Spring 2016

Petrographic Controls on Weathering of the Haney Limestone

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PETROGRAPHIC CONTROLS ON WEATHERING OF THE HANEY LIMESTONE

A Thesis
Presented to
The Faculty of the Department of Geography and Geology
Western Kentucky University
Bowling Green, Kentucky

In Partial Fulfillment
of the Requirements for the Degree
Master of Science

By
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May 2016

PETROGRAPIC CONTROLS ON WEATHERING OF THE HANEY LIMESTONE

Date Recommended April 20, 2016

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Dean, Graduate Studies and Research   4/25/16
Date

Acknowledgements

This study is the result of tremendous support from faculty, fellow graduate students, and property owners who have provided the needed tools that were required for the completion of this project. A special thanks to Dr. Michael May, my thesis advisor, for discussions relating karst geology with carbonate petrology from which this project emerged, and for his support throughout the project in providing guidance from crafting a research proposal to the finished product. Thanks to Dr. Chris Groves for providing his karst knowledge throughout the process and for providing crucial contacts that were key to the completion of this thesis. A thank you goes out to Dr. Aaron Celestian for usage of the XRD. Thanks also to Dr. Fred Siewers for assistance with the petrographic thin sections and providing knowledge of carbonate petrology throughout the process.

A special thanks goes to the Illinois Basin Group of Tyler Bodine, Kort Butler, Ryan Hart, and Andrew Reeder for their assistance throughout my graduate school career including, but not limited to, advice throughout the graduate school process, help in core- and thin-section analysis, and helping prepare for thesis-related presentations at the student research conference and the Geological Society of America’s 2014 conference in Vancouver, British Columbia. I especially want to thank Kort Butler for his assistance during field work at Alexander Creek in May, 2014, and Tyler Bodine and Andrew Reeder for access and assistance with the cores from Stampede Mine in Logan County. Special thanks go to Sarah Arpin for sharing her data and cave maps that were completed while she did her thesis, and for providing a framework for karst in the Haney Limestone.

Special thanks go to Kenneth Cowles and his family in Edmonson County for permission to use their property for this project. A special thanks goes to Linda Cook, the tour guide at Cub Run Cave, for her assistance and access to the cave site. I am appreciative of all of the support from my family, faculty/staff, friends, and fellow students who were supportive throughout the thesis process. I am especially thankful for my family and friends who all understood the time sacrifice that was required for this thesis.

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Directed by: Michael May, Chris Groves, and Fred Siewers

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Although karst processes in south central Kentucky have been studied extensively, the Haney Limestone Member of the Golconda Formation has not been studied in detail in contrast to limestones stratigraphically below it that are thicker. In addition, the relationship between petrographic features of the Haney Limestone and the formation of caves and karst features has not been studied extensively compared to lithographic, petrographic, or structural variables.

Petrographic data were collected using core and surface exposures across the study area of south central Kentucky from northern Logan and Warren counties up toward the Rough Creek Graben region, and stratigraphic columns were constructed. Twenty-three petrographic thin-sections were made from samples collected at these sites, described, and photo documented. These studies have revealed that grain size and silica content play a role in how the Haney weathers both in surface exposure and in a cave setting. Petrographic thin-section analysis suggests that the Haney possesses a complex diagenetic history that involves several generations of calcite cementation, dolomitization, silicification, and pressure-dissolution features in the form of microstylolites and stylolites. A basal shale in the Big Clifty occurs commonly at the Big Clifty/Haney contact and acts as a confining hydrogeologic unit, which is favorable for the development of springs and caves.

Studying the Haney Limestone petrographically provides an opportunity not only to study a lesser known unit, but also in the context of relating petrographic influences or controls on the morphology of Haney cave-passage development under both vadose and phreatic hydrologic regimens. Heretofore, the vast majority of cave morphological studies have only linked the hydrologic regimen to formation of cave passages, but such studies have not considered petrographic variance. This study not only relates karst features to petrographic variance, but also provides a petrographical description of the Haney across south central Kentucky, whereas many previous studies focused on Illinois and Indiana. Understanding Haney petrographic characteristics also provides context for potential carbonate hydrocarbon reservoirs and groundwater resources in the Illinois Basin region.

Chapter 1: Introduction and Study Area

1.1 Introduction, Scope, and Significance

The Haney Limestone Member is a classic example of a modern karst aquifer providing an analog to paleokarst aquifers such as the Ellenburger Group (Kerans, 1988), Knox Group (Anderson, 1991; Gooding, 2012), and the Yates Oil Field (Craig, 1988). Paleokarst aquifers contain Mississippi Valley Type (MVT) deposits such as lead, zinc, and barite, along with being plentiful hydrocarbon reservoirs. Modern karst is also a geohazard to everyday life due to sinkholes and the rapid spread of contaminants in groundwater. Numerous communities nationwide are negatively affected by the hazards of a karst landscape, and 10-15% of the world's land surface is karst (Palmer, 1991). Previous authors have addressed the hydrologic and geochemical aspects of karst, but this study addresses the Haney Limestone Member petrographically, in addition to those hydrologic and geochemical variables as they relate to weathering in surface exposure, development of karst features, and the resultant morphology of cave passages.

The Haney Limestone Member is part of the Late Mississippian Golconda Formation, which includes the Big Clifty Sandstone Member and the Beech Creek Limestone Member (Treworgy, 1990). Eastern Hardin County, Illinois, is the type section of the Haney where it was first described (Swann, 1963). The Haney outcrops, across western and south central Kentucky, and contains a semi-extensive cave system featuring nine caves of over 100 meters in length in Edmonson, Hart, and Warren counties, as well as over 40 mapped caves in the three-county area (Arpin, 2013). Due to proximity of the Mammoth Cave-Flint Ridge cave system, which is developed in the thicker and stratigraphically lower Girkin, Ste. Genevieve, and St. Louis limestones, the Haney in the

Mammoth Cave region has been relatively overlooked in comparison to those thicker carbonate units.

This study focuses on the petrographic nature of the Haney, which also includes consideration of carbonate porosity (Archie, 1952; Choquette and Prey, 1970; Lucia, 1995a, b; Palmer 1995; Loucks, 1999). Understanding porosity development in carbonate reservoirs is crucial for many aspects of geology, with applications in hydrocarbon explorations and development, groundwater resource identification and protection, mapping paleo-karst features, and better understanding modern karst features. One important aspect of this project is cavernous porosity, which is defined by Choquette and Prey (1970) as a porosity space that is large enough for a human to crawl through.

The purpose of this thesis is to provide a petrographic analysis of the Haney, and then relate these findings to the geomorphological features of the cave passages in a cave and weathering profiles at surface exposures. Questions that are addressed in this study include: 1) What are the dominant petrographic features, including both depositional and diagenetic? 2) How do such petrographic characteristics influence or control the formation of cave development and weathering? 3) How can these variables influence the reservoir and aquifer properties of the Haney? The main goal is to provide context for petrographic features that influence weathering, karst development, and development of porosity of potential hydrocarbon reservoirs and groundwater aquifers.

1.2 Study Area and Basinal Setting

The study area is situated along the southeastern margin of the Illinois Basin (Figure 1). The study area includes Edmonson, Grayson, Hart, and Warren counties in south central Kentucky. Stratigraphic columns for the area are shown in Figures 2 and 3 and sample locations relative to major tectonic features are illustrated in Figure 4. This is a classic karst area that encompasses both the Mammoth Cave-Flint Ridge cave systems and Haney Limestone karst areas. Hydrocarbon production occurs particularly in the Chesterian sandstone units such as the Big Clifty, Hardinsburg, and the Tar Springs, as well as in the Ste. Genevieve Limestone (Treworgy, 1990).

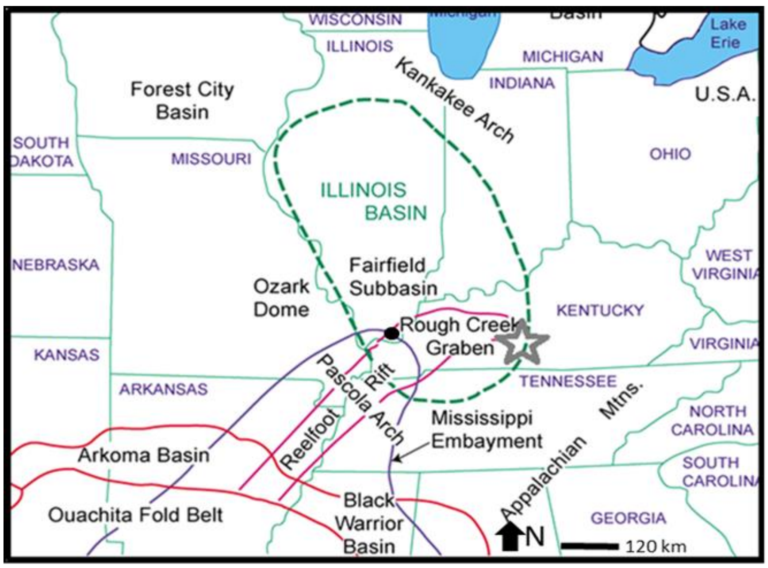

Figure 1. Map of the Illinois Basin and major structural features. The star is the approximate study area and the circle is the type section.
Source: Modified from Buschbach and Kolata (1990).

The Illinois Basin formed from an initial failed rift system and has been subjected to multiple generations of subsidence and compression, which have been related to sedimentary content and tectonics regimen (Kolata and Nelson, 1990). The Illinois Basin is surrounded by the Cincinnati Arch on the east, which is a positive structural feature, the Mississippian Embayment and Ozarks Uplift to the west, and the Wisconsin Uplands to the north (Weller and Bell, 1937). The interior of the basin is overlain by Pennsylvanian-aged siliciclastic sediments such as conglomerate, sandstone, siltstone, and shale, while carbonates and coal provide a minor contribution to the Pennsylvanian sediment package (Eble et al., 2001), with the older Mississippian-aged rock units flanking the basin and older units in the subsurface. The siliciclastic units were derived from the Canadian Shield area, with some coming from the rise of the Appalachians that formed later in the Paleozoic; these units thicken southwestwardly into the rift complex (Buschbach and Kolata, 1990). On the southeastern edge of the outcropping Pennsylvanian strata are the Mississippian outcrops in an area known as the Pennyroyal Plateau. This is where the research for this study is located, as the area features middle Mississippian carbonates and alternating siliciclastic/carbonate units of the late Mississippian. More information about the Illinois Basin is presented by Buschbach and Kolata (1990), Kolata (1990), Kolata and Nelson (1990a; b), Lamborg et al. (1990), Leighton (1990), Nelson (1990), and Treworgy (1990).

Period	Series	Unit Name	Unit Thickness (meters)
MISSISSIPPIAN	CHESTER	Leitchfield Fm.	45
		Glen Dean Limestone	15
		Hardinsburg Sandstone	18
		Haney Limestone Member	12
		Big Clifty Sandstone Member/ Fraileys Shale Member	**15-18**
		Girkin Limestone	40-43
	MERAMEC	Ste. Genevieve Limestone	34-37
		St. Louis Limestone	53-60
		Salem Limestone	20-27
		Harrodsburg Limestone	9-24

Chester Escarpment and Uplands (Leitchfield Fm. to Girkin Limestone)
Mammoth Cave (Girkin Limestone to St. Louis Limestone)
Sinkhole Plain (Ste. Genevieve Limestone to St. Louis Limestone)

Figure 2. Stratigraphic nomenclature of Middle to Upper Mississippian rocks in south central Kentucky in relation to landforms in the area. The Haney is in bold font. Source: Modified from Palmer (1981).

Period	Series	Unit Name	Unit Thickness (meters)
MISSISSIPPIAN	CHESTER	Buffalo Wallow Formation	44-67
		Tar Springs Formation	11-20
		Glen Dean Limestone	11-23
		Hardinsburg Sandstone	8-17
		Haney Limestone Member	**8-17**
		Big Clifty Sandstone/Fraileys Shale Member	11-23
		Beech Creek Limestone Member	2.5-5
		Elwren Sandstone	1-3
		Reelsville Limestone	4.5-14
		Sample Sandstone	1-14
		Beaver Bend Limestone	4.5-9
		Mooretown Formation	0-4.5
		Paoli Limestone	8-14
	MERAMEC	Ste. Genevieve Limestone	75
		St. Louis Limestone	73

Figure 3. Stratigraphic nomenclature of Middle to Upper Mississippian rocks in Ohio and Grayson counties. Unlike the Mammoth Cave region stratigraphic column, the Girkin Formation is replaced by the Paoli through Beech Creek Limestone Member sequence, due to increased siliciclastic deposition during Girkin time. The Tar Springs Formation and Buffalo Wallow Formation are equivalent to the Leitchfield Formation in Figure 2. Stratigraphic column is from the Caneyville, KY quadrangle. The Haney Limestone is in bold font. Source: Modified from Gildersleeve and Johnson (1978).

Rocks of the Mississippian Period in the study area are characterized as the mostly marine Meramec Series of the early Mississippian and the Chesterian Series which contain both siliciclastic and carbonate packages (Treworgy, 1990). In the Mississippian Period over 330 million years ago, south central Kentucky was covered by a clear and warm, shallow, tropical sea. This paleogeographic setting set the stage for deposition of carbonate units throughout the Mississippian. Periodically, there were deltaic influences from an ancient major river system known as the Michigan River, which brought an influx of siliciclastics to the basin from the Canadian Shield region

(Swann, 1963; Treworgy 1990). Siliciclastic sources from the Appalachians occurred during the Ordovician and Devonian, and this eastern sediment source potentially contributed to siliciclastic content later in the Paleozoic (Buschbach and Kolata, 1990).

The thick sequence of carbonate units followed by siliciclastic cap rocks of the Chester Series characterizes the central Kentucky karst. The Chester Escarpment separates the cap rock (Big Clifty Sandstone) from the soluble and thicker Girkin, Ste. Genevieve, and St. Louis Limestones (Figure 2). An exception to this occurs in Ohio and portions of Grayson counties, where periods of siliciclastic deposition occurred when the Girkin was being deposited. The Girkin is replaced by an alternating sequence of siliciclastics and carbonates at these locations (Figure 3). Below the escarpment is the sinkhole plain, where the Big Clifty has been removed by erosion, thus permitting development of a sinkhole plain, with a few scattered knobs. The sinkhole plain is formed within the St. Louis and Ste. Genevieve Limestones (White et al., 1970). Mammoth Cave National Park, which is formed in the Girkin, Ste. Genevieve, and upper half of the St. Louis, has its ground surface located atop of the escarpment above the Big Clifty Sandstone and, in some cases, atop the basal Pennsylvanian Caseyville Formation (Palmer, 1981). Caves in the Haney Limestone Member form in the Chester Cuesta (Chester Plateau) on top of the Chester Escarpment.

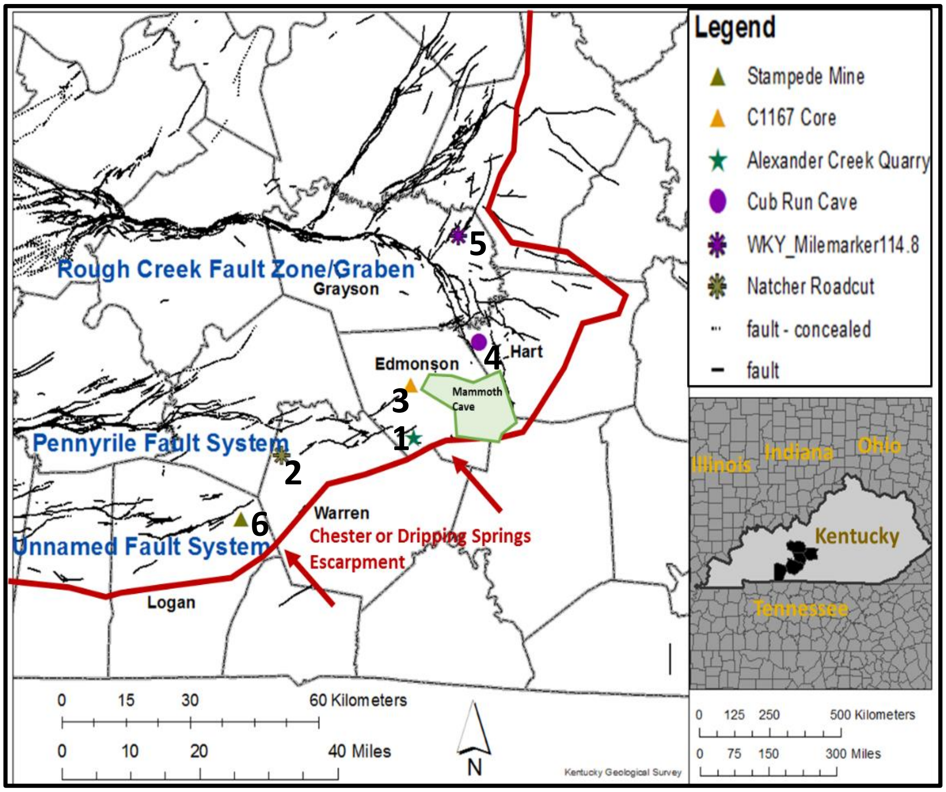

Figure 4. Study area map relative to major tectonic features. The green star at location 1 shows an abandoned quarry at Alexander Creek. The gold star at location 2 is a roadcut at the Natcher Parkway. Location 3 is core taken from a drill site in central Edmonson County. Location 4 is Cub Run Cave. Location 5 is a roadcut in eastern Grayson County. Location 6 is core taken from the Stampede Mine in northeastern Logan County. Source: Modified from KGS (2016a).

Chapter 2: Background on the Haney Limestone

2.1 Depositional Features of the Haney

2.1.1 Fossils

The Haney contains a classic Mississippian marine fauna, which includes echinoderms, bryozoans, foraminifera, and fragments of brachiopods, trilobites/ostracods, bivalves, mollusks, and some algae (Vincent, 1975; Treworgy, 1985; Treworgy, 1988; Foster, 1990). Identification of fossil assemblages is an important tool for understanding depositional environment. For example, different types of bryozoans prefer different substrate conditions. *Archimedes sp.*, a fenestrate bryozoan, prefers a relatively quiet bottom on the leeward side of a shoal versus other fenestrate bryozoans, which could live on the shoals themselves (McKinney and Gault, 1980).

2.1.2 Ooids

Among the Chester Series, the Haney has the greatest ooid content, which generally decreases further up into the Chester Series (Harris and Fraunfelter, 1993). Ooids in the Haney average about 0.8mm in diameter (Treworgy, 1985), have a radial internal texture (Keith and Zuppann, 1993) and commonly have a skeletal nucleus (Treworgy, 1985). Oolitic shoals represent an agitated and high-energy environment, and such shoals were influenced by eustatic and tectonic changes throughout the Mississippian (Keith and Zuppann, 1993). Oolitic shoals can also be related to mounds of skeletal material as skeletal grainstone is common beneath oolitic facies. Storm events and siliciclastic input that disrupted carbonate production would have necessarily disturbed these oolitic zones (Harris and Fraunfelter, 1993).

2.1.3 Peloids, Intraclasts, and Detrital Quartz

Peloids, intraclasts, and detrital quartz are other depositional constituents that occur in the Haney. Intraclasts are typically subrounded and are typically described as storm deposits or paleosols in the Golconda Formation (Treworgy, 1985). Peloids lack internal structure, and these can either be pellets of fecal origin or recrystallized ooids. Peloids are typically found in skeletal packstone-grainstone, oolitic grainstone, and carbonate mudstone. Detrital quartz is rare in the Haney but can occur as fine-grained subangular clasts (Treworgy, 1985).

2.2 Environments of Deposition

Skeletal/oolitic-dominated Haney Limestone is characterized by the movement of oolitic shoals in a high-energy shallow marine environment (Vincent, 1975; Treworgy, 1985; 1988). Facies in the Haney range from skeletal mudstone-wackestone to skeletal-oolitic grainstone, with the latter being the most dominant (Treworgy, 1985). There are also a few thin, interbedded shale partings throughout the Haney at various locations. Shale in the Haney increases in abundance toward the center of the basin (Nelson et al., 2002), and one possibility for the shale content is that there were times when fine-grained siliciclastic material was spread and deposited across the area by tides, especially in any topographic lows or low-energy environments (Treworgy, 1988). There is an increase of oolitic bodies along the margins of the basin in the Haney where conditions were favorable for the development of high-energy environments that allow oolitic shoals to be established (Harris and Fraunfelter, 1993).

The main depositional environment of the Haney Limestone is characterized by mobile oolitic shoals, similar to the modern Bahamas (Vincent, 1975). These oolitic shoals are relatively linear and form on a shallow platform (Vincent, 1975; Halley et al., 1983). The surrounding depositional environments, as seen in Figure 5, are influenced by the movement of these shoals. Protected shoal environments leeward from the shoal, have slightly lower energy (i.e., as manifested in the deposition of skeletal packstone) and feature a different facies compared to the windward unprotected shoals (i.e., deposition of skeletal grainstone). The top of oolitic shoals is represented by the deposition of oolitic grainstone facies. Oolitic shoals act as a barrier between relatively high-energy zones and create relatively low-energy lagoonal or protected shoal environments more proximal to shore (Vincent, 1975; Enos, 1983; Halley et al., 1983). One difference is noted between the Bahamas modern analog and the Haney is that unlike the Bahamas, there is an absence of a steep shelf break in the slope of the Haney seafloor, along with muddier facies occurring downdip into the central part of the Illinois Basin (Vincent, 1975: Treworgy, 1988). A carbonate ramp model such as the modern Persian Gulf is a more applicable analog for the Haney versus the Bahamas (Ahr, 1973; Halley et al., 1983, Foster, 1990; Keith and Zuppann, 1993).

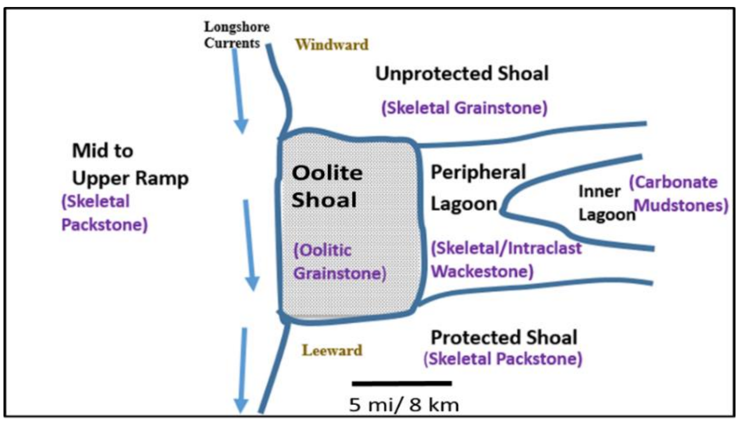

Figure 5. Depositional environment diagram for the Haney Limestone. Mobile oolitic shoals characterize the environment of the Haney; but, unlike the Bahamas the Haney is part of a carbonate ramp system and not a carbonate shelf system.
Source: Modified from Vincent (1975) and Foster (1990).

2.2.1 Middle to Upper Ramp

The middle to upper ramp is characterized by muddy facies downdip and grainstone and packstone units updip (Ahr, 1973). The middle to upper ramp facies in the Haney is typically a packstone or grainstone unit (Treworgy, 1985; 1988) and is typically influenced by the proximity to oolitic shoals and skeletal banks (Vincent, 1975; Foster, 1990). The Rough Creek lineament likely provided relief from shallow upper ramp conditions, to slightly deeper water, across the northern portion of the study area such as Grayson and Ohio counties (Treworgy, 1988).

2.2.2 Oolitic Shoals and Surrounding Environments

Oolitic shoals are also noteworthy depositional environments, as not only do the shoals represent a high-energy environment but the position of the shoals also influences the distribution of adjacent depositional environments. The oolitic shoals form on a platform, serve as barriers to the open sea, and thus create lagoonal facies closer to the shoreline (Vincent, 1975; Halley et al., 1983, Foster, 1990). Such shoals, are oriented along topographic high spots in a relatively linear form and are normal to the depositional strike (Vincent, 1975); these shoals also contain skeletal material (Harris and Fraunfelter, 1993).

2.2.3 Lagoonal Environments and Associated Facies

There are also a few wackestone to mudstone facies in the Haney that were interpreted to have formed in low-energy environments. Facies like these are typically representative of protected packstone-grainstone bars if they are associated with packstone to grainstone facies (Treworgy, 1985; Foster, 1990). The interpreted EOD is similar to the peripheral lagoon or lagoon sections of the depositional model shown in Figure 5. These muddy facies can also be interpreted as deeper parts of a shelf or ramp near-storm weather wave base and below-fair weather/effective wave base, with the coarse grained facies being landward facies (Ahr, 1973; Read, 1980; Treworgy, 1985).

2.3 Sequence Stratigraphy

Swann (1963) originally suggested conditions of maximum transgression during the deposition of the Haney, but Treworgy (1985) indicated two regressions from the depositional time of uppermost Big Clifty/Fraileys Shale to the base of the Hardinsburg Sandstone. The first regression occurs from the top of the Beech Creek throughout the deposition of the Big Clifty/Fraileys, where there is evidence of the shelf being exposed (Treworgy, 1985; 1988). The first transgressive phase occurs from the Big Clifty/Fraileys deposition to the basal Haney, which is interpreted as a carbonate ramp facies. The Haney Limestone is part of a regressive systems tract (RST) that was initiated at the base of the Haney, which is representative of a maximum flooding surface, and continues up into the middle part of the Hardinsburg (Smith and Read, 2001). This is in contrast to the transgressive phase as described by Swann (1963). An increase of siliciclastics into the basin led to the deposition of the overlying Hardinsburg Sandstone.

An important feature stratigraphically is the presence of incised fluvial valley fill prior to the deposition of the Hardinsburg Sandstone. The base of these incised valleys represents a sequence boundary, characterized by paleosol deposits that contain blocky mudstone, plant roots, coal, and carbonaceous shale (Nelson et al., 2002; Bodine, 2016). This sequence boundary is important because these incised valleys, in some cases, downcut into the Haney (Figure 6). Incised valleys impact the thickness of the Haney; therefore, the cave development contained within this limestone is limited in such cases.

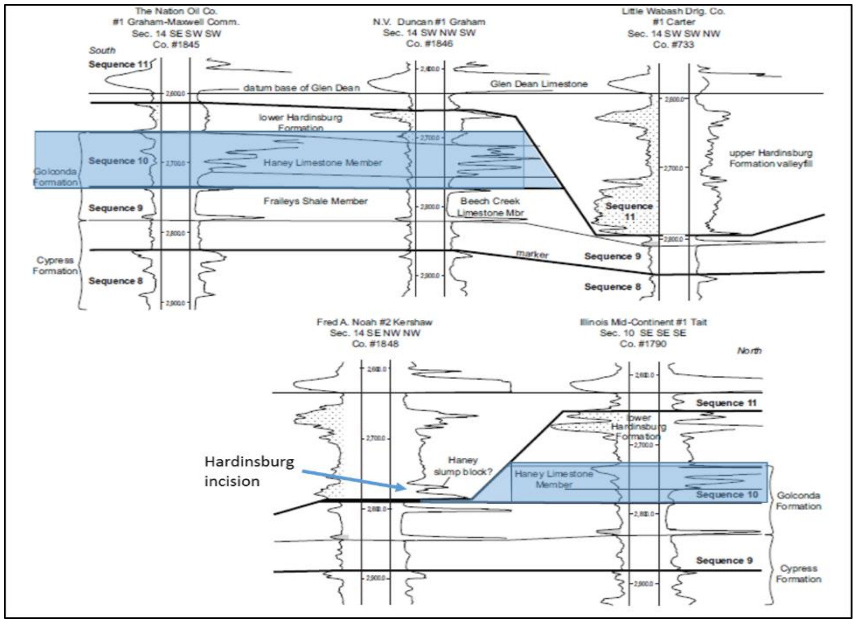

Figure 6. Cross section of the Haney and adjacent rock units from southeastern Illinois. The Haney along with the oldest half of the Hardinsburg and valley-fills of the Big Clifty are part of Sequence 10. Sequences 8, 9, and 11 include Chesterian units above and below the Haney and adjacent units. Notice the impacts of valley filling prior to the deposition of the Hardinsburg. Source: Modified from Nelson et al. (2002).

2.4 Diagenesis in the Haney

2.4.1 Calcite

Sparry cement between skeletal and oolitic grains of grainstone facies has been noted in the Haney throughout the basin (Treworgy, 1985). Vincent (1975) also observed both interstitial mosaic cement and isopachous cement around the grains. Such sparry cement is important to note, because it serves to decrease porosity. In both ramp and shelf environments, vadose-phreatic cementation decreases the porosity in a potential carbonate reservoir rock (Ahr, 1973; Scholle and Scholle, 2003).

2.4.2 Dolomitization

Dolomitization is significant because it decreases solubility in a karst system, but could potentially increase porosity in the rock. Dolomites subjected to burial processes retain their porosity better versus limestone (Saller and Henderson, 1998). The most prevalent replacement by dolomite involves matrix material (Treworgy, 1985). Since there is a replacement of micrite, this would be more common in the case of relatively fine-grained facies, such as the wackestone and mudstone units in the Haney, which is similar to observations made by Treworgy (1985; 1988) and Foster (1990). Due to lack of evaporates or any supratidal development in the Haney, the development of dolomitization does not appear to be primary and is probably influenced by dolomitizing fluids (Vincent, 1975; Treworgy, 1985).

2.4.3 Silicification

Silicification is a diagenetic change that is observable in the Haney across the study area and basin wide (Vincent, 1975; Treworgy, 1985), which will influence solubility of the unit. Silicification occurs as replacement of fossils, such as echinoderms and brachiopod fragments, or as localized zones of chert along bedding planes and joints (Treworgy, 1985). The silica is interpreted to be formed by percolating waters that are rich in silica or possibly derived from the Hardinsburg Sandstone, which is stratigraphically above the Haney (Treworgy, 1985). Silicification is also important, because the Haney can be used as a marker bed due to chert replacement in the residuum of oolitic/skeletal zones (Sable and Dever, 1990).

2.4.4 Stylolite Formation

Pressure dissolution manifests itself in the Haney as stylolite and microstylolite development. Vincent (1975) noted that microstylolites occur preferably in the skeletal packstone facies. These microstylolites are formed by increased pressure due to compaction, which allows the microstylolites to develop along orientated planes of non-soluble materials. Vincent (1975) mentioned it is possible for an original skeletal wackestone to compacted into a skeletal packstone due to these burial processes.

2.5 Karst Development and its Controls

South central Kentucky contains a classic karst landscape that features Mammoth Cave, which is the longest mapped cave system in the world at over 403 miles, but exploration continues (NPS, 2014). Karst is a complex process that is dependent on several controls: hydrological, geochemical, structural, climatological, biological, petrographic, and lithologic manifested at various scales.

2.5.1 Geochemical and Hydrological Controls on Karst Development

There are two major geochemical regimes in which carbonate cave systems form via dissolution: 1) carbonic acid (epigenic), or 2) by sulfuric acid (hypogenic). Epigenic caves form from a H_2O source above. This is usually carbonic acid from rainwater interacting with the soil with the rock as the main dissolution target. Such caves take on a typical branch-work morphology, but can also possess anastomotic and network morphologies as well. Network morphologies typically represent joint-controlled cave passageways (Palmer, 1991) (Figure 7). Hypogenic caves form due to deep seated acid (sulfuric acid), and such caves possess ramiform and spongework morphology (Palmer, 1991). Examples of hypogenic caves include Carlsbad Caverns and Lechugilla Cave in

New Mexico. The latter cave is the second deepest cave in the United States (Jagnow, 1989). Epigenic caves are the more common of the two types and this is the manner whereby caves in south central Kentucky formed, which is the focus of this thesis.

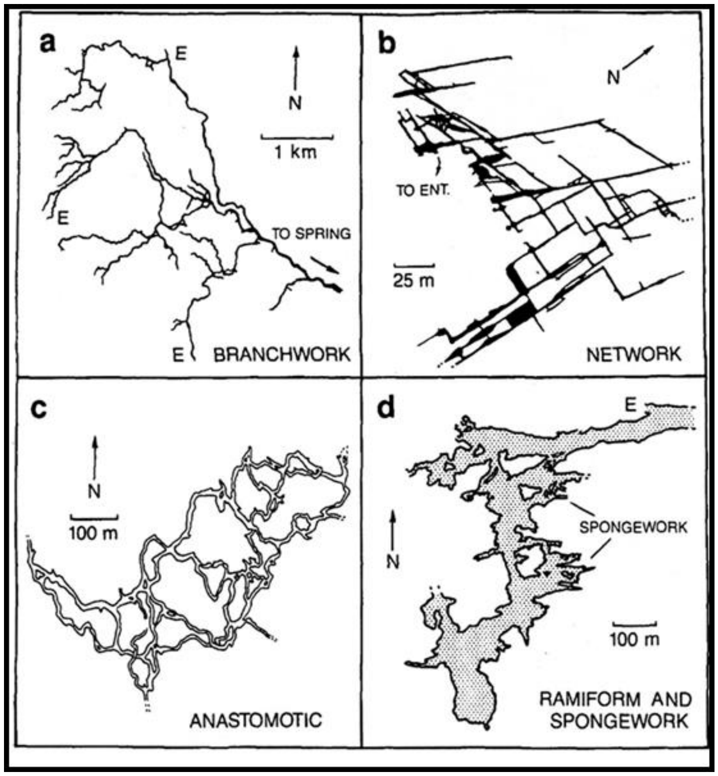

Figure 7. The types of cave morphologies. Source: After Palmer (1991).

2.5.1.1. Epigenic Geochemistry/Hydrology

Epigenic caves make up 90% of all caves in the world (Palmer, 1991). Carbonic acid is supplied from both the atmosphere and biological activity in the soil (Palmer, 2007). The result is the equation $CaCO_{3(s)} + H^+ = Ca^{2+}_{(aq)} + HCO_3^-{}_{(aq)}$ with HCO_3^- being bicarbonate and $CaCO_3$ being calcite. P_{CO2} is the partial pressure of carbon dioxide, which contributes to the system. The greater the P_{CO2} in the system, the more carbon dioxide can be absorbed by the water (Palmer,2007). In basic terms, if the water has a high P_{CO2} in the soil and it percolates down into the limestone, it will actively dissolve the rock until it reaches an air-filled cave, in which the CO_2 will escape into the cave atmosphere and the water cannot retain the Ca^{2+} or CO_3^{2-}. This will make the water supersaturated with respect to calcite, and thus unable to dissolve additional rock (Palmer, 2007). When the concentration of P_{CO2} in the water is higher and not lost to the cave atmosphere, the water typically is undersaturated with calcite, enabling greater rock dissolution to occur. When fluid is oversaturated with respect to calcite, the limestone cannot be dissolved, and precipitation occurs instead.

With the assumption made that the studied unit is a pure limestone (100% $CaCO_3$) the charge balance approach can be used, using the $CaCO_3$-CO_2-H_2O system. The H^+, $CaHCO^{3+}$, and mOH^- species are omitted because the concentration of the species is negligible in the typical pH range characteristic of the karst aqueous system. This can be determined by using the Bjerrum plot, which relates concentration of carbonate species to pH (Figure 8). The Bjerrum plot can be used to determine which species will be in great enough concentration to influence the overall system. The equation of $2mCa^{2+} = mHCO^{3-}$ is used for the charge-balance calculations in a situation where pure limestone is assumed (Thrailkill, 1968; Drever, 1997).

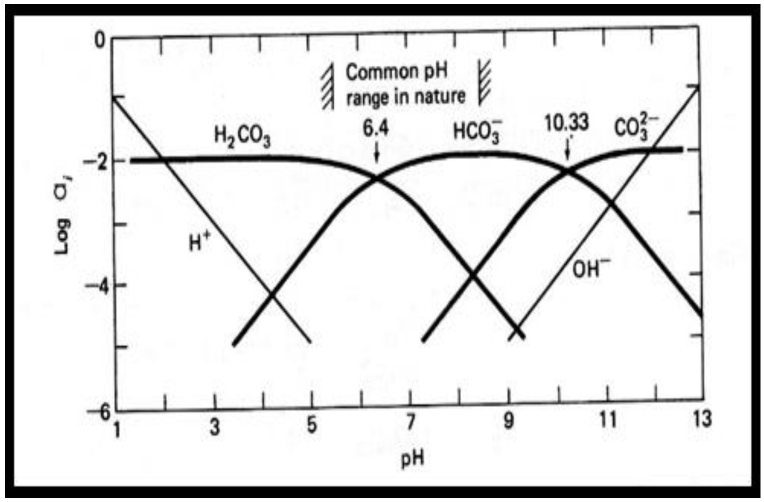

Figure 8. A Bjerrum plot. This graph depicts activities of different species of the carbonate system and their relation to pH. Source: After Drever (1997).

The path a chemical reaction takes and the reaction rate (kinetics) play a role in the dissolution of limestone. Buhmann and Dreybrodt (1985a; b), list the limiting steps that determine the dissolution and precipitation of carbonates: .

1) The phase boundary between $CaCO_3$-H_2O-CO^2 system and the limestone rock;

2) The conversion of carbon dioxide to carbonic acid; and

3) Mass transport of the dissolved species these include Ca^{2+}, HCO_3^-, CO_3^{2-}, CO_2, and H_2CO_3, and diffusion to and from any phase boundaries that exist in between these species.

2.5.1.2. Hydrology and Base Level

The base level is important because it is the lowest elevation in which karst development can occur, and is equivalent to the top of the phreatic zone (Powell, 1969). The base level changes as the climate and geomorphologic profile changes. Caves in Mammoth Cave National Park, formed at preferred elevations due to climatic changes from the late Pliocene to the present, which influenced the base level of the Green River (Palmer, 1981). Perched saturated zones can form if surface rejuvenation occurs and surface streams cut through impermeable units (Powell, 1969; Palmer, 1989). Caution needs to be taken however, when using the phreatic zone to describe the formation of cave-passages, because the phreatic zone in a karst region is highly irregular (Palmer, 1991).

2.5.2 Structural and Lithographic Controls on Karst Development

Structural elements and lithologic characteristics aid in the formation of karst landforms and determine their orientation. Fractures are locales for water to collect and be transmitted in the rock and dissolve it. Faults and fractures serve as passageways for groundwater movement, with oriented bedding planes and joints commonly being solution enlarged. Flow paths can be influenced by the development of these relatively small structural elements (White and Deike, 1989). Network caves, which are described as angular grids of passage intersections, are formed as major fractures are initiated in otherwise soluble rock and expand, forming a cave pattern that is similar to an aerial view of city streets (Palmer, 1991). The strike and dip of bedrock influences cave-passage development in both vadose and phreatic cave-passages. Vadose cave passages tend to be oriented down dip and, in well-bedded rocks, phreatic caves tend to follow favorable bedding planes that are parallel to strike (Palmer, 2007).

Macroscopic lithological control for cave formation includes the formation of chert and shale layers that serve as confining layers due to their low permeability. A common occurrence at the base of the Haney is a shale layer (Brown, 1966). A shale layer serves as a confining layer and contributes to spring development (Palmer, 2007). In Mammoth Cave, shales of the Aux Vases Sandstone Member act as confining units, which permit development of cave passages above those shales (Palmer, 1989). The

Cheat River Canyon, located in West Virginia, has cave patterns that are controlled by red shales, which serve as confining units in the area (Kite et al., 1997).

There are some relatively small-scale petrographic controls that can contribute to cave formation, although these are not studied as extensively as large-scale lithological controls. Impurities (e.g,, Fe, Mn, and Mg) in limestone can influence cave-passage morphology, as such carbonate units would not dissolve as readily compared to pure carbonate units (Palmer 2007). Dolomite layers likewise tend to jut out in caves as those layers are highly resistive to weathering and dissolution relative to calcite (Palmer 2007). Table 1 presents a comparison between the ion concentration products of common carbonate minerals in relation to their solubility and porosity generation. Fine-grained facies (e.g., mudstone and wackestone), in general, are more prone to weathering versus coarse-grained facies (e.g., packstone and grainstone). This potentially leads to variations in cave morphology in both vadose and phreatic settings (Palmer, 2007). The assumption here, of course, is that no other variables exist, such as dolomitization or elemental impurities.

Mineral Name	Ion Concentration Products (Ksp) at STP (Drever, 1997)	Effects on Solubility	Effects on Porosity Generation
Aragonite	$10^{-8.34}$	The most unstable/easiest to dissolve of the three common carbonate minerals.	Forms moldic porosity by dissolution
Calcite	$10^{-8.48}$	Dissolves about twice as readily as dolomite, but more stable than aragonite.	Makes up limestone but can diagentically occlude pore spaces resulting in decreasing porosity.
Dolomite	$10^{-17.2}$	Dissolves only at half the rate versus calcite.	A volumetric change occurs with dolomite replacement leading to increased porosity.

Table 1. Ion concentration products of common carbonate minerals. Ion concentration can be related to porosity development/solubility.

Studying paleokarst developed in the Permian-aged San Andres Dolomite in west Texas, Craig (1988) noted that cave/karst development was concentrated in oolitic or skeletal/oolitic grainstone, due to it being in a topographically high area, but also cave development was attributed to an increase in between-particle porosity (BP ϕ) of up to 35% (Choquette and Pray, 1970; Craig, 1988; Tinker et al., 1995). Powell (1969), when studying caves in southern Indiana, also found that relatively coarse-grained facies (i.e., packstone and grainstone) dissolved more readily, due to their increased porosity. Although fine-grained limestone weathers more efficiently versus coarse-grained limestone in general, considering higher specific surface area, grainstone, in contrast, contains (BP ϕ) (Choquette and Pray, 1970) that could increase weathering both in surface exposure and in cave settings. Eolian facies in the Ste. Genevieve outcrops in southern Indiana (Hunter, 1993), contained fine-grained facies that were recessive in outcrop while the grainstone-packstone units were more resistive. This is the opposite of what was found in cave development by Powell (1969). Hunter (1993) noted that some of the recessive units were dolosiltstone and shaly carbonates (fine grained) versus the resistant skeletal and oolitic packstone-grainstone.

2.5.3 Climatic and Biological Controls on Karst Development

A favorable climate, along with geochemical, hydrological, structural/lithologic, and petrographic controls, is also crucial in epigenic karst development. Temperature and precipitation are the main climatic variables in karst development, and cold water is more aggressive than warm water with respect to dissolution, but warm climates have increased carbon dioxide in the soil, which leads to increased dissolution when water comes into contact with the soil (Palmer, 2007). Increased rainfall rates, such as seen in monsoon climates or heavy rain events, cause karst landscapes to develop more rapidly (Groves and Meiman, 2005). Glaciers are a result of climate change; therefore, they influence development of karst landscapes by impacting annual precipitation averages, which would lead to a change in land cover. This influences groundwater infiltration and the overall acidity of the groundwater (Powell, 1969).

Climate influence was especially important for the formation of Mammoth Cave, creating different levels of cave passages throughout the St Louis, Ste. Genevieve, and Girkin limestones. This influence of climate can impact the base level of the streams and cause varying degrees of incision, which lead to multiple levels of cave-passage development across southern Indiana and the Mammoth Cave system of Kentucky. This was because of the glacial-interglacial stages, which controlled the level of the incising stream (Powell, 1969; Palmer, 1981, p. 134; Granger et al., 2001). Multiple cave levels developed in the Mammoth Cave System are designated A-B, which are the oldest cave passages that occur at 175-215 meters elevation and C-D are the youngest cave passages that occur at 166-168 (Level C) and 151-152 (Level D) (Granger et al., 2001). Biological processes can also speed up chemical reactions and contribute to reduction reactions in hypogenic caves (Palmer, 2007).

2.6 Karst Features in the Haney

The Haney contains an extensive karst system with 81 caves in Edmonson, Hart, and Grayson counties. Typical cave lengths are, however, dwarfed by the cave development in the thicker subjacent carbonate units, with the Haney containing nine caves that are over 100 meters in length (Arpin, 2013). There are other notable karst phenomena that exist throughout the Haney, which include springs, collapse features in outcrops, and sinkholes. The Haney contains solution channels throughout, which are best developed in the upper part of the member. Joints and fractures act as preferred pathways furthering dissolution and cave formation. Several springs and seeps form at the Haney/Big Clifty contact, including Three Springs, and serve as the Mammoth Cave National Park public water supply (Brown, 1966).

The largest Haney host rock cave is Cub Run Cave near the town of Cub Run in western Hart County (see Figure 4). The entrance was originally a small spring in bluffs along Little Dog Creek (Arpin, 2013). Presently, Cub Run is a show cave with an artificial cave entrance. The erosionally-resistant shale forms the hydrologic confining layer for the base of Cub Run Cave, which has a mapped length of over 2 km (Arpin, 2013). Other caves are much smaller in comparison to Cub Run Cave (Table 2). Hydrologic characteristics in the major Haney caves typically involve spring resurgences and stream passages. Sinkholes, sinking streams, and diffuse flow from the overlying Hardinsburg Sandstone possibly serve as recharge sources in the cave passages (Arpin, 2013). Hess and White (1993) took spring samples of Haney springs in the Mammoth Cave National Park region. Measurements showed water that was well undersaturated with respect to calcite and dolomite, low hardness (Mg^{2+} and Ca^{2+} concentrations), and P_{CO2} that peaks around July. Studies of saturation values suggest a low residence time in the Haney aquifer and that the soil is the major source for CO_2 (Hess and White, 1993).

Cave Name	Surveyed Length (m)	Entrance Setting	Hydrologic Characteristics	Possible Recharge Sources
Cub Run Cave	2105.7	Incised Valley Wall	Spring Resurgence	Sinkhole; Sinking Stream; Diffuse Flow
Lulu Mart Cave	871.2	Incised Valley Wall	Spring Resurgence	Sinking Streams; Diffuse Flow
Miller (Calyx) Cave	425.6	Sinkhole	Spring Resurgence	Sinkhole; Diffuse Flow
Beaver Dam Creek Cave	292.7	Incised Valley Wall	Spring Resurgence	Sinkhole; Diffuse Flow
Honaker Cave	245.4	Incised Valley Wall	Spring Resurgence	Sinkhole; Diffuse Flow
Chalybeate Cave	241.2	Incised Valley Wall	Stream Passage	Sinkhole; Sinking Stream; Diffuse Flow
Barner's Mill Cave	206.3	Incised Valley Wall	Spring Resurgence	Sinkhole; Diffuse Flow
Alaska Caverns	188.7	Incised Valley Wall	Stream Passage	Sinkhole; Sinking Stream; Diffuse Flow
Silent Grove Springhouse Cave	133.7	Incised Valley Wall	Spring Resurgence	Sinkhole; Sinking Stream; Diffuse Flow

Table 2. List of the nine largest caves in the Haney. These caves have several hydrologic settings. Source: After Arpin (2013)

2.7 Haney Karst versus Mammoth Cave Karst

The Haney's thickness of twelve meters (40 feet) is significantly less than the thickness of the St. Louis, Ste. Genevieve, and Girkin stratigraphic sections, which collectively are over 100 meters (328 feet) thick. Caves in the Haney, therefore, are not as laterally and vertically extensive, compared to large caves in the Mammoth Cave-Flint Ridge cave system (George, 1989; Arpin, 2013). The Haney caves are more joint controlled versus caves in the Mammoth Cave-Flint Ridge system (Table 3) that tend to be more controlled by bedding plains (Palmer, 1981). This is seen by the sinuous pattern of cave passages in the Mammoth Cave area.

Another difference between the Haney Limestone karst versus karst development in the St. Louis-Ste. Genevieve-Girkin limestones is the presence of two sandstones one above and one below the Haney. Caves developed in the Haney are inherently limited in height due to the insoluble Big Clifty Sandstone unit below the Haney and the poorly soluble Hardinsburg Sandstone above. Cave development is predictably nonexistent in locales with pre-Hardinsburg valley incision. This is because an insufficient amount of soluble bedrock would be exposed for karst development to occur (Nelson et al., 2002) (Figure 6).

Haney Karst	Non-Haney Karst in the Mammoth Cave Area
Joint-controlled passageways	Bedding plane-controlled passageways
The Haney on average is only 12 meters thick	St. Louis, Ste. Genevieve, and Girkin combine for over 100 meters in thickness
Contains a confining unit at its base	Contains shales and other confining units (such as the Lost River Chert at the top of the St. Louis Limestone) throughout
Low SI values (highly undersaturated with respect to calcite/dolomite) and vary greatly throughout the year	Saturation indices are undersaturated with respect to calcite/dolomite

Table 3. Haney karst versus non-Haney karst. Differences in karst development between the Haney and non-Haney karst in south central Kentucky. Source: Created by the author.

2.8 Relating Petrology to Karst

Research in carbonate petrology and its relation to karst development or weathering in surface exposures has been fairly limited, especially in small karst systems such as those developed in the Haney. The Haney does feature a coarsening upwards stratigraphy (Treworgy, 1988; 1990), so there could be favorable karst development in the coarse sediments near the uppermost portion of the stratigraphic unit. Fine-grained limestone may weather readily, but if dolomitized, such units resist weathering and will be prone to jutting outward into the cave passage (Palmer, 2007). A detailed petrographic study can provide a model for how the Haney weathers both in surface exposures and in caves.

Chapter 3: Data and Methodology

3.1 Method Introduction/Data Sources

The goal of this thesis is to analyze the facies of the Haney in surface-exposure, hand-sample, and thin-section views (Table 4) in order to identify the major depositional and diagenetic factors that influenced weathering on the surface and in cave passageways. Detailed surface exposure work was conducted at a quarry along Alexander Creek in Edmonson County (see Figure 4), which included measuring stratigraphic sections, photography, and sampling. These same steps were followed at the Natcher Parkway mile marker 18 roadcut, and a roadcut in eastern Grayson County at mile marker 114.8 (see Figure 4). Cores were analyzed from Edmonson and Logan counties in order to compare the surface to the subsurface, and compare those to gamma ray and porosity logs (i.e., density and neutron). Thin-section microscopy and X-ray powder diffraction (XRD) were used for petrographic and mineralogic characterization and compared to hand-sample and surface-exposure data. These data were used to relate the petrology to cave-passage morphology by comparing the resistive/recessive nature of the rock in Cub Run Cave to petrographic data collected at the surface.

Primary and secondary data were used to answer the research question relating rock properties to weathering in surface exposures and the cave. Primary data included the measurement of stratigraphic sections, hand-sample and petrographic thin-section analysis, and interpretation of core and well logs. Secondary data included use of a stratigraphic column from Vincent (1975) near a now-covered quarry located five miles north of Cub Run, as well as KGS well logs. Both qualitative (descriptions of the outcrop and cave, as well as its weathering patterns) and quantitative (i.e., measured section, neutron-and density-porosity values, estimate percentage of framework grains) data were used in this study.

Scale:	Features examined:
Outcrop View: (Lithologic)	Bedding planes, shale content, chert content, tectonic relationships, and relationship to the cap rock
Hand-sample/Rock Slab View: (Lithologic)	Dunham Classification (1962), lithofacies, and grains (spar, micrite, fossils, ooids, intraclasts)
Thin-section View: (Petrographic)	Chemical impurities (Mg, Mn, Fe, Sr) using XRD, limestone matrix, limestone cement, and microporosity

Table 4. Different scales of study for evaluating lithologic and petrographic variables. Such variables control surface exposure weathering and karst development.

3.2 Outcrop/Roadcut Work

Rocks from the surface exposures were selected in order to collect samples and determine petrographic variance at various locations: Alexander Creek, Natcher Parkway at mile marker 18, and Western Kentucky Parkway at mile marker 114.8. The first study location was in an abandoned quarry at Alexander Creek in southern Edmonson County (see Figure 4). The quarry was photo documented and depositional facies were described. Macroscopic features such as bedding, joints, and any unique features such as collapse and/or dissolution features that occurred in the Haney were noted. Two stratigraphic sections were measured at the quarry; the first section is located on the right side (east side) of the quarry and the second section on the left side (west side) of the quarry.

Spaced-out sampling was completed at Alexander Creek, with the spacing based on visual clues such as different facies, changes in weathering patterns, fossil content and abundance, and changes in bedding. Each sample was labeled ACL or ACR, with ACL designating the left (west) side of the quarry and ACR designating the right (east) side of the quarry (Figure 9), and with the increase in number signifying moving up stratigraphically. Large-scale features such as bedding, contact with the Hardinsburg Sandstone, and any clay or shale recesses were noted. Along with grain types that can be classified using both the Folk (1959) and Dunham (1962) classification schemes, the microfacies of the samples can be defined using a method developed by Wilson (1975). All samples were bagged and labeled with their appropriate numbers. Measuring these two vertical sections allowed for correlation across the study area.

Similar steps were followed at the roadcuts in Grayson and Warren counties. Spaced out representative samples were collected just like in the Alexander Creek quarry, a stratigraphic section was measured, and photo documentation occurred so that comparisons to the weathering profile could be made. Notes were made about any lateral variation of grain size or bedding. Samples were labeled NPN at Natcher Parkway, which designates Natcher Parkway northbound, and samples in Grayson County were labeled GC for Grayson County, since that accounts for the only field site in Grayson County. Regional data from these road cuts will show if there are any trends, both depositional and diagenetic, from the Rough Creek lineament area down to Warren County.

Once field work was completed, organization of these data into stratigraphic columns was required. Stratigraphic columns were constructed both by hand and by use of Sedlog®. It was key to note the correlations and see what type of variance existed laterally and vertically in the Haney. After constructing a number of stratigraphic columns, stratigraphic trends were determined, such as thickness (isopach) values, grain size, and depositional trends.

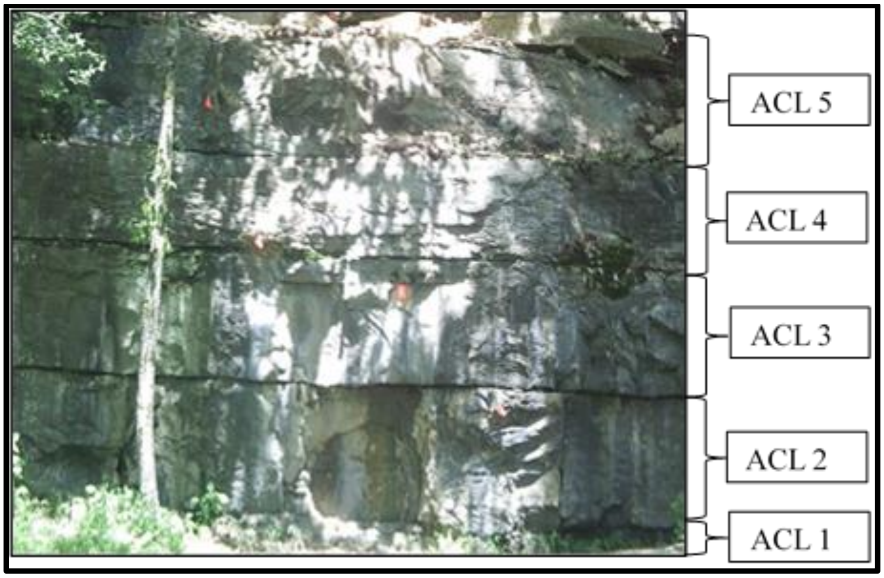

Figure 9. Alexander Creek sampling identification scheme. This is an example of the sample identification scheme using Alexander Creek. Shown here is the left (west) side of Alexander Creek (AC), with the L and R referring to the direction the section is from relative to the center of the quarry face. Source: Photo by the author.

3.3 Viewing Petrographic Variables in Cub Run Cave

The main purpose for entering Cub Run Cave was to examine the petrographic influence on weathering in a cave, and how it impacts the cave morphology. Cub Run Cave was chosen due to: 1) its ease of access compared to other Haney caves, and 2) that it covers the entire stratigraphic section of the Haney. Since sampling was not allowed in Cub Run Cave, because it is a commercial show cave, work conducted at Cub Run is more qualitative in nature. Cave work involved observation and photo documentation of how the rock weathers in the cave passages, and how that can lead to changes in cave-passage morphology. Cave photos, along with surface exposure data five miles to the north by Vincent (1975), help relate the weathering of the rocks in the cave to the lithology. Petrographic thin sections at similar Haney outcrops across the study area aid in characterizing the petrographic variables of types of facies that are observed in the cave. Profile sketches from photos taken and observations made can be used to construct a generalized weathering profile in the Haney in both the surface (road cuts and quarry) and near surface area of Cub Run Cave.

3.4 KGS and the Core Library

Studying cores accessed from the Kentucky Geological Survey office in Lexington, KY, and well logs accessed online from the KGS website, provided an opportunity for examination of the Haney subsurface. Studying well logs allows for a quantitative way of determining the lithology and porosity of the Haney Limestone in the subsurface. Thankfully, shallow logs were created by the Marathon Company in the 1980s for “tar sand exploration” in the asphaltic rocks of the overlying Hardinsburg Sandstone and the underlying Big Clifty Sandstones, which allowed for subsurface data of the Haney Limestone in part of the study area (Edmonson County/Brownsville, KY) to be analyzed by accessing well logs from the KGS. Core was recovered from operations at the Stampede Mine in northeastern Logan County during mining of asphalt rock deposits in the Big Clifty Sandstone. Log measurements of interest are GR (Gamma Ray), which measures the natural radioactivity in formations and can be used to examine shales or sandstones that contain radioactive material such as potassium feldspars, uranium, micas, or glauconite (Asquith and Krygowski, 2004); Neut. (Neutron), which measures hydrogen-ion concentration, and density that measures compton scattering from gamma rays that return information about bulk density of the matrix and overall density of the formation (Asquith and Krygowski, 2004). Cores from both the Stampede Mine and Edmonson County were photo documented, described, and measured in order to compare the surface to the subsurface. Examination of well logs assists in comparing the subsurface to the surface.

Neutron and density porosity were recorded using available geophysical logs. Typical logs are displayed with two-feet depth increments; therefore, a reading was taken every two feet. Then a lithologic crossplot was used to plot the bulk density, which is on the vertical axis versus the neutron density that is on the horizontal axis. The crossplots have a quartz (quartz sandstone), calcite (limestone), and a dolomite (dolostone) line, and porosity can be determined by drawing a straight line between the nearby lithologies. One weakness of the crossplot lithology determination method is that, without observation of samples, it is difficult to differentiate between a “clean” limestone and a sandy dolomite or a cherty dolomite, because the limestone line is positioned between the quartz/dolomite line. A type log for this study is shown in Figure 10 and an example crossplot is shown in Figure 11.

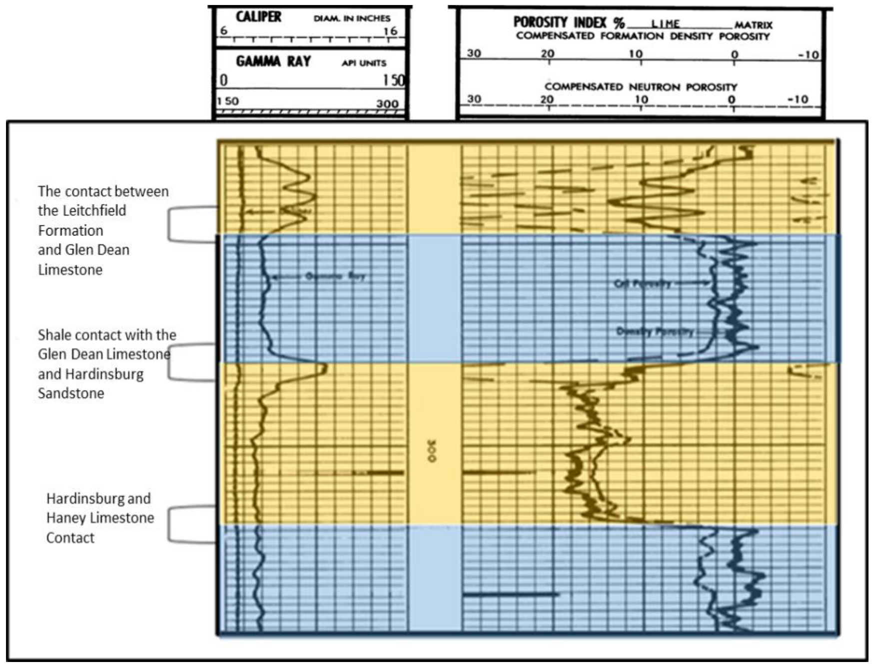

Figure 10. Neutron-density and gamma-ray type log. This is an example neutron-density log (C-1172) with a gamma ray well log run in Edmonson County by the Marathon Company during the 1980s. The blue highlighted sections are carbonates and yellow shaded areas represent siliciclastics. Source: Modified from KGS (2016b).

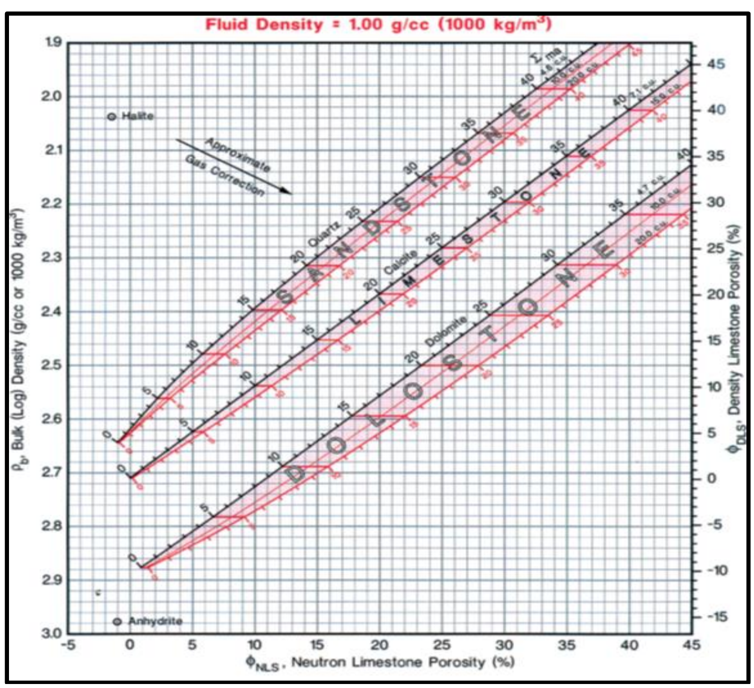

Figure 11. An example neutron-density cross plot. This is utilized for determination of lithology and respective porosity in a given lithology.
Source: After Halliburton Energy Services® (1994).

3.5 Analytical Methodology

3.5.1 Petrographic Thin Sections

A study of thin sections provided a detailed petrographic view of the Haney that cannot be seen with hand samples or out in the field. Twenty-three petrographic thin sections were made across the entire study area, twelve were taken from samples at the Alexander Creek Quarry, two from samples at Natcher Parkway, five from samples in Grayson County, and four from cores in northeastern Logan County. Thin sections were covered and treated with Alizarin Red S which stains calcite red to aid in distinguishing calcite from dolomite (Wilson, 1975). Initial thin sections were unstained; once dolomite was suspected, those thin sections and any future thin sections were stained with Alizarin Red S. Dolomitic samples of the Haney still contained a significant amount of calcite. Therefore, a simple HCL test is not sufficient to ascertain whether a rock is a limey dolomite, a dolomitic limestone, or limestone.

The goal of the petrographic study is to describe mineralogy, grain content, relative grain size and sorting, cement, and fossil content. The relative percentage data of dolomite vs. calcite was also recorded. Thin-section microscopy in both plain (PPL) and cross- polarized light (XPL) provided a microscopic view of the Haney, which can determine how both sedimentological and diagenetic characteristics impact weathering of carbonates and, therefore, karst development.

3.5.2 XRD Methodology

X-Ray powder diffraction (XRD) is used to determine bulk and, in some cases, trace elemental and mineralogical aspects of a rock. For this study, XRD was used to determine what minerals were present besides calcite. In XRD, if an incident X-ray beam encounters a crystal lattice of any mineral, then general scattering will occur. Most scattered waves are eliminated by destructive interference of the X-ray waves, but when scattering is in phase with other atomic planes in a sample then the waves will become diffracted. Each mineral possesses a different atomic structure that causes the X-rays to diffract in a pattern that is characteristic or unique for that mineral, which allows for identification of those minerals (Poppe et al., 2002).

Five samples were chosen for XRD powder diffraction to provide additional support for identifying the mineralogy of the Haney in addition to thin-section analysis, and to ascertain if there are any significant clay minerals. These five samples were ground into a fine powder and labeled, then acetic acid was applied by adding 1-part acid and 4-parts distilled water to dissolve the calcium carbonate so it would not mask the other minerals being analyzed. Stronger acids like hydrochloric acid (HCL) would damage the mineral lattices of clay materials, so they could not be used (Poppe et al., 2002).

3.6 Challenges and Limitation of Data

There were several challenges that occurred with this project. One challenge was that some of the samples at Alexander Creek were difficult to access due to a sloped and unstable ground in places. The limestone was well indurated at the Alexander Creek quarry with no significant protruding benches, which made sampling difficult. A limitation to consider is that samples were collected based on external lithology as the roadcut/quarry was not etched. At road cuts, especially the Grayson County location, the creation of the roadcut deformed some of the bedding, which made it difficult to determine the nature of bedding across portions of the road cut. Another challenge involved changes in facies over short distances, due to the migration of oolitic shoals during the time the Haney was deposited (Vincent, 1975; Foster, 1990). Therefore, facies changes could occur between the study locations and vary just over a few miles or even a few hundred meters.

A cave setting provided some challenges associated both with access and for photo documentation. Constant and consistent lighting had to be present in order to photo document the petrology of the limestone in the cave; therefore, it was a challenge to photograph continuous sections, especially if those were not illuminated. Some parts of Cub Run Cave were off trail and could not be accessed safely, so direct observation of portions of the Haney could not be conducted in the cave. The Vincent (1975) stratigraphic column, therefore, had to be relied upon significantly.

Chapter 4: Results

4.1 Field/Analytical Results

4.1.1 Alexander Creek Field Results

Alexander Creek is an abandoned quarry where the entire stratigraphic section of the Haney is exposed from the top of the Big Clifty Sandstone Member to the contact with the Hardinsburg Sandstone, with the exception of a few covered stratigraphic sections. Facies that are exposed at Alexander Creek include bryozoan packstone, echinoderm grainstone, oolitic grainstone-packstone, and dolomitized facies. A generalized location of Alexander Creek is shown in Figure 4.

The lower one-third of the Haney is predominantly a bryozoan packstone, and contains a lower percentage (40% or less) of echinoderms, brachiopods, foraminifera, gastropods, solitary rugose corals, and rarely an ostracod or trilobite fragment. This packstone can also grade into wackestone or grainstone in places. Microstylolite swarms are common throughout the lower part of the Haney and bedding is characterized as thick (65-90 centimeters).

The middle portion of the Haney at Alexander Creek consists of a variety of facies with variable bedding thickness. Rock units vary from thin- to thick-bedded bryozoan-echinoderm grainstone to dolomitized wackestone-packstone. The bryozoan-echinoderm grainstone and dolomitized wackestone to packstone facies possess different weathering patterns that are related to variable grain size (Figures 12, 13, and 14). Grain size plays a prominent role in how resistive the rock is in a hydrous environment, despite the fact that dolomite geochemically is more resistant to weathering in general. Dolomitized units at Alexander Creek tend to weather out more readily since they are fine grained, whereas the echinoderm packstone-grainstone units are more resistant because they contain large crinoid grains. This is similar to observations made from the weathering of the Ste. Genevieve Limestone by Hunter (1993) in his study of eolian deposits in southern Indiana.

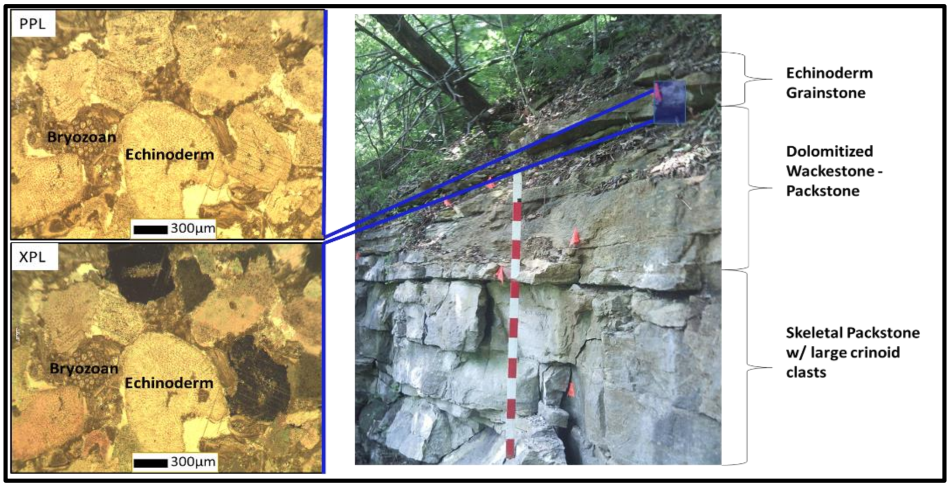

Figure 12. Weathering characteristics of an echinoderm grainstone. Note how the echinoderm grainstone is more resistant than the dolomitized wackestone-packstone units below (see Figure 13). Thin section stained with Alizarin Red S and calcite shows as red. Source: Created by the author.

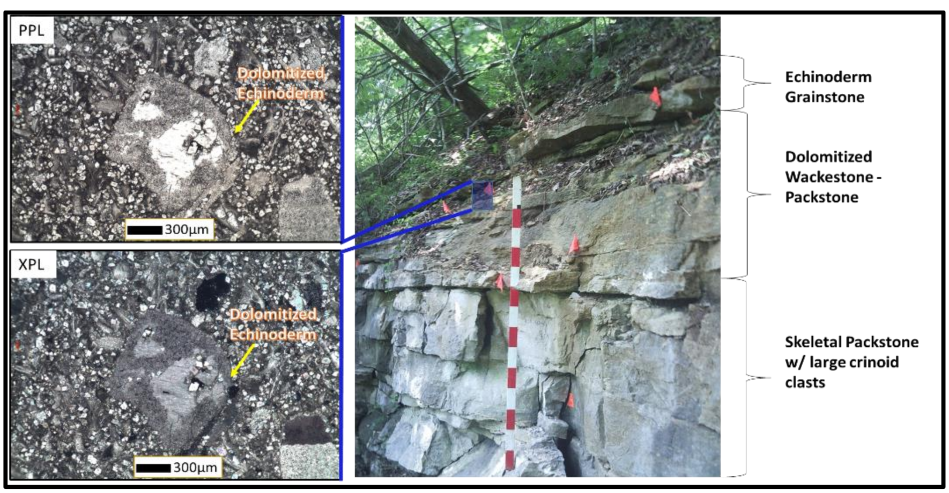

Figure 13. Weathering characteristics of a dolomitized wackestone-packstone. This facies is weathered more extensively versus the echinoderm grainstone, as is shown in Figure 12, and more resistant skeletal packstone beneath which contains large crinoid grains. Source: Created by the author.

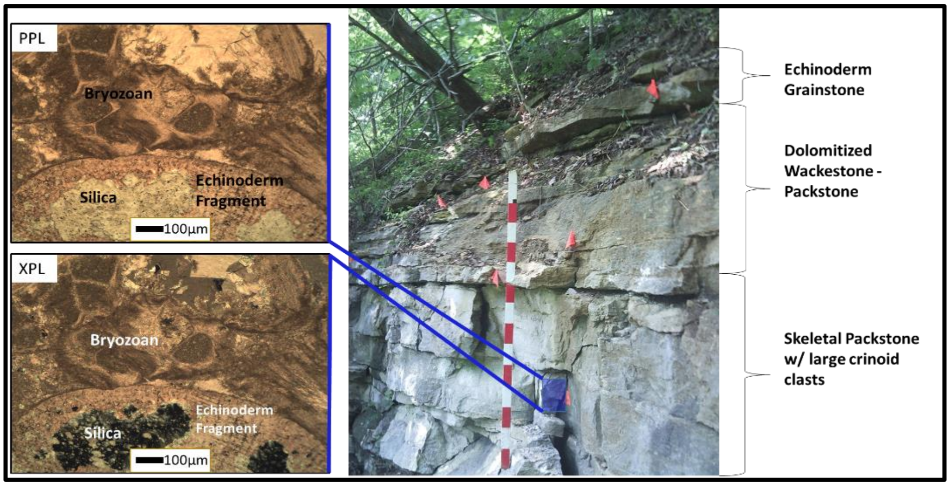

Figure 14. Weathering characteristics of a coarse-grained skeletal packstone. Note a bryozoan-echinoderm packstone containing large echinoderm grains with silica replacement. The thin section has been stained with Alizarin Red S and calcite shows as red. Such packstone units are more resistant to weathering versus the dolomitized wackestone-packstone facies (Figure 13). Source: Created by the author.

The top portion in both the ACL and ACR zones is predominantly echinoderm grainstone to echinoderm-oolitic grainstone. These rocks are coarsely crystalline and contain echinoderm fragments with few bryozoans, foraminifera, brachiopods, and gastropods. There is also a mud-free oolitic section about two-thirds of the way up the measured stratigraphic sections. Two important features noted in the upper section of the ACL and ACR sections include an increase in the number of joints ascending stratigraphically. Some of these joints are locally enhanced by solution and are widened or enlarged as a consequence of such epikarst activity, which would be expected near the top of the surface exposure (Palmer, 2007). Also present are concave upward solutional features that appear to be related to the jointing that occurs across the stratigraphic unit (Figure 15). This conveys that jointing, along with grain size, has an impact on how the

Haney weathers. Tables 5 and 6 depict a lithographic and weathering summary of both the ACR and ACL sections.

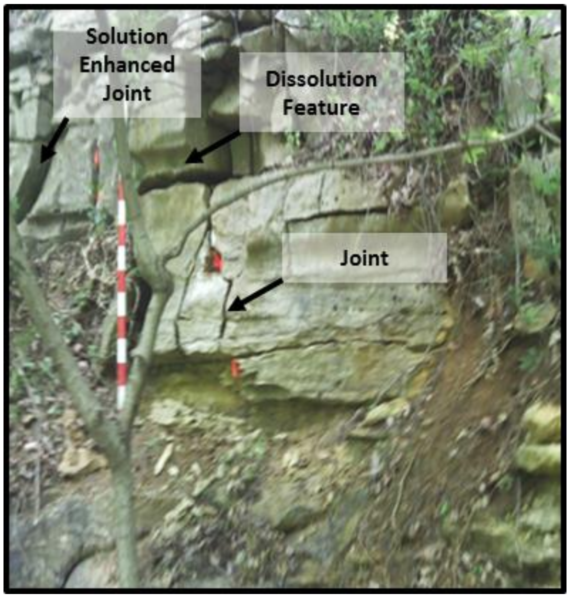

Figure 15. Joints and solution features in the upper part of the ACR section. View showing upper part of the ACR (eastern part of the outcrop) section. Joints, dissolution features, and a solution enhanced joint/grike influenced by epikarst processes are visible. Source: Created by the author.

Haney Section	Interval in Meters	Facies	Weathering Patterns & Other Factors
Upper	0-4.30 m	Predominantly echinoderm grainstone along with oolitic grainstone units.	These rocks are more resistant to weathering and joints influence the weathering. Dissolution features and solutionally enhanced jointing also occur.
Middle	4.30-7.70 m	Alternating between dolomitized mud-dominated units, bryozoan packstone-grainstone, and echinoderm grainstone units. Grain size varies throughout these units	Fine grained dolomitized units tend to weather more, while coarse-grained packstone and grainstone form resistant ledges for the most part.
Lower	7.70-12.00 m	Predominantly bryozoan packstone, but the bottom 1.9 meters is covered	Units have thick bedding. Not much change in weathering here relative to the interval except for recessive clay layers and stylolites

Table 5. Lithologic and weathering descriptions of the ACR Haney section. Source: Created by the author.

Haney Section	Interval in Meters	Facies	Weathering Patterns & Other Features
Upper	0-4.15 m	Predominantly echinoderm grainstone along with oolitic grainstone units.	Joints tend to be a greater control on surface weathering here. Dissolution features and solutionally enhanced jointing present.
Middle	4.15-7.00 m	Alternating between dolomitized mud-dominated units, bryozoan packstone-grainstone, and echinoderm grainstone units. Grain size varies throughout these units.	The fine grained dolomitized units tend to weather more, while coarse-grained packstone and grainstone form resistant ledges for the most part.
Lower	7.00-11.30 m	Predominantly bryozoan packstone-grainstone with an oolitic-skeletal packstone at the base.	Units have thick bedding. Not much change in weathering here relative to the interval except for recessive clay layers and stylolites

Table 6. Lithologic and weathering descriptions of the ACL section of the Haney. Source: Created by the author.

4.1.2 Natcher Parkway

Natcher Parkway, mile marker 18, contains a road cut that exposes the top half of the Haney; therefore, compared with data from Alexander Creek, the facies across the study area can be observed and identified. Many of the same facies that are seen on the top portion of the Alexander Creek quarry are observable at the Natcher Parkway roadcut, but there are some differences. There is a 2.1-meter-thick set of oolitic grainstone beds that make up the base of this exposure, which is equivalent to the middle portion of the Haney (i.e., the bottom part of the Haney is not exposed). Oolitic grainstone exists in the Alexander Creek section, but those beds are not as thick compared to the beds at the base of Natcher Parkway section. There are some skeletal packstone facies in the Natcher exposure, which are dolomitic in part above the oolitic beds; these beds contain fenestrate bryozoans, echinoderms, ostracods, foraminifera, and calcispheres or coated grains. The interpreted environment of deposition is on the leeward side of an oolitic shoal. This interpretation for the facies is based on it being proximal to the oolitic and skeletal-oolitic grainstone facies (Vincent, 1975; Foster, 1990). Stratigraphically above the packstone facies is an echinoderm-dominated skeletal grainstone with ooid content that is interbedded with shale in part. This is interpreted as a skeletal bank deposit marking the transition between intertidal oolitic environments below and the siliciclastic dominated marginal-marine environments above (Smith and Read, 2001). Such siliciclastics are representative of the Hardinsburg Sandstone positioned above the Haney (Figure 16). Present at this site is an example of a paleokarst feature, where the upper Haney has dissolved and the Hardinsburg has infilled a shallow channel (Figure 17). Paleokarstification and modern karst development of the Haney can limit the overall thickness of the Haney package (Nelson et al., 2002), limiting cave development in turn because of the lesser amount of limestone available as a host rock for karst development.

4.1.3 Grayson County Roadcut

The Grayson County surface exposure, located at mile marker 114.8 along the westbound lanes of the Western Kentucky Parkway near Leitchfield, Kentucky, provides a study area near the Rough Creek Lineament (see Figure 4 for location of this roadcut). Here, approximately the top 35 feet of the Haney is exposed, including the contact with the Hardinsburg Sandstone. Contact with the Big Clifty is not exposed at this location.

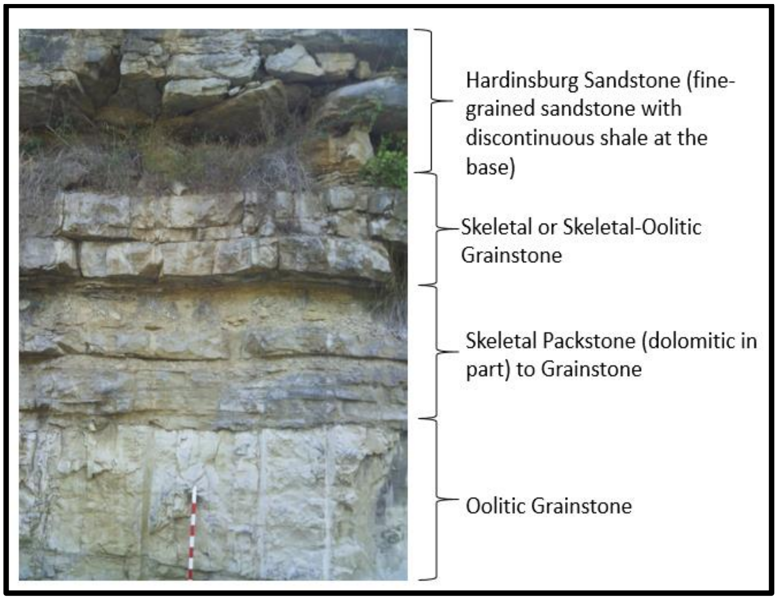

Figure 16. Weathering patterns for different facies at the Natcher Parkway roadcut. View showing upper half of the Haney section at Natcher Parkway mile marker 18 in Warren County. The red and white markings on the staff are in intervals of decimeters.
Source: Created by the author.

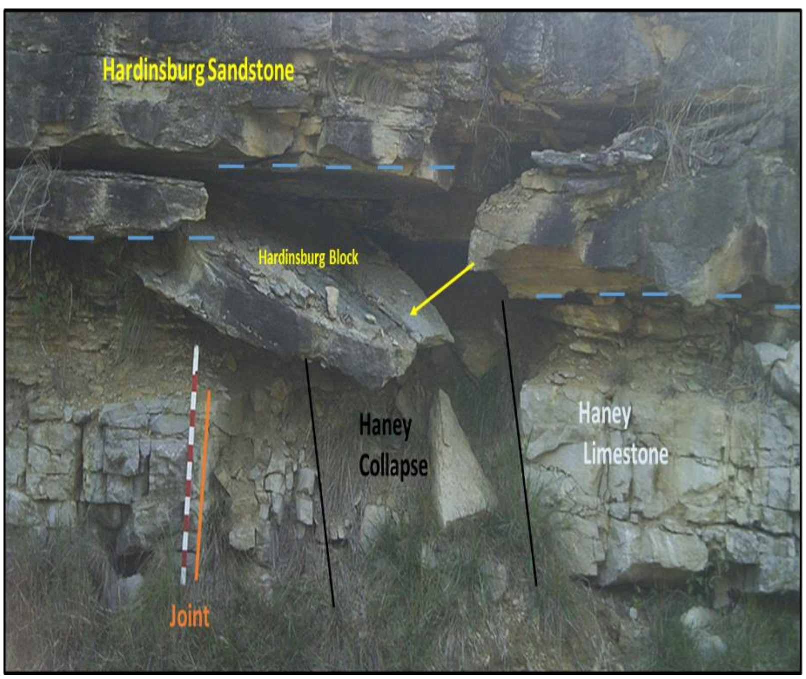

Figure 17. Collapse feature at the Natcher Parkway roadcut. Note collapse of the Haney representative of a paleokarst surface as well as modern epikarst. The red and white markings on the staff are in decimeters. Source: Photo by the author.

The base of the Grayson County exposure contains a bryozoan packstone with interbedded wackestone. There is an increase in dolomite content compared to the lower Haney facies in the Alexander Creek section. This is due to increased micrite, which led to higher specific surface area favoring dolomitization. Silica/chert rich lower beds are also present and are more resistant to weathering (Figure 18). The middle portion of the exposure contains predominantly bryozoan packstone (dolomitic in part) with a skeletal-oolitic grainstone bed positioned in between. Bedding becomes more obscured in sections of the outcrop due to the blasting operation. The top part of the Haney exposed at this location, contains an echinoderm-bryozoan packstone-grainstone with interbedded shale units. This is interpreted as a transitional carbonate/siliciclastic marginal-marine setting representative of a skeletal bank, or back bank, in close proximity to a siliciclastic source; such as, a fluvial-deltaic system. This interpretation is based on observation of increased shale content and stratigraphic proximity to the overlying Hardinsburg Sandstone (Smith and Read, 2001). Similar to Alexander Creek and Natcher Parkway, surface exposure grain size is a significant variable when relating the weathering properties of the rock at the Grayson County site (Figure 19).

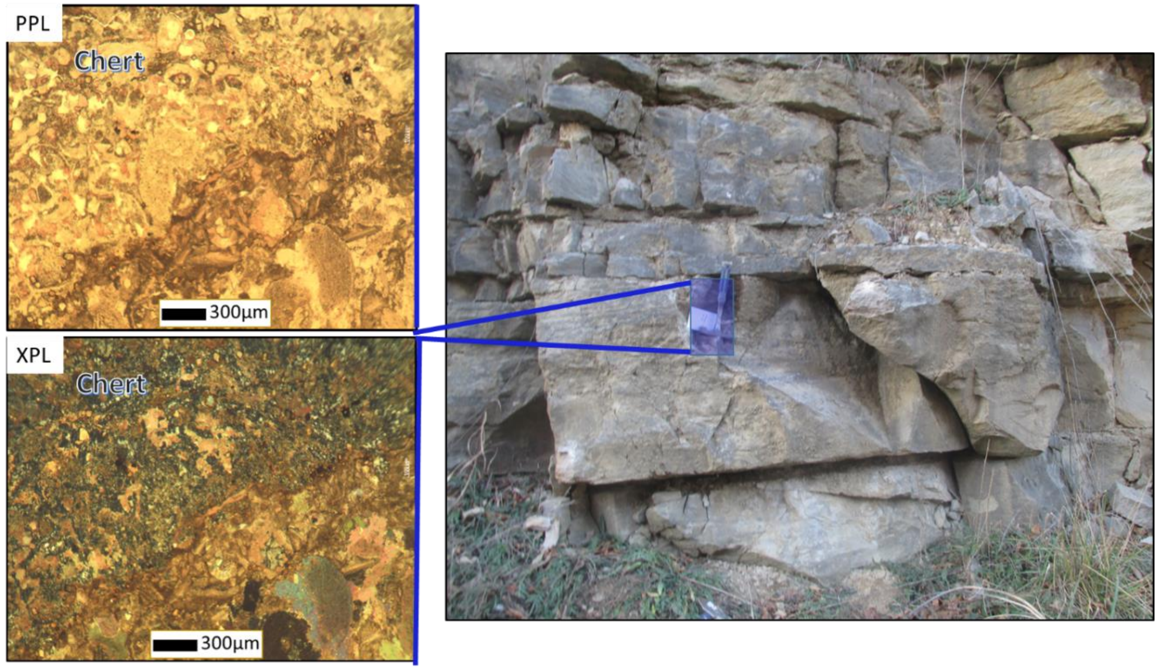

Figure 18. Outcrop and photomicrograph views of a cherty portion of the Haney. In this view is a resistant cherty bed in Grayson County. This bryozoan packstone bed is more resistant to weathering compared to the beds above and below, which are also packstone but contain less silica. The thin section has been stained with Alizarin Red S and calcite shows as red. Chert is displayed as a blue-gray color in XPL.
Source: Created by the author.

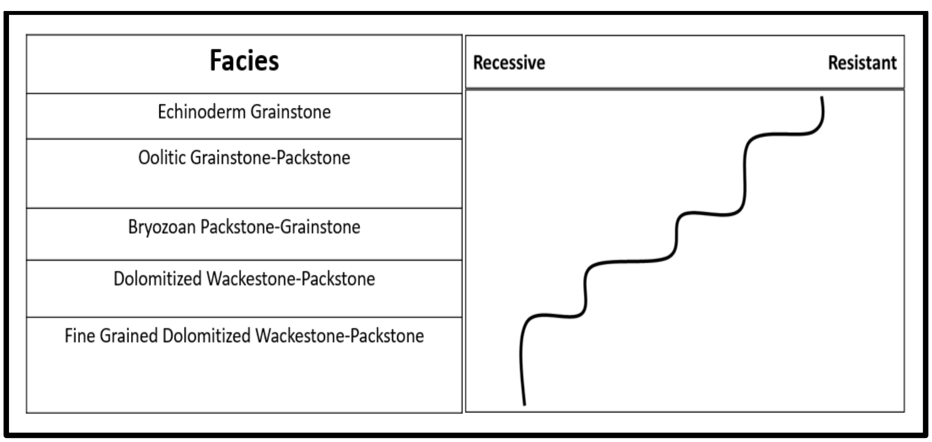

Figure 19. Generalized composite weathering profile. Diagram showing a conceptual weathering profile of the Alexander Creek quarry, Grayson County roadcut, and Natcher Parkway roadcut by lithofacies type. This diagram only accounts for facies type and does not factor in other variables (i.e. silica content, bedding planes, joints, etc.).
Source: Created by the author.

4.1.4 Cub Run Cave

Examination of how different petrographic units weather in exposures or outcrop applies to how they would be expected to weather in caves, and how petrographic variances impact a given morphologic development of cave passageways. Cub Run Cave is the longest known cave surveyed in the Haney Limestone (2105.7 meters) and is located in northwestern Hart County, near where the orientation of the Rough Creek Fault system changes from a west-east orientation to a northwest-southeast orientation. There are no known faults in Cub Run Cave itself, but a mapped fault has been noted about three kilometers to the east of the cave entrance. Joints aligned in an orientation similar to mapped faults are plentiful, however. Cub Run Cave is classified as a canyon passage, which is evidence of a vadose stream that downcut into the Haney (Arpin, 2013). A shale positioned at the base of the cave, observed at the entrance, acts as a resistant layer that the stream could not further incise (Figure 20).

Cub Run Cave (Figure 21) contains variations in weathering, similar to the outcrop. Cub Run is a commercial show cave and, because of that, collecting samples or staining for dolomite or calcite could not be performed, but by using stratigraphic data measured five miles north of the cave by Vincent (1975), in addition to observation of the outcropping rocks on the cave-passage level, comparisons could be made between types of facies and how the rocks weather in the cave. This stratigraphic column, along with direct field observation, suggests that the resistant rocks seen in Figure 22 would be echinoderm packstone-grainstone facies, with the recessive rocks being bryozoan-wackestone-packstone. The muddy rocks based on petrographic study would likely be dolomitized. Bryozoan-dominated rocks tend to be fine grained versus echinoderm-dominated rocks. Due to the presence of large echinoderm grains, the bryozoan-dominated rocks are prone to weathering in both cave and surface exposure settings compared with echinoderm-dominated rocks. With these observations, it is concluded that grain size plays a role in the cave wall retreat, which locally impacts cave-passage morphology (Figure 23).

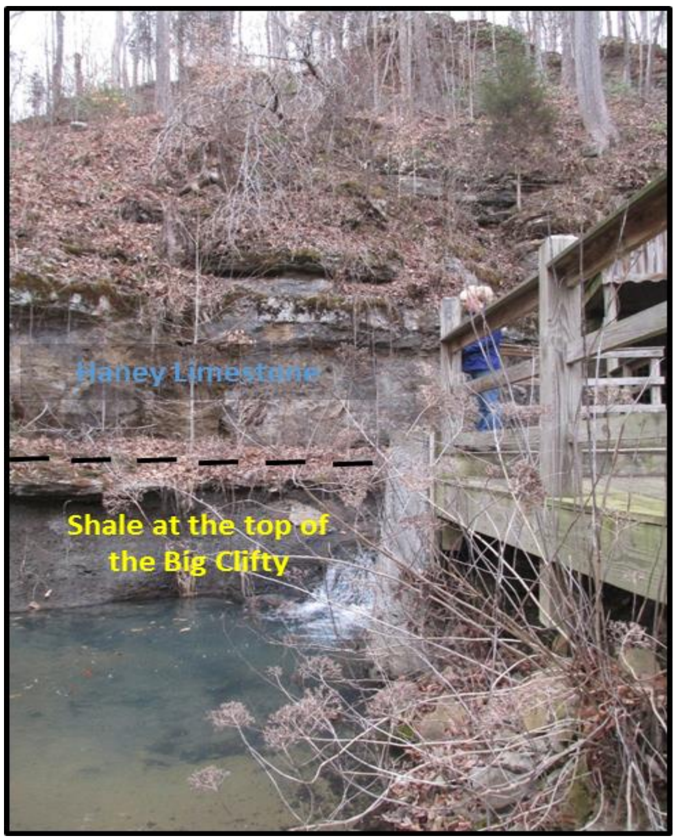

Figure 20. Basal shale at the entrance of Cub Run Cave. View showing a shale unit forming the base of the Haney at Cub Run Cave, which acts as a lower confining unit. Source: Created by the author.

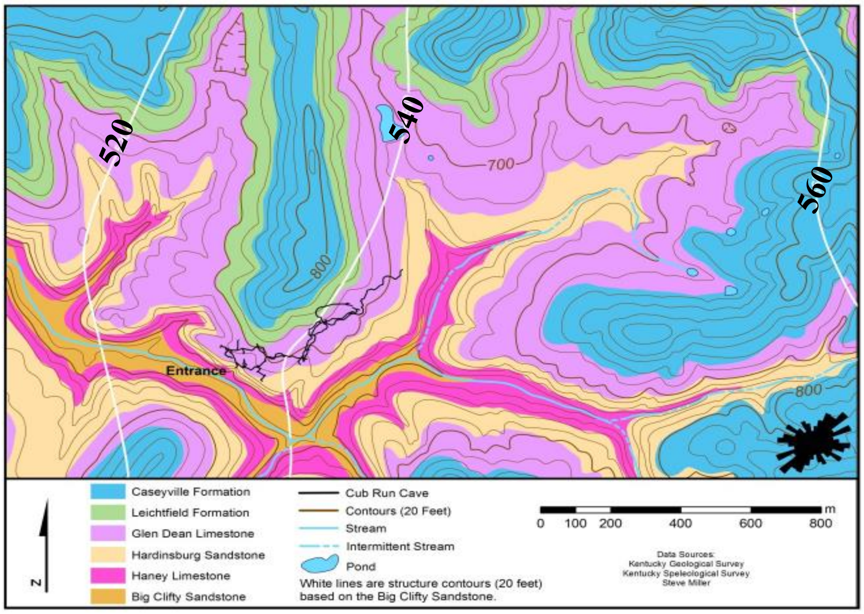

Figure 21. A geologic map featuring a plot of Cub Run Cave. The white lines are structure contours drawn on the top of the Big Clifty Sandstone that show bedrock dip to the west or northwest. Rose diagram at bottom right represents prominent joint directions measured. Source: Modified from Arpin (2013).

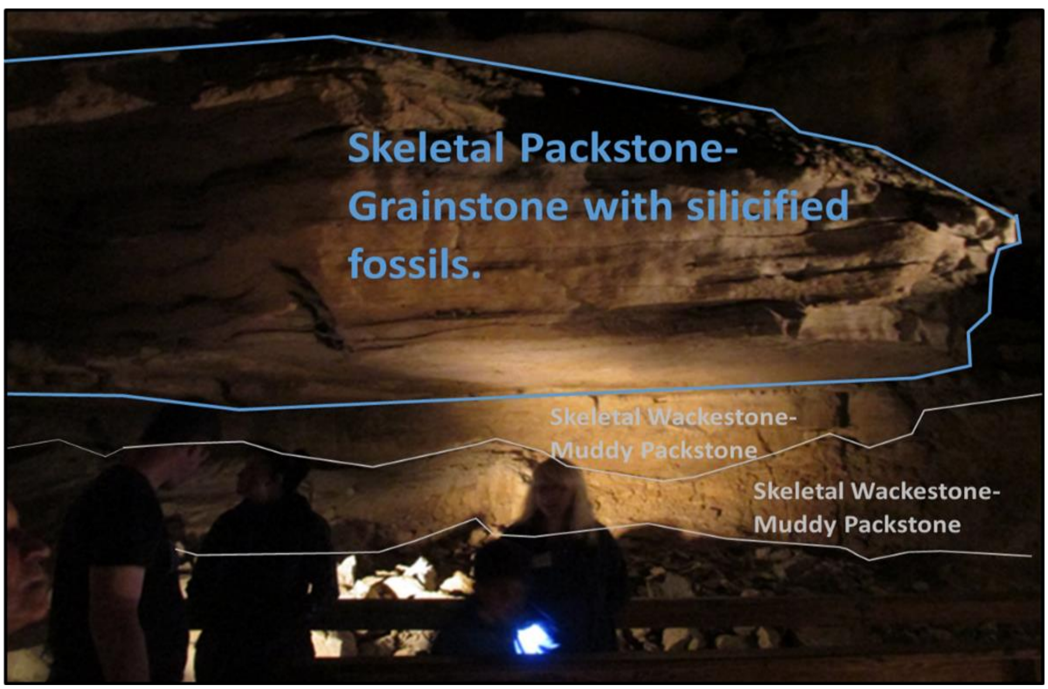

Figure 22. A generalized representative weathering profile in Cub Run Cave. Variation of weathering near the entrance of Cub Run Cave. The resistant unit is a skeletal packstone-grainstone with abundant crinoids and the surrounding rock, according to a stratigraphic column from Vincent (1975) is a skeletal wackestone-packstone. Source: Created by the author.

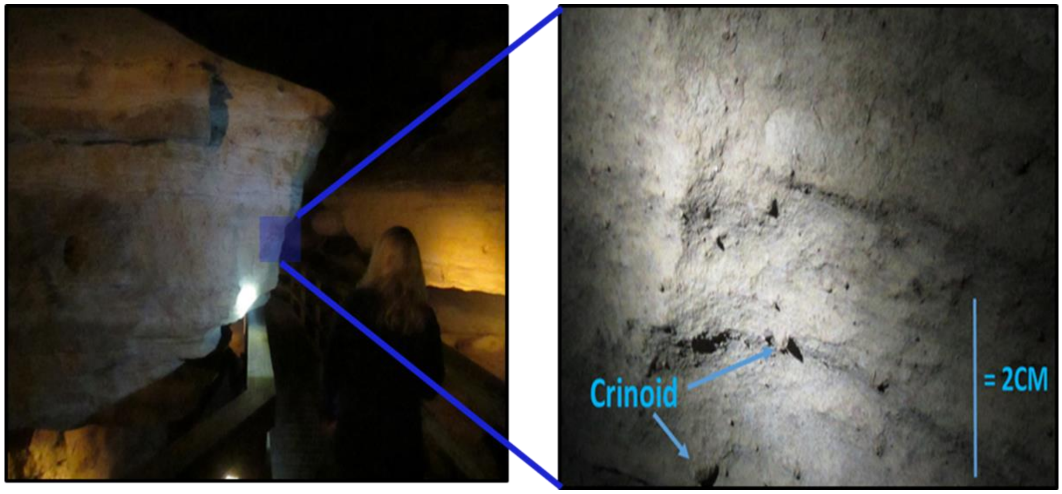

Figure 23. Resistant rock unit in Cub Run Cave. This resistant rock unit protruding out into the cave passageway (from left to right) contains abundant crinoid stems weathering in relief. Large crinoid grains make this bed more resistant to weathering in the cave. Source: Created by the author.

4.1.5 Sequence Stratigraphic Context

Sequence stratigraphy provides a model that takes into account relative sea-level or base-level changes and the relationship between transgressive and regressive facies development, that previous static shelf and ramp models could not achieve (Handford and Loucks, 1993). The concept of sequence stratigraphy is used to identify important petroleum resources and confining units/seals in a basin-wide setting. Previous research has conflicting views on where the Haney is situated in a sequence stratigraphic context (Table 7). Early studies considered the top of Haney as the height of the transgression (Swann 1963; Vincent 1975). Later research suggested a maximum transgression, or maximum flooding surface (MFS), in the lower Haney, with the remainder of the Haney characterized as a shoaling upwards sequence (Treworgy, 1985; 1988). Foster (1990) stated that the depositional rate equals basin subsidence, thus resulting in no significant change in sea level. Smith and Read (2001) and Nelson et al. (2002), in a sequence stratigraphic context, all described much of the Haney as a high-stand systems tract (HST) possessing an MFS in the lower Haney.

Field work supports the idea of an MFS in the lower Haney, such as described by Treworgy (1985; 1988), Smith and Read (2001), and Nelson et al. (2002). My study places the MFS at the first non-oolitic unit in the Haney, and designates the MFS as the first non-oolitic limestone unit above the Big Clifty Sandstone. The basal oolitic unit is interpreted as being deposited in shallow water, perhaps almost being subaerially exposed, due to the presence of well-sorted ooids and detrital quartz. Overlying the MFS, there is evidence of a gradual regression ascending stratigraphically up through the Haney and into the Hardinsburg Sandstone, with the latter being deposited as the amount of siliciclastics increased. Smith and Read (2001) described eustatic sea-level changes that they attributed to deposition and preservation of alternating siliciclastic/carbonate units of the Chester Series. They argued that the cyclic nature of deposition is due to a climate shift that was initiated as part of the transition between the mid-Paleozoic "hothouse" and later Paleozoic "icehouse" conditions (Smith and Read 2000; 2001).

Author	Sequence Stratigraphic Context
Swann (1963); Vincent (1975)	Maximum transgression is located at the top of the Haney.
Treworgy (1985); Treworgy (1988)	Maximum transgression at the base of the Haney followed by a shoaling upward trend.
Foster (1990)	Depositional rate equals basin subsidence with no change in sea level during Haney deposition.
Smith and Read (2001)	Part of a HST Tract with the MFS being the first laterally extensive limestone. This systems tract is bound by a paleosol at the top of the Big Clifty and a paleosol in the middle Hardinsburg.
Nelson et al. (2002)	TST is from top of Big Clifty to lower Haney. HST is from the upper Haney to the middle of the Hardinsburg. MFS is in the lower Haney.
This Thesis	TST is from top of Big Clifty to lower Haney. MFS is in the lower Haney and marks the first occurrence of a non-oolitic facies leading to a HST from the upper Haney into the Hardinsburg as described by Smith and Read (2001); Nelson et al. (2002).

Table 7. Sequence stratigraphic context for the Haney. Overlying and underlying stratigraphic units by several authors are displayed. Abbreviations: TST (Transgressive Sequence Tract), HST (High Stand Sequence Tract), and MFS (Maximum Flooding Surface). Source: Created by the author.

4.2 Subsurface Studies

4.2.1 Core Analysis in Edmonson County

A Kentucky Geological Survey (KGS) core from a well just west of Brownsville, KY (Edmonson County) exhibits features similar to field sites that have been described, including the presence of bryozoan packstone, enchinoderm and oolitic grainstone, and small shale breaks or clay recesses (Figure 24). Much of the Haney in this core is a bryozoan packstone with styolites and a few thin-shale/clay recesses that measure a few centimeters thick. There are some exceptions, as the top 1.3 meters of the core recovered a skeletal grainstone with coarse-grained crinoid fragments cemented by sparry calcite cement. A 1.2-meter oolitic grainstone bed is present in the middle portion of this core; this section is similar to the thick oolitic beds that were found at the base of Natcher

Parkway roadcut and could potentially be correlated. There are also sections that are mud rich, contain a sucrosic texture, and are potentially dolomitized; however, Alizarin Red S was not applied to the cores themselves due to time constrants and no sampling requests were made at the time of core examination to the KGS Core Library, in Lexington, KY.

Figure 24. A cored skeletal packstone with stylolites. Core retrieved from middle of the Haney. This is an oil well with a call number of C-1167 and a well record number of #8260. This well is located in Edmonson County and has the Carter coordinates of 9-I-39 920 feet FSL, 460 feet FWL. This core was not slabbed. Arrows designate up stratigraphic sections. Source: Photographed by the author.

4.2.2 Cross Plot/Quick Look Data

Analyzing well logs is a powerful tool for understanding lithology and porosity of stratigraphic units, especially if core or sample cuttings are available. Two of those methods are known as the quick-look method and cross plotting, which assist in determining porosity and lithology. Using the quick-look method, lithology can be determined along with an estimate of dolomite content in carbonates (Asquith and Krygowki, 2004). The density and neutron porosity logs throughout the Haney do not track together as closely as would be seen in a pure limestone, but instead there is distance representating a limestone with impurities (Figure 25). A shale layer at the top of the Big Clifty underlying the Haney acts as a confining layer for cave development (Brown, 1966). This shale is represented on the well log with a high gamma ray spike as a result of radioactive uranium-thorium material that occurs in low-energy environments conducive to shale formation (Asquith and Krygowki, 2004).

A neutron-density crossplot provides a lithology and porosity estimate by plotting the buk density or density porosity (percent) values versus neutron porosity. Bulk density and neutron porosity were read from four Marathon Oil wells across Edmonson County (see Figure 4) and plotted on a neutron-density crossplot to determine lithology. Porosity values are labeled on the lithology lines of the crossplot, which aid in determining a porosity estimate in addition to characterization of the lithology. Results from the lithologic crossplot show that the Haney is a dolomitic limestone with a porosity value of one to three percent (Figure 26), which is corraborated by field observations in exposures, petrographic thin-section ananylsis, and bulk mineralogy XRD analysis. When using crossplots, it is always important to use outcrop and/or core/cuttings data to verify the lithology, as geophysical tools yield indirect measurements of rock and fluid characteristics.

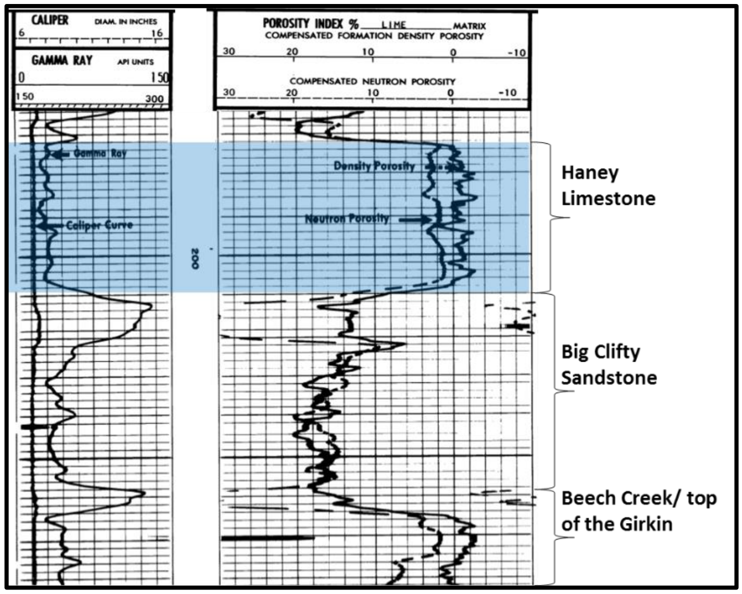

Figure 25. An example of a compensated neutron-density log with gamma ray of the Haney Limestone. Haney is highlighted in blue and note below are the Big Clifty and Beech Creek Limestone (top of Girkin). This is an oil well with a call number of C-1177 and record #8259 in Edmonson County with Carter coordinates of 7-I-39 3303 feet FSL, 698 feet FWL. Source: Modified from KGS (2016b).

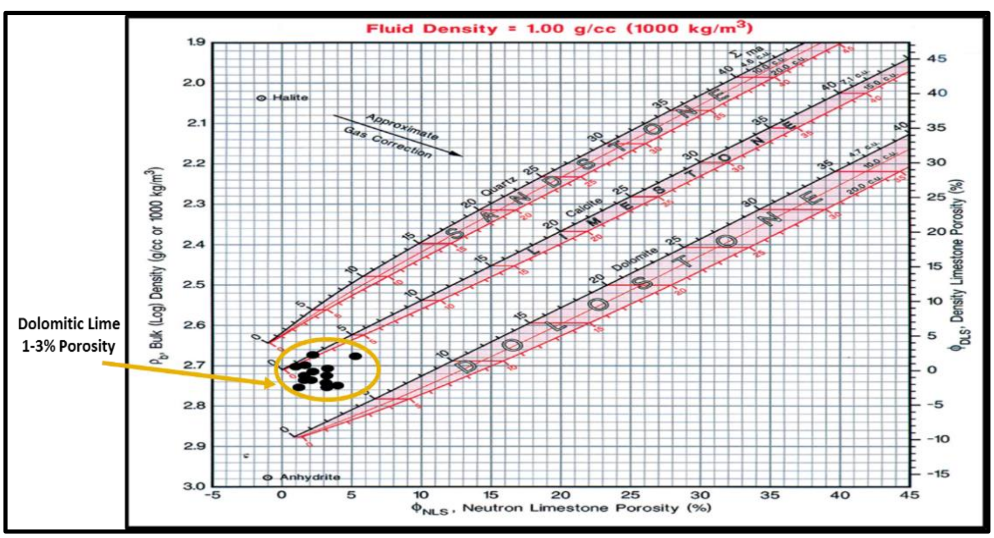

Figure 26. Lithologic cross plot from a log in Edmonson County. Crossplot from well C-1177. These data collected from the geophysical well log, plot between the calcite and dolomite lines, and also between the quartz sandstone and dolomite line. Surface geology (outcrop/roadcut/quarry) observations confirm that this is a limestone that is dolomitic in part as do XRD and standard petrographic study results. Source: Created by the author.

4.2.3 Core Data in Logan County

Cores were studied in northeastern Logan County (Stampede Asphalt Rock Mine), in addition to cores studied in Edmonson County. These cores were retrieved from northeastern Logan County for the purpose of assessing asphalt reservoirs from the Big Clifty Sandstone by the Stampede operators (a Canadian company), for which access was granted for this study. The upper half of the Haney and the contact with the Hardinsburg were not exposed in these cores, but approximately the lower half of the Haney was retrieved. Similar to the Alexander Creek section, a basal oolitic packstone-grainstone facies is overlain by a bryozoan-crinoid packstone. Most of the facies that are present are skeletal packstone, but there are also some skeletal wackestone to crystalline skeletal grainstone units as well. Thin-section analysis does show that some of the wackestone and packstone units are dolomitized in a similar fashion to what was observed at other field sites across the study area. A wash out or rugose borehole, that represents a potential karst feature in the bryozoan-dominated wackestone-packstone facies where a significant amount of water loss occurred (at least 1000 gallons), is also present (Reeder, 2015). Fractures probably contributed to the washout and the fine-grained nature of the rock may have been prone to weathering. An example of a core from Logan County is shown in Figure 27.

Figure 27. Core from Stampede Mine in northeastern Logan County. Note the stylolitescontaining clay and other insoluble residues and depth of core (about 35 feet from groundsurface). Stratigraphic up direction shown by arrow. Source: Photo by the author.

4.3 Facies Analysis

The goal in facies analysis is to identify associated facies types, which, along with the stratigraphic context are used to interpret the environment of deposition. Such analysis aids in placing the Haney into a sequence stratigraphic context. The Haney, for example, contains several distinctive facies including: bryozoan packstone-grainstone, echinoderm grainstone, oolitic packstone-grainstone, muddy dolomitized units, and interbedded shale units (Table 8). The environment of deposition controls the facies type observed, which, in turn, influences key rock attributes such as mineralogy, porosity, and permeability. These all play a key role in development of karst systems and hydrocarbon reservoirs (Choquette and Prey, 1970; Lucia, 1995a; b; Loucks, 1999).

	Facies 1	Facies 2	Facies 3	Facies 4	Facies 5	Facies 6	Facies 7
Dunham Classification (carbonates)	Bryozoan Packstone-Grainstone	Echinoderm Grainstone	Oolitic Packstone-Grainstone	Dolomitic Wackestone-Packstone	Dolomitic Mudstone-Wackestone	Skeletal Wackestone-Packstone	Shale and Limestone
Folk Classification (carbonates)	Biosparite	Biosparite	Oosparite or Oo-Biosparite	Dolomitic Biosparite	Dolomitic Biosparite	Biosparite	Shale and Limestone
Characteristics	▪ At least 50% bryozoan content ▪ Contains in less abundance echinoderms, foraminifera, solitary rugose corals ▪ Contains coated grains sometimes called calcispheres	▪ Echinoderm fragments are the most abundant fossil type ▪ Contains abundant pore filling cementation ▪ Coarse-grained	▪ Contains at least 15% ooid content ▪ Ooids are subrounded to rounded ▪ Contains abundant pore filling cementation	▪ Extensive dolomitization replaces both grains and matrix ▪ Coarse-skeletal grains occur	▪ Extensive dolomitization replaces both grains and over 50% of the matrix ▪ Fine-skeletal grains occur	▪ A bryozoan wackestone with interbeds of a skeletal packstone ▪ Suspected storm deposit to the poorly sorted natures of the grains in the packstone	▪ Shale can occur as thin-beds throughout ▪ The top portion of the Haney in Grayson County features alternating fossiliferous shale/skeletal packstone-grainstone
Environment of Deposition	Leeward of an Oolitic Shoal or Middle to Upper Ramp	Skeletal Bank or Windward of an Oolitic Shoal	Oolitic Shoal	Leeward of an Oolitic Shoal	Lagoonal or in Proximity to a Lagoon	Lagoonal or in Proximity to a Lagoon	Areas with Relatively Low-Energy

Table 8. Depositional lithofacies in the Haney Limestone.

4.3.1 Facies 1: Bryozoan Packstone-Grainstone

The bryozoan packstone-grainstone facies (Facies 1) in this study is defined as rock with more than 50% bryozoan content. This facies contains a lower abundance of echinoderms and coated grains, which were called calcispheres, with a suspected algal origin by Wilson (1975) and Foster (1990). However, due to the aragonite mineralogy of the algae (Scholle and Scholle, 2003) the preservation will be poor and there is not enough evidence to call these suspected calcispheres anything other than coated grains (Figure 28). This is one of the most common facies in the Haney, observable at all studied surface and subsurface locations. The lower portion of the Haney contains this facies; Foster (1990) noted a more dolomitized version of this facies at the base of her site in Sulphur, Indiana. This facies also contains echinoderm fragments, few solitary rugose corals, and foraminifera. Most of the bryozoans are disarticulated or broken pieces of colonies, although some are fully articulated. *Archimedes sp.* that still remain attached have been found, and these occur parallel to the bedding (Vincent, 1975; Treworgy, 1985; Foster, 1990). Most of these units are skeletal packstone, but grainstone and wackestone varieties also occur. Micrite in these units tends to be dolomitized, suggesting that the muddier the unit, the more dolomite that is present. Noted in this facies are microstylolites that are common to abundant (Vincent, 1975; Treworgy, 1985; Foster, 1990).

This facies was deposited in either an open-marine ramp setting positioned below fair weather wave base (Treworgy, 1985), or the leeward side of an oolitic shoal (Vincent, 1975; Halley et al., 1983; Treworgy, 1985). These environments are characterized by moderate energy with some water agitation. The leeward side of an oolitic shoal provides appreciable protection from longshore currents leading to increased mud content.

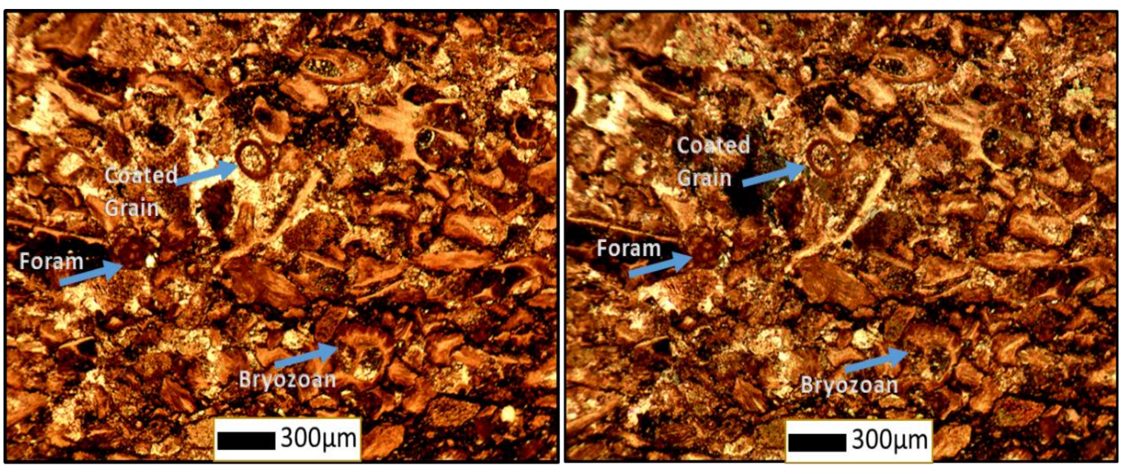

Figure 28. Photomicrograph of bryozoan packstone facies. Note coated grain in the upper center of the photo. Stained with Alizarin Red S showing calcite.
Source: Photomicrograph by the author.

4.3.2 Facies 2: Echinoderm Grainstone

Echinoderm grainstone facies (Facies 2) typically constitute the upper portion of the Haney. This facies correlates across the outcrop belt of south central Kentucky at

Natcher Parkway (Warren County), Alexander Creek (Edmonson County), Grayson County, and in cores across Edmonson County. It was also observed by Vincent (1975) in a now covered, abandoned quarry in Hart County. Fossil content includes abundant echinoderm fragments more than any other biota, but bryozoans, brachiopods, gastropods, foraminifera, ostracods, trilobites, and peloids are present (Foster, 1990). Ooids also occur, but they are not as common or dominant in this facies compared to the oolitic facies. Foster (1990) describes two facies within this assemblage: 1) an echinoderm-bryozoan grainstone, and 2) an echinoderm-bryozoan-brachiopod grainstone for those facies that have a significant amount of brachiopods. Figure 29 illustrates an example of an echinoderm grainstone facies that contains echinoderms, bryozoans, brachiopods, and gastropods.

This facies typically features skeletal grains that are poorly to moderately sorted and are commonly algal coated. Intraclasts are scattered throughout this facies, and the grain size of brachiopods and echinoderms are coarse, sometimes greater than 2000 microns along the greatest dimension. The bimodal size of grains in places, overall poor sorting, and presence of intraclasts, suggests a tidal influence as well as potentially a storm influence. Much of the available porosity in these grainstone units have been occluded by calcite cement; therefore, these units are very impermeable unless they possess interconnecting fractures or joints. This unit (Facies 2) is interpreted to be deposited in a shallow and high-energy environment due to the absence of mud and tendency to be crossbedded (Smith and Read, 2001).

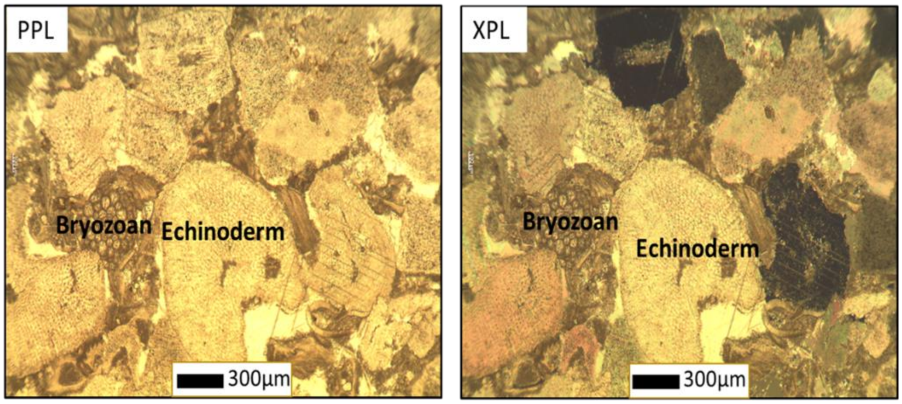

Figure 29. Photomicrograph of echinoderm grainstone facies. This designated facies is typified by coarse echinoderm fragments and syntaxial cement.
Source: Photomicrograph by the author.

4.3.3 Facies 3: Oolitic Packstone-Grainstone

The oolitic packstone-grainstone facies representing a shoal environment is also common in the Haney (Figure 30). A series of thick to massive beds up to one-meter-thick with significant oolitic content occurs along road cuts of the Natcher Parkway, as well as in core retrieved from Edmonson County. Echinoderm grainstone in the upper Haney commonly features isolated to scattered oolitic content, but the ooids are not as abundant compared to the oolitic packstone-grainstone facies. A significant amount of ooids (greater than 15%) are seen in the oolitic packstone-grainstone facies. Ooids are subrounded to well-rounded and range from fine-to-medium grained (0.3-0.8 mm in diameter). Skeletal material, which is primarily echinoderm fragments, is the most commonly occurring nuclei of ooids. Other grains, such as coated skeletal grains and pellets or peloids, are common both as individual grains and as ooid nuclei, but ooid centers possess can also possess sparry calcite cement. Porosity in this facies is occluded by calcite in what would originally be potentially good to excellent BP and WP porosity types (Choquette and Pray, 1970). Skeletal grainstone commonly occur beneath oolitic grainstone, which indicates that skeletal debris mounds could contribute to topographic high spots that lead to or encourage ooid formation (Harris and Fraunfelter, 1993).

At the base of the Haney stratigraphic section at a few sites, there is an oolitic packstone, which is similar to the oolitic grainstone facies but contains micrite. These likely were deposited in slightly more protected areas proximal to an oolitic shoal that contains lower energy. Where an oolitic packstone is absent at the base, the basal unit is a bryozoan packstone most typically.

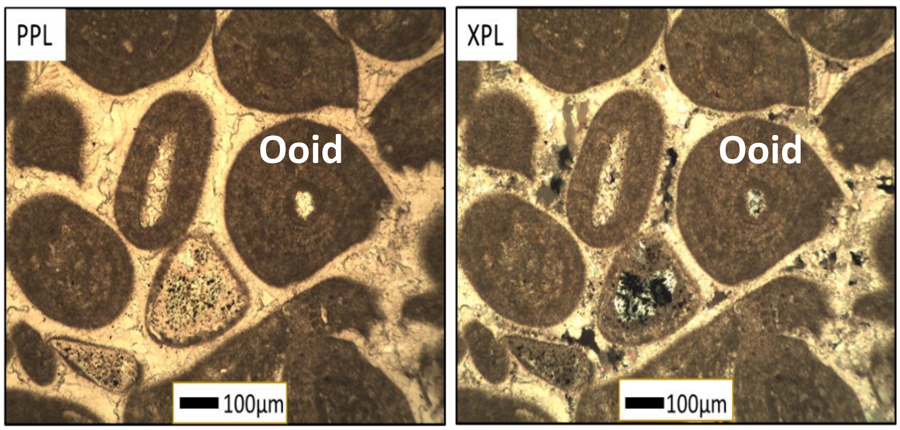

Figure 30. Photomicrograph of oolitic grainstone facies. Thin section was stained with Alizarin Red S revealing calcite. Source: Photomicrograph by the author.

4.3.4 Facies 4: Dolomitized Wackestone-Packstone

Dolomitized facies possess the salient feature of secondary replacement dolomite replacing both grains and original matrix. Here, extensive dolomitization has taken place in which micrite and even grains themselves have been partially to nearly completely dolomitized. The muddier the sample, the more dolomite there tends to be, as dolomite is not seen in abundance in the grainstone units, and insoluble minerals along stylolites have been replaced by dolomite. This is most likely attributable to micrite possessing a higher surface area, thus making it a more suitable substrate for initial nucleation or secondary mineralogic replacement (Gregg and Sibley, 1984; Sibley and Gregg, 1987). The morphology of the dolomite is Planar-E, according to Sibley and Gregg (1987), but was defined as Idiotopic-E by Gregg and Sibley (1984). However, the definition remains the same between the two terms. Idiotopic-E/Planar-E dolomite is classified as a crystal-supported system with the classic dolomite shape taking on the morphology of an equant rhomb with an intercrystalline area that is either porous or infilled with another mineral (Gregg and Sibley, 1984). This dolomite manifests itself as equant rhombs that replace both micrite and skeletal grains (e.g., echinoderms, bryozoans, brachiopods, trilobite and ostracod fragments, and foraminifera) (Figure 31).

Dolomitic facies are typically yellowish-gray (5Y 7/2) to light olive gray (5Y 5/2) in color (Munsell, 2009) and can occur both as beds that could be correlated across an outcrop or as interbeds within a single unit. It is difficult to correlate the dolomitic beds across counties, as current and previous research has suggested (e.g., Treworgy, 1985). The depositional environment of these dolomitic zones appears to be associated with the protected zone of an oolitic shoal for the packstone, with muddier samples representing a peripheral lagoon depositional environment. This is supported by being adjacent to oolitic or skeletal grainstone facies (Foster, 1990), and amount of overall mud content that has been dolomitized.

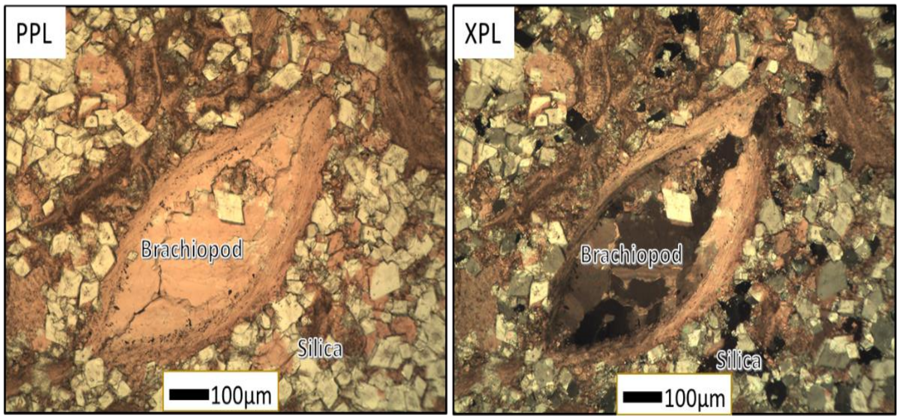

Figure 31. Photomicrograph of a dolomitic wackestone-packstone facies. Views show dolomitized wackestone-packstone facies with dolomite replacing grains and matrix. Thin section stained with Alizarin Red S revealing calcite.
Source: Photomicrograph by the author.

4.3.5 Facies 5: Fine Dolomitized Mudstone-Wackestone

Fine dolomitized facies (Facies 5) are similar to regular dolomitized facies, but the grains are fine. In order to relate grain size to weathering, it is important to make such a distinction. This facies contains grains that are similar to the regular dolomitized facies, with the only difference being fine grain size and additional mud, which is also dolomitized. Foster (1990) breaks into subcategories the fine dolomitized facies: 1) fine dolomitic bryozoan wackestone-packstone, and 2) fine dolomitic bryozoan wackestone facies. Dolomite rhombs (generally less than 50 microns across; e.g., Figure 30) are abundant and replace some grains. Ghost grains occur in this facies, as dolomitization destroys skeletal grains, and thus leaves only a micritic envelope or other remnant grain boundaries.

The interpreted depositional environment is a shallow low-energy lagoonal to near lagoonal environment. The basis for this interpretation is the occurrence of increased mud content (Foster, 1990). Dolomitized mudstone in the correlative Bangor Limestone, in the Black Warrior Basin at Alabama, has been interpreted as supratidal (Scott, 1978).

The Haney has “negative” porosity readings on the density log, a signal for possible anhydrate development in some stratigraphic intervals, but evaporates and mudcracks have not been observed. If present, this would signal a supratidal environment. Supratidal development cannot be completely ruled out as anhydrate and other evaporates dissolve readily in an active karst environment (Palmer, 2007); however, no anhydrite was noted either in cores or in previous studies.

4.3.6 Facies 6: Interbedded Skeletal Wackestone-Packstone

The interbedded skeletal wackestone-packstone facies (see Figure 6) is not as common as other facies discussed, but has been observed in field exposures and core. It is typified by a skeletal wackestone with interbeds of bryozoan-echinoderm packstone (Figure 32), and sometimes an extremely crystalline facies. The crystalline facies were described by Foster (1990) as an FCOP grainstone, which is a grainstone facies that contains foraminifera (forams), coated grains, ostracods, and peloids. This unit tends to occur as interbeds within the wackestone that contain bryozoans, and the skeletal grains in the packstone section tend to be poorly sorted and angular suggesting they are a possible storm deposit in a low-energy environment such as a lagoon. Foster (1990) interprets the crystalline grainstone as forming in a semi-restricted lagoonal facies due to the fine-grain size and presence of calcispheres or coated grains.

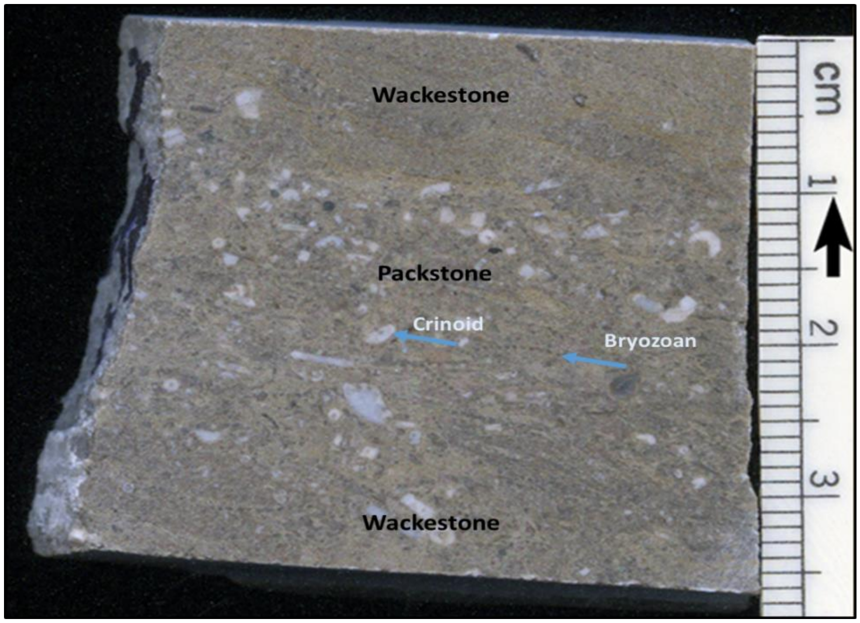

Figure 32. A skeletal packstone grading into an interbedded wackestone facies. The poorly sorted skeletal grains represent a skeletal deposit moved by tides or a storm in an otherwise low-energy environment of deposition. Easily identifiable grains include crinoids and bryozoans. The stratigraphic up direction is shown by the position of the black arrow on the scale. Source: Created by the author.

4.3.7 Interbedded Limestone/Shale Facies

The interbedded limestone/shale facies (Facies 7) refers to periods when carbonate deposition is interrupted, and fine-grained siliciclastics (muds) are deposited within the limestone. One example includes thin shale breaks that occur within the bryozoan packstone. Such fine-grained, intercalated intervals in carbonate are interpreted as episodes when fine siliciclastics entered the system and were carried by tides to fill lower areas of the seafloor. These do not appear in grainstone due to the relatively high-energy environment, which allows for mud to be winnowed (Treworgy, 1988).

Another example of mixed siliciclastics in this carbonate facies occurs near the contact of the Hardinsburg. Field work by Vincent (1975) revealed a 3.6-meter unit of interbedded shale and limestone in Ohio County, and a 1.1-meter thick unit of interbedded shale/limestone was observed in Grayson County. Since shale in a humid climate is prone to intensive mechanical weathering, several of the covered areas in other outcrops of the upper Haney may contain interbedded shale, but they are not directly observable. The limestone within the interbedded shale/limestone facies is typically an echinoderm grainstone (Facies 2). Rhythmic bedding is observed in this facies in Grayson County. Consideration of the above-discussed characteristics suggest a back-bank facies that marks a transition between times of predominately carbonate deposition and the depositional onset of the Hardinsburg Sandstone (Treworgy, 1988; Smith and Read, 2001).

4.4 Diagenetic Considerations

Identification of depositional facies is only one part required for proper petrophysical characterization of an aquifer or reservoir. Diagenetic changes are crucial and can manifest themselves as changes in mineralogy and modification of porosity and permeability. The development of stylolites, for example, can provide porosity, assuming that these are not mineralized. Alternatively, stylolites can form reservoir/aquifer partitions that obstruct flow or transmissivity if insoluble residues and/or mineralization occurs. Diagenetic cements in the Haney include isopachous calcite cement during early diagenesis (eogenetic), equant mosaic calcite cements during burial stages of diagenesis (mesogenetic), syntaxial or poikilotopic cementation, which is usually mesogenetic, dolomitization, silicification, and stylolite development. Minor diagenetic attributes include the formation of MnO nodules, and FeS_2 mineralization, noted by Foster (1990) in Sulphur, Indiana, as well as across my study area, although such mineralization is minor. Formation of caves, discussed in Chapter 2, and which will be discussed in later sections, is actually a form of late-stage diagenesis, or what is referred to as telogenesis (Palmer, 2007).

4.4.1 Sparry Calcite Cements

The Haney exhibits several types of calcite cements, including 1) isopachous cement, 2) blocky mosaic cement, 3) syntaxial and poikilotopic cements. There is also evidence of multiple generations of calcite cement from early eogenetic stages to mesogenetic, and perhaps even into telogenetic stages. Cementation in the Haney overall acts to decrease porosity by occluding pore space.

4.4.1.1 Isopachous Cement

Isopachous cementation, common in oolitic grainstone and echinoderm grainstone facies, represents marine phreatic cements. These cements formed when the grains were still submerged in marine waters (Scholle and Scholle, 2003). Meniscus cements form in the vadose zone; these, however, are not common in the Haney relative to the abundance of marine phreatic cements. Additionally, since pores are mostly occluded in the Haney by later marine calcite cements, the characteristic meniscus cement shape is lost or obscured (James and Choquette, 1987).

4.4.1.2 Blocky Mosaic Cement

Calcite cements can occur in voids resulting from dissolution of skeletal grains, especially if the original grain was aragonite or a similar metastable phase, which are more readily dissolved relative to low-Mg calcite (Scholle and Scholle, 2003). Mosaic cement is mostly equant and occludes the pore space, which is interpreted as a relatively deep water phreatic cement (James and Choquette, 1987), and occurs after the isopachous cements were precipitated (Figure 33). This cement type is common throughout all depositional facies of the Haney.

4.4.1.3 Syntaxial and Poikilotopic Cement

Syntaxial overgrowths that nucleate on an existing skeletal grain can be both vadose and phreatic (Scholle and Scholle, 2003). Poikilotopic cements tend to be associated with burial (mesogenetic) processes, but caution should be exercised in interpretation of such cements because syntaxial overgrowths can grow through eogenetic, mesogenetic, and telogenetic phases as well (Scholle and Scholle, 2003). It is important, therefore, to take into account a wider petrographic view when attempting to discern cement stratigraphy and, hence, the paragenetic sequence.

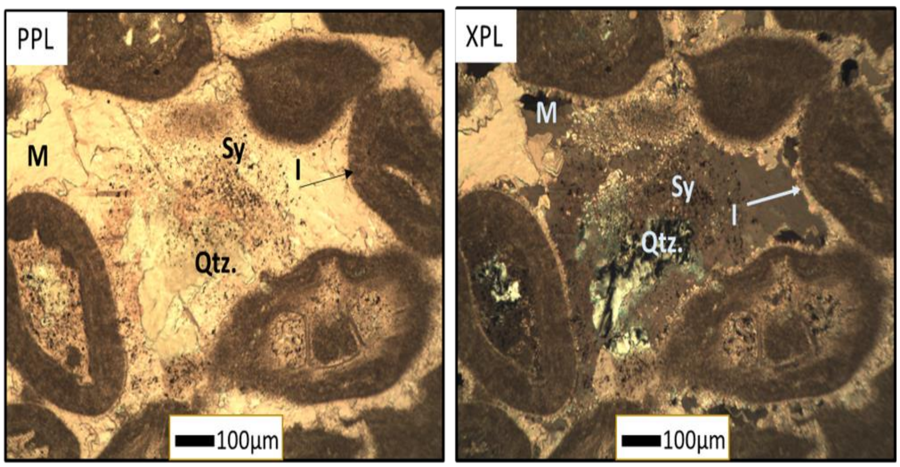

Figure 33. Photomicrographs showing multiple generations of calcite cement. Note calcite isopachous cementation, calcite mosaic cement, and silica replacement of grains and surrounding calcite cement. This section is stained with Alizarin Red S revealing calcite. Source: Photomicrograph by the author.

4.4.2 Silica Replacement

Silicification, along with dolomitization, in the Haney are two important non-calcite precipitation processes that result in an obvious change in mineralogy, which influences weathering properties of rock. Quartz is observable in some facies of the Haney, but these are depositional in nature (i.e., a result of silica grains being transported into a given depositional setting). A more common source of silica in the

Haney is diagenetic quartz, which specifically occurs in the case where the original limestone matrix and/or skeletal grains are converted from calcite to chert or chalcedony. Types of silica replacement in the Haney include chert, spherulitic chalcedony, and lutecite (Figures 33 and 34). Chert in the Haney can occur along bedding planes (Foster, 1990; Sable and Dever, 1990) and can be observed as a replacement feature of grains and the matrix (Figure 34). Spherulitic chalcedony, which is observable in the Haney, commonly replaces echinoderm grains and processes a spherical arrangement, as is noted upon rotating the microscope stage. Lutecite is a type of silica replacement manifesting as fibrous quartz crystals that radiate from multiple centers, which replace echinoderm and brachiopod fragments (Wilson, 1966; Nolte and Benson, 1998).

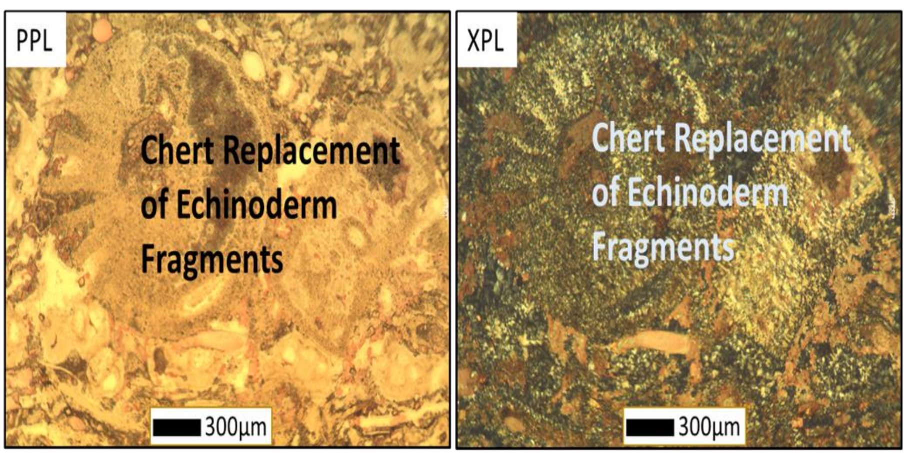

Figure 34. Photomicrograph showing chert replacement of grains. Views showing chert replacing both matrix and echinoderm fragments. Alizarin Red S staining reveals calcite. Source: Created by the author.

4.4.3 Dolomitization

Dolomitization (which was partially discussed in section 4.3.5) is a relatively common diagenetic process in the Haney. Dolomite replaces both grains and matrix with micrite being especially prone to replacement; hence, this is why mud-rich rocks in the

Haney tend to be dolomitized. As mentioned in the dolomite facies section (section 4.3.5), the dolomite is considered to be of Planar-E form (Sibley and Gregg, 1987), which is displayed as equant rhombs. Many of the pore spaces in the Haney are occluded by calcite mosaic cement, although there are still pore spaces that remain with about 2% porosity in many samples (Foster, 1990). Crystallization of such dolomite likely was at a low temperature between 50°-100°C, because at higher temperatures (>100°C) the morphology tends to exhibit more anhedral crystal development (Gregg and Sibley, 1984). The precipitating solution was more than likely supersaturated with respect to dolomite, due to the extensive replacement of micrite and even the grains themselves, as the extensiveness of dolomitization has a strong relationship to the saturation rate with respect to dolomite (Sibley and Gregg, 1987). Figure 35 shows an example of the matrix within and surrounding a brachiopod being extensively replaced by dolomite, but a micrite envelope retains its original calcite mineralogy. Previous research suggests that the migration of dolomitizing fluids is responsible for the development of dolomite in the Haney (Treworgy, 1985). Petrographic work conducted in this study suggests that dolomite precipitation occurred after extensive calcite cementation, and probably via several generations of crystallization.

Dedolomitization was observed in thin section, in which post-dolomite generations of calcite, have crystallized and initially replaced dolomite. Dedolomitization has been found to occur under four different diagenetic scenarios (Jie et al., 2011):

1) near-surface dedolomitization which is related to dissolution of dolomite and gypsum;
2) proximal to fractures;
3) proximal to stylolites; and
4) within gypsum nodules.

Fractures and stylolites possibly play a role in some of the dedolomitization observed in my study of the Haney. The process of dedolomitization can decrease porosity because it reverses the volumetric change that occurs when dolomitization occurs, but it can also increase porosity because calcite is more readily dissolved versus dolomite (Jie et al., 2011).

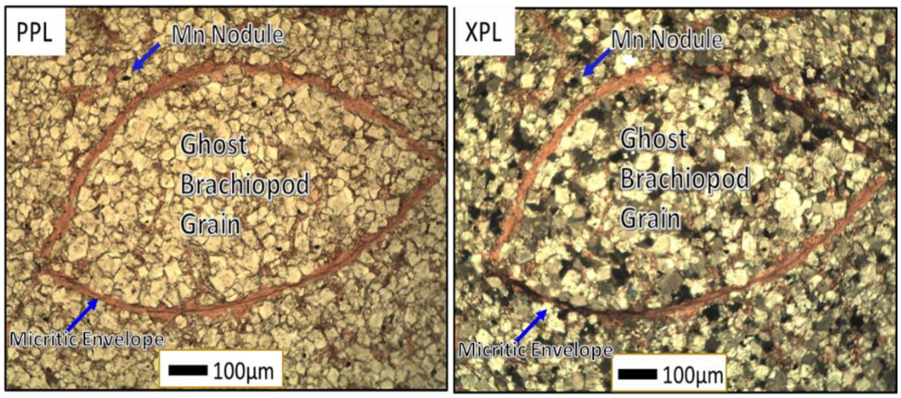

Figure 35. Photomicrograph of extensive dolomitization. Note micrite envelope of a brachiopod preserved (red) in otherwise dolomitized matrix with minor Mn. Thin section stained with Alizarin Red S staining revealing calcite.
Source: Photomicrograph by the author.

4.4.4 Stylolites/Microstylolites

The development of stylolites is caused by pressure dissolution forming in the mesogenetic zone, in which higher pressure (relative to surface or ground level) forms pressure dissolution features such as microstylolites and stylolites (Choquette and Pray, 1970). Microstylolites, which are proto-stylolite features, are common throughout the Haney, especially in the bryozoan packstone facies (Facies 1), although they also occur in the echinoderm grainstone units (Facies 2). Stylolites and microstylolites are parallel to bedding and can be very abundant especially in the bryozoan packstone facies (Facies 1). Vincent (1975) found these features in skeletal packstone and Foster (1990) noted microstylolitic swarms in bryozoan-dominated facies and stylolites in grainstone.

Petrographic work shows that, in some cases, stylolites are mineralized (Figure 36). Pressure dissolution destroys BP porosity at the site of dissolution and can place calcite into solution which creates calcite cements for other locations such as within available pore space (Railsback, 1993; Scholle and Scholle, 2003). When studying the Haney, a question remains whether or not stylolites act as permeable "fractures" that lead to the transportation of mineralized fluids or, alternatively, do they permit mineralization within stylolites? The latter could possibly be a case because the clay size insoluble material contains a large number of active sites due to having a high specific surface area fostering chemical reactions (Gregg and Sibley, 1984; Sibley and Gregg, 1987).

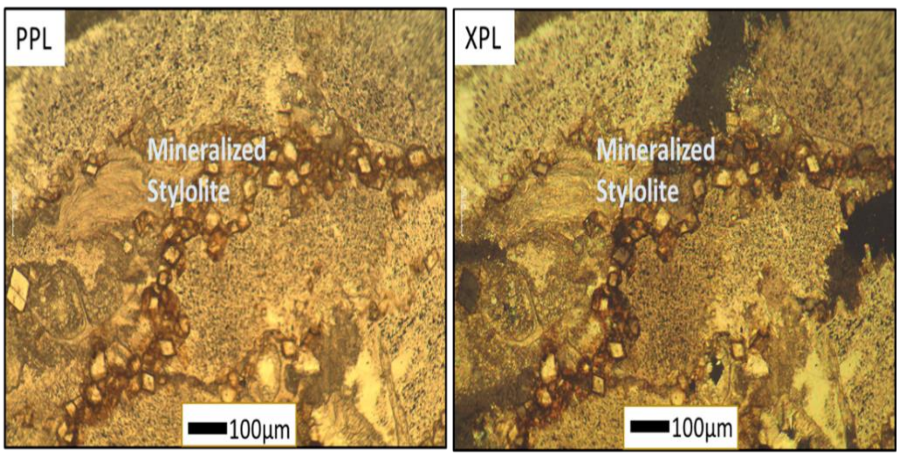

Figure 36. Photomicrograph of dolomite along a stylolite. Thin section stained with Alizarin Red S revealing calcite. Source: Photomicrograph by the author.

4.4.5 Cement Paragenesis

Cement stratigraphy provides an order for emplacement or precipitation of the cements, creating a diagenetic timeline, which is key for understanding how diagenetic processes influence or control porosity and mineralogic changes. The first and second diagenetic events in the Haney are the precipitation of phreatic marine isopachous cements along with meniscus cement types that occur in the vadose zone. Eventually, the

Haney gets buried, as is evident from the occurrence of microstylolites and compaction of grains representative of mesogenetic processes. The diagenetic order of cements is less clear in the mesogenetic and telogenetic stages for cements compared to early on in a given paragenetic sequence. Syntaxial, poikilotopic, and mosaic blocky cements are usually mesogenetic, but they can also occur earlier or even in the telogenetic stage (Scholle and Scholle, 2003). Evidence of additional generations of the equant calcite mosaic cement suggests that some cementation could occur before and after burial as well. Silica is seen to replace equant blocky cements or exhibits cross cutting in places; therefore, silica is interpreted as occurring after emplacement of calcite cements for the most part, but later generations of calcite clearly have precipitated after silica. Silica typically is formed in the mesogenetic (burial) stage of diagenesis (Scholle and Scholle, 2003). Dolomite has been observed to replace all varieties of calcite cement, suggestive of an occurrence during or after burial. Dolomite can form during early, middle, and late diagenesis (Scholle and Scholle, 2003) but, since dolomite observed in the Haney replaces calcite, it likely occurs in the mesogenetic stage and/or potentially early telogenetic stage. A cement stratigraphy summary can be viewed in Table 9.

Process	Depositional	Eogenetic	Mesogenetic	Telogenetic	Late Telogenetic
Cave Formation (modern)					■
Dedolomitization			■	■	
Dolomitization			■	■	
Isopachous Calcite Cement		■			
Mosaic Calcite Cement			■	■	
Micritization (Microcrystalline Calcite)	■				
Poikilotopic Calcite Cements		*Can occur here*	■	*Can occur here*	
Stylolite Development			■		
Silicification			■	■	
Syntaxial Calcite Cements		*Can occur here*	■	*Can occur here*	

Table 9. Interpretative paragenetic sequence of the Haney determined by petrographic analysis. Source: Created by the author.

Chapter 5: Interpretation of Results

5.1 Implications for Karst Development

This study has revealed that diagenetic and depositional variance significantly influenced the weathering properties of the Haney Limestone in surface exposures, the near surface (cave), and in the subsurface (core). These depositional and diagenetic attributes influence mineralogy, porosity, and permeability which control reservoir and aquifer quality. This section discusses how each of these variables influences the Haney both as a karst aquifer and potential hydrocarbon reservoir.

5.1.1 Outcrop-Scale Variables

Relatively large-scale lithologic variables (e.g., several meters or feet) in relation to cave development have been presented well in the cave and karst literature (White et al., 1970; Palmer, 1981; 1989; 2003; 2009) compared with documentation of lithologic variance in hand sample and microscopic/petrographic studies. Large-scale lithological variables (e.g., confining stratigraphic units, bedding planes, joints, fractures, etc.) are more predictable and easier to map in relation to the formation of caves versus the smaller-scale hand-sample and petrographic variables. Major lithologic variations that occur in surface exposure or outcrop view include two sandstone units that delineate the top and base of the Haney. These enveloping siliciclastic units include the Hardinsburg Sandstone (above) and the Big Clifty Sandstone (below). There is also a shale unit that makes up the top portion of the Big Clifty Sandstone. Finally, jointing and bedding planes provide control on fluid flow and hence cave-passage development.

A major large-scale feature is the presence of relatively insoluble sandstones above (Hardinsburg Sandstone) and below (Big Clifty Sandstone) the Haney. Once the groundwater flows to the sandstone or shale units of the Hardinsburg and Big Clifty, it becomes undersaturated with respect to calcite, which creates a hydrogeologic environment that is more favorable for dissolution when contact is eventually made with the Haney. The associated geochemical condition leads to increased undersaturation with respect to calcite (Palmer, 2007). The shale/limestone contact is, therefore, a favorable zone in which caves may form. This is especially true in the development of vadose-zone caves, in which dissolution is interrupted when the water meets the shale contact (Ford and Ewers, 1978). The limestone-shale contact is also a favorable location for springs (Brown, 1966). Spring outlets are observable at the Big Clifty/Haney contact at both the Alexander Creek Quarry and Cub Run Cave (Figure 37).

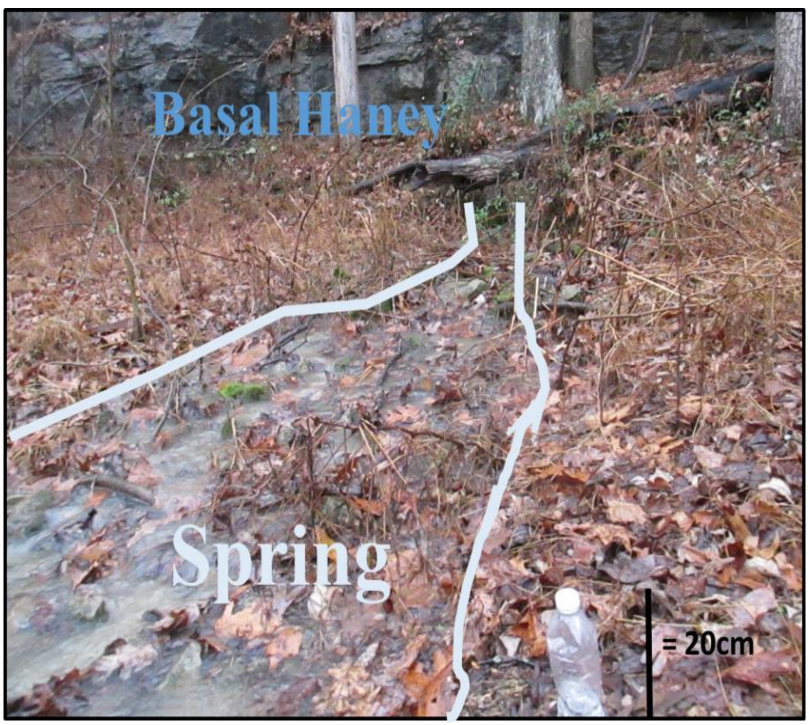

Figure 37. Spring at Alexander Creek**.** A small spring at the base of the Haney at the Alexander Creek Quarry. The water bottle height at the bottom right of the image is 20 centimeters. Source: Photo by the author.

Joints and bedding planes are key elements in cave development. Not only do these features provide horizontal and vertical permeability, but they also influence cave-passage morphology (Palmer, 1991; 2009). Caves that are dominated by horizontal bedding planes tend to have a sinuous cave-passage morphology, resembling a curvilinear branch work pattern that is similar to a river system (Palmer, 1991; 2003). Caves formed in the St. Louis, Ste. Genevieve, and Girkin Limestones in the Mammoth Cave region are classic examples of bedding-plane controlled caves. Caves that are predominantly joint controlled form rectilinear network caves that resemble a "street view" pattern replete with "city blocks" as seen in view b in Figure 7. Caves in the Haney contain bedding plane influence, as there is minor sinuosity in the cave-passage morphology, but the predominant control on cave-passage morphology on a scale of meters is jointing that allows for a rectilinear morphology to develop. Intersecting joints and bedding planes are prone to cave development (Doctor et al., 2008; Arpin, 2013). Joints play a significant part in the cave-passage morphology of both Lick Creek Cave (Figure 38) and Honaker Cave (Figure 39).

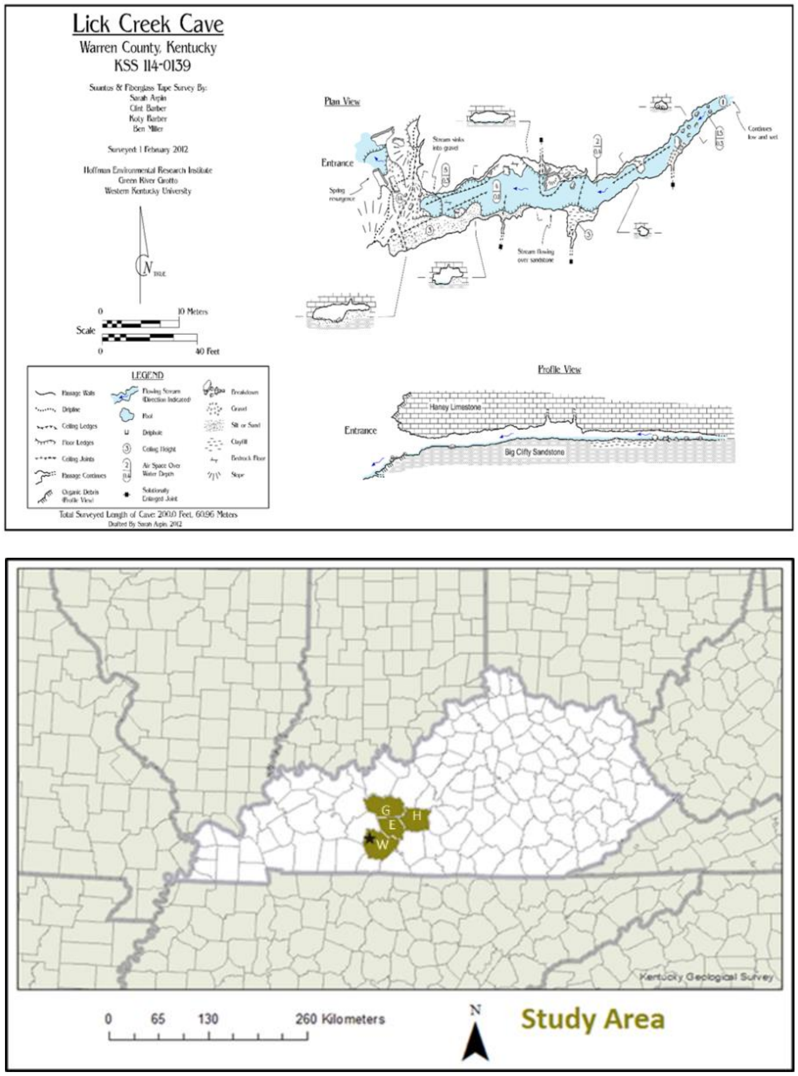

Figure 38. Lick Creek Cave map. This cave in Warren County is an example of one that forms along the Big Clifty/Haney contact. Joints and the contact at the base of the Big Clifty are major controls in the development of this cave. Approximate location of the cave is shown by star in lower map. Colored counties include Edmonson (E), Grayson (G), Hart (H), and Warren (W). Source: Modified from Arpin (2013).

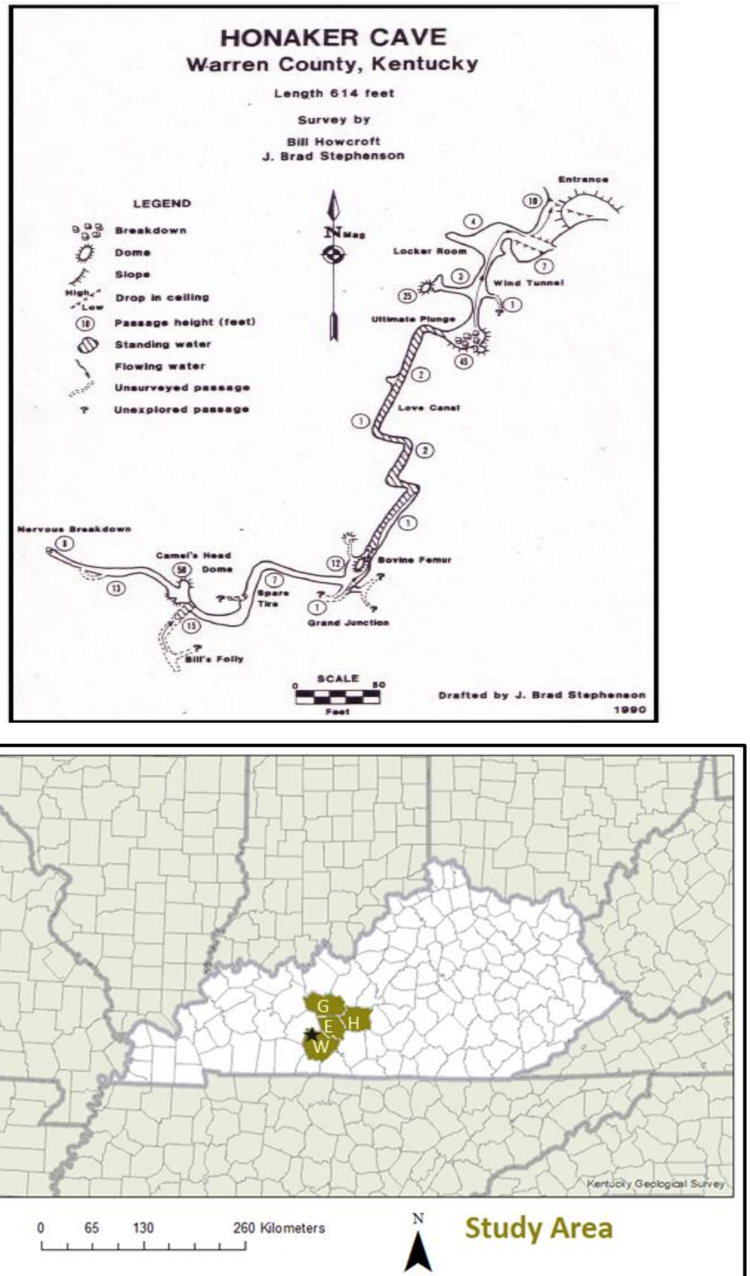

Figure 39. Honaker Cave Map. This cave in Warren County is an example of one with rectilinear passages representing strong joint control, while the sinuous passages represent a greater degree of control by bedding. Approximate location of the cave shown by star in lower map. Colored counties include Edmonson (E), Grayson (G), Hart (H), and Warren (W). Source: Modified from Arpin (2013).

5.1.2 Hand-sample Scale Variables

Hand-sample-view variables refer to those lithographic variables readily seen in hand sample, in relation to surface exposure outcrop view (meters). Compared to surface exposure or outcrop view, hand-sample variables have not been studied as frequently in relation to cave-passage morphology (White et al., 1970; Palmer, 1991; 2009). The most common lithographic features seen with hand samples are framework grains such as fossils, ooids, and intraclasts. These grain-content variables have an impact on development of cave-passage morphology by creating more resistant ledges (see Figures 21 and 22). Studies at Cub Run Cave suggest that grain size plays a role in creating resistant ledges in the cave passage. Echinoderm-rich packstone and grainstone (Facies 2), which are dominated by large crinoid pieces, are more resistant. These crinoid clasts are prone to silicification, which also increases the resistance of the rock unit. Those findings are in contrast to Powell's (1969) study, which suggested fine-grained rocks are more resistive to weathering versus coarse-grained rocks. He did not, however, conduct any petrographic studies in southern Indiana, where he studied karst regions. The presence of chert and silicified fossils plays an important role in the weathering of the rocks, as quartz has poor solubility (Drever, 1997), thus providing at least local influences on cave-passage morphology by not dissolving as readily, in relation to rocks that are fine grained and containing little silica (Palmer, 2007).

5.1.3 Microscopic-Scale Variables

A microscopic view refers to those petrographic variables that require investigation using thin-section microscopy and other petrographic tools, such as XRD, SEM, etc., which, to the knowledge of the author, has not been studied much in the context of understanding cave-passage development and morphology. The main petrographic variables that can influence, or even control, weathering or, more specifically, solutional resistivity of a given cave wall or on the outcrop/surface exposure, are extensive calcite cementation and dolomitization. Dolomitic units are typically resistant in a cave setting or any hydrous (humid) setting, because dolomite does not dissolve as easily as calcite (Drever, 1997; Palmer, 2007). This is not the case in the Haney, as dolomitic units are fine grained so, therefore, grain size becomes the dominant variable and these rock units weather readily despite dolomite being more chemically resistive than calcite. Porosity values of fine-grained dolomitic limestone (two to three percent) are higher than the grainstones (near zero percent). Such higher porosity in the former also likely contributes to the dolomitic units weathering more effectively (Table 9). Similar patterns were noted by Hunter (1993) in the Ste. Genevieve near Corydon, Indiana, and by Foster (1990) in the Haney at Sulphur, Indiana. The presence of extensive cementation in grainstone resulting in occluding BP and WP porosity (Choquette and Pray, 1970) leads to near zero percent primary porosity. This could contribute to the resistivity of these units in both cave and surface in comparison to fine grained units.

Structural, Mineralogical, and Depositional Influences	Weathering Observations
Bedding Planes	Thin-bedded units tend to be more prone to weathering. Bedding planes assist in cave development in the Haney, although jointing has a greater control on cave-passage morphology.
Dolomitization and Silicification	Dolomitic rocks in the Haney are fine grained and have more porosity than the grainstone so therefore they are prone to weathering. As silica content increases, the rock becomes increasingly resistant to weathering. Cherty rocks tend to jut out in cave passages.
Fabric Selective Porosity/Permeability	The near zero porosity of the Haney grainstone units at or near the surface contribute to those being more resistant in cave and surface exposures settings.
Fractures/Joints	Caves in the Haney tend to follow joint patterns. Jointed rocks weather more readily compared to non-jointed rocks of the same facies.
Grain/Crystal Size	Rocks in the Haney become more resistant to weathering as grain/crystal size increases. Grainstone units with large echinoderm fragments tend to jut out in cave passages.

Table 10. Petrographic variance and its relationship to weathering. Impacts of several lithological and petrographic variables of the Haney Limestone in relation to weathering and karst development and porosity. Source: Created by the author.

5.2 The Haney as a Potential Hydrocarbon Reservoir and Aquifer

Overall, the Haney is an extensively jointed skeletal-oolitic packstone to grainstone with low primary porosity and permeability, but potentially high secondary porosity and permeability due to the presence of horizontal and vertical fractures. This is an example of a fractured carbonate reservoir where the highest porosity is associated with breaks in the rock (Reynolds, 1983). Porosity values of one to three percent typify the Haney as low-porosity rock at or near the surface, due mostly to diagenetic calcite cementation, although the Haney contains fractures that could locally increase porosity as well as permeability. These fractures, or fracture-like breaks, are mostly vertical joints (although some can be oriented horizontally), bedding planes, and stylolites that are parallel to bedding. Karst elements tend to follow these features, as seen in the field and in the literature (White et al., 1970; Palmer, 1989; 1991; 2009). It is known that a low-porosity carbonate can become productive for hydrocarbons if an interconnecting fracture pattern exists (Reynolds, 1983).

Although the Haney is a low-porosity carbonate, some opportunities for hydrocarbon development are still possible. Interconnecting elements that could generate secondary porosity include stylolites and joints, but mineralization by calcite and/or dolomite can occur within these fractures, which would limit the connectivity of the reservoir. Grainstone at the surface or near surface contains nearly zero percent porosity due to extensive calcite cementation, but there is potential for good to excellent reservoirs in the skeletal grainstone/oolitic grainstone if subsurface conditions exist that inhibit porosity destruction. Various examples of subsurface carbonate reservoirs are present in the Illinois Basin; they include bryozoan grainstone in the Upper Harrodsburg Limestone (Jobe and Saller, 1995), oolitic zones of the Ste. Genevieve (Treworgy, 1990; Monsoon, 2015), and the Salem-Warsaw and St. Louis Limestones (Cluff, 2015). These reservoirs are prone to diagenetic calcite cementation in grainstone, thus limiting the porosity. They are good to excellent hydrocarbon reservoirs in places, if proper acidic conditions are present in the subsurface (Moore and Druckman, 1981).

Technological advances, especially horizontal drilling and fracking, have led to the potential for relatively low-porosity carbonates (e.g., less than three to four percent) to become productive (Cluff, 2015). The main carbonate reservoirs in the Illinois Basin are typically grainstone shoals and bryozoan aprons, and these lithofacies geometries can be exploited by horizontal drilling. Such effort can connect multiple shoals and aprons to maximize potential for hydrocarbons. These new technological advances allow for reservoirs with as little as three to seven porosity to become viable economically, as Cluff (2015) showed in a presentation about exploration in the Salem-Warsaw Limestones in the Illinois Basin. Thin and low porosity carbonates such as the Haney, could become profitable hydrocarbon producers now that technological innovation permits production in carbonates with increasingly lower porosity and permeability values. Future work should not ignore the hydrocarbon potential of the relatively thin carbonates of the Chester Series, as drilling, completion, and reservoir stimulation continue to improve and could make the U.S. a leader in hydrocarbon production, particularly in traditionally "tight" formations.

5.3 Significance of Study

To the author's knowledge, this study is one of the first to relate petrographic detail to cave and karst development. Previous studies heretofore related large-scale lithology (meters) to cave and karst development, such as shales, as confining lithographic layers and bedding planes/joints as controls on cave-passage morphology (White et al., 1970; Palmer, 1989; 1991; Arpin, 2013). These studies did not, however, address the role of petrographic controls on the development of caves and karst features in general. This thesis investigated variables such as grain size, diagenetic mineralogy, and porosity. These are key variables for better understanding and hence predicting weathering in cave and surface exposure settings and for reservoir and aquifer development (hydrocarbons and water).

Chapter 6: Conclusions and Future Research

6.1 Conclusions

This study addressed the depositional and diagenetic framework of the Haney at various scales (i.e., outcrop view, hand-sample view, and petrographic thin-section view) and relates those variables to weathering and karst development. These same variables that influence cave and karst development also influence the Haney as a potential reservoir and aquifer. The Haney is characterized by seven predominant facies: bryozoan packstone, echinoderm grainstone, oolitic packstone-grainstone, coarse and fine-grained dolomitized units, interbedded packstone-wackestone, and interbedded shale-limestone units. Diagenesis in the form of calcite cementation, dolomitization, silicification, and stylolite development were identified as key diagenetic features of the Haney. Each of these depositional facies, along with the diagenetic characteristics, influenced weathering of surface exposures and karst development.

Development of karst in the Haney is caused by a combination of waters that are greatly undersaturated with respect to calcite leading to sufficient dissolution (Hess and White, 1993), along with lithologic or petrographic variables, and a humid climate. Macroscopic controls on karst development include dissolution along conjugate joints with a SW-NE or W-E trend (Arpin, 2013), a basal shale at the Big Clifty-Haney contact that acts as a confining layer, bedding-plane controls, and the influence of subjacent and superjacent sandstones.

Mesoscopic and microscopic controls on weathering include grain-size variation, silica content, and porosity differences between facies. Large echinoderm grains, for example, are more resistant to weathering versus fine-disarticulated bryozoan grains, thus making the echinoderm grainstone more resistant than the bryozoan packstone or fine-grained dolomitized units. Silicification of grains and matrix also contribute to a more resistant rock unit, because quartz is a more resistant mineral versus calcite or dolomite.

The Haney is characterized as a fractured carbonate reservoir containing joints, stylolites/microstylolites, and bedding planes that typically possess porosity values of one to three percent. The intersection of horizontal and vertical fractures potentially leads to localized productive zones for fluids, as well as, being favorable zones for cave formation (Doctor et al., 2008). Although the Haney at the surface and near surface is a low porosity rock, under subsurface conditions, the unit may have significant effective porosity. The presence of H_2S and CO_2 byproducts in a brine solution from the development of hydrocarbons led to conditions that inhibit the formation of calcite cement (Moore and Druckman, 1981). Certain framework grains such as ooids are also known to resist burial compaction and thus preserve much of the original depositional porosity (Moore and Druckman, 1981). Collectively, all of the above factors can increase the porosity and permeability of the Haney, making it a viable hydrocarbon reservoir. Technological advances, such as fracking and horizontal drilling, can extract hydrocarbons from lower porosity rocks with porosity values as low as three percent. Such a low porosity cutoff value would be economically feasible in many fields in the basin; however, this also depends on the price of oil (Cluff, 2015). Advancements, plus additional subsurface studies, could potentially identify hydrocarbon reservoirs in thin Chesterian carbonates, such as the Haney Limestone throughout the Illinois Basin.

The Haney is also a potential aquifer source due to the presence of springs and seeps at the Big Clifty/Haney contact and secondary porosity due to fractures. Brown

(1966) mentioned Three Springs, which is part of the Mammoth Cave National Park public water supply, as an example spring in the Haney. This spring, and other springs and seeps common at the basal shale, should be studied more extensively as this has potential to be a localized supply of water in the area.

This study is unique, as it provides a detailed description and analysis of a number of petrographic variables that influence or control weathering in south central Kentucky that, heretofore, have not been studied in detail. In conclusion, macroscopic, mesoscopic, and microscopic lithology and petrographic controls influence weathering and karst development in the Haney. These variables contribute to the development of an aquifer source and potential reservoir.

The main conclusions of this research summarized include:

- Facies in the Haney range from oolitic packstone-grainstone to bryozoan packstone to fine-grained dolomitized units. Calcite cementation, dolomitization, silicification, and stylolite-microstylolite development are important diagenetic features;
- Joints, a shale at the base of the Haney, bedding planes, and position between two sandstones, are macroscopic controls that influence weathering and karst;
- Grain-size variation, silica content, and porosity differences are major mesoscopic and microscopic controls on weathering and karst development (Table 11);
- These lithologic variables control the reservoir and aquifer properties of the Haney. Future research should focus on porosity of oolitic zones predominantly in the middle to upper Haney (Figure 40) to identify viable hydrocarbon reservoirs deeper in the basin; and

- Springs at the base of the Haney are a potential groundwater resource.

Characteristics of the Haney Limestone	**Summary**
Depositional Facies	The predominant facies of the Haney include: bryozoan packstone-grainstone, echinoderm grainstone, dolomitized wackestone-packstone, fine-grained dolomitized mudstone, interbedded skeletal wackestone-packstone, and interbedded shale and limestone.
Diagenetic Effects	The major diagenetic effects of the Haney include: calcite cementation, silicification, dolomitization, and stylolite and microstylolite formation.
Karst Development	Caves in the Haney follow predominant joint patterns (Arpin, 2013). Cave morphology is also determined by bedding planes to a lesser extent. Coarse-grained units such as echinoderm grainstone tend to be more resistant to dissolution in cave/karst settings. Units that are cherty or contain many fossils that have been replaced by silica are more resistant in cave passages.
Weathering Properties in Outcrop	Rocks that are coarse-grained and/or contain a significant amount of silica are more resistant versus the fine-grained dolomitic mudstone to muddy packstone. This is due to grain size and porosity differences between the grainstone units (which have near zero percent porosity) and the fine-grained dolomitized units (which have pinpoint porosity).
Reservoir Properties	The Haney is a low-porosity carbonate containing porosity values of 1-3 percent. Future work and new technologies such as horizontal drilling and fracking could make the Haney and other thin Chester carbonates more viable hydrocarbon targets.

Table 11. Lithologic and petrographic summary for the Haney. This table shows the relationship between to weathering and karst development, and reservoir/aquifer properties. Source: Created by the author.

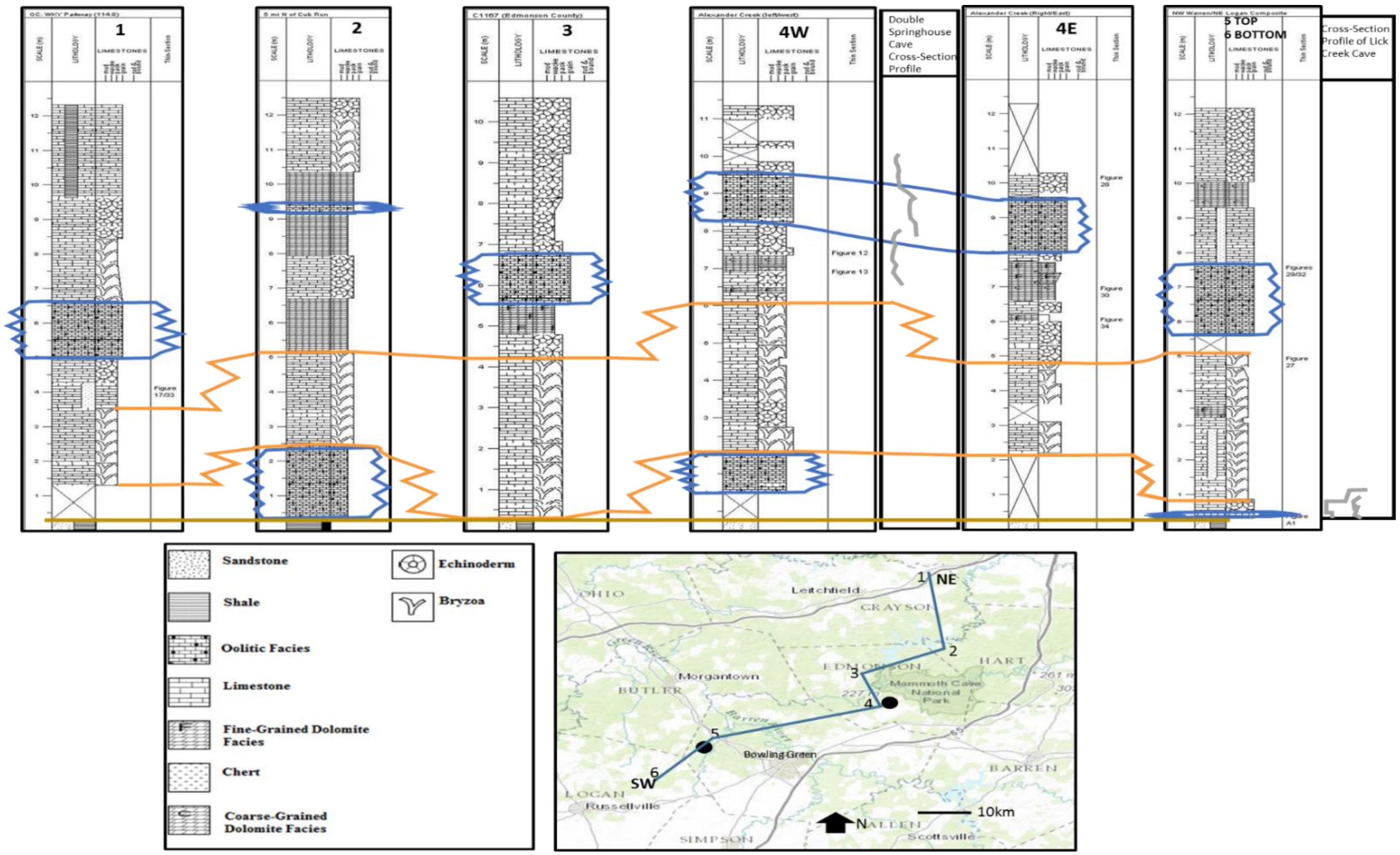

Figure 40. Summary diagram with stratigraphic columns and cave profiles. This figure displays correlated stratigraphic columns from northeast to southwest across the study area and are correlated to nearby cave data collected by Arpin (2013). The blue represents correlated oolitic zones (Facies 3), the orange represents correlated bryozoan facies (Facies 1), and the gold line represents the top of the Big Clifty Sandstone which is the datum for this section. The black dots at the bottom right map represent the two caves where profiles were drawn from and the numbers represent the locations where stratigraphic sections were measured, which are labeled on the stratigraphic columns. Due to the lack of a complete known section of Haney, the far right stratigraphic column represents a composite that uses data from Natcher Parkway (top half), Stampede Mine core data (bottom half), and the Sugar Grove GQ (Miller, 1963). Mixed data from the cave profiles suggest other controls such as, local hydrology, bedding thickness, joints, and mineralogy along with grain size likely play a role, in the recessive or resistive nature of the weathering in a given cave passage. Source: Created by the author.

6.2 Future Research

This research provided knowledge of the lithologic and petrographic variation of the Haney, and how those variables control the weathering in the Haney. Future study avenues should relate those variations to the local hydrology for a complete picture of cave and karst development within the Haney. Additional future studies should focus on reservoir and aquifer characteristics, as well as even more petrographic-detailed studies of the Haney and other Chesterian carbonates. Specific examples include relating hydrologic variables to the petrographic variables, more detailed reservoir studies, and studying the effects of stylolites on weathering. Below are salient proposed future studies summarized:

- Relate the hydrologic history to the lithology and petrographic variables for a more complete analysis of cave-passage morphology in the Haney;
- Cave and karst studies in other Chesterian carbonates (e.g., Glen Dean Limestone, Vienna Limestone, Kinkaid Limestone, etc.). Do these caves exhibit joint control such as the Haney or a bedding-plane control such as in the St. Louis, Ste. Genevieve, and Girkin? How do confining units such as shales or chert-rich zones influence karst development in these rock units?
- Detailed petrographic studies in other Chesterian carbonates and how does the influence of grain size and silica influence how these rocks weather in surface exposure? Are silica rich carbonates in the Beech Creek (Bodine, 2016) more resistant to weathering versus those that are not silica rich?

- Cathodoluminescence studies could be conducted on cements in Chesterian carbonates to provide a detailed paragenetic sequence;
- Reservoir- and aquifer-quality studies of the Haney and other less studied Chesterian carbonates;
- Acid etching of the Haney could be performed to provide a more detailed and continuous mesoscopic approach that could aid in creation of a more detailed weathering profile;
- Subsurface studies of the Haney, with the purpose of locating any oil shows and identifying any porosity zones in the oolitic units, could be initiated. More borehole imaging technology can provide a close up of key reservoir features such as fractures, which provide subsurface reservoir information; and
- Further studies on relating stylolites to fluid-flow are needed. Heap et al. (2014) call into question whether stylolites act as barriers to fluid-flow due to density of minerals and whether they are perpendicular to fluid flow. Alsharhan and Sadd (2000) note that stylolites in major Lower Cretaceous carbonate reservoirs act as barriers in hydrocarbon producing rocks.

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Appendices:

Appendix I: Select Field Photos and Photomicrographs

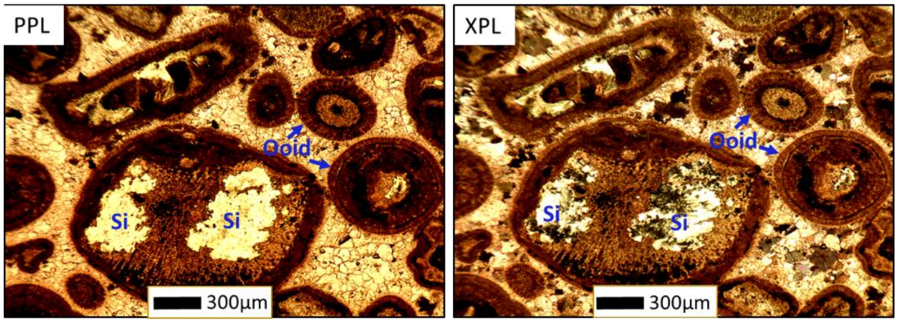

Figure A1. Oolitic facies from Stampede Mine core in northeastern Logan County. Note coated echinoderm grain with silica replacement (Si). This facies is located at the base of the Haney just above the top of the shale of the Big Clifty. Thin section has been stained with Alizarin Red S to differentiate between calcite and dolomite.
Source: Photomicrograph by the author.

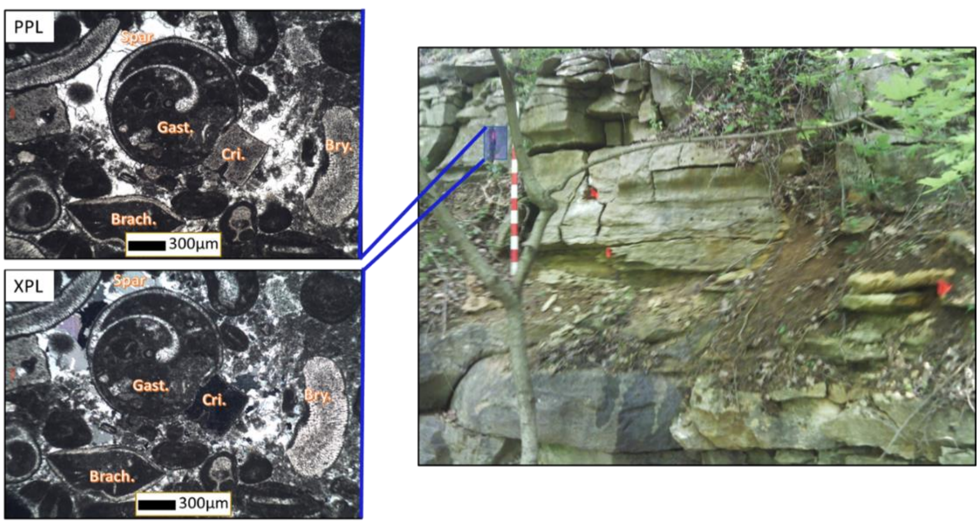

Figure A2. Echinoderm grainstone relative to field exposure. ACR section of the Alexander Creek quarry. Jointing also plays a role in the weathering properties of this grainstone. Source: Created by the author.

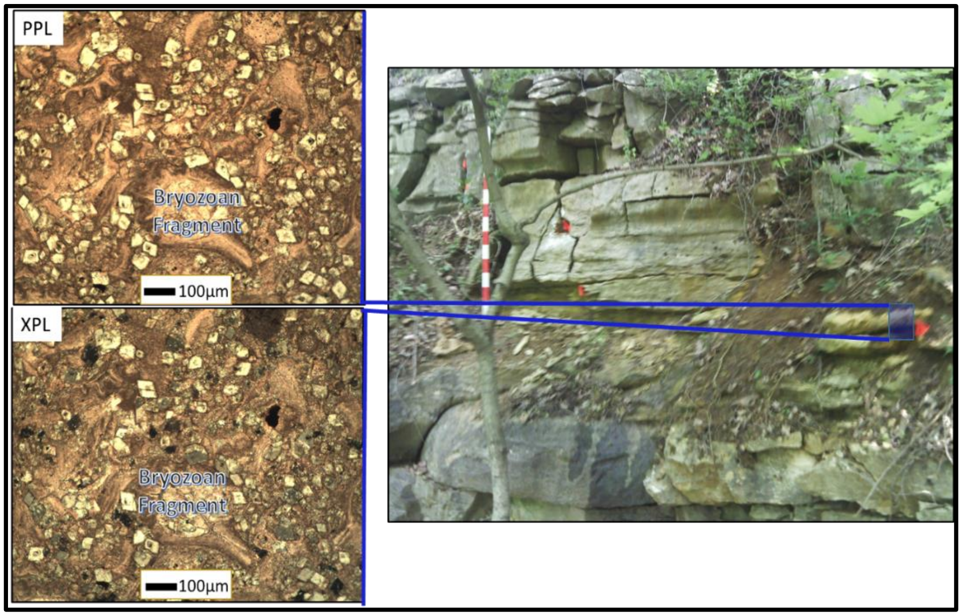

Figure A3. Fine-grained dolomitized unit relative to field exposure. Unit is more prone to weathering compared to the echinoderm grainstone above. Calcite has been stained red in thin section. Source: Created by the author.

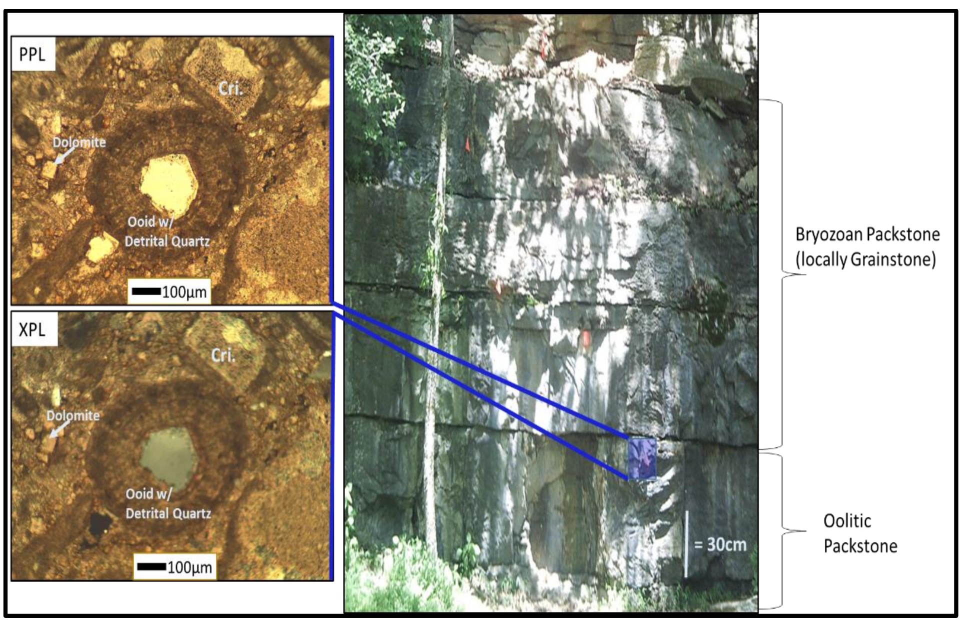

Figure A4. Oolitic packstone unit relative to field exposure. Sample of oolitic packstone in lower portion of the Alexander Creek quarry. Note dolomite and detrital quartz, which likely was brought in by the wind from an adjacent shore or nearshore environment or reworking from Chester sandstone units. Calcite has been stained red in thin section. Source: Created by the author.

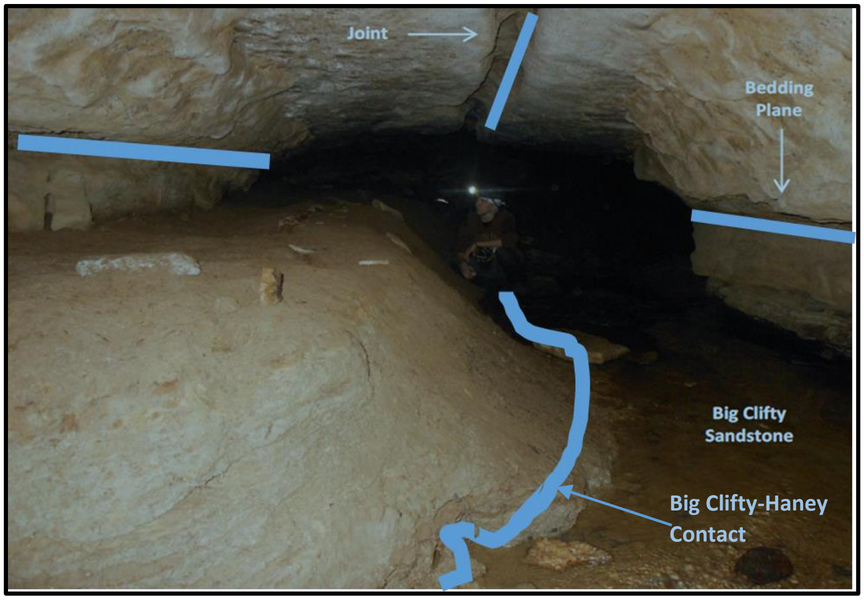

Figure A5. Lick Creek Cave passage. A typical Haney cave (Lick Creek Cave in Warren County) that shows the influence of bedding planes, joints, and the insoluble top of the Big Clifty. Source: Modified by Arpin (2013).

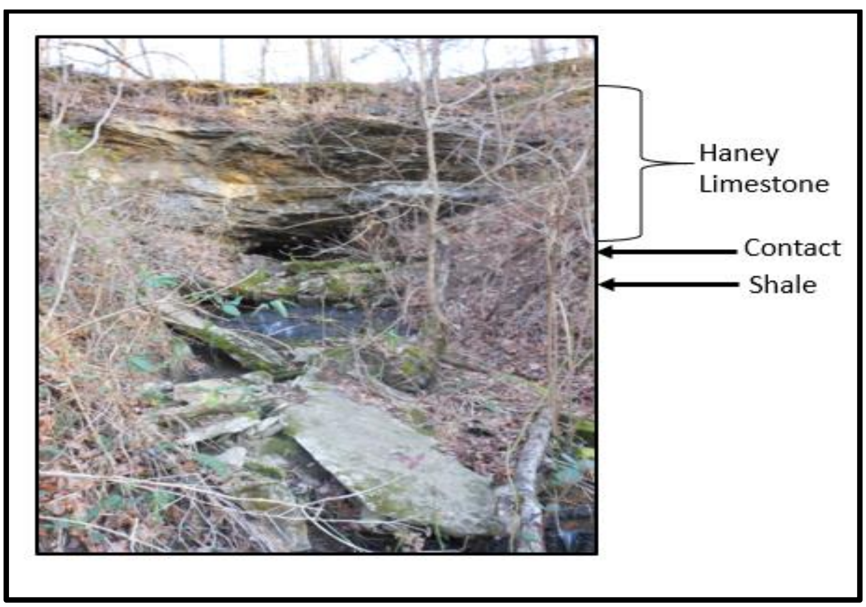

Figure A6. Entrance to Lick Creek Cave (NW Warren County). This cave is located at the Big Clifty/Haney contact in northwestern Warren County. Source: Modified from Arpin (2013).

Appendix II: Haney Host-Rock Cave Examples Courtesy of KSS

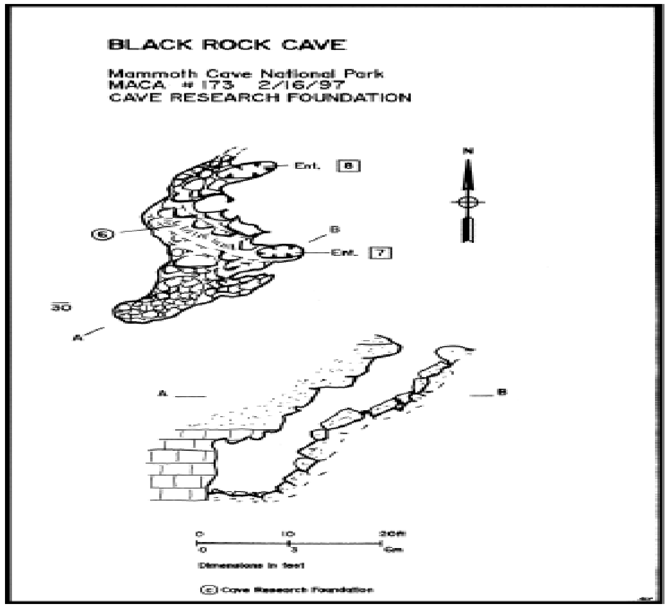

Figure A7. Map of Black Rock Cave. Surveyed by the Cave Research Foundation located in Mammoth Cave National Park. Source: After Arpin (2013).

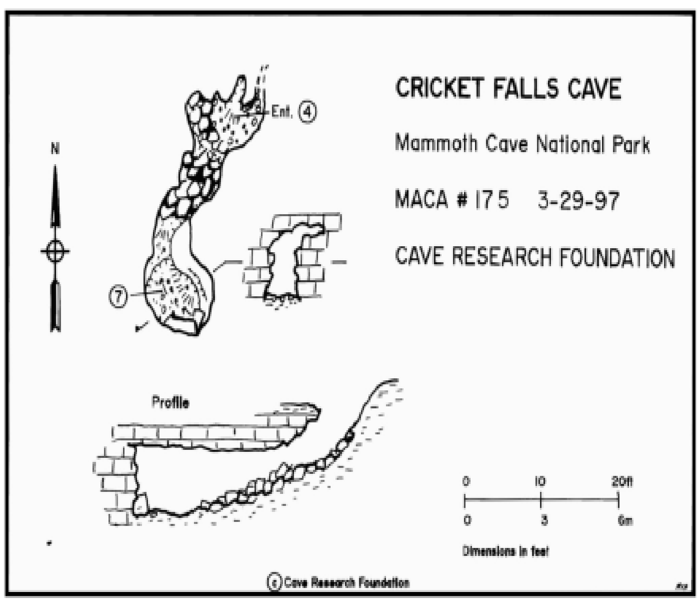

Figure A8. Map of Cricket Falls Cave. Surveyed by the Cave Research Foundation located in Mammoth Cave National Park. Source: After Arpin (2013).

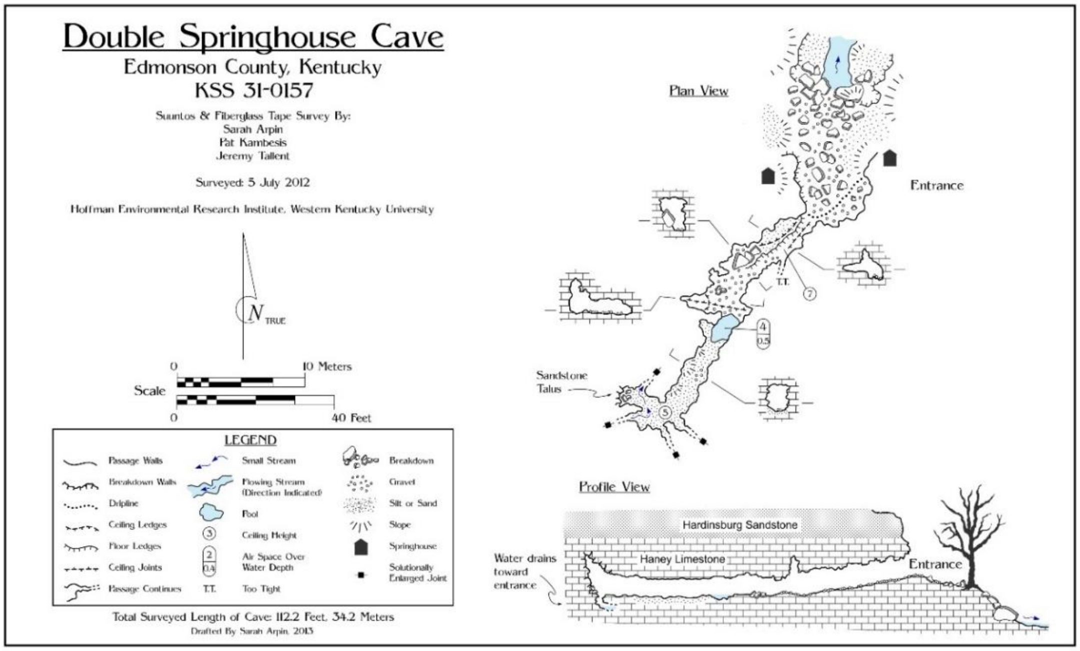

Figure A9. Map of Double Springhouse Cave. Located in southern Edmonson County near the Alexander Creek field site. This cave is described as having a strong joint influence and forms in the upper portion of the Haney. Source: After Arpin (2013).

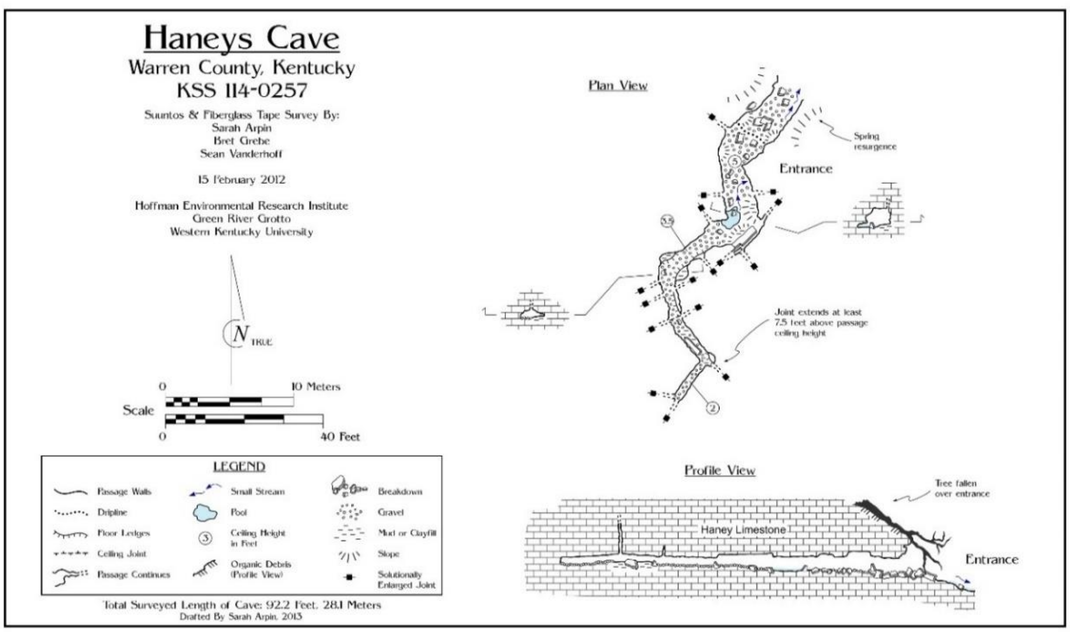

Figure A10. Map of Haney Cave. Survey of the NW Warren County cave shows it to be a small joint controlled cave. The morphology of this cave represents a mix of network and some curvilinear branchwork. This suggests a cave that is joint controlled, but also probably exhibits bedding plane controls. Source: After Arpin (2013).

Appendix III: XRD Analysis

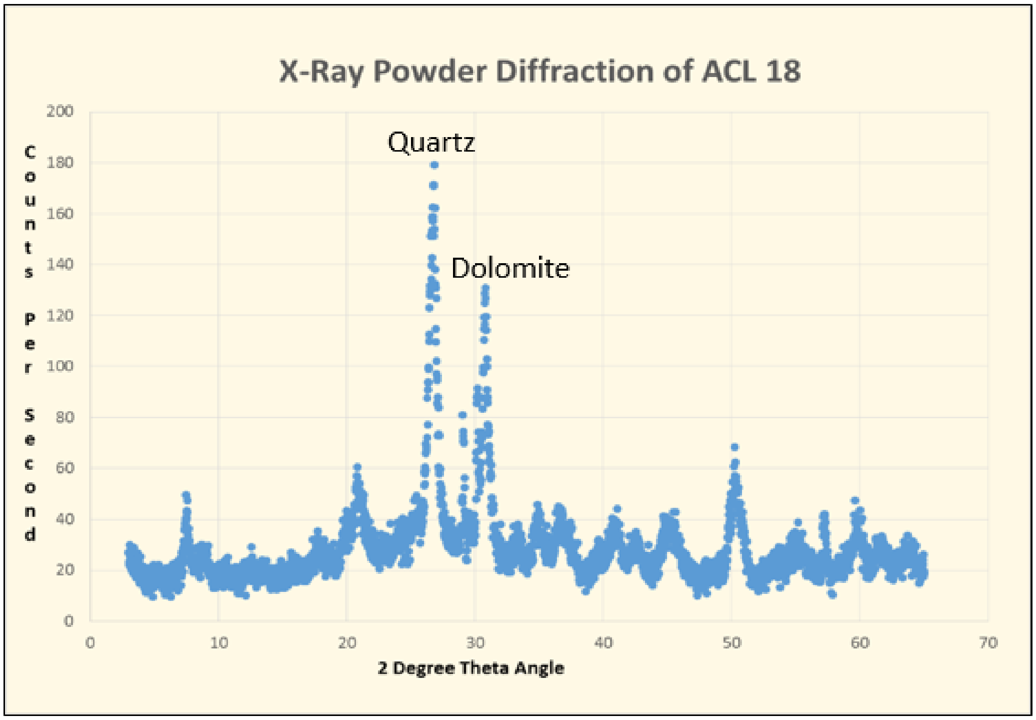

Figure A11. XRD Analysis. One of five XRD samples that was analyzed for this study. This is a sample which contains both quartz and dolomite as noted by the two predominant peaks. This limited analysis of the Haney is collaborated by quartz and dolomite observed in thin section. Other smaller peaks occurred but minerals could not be identified based on those peaks. The calcite was dissolved by acetic acid treatment and there was no quartz standard. Source: Created by the author.