Petrology and Weathering Environment of Sub-unconformity Limestone unit: The Kessler Limestone member of the Bloyd Formation, Morrowan (Pennsylvanian) Northwest Arkansas

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Petrology and Weathering Environment of sub-unconformity limestone unit: 
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Morrowan (Pennsylvanian) Northwest Arkansas
Petrology and Weathering Environment of sub-unconformity limestone unit: The Kessler Limestone Member of the Bloyd Formation, Morrowan (Pennsylvanian) Northwest Arkansas

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Geology

by

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This Thesis is approved for recommendation to the Graduate Council.

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ABSTRACT

In northwest Arkansas the thin, widespread Pennsylvanian Kessler Limestone of the Bloyd Formation is exposed in numerous locations. Comparison of various exposures shows the Kessler is heterogeneous in thickness and lithology. Thickening of the Kessler occurs southward into the Arkoma Basin where the interval has been commonly used as a horizon for natural gas exploration.

The Kessler Limestone is underlain by the Dye Shale Member of the Bloyd Formation and overlain by the Trace Creek Shale of the Atoka Formation. The contact between the Kessler Limestone Member and the Trace Creek is a regional unconformity in the midcontinent, marked by a manganese-enriched crust filled with various nodules and concretions.

Methods used in this study began with reviews of previous investigations of the Kessler Limestone and followed with a petrographic analysis of the interval. To further this study, the contact between the Kessler Limestone and the Trace Creek Shale was examined in three locations; I-49 Road-cut, Evansville, and Patrick. Examining this contact may better define the changes produced by Pennsylvanian weathering and the environmental conditions that resulted in the regional sub-unconformity.
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I. INTRODUCTION

The Carboniferous geology of northwest Arkansas is replete with Mississippian and Pennsylvanian exposures. Several ideas have been proposed as to how this Paleozoic lithology formed in the northwest Arkansas area. One such theory is sediment derived from the Ozark Plateau was deposited down slope during the Pennsylvanian; however, other theorists believe the plateau, while a recipient of sediment, was not the main source. This plateau is structurally higher in Missouri and trends into a gentle sloped platform into northwest Arkansas (Manger 1982). In this transition from a structurally high platform to a lower elevation, there is a change in Late Mississippian lithology to Early Pennsylvanian lithology. The transition on the southern edge of the Ozark dome in northwest Arkansas will be examined with a concentration on the Early Pennsylvanian lithology.

The Early Pennsylvanian in northwest Arkansas consists of two depositional intervals; the Morrow Group and the Atoka Formation. Within the Morrow Group there is the Hale Formation and the Bloyd Formation. The Atokan Series only has the Atoka Formation in this area. This study includes specific emphasis on the Kessler Limestone, the upper unit of the Bloyd Formation and the unconformity surface that the overlying Trace Creek Shale from the Atoka Formation rests on. The Kessler Limestone is a significant lithologic unit because it has long been a mapping horizon from mechanical well logs in the Arkoma Basin.

The Kessler Limestone is a carbonate unit that was deposited during the Pennsylvanian between 325 – 313 million years ago. It is heterogeneous in terms of its thickness and petrology. This unit was originally “named by Simonds in 1891” during an early geologic survey for exposures on Kessler Mountain, northwest Arkansas. Simonds grouped all Bloyd Pennsylvanian units together (i.e.) overlying Trace Creek Shale, Kessler Limestone, and underlying Dye shale
(Puckette 1976). Following several investigations, these units became separate members of the Bloyd Formation with the Trace Creek Shale assigned to the Atoka Formation.

Trace Creek Shale, where exposed, “appears as marine shale with a silty black to dark gray coloration. It contains thin limestone and sandstone lenses between that and the Kessler Limestone Member” (Williams 1975). Both the Kessler and Trace Creek are not uniform in thickness and are bound at an unconformable surface of regional extent (Sutherland and Henry 1978). This is depicted in Figure 1- Pennsylvanian Stratigraphy in NW Arkansas, shown by the squiggle lines which indicate that these units underwent several stages of deposition.

Previous petrographic studies completed by Williams (1975), Fouke (1976), and Puckette (1976) described the Kessler Limestone in its vertical extent; however, their studies were prior to Sutherland’s (1988) work and failed to critically describe the lithology in its horizontal extent. Therefore, a petrographic analysis to describe the surface, or the contact between the Kessler Limestone and Trace Creek Shale was performed with fifteen samples from three locations.

**Figure 1- Pennsylvanian Stratigraphy in NW Arkansas**, Schematic stratigraphic column depicting the Morrow Group and Atokan Series. The unconformity between the Atokan and Morrow Group is depicted (modified from W. Manger).
A. Purpose and Scope

The purpose of this investigation is to reconstruct the weathering environment that existed and resulted in the unconformity at the top unit of the Bloyd Formation (Early Pennsylvanian). The focus is to further define the regional unconformity by reconstructing depositional settings across the Morrow-Atokan boundary, analyze the Bloyd Formation thickness sequence compared to the Atoka Formation sequence with emphasis on the Kessler Limestone Member – Trace Creek Shale Member contact, and to perform a petrographic analysis on the unconformable surface of the Kessler Limestone in its horizontal extent from three outcrop exposures; I-49 Road-cut, Evansville, and Patrick, Arkansas

Several previous investigations described the regional unconformity that occurs in northwest Arkansas. Such investigations were carried out by Sutherland (1988), Manger (1982), and Zachry (1984). These investigations were analyzed and used to further this study.

Thickness analysis of the Kessler Limestone from the Bloyd Formation and the overlying Trace Creek Shale of the Atoka Formation was completed using standard measuring practices. Analysis was completed by comparing thickness intervals above the contact and using measurements from previous studies, as well as measurements from the field with a Jacob-Staff. With these measurements, isopach maps were completed.

The Kessler Limestone is exposed in several areas in northwest Arkansas; however, the overlying Trace Creek Shale is not as well exposed due to shale weathering into clay and creating a thick soil cover. Therefore, a look into the different lithofacies of the Kessler Limestone truncated surface was performed by a petrographic analysis. Examining lithofacies at the top of the uppermost Kessler (i.e. the contact or unconformity), for indications of the environment that caused the truncated surface and resulted in the unconformity. A petrographic
analysis of this contact defined the lithofacies in the top of the Kessler Limestone before deposition of the Trace Creek Shale and may give insights into environmental conditions.

Figure 2 - Ozark Strat Column in NW Arkansas (top), Environmental conditions schematic (bottom), depicts the purpose of this investigation by examining the petrography in an attempt to understand the weathering that occurred on the top of the Kessler Limestone (yellow circle), Morrow Group of the Pennsylvanian. Top figure depicts average thickness of the units and bottom figure has been enlarged (modified from Liner, Zachry, and Manger 2013).
B. Previous Investigations

Many geological studies of Pennsylvanian strata have been completed in northwest Arkansas; several of which were on the Bloyd Formation. Simonds and Smith (Williams 1975) are the first workers to have made interpretations about the Kessler Limestone unit. Henbest (1962) is credited for determining Kessler Limestone and Trace Creek locations and defining the specific units. Shewmake and Wetsel (1963) further mapped the outcrop areas in their studies. Williams (1975), Fouke and Puckette (1976) performed petrographic analyses on various exposures in northwest Arkansas. Corbin (1969) and Foshee (1980) used subsurface well log data to further define stratigraphic units and depositional settings in the Bloyd Formation. In addition to these studies, Manger (1982), Sutherland (1988), and Zachry (1984) completed several geologic investigations on the stratigraphy in northwest Arkansas.

The first individual began his investigation in the late 19th Century. Geologic surveyor, F.W. Simonds published The geology of Washington County: Arkansas Geological Survey Annual Report for 1888; and is credited naming the unit after Kessler Mountain; west of Fayetteville, Arkansas. He described it as the only “limestone unit above the coal bearing shale”, referring to the Kessler Limestone above the Woolsey Shale (Williams 1975). Joseph Walter Smith (1950) studied The Kessler Limestone of Northwest Arkansas, by measuring exposures and collecting samples in Washington, Madison and Boone Counties. Smith studied insoluble residues, to better define the stratigraphy within the area, but considered the Kessler, Trace Creek and Dye Shale as one depositional interval.

Henbest (1962), completed a study in 1953 on the Kessler Limestone, and later expanded his investigations of the stratigraphy in northwest Arkansas. Henbest is credited with designating type localities within the Bloyd Formation of the Trace Creek Shale, Kessler Limestone,
Woolsey Shale, and Brentwood Limestone. Daniel W. Shewmake (1963) studied the Geology of the Spirits Creek Area, and Eldon R. Wetsel (1963) wrote on Geology of the Cass Area, Watalula Quadrangle Franklin County, Arkansas. Wetsel’s main contribution was mapping the thickness and distribution of the Bloyd Formation, while Shewmake focused on structural features and general geology of the Bloyd.

In the 1970’s, the next round of investigations on the Kessler Limestone began. John G. Williams (1975) studied Sedimentary Petrology of Kessler Limestone, Washington and Crawford Counties, Arkansas. Using petrologic analysis to distinguish nine lithofacies and twenty-one sub-lithofacies. Michael Fouke (1976) used additional Kessler exposures in Washington and Crawford Counties for a petrographic study that identified seven facies classifications and nineteen sub-lithofacies categories. William Puckette (1976) analyzed the Stratigraphy and Petrology of Kessler Limestone Member of Bloyd Formation in Madison County, Arkansas, and proposed six Kessler lithofacies classifications and sixteen sub-lithofacies classifications. Each individual’s lithofacies and sub-lithofacies were similarly organized and categorized. Only identical classifications of these individuals work were used for the analysis and formed the basis of the petrographic analysis performed in this study.

Several individuals have contributed to understanding of the Bloyd Formation. In the Arkoma Basin, hundreds of wells have been drilled for natural gas south of the study area. The Kessler Limestone is often picked as an easily distinguished horizon in the subsurface from mechanical well logs. Corbin (1969) used well logs in Franklin and Johnson counties to identify and map the Kessler Limestone in the subsurface. Foshee (1980) also used wireline logs to pick horizons in an effort to better analyze the stratigraphy and define the depositional systems of the
Hale and Bloyd Formation of the Morrow Group. The research from these individuals will be used as well control in this study.

Patrick K. Sutherland (1988) is a main contributor to understanding of the Morrowan-Atokan boundary, and advancements in the understanding of the Morrow and Atoka Formations. Sutherland and Grayson (1977) defined Morrowan successions based on biostratigraphy, providing biostratigraphic evidence that the Trace Creek Shale Member is Atokan in age. Sutherland and Henry (1978) concluded a regional unconformity exists on the border of western Arkansas and eastern Oklahoma at the top of the Bloyd Formation – the base of the Trace Creek Shale Member and top of the Kessler Limestone (Zachry 1984). In later years, Sutherland’s work showed that biostratigraphy from Zone 20 to Zone 21 was absent to what would’ve been expected compared to exposures. This proved the Kessler Limestone was the top of the Morrow Group and was an unconformable surface (Sutherland and Manger 1982).

Manger (1982) discussed the problems in defining the Morrowan-Atokan unconformity with biostratigraphic considerations, concluding that Atoka type sections an unconformity based on Zone 20-21 in the subsurface. Zachry (1984) further linked depositional lithology and overall geology of the Atoka Formation between Arkansas and Oklahoma.

Previous studies completed on the petrology of northwest Arkansas, the Arkoma Basin, and surrounding areas have defined different biostratigraphic components for their analysis. Previous studies on the vertical extent of the Kessler have been completed; however, a petrographic analysis examining the lateral extent has yet to be completed. By examining the top layer of the Kessler, directly below the unconformity, details about the erosional environment were established. A petrographic analysis of several outcrops in northwest Arkansas were explored for this study.
C. Study Area

The study area is centrally located in Washington County, Arkansas; however, more data were collected from southwest Madison, north Crawford, as well as well log data from southern Crawford and Franklin Counties. These counties are located in geological provinces known as the Ozark Dome, Boston Mountain Plateau, and the Arkoma Basin. Mechanical well log information from the Arkoma Basin (Crawford and Franklin County) was tied back to surface exposures along a structural platform on the southwest edge of the Ozark Dome. Petrographic analysis involved samples were taken from I-49 Road-cut, Evansville, and Patrick. Evansville is located in south-west Washington County, I-49 Road-cut is located in the south-central region of Washington County, and Patrick is located to the south-east in Madison County (Figure 3).

The investigation is on the Morrowan-Atokan unconformity. The study area is of regional extent exposure in northwest Arkansas. Subsurface information obtained from mechanical well logs will also be utilized for thickness analysis. Outcrop exposure locations within the Ozark Dome region are on a structural platform on the southwest edge of the Ozark Plateau and mechanical well logs were obtained down slope in the Arkoma Basin. Mechanical well logs are located in southern Crawford, Franklin, Johnson, Logan, and Sebastian counties.

The area was selected based on the availability of data. Analysis of outcrop exposures took place in Washington, Madison, and northern Crawford Counties. The data locations from these counties came from Williams (1975), Fouke (1976), and Puckette’s (1976) research. Subsurface data within the Arkoma Basin was mostly used from Crawford and Franklin Counties; with few wells used from Johnson and Logan Counties. The subsurface data came from Corbin (1979), Foshee (1980) and Studebaker (2014).
The study area is summarized in Figure 3 – Arkansas Counties (top); NWA County Study Area (bottom). The top picture depicts the different counties and the state of Arkansas outlined in red. The black sinuous lines represent highways of Arkansas and the blue areas depict bodies of water. The thick double black lines in rectangular shape outline the area in the bottom figure. The bottom figure is the double black lines from the top figure and represents the area within the Ozark Plateau and show the study area of investigation. The yellow circles are locations of samples taken for petrographic study or areas visited for thickness analysis. This bottom figure is the enlarged area surveyed from Washington and Madison Counties. The only yellow point in Madison County is located near Patrick Arkansas. From Washington County, the most north yellow point is from Kessler Mountain, the point to the east is from I-49 Road-cut, the point from the south is from Devil’s Den, and the point to the west is from Evansville.
Figure 3- Arkansas Counties (top); NWA County Study Area (bottom). Yellow circles represent thickness measurements or petrology samples for the study in Washington and Madison County.
II. GEOLOGIC SETTING

Arkansas geology is divided into a Mesozoic-Cenozoic Region on the southeastern to northeastern part of the state and a Paleozoic Region on the northwestern side of the state. These regions could be easily visualized by stating the yellow-orange-tan is the Mesozoic-Cenozoic Region and the multiple color spectrum is the Paleozoic Region (Figure 4). The state is further subdivided into several different geologic provinces based on the areas characteristics. The geologic provinces located in the Mesozoic-Cenozoic Region are called the Mississippi Embayment and the Gulf Coastal Plain. The geologic provinces within the Paleozoic Region are the Ozark Dome, Arkoma Basin, and Ouachita Mountains. The study area of concern falls within the Paleozoic Region of northwest Arkansas. The geologic provinces of the Paleozoic Region will briefly be explained for the purposes of fully understanding the depositional setting of the Morrow Group and Atokan Series.

The main area of analysis is within the Ozark Dome and encompasses part of the Boston Mountain Plateau. Northwest trending faults extend through this region and lower the overlain Pennsylvanian beds from the Mississippian lithology (Figure 4). Further south of the Ozark Dome transitions into a structural platform that drops down into the Arkoma Basin. This basin has been exploited for natural gas and has thousands of wells that penetrate the subsurface. The Ouachita Mountains and Ozark Dome bound the Arkoma Basin (a.k.a. Arkansas Valley) on the southern-northern side and were formed during the Pennsylvanian by compressional tectonic events (Figure 5). This late Pennsylvanian compressional event is responsible for the uplift and creation of the Ozark Dome.
Figure 4- Geologic Map of Arkansas. The black box depicts NW trending faults located within the Paleozoic Region of northwest Arkansas on the edge of the Boston Mountain Plateau. Geologic Map of Arkansas also shows the difference between the Mesozoic-Cenozoic Region and the Paleozoic Region in the color contrast. (www.geology.ar.gov/)
A. Paleozoic Region
The Ozark Dome may also be referred to as the Ozark Mountains or the Ozark Plateau in studies of northwest Arkansas; however, it will solely be referred to as the Ozark Dome for the purposes of this study. This area is an uplifted region consisting mainly of Paleozoic rocks. The Ozark Dome was formed during the Late Pennsylvanian as an orogenic event caused by plate tectonics that simultaneously developed the Ouachita Mountains. During the Late Pennsylvanian, there was significant cratonic uplift by pressure being exerted on the Precambrian rock within the subsurface. The uplift forced Precambrian rocks to the surface and today outcrop in the St. Francois Mountains in Missouri. Several other topographically high surfaces developed in the uplift during the Pennsylvanian; the Salem Plateau, Springfield Plateau, and the Boston Mountains Plateau (Figure 5). These plateaus are grouped together with the Ozark Dome but are considered sub-plateaus.

The Salem Plateau is the largest of the sub-plateaus centered in the heart of the Ozark Dome in Missouri and trends to the south into Northern Arkansas, and Eastern Oklahoma. The plateau’s elevation is around 1,500 feet above sea level and occurs as an abrupt change in elevation seen in areas such as Eureka Springs, Arkansas. The Springfield Plateau, runs through Northwest Arkansas, Northeast Oklahoma, and northeast to southwest through Missouri. It wraps around the Salem Plateau in its northern, western, and southern borders; passing through Fayetteville, Arkansas. This plateau is around 1,800 feet in elevation. The Boston Mountains Plateau is the smallest of the three plateaus but has an elevation ranges up to 2,600 feet. The stratigraphy in this area ranges from Upper Mississippian to Late Pennsylvanian rocks with four “unconformity-bounded, transgressive-regressive cycles: Chesterian, Lower Morrowan, Upper Morrowan, and Atokan” (Manger 2009). The Upper Morrowan and Atokan are the depositional series that are the focus of this study.
Figure 5- Ozark Uplift and Plateaus of the Ozark Dome, depicts the geological provinces in Arkansas. The stripped section represents the Ozark Uplift, also referred to the Ozark Dome. The three plateaus within the Ozark Dome (blue) are the Salem Plateau (red), Springfield Plateau (green) and Boston Mountain Plateau (orange). The Arkansas River Valley (Arkoma Basin) and the Ouachita Mountains are the other geologic provinces of the Paleozoic Region in Arkansas (Suneson 1995).
The Upper Morrowan and Atokan Series are exposed in east to west trending belts on the northern Arkansas structural platform (shown in sky-blue in Figure 4). This structural platform lies within the region of the Boston Mountain Plateau. Trending from east to west the structural platform is around 40 miles in width and has numerous exposures of Pennsylvanian rocks. This platform represents the southern edge of the Ozark Dome and is north of the Arkoma Basin at a very gentle slope. Studies by Chinn and Konig (1973) describe this gentle sloped surface at 0°19’ but changes to 3°12’ upon approaching the Arkoma Basin at Gaylor Mountain- northwest corner of Crawford County (Figure 6- Pennsylvanian Structure and Stratigraphy in NW Arkansas).

Figure 6- Pennsylvanian Structure and Stratigraphy in NW Arkansas, shows schematic of transitions from the Ozark Dome, structural platform, Arkoma Basin, and the later Ouachitas. Figure is exaggerated vertically & horizontally (modified version from Chinn and Konig 1973).
III. STRATIGRAPHY

Carboniferous strata crop out in the Boston Mountains, the Arkoma Basin and in the Ouachita fold belt in Arkansas (Figure 5). The Carboniferous interval thickens from approximately 300 meters in northwest Arkansas where it is truncated by the modern erosion surface and thickens to over 8,000 meters in the Arkoma basin adjacent to the Ouachita Mountains. Strata assigned to the Morrowan Series (Morrow Group) in northwestern Arkansas include the Hale Formation at the base and the Bloyd Formation at the top in the Boston Mountains. Atoka Formation strata are assigned to the Atokan Series.

In northwest Arkansas the stratigraphy of the Carboniferous Systems has variations between the Ozark Dome Region, the Arkoma Basin Region, and the Ouachita Mountain Region. During deposition of the Pennsylvanian System, areas of the Ozark Dome Region became replete with Morrow Group and Atokan Series. Stratigraphy from mechanical well logs shows the Arkoma Basin is filled with Morrow-Atokan strata and shows thickening in the basin when compared to outcrop data. The Morrowan and Atoka Series are separated in terms of sequence by a regional unconformity that truncated the top surface of the Morrow Group; Deposition Sequence of the Morrow Group and Atokan Series is schematically shown (Figure 7). This figure goes from the Early Morrowan, Late Morrowan, Earliest Atokan, and Middle Atokan; while showing a conceptualized depositional environment of each unit. One thing to note about these diagrams is the variations in nomenclature between Oklahoma geologic investigations and Arkansas geologic investigations. For example, in the Late Morrowan the Kessler Limestone is seen throughout northwest Arkansas; however, this limestone unit is noted as the Wapanucka Limestone in Oklahoma. The Trace Creek Shale may also be referred to as the Spiro by Oklahoma scholars.
Figure 7 - Depositional Sequence of the Morrowan and Atokan (Sutherland 1988).
Deposition schematic for Early Morrowan, Late Morrowan, Earliest Atokan, and Middle Atokan.
A. Morrow Group

The Hale and Bloyd Formations were deposited during the Early Pennsylvanian. These formations consist of various sandstone, limestone and shale units. These strata also display a general thickening southward toward the Arkoma Basin; however, there is a decrease in sandstone and limestone rock and an increase in shale content (McFarland 2004). Stratigraphic Summary of Ozarks and Ouachitas shows Jackfork and Johns Valley Formations (Figure 8). Within the sedimentary section, the Morrowan Series consists of the Bloyd and Hale Formations which are part of the Morrow Group. The Bloyd Formation is distributed in northern Arkansas, the Ozark Plateau Region, and eastern Oklahoma. The Hale Formation is also deposited in these locations and can be seen in areas around southern Missouri to northeastern Oklahoma as well (McFarland 2004). Both of these formations are considered significant reservoirs for natural gas in the Arkoma Basin.

![Stratigraphic Summary of Ozarks and Ouachitas](image)

**Figure 8- Stratigraphic Summary of Ozarks and Ouachitas.** The stratigraphic column above shows the different formation names between the Ozarks and the Ouachitas (McFarland 2004).
Hale Formation

The Hale Formation is the lowest unit in the Pennsylvanian System in Arkansas. Its base is the contact that separates the Pennsylvanian System from the Mississippian System. The base of the Hale or contact of the Mississippian Limestone is the contact forming the Pennsylvanian Mississippian boundary in northwest Arkansas. Henbest (1962) named the Hale Formation for exposures on Hale Mountain in Washington County, Arkansas. The Hale Formation consists of the Cane Hill Member and the Prairie Grove Member (Figure 8).

The Cane Hill Member is composed primarily of sandstone and shale and is overlain by a regional unconformity at the top of the Mississippian Pitkin Formation. This unconformity is the Mississippian-Pennsylvanian boundary in northwest Arkansas. The Cane Hill was described by Manger (1971) and Liner (1979) as a complicated “series of interbedded or interfingering sandstone, siltstone, and shale lithologies in surface sections” (Foshee 1980). The Cane Hill depositional setting is a tidal current-dominated environment. This deposition occurred on a shallow water-platform after a period of regression during the Mississippian followed by a period of transgression in the Early Pennsylvanian.

The Prairie Grove Member varies in its thickness from the Ozark Dome into the Arkoma Basin. The units surface exposures in Washington County has three main components; sandy bryozoans-echinoderm biosparite, very sandy biosparite, and calcareous sandstone (Manger 1971). From the type area, the Prairie Grove Member is about 70 feet thick but may be as much as 300 feet in the subsurface (Foshee 1980).
-Bloyd Formation

The Brentwood Limestone is the lowest unit of the Bloyd Formation and conformably overlies the Prairie Grove Member of the Hale Formation (Foshee 1978). The Brentwood Limestone is recognized on mechanical well logs by its occurrence between two thick shale units (i.e. the Woolsey and Dye Shale). Furthermore, the signature this mechanical well log makes in this interval would show gamma ray content higher on the right side, representing the Woolsey Shale, and then kick left representing the Brentwood Limestone; this would then be followed by another kick to the right upon measuring the Dye Shale (Figure 9). The Brentwood shows various lithologic changes within the Arkoma Basin. Stratigraphic investigations suggest that the depositional environment of the Brentwood Limestone Member was a warm shallow sea ideal for carbonate production. There are several lenses of shale within the sequence which is indicative of a low-moderate shallow marine energy environment (McFarland 2004).

The Woolsey Shale and Middle Bloyd Sandstone range from 10 to 45 feet in thickness (McFarland 2004). These members are mixed siltstone-shale units that are heterogeneous in its lithologic succession. Siltstone tends to form the thinnest successions whereas shale is typically abundant in the thicker successions. The siltstone units within these members are abundant with “terrestrial plant remains” (Sutherland and Henry, 1977). Above the Woolsey, there is a cap rock at the base of the Dye Shale. It is a thin calcareous sandy limestone and sandstone interval. The cap rock represents marine sediment from the underlying Woolsey Member (McFarland 2004). The thin cap rock ranges from one to four feet in thickness. The Dye Shale, named by Henbest (1962) from the Bloyd Mountain type section, consists of fissile shale with various concretions in the unit. The depositional environment of the Dye Shale Member was shallow marine with low energy.
Figure 9- Type Log of the Lower Morrowan and Atokan- Kessler is shown above but was grouped with the Dye Shale but are distinguished by the shift in gamma ray from the right (Kessler Limestone) to the left (Dye Shale) (Studebaker 2014).
The Kessler Limestone marks the youngest, or the last deposited unit of the Bloyd Formation. The Kessler Limestone is also bounded above by a regional unconformity and is the top unit of the Morrow Group. This stratigraphic unit sits conformably on the underlying Dye Shale Member and is unconformably overlain by the Atoka Formation. Petrographic investigations from previous University of Arkansas studies have shown the Kessler Limestone to be highly heterogeneous in its lithic character and facies content. The top surface of the Kessler is a marine interval that is abundant in fossils with various occurrences of quartz sand and lithoclastic cobbles (Figure 10). Williams (1975) and Fouke (1976) described the Kessler as primarily composed of biosparite from fine calcarenite to medium calcirudite in grain size with localities abundant in micrite and quartz sand. The depositional environmental setting of the Kessler Limestone was a shallow marine shelf with sub-tidal wave energy. This shallow, stable environment makes for an excellent identifiable horizon for well log interpretation and mapping in the Arkoma Basin.

Figure 10- Top Lithoclasts cobbles of the Kessler Limestone (I-49 Road-Cut), note cobbles or lithoclasts embedded in the top of the Kessler Limestone. Hammer used for scale. (Photo Credit-T.D. Dolan)
B. Atoka Formation

The Atoka Formation is a thick sequence that was deposited during the Middle Pennsylvanian. In Arkansas the series includes the Atoka Formation and can be in the Boston Mountains of Arkansas – Ozark Dome, the Arkansas River Valley – Arkoma Basin, and the Ouachita Mountain Region. The Atoka Formation, named by Taff and Adams (1900), correlated the unit to outcrops near the town of Atoka, Oklahoma next to the western thrust belt portion of the Ouachita Mountains. In northwest Arkansas, the formation consists of one lithological member; the Trace Creek Shale.

The Trace Creek Shale Member was named by Henbest (1962) for the type section that he defined on Bloyd Mountain in Washington County just south of Fayetteville, Arkansas. This unit was originally assigned to the Bloyd Formation but was reassigned to the Atoka Formation after the investigation by Sutherland and Henry (1977). The depositional environment of the Trace Creek is a fairly broad, massive fluvial-deltaic sequence. Due to the ease of weathering of shale, Trace Creek is often non-exposed and covered by soil. Furthermore, this member also varies in thickness but averages around 80-120 feet in Washington and Madison County. This shale unit is distinguished as gray-black fissile shale with lenses of sandstone and siltstone embedded within the shale. There are occasional mixed sandstone-siltstone intervals that occur within this formation.
IV. METHODS

The methodology used in this study involved qualitative and quantitative analysis. Qualitative analysis was used in describing and characterizing the top of the Bloyd Formation and the bottom of the Atoka Formation. Detailed descriptions were used in classifying thin sections made from selected outcrop locations. Quantitative analysis was used in interpretation of modeling thickness measurements on a regional scale and also used in lithologically defining constituents into a percentage.

From previous studies, Williams (1975), Fouke (1976), and Puckette (1976) provided thickness measurements of the Kessler Limestone as well as limited exposures of the Trace Creek Shale. These measurements were used in partial fulfillment of this study. For further thickness analysis, measured successions were recorded from mechanical well logs drilled for natural gas production. This subsurface data was interpreted and analyzed by Corbin (1979), Foshee (1980), and Studebaker (2014). This previous research into the Bloyd Formation and Atoka Formation was the starting point of this study.

Previous petrographic studies were utilized from investigations completed by Williams (1975), Fouke (1976), and Puckette (1976). However, their analyses into the petrology of the Kessler Limestone failed to emphasize the contact between the Morrow-Atokan Boundary on a regional scale. Therefore, measurement thickness was taken from outcrop exposures around northwest Arkansas at this unconformity zone. Three additional areas were selected for petrographic analysis; I-49 Road-cut, Evansville, and Patrick. Outcrop descriptions from each location were recorded while taking samples.
A. Sampling

Two forms of sampling were utilized in this study; samples for thickness analysis and samples for petrographic analysis. Thickness samples from previous studies were analyzed and combined for a regional picture. Outcrops were analyzed separately and combined with subsurface thickness measurements from mechanical well logs. In total, sixty outcrop exposure measurements and one hundred and forty-nine subsurface measurements were used. Petrographic analyses of samples were from sixty outcrop exposures because core-data samples from the subsurface do not exist.

Twenty thickness measurements were used from Williams’s study (1975) and became measurements #1-20 for this investigation. Fifteen thickness intervals from Puckette’s study (1976) were used for this study. Puckette assigned abbreviations to his samples based on location using a numerical value to describe the thickness for each interval (e.g. PA-3.5). For simplicity, those samples were changed from their abbreviations to be consistent numerical values for this study; #21-36. Twenty thickness measurements were used from Fouke’s study but were reassigned numerical values from his samples #1-20, to this investigation samples #37-57. Thickness intervals from three additional exposure locations were recorded for analysis in this study #58-60. Sample #58 was taken from Patrick, Arkansas in Madison County where thickness and petrographic samples were collected. Sample #59 surveyed the I-49 Road-cut near West Fork, Arkansas in Washington County. Thickness and petrographic samples were collected from this location. Thickness sample #60 was taken from Devils Den State Park but a petrographic sample could not be used. Locations of samples #1-60 are shown in Figure 11-Exposed Sample Locations.
A total of sixty samples and their locations are plotted with the legend in the top left hand corner depicting all individual’s samples (Figure 11). Williams’s samples are identified with the red marker and have a general trend north to south. Puckette’s samples are clustered toward the east and are shown by the yellow marker (Figure 11). Samples clustered toward the southwest with a white marker are Fouke’s. The other samples on the map are identified by a purple pin (enlarged for emphasis) and display sites studied. Kessler Mountain, is a type section of the Bloyd Formation and is highlighted by a purple pin farthest north. These samples show locations of measured Kessler thickness values (samples #1-20 and #58-60 displayed in Figure 15). The black arrows and one red arrow represent a cross section plot (shown in Figure 16). In All samples marked on the map there is a completed petrographic analysis (except for sample #59-Devils Den and Kessler Mountain).

I-49 Road-cut south of Fayetteville in Washington was obtained from an outcrop directly off of the highway. This location can be reached by traveling south down I-49 from Fayetteville, Arkansas; pass exit 60 for West Fork and Hwy AR-170. Continue down Highway I-49 and within a quarter mile the outcrop is directly on the right after a bridge.

Samples from Evansville Mountain were selected for its thickness and accessibility. This location can be accessed by driving south on Highway 59 and pass the town of Evansville located near western border in Arkansas. Samples were retrieved from an outcrop just off of Highway 59 in the southwest corner of Washington County.

Samples from Patrick were selected because the interval of the Kessler Limestone is one of the thickest exposed successions in northwest Arkansas. Patrick is located in Madison County and is on Highway 16 before Combs and Highway 23.
Five samples from the top of the Kessler Limestone were obtained from these locations. Detailed analysis of these samples will be discussed in petrology analysis section. From previous investigations, two samples were used from Williams #7 (North) and #15 (South), one from Puckette #21 (East), and one from Fouke #37 (West). These four petrology locations can be shown in the legend on the bottom right hand corner (Figure 11). Samples are marked by symbols, such as diamond shapes for Williams’s (1975) samples and triangle shapes for Fouke’s (1976) and Puckette’s (1976) samples.

**Figure 11- Exposed Sample Locations.** The sample locations are shown above. The legend in the top left corner marked ‘Sample Names’ shows the symbols correlated to the individual regarding their thickness intervals. The legend in the bottom right hand corner shows the legend of the petrology analysis area. The black arrows and one red arrow depict a cross section shown in Figure 16.
Mechanical well logs in the subsurface and exposed samples in the surface are displayed below on an elevation base-map (Figure 12). Approximately all the samples below 35.7°N are from mechanical well logs and all samples above are from exposures. An example of a Type Log of the Lower Morrowan and Atokan is displayed in Figure 9 (Studebaker 2014).

Figure 12- Sample Locations from well logs and outcrop locations. Roughly points above 35.7°N are from exposures (figure 11) and points below 35.7°N are from the subsurface. Base-map (grey) is elevation, blue depicts bodies of water, and thick black lines are county outlines.
B. Procedures

The procedures used to complete this study involved thickness and petrographic analysis using various software and human interpretation. Software used for thickness analysis involved GMT and Python editor Canopy. For petrographic analysis, the main software used was JMicroVision. Python’s Canopy editor was also used with data visualization for petrology plots. These results are displayed under IV. Data, and interpreted under V. Interpretations.

Previous work on the Kessler Limestone from the Bloyd Formation was first reviewed. A collection of thickness and petrographic data from Williams (1975), Puckette (1976), and Fouke (1976) was assembled for interpretation. To determine accuracy of their locations, 7.5-minute quadrangle topographic maps from the USGS were used as overlays on GoogleEarth. After confirming locations, the next action involved compiling thickness data into GoogleEarth to collect latitude, longitude and elevation. This data was then saved into an Excel document for input into various programs for analysis on the stratigraphic thickness of the Kessler Limestone and Trace Creek Shale.

Samples were chosen based on characteristics (i.e. location, thickness, etc.). Locality #59, I-49 Road-cut, was chosen for sampling because it is a complete exposure and clearly shows manganese-rich weathered surface at the unconformity. Samples from this location were obtained from the top of Kessler Limestone Member. All samples obtained were chosen from various lithofacies locations horizontally across the top of the Kessler. Similar procedures for sampling followed with Evansville and Patrick samples.

These samples were then prepared for analysis under a microscope. After prepping the samples, the investigation focused on using observational techniques for compositional and textural assessment.
After collecting five samples from three unconformity locations; I-49 Road-cut, Evansville, and Patrick, thin sections were prepared. The first step involved using a Hillquist RF 20-24 Slab Saw. This procedure involved clamping the sample to the track and placing it close enough for excess rock to be cut away. Once excess was cut, a smooth surface of the specimen existed. Next the track-way was moved to a fingers width to cut a smooth slab approximately half an inch in width.

After completion of the smooth slab, the second step involved use of the Hillquist SF-8 Trim Saw. The area of interest in each slab was highlighted by placing a glass slide and tracing around that slide with a permanent marker. After area of interest was highlighted, trimming the excess of the sample began. It’s necessary to cut inside the permanent marker outline because the sample must be smaller than the glass slide in which it will be applied. After excess was trimmed, a smooth rectangular billet was achieved. After the billets were prepared they were sent to Burnham Petrographics to complete these samples into thin sections.

Upon receipt of the thin sections from Burnham Petrographics, analysis and classifications of the sampled specimens were made. Previous petrographic studies of the Kessler used the Folk Classification (1962) to characterize the specimens. Therefore, the Folk Classification was used for consistency of comparison to the previous petrographic investigations. Sublithofacies categories were made to compare previous petrographic studies to this current analysis.

JMicroVision software was used for quantitative analysis with the thin sections. JMicrovision was created for the purpose of classifying images but was made with intentions of quantifying components or constituents in images such as thin sections. In order to complete this petrographic study, different categories needed to be established. To do this, previous
petrographic studies needed to be integrated. Williams (1975) study didn’t recognize any ‘Skeletal Grains’ so several sublithofacies categories were combined. To simplify the categories, brachiopods-bryozoans were combined into one category from both Williams’s (1975) and Fouke’s (1976) study.

After obtaining all data, such as thickness measurements (Figure 13 and Figure 14), software was used to interpret the data. GMT stands for ‘Generic Mapping Tool’ and is open-source software used to process xyz data sets (i.e. - for this study; latitude, longitude, and thickness). GMT was used in this investigation to show specific areas where data points were selected and thickness values in those locations. With Python’s Canopy editor, several visualizations were produced using the data imported from an Excel spread-sheet.
Figure 13- **Kessler at I-49 Road-cut** – Trace Creek not exposed at this location. This area was used for thickness measurement and petrographic analysis (sample #59 in the study).

(Photo Credit-T.D. Dolan)
Figure 14- Kessler at Devils Den State Park - Thickness measurement of the base of the Kessler Limestone at Devils Den State Park on the Fossil Flats Trail using a Jacob staff.

(Photo Credit - T.D. Dolan)
V. DATA
   A. Thickness Analysis

   Williams (1975) recorded Trace Creek Shale and Kessler Limestone thickness in his study with a data table format and made into a plot (Figure 15). Selected thickness points were used extending from sample #7 in the north, to #6, to #14, to #59, and to sample #15 in the south. Sample #59 and Sample #4 (locations shown in Figure 11 for reference) were compared to each other (Figure 16). Besides for sample #59, these stratigraphic thicknesses were obtained from Williams's study (1975). This data was compared to determine a correlation between their thickness intervals and relation to the unconformity. The points enclosed by diamond shapes were sample #7 in the north and sample #15 in the south. Sample #59 (I-49 Road-cut) is depicted by a double rectangular shape and sample #4 by a triangular shape. Sample #7 and sample #6 are beneath a foot of Kessler thickness and shows the Trace Creek absent. Sample #15 shows the thickness in feet and the overlying Trace Creek at 139 feet thick. I-49 Road-cut, sample #59 has the Kessler at just over 12 feet thick. Comparing Sample #59 to sample #4 (Figure 16), examined differences in the cross section by placing sample #59 and then sample #4 between sample #7 to sample #15 (shown in the black and red lines on Figure 11).

   Thickness analysis was completed using GMT to model Kessler Thickness from the outcrop exposures (Figure 17). The basemap python package feature was used to analyze outcrop exposure thickness compared to Kessler thickness from mechanical well logs in the subsurface (Figure 18).
Figure 15-Trace Creek and Kessler Thickness Comparison shows Williams (1975) sample points (i.e. 1 - 20) and sample points obtained for this study (i.e. 58, 59, and 60). Four points were selected for a thickness profile view (Figure 16) sample 7 in the north, sample 15 in the south, and sample 59 to 4. Samples correlate to first 20 points and last 3 points from Figure 11.
Figure 16- Comparing Sample #59 to Sample #4 - Comparing trends of thickness for (I-49 Road-Cut) sample #59, on bottom graph to (Williams’s sample) sample #4 on the top. Note the absence of Trace Creek on the bottom and the 80 foot interval on the top. Trace creek is absent in the middle of I-49 (likely due to road-cut) and is not exposed at this measurement.
Figure 17- GMT Kessler Thickness. GMT (Generic Mapping Tool) can quickly contour data by properly importing an Excel file with the measured data. This figure imported xyz data such as latitude, longitude, and thickness. This Excel file only contained data from Kessler Limestone exposures. Dark brown represents areas of 0 to 5 feet. Dark blue represents exposure areas of maximum thickness 45 to 50 feet.
Figure 18- Python Kessler Thickness attached to subsurface wells. An Excel file imported to Python Canopy editor contained exposures and subsurface data. Excel files can be quickly imported into python for quick data analysis. Dark blue colors represent areas where the Kessler Limestone is thinnest and the light-tan color is the thickest interval.
B. Petrology Analysis

To aid in finding the diagenetic effects of sub aerial weathering on the upper surface of the Kessler Limestone, samples were collected near the top of the Kessler at Patrick in Madison County, at the I-49 Road-cut and Highway 59 Road-cut in Washington County near Evansville. Five thin sections were prepared from samples taken from each locality. Petrographic data were also used from previous theses by Williams (1975), Fouke (1976) and Puckette (1976). These workers emphasized depositional lithofacies.

Williams (1975) defined nine different lithofacies: 1) biosparite, 2) biomicrosparite, 3) oncolite, 4) oolite, 5) algal-foraminiferal micrite, 6) red algal biosparite, 7) spiculite, 8) shale and 9) siltstone-sandstone. He also included several subfacies in his study; Williams established the amount of spar, microspar, Fe dolomite, crinoids, brachiopods, gastropods, bryozoans, intraclasts, algal micrite, oncoliths, ooliths, bivalves, foraminifera, coated grains, trilobites, phyllloid algae, red algae, quartz, hematite, opaque matrix, and a category marked unidentified.

Fouke (1976) defined seven lithofacies: 1) intraclast, 2) oncolith, 3) oolith, 4) red algae, 5) bioclast, 6) sandstone-siltstone and 7) shale facies. Fouke had several subfacies included in his study; for each sample he analyzed for sparry calcite, matrix material, Fe dolomite, hematite, crinoids, brachiopods, gastropods, bryozoans, intraclasts, quartz, oncoliths, ooliths, bivalves, foraminifers, coated grains, anthropods, ammonoids, red algae, and skeletal grains.

Puckette (1976) defined six lithofacies: 1) skeletal biosparite, 2) red algal biosparite, 3) oncolith-intraclast, 4) biomicrite, 5) sandstone and 6) shale facies. Puckette first measured the percentage of ‘cement-matrix’ and ‘constituents’. Next, he defined several subfacies of the amount of cement, matrix, Fe dolomite, brachiopods-bryozoans, gastropods, echinoderms, skeletal grains, oncoliths, intraclasts, ooliths, coated grains, red algae, and quartz grains.
Four lithofacies were established for this study. These four categories consist of 1) skeletal biosparite, 2) oncolith-oolith, 3) biomicrite, and 4) sandstone-siltstone-intraclast or lithoclast. Sublithofacies were established using cement-matrix compared to constituents by percentage. This was accomplished with modal analysis or point-counting and converting to a total percentage amount. Cement to matrix was defined and constituents were counted. Sublithofacies categories consisted of 1) quartz sand, 2) oncoliths, 3) brachiopods-bryozoans, 4) coated-grains, 5) gastropods, 6) ooliths, 7) intraclasts, 8) red algae, and 9) skeletal grains.

Previous Petrographic Analysis samples from Williams’s samples (1975), Fouke’s samples (1976), and Puckette’s samples (1976) were pictured and described from the top of the Kessler Limestone and used for reference in this study. These samples are illustrated and described by those individuals in the following pages. After descriptions were made from previous petrographic analysis from the top of the Kessler Limestone, qualitative analysis on I-49 Road-cut, Evansville, and Patrick was completed.

Oncolith and Quartz percentage from four different locations were compared for analysis. These samples from the Kessler Limestone population were viewed in a percentage per location. At each location there were ten samples (n=10) taken vertically from the lithologic exposure. Therefore, sample #7(North), #15(South), #21(West), and #38 (East) were analyzed to describe distribution of these constituents for this regional exposure study. Petrology Analysis of Oncoliths and Quartz (Figure 19), depicts those samples and the percentage that each specimen contains. The body of the boxplot represents quartile percentage of these samples. The horizontal red line depicts the median. Vertical lines are referred to as whiskers and represent n-outlier data points for the outer quartiles with horizontal cap lines on the end. Plus signs represent outliers beyond the n-outlier data points.
Figure 19- Petrographic Analysis of Oncoliths and Quartz. Boxplots made in python show percentage of oncoliths and quartz. The top figure shows sample with the highest oncolith percentage is sample #38 found in the west. On the bottom the sample with the highest quartz percentage is sample #15 found in the south. The body of the boxplot represents quartile percentage of these samples. The horizontal red line depicts the median. Vertical lines are referred to as whiskers and represent n-outlier data points for the outer quartiles with horizontal cap lines on the end. Plus signs represent outliers beyond the n-outlier data points.
PREVIOUS PETROGRAPHIC ANALYSIS

Williams’s Samples

– **Sample 04-06: Figure 1**: Fine calcirudite: sandy unsorted oolitic biosparite with eight per cent ferroan dolomite cement. Note the fine sand filling the gastropod. Indicated filling of the snail in one environment followed by transport to a more turbulent environment, sample 04-06, plane-polarized light, x 2.5.

- **Sample 06-03: Figure 3**: Biosparite facies: Fine calcarenite: poorly washed biosparite with 50 per cent blocky calcite cement, sample 06-03, plane-polarized light, x 2.5

- **Sample 09-02: Figure 2**: Siltstone-sandstone facies. Very fine sand: calcareous immature quartzarenite with 59 per cent quarts sand, sample 09-02, plane-polarized light x 2.5.
Sample 17-05 (x3)

~Sample 17-05: Figure 1: Oncolite facies: Medium calcirudite: packed oncolitic biomicrosparite. Note foraminiferal micrite ball in lower left without a nucleus. A much larger oncolith is in the upper right. Associated with rounded skeletal debris, sample 17-05, plane-polarized light, x 2.5.

~Sample 17-05: Figure 2: Oncolite facies: Medium calcirudite: packed oncolitic biomicrosparite. Note large oncolith with a crinozoan fragment as a nucleus and encrusting foraminifers, blue-green algae, and micrite composing the coating, sample 17-05, plane-polarized light, x 2.5.

~Sample 17-05: Figure 3: Oncolite facies: Medium calcirudite: packed oncolitic biomicrosparite. Note the two oncoliths serving as a double nuclei for a larger oncolith, sample 17-05, plane-polarized light, x 2.5.
**Sample 11-11: Figure 4:*** Oncolite facies: Medium calcirudite: packed oncolitic intramicrosparite. Viewing a bored oncolith coating which is dominantly encrusting foraminifers and micrite. Bore is filled with microspar and quartz sand, sample 11-11, plane-polarized light, x 2.5.

**Fouke’s Sample**

**Sample 17.6: Figure 4:** Microspar-micrite bioclast subfacies. Fine calcirudite: sparse, crinozoan bryozoan biomicrite. Note fossil fragments in matrix. Sample 17.6. Plane-polarized light x 2.5.

**Puckette’s Sample**

**PA-3.5: Figure 1:** Skeletal biosparite facies; coarse calcarenite, bryozoan (B), echinoderm (E), unsorted biosparite. Slide PA-3.5, x 2.5, and plane-polarized light.
**I-49 Road-Cut**

01- Intrasparrite- Intraclasts or lithoclasts, sparry cement in grey-white, immature very fine-medium angular quartz with some skeletal fragments and sandy lithoclasts throughout specimen noted in brown in the top left region. Red-globs present in carbonate cement. Seen at higher magnification, clay matrix with minerals such as hematite and ankerite. Plane-polarized light, x 2.5.

02- Oosparite- Skeltal Biosparite. Oolites in sparry calcite cement and skeletal grains such as bryozoans, brachiopods, and red algae are present in this specimen. Elongated crystals with possible dolomite. Skeletal fragments with ankerite, possible dissolution with places of sheer ankerite seen at plane-polarized light x 10. Plane-polarized light, x 2.5.

03- Biosparite- Brachiopods in sparry calcite cement and other skeletal grains some coated grains. Very little to no quartz is present. Plane-Polarized light, x 2.5.
04- Oosparite- Oncolists pelsparite with very fine sand coated in some grains, sparry calcite cement abundant and micrite mud in the upper right hand corner. Sample is abundant with skeletal grains and has very little to no quartz present. Plane-Polarized light, x 2.5.

05- Biomicrite- Siltstone-sandstone facies – very fine sand with calcareous quartzarenite Abundance of quartz ranging from immature to submature, fine to coarse and micrite matrix present. Sample is poorly sorted with skeletal grains present. Plane-Polarized light, x 2.5.

Evansville

06- Intrasparite- Specimen has echinoderms, intraclast present, skeletal biosparite, possibly traverse byozoan; coarse calcarenite with coated grains. Plane-polarized light, x 2.5.
007- Intrasparite- Skeletal biosparite, echinoderm, limited coarse calcarenite, skeletal fragments, limited micrite mud, high compaction. Limited amount of sub-mature quartz. Plane-polarized light, x 2.5.

08- Pelsparite - Biosparite, echinoderms, bryozoans, skeletal grains, coarse calcarenite, highly compacted with subangular quartz grains present. Plane-Polarized light, x 2.5.

09- Biomicrite- Skeletal fragments and grains well to fairly sorted fine calcarenite, bryozoans, brachiopod, matrix is filled with micrite mud. Small mature quartz is present. Plane-polarized light, x 2.5.
10- Pelsparite - skeletal biosparite, echinoderms, with brachiopod or bivalve in filled with mature quartz, coarse calcarenite highly compacted. Plane-polarized light, x 2.5.

Patrick

11- Pelmicrite - skeletal biomicrite, echinoderms, bryozoans, skeletal grains with high compaction and little micrite matrix material. Little to no quartz was present in specimen. Plane-polarized light, x 2.5.

12- Pelsparite- brachiopod fragments, skeletal fragments, echinoderm; sparry calcite cement throughout specimen. Plane-polarized light, x 2.5.
13- Pelsparite- brachiopods, transverse bryozoans, ooliths, echinoderms, coated grains; sparry calcite cement.
Plane-polarized light, x 2.5.

14- Pelsparite- echinoderms, brachiopods, ooliths, skeletal fragments; with high compaction sparry calcite cement.
Plane-polarized light, x 2.5.

15- Biosparite- brachiopods, sparry calcite cement, coated grains with, fracture porosity present in blue.
Plane-polarized light, x 2.5.
VI. DISCUSSION

A. Kessler Limestone Thickness

Stratigraphic analysis of the Kessler Limestone and Trace Creek Shale deposition has some relationship based on the thickness of successions. In areas where the Kessler is thicker, there is a thicker section of Trace Creek Shale (Figure 15- sample 15). This relationship is adversely seen when comparing Kessler Limestone thickness to elevation; it appears that there is an inverse relationship between the two (Figure 12). Areas in the Ozark Dome with a higher elevation show Kessler Limestone in its thinnest or completely absent. Contrarily areas where the Kessler Limestone is thicker the elevation is less. This is observed in the subsurface of the Arkoma Basin or the measurements collected from Patrick in Madison County.

From the data collected, geometry of the Kessler Limestone (Figure 17) is thinnest stratigraphy from exposures in the north. The thickest stratigraphy appears in the subsurface; where the Kessler Limestone undergoes thinning or is absent more towards the North and East but data points show thickening in the South and West (Figure 18). These geometries support the Sutherland’s (1988) schematics (Figure 10); where the Kessler Limestone developed in a shallow, low energy, marine environment with a gentle slope to the south (which supports thickening and extent of Kessler). The overlying Trace Creek Shale thickness relates to the transitional environment (i.e. the exposure and erosion) of the regressional sequence that caused the unconformity, or the truncated surface. The thickness of the Kessler is so heterogeneous due to the regression, or change in sea level that it was momentarily above sea level, left exposed followed by erosion and deposition of the Trace Creek Shale. Petrology of the unconformity will better examine these conditions.
B. Petrology of the Kessler Limestone Unconformity

Examining the oncoliths and quartz from a vertical interval of ten thin sections (n = 10) from samples #7 (North), # 15 (South), #21(East), and #38(West) showed intriguing characteristics about the distribution of these two constituents (Figure 19). Data from these four samples shows there are more oncoliths abundant toward the west in sample #38. This higher abundance is indicative of a photic zone in a shallow marine environment with low energy. Furthermore, the other constituent tested in these four samples was quartz. Comparing quartz percentage showed that there is a higher abundance of quartz present in the south from sample #15 (Figure 19). This higher abundance of quartz is indicative of a terrigenous zone.

The data presented in Figure 19 was quantitative data presented in a boxplot; however, qualitative data from the Previous Petrographic Analysis described by Williams (1975), Fouke (1976) and Puckette (1976) is necessary to mention. Williams (1975) sample 04-06 and his sample 06-03 both are classified as skeletal biosparite; furthermore, his samples that are to the southeast, i.e. sample 17-05 and sample 11-11 are classified as oncolites. The interesting sample from Williams (1975) is sample 9-02 which is classified as a siltstone-sandstone facies and was examined further. Fouke’s (1976) sample 17.6 was one of the very few samples that contained a micrite mud matrix and was classified as biomicrite. Puckette’s (1976) sample PA-3.5 was classified as skeletal biosparite with coarse calcarenite. The cement in this location is unlike any of the other previous samples.

Exposure and weathering effects on the Kessler Limestone are factors that developed the heterogeneous Kessler that is seen today. The boundary between the Kessler Limestone Member of the Bloyd Formation and the overlying Trace Creek Shale Member of the Atoka Formation is a disconformity widely developed in the Midcontinent of the United States. The Trace Creek
Member of the Bloyd Formation was formally assigned to the Bloyd Formation and existed as
the upper member of the Bloyd.

Direct evidence for the unconformity is supported by the erratic thickness of the Kessler. This inconsistent nature was caused by exposure and partial or complete truncation in northwest Arkansas. This is observed in several localities (Figure 17) where fairly close thickness samples points have large differences (e.g.) in northcentral Crawford County there is a Kessler thickness near 0 feet and slightly to northeast a thickness sample of 26.03 feet. Also not seen within the stratigraphy of the Kessler is interfingerin with the overlying Trace Creek. This supports the Kessler experiencing lithification, exposure, diagenetic alteration and then truncation prior to Atoka deposition. Further evidence to support this interpretation is the pebble conglomerate composed of lithoclasts and pebbles eroded from the Kessler Limestone at the upper surface. The upper surface of the Kessler in many localities is a manganese enriched crust and frequently with manganese nodules; (Figure 20) – Upper Kessler Eroded Pebble Conglomerate Surface (I-49 Road-cut).

Figure 20 was taken from the exposed Kessler Limestone surface off of I-49 (formally known as I-540). This location hasn’t always been an exposure. Recent upgrades to I-540 took place in the mid-1990’s uncovering the Kessler Limestone. A historical aerial photograph (Figure 21) taken on 12/20/1982 shows the Kessler unexposed. The double-white line with the tree-line exposed is the area where the I-49 Road-cut will take place in the mid-1990’s. This outcrop shows severe signs of weathering where samples were collected. These samples came from a well lithified rock but had ankerite \[\text{Ca(Fe,Mg,Mn)} (\text{Co}^+) 2\] – a manganese carbonate mineral that forms in weathering environments; (Figure 22 - plane-polarized light, x 10).
Figure 20 – Upper Kessler Eroded Pebble Conglomerate Surface (I-49 Road-cut). Seen around both rock-hammers are eroded conglomerate pebbles or lithoclasts. This indicates a period of conglomerate deposition, lithification, and erosion. (Photo Credit- T.D. Dolan).
Figure 21- Aerial Historical Photograph (1982) of the I-49 Road-Cut – This historical photograph (12/20/1982) south of West Fork, shows the I-49 Road-Cut in double white lines. This photograph indicates that road-cut has not been developed and is unexposed at the surface.
Figure 22- Ankerite in the I-49 Road-Cut (Sample 02) – Both top and bottom images are from Sample 02. The brown-orange represent the mineral ankerite. Ankerite is highly abundant in this sample and represents exposure of a Paleozoic weathering environment. Plane-polarized, x 10.
Samples from the upper two feet of the Kessler Limestone were thin sectioned. The samples are well lithified, bear no resemblance to unconsolidated modern soils and are interpreted to be the product of post Kessler pre-Trace Creek weathering.

The Kessler Limestone in most localities is a skeletal grainstone with well-developed calcite cement (Figure 23). Crystals are finely crystalline adjacent to multi crystalline fossil fragments. Crystal size increases away from skeletal grains filling existing porosity. Overgrowths of calcite encompass echinoderm fragments. The cement is consistent with precipitation in the meteoric, phreatic environment. Calcite cements were selectively removed in the upper 10 cm of the Kessler creating porosity now filled with blue epoxy or clay (Figure 23). Pyrite is prominent in the weathering zone as cubic crystals that in places have been removed leaving molds (Figure 24). Intergranular clay is pervasively stained with hematite (Figure 24).

![Figure 23- Skeletal grainstone with calcite cement (upper); epoxy or clay matrix (lower). Sample 03 displays a skeletal grainstone in the upper portion with calcite cement and the lower portion displays a blue epoxy in the lower portion. Plane-polarized x 2.5.](image-url)
Figure 24- Clay matrix with quartz, pyrite, and hematite. Clay matrix (orange) with quartz, hematite (black) cutting diagonally through sample. Sample 01. Plane-polarized, x 10.

I-49 Road-Cut

The cement in thin sections from this location was very distinctive compared to Patrick and Evansville. The thin sections primarily were composed of sparry calcite cement with a great abundance of skeletal fragments and ooliths. Although present at all locations, quartz has the most abundant in sample 05. In this sample there was also a binding matrix of micrite-carbonate mud opposed to the sparry calcite cement in the other samples held.

Sample 01 - Intraclasts or lithoclasts are present throughout the sample. The lithoclasts are due to a higher energy environment during the erosion phase of deposition that resulted before the exposure. The higher energy environment is supported by the angular-subangular well sorted quartz grains in this sample. The cement in this sample is primarily sparry calcite cement. This sample also has areas of micrite mud that are indicative of a lower energy environment.
Sample 02 - Oosparite- Biosparite. Oolites and skeletal grains are very abundant in this sample. The sample is also bounded by sparry calcite cement. Quartz sand is less abundant in this sample but is angular-subangular and well sorted. Ankerite, a rhombic shaped mineral associated with weathering is also shown throughout this sample.

Sample 03- Biosparite- brachiopods and other skeletal grains are abundant in this sample. Quartz is almost completely absent, one grain was observed.

Sample 04- Oosparite; Oncoliths pelsparite – with very fine sand, calcite cement, and micrite are present. Sample has abundant skeletal grains and has very little to no quartz.

Sample 05- Biomicrite- Siltstone-sandstone facies –Very fine sand that with calcareous quartzarenite Sample varies from other samples in this location in that there is an abundance of quartz and micrite matrix present. The quartz sand ranges from medium coarse, to very coarse, well rounded to subangular, and poorly sorted.

Evansville

The cement at this location consists of a less abundant calcite cement and more of a mud matrix than compared to I-49 Road-cut location. Sample #9 consists primarily of a micrite mud matrix which is indicative of a lower energy environment compared to the other samples. This sample is also loaded with skeletal fragments and a moderate percentage of quartz compared to I-49 Road-cut location and Patrick.

Patrick

The samples from this location are more compacted and have less cement and matrix present. These samples also contain more constituents than compared to the other two locations. The higher compacted constituents and the lower percentage of cement and matrix may have
resulted from a number of scenarios. The Patrick locations exposure is one of the thickest exposed successions of the Kessler Limestone and can be up to 50 feet thick. The Kessler is absent in the surface any farther East of this location. Explanation of the increased thickness and extreme compaction may translate this area to have been a carbonate self-edge.

After the cement-matrix and constituents were estimated, the exact percentage of cement, matrix, and constituents was established. Then several subfacies categories were also made to characterize these samples. These subfacies categories consisted of quartz, oncoliths, brachiopods-bryozoans, coated-grains, gastropods, ooliths, intraclasts, red algae, and skeletal grains. These samples were examined based off of their porosity, cement, matrix, framework, composition, and texture. There are other explanations as to the extent of the compaction at this area. One explanation is human error. The contact between the Trace Creek and Kessler is difficult to determine at this locality and the samples taken may have not been at the contact.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cement-Matrix</th>
<th>Constituents</th>
<th>Classification</th>
<th>Quartz (&gt; 50 %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>71%</td>
<td>29%</td>
<td>Intrasparite</td>
<td>Yes</td>
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<tr>
<td>2</td>
<td>69%</td>
<td>31%</td>
<td>Oosparite</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>58%</td>
<td>42%</td>
<td>Biosparite</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>68%</td>
<td>32%</td>
<td>Oosparite</td>
<td>No</td>
</tr>
<tr>
<td>5</td>
<td>55%</td>
<td>45%</td>
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<td>Yes</td>
</tr>
<tr>
<td>6</td>
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<tr>
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</tr>
<tr>
<td>9</td>
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<td>60%</td>
<td>Biomicrite</td>
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</tr>
<tr>
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<td>44%</td>
<td>Biomicrite</td>
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<td>59%</td>
<td>41%</td>
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<td>No</td>
</tr>
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</table>

**Table 1**- **Cement to matrix percentage and constituent percentage.** Samples were analyzed based off of a total percentage of cement-matrix and constituents. Samples were then classified on constituents and cement within the sample. Samples with an abundance of quartz also noted.
VII. CONCLUSION

The Kessler Limestone is a complicated geologic unit but with the current data available a few generalizations can be made. A stratigraphic analysis on the Kessler Limestone compared to the Trace Creek Shale showed a thickness interval relationship primarily based on location. In areas where the Kessler and Trace Creek were exposed the thickness seemed to be related (i.e. a thick area of thickness in the Kessler represented a thick area of thickness in the Trace Creek). The boundaries of the Kessler Limestone also appear to be consistent with the depositional models made by Sutherland (1988); the Kessler is thickest toward the southwest and thins out toward in the southeast. When compared with elevation, there is also an inverse relationship between the Kessler thicknesses; areas with higher elevation showed thin Kessler and areas with lower elevation showed thicker Kessler. In higher elevation areas, erosion took place during a period of subaerial exposure or from the deposition of the Lower Atoka Formation.

Petrographic analysis of selected samples (Figure 19) from previous studies revealed that there is a greater abundance of oncoliths towards the West locations and the greatest abundance of quartz towards the South. This analysis suggests the West being a Photic zone environment and the South being a terrigenous zone environment. Furthermore, seen in both the quartz and oncoliths samples in the north, there is a smaller amount of quartz where erosion removed the upper Kessler Limestone. However, petrographic analysis from this study revealed oncoliths are also found in the Southeast and biomicrite is present toward the west. Biosparite seemed to be scattered throughout the region. Qualitative and quantitative descriptions were made upon the deposition but more analysis is needed to truly define the weathering environment in which the unconformity occurred.
Weathering of the Kessler Limestone in Washington County, Arkansas shows mineralogical implications upon the unconformity surface. In most localities the petrography analysis shows the Kessler Limestone is a skeletal grainstone bounded by calcite cement. However, seen in sample 02 and sample 03 (Figure 22 and Figure 24), taken from within the upper 10 cm of the Kessler displays removal of calcite cement and abundance of ankerite, hematite and pyrite. The absence of calcite cement and the presence of these minerals formed during subaerial exposure in Pennsylvanian weathering due to precipitation of meteoric water from within the phreatic zone.
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IX. APPENDIX
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