EFFECT OF STRUCTURAL DEFORMATION ON THE PETROLOGY AND DISTRIBUTION OF DIAGENETIC ALTERATION WITHIN THE ORISKANY SANDSTONE IN LITTLE MOUNTAIN ANTICLINE OF THE SMOKE HOLE REGION OF EASTERN WEST VIRGINIA

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The Lower Devonian Oriskany Sandstone is a quartz arenite formation that is located throughout the Appalachian Basin and extends from New York to Virginia. In West Virginia, Oriskany Sandstone found in the western and central part of the state possesses favorable reservoir porosity values of ~6% and permeability values of ~10md. In the structurally complex northeastern part of West Virginia, the Oriskany Sandstone contains much lower porosity and permeability values due to diagenetic alteration. This study focuses on identifying the diagenetic alterations that create and destroy porosity in northeast West Virginia Oriskany Sandstone. An Oriskany Sandstone bed, located in Little Mountain Anticline of the Smoke Hole Region in northeast West Virginia, was divided into three fold zones and analyzed through thin section. Petrographic and diagenetic analysis was accomplished by using the 300 point count method on samples in thin section. Mineralogically the sandstone contains 63%

quartz, 23% feldspar, 7% carbonate, 5% argillaceous and accessory minerals, and the remainder was porosity. Porosity occluding diagenetic alterations observed in Little Mountain Anticline include cementation by quartz, feldspar, and carbonate. All microscopic primary porosity was occluded. Secondary porosity (<2%) is associated with grain dissolution and the formation of solution seams and stylolites. Solution seams and stylolites are oriented parallel to bedding, having formed due to overburden stresses, and at acute angles to bedding, resulting from deformational stresses. Porosity differs between zones. South limb and axis zones show dissolution and solution seam-related porosity whereas the north limb zone shows only solution seam-related porosity. These microscopic-scale properties are not favorable for natural gas extraction, and unsuitable for potential future CO_2 sequestration.

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by

Brian Daniel Klipp

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EFFECT OF STRUCTURAL DEFORMATION ON THE PETROLOGY AND DISTRIBUTION OF DIAGENETIC ALTERATION WITHIN THE ORISKANY SANDSTONE IN LITTLE MOUNTAIN ANTICLINE OF THE SMOKE HOLE REGION OF EASTERN WEST VIRGINIA

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CHAPTER ONE: INTRODUCTION AND OBJECTIVE

The Lower Devonian Oriskany Sandstone is a carbonate cemented quartz sanstone located in the central Appalachian Basin. The Oriskany Sandstone extends continuously from New York to West Virginia (Fig. 1). The amount of carbonate cement varies both laterally and vertically within the formation. Due to these variations in the amount of carbonate cement, the Oriskany Sandstone is variably classified as quartz arenite, calcareous sandstone, and sandy limestone. It is widely accepted that the Oriskany was deposited in a marine environment. Interpretations of depositional environment range from shallow-to-deep subtidal environments (Barret and Isaacson, 1977) to nearshore-shallow water environments (Stowe, 1977). During the 1930s and 1940s large quantities of natural gas was produced from the Oriskany Sandstone (Bruner, 1991). Sixty-six fields were producing from the Oriskany by 1949 and were located across New York, Pennslyvania, West Virginia, and Ohio. The database for The Atlas of Major Appalachian Gas Plays contains records for 141 Oriskany fields. These fields had been developed with an estimated total reserve of 1.6 trillion cubic feet (Tcf) of natural gas (Finn, 1949). Estimated production from the four Oriskany plays from the Gas Atlas is over 3 Tcf. Estimated reserves are over 4 Tcf. Interest in the Oriskany waned as primary production depleted. Most fields were abandoned or converted to potential gas storage sites.

The Oriskany Sandstone is found as an extensive lithologically diverse unit all throughout West Virginia, and ranges in thickness from over 300 feet in the northeast to a pinch-out in the west. Gas accumulation varies due to location dependent controls that affect the rocks ability to store gas. Combination trap-plays and updip permeability pinch-out plays predominate central and western West Virginia, whereas fracture porosity and anticlinal entrapment plays are common in the east and northeast (Harper and Patchen, 1996). Over the past thirty years there has been a renewed interest in the Oriskany Sandstone due to the development of more advanced, and economical, extraction methods. The primary objective of this study is to document diagenetic alterations in the Oriskany Sandstone of the Smoke Hole Region of northeastern West Virginia, and describe how these alterations can form, preserve, and destroy porosity. Specifically, how diagenesis can cause porosity and permeability alterations in the structurally complex fracture porosity plays of northeastern West Virginia.

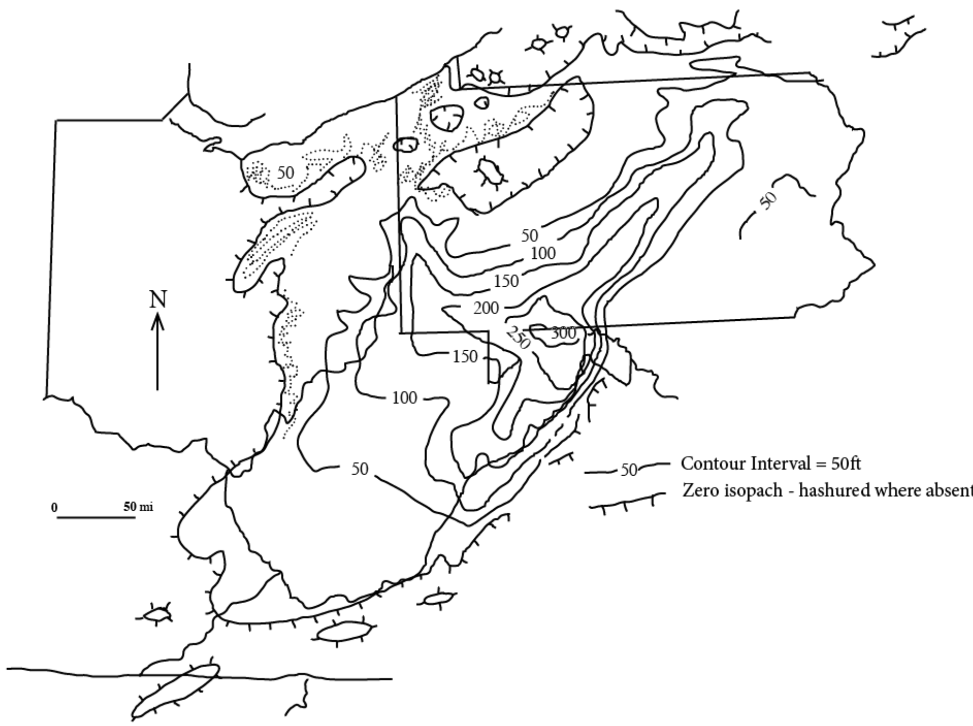


Figure 1: Thickness and areal extent map of the Oriskany Sandstone from Diecchio and others, 1984 and Diecchio, 1985.

CHAPTER TWO: BACKGROUND

GEOLOGIC SETTING AND STRATIGRAPHY

The Oriskany Sandstone was deposited in the Appalachian Foreland Basin during the Early Devonian. The Appalachian Basin is approximately 310 miles (mi) wide, and 621 miles (mi) long. Thickness of the Oriskany Sandstone varies throughout the region. At 300 feet, it is thickest in the structurally complex Valley and Ridge Province of eastern West Virginia. This province is characterized by the long, even ridges of the mountains with continuous valleys in between (Stanley, 1999). These features are the erosional remnants of an ancient fold-and-thrust belt formed during the Alleghenian orogeny (Stanley, 1999).

Generally, the Oriskany Sandstone in the eastern United States is classified as a fossiliferous quartz-arenite cemented by variable amounts of quartz and calcite. Outcrops of the Oriskany Sandstone can be found throughout the Valley and Ridge Province. The Oriskany in this specific area ranges from 250-300 feet in thickness. The amount of carbonate material in the rock varies as a function of the depositional environment. The Oriskany Sandstone contains a mixed origin of extrabasinal and intrabasinal components. Due to this, the Oriskany is commonly labeled as a hybrid sandstone (Bruner, 1991). The Oriskany Sandstone thins towards the northern and western basin margins and is absent in other parts of the basin. Early Devonian shales overlie the Oriskany Sandstone across the eastern United States. Locally, the Needmore Shale, which is composed of three subfacies black shale, calcitic shale, and calcitic shale with limestone, overlies the Oriskany (Dennison, 1960). The Oriskany Sandstone is underlain by the predominantely carbonate with interbedded silicilastics and chert of the Silurian-Devonian Helderberg

Group (Fig. 2) (Lewis et al. 2009). This local stratigraphy contributes to the regional transition of limestone to chert to shale from west to east across the basin (Bruner, 1991; Kostelnik and Carter, 2009).

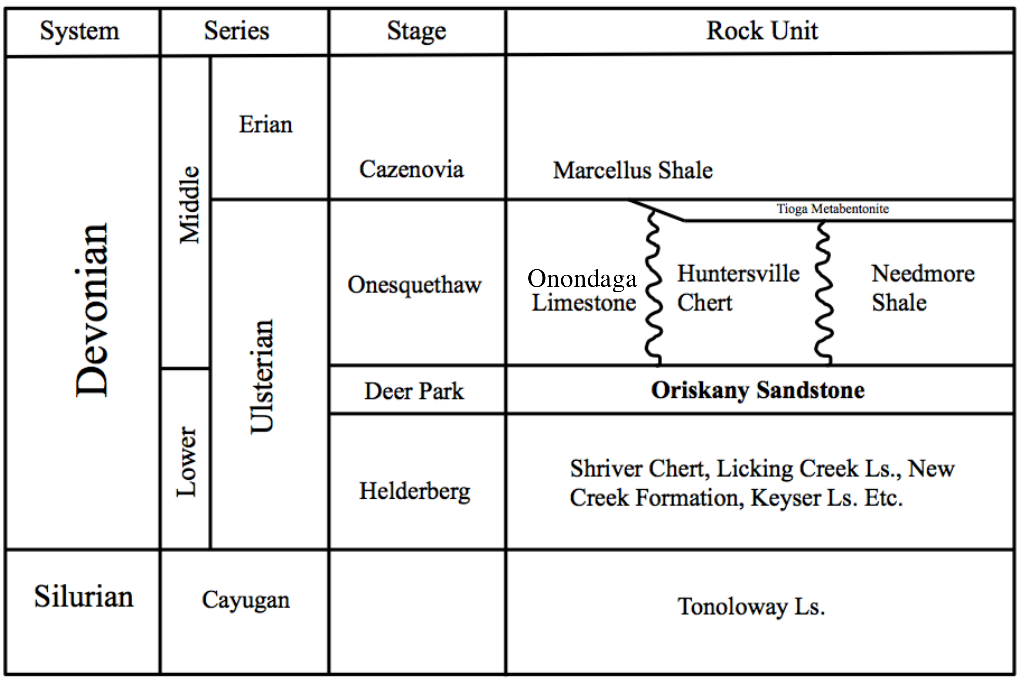


Figure 2: Stratigraphic nomenclature of Devonian Appalachian Basin formations (Cardwell, 1982.)

DEPOSITIONAL ENVIRONMENT

The depositional environment of the Oriskany Sandstone is widely accepted to have been a marine environment, due to a widespread shallow seaway that was located in the site of the Appalachian basin during the early Devonian (Seilacher, 1968; Bruner, 1991; Kostelnik and Carter, 2009) (Fig 3). Specifically, it was deposited in a near-shore shallow-water environment (Seilacher, 1968, Bruner, 1991). Deposition of the underlying Helderberg Group occurred during a period of basin stability. However, the stratigraphic position of the Oriskany Sandstone and adjacent sandy units suggest deposition occurred during intermittent tectonic activity (Rosenfeld, 1953; Bruner, 1991). Tectonic interaction between the Devonian paleocontinents of Laurentia and Baltica influenced the depositional environment. The Helderberg and Oriskany sequence represents shallow marine conditions that received clastics from eastern, southern, and western sources.

Within this environment, the sediments were frequently subjected to wave action and a changing sediment supply (Bruner, 1991). The thick-shelled brachiopods *Cortispirifer arenosus* and *Rensselaeria marylandica* found in the Oriskany are suited for turbulent high-energy environments (Seilacher, 1968). The burial of entire brachiopod colonies suggests that sedimentation rates were rapid. Brachiopod shell fragments show breakage and abrasion, and the abundance of them suggests there was limited transport (Seilacher, 1968).

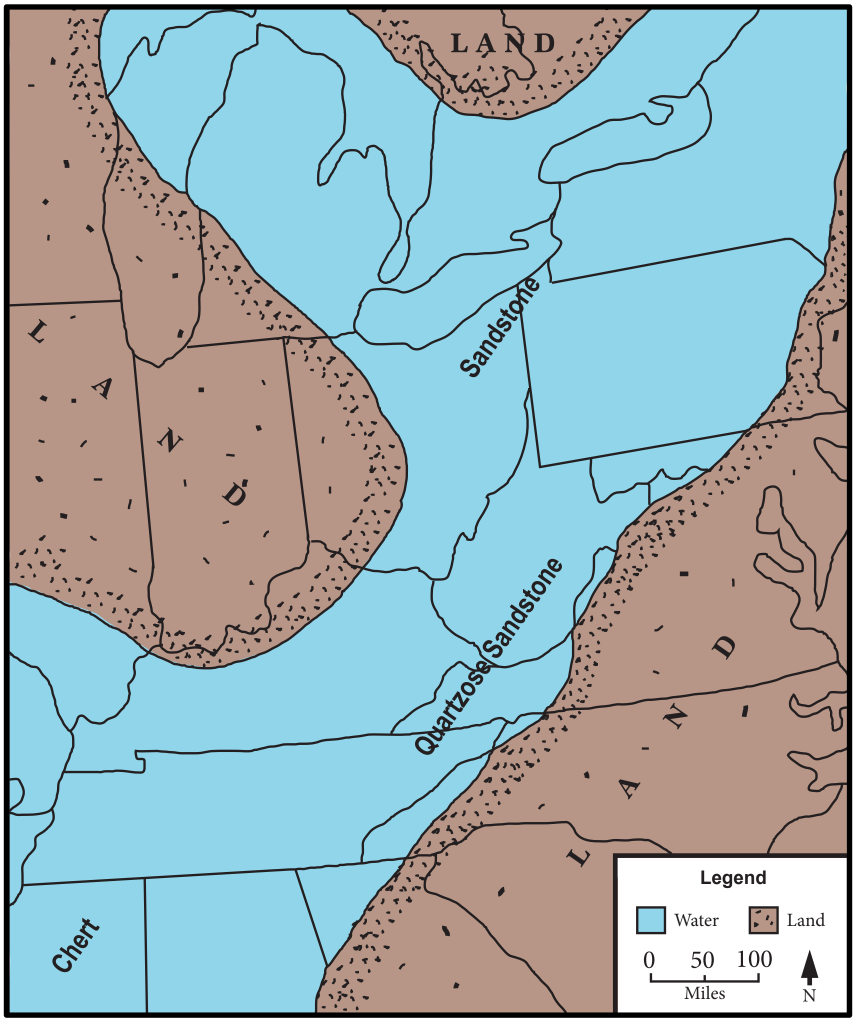


Figure 3: Paleogeographical interpretation of Early Devonian seaway as interpreted by Murray (1971) and Boucot and Johnson (1967).

REGIONAL STRUCTURE AND SUBPLAYS

The physiographic provinces of West Virginia, from west to east, are the Appalachian Plateau, the Allegheny Mountain Section, the Valley and Ridge Province, the Great Valley, and the Blue Ridge Province (Fig. 4a). The Allegheny Mountain section is separated from the Valley and Ridge by the Allegheny front. The study area is located in the Valley and Ridge subplay of the Oriskany Structural Play, so it will be the focus of this section. Oriskany Sandstone structural trap subplays can be distinguished by structural type and the presence or absence of stratigraphic trapping mechanisms (Fig. 4b) (Harper and Patchen, 1996). These subplays have been segregated geographically, and are called the Valley and Ridge subplay, the structural pinchout subplay, and the Appalachian plateau subplay.

The Valley and Ridge subplay is the easternmost subplay and consists of multiple east-dipping thrust sheets. This subplay is situated within the Wills Mountain anticlinorium and Broadtop synclinorium (Fig. 4b) (Harper and Patchen, 1996). Anticlinoriums and synclinoriums both are defined as broad folds having limbs that contain numerous minor folds, both anticlines and synclines. Generally these folds are asymmetrical. Both the Wills Mountain anticlinorium and the Broadtop synclinorium are 15 to 20 miles wide and extend for roughly 250 miles. The surface structures in the Valley and Ridge area consist of doubly plunging folds, and large-scale low-angle thrust faults. Extensive fracturing of the reservoir rock is a common occurrence in the structural plays region and results in enhanced storage and deliverability of natural gas (Basilone, 1984).

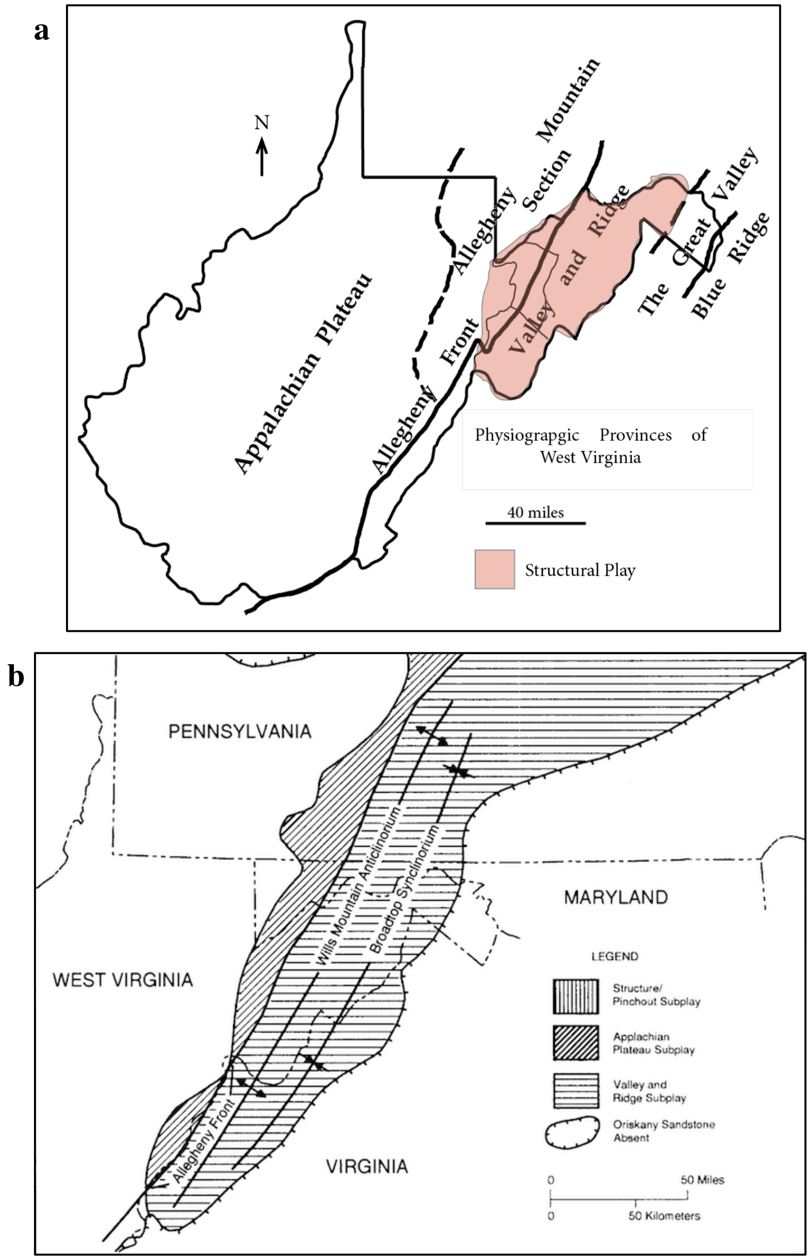


Figure 4 (a): A map created by the West Virginia Geological and Economic Survey (WVGES) showing the physiographic provinces of West Virginia. The structural trap plays of West Virginia are located in the area highlighted in red (Harper and Patchen, 1996, Kostelnik and Carter, 2009). **(b)** This map shows the general location of two of the three structural trap plays defined by Harper and Patchen (1996). Not visible is the Structure/Pinchout Subplay that is located in northern Pennsylvania and southern New York.

Gas fields located in the structural traps play are generally situated on thrust-fault anticlines. Core analysis done by Kostelnik and Carter, 2009, found structural play Oriskany Sandstone to have porosity values between <0.1 to 0.4%, and permeability values between 0.8 to 1.8 md. This study found that the Oriskany Sandstone in the structural play region was tightly cemented by both carbonate and quartz overgrowth cements, resulting in low porosity and permeability.

RESERVOIR PROPERTIES AND POTENTIAL

Ideal conventional oil and gas reservoirs consist of a trap, seal, high porosity and permeability values, and an easy and economic extraction process. Controls on gas accumulation within the Oriskany vary throughout the basin. These controls stem from lithologic diversity. To reiterate, "*The Atlas of Major Appalachian Gas Plays*," compiled by Roen and Walker, 1996, classifies the Oriskany Sandstone into four different plays based off of reservoir properties. Porosity and permeability are the two most important rock characteristics for oil and gas extraction, and determine how much of a natural resource the reservoir rock can hold, and how easily it can be extracted. Conventionally, porosity values between 10 to 15%, and permeability values between 10 to 100 md are ideal. The Oriskany Sandstone of the Structural traps play region features adequate porosity (6.6%) and permeability (8 md) rates (Kostelnik and Carter, 2009), is overlain by Early Devonian Shales which act as a seal for the natural gas due to their extremely low-porosity and permeability (Lee et al., 2011), and the folds act as a trap. Due to these favorable reservoir characteristics and vast distribution, the Oriskany Sandstone has been a major gas-producing formation in the central Appalachian Basin. In areas where production is not ideal, the Oriskany Sandstone has been identified as a deep-saline formation with the capabilities to sequester carbon dioxide (CO_2) (Wickstrom et al, 2005; Kostelnik and Carter 2009). However, using the Oriskany Sandstone as a CO_2 storage unit has only been proposed. There has not yet been any attempts to sequester CO_2 in the Oriskany Sandstone.

STRUCTURAL DIAGENESIS

Following deposition, sediments experience diagenesis, which is the physical, chemical, and biological processes that cause compaction, cementation, recrystallization, and other changes to the original sediment (Tucker, 2001). Diagenesis results in grain-scale changes in sandstone, as both compaction and chemical processes alter the rock structure. These changes are known to affect both the mechanical properties and permeability of the resulting lithified material (Beard and Weyl, 1973; Houseknecht, 1987). Fracture growth profoundly affects the evolution of crustal attributes such as permeability, strength, and seismic response (National Academy of Sciences, 1996), yet little is known about rates of fracture growth in the Earth's crust (Lander and Laubach, 2015). The precipitation of cement should result in changes to the host material dependent on cement and mineralogy (Cook, 2010). Insight into the evolution of rock strength can be gathered by knowing compositional and diagenetic details acquired through thin-section analysis.

Quartz cement is a prevalent component of most fracture systems in deeply buried sandstones and has proven to be a useful source of constraints on fracture-opening history (Lander and Laubach, 2015). Quartz overgrowths are the most common authigenic cement in sandstones and are responsible for significant reductions to porosity and permeability. In sedimentary rocks, cements often occur as thin veneers or rinds on fracture walls, interspersed with highly localized, much thicker deposits known as bridges (Bons et al., 2012). Fault-slip and associated fracture may increase or decrease fault-zone porosity and permeability, potentially focusing or impeding fluid flow, perturbing thermal gradients, enhancing or restricting reactions and transport of chemical components, and altering porosity, permeability, mineralogy, texture, and mechanical properties of fault and host rock (Chester et al., 1993). These factors can result in fold-and-thrust belts becoming compartmentalized. Local structures can cause a complex series of deformation due to the heterogenous distribution of cement (Breesch et al., 2009; Vandeginste et al., 2012). These features are a control on the porosity and permeabilities in structural trap play Oriskany Sandstone. Due to the tight cementation of the Oriskany in these plays, fracturing of the rock creates viable porosity.

STUDY AREA: LITTLE MOUNTAIN ANTICLINE IN THE SMOKE HOLE REGION OF WEST VIRGINIA

The Smoke Hole Canyon Recreation Area is located in Pendleton and Grant counties in northeastern West Virginia (Fig. 5). It is located within the Appalachian Mountains and formed due to erosion by the South Branch Potomac River. Smoke Hole Canyon encompasses approximately 40 square miles and is located within the Monongahela National Forest. Overall, Smoke Hole Canyon and the surrounding region exhibit roughly 3,000 feet of relief. The Cave Mountain anticline is the predominant topographical feature of the Smoke Hole Region.

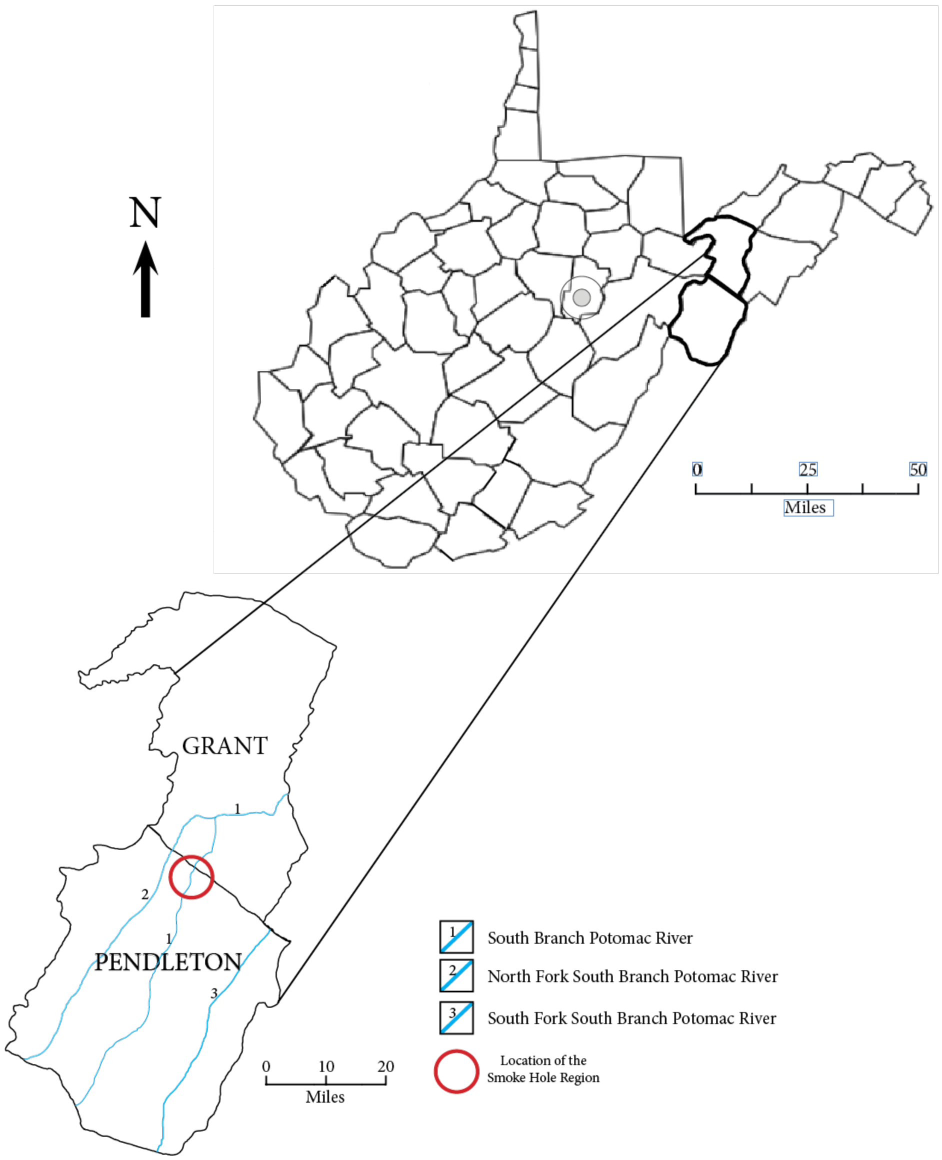
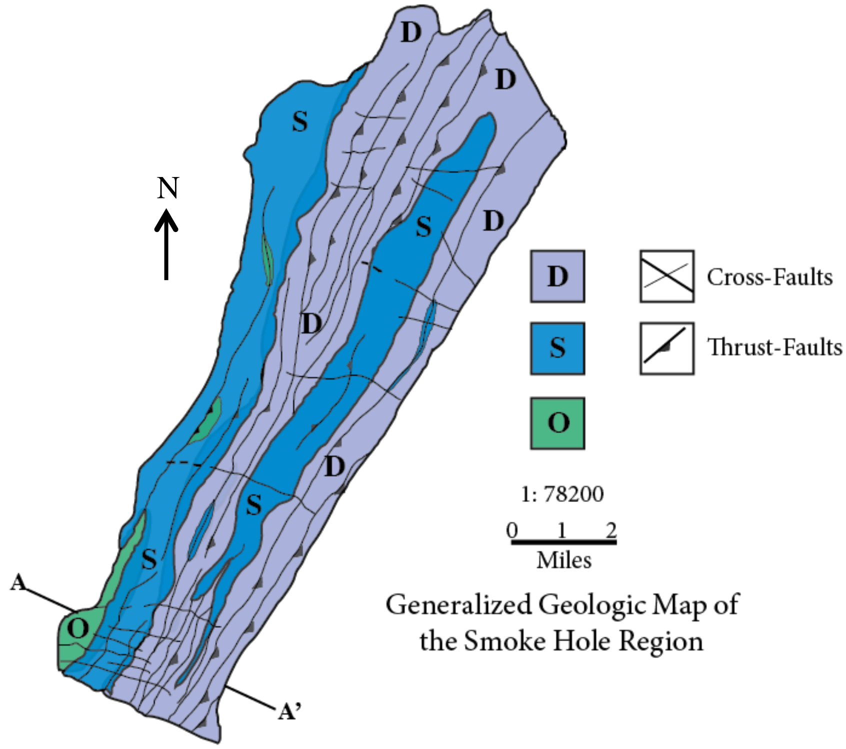


Figure 5: A map view showing the general location of the Smoke Hole Region in Pendleton and Grant counties in West Virginia.

In this area, deformed Lower Silurian to Middle Devonian sedimentary rocks are exposed (Fig. 6a). This area is highly folded and faulted, containing a system of plunging anticlines and synclines (Sites, 1973). The Cave Mountain fold and thrust system contains northeast-trending folds, and southeast dipping thrust faults. The majority of these complex central Appalachian macro-scale structures are comprised of a packaging, and at times unique arrangement, of Silurian-Devonian rocks. Faulting in this area has resulted in a maximum stratigraphic displacement of approximately 1,900 feet (Fig. 6b) (Sites, 1973), with Lower Silurian rocks thrust atop Lower Devonian rocks. Associated with the Cave Mountain fold and thrust is a large-scale shear zone (Fig. 7). There are five Oriskany Sandstone exposures in this area that have all been thrust one on top of another. These structures are thought to have originally been more symmetrical, but were later squeezed causing the rocks to tighten up as the Cave Mountain thrust moved material over them (Sites, 1982).

Exposed, lightly vegetated outcrops can be found along the South Branch Potomac River, within Smoke Hole Canyon. These exposures provide accessible locations for sample collection, allowing the examination of diagenetically altered sandstones within the fold and thrust system.

a



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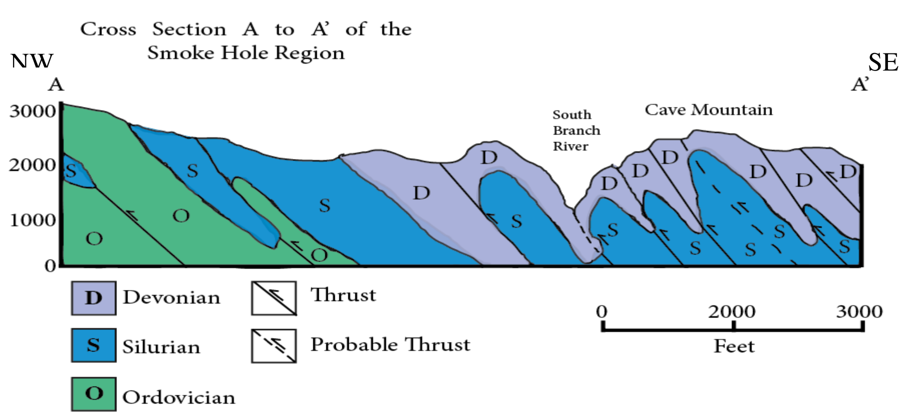


Figure 6 (a): Generalized geologic map of the Smoke Hole Region by Roy Sites, 1971. The study location for this document is located in the southeast of the A-A' cross-section line. **(b):** A cross-section of the Cave Mountain fold and thrust system, interpreted by Roy Sites, 1971. This figure illustrates sheets of Oriskany Sandstone (D) being thrust one on top of another.

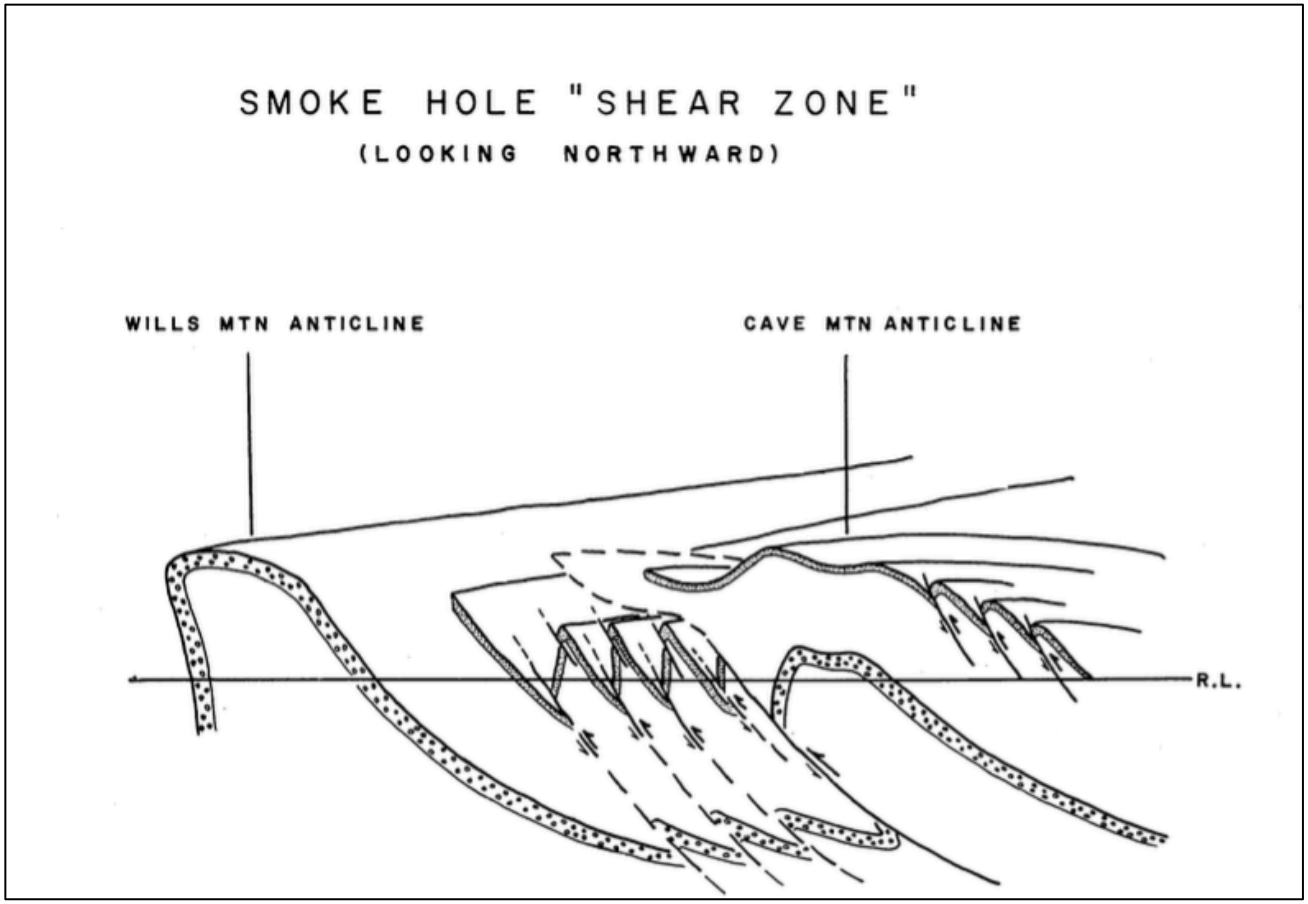


Figure 7: The Smoke Hole "Shear Zone," interpreted by Roy Sites, 1971. R.L. stands for "road level." This figure illustrates the thrusting and folding the Oriskany Sandstone on Cave Mountain Anticline

LITTLE MOUNTAIN ANTICLINE

Big Mountain and Little Mountain are the defining features in the southern Smoke Hole region (Fig. 8). Both mountains are parallel, and are perpendicular to the South Branch Potomac River. Synforms and antiforms are prevalent within the area located between Big Mountain and Little Mountain. An exposed antiform, which will be referred to as Little Mountain Anticline (LMA), crops out along the northern part of Little Mountain and is a small structure on the east side of the Cave Mountain Anticline (Fig. 8). The northeast-trending, asymmetric, slightly overturned Cave Mountain Anticline is a allochthonous block that was thrust along high-angle listric faults that branched from a decollement in the Ordovician Reedsville Formation (Sites 1973; Wilson, 1987). The LMA is 500 feet long and 80 feet high. It is composed of Oriskany Sandstone that gently dips ~5 degrees to the southeast, and ~3 degrees to the northwest (Fig. 9). The Oriskany Sandstone has an estimated thickness of 200 feet in this area (Dieccho, 1985; Bruner 1991). LMA runs parallel to the South Branch Potomac River and the inferred axial plane is perpendicular to the river. The fold is accessible by foot on the south side of the river.

The Oriskany Sandstone in this area is a calcitic quartz sandstone with very low porosity (Kostelnik and Carter, 2009). The deformation of the Oriskany Sandstone in the LMA makes it an ideal unit for observing and characterizing how structural deformation is related to diagenetic processes. To observe and characterize this relationship, samples were collected from a single Oriskany bed. This location was favorable due to its reachable exposures along the south limb, axis, and north limb (Fig. 9). The prominent folds that surround LMA are the Middle Mountain Syncline to the east and Wills Mountain to the west (Wilson, 1987). The northeast-trending, asymmetric, slightly overturned Cave Mountain anticline is an allochthonous block that was thrust along high-angle listric faults that branched from a decollement in the Ordovician Reedsville Formation (Sites, 1971; Wilson, 1987).

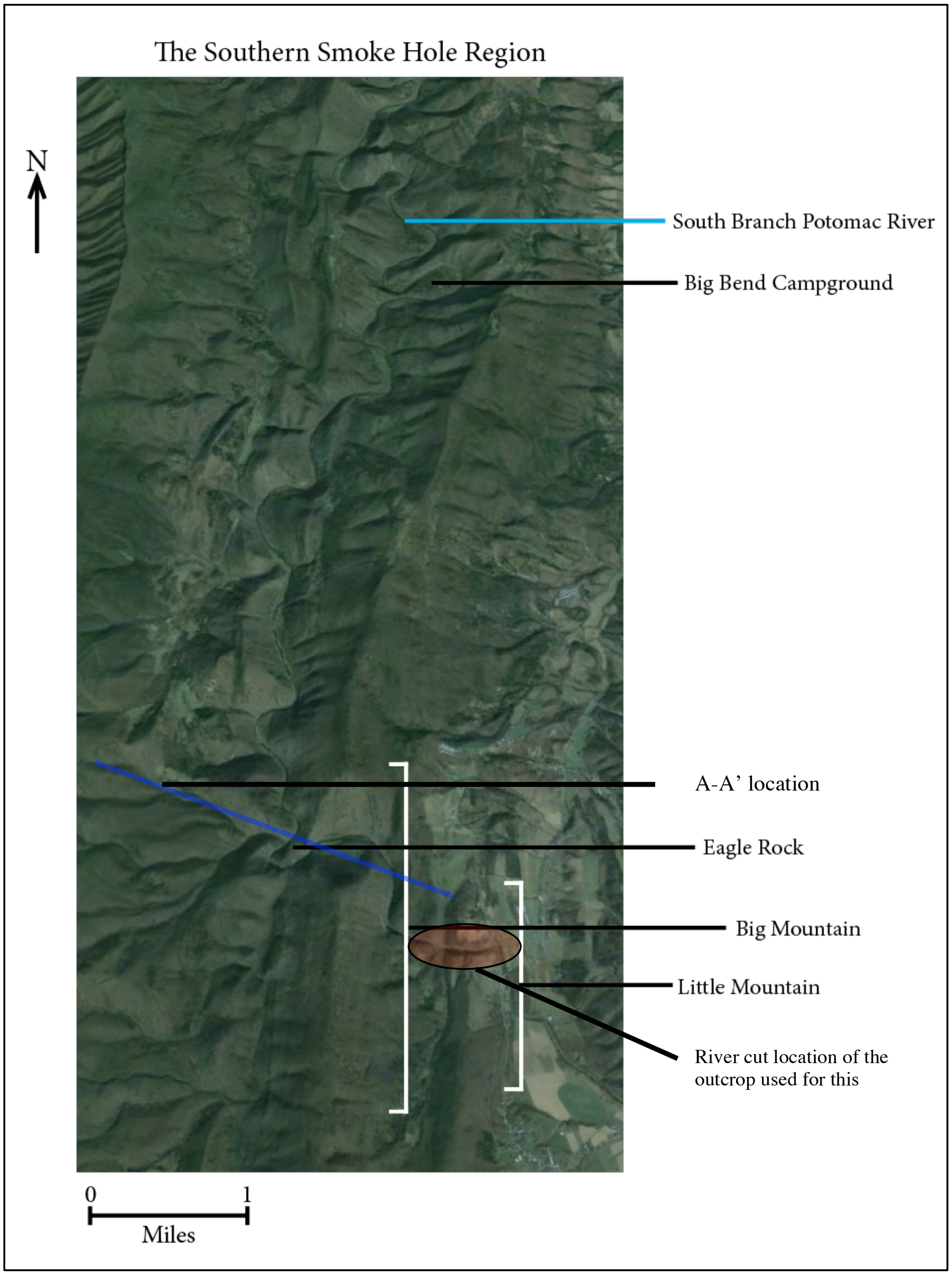


Figure 8: The southern Smoke Hole Region captured by Google Earth. The main topographic features in the study area are Big Mountain and Little Mountain. The roadside exposure formed by river erosion is located in the red circle at the northern part of Little Mountain. The blue line is the estimated location of Roy Site's A-A'cross-section in figure 6a.

The block consists of Upper Ordovician through Lower Devonian rocks and is thrust atop the southeast side of the Wills Mountain anticline. LMA is a part of the series of chevron folds that lie in the highly sheared northwestern zone of Cave Mountain anticline, among subparallel, southeast-dipping, high-angle, listric, reverse faults (Sites and Wheeler, 1977). The Wills Mountain anticlinorium is one of the largest and longest folds in the Appalachian foreland and was interpreted to have initiated as a fault-bend fold (Harrison and Onasch, 2000). The Oriskany Sandstone in this area is a calcitic quartz sandstone with very low porosity (Kostelnik and Carter, 2009). The deformation of the Oriskany Sandstone in the LMA makes it an ideal unit for observing and characterizing how structural deformation is related to diagenetic processes (Fig. 9).

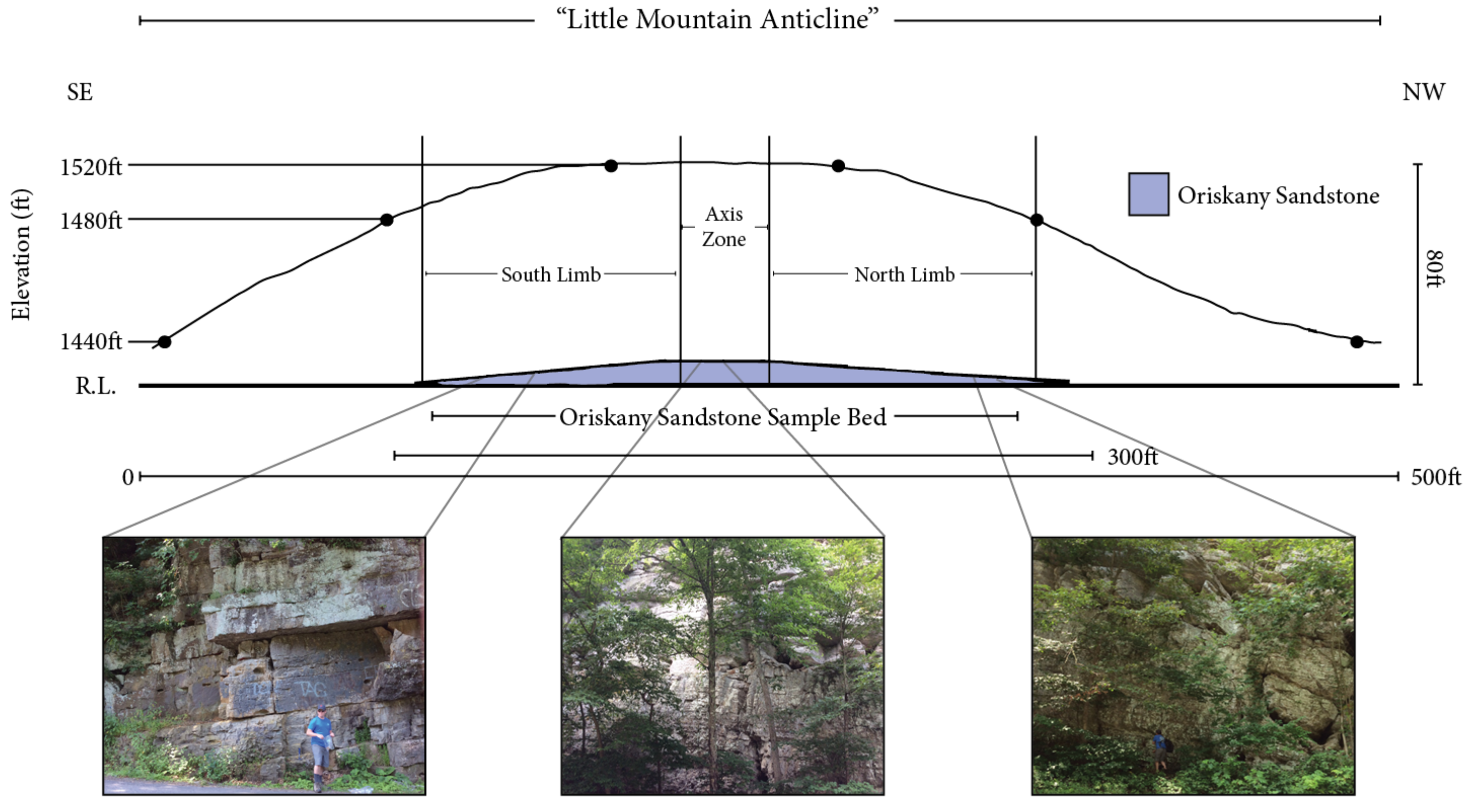


Figure 9: Illustration of "Little Mountain Anticline," (LMA). The Oriskany bed uses for samples is highlighted in blue and located centrally in the LMA along the road. The areas interpreted as the "south limb," "axis zone," and "north limb" are labeled.

CHAPTER THREE: METHODS

SAMPLE COLLECTION

Twenty-two sandstone samples were collected along a roadside outcrop of Oriskany Sandstone in the LMA (Fig. 10). Samples were collected from an Oriskany Sandstone bed that was 8 feet thick, and 300 feet long. Samples were collected from three different zones that were inferred to be the limbs and axis zone of the fold. Specifically, these collection zones will be referred to as the, "south limb," "axis zone," and "north limb." The "south limb" sample collection zone dips 5° to the southeast and is the first ~110 feet of the bed when measured from left to right. The "axis zone" has no dip, and is the area along the bed that is located between 110 to 160 feet when measuring left to right. The "north limb" sample collection zone is represented by the remaining 140 feet of the outcrop and dips 3° to the northwest (Fig. 10). Samples were collected every ~2 to 5 feet along the outcrop. In total, eight samples were collected from the south limb, eight from the axis zone, and six from the north limb.

THIN SECTION ANALYSIS

Twenty-two slabs were cut from the collected samples and were processed into thin section slides and stained by National Petrographic Service, Inc. in Houston, Texas. The twenty-two thin sections were then analyzed by petrographic microscope. Each slide had a distinct top of bed and base of bed orientation with the northern direction being perpendicular to the top face of the slide (Fig. 11). The slides under went "vacuum impregnation" to fill pore spaces with blue epoxy. Slides were stained with sodium

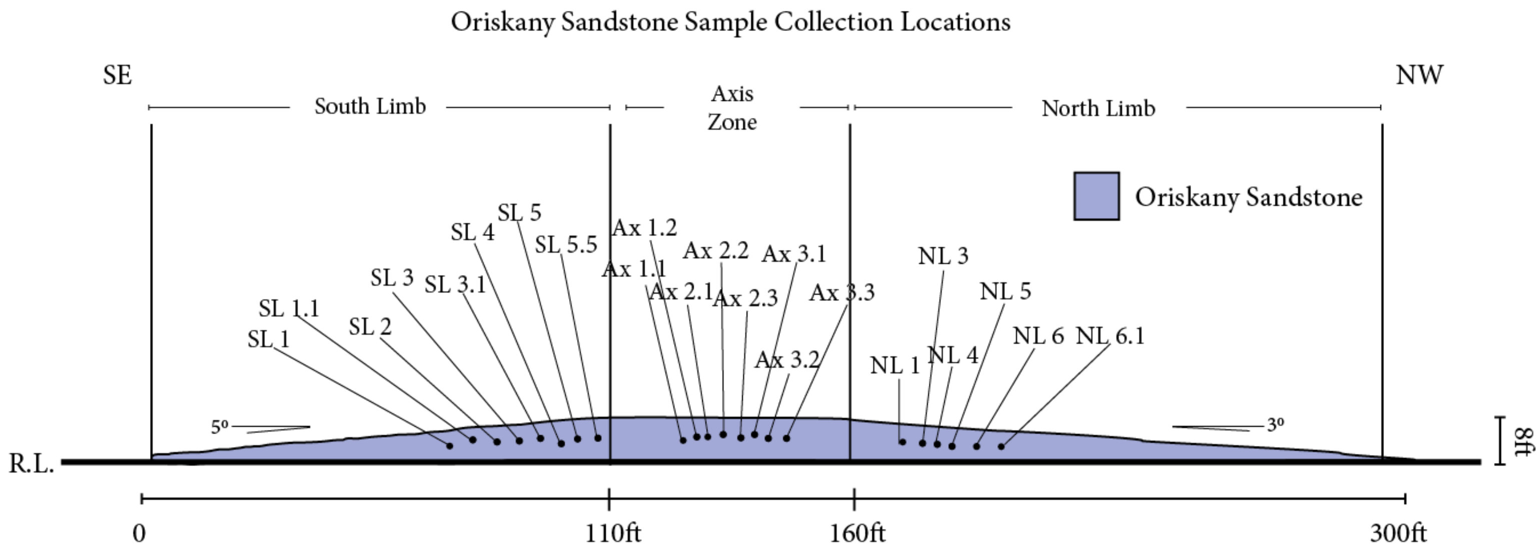


Figure 10: Sample collection sites are labeled in the south limb (SL), axis zone (Ax), and north limb (NL). Each black dot represents the spot where a sample was collected along the Oriskany Sandstone bed used for this study.

cobaltinitrite to give potassium feldspar a “rusted” yellow appearance, and with alizarin red S to give calcite a pinkish hue.

A three hundred-point count method was used on all twenty-two slides to identify the lithological composition of the samples. Grain-size was recorded during point counts by measuring the long-axis of each grain on the millimeter (mm) scale. After point counts were recorded, each slide was thoroughly examined for any diagenetic alterations. Each alteration found was identified, oriented, and then recorded. By using these methods, a table was created in order to present the mineral composition, diagenetic features, and pore space found in each sample.

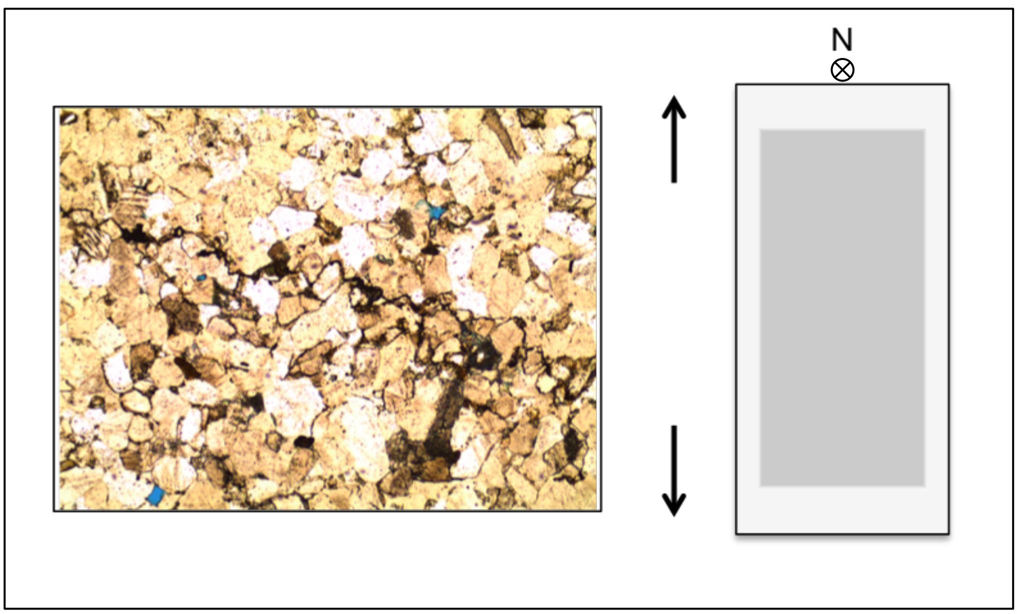


Figure 11: Photomicrograph example (left) next to an illustrated representation of an oriented thin section (right). “N” means north and the north direction is going into the plane of the page.

CHAPTER FOUR: RESULTS AND DISCUSSION

PETROGRAPHY

The general mineral composition of each sample consists mainly of quartz, potassium feldspar, plagioclase, calcite, dolomite, argillaceous and accessory minerals. The qualities and quantities of these minerals vary throughout the bed. Percentages of the components and pore space in the bed are given in Table 1 and a summary table of petrographic characteristics is provided in table 2.

Sample	Qm	K	P	Qp	Cal	Dol	Arg	Por
SL 1	64.67	10.67	8.00	4.33	5.00	0.00	5.33	2.00
SL1.1	66.67	12.67	5.33	4.00	5.67	0.67	2.67	2.33
SL 2	64.33	13.67	7.00	2.33	6.00	0.00	5.00	1.67
SL 3	62.33	13.00	9.00	3.00	7.33	0.33	3.33	1.67
SL 3.1	68.00	10.67	6.33	5.00	4.00	0.00	3.00	3.00
SL 4	61.00	16.00	9.33	2.00	2.67	0.00	7.33	1.67
SL 5	68.00	11.00	6.33	2.33	4.33	0.67	6.00	1.33
SL 5.1	64.67	14.00	7.00	4.00	5.67	0.00	1.33	3.33
Ax 1.1	41.33	31.33	9.33	0.67	7.67	1.67	5.33	2.67
Ax 1.2	44.67	29.33	12.33	0.67	5.33	1.00	4.67	2.00
Ax 2.1	44.33	32.67	6.00	1.00	9.67	0.00	4.33	2.00
Ax 2.2	55.00	25.00	7.67	0.67	6.33	0.67	2.33	2.33
Ax 2.3	53.33	26.00	5.00	1.33	7.00	1.00	3.67	2.67
Ax 3.1	55.33	28.33	9.67	0.67	2.33	0.00	1.67	2.00
Ax 3.2	57.33	24.00	9.33	1.67	3.33	0.00	1.67	2.67
Ax 3.3	51.33	28.67	8.33	0.67	5.33	0.00	3.00	2.67
NL 1	51.67	3.67	3.33	20.67	7.00	3.00	10.33	0.33
NL 3	51.67	3.00	2.67	21.67	8.00	2.67	9.33	1.00
NL 4	55.33	4.33	3.67	17.00	6.33	2.00	10.67	0.67
NL 5	52.00	7.33	5.00	14.67	7.67	3.67	9.00	0.67
NL 6	50.67	6.00	2.33	21.00	6.00	3.33	9.33	1.33
NL 6.1	54.33	4.00	3.00	19.67	6.33	3.00	8.67	1.00
Average	**56.27**	**16.15**	**6.64**	**6.77**	**5.86**	**1.08**	**5.36**	**1.86**

Table 1. Percentages of components and pore space in the Oriskany Sandstone in the Little Mountain anticline. Samples listed as south limb (SL), axis (Ax), north limb (NL).
Labels: Monocrystalline quartz (Qm), potassium feldspar (K), plagioclase (P), polycrystalline quartz (Qp), calcite (Cal), dolomite (Dol), argillaceous components and accessory (Arg), and pore space (Por).

Feature	South Limb	Axis	North Limb
Composition Percentage			
Monocrystalline Quartz (Qm	65%	50%	53%
Potassium Feldspar (K)	13%	28%	5%
Plagioclase (P)	7%	9%	3%
Polycrystalline Quartz (Qp)	3%	1%	19%
Calcite	5%	6%	7%
Dolomite	2%	1%	3%
Argillaceous Minerals	4%	3%	9%
Pore Space	2%	2%	1%
Grain Size Average (mm)	0.030	0.028	0.015
Grain shape	Subrounded-Subangular	Subrounded-Subangular	Subangular-Poorly Rounded
Sorting	Well Sorted	Well Sorted	Well Sorted

Table 2: A summary of composition and characteristics seen within the three fold zones in the Little Mountain Anticline.

Quartz

Quartz is the most abundant mineral found in all samples (Fig. 12), making up 42% to 73% of sample compositions. In general, quartz grains have an irregular shape, are colorless in plane-polarized light, and may show strained extinction. The south limb and axis samples quartz grain size varies between 0.2 and 0.8 mm. Quartz grain size in the north limb samples is generally smaller, ranging between 0.1 to 0.3 mm. Monocrystalline quartz grains dominate, but polycrystalline quartz grains are also present throughout the samples. Polycrystalline is common in north limb samples, but is a minor constituent within south limb and axis samples. Monocrystalline quartz grains typically have straight to slightly undulose extinction, and polycrystalline quartz grains generally possess strong undulose extinction. As a whole, monocrystalline quartz grains generally show unit extinction. Overgrowth cement is common, giving most grains an angular appearance. Overgrowths can easily be seen on monocrystalline quartz grains in the samples, but are harder to recognize on polycrystalline grains due to the much smaller grain size. Chalcedony is also present in a few samples, having a fibrous appearance (Fig. 12d).

Potassium Feldspar & Plagioclase

Potassium feldspar and plagioclase are both present in each sample (Fig. 12). Potassium feldspar ranges from 3% to 33% of overall sample composition throughout the anticline bed. Plagioclase is found in lesser amounts, accounting for 2.3% to 12.3% of sample compositions. Potassium feldspar grains typically measure between 0.4-0.6 mm, and plagioclase grains are typically 0.3-0.4 mm. Potassium feldspar grains are somewhat angular to sub-angular, whereas plagioclase grains exhibit rounded grain shape. Feldspar is abundant in axis and south limb samples, and has undergone extensive weathering in both. In these samples feldspar grains can be seen with feldspar overgrowths and some exhibit dissolution. Potassium feldspar grains and quartz grains tend to be very similar in appearance throughout the samples. They are distinguished by a cloudy appearance within the center of the grain, a change that results from weathering. Potassium feldspar grains contain inclusions and 90° cleavage angles. Feldspar overgrowths are common throughout the samples. Little to no Carlsbad twinning is observed. Microcline is common within the samples and is easily identifiable by its tartan twinning (Fig. 12b). Plagioclase minerals were identified due to their own unique twinning patterns and low relief of the grains.

Calcite & Dolomite

Calcite is also colorless in plane-polarized light in thin section, but the relief also changes as the stage is rotated. Calcite is seen in all samples, usually as shell fragments or cement. Shell fragments vary greatly in size, and range from 0.3 to 5.0 mm in length (Fig. 12). Dogtooth calcite is found in a few samples filling in fractures and shell fragment voids (Fig. 12a). Dolomite is a secondary mineral, having replaced calcite. Rhombohedral shape is distinct in observed dolomite grains. Calcite and dolomite, combined, accounts for roughly 3% to 11% of sample composition.

Argillaceous and Accessory Minerals

Argillaceous minerals are found throughout all samples. They are generally found in association with iron oxide. Iron oxide is present in pore-filling cement, fracture fill, and stain on grain coatings. Argillaceous minerals accounted for 2% to 11% of sample compositions. Argillaceous minerals can be seen within fractures in south limb and axis samples. Larger spacing patterns of argillaceous minerals are observed through north limb samples. The most common accessory minerals were pyrite, amphibole, hematite, and illmenite.

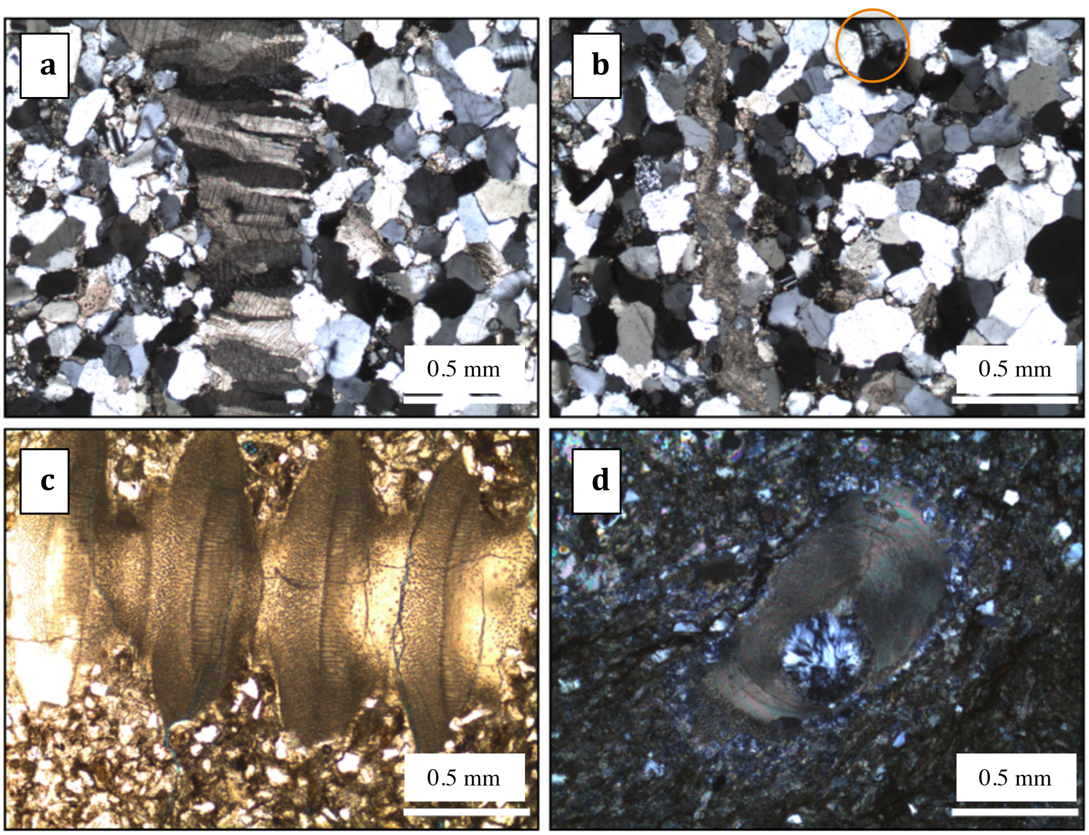


Figure 12: Thin-section photomicrographs of Little Mountain Anticline samples, **(a)** *South Limb* A large opening that has been filled with dogtooth calcite, **(b)** *South Limb* Quartz and feldspar surround a seam of carbonate rich material. The orange circle represents microcline tartan twinning, **(c)** *North Limb* A large fossil calcareous fossil fragment surround by sub-angular quartz grains, **(d)** *North Limb* Chalcedony fills a void within a calcareous fossil fragment. Scale = 1mm

DIAGENETIC STRUCTURES

Diagenetic alterations in south limb, axis, and north limb samples vary in type and intensity. These alterations take the form of mechanical compaction, primary porosity occlusion, and variance in cementation, pressure solution, and secondary porosity.

South Limb

Grain contacts show interpenetration and general dissolution. Clay minerals and iron oxides are seen lining the boundaries between grains. Both quartz and feldspar grains can be seen with overgrowths (Fig. 13a, b). Areas of extensive dissolution have been filled in with a fine-grained carbonate. Numerous large fractures are filled in by a coarse-crystalline calcite. South limb samples lack any intact carbonate fossils. Fossils have been dissolved and filled in or replaced by carbonate material. Coarse-crystalline calcite is also found in areas of fossil recrystallization. Some feldspars have undergone extensive weathering and are filled with quartz lenses, or replaced by polycrystalline quartz. Primary porosity in south limb samples is nearly non-existent. Secondary porosity in south limb samples is present in small amounts through fractures and grain dissolution. South limb grains are cemented predominately by carbonate cements.

Axis

Grain contacts in the axis samples are not as clear in comparison to south limb samples. Grain boundaries are marked by dark clays, and exhibit no intergranular pore space. The dominant structures in the axis samples are large solution seams found running both parallel and perpendicular to the bedding (Fig. 13c). Clay minerals are relatively abundant in the axis, filling most intergranular space. Like the south limb, there is no primary porosity within the axis. Secondary porosity exists primarily through dissolution of framework grains and solution seams.

North Limb

North limb samples are generally similar to axis samples, but include more fossil material. Patches of polycrystalline quartz (Fig. 13f) are mixed within the dense clay and carbonate-rich matrix. Similar to the south limb and axis, the north limb lacks any sort of primary porosity. Stylolites are common in north limb samples (Fig. 13d), but visible secondary porosity is scarce. Fractures filled with coarse-calcite can be seen in the north limb as well (Fig. 13f). Recrystallized fossil fragments (Fig. 13e) are scattered throughout the north limb. Some fossil fragments recrystallized as coarse-calcite, others as a mix of microcrystalline calcite and quartz.

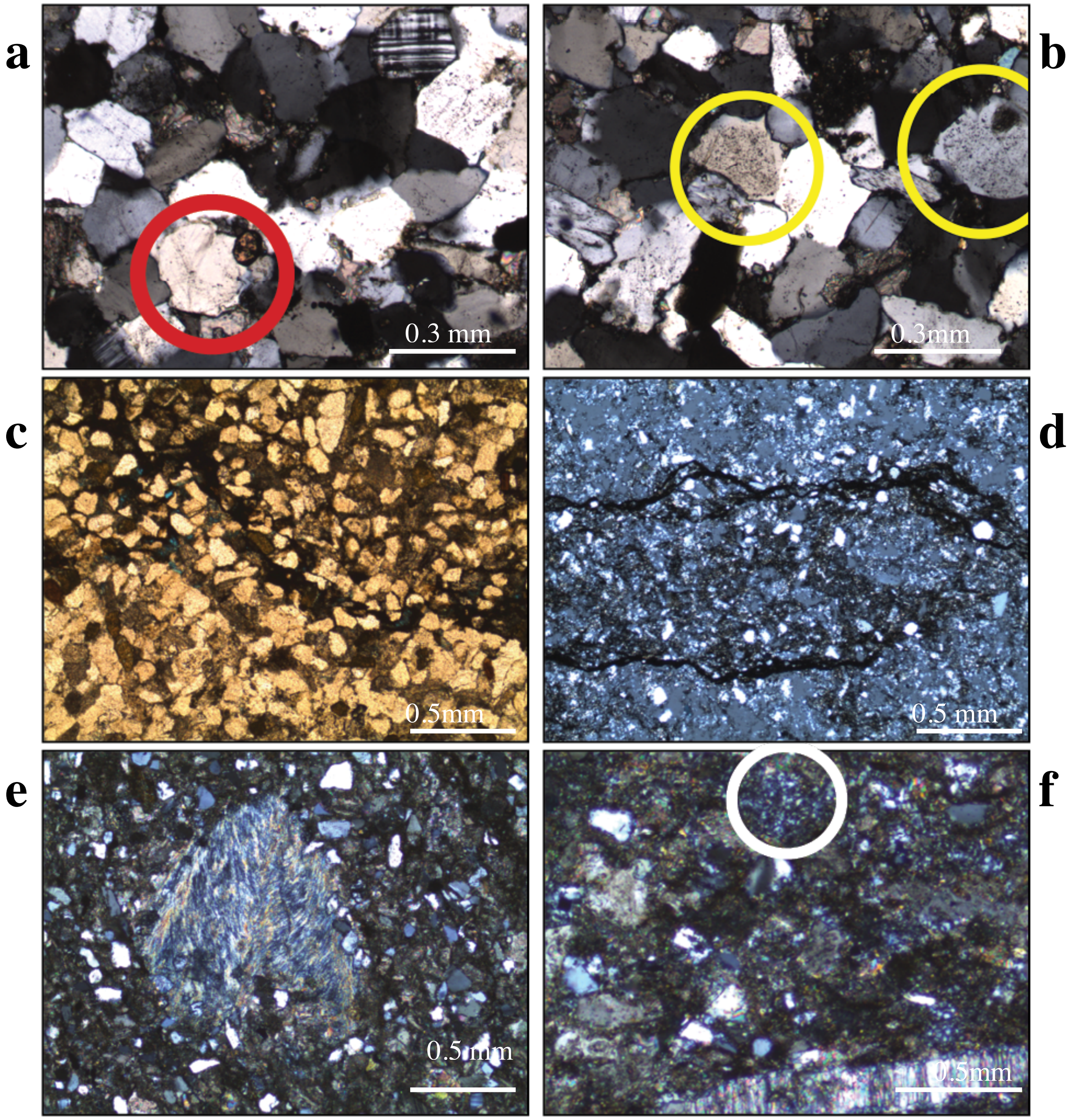


Figure 13 (a) A quartz overgrowth (red circle) in a south limb sample (XPL). A grain of microcline can be seen in the top right, **(b)** Two feldspar overgrowths (yellow circles) in a south limb sample (XPL). There is extensive weathering of the grains, (**c)** A solution seam runs diagonally through an axis sample (PPL), **(d)** Parallel running stylolites in a north limb sample (XPL), (**e)** A fossil fragment recrystallized by microcrystalline calcite in a north limb sample (XPL), (**f)** A patch polycrystalline quartz (white circle) within a fine carbonate material in the north limb (XPL). At the bottom of the photomicrograph a fracture has been filled in by coarse-calcite.

COMPOSITION AND DEPOSITION

Petrographically, the LMA Oriskany is a coarse- to very fine- grained calcareous sandstone to sandy limestone. The overall combined quartz composition of the bed ranges from 51% to 72%. Calcite, dolomite, and calcareous fossil fragments make up ~7% of sample composition. The south limb of the anticline had the highest monocrystalline quartz composition making up roughly 65% of the samples. In samples nearer to the axis of the anticline the monocrystalline quartz composition declined down to 50% of the samples. The north limb samples showed slightly higher numbers, rising to 53% composition. The axis samples contained the highest amount of potassium feldspar, making up 28% of the points counted. The north limb samples had the most polycrystalline quartz, accounting for 19% of points counted. Clastic framework grains are commonly well-rounded throughout the bed. Fine to very fine grains are generally rounded to sub-angular. Overall, the grains within anticline samples ranged from well sorted to moderately-sorted. Grain size decreases throughout the bed (Fig. 14), with the largest grains in the south limb, and the smallest in the north limb.

Fossil fragments are found throughout the bed. This high concentration of fossil fragments is what causes the Oriskany, despite being generally classified as a quartz arenite, to have high values of calcite. However, this is not uncommon within the Oriskany Sandstone. The amount of carbonate material in the Oriskany varies as a function of the depositional environment (Bruner, 1991). In higher energy depositional environments, there would be a lack of finer grained material and fossil material. In contrast, the presence of fossil fragments and grain size show that this particular bed of

Oriskany was deposited in a lower energy environment, which is interpreted as a normal, fair-weather, open shelf environment.

Comparison of grain size and the amount of carbonate material illustrates a trend in the north to south formation (Fig. 14). South limb samples are coarser grained (0.030 mm) and less calcareous (5%). Axis samples show a slight decrease in grain size (0.028 mm) and an increase in carbonate material (6%), but still lack large intact fossil fragments. The transition to the north limb brings large fossil fragments, and an abundance of microcrystalline calcite and quartz. North limb quartz grains are smaller (0.015 mm) and erratically dispersed within a fine-grained carbonate material (7%).

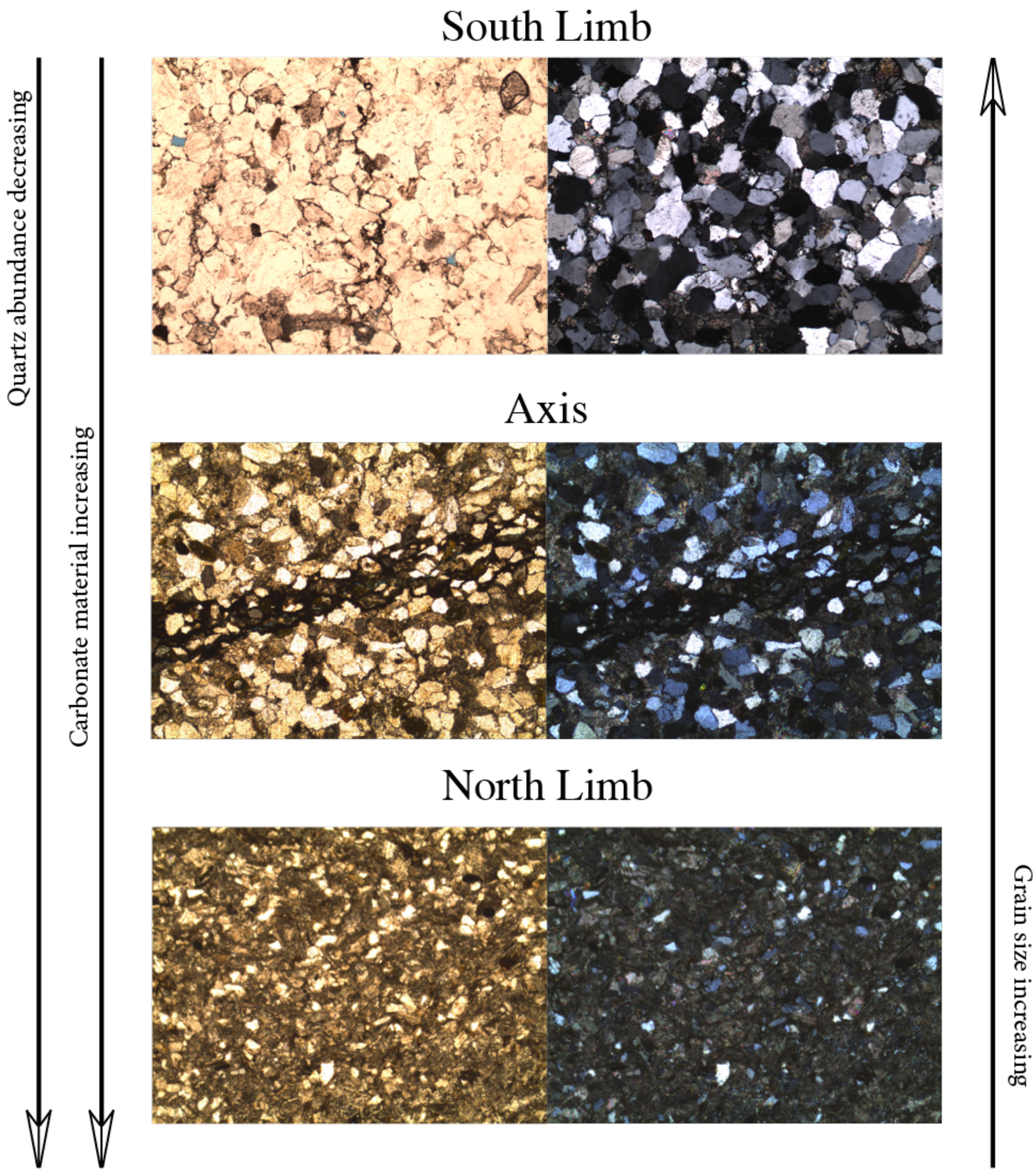


Figure 14: Representation of the decrease in quartz and grain size, and the increase in carbonate material as the bed transitions from the south limb to the north limb.

DIAGENESIS

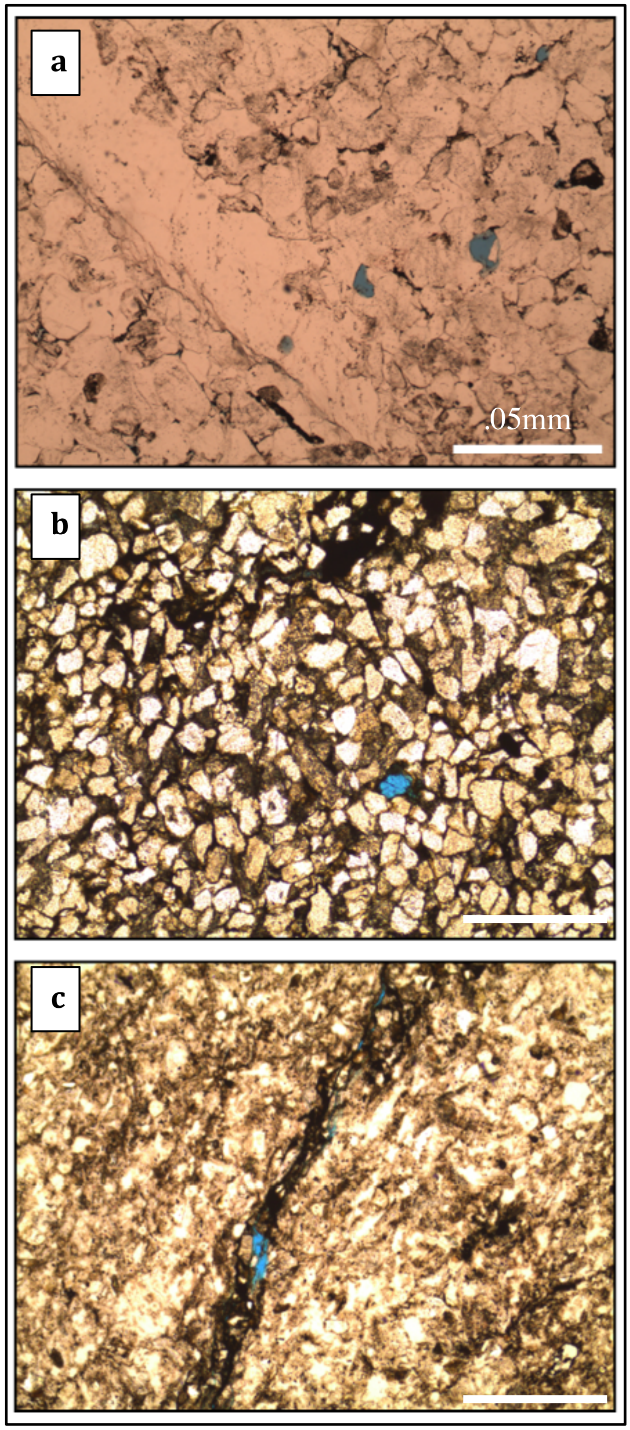
Porosity

Compaction and dissolution occurred within all three zones of the fold (Fig. 15). Initial compaction resulted in the reorientation and repacking of grains and dissolution resulted in the loss of primary porosity and development of secondary porosity. Porosity values for the Oriskany Sandstone in the Valley and Ridge Province range from <0.1% to 0.4% (Kostelnik and Carter, 2009). Samples collected from the three fold zones yield pore counts with values of <1% to 2%. Primary porosity in the samples cannot be seen in thin section, and most likely is only present on the nanoscopic level. South limb and axis samples show dissolution of detrital silicate grains leading to secondary porosity (Fig. 15a). Observable pore space in north limb samples can only be seen within solution seams (Fig. 15c). The lack of observable primary porosity within the fold zones is a result of calcite cementation. Calcite cementation led to weakened grain contacts, increasing the effects of compaction.

Calcite

Calcite is an abundant post-diagenetic mineral found throughout all three fold-zones, and is common in diagenetically altered shelf deposited sandstones. Calcite commonly occurs as pore filling intergranular cement prior to compaction (Wei, 2016; Bruner 1991). The abundance of calcite enhances compaction in sandstones, further eliminating large scale primary porosity. Microcrystalline calcite occurs as intergranular cement within south limb, axis, and north limb samples. Coarse-crystalline calcite can be seen in south limb and north limb samples as a result of recrystallization. This is due to neomorphism, causing unstable fossil fragments to be replaced by coarse calcite (Folk, 1965).

Figure 15: Examples of secondary porosity in south limb, axis, and north limb thin section samples, **(a)** *South Limb* Secondary porosity in south limb sample is shown by the blue coloring. These pore spaces are a result of dissolution, and are ~ 0.10 to 0.20 mm in diameter. Photomicrograph taken in plane-polarized light, **(b)** *Axis* The blue color represents a pore space in an axis sample created by dissolution. Pore space is ~ 0.15 mm in diameter and is surrounded by iron oxide. Photomicrograph taken in plane-polarized light, **(c)** *North Limb* A solution seam runs from the top of the slide to the bottom in a north limb sample. The presence of the solution seam creates secondary porosity. Pore spaces are ~ 0.10 to 0.15 mm in diameter. Photomicrograph taken in plane-polarized light.



Overgrowths

Quartz and feldspar overgrowths are abundant in south limb samples, are less common in axis samples, and are not noticeable in north limb samples. Diagenetic cements and clays influence the distribution and extent of alteration, such as overgrowths (Wei et al, 2016). It is likely that the abundance of calcite cement and clay in axis and north limb samples resulted in the lack of observable overgrowths. Removing grain-to-grain contacts between detritial quartz grains would ultimately remove, or prevent overgrowth development (Vincent et al, 2015).

Stylolites & Solution Seam

Stylolites and solution seams are found in samples from all three fold-zones (Fig. 16). Generally stylolites are defined as sutured surfaces that cut grains, cement, and matrix indiscriminately, and solution seams pass around grains and early diagenetic nodules (Tucker, 2001). Stylolites and solution seams usually form parallel to bedding due to overburden pressure, but they can also be perpendicular to bedding as a result of tectonic activity (Andrews and Railsbak, 1997). These stylolites and solution seams were formed during diagenesis, while the sandstone was subject to stress (Merino et al, 1983). These generally occur after initial lithification compaction. While stylolites and solution seams are common along bedding planes due to porosity instability, they can form in any zone of weakness. The abundance of carbonate material within the Oriskany Sandstone decreases the overall integrity of the rock, enhancing susceptibility to dissolution.

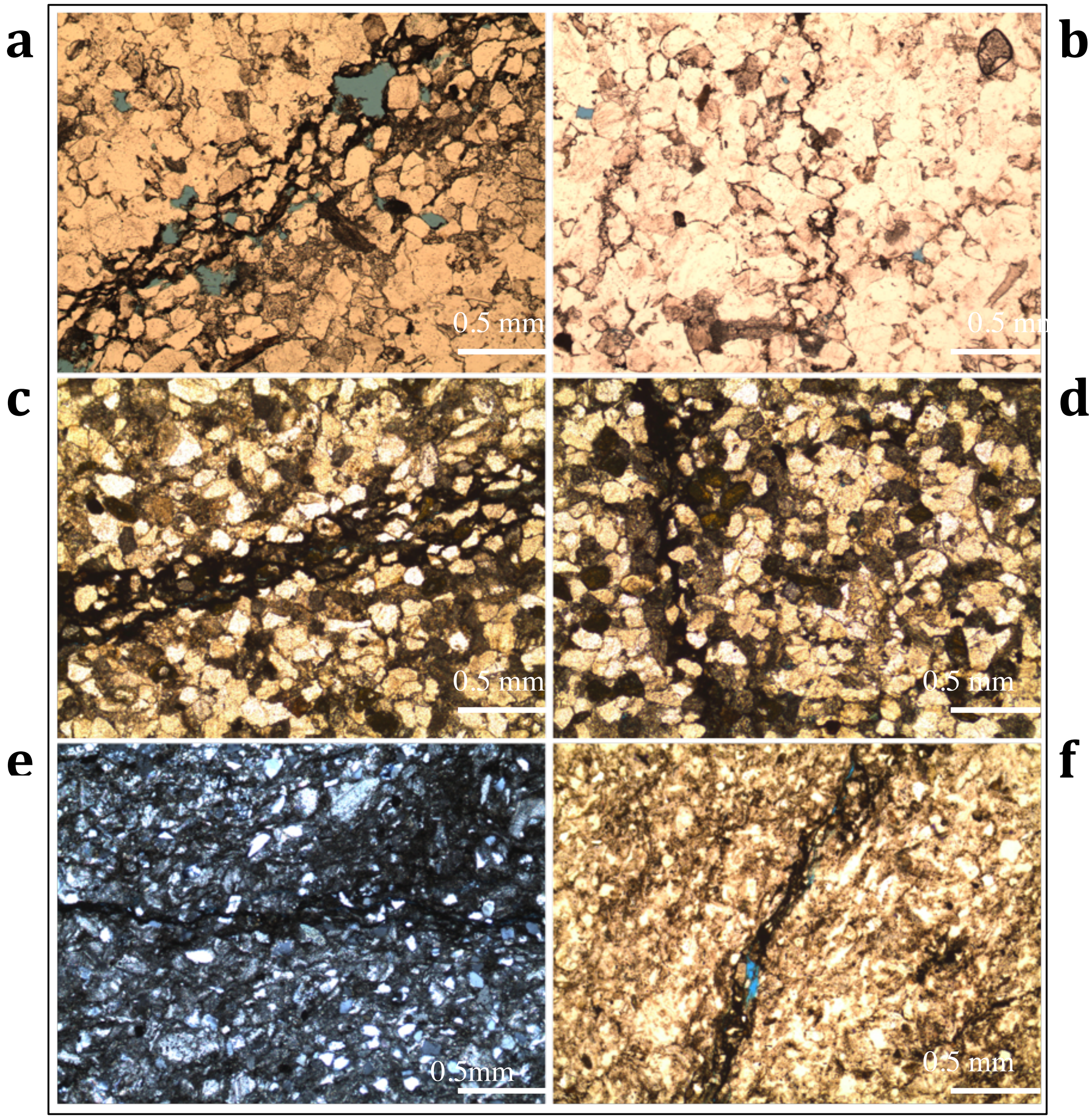


Figure 16: Stylolites and solution seams are pictured in thin sections from the south limb **(a, b)**, from the axis **(c, d)**, and from the north limb **(e, f)**. Seam development has led to secondary porosity development within all three of the fold zones. These pores can be seen in south limb **(a)**, and north limb **(f)**, and are visible due to blue apoxy.

The dominate stylolite and solution seams observed in LMA samples were recorded and oriented with the Oriskany collection bed in an attempt to infer pressure history (Fig. 17). The majority of stylolites and solution seams recorded show parallel and perpendicular orientation to bedding.

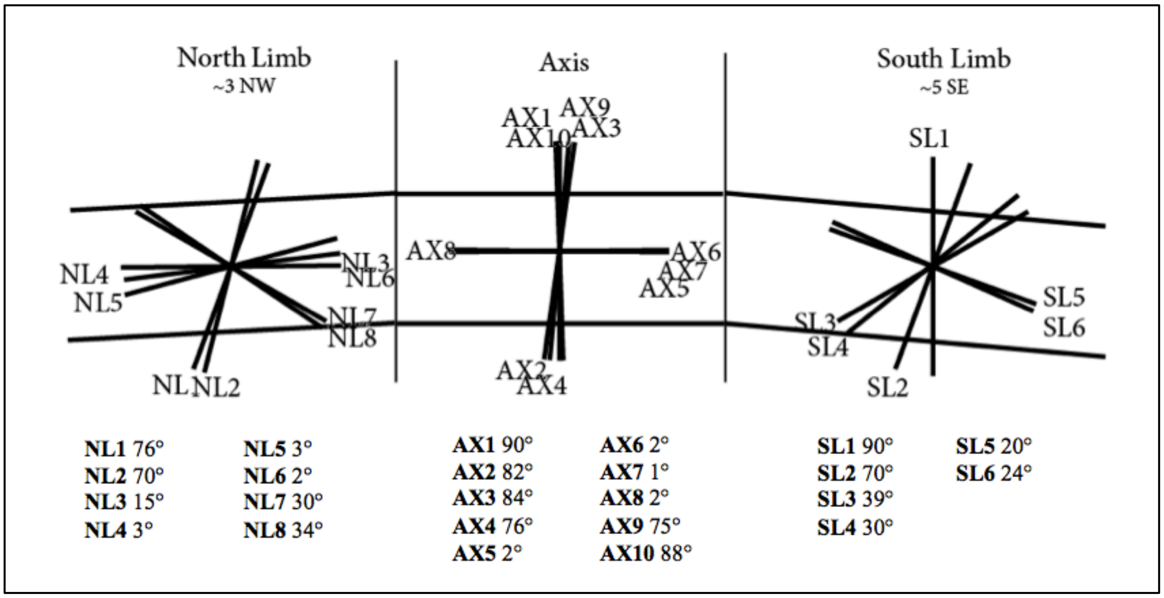


Figure 17: Orientations of major stylolite and solution seams in the three LMA fold zones. This figure was created using a topographic map of the Smoke Hole Region and was oriented as if one was facing the road from sample bed.

Paragenetic Sequence

Framework grain alteration and authigenic mineral precipitation are prevalent in the complex sequence of diagenetic processes in the in the Oriskany Sandstone. The paragenetic sequence is constructed on the basis of observations and interpretation (Fig. 18). To simplify the sequence, only major diagenetic processes are included. The development of diagenetic cements is greatly influenced by the mineralogy of detrital grains. Quartz is the predominant framework grain in the majority of LMA Oriskany Sandstone samples (primarily in SL and Ax samples). In these samples quartz overgrowths form the first major cement in the rock. Quartz cements filled voids and replaced other framework grains and fossil fragments. Quartz overgrowths continue to grow and are the dominant cement during effective burial. This remains the case during any periods of uplift and structural inversion as well (Burley and Warden, 2009). Small overgrowths will develop into solution pores and quartz will replace fossils and fill fractures.

Due to the abundance of fossil allochems in north limb samples, calcite cements would precipitate as early cements in the form of overgrowths and bladed spar. The timing of chert and chalcedony replacement of fossils is difficult to determine since the stability of shell mineralogy results in selective silicification (Bruner, 1991). Dolomite occurs during the late stages of diagenesis as a replacement mineral. Generally replacing quartz and calcite cements, as well as framework grains. The Fe-calcite seen along seam surfaces occurs as late stage cements. Stylolite and solution seams seen in LMA occurred during the later stages of diagenesis. This interpretation is made due to solution surfaces being lined with the fine carbonate material that is typical in the later stages of diagenesis in the Oriskany Sandstone (Torok, 1999).

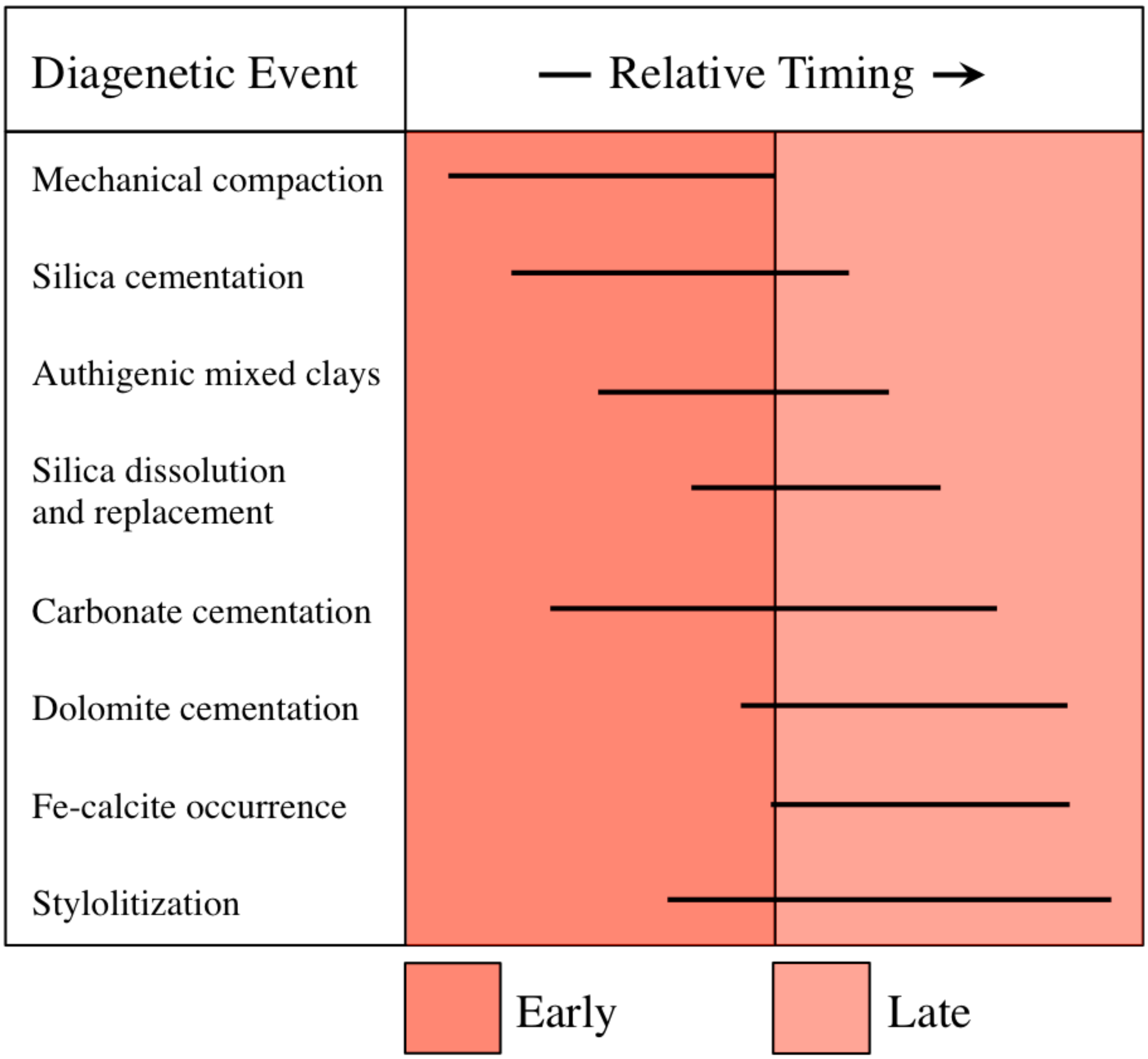


Figure 18: An illustrated representation of the parageneic sequence of events in the LMA Oriskany Sandstone.

Diagenetic Structural Influence on Little Mountain Anticline and its Implications

Carbonate abundance within the three fold zones is a direct result from depositional environment and burial history. Cement deposits strongly influence the way fractures conduct fluid. Cement deposits have been known to form from opening-mode fractures, but the influence that diagenesis has on the fracture system is still relatively unknown. This relationship stresses the importance of the role calcitic cements play in the three fold-zones. Previous work suggests cementation can play a more important role than compaction in increasing grain contact length and increasing the number of grain-to-grain contacts (Cook, 2010).

Due to tight cementation, and the lack of visible porosity, the Oriskany Sandstone that composes LMA is unsuitable for both sequestration and natural gas extraction. The abundant fracturing at the meso-scale observed throughout the three zones suggests that there would be sufficient levels of porosity and permeability, but thin section analysis showed that this was not the case at the microscopic scale. Extensive physical variations throughout the three fold zones could potentially lead to seal failure regardless of any quality reservoir properties. However, further study would be necessary to evaluate if a specific structural type could create potential stratigraphic traps and pinch-outs, but this would be entirely dependent on observing the level of nano-porosity in the three fold zones. Even with the addition of detailed porosity, nano-porosity, and permeability data, a sandstone at depth with similar characteristics to the LMA Oriskany Sandstone would most likely still be unsuitable.

CHAPTER FIVE: SUMMARY AND CONCLUSIONS

Cementation during deposition and resulting mechanical properties are sensitive to burial history. Structures usually have differing cement patterns and thermal histories, influencing forms such as anticlines and synclines to vary diagenetically (Laubach, et al 2010). The diagenetic features seen throughout the south limb, axis, and north limb samples stem from both depositonal environment and burial history, and then were influenced through structural deformation. Diagenesis can inform structural information, and structural information can constrain timing of diagenetic processes (Burley et al., 1989). The dominant controlling factor in these processes is fluid-rock reaction. Within a system, frictional failure and slip, along with compaction and fracture growth, interact with fluid-rock reactions (Laubach, et al 2010).

Thin-section analysis of the Oriskany Sandstone located in LMA shows how extreme variability in composition can occur within a single bed over a short distance. Composition variation and structural deformation influenced diagenetic alteration in the sandstone. Although the information presented here provides insight into how structural deformation can effect the reservoir properties of a sandstone, it also shows the importance of how small scale data collection can prevent attempted sequestration in an unsuitable unit.

The conclusions of this study are:

- In the LMA of the Smoke Hole region of West Virginia, the Oriskany Sandstone is a calcareous quartz sandstone that has undergone extensive diagenetic alteration.

- Petrographic analysis of the LMA found that there is few mineralogical differences between the three fold zones. Observed differences in mineralogy and grain characteristics are attributed to slight variations in the depositional setting.
- Porosity differs between zones. South limb and axis zones show dissolution and solution seam porosity whereas the north limb only shows solution seam porosity. Despite minor fracture porosity, authigenic minerals and clays combined with tight cementation have removed nearly all microscopic traces of primary porosity.
- Favorable reservoir characteristics were not observed in any of the three anticline zones found in LMA.
- These findings support previous works that the Oriskany structural plays in the Valley and Ridge province of West Virginia are unsuitable for effective sequestration.

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