A day at the beach in Cumberland, Kentucky: The influence of tidal channel deposition on the geology of the Warix Run Member of the Slade Formation

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Abstract

The Slade Formation, as observed in the Daniel Boone National Forest (DBNF) in northeastern Kentucky, consists of sediments transitioning from a deep water marine depositional environment to fluvial conditions in the Late Mississippian Period. This transition is marked by a series of fossiliferous limestones, dolostones, calcarenites, calcilutites, and cherts (Ettensohn et al., 1984). The depositional environments associated with all of the members of the Slade Formation are well known, except for the Warix Run Member. In an unpublished master's thesis, Klekamp (1971) conducted a petrographic study of the Warix Run and tentatively concluded that it is made up of calcarenite deposited in tidal channels or on carbonate barrier islands. Subsequent studies referred to Klekamp's work and discussed his interpretations of the Warix Run Member with similar tentative language. To build upon Klekamp's hypothesis, this thesis utilizes a petrographic and scanning electron microscopic study of samples collected from the Red River Gorge area of the DBNF to determine the depositional environment of the Warix Run Member as well as the overlying Mill Knob Member of the Slade Formation. This analysis reveals that the Warix Run Member is composed of quartz-rich calcarenite sandstone, verifying the marine deposition of the member identified by Klekamp (1971). In addition, this analysis found that the Mill Knob Member is primarily composed of limestone with calcium-rich ooids in a micrite matrix. This is consistent with the depositional environment of this member, determined by Ettensohn et al. (1984) to be made up of carbonate sands and tidal flat deposits during periods of transgression and regression in sea level.

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Introduction

Sedimentary rocks can be put into context based on the depositional environment in which they formed. In coastal areas, strong currents generated by a variety of processes alter the environment and local marine circulation patterns (Longhitano et al., 2012). Bedforms on the seafloor, such as ripples and underwater sand dunes, can be formed in a matter of hours by tidal currents. On longer timescales, sediments can be transported to coastal zones by rivers, which produce deltas or estuarine deposits that record transport directions and conditions essential to understanding the history and environment of sedimentation (Longhitano et al., 2012). Another transport mechanism is longshore currents, which are generated by high-energy waves that crash against a coastline and move sediments parallel to the shore, often forming a pattern of barrier islands along a coast (National Ocean Service, 2024). The combination of transport and depositional processes in coastal areas leads to the accumulation of sediments in shallow subtidal and intertidal zones, which may eventually form sandstones, shales, and limestones that provide information about their deposition (Longhitano et al., 2012).

During the Late Mississippian Period, an interior seaway covered the area in and around what is today the state of Kentucky (Figure 1; Ettensohn et al., 1984). A sequence of sedimentary rocks were deposited that reveal a number of different marine depositional processes and environments. The Warix Run Member of the state's Slade Formation is made up of quartzose calcarenite sandstone and limestone 358.9 to 298.9 million years in age. Calcarenites are porous sedimentary rocks composed primarily of sand-sized calcite and dolomite particles as well as abundant marine fossils (Hudson Institute of Mineralogy, 2014). The Warix Run additionally contains breccia zones that may indicate lag deposits in tidal channels (Ettensohn, 1975). These zones are composed of angular clasts of chert and various other rock fragments in arenaceous calcarenite, or sandstone with muddy matrix material (Klekamp, 1971). Northeastern Kentucky, where a section of the Warix Run Member is located, is bordered to the west by the Appalachian Basin. The basin includes a low-lying regional arch known as the Cincinnati Arch, which was formed during the early Paleozoic. In his unpublished master's thesis, Klekamp (1971) verified that the Cincinnati Arch did not contribute to the formation of the breccia zones of the Warix Run.



Figure 1: The geographic context of the world at the time of formation of the Warix Run Member of the Slade Formation (Garrity, 2005). Note that the study site was underwater when the sandstone and limestone beds formed.

Klekamp (1971) discussed the Ste. Genevieve Member of the Newman Limestone as observed in Carter County, Kentucky, which includes the Warix Run Member. The terminology of the Slade Formation and its members varies between authors working in different locations and publishing at different times, but for the purposes of this thesis, the Ste. Genevieve and Warix Run Members can be considered to contain the same rock sequence. Klekamp found that the sediments of the Warix Run Member included evidence of migrating large-scale sand waves that transported sediments northeastward (1971). This sedimentation pattern is indicative of the configuration of the coastline of the interior seaway covering the area at that time, and the channel lags between the sand waves demonstrate that the tidal channel was dominated by flood and ebb patterns. Klekamp (1971) used this information to infer that the Warix Run Member was formed in a tidal channel-tidal flat sequence characterized by sea level regression (Figure 2).



Figure 2: The sand-shoal depositional environment that characterizes the tidal channel-tidal flat sequence of the Warix Run Member of the Slade Formation, proposed by Klekamp (1971) (Loucks et. al, 2003). A sand-shoal environment describes a submerged ridge or bank that is covered by sand (Pickens et al., 2021).

Above the Warix Run Member lies the younger Mill Knob Member, which contains sequences of dolomitic calcilutite and calcarenite, as well as chert associated with secondary silification in exposure points in the rock (Ettensohn et. al., 1984). Calcilutite is a mud-graded limestone composed of clay- and silt-sized particles of calcium carbonate (Halverson, 2014). Both rock types contain abundant fossils, such as pelmatozoan plates, brachiopods, blastoids, crinoids, and gastropods in discontinuous and wavy beds (Greb & Mason, 2005; Haban, 1985). Since carbonate rocks such as those that make up the Mill Knob Member weather easily, they are typically deposited close to their place of origin (Selley, 1988). Mud-coated carbonate grains can be classified as ooids, which are created when a sand grain collects carbonate mud to form a concentric arrangement of crystals around a central nucleus (Selley, 1988). Another carbonate grain type that is deposited in marine settings is peloids, which are often composed of fecal pellets and differ from ooids in their shape (Selley, 1988). They typically form oval grains that do not have the concentric layers of mud characteristic of ooids. Peloids are deposited in lagoons or other shallow marine environments such as the sheltered inner-shelf (Selley, 1988).

The environment at the time of formation for the Mill Knob Member, about 300 million years ago, included subtidal, intertidal, and supratidal zones consistent with a decline in sea level (Ettensohn et al., 1984). In modern coastal environments, the subtidal zone lies below the mean low-tide level and is influenced by tidal and wave currents (Figure 3). This environment is primarily composed of tidal channels, as well as shorefaces and delta fronts that interact with waves and tides (Longhitano et al., 2012). The grain size of this environment ranges from

clay-sized to medium-sand-sized particles and there is often evidence of bioturbation by marine organisms (LibreTexts, n.d.; Loucks et. al, 2003). The intertidal zone lies above the subtidal zone between mean low and high tide. This zone is usually exposed to the atmosphere twice a day at low tide and is characterized by a sloping fine-grained surface interrupted by tidal channels (Loucks et. al, 2003). Sedimentary structures observed in intertidal zones include fine laminations, thin rippled sands, and crustacean burrows (Loucks et. al, 2003). The supratidal zone is the coastal area above high-tide level made up of the uppermost area of beach ridges, and floods only during high tides and heavy storms (Longhitano et al., 2012). The supratidal zone includes salt marshes, mangrove swamps, and washover fans of fine-grained sediments.



Figure 3: An example of subtidal, intertidal, and supratidal depositional environments (Morales, 2022).

The evidence of sediment deposits in tidal-flat and supratidal zones can be readily observed in the fining-upwards sequences of the Mill Knob Member (Ettensohn et al., 1984). This sequence type describes a gradient of grain sizes that decrease in size from the bottom to the top of a rock outcrop, characteristic of a regression pattern with clay-sized grains being deposited on top of sand-sized grains. These sequences allowed Ettensohn et al. (1984) to confirm that the deposition of the Mill Knob Member took the form of carbonate-sand belts in a coastal environment.

Though the Mill Knob Member appears to be well understood, the processes and environment that created the Warix Run are less straightforward. Ettensohn et al. (1984) state that the "calcarenites of the Warix Run Member in northeastern Kentucky are *probably* tidal-channel deposits (Klekamp, 1971) and carbonate-barrier-island and tidal-bar-belt deposits (Horne and others, 1974)" (p. 11, emphasis added by me). The use of the word "probably" indicates that the authors were not able to conclusively determine the depositional setting at the time of formation for the Warix Run Member. This trend of uncertain language continues in other papers that discuss this member. For example, Greb and Mason state that "these limestone crossbeds were deposited as bars or sand waves in tidal channels...or *possibly* tidal-bar-belt deposits" (2005, p. 25, emphasis added by me). Similarly, Sable and Dever (1990) reference the Klekamp thesis that Ettensohn et al. base their results on but in no way clear up the issue: "Klekamp suggested that northeastward transport in the area did not necessarily reflect regional paleocurrent directions, but *may have resulted* from coastline configuration, wind direction, or flood- and ebb-dominated tidal currents" (p. 69, emphasis added by me). These papers are all from the late twentieth to early twenty-first centuries, and they cite an unpublished master's thesis that was written more than fifty years ago. There is a gap of knowledge in the depositional environments that led to the creation of the Slade Formation, which suggests a need to consolidate previous research and utilize current technology to conclusively determine the depositional patterns that developed this formation.

This thesis evaluates the claims of tidal channel and carbonate barrier island deposition of the Warix Run Member of the Slade Formation put forth by Klekamp (1971). It utilizes a petrographic and scanning electron microscopic study of samples collected from the Red River Gorge area of the Daniel Boone National Forest in pursuit of this goal. This thesis also investigates the overlying Mill Knob Member to confirm the depositional environment determined by Ettensohn et al. (1984) of carbonate sands and tidal flat deposits during periods of transgression and regression in sea level.

Study setting

The Red River Gorge Geologic Area is located within the Daniel Boone National Forest (DBNF) in northeastern Kentucky (Figure 4). The geology of the area, in stratigraphic order, is made up of a 1) Devonian shale, 2) the Mississippian Slade Formation, 3) a shale transition layer also formed in the Mississippian Period, and 4) a Pennsylvanian-age sandstone conglomerate (D. Taylor, personal communication, July 2023). There are three geologic processes that led to the formation of the gorge. The first process is thought to have been the accumulation of sediments in a coastal environment more than 340 million years ago, which includes the time of formation of the Warix Run and Mill Knob Members of the Slade Formation (Red River Gorge, 2020). The principal rock types that were deposited in the area of the gorge demonstrate the depositional environments of the location. Terrigenous clastic rocks were deposited to the east and northeast of this area, which indicate a deltaic environment (Klekamp, 1971). Argillaceous and carbonate rocks in the center of the Appalachian Basin as well as to the west of the basin indicate a shelf or platform environment (Klekamp, 1971). The second process involved in the formation of the gorge was diagenesis, in which sediments were buried and pressure and slightly elevated

temperature turned them into the rock that makes up the Appalachian Orogeny (Red River Gorge, 2020). This process was essential for the creation of oil and iron deposits that are important to the Kentucky economy today. The final process was the erosion of the bedrock by the Red River about 100 million years ago with uplift and erosion of the Appalachian Mountains (Red River Gorge, 2020).



Figure 4: The location of the Red River Gorge within the Cumberland District of the Daniel Boone National Forest (Forest Service, n.d.). a) The red box shows the location of the area depicted in b).

The Red River Gorge is a popular tourist and climbing spot in the DBNF, famous for its "Natural Bridge" eroded over time by running streams (Red River Gorge, 2020). This feature differs from "natural arches," in which rock is weathered into various structures without the presence of streams. 41,000 acres of the Red River Gorge are designated as part of the Forest Service's "National Archaeological District," as they include early evidence of Native American plant use and domestication (Bonaccorso, n.d.). Within this acreage, 29,000 acres of the forest are labeled as either a "National Natural Landmark" or a "National Geological Area" (Bonaccorso, n.d.), and a further 13,000 acres are designated as Clifty Wilderness to protect rare flora and fauna from human impact.

The study site is an outcrop near a landform known as Balanced Rock, along the Balanced Rock Trail at coordinates 37.77529° N, 83.68091° W. This outcrop makes up a section of the upper Mississippian Slade Formation, with samples taken from the Warix Run Member (Mswr) and Mill Knob Member (Msmk) (Figure 5).



Figure 5: A diagram of the Slade and adjacent formations. The Warix Run and Mill Knob Members, the two members present in the studied outcrop, are highlighted by the red box (Harris et al., 2020).

Methods

Sample Collection

I collected six samples at the study site on July 23rd, 2023 (Figure 6). For the purpose of this study, the outcrop location has been split into four sections, labeled A through D. Section A, from which Sample 1 was taken, is the oldest section of the outcrop, the Warix Run Member of the Slade Formation. Section B, from which Sample 2 was taken, marks the transition in the outcrop from the Warix Run Member to the Mill Knob Member, with a distinct change from sandstone to limestone. Section C, from which Sample 3 was taken, and Section D, which yielded Samples 4 and 5, contains rock from the youngest member of the outcrop, the Mill Knob Member. Finally, Sample 6 is a singular rock that was taken from the ground next to the outcrop. This rock did not have distinct physical characteristics that could identify the layer from which it came.



Figure 6: The sample site in July 2023, from which all of the samples analyzed in this thesis were taken. Sections A through D, as well as Sample 6, are labeled on the outcrop.

Hand Sample Analysis

After bringing the samples to the rock analysis lab at Vassar College, I tested each of them with 5% hydrochloric acid to determine whether they contained carbonate ions. I also conducted a thorough hand sample analysis to describe what the rocks looked like in the outcrop.

Thin Section Preparation

I cut thick sections of the samples using a rock saw. I ground one side of each of the thick sections to have a smooth side to attach to petrographic microscope slides. I first used 120-grit

particles to grind down large variations in the surface, and then 220-grit particles until the samples were smooth, with no large scratches, and appeared to be completely flat to the eye. I used a sonifier to blast dust and dirt out of the pores of the samples. The setting of the sonifier for my samples was a constant duty cycle with a one to two minute timer and an output control of 10 pulses. After all of the samples were cleaned, they were placed in a drying oven.

Once the samples were dry, they were placed on a hot plate at 135° Fahrenheit for five minutes. After the samples were heated, a dot of epoxy was placed on the smooth surface, and a labeled glass slide was placed on top of the sample. Gentle force was applied to the top of the slide to ensure that the corners and sides of the sample were covered with the epoxy. The slide and sample were then flipped over and placed on the hot plate for 24 hours to allow the epoxy to harden.

Sample 1 of Section A was a fragile and porous rock, so a technique known as vacuum impregnation was implemented to preserve the sample for thin section analysis. The samples were first broken into small pieces of about 1 inch x 1 inch. They were then placed in a plastic cup that was filled with epoxy, and the cup was put into a vacuum bowl with a lid. Once the vacuum was on, the air in the bowl was sucked out until the atmospheric pressure of the bowl was between 20 and 25 units below zero. Once there were no more bubbles rising to the surface of the epoxy from within the sample, the vacuum was turned off and the valve of the bowl was closed. This process was repeated four more times to impregnate the sample with epoxy, with each sample going through five total vacuum cycles.

Once the impregnated samples were attached to the slides, I used a small rock saw to cut them down to thinner pieces. I then ground them with 220-grit particles on glass and with

1200-grit MicroCut discs until they were a singular layer of minerals, which was verified with the petrographic microscope. I used a thin section scanner to take photos of each sample.

Thin Section Analyses

I used a Leica Model DM 2700 P petrographic microscope with both plane-polarized and cross-polarized light and a Michrome 5 Pro color microscope camera to analyze the thin sections. I studied the size and shape of the grains under plane-polarized light. I observed the interference colors and patterns of the grains under cross-polarized light, as well as noting whether they exhibited undulatory extinction or twinning to determine the mineralogy of the thin sections. Quartz grains display undulatory extinction, in which the grain fades into extinction colors and may exhibit different stages of extinction across a single grain. Feldspar and calcite grains display twinning, in which a criss-cross pattern appears on the grain with different stages of extinction. The twinning pattern of feldspar grains, tartan twinning, forms 90° angles. Calcite grains display a twinning pattern that forms 60° and 120° angles, which differentiates it from tartan twinning. For the sample identified as sandstone, I determined its depositional environment with a quartz-feldspar-lithics diagram, which categorizes rocks by the percentage of each mineral type that they contain (Figure 7). For the limestone samples, I determined the depositional environment of each sample with a carbonate classification diagram (Figure 8).



Figure 7: The quartz-feldspar-lithics diagram used in this thesis for sandstone thin section analysis (Learning Geology, 2015).



Figure 8: The carbonate classification diagram used in this thesis for limestone thin section analysis (SEPM STRATA, 2024).

Scanning Electron Microscope Analyses

A scanning electron microscope (SEM) utilizes a high-voltage beam of electrons to identify the elements of a rock. If a grain is conductive, electrons within it will spread outward when they are hit with a focused electron beam. This electron movement creates an x-ray of a certain frequency, which informs the identity of the element. In this way, I used the energy dispersive x-ray spectroscopy system of a PhenomXL SEM to identify the elements of the individual grains and matrix material of my thin sections. This elemental analysis enabled me to confirm whether the grains were silicates or carbonates in composition, as well as to compare my samples to one another based on the variations in proportion of silicon and calcium in the grains of each sample. In addition, I analyzed a larger area of each thin section for silicon cations to determine the percentage of quartz in each section.

Results

Initial Observations

The hand samples demonstrate the initial appearance of each section before being cut into thick sections (Figure 9).



Figure 9: The individual samples, split into the sections from which they were collected, in a) hand samples and b) thick sections.

Sample 1 of Section A was light gray with sand-sized grains. The grains had a weak reaction when tested with 5% hydrochloric acid. The light gray grain matrix contained white mineral streaks and large dark minerals that were visible with a hand lens. The grains appeared to be angular and irregular in shape in hand sample analysis.

Sample 2 of Section B was light tan in color, with sand- to silt-sized grains. There were dark brown mineral streaks as well as quartz grains visible with a hand lens. Since the sample was fine-grained, the grain shape was unable to be identified with hand sample analysis. The sample had a strong reaction when tested with hydrochloric acid.

Sample 3 of Section C was light gray to tan in color with a silt grain size. The sample reacted strongly with hydrochloric acid. The sample was fine-grained, and thus the grain shape was unable to be identified with hand sample analysis.

Samples 4 and 5 of Section D were light gray to white in color. There was lichen and iron oxidation present on the surface of the samples, which made them appear green and red, respectively, in certain areas. The samples contained silt-sized grains with white mineral veins visible to the naked eye. The shape of the grains was unable to be identified with hand sample analysis. Both samples had a strong reaction when tested with hydrochloric acid.

Sample 6 was brown in color with sand-sized grains and large, dark brown minerals visible with a hand lens. The sample was orange in areas due to iron oxidation and contained a large root cast. Sample 6 had no reaction when tested with hydrochloric acid. The grains in the sample were angular in shape and irregular in size.

Thin Section Results

Thin section scans illustrate the grain size and structure of each sample (Figure 10).



a.





c.



d.



Figure 10: Thin section scans of each section of the Slade Formation. a) is from Sample 1 of Section A; b) Sample 2 of Section B; c) Sample 3 of Section C; d) Sample 4 of Section D; e) Sample 5 of Section D; and f) Sample 6. The blue circles are the places where scanning electron microscope (SEM) spot analysis was conducted, with the numbers corresponding to the figure number of the SEM data. The blue squares are the places where SEM map analysis was conducted.

Sample 1, collected from Section A, contained grains that were angular in shape and tightly packed together (Figure 11). The sample was primarily composed of quartz grains and

lithics, with almost no feldspar grains, classifying it as a litharenite (Figure 7). The quartz grains displayed undulatory extinction (Figure 12).



Figure 11: The angled grain shape of Sample 1 of Section A thin sections in plane-polarized light. Each image shows a different part of the thin section to highlight the cohesiveness in grain shape throughout the thin section.



Figure 12: The undulatory extinction pattern of quartz grains in Section A in cross-polarized light, which can be seen in the difference in shade of the central quartz grain when the microscopic stand is rotated.

Sample 2 of Section B was composed of grains that were a mixture of ooids and peloids, which were cemented with a micrite matrix, characteristic of oopelmicrite (Figure 8). The matrix also contained quartz grains, which displayed undulatory extinction in cross-polarized light (Figure 13). There were several grains that demonstrated interference colors not characteristic of quartz grains, which were flagged for further analysis with the scanning electron microscope (Figure 14).



Figure 13: The undulatory extinction pattern of a quartz grain in Section B in a) plane-polarized light and b) and c) cross-polarized light with a change in grain orientation. Notice the circular layered ooids and pellet-like peloids present in the micrite matrix of Sample 2.



Figure 14: A rounded grain in Section B with interference colors not characteristic of quartz in a) plane-polarized, b) cross-polarized light, and c) cross-polarized light with a change in grain orientation.

Section C was made up of a light-gray dense micrite matrix, composed of silt- and clay-sized carbonate mud grains (Figure 15). There were few individual grains visible and the sample was thus classified as micritic, a fine-grained limestone with no obvious fossils, ooids, or

other grains (Figure 8). There were sparse silicates that displayed undulatory extinction within the micrite matrix (Figure 16).



Figure 15: The micrite matrix of Sample 3 of Section C in plane-polarized light, in two different microscopic views.



Figure 16: The undulatory extinction of a segment of a silicate grain in Sample 3, shown in cross-polarized light.

The grains of Section D were extremely rounded in shape, similar to the ooids observed in Section B but smaller and more rounded. The matrix that cemented the ooid and peloid grains together was a micrite, classifying Samples 4 and 5 as oopelmicrite (Figure 8). There was a weathering rind on the surface of the sample, which appeared as brownish ripples across the grains in microscopic view (Figure 17). The quartz grains displayed undulatory extinction similar to that of Sections B and C, often within larger grains (Figures 18 and 19).



Figure 17: A weathering rind present on the surface of the thin section of Sample 4 of Section D in plane-polarized light.



Figure 18: The ooid and peloid grains of Sample 4 of Section D in plane-polarized light.



Figure 19: The ooid and peloid grains of Sample 5 of Section D in plane-polarized light.

Sample 6 was made up of angular grains that were packed closely together. The grains displayed undulatory extinction indicative of quartz, and there were lithic materials present in the thin section (Figures 20 and 21).



Figure 20: The undulatory extinction of quartz grains in Sample 6 in cross-polarized light with a change in grain orientation.



Figure 21: A second example of the undulatory extinction pattern of quartz in Sample 6 in cross-polarized light with a change in grain orientation.

Scanning Electron Microscope Results

Each thin section was analyzed with the scanning electron microscope (SEM) to determine the elemental composition of different grains and the background matrix material. This analysis also mapped the presence and percentage of silicon and calcium in each outcrop member.

The grains of Sample 1 of Section A were primarily silicates, which indicates that the sample is composed of quartz grains (Figure 22). The presence of iron and aluminum in lower proportions in grains identify other lithic rocks in the sample (Figure 23). The quartz grains may have been held together by an iron oxide cement, which would explain the high proportion of iron in the sample.



Figure 22: The high proportion of silicon in an individual grain of Sample 1 of Section A indicates that the sample is primarily composed of quartz grains.



662 292 counts in 0:00:30 (21 966 c/s)

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.	Oxide Symbol	Stoich. Weight
8	0	Oxvgen	76.346	60.500		Conc.
11	Na	Sodium	0.000	0.000	Na2O	0.000
12	Mg	Magnesium	0.000	0.000	MgO	0.000
13	Al	Aluminum	4.417	5.900	Al2O3	15.775
14	Si	Silicon	13.154	18.300	SiO2	55.386
15	Р	Phosphorus	0.000	0.000	P2O5	0.000
19	K	Potassium	0.516	1.000	K2O	1.704
20	Ca	Calcium	1.108	2.200	CaO	4.355
22	Ti	Titanium	0.590	1.400	TiO2	3.304
26	Fe	Iron	3.868	10.700	FeO	19.475

1



Figure 23: A small proportion of grains in Sample 1 contained aluminum and iron, which are lithic rocks that were mixed into the quartz matrix of the sample during deposition.

The grains of the matrix of Sample 2 of Section B were calcium-rich, with few other elements present (Figure 24). There were also silicates embedded in the calcium matrix, indicating the presence of quartz grains in Section B (Figures 25 and 26).





Figure 24: The primary element present in Sample 2 of Section B was calcium, providing further evidence of ooids in the sample that were observed in the thin section analysis of Section B (refer to Figure 11).





1



590 389 counts in 0:00:30 (19 609 c/s)

Element	Element	Element	Atomic	Weight	Oxide	Stoich.
Number	Symbol	Name	Conc.	Conc.	Symbol	Weight
	-				-	Conc.
8	0	Oxygen	63.568	45.554		
11	Na	Sodium	0.873	0.899	Na2O	1.308
12	Mg	Magnesium	1.376	1.499	MgO	2.681
13	Al	Aluminum	5.954	7.193	Al2O3	14.667
14	Si	Silicon	15.087	18.981	SiO2	43.812
15	Р	Phosphorus	0.648	0.899	P2O5	2.223
19	K	Potassium	4.107	7.193	K2O	9.349
20	Ca	Calcium	4.341	7.792	CaO	11.764
22	Ti	Titanium	0.373	0.799	TiO2	1.438
26	Fe	Iron	3.674	9.191	FeO	12.758



10

463 885 counts in 0:00:30 (15 428 c/s)

Figure 26: A grain in Sample 2 of Section B with a high proportion of aluminum and iron in addition to silicon, which was discovered with high interference colors in thin section analysis (refer to Figure 14). The mineralogy of this grain indicates that it may be feldspar.

Similar to Section B, the SEM analysis of the grains of Sample 3 of Section C revealed a calcium-rich matrix (Figure 27). There were silicon-rich sections of the thin section that were angular in shape and displayed cleavage. These minerals may be chert, a non-clastic sediment made up of microcrystalline quartz that deforms during the process of diagenesis (Selley, 1988). Specifically, these crystals may be chalcedony, a type of chert that displays fibrous and radial habits (Selley, 1988). They may also represent a silica-rich fluid that entered the micritic rock during formation and formed replacement quartz in the matrix (You et al., 2018). The silicate minerals were surrounded by a darker material that contained a high proportion of both calcium and silicon (Figure 28). This mineral may be wollastonite, which forms when a limestone is subjected to temperature and pressure in the presence of a silica-rich fluid (Rashid et al., 2014).



Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.	Oxide Symbol	Stoich. Weight
						Conc.
8	0	Oxygen	67.142	52.753		
11	Na	Sodium	0.266	0.300	Na2O	0.420
12	Mg	Magnesium	0.754	0.901	MgO	1.548
13	Al	Aluminum	0.076	0.100	Al2O3	0.196
14	Si	Silicon	28.737	39.640	SiO2	87.887
15	Р	Phosphorus	0.592	0.901	P2O5	2.139
19	Κ	Potassium	0.209	0.400	K2O	0.500
20	Ca	Calcium	1.221	2.402	CaO	3.484
22	Ti	Titanium	0.383	0.901	TiO2	1.558
26	Fe	Iron	0.620	1.702	FeO	2.269



a. 544900 counts in 0:00:30 (18 054 c/s)



Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.	Oxide Symbol	Stoich. Weight Conc.
5	В	Boron	25.082	14.500		
8	0	Oxygen	56.916	48.700		
11	Na	Sodium	0.488	0.600	Na2O	1.519
12	Mg	Magnesium	0.692	0.900	MgO	2.803
13	Al	Aluminum	0.139	0.200	Al2O3	0.710
14	Si	Silicon	1.198	1.800	SiO2	7.233
15	Р	Phosphorus	0.121	0.200	P2O5	0.861
19	Κ	Potassium	0.000	0.000	K2O	0.000
20	Ca	Calcium	15.163	32.500	CaO	85.424
22	Ti	Titanium	0.000	0.000	TiO2	0.000
26	Fe	Iron	0.201	0.600	FeO	1.450

12



10

b. 340 337 counts in 0:00:30 (11 312 c/s)

Figure 27: a) The darker grains in Sample 3 of Section C are silicates that may either be chert or the deposition of a silica-rich fluid while the section was forming. b) The matrix material is a fine-grained calcium-rich mineral characteristic of micrite.



Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.	Oxide Symbol	Stoich. Weight Conc.
8	0	Oxygen	67.715	53.954		
11	Na	Sodium	0.000	0.000	Na2O	0.000
12	Mg	Magnesium	0.661	0.801	MgO	1.385
13	Al	Aluminum	0.373	0.501	Al2O3	0.987
14	Si	Silicon	29.482	41.241	SiO2	92.059
15	Р	Phosphorus	0.260	0.400	P2O5	0.957
19	K	Potassium	0.051	0.100	K2O	0.126
20	Ca	Calcium	1.254	2.503	CaO	3.654
22	Ti	Titanium	0.168	0.400	TiO2	0.697
26	Fe	Iron	0.036	0.100	FeO	0.134



a. 477966 counts in 0:00:30 (15 834 c/s)



Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.	Oxide Symbol	Stoich. Weight Conc.
8	0	Oxygen	76.095	56.743		
11	Na	Sodium	0.280	0.300	Na2O	0.646
12	Mg	Magnesium	0.176	0.200	MgO	0.530
13	Al	Aluminum	0.397	0.500	Al2O3	1.510
14	Si	Silicon	1.679	2.198	SiO2	7.521
15	Р	Phosphorus	0.138	0.200	P2O5	0.732
19	K	Potassium	0.055	0.100	K2O	0.193
20	Ca	Calcium	20.911	39.061	CaO	87.429
22	Ti	Titanium	0.000	0.000	TiO2	0.000
26	Fe	Iron	0.269	0.699	FeO	1.439

1



b. 351 700 counts in 0:00:30 (11 667 c/s)



Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.	Oxide Symbol	Stoich. Weight Conc.
5	В	Boron	48.161	31.600		
8	0	Oxygen	36.040	35.000		
11	Na	Sodium	1.504	2.100	Na2O	5.861
12	Mg	Magnesium	0.542	0.800	MgO	2.746
13	Al	Aluminum	1.344	2.200	Al2O3	8.609
14	Si	Silicon	2.757	4.700	SiO2	20.819
15	Р	Phosphorus	0.691	1.300	P2O5	6.167
17	Cl	Chlorine	1.022	2.200		
19	K	Potassium	2.191	5.200	K2O	12.971
20	Ca	Calcium	4.686	11.400	CaO	33.029
22	Ti	Titanium	0.206	0.600	TiO2	2.072
20	n .	T	0.055	2,000	E O	2 205



Figure 28: The silicate grains in a) are surrounded by a cement revealed in b) to be a calcium-rich micrite matrix. The darker mineral between the silicates and the micrite matrix, seen in c), indicates the presence of wollastonite with a high proportion of both silicon and calcium.

The grain composition of Section D, as analyzed with Samples 4 and 5, was rich in calcium (Figures 29 and 30). There were very few silicate minerals present in the samples. The high calcium content of Section D is further supported by the ooids observed in thin section analysis (refer to Figure 19).



Figure 29: The grain composition in Sample 4 of Section D was almost completely made up of calcium, with less than 1% silicon in the grain matrix.



304 244 counts in 0:00:30 (10 112 c/s)

	Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.	Oxide Symbol	Stoich. Weight Conc.
Γ	8	0	Oxygen	68.276	46.700		
ſ	11	Na	Sodium	0.712	0.700	Na2O	1.246
	12	Mg	Magnesium	0.481	0.500	MgO	1.095
Γ	13	Al	Aluminum	0.434	0.500	Al2O3	1.248
Γ	14	Si	Silicon	0.416	0.500	SiO2	1.413
Γ	15	Р	Phosphorus	0.378	0.500	P2O5	1.513
Γ	19	K	Potassium	0.598	1.000	K2O	1.591
Γ	20	Ca	Calcium	27.840	47.700	CaO	88.161
Γ	22	Ti	Titanium	0.488	1.000	TiO2	2.203
Γ	26	Fe	Iron	0.377	0.900	FeO	1.529



Figure 30: The calcium-rich grains of Sample 5 of Section D, along with the oval-like shape from which the analysis was taken, indicate the presence of ooids.

Sample 6 was made up of silicate grains with a grain composition similar to that of Sample 1 in Section A (Figure 31). The quartz grains were cemented with iron oxide (Figure 32). These grains were accompanied by grains with high proportions of titanium, which may be rutilated quartz (Figure 33). The presence of zirconium in the sandstone indicates that there may be zircon grains in the sample as well (Figure 34).



Element	Element	Element	Atomic	Weight	Oxide	Stoich.
Number	Symbol	Name	Conc.	Conc.	Symbol	Weight
	-				-	Conc.
8	0	Oxygen	67.965	53.754		
11	Na	Sodium	0.000	0.000	Na2O	0.000
12	Mg	Magnesium	0.000	0.000	MgO	0.000
13	Al	Aluminum	0.000	0.000	Al2O3	0.000
14	Si	Silicon	30.278	42.042	SiO2	93.697
15	Р	Phosphorus	0.261	0.400	P2O5	0.956
19	Κ	Potassium	0.052	0.100	K2O	0.126
20	Ca	Calcium	0.253	0.501	CaO	0.730
22	Ti	Titanium	0.211	0.501	TiO2	0.870
26	Fe	Iron	0.979	2,703	FeO	3.622



Figure 31: Sample 6 was primarily composed of silicates, indicated by the high proportion of silicon in SEM analysis.

	Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.	Oxide Symbol	Stoich. Weight Conc.
and the second of the	8	0	Oxygen	67.615	54.100		
	11	Na	Sodium	0.000	0.000	Na2O	0.00
	12	Mg	Magnesium	0.247	0.300	MgO	0.51
the second se	13	Al	Aluminum	0.741	1.000	Al2O3	1.95
	14	Si	Silicon	30.967	43.500	SiO2	96.03
The second second	15	Р	Phosphorus	0.000	0.000	P2O5	0.00
Las Post All A start	19	K	Potassium	0.051	0.100	K2O	0.12
	20	Ca	Calcium	0.050	0.100	CaO	0.14
	22	Ti	Titanium	0.042	0.100	TiO2	0.17
Mode FW MV MA MAL MO Prost 2011/01 L3 10 41 200 pm Mode MODe Mode MOD Prost 2011/01 L3 10 41	26	Fe	Iron	0.286	0.800	FeO	1.06

10



534 101 counts in 0:00:30 (17 731 c/s) a.



Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.	Oxide Symbol	Stoich. Weight Conc.
8	0	Oxygen	71.254	47.852		
11	Na	Sodium	0.000	0.000	Na2O	0.000
12	Mg	Magnesium	0.000	0.000	MgO	0.000
13	Al	Aluminum	2.647	2.997	Al2O3	7.172
14	Si	Silicon	9.659	11.389	SiO2	30.848
15	Р	Phosphorus	0.077	0.100	P2O5	0.290
19	K	Potassium	0.487	0.799	K2O	1.219
20	Ca	Calcium	0.356	0.599	CaO	1.062
22	Ti	Titanium	0.348	0.699	TiO2	1.477
26	Fe	Iron	15.171	35.564	FeO	57.933

12



Figure 32: The silicate grains in a) were surrounded by a lighter grain matrix, which was revealed in b) to be iron oxide cementing the quartz grains together.

0.000 0.513 96.033 0.000 0.124 0.144 0.172 1.062









	Element	Element	Element	Atomic	Weight	Oxide	Stoich.
	Number	Symbol	Name	Conc.	Conc.	Symbol	Weight
							Conc.
\square	8	0	Oxygen	76.080	53.293		
	11	Na	Sodium	0.198	0.200	Na2O	0.347
	12	Mg	Magnesium	0.281	0.299	MgO	0.640
	13	Al	Aluminum	3.550	4.192	Al2O3	10.207
	14	Si	Silicon	11.848	14.571	SiO2	40.163
	15	Р	Phosphorus	0.589	0.798	P2O5	2.357
	19	K	Potassium	0.991	1.697	K2O	2.633
	20	Ca	Calcium	0.057	0.100	CaO	0.180
	22	Ti	Titanium	0.286	0.599	TiO2	1.287
	26	Fe	Iron	0.122	0.299	FeO	0.496
	40	7r	Zirconium	5 998	22.052	7:02	41 600

Stoich. Weight

Conc.

0.000

4.389 16.659

1.565 0.658 0.956 52.643 21.091



Figure 34: The high proportion of zirconium in a grain in Sample 6 indicates that there may be zircon sand in the sample.

In addition to the spot analyses shown above, each sample was tested with a map analysis in the SEM to determine the proportion of silicon in each sample in order to verify that the spot samples were representative of the entire thin section. Sample 1 of Section A contained a high proportion of silicon, which is indicated by the pink color throughout the analysis image (Figure 35). Sample 2 of Section B and Sample 3 of Section C both contained several grains that were high in silicon, but the matrix did not contain abundant silicates (Figures 36 and 37). Both Sample 4 and Sample 5 of Section D contained a very low proportion of silicon, as there were almost no pink areas in the analysis (Figures 38 and 39). Sample 6 contained a high proportion of silicon, similar to that of Sample 1 of Section A (Figure 40).



Figure 35: The high proportion of silicon in Sample 1 of Section A is demonstrated by the pink coloring on the SEM image. The only parts of the sample that do not contain silicon are the spaces between the grains, which are made up of a calcium- and iron-rich cement.



Figure 36: As seen by the individual pink grains in the image, the silicon found in Sample 2 of Section B is confined to a few quartz grains within an otherwise calcium-rich set of ooids and matrix.



Figure 37: The silicon in Sample 3 of Section C forms in a pattern that may indicate deposition by fluid. Notice the connectivity between the different pink areas, which demonstrate the presence of silicon in the sample. The light-colored mineral in the figure is an iron-oxide-rich mineral.



Figure 38: The silicon proportion of Sample 4 of Section D is extremely low, limited to sparse quartz grains in a dominant micrite matrix.



Figure 39: Similar to Sample 4, Sample 5 of Section D contains a low proportion of silicon, with only a few quartz grains in the left of the image being highlighted.



Figure 40: Sample 6 contains a high proportion of silicon, which is demonstrated by the amount of highlighted pink areas in the SEM map analysis.

Discussion

The results from hand sample, thin section, and scanning electron microscope (SEM) analysis confirmed that Sample 1 of Section A of the outcrop is a sandstone. The sample had a weak reaction to hydrochloric acid in hand sample analysis, indicating that it only contained trace amounts of carbonates and was therefore not a limestone. The thin section microscopic study revealed that the grains of Sample 1 were angular in shape and tightly crowded together, which suggests that they were formed in a marine environment with a lack of strong wave motion that would have otherwise created rounded grains. In addition, the sample was primarily composed of quartz grains with a lesser amount of lithic materials. This was confirmed by the SEM analysis, which revealed that Sample 1 contained more than 90% silicon, higher than any of the other samples analyzed. These results indicate that the sample is a quartz arenite sandstone, which is most commonly deposited in marine sand-shoal environments in the subtidal zone (Selley, 1988; Figure 2).

Sample 2 of Section B was much different in composition to Section A when comparing hand samples. The sample reacted strongly when tested with hydrochloric acid, indicating that it contained carbonate grains and was most likely a limestone with sand- to silt-sized grains. The thin section analysis of Section B revealed that the sample was an oomicrite composed primarily of ooids embedded in a carbonate mud matrix (Figure 8). Ooids are commonly formed in high-energy marine environments, including sand banks and tidal deltas in the intertidal zone (Selley, 1988). In the SEM analysis of Sample 2, the grains were found to be calcium-rich, with several silicate grains present, suggesting that the section was primarily limestone with a few sand-sized quartz grains scattered in a calcite-rich matrix.

Both Sample 1 of Section A and Sample 2 of Section B were hypothesized to have been taken from the Warix Run Member of the Slade Formation upon initial collection. Section A was expected to be a quartzose calcarenite sandstone representative of the Warix Run Member; however, the lack of calcite in the sample indicates that it is not a calcarenite. This sample may have been taken from a chenier deposit of the Warix Run, which are wave-built ridges composed almost entirely of sandstone (Otvos, 2005). Section B is the limestone portion of the outcrop that indicates the contact between the Warix Run Member and the overlying Mill Knob Member. These sections indicate that the Warix Run Member of the Slade Formation was deposited in a marine environment with shallow water and low activity, such as a tidal channel-tidal flat sequence. The classification of Sample 1 of Section A as part of a chenier provides further evidence of the subtidal depositional environment of the Warix Run. The oolitic qualities of Section B of the Warix Run Member indicate the sea level regression that characterizes its formation, as deposition transitioned from a subtidal channel to a high-energy intertidal delta environment.

In comparison, Sample 3 of Section C was fine-grained and reacted strongly with hydrochloric acid, indicating that it was limestone. The section was composed of a micrite matrix with few ooids and quartz grains present, and SEM analysis revealed that the sample was made up of a calcium-rich matrix with individual silicate grains, similar to that of Section B. The lack of ooids indicate that this section may represent a transgression of sea level, in which fine-grained micrite was deposited above the oopelmicritic rock of Section B.

Samples 4 and 5 of Section D reacted strongly with hydrochloric acid, providing evidence of the section being limestone. The grains of Section D were a mixture of round ooids and peloids with a micrite matrix, as observed in thin section analysis. SEM analysis revealed that the samples were almost completely composed of calcium with few fragmented silicate grains. The proportion of oolitic carbonate grains in the section indicate that the depositional environment of this section was marine and contained stronger current activity than that of the previous sections, such as that of a sand bank or tidal delta (Selley, 1988). In addition, the ooid-rich micrite of Section D represents a regression of the sea level in the environment from the time of formation of the micrite of Section C. This coastal environment describes the depositional environment at the time of formation of the Mill Knob Member of the Slade Formation, which took the form of carbonate-sand belts in a coastal environment during transgressions and regressions in sea level (Ettensohn et. al, 1984).

Sample 6 was composed of angular sand-sized grains that had no reaction when tested with hydrochloric acid, indicating that the sample was not limestone. Thin section analysis revealed that the sample was primarily composed of quartz grains with few lithic materials, characteristic of a quartz arenite sandstone, a result confirmed by SEM analysis, which showed that the sample was made up of silicate grains with an iron oxide matrix. This analysis

demonstrated that Sample 6 is identical in composition to Section A and is part of the Warix Run Member of the Slade Formation.

The results from hand sample, thin section, and SEM analysis are consistent with the original hypothesis put forth by Klekamp (1971) regarding the depositional environment of the Warix Run Member of the Slade Formation. The angular arenite sandstone grains of Section A were most likely part of a subtidal chenier ridge formed in a low-energy marine environment, such as the tidal channel-tidal flat sequence recommended by Klekamp (1971). The oolitic and pelitic limestone grains of Sections B and C indicate a high-energy marine environment and demonstrate the transition from the tidal channel environment of the Warix Run Member to the sandbank environment of the Mill Knob Member. The carbonate-rich ooids and peloids of Section D were most likely formed in a marine environment with strong current activity, such as that of the carbonate-sand belts postulated by Ettensohn et. al (1984). In this way, the geology of the Daniel Boone National Forest demonstrates the transition from the silicate-rich Warix Run Member to the carbonate-rich Mill Knob Member of the Slade Formation.

There were several limitations to the study that must be addressed. The samples collected from the outcrop were not in a vertical line due to the difficulty in reaching the higher sections of the outcrop. Only one sample was taken from each section for analysis with the exception of Section D, from which two samples were taken, which may have had an impact on locating the contact between the Warix Run and Mill Knob Members as determined in this thesis. The study only had one person completing thin section grinding and analysis, which may have impacted the accuracy of the scanning electron microscope analysis if the thin sections were too thick in certain areas. Finally, there may have been aspects of the thin sections that were not taken into account in analysis in this thesis due to the time constraints of the task.

A more in-depth study of the outcrop selected in this thesis may be completed with more samples taken from each section to determine the exact contact point between the Warix Run Member and the Mill Knob Member. In addition, the thin sections from this thesis may be further analyzed with the x-ray diffractometer at Vassar College to verify the mineralogy of the samples. A study of other outcrops in the Daniel Boone National Forest could be completed with a replication of the methods that were used in this study to determine the accuracy of these results and further confirm Klekamp's original hypothesis on the depositional environment of the Warix Run Member (1971). Finally, this study could be expanded to include outcrops outside of the Daniel Boone National Forest that also contain the Warix Run and Mill Knob Members of the Slade Formation to identify depositional patterns across Kentucky and its surrounding states.

There is a gap in the knowledge of the depositional environments of rock formations such as the Slade Formation, which this thesis aims to fill in the study of a single outcrop in the Daniel Boone National Forest. Studying depositional environments is an essential component in understanding how the world has evolved over time and the processes that have led to its current appearance. The Daniel Boone National Forest is one of many possible sources of information about the sedimentology of these less-understood rock formations, which is why there needs to be further resources invested by the Forest Service into geology and sedimentology research at these sites.

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