FIELD STUDY: DETERMINING THE RELATIONSHIP OF THE SUBSURFACE “CLEVELAND” SANDSTONE TO THE SEMINOLE FORMATION IN SOUTHERN OKLAHOMA

By

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FIELD STUDY: DETERMINING THE RELATIONSHIP OF THE SUBSURFACE "CLEVELAND" SANDSTONE TO THE SEMINOLE FORMATION OUTCROPS IN SOUTHERN OKLAHOMA

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Abstract: The Cleveland sandstone is a fluvial-deltaic, Pennsylvanian Age formation in Oklahoma that produces hydrocarbons in the subsurface and is exposed at the surface in the outcrop trend that extends from Seminole County north-northeast into Hughes, Okmulgee, Okfuskee and Tulsa counties, where it is known as the Seminole Formation. The purpose of this study is to verify the relationship between the Cleveland sandstone and the Seminole Formation, and to determine the provenance of these sediments. Previous works evaluated either the subsurface Cleveland sandstone or studied the Seminole Sandstone in outcrop, but this study correlates subsurface stratigraphy to the surface. Eight outcrops of the Seminole Formation were sampled for petrographic analysis, and surveyed with a gamma ray spectrometer readings to identify the Nuyaka Creek “hot” Shale marker that is exposed in two of the southern outcrops. Based on previous work by Bacon (2012), and corroborated by this study, the Nuyaka Creek Shale is the key marker bed for the Desmoinesian-Missourian boundary. The field API gamma ray readings allowed correlation to API gamma ray signatures in nearby wells. Three cross sections were prepared. Cross-section A-A” is a stratigraphic cross section containing 21 wireline logs, hung on the Checkerboard Limestone, (tied to Cross-section A-A’ by Bacon (2012)), that starts in central Oklahoma (Kingfisher County) and extends southeast across the Anadarko Shelf, the Nemaha Ridge, the Cherokee Shelf, and into the Arkoma Basin (Seminole County). Cross-section B-B’ is a to scale structural dipline trend, that correlates the Seminole Formation from the outcrop into the subsurface. Cross-section C-C’ shows the stratigraphy along the outcrop trend. This study confirms work by Bacon (2012) that the Nuyaka Creek “hot” Shale marker, identified in both subsurface and outcrop, is a useful lithostratigraphic boundary between the Missourian Stage and Desmoinesian Stage. Petrographic analysis of outcrop samples demonstrates two sediment source areas: Ouachita Uplift (cryptocrystalline chert) and metamorphic rock fragments. Finally, this study agrees with previous work and concludes, that where the Checkerboard Limestone is absent as it approaches the outcrop trend, it is likely stratigraphically equivalent to the DeNay Limestone.

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CHAPTER I

INTRODUCTION

General Overview

The Cleveland sandstone is an informal subsurface term for sandstone bodies of Early Missourian-Late Desmoinesian (Pennsylvanian), which formed as a result of fluvial-deltaic deposition stretching in the Anadarko Basin (Hentz, 2011), Nemaha Ridge (Bacon, 2012) and the Cherokee Platform (Krumme, 1981). Surface equivalents to the Cleveland sandstone are the Seminole Sandstone in eastern Oklahoma (Campbell, 1997) and the Hepler Sandstone in Kansas and Missouri (Heckel, 1991). The Seminole-Hepler outcrop belt extends from southern Seminole County, Oklahoma, north-northeastward through northeastern Oklahoma, eastern Kansas to Missouri, about 30 miles east of Kansas City (Heckel, 1991). The term Seminole Formation as referred in Boardman et al. (1990), is used in this study for outcrops. For the subsurface, the referenced informal/operational term of Cleveland sandstone is used. The Cleveland sandstone reservoir first produced oil and gas in 1904 in Indian Territory (modern day Pawnee County) in Sec. 17, T. 21 N., R. 8 E., south of the Cleveland townsite (Campbell, 1997). Informal use of the term Cleveland sand/sandstone has resulted in correlation issues and complicated provenance identification (Campbell, 1997; Bacon, 2012).

Previous Work/Literature Review

This study primarily builds on the previous work by the following authors: Heckel (1991), who identified and compiled surface outcrops of the Seminole Formation, Campbell (1997) who provided a broader overview of the Seminole Formation/Cleveland sandstone, and Bacon (2012), who provided a comprehensive subsurface analysis of the Cleveland sandstone in central Oklahoma.

Problem

As used informally by the petroleum industry, the time stratigraphic position of the Cleveland sandstone is not well defined. Its temporal, depositional and compositional complexity is partially the result of the Cleveland being sourced by at least three sediment dispersal systems (Campbell, 1997). While it is widely accepted among geologists that the Ouachita uplift is the primary source of detrital material for the Cleveland sandstone (Campbell, 1997), other sources are proposed including one to the northwest (Hentz, 1994), and another to the east and northeast (Krumme, 1981). Sediments eroded from the Ouachita Uplift formed a Pennsylvanian siliciclastic source and the dominance of crystocrystalline chert in the sandstones and Seminole Formation supports this interpretation (Campbell, 1997; Cecil, 2016). In contrast, the abundance of schistose metamorphic rock fragments in the Cleveland sandstone and the subsurface (Bacon, 2012) indicate an eastern and/or northern provenance.

Despite the extensive research of the Cleveland interval in the subsurface, the surface exposures are only described from field observations by Barrick (1991), Bennison (1982), Boardman (1991), Dott (1981), and Heckel (1991). No recent evaluations of these outcrops are available that include thin section analysis and gamma-ray spectrometer readings. Furthermore, no published reports have correlated the outcrop stratigraphy from surface rocks of the Seminole

Formation to the subsurface stratigraphy identified as both the Seminole Formation (Tanner, 1956) and Cleveland sandstone.

Purpose of Study

The principal objectives of this study are to (1) bridge the gap between the surface and subsurface “Cleveland” intervals for central and eastern Oklahoma through a field study that incorporates mineralogical analysis and wireline log curve correlations, and (2), determine the provenance of the Cleveland sandstone using detrital framework grains. Key stratigraphic markers, including the Nuyaka Creek Shale and the Checkerboard Limestone, along with other deeper formations commonly identified on wireline logs, are used to clarify the Cleveland to Seminole Formation correlations.

In Oklahoma, the Cleveland/Seminole outcrop study area (Fig. 1) extends from T. 5 N., R. 7 E. (in Seminole County), to T. 17 N., R 12 E. (in Tulsa County). Heckel (1991) compiled and defined the locations of outcrops for the Lost Branch Formation, in Kansas and Missouri, which is the equivalent stratigraphic section to the Seminole Formation. The Lost Branch Formation contains the Hepler Sandstone, which was sampled. For this study, outcrop data consists of locale identification, stratigraphic measurements, rock sampling (for thin section analysis), and gamma-ray spectrometer surveys. Outcrops identified by Dott & Bennison (1982), and Heckel (1991) in the Lost Branch Formation study were examined.

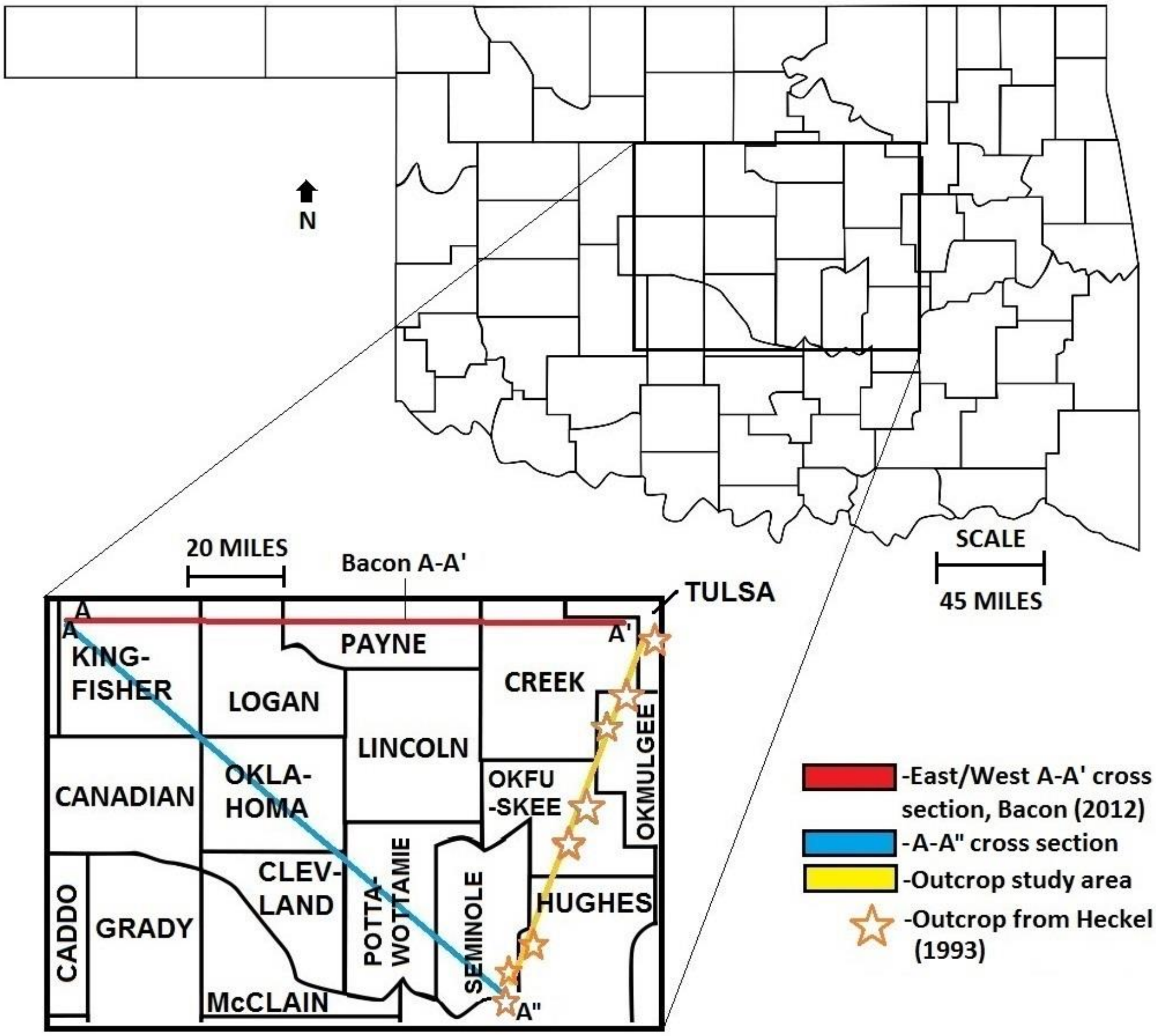


Fig. 1 - Area of study featuring the Oklahoma counties map with the specific surface and subsurface zones identified in the box.

Another objective of this study is to establish generalized composition of outcrop sandstones. Provenance is determined by using thin section petrography. Unfortunately, only outcrop samples are included as the shallow cores of the Seminole Formation identified by Heckel (1991) are believed to be lost.

Hypothesis

The principal hypothesis considered in this study is that the Seminole Formation correlates to the Cleveland sandstone as defined by Bacon (2012). A second hypothesis is that the southern Oklahoma outcrop (Seminole Formation) is sourced from the Ouachita Uplift, whereas the equivalent Seminole Formation in northeastern Oklahoma and the Hepler Sandstone of Kansas have different provenance.

If this secondary hypothesis is supported by data, this study will verify the transition from the Ouachita Uplift sources (Graham, 1976) in the most southern outcrops, to the non-Ouachita source(s) in outcrops found to the north and northeast into Kansas (Moore, 1979) (Fig. 2).

In addition, this study will use surface gamma-ray profiles to correlate subsurface wireline logs, thereby better defining the lithostratigraphy associated with the Desmoinesian and Missourian boundary. Gamma-ray signatures in the well logs will be correlated to surface gamma-ray readings. A wireline-log cross section will be constructed that extends from the western end of section A-A' by Bacon (2012) and trends to the Seminole Formation outcrop (Heckel Outcrop #35) in southeastern Seminole county. This cross section, A-A'', illustrates the stratigraphic and structural characteristics over an area of approximately 100 miles in length from the Anadarko Shelf across the Nemaha Ridge and into the Arkoma Basin, thereby correlating the surface "Seminole" formation with the subsurface lithostragraphic equivalent "Cleveland" sandstone.

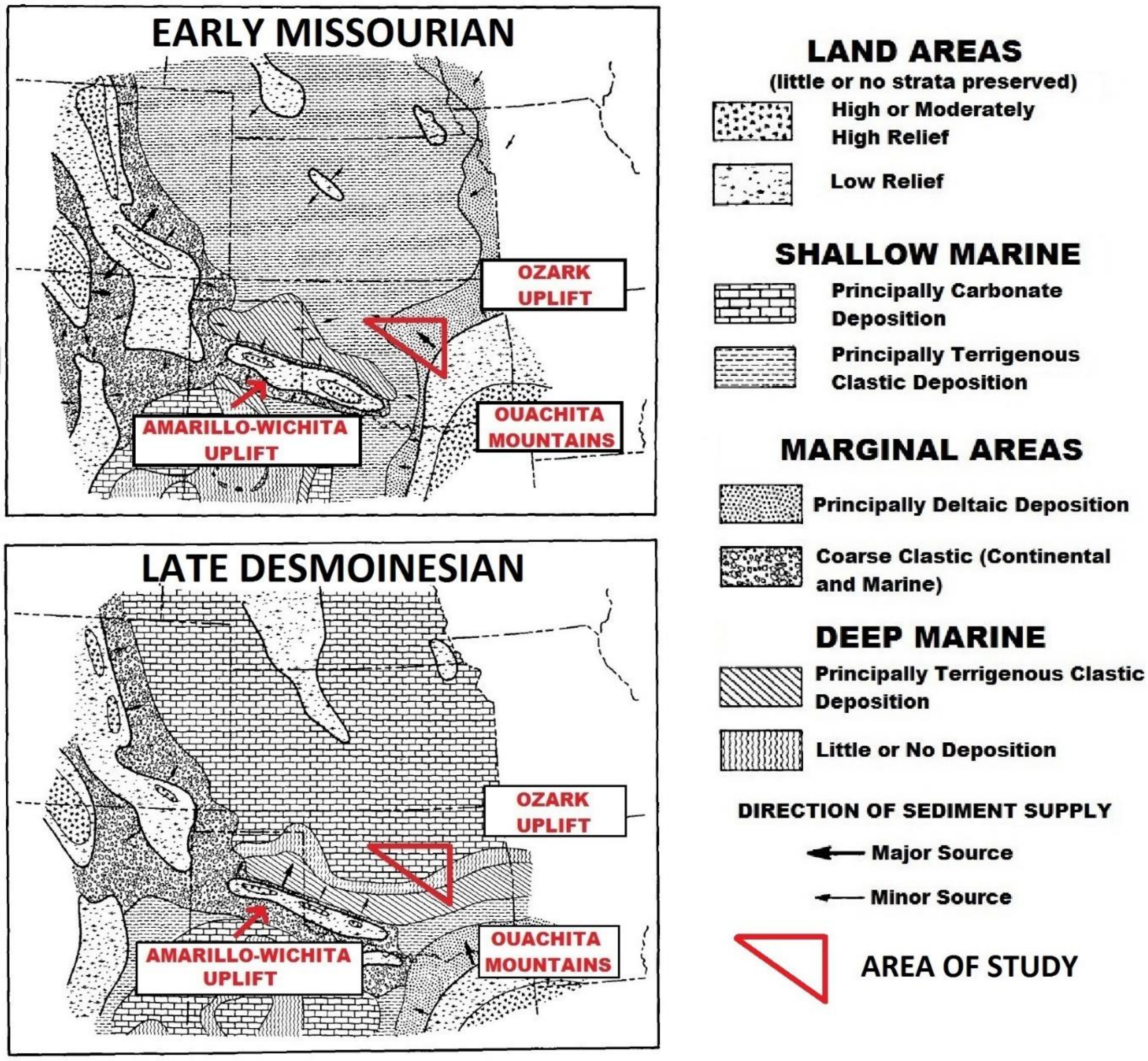


Fig. 2 - Generalized paleogeography and paleoenvironments of the Early Missourian (~310-300 Ma) and the Late Desmoinesian (310-315 Ma). Area of study in red, with names of key uplifts shown in boxes. Modified from Moore (1979).

CHAPTER II

OVERVIEW OF CLEVELAND SANDSTONE & SEMINOLE FORMATION

Seminole Formation

Taff (1901) mapped the Coalgate Quadrangle and first identified the “Seminole conglomerate” in the Seminole Nation of Indian Territory, now known as Seminole County, Oklahoma. Taff characterized the Seminole Formation as laminated or stratified subangular chert with quartz pebbles in a cement of ferruginous sand and brown sandstone (Taff, 1901).

The Seminole Formation in the study area is predominantly composed of well-sorted, sandstones, with occasional beds of shale, and the rare occurrence of coal, mudstone and chert pebble conglomerate (Heckel, 1991). The exposures are typically found in creeks or rivers, or in roadcuts and areas excavated for oil and gas industry well pads. Outcrop strata exhibit low angle dips of less than <5 degrees to the west, and generally strike 15 to 30 degrees NNE.

Surface & Subsurface Variations in Stratigraphic Nomenclature

The primary source for information about the Seminole Formation was compiled by Heckel (1991), who studied the Lost Branch Formation (Fig. 4). This study included previous field work by several geologists including Barrick (1991), Bennison (1982), Boardman (1991), and Dott (1981). A total of 36 outcrops are described that span the entire Midcontinent outcrop area from Oklahoma, northward into Kansas, Missouri and Iowa (see Heckel, Figure 7). Nine of these outcrops in Oklahoma contain the Seminole Formation. The remaining outcrops in Kansas, Missouri and Iowa identify as the “Hepler” unit/sandstone. For this study, the outcrops identified in Heckel (1991) and that have published coordinates were chosen for examination.

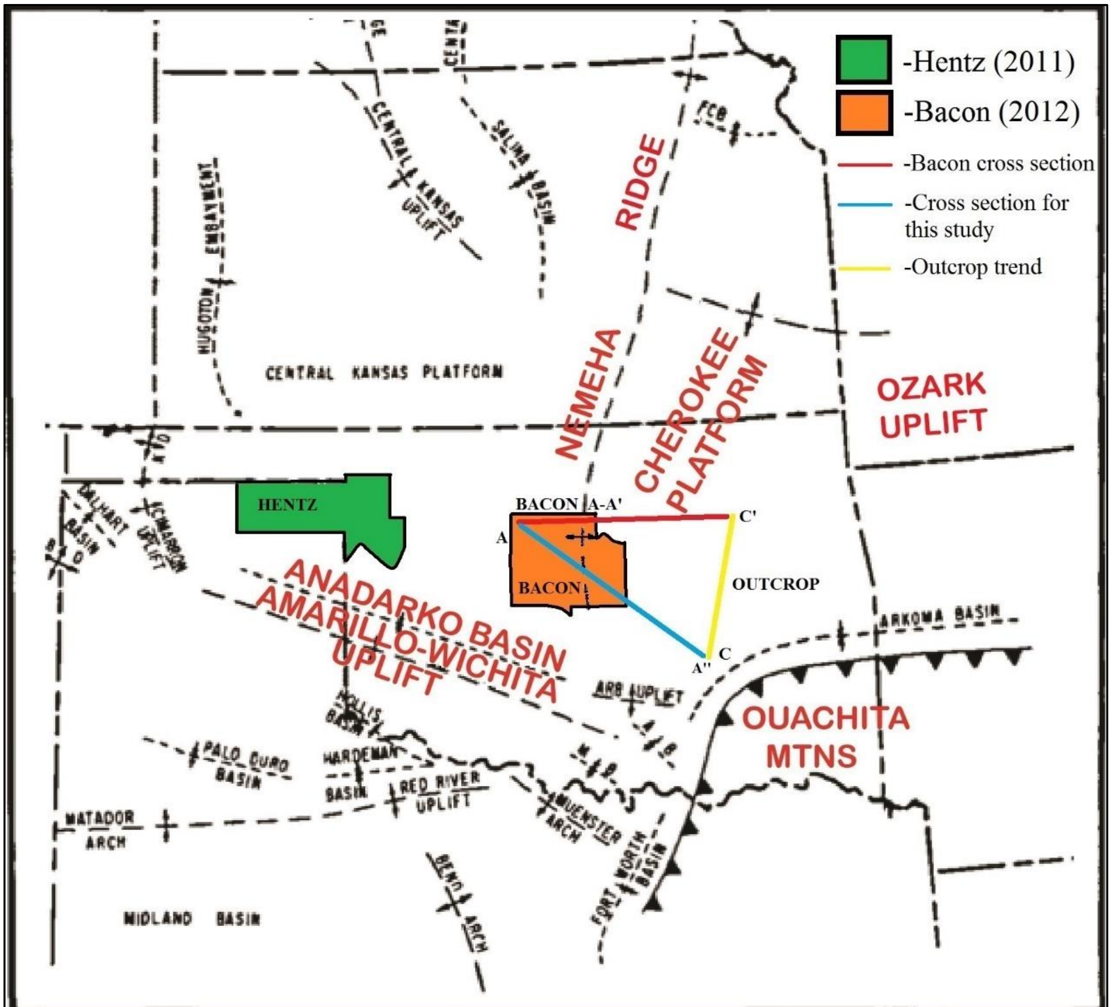


Fig. 3 - Location of subsurface Cleveland sandstone studies by Hentz (2011) and Bacon (2012), cross sections A-A' (Bacon, 2012), A-A'', and C-C', this study and major tectonic features and provinces from Moore (1979).

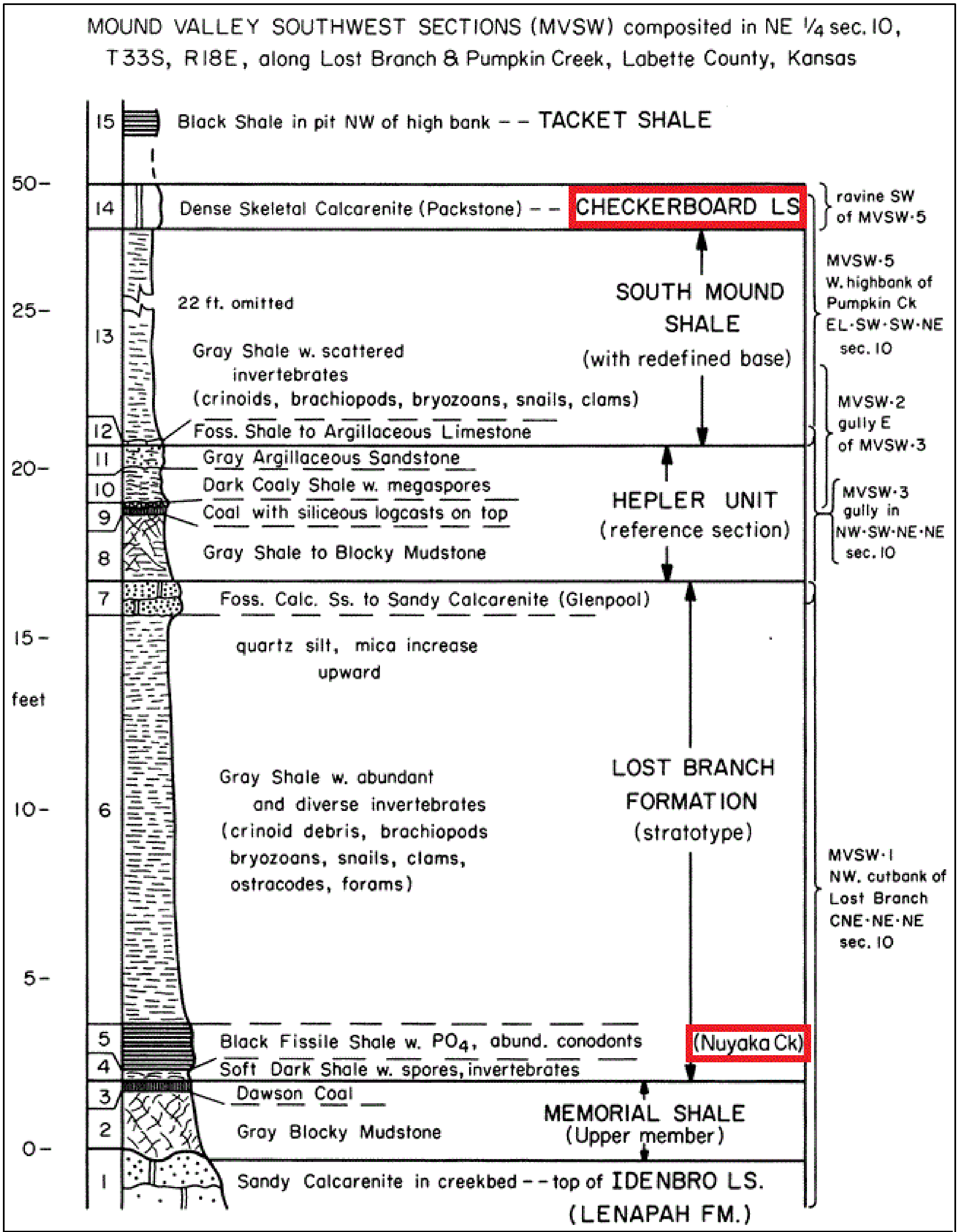


Fig. 4 - Measured section of stratotype of the Lost Branch Formation (Heckel, 1991). Key stratigraphic markers (Nuyaka Creek Shale and Checkerboard Limestone) are outline in red.

Cleveland Sandstone

Subsurface studies of the Cleveland Sandstone include Hentz (2011) for the Anadarko Basin in western Oklahoma and the Texas Panhandle, Bacon (2012) for the Cherokee Platform in central Oklahoma (Fig. 3), and Krumme (1981) for the Cherokee Platform and the Arkoma Basin.

Bacon (2012) mapped the Cleveland sandstone in central Oklahoma (Kingfisher, Oklahoma, Logan and Canadian Counties) and identified three key intervals: A, B and C, and demonstrated how the Nuyaka Creek Shale separates the Marmaton Group from the Skiatook Group, and is used to identify the "true" Cleveland sandstone interval equal to the Seminole Formation at the surface. The petroleum industry commonly assigns the title "Cleveland Sand" to all producing reservoirs beneath the Checkerboard Limestone, and above the uppermost Marmaton carbonate. Prior to Bacon (2012), Knapp and Yang (1997) described the Cleveland sandstone as containing four sections – A, B, C and D – in the Pleasant Mound Field in Lincoln, Oklahoma. Knapp and Yang (1997) did not attempt to identify the "True" Cleveland of Bacon (2012), using the Nuyaka Creek Shale. This study focuses on the section above the Nuyaka Creek Shale that is considered to be the subsurface equivalent to the Seminole Formation.

Campbell (1997) illustrates the confusion concerning using the term Cleveland for multiple stratigraphic positions (Fig. 5). Campbell (1997) indicates the importance of the Nuyaka Creek Shale as a Cleveland sandstone marker bed, and matched the "Cleveland sand" to the Seminole Formation at the surface. Boyd (2008) also places the Nuyaka Creek Shale between the "Upper Cleveland" and "Lower Cleveland" (Fig. 6). Bacon (2012) proposed that Cleveland sandstones above the Nuyaka Creek Shale are "True Cleveland," and part of the Skiatook Group, Missourian Series, whereas "Cleveland" sandstones below the Nuyaka Creek Shale are in the Desmoinesian Series, specifically the Marmaton Group.

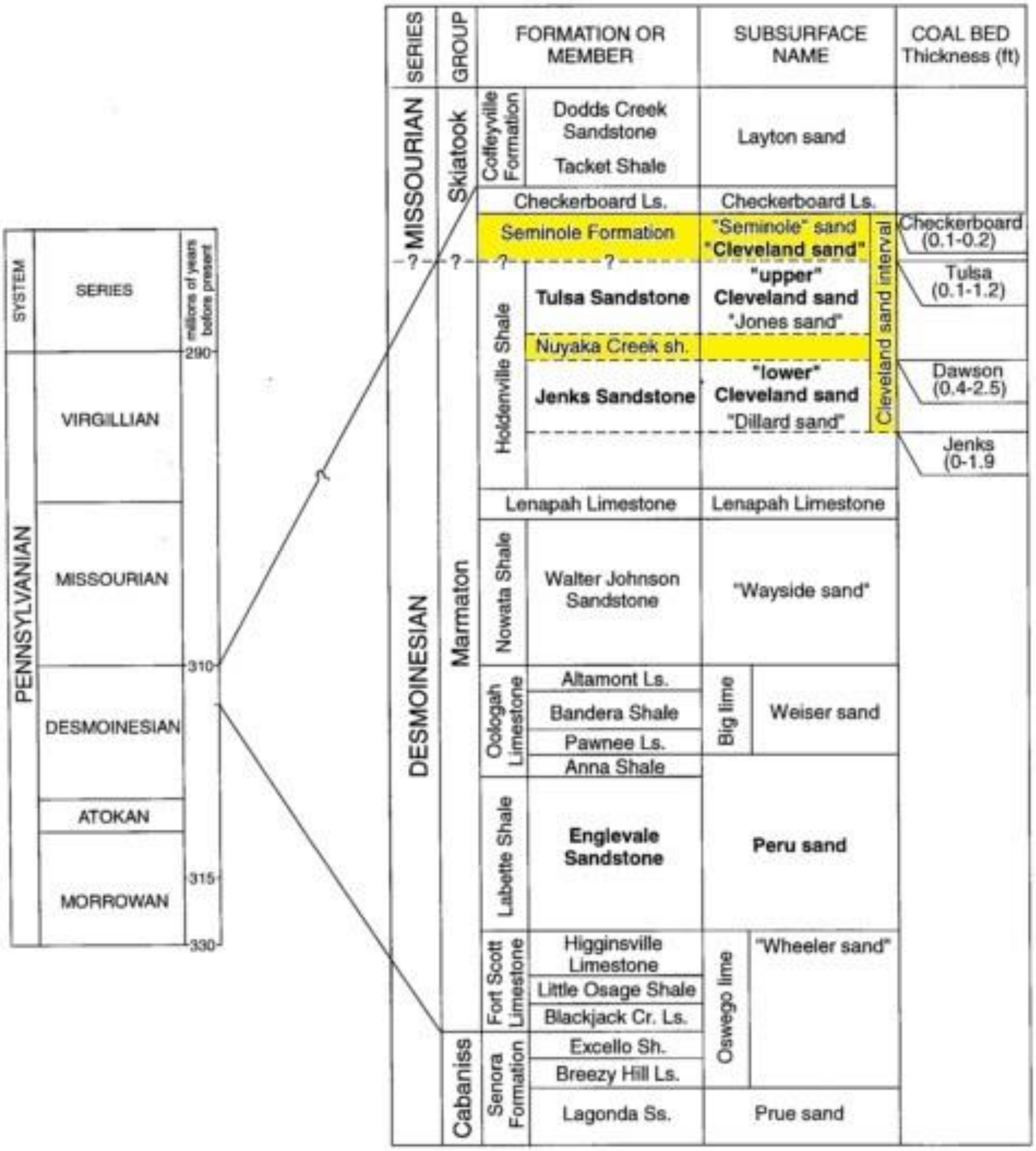


Fig. 5 - Stratigraphic nomenclature of the Marmaton Group (Late Desmoinesian) and adjacent strata on the Cherokee Platform of northeastern Oklahoma (Modified from Figure 15, Campbell, 1997.

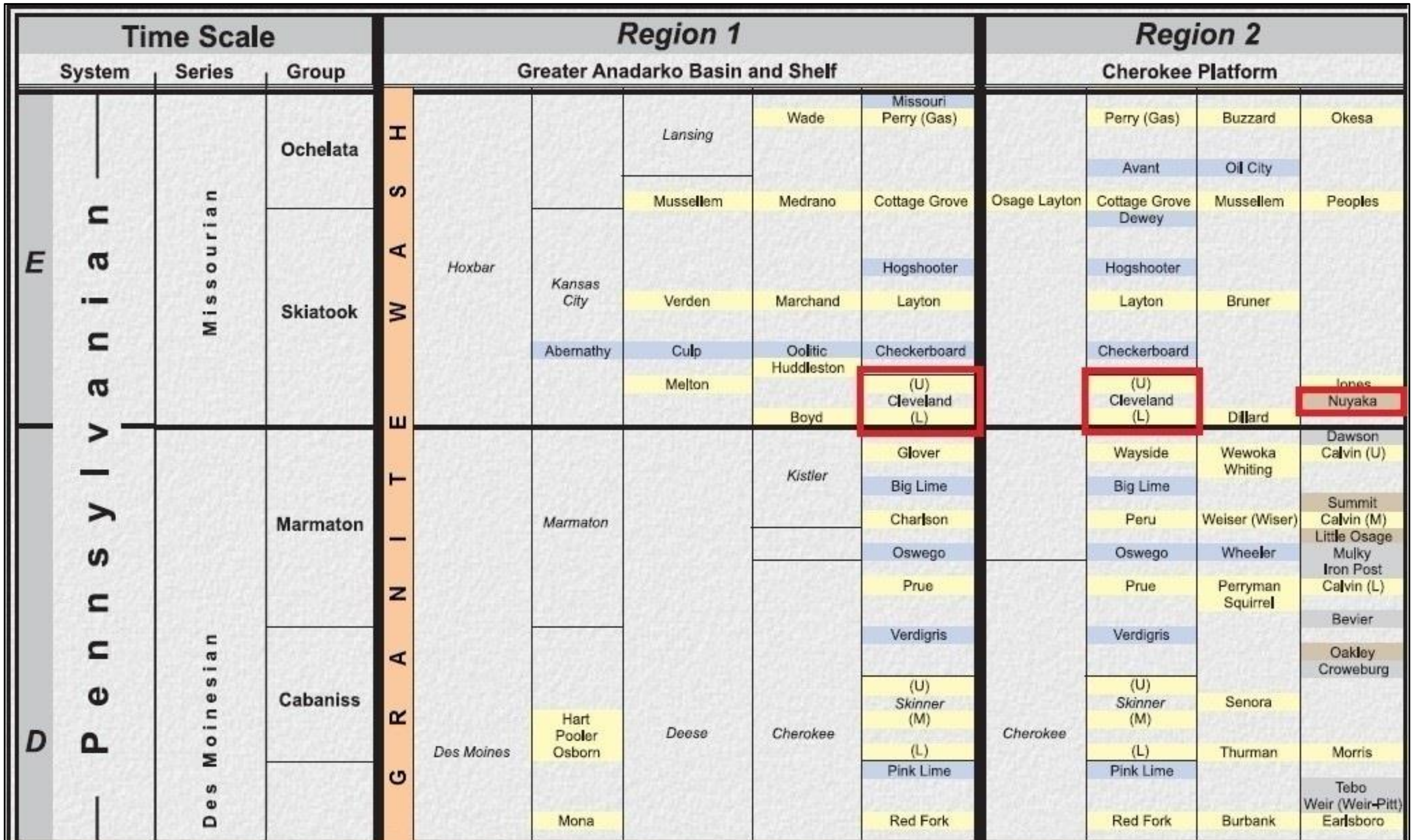


Fig. 6 - Formal and operational stratigraphic nomenclature for the Desmoinesian and Missourian Series of the Pennsylvanian System, with the Cleveland interval marked in red, along with the Nuyaka Creek Shale, which is shown occupying a position between the upper and lower sandstones (modified from Boyd, 2008).

Contact Relationships

Taff (1901) named and described the lower Seminole Formation in the Coalgate Quadrangle (96° to 96° 30' N and 34° 30' to 35° W), defined its lower limit as the top of the Holdenville Shale, but did not define its upper limit. Morgan (1922) proposed that the DeNay Limestone of the Stonewall Quadrangle in southern Oklahoma is the basal layer of the Francis Formation, which overlies the Seminole Formation. The DeNay Limestone is approximatley 150 feet above the base of the Seminole Formation in the Stonewall Quadrangle (Morgan, 1922). Moore et al. (1937) designated the base of the Checkerboard Limestone in Oklahoma as the upper limit of the Seminole Formation. Oakes (1953) confirmed the interpretations of Moore et al. (1937), based on later studies and surface mapping efforts that show the Checkerboard and DeNay limestone beds are stratigraphically equivalent.

According to Bacon (2012), Boyd (2008) and Heckel (1991), the Nuyaka Creek Shale is an important marker bed and recognized by its dark color and radioactive nature. Identifying the Nuyaka Creek Shale in the field and on the wireline logs should allow correlation of outcrop sections to the subsurface. The Nuyaka Creek Shale is widely distributed across Oklahoma and Kansas, and is recognized by its radioactive signature (gamma-ray value > 150 API units). This shale marker bed is found at the surface within the Holdenville Shale (Heckel, 1991) (Fig. 4).

According to Bacon (2012), the “True Cleveland” interval (equal to the Seminole Formation at the surface) contains sand bodies deposited above the Nuyaka Creek Shale and below the Checkerboard Limestone (Fig. 7). The Checkerboard Limestone, which is also identified in outcrop, is a primary marker bed used to identify the Cleveland sandstone in the subsurface using wireline data. The equivalent of the Checkerboard Limestone in Outcrop #35 is the Sasakwa Limestone according to Heckel (1991) (Fig. 17), which contradicts Moore et al. (1937).

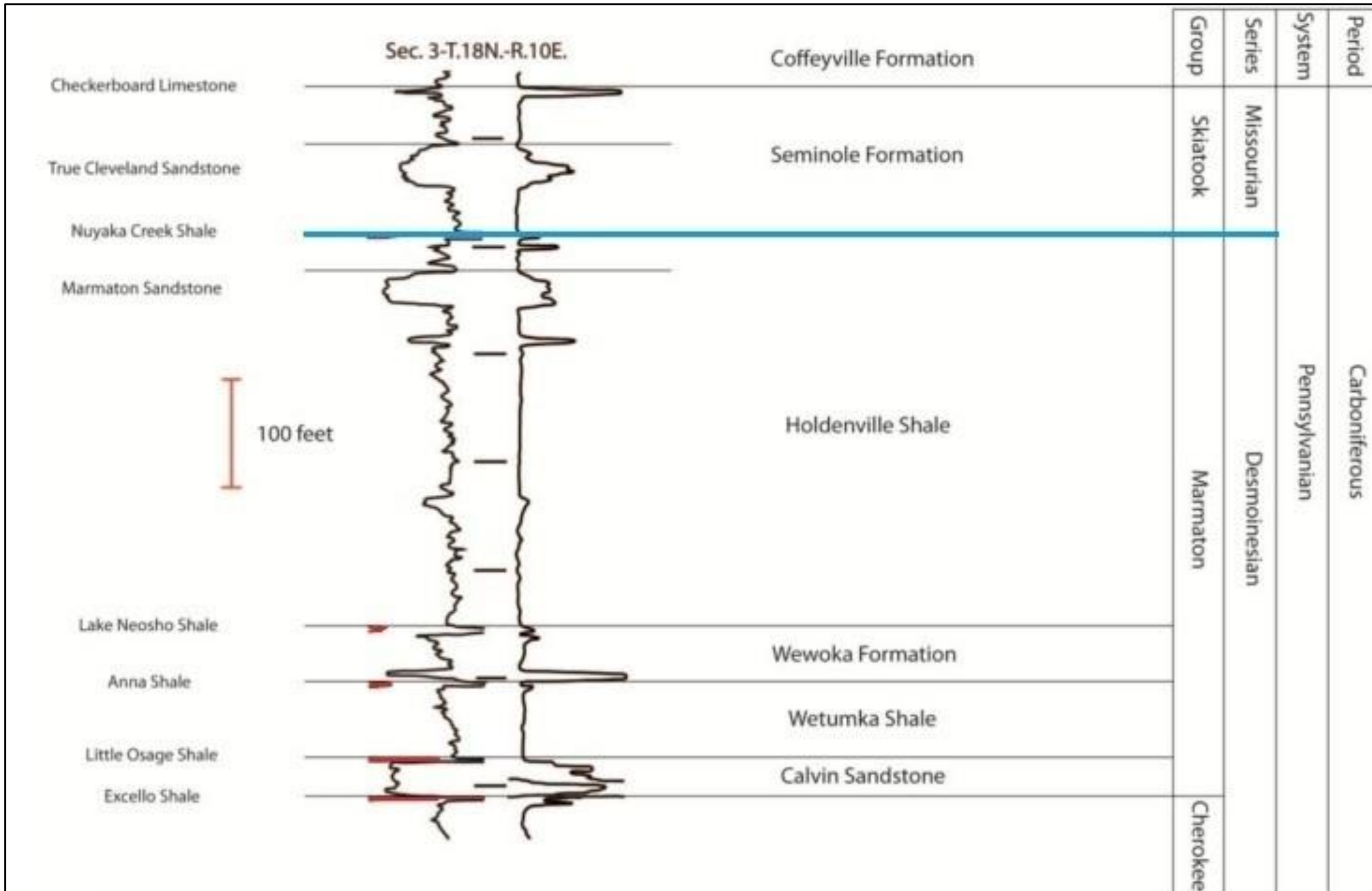


Fig. 7 - The "True" Cleveland sandstone is identified in the Seminole Formation. The Nuyaka Creek Shale is marked by the blue line. Radiogenic shale markers in the Marmaton Group below the Nuyaka Creek Shale are marked red (Modified from Bacon, 2012). Log signatures are for the "Hill D-3" well in Kingfisher County, Oklahoma.

Regional Distribution & Structural Analysis

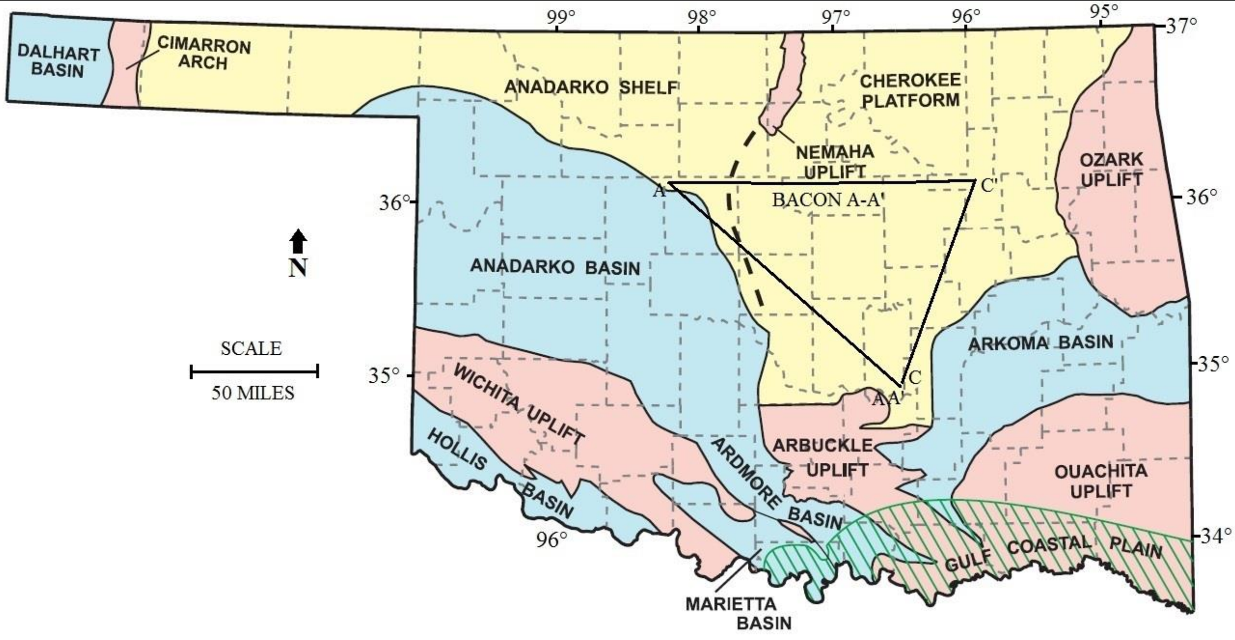


Fig. 8 - Map of major tectonic provinces of Oklahoma, with study area outline (Modified from Johnson, 2008)

Pennsylvanian deposition of the southern Midcontinent was influenced by the Wichita, Arbuckle and Ouachita orogenies (Fig. 9) that contributed to subsidence of the Anadarko, Arkoma, Ardmore and Marrieta basins and elevation, and erosion along the Nemaha Uplift (Fig. 8). The Ouachita orogeny deformed in pulses as plate collision resulted in folding and thrusting that progressed northward before ceasing (Johnson, 2008).

Krumme (1981) constructed several cross sections across the study area including one that runs sub-parallel to the outcrops studied (Fig. 10). This cross section visually demonstrates the subsurface relationship of the Cherokee Platform to the Arkoma Basin (Fig. 11). Sandstone bodies in the Seminole, Holdenville, Wetumka, Wewoka and Calvin sequences appear to terminate before reaching the Cherokee Platform (Fig. 11).

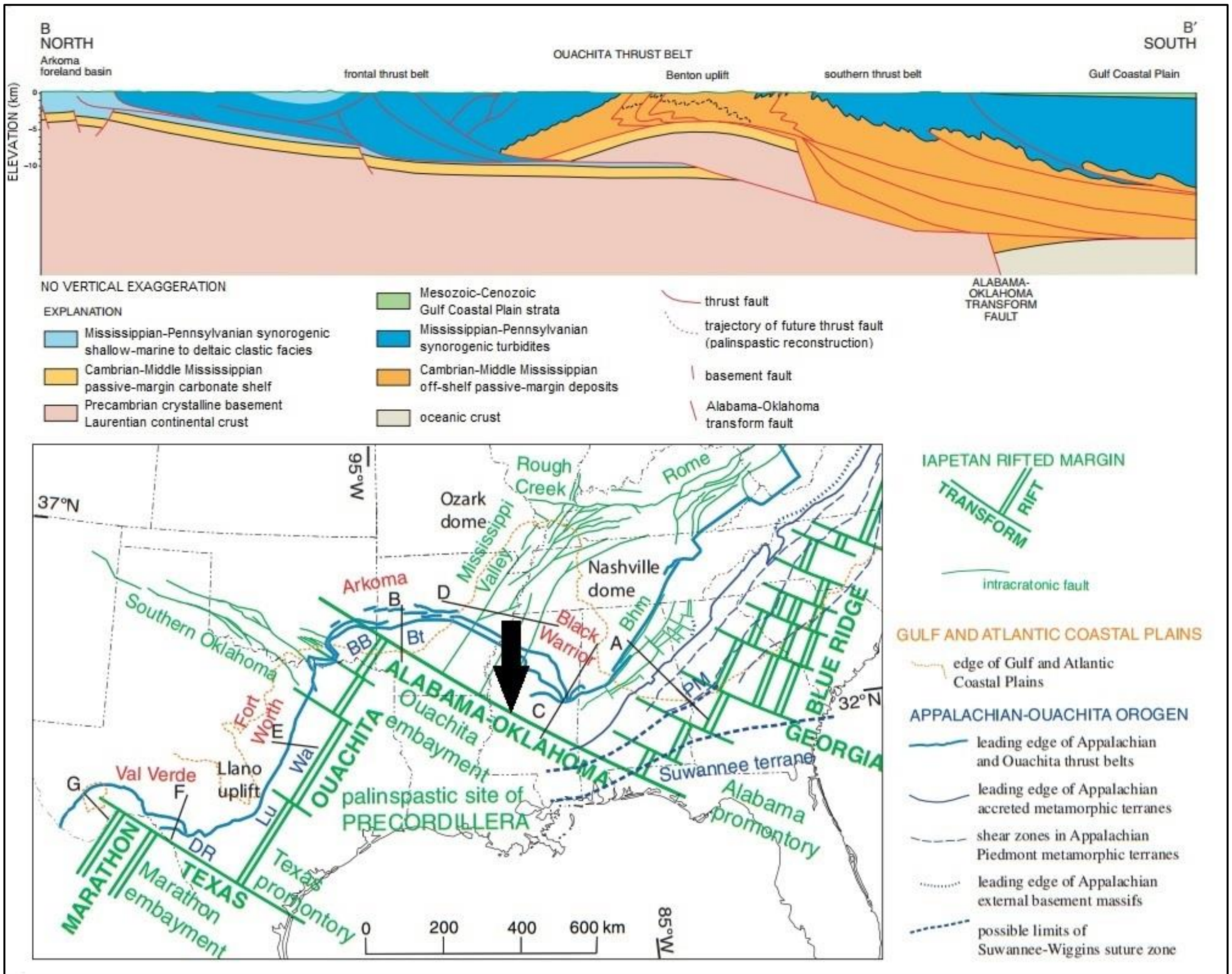


Fig. 9 - Structural cross section (B-B') of the Ouachita thrust-belt structures and palinspastic reconstruction of Iapetan margin along the Alabama-Oklahoma transform fault beneath the Oucahita thrust belt in Arkansas (above), and the accompanying outline map showing where B-B' runs from Oklahoma to Alabama (below). Modified from Thomas (2011).

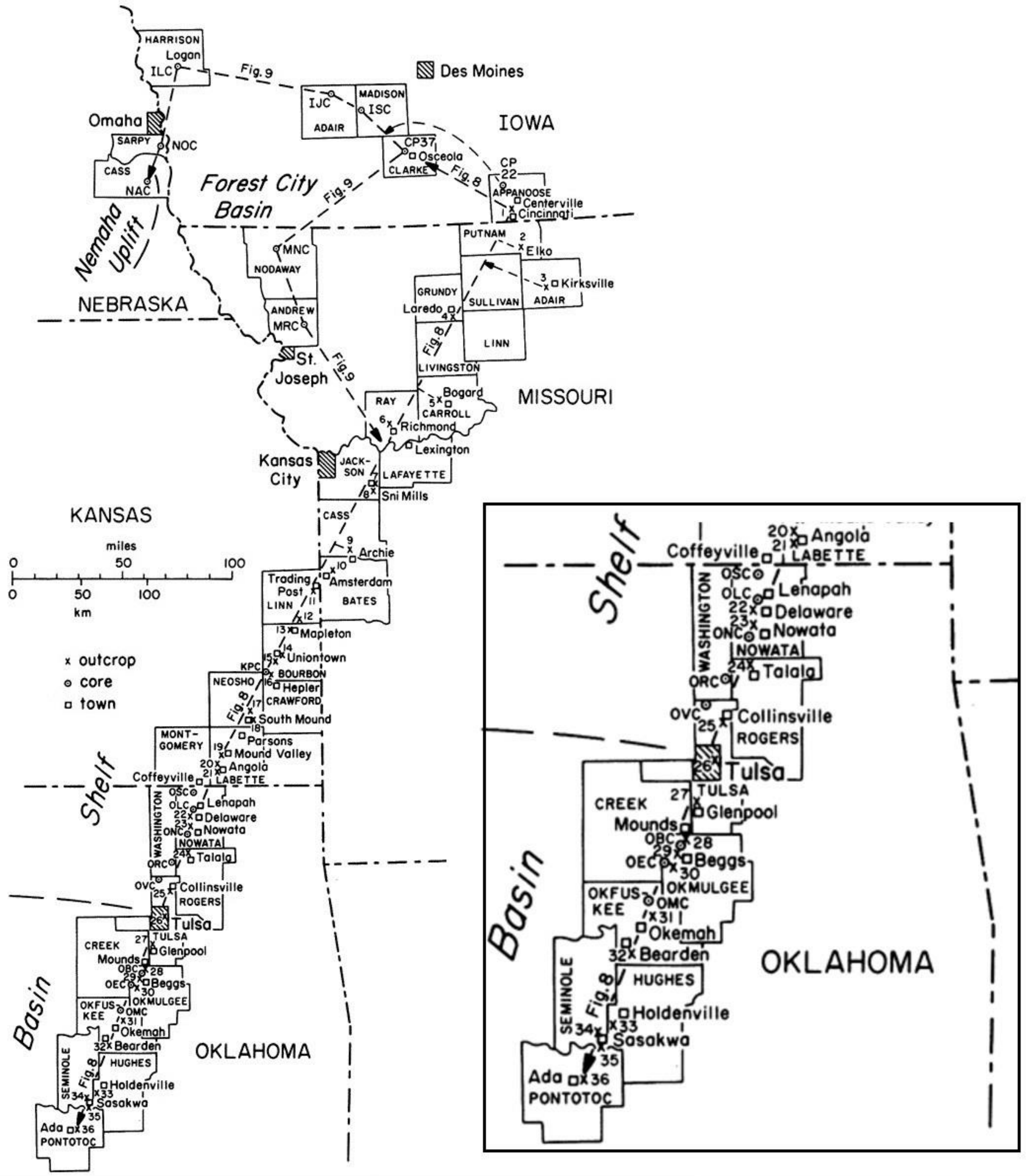
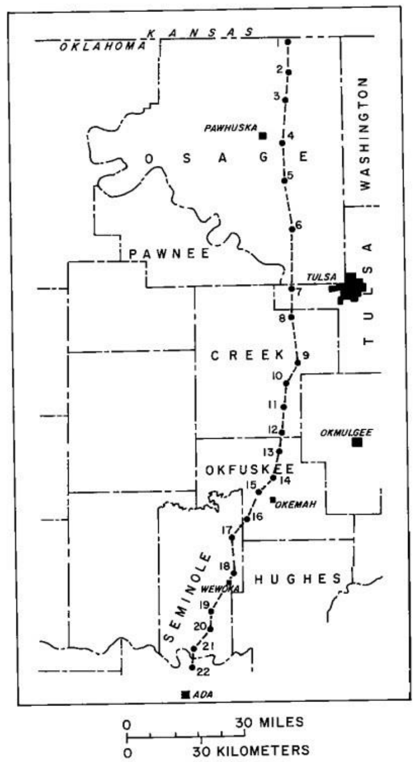


Fig. 10 - Locations of exposures for the Lost Branch Formation and associated units along the outcrop belt, with cores (lettered circle with dot) that contain Lost Branch strata (modified from Heckel, 1993). Enlarged view of locations of Oklahoma and southeastern Kansas outcrops, and cores.



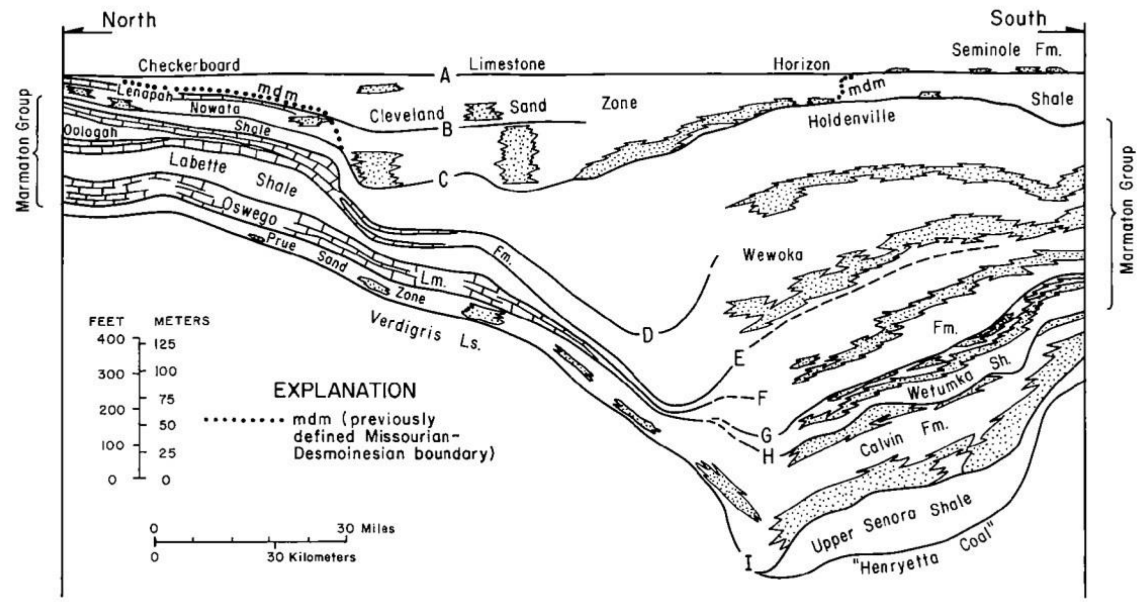


Fig. 11 - From Krumme (1981). North-south electric log cross section of the study interval from Kansas line to Pontotoc County, Oklahoma, and the accompanying stratigraphic profile (top). A) Missourian-Desmoinesian boundary marked by Checkerboard Limestone. B) Approximate boundary where Lenepah Limestone separates "Upper" and "Lower" Cleveland sands. C) Boundary for Base of Lower Cleveland and top of Holdenville Shale.

CHAPTER III

METHODOLOGY

Field Sampling & Measuring

In this study, the Seminole Formation outcrops described in Dott and Bennison (1982) and Heckel (1991) were revisited (see Table 1). The outcrops were relocated using a combination of the section-township-range governmental land survey descriptions and photographic inspection using Google Earth. Once located, these outcrops were remeasured using a Jacob staff. Representative samples were collected, and marked with a unique identifier including outcrop number, placed into plastic sealable bags and labeled.

Fig. 12 - The gamma-ray spectrometer tool used in the field for this study (stock photo courtesy Radiation Solutions).

Gamma-Ray Spectrometer Surveys

Gamma-ray readings were collected from the known outcrops using a gamma-ray spectrometer. These readings were converted into an American Petroleum Institute (API) gamma-ray curve and correlated with wireline logs from nearby wells, as proposed by (Ettensohn, et al., 1979). Chamberlain (1984) advised five foot intervals when surveying to provide for optimal results. Four outcrops, #35, #32, #31 from Heckel (1991) and Southern Hills in Tulsa County, were selected for this study. These outcrops contain the stratigraphic units of interest and were surveyed using a gamma ray spectrometer (Fig. 12). The gamma-ray spectrometer (RS 230 model by Radiation Solutions) measures uranium, thorium and potassium values, which were then converted to an API value for total gamma ray. The formula for conversion is:

API value: *(16 x K) + (8 x U) +(4 x Th)*

where: K = pottasium
U = uranium
Th = thorium

Location	Description	County	Latitude and Longitude	Township
Outcrop #35	Roadcut and Wellsite	Seminole	34.91361111 N, -96.51694444 W	Sec. 12, T. 5 N., R. 7 E.
Outcrop #34	In River Bed	Seminole	34.96444444 N, -96.51083333 W	Sec. 25, T. 6 N., R. 7 E.
Outcrop #33	Roadcut	Hughes	35.02305556 N, -96.50472222 W	Sec. 5, T. 6 N., R. 8 E.
Outcrop #32	In Stream	Hughes	35.34138889 N, -96.36250000 W	Sec. 15, T. 10 N., R. 9 E.
Outcrop #31	In Nuyaka Creek	Okfuskee	35.47888889 N, -96.28972222 W	Sec. 32, T. 12 N., R. 10 E.
Outcrop #30	In Stream	Okmulgee	35.71888889 N, -96.16361111 W	Sec. 4, T. 14 N., R. 11 E.
Outcrop #28	In Stream	Okmulgee	35.83833333 N, -96.09722222 W	Sec. 30, T. 16 N., R. 12 E.
Southern Hills	Roadcut	Tulsa	36.07027778 N, -95.97305556 W	Sec. 5, T. 18 N., R. 13 E.
Outcrop #11	In River Bank	Linn (KS)	38.25000000 N, -94.70166667 W	Sec. 5, T. 21 S., R. 25 E.

Table 1 - Locality register of outcrops examined in this study.

Lithological Analysis & Provenance Designation

Selected samples from outcrops were cut into billets and thin sectioned. Thin section microscopy was conducted using an Olympus BX 51 petrographic microscope. Lithology was determined based on the classification of Dott (1964). Point counts (Fig. 13) were based on 6 views with 60 points per viewing, for a total of 360 counts. The lithologic designation was based on a series of framework modes compiled by Dickinson & Suczek (1979). A quartz, feldspar and lithofragment (QFL) was used to establish detrital framework grain percentages and classify each sample. Detrital composition of each sandstone was compared with earlier and concurrent studies to determine sand provenance.

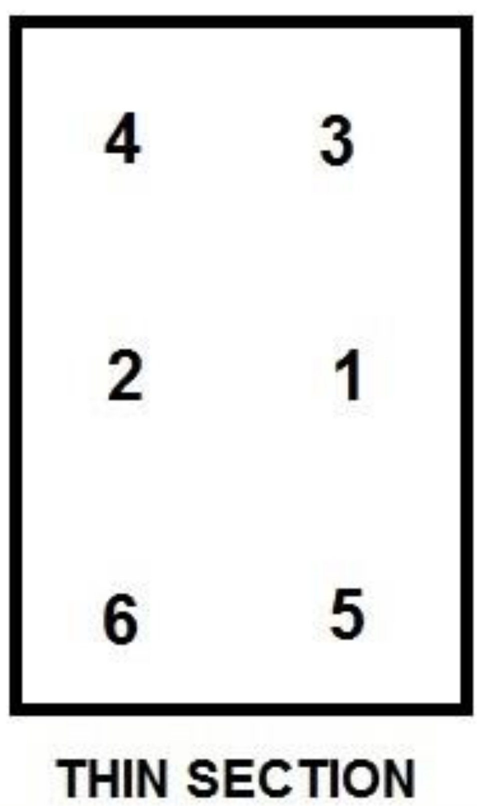


Fig. 13 - Point count numbering system used for this study.

Regional Cross Section

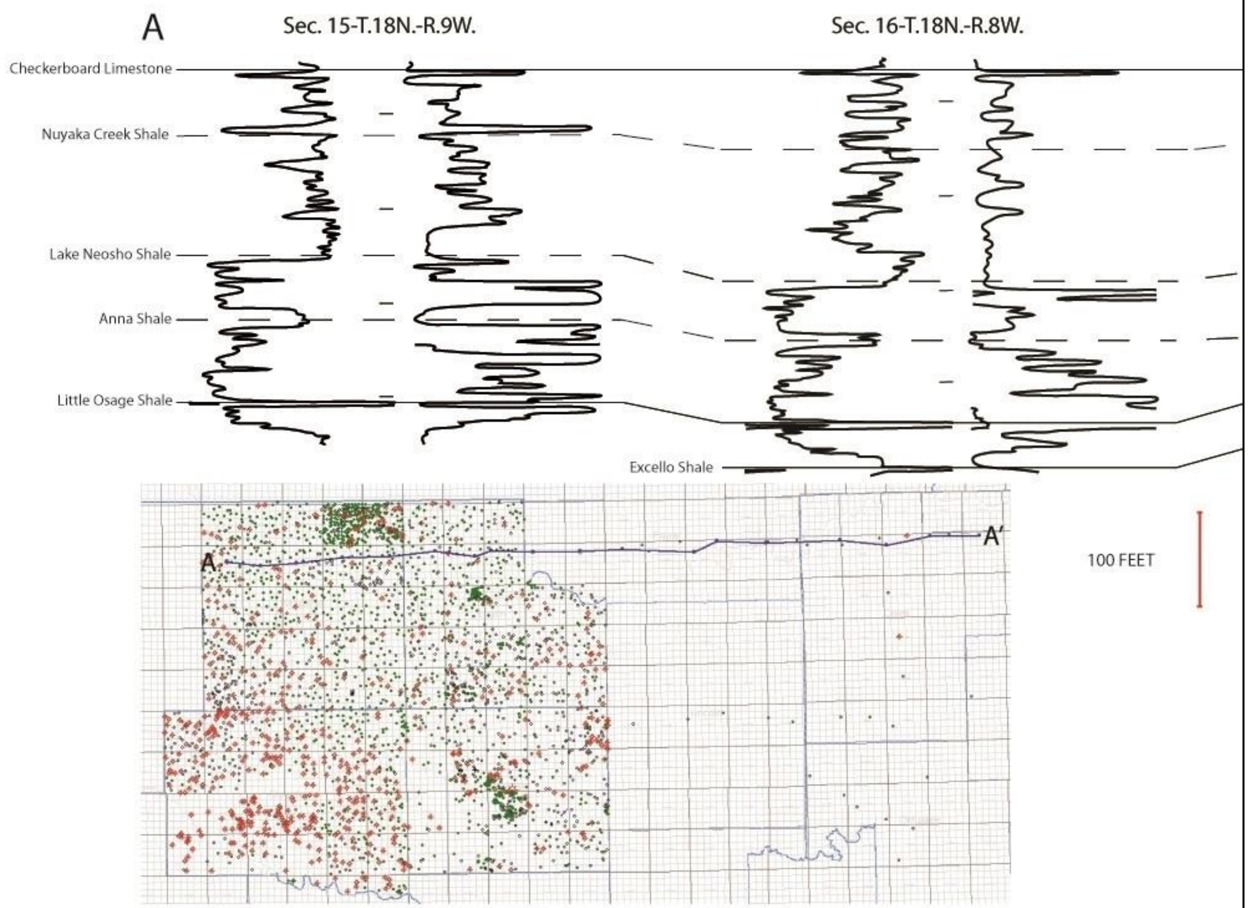


Fig. 14 - The west-east correlation section A-A' by Bacon (2012), truncated to fit in this study. Point A is the Hill D-3 well in Kingfisher Count, and runs east to Point A' in Tulsa County (well not identified). The top layer is the Checkerboard Limestone, followed by the "hot shales" of Nuyaka Creek, Lake Neosho, Anna, Little Osage and Excello.

Because the middle Pennsylvanian contains radiogenic shales known as core shales (Heckel, 1991) that are detected by the gamma-ray tool and easily recognized on gamma-ray curves as anomalously API values, they provide confident markers used for correlation.

Wireline logs provide a means to the correlate from the outcrop gamma ray spectrometer readings to the subsurface by identifying repeatable wireline log patterns. Wireline log cross section A-A'' (not to be confused with A-A' by Bacon, 2012) (Fig. 14) was constructed, extending from the best exposed section in southeastern Seminole County (Outcrop #35), to the western end of cross section A-A' prepared by Bacon (2012). Point A in both cross sections is the "Hill D-3" well in Sec. 15, T. 18 N., R. 9 W. (Fig. 14). Cross section A-A'' spans roughly 200 kilometers (125 miles) and illustrates the stratigraphic relationships in the western Arkoma Basin, across the Cherokee Platform and Nemaha Uplift to the northern shelf of the Anadarko Basin (Fig. 3). This cross section is roughly perpendicular to the outcrop trendline. Cross-section A-A'' contains twenty wells that were selected for their gamma-ray curves. The cross section was generated using Petra (IHS) geologic interpretation software with the base of the Checkerboard Limestone serving as the stratigraphic datum. The wells were selected based on the following criteria: 1) proper depth to include the Checkerboard Limestone and either the Caney or Woodford "hot shales," 2) adequate spacing by township-range between each selection (about 1-2 townships apart), and 3) having a gamma ray signature. Seven wireline logs for wells in Seminole County, near Outcrop #35, were selected with a spacing of approximately one mile between each well, in order to extend the eastern end of cross-section A-A'' to the stratigraphy of Outcrop #35 (Fig. 15). This cross section constructed using near-surface logs is referred to as B-B'.

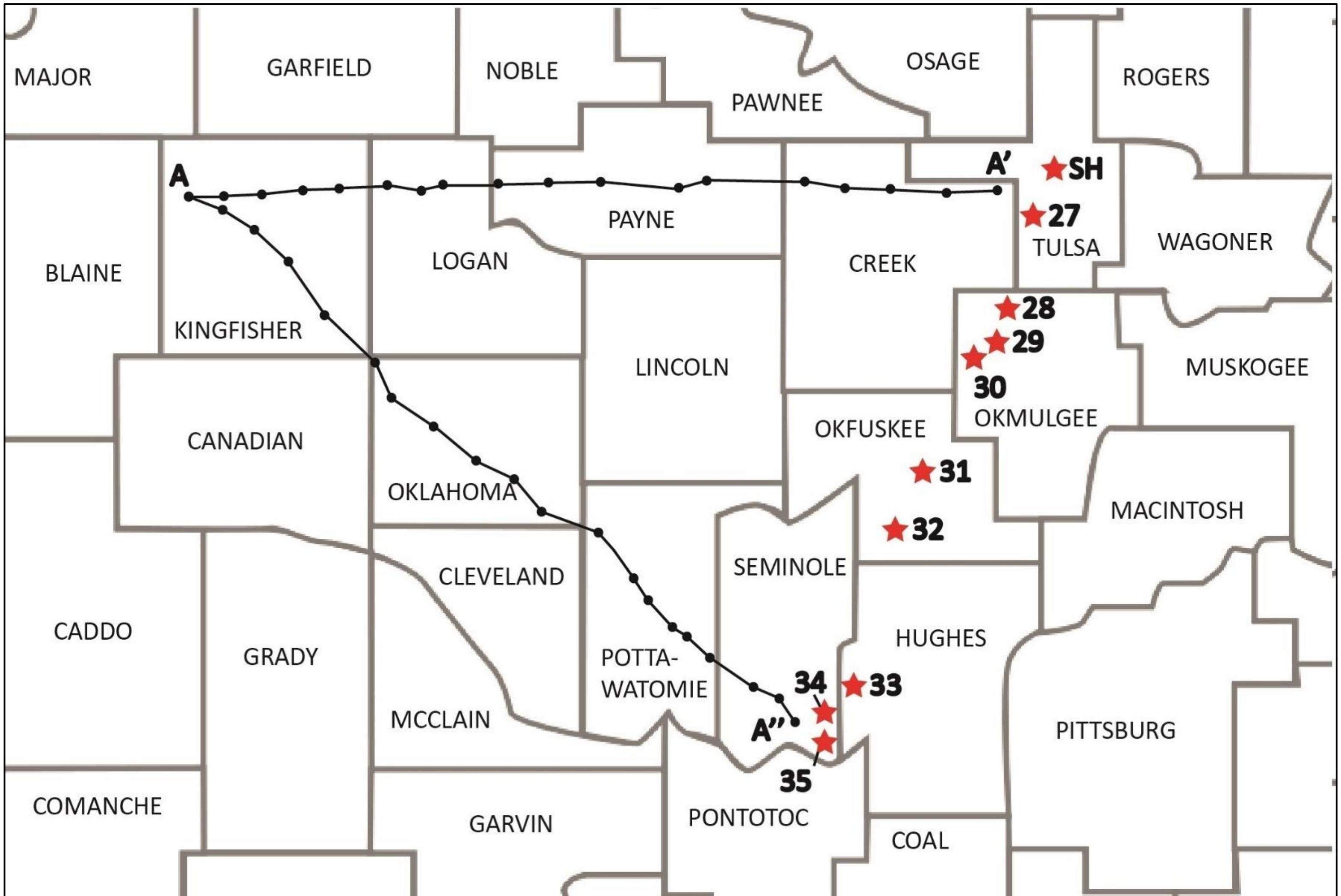


Fig. 15 - Locations of Cross Section A-A' (Bacon, 2012), A-A" from this study, and the outcrops identified by Heckel (1991) (red stars).

CHAPTER IV

FIELD WORK AND LAB RESULTS

Generalized Petrographic Overview

The average grain size in the collected sandstone and conglomerate samples of the Seminole Formation is predominantly fine sandstone (0.01-0.02 mm). The coarsest sediment samples are of pebble-sized (5.0 mm – 10.0 mm) conglomeratic chert at two outcrops in the southernmost locales of the study area (Outcrops #33 and #35). Most quartz grains are subangular to subrounded, with occasional angular grains. Calcite cement is ubiquitous in the conglomerate samples, and also appears in the some of the sandstone samples.

Component mineral grains identified in thin sections include: quartz, polycrystalline quartz, chert, feldspar, muscovite, metamorphic rock fragments and heavy minerals including tourmaline. Quartz is the most abundant detrital grain, with the exception of the conglomerate samples where chert pebbles are present. Chert occurs as either detrital grains or as pore-lining cement. Feldspar grains are predominantly plagioclase, with rarer occurrences of orthoclase (Outcrop #35).

Outcrop #35

Location and General Description

The most southern outcrop examined is also the thickest at ~75 feet. It is located about 2.0 miles southeast of Sasakwa, Oklahoma, in the SE SW SE sec. 12, T. 5N., R. 7 E (34.91361111 N, -96.51694444 W) (Fig. 16). The outcrop consists of a roadcut and the bank of a drilling pad to the north of the road. Excavation of the drilling pad exposed in the upper part of the Seminole Formation. The section along the road was measured by Dott and Bennison (1982), and described by Heckel (1991) (Fig. 17).

Fig. 16 - Map view of Sec. 12, T. 5 N., R. 7 E., containing Outcrop #35 about 2 miles south of Sasakwa in Seminole County, Oklahoma. The area of study is marked with a white star.

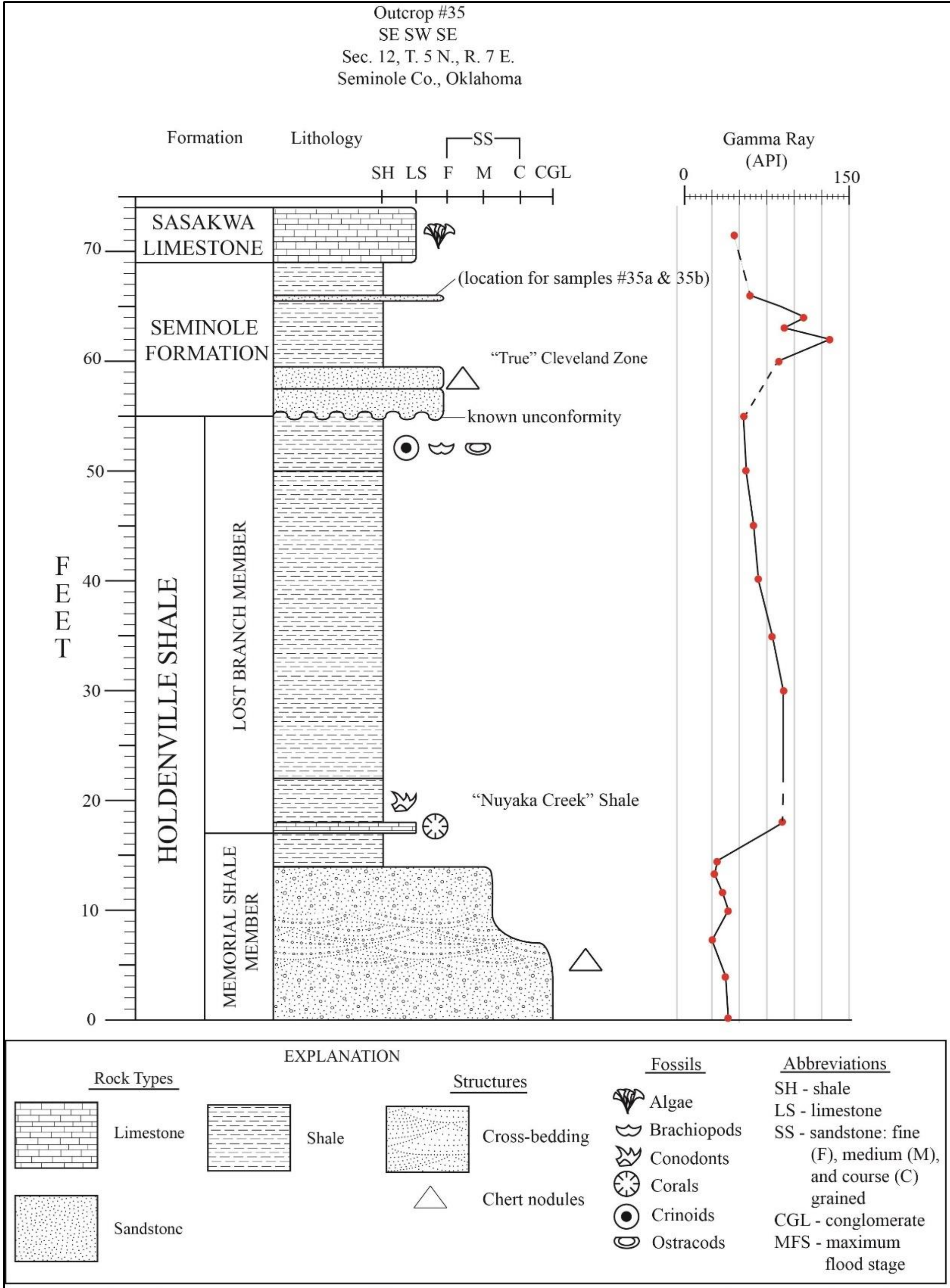


Fig. 17 - Stratigraphy of Outcrop #35 near Sasakwa, Oklahoma, and correlated to the gamma ray profile (right). Red circles on gamma-ray plots indicate location of spectrometer reading measurements. Section measurements by Dott and Bennison (1981), and published in Heckel (1991). Position of known unconformity based on Tanner (1956).

Stratigraphy and Lithologic Description

Outcrop #35 was subdivided by Dott and Bennison (1982) into three units: The Holdenville Shale (55.0+ feet), the Seminole Formation (14.0 feet), and the Sasakwa Limestone (5.0 feet). The Holdenville Shale is divided into the Memorial Shale Member and the Lost Branch Member (Heckel, 1991). The Memorial Shale is mostly tan to brown sandstone and pebble conglomerate, which totals 15.0 feet. The sandstone is trough cross-bedded with cross stratification surface 1.0-1.5 feet in height, and contains rounded to sub-angular chert pebbles up to 1.0 cm in length.

The sandstone and conglomerate in the Memorial Shale is overlain by 3.0 feet of gray, sandy shale. The base of the overlying Lost Branch Member is the Homer School Limestone (1.0 foot) (Heckel, 1991), which is now known as the Homer Limestone (USGS, 2017). The Nuyaka Creek Shale overlies the Homer School Limestone, but is not exposed. Heckel (1991) reports the Nuyaka Creek Shale is 4.0 feet of thick, but excavation above the Homer School Limestone (Fig. 18) failed to reach it (see Fig. 19 for Google Earth overview of assumed location for Nuyaka Creek Shale in proximity to Seminole Formation).

The poorly exposed Lost Branch Member above the Nuyaka Creek Shale is a gray shale (28.0 feet) that Heckel (1991) reports containing scattered fossils not sampled. Above it is another unit of gray shale (5.0 feet) with lenses containing brachiopods, crinoid pieces, fish debris, ostracods, and sparse conodonts (Heckel, 1991).

The slope-forming shale extends upward to the basal sandstone of the Seminole Formation. The Seminole Formation consists of 2.5 feet thick of gray sandstone, 2.0 feet of sandstone with chert pebbles, 6.0 feet of reddish to green-gray shale with caliche nodules and marine invertebrates (crinoids and brachiopods), 0.5 feet of yellow to brown sandstone, and 3.0 feet of gray-brown mottled mudstone. Overlying the Seminole Formation is the Sasakwa Limestone, which is poorly exposed, but described by Heckel (1991) as 5.0 feet of skeletal algal limestone that is equivalent to the Checkerboard Limestone that outcrops in Tulsa County (see Discussion).

Gamma ray spectrometer readings were collected at least every 5.0 feet across the outcrop, and in well exposed beds every 1.0 foot (i.e. Memorial Shale Member and Seminole Formation).

Fig. 18 – Trench at Outcrop #35. Attempts to find the Nuyaka Creek Shale were unsuccessful. Shovel rests on the Homer School Limestone.

Fig. 19 - Overview of Outcrop #35 from Google Earth showing the approximate stratigraphic boundary.

Fig. 20 - Photograph of chatetes is Homer School Limestone on hillside north of Outcrop #35. Rock hammer for scale.

Rock Samples and Thin Sections

Figure 21 - Photos from Outcrop #35 at the top sandstone layer of the Seminole Formation. Picture a) is a panoramic view of the outcrop, with white circles indicating where samples 35a and 35b were taken; b) a close-up view of where sample 35b was taken, corresponding to the white circle on the left; c) a close-up view of where sample 35a was taken, corresponding to the white circle on the right. Field tools used for scale.

Two representative samples were collected from the Seminole Formation at Outcrop #35. Both samples were collected from the uppermost sandstone body toward the top of the Seminole Formation (Fig. 21).

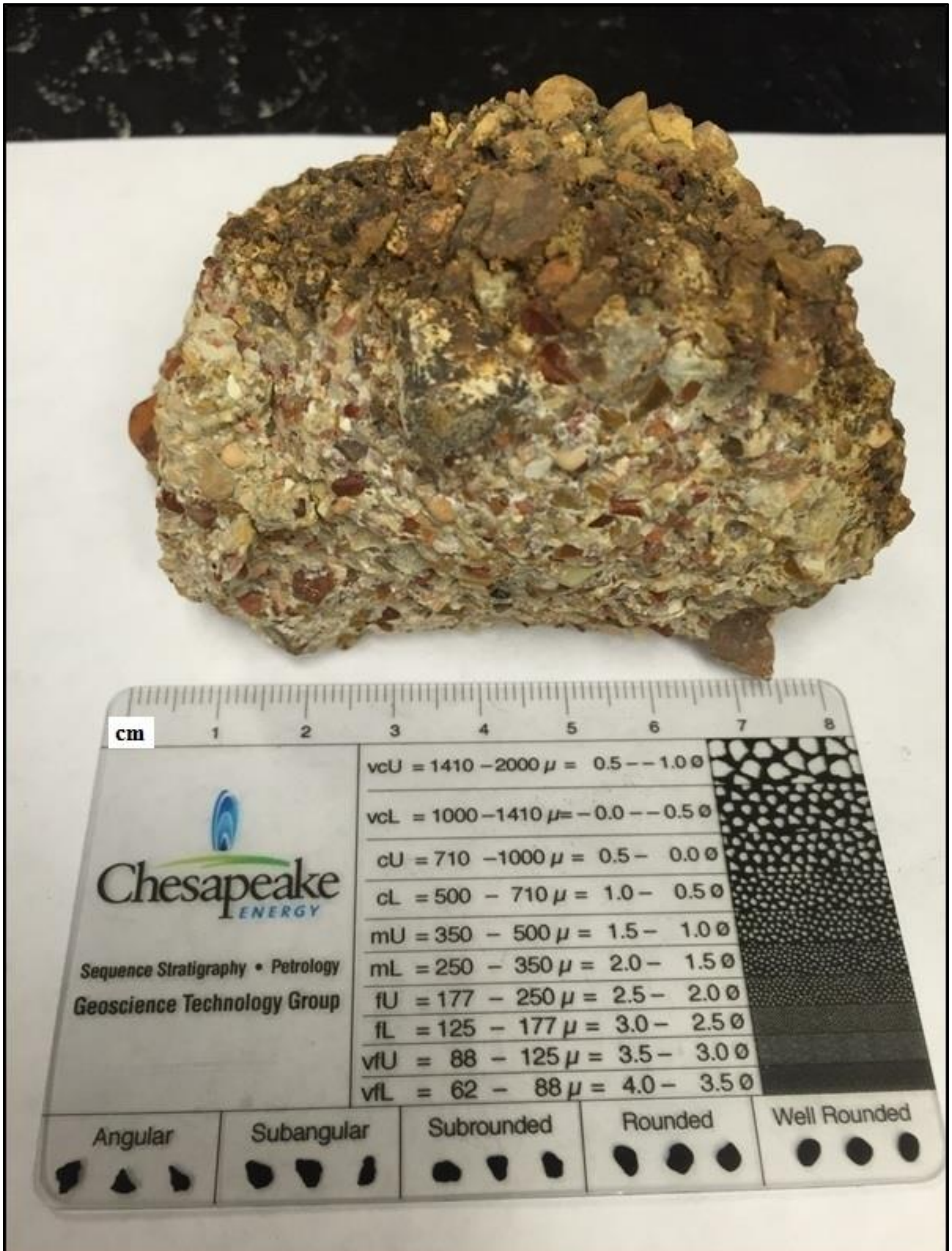


Fig. 22 - Hand sample of chert pebble conglomerate from Outcrop #35. Thin section "35a" is from this sample.

Sample 35a is a pebble conglomerate (Fig. 22) comprised of rounded to sub-rounded chert fragments typically ranging in size from 2.0-5.0 mm, but reaching lengths of 1.0 cm along the longest axis. The matrix is mostly rounded quartz and chert grains that are commonly 0.2 mm in length. Calcite cement is abundant and evident in thin section by its birefringence and differential relief.

Composition

Sample 35a was stained with alizarin red-S to identify calcite. The detrital grains include: sutured grains (Fig. 23 and 24); 1) 49% rock fragments of micro-to crypto-crystalline chert; 29% calcite cement; 2) 14% mono-crystalline quartz. Authigenic syntaxial components are dominantly silica cement on grain boundaries, and pore occluding calcite cement (29%). A solid residue that partially fills porosity appears to be bitumen.

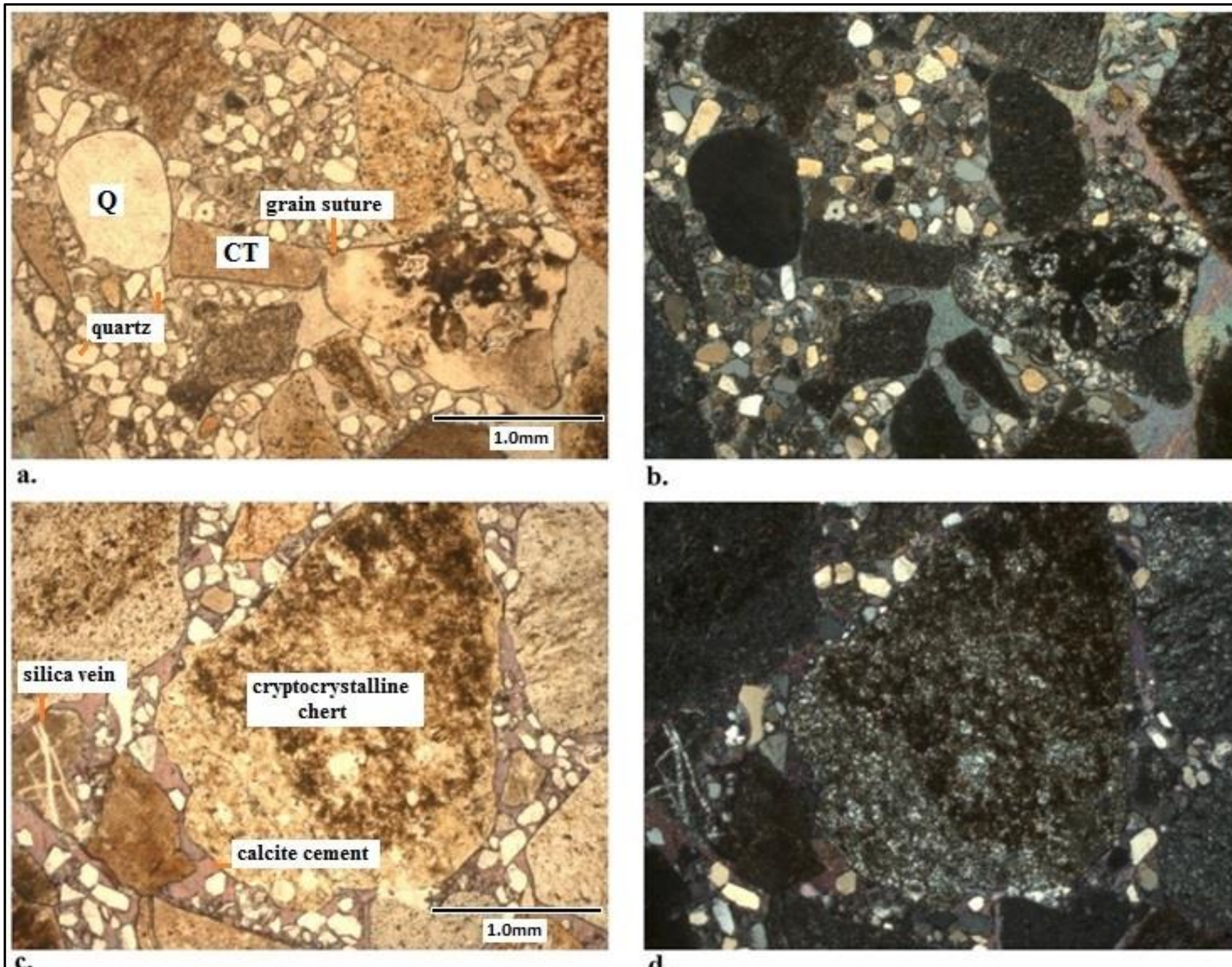


Fig. 23 - Thin section photomicrographs for Sample 35a: a) Plane-polarized light (PPL), with chert (CT) clasts and quartz (Q) grains; b) Same view in cross-polarized light (CPL); c) Enlarged view of rounded chert (CT) clasts with interclast quartz (Q) grains (0.01-0.02 mm) and small (0.1-0.2 mm) chert grains in PPL and d) CPL.

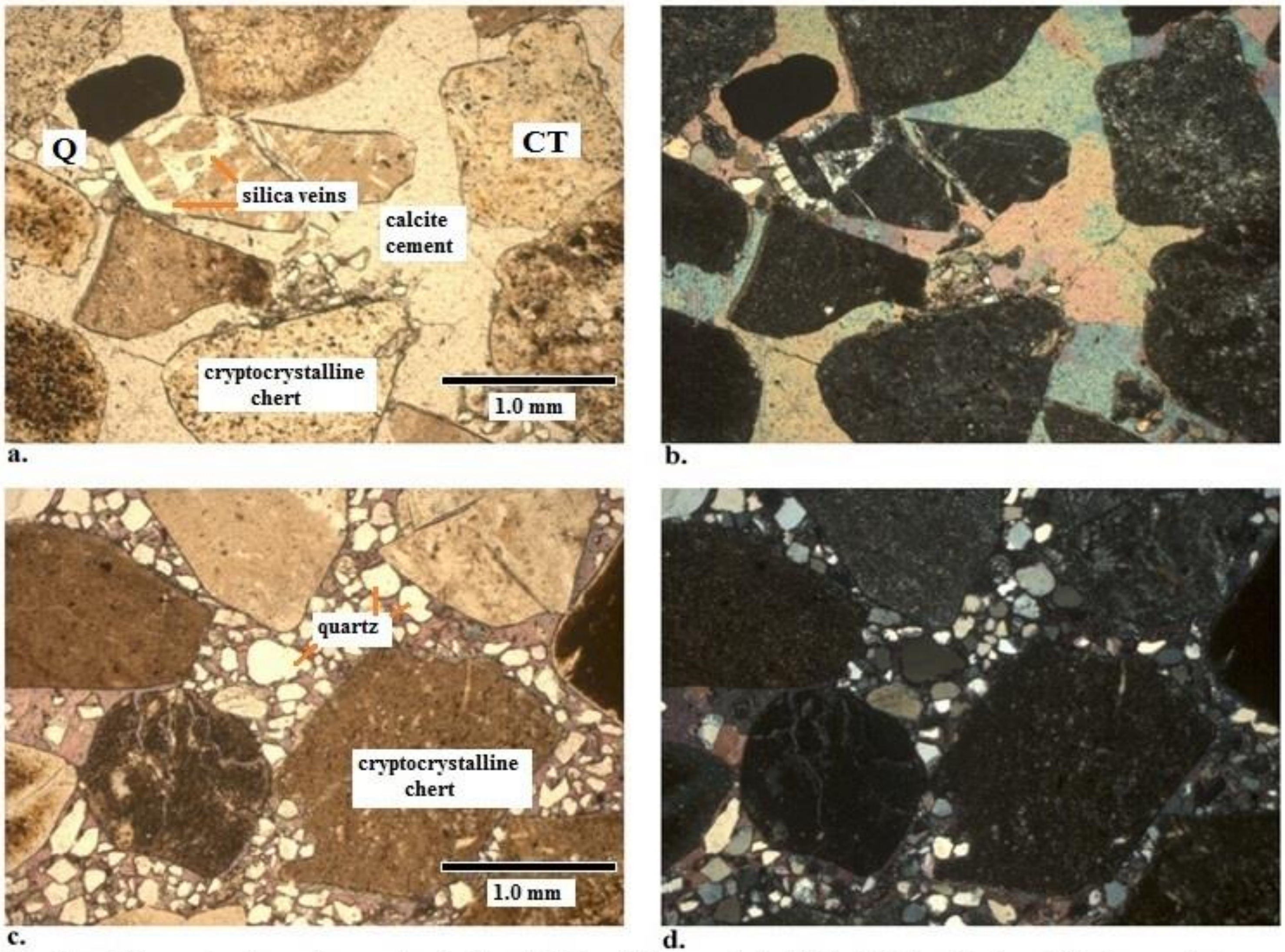


Fig. 24 - Thin section photomicrographs for Sample 35a: a) Plane-polarized light (PPL), with chert (CT) clasts, calcite cement and quartz (Q) grains; b) Same view in cross-polarized light (CPL); c) Sub-angular and rounded chert (CT) clasts (~1.0-1.5 mm) and quartz grains (0.01-0.02 mm) in PPL and d) CPL.

Fig. 25 - Hand sample of fine-grained sandstone from Outcrop #35. Thin section "35b" is from this sample.

Sample 35b (Fig. 25) is a fine-grained sandstone with a yellow-to-light brown color, which varies across 1.0-2.0 mm thick parallel laminations. The sandstone is poorly indurated and sand grains break off the sample when it is lightly rubbed with a fingertip. The sample does not react with hydrochloric acid, indicating silica is the dominant cement, which is common in samples for the Seminole Formation collected in this study. Quartz grains average 0.01 mm in size, and rarely go above or below this average. All quartz grains (comprising 47% of the total sample) are mono-crystalline, with no presence of poly-crystalline quartz (Fig. 26).

The detrital grains are quartz (47%) and chert (10%), which are well sorted and angular-to-subangular. The authigenic components are silica cement (7%) and minor calcite cement (1-2%). Solid oil/bitumen is about 10.0%. Silica cement partially fills porosity, with quartz grains occasionally appearing corroded.

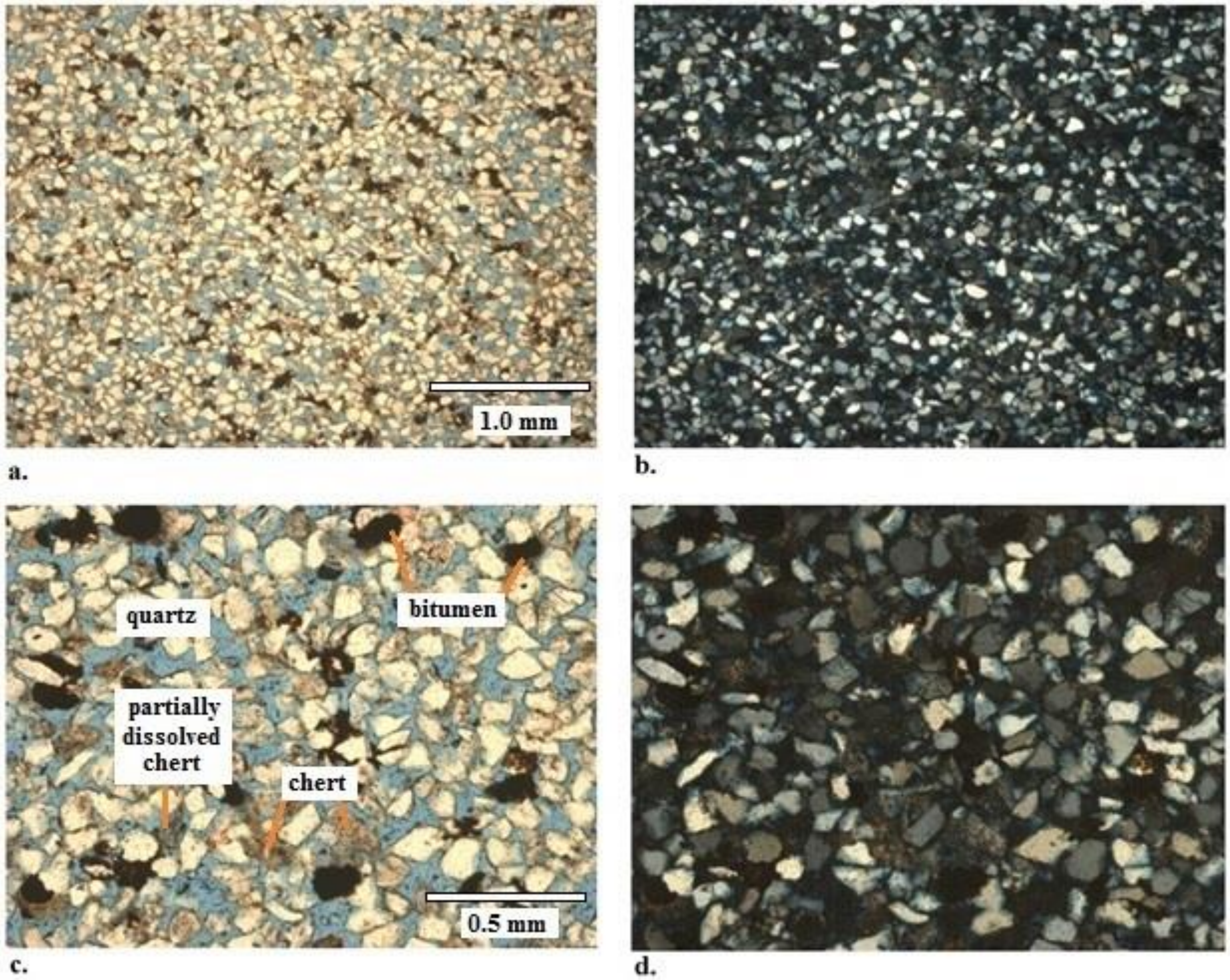


Fig. 26 – Thin section photomicrographs of Sample 35b at 2X magnification in plane-polarized light (a) and cross-polarized light (b), and 5X magnification in plane-polarized light (c) and cross-polarized light (d). Key mineral constituents are quartz, chert, partially-dissolved chert and the presence of bitumen.

Outcrop #34

Location and General Description

This outcrop is north of Outcrop #35 in the bank of Little River about 1.0 mile north of Sasakwa, Oklahoma, in SW NE SE NW sec. 25, T. 6 N., R. 7 E. (34.96444444 N, -96.51083333 W) (Fig. 27). The section was measured by Dott and Bennison (1982) and described by Heckel (1991) (Fig 28). This outcrop is poorly exposed, with bedrock partially or completely covered by mud and water, which prevented the gamma ray spectrometer surveying. One sample of sandstone in the Seminole Formation was collected and thin sectioned.

Fig. 27 - Map view of Sec. 25, T. 6 N., R. 7 E., containing Outcrop #34 about 1 mile north of Sasakwa in Seminole County, Oklahoma. The area of study is marked with a white star.

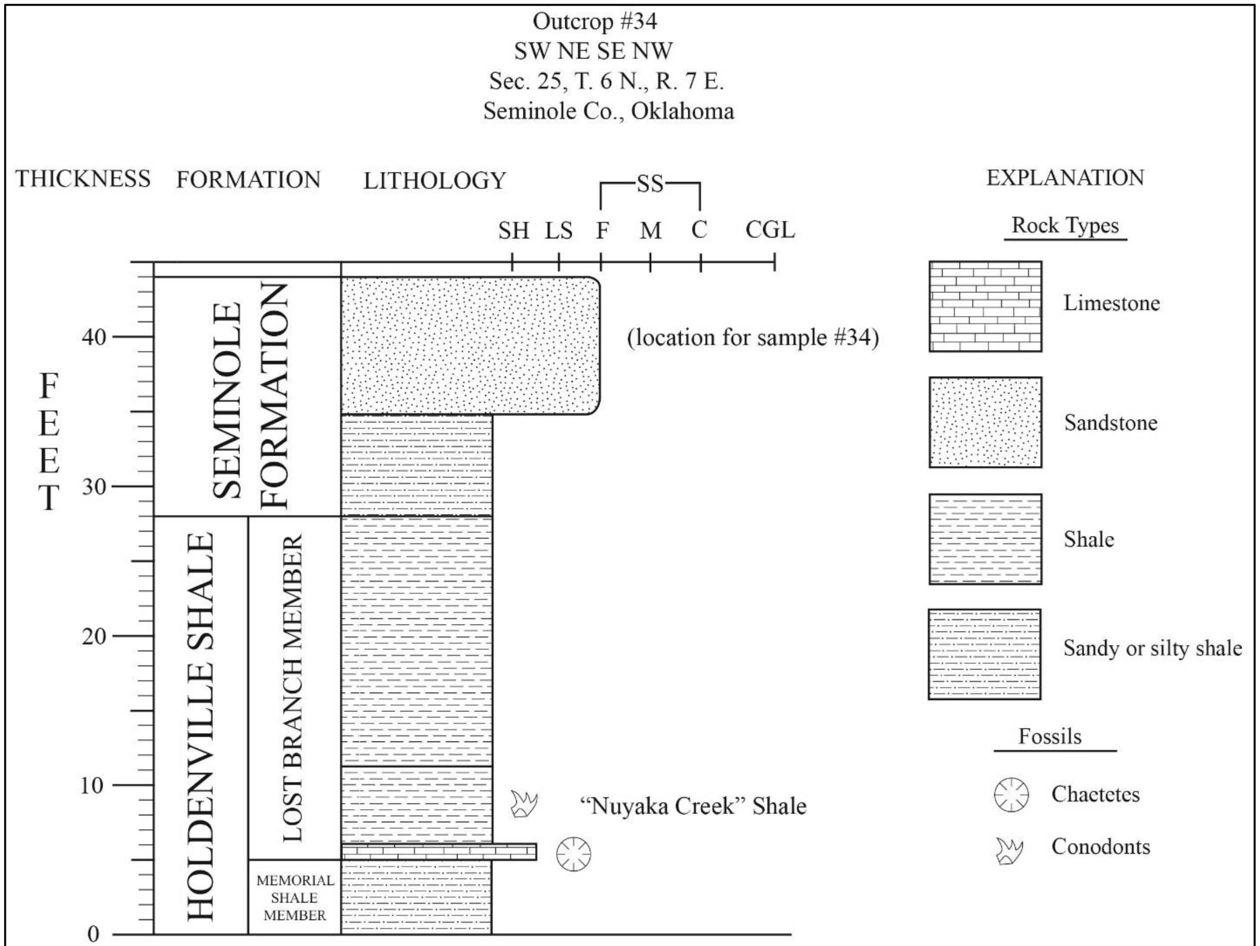


Fig. 28 - Stratigraphic column for Outcrop #34 on Little River, 1 mile north of Sasakwa in Seminole County, Oklahoma. Measured section by Dott and Bennison (1981) and published in Heckel (1991).

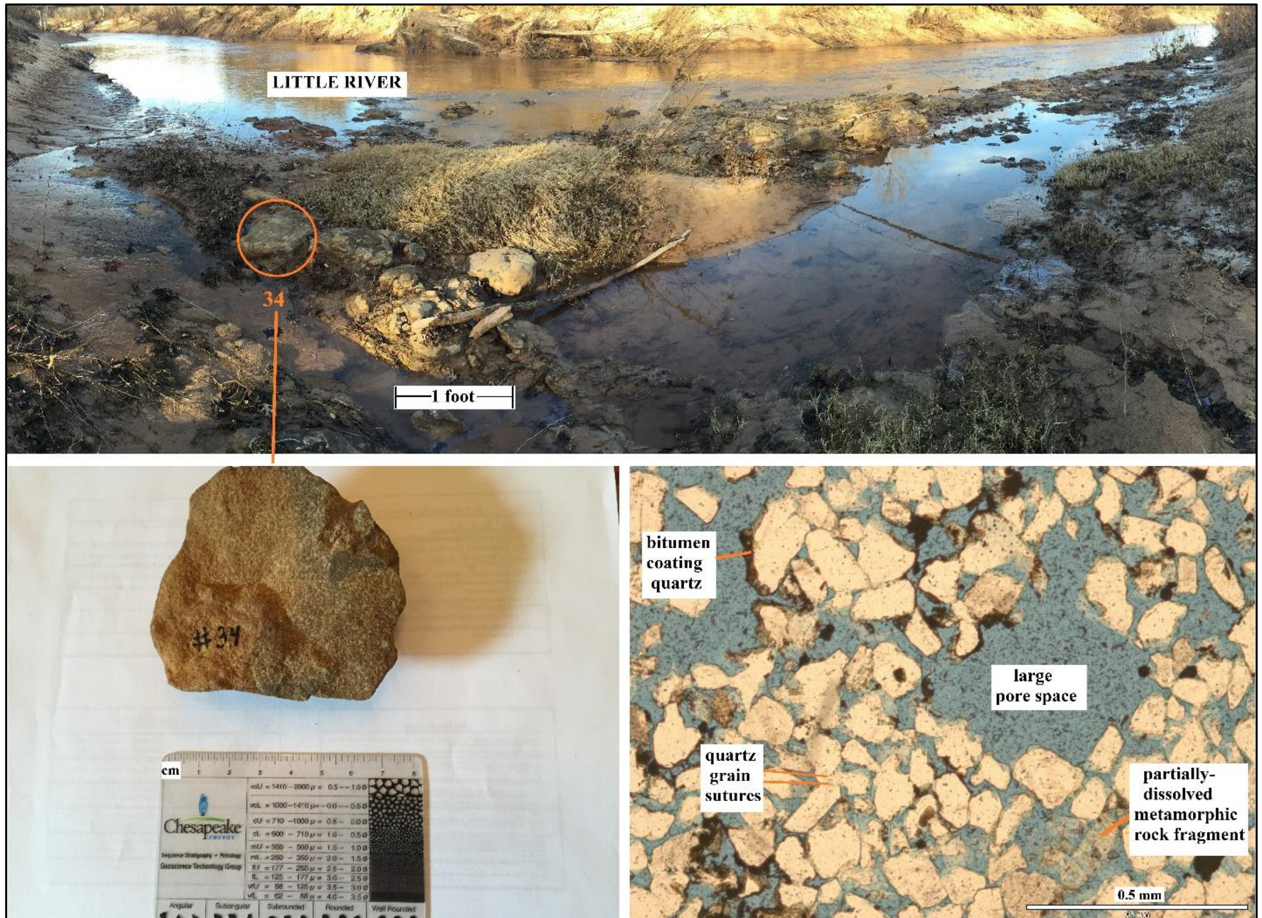


Fig. 29 – Outcrop #34 in Sec. 25, T. 6 N., R. 7 E. with the limited exposure shown in panoramic view (top). Sample from Outcrop #34 shown (bottom left). Bottom right is a thin section photomicrograph of sutured grain contacts, oversized pores, partially dissolved detrital grains, and bitumen coating face of quartz grains.

Stratigraphy and Lithology

According to Dott and Bennison (1981), outcrop #34 consists of Holdenville Shale (28.0+ feet) and Seminole Formation (16.0 feet). The Holdenville Shale features the Memorial Shale Member (5.0+ feet) at the base, containing gray shale and shaly sandstone. Above it is the Lost Branch Member (23 feet), with a calcilutite (1.0 foot) basal layer equivalent to the Homer School Limestone, the black Nuyaka Creek Shale (5.0 feet) above the limestone, and a gray shale layer (17 feet) at the top. The Seminole Formation (16.0 feet) contains a red-to-green shale (7.0 feet) with siltstone lenses at the base, and a brown sandstone (9.0 feet) at the top (Dott and Bennison, 1981; Heckel, 1991).

Rock sample and Thin Section

Sample "34" (Fig. 29) contains detrital grains of quartz (58%) and chert (9%), which are well-sorted, and angular to sub-angular. Authigenic components are silica cement (<1%) and calcite cement (0.5%).

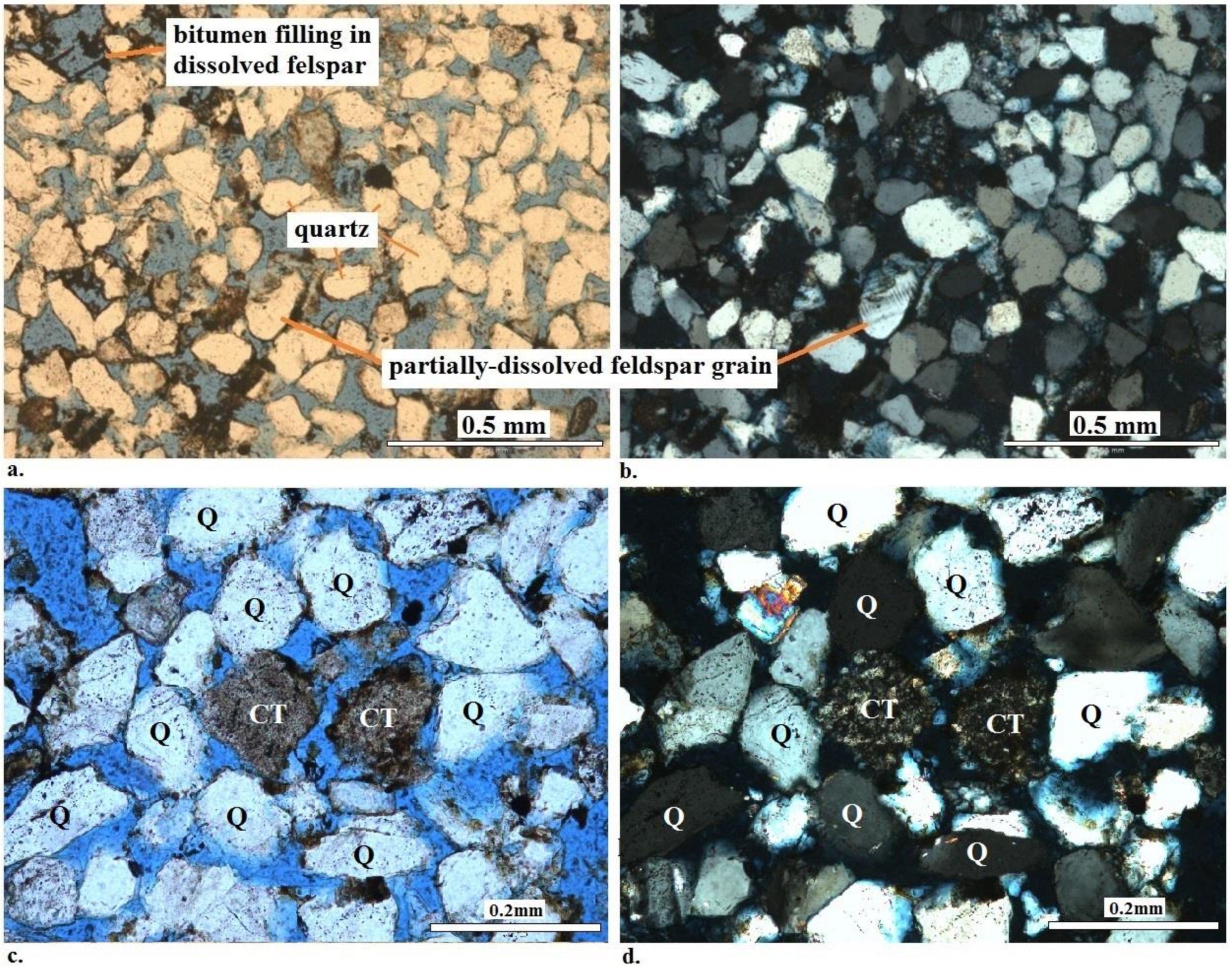


Fig. 30 – Thin section photomicrograph of Sample 34 showing detrital quartz (Q) and schistose metamorphic rock fragments. **A.** Plane-polarized light, featuring bitumen filling dissolved feldspar. Detrital quartz grains common throughout. **B.** Cross-polarized light. **C & D.** Monocrystalline quartz (Q) and weathered chert (CT) fragments in porous sandstone. Note the absence of meamorphic rock fragments. Blue is pore space. Left – PPL. Right - XPL. Outcrop 34, Little River outcrop of Heckel (1991); Dott and Bennison (1982).

Outcrop #33

Location and General Description

Outcrop #33 is located along a country road about 2.5 miles west of Spaulding, in Hughes County Oklahoma, in SW SE sec. 5, T. 6 N., R. 8 E. (35.02305556 N, -96.50472222 W) in the Holdenville Quadrangle (Fig. 31). This outcrop was measured by Dott and Bennison (1982) and described by Heckel (1991) (Fig. 32).

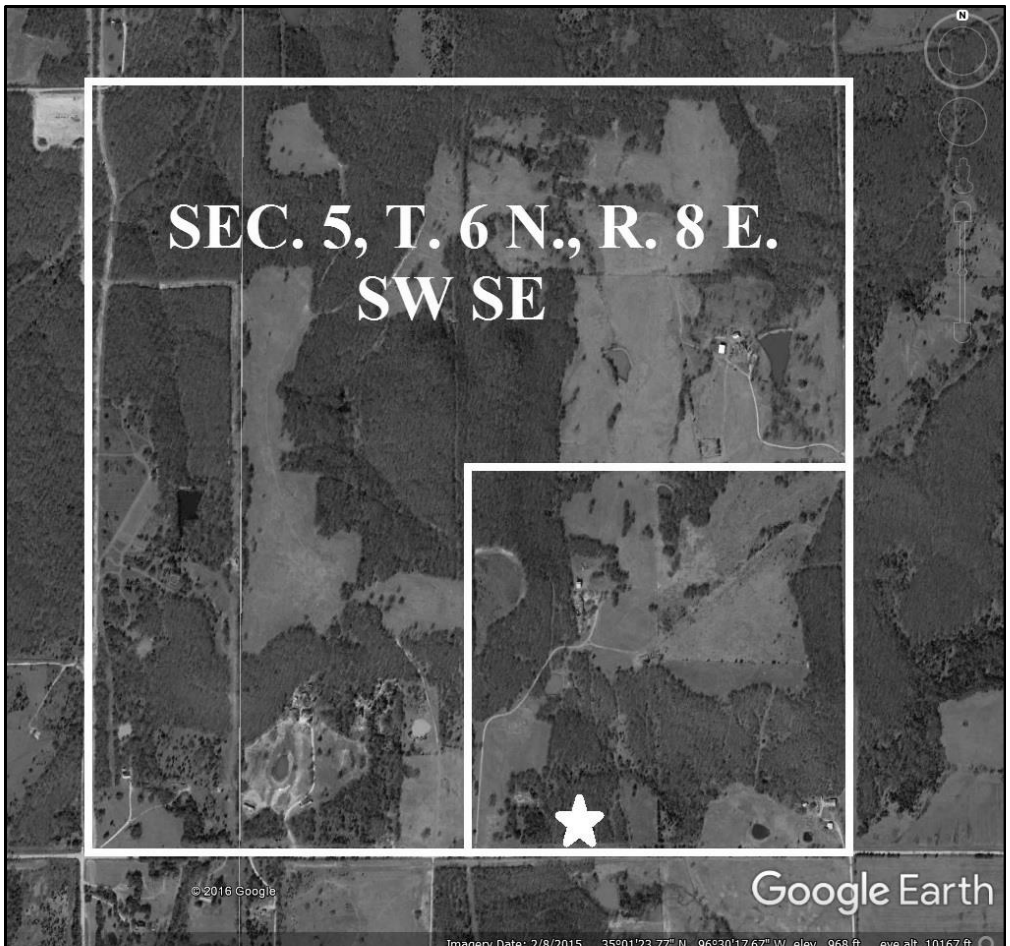


Fig. 31 - Map view of Sec. 5, T. 6 N., R. 8 E., containing Outcrop #33 about 2.5 miles west of Spaulding in Hughes County, Oklahoma. The area of study is marked with a white star.

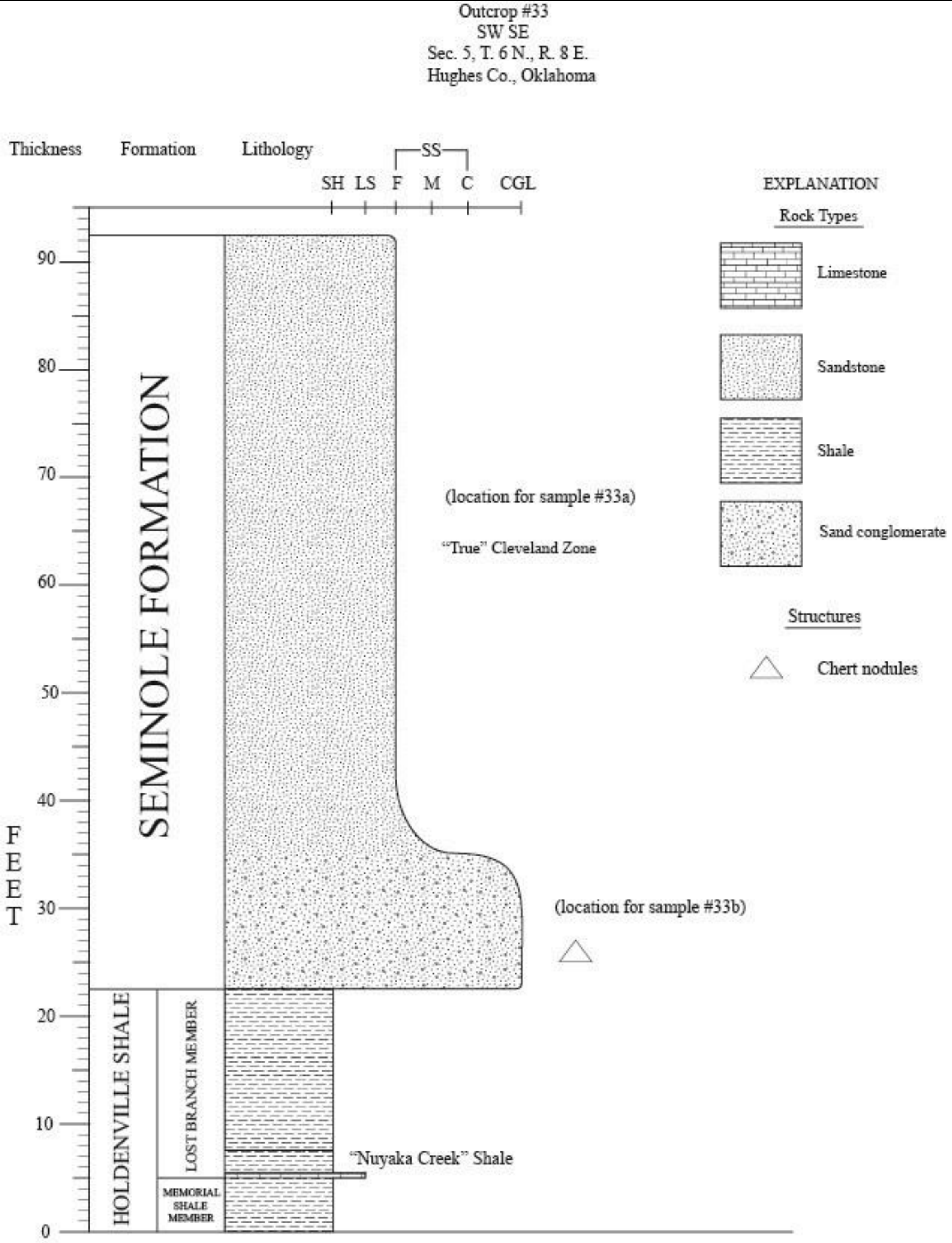


Fig. 32 - Stratigraphic column for Outcrop #33 near Spaulding, Oklahoma in Hughes County. Measured by Dott and Bennison (1981) and republished in Heckel (1991).

Fig. 33 – Outcrop #33, near Spaulding, Oklahoma, in Hughes County. Samples 33a (sandstone) and 33b (pebble conglomerate) were collected from this bed of Seminole Formation.

The outcrop was first described by Taff (1901), and became the type area for the Seminole Formation (Heckel, 1991). For this study, the outcrop was not remeasured or surveyed with the gamma ray spectrometer. The Nuyaka Creek Shale could not be identified, which is also noted by Heckel (1991).

Stratigraphy and Lithology

According to Dott and Bennison (1981) and Heckel (1991), this outcrop contains the Holdenville Shale (22.5+ feet) and the Seminole Formation (70.0+ feet).The Holdenville Shale contains the Memorial Shale Member (5.0 feet) at the base featuring green over red shale, and above it is the Lost Branch Member (15 feet). Within the Lost Branch Member is the Homer School Limestone (0.5 feet) at the base, with black Nuyaka Creek Shale (2.0 feet) above it, and gray shale (15 feet) at the top. The Seminole Formation is a massive sandstone bed with approximately 12 feet of chert pebble conglomerate at the base. The contact between the Holdenville Shale and overlaying Seminole Formation is recognized in the field by locating chert conglomerate. Two rock samples were collected from the Seminole Formation, Sample 33b from the chert conglomerate and Sample 33a from the sandstone above. Both samples were thin sectioned.

Rock Samples and Thin Section

Sample 33a is fine-grained sandstone with predominantly angular to subanguler grains of quartz (55%) which commonly have sutured contacts (Fig. 34, a and b). Polycrystalline quartz (4%) and chert (10%) are present. Some rock fragments are up to 1.0 mm in size. There are pockets of silica cement (~6%) and the presence of bitumen (4%). Chert grains are subangular to subrounded, and are up to 0.4 mm in size. One rock fragment contained biotite.

Sample 33b is a pebble conglomerate with chert fragments of 1.0-1.5 mm in size, surrounded by smaller quartz grains (0.05-0.25 mm) and chert (Fig. 34, c and d). Bitumen (9%) is present. Calcite cement is rare (~1%) and forms along grain boundaries. Some rock fragments fill the entire view of the lens at a 4X magnification. Quartz grains are mostly monocrystalline, although there is a minor presence of polycrystalline quartz material (2%).

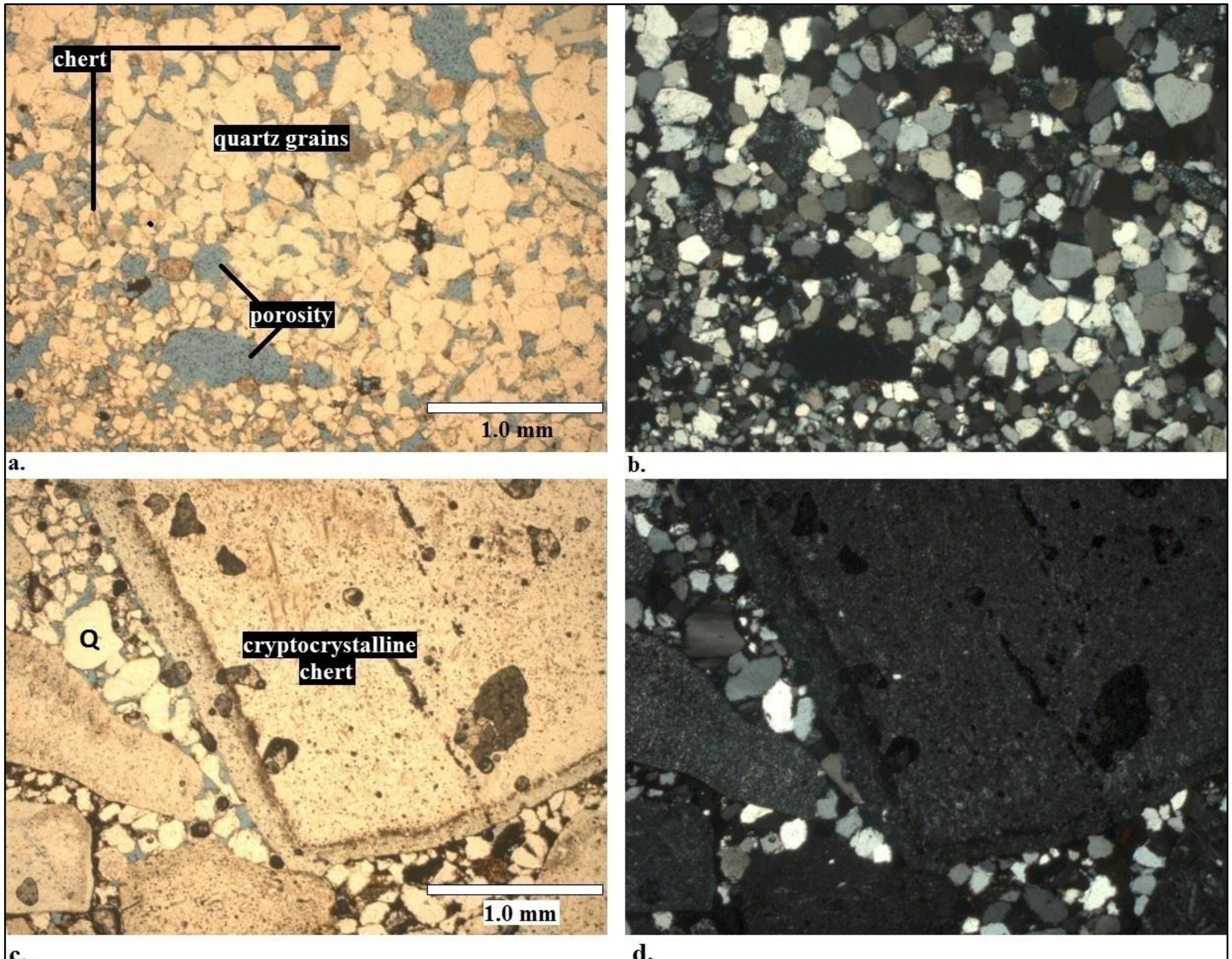


Fig. 34 (a) – Thin section photomicrograph of Sample 33a showing detrital quartz, chert and porosity (blue) for A. Plane-polarized light. B. Cross-polarized light. Thin section photomicrograph of Sample 33b showing cryptocrystalline chert. C. Plane-polarized light. D. Cross-polarized light. Outcrop #33 (A) near Spaulding, Oklahoma, in Hughes County of (Heckel, 1991), and Dott and Bennison (1981).

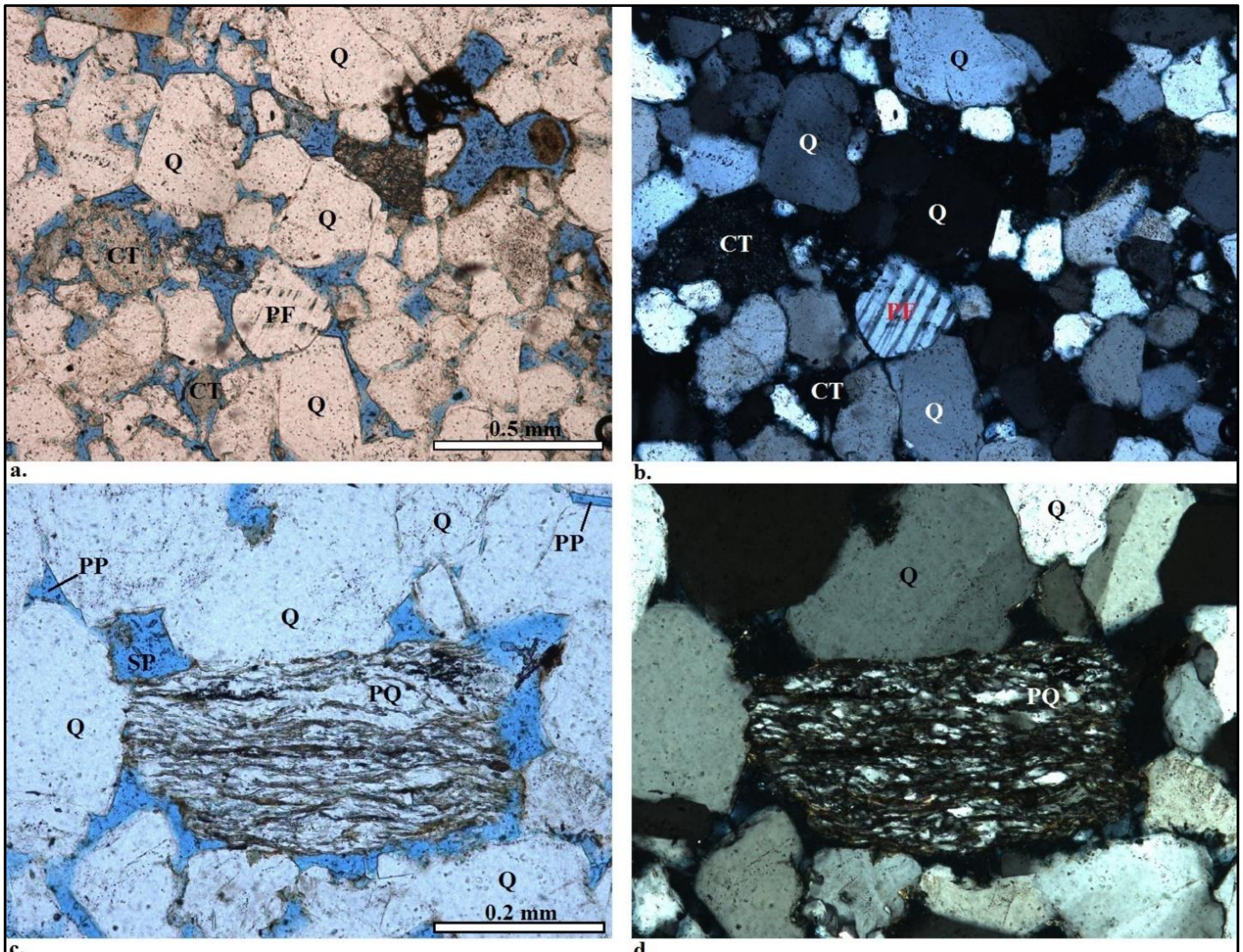


Fig. 34 (b) – **A & B**. Photomicrograph of detrital grains including monocrystalline quartz (Q), chert (CT), and plagioclase feldspar (PF). Some chert fragments are partially dissolved and porous. Porosity is shown by blue-colored epoxy. Note the lack of metamorphic rock fragments. Left is plane-polarized light (XPL). Right is plane-polarized light (PPL). **C & D.** Photomicrograph of foliated metamorphic rock fragment containing polycrystalline quartz (PQ) and mica, as well as monocrystalline quartz (Q). Porosity is both primary (PP) and secondary (SP). Left - PPL. Right - XPL. Outcrop #33 (A) near Spaulding, Oklahoma, in Hughes County of Heckel (1991), and Dott and Bennison (1981).

Outcrop #32

Location and General Description

Outcrop #32 is 2 miles southeast of Bearden, Oklahoma, in Okfuskee County, in SW SW sec. 15, T. 10 N., R. 9 E (35.47888889 N, -96.36250000 W). The outcrops (Fig. 35) are along a ravine where eroded banks form natural exposures of the Seminole Formation and Holdenville Shale.

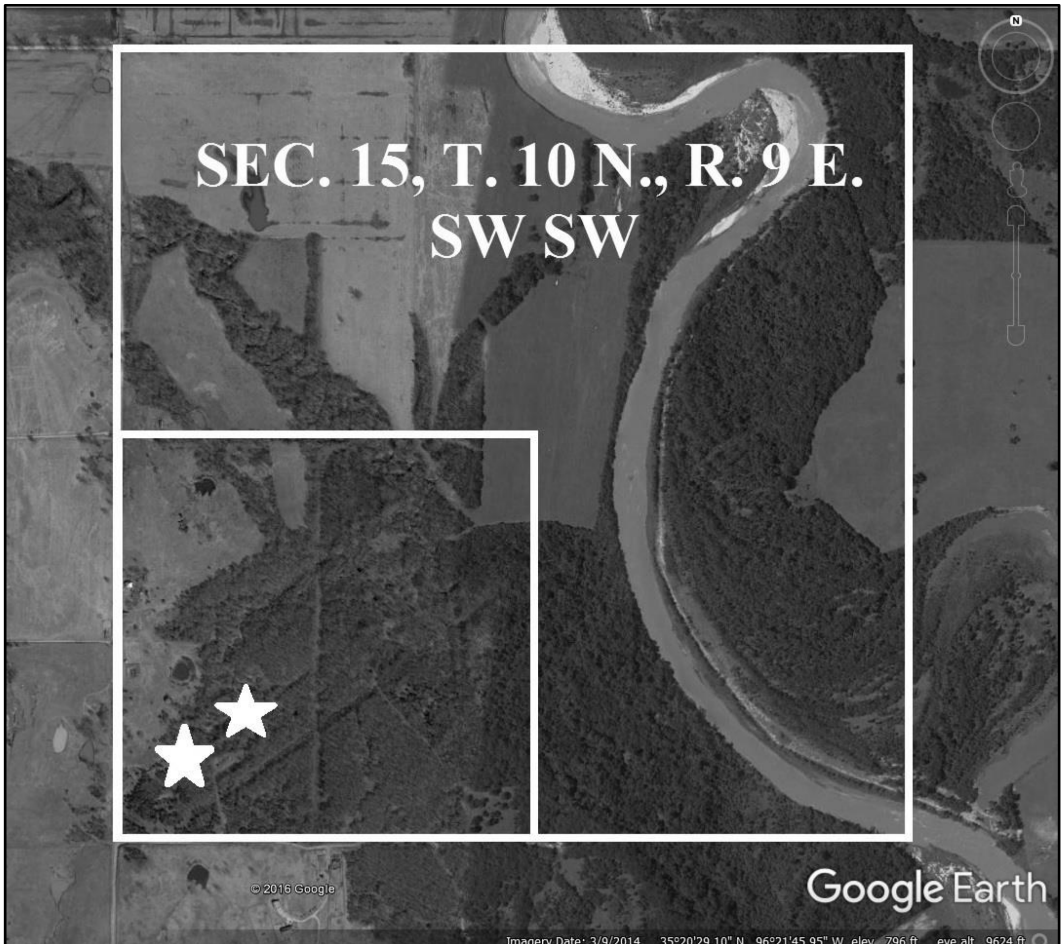


Fig. 35 - Map view of Sec. 15, T. 10 N., R. 9 E. containing Outcrop #32 in the ravine, 2.0 miles southeast of Bearden in Okfuskee County, Oklahoma. The areas of study are marked with white stars.

Outcrop #32 was measured and described by Bennison, and later sampled by Heckel in 1983 (Heckel, 1991). It is considered the primary reference section for the Nuyaka Creek Shale because it is the best exposure of the vertical sequence (Heckel, 1991). A gamma-ray spectrometer survey was taken at the Nuyaka Creek Shale exposure (Fig. 37).

Stratigraphy and Lithology

According to Bennison (1981) and Heckel (1991), outcrop #32 (Fig. 36) contains the Seminole Formation (5.0+ feet) and the Holdenville Shale (55.0+), with the basal Memorial Shale Member (21.0+ feet) and the upper Lost Branch Member (34 feet). The Memorial Shale Member has a brownish sandstone (4.0+ feet) at the base, followed by gray to reddish shale (10 feet), calcareous sandstone (5.5 feet), and gray mudstone (1.3 feet), and topped with a thin dark-gray shale (0.1 feet), which is the Dawson Coal equivalent (Bennison, 1981). The Lost Branch Member is dark-gray shale (2.0 feet) at the base, the black Nuyaka Creek Shale (7.0 feet) above it, and a gray shale (25 feet) at the top. The Seminole Formation is a brown-gray, thin-bedded sandstone.

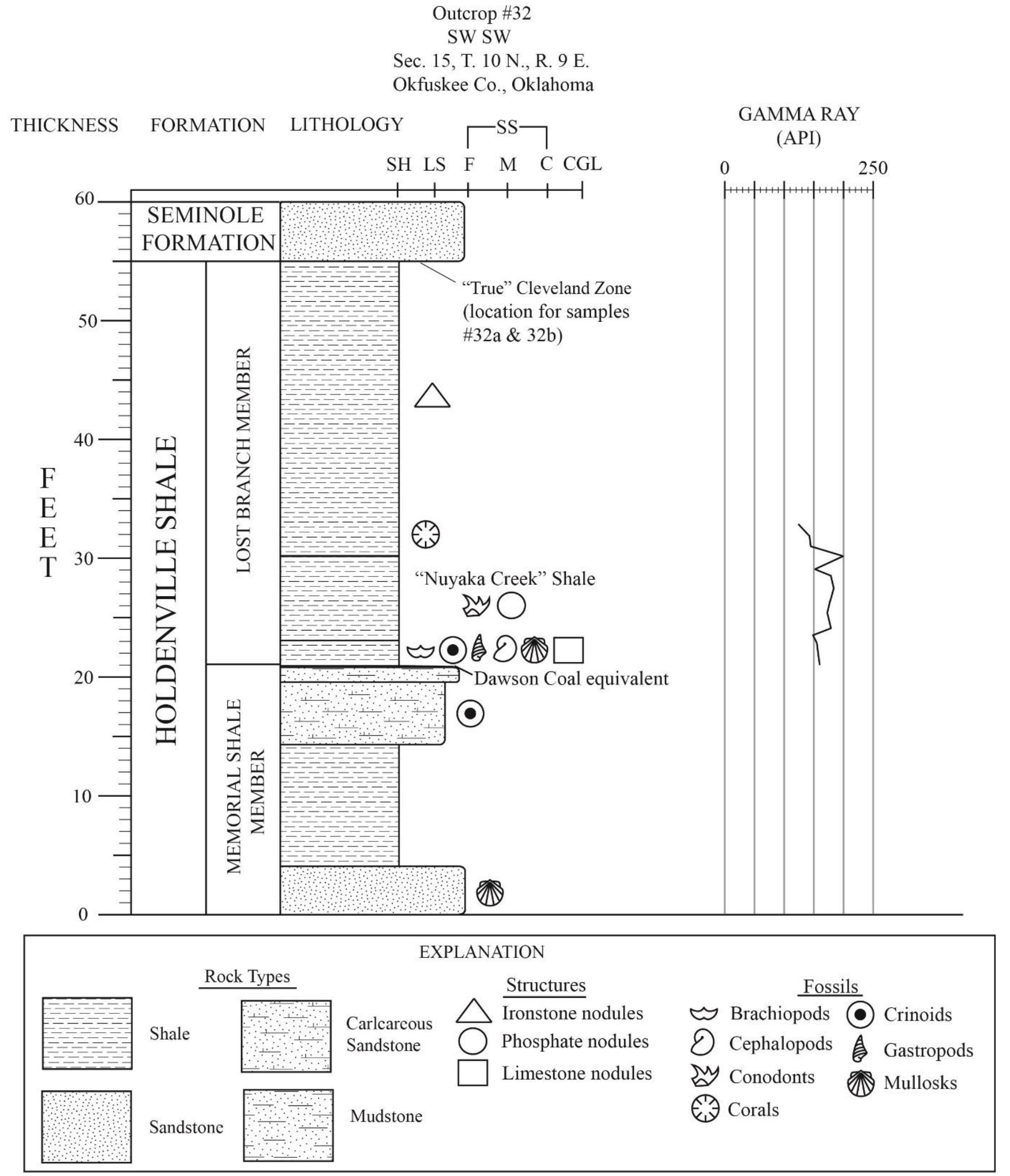


Fig. 36 – Measured section of Outcrop #32 from Bennison (1981) and Heckel (1983; 1991), with gamma-ray survey acros the Nuyaka Creek Shale interval.

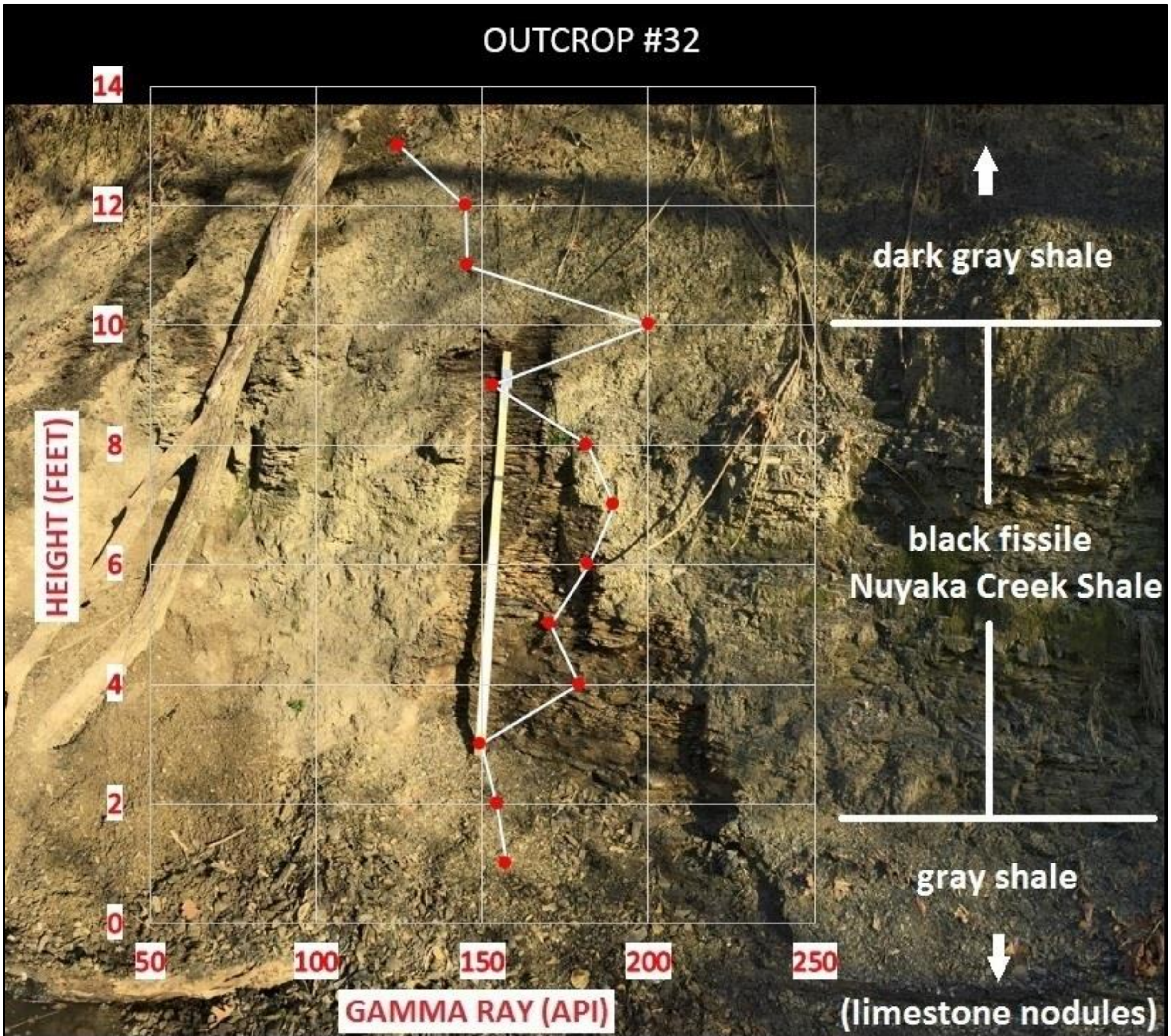


Fig. 37 - Gamma-ray readings in API units across the interval containing the Nuyaka Creek Shale at Outcrop #32 near Bearden, Okfuskee County, Oklahoma. Jacob staff (6.0 feet) for scale.

Unique field observations from this study

The Nuyaka Creek Shale outcrops about 600 feet east-northeast of the Seminole Formation outcrop, along the south bank of the east-west trending ravine. The Nuyaka Creek Shale is a hard, fissile shale that forms a steep slope. The outcrop was trenched with an Estwing Paleo Pick to provide a fresh exposure (Fig. 38) Phosphate nodules toward the top of the Nuyaka Creek Shale are spheroidal to laminar. Above this phosphate-bearing layer is dark gray shale containing horn corals and chonetid brachiopods. This shale, which is fissile, but softer than the Nuyaka Creek Shale bed, is thin bedded, and becomes silty and blocky upward. Beneath the black Nuyaka Creek Shale is gray shale that contains a layer of limestone concretions (Fig. 39).

Fig. 38 - The Nuyaka Creek Shale layer being exposed using a paleopic tool (left). The limestone concretions (circled) in the gray shale layer below the Nuyaka Creek Shale layer (right). Both field pictures are from Outcrop #32 near Bearden, OK.

Fig. 39 - Field attendant (J. Puckette) with his left index finger on the contact between the Nuyaka Creek Shale and the underlying dark gray shale at Outcrop #32 near Bearden, Okfuskee County, Oklahoma.

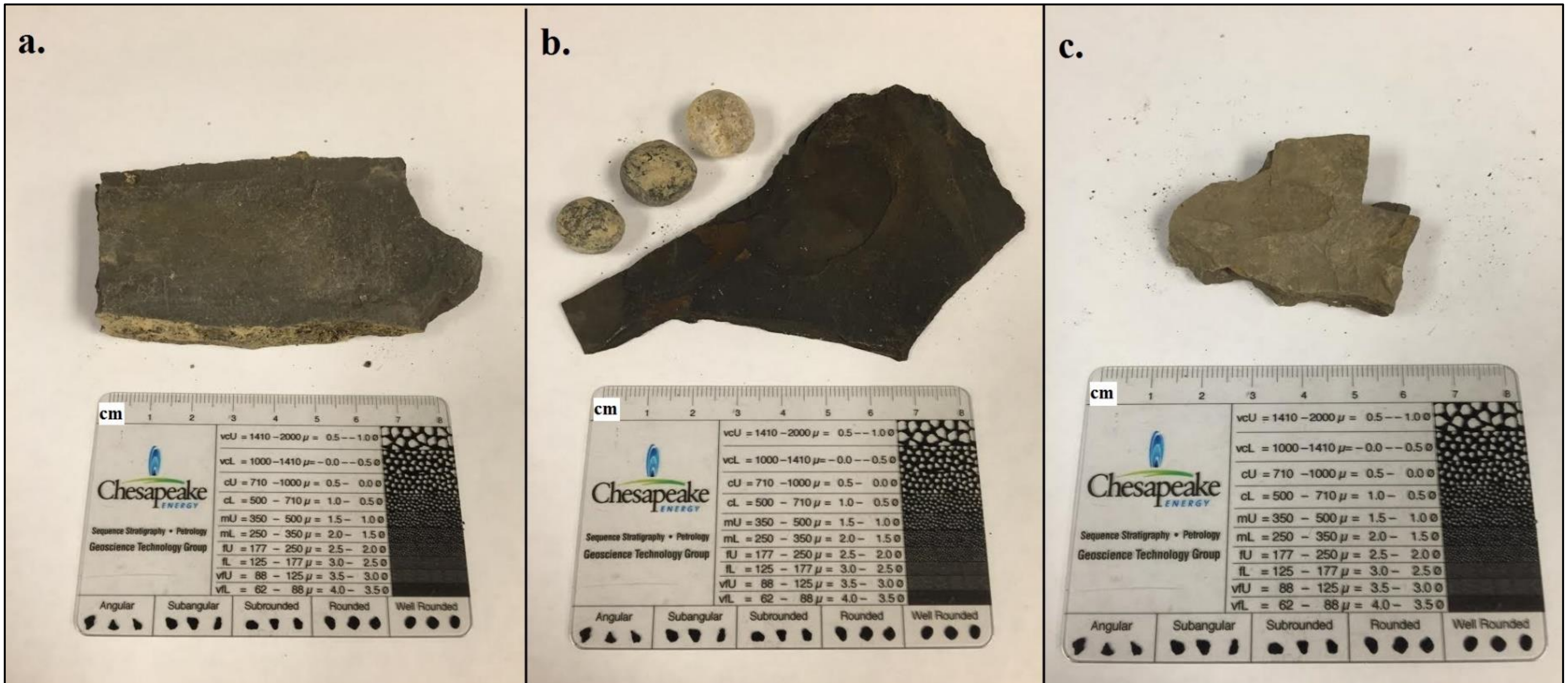


Fig. 40 - The variance in shale colors from Outcrop #32 near Bearden, Oklahoma: a) the upper, dark gray shale; b) the black, fissile Nuyaka Creek Shale with phosphate nodules; c) the lower gray shale.

a.

b.

c.

d.

Fig. 41 – Photos of the Seminole Formation from Outcrop #32 near Bearden, Okfuskee County, Oklahoma. Fig. 41.a is closeup image of sandstone sample circled in Fig. 41.c. Fib. 41.b is a closeup of the sample circled in Fig. 41.d.

Rock Samples and Thin Sections

Seminole Formation sandstone samples were collected from Outcrop #32, and two of these samples were thin sectioned for petrographic analysis and labeled "32a" and "32b" (Fig. 41). Shale samples were collected for color comparison, but not thin sectioned (Fig. 40).

Sample 32a (Fig. 42) is dominantly quartz (58%) averaging 0.005-0.2 mm in size with lesser amounts of chert (6%), plagioclase (<1%) and muscovite (<1%). Laminae of larger quartz grains (0.01-0.02 mm) alternate with laminae of smaller quartz grains. Laminae with smaller grain sizes appear to be lower porosity and contains calcite (6%) and silica (1.4%) cement. Porosity (8%) is in the form of elongated to over-sized pores (~0.5mm in length).

Sample 32b (Fig. 43) is dominantly quartz (58%) that is subrounded to angular, and in some examples, triangular. The margins of some quartz grains are corroded. Chert (7%), silica cement (5%) and calcite cement (2%) are minor components. Solid oil (11%) fills pore space. There are some sutured contacts between quartz grains, but most appear to float in the "matrix" of smaller grains. Porosity (14%) occurs as elongated pores and occasionally oversized pores.

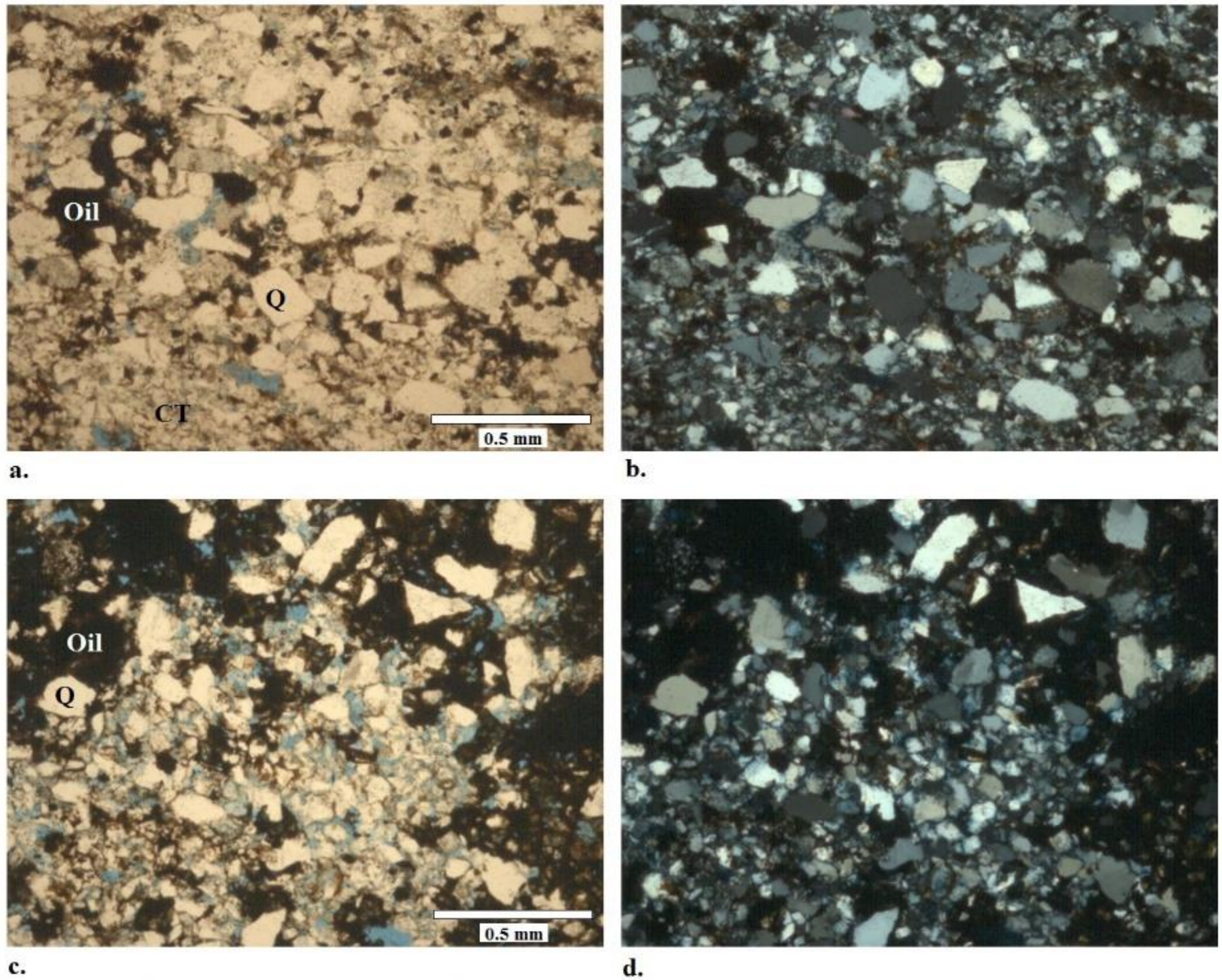


Fig. 42 - Thin section photomicrographs for Sample 32a: a) Plane-polarized light (PPL), with quartz (Q) and chert (CT) grains, and solid oil; b) Same view in cross-polarized light (CPL); c) Plane-polarized light (PPL), with quartz (Q) and chert (CT) grains, and solid oil; d) Same view in cross-polarized light (CPL).

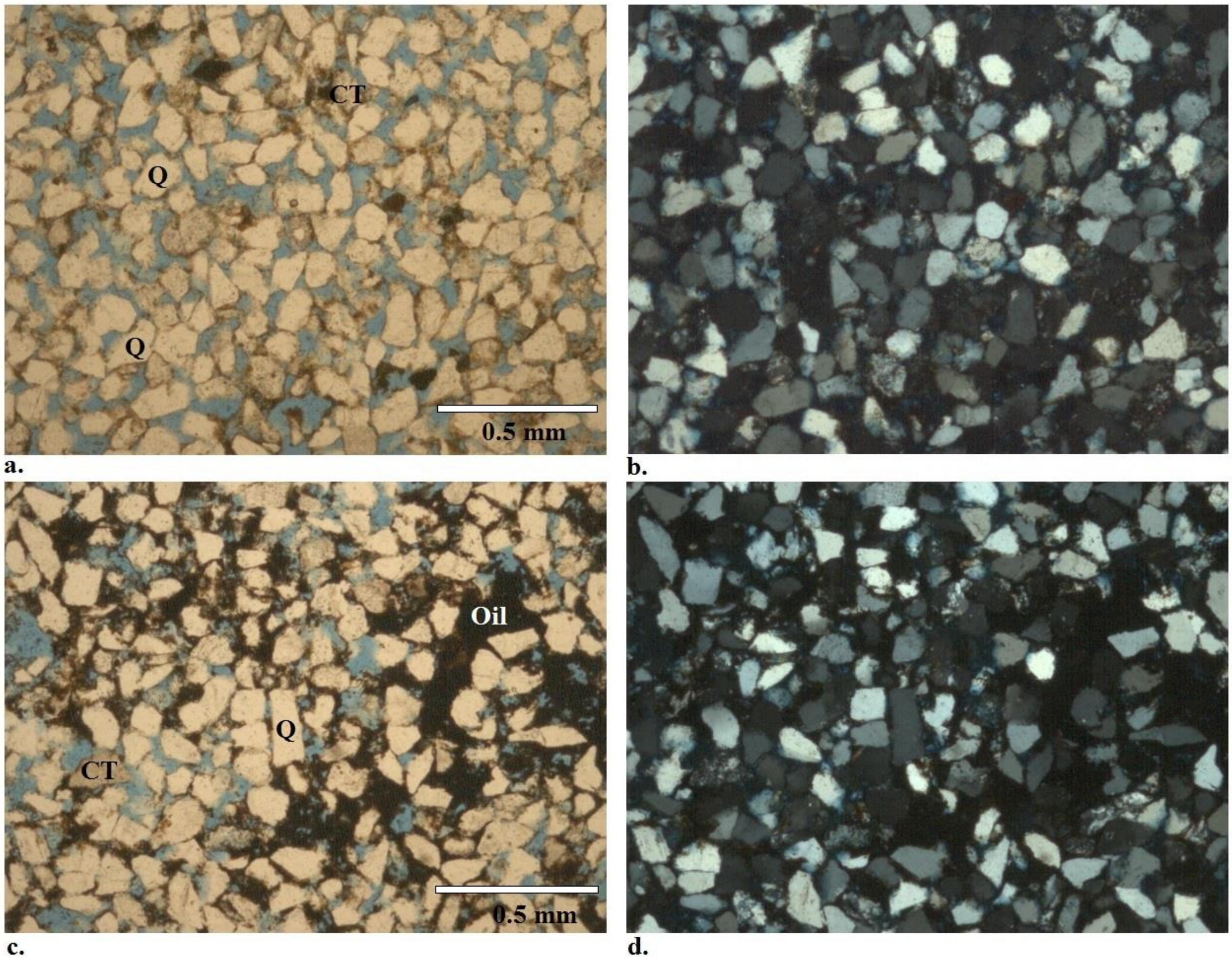


Fig. 43 - Thin section photomicrographs for Sample 32b: a) Plane-polarized light (PPL), with chert (CT) and quartz (Q) grains; b) Same view in cross-polarized light (CPL); c) a) Plane-polarized light (PPL), with chert (CT) and quartz (Q) grains; b) Same view in cross-polarized light (CPL).

Outcrop #31

Location and General Description

Fig. 44 - Map view of sec. 32, T. 12 N., R. 10 E., containing Outcrop #31 about 3.0 miles northeast of Okemah in Okfuskee County, Oklahoma. The area of study is marked with a white star.

Outcrop #31 is located on Nuyaka Creek, about 3.0 miles northeast of Okemah, Okfuskee County, Oklahoma in NE SE NE sec. 32, T. 12 N., R. 10 E (35.47888889 N, -96.28972222 W) (Fig. 44). Dott and Bennison (1981) designated this the type locality of the Nuyaka Creek Shale (Heckel, 1991). The Seminole Formation is not present, therefore no rock samples were collected for thin section. Gamma-ray spectrometer readings were recorded (Fig. 46).

Fig. 45 - Field pictures from Outcrop #31 near Okemah, Okfuskee County, Oklahoma. A panorama of the outcrop, with the gamma-ray spectrometer and an orange field book for scale (top). Limestone septarian concretions in the basal gray shale layer with rock hammer for scale (bottom left). Structural deformation: sub-parallel striations in the contact zone of the basal shale layer and the Nuyaka Creek Shale, with rock hammer for scale (bottom right).

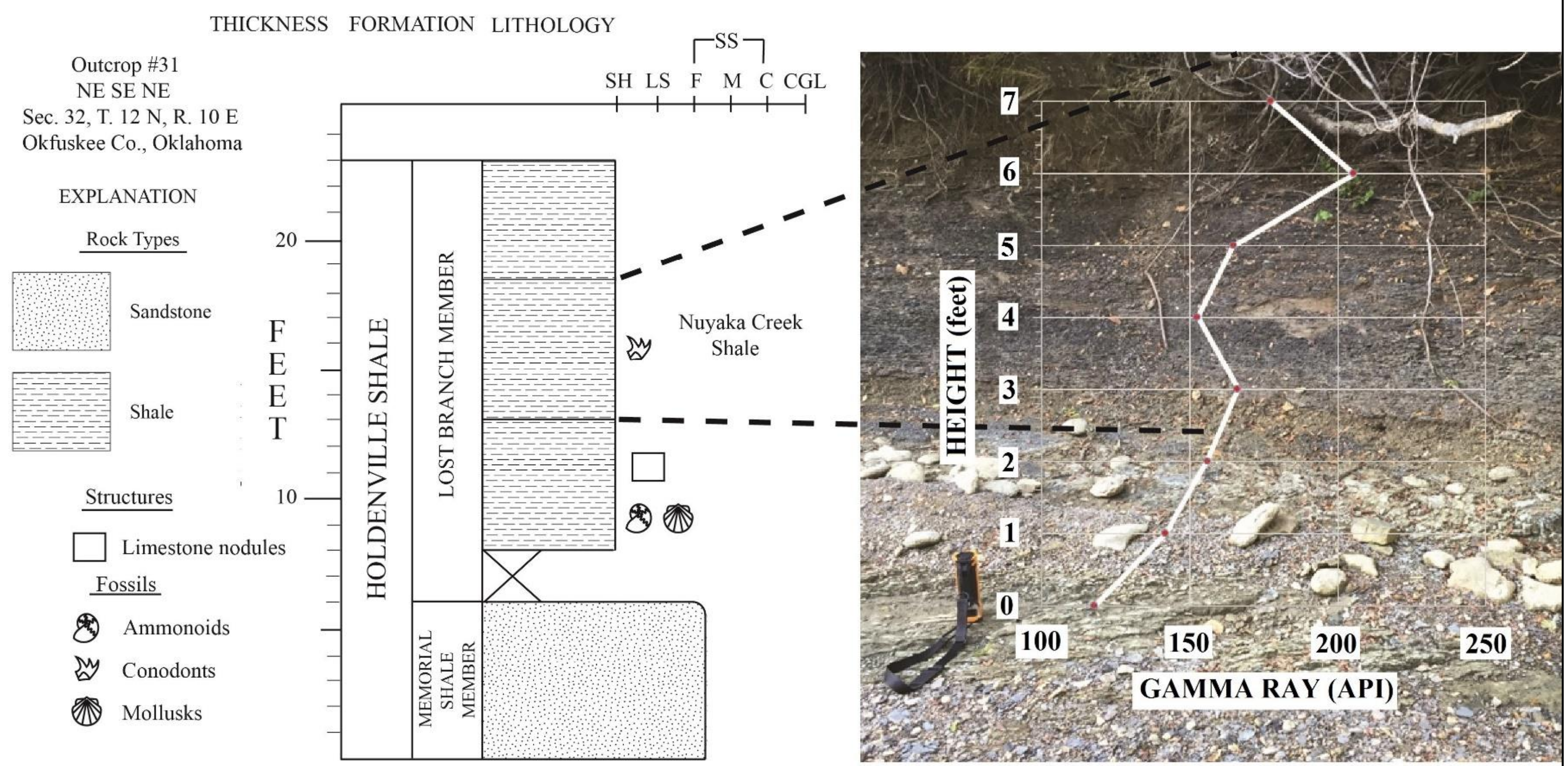


Fig. 46 – Stratigraphic column from Dott and Bennison (1981) and Heckel (1991), and gamma-ray curve for Outcrop #31. On right, the black Nuyaka Creek Shale above the boulder-size, septarian concretions. With API gamma-ray curves overlain to scale, maximum reading in the Nuyaka Creek Shale exceeds 200 API units.

Stratigraphy and Lithology

The Lost Branch Member of the Holdenville Shale is the only stratigraphic unit observed at Outcrop #31. The sandstone in the Memorial Shale Member was reported at the bridge footing, but has since either been removed or covered by new construction (Heckel, 1991). The lowest exposed unit is gray shale (5.0 feet) with a zone of limestone concretions at the contact with the overlying Nuyaka Creek Shale layer (5.5 feet). Above the black Nuyaka Creek Shale is 5 feet of gray shale that contains limestone concretions.

Septarian Concretions

Septarian concretions at Outcrop 31 (Fig. 45 and 47) are cobble- (6.4-25.6 cm) to boulder-size (>25.6 cm) in length with cobble size widths and heights. These concretions are partially exposed in the face of the eroding shale layer, or are float that litter the outcrop leading to the bridge. Astin (1986) concluded septarian cracks form as tensile fractures that occur during shale over-pressuring, which is most likely to occur during rapid burial. The two analogues Astin studied are of similar size (30cm in width and 50cm in length), however they occurred during the Eocene Epoch and Jurassic Period, respectively. The septaria veins in the limestone concretions in the Nuyaka Creek Shale were previously described as limestone nodules. They are concave, with a dark-colored center of calcite and containing septarian cracks. The nodules exposed at the surface are a light gray color, whereas the portions covered and surrounded by the host shale rock maintain a dark gray (near black) color, similar to the host shale. Astin (1986) and McBride et al (2003) found septarian veins to be 5% to 7% of the total rock volumes they appear in.

Fig. 47 – A close up of the septarian concretions from the Nuyaka Creek Shale at Outcrop #31, where septaria litter the outcrop as float. The surficial, light gray portion pictured on the left is the portion exposed (seen in situ in Fig. 45, lower left), while the darker portion was covered before removed for sampling. The color is similar to the core of the concretion, and the shale layer it formed in.

Outcrop #30

Location and General Description

Fig. 48 - Map view of Sec. 4, T. 14 N., R. 11 E., containing Outcrop #30 in a creek bed about 2.5 miles southwest of Beggs in Okmulgee County, Oklahoma. The area of study is marked with a white star.

Outcrop #30 is located in a creek ~5.0 miles southwest of Beggs in Okmulgee County Oklahoma, approximately in the NW NE NW NW sec. 12, T. 14 N., R. 11 E. (35.71888889 N, -96.16361111 W) (Fig. 48). Heckel (1983) measured the outcrop and it is the only one in this study without a sandstone bed in the Seminole Formation.

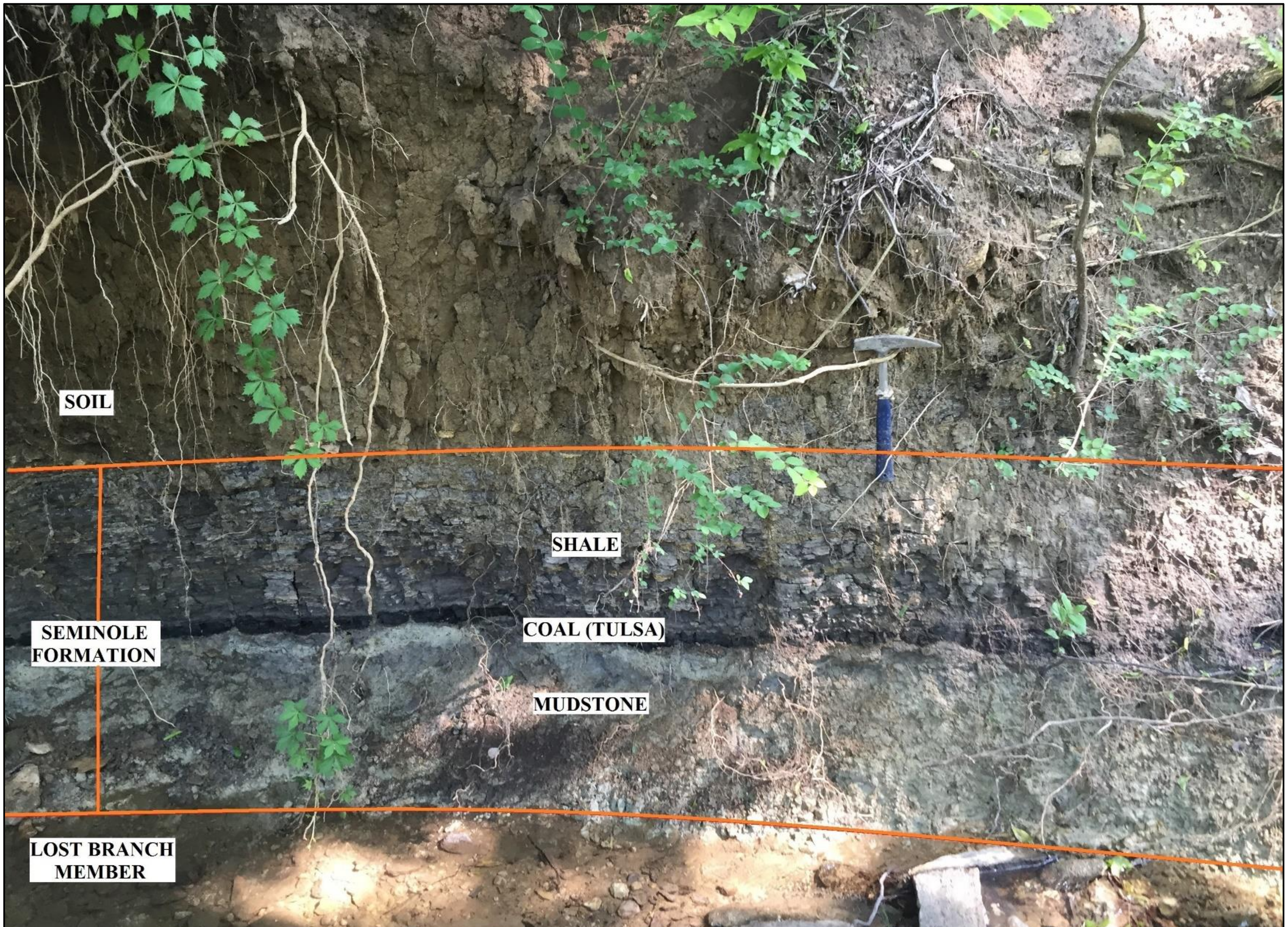


Fig. 49 – The exposure of the Seminole Formation of Outcrop #30. The lowest layer is mudstone where Sample #30b was sampled, at the top of the Lost Branch Formation in the Holdenville Shale. Above is gray mudstone, followed by a thin "Tulsa" coal layer, and at the top, a gray shale that lightens upward.

Stratigraphy, Lithology and Paleontology

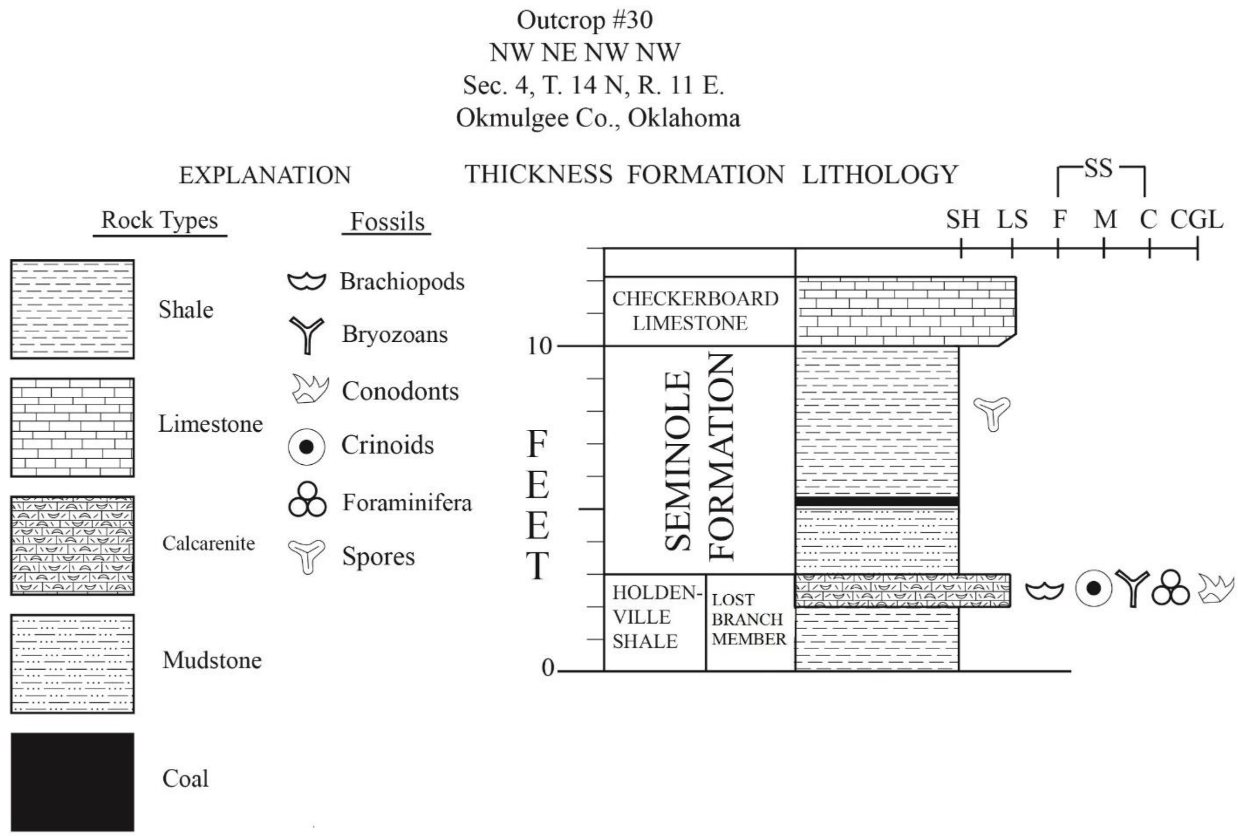


Fig. 50 – Measured section for Outcrop #30 near Beggs, Oklahoma. From Bennison (1981) and Heckel (1991).

According to Bennison (1981) and Heckel (1991), this outcrop contains three intervals, with the Lost Branch Member of the Holdenville Shale (3.0+) at the base, the Seminole Formation above it, and the Checkerboard Limestone (2.0 feet) at the top (Fig. 50). The Lost Branch Member contains a 0.5 foot sandy calcarenite layer with brachiopods, crinoid debris, bryozoans, foraminifers, and sparse conodonts (Bennison, 1982; Heckel, 1991). Heckel (1991) notes this layer is equivalent to the Glenpool Limestone. The Seminole Formation contains a 2.0 foot underclay mudstone, followed by a thin, 3.0 cm layer of "Tulsa" coal, and above it a 5.0 feet of gray shale.

Rock Samples and Thin Sections

Fig. 51 – The Checkerboard Limestone at Outcrop #30, with well-defined joints. Locations of sample #30a, circled in orange (with rock hammer and backpack for scales).

One sample was collected from the Checkerboard Limestone (Fig. 51) and one from the top of the Holdenville Formation (Fig. 49) for thin section analysis. The sample from the Checkerboard Limestone, 30a (Fig. 52), features fusulinid foraminifera and brachiopods, along with calcite cement recrystallized in a dissolution cavity. The sample from the Holdenville Shale, 30b (Fig. 53), is a sandy calcarenite containing brachiopods, crinoid debris, bryozoans, foraminifers, and sparse conodonts (Heckel, 1991). Both of these thin section samples were not used to establish sediment provenance.

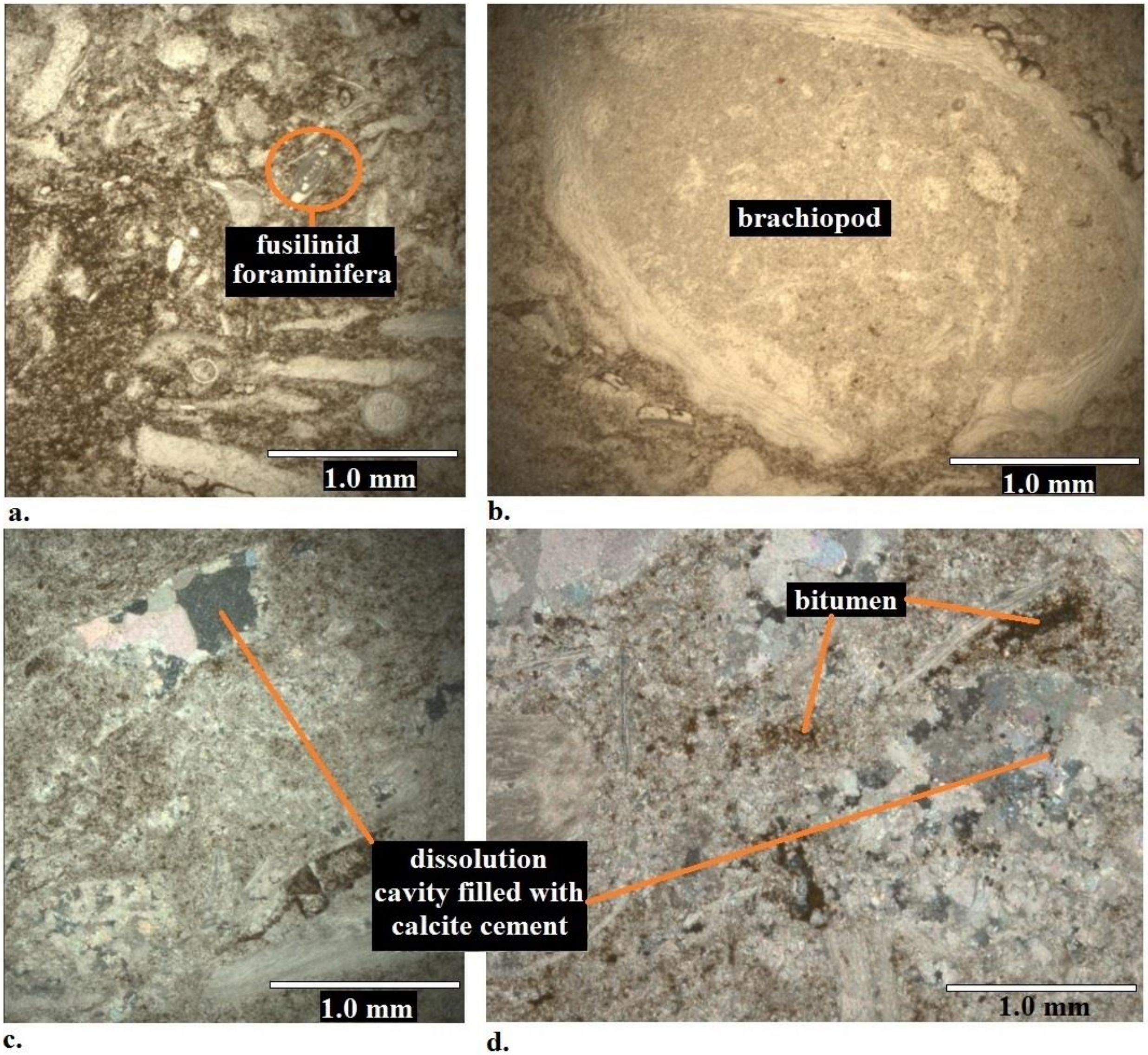


Fig. 52 - Thin section photomicrographs for Sample 30a, all in plane-polarized light: a) fusilinid foraminifera; b) brachiopod; c) & d) calcite cement filling a dissolution cavity.

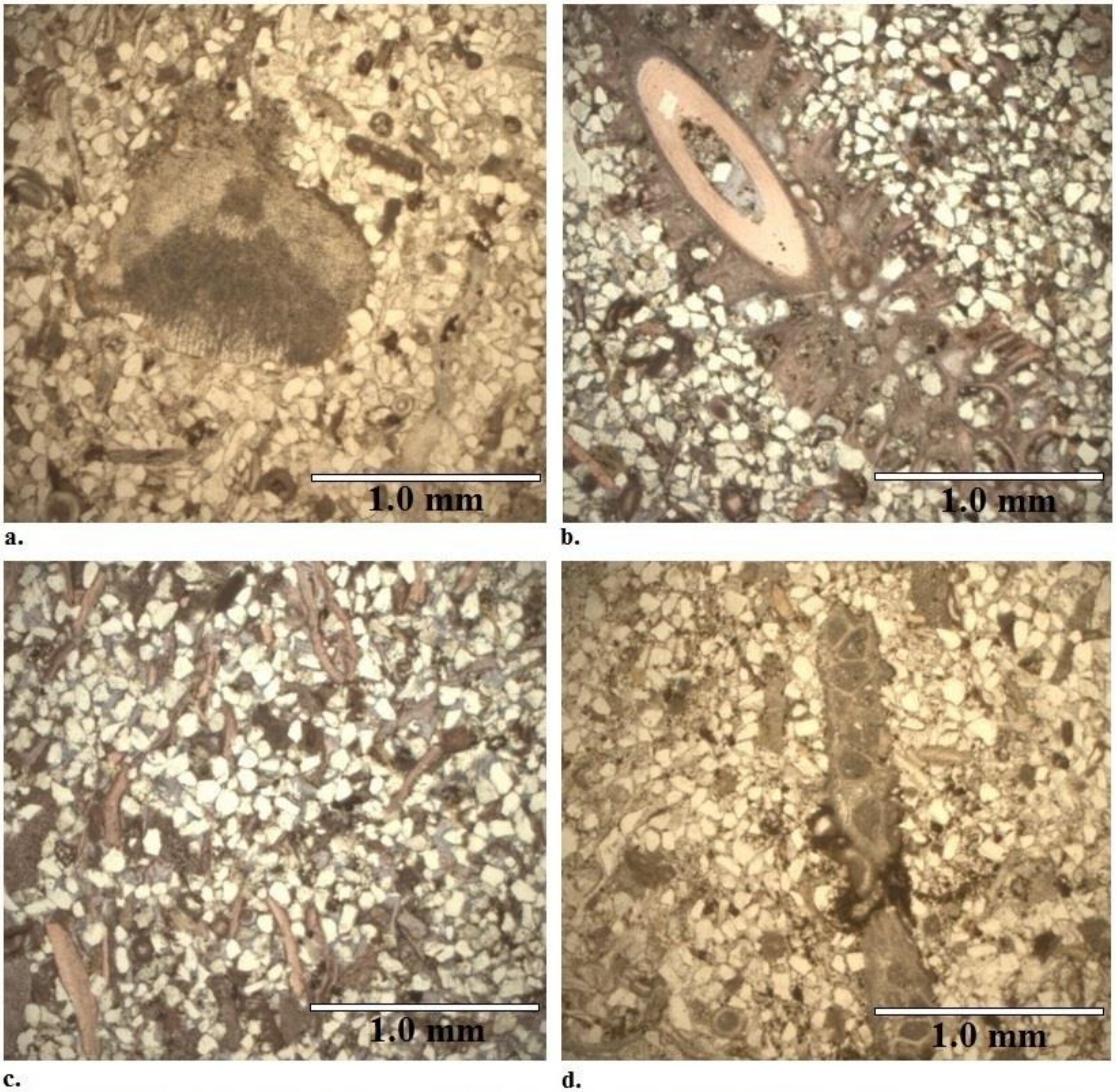


Fig. 53 - Thin section photomicrographs for Sample 30b: a & b) echinoderm fragments coated by bryozoans in a matrix of very fine-grained sandstone; c) ostracod fragments in very fine-grained sand; d) bryozoan and crinoid fragments in very fine-grained sandstone.

Outcrop #28

Location and General Description

Fig. 54 - Map view of Sec. 30, T. 16 N., R. 12 E., containing Outcrop #28, 2.5 miles south of Mounds, Okmulgee County, Oklahoma. The area of study is marked with a white star.

Outcrop #28 is located 2.5 miles south of Mounds, Okfuskee County, Oklahoma, in the SE NE of Sec. 30, T. 16 N., R. 12 E. (35.83833333 N, -96.09722222 W) (Fig. 54). The outcrop is in the south bank of the South Duck Creek, west of the Alt. US-75 bridge. It is within 150 feet of a railway, which was used to access this location after parking at E-0810 (or Hectorville) Road railway crossing gravel turnoff. It is the most difficult outcrop in this study to access, based on the terrain and distance from parking. It was measured by Bennison (1981) and reexamined by Heckel (1991). The Heckel description is the basis for the stick figure in this study. The outcrop was sampled for thin sections and surveyed using the gamma-ray spectrometer.

Stratigraphy and Lithology

According to Bennison (1981) and Heckel (1991), Outcrop #28 contains two intervals: The Holdenville Shale (12+ feet) and the Seminole Formation (10.2+ feet) (Fig. 55). The Holdenville Shale features only the Lost Branch Member. It consists of a gray shale (11.0 feet) with thin sandstone/siltstone laminae, sparse brachiopods and foraminifers, overlain by calcilutite (0.6 feet; equivalent to the Glenpool Limestone). The gray shale layer features ripple bedding in sandy beds and varies in color from light gray to gray (Fig. 56 c).

The Seminole Formation contains a calcareous sandstone layer (the "Tulsa" Sandstone) at the base (Heckel, 1991), a gray mudstone (underclay) with silicified wood (1.8 feet), the "Tulsa" coal (0.2 feet), a dark gray, coaly shale (0.4 foot), a brownish-gray shale (1.0 foot), and a gray, thin-to-medium bedded sandstone at the top (6.0+ feet). The interval between the upper sandstone and the mudstone layers below features fissile bedding with very thin, clay-to-shale and sandstone, siltstone beds with variations in color from brown to light gray, and cement fractions, including ripple marks.

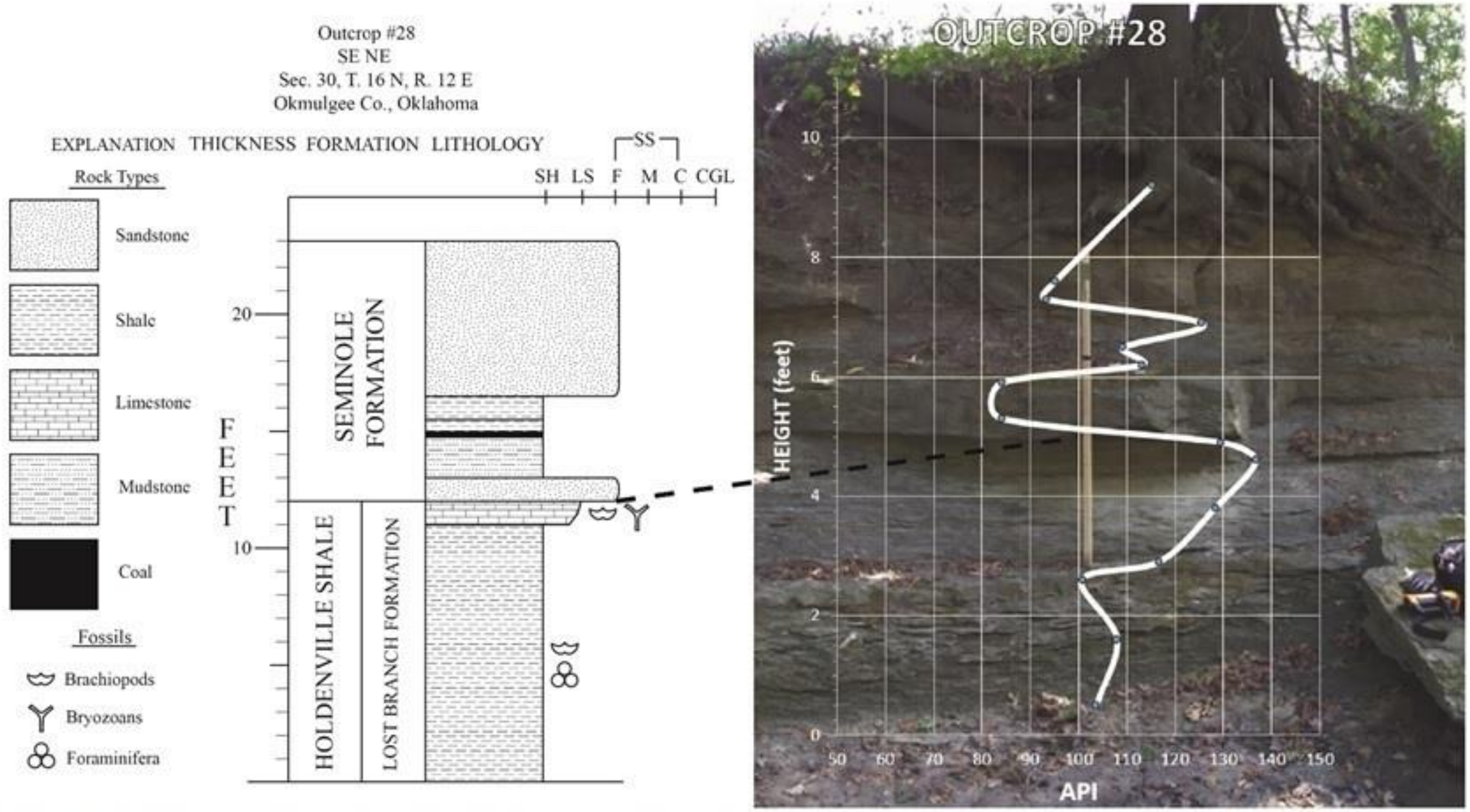


Fig. 55 – Measured section (left) from Bennison (1981) and gamma-ray profile (right) for Outcrop #28 of Mounds, Okmulgee County, Oklahoma. Jacob staff for is used for scale.

a. b. c.

Fig. 56 – Photographs of Outcrop #28 near Mounds, Oklahoma. a) Panoramic view of the outcrop with a Jacob staff for scale (top); b) Rippled, thin-laminated basal sandstone of the Seminole Formation with field notebook for scale; c) Rippled, laminated sandy shale of the Lost Branch Formation of the Holdenville Shale, with rock hammer for scale (bottom right).

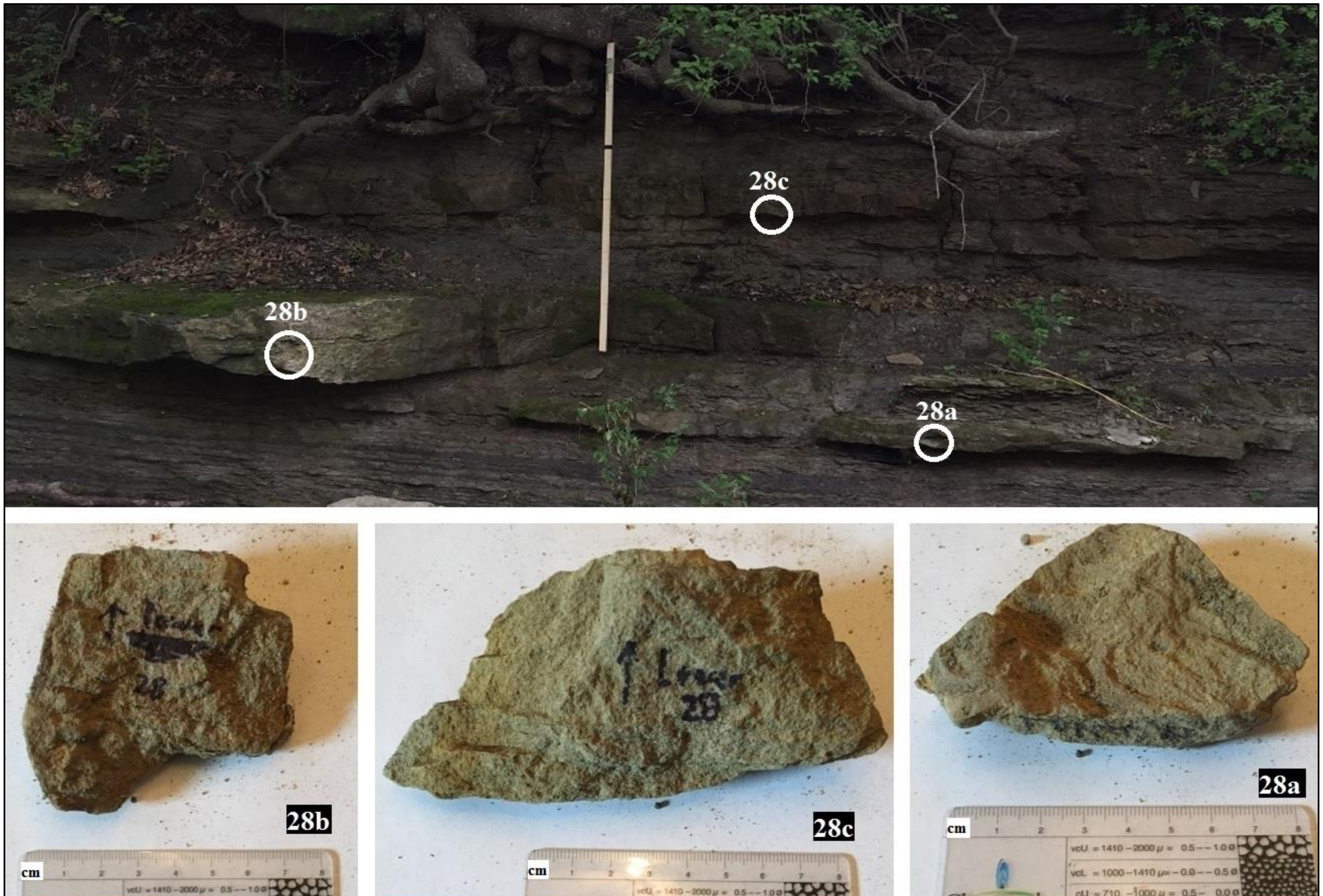


Fig. 57 - Photograph of the Seminole Formation at Outcrop #28 near Mounds, Okmulgee County, Oklahoma. Numbers indicate positions of samples 28a, 28b & 28c, shown in images below outcrop photograph.

Petrography

Three samples were collected from the Seminole Formation sandstone at Outcrop #28, and labeled "28a," "28b" and "28c." Samples 28a and 28b are from the "lower" sandstone bed shown in Figure 57, while 28c is from the "upper" sandstone bed (Fig. 57). Samples from the lower bed (28a & 28b) have calcareous cement and react to hydrochloric acid.

Sample 28a (Fig. 58) contains monocrystalline quartz (31%), polycrystalline quartz (8%), chert (4.4%) – averaging 0.04-0.12 mm in size – and metamorphic rock fragments (15%). Sutured contacts are evident between quartz grains and occasional embayment is observed. Silica cement appears commonly within pore spaces, next to calcite cement, and in between quartz grains. Calcite cement (2%) fills pores and appears to replace chert grains. In some instances, calcite cement appears in laminar streaks alongside solid oil infilling. Porosity (12%) displays concave pore throats and in places allows floating grains. Solid oil (11%) is consistent throughout the sample, with stained areas averaging 0.5 mm in size, up to 1 mm in size. Other detrital grains are plagioclase (2%), muscovite (4%), biotite (<1%), and tourmaline (trace).

Dominant detrital components in Sample 28b are quartz (39%), chert (2%), and metamorphic rock fragments (22%). The quartz grains are typically about 0.1 mm in size, well sorted, and angular to subangular, and occasionally elongate. Other grains present are plagioclase (1%), collophane (trace) and muscovite (4%). Porosity is evident (9%), but oversized pores are lacking. Silica cement as quartz overgrowth make up about 5% of the rock, and calcite cement (6%). Bitumen is approximately 12% of the total rock.

Sample 28c (Fig. 59) contains detrital components of quartz (39%), chert (10%), and metamorphic rock fragments (17%), muscovite (3%) and tourmaline (<1%). The quartz grains are angular to subangular, well sorted, and primarily monocrystalline, with a minor presence of polycrystalline quartz (1%). Porosity (10%) is mostly elongate between floating grains. Solid oil (13%) is present and is pore filling, but is not connected in pores when calcite cement (6%) is present.

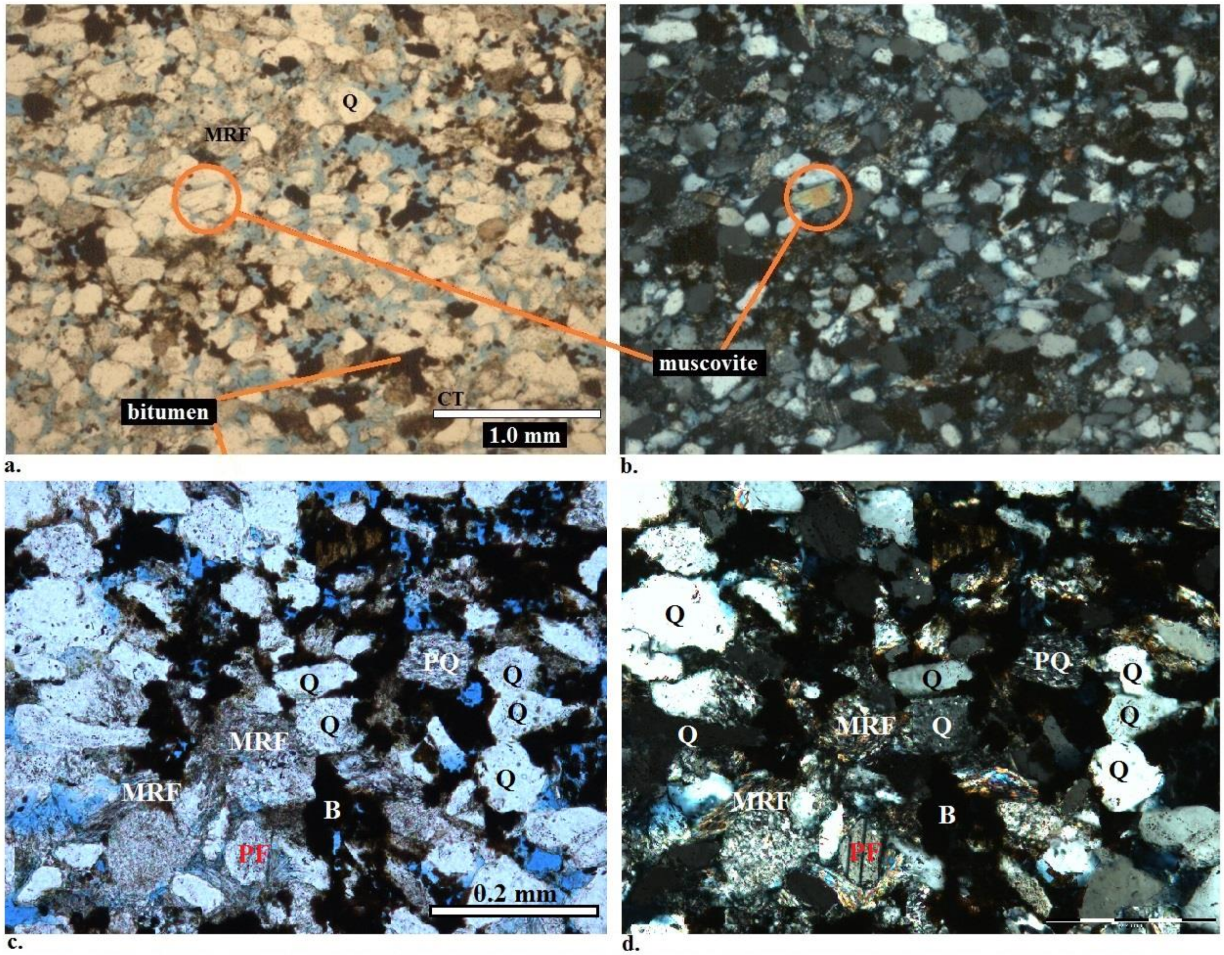


Fig. 58 – **A & B**. Photomicrograph showing detrital grains including chert (CT), quartz (Q) and schistose metamorphic rock fragments (MRF) identified. Left – plane polarized light (PPL). Right – cross polarized light (CPL). Outcrop #28 (A). **C & D**. Photomicrograph showing detrital grains including monocrystalline quartz (Q), foliated (schistose) metamorphic rock fragments (MRF), polycrystalline quartz (PQ) and plagioclase feldspar (PF). Black material in pores is bitumen (B). Some rock fragments are partially dissolved and porous. Porosity is shown by blue-colored epoxy. Note the abundance of metamorphic rock fragments. Left - PPL. Right - CPL. Outcrop #28 (B).

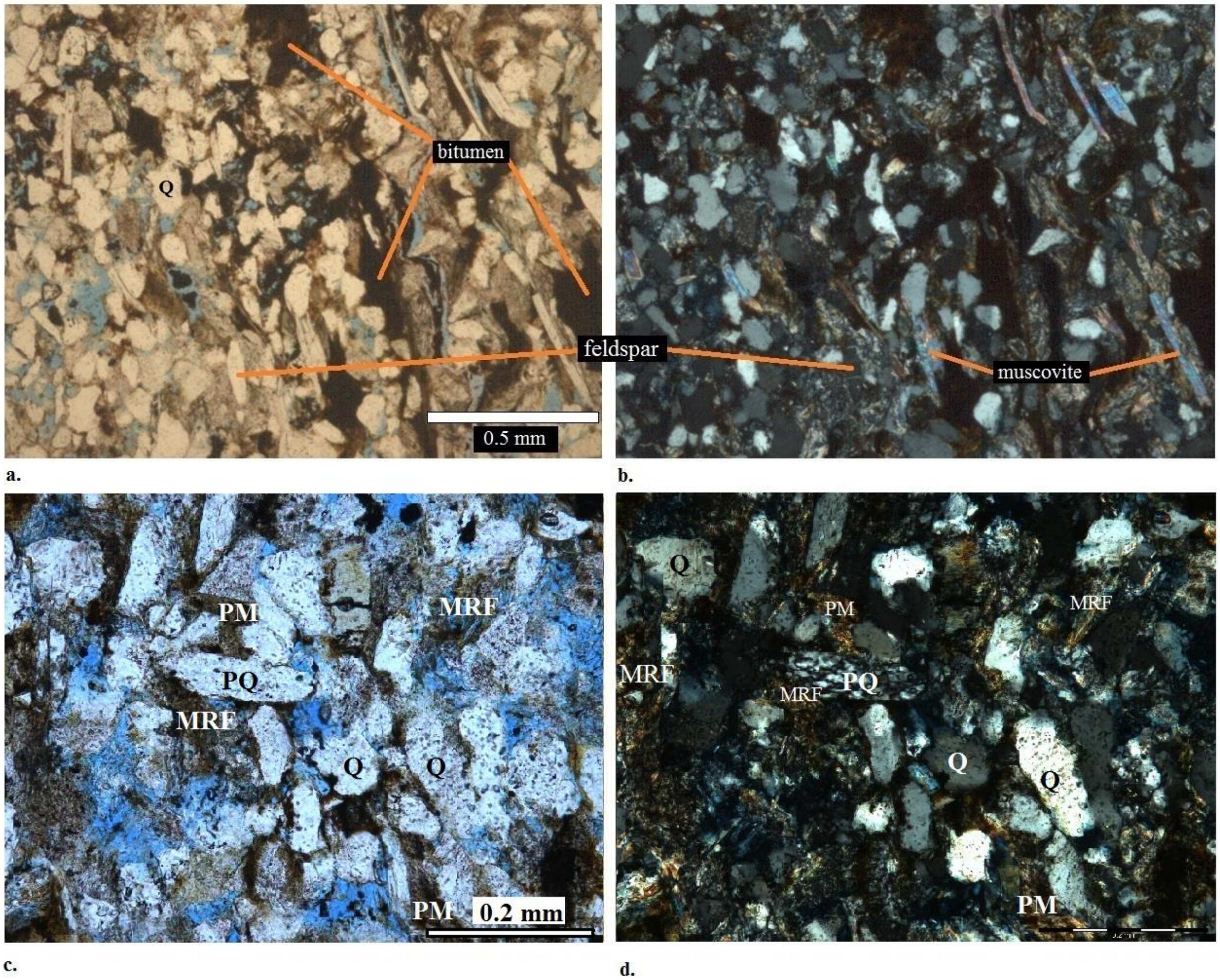


Fig. 59 – **A & B**. Thin section photomicrographs of detrital grains including chert (CT) and quartz (Q) grains, and schistose metamorphic rock fragments (MRF). Left – plane polarized light (PPL). Right - cross-polarized light (CPL). **C & D.** Photomicrograph showing detrital grains including monocrystalline quartz (Q), foliated (schistose) metamorphic rock fragments (MRF), polycrystalline quartz (PQ). Some schistose metamorphic rock fragments are compacted to form pseudomatrix (PM). Many rock fragments are partially dissolved and porous. Porosity is shown by blue-colored epoxy. Note the abundance of metamorphic rock fragments. Left PPL. Right CPL. From Outcrop #28 (C).

Southern Hills Outcrop

Location and General Description

This outcrop which is within the city limits of Tulsa is the only outcrop not classified by Heckel (1991) as part of the Lost Branch Formation, adjacent to an outcrop identified by Bennison (1968) (Fig. 61) and was exposed by home construction in 2008. This outcrop is on the east edge of the Southern Hills Golf Course along Harvard Ave., two blocks south of 61st St. in the NE NE SE of Sec. 5, T. 18 N., R. 13 E. (35.83833333 N, -95.97305556 W) (Fig. 60).

Fig. 60 - Map view of Sec. 5, T. 18 N., R. 13 E., containing the Southern Hills outcrop in Tulsa County, Oklahoma. The area of study is marked with a white star.

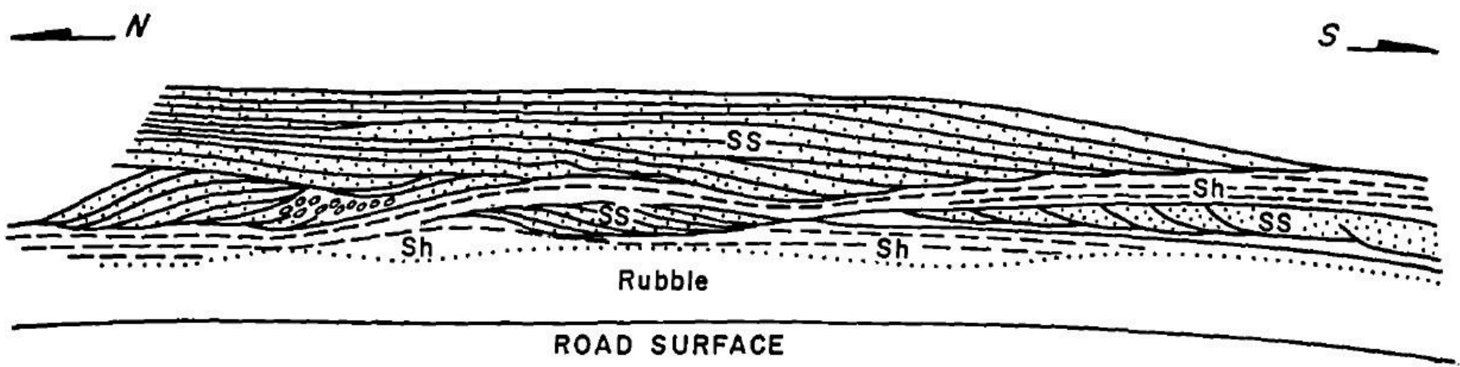


Fig. 61 – Figure 1 from Bennison (1968) depicting the outcrop exposed along Harvard Ave. just south of 61st Street in Tulsa County, Oklahoma. This outcrop is now covered by vegetation. This same interval (Seminole Sandstone-Holdenville Shale) is now exposed (see Figure 63) on the west side of the street. It is the “Southern Hills” outcrop of this study.

A Tulsa Geological Society guidebook by Bennison (1968) identified a road cut on the east side of Harvard Ave., two blocks south of 61st Street, referred to as “Stop 3.” This exposure is now covered by foliage, but a new roadcut of the same interval is exposed on the west side of Harvard Avenue. This new exposure is the result of for a home built in 2008, according to personal communication with the home owner. Rock samples for thin sections and gamma-ray spectrometer readings were taken for this outcrop, along with original thickness measurements used for the stratigraphic column.

Stratigraphy and Lithology

The exposure features a total thickness of 10 feet including the Holdenville Shale (4.0 feet) and the Seminole Formation (6.0 feet) (Fig. 62). Both are the same light-brown color. The Seminole Formation consists of 4.0 feet of medium-grained sandstone at the base overlain by 2.0 feet of fine-grained sandstone. The figure by Bennison (Fig. 61) depicts cross-bedding in the sandstone toward the south end, and a disconformity on the north end, with a continuous shale layer sitting above cross-bedded sandstone lenses. The figure is reversed in Figure 62 to generalize the new exposure and the stratigraphic relationships observed on the west side of the road.

Petrography

Two samples were collected from the Southern Hills outcrop labeled “SHa” and “SHb” (Fig. 63). Both were thin sectioned.

Sample SHa (Fig. 64) is predominantly monocrystalline quartz (44%), polycrystalline quartz (7%), chert (4%), metamorphic rock fragments (6%), plagioclase (2%) and muscovite (2%). Grains are subangular to subrounded, averaging 0.1-0.3 mm in size. Authigenic components include calcite cement (1%) and kaolinite (3%). Bitumen is approximately 17% of the total rock and open porosity as indicated by blue epoxy (13%). Sample SHb (Fig. 65) contains quartz grains (51%) that are angular to sub-angular, averaging 0.1-0.2 mm in size, and in some cases sutured together. Other detrital grains are chert (4%) and metamorphic rock fragments (7%). Porosity (16%), occasionally exhibits elongated pore throats. Calcite cement (4.4%) is pore-occluding. Solid oil (9%) fills porosity. Other grains are plagioclase feldspar (2%) and muscovite (2%).

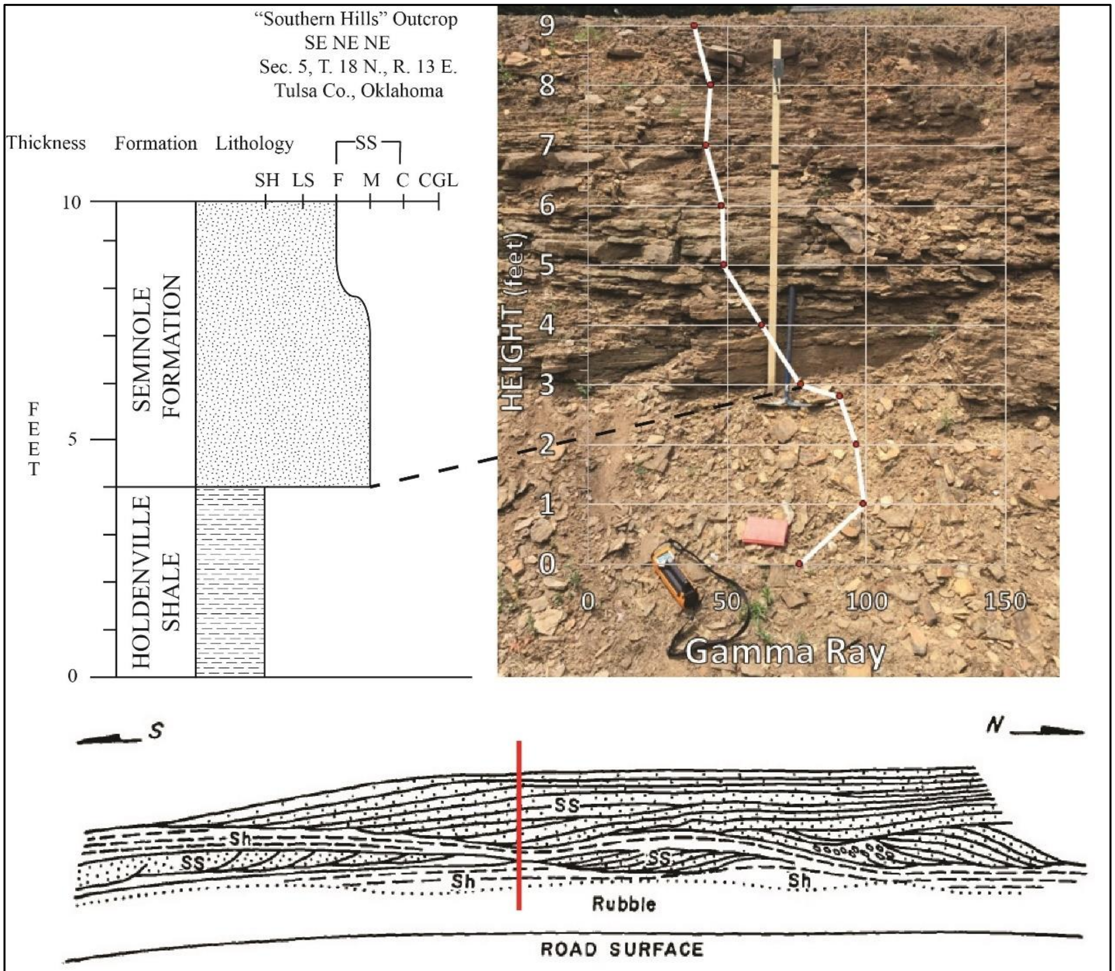


Fig. 62 - Measured section, photograph and sketch of the Southern Hills outcrop in Tulsa County, Oklahoma. API gamma ray curve superimposed on outcrop image with Jacob staff for scale (top right). The drawing by Bennison (1968) is reversed to show stratigraphic relationship of the roadcut. Red line is the estimated gamma-ray survey location.

Fig. 63 - Panoramic view of the Southern Hills outcrop in Tulsa, Oklahoma with sample locations circled (top). Sample "SHb" (left) and "SHa" (right) were thin sectioned.

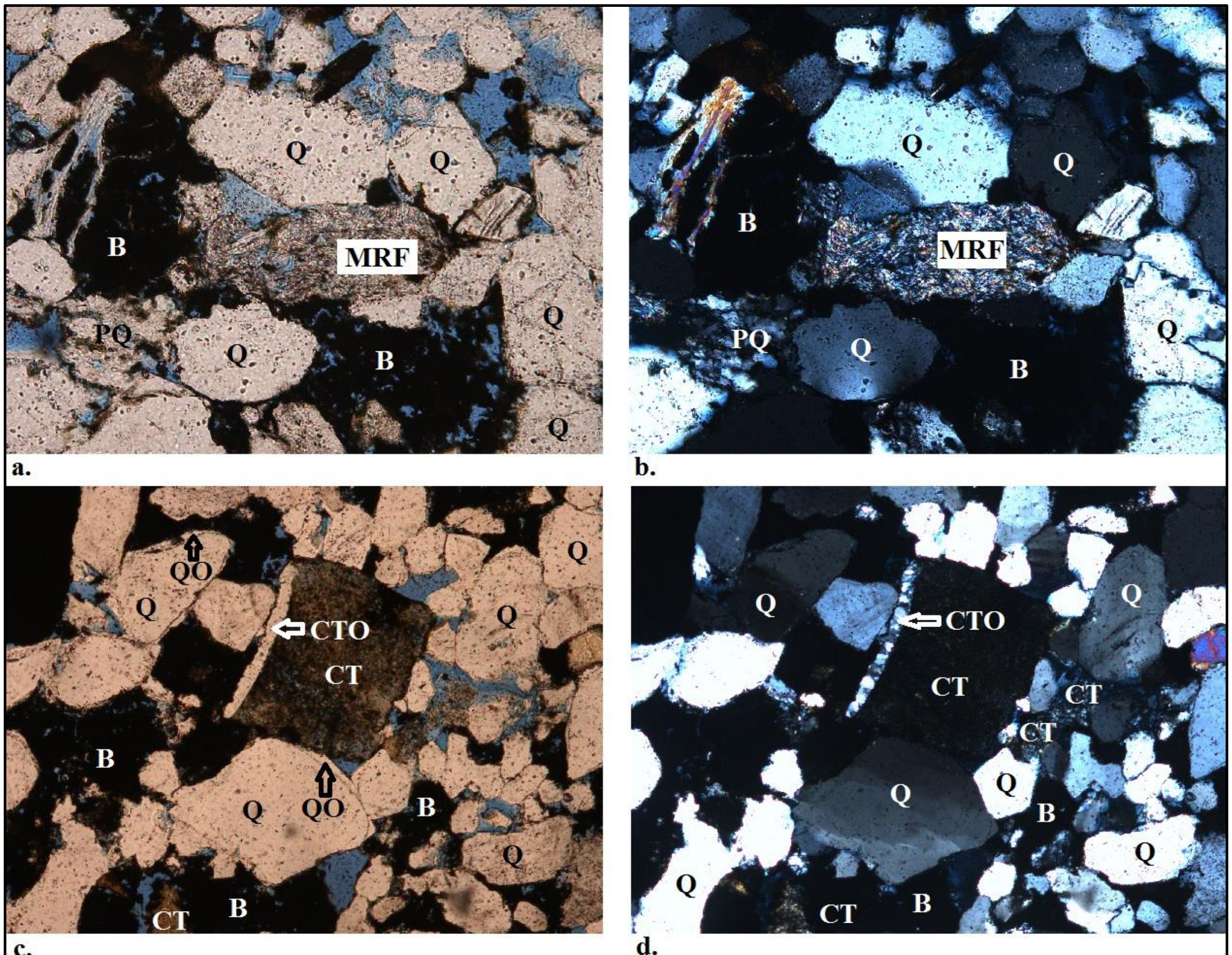


Fig. 64 – A & B. Photomicrograph showing detrital grains including monocrystalline quartz (Q), foliated (schistose) metamorphic rock fragments (MRF), polycrystalline quartz (PQ), and muscovite (M). Black pore-filling material is bitumen (B). Polycrystalline quartz is partially dissolved and porous. Porosity is shown by blue-colored epoxy. Note the abundance of metamorphic rock fragments. Left - PPL. Right - CPL. Outcrop "SH" (A). **C & D**. Photomicrograph showing detrital grains monocrystalline quartz (Q) and chert (CT), and pore occluding bitumen (B). Chert overgrowth (CTO) (arrow) borders the weathered chert grain in the center of the image. Quartz overgrowths (QO) are abundant. Porosity is shown by blue-colored epoxy. Left - PPL. Right - CPL. Outcrop "SH" (A).

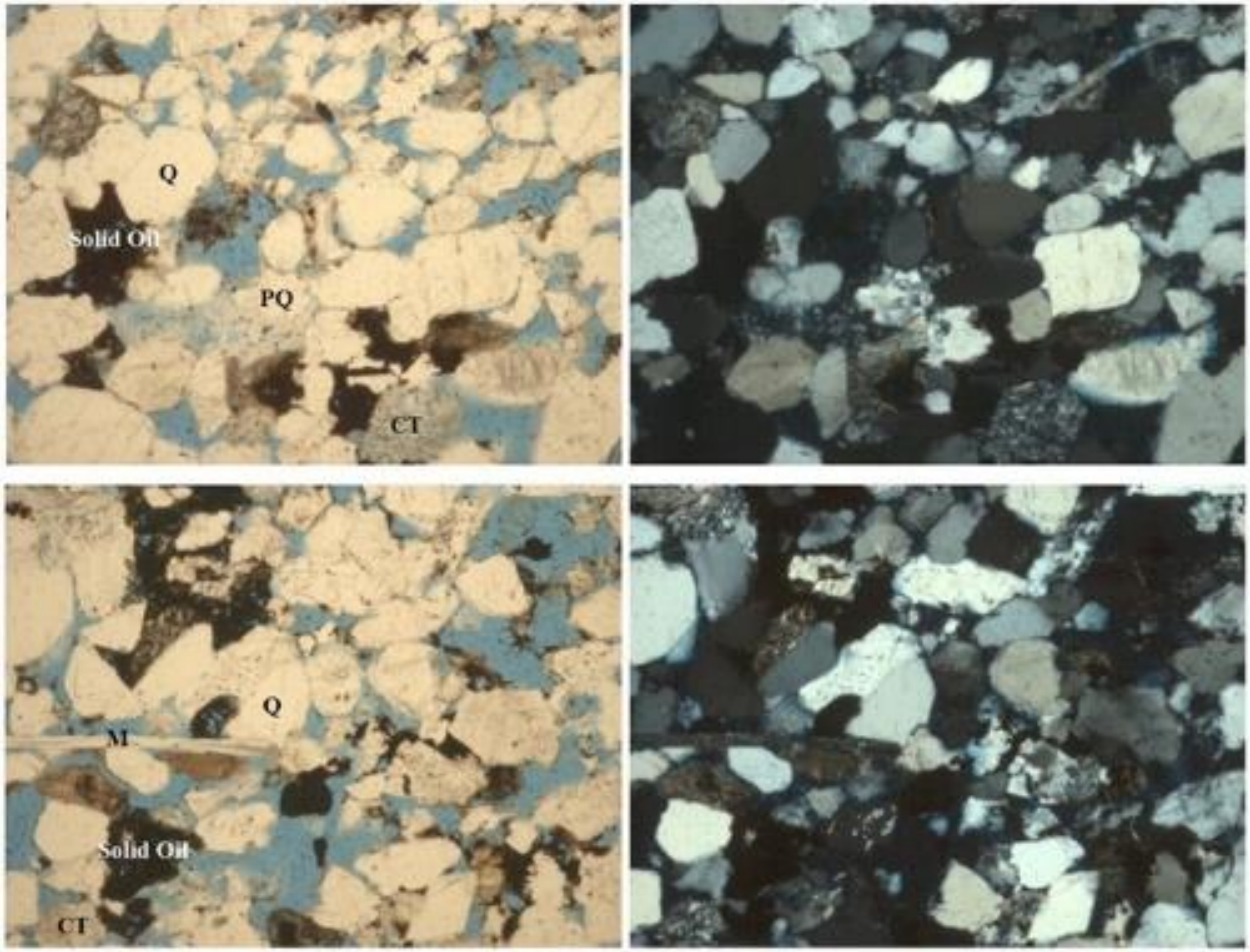


Fig. 65 - Photomicrograph for sample SHb: a) Plane-polarized light (PPL) of Picture 04, with chert (CT) and quartz (Q) grains, and solid oil; b) Same view in cross-polarized light (CPL); c) Plane-polarized light (PPL) of Picture 02, with chert (CT) and quartz (Q) grains, solid oil and muscovite (M); Same view in cross-polarized light (CPL).

Outcrop #11

Location and General Description

Outcrop #11 is located along the Marias des Cygnes River at Trading Post in Linn County, Kansas, in sec. 5, T. 21 S., R. 25 E. (38.25000000 N, -94.70166667 W) (Fig. 66). It was measured by Heckel (1981). This outcrop is included in the study to compare the composition of the Hepler Sandstone with coeval units in Oklahoma.

Fig. 66 - Map view of Sec. 5, T. 21 S., R. 25 E., containing Outcrop #11 along the Marias des Cygnus River at Trading Post, Linn County, Kansas. The area of study is marked with a white star.

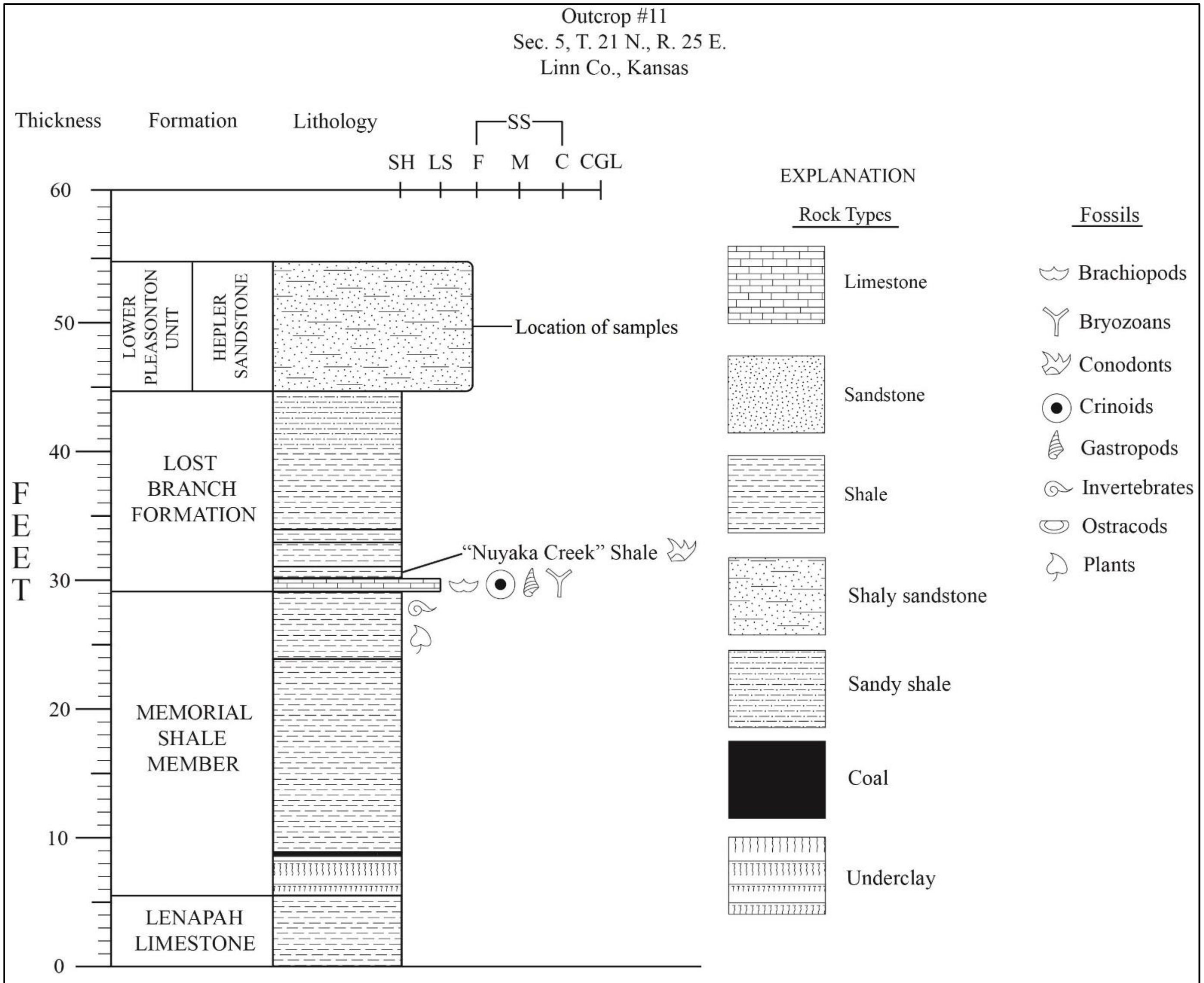


Fig. 67 – Measured section for Outcrop #11 at Trading Post, Kansas, from Heckel (1991). Kansas nomenclature was used for stratigraphy following Heckel (1991).

Stratigraphy and Lithology

This outcrop was measured and described by Heckel (1981), and contains four units that total 54.8 feet. The base is the Lenapah Limestone (5.5 feet), which is a sandy, skeletal calcarenite containing brachiopods (Fig. 67). Above it is the Memorial Shale Member (23 feet) divided into four subunits, starting with 3.0 feet of blocky mudstone at its base, followed by 0.3 feet of coal, 15 feet of gray shale containing ironstone concretions, and 5.0 feet of gray shale to mudstone with scattered invertebrates and plant fossils (Heckel, 1981). The Lost Branch Formation contains five subunits, including the fossiliferous Sni Mills Limestone member (1.0 foot) at its base (Fig. 67). The black Nuyaka Creek Shale contains characteristic phosphate nodules and conodont fauna (Heckel, 1981). The Lost Branch Formation above the Nuyaka Creek Shale is gray shale (2.0 feet), gray shale (1.0 foot) with ironstone nodules, and a gray shale (11.0 feet) that becomes sandy upward. The top unit at this outcrop is the Hepler Sandstone (10.0 feet), which according to Heckel (1981), is the equivalent to the Seminole Formation in Oklahoma.

Petrography

The two thin sections examined to compare composition of the Hepler Sandstone with the Seminole Formation. The composition of sample Hepler1 (Fig. 68) includes monocrystalline quartz (36%), polycrystalline quartz (2%), chert (4%), and schistose metamorphic rock fragments (17%). The quartz grains are subangular, to occasionally subrounded and angular. Their average size is 0.01 mm, with length up to 0.02 mm. Authigenic components are in the form of silica (18%) and calcite (16%) cement. Calcite occasionally coats quartz grains. Solid oil is 5% of the total rock, and porosity is not apparent.

Sample Hepler2 (Fig. 69) contains mono-crystalline quartz (26%), polycrystalline quartz (2%), chert (10%), and schistose metamorphic rock fragments (21%). Grain sizes are predominantly 0.01 mm, and occasionally 0.02 mm. Grains are subangular to subrounded, and are moderately sorted. Authigenic components are dominantly silica cement (5%) and calcite cement (16%). Porosity, as indicated by blue epoxy, is 8%.

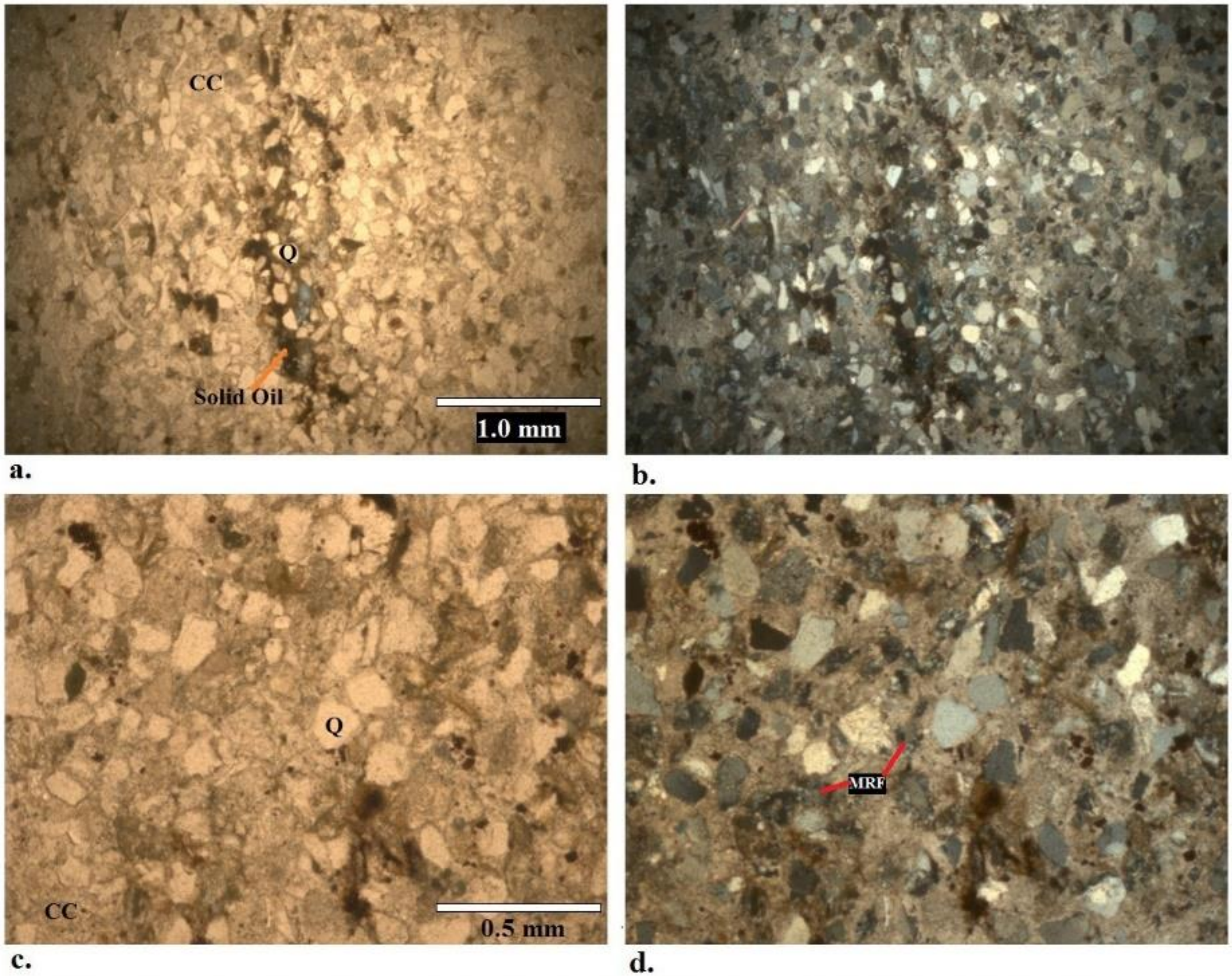


Fig. 68 - Thin section photomicrographs for Sample Hepler1 in plane-polarized light (a & c) with quartz (Q), solid oil and calcite cement (CC), with same view in cross-polarized light (b & d). Schistose metamorphic rock fragments (MRF) are present.

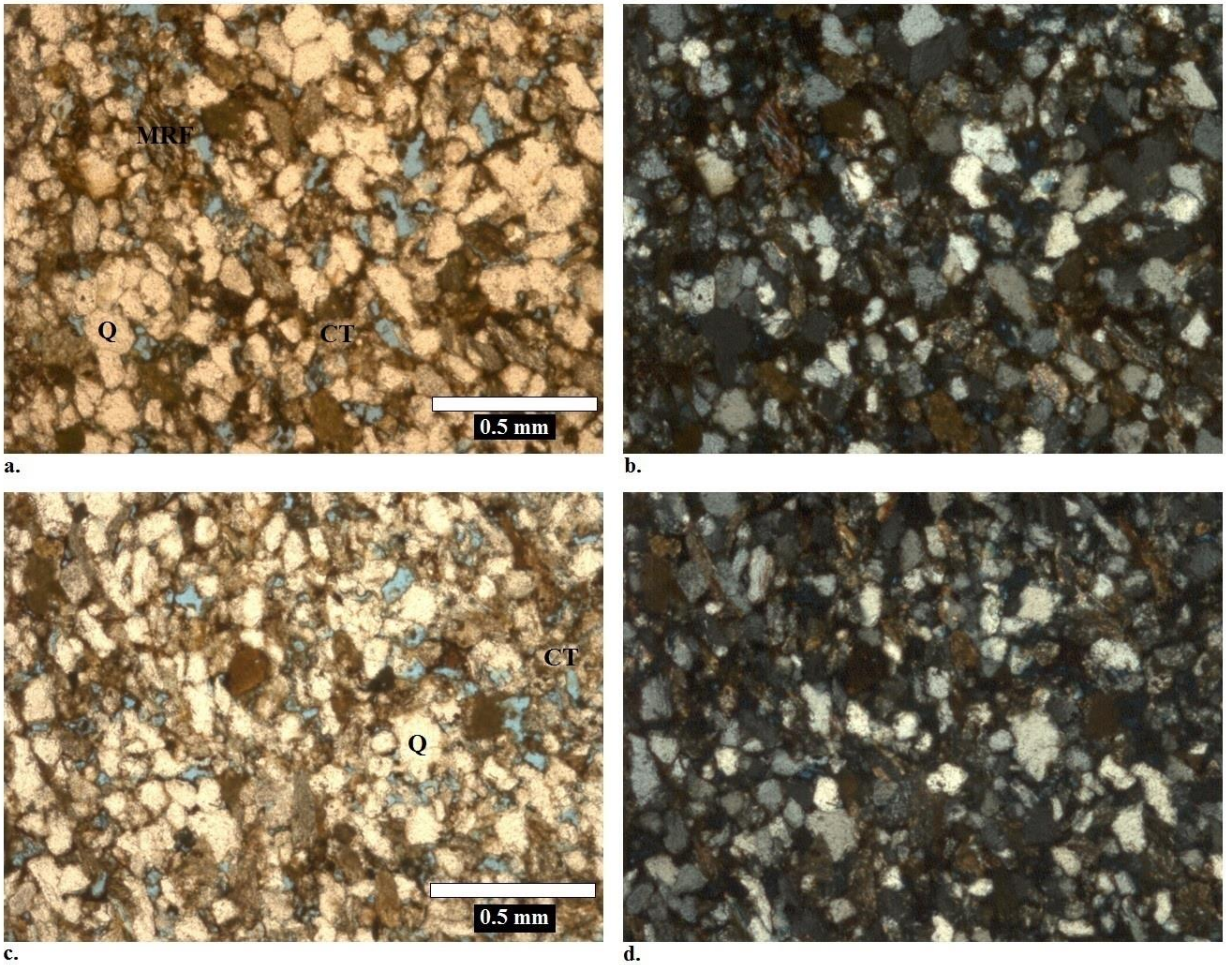


Fig. 69 - Thin section photomicrographs for Sample Hepler 2. A. Chert (CT), quartz (Q) and schistose metamorphic rock fragments (MRF) in plane-polarized light). B. Same view in cross-polarized light. C. Chert (CT) and quartz (Q) in plane-polarized light. D. Same view in cross-polarized light.

Classification & Ternary Diagram

The Seminole Formation in Seminole, Okfuskee and Hughes counties contain an abundance of quartz grains and chert with a limited presence of metamorphic rock fragments and the rare occurrence of feldspars. This composition is consistent with a provenance in the Ouachita Uplift as the primary and singular source of detrital material (Dickinson & Suczek, 1979) (Fig. 71). However, the appearance of metamorphic rock fragments in Okmulgee and Tulsa County suggests a different detrital sediment source, possibly to the north and east. Therefore, the ternary diagram for this study is divided into quartz (Q), chert (CT), and metamorphic rock fragment (MRF), which are the primary constituents. To classify the Seminole Formation sandstone, the most abundant detrital framework grains are quartz, chert and metamorphic rock fragments, counted and normalized to 100% and plotted on a ternary diagram designed for this composition (See Table 2 for the breakdown of quartz, chert and metamorphic rock fragments by individual sample percentage and their normalization factors). Normalization is calculated into an x-y projection for placing the samples on the ternary diagram (Fig. 70).

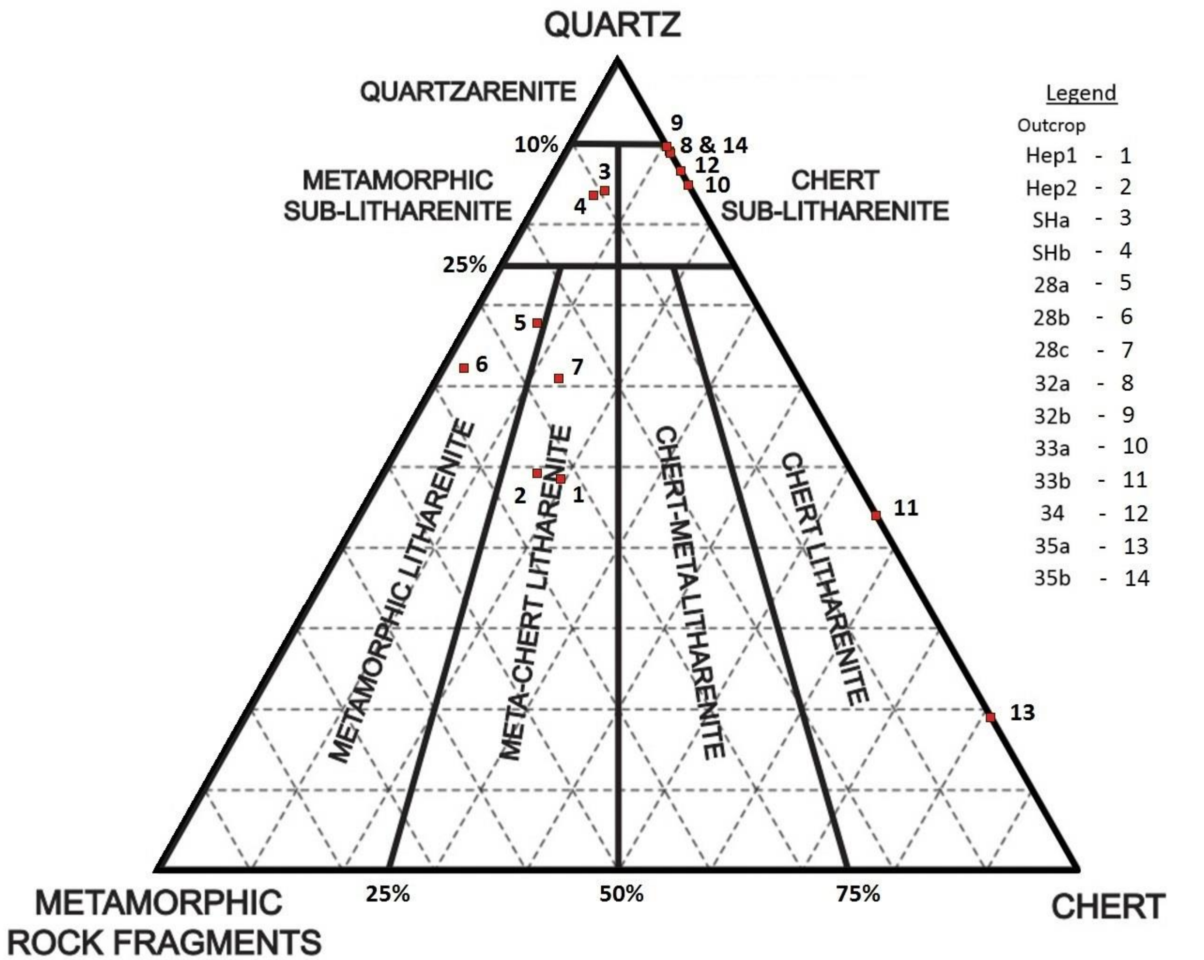


Fig. 70 – Ternary diagram for the classification of the Seminole Formation based on the normalized abundance of quartz, chert and metamorphic rock fragments. Corresponding symbol and outcrop sample identified (right). Modified from Folk (1974, 1980).

Table 2 **TOTAL ROCK (PERCENTAGES)**

	Detrital Components (DC)				Authigenic Components (AC)			Other		
Sample	Quartz (Q)	Chert (CT)	Metmorphic Rock Fragment (RF)	% of rock	Silica Cement	Calcite Cement	% of rock	Porosity	Oil Stains	Misc.
35a	13.06	56.39	0	69.45	0	29.44	29.44	0	0	0.83
35b	46.67	10.28	0	56.95	7.22	1.67	8.89	22.22	10	1.94
34	57.58	9.44	0	67.02	0.83	0.56	1.39	18.61	9.72	2.78
33a	55	10.28	0	65.28	5.83	3.33	9.16	21.11	3.89	1.11
33b	31.39	40.56	0	71.95	8.33	0.83	9.16	9.44	9.44	0.28
32a	57.78	7.78	0	65.56	1.39	5.83	7.22	7.78	18.88	0.83
32b	58.06	7.22	0	65.28	5.28	2.22	7.5	13.89	11.11	2.5
28a	38.89	4.44	14.72	58.05	8.06	1.94	10	11.94	11.39	8.33
28b	38.61	1.67	22.22	62.5	4.72	5.56	10.28	9.17	12.22	5.56
28c	39.44	9.72	17.22	66.38	0	5.56	5.56	10.28	12.77	5
Sha	51.39	4.44	5.83	61.66	0	0.83	0.83	13.33	17.22	6.67
SHB	51.38	3.89	6.94	62.21	0	4.44	4.44	16.11	8.89	8.33
Hepler1	36.11	4.17	16.94	57.22	17.78	15.83	33.61	0	4.72	4.44
Hepler2	27.78	9.45	20.56	57.79	5	16.39	21.39	7.78	10.28	2.7

Table 2. Percentages of detrital and authigenic components in thin sections as determined by point counting. Schistose metamorphic rock fragments are absent to trace in samples from Outcrops 35, 34, 33 and 32.

Table 3 **TERNARY DIAGRAM PLOT NUMBERS**

Location	Original data Q	Original data MRF	Original data CT	1st normalization Q	1st normalization MRF	1st normalization CT
35a	13.06	0.00	56.39	0.19	0.00	0.81
35b	46.67	0.00	10.28	0.82	0.00	0.18
34	57.58	0.00	9.44	0.86	0.00	0.14
33a	55.00	0.00	10.28	0.84	0.00	0.16
33b	31.39	0.00	40.56	0.44	0.00	0.56
32a	57.78	0.00	7.78	0.88	0.00	0.12
32b	58.06	0.00	7.22	0.89	0.00	0.11
28a	38.89	14.72	4.44	0.67	0.25	0.08
28b	38.61	22.22	1.67	0.62	0.36	0.03
28c	39.44	17.22	9.72	0.59	0.26	0.15
SHA	51.39	5.83	4.44	0.83	0.09	0.07
SHB	51.38	6.94	3.89	0.83	0.11	0.06
Hepler1	36.11	16.94	4.17	0.63	0.30	0.07
Hepler2	27.78	20.56	9.45	0.48	0.36	0.16

Table 3. Percentages of quartz (Q), metamorphic rock fragments (MRF) and chert (CT) for the ternary diagram seen in Figure 70. Percentages are normalized from the original data, eliminating authigenic components, matrix, porosity.

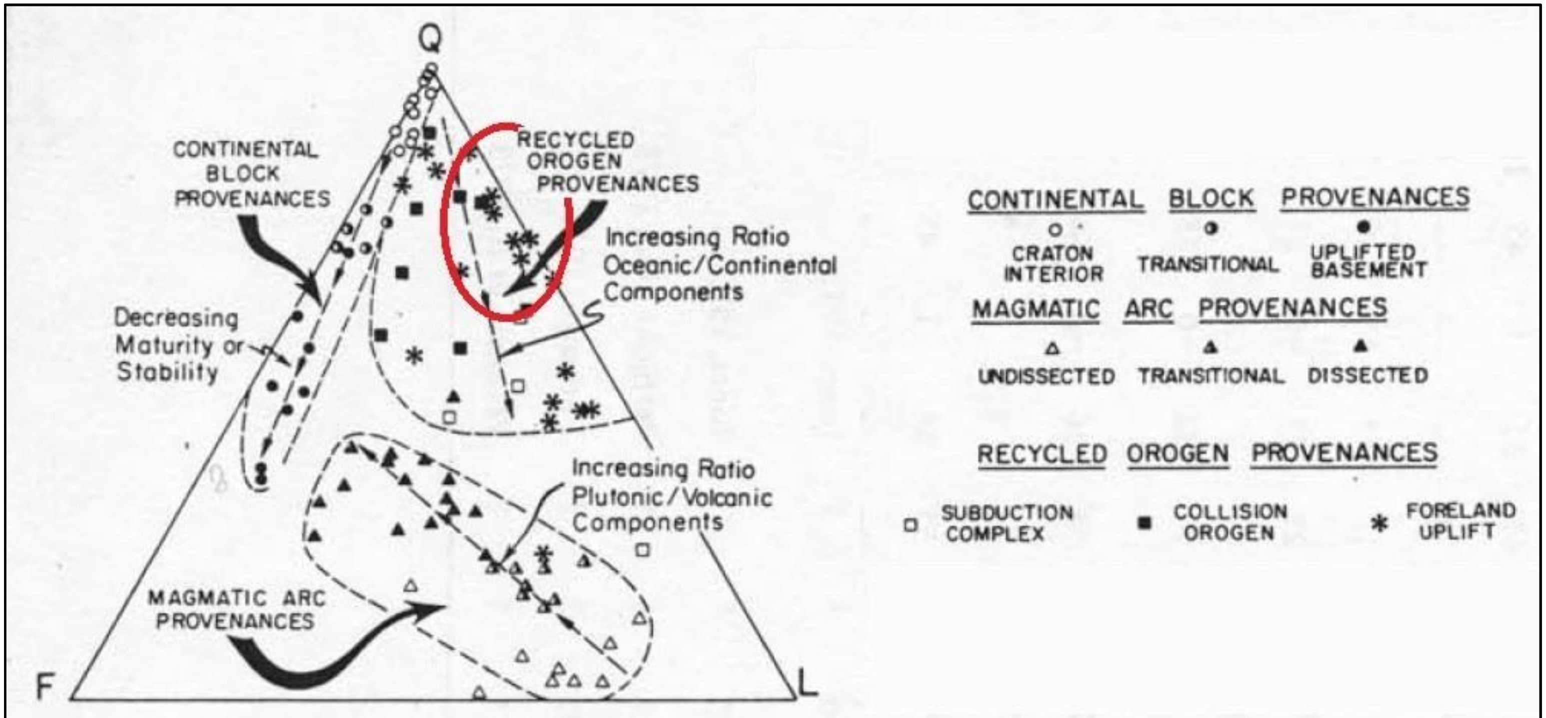


Fig. 71 - Triangular QFL plot showing mean framework modes for selected sandstone suites derived from different types of provenances. Q is total quartzose grains, including monocrystalline Qm and polycrystalline Qp varieties; F is total feldspar grains (all are monocrystalline); L is total unstable lithic fragments (all are polycrystalline). Red circle indicates approximate range for the Seminole Formation sandstones for this study. Modified from Dickinson and Suczek (1979).

CHAPTER V

CROSS SECTION RESULTS & INTERPRETATION

Cross-section A-A”

Subsurface correlation section labeled A-A” (see Plate 1-A) includes wireline logs of 21 wells that are separated by approximately one township between each well (see Plate 1-B). To the northwest end, this cross section ties to Cross-section A-A’ by Bacon (2012) in Kingfisher County with the Hill D-3 (Sec. T. 18 N., R. 9 W.) and then extends 114.5 miles southeast to the Neon Moon 32-1 well (Sec. 32, T. 6 N., R. 7 E.) in Seminole County, which is 5.5 miles from the measured section in Outcrop #35 (Sec. 12, T. 5 N., R. 7 E.).

This stratigraphic cross section uses the Checkerboard Limestone for the datum, which has an easily identifiable, regionally correlative higher resistivity signature on wireline logs. In addition to the stratigraphic relationships in Pennsylvanian (Desmoinesian to Missourian) formations, this cross section demonstrates the influence of pre-Pennsylvanian structure and erosional features on Pennsylvanian depositional sequences. Four regions are indicated on the cross section. From northwest to southeast, these are:

1. <u>Anadarko Shelf</u>: Five wells in Kingfisher County from the “Hill D-3” well (Sec. 15, T. 18 N., R. 9 W.) to the “Metzger 6 No. 2” well (Sec. 6, T. 15 N., R. 5 W.)

2. <u>Nemaha Ridge</u>: Three wells in Oklahoma County from the "C.W.D. 1-6" well (S. 6, T. 14 N., R. 4 W.) to the "Glenaire 1-28" well in (Sec. 28, T. 13 N., R. 3 W.)

3. <u>Cherokee Shelf</u>: Eight wells from the "Oklahoma County 2" well (Sec. 22, T. 12 N., R. 2 W.) in Oklahoma County, to the "Raper 16-1" well (Sec. 16, T. 7 N., R. 5 E.) in Pottawatomie County.

4. <u>Arkoma Basin</u>: Three wells in Seminole County from the "Katherrine 1-5" well (Sec. 5, T. 6 N., R. 6 E.), to the Neon Moon 32-1" well (Sec. 32, T. 6 N., R. 7 E).

1. The wells on the Anadarko Shelf have a pre-Pennsylvanian section that is a consistent thickness and log characteristics from the Mississippian Chester limestone downward through the Meramec/Osage limestone, Woodford Shale, Hunton Group and Sylvan Shale. The Pennsylvanian section from the Pennsylanian-Mississippian unconformity upward to the carbonate and radiogenic shale that forms the "Oswego Marker" consists of a 900 to 400 foot thick siliciclastic sequence capped by 100 to 150 feet of Oswego carbonate that thins toward the Nemaha Uplift. The stratigraphic interval above the "Oswego Marker" to the base of the Checkerboard Limestone thickens from about 200 feet to approximately 400 feet thickness moving southeast from the northern Anadarko Shelf toward the Nemaha Ridge.

2. The wells on the Nemaha Ridge illustrate pre-Pennsylvanian structural uplift with truncation of Mississippian carbonate (Chester and Meramec/Osage), Woodford Shale, Hunton Group and Sylvan Shale northwest of the Nemaha Fault, leaving the Viola Limestone exposed below the pre-Penn unconformity at the crest of the Nemaha Ridge. The interval below the "Osage Marker" thins from 380 feet to approximately 200 feet at the crest of the structure. The

stratigraphic interval from the base of the Checkerboard Limestone to the “Oswego Marker” is approximated 450 feet thick across the structural high.

3. Cherokee shelf wells internal thickness, stratigraphic relationships, and lithofacies are observed southeastward from Oklahoma County into Pottawatomie County. Increasingly younger formations subcrop beneath the pre-Penn unconformity with the Hunton Group in Oklahoma County to the Mississippian Caney Shale in Pottawatomie County.

Pennsylvanian markers that were easy to follow from the Anadarko Shelf across the Nemaha Ridge become less distinct in southeastern Oklahoma County. The “Oswego Marker” cannot be followed east of the Beth Ann No. 1 (Sec. 27, T. 9 N., R. 3 E.) in Pottowatomie County. The distinct, high-resistivity character of the Checkerboard Limestone observed in the “Melissa & Scott Wilson 1” well in Oklahoma County, changes significantly to the “Julia Watts 1” well in Pottawatomie County, where it is indistinct. With the Checkerboard Limestone unrecognizable in wireline logs, other stratigraphic markers were employed for correlating. These new stratigraphic markers are grounded in the work of Tanner (1956), and include the Coffeyville, Seminole, Wewoka and Senora formations. To the southeast of the Beth Ann No. 1 (Sec. 27, T. 9 N., R. 3 E.), the formation names used on this cross section are based on Tanner (1956). The thickness of the section from the base of the Checkerboard to the Calvin-Seminole interval remains fairly constant at 500 feet thick. In addition, correlations shown on this cross section place the top of the Calvin interval at a position that laterally is equivalent to the radiogenic shales of the “Oswego Marker,” which no longer contain log-recognizable carbonate.

4. The last three wells on the cross section show the thickening of the Pennsylvanian section into the Arkoma Basin. To the east of the Wilzetta Fault, the pre-Pennsylvanian section rests unconformably on the Mississippian Caney Shale. The Pennsylvanian siliciclastic section

thickens dramatically into the basin. The interval from the top of the Calvin Sandstone interval to the unconformity in the Raper 16-1 (Sec. 16, T. 7 N., R. 5 E.) is 850 feet thick. This same interval in the Mr. Jones 13-5 (Sec. 13, T. 6 N., R. 6 E.) is 1,800 feet thick. The thickness of the section from the top of the Calvin interval to the base of the Checkerboard also increases from 650 feet to 800 feet thick between the same wells. In addition, older siliciclastic units common to the Arkoma Basin, including the Atoka, Gilcrease sandstone, Marrowan and Union Valley limestones, and Cromwell sandstone intervals are present.

Cross-section B-B'

Cross Section B-B' (Plates 2a and 2b) a cross section flattened on a sea level datum, and was prepared to connect subsurface Cross Section A-A" to the outcrop. Eight wells were chosen because of their location close to the outcrop and complete log curves. Cross Section B-B' is horizontally scaled with a vertical exaggeration of 13.9/1. This cross section begins with the last two wells shown on Cross Section A-A", Mr. Jones 13-5 (Sec. 13, T. 6 N., R. 6 E.), and Neon Moon 32-1 (Sec. 32, T. 6 N., R. 7 E.) and extends to Outcrop #35. Cross Section B-B' shows that the Seminole Formation is at the surface in Outcrop #35. This cross section also shows that the Sasakwa Limestone of Heckel (1991) is equivalent to the Checkerboard Limestone in the subsurface. Therefore, it is possible to interpret the significance of the Sasakwa Limestone with Cross-section C-C'.

Cross-section C-C'

Correlation section C-C' (Plate 3) is a stratigraphic cross section of outcrop schematic diagrams flattened on the Nuyaka Creek Shale. The schematic diagrams are based on the outcrop measurements and include descriptions made by Dott & Bennison (1982), Heckel (1991) and this study. The schematic diagrams show stratigraphy, lithologic variation, fossils, sedimentary structure, and other forms of evidence. The stratigraphy presented is limited to exposures at the surface.

Outcrop #33 (Sec. 25, T. 6 N., R. 7 E.) is the thickest exposure (93 feet) and the Southern Hills Outcrop (Sec. 5, T. 18 N., R. 13 E.) is the thinnest (10 feet). The Seminole Formation is present in all outcrops except Outcrop #29 (Sec. 23, T. 15 N., R. 11 E.). The Seminole Formation is thinnest at Outcrop #32 (Sec. 15, T. 10 N., R. 9 E.) where it is only 5 feet thick. The Seminole Formation contains both sandstone and shale in Outcrop #35 (Sec. 12, T. 5 N., R. 7 E.), Outcrop #34 (Sec. 25, T. 6 N., R. 7 E.), and Outcrop #27 (Sec. 2, T. 17 N., R. 12 E.). The Seminole Formation is principally sandstone in Outcrop #33 (Sec. 5, T. 6 N., R. 8 E.), Outcrop #32 (Sec. 15, T. 10 N., R. 9 E.) and the Southern Hills Outcrop (Sec. 5, T 18 N., R. 13 E.). There is no sandstone at Outcrop #30, where the lithologies are shale, coal and siliciclastic mudstone. The Seminole Formation contains a thin coal seams (<1 foot thick) in Outcrop #30 (Sec. 4, T. 14 N., R. 11 E.) and Outcrop #28 (Sec. 30, T. 16 N., R. 12 E.).

The Holdenville Shale is present in all outcrops. It is thickest at Outcrop #35 where it is 37 feet thick and thinnest at Outcrop #30 where it is 3 feet thick. The Holdenville contains the Nuyaka Creek Shale in all but Outcrop #30, Outcrop #28 and the Southern Hills Outcrop. The Nuyaka Creek Shale is thickest at Outcrop #32. The Checkerboard Limestone is only present at Outcrop #30, where it is 2 feet thick. Exposure thicknesses range from 40 to 90 feet from Outcrop #35, #34, #33 and #32. The remaining Holdenville Shale exposures on the cross section thin to 10 to 20 feet in thickness, moving toward the northeast. The exception is Outcrop #27 (Sec. 2, T. 17 N., R. 12 E.), which has 40 feet (Heckel, 1991).

CHAPTER VI

DISCUSSION

Desmoinesian-Missourian Boundary

The litho-stratigraphic boundary between the Pennsylvanian Desmoinesian and Missourian stages, is not clearly defined in the literature. Subsurface correlations (e.g. Campbell, [1997], and Boyd, [2008]) are inconsistent and do not provide a context for this stratigraphic boundary. Based on biostratigraphic evidence, Boardman et al, (1989 and 1990) place the Desmoinesian-Missourian boundary at the top of the Holdenville Formation, where the Nuyaka Creek Shale occurs within. Heckel (1991), based on biostratigraphy, states the Desmoinesian-Missourian lithostratigraphic boundary is diachronous.

Bacon (2012) proposed a lithostratigraphic separation of the Desmoinesian-Missourian boundary in the subsurface using the Nuyaka Creek Shale as the base of the "True Cleveland." According to Bacon (2012), the "True Cleveland" sandstones are Missourian age and are located above the Nuyaka Creek Shale. Because this shale is radiogenic and gives a high gamma ray log curve signature, the location of the Desmoinesian-Missourian boundary can be easily identified in the subsurface when gamma ray logs are available. Prior to Bacon's study and identification of the importance of the Nuyaka Creek Shale marker, subsurface correlations resulted in the use of the term "Cleveland" for both upper Desmoinesian and lower Marmaton Group sandstones. Bacon's regional west to east Cross-section A-A' demonstrates the use of the Nuyaka Creek Shale to mark the Desmoinesian to Missourian boundary. This study coextends Bacon's correlations from northwest Kingfisher County to southeast Seminole County.

Based on log correlations, this study shows that "True Cleveland" in the subsurface is equivalent to the Seminole Formation at the surface, and that the Nuyaka Creek Shale in outcrop is in the Holdenville Shale approximately 10 to 30 feet below the base of the Seminole Formation (see Plate 4). Based on these outcrop sections (Bennison, 1982; Heckel, 1991), the Nuyaka Creek Shale is placed typically at the base of the Lost Branch Member (ex. Fig. 17, 28, 32 and Plate 4), which is the upper member of the Holdenville Shale. The Nuyaka Creek Shale is not the top of the Holdenville Shale, as some 10-30 feet of gray shale separate the Nuyaka Creek Shale from the base of the superjacent Seminole Formation. Nevertheless, the Nuyaka Creek Shale serves as an excellent subsurface marker because of its recognizable high gamma-ray value on wireline logs. This study suggests that the Desmoinesian-Missourian boundary can be inferred in the subsurface to be located in the shale interval (Lost Branch Member of the Holdenville Formation) between the high gamma-ray value on the (Nuyaka Creek Shale) gamma-ray curve and the base of the "True Cleveland" sandstones (Seminole Formation).

The boundary between the Seminole Formation and the Holdenville Shale is an unconformity (Oakes, 1963). The Southern Hills Outcrop (Sec. 5, T. 18 N., R. 13 E.) in Tulsa County is the only exposure in this study to clearly show the channel erosion for this contact (Fig. 62, 63), as demonstrated by Bennison (1968) with the drawing of the outcrop on the east side of Harvard Ave., which is now covered (Fig. 61).

Depositional Environment of the Lost Branch and Seminole Formations

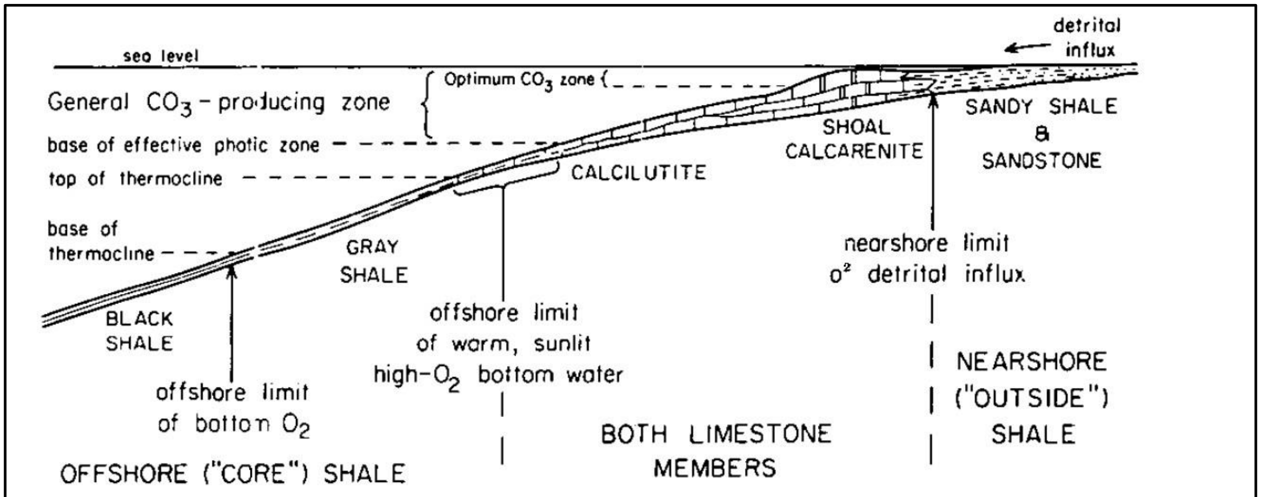


Fig. 72 - General model for limits of carbonate deposition on a sloping tropical shelf, showing positions of rock types that become superposed with transgression to produce Kansas cyclothem (from Heckel, 1984).

It is interpreted that the Seminole Formation marks the beginning of a eustasy-driven regression (Heckel, 1991), with the Nuyaka Creek Shale indicating maximum flooding prior to the Seminole regression. Heckel described this "cyclothem sequence" as the Lost Branch transgression and regression, with the Seminole Formation and the Hepler Sandstone (Kansas age-equivalent to Seminole Formation) representing the regression. In the Midcontinent region, the black core shales of Heckel (1984) formed in an epeiric (inland) sea, below the photic zone and thermocline, in an anoxic, offshore environment; whereas gray shales formed within the thermocline, below the photic zone, but in a setting changed by the introduction of oxygen. This interpretation of an arm of an inland sea with anoxic conditions followed by a shallowing and increased circulation is obvious in the Outcrop #34 exposure. In this outcrop, black Nuyaka Creek Shale is succeeded by gray shale with horn corals and chonetid brachiopods. This gray shale is the Lost Branch Member of Holdenville Shale, which is located immediately above the black, hard-fissile Nuyaka Creek Shale. This section becomes siltier/sandier updward, indicating the opening of the Nuyaka epeiric sea to more normal marine circulation. This relationship between Nuyaka Creek Shale, the gray shale of the Lost Branch Formation and Seminole Formation can be observed at Outcrops #35, #34, #33 and #32 with the idea that sandy shale and sandstone formed proximally, closer to the detrital influx (Heckel, 1984; Figure 72).

Lack of Nuyaka Creek Shale at Outcrop #33 and Outcrop #35

This study was unable to locate the black fissile Nuyaka Creek Shale at Outcrop #33 and Outcrop #35, despite attempts to dig out the section along the roadside at Outcrop #35. The Homer School Limestone, which contains chaetetes fossils (Fig. 20), is 1.0 foot thick at Outcrop #35, and is located immediately below the Nuyaka Creek Shale. The limestone is traceable along the roadcut and several hundred feet north of the road. Although Heckel (1991) reported the presence of the Nuyaka Creek Shale at this location, this study found no natural exposures of the Nuyaka Creek Shale above the Homer School Limestone. The Nuyaka Creek Shale was apparently exposed at Outcrop #33 when previous studies were conducted (Dott and Bennison, 1982, Heckel, 1991), but this exposure has since been modified by recent utility work along the roadside. The Nuyaka Creek Shale was observed at Outcrop #32 and Outcrop #31.

Source for Chert in Seminole Sandstone

Outcrops in the southern part of the study area, 32, 33, 34 and 35, classify as chert litharenites and chert sublitharenites (Fig. 70). In contrast, outcrops in the northern part of the study area, Hepler, Southern Hills, and 28, plot as metamorphic litharenite, metamorphic sub litharenites, and meta-chert litharenites (Fig. 70). This striking change in composition is interpreted to indicate differences in sediment provenance.

The occurrence of chert pebbles in the base of the Seminole Sandstone in both Outcrop #35 (Sec. 12, T. 5 N., R. 7 E.) and Outcrop #33 (Sec. 5, T. 6 N., R. 8 E.) indicates the potential for a similar southerly source that is not found in outcrops farther north. The basal sandstone and conglomerate of the Seminole Formation contain chert pebbles and sand-sized chert grains. It is interpreted that this influx of coarse clastic sediment came from a nearby source rich in chert. This inference is supported by the composition of the basal sandstone unit of the Seminole Formation in outcrops farther north, which do not contain chert pebbles, but instead contain abundant metamorphic rock fragments and sand-sized chert grains.

Previous theses by two Oklahoma State University students provide the petrographic analyses for the conglomerates from these two possible southerly source areas: the Stafford (1990) study of the Deese Conglomerate of the Arbuckle Uplift, and the Cecil (2016) study of the Arkansas Novaculite of the Ouachita Uplift. The Deese Conglomerate in the Arbuckle Uplift is matrix-supported with subrounded to rounded clasts of limestone ranging from pebbles to boulders, and sometimes, the presence of pebble-sized, angular chert. The clasts are poorly sorted, and contain rounded mudstone clasts. The conglomerate samples taken from the Seminole Formation contain neither limestone nor mudstone. The Arkansas Novaculite outcropping in the Ouachita Uplift contains an abundance of cryptocrystalline silica (Cecil, 2016). The samples from Outcrops #35 and #33 contain the cryptocrystalline chert fabric. Therefore, it is believed that the source for this chert is the Ouachita Uplift.

Based on the ternary diagram for Seminole Formation samples (Cross-section C-C', Fig. 70), samples from Seminole and Hughes counties, in the southern part of the outcrop trend, show a marked difference from samples collected to the north in Okfuskee, Okmulgee and Tulsa counties. Seminole and Hughes counties occasionally contain cryptocrystalline chert, but no metamorphic rock fragments. Okfuskee, Okmulgee and Tulsa counties commonly contain metamorphic rock fragments throughout, but never cryptocrystalline chert. The two samples provided from an outcrop outside the study area in Linn County, Kansas (Outcrop #11), appear similar to the samples in Oklahoma because of the presence of metamorphic rock fragments. It is unlikely the Ouachita Uplift is the primary detrital source for samples from Outcrop #11. This suggests that a source of metamorphic rock fragments is the Appalachians or other metamorphic province such as the Canadian Shield contributed sediment to the Seminole Formation in Okfuskee, Okmulgee and Tulsa counties. A similar northerly or easterly source for metamorphic rock fragments likely existed from Desmoinesian time based on the detrital composition of the Cherokee Group sandstones (Mason, 1982; Kuykendall, 1983; Lojck, 1983; Tate, 1985; Puckette 1990).

Cross Section C-C' and Previous Literature on Outcrops

Strata observed at outcrops #35, #34, #33 and #32 reflect Arkoma Basin infilling compared to the outcrops north on the Cherokee Platform. Cross sections by Krumme (1981) and Johnson (2008) demonstrate the accommodation and proximal termination upward to the Cherokee Platform and Ozark Uplift, respectively.

At outcrop #32, the Dawson Coal appears above a limestone bed. The Tulsa Coal at Outcrop #28 sits above a mudstone with silicified wood and is covered by a thin coaly shale layer. The thin coal layers that appear in the northern half of the outcrops in this study indicate a brief periods when a swamp or marine marsh environments developed along a shoreline during transitions of the sea level associated with the Lost Branch and Hepler regressions.

Cross-section A-A''

The pre-Pennsylvanian unconformity surface influenced deposition along the line of this cross section section. During the Morrowan, siliciclastics sourced from the north and east were deposited and formed sandstones in the Cromwell, Union Valley and Gilcrease Formations in the Arkoma Basin. The Arkoma Basin underwent rapid subsidence in the Atokan with 17,000 to 18,000 feet of sediment being deposited in the Ouachita trough. Desmoinesian siliciclastic sediments found across the Anadarko Shelf (thickest in the most northwestern log on this cross section) and Cherokee Platform were sourced to the north (perhaps from the Canadian Shield or the Appalachians). They form a siliciclastic wedge that is capped by the Marmaton Group carbonate sequence indicated on the cross section as part of the "Oswego (limestone) Marker." This interval contains multiple clastic fluvial-deltaic sequences, including Booch, Hartshorne, Bartlesville, Red Fork, Skinner and Prue sandstones formed as each fluvial-deltaic system developed and adjusted its location laterally due to accommodation of the previous sequence. Desmoinesian "Cherokee" Group fluvial deposits thin dramatically across the Nemaha Ridge, indicating that the Nemaha was a positive area during Cherokee deposition. Moving farther to the east, the Marmaton Group carbonates above the Cherokee Group thin to the southeast until absent.

Checkerboard and DeNay Limestones – Information from Previous Outcrop Studies

An important issue for this study was the ability to correlate wireline well logs across the area. Cross-section A-A'' uses on the base of the Checkerboard Limestone marker as datum. In the area of the outcrops of Tulsa County and Okmulgee County, the "Checkerboard Lime" is exposed. Therefore, the question is, what is the equivalent to the "Checkerboard Lime" in the area of the southernmost Seminole sandstone outcrops?

To answer this question, additional information concerning the Desmoinesian-Missourian stratigraphy was retrieved from geologic published for individual counties by the Oklahoma Geological including Tanner (1956), Weaver (1954), Ries (1954), and Oakes (1963). These sources confirm that in the northern portion of Hughes County, the Seminole Formation lies above the Holdenville Shale and below the Checkerboard Limestone (Weaver, 1954). However, in the southern and western part of Hughes County, the Seminole Formation is below the DeNay Limestone as identified by Tanner (1956). In Okfuskee County, according to Ries (1954), there is little evidence of truncation due to erosion between the Seminole Formation and the Holdenville Shale. In addition, the DeNay Limestone and Checkerboard Limestone occupy approximately the same stratigraphic position. Furthermore, the lower part of the Seminole Formation is a sandy shale that rests on an erosion surface with channel fill and valleys cut into older formations. Oakes (1963) interpreted that the boundary between the stable northern shelf and the subsiding Arkoma Basin is located in Okmulgee County. Where the formation has abundant sandstone and chert, and indicates a southern source; whereas at least in the northern part of the county, the upper portion of the Seminole Formation has a different and northern source, which this study verifies.

Therefore, based on the outcrop work by Weaver (1954), Tanner (1956) and Reis (1954), the Checkerboard Limestone is considered to be stratigraphically equivalent to the DeNay Limestone.

CHAPTER VII

CONCLUSIONS

Based on the identification and analysis of features observed in Holdenville Shale and Seminole Formation outcrops (including mineral identification and point count of grains in thin section), and regional correlation of subsurface wireline logs to outcrops, several conclusions are proposed for the Seminole Formation and other Desmoinesian-Missourian beds examined in this study.

1. The Nuyaka Creek Shale at the surface reflects the same “hot shale” marker bed identified in wireline well logs in the subsurface. This confirms the proposal by Bacon (2012) that the Nuyaka Creek Shale is correlative and an easily identified stratigraphic marker in the subsurface between the Missourian “True Cleveland” (Skiatook Group) and other “Cleveland Sands” that are in the Marmaton Group (Desmoinesian).

2. The Seminole Formation contains sandstone that classifies as chert litharenite and chert sublitharenite in the southerly areas, whereas Seminole and Lost Branch samples to the north contain significant metamorphic rock fragments and classify as metamorphic sublitharenite, metatmorphic litharenite and meta-chert litharenite.

3. Based on the petrography and the relative abundance of chert and metamorphic rock fragments, multiple sediment sources are proposed for the Seminole Formation (Oakes, 1963; Campbell, 1997), proposing the Ouachita Uplift as a source of chert, whereas metamorphic rock fragment samples from Tulsa and Okmulgee counties were derived from eroding highlands in Appalachia, Transcontinental Arch, or Canadian Shield.

4. It is not possible to correlate the Checkerboard Limestone from the subsurface in central Oklahoma to the outcrop, because the Checkerboard is not recognizable using wireline logs close to the outcrop. Previous works established the DeNay Limestone as equivalent to the Checkerboard and this study corroborates that finding.

CHAPTER VIII

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VITA

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