diagenetic change. Diagenesis in addition to compaction within the Jackfork and Stanley sandstones of the Rex Timber has resulted in porosity destruction. The initial process of physical compaction of the sands resulted in diminishing the primary porosity as evidenced by long grain and concavo-convex grain contacts with some interpenetrative fabric. The most significant and detrimental diagenetic effect in the sandstones is pervasive silicification. This ubiquitous induration effect destroyed much of the primary porosity and may have inhibited the migration of fluids, which are necessary for the later creation of secondary porosity. The predominance of sutured detrital quartz grains, planar and concavo-convex detrital grain contacts, and a paucity of syntaxial quartz overgrowths suggest that most of the silica induration is due to pressure solution processes. Detrital quartz is differentiated from authigenic quartz (syntaxial overgrowths) by luminescence petrography (Plate 2). The lack of authigenic quartz development may have been due to silica under saturated pore fluids. In addition, most overgrowths are associated with poorly packed, elongate quartz grains. The pressure solution process may have resulted in the destruction of the intergranular porosity between equant shaped grains quicker than porosity that is associated with the elongate grains. Pore fluids would then have been enriched with silica allowing precipitation of authigenic quartz in the remaining pore spaces now restricted to areas with elongate grains and poor primary packing.

The process of pressure solution is the result of overburden pressure created by continued sedimentary loading or the compressional effects of tectonism. Extensive

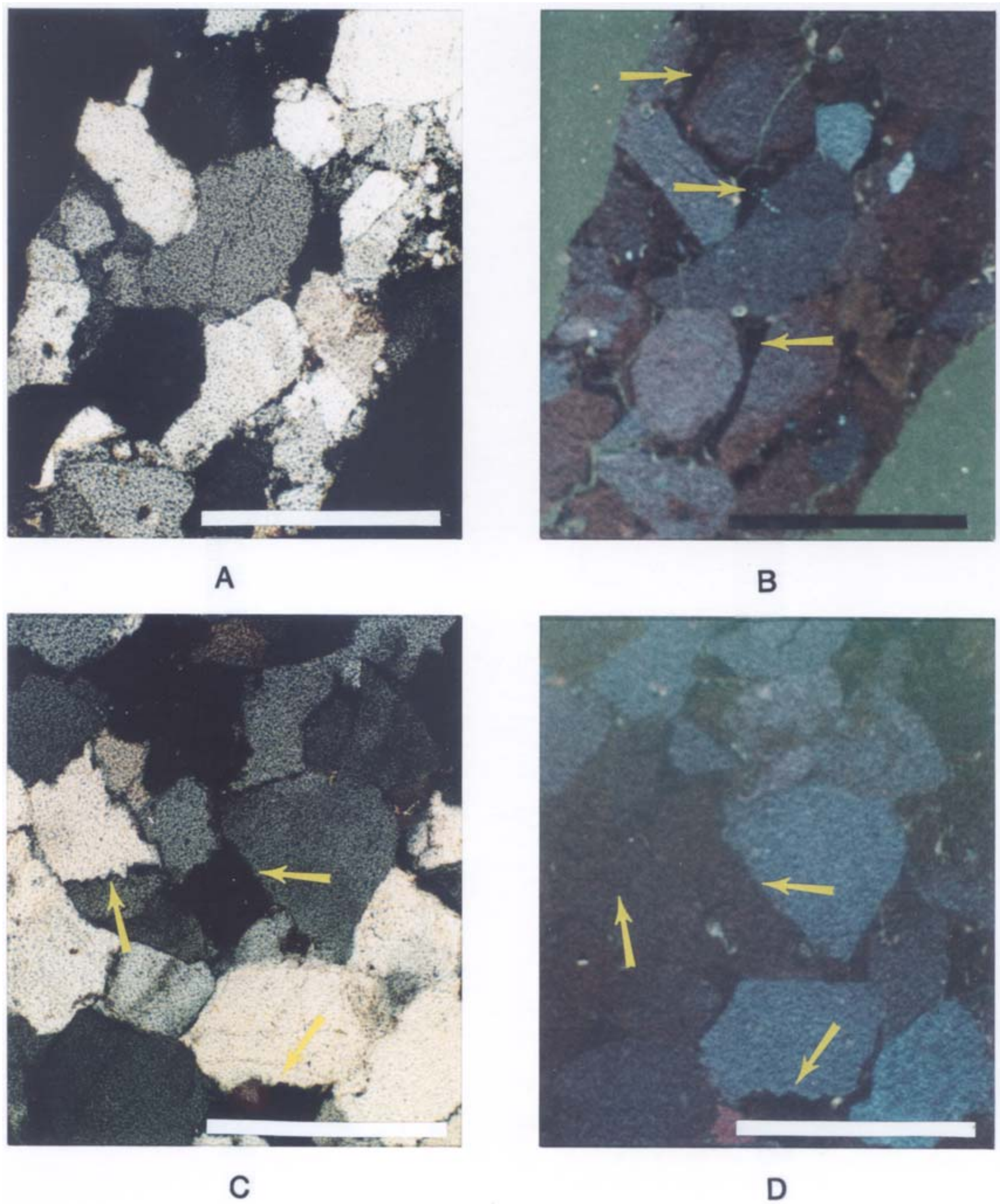

Plate 2. Photomicrographs and petrographic descriptions. A) 5,040 – 5,050 ft (1,536 – 1,539 m): Planar and concave-convex grain contacts (80X, crossed nicols). B) 5,040 – 5,050 ft (1,536 –1,539 m): Arrows point out very dull luminescence of quartz overgrowths. Rounded to sub-rounded detrital grains display brighter red and blue luminescence (80X, luminescence). C) 2,370 – 2,380 ft (722 – 725 m): Quartz displaying sutured, planar and concave-convex grain contacts (80X, crossed nicols). D) 2,370 – 2,380 ft (722 – 725 m): Contacts are between detrital grains, not the interfacing of syntaxial quartz overgrowths. Note absence of dark, nonluminescent authigenic quartz at arrows. (80X, luminescence). Bar scales are 0.5 mm.

fracturing is associated with the formation of the anticlinal structure drilled by the Rex Timber well. These fractures cut through detrital grains, grain contacts, and cements (Plate 3A). This cross-cutting relationship dates these pressure solution effects as pre-fracture, therefore, pre-structure formation.

Pressure solution of grains was inhibited in numerous samples. Detrital clays initially inhibited grains from undergoing pressure solution. Other inhibiting agents include early authigenic quartz, clay cements, and carbonate cements. Although these pressure solution inhibitors do exist, most of these minerals resulted in the filling of primary pores (Plate 3B, C, and D).

Alteration and dissolution of feldspars and rock fragments also occurred as the grains converted to clays, usually kaolinite (Plate 8A, B). As a result of high levels of compaction and pressure solution, these more labile grains had smeared the rock fragment around more rigid grains, effectively destroying still more intergranular porosity (Plate 4A).

Fracture cementation also occurred in the sandstones further reducing the reservoir potential. Potential for fracture porosity was greatly reduced by authigenic quartz cementation and later carbonate cementation. The only intragranular porosity is secondary in nature and is observed to be filled with late authigenic clay and quartz (Plate 4C, D).

In addition to the destructive diagenetic events in the Rex Timber well, there are several processes that made some, but small amounts of secondary porosity. They include the alteration and replacement of the original constituents of the rocks. The most important of these is the introduction of carbonates as a replacement material.

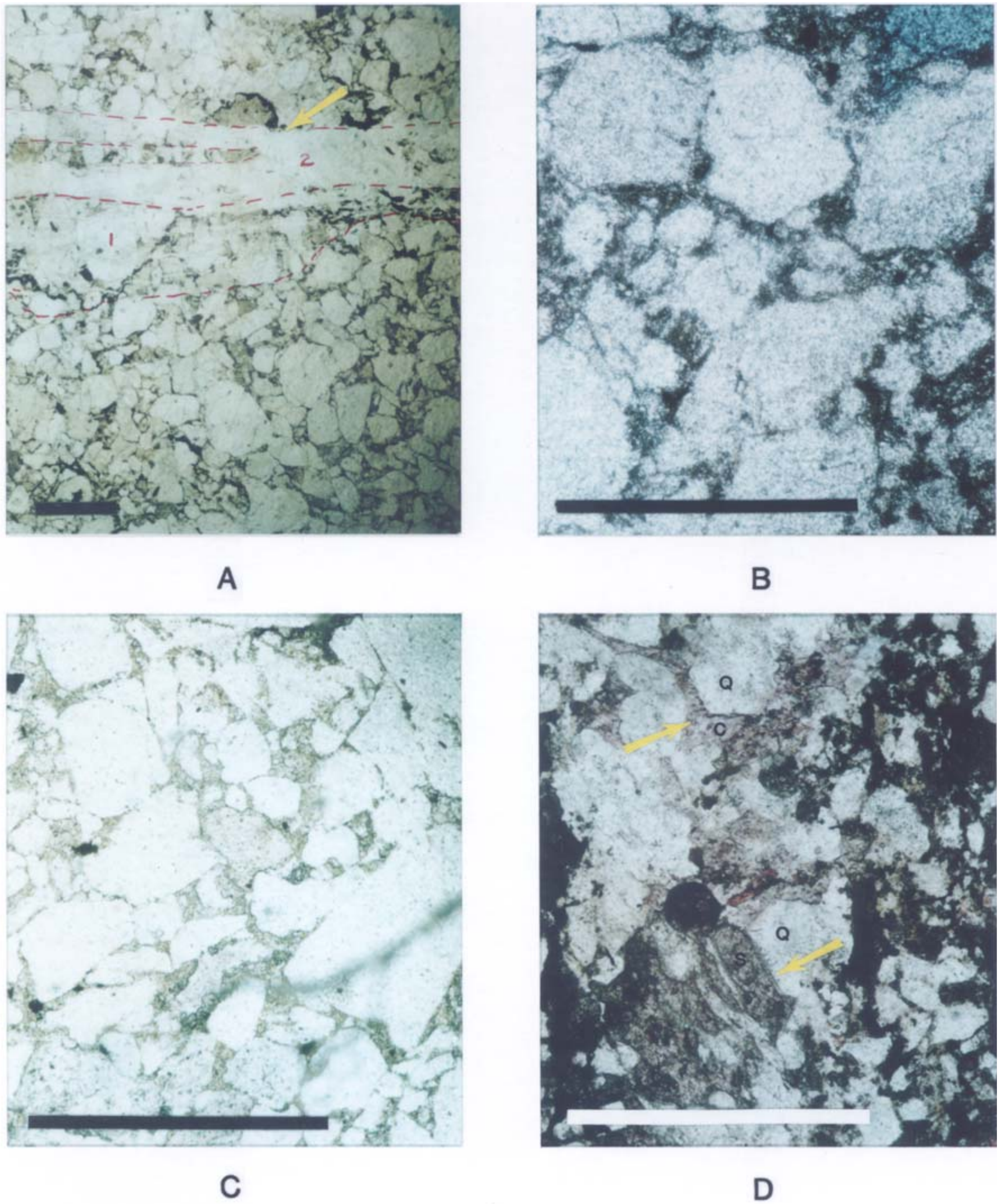

Plate 3. Photomicrographs and petrographic descriptions. A) 1,530 – 1,540 ft (466 – 469 m): Quartz filled fracture cutting through grains, sutured contacts and cement (25X, plain light). B) 5,210 – 5,220 ft (1,588 – 1,591 m): Detrital clay inhibiting pressure solution and filling pores (100X, plain light). C) 4,670 – 4,680 ft (1,423 – 1,426 m): Clay cement (chlorite) inhibiting pressure solution and filling pores (100X, plain light). D) 2,620 – 2,630 ft (799 – 802 m): Alizarin red stained calcite cement (C), with quartz grains (Q) being replaced by siderite (S) (100X, plain light). Bar scales are 0.5 mm.

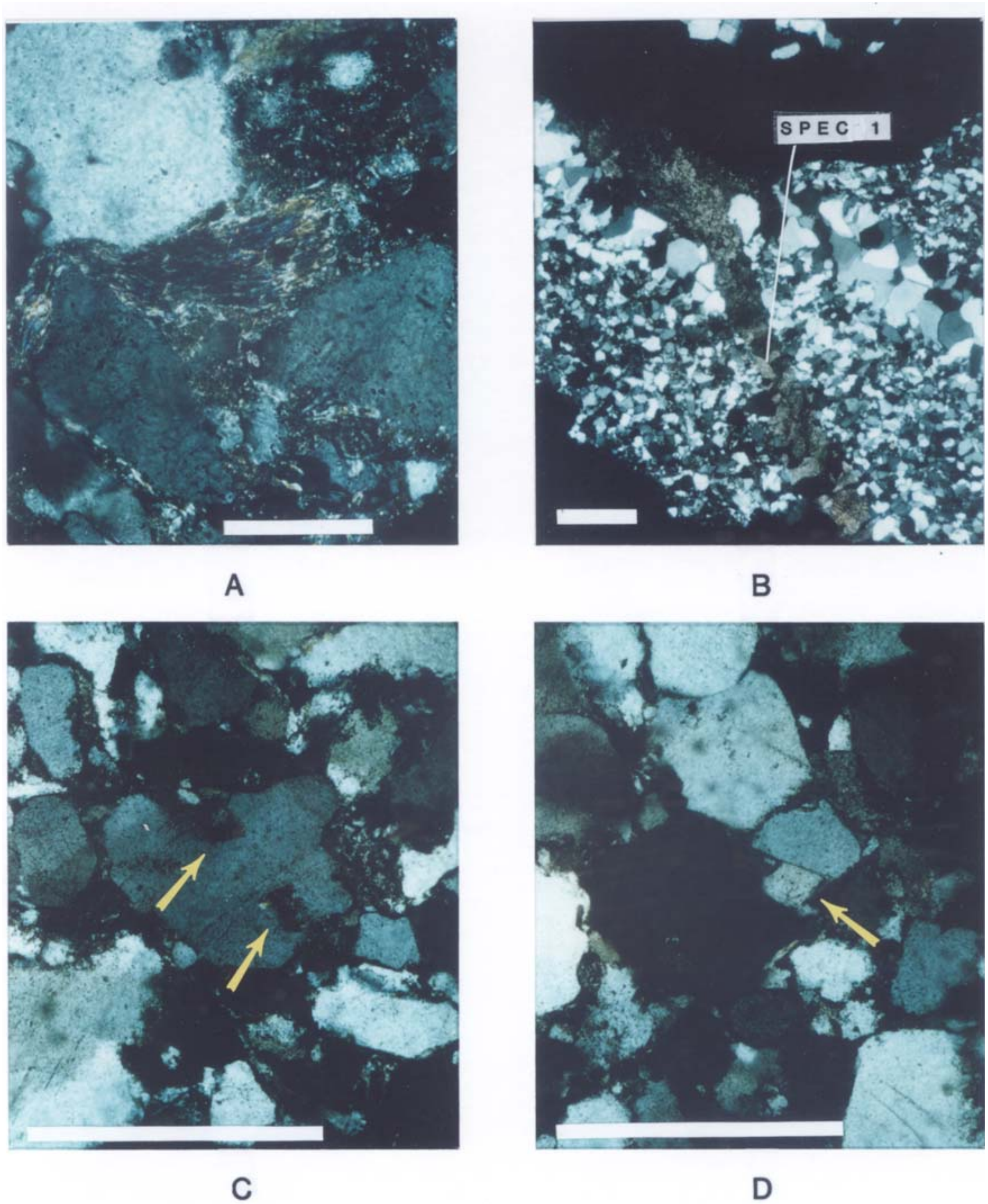

Plate 4. Photomicrographs and petrographic descriptions. A) 3,790 – 3,800 ft (1,155 – 1,158 m): Deformed metamorphic rock fragment. Bar scale is 0.1 mm (250X, crossed nicols). B) 3,508 ft (1,069 m): Carbonate filled fracture cross-cutting quartz-filled fracture (25X, plain light). C) 1,480 – 1,490 ft (451 – 454 m): Rhombohedral intragranular porosity filled with clay (100X, crossed nicols). D) 1,480 – 1,490 ft (451 – 454 m): Apparent rhombohedral intragranular porosity filled with quartz (100X, crossed nicols). Bar scales for B, C and D are 0.5 mm.

The carbonate content of the sandstones in the Rex Timber well varied considerably. The average amount of carbonate determined by petrographic examination is 6%, and ranged from 1 to 15%. The presence of carbonate would potentially enhance the creation of secondary porosity creation as carbonate cement is more easily dissolved than silica (note: outcrop porosities are greater due to surface leaching). The most dominant carbonate observed in the Stanley and Jackfork sandstones is siderite ($FeCO_3$). Calcite cement and dolomite are present in minor amounts (Plate 3D and Plate 8C). An EDAX elemental spectrum displayed siderite as prominent in iron peaks and is absent in calcium peaks (Figure 12). Siderite is a widespread replacive agent, occurring with quartz, feldspar and chert (Plate 5) and is also observed as very fine-grained crystalline cement (Plates 6C, D). This cement may be a secondary pore-filling material or a replacement of an earlier clay cement (Plate 6A, B). In some samples, siderite has clearly replaced the earlier carbonate. Blade-shaped crystals of siderite are observed filling dolomitic fractures (Plate 8D). The EDAX elemental spectrum analysis showed a definite increase in iron and decrease in calcium adjacent to the siderite crystals suggesting that the dolomite was converted to siderite (Figure 12).

The source of the carbonate is not easily determined. Within the Ouachita stratigraphic section there are no significant limestones in proximity to the Jackfork and Stanley Formations to allow the redistribution of carbonates. The shales penetrated by the Rex Timber well are not calcareous. Therefore, the water expelled during compaction of the shales was probably undersaturated with carbonate. The most plausible source for carbonate is the dissolution of carbonate skeletal grains. Fragments of bryozoans and other unrecognizable fossil fragments are observed in minor amounts in

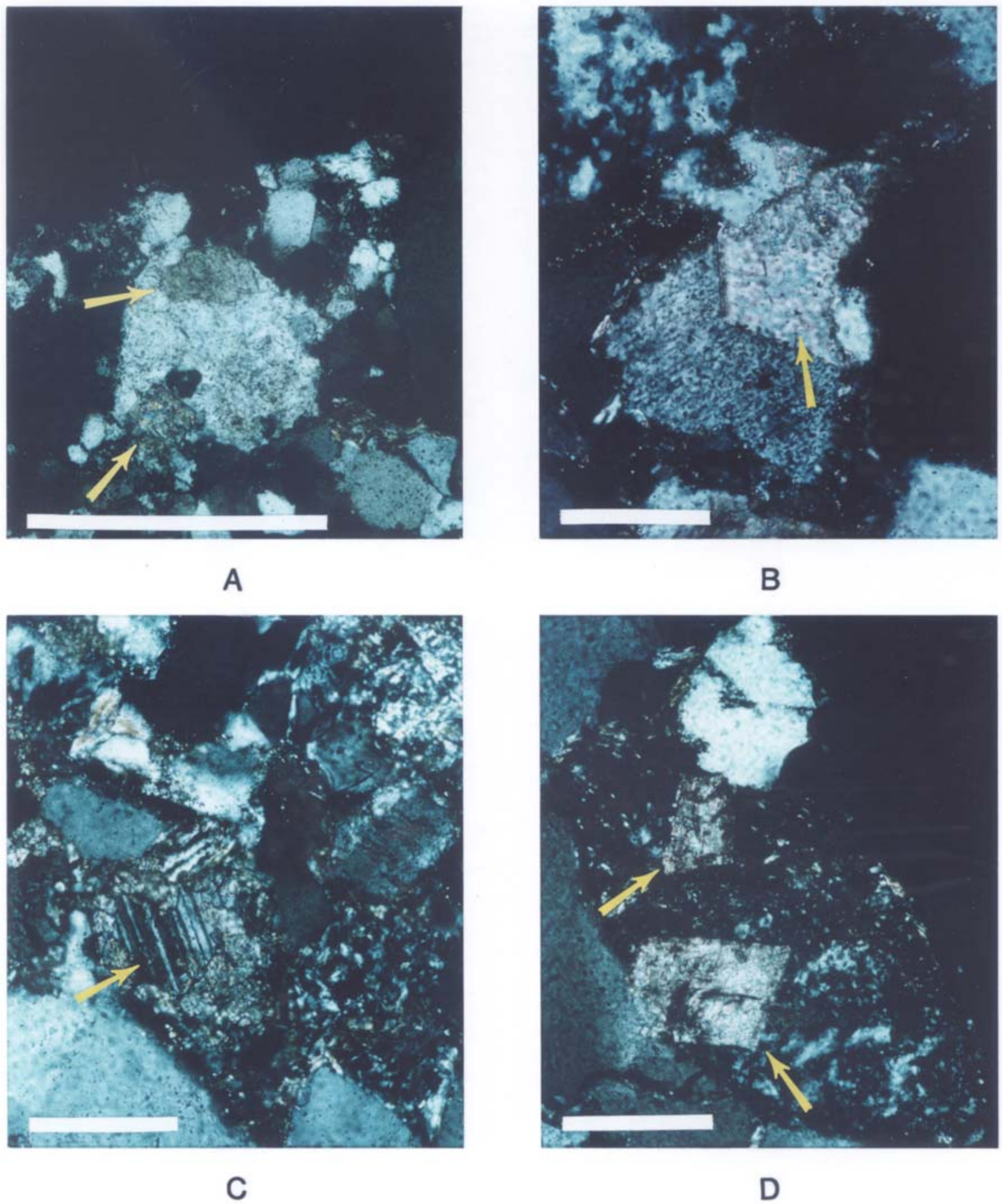

Plate 5. Photomicrographs and petrographic descriptions. A) 1,480 – 1490 ft (451 – 454 m): Quartz replaced by siderite (100X, crossed nicols). B) 5,210 – 5,220 ft (1,588 – 1,591 m): Quartz replaced by siderite (250X crossed nicols). C) 3,860 – 3,870 ft (1,177 – 1,180 m): Feldspar being replaced by siderite (250X crossed nicols). D) 5,300 – 5,310 ft (1,615 – 1,618 m): Rock fragment being replaced by siderite (250X crossed nicols). Bar scale is 0.5 mm in A and 0.1 mm in B, C and D.

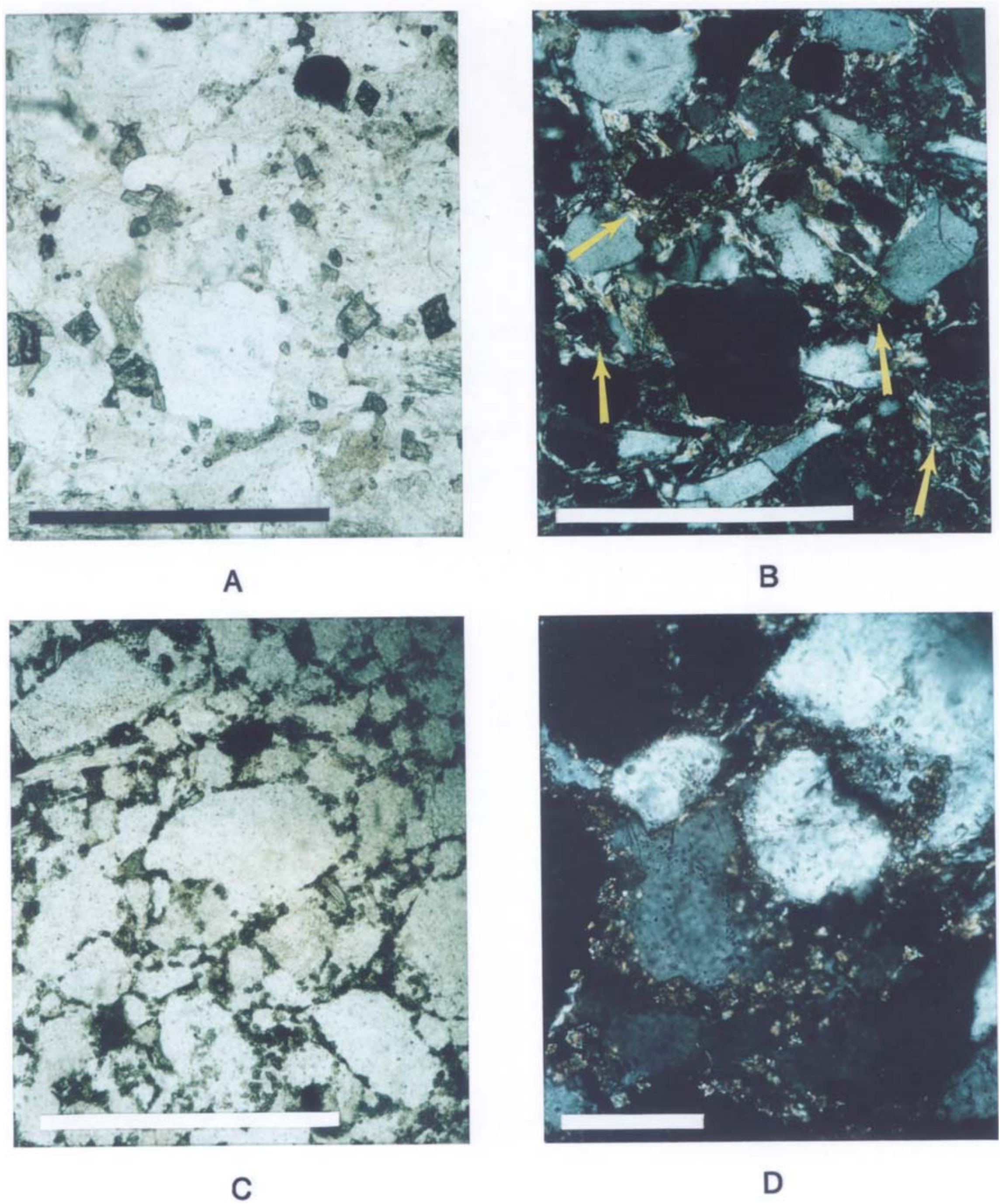

Plate 6. Photomicrographs and petrographic descriptions. A) 4,570 – 4,580 ft (1,393 – 1,396 m): Siderite replacing cement (clay?) (100X, plain light). B) 4,570 – 4,580 ft (1,393 – 1,396 m): Same as A (100X, crossed nicols). C) 4,670 – 4,680 ft (1,423 – 1,426 m): Siderite present as a very fine, crystalline cement (100X, plain light). D) 4,670 – 4,680 ft (1,423 – 1,426 m): Close up of siderite cement (250X, crossed nicols). Bar scale is 0.5 mm in A, B and C, and 0.1 mm in D.

thin section (0-1%) (Plate 7). Some pores filled with anthraxolite (thermally dead oil) are fossil moldic, indicating the definite dissolution of skeletal carbonates (0-1%) (Plate 7C, D). All the fossil fragments have been converted to siderite. Siderite formed because the pore fluids were probably undersaturated with Ca^{2+} but enriched with Fe^{2+}. Furthermore, pyrite is commonly observed in thin sections which also indicate availability of Fe^{2+}.

The final type of diagenesis to be addressed is that which created the only porosity measured today, which is secondary porosity. Pressure solution and other destructive processes destroyed most of the primary porosity in Jackfork and Stanley sandstones. Secondary porosity is observed in the following two forms: (1) open pores, and (2) pores filled with solid hydrocarbons (anthraxolite) representing paleoporosity. The majority of pores appear to be the result of grain dissolution. Pore geometries provide clues to the type of grains removed. Rhombohedral pores are indicative of carbonate dissolution (Plate 9C, D). Other pores filled with anthraxolite have partially rhombohedral pores (Plate 10A, B). Simple, rounded pores resembled any number of grain types (Plate 9 A, B). However, they could also be due to the dissolution of carbonate as indicated by the shape of altered fossil fragments (Plate 10 C, D). Based on the shape of pores filled with solid hydrocarbons, the majority of the paleoporosity is most likely due to the dissolution of fossil fragments and carbonate filled pores (Plate 11).

The amount of porosity due to the dissolution of rock fragments, feldspar, and quartz appears to be minimal. All observed porosity could be explained by carbonate dissolution. Partially corroded or removed rock fragments and feldspars were not observed. They were altered to clay or replaced by carbonates. Quartz does not show

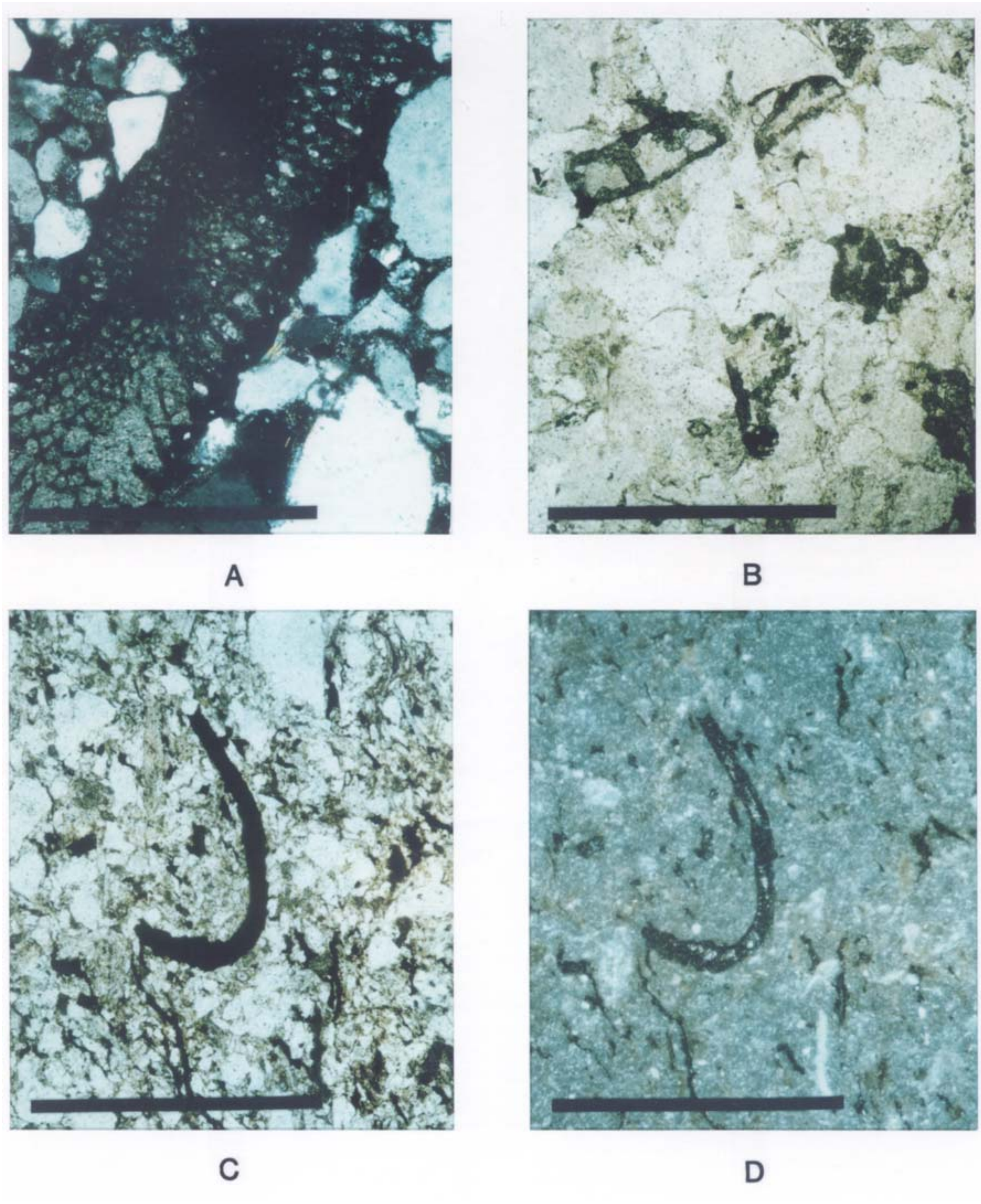

Plate 7. Photomicrographs and petrographic descriptions. A) 1,530 – 1,540 ft (466 – 469 m): Abraded bryozoan fragment, altered to siderite (100X, crossed nicols). B) 3,100 – 3,110 ft (945 – 948 m): unrecognizable relic fossil fragments, altered to siderite (100X, plain light). C) 1,460 – 1,470 ft (445 – 448 m): Moldic porosity filled with anthraxolite (100X, plain light). D) 1,460 – 1,470 ft (445 – 448 m): Same as C (100X, reflected light). Bar scales are 0.5 mm.

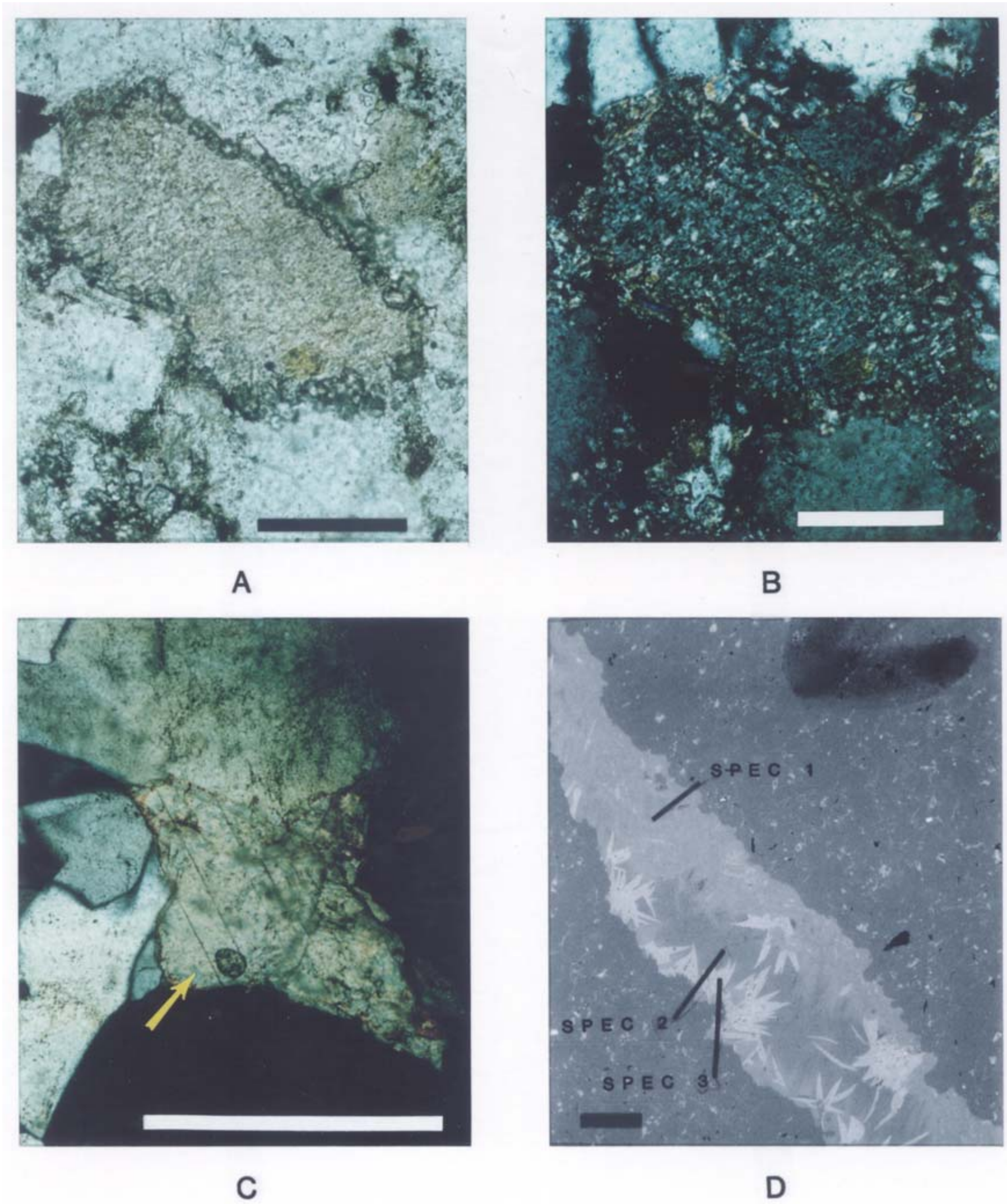

Plate 8. Photomicrographs and petrographic descriptions. A) 3,860 – 3,870 ft (1,177 – 1,180 m): Feldspar being replaced by siderite at margins of the grain (250X, plain light). B) 3,860 – 3,870 ft (1,177 – 1,180 m): Same as A, (100X, cross nicols). C) 5,520 – 5,530 ft (1,682 – 1,686 m): Fracture-filled calcite (alizarin red stain) almost completely replaced by dolomite (100X, crossed nicols). D) 5,510 – 5,520 ft (1,679 – 1,682 m): Carbonate fracture fill. The brighter portions are due to iron concentrations. Dolomite is altered to siderite. (20X, SEM back scatter image). Bar scale for A and B is 0.1 mm, and for C and B is 0.5 mm.

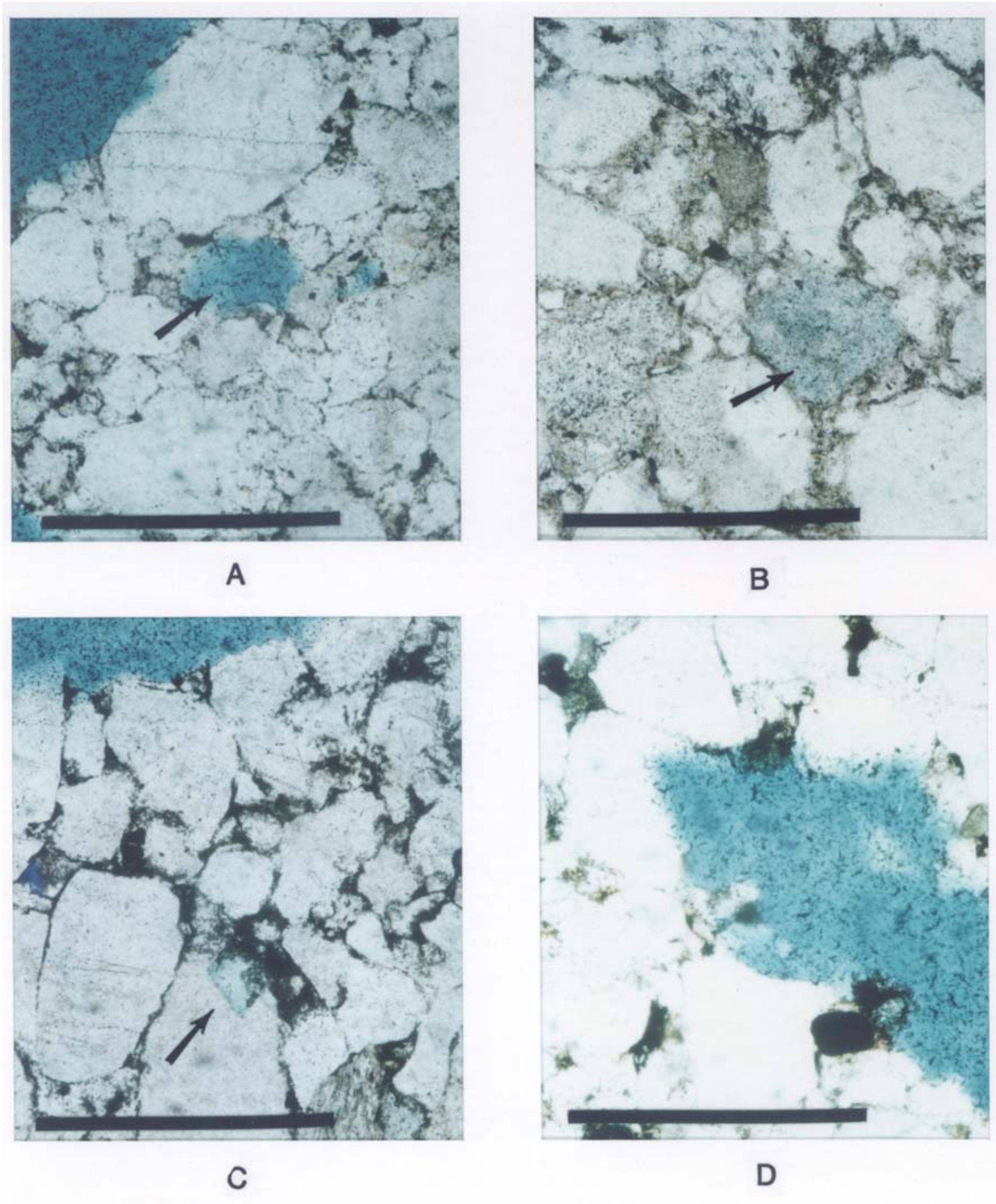

Plate 9. Photomicrographs and petrographic descriptions. A) 3,370 – 3,385 ft (1,027 – 1,032 m): Secondary porosity formed by grain dissolution (100X, plain light). B) 1,210 – 1,220 ft (369 – 372 m): Porosity formed by grain dissolution (100X, plain light). C) 1,160 – 1,170 ft (354 – 357 m): Rhombohedral moldic porosity partially filled with clay (100X, plain light). D) 3,370 – 3,385 ft (1,027 – 1,032 m): Rhombohedral moldic porosity (100X, plain light). Epoxy is stained blue. Bar scale is 0.5 mm.

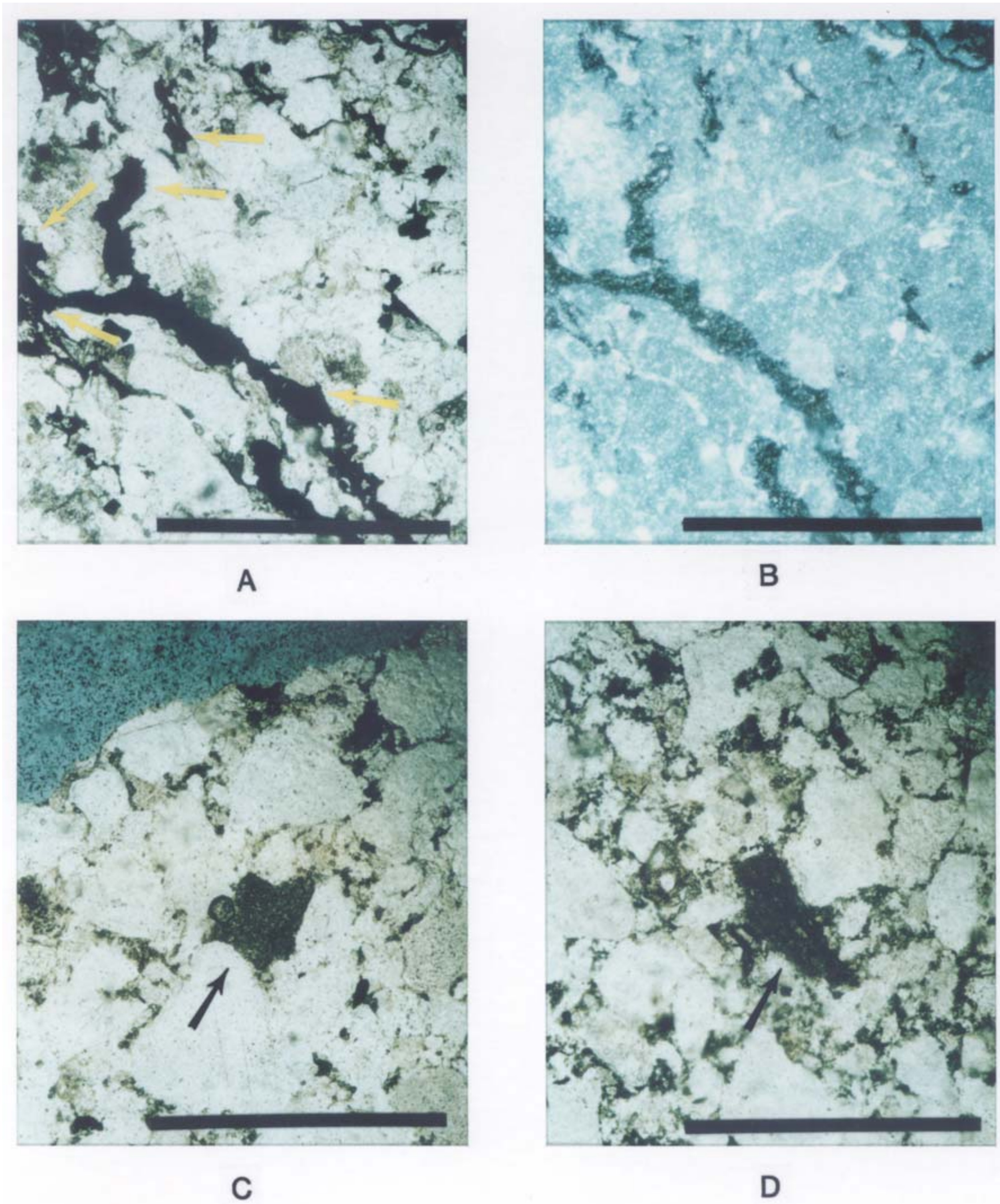

Plate 10. Photomicrographs and petrographic descriptions. A) 5,110 – 5,120 ft (1,558 – 1,561 m): Fracture filled with anthraxolite. Note edges of fracture with rhombohedral shape (100X, plain light). B) 5,110 – 5,120 ft (1,558 – 1,561 m): Same as A (100X, reflected light). C) 3,790 – 3,800 ft (1,155 – 1,158 m): Siderite grain; possibly an altered and deformed fossil fragment (100X, plain light). D) 3,790 – 3,800 ft (1,155 – 1,158 m): Siderite grain; possibly an altered and deformed fossil fragment (100X, plain light). Bar scale is 0.5 mm.

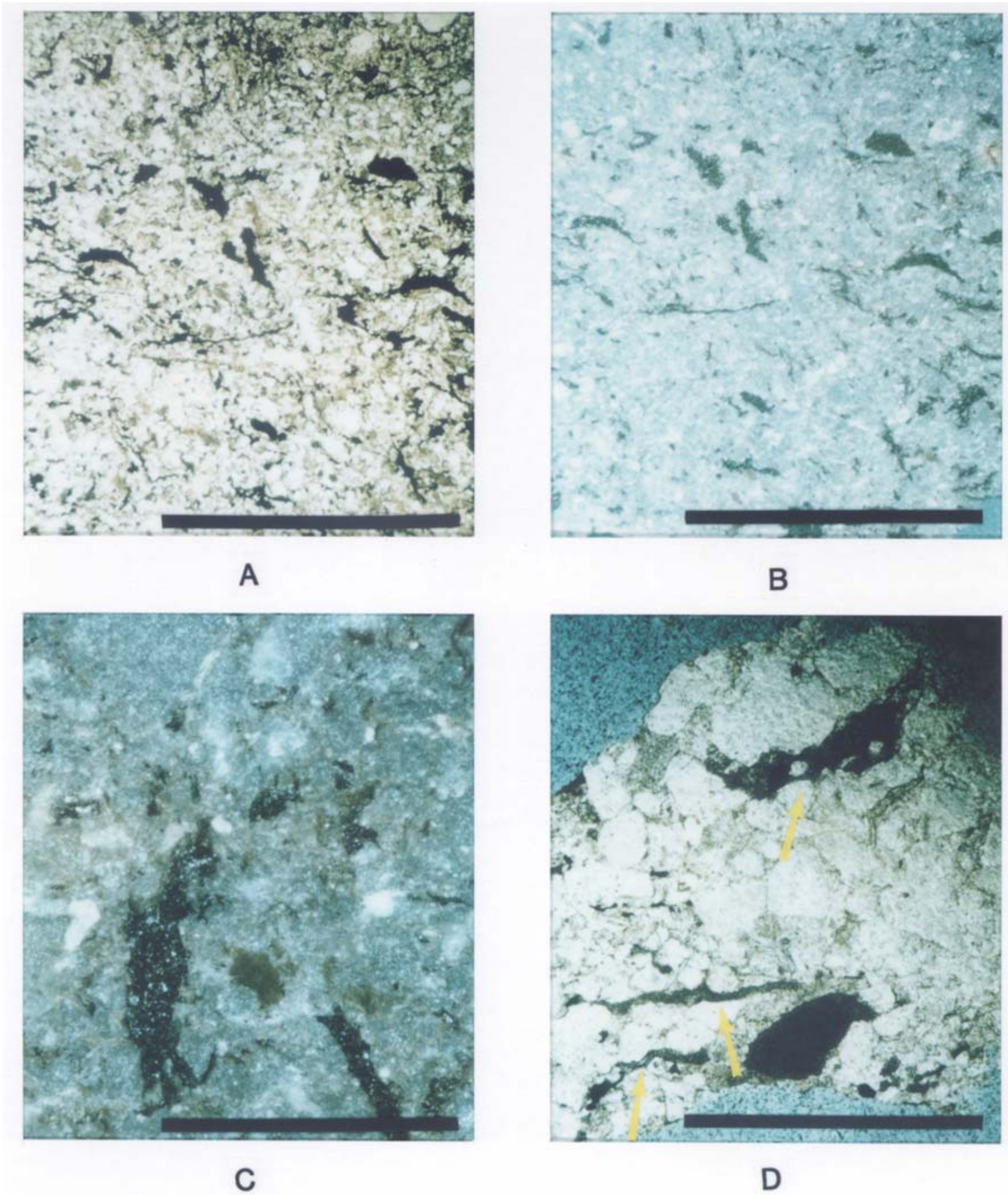

Plate 11. Photomicrographs and petrographic descriptions. A) 5,520 – 5,530 ft (1,682 – 1,686 m): Moldic porosity filled with anthraxolite. Possibly dissolution of abraded fossil hash (100X, plain light). B) 5,520 – 5,530 ft (1,682 –1,686 m): Same as A (100X, reflected light). C) 1,460 – 1,470 ft (445 – 448 m): Moldic porosity, filled with anthraxolite (100X, reflected light). D) 5,110 – 5,120 ft (1,558 – 1,561 m): Siderite; either fracture fill or altered and heavily deformed fossil fragments (100X, plain light). Bar scale is 0.5 mm.

any signs of corrosion other than through replacement by carbonate. The late geochemistry of the pore fluids seems to favor carbonate dissolution.

Scientific literature have provided numerous discussions regarding the generation of carbon dioxide and organic acids associated with organic matter maturation and subsequent dissolution of carbonates (Schmidt and McDonald, 1979; Al-Shaieb and Shelton, 1981; Surdam et al., 1984). The Ouachita stratigraphy displays an abundance of organically rich shales (Figure 2). As these shales became thermally mature, they may have expelled carbon dioxide, which upon mixing with water formed carbonic acid. The carbonic acid could then easily become the dissolution agent for the carbonate. The expulsion and migration of oil could easily fill the recently formed pores and would likely be concurrent with or immediately following the expulsion of carbon dioxide. Continued burial and heating of the stratigraphic sequence would initiate the cracking of oils into gas and solid hydrocarbons. In the Stanley and Jackfork sandstones, the majority of pores are filled with anthraxolite (thermally dead oil) (Plate 12). The close relationship between the dissolution of carbonate and emplacement of oil can be seen in Plate 12C and D.

An overall diagenetic history can be summarized as follows. Deposition and initial compaction of the sand preceded the chemical diagenetic succession and porosity modification. Minor authigenic quartz and clay cements were formed early. With additional burial and increased overburden pressure, a pervasive induration of the sand occurred by pressure solution processes. During this time period, rock fragments were deformed and feldspars were altered to clay. In the later diagenetic sequence, siderite began to replace quartz, feldspar, chert, clay and early carbonates. With the maturation

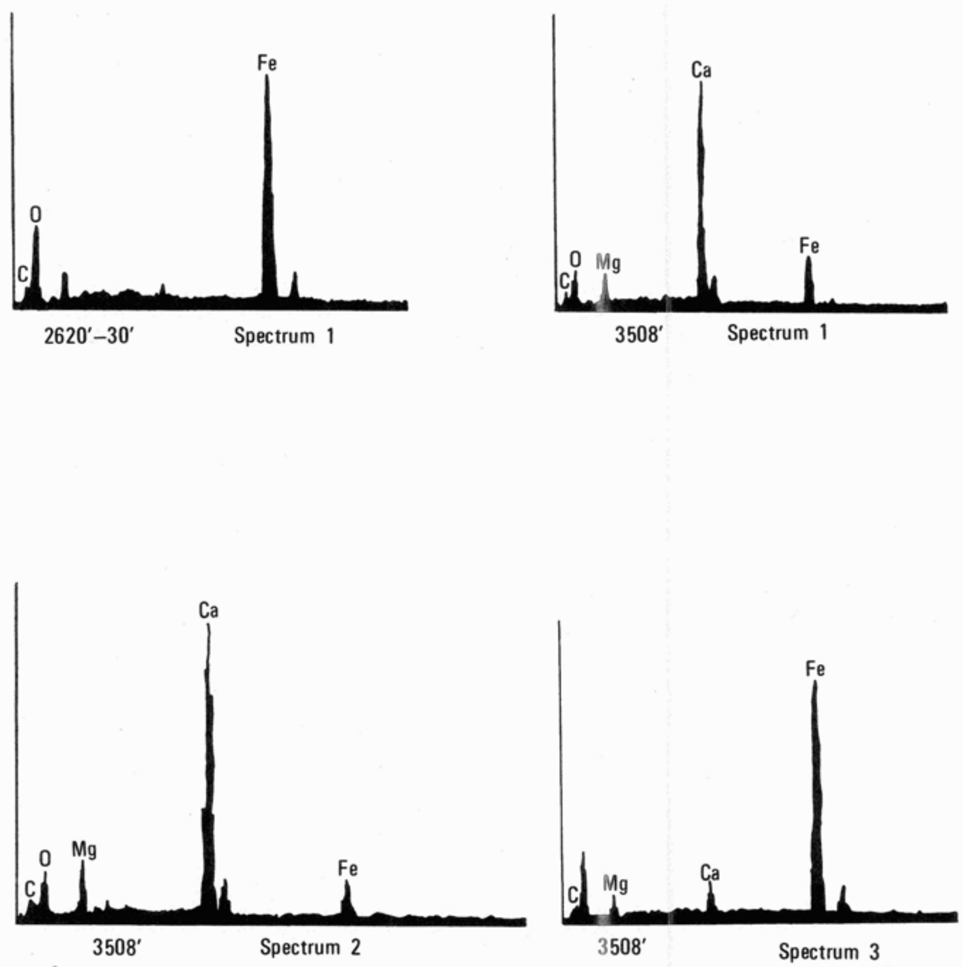

Figure 12. EDAX elemental analysis spectrums of selected carbonates in the Rex Timber No. 1-9. Spectrums displayed from thin sections shown on Plate 4B and Plate 7D.

of surrounding and underlying source rocks, carbonic acid was formed and created secondary porosity by the dissolution of carbonate grains and cements. This was followed by oil charge. The oil was then cracked to gas. The lack of an adequate seal resulted in the loss of gas and the presence of pore plugging anthraxolite.

Discussion

Assuming adequate charge, timing, and migration scenario, the lack of significant hydrocarbons in the Rex Timber well appears to be attributed to two main reasons: seal and reservoir quality. Although brittle fractures can potentially help permeability, it was determined that the thin shales were not thick enough to block vertical transmissibility of hydrocarbons from sand to sand out of the trap. Thicker shales were expected to be encountered in the lower portion of the Stanley, but the well did not penetrate to those depths. The decision to stop drilling the well short of the 10,000 ft (3,048 m) proposed total depth was primarily because of poor reservoir development and severe mechanical problems with the drill rig.

Poor reservoir development is also a more likely reason for not finding commercial hydrocarbons. Some oil did locally migrate into the Jackfork sands inferring that some paleoporosity existed for a time. However, significant cementation occurred due to more burial and heating which “cracked” the oil leaving behind only the solid hydrocarbon (anthraxolite). Examination of the sandstones in the well showed that low porosity is characteristic of the Jackfork and Stanley sandstones. Hydrocarbon-filled pores were formed dominantly by carbonate dissolution that did not develop enough effective porosity. Based on outcrop analogs, there is adequate potential for the development of reservoir quality sandstones by the creation of secondary porosity. Leaching or dissolving of carbonate is well developed at the outcrops by downward movement of surface waters. In part, the Rex Timber well was a test to determine if subsurface leaching had occurred and enhanced reservoir potential leaving space available for hydrocarbon entrapment. Finally, the timing of the charge and structural formation could be another consideration for exploration failure.

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Appendix 1. Total Organic Carbon (TOC) Analysis for Rex Timber No. 1-9 well.

Top (ft)	Bottom (ft)	TOC (wt. %)	Top (ft)	Bottom (ft)	TOC (wt. %)	Top (ft)	Bottom (ft)	TOC (wt. %)
CRETACEOUS								
63	70	0.63	120	130	0.18	170	180	0.14
70	80	0.46	130	140	0.13	180	190	0.17
80	90	0.94	140	150	0.16	190	200	0.10
100	110	0.22	150	160	0.19	200	210	0.26
110	120	0.24	160	170	0.19	210	220	0.60
JACKFORK								
220	230	0.74	630	640	0.12	1010	1020	0.28
270	280	0.83	640	650	0.10	1020	1030	0.18
280	290	0.86	650	660	0.09	1040	1050	0.47
290	300	0.8	660	670	0.10	1050	1060	0.34
300	310	0.82	670	680	0.22	1060	1070	0.24
310	320	0.36	680	690	0.57	1070	1080	0.44
320	330	0.62	690	700	0.86	1080	1090	0.55
330	340	0.55	700	710	0.44	1090	1100	0.47
340	350	0.88	710	720	0.51	1100	1110	0.54
350	360	1.05	720	730	0.52	1110	1120	0.47
360	370	0.88	730	740	0.34	1120	1130	0.81
370	380	0.79	740	750	0.47	1130	1140	0.83
380	390	0.51	750	760	0.51	1150	1160	0.27
390	400	0.39	760	770	0.31	1160	1170	0.16
400	410	0.24	770	780	0.21	1170	1180	0.35
410	420	0.16	780	790	0.31	1180	1190	0.33
420	430	0.21	790	800	0.29	1190	1200	0.18
430	440	0.16	800	810	0.64	1200	1210	0.27
440	450	0.32	810	820	0.70	1210	1220	0.39
450	460	0.32	820	830	0.50	1230	1240	0.29
460	470	0.16	830	840	0.43	1240	1250	0.29
470	480	0.22	840	850	0.49	1250	1260	0.22
480	490	0.16	850	860	0.44	1260	1270	0.21
490	500	0.09	860	870	0.33	1270	1280	0.13
500	510	0.47	870	880	0.46	1280	1290	0.2
510	520	0.36	880	890	0.51	1290	1300	0.71
520	530	0.11	890	900	0.33	1300	1310	0.83
530	540	0.2	900	910	0.28	1308	1309	0.93
540	550	0.23	910	920	0.31	1308		0.96
550	560	0.13	920	930	0.49	1309	1310	0.93
560	570	0.82	930	950	0.34	1310	1311	1.29
570	580	0.57	950	960	0.34	1310	1320	1.15
580	590	0.14	960	970	0.26	1311	1312	1.96
590	600	0.11	970	980	0.22	1314	1315	1.47
600	610	0.13	980	990	0.25	1315	1316	1.31
610	620	0.12	990	1000	0.19	1316	1318	1.21
620	630	0.34	1000	1010	0.48	1318	1320	1.14

Top (ft)	Bottom (ft)	TOC (wt. %)	Top (ft)	Bottom (ft)	TOC (wt. %)	Top (ft)	Bottom (ft)	TOC (wt. %)
1320	1321	1.23	1790	1800	0.63	2280	2290	0.30
1320	1330	0.90	1800	1810	0.72	2290	2300	0.48
1321	1323	1.33	1810	1820	0.40	2300	2310	0.66
1323	1324	1.28	1820	1830	0.37	2310	2320	0.54
1330	1340	0.60	1830	1840	0.71	2320	2330	0.65
1340	1350	0.67	1840	1850	0.78	2330	2340	0.73
1350	1360	0.87	1850	1860	0.97	2340	2350	0.76
1360	1370	0.79	1860	1870	0.93	2350	2360	0.68
1370	1380	0.58	1870	1880	0.84	2360	2370	0.67
1380	1390	0.70	1880	1890	0.16	2370	2380	0.65
1390	1400	0.70	1890	1900	0.17	2380	2390	0.91
1400	1410	0.42	1900	1910	0.23	2390	2400	0.76
1410	1420	0.32	1910	1920	0.37	2400	2410	0.83
1420	1430	0.18	1920	1930	0.20	2410	2420	0.65
1430	1440	0.18	1930	1940	1.18	2420	2430	0.79
1440	1450	0.09	1940	1950	0.17	2430	2440	0.54
1450	1460	0.23	1950	1960	0.24	2440	2450	0.41
1460	1470	0.49	1960	1970	0.21	2450	2460	0.39
1470	1480	0.44	1970	1980	0.56	2460	2470	0.37
1480	1490	0.40	1980	1990	0.25	2470	2480	0.74
1490	1500	0.96	1990	2000	0.41	2480	2490	0.34
1500	1510	0.71	2000	2010	0.53	2490	2500	0.26
1510	1520	0.43	2010	2020	0.77	2500	2510	0.49
1520	1530	0.86	2020	2030	1.01	2510	2520	0.37
1530	1540	0.50	2030	2040	0.70	2520	2530	0.56
1540	1550	0.38	2040	2050	1.21	2530	2540	0.37
1550	1560	0.25	2050	2060	0.81	2540	2550	0.96
1560	1570	0.38	2060	2070	0.89	2550	2560	0.84
1570	1580	0.37	2070	2080	0.93	2560	2570	1.02
1580	1590	0.52	2080	2090	1.11	2570	2580	0.87
1590	1600	0.59	2090	2100	0.78	2580	2590	0.96
1600	1610	0.60	2100	2110	0.84	2590	2600	0.83
1610	1620	0.58	2110	2120	0.44	2600	2610	0.85
1620	1630	0.68	2120	2130	0.51	2610	2620	0.65
1630	1640	0.66	2130	2140	0.76	2620	2630	0.76
1640	1650	0.40	2140	2150	0.91	2630	2640	0.55
1650	1660	0.32	2150	2160	1.16	2640	2650	0.64
1660	1670	0.72	2160	2170	0.88	2650	2660	0.83
1670	1680	0.28	2170	2180	0.82	2660	2670	0.77
1680	1690	0.33	2180	2190	0.77	2670	2680	0.98
1690	1700	0.69	2190	2200	0.99	2680	2690	1.05
1700	1710	0.68	2200	2210	0.88	2690	2700	0.96
1710	1720	0.66	2210	2220	0.42	2700	2710	0.98
1720	1730	0.73	2220	2230	0.33	2710	2720	0.80
1730	1740	0.70	2230	2240	0.61	2720	2730	1.51
1750	1760	0.76	2240	2250	0.69	2730	2740	0.54
1760	1770	0.58	2250	2260	0.66	2740	2750	0.46
1770	1780	0.72	2260	2270	0.51	2750	2760	0.54
1780	1790	0.84	2270	2280	0.44	2760	2770	0.63

Top (ft)	Bottom (ft)	TOC (wt. %)	Top (ft)	Bottom (ft)	TOC (wt. %)	Top (ft)	Bottom (ft)	TOC (wt. %)
2770	2780	0.41	3270	3280	0.68	3700	3710	0.50
2780	2790	0.44	3280	3290	0.80	3710	3720	0.51
2790	2800	0.25	3290	3300	0.85	3720	3730	1.18
2800	2810	0.29	3300	3310	0.98	3730	3740	0.73
2810	2820	0.58	3310	3320	0.84	3740	3750	0.63
2820	2830	0.62	3320	3330	1.03	3750	3760	0.76
2830	2840	0.56	3330	3340	0.82	3760	3770	0.82
2840	2850	0.87	3340	3350	0.65	3770	3780	0.25
2850	2860	0.76	3350	3360	0.40	3790	3800	0.38
2860	2870	0.67	3360	3370	0.61	3800	3810	0.50
2870	2880	0.73	3370	3380	0.71	3810	3820	0.39
2880	2890	0.66	3380	3390	0.80	3820	3830	0.34
2890	2900	0.40	3390	3400	0.75	3830	3840	0.53
2900	2910	0.64	3400	3410	0.86	3840	3850	0.45
2910	2920	0.60	3410	3420	0.70	3850	3860	0.56
2920	2930	0.58	3420	3430	0.56	3860	3870	0.67
2930	2940	0.55	3430	3440	0.44	3870	3880	0.66
2940	2950	0.48	3440	3450	0.50	3880	3890	0.47
2950	2960	0.47	3450	3460	0.41	3900	3910	1.11
2960	2970	0.38	3460	3470	0.46	3910	3920	1.24
2970	2980	0.85	3470	3480	0.53	3920	3930	0.70
2980	2990	0.70	3480	3490	0.73	3930	3940	0.43
2990	3000	0.75	3490	3500	0.29	3940	3950	0.34
3000	3010	0.51	3500	3504	1.83	3950	3960	0.28
3010	3020	0.60	3500	3510	0.53	3960	3970	0.39
3020	3030	0.63	3504	3504.5	1.45	3970	3980	0.45
3030	3040	0.73	3508.3		1.88	3980	3990	0.51
3040	3050	0.61	3510	3526	1.12	3990	4000	0.52
3050	3060	0.71	3511	3520	0.86	4000	4010	0.74
3060	3070	0.62	3512		3.66	4010	4020	0.81
3070	3080	0.41	3514.5		1.38	4020	4030	0.86
3080	3090	0.47	3516		1.48	4030	4040	0.85
3090	3100	0.27	3520	3530	1.34	4040	4050	0.97
3100	3110	0.23	3530	3540	1.03	4080	4090	0.88
3110	3120	0.78	3540	3550	1.26	4090	4100	0.91
3120	3130	0.64	3550	3560	1.04	4100	4110	0.96
3130	3140	0.50	3560	3570	0.76	4110	4120	1.00
3140	3150	0.56	3570	3580	1.10	4120	4130	0.78
3150	3160	0.34	3580	3590	0.91	4130	4140	0.87
3160	3170	0.53	3590	3600	1.09	4140	4150	0.86
3170	3180	0.51	3600	3610	0.68	4150	4160	0.79
3180	3190	0.38	3610	3620	0.76	4160	4170	0.39
3190	3200	0.29	3620	3630	1.19	4170	4180	0.42
3200	3210	0.42	3630	3640	1.25	4180	4190	0.47
3210	3220	0.53	3640	3650	1.05	4190	4200	0.57
3220	3230	0.36	3650	3660	0.95	4200	4210	0.64
3230	3240	0.78	3660	3670	1.14	4210	4220	0.68
3240	3250	0.84	3670	3680	1.61	4220	4230	0.38
3250	3260	0.64	3690	3700	0.60	4230	4240	0.53

Top (ft)	Bottom (ft)	TOC (wt. %)	Top (ft)	Bottom (ft)	TOC (wt. %)	Top (ft)	Bottom (ft)	TOC (wt. %)
4240	4250	0.51	4730	4740	0.44	5230	5240	0.87
4250	4260	0.54	4740	4750	0.59	5240	5250	0.89
4260	4270	0.44	4750	4760	0.65	5250	5260	0.85
4270	4280	0.49	4760	4770	0.43	5260	5270	0.79
4280	4290	0.72	4770	4780	0.45	5270	5280	0.77
4290	4300	0.99	4790	4800	0.53	5280	5290	0.79
4300	4310	0.85	4800	4810	1.02	5290	5300	0.71
4310	4320	0.97	4810	4820	0.57	5300	5310	0.82
4320	4330	0.90	4820	4830	0.52	5310	5320	0.72
4330	4340	0.79	4830	4840	0.40	5320	5330	0.73
4340	4350	0.58	4840	4850	0.30	5330	5340	0.59
4350	4360	0.53	4850	4860	0.31	5340	5350	0.54
4360	4370	0.62	4860	4870	0.21	5350	5360	0.62
4370	4380	0.45	4870	4880	0.57	5360	5370	0.59
4380	4390	0.64	4880	4890	0.61	5370	5380	0.63
4390	4400	0.45	4890	4900	0.52	5380	5390	0.63
4400	4410	0.40	4900	4910	0.56	5390	5400	0.79
4410	4420	0.45	4910	4920	0.60	5400	5410	0.71
4420	4430	0.39	4920	4930	0.81	5410	5420	0.69
4430	4440	0.54	4930	4940	0.86	5420	5430	0.56
4440	4450	0.75	4940	4950	0.88	5430	5440	1.08
4450	4460	0.74	4950	4960	0.83	5440	5450	0.39
4460	4470	0.59	4960	4970	0.84	5450	5460	0.60
4470	4480	0.75	4970	4980	0.98	5460	5470	0.49
4480	4490	0.79	4980	4990	0.76	5470	5480	0.64
4490	4500	0.86	4990	5000	0.73	5480	5490	0.43
4500	4510	0.83	5000	5010	0.81	5490	5500	0.62
4510	4520	0.82	5010	5020	0.76	5500	5510	0.62
4520	4530	0.64	5020	5030	0.91	5510	5520	0.77
4530	4540	0.58	5030	5040	0.80	5520	5530	0.59
4540	4550	0.57	5040	5050	0.79	5530	5540	0.69
4550	4560	0.71	5050	5060	0.52	5540	5550	0.70
4560	4570	0.47	5060	5070	0.60	5550	5560	0.65
4570	4580	0.52	5070	5080	0.51	5560	5570	0.65
4580	4590	0.48	5080	5090	0.69	5570	5580	0.68
4590	4600	0.62	5090	5100	0.80	5580	5590	0.82
4600	4610	0.50	5100	5110	0.73	5590	5600	0.56
4610	4620	0.70	5110	5120	0.99	5600	5610	0.81
4620	4630	0.86	5120	5130	0.78	5610	5620	0.92
4630	4640	0.69	5130	5140	0.69	5620	5630	0.66
4640	4650	0.92	5140	5150	0.70	5630	5640	0.51
4650	4660	0.90	5150	5160	0.45	5640	5650	0.41
4660	4670	0.80	5160	5170	0.44	5650	5660	0.33
4670	4680	0.70	5170	5180	0.51	5660	5670	0.50
4680	4690	0.69	5180	5190	0.45	5670	5680	0.31
4690	4700	1.28	5190	5200	0.32	5680	5690	0.74
4700	4710	0.93	5200	5210	0.49	5690	5700	0.73
4710	4720	0.91	5210	5220	0.57			
4720	4730	0.48	5220	5230	0.83			

Top (ft)	Bottom (ft)	TOC (wt. %)	Top (ft)	Bottom (ft)	TOC (wt. %)	Top (ft)	Bottom (ft)	TOC (wt. %)
				STANLEY				
5700	5710	0.39	6180	6190	0.54	6600	6610	0.73
5710	5720	0.44	6190	6200	0.59	6610	6620	0.73
5720	5730	0.47	6200	6210	0.62	6620	6630	0.87
5730	5740	0.57	6210	6220	0.74	6630	6640	0.95
5740	5750	0.41	6220	6230	0.79	6640	6650	0.81
5750	5760	0.39	6230	6240	0.71	6650	6660	0.65
5760	5770	0.73	6240	6250	0.51	6660	6670	0.68
5770	5780	0.79	6250	6260	0.36	6670	6680	0.43
5780	5790	0.82	6260	6270	0.40	6680	6690	0.33
5790	5800	0.89	6270	6280	0.52	6690	6700	0.28
5800	5810	0.87	6280	6290	0.28	6700	6710	0.20
5810	5820	0.88	6290	6300	0.60	6710	6720	0.26
5820	5830	0.95	6300	6310	0.49	6720	6730	0.73
5830	5840	0.89	6310	6320	0.52	6730	6740	2.96
5840	5850	0.94	6320	6330	0.86	6740	6750	1.07
5850	5860	0.84	6330	6340	0.89	6750	6760	0.84
5860	5870	0.59	6340	6350	0.70	6760	6765	0.95
5870	5880	0.68	6350	6360	0.69			
5880	5890	0.73	6360	6370	0.78			
5890	5900	0.50	6370	6380	0.89			
5900	5910	0.58	6380	6390	0.56			
5910	5920	0.56	6390	6400	0.68			
5920	5930	0.59	6400	6410	0.83			
5930	5940	0.66	6410	6420	0.80			
5940	5950	0.90	6420	6430	0.91			
5950	5960	0.92	6430	6440	0.91			
5960	5970	1.05	6440	6450	0.75			
5970	5980	0.69	6457	6460	0.80			
5980	5990	0.86	6457.9		1.34			
5990	6000	0.93	6458.8		2.58			
6000	6010	0.80	6459	6460	1.26			
6010	6020	0.66	6460	6463	1.37			
6020	6030	0.70	6460	6470	0.86			
6030	6040	0.65	6468.2		1.75			
6040	6050	0.55	6469		1.25			
6050	6060	0.41	6480	6490	0.48			
6070	6080	0.54	6490	6500	0.31			
6080	6090	0.67	6500	6510	0.32			
6090	6100	0.64	6510	6520	0.67			
6100	6110	0.81	6520	6530	0.89			
6110	6120	0.67	6530	6540	1.03			
6120	6130	0.68	6540	6550	0.54			
6130	6140	0.81	6550	6560	0.59			
6140	6150	0.39	6560	6570	0.60			
6150	6160	0.34	6570	6580	0.67			
6160	6170	0.46	6580	6590	0.62			
6170	6180	0.49	6590	6700	0.78			

Appendix 2. Thin section point counts from Rex Timber No. 1-9 well.

Depth (ft)	Q	CH	F	RF	CG	CC	AC	HC	M	CL	CEM	POR	PY
520-530	253	5	1	1	2	14	0	0	2	11	3	6	2
(%)	84	1	1	1	1	5	0	0	1	4	1	2	1
1230-1240	252	1	5	1	3	12	1	1	2	16	1	1	4
(%)	84	1	3	1	1	4	1	1	1	5	1	1	1
1430-1440	261	3	1	5	0	1	3	2	1	20	1	0	2
(%)	87	1	1	3	0	1	1	1	1	7	1	0	1
1530-1540	232	6	3	4	1	40	3	1	1	8	0	1	0
(%)	77	2	1	1	1	13	1	1	1	3	0	1	0
(257 PTS.)	217	5	3	2	1	9	8	1	1	9	0	1	0
(%)	84	2	1	1	1	3	3	1	1	3	0	1	0
1950-1960	235	9	1	10	0	19	4	0	5	14	1	0	2
(%)	78	3	1	3	0	6	1	0	2	5	1	0	1
2000-2020	234	6	5	6	1	17	6	3	4	17	0	1	0
(%)	78	2	2	2	1	6	2	1	1	6	0	1	0
2370-2380	270	1	4	6	0	3	11	1	2	1	0	1	0
(%)	90	1	1	2	0	1	4	1	1	1	0	1	0
2750-2760	238	8	8	15	1	11	4	1	2	7	2	0	3
(%)	79	3	3	5	1	4	1	1	1	2	1	0	1
3090-3100	252	6	7	10	0	4	6	2	4	6	0	0	3
(%)	84	2	2	3	0	1	2	1	1	2	0	0	1
3370-3385 (287 pts.)	235	4	7	4	0	21	6	0	0	5	2	1	2
(%)	82	1	2	1	0	7	2	0	0	2	1	1	1
3690-3700	230	3	13	9	1	12	12	2	3	13	1	0	1
(%)	77	1	4	3	1	4	4	1	1	4	1	0	1
3860-3870	212	9	8	20	3	9	6	2	6	15	5	0	5
(%)	71	3	3	7	1	3	2	1	2	5	2	0	2
4170-4180	219	7	4	6	0	3	10	4	6	30	9	0	2
(%)	73	2	1	2	0	1	3	1	2	10	3	0	1
4500-4510	172	3	6	8	2	6	7	4	4	81	6	0	1
(%)	57	1	2	3	1	2	2	1	1	27	2	0	1
4670-4680	212	7	8	11	0	27	5	0	4	20	5	0	1
(%)	71	2	3	4	0	9	2	0	1	7	2	0	1
5040-5050	237	3	10	10	0	6	3	1	2	25	0	0	3
(%)	79	1	3	3	0	2	1	1	1	8	0	0	1
5300-5310	221	6	8	8	1	7	12	6	3	20	6	0	2
(%)	74	2	3	3	1	2	4	2	1	7	2	0	1
5730-5740	240	4	4	10	0	7	8	1	0	22	1	1	2
(%)	80	1	1	3	0	2	3	1	0	7	1	1	1
6070-6080	245	4	4	5	0	25	2	2	2	3	7	0	1
(%)	82	1	1	2	0	8	1	1	1	1	2	0	1
6380-6390	222	4	4	15	0	10	12	3	1	17	5	2	5
(%)	74	1	1	5	0	3	4	1	1	6	2	1	2
Total	5133	169	113	175	16	264	132	49	56	382	56	15	24
(%)	78	2	2	3	<1	4	2	1	1	6	1	<1	<1

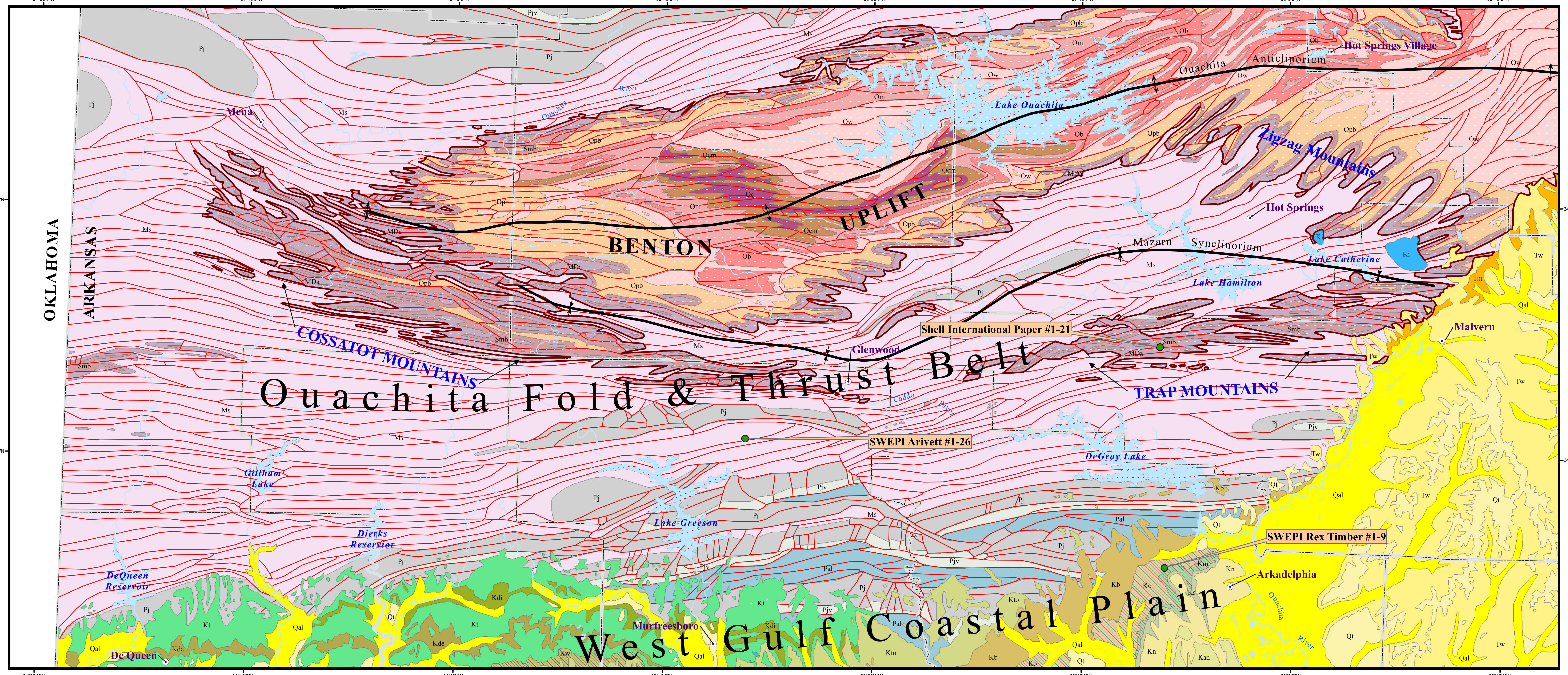
Q = Quartz
CH = Chert
F = Feldspar
RF = Rock Fragment
CG = Carbonate Grain / Fragment
CC = Carbonate Cement (Intergranular)
AC = Authigenic Carbonate (Intragranular)
HC = Solid Hydrocarbon
M = Mica
CL = Clay
CEM = Cement (other than carbonate)
POR = Porosity
PY = Pyrite

Arkansas Geological Survey
Bekki White, Director and State Geologist

Information Circular 39A
FF-OG-OU-011

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

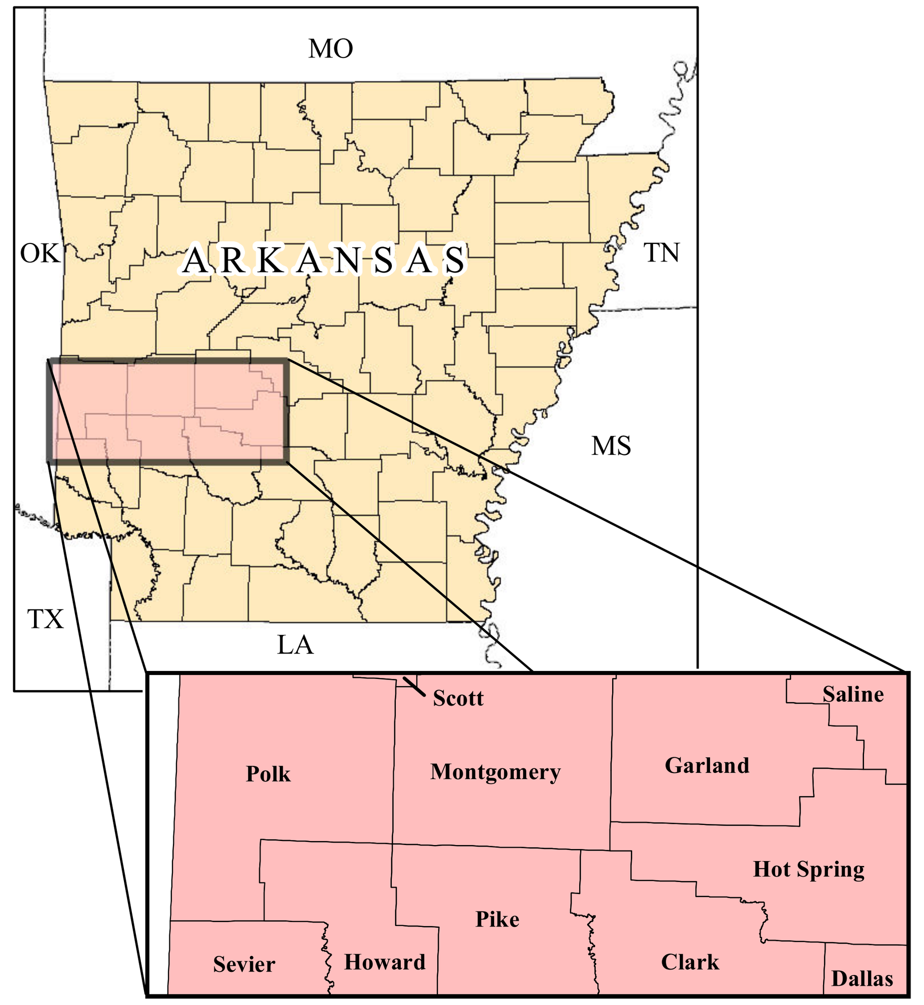
Middle Ordovician
- Ow — Womble Shale

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

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