Matrix Porosity Controls on Karst Morphology in the Mooney Falls Member of the Redwall Limestone of the Grand Canyon

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The Mississippian Redwall Limestone is an important constituent of the regional karstic R-aquifer, which is the sole source of drinking water in Grand Canyon National Park and a major source of water in the region. Although faults and fractures have been recognized as focal points for localizing karst development in the aquifer (Huntoon, 1974, 1996, 2000b; Hill and Polyak, 2010; Jones et al.2017), the cause of the high concentration of caves in the Mooney Falls Member of the Redwall Limestone is not well understood. We propose an explanation for stratigraphic localization of karst networks and relate this to preferential dissolution of dolomitized facies in the Mooney Falls Member. This member has over 20 dolomite-rich dolowackestone beds with moldic and intracrystalline porosity ranging from 0-35%, with an average of 18% (Dohm et al., 2017). We posit that the localization of caves in the Mooney Falls Member of the Redwall Limestone can be attributed to the preferential dissolution of these highly porous dolomite beds. Photographic analyses of karst exposed within the canyon demonstrate that cave width and location are primarily controlled by faults and fractures, and secondarily controlled by the location of dolomite bands. These porous dolomites continue to be a pathway for groundwater, with springs of a wide range of flow discharging from dolomite bands. These findings are significant for understanding both the characteristics and behavior of the R-aquifer, and more broadly, the interaction of dolomitization and karst genesis.

Keywords: Karst (cave), permeability, stratigraphy, morphology, Grand Canyon

INTRODUCTION

The Grand Canyon of northwest Arizona is host to a regional karstic aquifer; the R aquifer, which comprises the Mississippian Redwall Limestone, Devonian Temple Butte Limestone, and Cambrian Muav Limestone, referred to as the lower Paleozoic carbonates (Huntoon, 1974). Almost all of the water draining the Kaibab plateau discharges through perennial karst springs developed in the lower Paleozoic carbonates 3000 feet below the rims of Grand and Marble Canyons (Huntoon, 1974). An extensive karst conduit system has been developed in the Redwall and Muav Limestones, with a localization of caves documented in the Mooney Falls Member of the Redwall Limestone (Huntoon, 1974, 1996, 2000b; Hill and Polyak, 2010; Jones et al. 2017) (Figure 1).

Figure 1. Karsting (green) in the Mooney Falls Member of the Redwall Limestone, looking southwest towards Vasey's Paradise.

Despite the Redwall Limestone's important role in conveying regional groundwater, little research has been conducted regarding rock type-controlled porosity in relation to cave morphology and storage capacity of the regional R-aquifer. Recent research conducted by Fort Lewis College faculty and students (Dohm et al., 2017) documented a correlation between dolomitized layers in the Mooney Falls Member of the Redwall Limestone with zones of up to 36% porosity, as demonstrated by spring seepages and caves localized along dolomite bands (Figure 2). Highly porous dolomite bands have implications for yielding high flow capacities where hydraulic gradients are steep, and large water storage reservoirs where the hydraulic gradient is shallow.

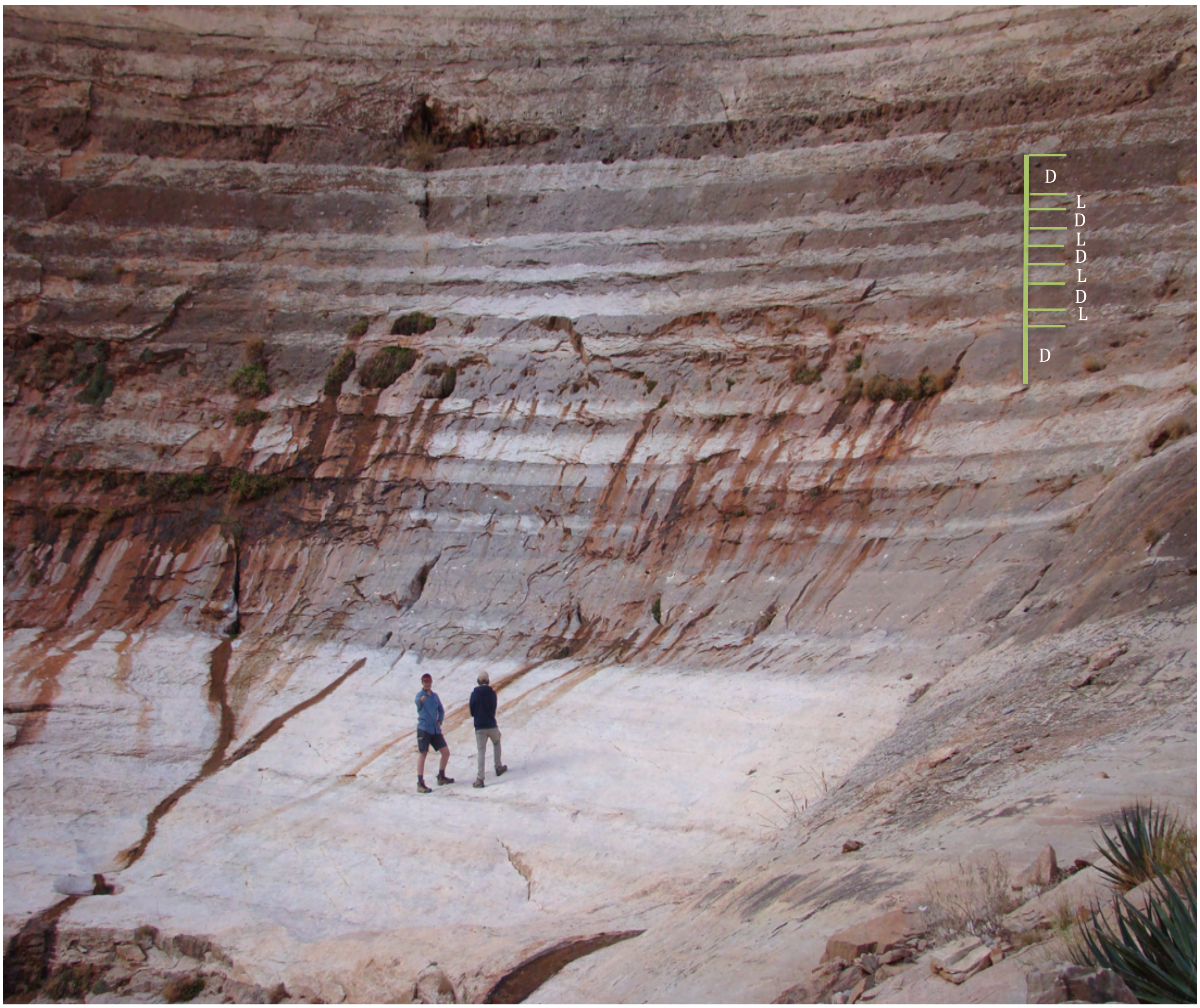


Figure 2. Spring seepages preferentially discharging from dolomite beds. Dolomite (D) and Limestone (L). Photo courtesy of G. Gianniny.

This study aims to integrate analyses of matrix porosity and permeability with sequence stratigraphy, scanning electron microscopy, and digital cave modeling to understand the controls on karst genesis and morphology in the Mooney Falls Member of the Redwall Limestone. Understanding the controls behind the localization of karst features is pertinent to understanding the characteristics and behavior of the regional R-aquifer, including aquifer storage capacity, flow pathways, and spring discharge behavior in response to climate change.

The importance of this research stems from resource management interests from within the National Park Service and compliments current research conducted by both graduate students at Northern Arizona University and NPS hydrologists. The Grand Canyon can be a hostile environment with limited access to clean and reliable drinking water. In 2017 alone, Grand Canyon National Park saw over 5 million visitors (https://www.nps.gov/grca/learn/management/statistics.htm), all of which depend on the regional R-aquifer as the sole source of drinking water to the park. Since the aquifer inhabits and flows through many caves, there is much interest in the variables that may define the quality and quantity of the water sourced from them. In addition, researching the formation and behavior of the R-aquifer will provide a more coherent understanding of how other karstic aquifers may function (e.g., Mammoth Cave, Kentucky).

Study Area

The Grand Canyon of northwest Arizona is located within the Colorado Plateau Province of western North America (Figure 3). Grand Canyon is a unique geologic landscape, with over 1.6 km (1 mile) of strata exposed, ranging from Proterozoic to Mesozoic age. The Kaibab plateau was chosen for karst morphology studies in order to be consistent with previous work conducted on the formation, and because the Redwall is clearly exposed and gently dipping for at least 35 kilometers between South Canyon and the north Kaibab trail (Dohm, 2017). The Kaibab plateau is one of the most elevated portions of the Colorado Plateau, and encompasses 950 mi^2, lying between elevations of 6400 and 9300 feet (Huntoon, 1974). The plateau is bound by the East Kaibab Monocline to the east, the Kanab Plateau to the west, and abruptly terminates at the Grand Canyon of the Colorado River to the south (Figure 3).

The R-aquifer is a well-developed karst system which lies over 1000 meters below the Kaibab Plateau of the north rim of the Grand Canyon (Huntoon, 1974). The R-aquifer has a combined thickness of 400 m (1,300 ft) in the eastern Grand Canyon and thickens to 750 m (2,500 ft) in the west (Kent and Rawson, 1980). This study was conducted in the lower Paleozoic carbonates within the R-aquifer, specifically the Mooney Falls Member of the Redwall Limestone. Stratigraphic controls on unconfined cave morphology were studied near the mouth of South Canyon, where the Colorado River is at the level of the Redwall Limestone.

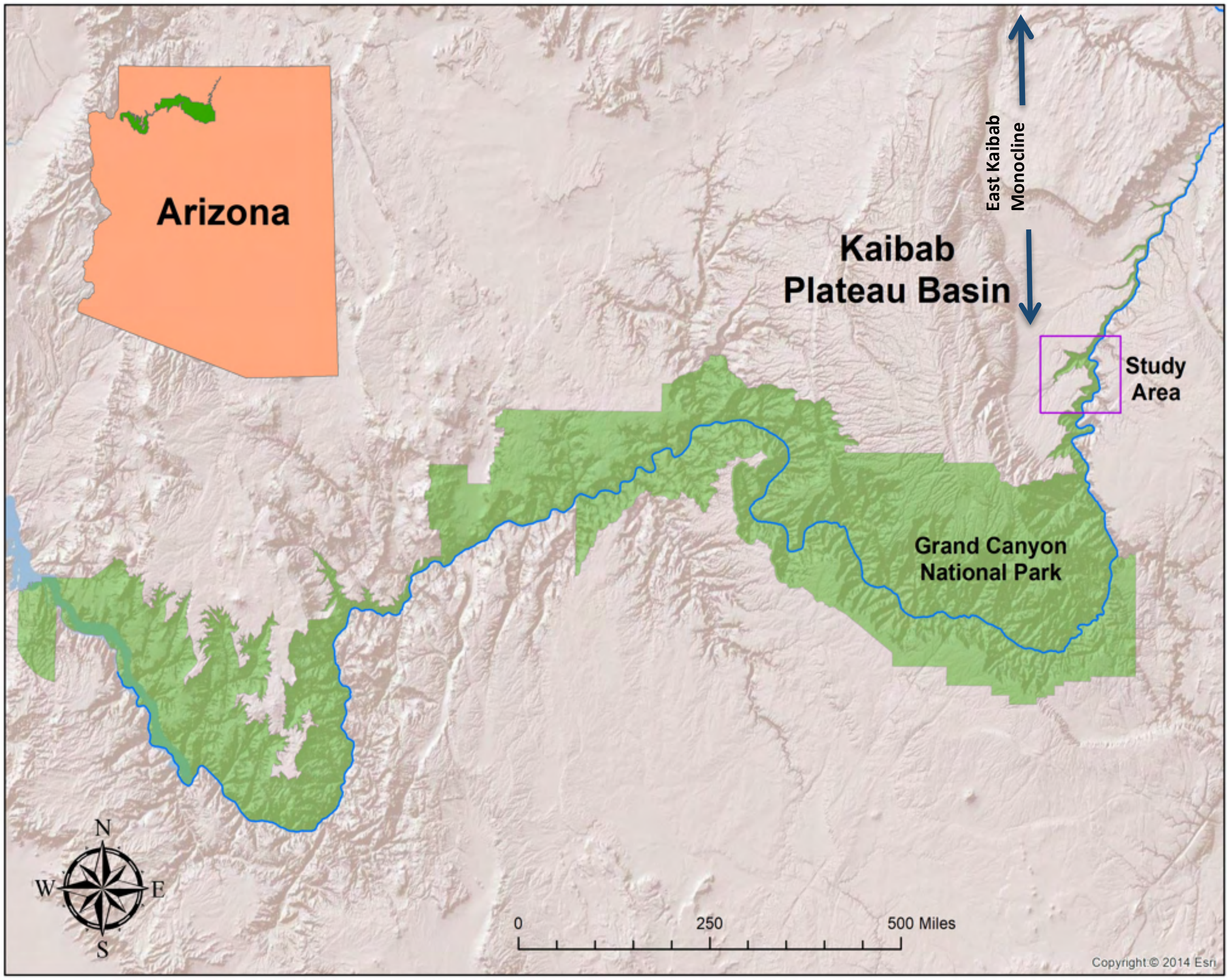


Figure 3. Study area within Grand Canyon National Park.

Geologic Setting

The Redwall Limestone and its counterparts (Madison and Leadville) were deposited on a shallow epeiric carbonate shelf (Mckee and Gutschick, 1969). Figure 4 depicts the early Mississippian Antler orogeny being responsible for the low relief ramp of carbonates westerly bound by the Antler orogenic belt and easterly bound by the transcontinental cratonic arch (Blakey, 2008). The Yucatan peninsula is a modern day analogue to the epeiric conditions of the Mississippian (Kent and Rawson, 1980).

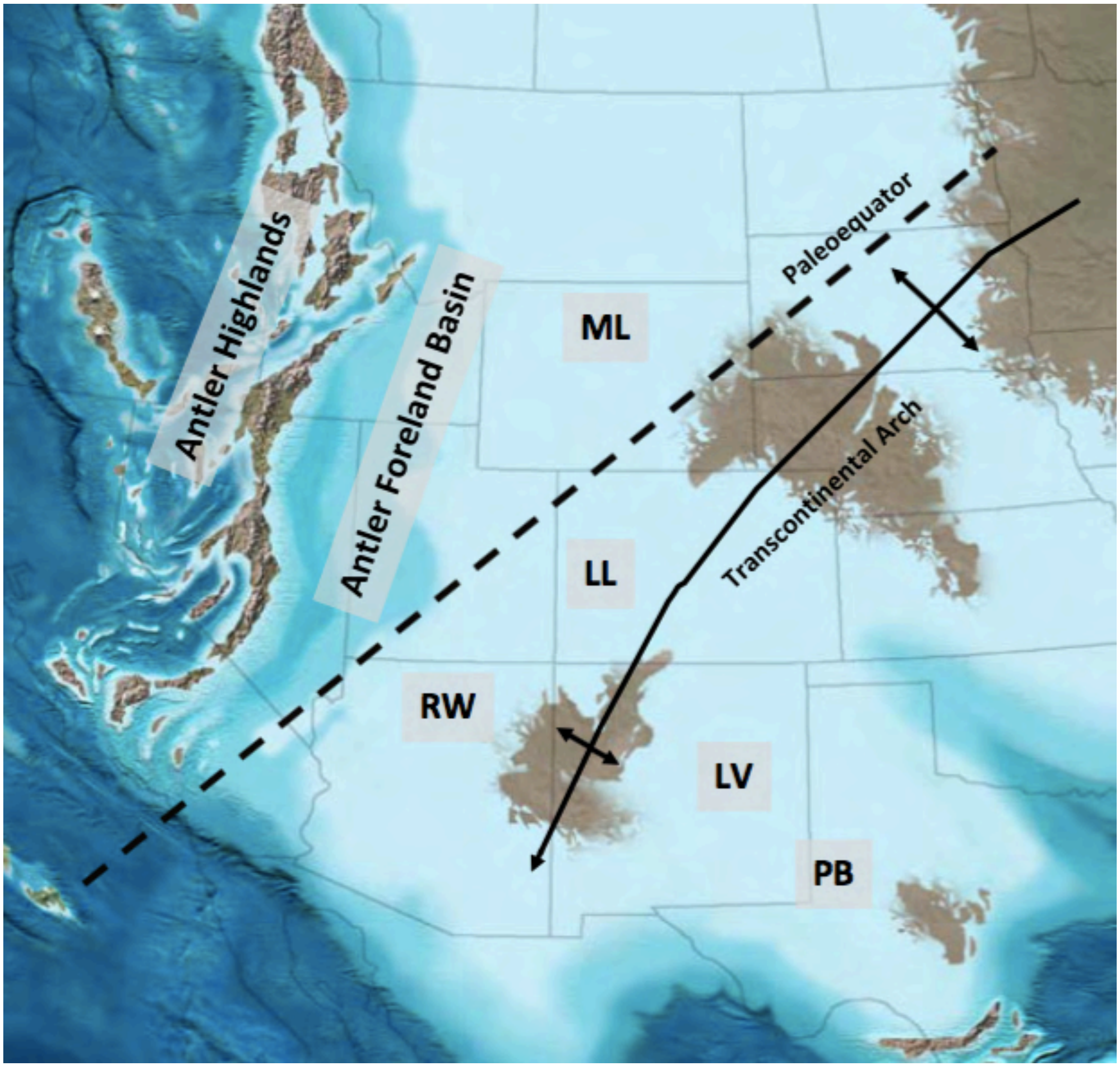


Figure 4. Paleographic map of the Mississippian epeiric carbonate shelf during the late Kinderhookian-Osagean. Modified from Blakey (2008).

Today, a massive, sheer walled canyon has been carved some 5,000 feet from the Permian Kaibab plateaus that surround the Grand Canyon to the Precambrian rock where the Colorado River flows. Regional uplift during the Laramide orogeny caused consequential subdivisions of the Colorado Plateau into subsequent uplifts and basins, which established new hydrologic basins and gradients (Huntoon, 1974). Western Grand Canyon is older than the Eastern side, and fits nicely with Miocene extensional activity that may represent uplift of the western edge of the Colorado plateau just prior to 20 Ma (Polyak, 2008). The eastern portion of the Grand Canyon appears to have undergone rapid incision in as little as ~5 Myr from simple knick-point propagation, lake overflow, or karst capture (Polyak, 2008). Differential incision of the Grand Canyon has revealed multiple generations of karst networks scattered throughout the lower Paleozoic carbonates.

Hydrostratigraphy

The Paleozoic section of the Colorado plateau (and Grand Canyon) contains four hydrostratigraphic zones (Huntoon, 2000). Listed from youngest to oldest (in the order groundwater moves through): 1.Coconino aquifer (C-aquifer). 2. Supai confining layer. 3. Redwall-Muav aquifer (R-aquifer). 4. Basal Bright Angel confining layer (Figure 5). Recharge on the Kaibab plateau is supplied from snowmelt and summer monsoon storms via surface collector structures such as sinkholes and dolines. Other water channeled into the R-aquifer from the Kaibab Plateau is collected from multiple groundwater basins encompassing 950 square miles. Once in the 4000-foot sequence of Paleozoic rocks, water is actively channeled into the groundwater system through faults and joints. Huntoon (1974) describes prominent master joints enhancing the hydraulic conductivity of Paleozoic rocks, occurring as intersecting suborthogonal sets. These regional faults, master joints, and areas of increased permeability (heightened intercrystalline and intergranular porosity) provide conduits for water to drain the plateaus surrounding the Grand Canyon. Caves and other karst systems in the Grand Canyon are susceptible to flash flooding, indicating an open hydraulic connection between the plateau surface and the karst springs in the lower carbonates (Huntoon, 1974).

The Redwall –Muav aquifer, which is the hydrostratigraphic zone of interest in this study, consists of the Mississippian Surprise Canyon Formation and Redwall Limestone, Devonian Temple Butte Formation, and unconformity bound Cambrian Muav Limestone (Mckee and Gutschick, 1969). The Surprise Canyon formation is a laterally discontinuous clastic/carbonate unit that has infilled regionally widespread paleokarst formed on the Redwall Limestone in the Mississippian. The Redwall and Temple Butte Formations are composed of microcrystalline limestones and dolomites (Kent and Rawson, 1980). Cambrian carbonates and the Muav are dense, and the Muav commonly contains silt and clay impurities. Negligible permeabilities have been reported for the Redwall-Muav aquifer, attributing water flow through to fractures and karst (Huntoon, Jones, Hill/Polyak). Huntoon (1974) documents fracture zones in the lower Paleozoic carbonates having large permeabilities and having been rendered even more permeable by cavern development in zones of groundwater circulation. The Bright Angel Shale confining layer resides below the Redwall-Muav aquifer, and acts as an effective seal, even where it is intersected by faults. All 700 springs draining the Kaibab Plateau discharge above the Bright Angel Shale.

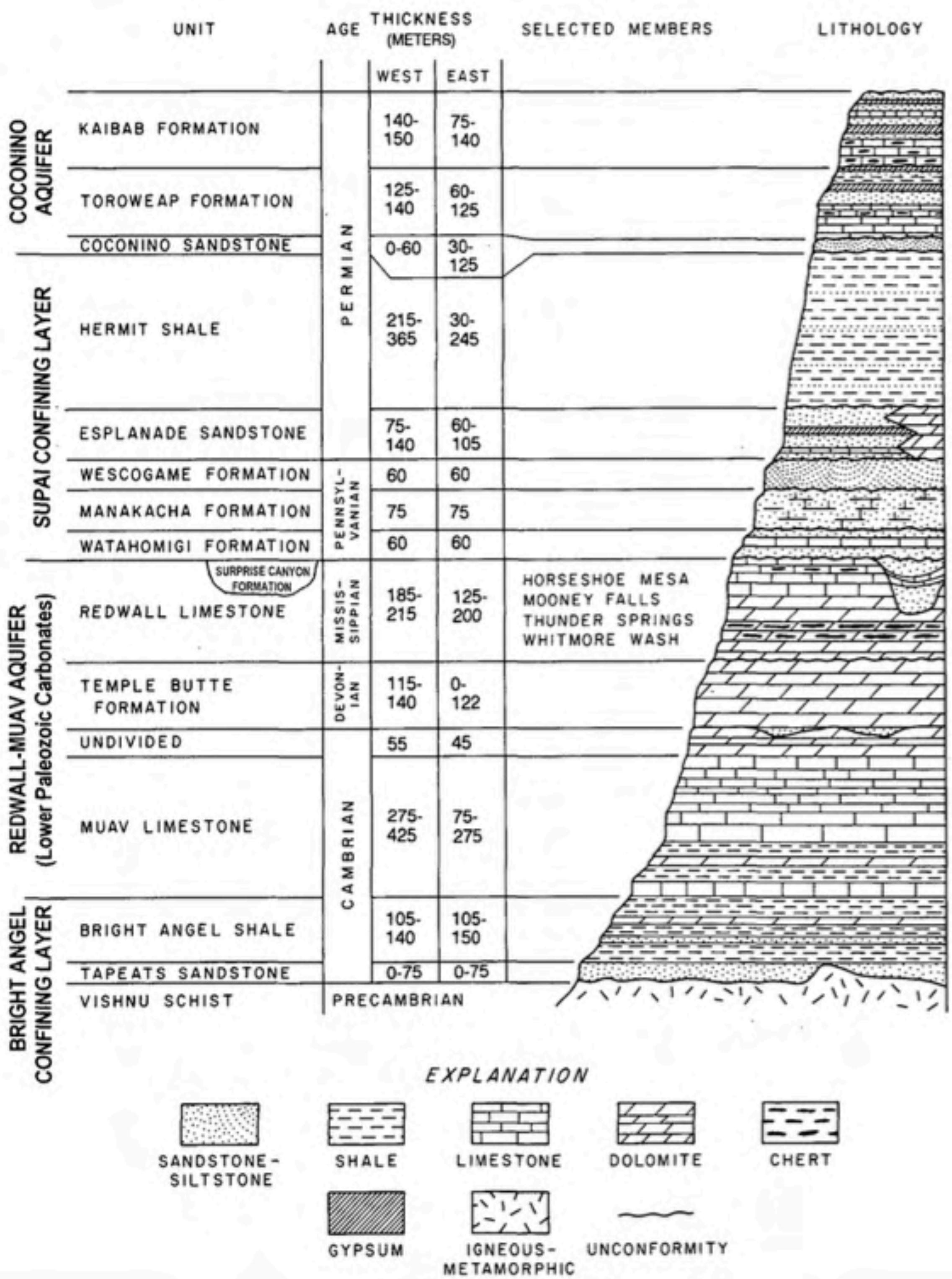


Figure 5. Stratigraphic and hydrostratigraphic units in the Grand Canyon (taken from Huntoon, 1974.)

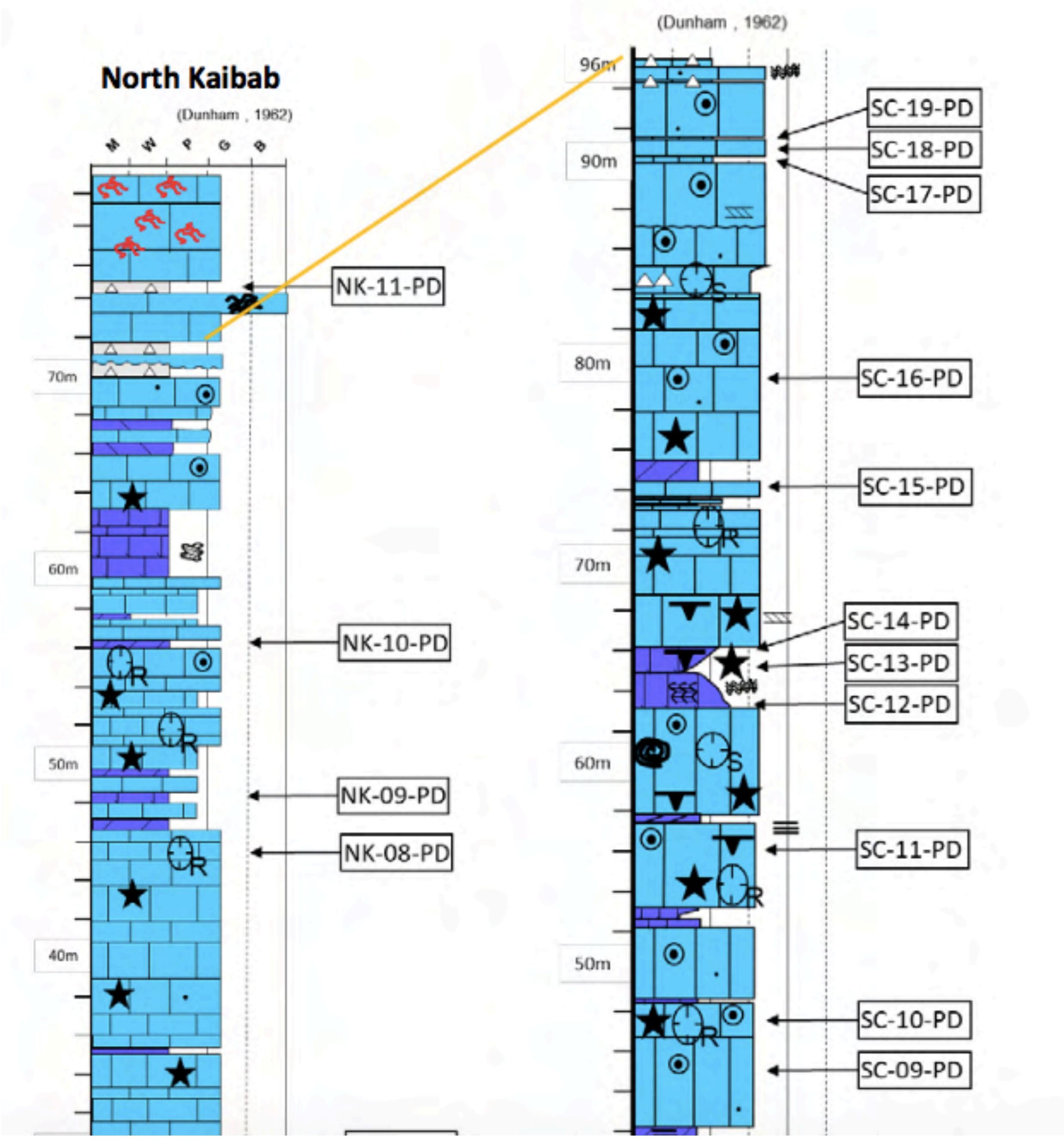
Stratigraphy and Sedimentology of the Redwall Limestone

The Redwall Limestone forms a sheer cliff that stands up to 700 feet tall in western Grand Canyon (Figure 6). The conspicuous iron-red unit is represented by two major transgressions and regressions that occurred during the Mississippian from the late Kinderhookian to Chesterian (Mckee and Gutschick, 1969; Kent and Rawson, 1980). Mckee (1963b) first assigned formal member names to the four distinct lithologic units of the Redwall Limestone. Listed in descending order, the Horseshoe Mesa Member, Mooney Falls Member, Thunder Springs Member, and Whitmore Wash Member.

The first transgression deposited the Whitmore Wash and Thunder Springs Members and the Mooney Falls and Horseshoe Mesa members constitute the second "upper" transgression. Kent and Rawson (1980) established a relation between depositional textures in the Redwall to environments of deposition and resulting depositional facies. The four transgressive facies established range from below sea wave-base to supratidal (in descending order), and coincide with the four members of the Redwall.

Figure 6. The sheer-walled Redwall Limestone cliff face adjacent from the entrance to Stanton's Cave, Marble Canyon.

Dohm et al. (2017) identified 5 facies in the Mooney Falls Member: dolowackestone, dolopackstone, crinoidal-peloidal grainstone, skeletal-ooilitic grainstone, and ooilitic grainstone. Their findings indicate a progradational shift from low energy, deeper water lithologies in the Thunder Springs Member to high energy, shallow water lithologies in the Mooney Falls Member (Figure 7). The dolowackestone was deposited in a deep-subtidal environment, representing the deepest and most seaward depositional environment in the Mooney Falls Member. The dolowackestone facies is significant because it exhibits zones of moldic and intercrystalline porosities of 0-36%, with an average of 18% (Figure 8). Dohm et al. (2017) provides an explanation for distinctive "banding" seen in outcrop in the Mooney Falls Member as alternating facies reflecting the lateral intertonguing of highly porous dolowackestone and packstones with low-porosity (2%) syntaxially cemented crinoidal and ooilitic grainstone facies.



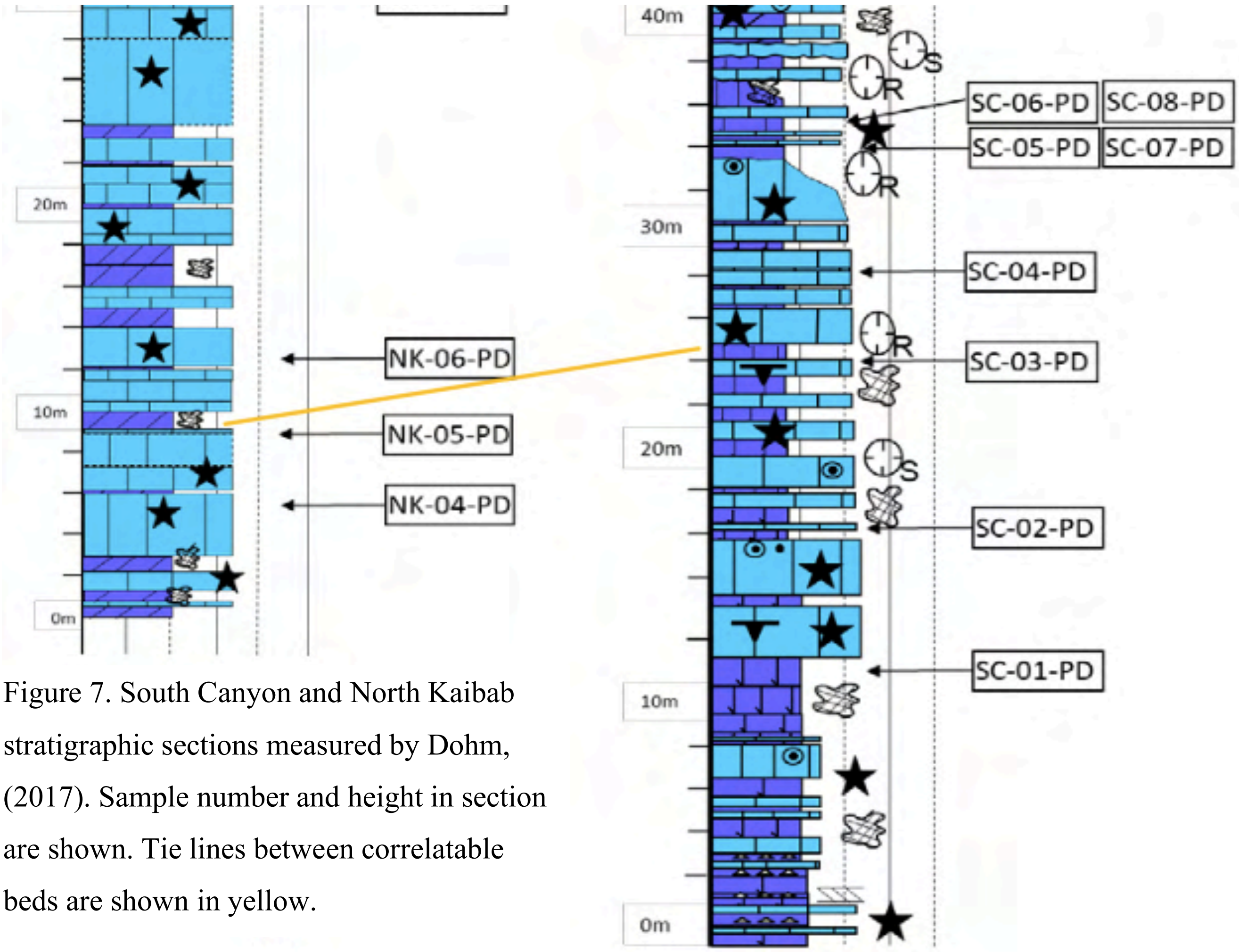


Figure 7. South Canyon and North Kaibab stratigraphic sections measured by Dohm, (2017). Sample number and height in section are shown. Tie lines between correlatable beds are shown in yellow.

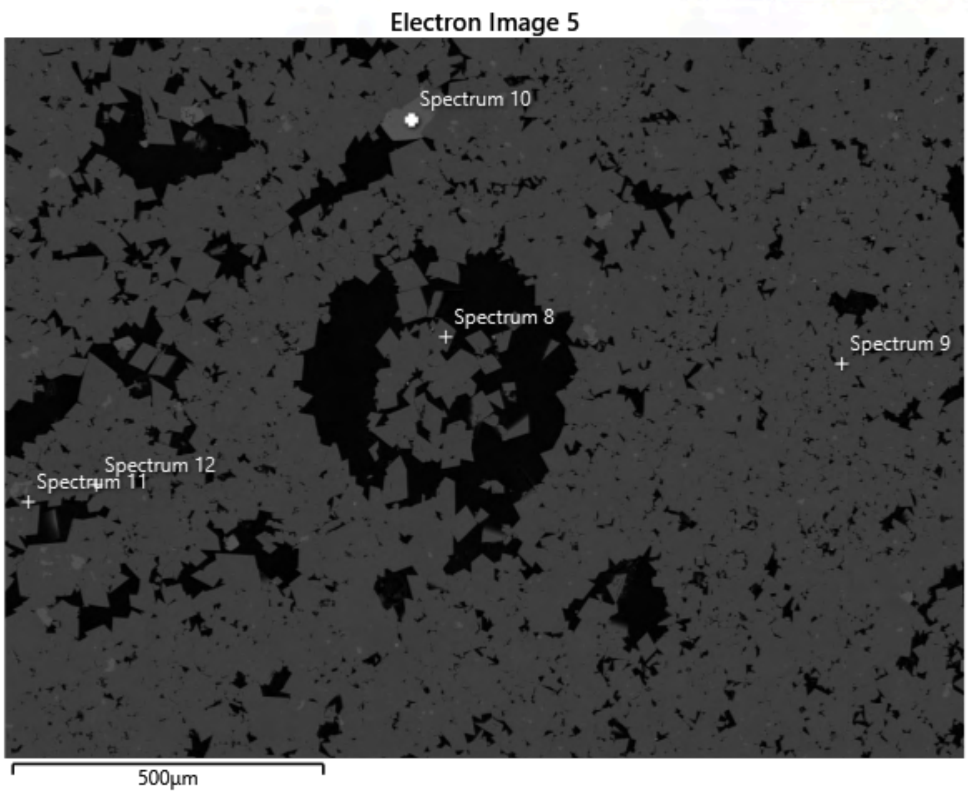


Figure 8. Secondary crinoidal moldic and intercrystalline porosity in the dolomite rich dolowackestone facies of the Mooney Falls Member.

Previous Work

The Redwall Limestone and R-aquifer have been featured in numerous masters' theses, journal articles, and books. Mckee and Gutschick (1969) provide an exhaustive compilation on the stratigraphy and environment of deposition of the Redwall Limestone. Carol Hill and Peter Huntoon provide the basis for the vast majority of work conducted on the cave and karst dynamics of the Redwall Limestone. While Hill (2008, 2010) focuses on summarizing Huntoon's (1974,1996,2000) work and describing a geochemical environment of dissolution, Huntoon characterizes Grand Canyon groundwater basins and hypothesizes on the origins and diagenesis of cave and karst features in the Mooney Falls Member of the Redwall Limestone. Additionally, Dohm et al., 2017 provided the stratigraphic section documenting detailed facies transitions and trace fossils of the Redwall Limestone.

Despite interest in the stratigraphy of the Redwall Limestone and the hydrogeology of the R-aquifer, there is minimal research addressing the relationship between matrix porosity and karst morphology. Many researchers have claimed negligible porosity and impermeability (unless fractured) in the Mooney Falls Member of the Redwall Limestone (and in the R-aquifer itself). Huntoon (1974) stated that the apparent disparity between the zones of permeability and the spring locations is caused by secondary porosity resulting from solution along fault zones that control the locations of the large springs. While the above statement is correct, Huntoon (2000) reported " dissolution permeability is localized on fractures, but that the variable controlling localization is unknown, requiring further research". Dohm et al. (2017) was the first to propose an alternative model for fluid flow in the Mooney Falls Member, documenting moldic and intercrystalline porosities as high as 36%.

Research Goals

Previous researchers have documented that faults, folds, and joints concentrate and channel large quantities of water from the Kaibab plateau to the Grand and Marble Canyons. While faults establish vertically and horizontally integrated zones of higher permeability, I hypothesize that these caves are secondarily controlled by the stratigraphic location of dolomite bands (Figure 9). The location of karst springs draining the Kaibab Plateau in the Grand Canyon can be directly related to the spatial distribution of individual faults; the primary control on cave location. This thesis identifies dolomite bands as lateral conduits of increased permeability allowing for a secondary control on cave morphology and spatial distribution.

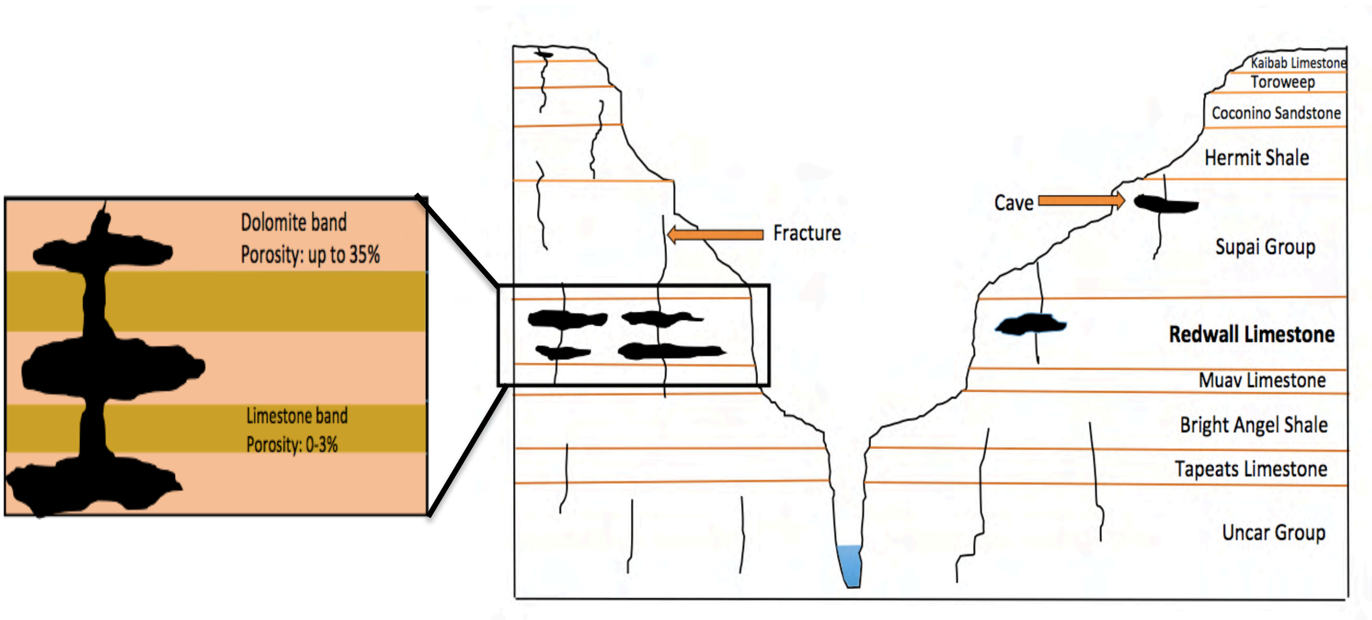


Figure 9. Cave localization is primarily controlled by the location of fractures, and secondarily controlled by the presence of dolomite bands.

METHODS

The methods utilized in this study initially involved fieldwork to collect structural data, evaluate existing stratigraphic sections, perform Structure for Motion image analysis on the outcrops of the Mooney Falls Member, and collect samples for permeability analysis. Strike and dip measurments were collected in South Canyon and near the mouth of South Canyon, proximal to Vasey's Paradise. A TruPulse200 X Laser Range Finder was used to constrain both strike and dip. The TruPulse has an approximate accuracy of 2 centimeters at a range of 2 kilometers with perfect conditions of reflectance. The laser range finder was also used to evaluate the unit thicknesses of individual beds in the MFM and identify the stratigraphic position of Falls Cave in the stratigraphic section measured by Dohm et al. (2017). The relative differences between each point location dolomite bed were calculated while simultaneously referencing marker beds from the stratigraphic section to accurately reference karst feature heights in section. This method confirmed the accuracy of the stratigraphic section with an error of approximately 1meter. The Olympus Tough 5g was used to collect 206 images of a karsted portion of Mooney Falls Member cliff face. In order to comprehensively capture the cliff face with 70% overlap between images, an extended painter's pole was used to mount the camera from. Samples for permeability analysis were collected from various dolomite beds near Falls Cave, encompassing strata both below and at the same stratigraphic position as Falls Cave.

The analysis portion of this study included backscattered electron (BSE) imaging and mineral spectrum identification using an SEM (Scanning Electron Microscope), 3D modeling of

Vasey's Paradise within the Redwall Limestone using ArcScene, Structure for Motion on a karsted cliff face, and permeability results for dolomitized and non dolomitized facies near Vasey's Paradise in the Mooney Falls Member of the Redwall Limestone.

Scanning Electron Microscopy

In order to understand the influences of dolomitization on karst formation, analyses of the porosity and permeability of the Mooney Falls Member of the Redwall Limestone were employed using Scanning Electron Microscopy (SEM) and permeability testing. After cutting thin sections and carbon coating samples, the backscattered electron images were generated from the SEM, highlighting porosity contrasts between the dolomitized and non-dolomitized, calcite rich portions of the sample. Multiple BSE images were collected from thin section SC-05 with additional x-ray mineral identification spectrums denoting the differences between calcite and dolomite.

Permeability

In order to test whether a correlation exists between low porosity crinoidal grainstones and high porosity dolowackestones and their associated permeabilities, six samples were collected from the dolowackestone and crinoidal grainstone facies near Falls Cave to be tested for their permeabilities with respect to both gas and liquid. The samples were vacuum oven dried at 140° F with a net confining stress of 800 pounds per square inch (psi). Weatherford Inc. processed the samples, performing routine core analyses to produce thin section and permeability values for each of the six samples. Thin section images were captured for each sample as a visual representation of porosity variations between successive crinoidal grainstone and dolowackestone beds.

Geographic Information Systems

In order to visualize an accurate depiction of Falls Cave in reference to the Mooney Falls Member of the Redwall Limestone, three-dimensional shapefiles of both survey lines (as a vectorized line) and passage dimensions (as a vectorized polygon with an x, y, and z factor) were obtained from Jason Ballensky, a freelance cave researcher who acquired COMPASS data via surveying Falls Cave. COMPASS data is easily imported into GIS. Latitude and longitude collected during fieldwork were needed to georeference the cave entrance in order to tie the aforementioned shapefiles to their position on Earth. Once georeferenced, it was possible to determine if dolomite bands stratigraphically control passageway in Vasey's Paradise. Using the stratigraphic section created by Dohm et al. (2017), a series of planer raster surfaces were created to represent different facies or "bands" in the MFM using the Raster Calculator in ArcMap. 3D shapefiles of Vasey's Paradise were overlain with the Mooney Falls Member 3D shapefile distinguishing the dolomite bands in the Mooney Falls Member to evaluate the spatial relationship between them.

In order to understand the influence of regional faults and joints on cave formation, ArcMap was employed to perform an orientation analysis of regional joint sets in relation to cave passageway orientations. 128 joints were traced in ArcMap. The mean directional line tool was used to associate an azimuth with each subsequent joint drawn. Prominent groups of similar orientations were separated into three distinct joint sets (5-15°, 45-65°, and 89-98°). The same parameters were then used to evaluate the percentage of the cave controlled by regional jointing. The cave was broken up into individual line segments based on the location of each vertex built into the line shapefile. The mean directional line tool was used once again, but this time on the cave passageway segments. The symbology of the cave was then altered to show which segments are oriented parallel to regional joint sets and those oriented independent of joint sets.

RESULTS

Scanning Electron Microscopy

Two distinct minerals were identified under the scanning electron microscope: dolomite and calcite. Imaging highlights the distinct differences in porosity between calcite and dolomite (Figure 10). Elemental mineral spectrum identifications were generated at each point location (Figure 11) identifying calcite and dolomite as such.

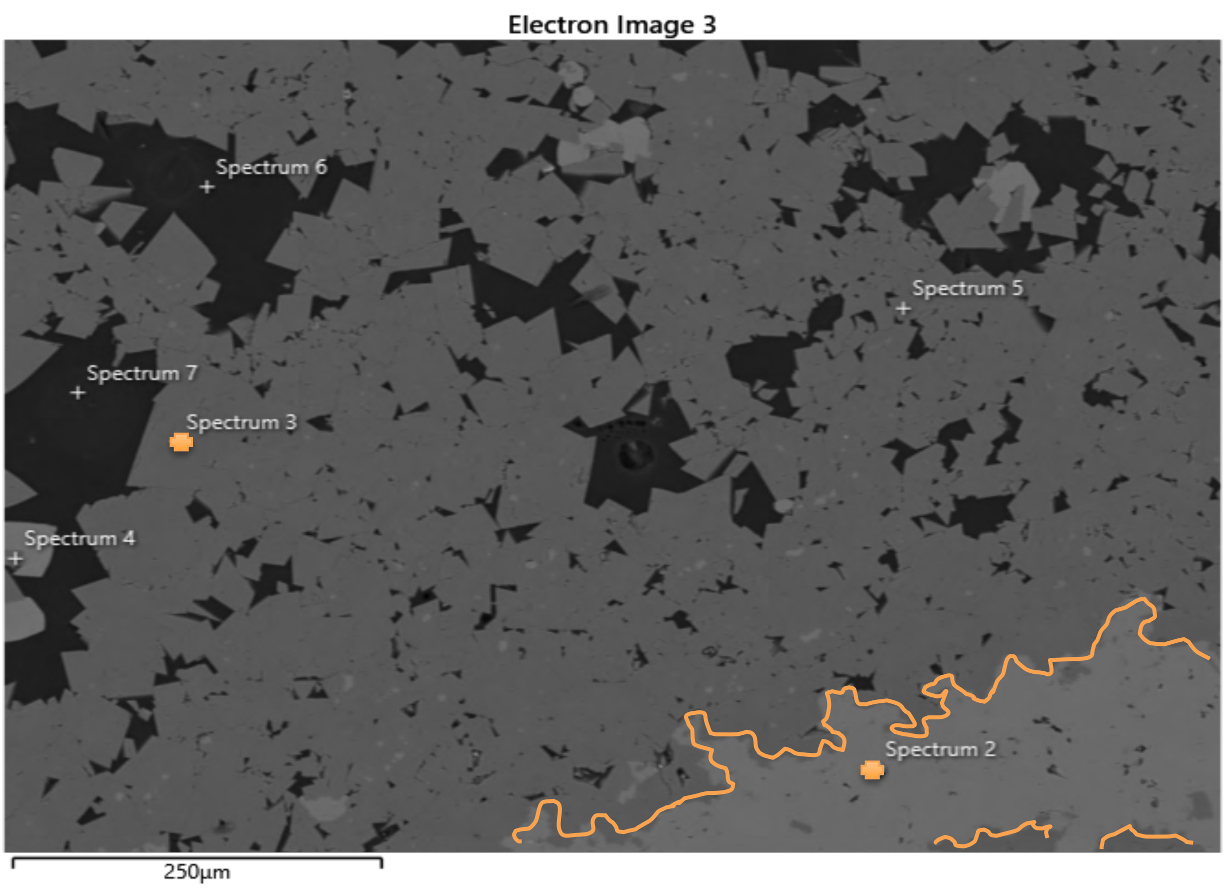
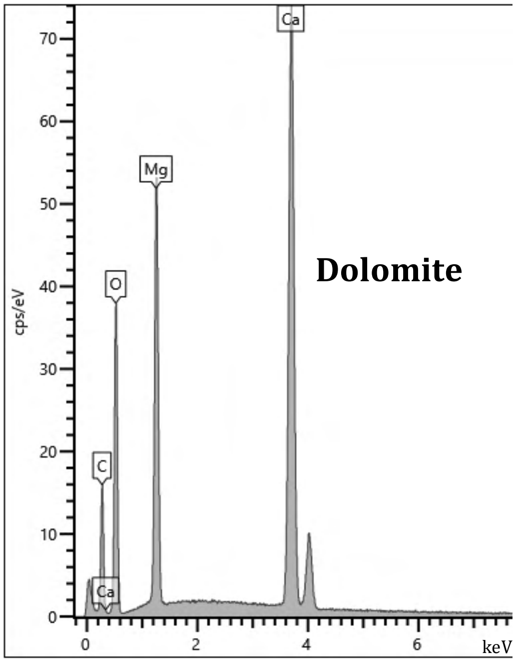


Figure 10. Backscattered electron image showing point locations of x-ray mineral spectrums in sample SC 05. Calcite is highlighted in orange. Notice the beautiful rhomb-shaped porosity existent in the dolomites and the lack of porosity in the calcite (orange).



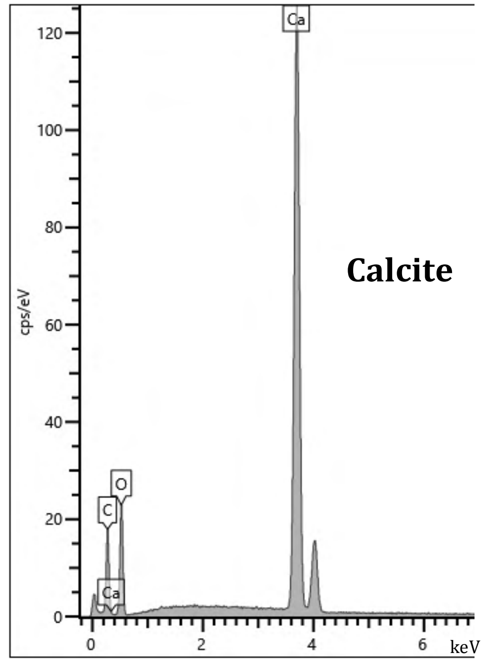


Figure 11. X-ray mineral continuum spectrums depicting dolomite and calcite.

Permeability and Petrographic Analyses

Six samples were cored and analyzed for their permeabilities with respect to air and the Klinkenberg effect as seen in Table 1. The Klinkenberg effect exists because of the difference between the flow of a gas and a liquid through a reservoir, affecting absolute permeability. Gas flow is less impeded by grain surfaces than liquid flow, known as the Klinkenberg effect. This explains why values for permeabilities with respect to a liquid (Klinkenberg) are less than values for permeability to air.

			Permeability, milidarcys		Porosity, percent		
Core Number	Sample Number	Height in Section (m)	to Air	Klinkenberg	Ambient	NCS	Grain Density, gm/cc
1	SC 05	34	3.33	2.68	14.8	14.6	2.85
2	SC 08	34.5	0.0008	0.0002	0.7	0.7	2.71
3	SC 09	45.5	0.0003	<0.0001	0.7	0.7	2.71
4	SC 50	17.5	2.71	2.1	11.3	11.1	2.86
5	SC 51	16.5	10.37	8.5	17.7	17.4	2.86
6	SC 52	40.9	0.125	0.086	7.1	7	2.84
		Average values:	2.75	2.67	8.7	8.6	2.8

Table 1. Summary of routine core analyses results.

Permeabilities with respect to fluid were plotted on a logarithmic scale against porosity at the net confining stress (NCS) (Figures 12). Net confining stress in defined as the difference between isostatic (or hydrostatic) confining stress and the average pore pressure. 800 pounds per square inch (PSI) was used as the NCS, this is equivalent to 1600 feet of overburden pressure. The crinoidal grainstones and dolowackestones were symbolized accordingly along the line of best fit for the data. The crinoidal grainstones range from 0.001 to 0.008 and plot as clusters. The dolowackestones range from 0.125 to 10.37. The wide range in permeabilities are due to sample SC 52 which is the outlier represented in the data between the clusters of crinoidal grainstones and dolowackestones. Omitting the outlier, the dolowackestones range from 2.71 to 10.37, which are also clustered together. Petrographic microscope images of sample SC 52 depict secondary calcite filling many pores in the sample (Figure 13). Further, petrographic microscope images of samples SC 08 and 09 (the crinoidal grainstones) show minimal porosity and an abundance of peloids, ooids, and large calcite crystals. Images of samples SC 05, 50, and 51 show high moldic and intercrystalline porosity between dolomite rhombs and small amounts of calcite bordering grains.

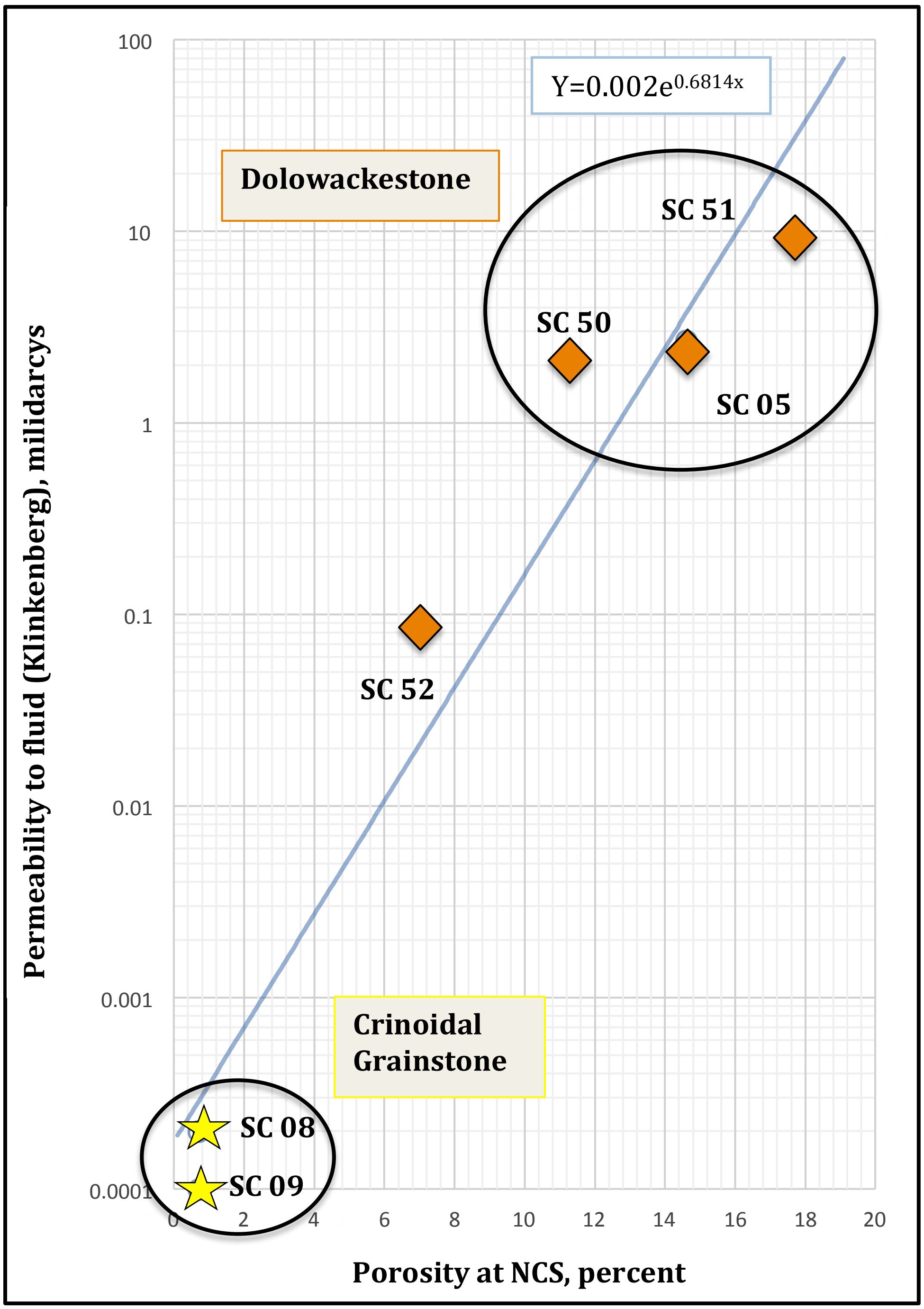
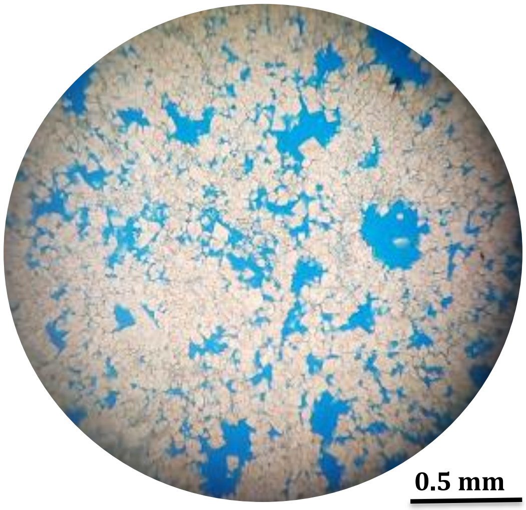
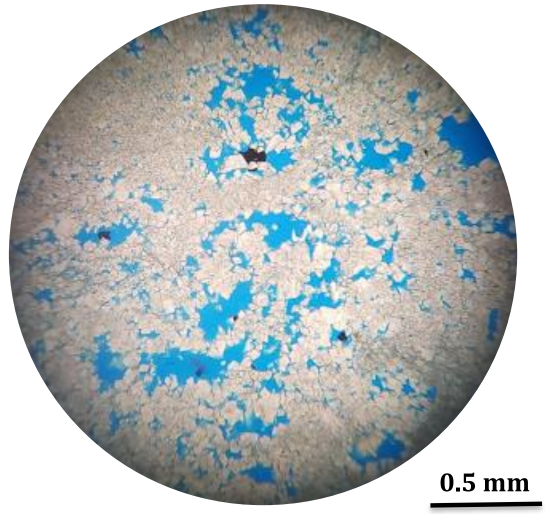


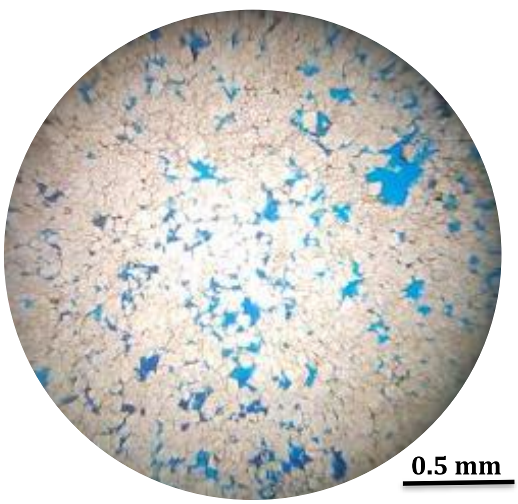
Figure 12. Permeability with respect to fluid versus porosity



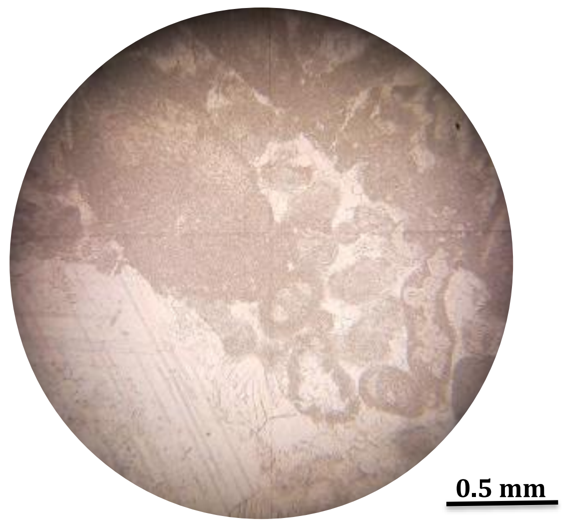
Sample SC 51: Dolowackestone



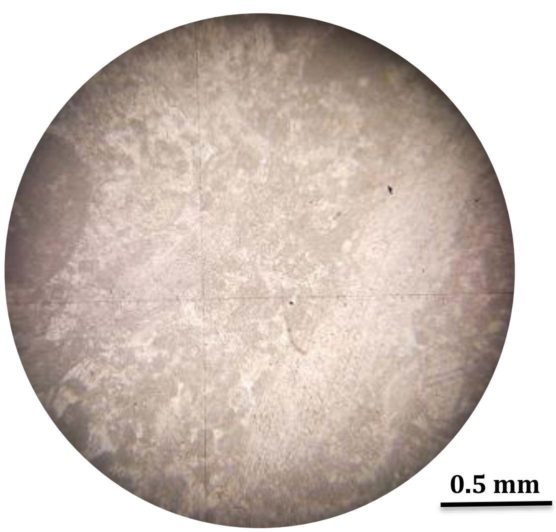
Sample SC 05: Dolowackestone



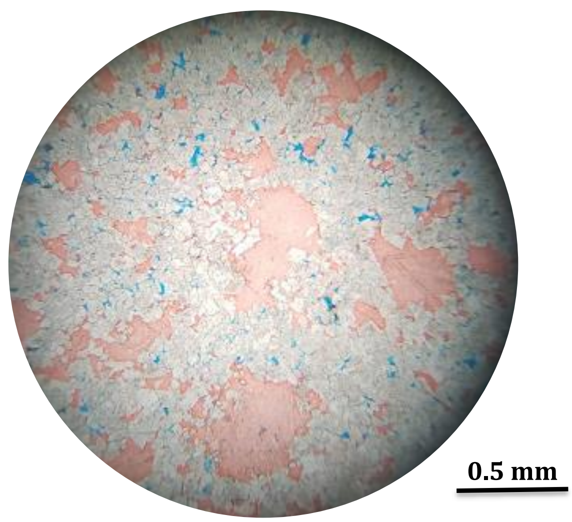
Sample SC 50: Dolowackestone



Sample SC 08: Crinoidal Grainstone



Sample SC 09: Crinoidal Grainstone



Sample SC 52: Dolowackestone

Figure 13. Petrographic microscope images of thin sections samples tested for permeability.

Stratigraphic Referencing

Analyses of stratigraphic section accuracy in South Canyon using the laser range finder provided a context for which to stratigraphically reference Falls Cave. Figure 14 shows six point location dolomite beds identified by the laser range finder and used to calculate the cave entrance to its subsequent dolomite bed. Laser range finder data calculates the entrance of Falls Cave at 40.9 meters in section above the base of the Mooney Falls Member.

Figure 14. Point locations (periods) on key dolomite beds used to derive the position of Falls Cave entrance within the measured stratigraphic section.

ArcScene Geographic Information Systems Model

Before Falls Cave could be modeled in ArcScene in 3 dimensions, the structural orientation of the Mooney Falls Member was needed to generate raster planes representing the top and bottom of individual dolomite bands (Figure 15).

Figure 15. Point locations (periods) of a conspicuous marker bed used to quantify dip with a TruPulse 200 X laser range finder.

A laser range finder was used to obtain structural data to find strike and dip of the Mooney Falls Member is this part of Marble Canyon. Strike is approximately 63°, and maximum (true) dip is identified at 2.1° to the northwest. The resulting raster planes reflecting the orientation of the Mooney Falls Member can be juxtaposed against a line feature representing cave passageway (Figure 16). It should be noted that the line shapefile only represents the position of the laser used to survey cave passageway, not the actual dimensions of the cave passageway itself. Using these methods, the cave is 98% constrained within the Mooney Falls Member of the Redwall Limestone.

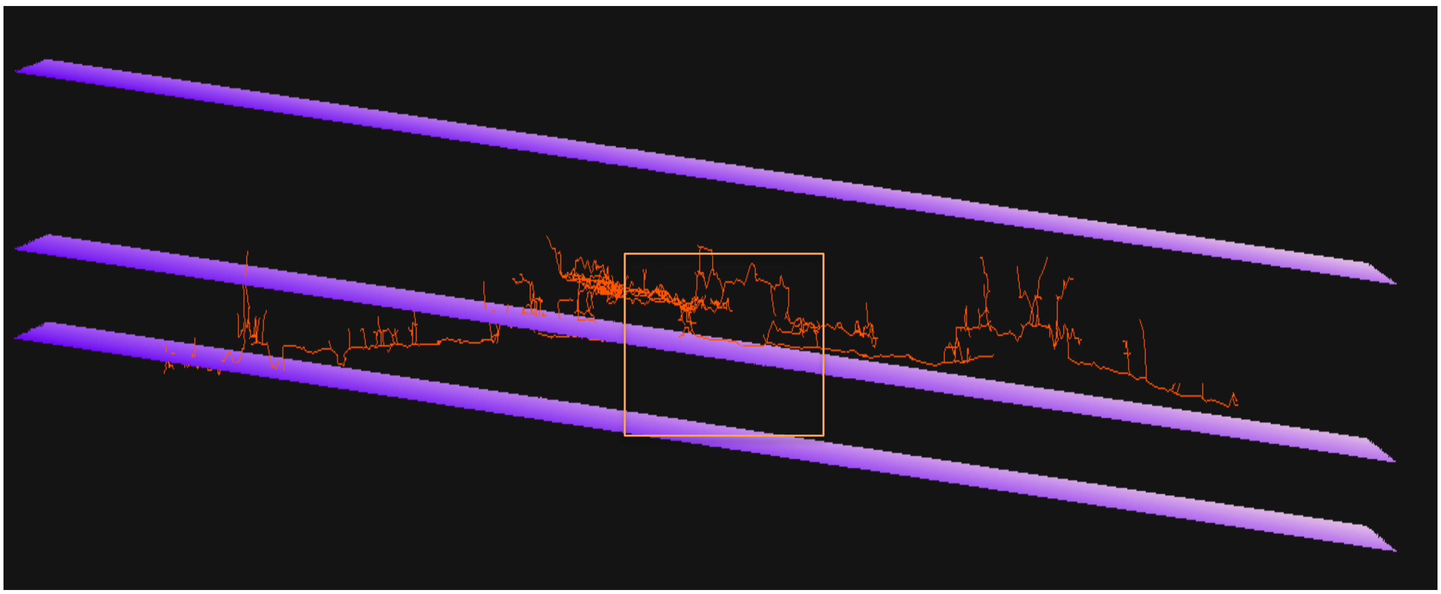


Figure 16. Falls Cave (orange) displayed with planes representing the top and bottom of the Mooney Falls Member in addition to a plane at the entrance of the cave (purple). The cave is modeled as almost completely constrained within the Mooney Falls Member with the exception of a small passageway at the end of the cave (far left) leaving the Mooney Falls Member and entering the Thunder Springs Member.

ArcMap Geographic Information Systems Model

39% of Falls Cave is recognized as having the same orientation as any one of the three regional joint sets. Leaving the possibility that up to 61% of the orientation of passageway in Falls Cave may have been influenced by stratigraphy (Figures 17 and 18).

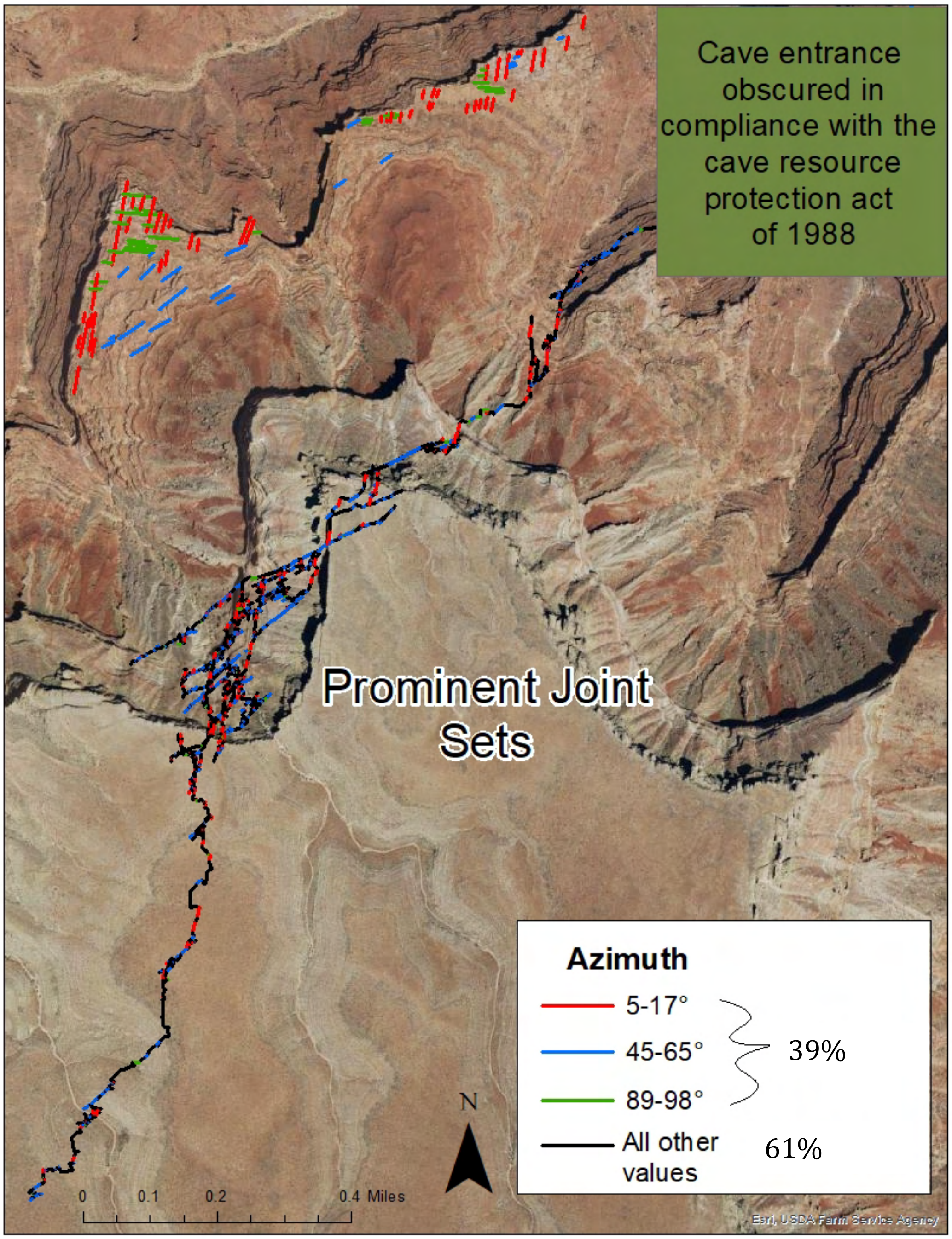


Figure 17. Aerial location map highlighting the regional joint sets and the subsequent color-coded and joint controlled passageways of Falls Cave.

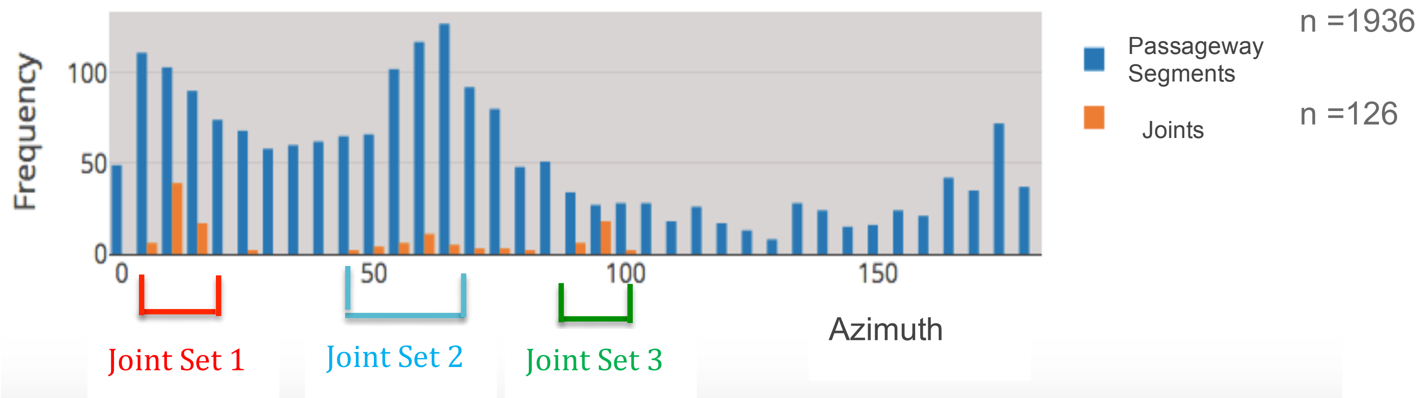


Figure 18. Histogram depicting the orientation of cave segments and regional joints. Notice the frequency pattern of how similar orientations from regional joint sets and cave passageway overlap.

DISCUSSION AND CONCLUSION

In order to confirm or disprove our hypothesis, we sought to analyze the stratigraphic controls on karst formation from both a microscopic and regional scale. Micro scale analyses of porosity and permeability help to establish different hydrologic properties between dolowackestones and crinoidal grainstone facies. Regional scale joint analyses and modeling of Falls Cave within the Mooney Falls Member shows the influence of structure on karst formation and aids in visualization of the spatial relationships between regional structures, stratigraphy, and Falls Cave itself.

Initial field observations of enhanced dissolution in dolowackestone facies adjacent to crinoidal grainstone facies first documented and posited whether dolomites in the Mooney Falls Member were more porous or permeable than their counterparts. Scanning electron microscopy and petrographic thin section images both show enhanced porosities up to 36%, and averaging 18% in the dolomites, while only averaging 2% porosity in the crinoidal grainstones. Permeability data was needed to correlate the relationship between porosity and permeability in order to prove that fluid flow is concentrated through dolomites in the Mooney Falls Member. The correlation is positive as indicated by the permeability and fluid saturation versus porosity analyses, justifying the claim that dolomites are controlling karst formation in the Mooney Falls Member. It should be noted that the origin of dolomitization is unknown and it is disputed whether burial and compaction can achieve regional dolomitization in mesogeneic settings via the expulsion of basinal fluids, which may explain the preferential dolomitization of individual, more permeable, beds. Telogenic calcite filling may be responsible for decreased porosity and permeability in dolowackestones. In order to justify this claim, coring or exploration of caves first hand is needed, and is reserved for future work on this research.

Stratigraphy may play a large role (up to 61% of cave formation) in the orientation of passageways between joints. Passageway orientation influenced by joint pattern orientations has been coined joint piracy. Only 39% of the cave passageway orientations were explained by regional joint set orientations. While this helps support our claim that stratigraphy heavily influences karst morphology in this part of Grand Canyon, our methods may have overestimated stratigraphic influence on karsting. Line shapefiles representing cave passageway were broken up into individual segments based on their associated vertices, and may have been broken into segments too frequently resulting in segments that are perhaps to small to count alone. The COMPASS data was encoded with such vertices, and has not yet been edited in ArcMap to define a minimum segment length.

While plan view suggests that porous dolomite layers influence over half of the orientations in Falls Cave, profile view is even more convincing that the dolowackestone facies is a target for preferential dissolution. 98% of Falls Cave is bound between the top and bottom of the Mooney Falls Member while only 2% of Falls Cave appears to deviate from the Mooney Falls Member and enter the Thunder Springs Member towards the end of the cave. It has been reported by Jason Ballensky that a fault exists about 800 feet from the back of the cave. The ArcScene model used to georeference the cave to the Mooney Falls Member does not take this fault into account, and so Falls Cave may solely exist in the Mooney Falls Member. The only way to test this would be to venture to the far reaches of passageway at the end of Falls Cave in search of the conspicuous chert beds of the Thunder Springs Member or dolomite beds of the Mooney Falls Member. Other sources of error that could mis-georeference Falls Cave in relation to the Mooney Falls Member include cumulative error in using survey equipment deep underground and/or using a slightly wrong dip in raster planes projection representing the Mooney Falls Member in ArcScene.
While Falls Cave itself runs parallel to the Mooney Falls Member in stretches, individual passageways appears to cross cut the stratigraphy in some cases while paralleling dolomite beds in others (Figure 19).

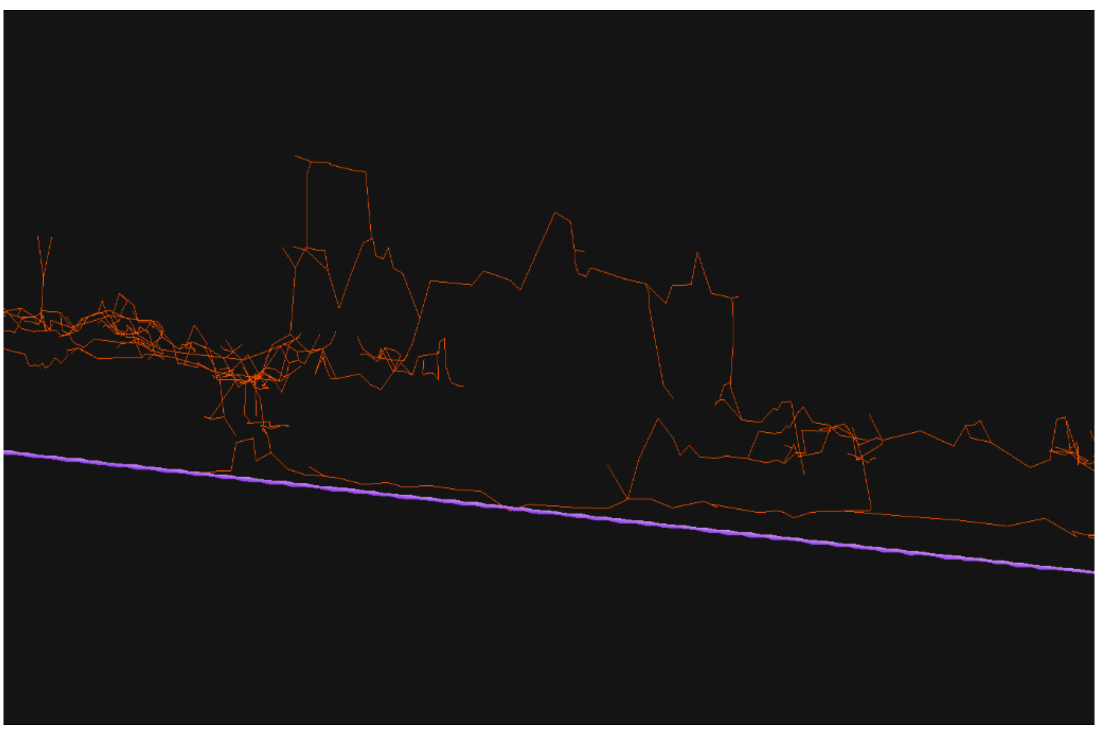


Figure 19. Cross cutting relationships are apparent in some stretches of Falls Cave (orange) in relation to specific dolowackestone beds (purple).

This type of geometry may suggest a paleo water table represented by the angle of the dolowackestone bed in relation to cave passageway. Further research investigating the age of Falls Cave karsting is needed to explain cross cutting relationships of dolowackestone layers in Falls Cave.

In summary, flow is a function of lithology and degree of jointing. The orientations and morphologies of Falls Cave are influenced by intrastratal (dolomite) karstification which refers to the preferential dissolution of dolowackestone facies. Patterns of interconnected conduits created by bedrock dissolution of dolowackestone layers have determined the characteristic behavior and passageway patterns within the well-developed karstic R-aquifer. Highly porous dolomite layers leave implications for large water storage capacities within stretches of the R-aquifer that belong to the confined cave system and are within the Mooney Falls Member. Grand Canyon National Park's 5 million annual visitors, numerous Native American tribes, and wild land fire fighters all rely on the R-aquifer as their sole source of clean drinking water in the region. The dolowackestone facies of the Mooney Falls Member should be considered a significant resource for water resource managers given its importance in karst genesis and water storage capacity.

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