TESTING EROSION POTENTIAL OF HETEROGENEOUS LITHOLOGIES TO UNDERSTAND ATYPICAL VALLEY MORPHOLOGY IN THE BUFFALO NATIONAL RIVER WATERSHED, ARKANSAS

By

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Abstract

The effect of heterogeneous lithologies on valley morphology in tectonically stable landscapes is an unresolved question in fluvial geomorphology. The upper reaches of the Buffalo National River incise the Mississippian Boone Formation, a cherty limestone, forming a wide gently sloping valley. As the Boone Formation gives way to the Ordovician Everton Formation, an interbedded dolostone, limestone, and sandstone, a significant narrowing of the valley is observed. This pattern is repeated in the middle reaches of the river when a fault brings the Boone Formation back to the surface. To tease out what processes are driving the atypical valley morphology, laboratory tests were conducted to analyze the mechanical and chemical weathering characteristics of the primary cliff-forming lithostratigraphic units in the Buffalo River watershed. Specifically, mechanical weathering characteristics were evaluated using a vertical abrasion mill, and chemical weathering characteristics were evaluated using dissolution experiments. The abrasion mill experiments were conducted on samples from four different lithologies - the Everton Formation (dolostone), the St. Joe Limestone, the Boone Formation (limestone), and the Batesville Sandstone - with abrasive aggregate sampled from modern gravel bars in the watershed. The final erosion rates of the Everton, St. Joe, Boone, and Batesville samples were 10.2 g/hr, 18.9 g/hr, 9.3 g/hr, and 30.9 g/hr respectively. Fragments of the samples were crushed and dissolved in a hydrochloric acid solution. The two limestones, the Boone and St. Joe, dissolved almost completely at 99% and 90% respectively. 37% of the Everton dissolved and only 2% of the Batesville dissolved reflecting much lower carbonate content of these samples. The abrasion mill results indicate that there is

minor variability in mechanical resistance of the lithologies tested. Therefore, the primary control on valley morphology within the watershed is the variability in the chemical competence of the lithologies. Similar patterns in valley morphology have been documented in watersheds that transition from hard crystalline rock to soft sedimentary rock. This experiments suggests that even small variation in rock characteristics can influence valley evolution in tectonically stable landscapes.

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Table of Contents

List of Tables

List of Figures

List of Abbreviations

AU	Auburn University
BNR	Buffalo National River
DI	Deionized
hr	Hour
rkm	River Kilometer

INTRODUCTION

The Buffalo National River (BNR), the first National River in the U.S.A. flows through Paleozoic rocks of the Ozark Plateaus physiographic province in northern Arkansas (Fig.1). As the BNR flows downstream, it incises into two of the major cliff-forming lithostratigraphic units present within the BNR watershed: the Mississippian Boone Formation and the Ordovician Everton Formation. The Boone Formation is a limestone with up to 70% chert in some locations (Hudson, 1998). The Everton Formation is composed of interbedded dolostone, limestone, and sandstone (Hudson, 1998). According to Schumm (1977), normally rivers have the narrowest valley at their headwaters and progressively develop a wider valley as they flow downstream. This expected transition is attributed to a decrease in gradient and an increase in sinuosity as the river nears base level (Schumm, 1977). As reported in Keen-Zebert et al. (2017), although channel gradient decreases and sinuosity generally increases, the valley of the BNR does not adhere to Schumm's model; valley width does not increase systematically but instead locally narrows and expands downstream. Hence, in the BNR watershed, variables other than gradient and sinuosity must be responsible for valley width.

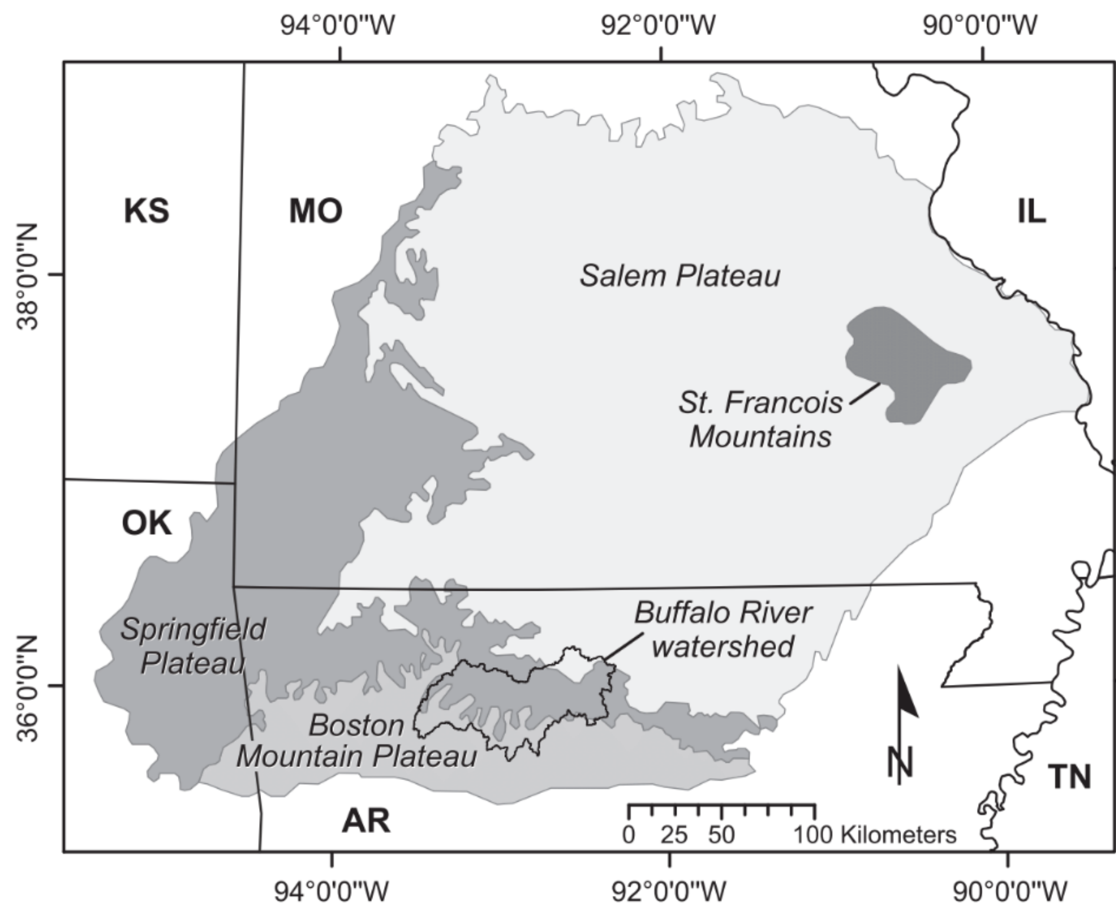

Figure 1: The BNR watershed, located near the southern boundary of the Ozark Plateaus. The BNR is incised into the Boston Mountain and Springfield Plateau subdivisions of the larger Ozark Plateaus physiographic province in southern Missouri and northern Arkansas (Keen-Zebert et al., 2017).

It is often stated that lithology is a fundamental control factor on landscape evolution. Harder, more competent rock is expected to resist erosion to produce relatively steeper slopes (e.g., Marshall and Roering, 2014). Gilbert (1877) noted that the ability of channels to carve wide floodplains is directly related to lithology. Individual characteristics of each lithology result in unique channel slope, sediment supply, sediment transport, and bed-cover features (Gilbert, 1877; Montgomery, 2004). As pointed out by Sklar and Dietrich (2001), the ability of rivers to incise bedrock is controlled by the exposure of bedrock in contact with the fluvial processes of erosion. This exposure is directly proportional to the sediment supply within the system as it provides tools to abrade, pluck, cavitate, and cover the bedrock. Maximum erosion is observed at moderate sediment supplies, when the bedrock is exposed and sediment supply is sufficient enough to generate erosive action (Gasparini et al., 2007; Bursztyn, 2015).

The result of these observations is the generalization that rivers cutting through hard rock will have narrow, steep stream channels surrounded by steep hillslopes, whereas rivers cutting through softer lithologies will have wide, gentle streambeds surrounded by gentler hillslopes (Gilbert, 1877; Powell, 1895; Lifton et al., 2009). As a river transitions from a harder lithology to a softer lithology, river incision will outpace river migration, resulting in narrower river valleys as well as fewer terraces (Schumm and Etheridge, 1994). Slope formation, and inevitable slope failures, are controlled by the characteristics of the rocks and soils through which a river cuts, and hence quantitative analysis of lithologies has become more common in fluvial geomorphologic studies (Goudie, 2016). A Schmidt Hammer, which measures the compressive strength of a rock, was used to compare surface hardness of various limestones within the BNR by Keen-Zebert et al., (2017). The conclusions drawn from these tests show that the main lithologies in the BNR watershed, the Boone and the Everton Formations, have similar mechanical resistance characteristics, which leads to the question: what is controlling the atypical changes in valley width?

The resulting valley morphology of a river transitioning from narrow, steep streambeads in hard crystalline rock to wider, more gentle streambeds of softer sedimentary rock is well established (e.g., Lifton et al., 2009). An outstanding and understudied question within fluvial geomorphology is the effect of heterogeneity among sedimentary layers. Within the BNR, weathering of heterogeneous sedimentary layers, with only minor dissimilarities, has resulted in similar geomorphological characteristics as rivers that incise both hard crystalline rocks and soft sedimentary rock.

The atypical narrowing of the river valley observed in the BNR watershed is thought to stem from differential weathering related to the heterogeneity among exposed lithostratigraphic units (Keen-Zebert et al., 2017). Variability in the mechanical and chemical weathering characteristics of the units within the BNR watershed could control river incision and result in the observed cliff formation. This thesis addresses this hypothesis by utilizing standard laboratory-based experiments to analyze the mechanical and chemical weathering characteristics of the primary cliff-forming lithostratigraphic units within the BNR watershed. Specifically, mechanical weathering characteristics were evaluated using a vertical abrasion mill, and chemical weathering characteristics were evaluated using dissolution experiments. The results generated from this work help elucidate the relationship between lithology and valley morphology within the BNR watershed. Extending out from the BNR watershed, the results of this research will improve our understanding of valley formation in relatively stable tectonic regions with heterogeneous lithologies of the same rock type.

GEOLOGIC SETTING

The Ozark Plateaus physiographic province is composed of Paleozoic sedimentary rocks that are generally flat-lying with a gentle dip to the south. Structurally, the Ozark Plateaus are formed by an asymmetrical low dome that has been eroded to form a series of east-west trending ridges and valleys. The Ozark Plateau is located in southern Missouri, eastern Oklahoma, and northern Arkansas (Fig. 1).

Stratigraphy

The Stratigraphy underlying the BNR watershed is summarized in figure 3. Stratigraphic units most pertinent to this study include the middle Ordovician Everton Formation, the Mississippian Boone Formation, and Batesville Sandstone.

The Everton Formation is 98 m thick and is divided into upper and lower parts (Turner and Hudson, 2010) (Fig. 2). The lower part of the Everton Formation comprises interbedded finely crystalline to micritic, dark to light-gray, locally stromatolitic limestone, limey sandstone, and sandy limestone. Medium to thick beds exhibit planar to wavy laminations. The upper part of the Everton Formation includes, in ascending order, the Newton Sandstone Member (McKnight, 1935), and the Jasper Member (Glick and Frezon, 1953). The Newton Sandstone Member consists of dark to light-grey, locally stromatolitic, micritic to finely crystalline dolostone, limey dolostone, and carbonate-cemented sandstone. Dolostone and limey dolostones are planar-laminated to medium-bedded and commonly contain fine- to medium-grained quartz arenites cemented by dolomitic or limey-dolomite. The upper parts of the Newton Sandstone Member contain collapse breccias with clasts of the overlying Jasper Member. The Jasper Member is up to 24 m thick and is composed of light grey, finely crystalline to micritic, medium-bedded limestone and sandy limestone.

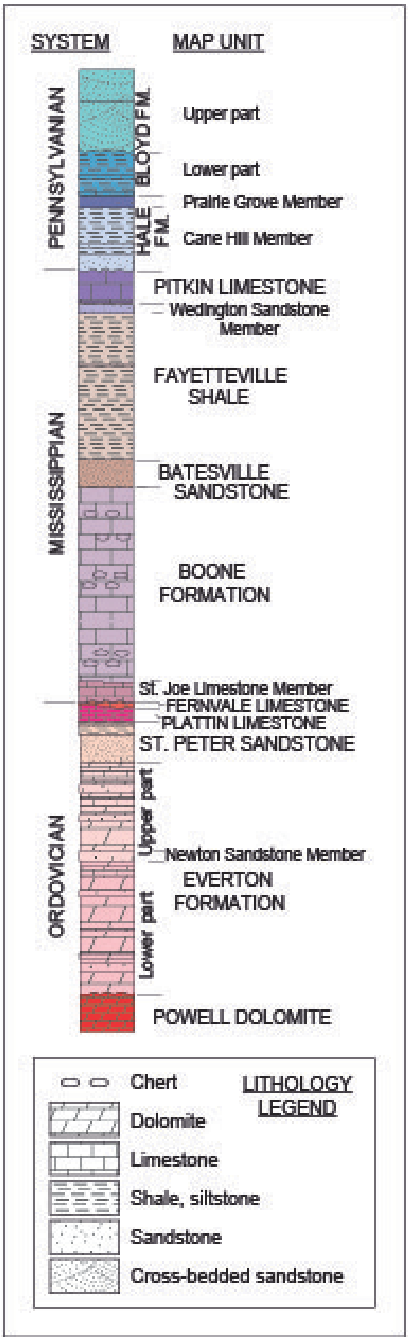

Figure 2: Stratigraphic column of the BNR study area. (modified from Keen-Zebert et al., 2017).

The Middle-Lower Mississippian Boone Formation is ~ 110- 115 m thick and includes, in ascending order, the St. Joe Limestone, and a thicker unnamed member. The St. Joe Limestone is thin (9-18 m) and rests unconformably upon Silurian and, further to the northwest, Ordovician rocks (Braden et al., 2003; Hutto et al., 2008; Turner and Hudson, 2010). The lower part of the St. Joe Limestone is ~ 0.3- 3.0 m and includes fine-grained, moderately sorted sandstone containing phosphate pebbles and discontinuous conglomerates containing clasts from underlying units. The Bulk of the St. Joe Limestone is characterized by thin to medium-bedded, fine- to coarse-grained crinoidal limestone with greenish-grey, tan, and yellow interbedded shales. Coarsely crystalline limestones support abundant white or pink crinoid fragments in thin to medium, parallel wavy beds. Locally, the St. Joe contains pyrite in the form of single crystals, clusters, or rusty blebs where weathered, and dark grey, manganese-rich shaly zones. Chert is generally rare but lenticular chert becomes more common near the top of the member where it grades into the main body of the Boone Formation.

The main body of the Boone Formation is characterized by planar to wavy bedded, fine- to coarse-grained crystalline to coarse-grained crinoidal limestones with anastomosing or discontinuous, thin interbeds of chert. Chert content is highly variable both laterally and vertically; horizons with abundant chert are typically poorly exposed and only chert lag is observed. Higher in the section, chert is typically white to dark-gray and may contain crinoid columnals or brachiopod fossils. Blue, orange, or reddish chert is common near the gradational contact with the St. Joe Limestone Member. The upper part of the Boone is marked by a 0.33- to

1.0-meter-thick bed of oolitic limestone. The top of the Boone is karstified and includes spring, sinkholes, and small caves arte common.

The Upper Mississippian Batesville Sandstone, 12- 18 meters thick, lies unconformably on the Boone Formation. This formation is described as very fine to medium-grained, subangular, moderately sorted, iron and calcite-cemented, calcareous sandstones (Braden et al., 2003). The Batesville Sandstone is medium-bedded, commonly exhibit low-angle cross stratification or parallel lamination. Sandstones are rarely fossiliferous but locally contain burrows or fossil molds on the bedding-plane surfaces. The unit contains oxidized pyrite framboids 2.54- 12.70 mm in diameter; framboids weather to reddish-brown spheres. Where the overlying Fayetteville Shale has been eroded, topographic flats, underlain by the Batesville, contain sinkholes resulting from collapses in the underlying Boone Formation.

Geomorphology of the BNR

Four reaches within the BNR are identified based on the lithostratigraphic units exposed at river level (Figs. 3, 4). Reach 1 incises the Boone Formation from river kilometer (rkm) 17 to rkm 30. Reach 2 incises the Everton Formation from rkm 33 to rkm 113. At approximately rkm 113, the Horn Mountain Fault, a normal fault, reintroduces the Boone Formation at the surface. Downstream of the Horn Mountain Fault, reach 3 incises the Boone Formation from rkm 113 to rkm 152. The final reach, reach 4, incises the Everton Formation from rkm 154 to rkm 172 (Keen-Zebert et al., 2017). The Boone, Everton, as well as the Batesville lithostratigraphic units are all major cliff formers of significant thickness in the watershed and all but the Batesville formation have outcrops at river level (Hudson, 1998). Of these three lithostratigraphic units, four samples were tested in this study: a fine-grained to very fine-grained sandstone sample of the Batesville Sandstone; a medium- to thick-bedded bioclastic limestone sample of the main body of the Boone Formation; a medium-grained thin-bedded crinoidal limestone of the St. Joe Limestone member of the Boone Formation; and a fine- to medium-crystalline dolomite sample of the Everton Formation (Fig. 2).

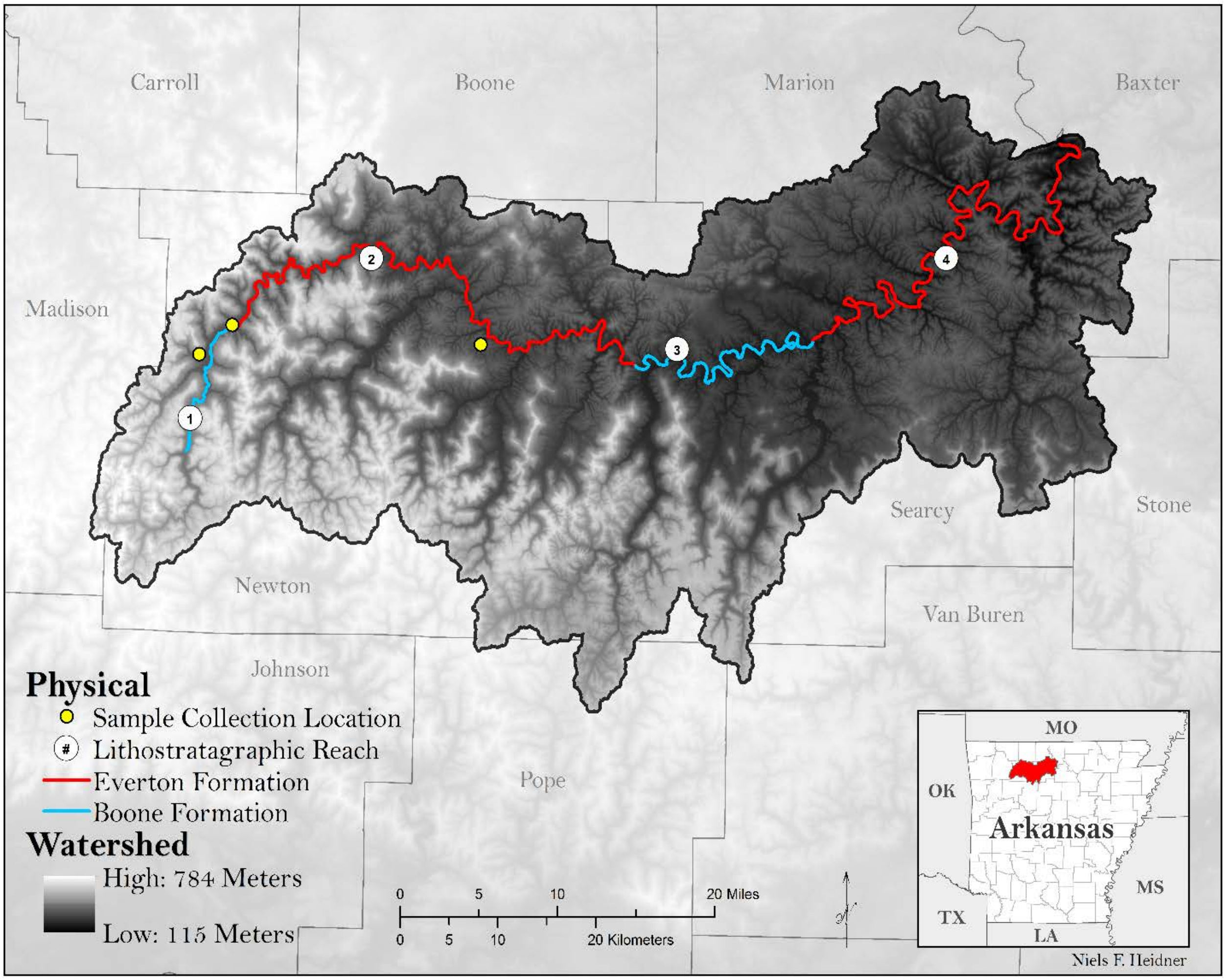

Figure 3: Map of the BNR watershed, located in northern Arkansas (inset map). The map shows the distribution of two major lithostratigraphic units occurring along the four river reaches (1-4), and the location of samples used in this study.

The channel sinuosity increases where the BNR incises the Boone formation downstream of the Horn Mountain Fault at reach 3. The sinuosity of reach 3 is not matched in either reach 2 or 4 (where the BNR incises the Everton Formation), with an atypical decrease in channel sinuosity where the BNR transitions from reach 3 to reach 4. It is unsurprising that the observed decrease in channel sinuosity resulting from the loss of accommodation space as the BNR river valley narrows following the transition to incise the Everton Formation.

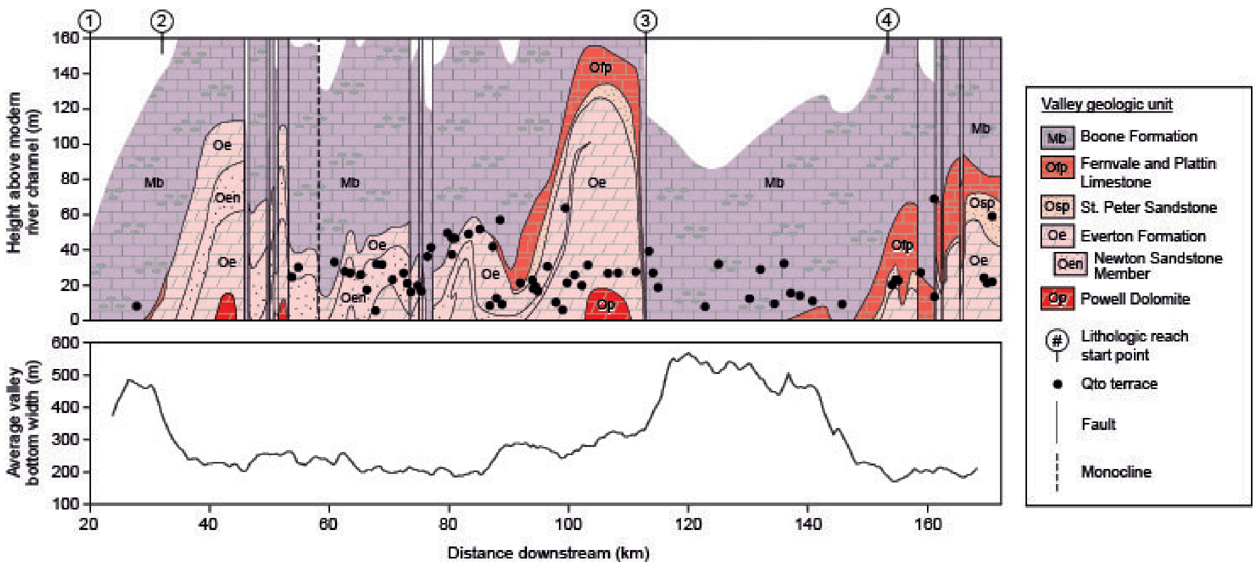

Figure 4: Valley lithology and average valley width within each of the four lithologic reaches in the study area, circled numerals denote the beginning of each reach. Note differences between vertical scales and horizontal scale. Figure modified from Keen-Zebert et al. (2017).

The under-saturation of the BNR in calcite and CO_2 results in an environment that could continue to produce the karst features observed in the Boone Formation. The pronounced karst features of the Boone, including more than 500 caves and sinks within the BNR watershed, have developed over millennia but act as evidence of the vulnerability of the lithostratigraphic unit to chemical weathering processes (Keen-Zebert et. al., 2017). Schmidt Hammer tests, which measure the surface hardness and penetration resistance of a rock, previously-collected within the BNR watershed revealed that the Everton and Boone formations do not differ significantly with respect to their compressive strength. Other lithologies also tested were the Bloyd Sandstone, Batesville Sandstone, St. Joe Member, Newton Member, and St. Peter Sandstone (Keen-Zebert et al., 2017). Hence, it is unlikely that the variability in mechanical resistance of the formations would have significantly different mechanical weathering characteristics.

With low to no isostatic rebound and/or tectonic uplift in the BNR or greater Ozark Plateaus physiographic province, another factor must be causing the atypical valley morphology present within the BNR. Lithology has been suggested as the primary factor within the BNR due to the lack of more commonplace drivers. According to Keen-Zebert et al. (2017), the pattern of valley width demonstrates that in relatively stable landscapes with only mildly dipping stratigraphy, lithology and structure can have a strong influence on the spatial pattern of bedrock channel processes. Conceptually, as a river incises a more weathering resistant lithology, channel migration outpaces channel incision. This results in wider river valleys and can also lead to terrace formation. As the river incises through a less weathering-resistant lithology, channel incision, or down cutting, may outpace channel migration. This erosional pattern would theoretically result in narrower river valleys as well as fewer terraces.

<u>PREVIOUS EXPERIMENTAL WORK</u>

Experimental studies have been performed to address both mechanical and chemical weathering processes in environments relevant to the BNR. The two commonly used approaches include: (1) utilizing abrasion mills to test mechanical weathering processes, and (2) the use of hydrochloric acid (HCl) to test chemical weathering processes.

<u>Mechanical Weathering</u>

The natural processes of mechanical weathering due to bedload transportation—i.e. saltation and traction—that contribute to a stream's incising power can be replicated in a laboratory setting. Experiments allow the constraint of parameters, including water volume, gravel size and mass, current speed, temperature, and time. Common approaches to studying gravel abrasion include tumbling mills, circular flumes, and abrasion mills (Kodama, 1994; Bursztyn et al., 2015). Due to the variable characteristics associated with natural systems, constraints that could otherwise be controlled in a laboratory setting, for example the discharge rate of the stream, water temperature, and pressure, are sources of error that may compound to produce unreliable results.

Tumbling mills, such as the ERC Abrasion Mixer used by Yoshinori Kodama (1994), simulate stream erosional processes by rotating a barrel or cylinder horizontally along its b-axis (Fig. 5A). This process allows a very detailed analysis of the size reduction of gravel during downstream transport. However, the disadvantage to this approach is its inherent lack of feedback on the interaction between bedrock and bedload. Since tumbling mills such as the ERC

Abrasion Mixer do not easily incorporate bedrock samples into the study parameters and the interactions between the bedrock and bedload are the primary focus of the current study, a tumbling mill was not considered.

Other scientists have employed vertical circular flumes. One operated by Attal and Lavé (2009) involved injecting water to drive gravel abrasion (Fig. 5B). This method requires the use of injectors to create a current rather than a physical device within the system, thus removing any possibility of physical interactions between the abrasive aggregate and a propulsion device. Attal and Lavé's circular flume facilitated the abrasion of gravel samples against removable plates within the flume. The removable plates allowed for the alteration of conditions and the isolation of variables depending on the experiment. This technique was used to isolate the driving forces and factors that control gravel abrasion in mountainous fluvial transport systems. Although this approach allows for testing of a wide range of variables, it requires a significantly large area, and the cost to setup and run experiments can be prohibitive.

The apparatus constructed by Small et al. (2015), based on the design of Sklar and Dietrich (2001), used a bar-stock paddle-bit to generate a current within the abrasion mill (Fig. 5C). A drill press drove a paddle bit to create a vortex that suspended the bedload and drove abrasion. The abrasion mill used in this experiment is very adaptable and comparatively inexpensive to operate. For these reasons, as well as the ability to address our research objectives, we modeled our experiment after Small et al. (2015).

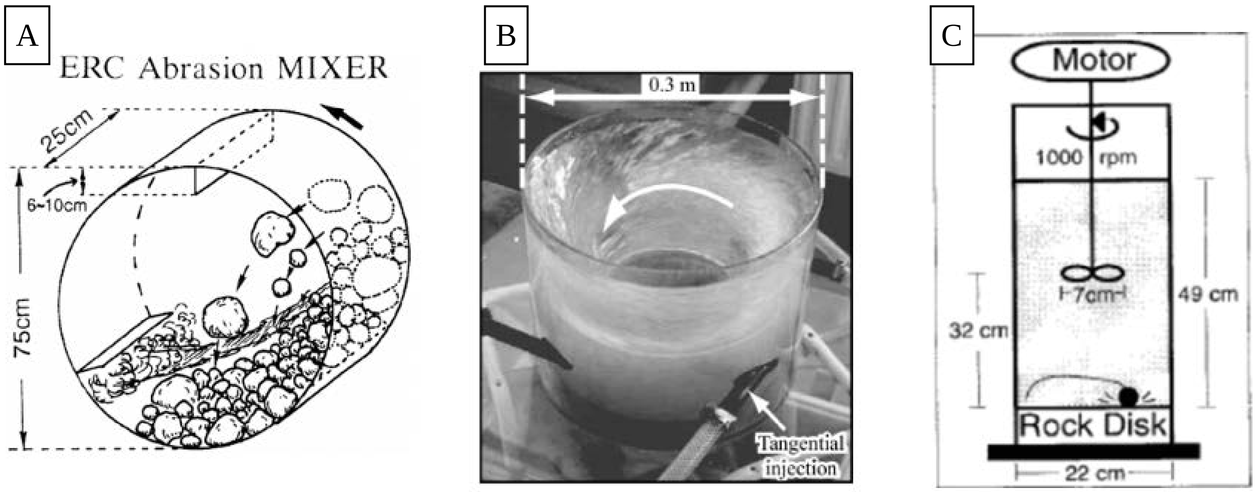

Figure 5: Previous abrasion mill designs. (A) The ERC Abrasion MIXER (Kodama, 1994). (B) Tangential injection circular flume (Attal and Lavé, 2009). (C) The circular flume referred to as an abrasion mill (Sklar and Dietrich, 2001).

Chemical Weathering

Solubility experiments run by Keen-Zebert et al. (2017) were used to analyze the chemical weathering competence of several major cliff-forming lithostratigraphic units from within the BNR. The solubility of the lithologic units tested are as follows: Batesville Sandstone (3%), Boone Formation (100%), St. Joe Member (98%), Everton Formation (63%), and St. Peter Sandstone (33%) (Keen-Zebert et al., 2017). The variation in the composition of the lithostratigraphic units was expected to result in variable rates of chemical weathering. Chemical weathering characteristics can be calculated through solubility testing modeled after Suarez et al. (2013). The chemical characteristics of each lithology play a major role in percent loss *(final sample weight/original sample weight × 100)* during solubility testing. During solubility experiments, calcium carbonate ($CaCO_3$) within the sample is dissolved by 3 molar hydrochloric acid (Eq. 1). The downside to this technique is the destruction of the sample during the experiment. With ample sample availability, this was not a concern in the present study. This experiment relies on the assumption that the percentage of carbonate varies among lithologies, and that there will be meaningful and measurable differences in dissolution percentage among lithologies tested.

$$CaCO_{3(S)} + 2HCl_{(L)} \rightarrow CaCl_{2(L)} + CO_{2(G)} + H_2O_{(L)} \quad \text{Eq. 1}$$

In nature, rain water is slightly acidic (pH = 5.6), causing the dissolution of carbonate. In limestone or carbonate-rich environments, the dissolution of carbonate may lead to karst topography. A lithology with a higher percentage of carbonate should be less resistant to chemical weathering than lithologies with lower percentages.

METHODS

Abrasion Mill Experiments

The abrasion mill built for this study, based on the design of Small et al. (2015), consists of a single 22.5-cm-diameter acrylic cylinder sandwiched between two pieces of plywood using four 1.5875-mm threaded rods (Fig. 6). A rubber hose, secured in the precut grooves of the plywood, acted as a seal. The abrasion mill, was powered by a drill press, that rotated a propeller at ~890 rpm. The speed of the drill press was monitored with a Nidec PT-110 noncontact tachometer that is accurate to within ± 0.1 rpm. Over the course of the study, the drill press was operated for a period in excess of 150 hours. Gradually the drill press slowed to ~883 rpm, which equates to a loss of 7 rpm or 0.787% (Appendix A). This is likely due to wear and/or stretching of the drive belts within the drill press.

Test samples consisted of discs (22.5-cm-diameter) cut from larger samples collected from the main part of the Boone Formation, Everton Formation, St. Joe Member of the Boone Formation, and Batesville Sandstone. Due to the availability of samples, only one disc was analyzed from each lithostratigraphic unit. Prior to each abrasion cycle, the disc thickness was measured at six locations using digital calipers accurate to within ± 0.01 mm. The locations were equally spaced and marked with black permanent marker on the bottom side of each disc. Following the methods of Sklar and Dietrich (2001), the sample discs were submerged in deionized (DI) water for one week prior to the first of the abrasion cycles. This allowed the samples to become saturated as they would be in the bed of a river.

Figure 6: Abrasion mill constructed of a clear acrylic cylinder with a spigot, two wooden plywood boards, and four threaded rods (with washers and nuts). The paddle bit was inserted through the hole in the top wooden board and then inserted into the chuck of the drill press.

The abrasive aggregate used in this experiment consisted of gravel collected from modern gravel bars along the BNR. The gravel was separated by size class using a gravelometer. Each size class (90 mm, 60 mm, 45 mm, 32 mm, 22.5 mm, 16 mm, 11.3 mm, 8 mm, 5.7 mm, and 4 mm) was weighed and the resulting values were used to calculate a mass-percent for each class in the samples. The largest and smallest class sizes were removed due to a limitation in quantity. The size mass-percent was recalculated from the subsample. This size distribution was closely approximated for the gravel used in each abrasion cycle.

Approximately 1 kg of gravel, with a size distribution that closely approximates the size-mass percent of the modern gravel bars, was placed in the mill (Appendix B). The cylinder was then filled to a depth of 49.5 cm with DI water. Each disc was abraded for five, 5-hour abrasion cycles. Discs were re-submerged overnight between each abrasion cycle and their mass was monitored daily to ensure the samples were 100% saturated prior to the first abrasion cycle. The discs were patted dry to remove surface water, weighed, and measured at the six marked locations before being placed in the mill for each abrasion cycle. After the first three abrasion cycles, a control run was conducted without gravel, to test if any weathering was occurring due to the motion of the water in the mill. At the conclusion of each abrasion cycle, the gravel and any sediment eroded from the disc during the abrasion cycle were removed, sieved, dried, and then weighed. The water column was drained through a #230 (63 micron) sieve in order to catch sand-sized or coarser sediment. The mill was transferred and disassembled in a catchment bucket where all of the equipment was rinsed and loose sediment was contained. The contents of the bucket were drained through the #230 sieve as well to catch any remaining sediment, and the contents were dried overnight in an oven. The dried sediment generated from the abrasion cycle was then weighed after cooling to room temperature and recorded. New gravel was used for every abrasion cycle.

In the event that the gravel imbricated against the spigot nut, the drill chuck was lowered through manual operation of the quill downfeed lever. The lowering of the paddle-bit increased the current at the surface of the sample disc and was generally sufficient to dislodge the imbricated gravel. In extreme cases, the drill press was turned off and the imbricated gravel was manually dislodged with a wooden dowel inserted through the top of the abrasion mill. Imbrication events were resolved in the matter of seconds to a few minutes, and thus should not have had any measurable effect on the outcome of the mechanical weathering results. Relative susceptibility to mechanical abrasion of tested lithostratigraphic units was assessed primarily by mass-percent loss and thickness loss of test discs through time.

Dissolution Experiments

Tests were conducted to determine the percent of soluble carbonate minerals as a proxy for chemical weathering potential of the Everton, St. Joe, Batesville, and Boone lithostratigraphic units using methods described by Suarez et al. (2013).

Fragments of the rock samples cut for the abrasion mill were pulverized using a jaw crusher and further processed into a fine powder using a disc mill. One gram (weighed to 0.0001 gram) of each sample was transferred into a 45-mL centrifuge tube and mixed with 30 mL of 3M HCl (Eq. 1). The sample was covered and agitated manually to initiate the 24-hour dissolution experiment. The samples were re-agitated every 6 hours and opened to release any CO_2 gas produced during the reaction. After 24 hours, the samples were placed into a centrifuge for 2 minutes at 3000 rpm. The acid supernatant was then decanted into a large glass beaker and discarded. The remaining precipitate was rinsed with DI water and re-centrifuged for 5-7 minutes. This process was repeated until the pH of the sample was neutral. The pH was monitored with an Oakton WD-35614-90 Oakton Waterproof pH 150 Meter Kit accurate to within ± 0.1. Samples were then transferred to a glass beaker and placed in an oven to dry for 12 hours. The dry insoluble residues were re-weighed, and pre-treatment and post-treatment weights were compared to calculate percent solubility (*Ps*):

$$Ps = 100 - [\left(\frac{mf - mb}{ms}\right)(100)] \qquad \textit{Eq. 2}$$

where *mf* is the final mass (grams) of the beaker and sample, *mb* is the mass of the beaker, and *ms* is the original mass of the ground sample.

RESULTS

Primary findings confirm the presence of significant variability among the weathering characteristics of the BNR lithostratigraphic units and indicate that this variance is, at least in part, responsible for the atypical valley morphology observed within the BNR watershed. Two key differences were recognized in this research: (1) samples prominently composed of carbonate displayed a higher degree of resistance to mechanical weathering than the samples with a dominantly siliceous composition; and (2) samples prominently composed of carbonate displayed a lower degree of resistance to chemical weathering than the sample prominently composed of siliceous material.

Abrasion Mill Experiments

Over the course of the mechanical weathering tests, the Batesville sandstone sample lost 46.70% of its initial mass. The measured mass-loss for the St. Joe, Everton, and Boone samples were 13.39%, 3.46%, and 1.96%, respectively (Fig. 7, Appendix A).

Sample thickness was measured at the six pre-marked locations prior to and following each abrasion cycle. Total thickness losses, in millimeters averaged across the six marked locations ± the standard deviation value, of the Batesville, St. Joe, Everton, and Boone samples were 28.36 ± 17.75, 15.42 ± 3.64, 6.546 ± 6.29, and 2.80 ± 0.85, respectively (Fig. 8).

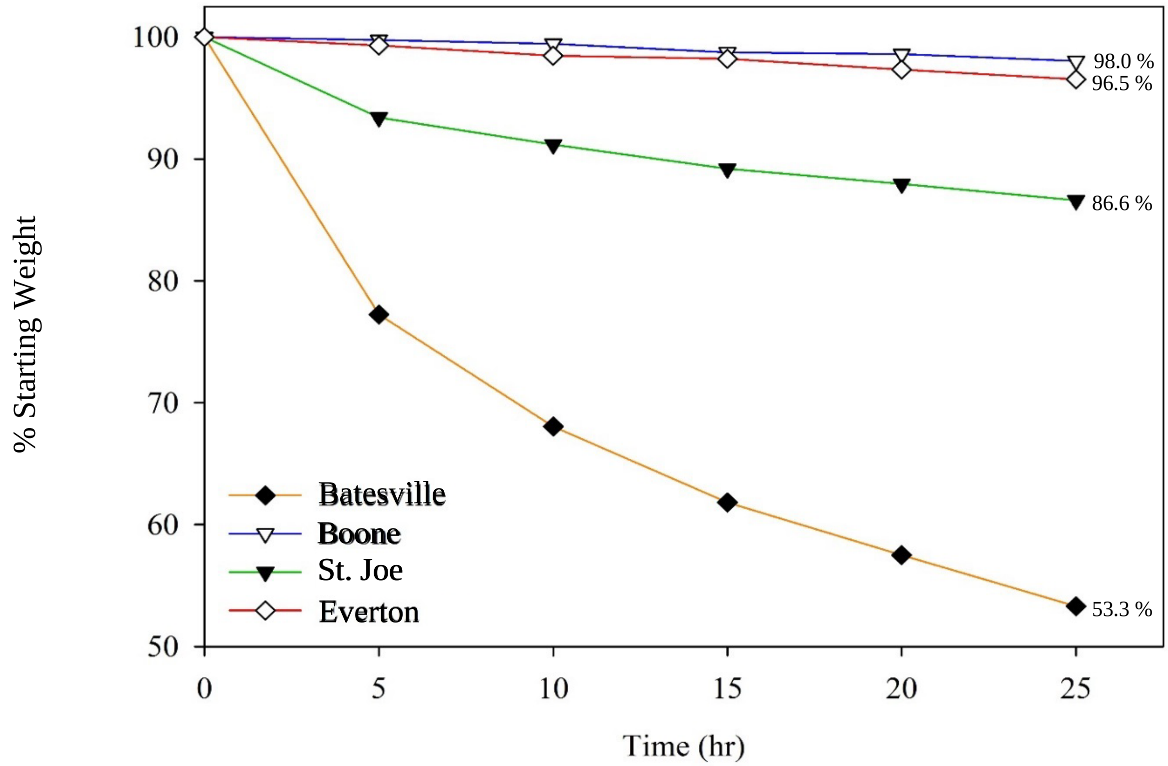

Figure 7: Change in mass of the sample discs over time during abrasion-mill experiments.

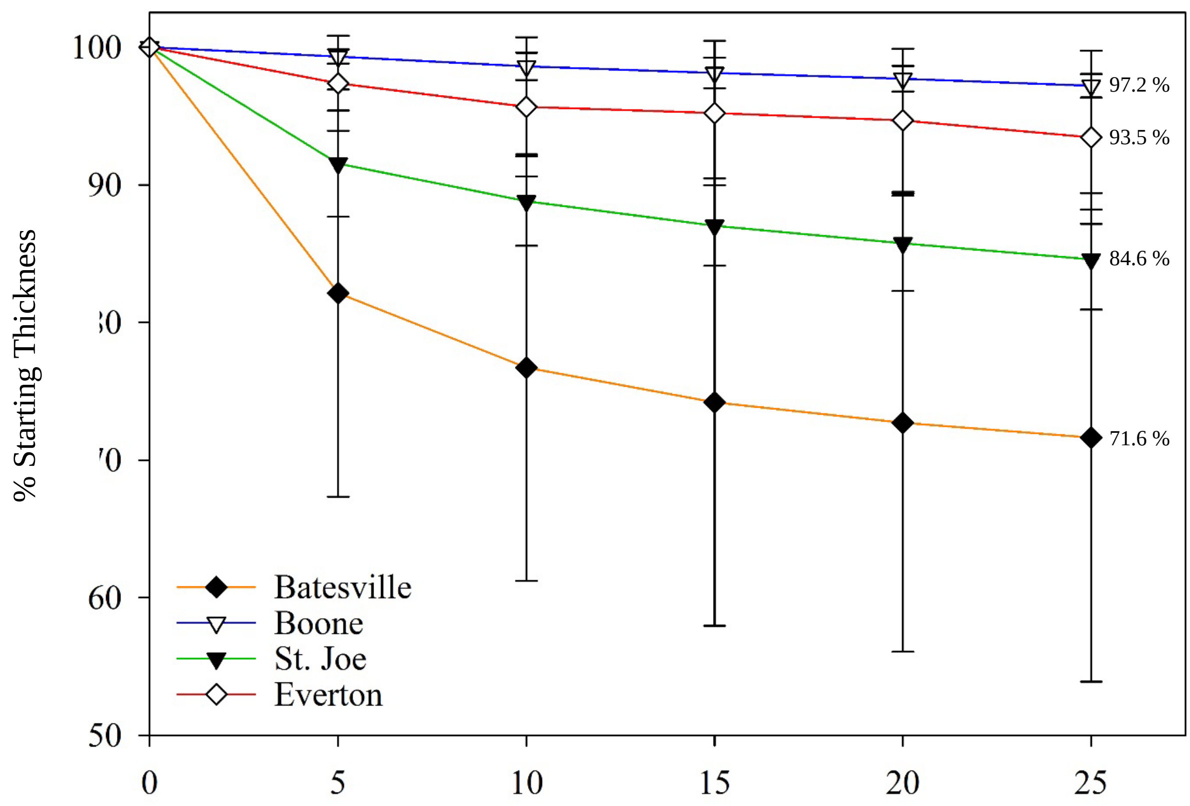

Figure 8: Change in thickness of sample discs over time during abrasion-mill experiments.

Throughout the abrasion mill experiment, the Batesville sample had the most significant and erratic thickness change in weight and thickness. During the initial abrasion cycle, the interaction of the disc with the abrasive aggregate resulted in an uneven failure along the bedding planes within the sandstone, which resulted in ~23 % and ~18 % reductions in weight and thickness respectively (Figs. 9, 10). Once established, this asymmetric feature continued to grow with continued abrasion cycles, resulting in continued significant but progressively lower weight and thickness loss (Figs. 7, 8). In contrast, the remaining samples had a very consistent erosion pattern with minor evidence to support the presence of an erosion track, or ring of concentrated mechanical erosion approximately 3 cm from the edge of the disc consistent with Sklar and Dietrich (2001) and Small et al. (2015). The erosion track is caused by a secondary circulation of aggregate within the mill, upward in the center of the mill, and downward along the acrylic cylinder (Small et al., 2015). The erosion track is much more prevalent on the St. Joe and Everton samples.

The Batesville sample displayed an initial erosion rate of 266.90 g/hr, the highest rate of erosion measured within this experiment (Fig. 11). Over the course of the abrasion cycles, the erosion rate of the Batesville sample decreased to 30.90 g/hr. The St. Joe sample had an initial erosion rate of 104.80 g/hr that quickly decreased to, and leveled out around, 18.90 g/hr. The Everton and Boone samples had a much more linear progression over the course of the experiment with initial erosion rates of 9.00 g/hr, 4.00 g/hr, respectively. The final erosion rates for these samples were 10.20 g/hr and 9.30 g/hr. The negative control cycle failed to generate any sediment from the interaction of the current on the sample discs. It can be concluded that all sediment generated throughout the abrasion mill experiments resulted from bedload interactions.

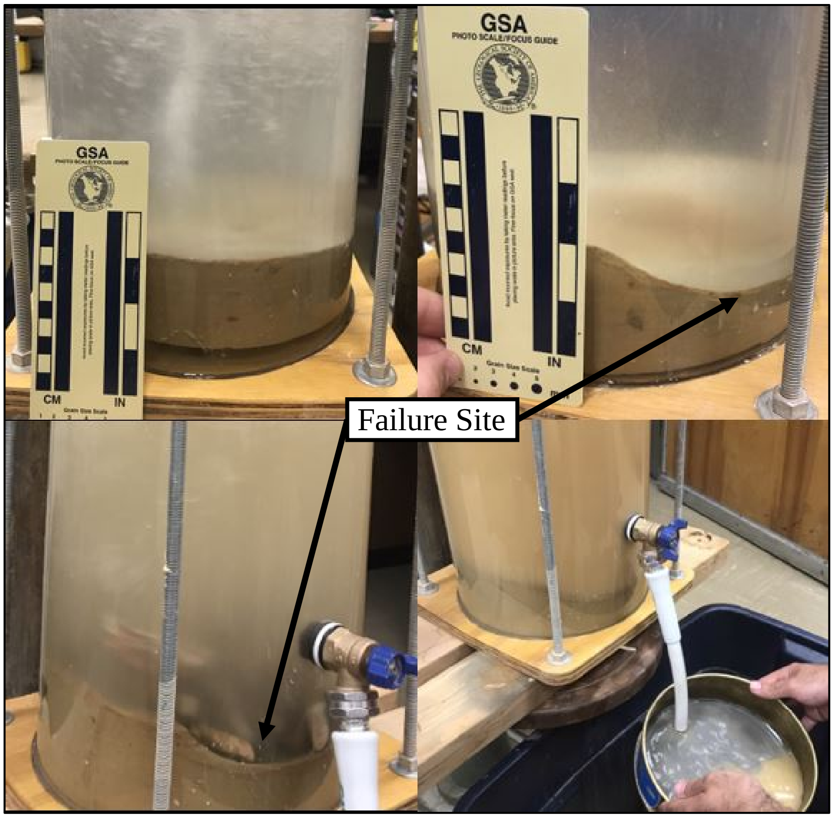

Figure 9: Photo depicting the development of the failure site along the bedding plane of the Batesville Sandstone sample during the abrasion cycles.

Throughout the five abrasion cycles, the sediment generated from the Batesville sample remained continuously suspended in the water column. The sample disc and aggregate were completely obscured by the slurry in as little as 10 minutes. Short glimpses of the aggregate were afforded when the aggregate impacted the clear acrylic cylinder. The sides of the sample disc were also partially visible through the acrylic cylinder until the settling of sediment filled the narrow gap between the cylinder and the disc. A similar issue happened with the St. Joe sample. Loss of visual contact with the sample took as little as 15-20 minutes. The water within the abrasion mill turned a brown/red color from the suspended sediment. Again, this issue persisted for the entirety of the five abrasion cycles, with a slight increase in visibility in the final two runs. In contrast, the Everton and Boone samples took almost an hour to generate enough

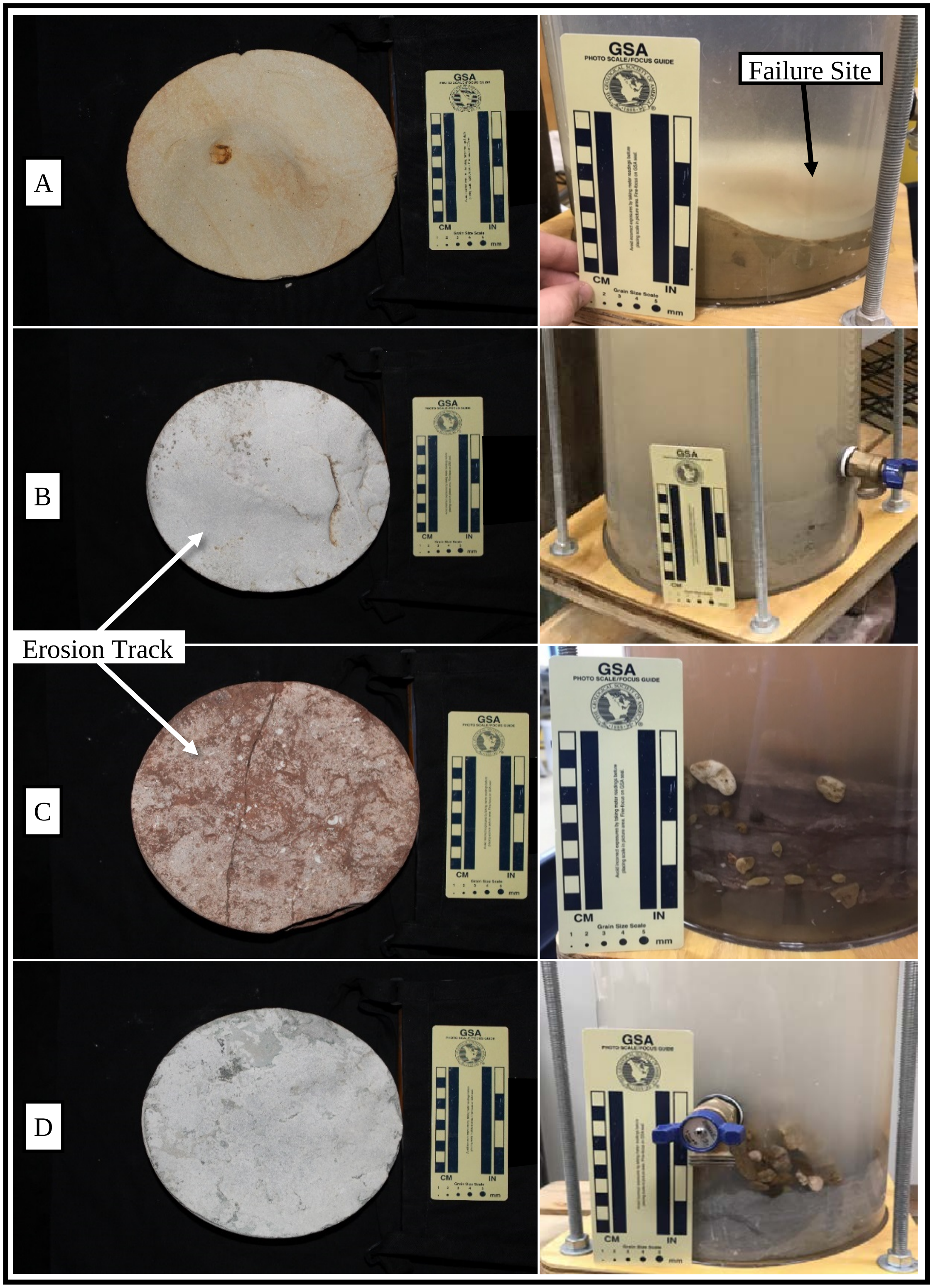

Figure 10: Photographs of the samples throughout the mechanical weathering tests. The images are arranged in stratigraphic order. A) Batesville Sandstone sample. B) Boone Formation sample. C) St. Joe Limestone sample. D) Everton Formation Sample. Two of the erosion tracks and the failure site are marked within the images.

suspended sediment to lose visual contact with the sample discs. Due to the loss of visual contact with the sample discs, continued interaction between the aggregate and sample discs was monitored through audible feedback. If and when the aggregate imbricated against the spigot nut, a distinct change in auditory feedback signaled a need to resolve the issue.

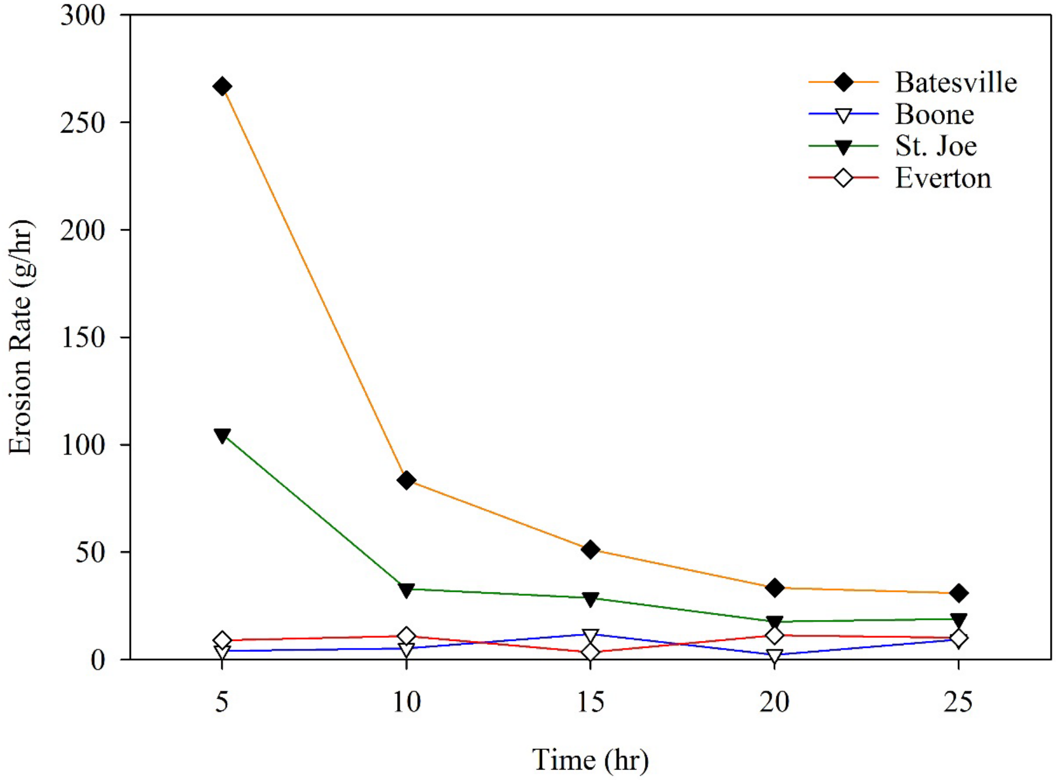

Figure 11: Erosion rate of the samples over time. Each point represents the time-averaged erosion rate for each individual mill run.

The general trend observed from the abrasion mill experiments is that the siliceous Batesville sample eroded at a very high rate compared to other samples. The Boone and Everton samples displayed a higher degree of competency to mechanical weathering processes generated in the abrasion mill. The St. Joe sample consistently exhibited intermediate susceptibility between the Batesville Sandstone and the Boone/Everton samples which displayed very similar mechanical weathering characteristics (Figs. 7-11).

Dissolution Experiments

Clear variations in the chemical weathering susceptibility of the samples were observed over the course of the 24-hour dissolution experiments. During the abrasion mill experiments, the Boone and the Everton samples displayed similar susceptibilities to mechanical weathering. In contrast, the Boone was significantly more susceptible to chemical weathering than the Everton sample. The Boone had an average dissolution of 98.8082% with a standard deviation of 0.1682%. The Everton had an average dissolution of 36.5210% on average with a standard deviation of 1.2967%. The Batesville had an average dissolution of 2.0394% on average with a standard deviation of 0.3099%. The St. Joe had an average dissolution of 89.6707% with a standard deviation of 0.4863% (Table 1) (Appendix C).

The Boone sample displayed the highest susceptibility to chemical weathering. Compared to the other samples tested, the Boone sample had an average dissolution ~2.71 times greater than the Everton, ~1.10 times greater than the St. Joe sample, and ~48.45 times greater than the Batesville sample.

In summary, the sample composed of siliceous material, despite containing carbonate cement, experienced the least dissolution of the samples tested. Variability was observed among the samples dominated by carbonate material. The Boone Formation samples, Boone (main body) and St. Joe, displayed nearly total dissolution susceptibility.

Table 1: Summarized result of the solubility test with samples in stratigraphic order.

Sample	*Average Dissolution (%)*	*Standard Deviation*
Batesville	2.0394	0.3099
Boone	98.8082	0.1682
St. Joe	89.6707	0.4863
Everton	36.5210	1.2967

DISCUSSION

Paired with the knowledge that the BNR is characterized by an atypical valley morphology that is not related to slope variation across heterogeneous lithologies, the variations observed must have another source. Based on the results of the tests performed for this thesis, the primary driver of the atypical valley morphology is the variations in the chemical weathering characteristics of the lithologies tested.

The key difference highlighted by this research is the observation that samples with a primary composition of carbonate displayed higher degrees of mechanical competency and lower degrees of chemical weathering resistance. The non-calcareous samples, as a whole, displayed a higher degree of chemical competency and lower degrees of mechanical weathering resistance.

Mechanical Weathering

The Boone and Everton Formation samples exhibited similar mechanical competency over the course of the abrasion mill tests, supporting the previous results from Schmidt Hammer tests in the field. At the conclusion of 25 hours in the abrasion mill, the Boone sample had lost 1.9576% of its initial mass while the Everton sample had lost 3.4605% of its initial mass. This difference is insignificant in the context of the other samples tested, the St. Joe Limestone Member and Batesville samples lost 13.3871% and 53.2982% of their initial mass, respectively.

The increased mass loss of the St. Joe Limestone Member sample may be related to the results from the thin-bedded bioclastic nature of the limestone. The decreased homogeneity of the St. Joe Limestone Member sample due to the inclusion of the 3-6 mm crinoid fragments could explain the increased mass-percent loss over the main body of the Boone sample. Small failures could propagate between these bioclastic fragments ultimately resulting in a marked increase in surface erosion. By far, the lithology most susceptible to mechanical erosion in this study was the Batesville Sandstone. Structural failures along the thin parallel laminations and crossbeds exposed during the abrasion cycles accounted for the unparalleled erosion rates (Figs. 9 and, 10).

The structural failures observed in the Batesville tests may also be used to explain the unparalleled erosion rate of this sample. The Batesville and St. Joe Limestone Member samples had initially very high erosion rates that decreased and stabilized after the third abrasion cycle (15 hours) (Fig. 10). The final erosion rate of these samples were 30.90 g/hr and18.9 g/hr, respectively. A possible explanation for this is increased surface area exposed to bedload interaction during the initial abrasion run. With an increased depth of erosion, the erosion rate approaches a linear value, consistent with experiments by Small et al (2015). The observed variation in the erosion rate with depth are consistent with the theoretical result of natural interactions between weathering and erosive forces in a stream channel (Howard, 1998; Hancock et al., 2011).

The rates of erosion of the Boone and Everton samples were linear through time. These samples had the same natural surfaces as the other samples tested, but did not display an exponential progression. The samples could have been exposed to the atmosphere for different amounts of time causing a difference in initial weathering. Varying degrees of heterogeneity could have resulted in the observed variation in the overall competency of the samples to mechanical weathering within the abrasion mill. Without the presence of the bedding planes that resulted in mechanical failures with the Batesville sample and a lack or decrease of bio-clastic crinoid fragments, that propagated fractures within the St. Joe sample, a more linear erosion rate could have been possible. One, or a combination of, these variables resulted in the linear erosion rate of these samples throughout the abrasion mill experiment (Fig. 10). The two components that controlled the erodibility of the samples throughout the abrasion mill experiments were: (1) the mechanical strength of the rock, which controls the erosion rate (Sklar and Dietrich, 2004; Small et al., 2015) and, (2) the surface roughness of the sample discs. Surface roughness can affect the kinetic interactions of the saltated abrasive aggregate with the sample surface (Huda and Small, 2014).

The initial erosion rates of the samples indicated a significant variation among the mechanical weathering characteristics of the BNR lithostratigraphies. Once the surface of the sample discs had been weathered smooth, as they would be in a natural environment, the erosion rates became significantly less variable. Once the four sample discs had a smooth, weathered surface, they displayed a similar response and comparable down-cutting rate. The sample disc with the highest erosion rate, the Batesville Sandstone sample, had an initial erosion rate 66.7 times higher than the disc with the lowest erosion rate, the Boone Formation. Through time, the four sample discs approached comparable erosion rates and the Batesville Sandstone sample, only eroded at a rate 3.3 times greater than the Boone Formation. With insignificant differences in the mechanical weathering of the four sample lithologies, it is not likely that the heterogeneity of the BNR lithologies plays a critical role in the mechanical weathering processes within the BNR watershed.

The samples used in this experiment were not collected from within the river channel, but instead from representative, accessible locations of outcrops within the watershed. It should be noted that the Batesville sample was collected from outside of the watershed, specifically north of the watershed at an accessible outcrop. However, the outcrop from which it was collected is representative of the Batesville as it appears within the watershed.

Chemical Weathering (Dissolution)

Within the chemical weathering tests, the variation among the chemical weathering potential of the Boone and Everton samples highlights the lithologic variable resulting in the atypical valley morphology. The 271% increase in chemical weathering potential of the Boone sample over the Everton sample could allow the lateral erosion rate of the BNR to outpace the vertical erosion rate. This relationship could explain the wider river valleys associated with the Boone Formation. In studies comparing hard crystalline rock to soft sedimentary rock, the established knowledge is that rock erodibility exerts a first-order control on channel morphology and incision (Goudie, 2016).

The contribution of dissolution experiments is the understanding that chemical properties of a sample are defining characteristics of the erodibility of a lithology. Although the Boone and Everton samples displayed similar mechanical weathering characteristics, the significant control on valley morphology within the BNR is the variability among chemical weathering characteristics of the cliff-forming lithostratigraphies present within the watershed. The previous solubility results closely parallel the results of this thesis (Table 2). Both studies, Keen-Zebert et al. (2017) and I, used the standard methods of Suarez et al. (2013) to analyze the chemical properties of the main cliff forming lithologies in the BNR watershed. The major difference between the results relies in the variability in the average dissolution percent of the Everton Formation. This variance could directly result from the inherent heterogeneity of the Everton Formation.

It has often been stated that lithology is a fundamental control on landscape evolution (Marshall and Roering, 2014), and the evolution of BNR is no different. The chemical weathering characteristics of the BNR lithologies dictates the BNR's geomorphological characteristics (Gilbert, 1877, Bursztyn et al., 2015; Goudie, 2016). The techniques used to analyze the BNR lithostratigraphies, could be used to study other watersheds in tectonically stable regions which incise heterogeneous lithologies or multiple rock types.

Table 2: Mechanical and chemical properties of the main lithologies of the Buffalo National River watershed adapted from Keen-Zebert et al. (2017).

Lithologic Unit[a]	*Main Lithology Type*	*N*[b]	*Schmidt hammer Q-value (Mean, Std. Dev.)*	*Solubility*[c] *(%)*
Middle Bloyd Formation	Sandstone	56	57, 11	-
Batesville Sandstone	Sandstone	104	63, 8	3
Boone Formation	Limestone	254	61, 10	100
St. Joe Member	Limestone	-	-	98
Everton Formation	Sandy Dolomite	202	54, 11	63
Newton Member	Sandstone	58	52, 6	-
St. Peter Sandstone	Sandstone	-	-	33

[a]For stratigraphic context, see Fig. 2.
[b]N is the number of rebound measurements made on each lithologic unit. Schmidt hammer rebound measurements were made on 1-4 sites per unit and a minimum of 50 measurements were made per site.
[c]Three samples from each lithologic unit were tested and the mean is given.

CONCLUSIONS

This study, which evaluated the physical and chemical weathering characteristics of major cliff-forming lithostratigraphies within the BNR watershed, establishes that heterogeneity among sedimentary layers may produce similar geomorphological characteristics as rivers which incise, and transition between, hard crystalline rock and soft sedimentary rock. Through the experimental adaptation of abrasion mill tests (Sklar and Dietrich, 2001; Small et al., 2015) and dissolution experiments (Suarez et al., 2013), this study yielded a useful approach that can be scaled to examine variations in the mechanical weathering characteristics between watersheds in a physiographic region. As a result of this research, it is established that within the BNR watershed, lithology is a key factor controlling the observed atypical valley morphology.

Mechanical weathering characteristics analyzed in the lab closely correlate with the field-based measurements collected prior to this study. The primary control on valley morphology within the BNR watershed is the variability in the chemical competence of the lithostratigraphies currently at river level. The more chemically competent Everton Formation is characterized by narrower river valleys with a complete uncoupling from the Schumm (1977) downstream progression models. Although the Everton and Boone Formations are both sedimentary, this river morphology resulting from their heterogeneity closely aligns with the previously established knowledge from research in hard crystalline versus soft sedimentary rocks.

Additional avenues that must now be explored include: (1) a petrographic study of current and future samples; (2) analyze more samples throughout the lithostratigraphies to characterize the heterogeneous formations more completely; (3) consideration of joint spacing as a possible control or variable in valley evolution.

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APPENDIX: A

Abrasion Mill Experiment

Data Tables

Color Code Key	
Sample	Color
Batesville	
Boone	
St. Joe	
Everton	

Table A1: The measurements collected throughout the abrasion-mill experiments are organized by sample type and separating the disc measurements and aggregate characteristics. NC stands for negative control.

Disc							***Aggregate***			
St. Joe Limestone Member										
Run #	**Duration (min)**	**Initial Disc Wt.**	**Final Disc Wt.**	**Sieved Wt.**	**% Not Recovered**	**% Loss**	**Initial Wt. (g)**	**Wt. After**	**Sieved Wt.**	**% Not Recovered**
1	300	7940.5	7416.5	344.43	2.26	6.60	905.81	879.00	13.69	1.45
2	300	7416.5	7252.5	107.15	0.77	2.21	1049.15	1017.67	4.90	2.53
3	300	7252.0	7108.5	88.43	0.76	1.98	914.36	868.12	8.31	4.15
4-NC	300	7108.5	7108.0	0.13	0.01	0.01	0.00	0.00	0.00	0.00
5	300	7108.0	7019.5	56.44	0.45	1.25	982.23	925.02	3.65	5.45
6	300	7020.0	6925.5	41.77	0.75	1.35	999.34	954.20	9.83	3.53
Batesville Sandstone										
Run #	**Duration (min)**	**Initial Disc Wt.**	**Final Disc Wt.**	**Sieved Wt.**	**% Not Recovered**	**% Loss**	**Initial Wt. (g)**	**Wt. After**	**Sieved Wt.**	**% Not Recovered**
7	300	5864.5	4530.0	915.92	7.14	22.76	1014.71	953.57	12.96	4.75
8	300	4530.0	4113.0	246.98	3.75	9.21	925.69	883.56	3.41	4.18
9	300	4113.0	3857.0	143.99	2.72	6.22	983.49	941.10	0.00	4.31
10-NC	300	3857.0	3857.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00
11	300	3857.0	3690.0	93.00	1.92	4.33	1033.14	990.80	4.57	3.66
12	300	3690.0	3535.5	87.37	1.82	4.19	988.22	945.72	3.65	3.93

Everton Formation										
Run #	**Duration (min)**	**Initial Disc Wt.**	**Final Disc Wt.**	**Sieved Wt.**	**% Not Recovered**	**% Loss**	**Initial Wt. (g)**	**Wt. After**	**Sieved Wt.**	**% Not Recovered**
13	300	6561	6516	8.22	0.56	0.69	888.59	865.49	0.71	2.52
14	300	6516	6461.5	17.01	0.58	0.84	1119.21	1066.44	0.63	4.66
15	300	6461.5	6444.5	5.51	0.18	0.26	875.61	862.50	1.19	1.36
16-NC	300	6444.5	6444.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00
17	300	6444.5	6388	19.25	0.58	0.88	892.72	841.11	3.54	5.38
18	300	6388	6337	15.08	0.56	0.80	1111.68	1063.88	2.65	4.06
Boone Formation										
Run #	**Duration (min)**	**Initial Disc Wt.**	**Final Disc Wt.**	**Sieved Wt.**	**% Not Recovered**	**% Loss**	**Initial Wt. (g)**	**Wt. After**	**Sieved Wt.**	**% Not Recovered**
19	300	8387	8367	9.3408	0.13	0.24	1594.91	1578.23	0.92	0.99
20	300	8367	8341	16.2108	0.12	0.31	1119.9	1083.53	0.46	3.21
21	300	8341	8281.5	22.1167	0.45	0.71	851.51	800.42	4.40	5.48
22-NC	300	8281.5	8281.5	0.0000	0.00	0.00	0.00	0.00	0.00	0.00
23	300	8281.5	8270.5	4.4418	0.08	0.13	752.58	744.66	0.94	0.93
24	300	8270.5	8224.0	20.0474	0.32	0.56	609.22	576.89	0.96	5.15

Table A2: The characteristics of the sediment created in each abrasion cycle.

Abrasion Mill DATA					
St. Joe Limestone Member					
Run#	***Gravel wt.***	***< 2mm wt.***	***Ratio-G***	***Ratio- Sand***	***Total***
1	63.2166	281.2150	18.3539	81.6461	344.4316
2	12.4083	94.7387	11.5806	88.4194	107.1470
3	17.4206	71.0087	19.7000	80.3000	88.4293
4-NC	0.0000	0.1300	0.0000	100.0000	0.1300
5	4.4758	51.9620	7.9305	92.0695	56.4378
6	4.4785	37.2872	10.7229	89.2771	41.7657
Batesville Sandstone					
Run#	***Gravel wt.***	***< 2mm wt.***	***Ratio-G***	***Ratio- Sand***	***Total***
7	10.0026	905.9172	1.0921	98.9079	915.9198
8	4.6945	242.2811	1.9008	98.0992	246.9756
9	11.0366	132.9490	7.6651	92.3349	143.9856
10-NC	0.0000	0.0000	0.0000	0.0000	0.0000
11	4.5472	88.4537	4.8894	95.1106	93.0009
12	2.9227	84.4473	3.3452	96.6548	87.3700

Everton Formation

Run#	***Gravel wt.***	***< 2mm wt.***	***Ratio-G***	***Ratio- Sand***	***Total***
13	0.1886	8.0356	2.2932	97.7068	8.2242
14	0.9558	16.0579	5.6178	94.3822	17.0137
15	1.4305	4.0816	25.9520	74.0480	5.5121
16-NC	0.0000	0.0000	0.0000	0.0000	0.0000
17	1.5844	17.6629	8.2318	91.7682	19.2473
18	1.9861	13.0938	13.1705	86.8295	15.0799

Boone Formation

Run#	***Gravel wt.***	***< 2mm wt.***	***Ratio-G***	***Ratio- Sand***	***Total***
19	0.8641	8.4767	9.2508	90.7492	9.3408
20	0.5441	15.6667	3.3564	96.6436	16.2108
21	1.42	20.6992	6.4092	93.5908	22.1167
22-NC	0.00	0.0000	0.0000	0.0000	0.0000
23	1.08	3.3588	24.3820	75.6180	4.4418
24	2.21	17.8377	11.0224	88.9776	20.0474

Table A3: The mass of the sample discs with cataloged measurements taken throughout the abrasion-mill experiments.

Name	Wt. Dry(g)	Wt. Wet	Run #	RPM	Aggregate #	D-Wt. Start	D-Wt. End	Wt. Loss	Wt. Sieved	%Not Recovered
Batesville	**5672.25**	5864.5	1	884	1	5864.5	4530.0	1334.5	915.92	7.14
Batesville			2	883	5	4530.0	4113.0	417.0	246.98	3.75
Batesville			3	885	9	4113.0	3857.0	256.0	143.99	2.72
Batesville			4-NC	885	NC	3857.0	3857.0	0.0	0.00	0.00
Batesville			5	883	14	3857.0	3690.0	167.0	93.00	1.92
Batesville			6	883	27	3690.0	3535.5	154.5	87.37	1.82
Final	**3300.5**									

Name	Run #	Rate of Wt. Loss (g/hr.)	Wt.%-Loss	Total Δ Wt.%	Beaker #
Batesville	1	266.90	22.76	22.76	11,15
Batesville	2	83.40	9.21	31.96	7
Batesville	3	51.20	6.22	38.19	2
Batesville	4-NC	0.00	0.00	38.19	NA
Batesville	5	33.40	4.33	42.51	3
Batesville	6	30.90	4.19	46.70	9

	Name	Wt. Wet	Run #	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6
Baseline	**Batesville**	5864.5	0	72.03	83.87	81.43	75.09	72.07	72.53
2018/6/7	**Batesville**	4530.0	1	63.79	77.28	46.63	53.04	65.56	67.62
2018/6/8	**Batesville**	4113.0	2	59.00	76.17	41.28	49.01	62.56	61.53
2018/6/11	**Batesville**	3857.0	3	56.47	75.57	39.07	45.76	60.93	60.35
2018/6/12	**Batesville**	3857.0	4-NC	56.47	75.57	39.07	45.76	60.93	60.35
2018/6/13	**Batesville**	3690.0	5	55.90	74.59	37.74	43.75	60.08	59.29
2018/6/14	**Batesville**	3535.5	6	55.71	74.18	35.56	41.92	59.92	59.06

Name	Wt. Dry (g)	Wt. Wet	Run #	RPM	Aggregate #	D-Wt. Start	Wt. End	Wt. Loss	Wt. Sieved	% Not Recovered
Everton	**6547.5**	6561	1	883	24	6561.0	6516.0	45.0	8.22	0.56
Everton			2	883	18	6516.0	6461.5	54.5	17.01	0.58
Everton			3	883	20	6461.5	6444.5	17.0	5.51	0.18
Everton			4-NC	883	NC	6444.5	6444.5	0.0	0.00	0.00
Everton			5	883	29	6444.5	6388.0	56.5	19.25	0.58
Everton			6	883	26	6388.0	6337.0	51.0	15.08	0.56
Final	**6323**									

Name	Run #	Rate of Wt. Loss (g/hr.)	Wt.%-Loss	Total Δ Wt.%	Beaker #
Everton	1	9.00	0.69	0.69	27
Everton	2	10.90	0.84	1.52	26
Everton	3	3.40	0.26	1.79	25
Everton	4-NC	0.00	0.00	1.79	NA
Everton	5	11.30	0.88	2.66	30
Everton	6	10.20	0.80	3.46	29

DATE	Name	Wt. Wet	Run #	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6
Baseline	**Everton**	6547.5	0	58.43	64.10	74.87	72.89	72.71	65.81
2018/10/5	**Everton**	6561.0	1	57.25	63.74	74.32	71.50	72.00	59.52
2018/10/6	**Everton**	6516.0	2	56.71	62.99	73.79	70.90	70.85	56.23
2018/10/7	**Everton**	6444.5	3	56.56	62.50	73.48	70.62	70.81	55.64
2018/10/8	**Everton**	6444.5	4-NC	56.56	62.50	73.48	70.62	70.81	55.64
2018/10/9	**Everton**	6388.0	5	56.41	61.68	73.41	70.26	70.32	55.38
2018/10/10	**Everton**	6337.0	6	56.51	60.06	73.18	69.65	69.87	53.24

Name	Wt. Dry (g)	Wt. Wet	Run #	RPM	Aggregate #	D-Wt. Start	Wt. End	Wt. Loss	Wt. Sieved	% Not Recovered
St. Joe	**7893.5**	7940.5	1	885	2	7940.5	7416.5	524.0	344.43	2.26
St. Joe			2	883	4	7416.5	7252.0	164.5	107.15	0.77
St. Joe			3	883	11	7252.0	7108.5	143.5	88.43	0.76
St. Joe			4-NC	885	NC	7108.5	7108.0	0.5	0.13	0.01
St. Joe			5	885	17	7108.0	7020.0	88.0	56.4378	0.44
St. Joe			6	883	21	7020.0	6925.5	94.5	41.7657	0.75
Final	**6887.5**									

Name	Run #	Rate of Wt. Loss	Wt. %-Loss	Total Δ Wt. %	Beaker #
St. Joe	1	104.80	6.60	6.60	19
St. Joe	2	32.90	2.22	8.82	16
St. Joe	3	28.70	1.98	10.80	20
St. Joe	4-NC	0.10	0.01	10.80	10
St. Joe	5	17.60	1.24	12.04	17
St. Joe	6	18.90	1.35	13.39	21

	Name	Wt. Wet	Run #	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6
Baseline	**St. Joe**	7940.5	0	84.18	91.91	94.95	90.48	71.99	78.78
2018/5/30	**St. Joe**	7416.5	1	78.97	86.80	80.91	84.18	67.96	69.59
2018/5/31	**St. Joe**	7252.0	2	78.05	81.03	79.80	82.16	65.42	68.00
2018/6/1	**St. Joe**	7108.5	3	74.10	80.30	79.62	81.97	64.15	65.57
2018/6/4	**St. Joe**	7108.0	4-NC	74.18	80.10	79.80	82.07	63.90	64.88
2018/6/5	**St. Joe**	7020.0	5	73.06	79.48	79.34	80.91	63.55	63.00
2018/6/6	**St. Joe**	6925.5	6	72.51	77.85	77.99	80.51	62.45	62.06

Name	Wt. Dry (g)	Wt. Wet	Run #	RPM	Aggregate #	D-Wt. Start	Wt. End	Wt. Loss	Wt. Sieved	% Not Recovered
Boone	**8358.5**	8387	1	883	7	8387.0	8367.0	20.0	9.34	0.13
Boone			2	883	8	8367.0	8341.0	26.0	16.21	0.12
Boone			3	883	15	8341.0	8281.5	59.5	22.12	0.45
Boone			4-NC	883	NC	8281.5	8281.5	0.0	0.00	0.00
Boone			5	883	16	8281.5	8270.5	11.0	4.44	0.08
Boone			6	883	22	8270.5	8224.0	46.5	20.05	0.32

Name	Run #	Rate of Wt. Loss (g/hr.)	Wt. %-Loss	Total Δ Wt. %	Beaker #
Boone	1	4.00	0.24	0.24	28
Boone	2	5.20	0.31	0.55	31
Boone	3	11.90	0.71	1.26	32
Boone	4-NC	0.00	0.00	1.26	NA
Boone	5	2.20	0.13	1.40	33
Boone	6	9.30	0.56	1.96	34

DATE	Name	Wt. Wet	Run #	Measure 1	Measure 2	Measure 3	Measure 4	Measure 5	Measure 6
Baseline	**Boone**	8387.0	0	67.52	79.51	102.74	96.52	85.96	78.39
2018/11/29	**Boone**	8367.0	1	67.26	79.23	102.6	95.43	85.44	77.23
2018/11/30	**Boone**	8341.0	2	66.76	79.02	101.18	95.40	85.40	75.81
2018/12/1	**Boone**	8281.5	3	66.11	78.94	100.88	94.79	85.11	75.36
2018/12/2	**Boone**	8281.5	4-NC	66.11	78.94	100.88	94.79	85.11	75.36
2018/12/3	**Boone**	8270.5	5	66.11	77.75	100.37	94.73	84.89	75.23
2018/12/4	**Boone**	8224.0	6	65.42	77.19	100.15	94.17	84.57	75.11

APPENDIX: B

Abrasive
Aggregate

Table B1: Size characteristics of the abrasive aggregate sampled from modern gravel-bars within the BNR watershed. T= theoretical or ideal weight. A= the actual weight of the samples. The pound sign (#) represents the number of individual constituents are in each class size. Green bars denote the representative grain size that the rest of the c class' were calculated against to preserve representative size-weight distribution.

#	Class	Run 1-T	Run 1- A
2	60	272.27	263.92
5	45	356.01	354.46
4	32	201.18	200.58
11	22.5	104.52	104.58
6	16	33.04	33.42
8	11.3	13.43	13.79
6	8	4.00	4.00
5	5.7	0.89	0.89
		Total=	
		985.33	975.64

#	Class	Run 11-T	Run 11-A
1	60	247.25	245.98
4	45	323.29	320.33
9	32	182.69	180.78
9	22.5	94.92	94.53
7	16	30.00	29.97
5	11.3	12.20	11.88
9	8	3.63	3.63
4	5.7	0.81	0.81
		Total=	
		894.78	887.91

#	Class	Run 21-T	Run 21-A
1	60	267.06	267.04
5	45	349.20	347.19
7	32	197.33	197.85
8	22.5	102.52	102.98
7	16	32.40	32.50
6	11.3	13.18	13.16
10	8	3.92	4.04
3	5.7	0.87	0.91
		Total=	
		966.49	965.67

#	Class	Run 2-T	Run 2-A
2	60	251.15	246.24
3	45	328.39	330.84
4	32	185.57	184.81
7	22.5	96.41	96.37
3	16	30.47	30.93
9	11.3	12.39	12.14
6	8	3.69	3.66
6	5.7	0.82	0.82
		Total=	
		908.89	905.81

#	Class	Run 12-T	Run 12-A
2	60	300.67	300.36
4	45	393.14	391.17
4	32	222.17	222.00
9	22.5	115.42	115.63
9	16	36.48	36.44
12	11.3	14.83	14.58
6	8	4.41	4.41
5	5.7	0.98	0.98
		Total=	
		1088.11	1085.57

#	Class	Run 22-T	Run 22-A
1	60	160.83	160.82
3	45	210.30	211.04
5	32	118.84	117.57
6	22.5	61.74	61.70
5	16	19.52	19.00
6	11.3	7.94	7.70
4	8	2.36	2.48
3	5.7	0.52	0.56
		Total=	
		582.05	580.87

#	Class	Run 3-T	Run 3- A
2	60	330.23	338.23
4	45	431.80	433.79
8	32	244.01	243.72
7	22.5	126.77	126.34
7	16	40.07	40.30
10	11.3	16.29	16.06
7	8	4.85	4.86
5	5.7	1.08	1.08
		Total=	
		1195.11	1204.38

#	Class	Run 4-T	Run 4-A
2	60	282.92	278.57
3	45	369.94	368.65
9	32	209.05	209.78
7	22.5	108.61	108.23
6	16	34.33	34.80
10	11.3	13.96	13.74
5	8	4.15	4.13
5	5.7	0.92	0.92
		Total=	
		1023.89	1018.82

#	Class	Run 5-T	Run 5- A
2	60	244.33	246.96
5	45	319.48	317.12
5	32	180.54	181.58
8	22.5	93.80	92.95
6	16	29.65	29.87
9	11.3	12.06	12.28
6	8	3.59	3.61
5	5.7	0.80	0.80
		Total=	
		884.22	885.17

#	Class	Run 13-T	Run 13-A
1	60	192.10	195.02
3	45	251.19	252.22
5	32	141.95	141.33
4	22.5	73.75	73.98
6	16	23.31	23.65
7	11.3	9.48	9.22
9	8	2.82	2.79
5	5.7	0.63	0.63
		Total=	
		695.22	698.84

#	Class	Run 14-T	Run 14-A
1	60	277.61	270.20
4	45	362.99	363.94
8	32	205.13	206.84
9	22.5	106.57	105.97
8	16	33.68	33.93
9	11.3	13.70	13.31
8	8	4.07	4.07
5	5.7	0.90	0.90
		Total=	
		1004.67	999.16

#	Class	Run 15-T	Run 15-A
1	60	223.27	222.65
3	45	291.94	291.43
8	32	164.97	165.67
6	22.5	85.71	85.69
5	16	27.09	27.55
8	11.3	11.02	11.61
8	8	3.28	3.28
5	5.7	0.73	0.73
		Total=	
		808.00	808.61

#	Class	Run 23-T	Run 23-A
1	60	181.52	181.51
3	45	237.35	236.97
6	32	134.13	135.45
7	22.5	69.69	69.23
6	16	22.03	22.77
7	11.3	8.96	9.23
5	8	2.66	2.72
6	5.7	0.59	0.58
		Total=	
		656.93	658.46

#	Class	Run 24-T	Run 24-A
1	60	232.02	232.00
4	45	303.38	304.51
6	32	171.44	171.84
8	22.5	89.07	89.94
7	16	28.15	28.32
8	11.3	11.45	11.52
8	8	3.41	3.32
2	5.7	0.76	0.77
		Total=	
		839.67	842.22

#	Class	Run 25-T	Run 25-A
1	60	161.06	161.05
3	45	210.60	211.70
5	32	119.01	120.62
5	22.5	61.83	61.49
5	16	19.54	19.08
5	11.3	7.95	7.87
16	8	2.36	7.67
4	5.7	0.52	0.56
		Total=	
		582.88	590.04

#	Class	Run 6-T	Run 6-A
2	60	310.03	311.86
5	45	405.39	406.14
8	32	229.09	229.72
10	22.5	119.02	118.79
7	16	37.62	37.54
6	11.3	15.30	15.19
6	8	4.55	4.52
5	5.7	1.01	1.01
		Total=	
		1122.00	1124.77

#	Class	Run 16-T	Run 16-A
1	60	197.40	197.38
4	45	258.11	257.46
3	32	145.86	145.77
9	22.5	75.78	75.89
8	16	23.95	24.17
4	11.3	9.74	9.33
6	8	2.90	2.76
3	5.7	0.64	0.65
		Total=	
		714.37	713.41

#	Class	Run 26-T	Run 26-A
1	60	293.32	293.30
4	45	383.54	385.90
7	32	216.74	215.04
11	22.5	112.60	112.96
9	16	35.59	35.79
10	11.3	14.47	14.75
10	8	4.31	4.27
5	5.7	0.96	0.93
		Total=	
		1061.53	1062.94

#	Class	Run 7-T	Run 7- A
2	60	422.59	425.15
5	45	552.56	552.02
10	32	312.25	311.07
14	22.5	162.23	163.00
11	16	51.28	51.10
15	11.3	20.85	20.67
12	8	6.20	6.24
5	5.7	1.38	1.38
		Total=	
		1529.33	1530.63

#	Class	Run 17-T	Run 17-A
1	60	260.08	260.06
4	45	340.07	340.21
9	32	192.18	192.84
7	22.5	99.84	100.73
7	16	31.56	31.08
8	11.3	12.83	13.03
8	8	3.82	3.97
5	5.7	0.85	0.80
		Total=	
		941.22	942.72

#	Class	Run 27-T	Run 27-A
1	60	265.79	265.77
3	45	347.54	347.05
9	32	196.40	197.34
6	22.5	102.03	102.72
11	16	32.25	32.20
6	11.3	13.11	13.37
12	8	3.90	3.85
5	5.7	0.87	0.89
		Total=	
		961.89	963.19

#	Class	Run 8-T	Run 8-A
2	60	298.64	297.03
5	45	390.49	388.39
8	32	220.67	220.36
11	22.5	114.65	114.98
6	16	36.24	36.02
9	11.3	14.73	14.49
9	8	4.38	4.36
5	5.7	0.97	0.97
		Total=	
		1080.78	1076.60

#	Class	Run 18-T	Run 18-A
1	60	295.66	295.64
6	45	386.60	386.37
9	32	218.47	217.77
10	22.5	113.50	112.59
8	16	35.88	35.20
10	11.3	14.59	14.78
8	8	4.34	4.54
6	5.7	0.96	0.94
		Total=	
		1070.00	1067.83

#	Class	Run 28-T	Run 28-A
1	60	202.41	202.39
5	45	264.66	266.91
4	32	149.56	150.67
7	22.5	77.70	77.26
7	16	24.56	24.34
8	11.3	9.99	10.12
8	8	2.97	3.06
4	5.7	0.66	0.67
		Total=	
		732.50	735.42

#	Class	Run 9-T	Run 9- A
2	60	259.00	261.87
5	45	338.67	340.55
6	32	191.38	191.89
9	22.5	99.43	99.26
8	16	31.43	31.95
9	11.3	12.78	12.95
5	8	3.80	3.87
5	5.7	0.84	0.84
		Total=	
		937.33	943.18

#	Class	Run 19-T	Run 19-A
1	60	387.44	387.41
7	45	506.60	503.56
8	32	286.28	258.55
10	22.5	148.74	148.18
13	16	47.01	47.12
13	11.3	19.12	19.24
8	8	5.69	5.62
6	5.7	1.26	1.24
		Total=	
		1402.14	1370.92

#	Class	Run 29-T	Run 29-A
1	60	233.51	233.49
5	45	305.33	306.40
4	32	172.54	171.23
6	22.5	89.64	90.10
7	16	28.33	28.70
7	11.3	11.52	11.62
11	8	3.43	3.48
3	5.7	0.76	0.77
		Total=	
		845.06	845.79

#	Class	Run 10-T	Run 10-A
2	60	338.74	335.64
5	45	442.92	443.89
6	32	250.30	249.30
12	22.5	130.04	130.19
10	16	41.10	41.54
12	11.3	16.71	16.93
9	8	4.97	4.99
5	5.7	1.10	1.10
		Total=	
		1225.89	1223.58

#	Class	Run 20-T	Run 20-A
1	60	228.94	228.92
3	45	299.35	302.32
7	32	169.16	170.26
8	22.5	87.89	87.67
6	16	27.78	27.84
11	11.3	11.30	11.41
9	8	3.36	3.31
3	5.7	0.75	0.78
		Total=	
		828.52	832.51

#	Class	Run 30-T	Run 30-A
1	60	214.13	214.11
4	45	279.98	278.25
6	32	158.22	158.65
9	22.5	82.20	82.61
9	16	25.98	25.79
8	11.3	10.56	10.96
7	8	3.14	3.20
5	5.7	0.70	0.68
		Total=	
		774.92	774.25

APPENDIX: C

Chemical
Dissolution Results

Table C1: Powdered sample weights and dissolution results.

Sample #	Source	Rock Type	Date	Sample Wt. (g)	Beaker Wt.	Total Wt.	Final Sample Wt.	%Dissolved	AVG
16	Rock 6	St. Joe	5/24/2018	1.0008	47.8242	47.93	0.1022	89.7915	
17	Rock 6	St. Joe	5/24/2018	1.0005	52.0173	52.13	0.1087	89.1354	
18	Rock 6	St. Joe	5/24/2018	1.0002	50.8604	50.96	0.0992	90.0853	89.67
19	Rock 2	Everton	5/25/2018	0.9999	49.2146	49.84	0.6209	37.9038	
20	Rock 2	Everton	5/25/2018	0.9999	52.4780	53.11	0.6367	36.3270	
21	Rock 2	Everton	5/25/2018	0.9989	53.3890	54.04	0.6460	35.3322	36.52
22	Rock 4	Bloyd SS	5/25/2018	0.9981	51.6599	52.63	0.9701	2.8087	
23	Rock 4	Bloyd SS	5/25/2018	0.9995	52.3314	53.31	0.9801	1.9376	
24	Rock4	Bloyd SS	5/25/2018	1.0005	54.1452	55.13	0.9852	1.5292	2.09
25	Rock 5	Batesville	1/22/2019	1.0008	74.3231	75.30	0.9778	2.2957	
26	Rock 5	Batesville	1/22/2019	1.0010	74.9083	75.89	0.9840	1.6950	
27	Rock 5	Batesville	1/22/2019	1.0007	75.5978	76.58	0.9794	2.1277	2.04
28	Rock 7	Boone	1/22/2019	1.0008	75.6611	75.67	0.0128	98.7235	
29	Rock 7	Boone	1/22/2019	1.0003	76.0658	76.08	0.0100	99.0020	
30	Rock 7	Boone	1/22/2019	1.0007	75.9499	75.96	0.0130	98.6992	98.81