

CHARACTERIZATION AND DEVELOPMENT OF FRACTURE PATTERNS IN DOMED SEDIMENTARY STRATA, PULPIT ARCH, HENRY MOUNTAINS, UTAH

by

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Fractures in sedimentary rock can be an important factor in influencing fluid migration in the subsurface. In high-porosity sandstones in the upper crust, deformation such as folding typically results in the production of deformation bands rather than joints or shear fractures. Deformation bands are zones of very low porosity and therefore tend to impede or redirect fluid rather than serve as preferential conduits like joints or shear fractures tend to. This project is designed to provide a rigorous characterization of deformation band patterns that developed during doming of high-porosity sandstone in the shallow crust.

The Pulpit Arch, located in the Henry Mountains of southeastern Utah, is a dome of sedimentary rock located above an unexposed component lobe of the Mt. Hillers laccolithic igneous center. The intrusion underlying the Pulpit Arch uplifted and folded the overlying strata, including the high-porosity Navajo Sandstone studied in this project, into a 3-dimensional dome with a diameter of roughly 2.5 km and an amplitude of approximately 200 m. Within the Navajo Sandstone, 690 deformation bands were characterized and mapped across 23 fracture stations in the Pulpit Arch and 4 in a nearby undeformed area. At every station a variety of characteristics were recorded, including fracture type, planarity, orientation, length, and termination style. Fracture intensity was calculated by measuring total fracture length per unit area for each

fracture station. Hand samples were collected at each fracture station for thin section examination in the laboratory.

Growth of the dome strongly influenced both the intensity and orientation of fractures in the Pulpit Arch. Deformation bands with orientations generally NE - SW and E - W were observed exclusively within the Pulpit Arch, while NW to SE trending fractures occurred in both areas. Average fracture intensity in the Pulpit Arch was calculated to be 0.30 m^{-1} and 0.03 m^{-1} in the control area. Porosity values in undeformed samples, deformed samples and deformation bands were calculated to be 13.1%, 22.5%, and 2.2%, respectively. These measurements agree with other published values for undeformed and deformed Navajo Sandstone, and deformation bands.

Overall, considerable differences in fracture characteristics between the Pulpit Arch and control area were visible. However, fracture characteristics like intensity and orientation vary considerably across the Pulpit Arch. The Pulpit Arch is an extremely early stage dome (extension magnitudes are approximately 1%), and it is likely that the fracture system on the dome has not developed enough for clear fracture patterns to occur. Similar studies on more advanced domes would further understanding of how fracture systems evolve with progressive doming.

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HENRY MOUNTAINS, UTAH**

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Master of Science in Geology

by

Matthew Scott McDaniel

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Table of Contents

List of Tables.....	vii
List of Figures.....	viii
Introduction.....	1
Background.....	4
Fractures.....	4
Deformation Bands.....	5
Folding in the Upper Crust.....	8
Igneous Intrusions in the Upper Crust.....	9
Laccoliths.....	10
Fracturing During Doming.....	12
Geologic Setting.....	18
Colorado Plateau.....	18
The Henry Mountains.....	22
Previous Work in the Henry Mountains.....	22
Mt. Hillers.....	24
The Pulpit Arch.....	27
The Control Area.....	31
The Navajo Sandstone.....	32
Methodology.....	35
Field Methodology.....	35
Fracture Measurement.....	36
Laboratory Methods.....	42
Creation of Geologic Maps.....	42
Strain Analysis.....	43
Fracture Analysis.....	44
Thin Section Analysis.....	47
Results.....	51

Construction of the Geologic Map and Cross Sections.....	51
Extension Across the Pulpit Arch.....	58
Fracture Analysis.....	62
Fracture Variation Across the Dome.....	77
Porosity Analysis.....	84
Discussion.....	87
Regional Fracture Systems.....	87
Fractures in the Pulpit Arch.....	88
Analogue to Other Domes.....	93
Conclusions.....	95
Reference List.....	97
Appendix A – Fracture Trace Data.....	103
Appendix B – Raw Fracture Data.....	115
Appendix C – Stereonets.....	138
Appendix D – Thin Section Photographs.....	150
Appendix E – UTM Coordinates for Stations.....	187

List of Tables

Table 1: Stratigraphic column of Jurassic sedimentary rocks in the Henry Mountains.	34
Table 2: Fracture intensity values for all fracture stations.	63
Table 3: Fracture characteristic data for PA17.	66
Table 4: Fracture characteristic data for PA10.	68
Table 5: Fracture characteristic data for PA25.	70
Table 6: Average bedding values for Pulpit Arch fracture stations.	80
Table 7: Porosity values for undeformed samples.	85
Table 8: Porosity values for deformed samples.	86
Table 9: Porosity values for deformation band samples.	86

List of Figures

Figure 1: Schematic diagram of the predicted fracture patterns in a periclinal dome.	1
Figure 2: Geologic map of the Henry Mountains area.	3
Figure 3: Photograph and photomicrograph of a deformation band.	6
Figure 4: Field photographs of deformation bands.	7
Figure 5: Schematic diagram comparing buckle folding and bending folding.	8
Figure 6: Schematic sketches of ideal laccoliths.	10
Figure 7: Fracture plots from Hennings et al. (2000).	14
Figure 8: Map of the Colorado Plateau.	19
Figure 9: Simplified stratigraphic column of the Henry Mountains.	21
Figure 10: Structure contour map of Mt. Hillers.	25
Figure 11: Cross section of Mt. Hillers.	26
Figure 12: Schematic cross-sectional diagram of the Pulpit Arch.	28
Figure 13: Geologic map of the Pulpit Arch.	29
Figure 14: Aerial photograph of the Pulpit Arch highlighting map-scale joints.	30
Figure 15: Geologic map and aerial photograph of the control area.	31
Figure 16: Field photograph of the Navajo Sandstone.	33
Figure 17: Field examples of deformation band types.	39

Figure 18: Field examples of different deformation band characteristics.	40
Figure 19: Workflow for the creation of fracture trace polyline files.	45
Figure 20: Example of photomicrograph segmenting.	49
Figure 21: Color thresholding procedure for thin sections.	50
Figure 22: Original geologic map of the Pulpit Arch.	52
Figure 23: Updated geologic map of the Pulpit Arch.	53
Figure 24: Map of cross section transects.	54
Figure 25: NW to SE cross section of the Pulpit Arch.	55
Figure 26: NE to SW cross section of the Pulpit Arch.	56
Figure 27: Field photograph of the Navajo Ss., Page Ss., and Carmel Fm.	57
Figure 28: Transects used for extension calculations across the Pulpit Arch.	59
Figure 29: Fracture station distribution in the Pulpit Arch.	60
Figure 30: Fracture station distribution in the control area.	61
Figure 31: Map of fracture intensity.	64
Figure 32: Example photographs of fracture stations.	65
Figure 33: Fracture traces for PA17.	67
Figure 34: Stereonet for PA17.	67

Figure 35: Fracture traces for PA10.	69
Figure 36: Stereonet for PA10.	69
Figure 37: Fracture traces for PA25.	70
Figure 38: Stereonet for PA25.	71
Figure 39: Rose diagram of fracture orientation measure in the control area.	72
Figure 40: Rose diagram of fracture orientation measured in the Pulpit Arch.	72
Figure 41: Rose diagram of all fracture orientations measured, categorized by intensity.	73
Figure 42: All fracture lengths measured, categorized by intensity.	74
Figure 43: Fracture termination styles per fracture length.	75
Figure 44: Fracture termination styles per fracture orientation.	75
Figure 45: Dip magnitudes for all fractures measured in the field.	76
Figure 46: Radial, tangential, and “other” fractures per termination style.	77
Figure 47: Map of bedding measurements across the Pulpit Arch.	81
Figure 48: Structure contour map of the Navajo/Page contact in the Pulpit Arch.	82
Figure 49: Curvature map of Navajo Sandstone exposure in the Pulpit Arch.	83
Figure 50: Curvature values at Pulpit Arch fracture stations.	84
Figure 51: Fracture traces for PA26.	89
Figure 52: Fracture traces for PA21.	89

Figure 53: Stereonets overlain on fracture station locations.	95
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Introduction

Reservoirs in Earth's subsurface can store many economically important fluids and gases, such as groundwater, oil and gas, and CO₂ (Allen et al., 2013; Petrie et al., 2013). These fluids are not static and can migrate along preferential pathways in host rock. Porous sandstones compose many traditional reservoirs, and their capacity for fluid storage can vary, dependent on the amount of deformation the rock body has undergone. A fracture may act as either a barrier to or conduit for fluids, depending on its porosity and permeability relative to surrounding rock (e.g. Fossen, 2007; Fossen and Bale, 2007). Similarly, a network of fractures can either compartmentalize portions of a rock volume or provide connectivity and enhanced fluid flow.

In the upper crust, folding is one important process through which fractures initiate and, with progressive deformation, develop. Folding in the upper crust occurs through two primary mechanisms, buckle folding and bending folding (Stearns, 1978). Buckling and bending produce different fold shapes, and therefore fracture patterns that form within these folds are distinct (Stearns, 1978; Cosgrove and Ameen, 1999; Smart et al., 2009; Watkins et al., 2017).

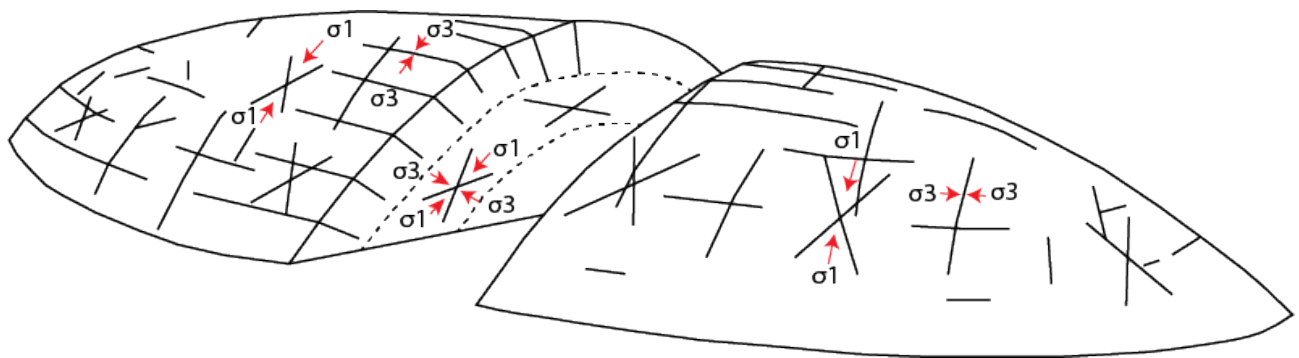


Figure 1: Schematic diagram of the predicted fracture patterns in a periclinal dome. (Modified after Stearns, 1978)

While both two-dimensional and three-dimensional bending folds are common, most field studies involving bending folds examine features that are essentially two-dimensional in their geometry, like monoclines above offset, faulted basement rock (e.g. Smart et al., 2009; Zuluaga et al., 2014; Smart and Ferrill, 2018). Few studies consider bending folds with three-dimensional shapes, like periclinal domes (Fig. 1) that form above diapirs or intrusive bodies in the subsurface. Models of three-dimensional bending folds that predict fracture patterns do exist (e.g. Cosgrove and Ameen, 1999, Smart et al., 2009), and suggest fracture intensity will increase in areas of higher curvature, such as the hinge regions of the domes. However, relatively few substantive field tests of these models have been published (e.g. Watkins et al., 2017).

The primary goal of this study is to thoroughly characterize fracture patterns that have developed on a periclinal dome, using the Pulpit Arch as one of these naturally formed domes. These observations can be used to test existing models of fracture development during three-dimensional bending folding. By testing these models with field data, the presence of a consistent natural fracture pattern that develops in domes can be determined.

Within the Henry Mountains of southern Utah, several intrusion-fed domes are present. These domes offer an excellent location to examine fracture patterns that form in these domes. The Henry Mountains are a series of five Oligocene intrusive centers (Fig. 2A). These intrusive centers often feature numerous satellite intrusions that radiate outward from larger laccolithic central igneous bodies. The eastern side of the Mount Hillers (Fig. 2B) features one of these satellite intrusions, which has domed the overlying sedimentary strata. The dome, the Pulpit Arch (Fig. 2C), is composed of Jurassic and Triassic sedimentary units. This research focuses on Jurassic Navajo Sandstone, the unit that makes up the crest of the dome. Here, the underlying

intrusive body is not exposed at the surface, which allows fractures to be measured across the entirety of the dome.

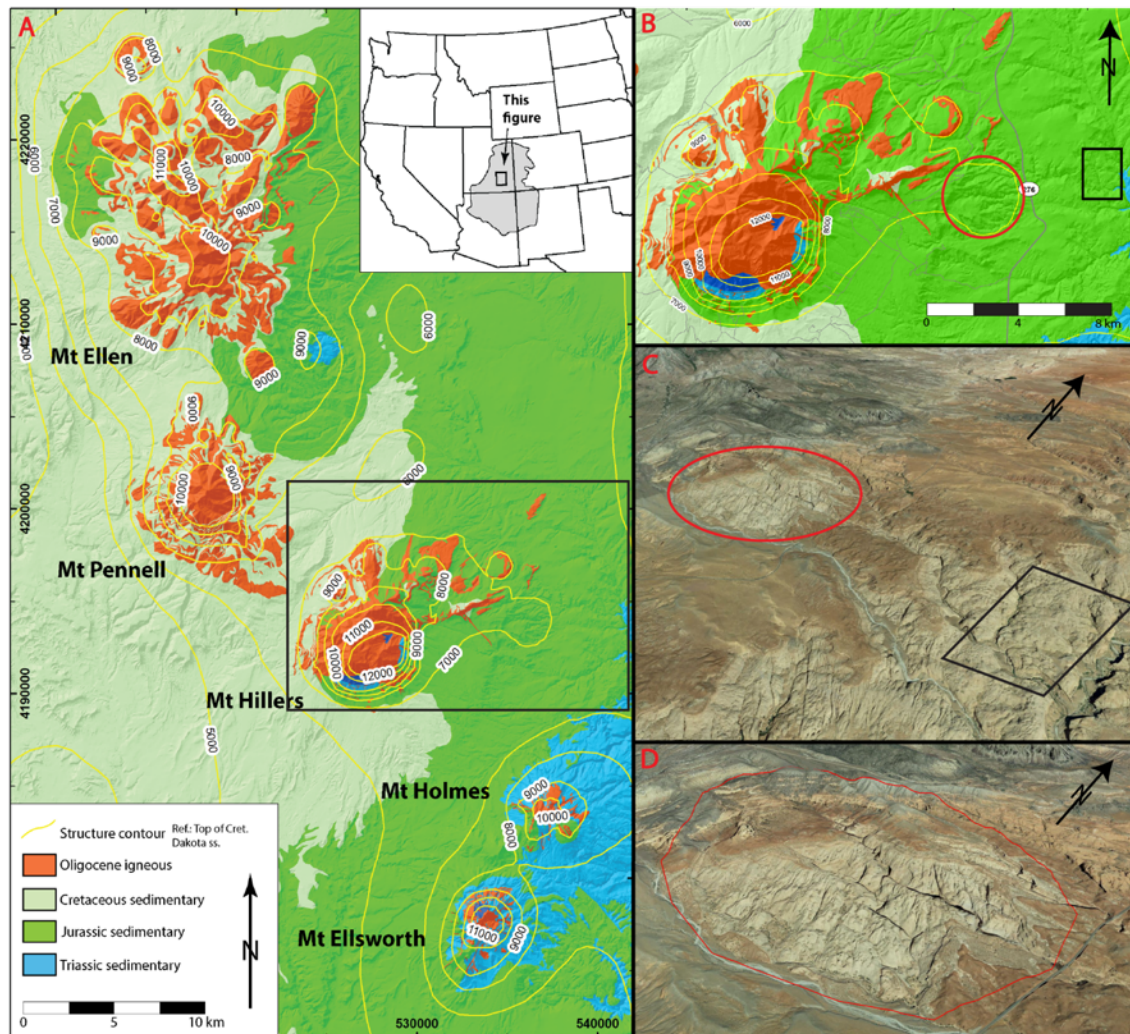


Figure 2: (A) Geologic map of the Henry Mountains. Black box corresponds to Figure 2B (Modified from Horsman et al., 2017). (B) Geologic map of Mount Hillers. Red circle corresponds the main field site, the Pulpit Arch. The black box corresponds to the control area. (Modified from Horsman et al., 2017). (C) Oblique aerial photo of the Pulpit Arch and control area, looking to the northwest. (D) Oblique aerial photo of the Pulpit Arch, looking to the northwest. The light tan unit in the center of the photo is the Navajo Sandstone, the focus of this project. This image is approximately 2 kilometers across. Photos from Google Earth.

Background

Fractures

Fractures are discontinuities that form in rocks in the shallow subsurface or on the surface of the Earth. A blanket term, “fractures,” refers to joints, faults, veins, deformation bands, etc. (Manda and Horsman, 2015). Fracture type can vary with location due to the lithological and mechanical properties of the host rock (Laubach et al., 2009; Smart et al., 2009), as well as the amount of deformation an area has undergone. As a result, different fracture types have unique physical characteristics.

While fractures can form individually, it is more common for fractures to form in groups, called fracture sets. Fracture sets are localized groups of fractures with similar orientation. Two or more different fracture sets can occur in the same area and intersect one another. When multiple fracture sets form, there are dominant fracture sets which are often complemented by one or more auxiliary fracture sets. Fracture sets can develop atop one another over time, allowing for increased fracture connectivity, an important variable for fluid flow through a rock body.

Depending on their physical characteristics, fractures can either increase or decrease the permeability of a rock, acting as preferential migration pathways or baffles for fluid flow, respectively. Joints, fractures with no visible offset, are preferential pathways for fluids moving through strata. Deformation bands often reduce permeability by several orders of magnitude (Fossen, 2007; Fossen and Bale, 2007), which in turn can inhibit fluid flow. Faults can do both, depending on their structure, sometimes accelerating fluid flow, in other cases restricting fluid flow (Kurz et. al., 2008).

Knowledge of fracture patterns in a subsurface rock body is useful for determining how fluids may move through the material. The lithological focus of this project, the Navajo Sandstone, is considered a good analogue for a petroleum reservoir (Ugyur and Picard, 1980). By examining fracture patterns that have formed in this sandstone, the findings of this research can be applied to other fractured subsurface bodies.

Deformation Bands

Deformation bands are a type of fracture that form exclusively in rock bodies with porosity higher than ~15% (Fossen and Bale, 2007), and primarily in sandstones. Though the term “deformation band” can be used to describe different fractures that form in porous media, the traditional definition refers to cataclastic deformation bands, first described by Aydin (1978). In this paper, the term “deformation band(s)” will explicitly refer to cataclastic deformation bands, unless otherwise specified. Deformation bands form during deformation, when individual grains are crushed and forced together (Aydin, 1978, Fossen and Bale, 2007). Fractured grains become interlocked, largely eliminating pore space from the “core” of the deformation band. Outside of this central zone, there is little to no grain fracturing (Fossen, 2007). This results in a compact millimeter-scale zone of deformation (Fig. 3).

Due to this, deformation bands are mechanically strong compared to the rock around them, whereas most fractures are relatively weak compared to their host media. Deformation bands, unlike some other fractures, do not represent a slip surface. Instead, slip surfaces can form inside bands or along deformation bands, though not always (Fossen, 2007). Deformation bands feature relatively little offset compared to other types of fractures. It is not uncommon for

a deformation band with length over 100 m to have a maximum displacement of only a few centimeters (Fossen, 2007). For comparison, most faults have a maximum displacement of $\sim 10^{-2}$ of their length (Kim and Sanderson, 2005). Like other fractures, deformation bands can form individually (Fig. 4A), or as clusters (Fig 4B). While individual deformation bands are relatively thin, clusters are thicker, typically centimeters or decimeters wide. These clusters of deformation bands have been observed to be precursors to faults (Aydin and Johnson, 1978). As clusters of deformation bands mature, slip surfaces begin to appear in and around the bands. Eventually, the fractures and the slip surfaces link together and, should the cluster fail, a fault may form (Aydin and Johnson, 1978; Pollard and Fletcher, 2005).

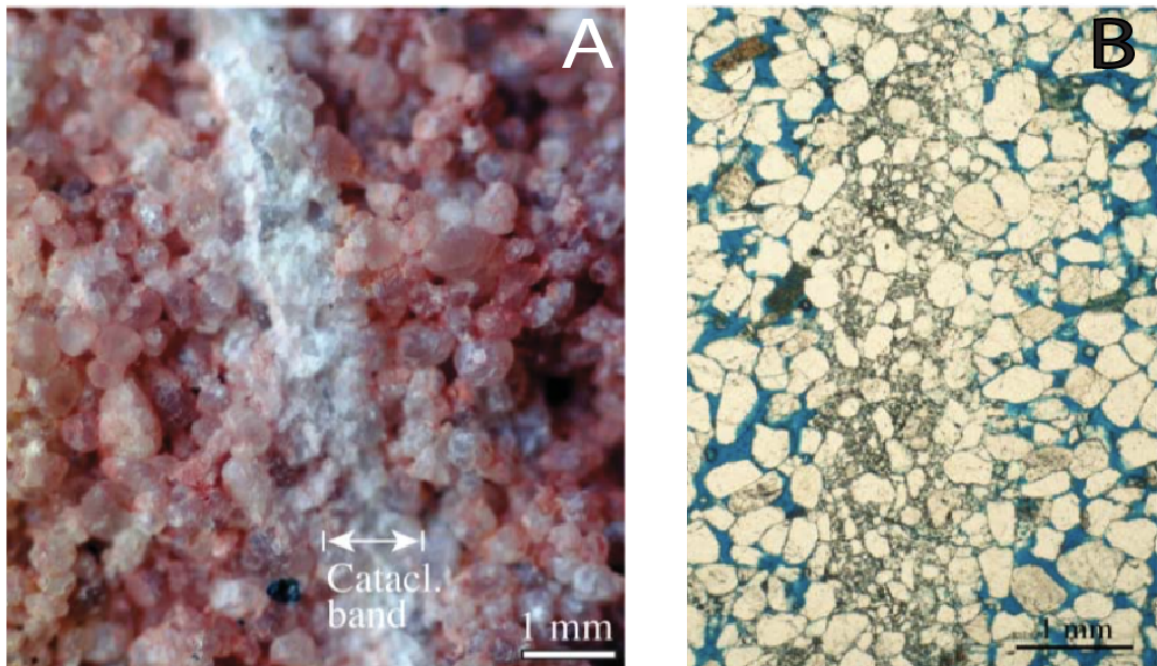


Figure 3: (A) Photograph of a deformation band. (B) Photomicrograph of a deformation band. Blue epoxy indicates open pore spaces (Fossen, 2007).

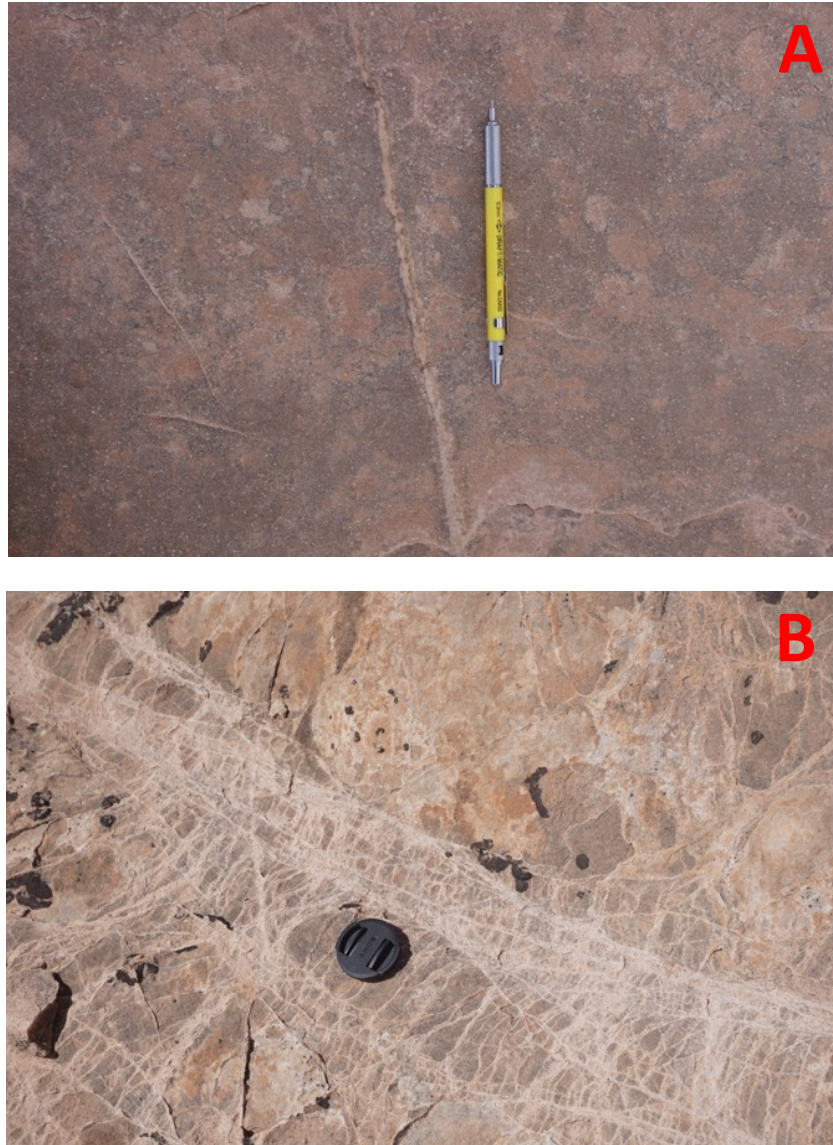


Figure 4: (A) An individual deformation band. (B) A large cluster of deformation bands. Both photos taken within the Pulpit Arch, the field site. Pencil and lens cap for scale.

Most importantly, whereas many types of fractures increase permeability and the ease of fluid flow, deformation bands are generally barriers to fluid movement (Antonellini and Aydin, 1994; Fossen and Bale, 2007). Consequently, clusters of deformation bands can significantly impact the overall permeability of a porous sandstone unit. Fossen and Bale (2007) examined

evidence of fluid flow in porous sandstones with deformation bands. They examined bleaching of the sandstones, which is interpreted to record fluid flow through the rock. In theory, should deformation bands halt fluid movement, the staining would also stop at deformation bands. Surprisingly, Fossen and Bale (2007) discovered that staining occurred in rock despite the presence of deformation bands. Their findings indicated that while the physical properties of individual bands allow them to act as baffles to fluid flow, it is probable that deformation bands have neither the size nor connectivity to prevent most fluid movement through an entire rock body. However, deformation bands may help direct fluid movement through a host rock, meaning they could constrain fluid migration pathways in a potential reservoir (Fossen and Bale, 2007).

Folding in the Upper Crust

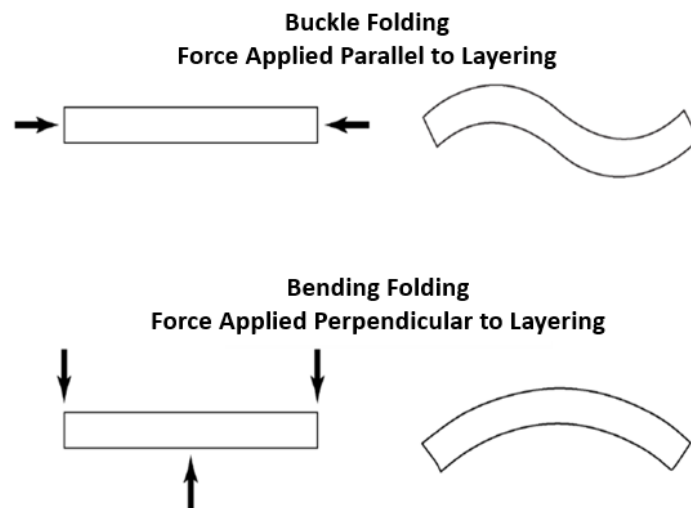


Figure 5: Schematic diagram comparing buckle folding (above) and bending folding (below).

As rocks undergo stress in the upper crust, they may begin to fold, which is a key process through which fracturing occurs. Folding in the upper crust occurs through two primary mechanisms: buckle folding and bending folding (Fig. 5). Buckle folding occurs when force is applied parallel to layering within the rock, and is common in environments undergoing shortening. Bending folds, also known as forced folds (Stearns, 1978), form when force is applied perpendicular to layering, commonly due to vertical displacement of underlying rocks. Examples include monoclines in strata above basement faults, domes above shale or salt diapirs, or folds above vertically growing igneous bodies like sills and laccoliths. Buckling and bending produce different fold shapes (Fig. 5), and therefore fracture patterns that form within these folds are distinct (Stearns, 1978; Cosgrove and Ameen, 1999; Smart et al., 2009; Watkins et al., 2017).

Igneous Intrusions in the Upper Crust

Igneous rocks can crystallize at the surface, through events such as volcanic eruptions. They can also be emplaced underground, affecting the surrounding rock bodies. Igneous rocks that crystallize in the subsurface are generally referred to as intrusions and are distinguished based on geometry of the body and the relationship with the surrounding rock. Dikes, sills, and laccoliths are all well-known types of intrusions that are found in nature. Dikes, the main mechanism through which magma ascends in the upper crust, are narrow, tabular discordant bodies that can feed other intrusions, such as sills or laccoliths. Sills are concordant tabular bodies that intrude between layers of host rock. Over time, sills can begin to expand vertically, uplifting the overlying host rock and creating an intrusion with a flat concordant base and upward domed roof, called a laccolith (Fig. 6).

Laccoliths



Figure 6: Schematic sketches of idealized laccoliths (Modified from Gilbert, 1877). (A) A basic laccolith. (B) A laccolith with associated dikes and sills. (C) Multiple laccoliths in one location.

Based on field observations in the Henry Mountains, Gilbert (1877) described a simple model for the formation of ideal laccoliths, which he called “laccolites” (Fig. 6). In his model, magma ascends in a dike until the density of the overlying rock is lower than that of the magma. At this stage, the magma begins to radiate outward from the dike, transitioning to a concordant sill. The sill follows the mechanically easier path, expanding laterally until resistances become equal on all sides. Once this occurs, the intrusion is able to gain leverage on the overburden and begins to propagate upward. The overlying strata are uplifted until the injection of magma ceases and the intrusion is able to fully crystallize. Gilbert’s (1877) evidence for this deformation was the orientation of the sedimentary rock surrounding the intrusion, which were similar to the intrusion itself. He also noted that multiple laccoliths could be emplaced around one another, leading to further deformation of the host rock.

More detailed characteristics of laccoliths were described by Corry (1988), who compiled studies of these intrusions. Corry (1988) noted that laccoliths can sometimes be asymmetric or irregular, expanding upon the idealized geometry proposed by Gilbert (1877). Gilbert (1877)

theorized a connection between sills and laccoliths, and future studies (e.g. Corry, 1998; Horsman et al., 2010) would support his hypothesis that intrusions which begin as sills may eventually evolve into laccoliths, through progressive magma injection over time.

Many laboratory experiments have been performed to determine how these intrusions can grow and subsequently deform the overlying strata (e.g. Pollard and Johnson, 1973; Rivalta and Dahm, 2006; Kavanagh et al., 2006; Currier and Marsh, 2015). Typically, in these experiments, a magma analogue is injected into a medium meant to represent a host rock, often sand or gelatin. Air, water, grease, and corn syrup are popular choices as the fluid analogue (e.g. Rivalta and Dahm, 2006; Kavanagh et al., 2006).

For example, Pollard and Johnson (1973) tested intrusion growth in a laboratory setting, by injecting grease into a gelatin body to simulate the injection of an igneous body into host rock. Their experiments found that laccolith formation was not defined by an arbitrary length that a sill must grow to, but instead when the driving pressure of the magma body was uniform across the overburden above the intrusion. Once this occurs, the overburden begins to bend and fail, allowing the sill to begin transitioning into a laccolith. Pollard and Johnson (1973) suggest that various factors influence when this bending occurs, such as the length over which the pressure is applied, and thickness and lithology of the overburden. Pollard and Johnson (1973) state that stratigraphic layers within overburden will slip past each other and act as distinct individual layers instead of one homogenous body. This allows layers to slip past each other, which can affect rate of bending in the overburden. They use the term “effective thickness” to describe how thick rock bodies with overburden layers slipping past each other will behave and bend like much thinner homogenous bodies.

In their experiments, Currier and Marsh (2015) compared models of laccolith growth by injecting water or heated wax into a gelatin host body. They hypothesized that, in contrast to water, the wax would solidify as it cooled, making it a more accurate analogue to a magma during emplacement. Gelatin was used as a host because of its transparency, so the growth of the intrusion under the surface could be viewed. Currier and Marsh (2015) designed an apparatus which would allow the analogue fluid to be pumped into the host medium and filmed the growth of each intrusion over time.

When water was used, the analogue intrusion grew laterally in all directions at a constant rate. In each wax experiment, the intrusion laterally expanded over a period of time, followed by alternating periods of no lateral growth and sudden bursts of growth. Lateral growth in the wax was not radially consistent and grew vertically as well as laterally. Currier and Marsh (2015) concluded that the wax was an imperfect but better rheological representation of a magma body. Their findings generally support Gilbert's (1877) hypothesis: as the laccoliths grow over time, radial intrusions can form around a large central body. This eventually leads to large laccolithic intrusive centers that feature numerous satellite intrusions. As described later, the Henry Mountains feature several examples of these geometries.

Fracturing During Doming

Several studies (e.g. Stearns, 1978; Jackson and Pollard, 1990; Cosgrove and Ameen, 1999; Smart et al., 2009; Watkins et al., 2017) have examined how fractures can form as a result of the development of forced folds in the upper crust. Stearns (1978) recognized that bending

folds and buckle folds have different geometries, and therefore will produce different fracture patterns. More recent work (e.g. Cosgrove and Ameen, 1999; Smart et al., 2009) further expanded these ideas. While all folds are three-dimensional, the geometry of some, called cylindrical folds, can be approximated through two-dimensional representations, like cross-sections. Theoretical models of fracture patterns in both two-and-three dimensional bending and buckle folds (e.g. Cosgrove and Ameen, 1999; Smart et al., 2009), suggest that fractures form most extensively in the regions of highest curvature in these folds. While these theoretical models provide some insight, most field studies of bending folds focus on effectively two-dimensional bending folds, such as monoclines (e.g. Zuluaga et al, 2014; Smart and Ferrill, 2018).

Field studies of fracturing above bending folds (e.g. Hennings et al., 2000; Zuluaga et al., 2014; Watkins et al., 2017) agree with the predictive models. Hennings et al. (2000) created a three-dimensional structural model of fracture intensity on the Oil Mountain anticline near Caspar, Wyoming. They examined joints present in the Frontier Formation, a Cretaceous unit found on the Oil Mountain anticline, to examine if field data agreed with their theoretical model. Hennings et al. (2000) found that field measurements did generally agree with their predictive models, though there were some areas of higher fracture intensity, which they attribute this to local variation in the sedimentary units. Hennings et al. (2000) produced several plots comparing fracture intensity with other factors (Fig. 7).

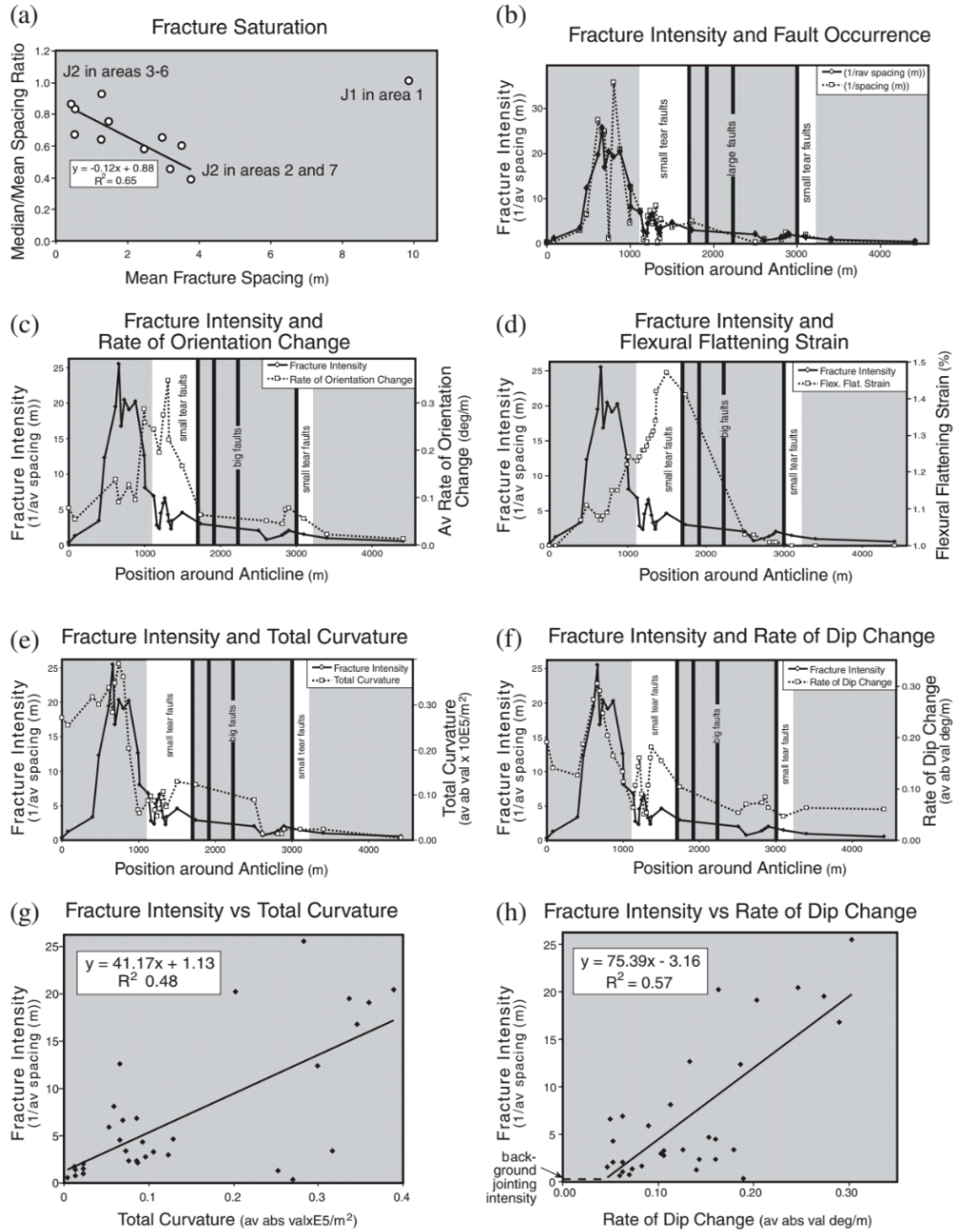


Figure 7: Plots created by Hennings et al. (2000) summarizing their characterization of fracture and fault intensity in the Oil Mountain anticline.

Zuluaga et al. (2014) examined deformation band evolution in the Navajo Sandstone on the San Rafael monocline in Eastern Utah. They mapped fractures across the monocline and hypothesized how deformation bands develop during the evolution of fault propagation folds. Zuluaga et al. (2014) discovered that bedding parallel deformation bands are among the first indicators of deformation to appear, and their intensity is closely linked to the dip of the fold's forelimb. As the dip magnitude of the limbs increases and the fold gets tighter, deformation band density and development increase exponentially.

In the Moine Thrust Belt in NW Scotland, Watkins et al. (2017) examined fracture distribution in the Torridon Group sandstone, an analogue for potential reservoirs (Watkins et al., 2017). They mapped fractures throughout their field area and produced three-dimensional models of fracture connectivity. Watkins et al. (2017) concluded that fracture intensity and connectivity were generally higher in areas of higher deformation, though several factors influence fracture development, including fold curvature, structural position, and lithology of the deformed body.

Some studies have examined formation of fractures in the sedimentary rock specifically in the Henry Mountains. Jackson and Pollard (1990) examined how progressive faulting accommodated bending of the sedimentary host rock as the underlying intrusions grew. Examining fault systems around Mt. Holmes, Mt. Ellsworth, and Mt. Hillers, Jackson and Pollard (1990) suggested that in early stages of doming, bedding-parallel faults began to form, which divided the overlying host rock into packages, distinguished by mechanical properties. These fault-bonded packages would allow the overburden to deform more easily than the entire unfaulted stratigraphic section. It is important to note that based on Jackson and Pollard's (1990)

definitions, the primary field area for this project, the Pulpit Arch, is not deformed sufficiently to even be considered an early stage dome.

Jackson and Pollard (1990) defined their stages of doming by extrapolating relative principal stress magnitudes from structural data collected on faults in the field. With progressive deformation, complex networks of radial and tangential faults formed in the host rock. Faults radial to the intrusive center were observed frequently through all parts of the dome. Tangential faults were only common at the edge of flexure. Jackson and Pollard (1990) observed that tangential faults generally offset radial faults, indicating that radial faults form first during the doming process.

As shear stress began to build with growth of the intrusion, these faults propagated and slipped. Jackson and Pollard (1990) further stated that the displacement along the large faults around each central intrusion in the area would be able to better accommodate stress during the early stages of laccolith growth. In later stages of doming, slippage and rate of fault displacement of both bedding-parallel faults and high-angle faults decreased, eventually coming to a halt as the sedimentary strata stretched and bent into its final configuration (Jackson and Pollard, 1990). Some fault blocks likely moved and settled near the top of the laccolith at Mt. Ellsworth (Jackson and Pollard, 1990). The hinge zones of all three domes seemed to remain spatially consistent, indicative of little-to-no movement of the hinges during the stages of doming.

In his study of deformation in the Colorado Plateau, Davis (1999) examined deformation bands across the entire region and recognized both cataclastic and non-cataclastic deformation bands. Davis (1999) established 14 stations in the Henry Mountains region, with one directly east of the Pulpit Arch. Of these 14 stations, 7 were located within areas directly affected by

laccolith development. These 7 stations we located within, or close to, the extent of the Mt. Hillers, Mt. Ellsworth, and Mt. Holmes intrusive centers. Within these 14 stations, Davis (1999) measured the orientations of 478 deformation bands. He observed two predominant sets with orientations of NW - SE and NE - SW, respectively. Davis (1999) noted that the more common NW to SE orientation often aligned radially with the nearest intrusive center.

After examining his stations, Davis (1999) suggested that the formation history of deformation bands in the Henry Mountains is a result of multiple evolving strain environments. Davis (1999) hypothesized that deformation bands formed continuously throughout the laccolith doming process. With progressive deformation, bedding would rotate, curvature would increase, and more deformation bands would form. Over time, this would result in the complex network of fractures in the Henry Mountains, such as those observed by Jackson and Pollard (1990).

Geologic Setting

Colorado Plateau

The Colorado Plateau is a geologic province that covers approximately 390,000 km² of the southwestern United States (Hunt, 1956) extending into Utah, Arizona, Colorado, and New Mexico (Fig. 8). The region is composed of Paleozoic to Cenozoic sedimentary strata, which overlie Precambrian basement rocks, and has remained relatively stable throughout the Phanerozoic.

Surrounding the Colorado Plateau are four major folded and faulted geologic areas: The Mogollon Rim to the south, the Rio Grande Rift to the southeast, the Basin and Range to the west, and the Rocky Mountains to the east and north (Trexler, 2014). These areas did not form concurrently, instead forming individually throughout the Phanerozoic. For example, the Rocky Mountains formed near the end of the Laramide Orogeny, ~70 Ma (Coney and Reynolds, 1977), while the extension currently developing the Basin and Range did not initiate until ~17 Ma (Hamilton, 1987). Though the rest of the North American Cordillera has undergone complex Phanerozoic deformation, the Colorado Plateau itself has experienced relatively little deformation, hypothesized to have resulted from a thickened section of lithosphere under the Colorado Plateau (Flowers, 2010).

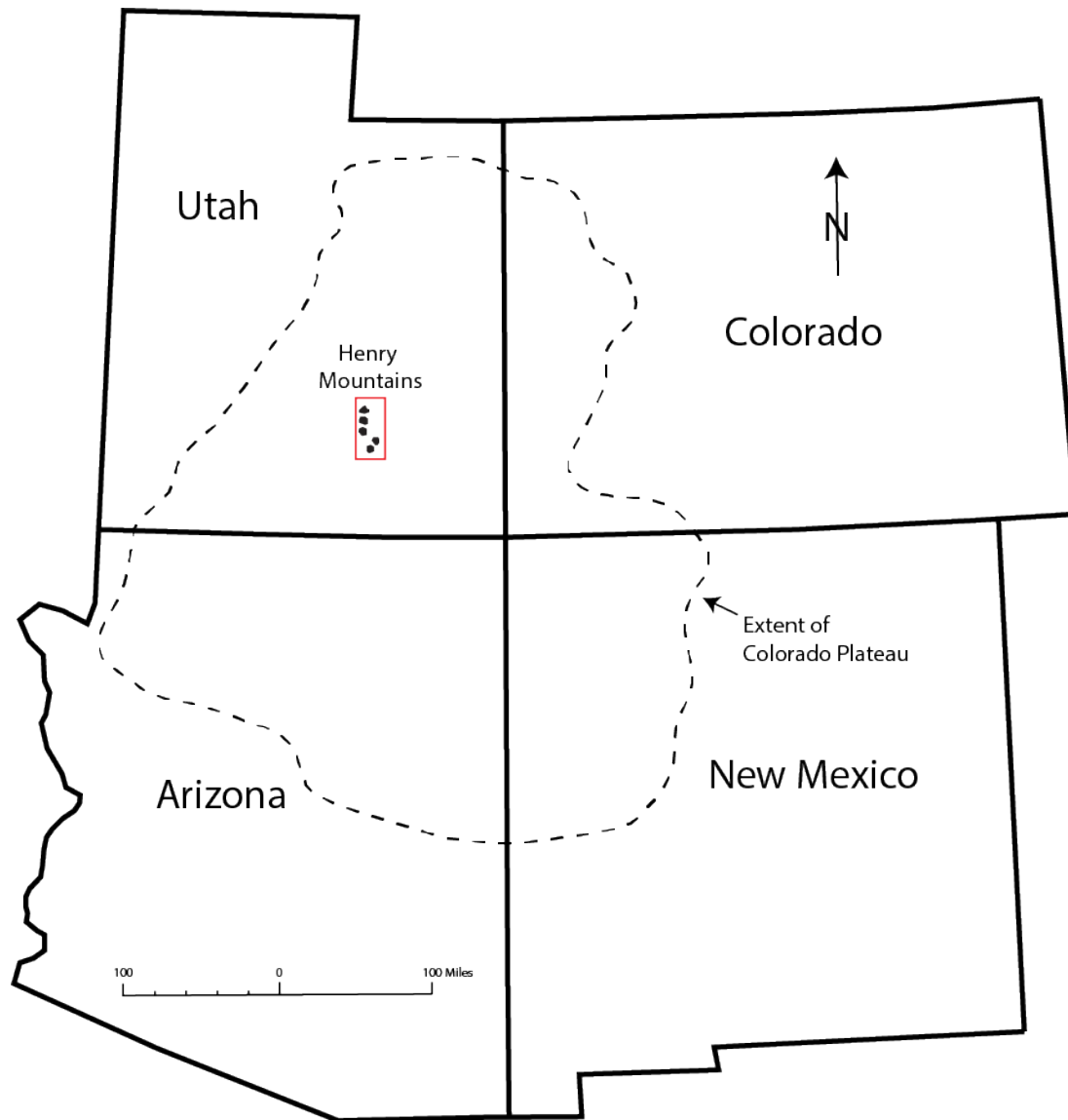


Figure 8: Map of the Colorado Plateau. The location of the Henry Mountains is marked by the red box.

Perhaps the most noticeable remnants of deformation on the Colorado Plateau are the monoclines found throughout the region. Stearns (1978) suggested these monoclines formed as a result of sedimentary strata being “draped” over faulted basement rock. Ancient shear zones and fault systems are found at depth throughout the area (Marshak et al., 2003; Davis and Bump, 2009). These were caused by various tectonic events throughout the Colorado Plateau’s history,

which is observable in their wide range of orientations. Deformation in the region likely reactivated the shear zones and fault systems, which subsequently resulted in the growth and development of monoclines in the area (Marshak et al., 2003; Davis and Bump, 2009).

Southeastern Utah, located near the geographic center of the Colorado Plateau, is home to three notable mountain ranges with similar geologic histories, the Henry Mountains, La Sal Mountains, and Abajo Mountains. Each range formed through the emplacement of laccoliths during the Oligocene (Gilbert, 1877; Jackson and Pollard, 1988; Ross, 1992; Witkind, 1964). The main intrusive bodies that form each respective mountain system were emplaced at similar depths, and each igneous body is mineralogically classified as a porphyritic andesite, and some studies have hypothesized that the Henry, La Sal, and Abajo Mountains were all part of the same volcanic arc system (e.g. Nelson et al., 1992; Nelson and Davidson, 1997).

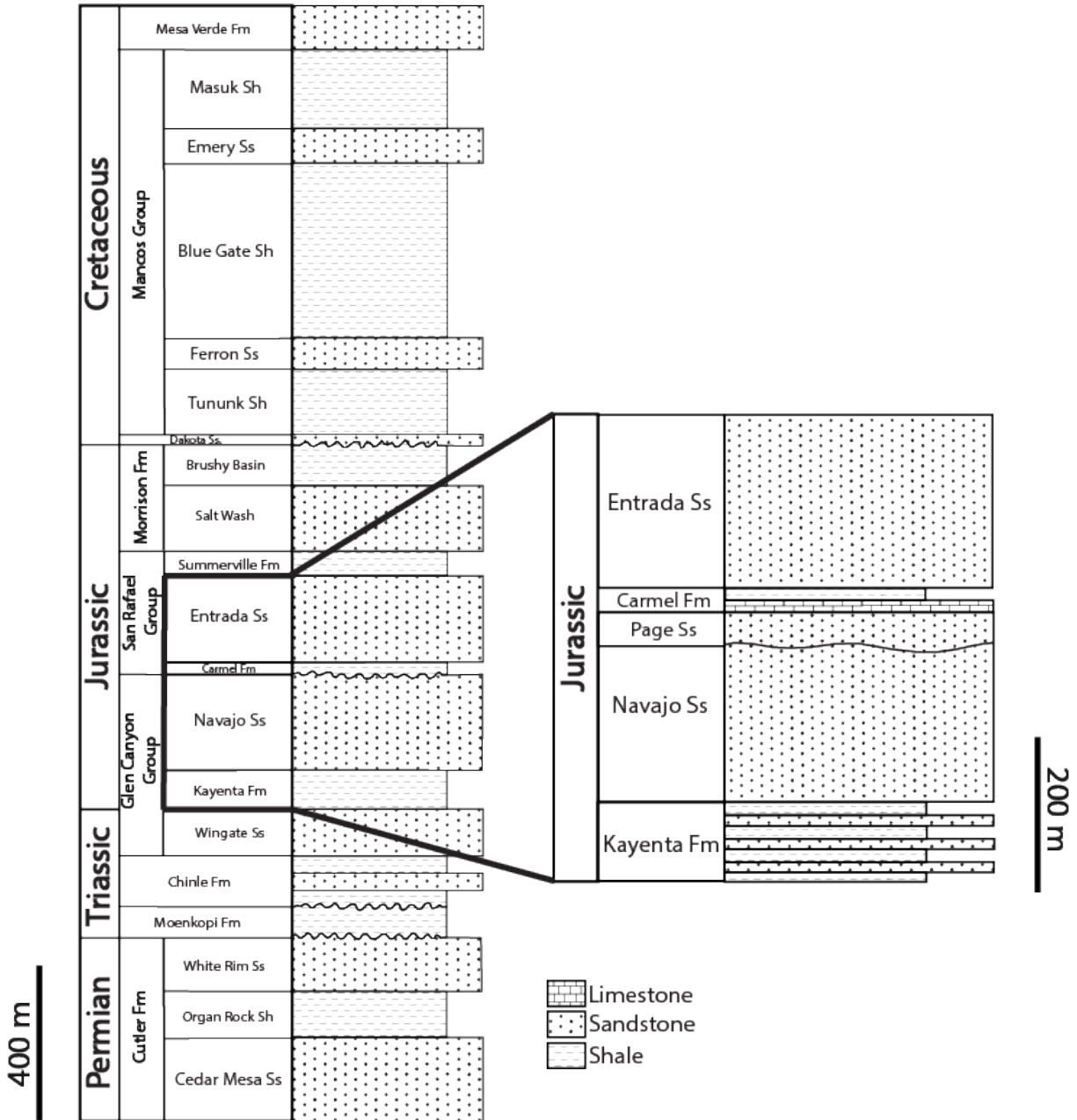


Figure 9: Simplified stratigraphic column of the Henry Mountains region of the Colorado Plateau. The specific stratigraphic column for the Pulpit Arch and surrounding area has been highlighted.

The Henry Mountains

The Henry Mountains are a group of five principal mountains, located on the Colorado Plateau in southeastern Utah. Each of these mountains formed due to the doming of sedimentary strata above a separate Oligocene-aged igneous intrusive center (Gilbert, 1877; Hunt et al., 1953; Jackson and Pollard, 1988). At each intrusive center, strata were deflected upward from a regional sub-horizontal dip by the emplacement of underlying magma bodies. Each intrusive center is built from sheet-like component igneous intrusions, which were emplaced incrementally (Horsman et al., 2005; Morgan et al., 2008; Horsman et al., 2010). Separate mountains preserve distinct stages of doming, and early-, mid-, and late- stage doming can be seen at Mt. Ellsworth, Mt. Hillers, and Mt. Ellen, respectively (Fig. 2A). In the late stages of main laccolith development, smaller, tongue-shaped intrusions can begin to radiate outward from the central body. For this study, the main focus area will be the Pulpit Arch, a small dome underlain by one of these satellite intrusions on the edge of Mt. Hillers.

Previous Work in the Henry Mountains

The earliest research in the Henry Mountains was concerned with both the geomorphology of the area and the intrusions present (Gilbert 1877). Gilbert (1877) concluded that each of the five peaks of the Henry Mountains is cored by a laccolithic intrusive center. As these laccoliths matured, smaller radial intrusions, also called satellite intrusions, would begin to form around the intrusive center, which resulted in complex laccolithic complexes centered on each peak. Based on a more thorough study, Hunt et al. (1953) suggested that each of the

mountains was cored by a large, cylindrical stock. They hypothesized that each stock expanded radially, which deformed the host rock and supplied surrounding satellite intrusions with magma. Immediately around the stocks existed a small, highly metamorphosed region that Hunt et al. (1953) called the shatter zone.

Johnson and Pollard (1973) studied laccolith growth in the Henry Mountains, expanding on Gilbert's (1877) work. They found that sills in the area had to spread over approximately 1 km before being to transition to laccoliths. At that point, the intrusion would have enough hydraulic leverage on the overburden to begin vertical expansion. Additionally, Johnson and Pollard (1973) suggested that magma driving pressures strong enough to cause uplift above intrusions did not necessarily have to be caused by tectonic events. Instead, the driving pressure is primarily controlled by the vertical extent of the feeder dike. Uplift could be further influenced by a significant difference in densities between an intrusive body and host rock. This density contrast would vary based on the physical properties of the magma and surrounding rock body, so laccolith growth would not necessarily be consistent across locations.

Pollard and Johnson (1973) further expanded on the process of sill-laccolith transition, and the resultant deformation, by examining intrusions in the Henry Mountains. Pollard and Johnson found that with decreasing depth, relative to the emplacement of the sill, the affect the intrusion has on the overburden decreases dramatically. Sills instead only feature local deformation, while rock at the surface would be largely unaffected. Pollard and Johnson (1973) calculated that sills must expand to a radial distance $\sim 3.2x$ that of the effective thickness of the overburden before the intrusion can begin to uplift overlying strata. This point acts as sill-laccolith transition, and laccolith growth is able to deform the entire overburden.

Later, Jackson and Pollard (1988) examined the region in detail to determine the geometry of the intrusive bodies. They noted the lack of buckle folds around the intrusions, which would have been caused by horizontal compression if a stock had radially expanded, as Hunt et al. (1953) hypothesized. Instead, each laccolith dome is a bending fold. Jackson and Pollard's (1988) data strongly support Gilbert's (1877) laccolithic model over the cylindrical stock model that Hunt et al. (1953) suggested.

Mt. Hillers

The laccolithic intrusive body that underlies Mt. Hillers (Fig. 10) has a diameter of ~ 13 km (Gilbert, 1877). Jackson and Pollard (1988) suggested that the Hillers laccolith had an estimated volume of 35 km^3 , and the sedimentary strata were deflected at least 2.5 km upward. There are numerous satellite intrusions surrounding the central Hillers body, including the focus of this project, the Pulpit Arch.

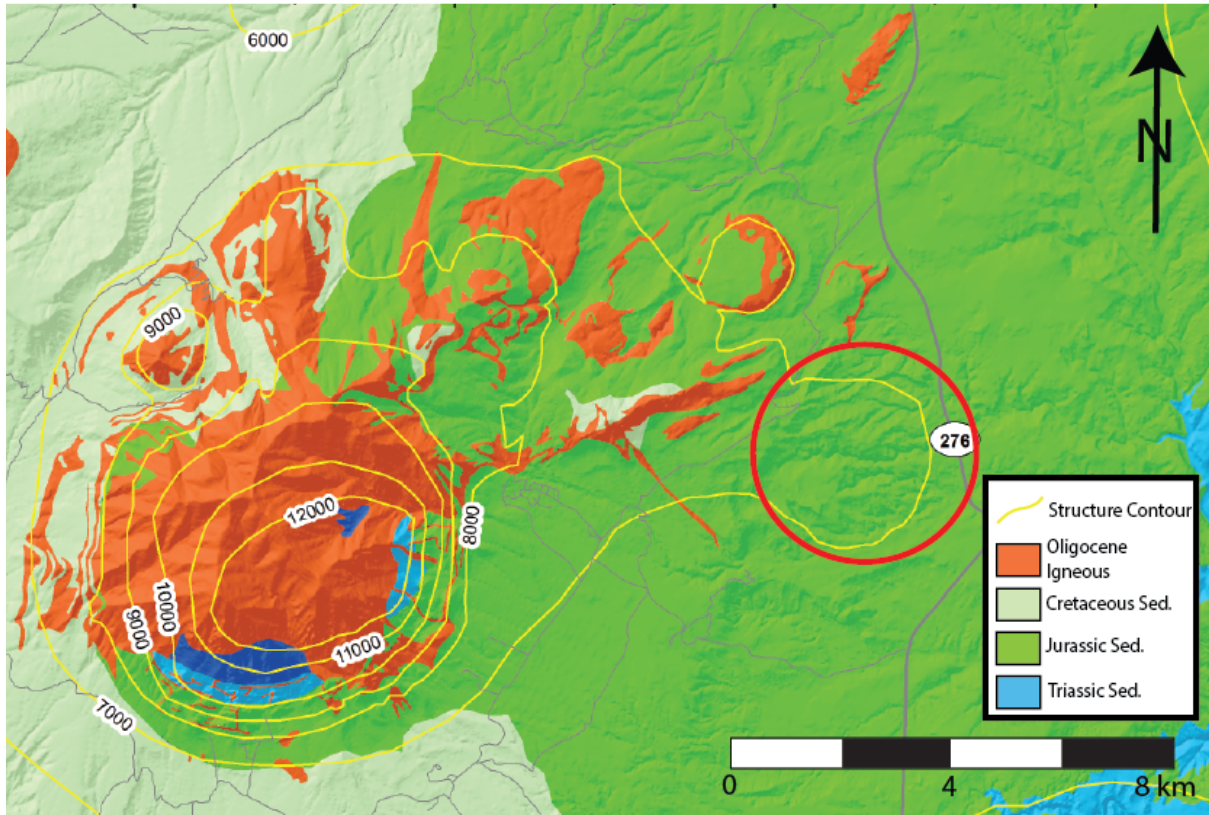


Figure 10: Structure contour map of Mt. Hillers (Modified from Horsman et al., 2017). The red circle corresponds to the Pulpit Arch.

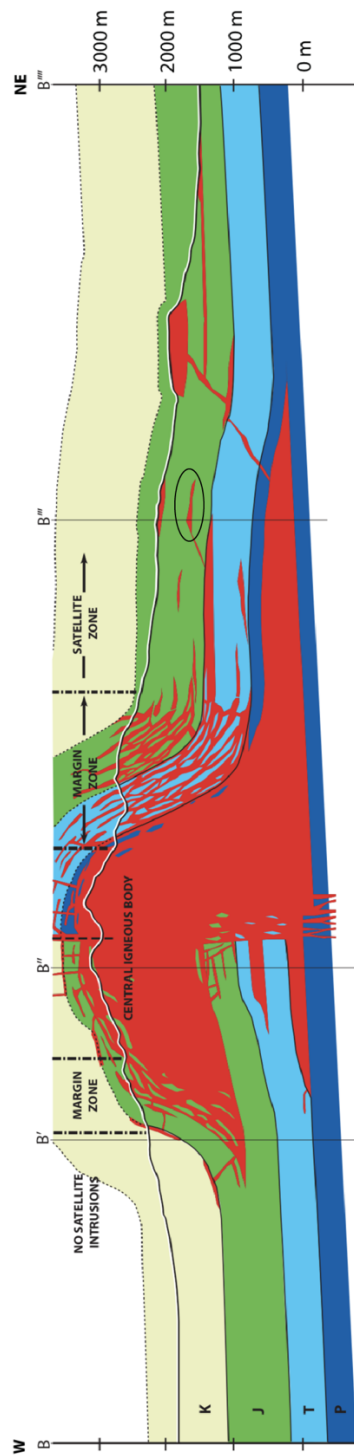


Figure 11: Cross section of Mt. Hillers. Note the satellite intrusions around the central laccolith (From Horsman, 2017). The focus of this project is host rock deformation above a buried intrusion, similar to the one circled.

The Pulpit Arch

The Pulpit Arch is an asymmetrical dome approximately 2.5 km in diameter located on the eastern side of Mt. Hillers (Fig. 2B). The dome is underlain by an unexposed satellite intrusion fed from the central Mt. Hillers igneous body (Fig. 11). The strata above the intrusion are deflected upward ~200 m. The magma body intruded from the northwest, and then inflated, resulting in the deformation of the sedimentary host rock. From the current shape of the Pulpit Arch, the first order geometry of the underlying intrusion is known, though the exact shape and depth of the intrusion is not well constrained. At the Pulpit Arch, the underlying intrusion is not exposed at the surface. Instead, the surface of the Pulpit Arch is entirely an area of domed sedimentary rock. Exposed units include the Jurassic Navajo Sandstone, Page Sandstone, Carmel Formation, and Entrada Sandstone (Fig. 12). Because the intrusion is not exposed at the surface, fracture characteristics can be mapped across the entire dome. The field area for this project is located exclusively within the Navajo Sandstone and is just the crest of a more extensive structure.

Outside of the fracture stations (Fig. 13) there are several large, map-scale fractures present in the Navajo Sandstone of the Pulpit Arch (Fig. 14). These features have a clearly visible NW to SE orientation in map view and no visible offset, and are classified as joints. In the field, these joints often appeared as steep drainages that dissected the rolling knobs of the Navajo. No smaller joints were seen in the Navajo of either site during field work.

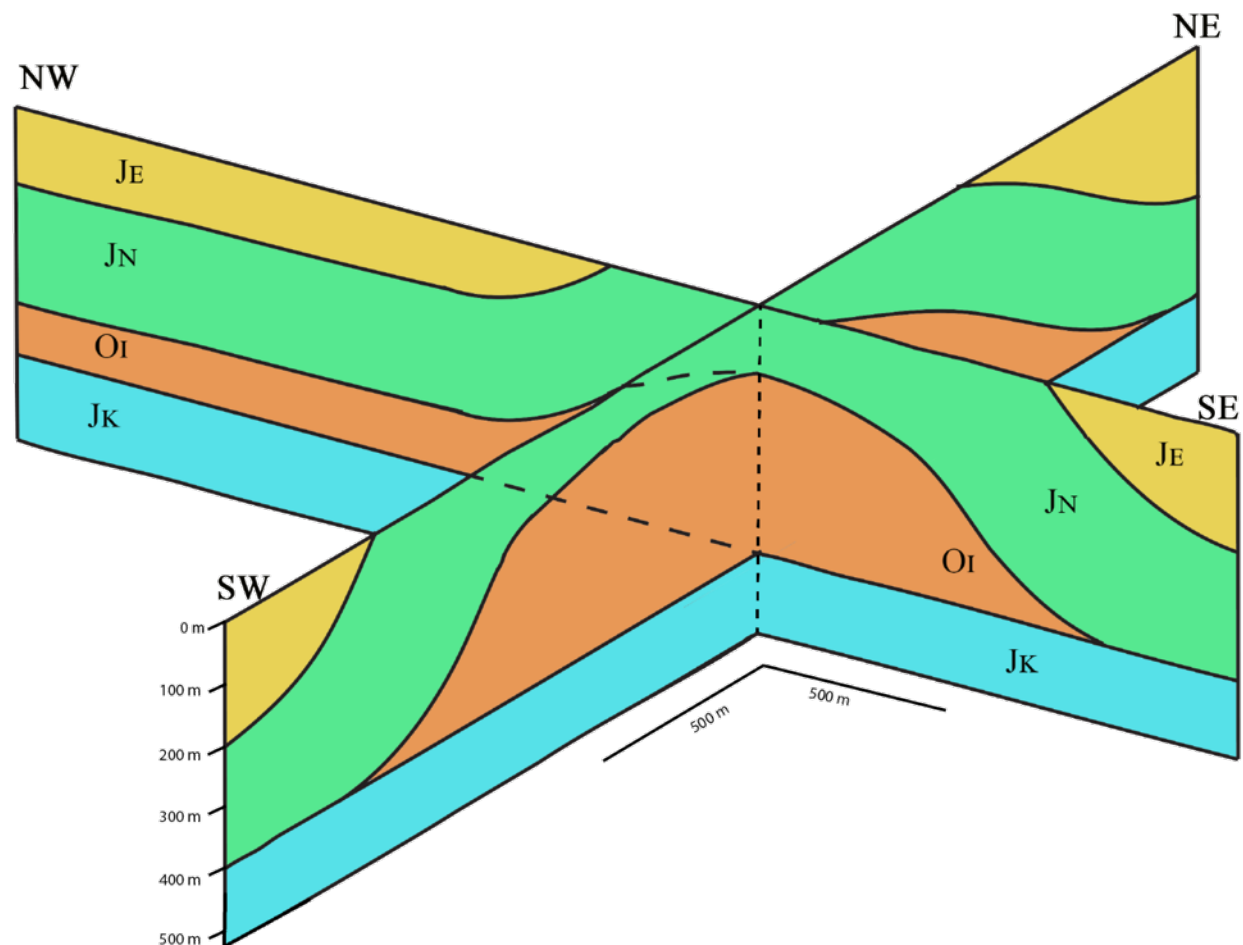


Figure 12: Schematic cross-sectional fence diagram of the Pulpit Arch. Geologic units represented are: JK, Kayenta Formation; JN, Navajo Sandstone; JE, Entrada Sandstone; and OI, Oligocene Igneous. Actual stratigraphic level of the emplacement of the igneous rock may be deeper than shown. Scales are approximate, 2x vertical exaggeration.

Note, upward deflection of strata shown here is greater than observed uplift of strata.

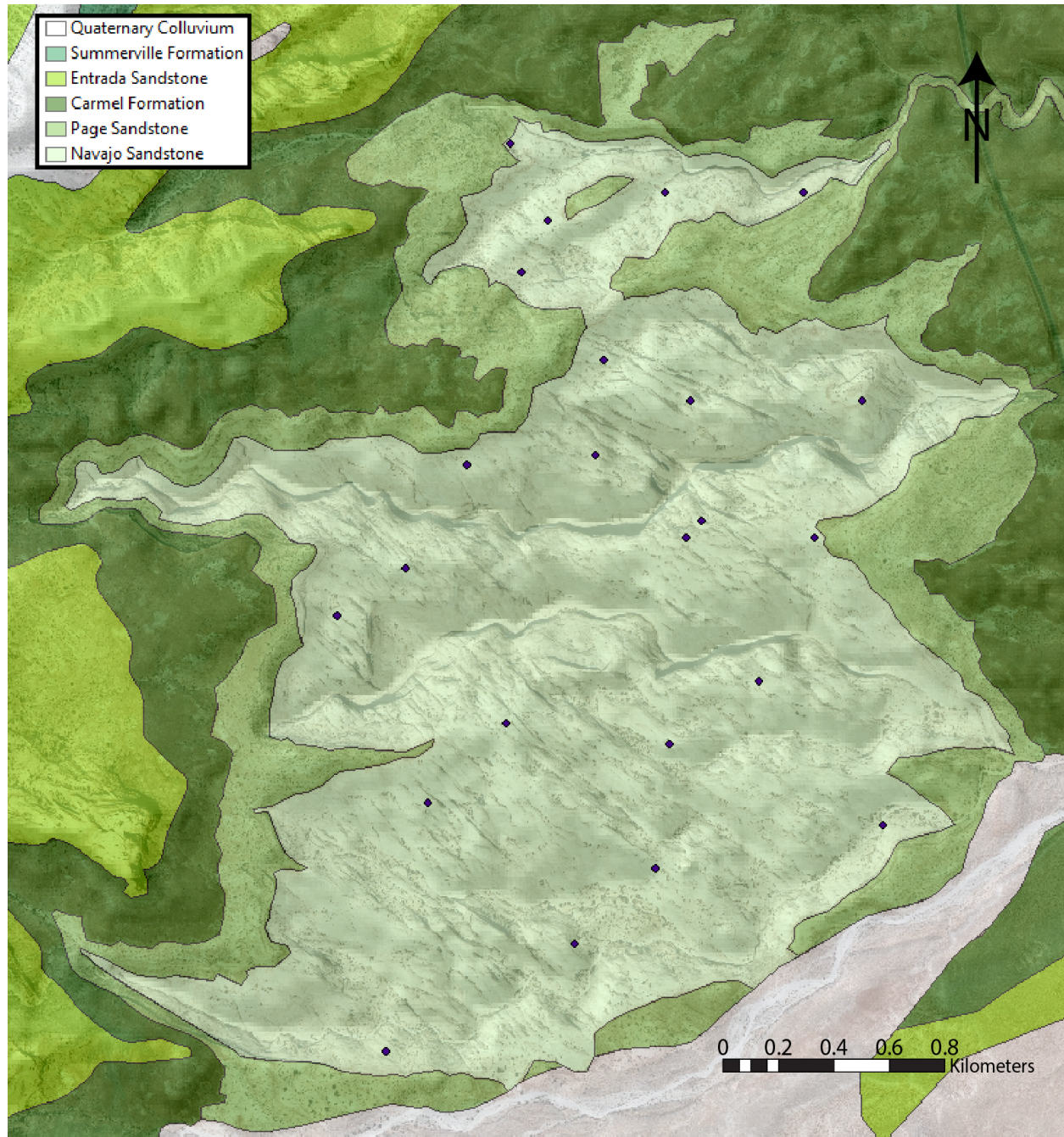


Figure 13: Geologic map of the Pulpit Arch. Blue dots represent fracture station locations.

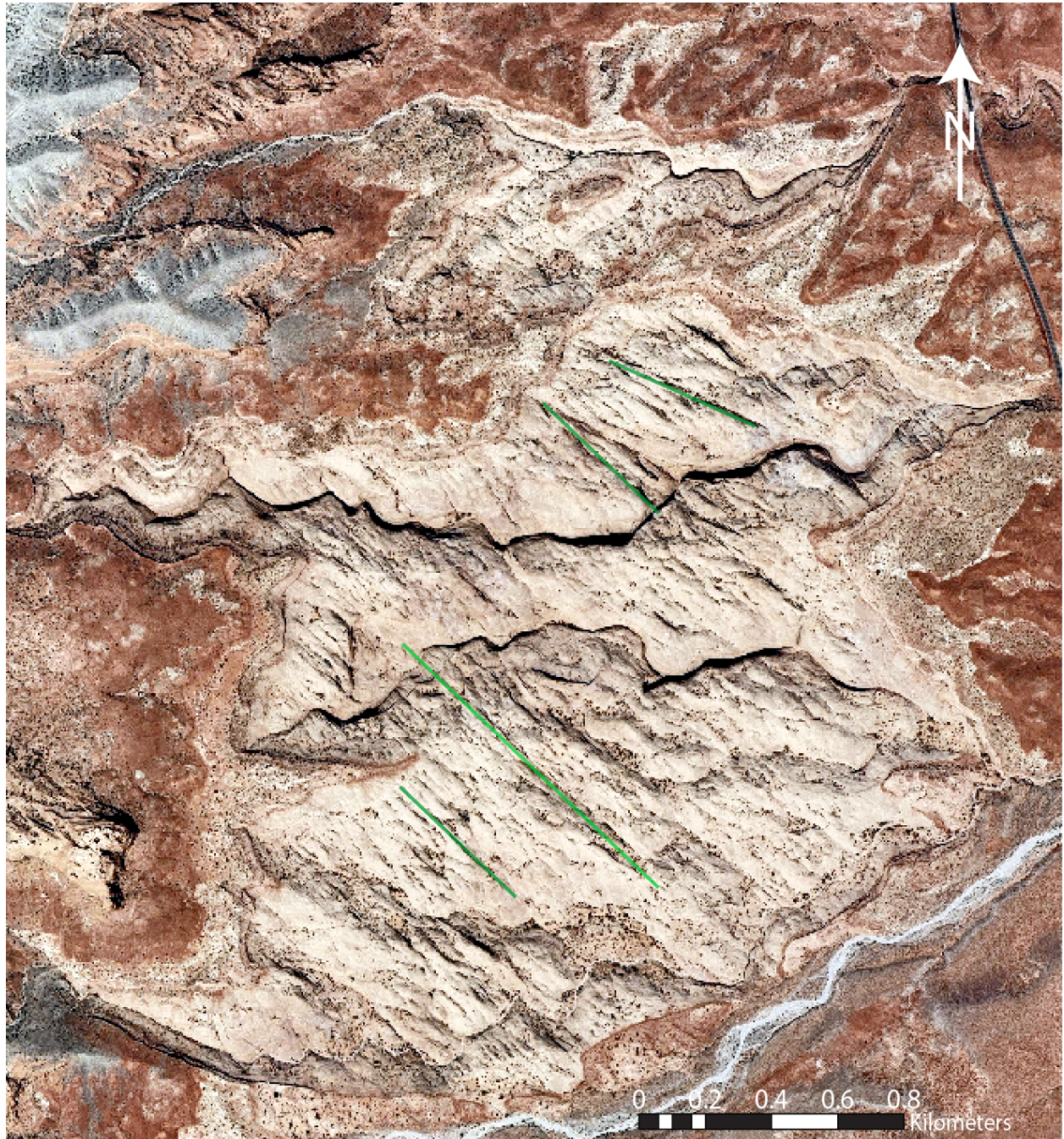


Figure 14: Aerial photograph of the Pulpit Arch. Note the many NW to SE oriented joints, some of which have been highlighted by the green lines. The Navajo Sandstone is distinguishable by its light-yellow coloring.

The Control Area

To act as a control for fracture patterns in the area, the closest location to the Pulpit Arch featuring unfolded subhorizontal Navajo was chosen as a control area (Fig. 15). By examining fracture characteristics found in the Navajo Sandstone in this area, fracture characteristics away from the Pulpit Arch can be identified. This will help better determine which fracture patterns seen in the Pulpit Arch are caused directly from the doming process. Other studies (e.g. Kelley and Clinton, 1960; Davis, 1999; Bump and Davis, 2003) have suggested that a regional fracture pattern does exist in the Colorado Plateau, generally trending NW - SE. This fracture pattern appears to be visible within the Pulpit Arch, as several meter-long fractures are visible in aerial views of the area (Fig. 14).

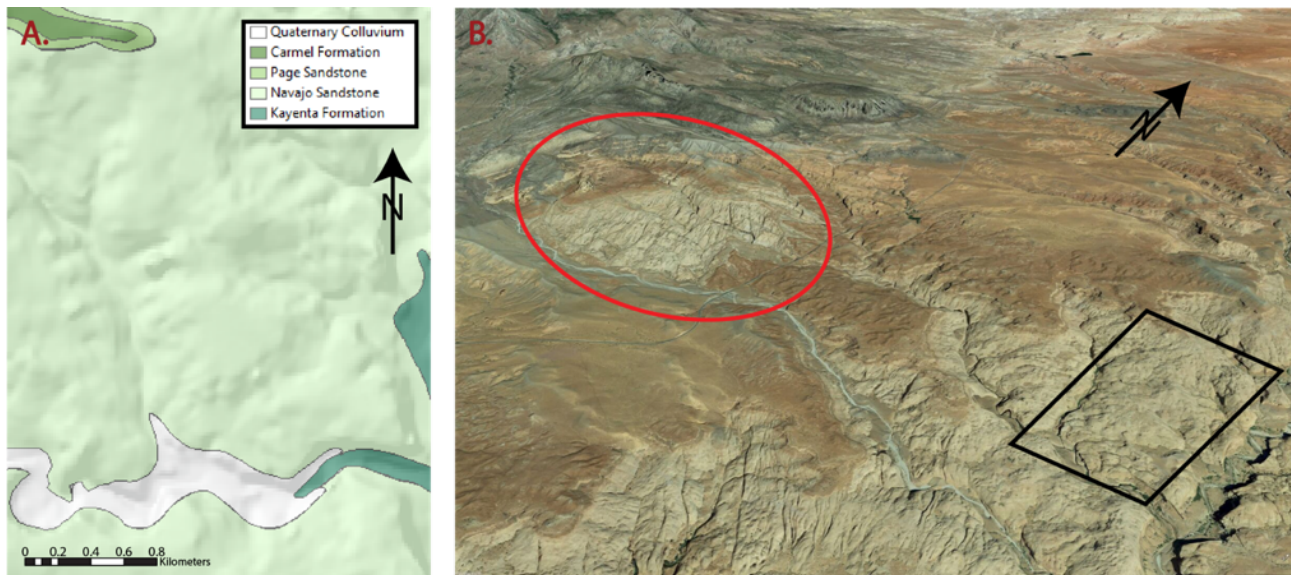


Figure 15: (A) Geologic map of the nearby control area. (B) Oblique aerial photograph of both field areas, the location of the Pulpit Arch field area is marked by the red circle. The black box roughly corresponds to the location of the control area. The red circle has a diameter of approximately 2 km. Photo from Google Earth.

The Navajo Sandstone

This project focuses on data collected from one sedimentary unit, the Navajo sandstone. The Navajo Sandstone is a Jurassic-aged, massive, cross-bedded, highly porous, aeolian sandstone (Fig. 16). The Navajo Sandstone is present throughout much of the Colorado Plateau. In the Henry Mountains, the Navajo overlies the Kayenta Formation, a maroon sandstone with lenticular shale beds present throughout (Hunt et al., 1953). The Navajo is overlain in this region by the Page Sandstone, a thin, reddish sandstone. Further above the Navajo are the Carmel Formation, an orange-brown shale and limestone unit, and the Entrada Sandstone, a vibrant orange unit found throughout the Colorado Plateau (Table 1).

Lithologically, the Navajo is primarily arkose and quartz arenite. It is a fine-grained, well to moderately well-sorted, and mature sandstone. Outside of some slight variation in color, the Navajo Sandstone does not vary lithologically. Mineralogy, grain size, and sorting remain consistent across the extent of the Navajo (Uygur and Picard, 1980). The thickness of the Navajo varies across the Colorado Plateau, but is ~200 m thick within the field areas. The Navajo Sandstone features meter-scale cross-beds, and average porosity of 14%, though the value can range from ~10% to ~19% across different locations (Uygur and Picard, 1980). In porous sandstones like the Navajo, the primary type of fractures to form are commonly deformation bands (Fossen, 2007; Fossen and Bale, 2007).

Due to its relative homogeneity, the Navajo was chosen as the focus for field work. Examining a single, homogeneous body prevented any potential variation that lithological differences between units may have on fracture development. The lack of significant lithological variation within the Navajo also meant mechanical characteristics would have been consistent throughout the field area prior to folding. Uygur and Picard (1980) identified the Navajo Sandstone as a good analogue for a reservoir rock. This suggests that any analysis completed on the Navajo Sandstone could be applied to other bodies that may hold important fluid resources.



Figure 16: Field photograph of the Navajo Sandstone. Paleohorizontal bedding surfaces are indicated by the red lines. Note the visible cross-bedding.

Generalized section of sedimentary rocks exposed in the Henry Mountains region—Continued

System	Series	Group, formation, and member		Thickness (feet)	Lithology
Jurassic.	Upper Jurassic.	San Rafael group.	Summerville formation.	40-250	Evenly bedded, reddish-brown sandstone and sandy shale; minor amounts of greenish-white sandstone, gypsum and limestone.
			Curtis formation.	0-175	Evenly bedded gray sandstone and shaly sandstone, glauconitic(?), numerous siliceous geodes and concretions at some places. Local thin basal conglomerate; marine.
			—Unconformity—		
			Entrada sandstone.	300-700	Thick-bedded and cross-bedded buff sandstone; weathers in rounded forms; thinner bedded earthy sandstone to north; forms flat sandy areas.
Jurassic(?).		Glen Canyon group.	Carmel formation.	100-626	Thin-bedded red sandstone, shaly sandstone and shale; thin limestone and, in northwest part of the area, thick beds of gypsum.
			—Unconformity—		
			Navajo sandstone.	515-815	Tan to light-gray, massive, cross-bedded sandstone; thin lenses of limestone.
			Kayenta formation.	240-320	Red sandstone and shaly sandstone, well-bedded; some cross bedding; minor amounts of red shale and green clay.
			Wingate sandstone.	270-380	Red and buff, cross-bedded sandstone; cliff-maker.
			—Unconformity—		

Table 1: Stratigraphic column of Jurassic sedimentary rocks in the Henry Mountains. (From Hunt et al., 1953)

Methodology

For this project, both field and laboratory methods were used to identify and quantify fracture characteristics, quantify folding of the strata, and determine lithology in the Pulpit Arch and control area. The same field and laboratory methods were used for data collection and analysis within both field areas.

Field Methodology

The Navajo Sandstone on the Pulpit Arch is exposed as large, rolling knobs of rock. Vegetation is sparse, and the area is dissected by several deep, narrow canyons. The Navajo features large, meter-scale aeolian cross-bedding, and paleohorizontal main bedding surfaces are difficult to see up close. Instead, these features were best viewed from a distance (e.g. Fig. 16). While a majority of the field site was accessible, the topography of the area made some sections of the dome difficult or likely impossible to reach without protective gear. The control area was topographically similar, but a more expansive exposure of the Navajo allowed the area to be more easily traversed.

While in the control area, the stratigraphic section of the Navajo Sandstone was measured. This allowed any lithologic variation that occurred throughout the Navajo to be noted, which allowed for more accurate estimation of stratigraphic depth while in the Pulpit Arch.

Due to field work in the Pulpit Arch taking place stratigraphically close to the Navajo/Page contact, the location of this contact was recorded while in the field. Accurate

measurement of this contact allowed for the geologic maps of the units exposed on the crest of the dome originally mapped by Hunt et al. (1953) and Larson et al. (1985) to be updated.

In total, 46 stations were established in both field areas, with 27 of those being fracture stations. The remaining 19 stations were established to record bedding measurements, pinpoint the Navajo/Page contact, or both where clear bedding was visible. Bedding plane data were collected by extending the plane with a field notebook, then measured with a Brunton compass. Multiple bedding measurements were recorded at each station. Some large-scale bedding measurements were collected away from the fracture stations at inaccessible areas along the extent of Navajo exposure through the use of the StereonetMobile program for iPad.

Samples of the Navajo Sandstone were collected at each fracture station to be made into thin sections for laboratory analysis. Each sample included fractures, if any were present at the station. Photographs of each field site were taken for lab fracture analysis. At each station, stratigraphic position within the Navajo was estimated relative to the Navajo-Page contact.

Fracture Measurement

The principal field method of data collection for this project was measurement and characterization of fractures across the field areas. To do this, fracture stations were established in both field areas. Criteria for determining location of stations was different for each field area, but each station was located on an approximately horizontal outcrop surface. In total, 23 fracture stations were placed in the Pulpit Arch, and 4 were placed in the control area.

Within the Pulpit Arch, stations were placed as homogenously as possible throughout the dome, to maximize coverage of the exposed Navajo Sandstone. Locations were chosen by

proximity to other fracture stations, and exposure of the Navajo. On average, stations were spaced ~300 m away from one another. However, some areas were not accessible due to several large, deep canyons present in the area, which resulted in some clustering of stations. These stations were all estimated to be at a depth within 50 m from the stratigraphic top of the Navajo. Areas stratigraphically deeper within Navajo were searched for, but either did not offer a suitable area to collect data or were inaccessible.

In the control area, stations were established at specific stratigraphic intervals. This allowed for fracture characteristics at various stratigraphic positions within the Navajo Sandstone to be recorded. Studies of stratigraphy in this area (Hunt et al., 1953) suggest the Navajo's thickness is ~200 m, and the stratigraphic section measured during this study agrees with this. Stations were placed at ~50 m intervals of stratigraphic position, with varying lateral distances between one another.

At each station, location data was collected using a handheld GPS device and the iGIS program for iPad. Once an accurate location was determined, a rope was used to delineate a square 16 m² station area. The full 16 m² station was divided into 4 smaller, equal-area quadrants, labeled A, B, C, and D. In locations with exceptionally high fracture intensity or where terrain did not allow for the placement of a full-sized station, a single 4 m² square was used. This allowed for area to be normalized.

At each fracture station, all fractures with length equal to or greater than 10 cm were measured and the following characteristics were recorded: type of fracture, planarity of fracture, fracture orientation, fracture length, style of termination of the fracture, and the presence of cross-cutting relationships. Each of these terms is explicitly defined in subsequent pages. If

cross-cutting fractures were present, the amount of separation, measured in centimeters, was also recorded.

Prior to the individual fracture measurements, the overall station was examined for the presence of fracture sets. The station was examined as a whole, to determine if any fractures had similar orientations. If sets were present, the approximate orientation of the fracture set and the number of fractures in that set were recorded, then that fracture set was assigned a number (Set 1, Set 2, etc.). No station had more than 3 fracture sets present. At some stations, fractures that did belong to any set were also present. These fractures were noted and referred to as isolated fractures.

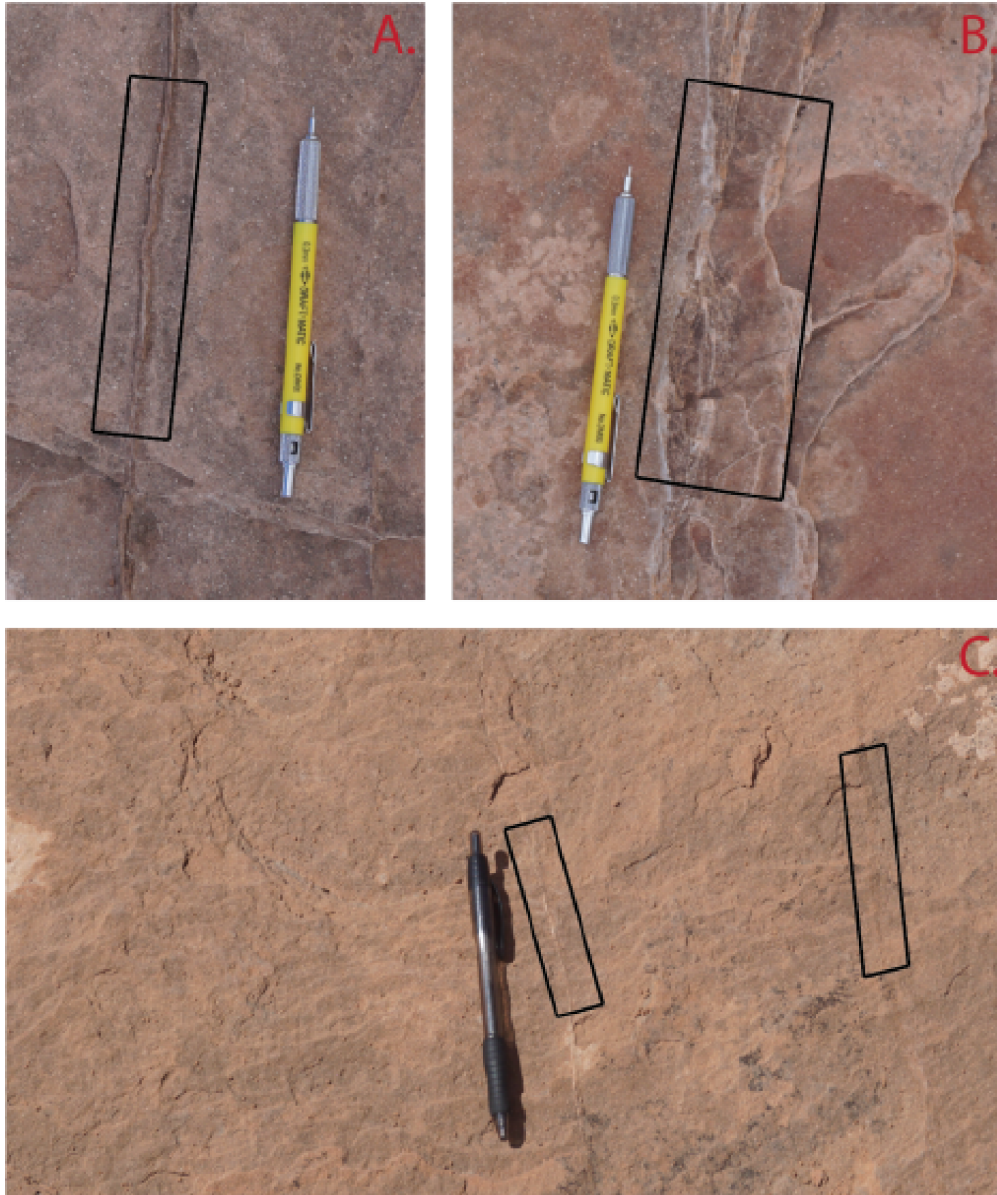


Figure 17: Typical examples of the three deformation band types seen in the field. (A) A single deformation band (SDB). (B) A cluster deformation band (CDB). (C) Two proto deformation bands (PDB). Note the visibility of PDBs compared to that of a typical SDB or CDB.

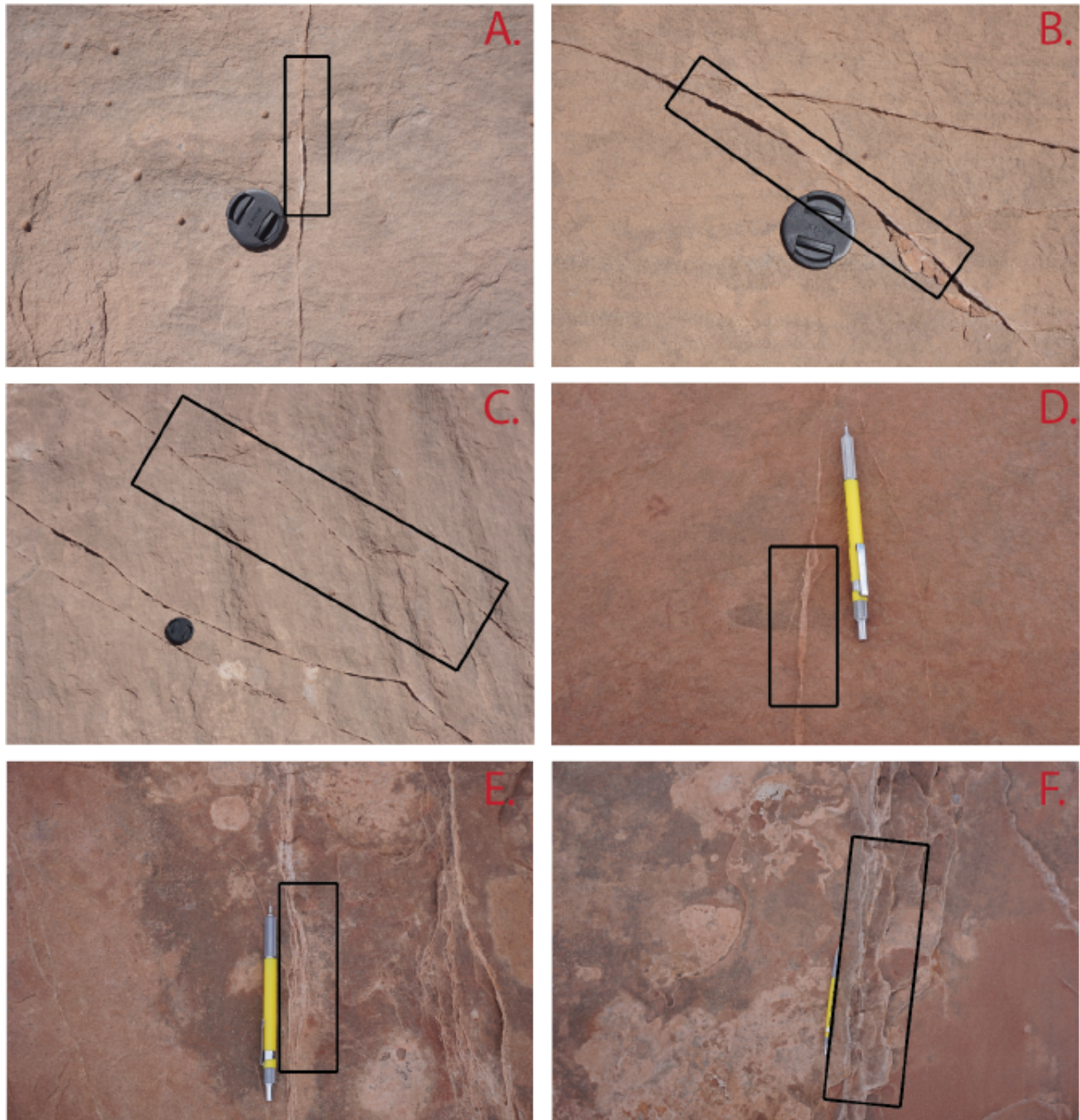


Figure 18: Examples of different characteristics of deformation bands observed in the field. (A) SDB with planarity value of 1. (B) SDB with planarity value of 2. (C) SDB with planarity value of 3. (D) CDB with clustering value of 1 and planarity value of 1. (E) CDB with clustering value of 2 and planarity value of 2. (F) CDB with clustering value of 3 and planarity value of 1.

Within both field areas, fracture types observed were exclusively cataclastic deformation bands. Deformation bands were distinguished into three major categories: single deformation bands, cluster deformation bands, and proto-deformation bands (Fig. 17). Single deformation bands (SDB) were classified as deformation bands that existed as individual fractures (Fig. 17A).

Cluster deformation bands (CDB) were identified as tightly grouped deformation bands that all had the same general orientation (Fig. 17B). CDBs were classified by how tightly the individual deformation bands clustered using a qualitative scale ranging between 1 and 3. A CDB with clustering of 1 represented a tightly packed group, and was often referred to as a “planar” cluster. A clustering of 3 represented a broadly spaced group of deformation bands and was referred to as an “anastomosing” cluster (Fig. 18F). A CDB with clustering of 2 represented a deformation band cluster with an intermediate geometry.

Proto-deformation bands (PDB), were identified as faint and planar deformation bands (Fig. 17C). These deformation bands may have been in early stages of development, which could explain their faintness and simple geometries. PDBs were observed at only a single fracture station in the control area, and not observed in the Pulpit Arch. All of the proto-deformation bands recorded were individual bands.

Like clustering, planarity was recorded on a qualitative scale ranging from 1 to 3 (Fig. 18). This scale was applied to all types of deformation bands. A fracture or fracture cluster with a recorded planarity of 1 was planar, indicating no angular change across its length. A fracture with recorded planarity of 3 was curved, indicating relatively intense ($\geq 10^\circ$) angular change over its length. A measurement of 2 reflected a fracture or fracture cluster not explicitly planar

or curved. Often, planarity of 2 was used for fractures that were not planar, but featured a relatively low angular (between 0° and 10°) change over its length.

Style of fracture termination was divided into three categories: Border (B), in which the fracture extended into contact with the limits of the fracture station; truncation (T), in which a fracture truncated into another fracture present within the fracture station; and end (E), in which the fracture ended within the fracture station. If a fracture was observed as terminating via truncation, the fracture set against which the interpreted younger fracture set terminated was recorded.

Laboratory Methods

Several laboratory methods were used to analyze and interpret the field data, including mapping in ArcGIS, extension calculation across the Pulpit Arch, fracture analysis, and thin section petrography. Each of these methods is described in this section.

Creation of Geologic Maps

To better constrain the extent of the Navajo Sandstone within the field area, the location of the contacts between stratigraphic units exposed on the crest of the Pulpit Arch was re-mapped. GPS coordinates of fracture stations were imported into ArcGIS. These points were joined to a pre-existing geologic map (Larson et al., 1985) of the area. Using the locations of these data points, the contacts were moved to better represent field observations. Other data

values for each station, such as bedding orientation and estimated stratigraphic depth, were used to produce various maps of the area and conduct subsequent spatial analysis.

A 10 Meter Digital Elevation Model (DEM) of the Pulpit Arch was downloaded from the Utah Automated Geographic Reference Center. Elevation values along the Navajo/Page Contact were extracted from this DEM combined with estimates of stratigraphic depth in the Navajo from each fracture station in ArcGIS. This field produced an approximate structure contour map of the Navajo/Page contact prior to erosion. This contour map was then used to create a curvature map of the Navajo exposure in the Pulpit Arch.

The updated location of the Navajo/Page contact in the Pulpit Arch, mapped from field observations, and the known stratigraphic thickness of geologic units in the area allowed for two cross sections of the Pulpit Arch to be created. One cross section was created parallel to the inferred direction the intrusion was emplaced (i.e. NW to SE), and another was created perpendicular to the emplacement direction (i.e. NE to SW).

Strain Analysis

Extension was also calculated along four transects across the Pulpit Arch using the equation:

$$e = \frac{l_f - l_i}{l_i}$$

where e is total extension, l_f is final length, and l_i is the initial length. The ground length along each transect was measured for the l_i value, and the magnitude of deflection in the area, ~200 m,

represented two limbs of a right triangle. The hypotenuse, the l_f value, was calculated using the Pythagorean Theorem. Jackson and Pollard (1990) previously calculated extension along the tops and peripheries of several first-order domes in the Henry Mountains. They found that inferred strain components at the crests of domes were compressional, while the values near the peripheries were extensional. The field area for this study, the Navajo Sandstone exposure on the Pulpit Arch, has been hypothesized to lie entirely within the crest of the dome. If this is true, the extension values calculated here should all be negative, reflecting the shortening produced during folding.

Fracture Analysis

Photographs taken of each fracture station and fracture measurements collected at each station were both analyzed in the laboratory. Fracture station photographs were digitized to create accurate representations of each station that were not skewed by the angle of photographs taken in the field. Photographs of each quadrant of a selected fracture station were uploaded into Adobe Illustrator. Individual images of the quadrants were merged together to create a single, cohesive image of each fracture station. Each fracture was traced to produce a corresponding polyline. The station border trapezoid and traced polylines were scaled in Adobe Illustrator, and the trapezoid restored to a square, reflecting the original geometry of the fracture station. Scaling the traced polylines allowed for the fracture traces to be corrected to their original geometries. The polylines were saved as a scalable vector graphics (.svg) file for further analysis in FracPaQ. This process (Fig. 19) was repeated for each fracture station.

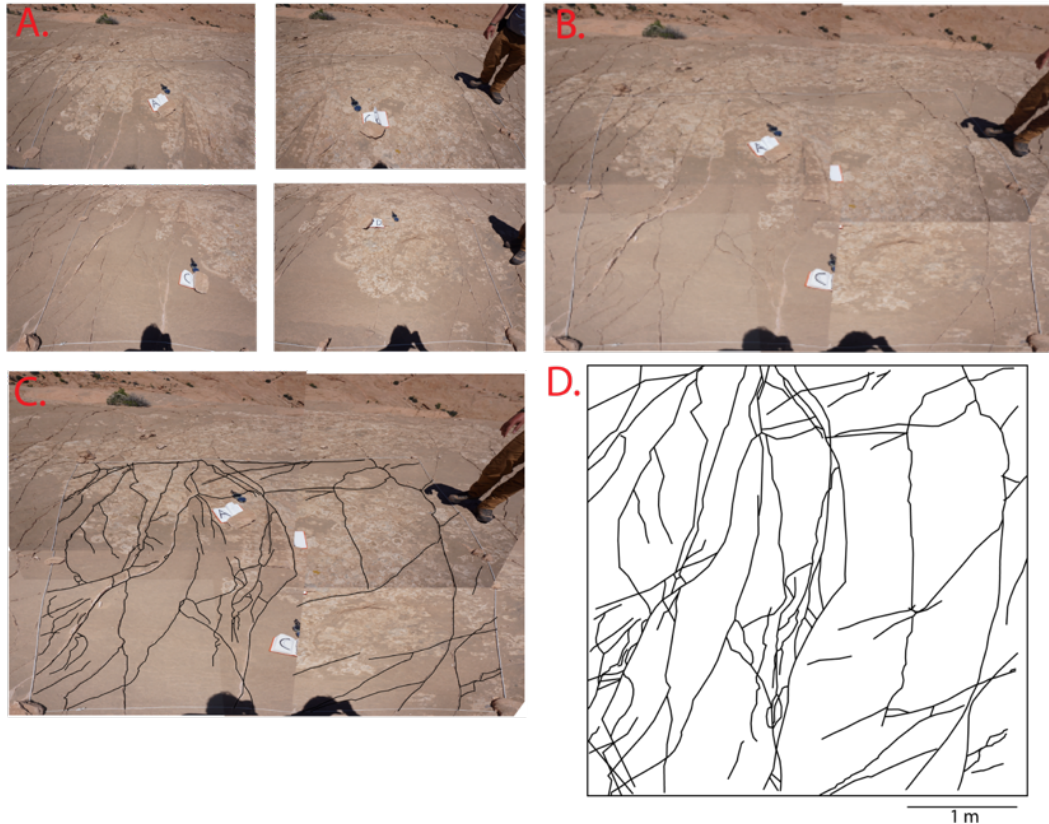


Figure 19: Workflow for the creation of fracture trace polyline files. (A) Images of each quadrant are uploaded into Adobe Illustrator. (B) The images are scaled and joined together to form a single image of the fracture station. (C) Polygons are traced over the fractures at each station. (D) Once tracing is completed, polygons are scaled and saved as a .svg file for future analysis.

The .svg file for each fracture station then uploaded through the FracPaQ program developed by Healy et al. (2017). The purpose of the program is to quantify fracture patterns from a two-dimensional image, and produce figures and graphs based on this data. FracPaQ assumes that the fracture polylines lie on a two-dimensional surface, meaning that fractures are not corrected for variation in topography. For this reason, all field measurement stations were located on approximately planar outcrops. The program is designed to be user-friendly, allowing the user to quickly choose which fracture characteristics are desired for output. Input data can be

either an image file or a text file, and FracPaQ is able to quantify fracture characteristics such as fracture length, orientation, intensity, density, connectivity, and permeability (Healy et al., 2017).

In order to examine variation of fracture intensity across the dome, fracture intensity needs to be defined. Previous workers have defined fracture intensity with various parameters. For this project, the definition of Dershowitz and Herda (1992) was used. Dershowitz and Herda (1992) defined fracture intensity measurements in one, two, and three dimensions, both by dimensionality of the fracture and the dimensionality of the measurement area. Fracture intensity was characterized by the notation P_{xy} . P represents persistence, the subscript x represents dimensionality of the region of measurement, and the subscript y represents dimensionality of the fractures. Using this notation, fracture intensity can be characterized in several ways:

- P_{10} : Linear fracture intensity, the number of fractures per unit length (L^{-1})
- P_{20} : Areal fracture intensity, the number of fractures per unit area (L^{-2})
- P_{30} : Volumetric fracture intensity, the number of fractures per unit volume (L^{-3})
- P_{21} : Areal fracture intensity, the length of fractures per unit area (L^{-1})
- P_{32} : Volumetric fracture intensity, the area of fractures per unit volume (L^{-1})
- P_{33} : Fracture porosity, the volume of fractures per unit volume (dimensionless)

Generally, fracture measurements per unit volume (P_{30} , P_{32} , or P_{33}) would be best to interpret porosity from fracture intensity, due to the measurements being made over a three-dimensional surface. However, field measurement of 3-D fracture populations is commonly impractical or impossible. For this project, fracture measurements were collected per unit area, meaning P_{20} or

P₂₁ would be the best potential ways to measure fracture intensity. Of the six theoretical frameworks developed by Dershowitz and Herda (1992), P₁₀, P₂₁, and P₃₂ are not dependent on orientation or scale. From this, P₂₁ can be determined as the best method of measuring fracture intensity for this project. The resultant measurements are independent of scale, meaning they could be more easily compared to measurements collected in different locations. For this project, fracture intensity was calculated using the equation:

$$I = \frac{L}{A}$$

where I is estimated fracture intensity, L is the total fracture length at a given station, and A is the area for the respective station.

Thin Section Analysis

Thin section analysis was conducted for this project to more thoroughly examine porosity variation caused by deformation. Other studies (e.g. Chayes and Faribairn, 1951; Ehrlich et al., 1984; Iscan et al., 2009) have determined porosity values in sandstones by examining high quality petrographic images. For this project, 10 samples collected from various fracture stations were sent to Vancouver Petrographics for thin section production. The samples selected allowed for porosity measurements to be calculated across the Navajo exposure of the Pulpit Arch. Each thin section accounted for an approximately 1,242 mm² area of the sample. Each sample was impregnated with blue epoxy to highlight pore space in the rock.

Of the 10 samples, 8 were chosen from within the Pulpit Arch, and 2 were selected from the control area. Samples from the Pulpit Arch were used to measure porosity variation in deformation bands and deformed sandstones, while samples from the control area were used to measure porosity in undeformed sandstone. 6 of the 8 Pulpit Arch samples included visible deformation bands within the thin section. In these 6 samples, porosity was measured both within the fractures and away from the fractures to ascertain the differences between the two.

For each sample, the entire thin section was photographed at high resolution using a petrographic microscope. Sections of each image were isolated (Fig. 20) to compare deformation bands against areas lacking deformation bands. Each image segment was processed using color thresholding with the ImageJ software, manipulating hue, saturation, and brightness thresholds on the image to select only blue colors (Fig. 21). The percentage of blue colors in the image (i.e. the percentage of pore space in the sample), was calculated by comparing the number of blue pixels with the total number of pixels in each image. The percentage porosity of each photomicrograph segment was averaged to calculate the approximate porosity of the entire photomicrograph. Some photomicrographs were taken with different lighting, so the color thresholding values were modified slightly to account for this variation.

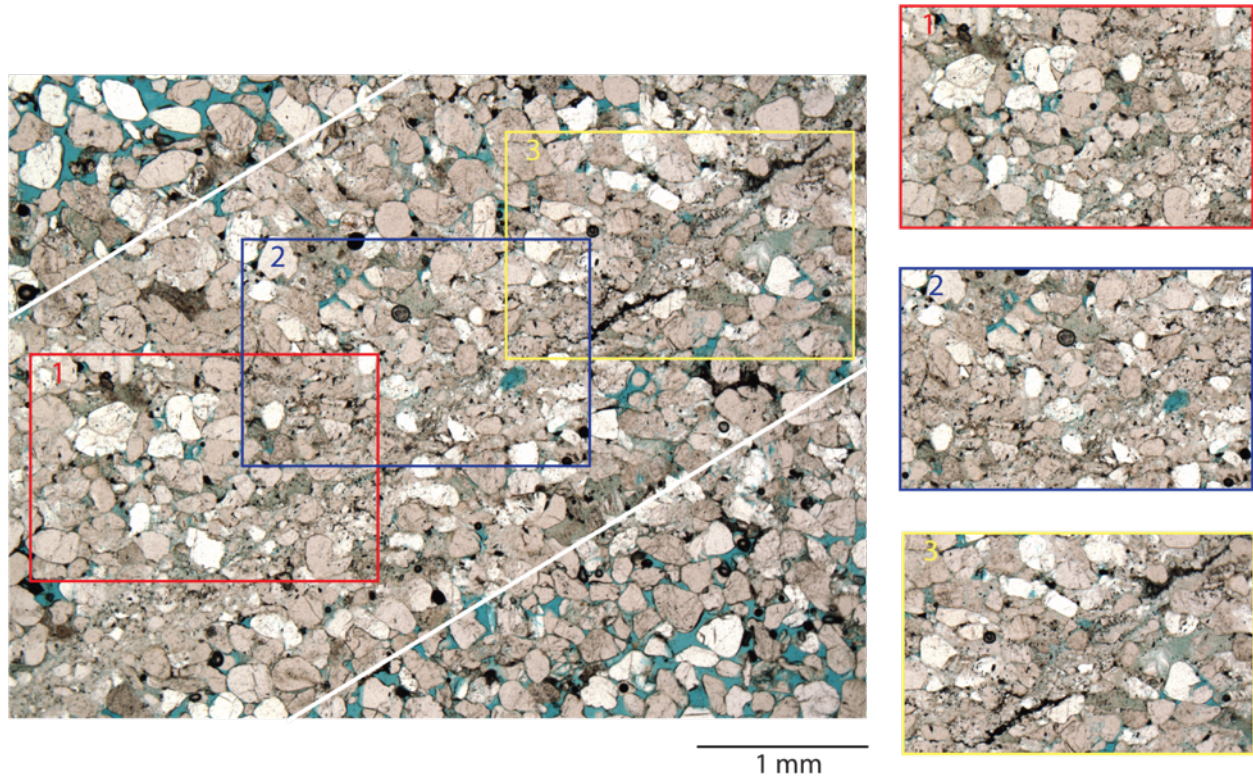


Figure 20: Example of photomicrograph segmenting. The general extent of the deformation band in the above photomicrograph is indicated by the white lines. Segments 1, 2, and 3 were created to prevent areas outside of the deformation band from influencing porosity measurements.

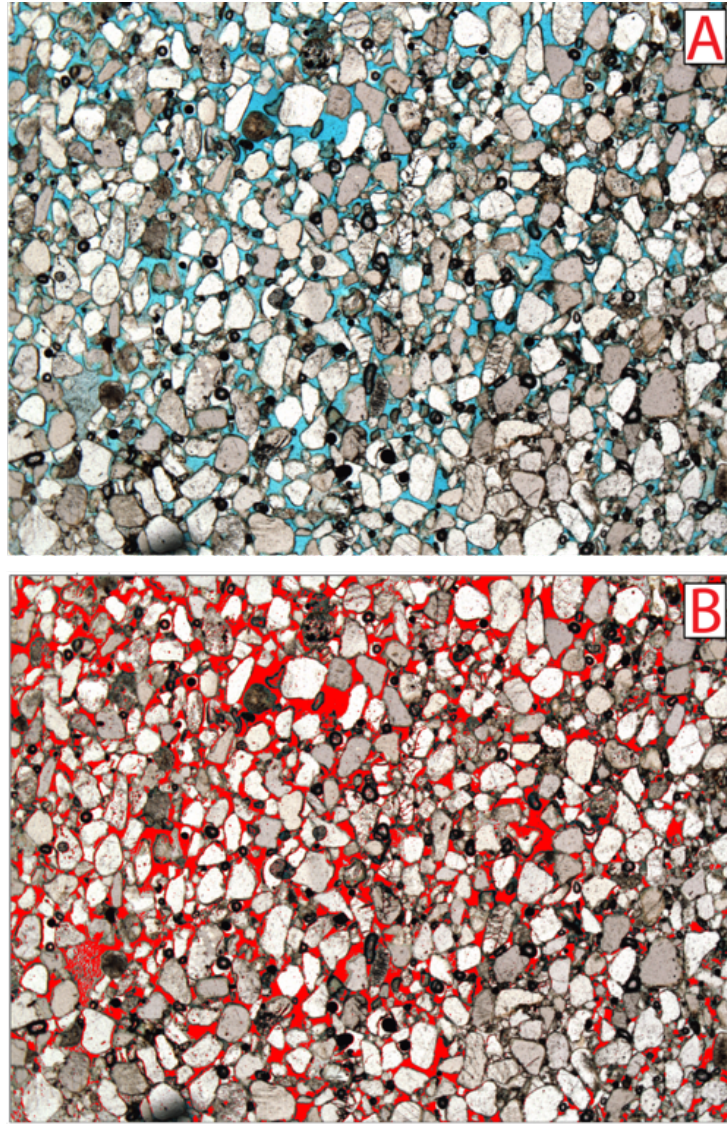


Figure 21: Color thresholding procedure for thin sections. (A) The unaltered photomicrograph. (B) The blue pixels, indicated by the red color, are highlighted through thresholding.

Results

Construction of the Geologic Map and Cross Sections

Prior to arrival to the field areas, geologic maps of the region (Hunt et al., 1953; Larson et al., 1985) were examined to gain general knowledge of the extent of the Navajo. This existing map of the area, which covered both field sites (Fig. 22) was updated to more accurately reflect the location of the contacts between sedimentary units in the area (Fig. 23). Though the Page Sandstone is present in this area, it is absent in other regions where the Navajo is found and is sometimes considered to be part of the Navajo Sandstone in literature (Peterson and Pippingos, 1979). The updated contact was also used to make two cross sections through the Pulpit Arch region (Fig. 25). These cross sections were constructed, along a NW to SE transect (Fig. 25) and a NE to SW transect (Fig. 26).

Upon arrival to the field site, the differences between the Navajo and the Page were distinct, and the contact between the two was clear (Fig. 27). In both field sites, the Navajo was a massively bedded sandstone with color ranging from yellow to tan. Though drainages in the Pulpit Arch results in steep canyons in the area, the Navajo generally erodes to form large, gently-sloped knobs. The Page outcrops as a darker, reddish-brown color. The unit is relatively thin (~ 10-15 m), and it occasionally erodes into knobs like those formed by the Navajo. More often, the Page erodes into cliffs, which stands out atop the gentler slopes of the Navajo. The stark difference between the two units allows location of the contact to be relatively straightforward.

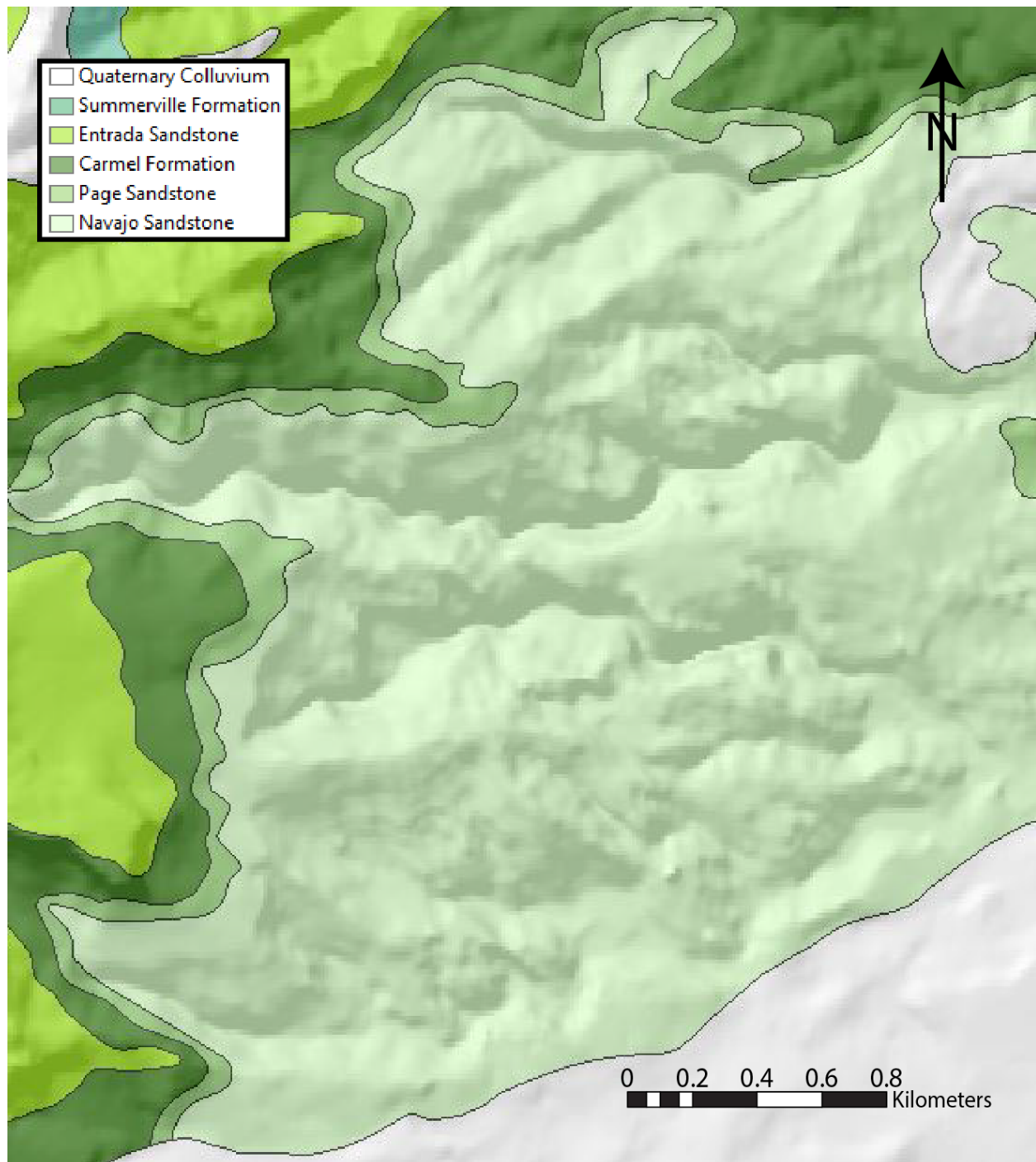


Figure 22: Original geologic map of the Pulpit Arch field area (After Larson et al., 1985).

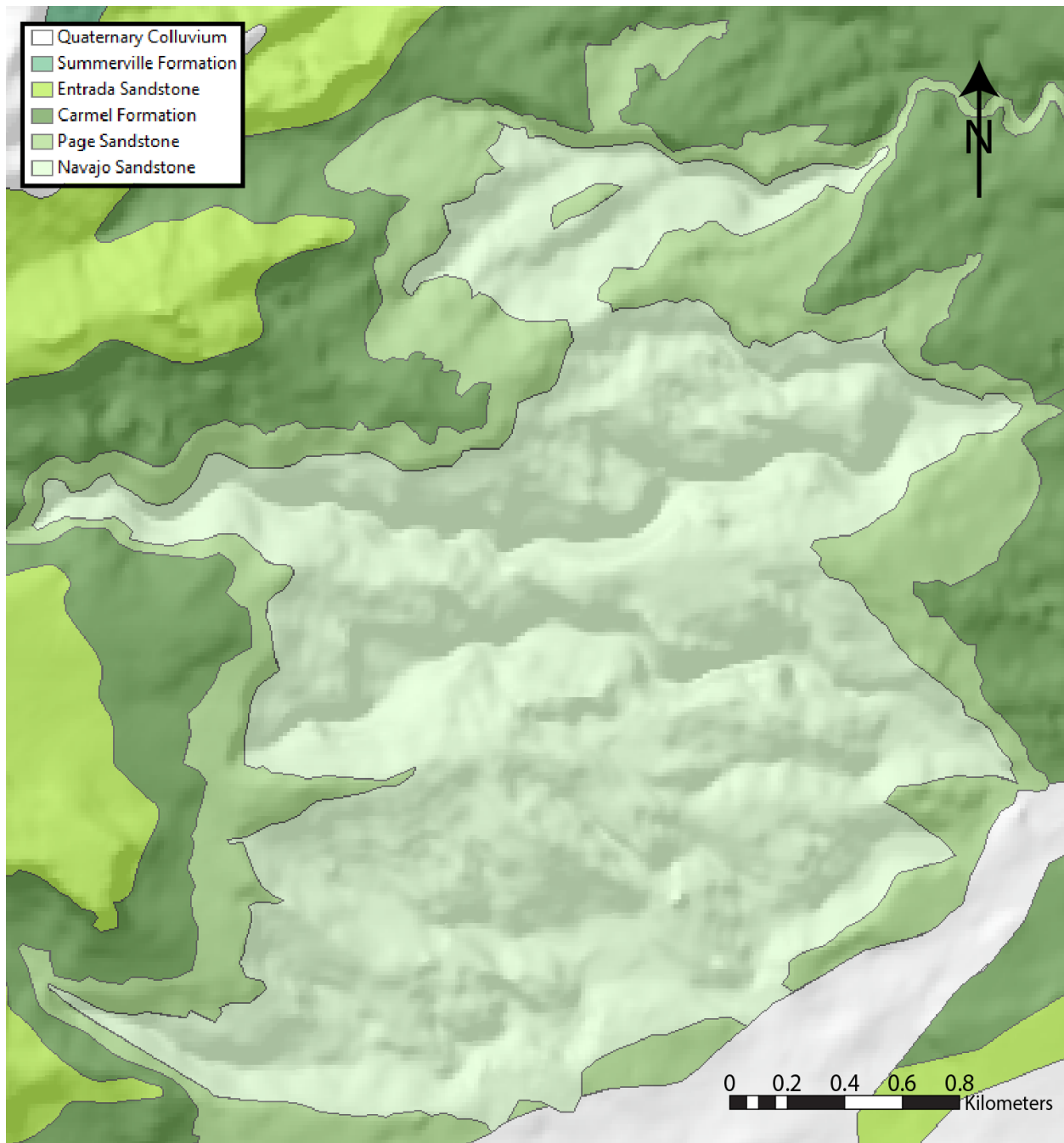


Figure 23: Updated geologic map of the Pulpit Arch field area, made from field observations.



Figure 24: Map of cross section transects. A-A' corresponds to Figure 24, and B-B' corresponds to Figure 25.

Photo from Google Earth.

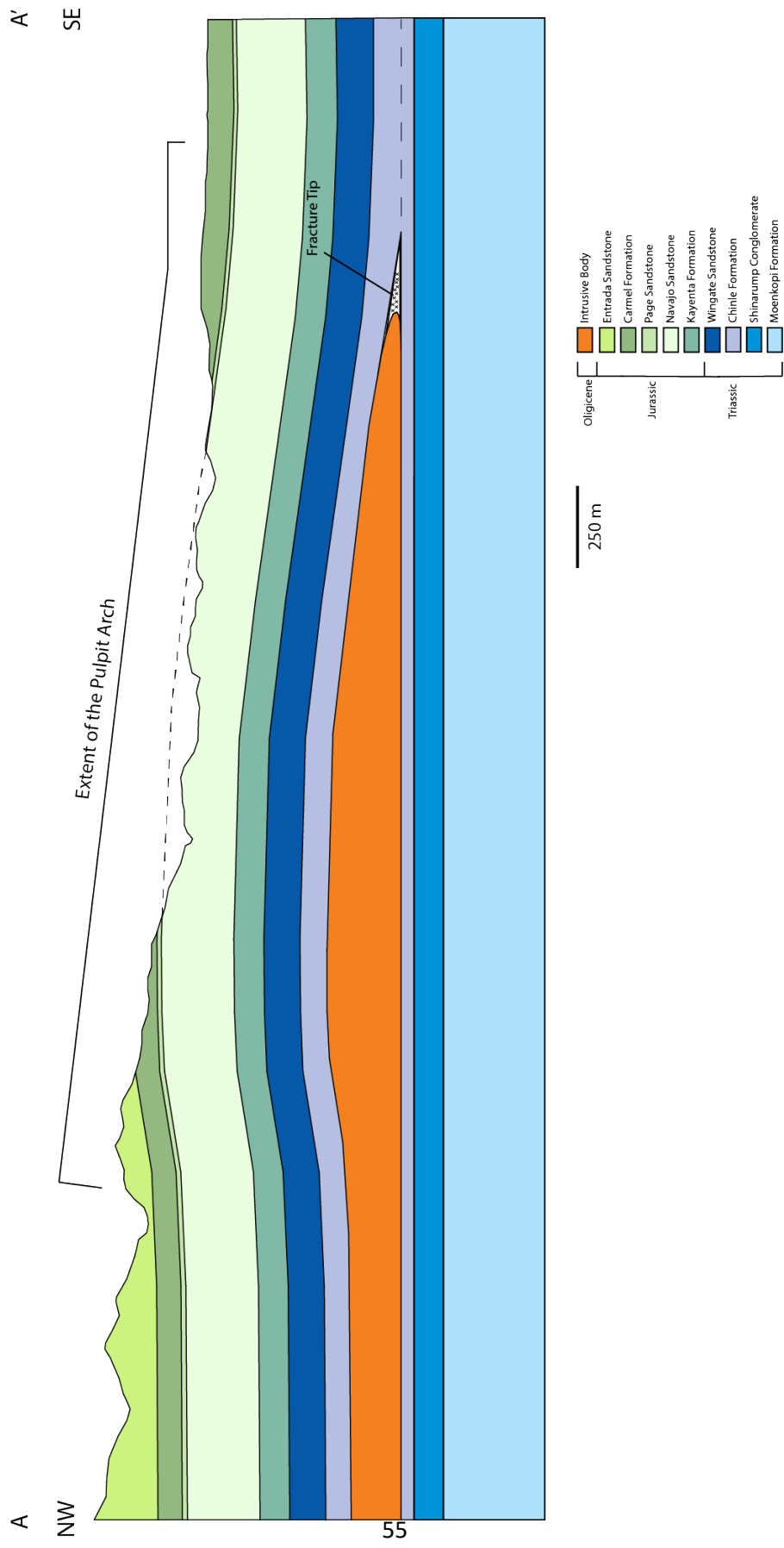


Figure 25: NW to SE cross section of the Pulpit Arch. The dashed line denotes the Upper Chinle Formation from the Lower Chinle Formation. Note, the actual depth of emplacement for the intrusion is unknown.

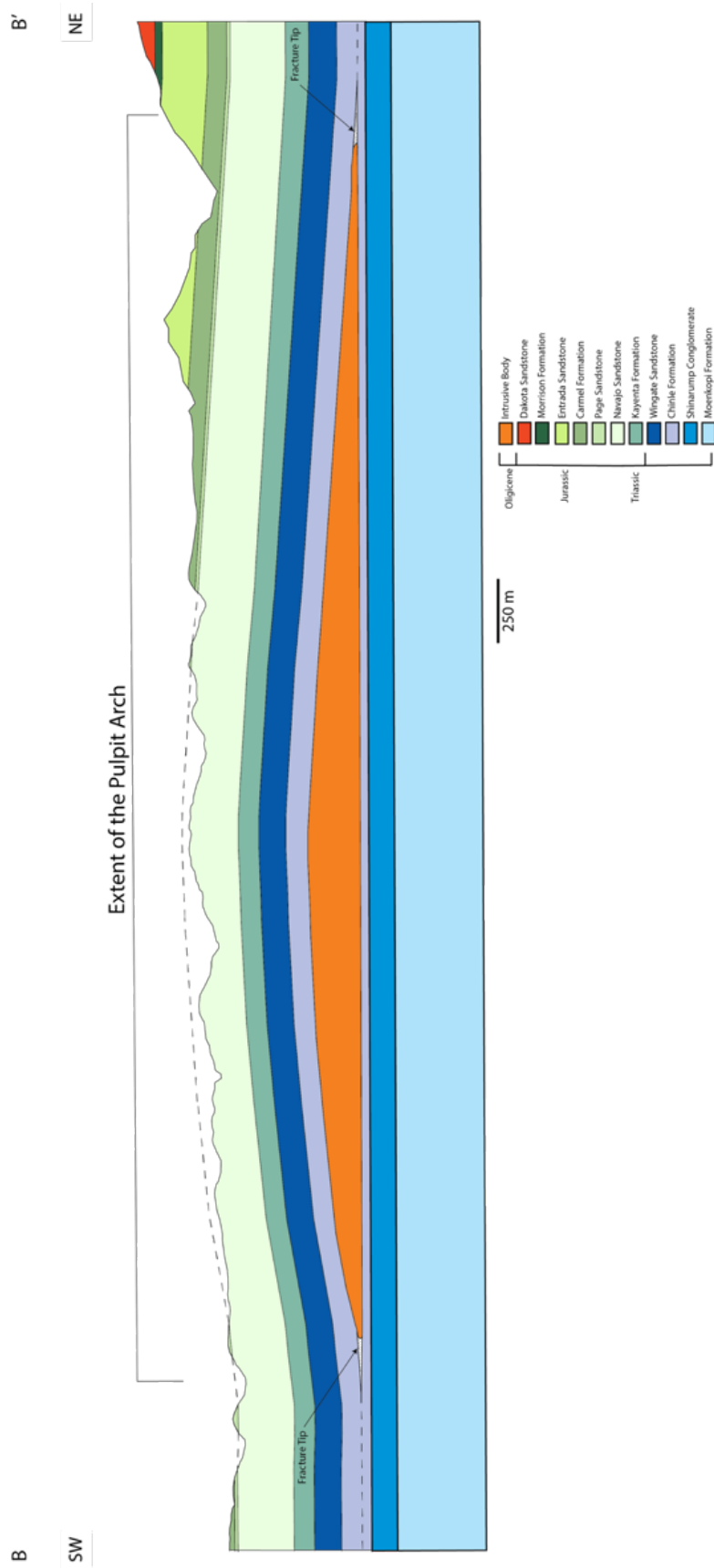


Figure 26: NE to SW cross section of the Pulpit Arch. The dashed line denotes the Upper Chinle Formation from the Lower

Chinle Formation. Note, the actual depth of emplacement for the intrusion is unknown.

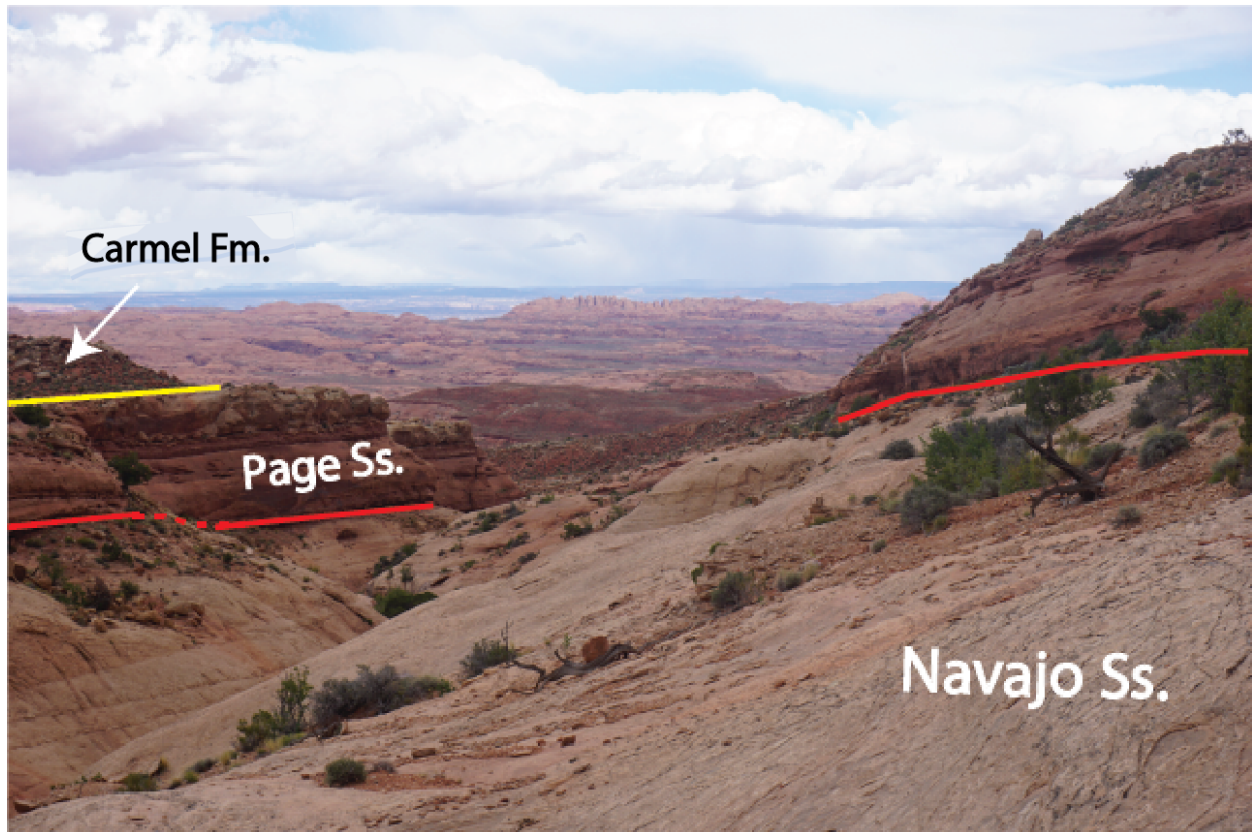


Figure 27: Field photograph of the Navajo Sandstone, Page Sandstone, and Carmel Formation. The Navajo/Page contact is indicated by the red line, and the Page/Carmel contact is indicated by the yellow line.

While defining the contact between the Navajo and the Page was the primary goal of the mapping process, some observations were made about the unit directly above the Page Sandstone, the Carmel Formation which is composed of shale and limestone. This was important in determining the extent of the Page Sandstone, so an accurate thickness for the Page could be mapped. The Carmel Formation outcrops were orange-to-brown in color, and exposed as gentler cliffs atop the steep exposures of the Page. The contact between the Page and the Carmel was mapped from overhead images of the Pulpit Arch after return from the field, where the color distinction is clearly visible.

Extension Across the Pulpit Arch

Four transects were selected across the Pulpit Arch along which to measure extension (Fig. 28). One transect was created along each of the following orientations: N to S, NE to SW, E to W, and NW to SE. The intersection point of the transects is approximated to the center of the dome. Extension values were calculated in the method used by Jackson and Pollard (1988). The general shape of the dome allows the radial distance to the center of the structure (i.e. $\frac{1}{2}$ of a transect length) and the thickness of the Navajo (~200 m) to represent two legs of a right triangle. The hypotenuse can be calculated using the Pythagorean Theorem, and is used as final length. The radial distance acts as the initial length and calculated hypotenuse acts as the final length for a respective transect, allowing extension to be calculated.

Extension values calculated ranged from 0.63% to 0.96% (Fig. 29). Jackson and Pollard (1988) calculated extension values of 4% for Mt. Holmes and 12% for Mt. Ellsworth, so the values calculated for this project are much lower. Jackson and Pollard (1990) classified Mt. Holmes as an early-stage dome and Mt. Ellsworth as a late-stage dome. Based on the extension values calculated for this project, the Pulpit Arch would not even be considered an early-stage dome by Jackson and Pollards' (1990) standards.

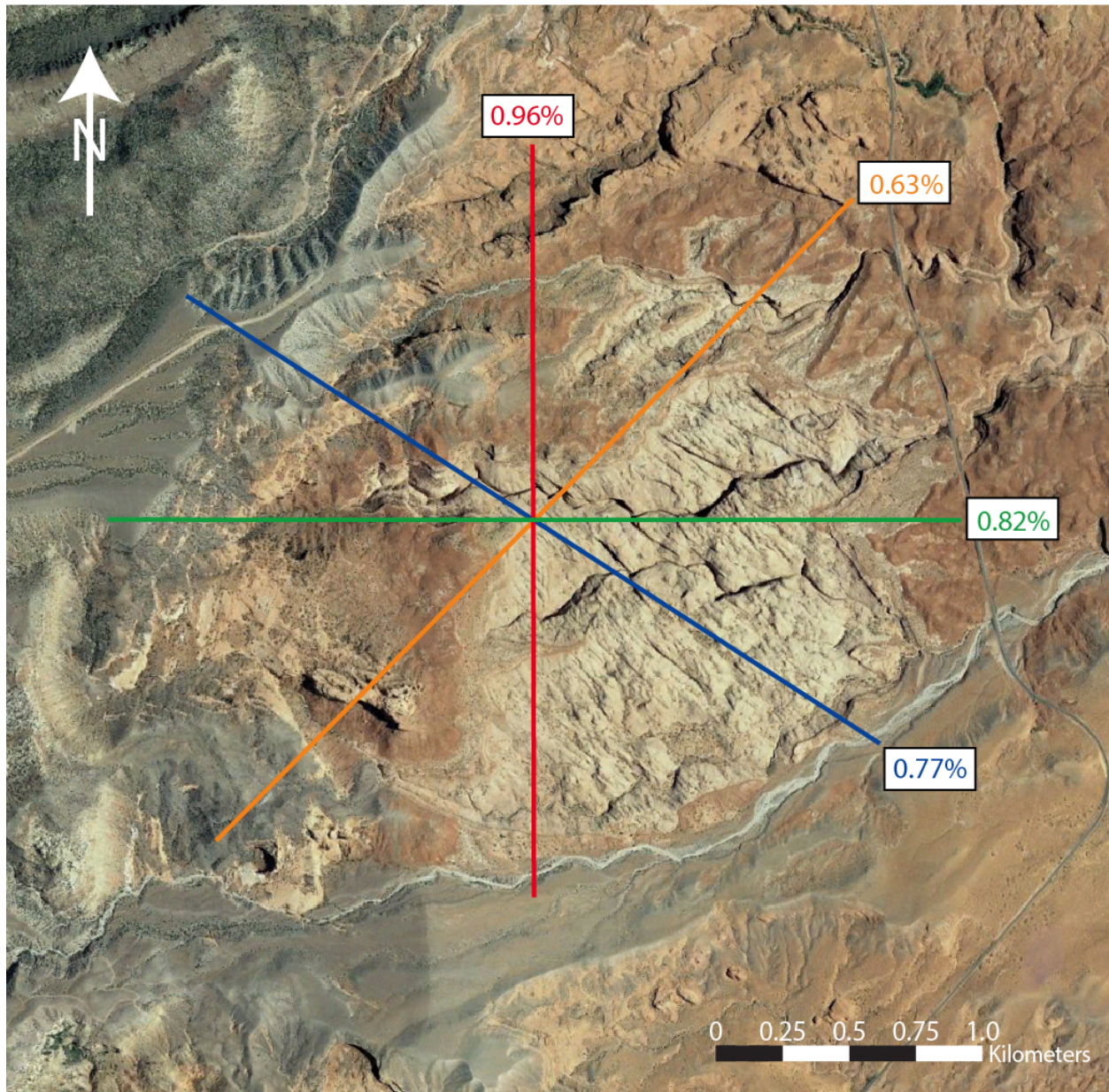


Figure 28: Extension values calculated along the Pulpit Arch.

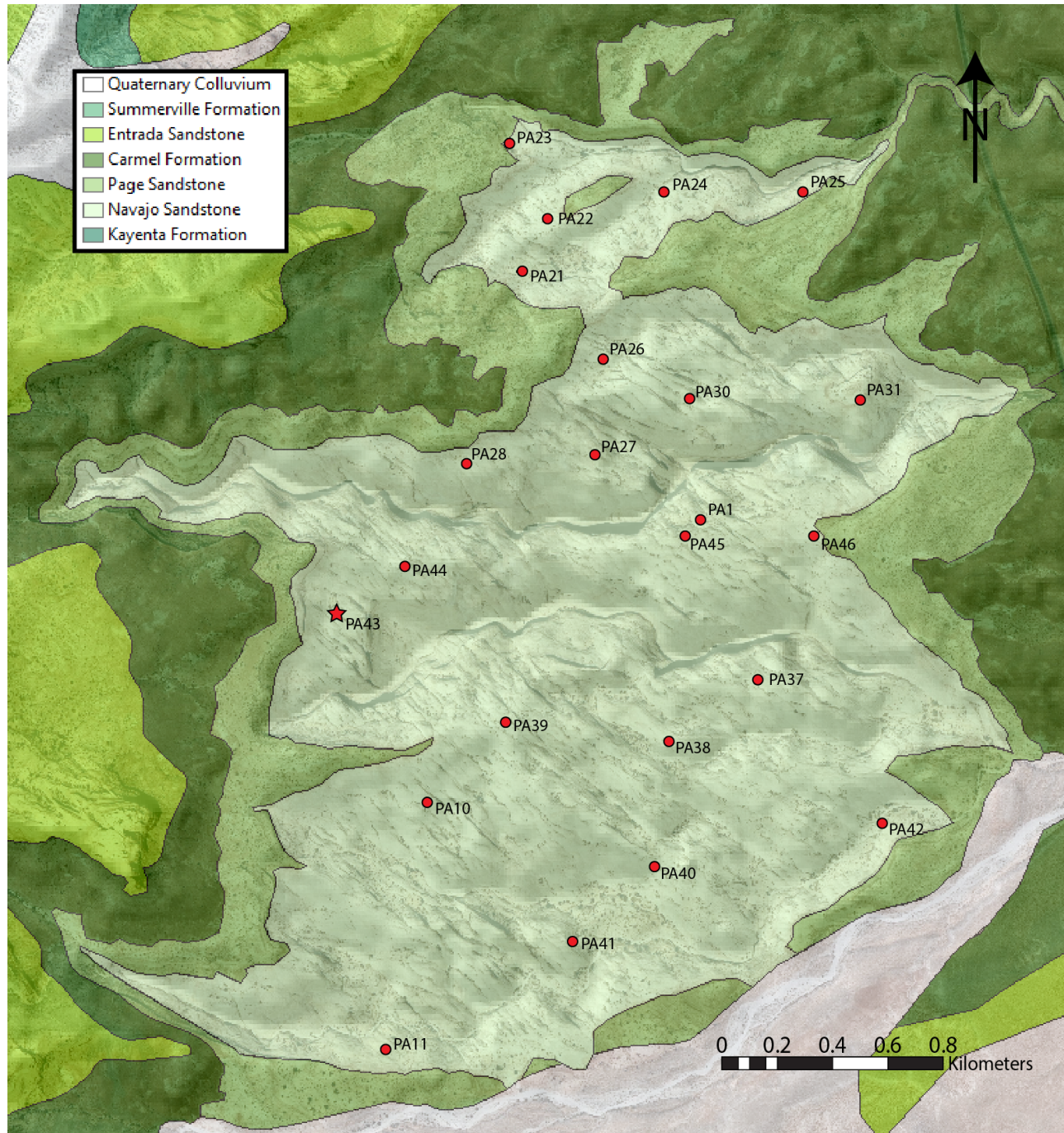


Figure 29: Fracture station distribution in the Pulpit Arch. The station symbolized by a star was absent of fractures.

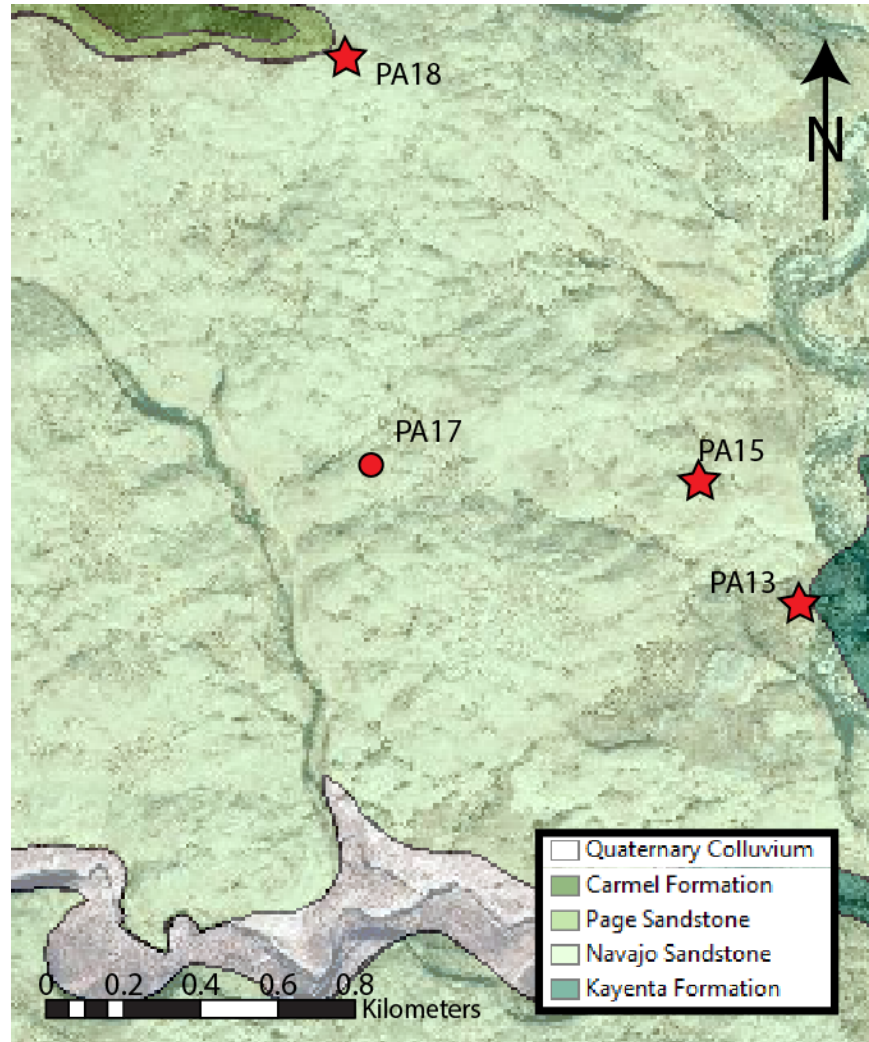


Figure 30: Fracture station distribution in the control area. Stations symbolized by stars were absent of fractures.

Fracture Analysis

Fracture data were analyzed in several ways. Fracture stations were categorized by fracture intensity. Raw fracture measurements and field photographs were used to create a fracture data table and fracture trace diagram for each station, respectively. Fracture data tables were used to create stereonet for each fracture station. Fracture data were compared between stations to identify any potential patterns in fracture characteristics. Other data collected in the field (e.g bedding data, elevation data, etc.) was loaded in ArcGIS to create several maps of the Pulpit Arch.

Fracture intensity was calculated by measuring total fracture length per unit area for each fracture station, in accordance with the P_{21} method defined by Dershowitz and Herda (1992). Based on the intensity values, stations were distinguished into four groups (Table 2). The average intensity value for all stations was 0.30 m^{-1} , with a standard deviation of 0.12 m^{-1} . Fracture intensity values between 0.30 m^{-1} and 0.42 m^{-1} were labeled “Med-High Intensity Stations”, while intensity values between 0.18 m^{-1} and 0.30 m^{-1} were labeled “Med-Low Intensity Stations”. Intensity values equal to or greater than 0.42 m^{-1} were labeled “High Intensity Stations” and intensity values equal to or less than 0.18 m^{-1} were labeled “Low Intensity Stations”, respectively. The four types of stations were categorized and labeled on a map of the area (Fig. 31).

Station Number	Total Fracture Length (m)	Station Area (m²)	Fracture Intensity (m⁻¹)	Relative Fracture Intensity
PA-1	8.48	16	0.53	High
PA-10	5.59	16	0.35	Med-High
PA-11	1.13	4	0.28	Med-Low
PA-13*	0.00	16	0.00	Low
PA-15*	0.00	16	0.00	Low
PA-17*	1.83	16	0.11	Low
PA-18*	0.00	16	0.00	Low
PA-21	3.46	16	0.22	Med-Low
PA-22	5.20	16	0.33	Med-High
PA-23	5.73	16	0.36	Med-High
PA-24	1.66	4	0.42	High
PA-25	2.08	16	0.13	Low
PA-26	5.10	16	0.32	Med-High
PA-27	4.79	16	0.30	Med-High
PA-28	3.03	16	0.19	Med-Low
PA-30	4.28	16	0.27	Med-Low
PA-31	2.00	4	0.50	High
PA-37	4.16	16	0.26	Med-Low
PA-38	3.08	16	0.19	Med-Low
PA-39	4.67	16	0.29	Med-Low
PA-40	4.08	16	0.26	Med-Low
PA-41	1.52	4	0.38	Med-High
PA-42	2.27	16	0.14	Low
PA-43	0.00	16	0.00	Low
PA-44	1.42	4	0.36	Med-High
PA-45	4.45	16	0.28	Med-Low
PA-46	2.13	4	0.53	High

* = Control area station

Table 2: Fracture intensity values for Pulpit Arch fracture stations.

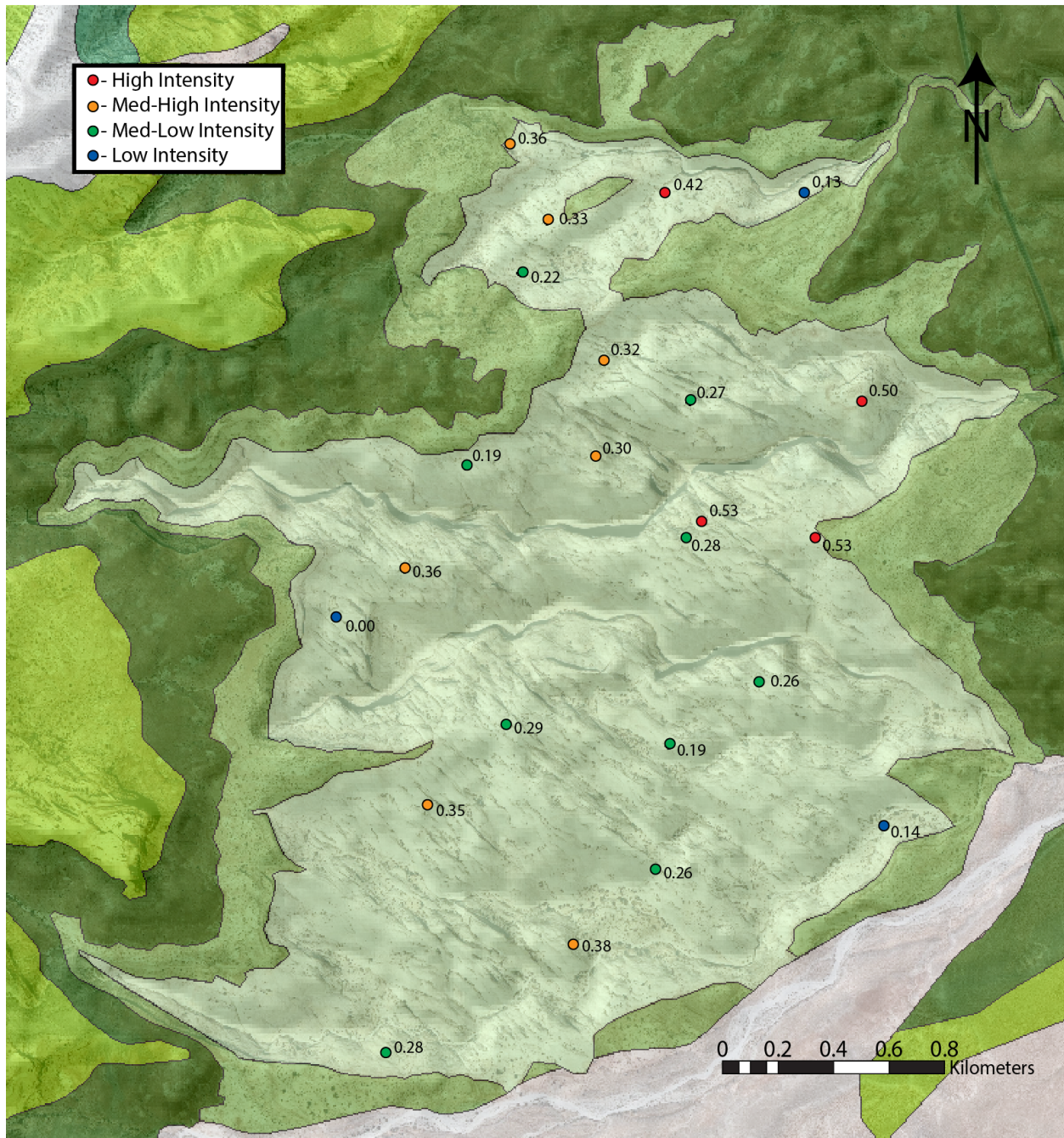


Figure 31: Map of fracture intensity. Intensity values are in m⁻¹.

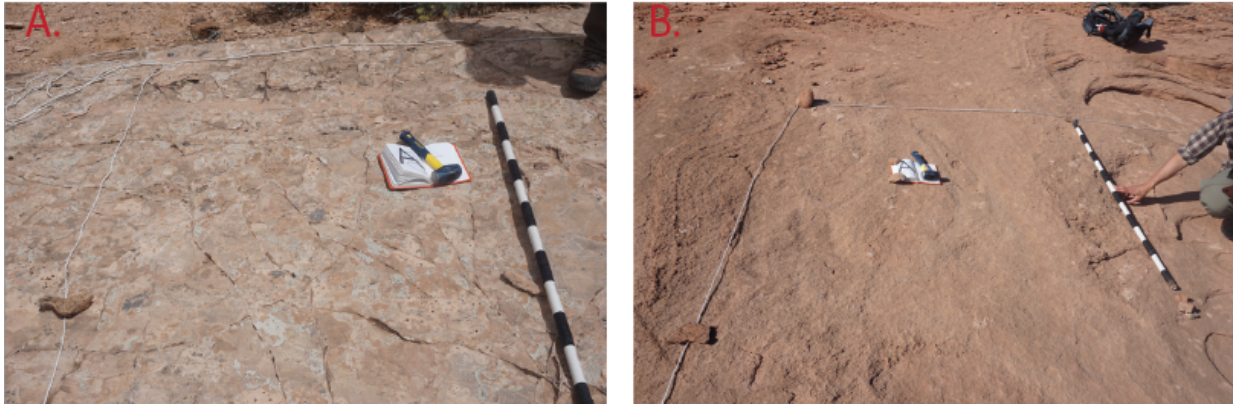


Figure 32: (A) A typical fracture station quadrant within the Pulpit Arch. (B) A typical fracture station quadrant within the control area.

A clear distinction exists between the fracture patterns in the two field areas (Fig. 32). In the subhorizontal Navajo of the control area, the 4 fracture stations were distributed throughout the full stratigraphic extent of the Navajo Sandstone. Of the 4 fracture stations in the control area, 3 lack fractures entirely. PA13, PA15, and PA18, located at the base of the Navajo, approximately 50 m above the base of the Navajo, and the stratigraphic top of the Navajo, respectively, exhibit no fracturing.

PA17, approximately 100 m above the base of the Navajo, exhibits fracturing, though relatively minor compared to the fracturing observed in the Pulpit Arch (Table 3, Fig. 33 and 34). The fractures at PA17 are classified as proto deformation bands (PDB), all of which have orientations generally NW to SE. PDBs were unique to this station, and not found at any other location in the control area or the Pulpit Arch.

Within the Pulpit Arch, 22 of the 23 fracture stations exhibit fracturing. PA10 (Table 4 and Fig. 35 and 36) and PA25 (Table 5 and Fig. 37 and 38) are examples of typical fracture stations within the Pulpit Arch. Measurements for all fracture stations can be found in Appendix A. Definitions for terms as used here are provided in the Methodology section. Abbreviations for these tables are: FT, Fracture type; C, Clustering; P, Planarity; DM, Dip magnitude; DD, Dip direction; S, Strike; L, Length (expressed in dm), T, Terminations; B, Border termination; E, End termination; T/x, Truncation termination/Fracture set # truncation occurs at; Set #, ISO, Isolated fracture set; X-C, Presence of cross-cutting (Y, Yes; N, No). Cross-cutting offset is measured in cm.

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C	
A	PDB		1	88	66	336	18	B,B	1	N	
A	PDB		2	84	52	322	18	B,B	1	Y	8
A	PDB		2	83	65	335	4	B,B	1	N	
B	PDB		2	83	65	335	18	B,B	1	N	
B	PDB		2	84	52	322	15	B,E	1	Y	8
B	PDB		2	82	65	335	16	B,B	1	Y	6
C	PDB		1	88	67	337	16	B,B	1	N	
C	PDB		2	80	66	336	11	B,B	1	N	
C	PDB		1	80	68	338	20	B,B	1	N	
C	PDB		1	86	76	346	4	B,E	1	N	
C	PDB		1	86	80	350	7	B,E	1	N	
D	PDB		2	83	57	327	4	B,B	1	N	
D	PDB		2	86	56	326	13	E,E	1	N	
D	PDB		1	89	59	329	9	B,E	1	N	
D	PDB		1	83	70	340	10	B,E	1	N	

Table 3: Fracture characteristic data for PA17.

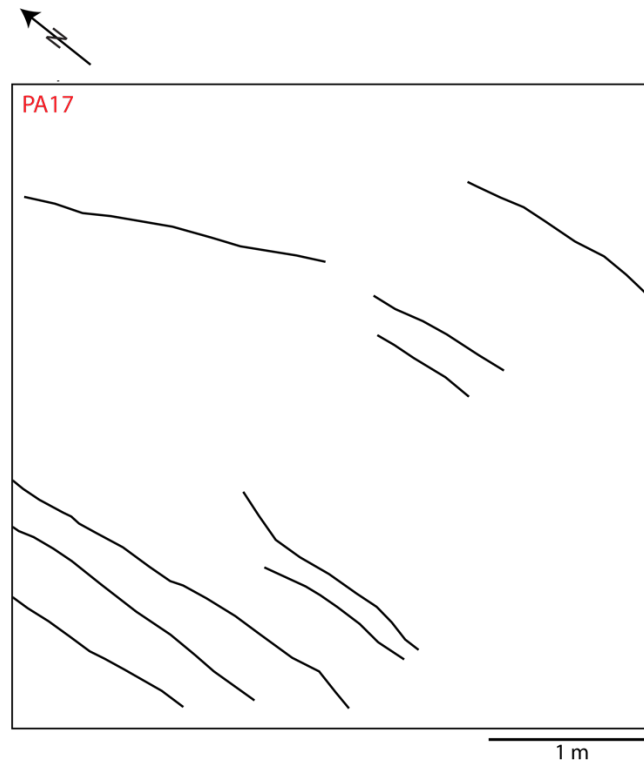


Figure 33: Fracture trace data for PA17. Strata is subhorizontal at this location.

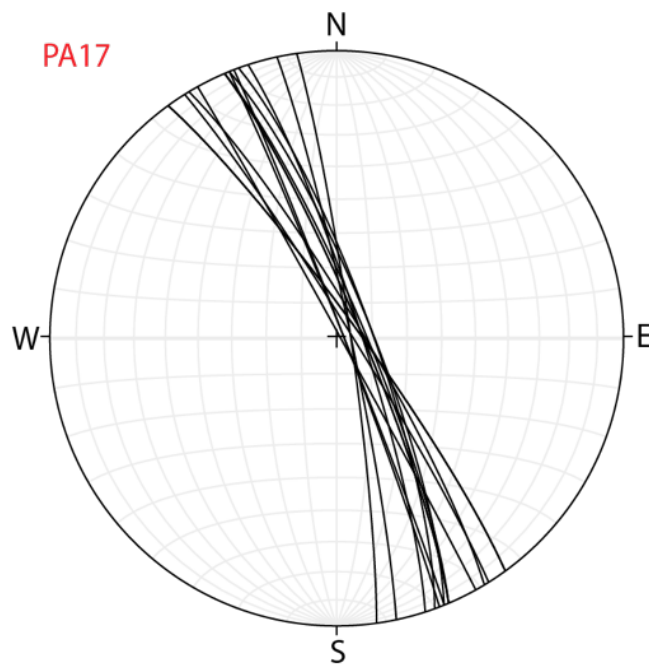


Figure 34: Stereonet for PA17.

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
A	SDB		3	72	120	30	21	B,B	1	N
A	CDB	1	2	84	290	200	22	B,B	1	N
A	SDB		2	88	124	34	10	T/2,T/2	1	N
A	SDB		2	86	275	185	3	T/2,E	1	N
A	SDB		3	88	265	175	4	T/2,T/2	1	N
A	CDB	3	2	82	312	222	21	B,B	2	N
A	SDB		1	87	141	51	21	B,B	2	N
A	SDB		3	89	307	217	19	B,B	2	N
A	SDB		2	81	323	233	19	B,B	2	N
A	SDB		2	83	150	60	5	T/1,E	2	N
A	SDB		3	82	310	220	5	T/2,B	2	N
A	SDB		1	84	164	74	13	T/1,B	3	N
A	CDB	1	2	72	10	280	11	T/2,B	3	N
A	SDB		1	76	14	284	4	T/2,T/2	3	N
A	SDB		3	78	186	96	5	T/1,T/2	3	N
A	SDB		2	75	180	90	5	T/1,T/2	3	N
A	SDB		2	76	270	180	5	T/2,E	ISO	N
B	SDB		3	74	118	28	20	B,B	1	N
B	SDB		3	80	300	210	24	B,B	1	N
B	SDB		1	89	180	90	5	T/1,B	2	N
B	SDB		1	89	167	77	4	T/1,B	2	N
B	SDB		2	88	175	85	2	T/1,B	2	N
B	SDB		2	88	335	245	11	T/3,B	2	N
B	SDB		2	86	14	284	9	T/2,B	3	N
B	SDB		3	85	200	110	17	T/1,B	3	N
B	SDB		2	89	209	119	10	T/1,B	3	N
B	SDB		2	89	173	83	14	B,B	3	N
B	SDB		2	78	0	270	10	B,B	3	N
B	SDB		2	80	190	100	5	B,E	3	N
B	SDB		3	80	20	290	6	T/1,B	3	N
C	SDB		3	62	290	200	6	B,T/2	1	N
C	SDB		2	66	74	344	4	T/2,T/2	1	N
C	SDB		2	70	74	344	6	T/2,T/2	1	N
C	SDB		3	81	140	50	6	B,E	2	N
C	CDB	2	3	78	315	225	21	B,B	2	N
C	SDB		2	78	135	45	15	B,T/2	2	N
C	SDB		2	78	150	60	20	B,B	2	N
C	CDB	3	3	72	310	220	21	B,B	2	N
C	SDB		2	72	150	60	7	B,T/2	2	N
C	SDB		2	80	5	275	6	B,T/1	ISO	N
D	CDB	2	2	79	150	60	13	B,B	1	N
D	SDB		1	81	130	40	21	B,B	1	N
D	SDB		2	80	295	205	15	B,E	1	N
D	CDB	1	2	86	315	225	4	B,E	1	N
D	SDB		2	87	5	275	17	B,E	2	N
D	SDB		2	86	185	95	9	B,E	2	N
D	SDB		1	79	350	260	4	T/1,T/1	2	N
D	CDB	1	1	86	354	264	10	B,T/1	2	N
D	SDB		2	32	348	258	10	B,T/1	2	N
D	SDB		1	76	315	225	1	T/2,T/2	1	N
D	SDB		2	80	180	90	7	B,T/1	2	N
D	CDB	3	2	80	180	90	4	B,E	2	N
D	SDB		1	81	185	95	2	B,E	2	N

Table 4: Fracture characteristic data for PA10.

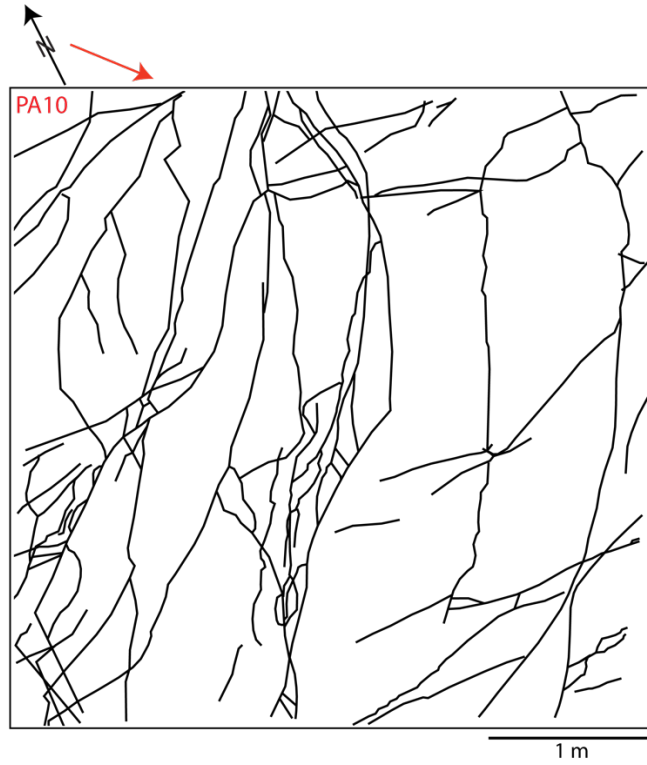


Figure 35: Fracture traces for PA10. Radial direction is indicated by the red arrow.

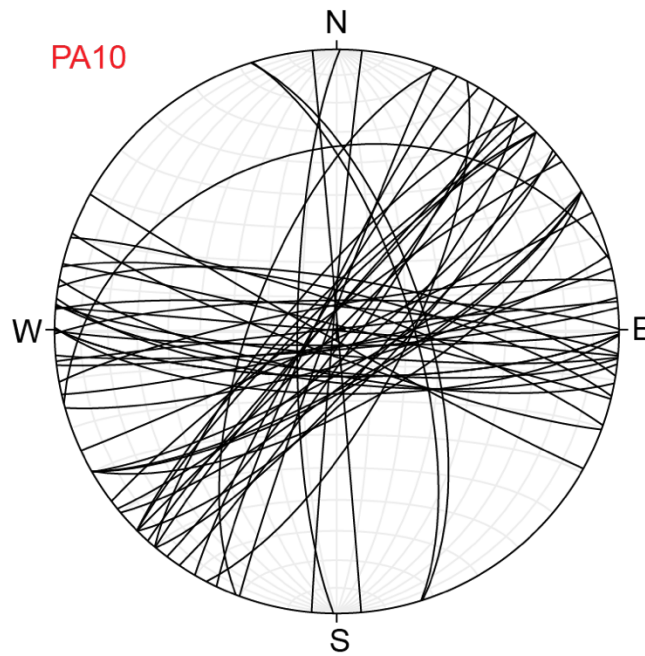


Figure 36: Stereonet for PA10.

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
A	CDB	3	2	78	124	34	15	B,B	1	N
A	CDB	3	3	80	137	47	14	B,T/2	1	N
A	CDB	1	2	82	145	55	15	B,T/2	1	N
A	CDB	3	2	86	350	260	11	B,B	2	N
A	CDB	2	2	78	5	275	9	B,B	2	N
A	CDB	3	2	80	295	205	17	B,B	2	N
B	CDB	2	3	80	340	250	15	B,B	1	N
B	CDB	1	2	80	335	245	15	B,B	1	N
B	CDB	1	2	84	349	259	17	B,B	1	N
B	CDB	2	1	85	350	260	14	B,B	1	N
B	CDB	2	2	86	10	280	17	B,B	2	N
C	CDB	3	2	72	140	50	21	B,B	ISO	N
D	CDB	3	2	72	147	57	8	B,B	1	N
D	CDB	1	2	74	146	56	9	B,E	1	N
D	CDB	3	2	74	152	62	11	B,E	1	N

Table 5: Fracture characteristic data for PA25.



Figure 37: Fracture traces for PA25. Radial direction is indicated by the red arrow.

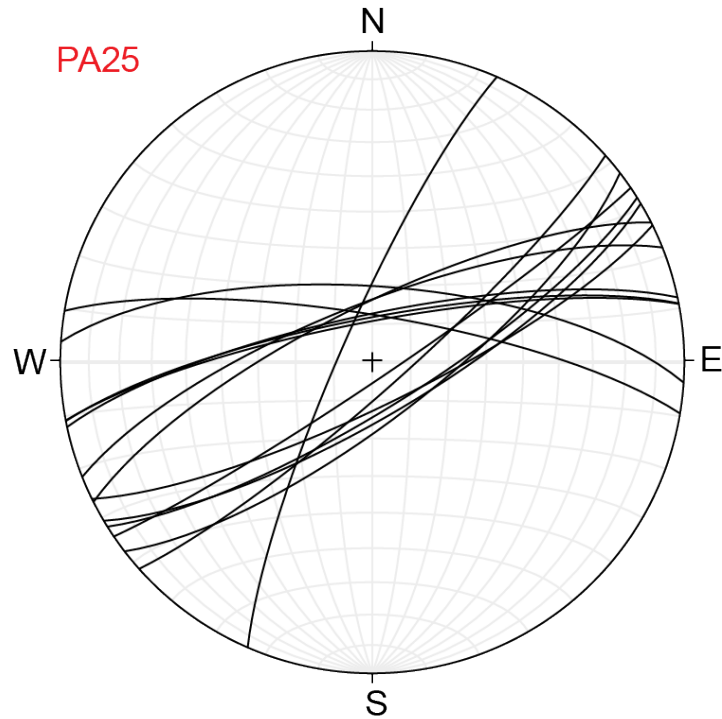


Figure 38: Steronet for PA25.

Fracture orientations vary across the Pulpit Arch, but fractures generally follow 1 of 3 broad orientations: NE to SW, E to W, and NW to SE (Fig. 40). NE to SW and E to W were the 2 more dominant orientations observed, but fractures with NW to SE orientations were still numerous enough to be noticeable in the data. Low intensity stations favored NW to SE and E to W orientations, while all three orientations were common in Med-Low, Med-High, and High intensity fracture stations (Fig. 41).

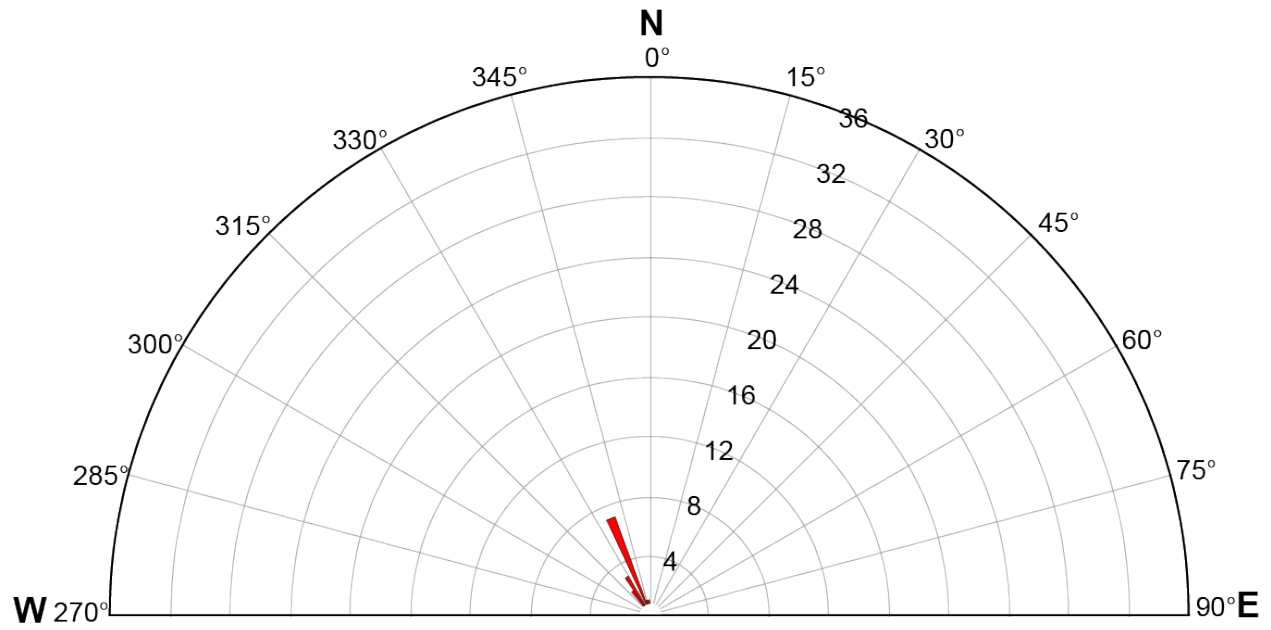


Figure 39: Rose diagram of fracture orientations measured in the control area. (n = 15)

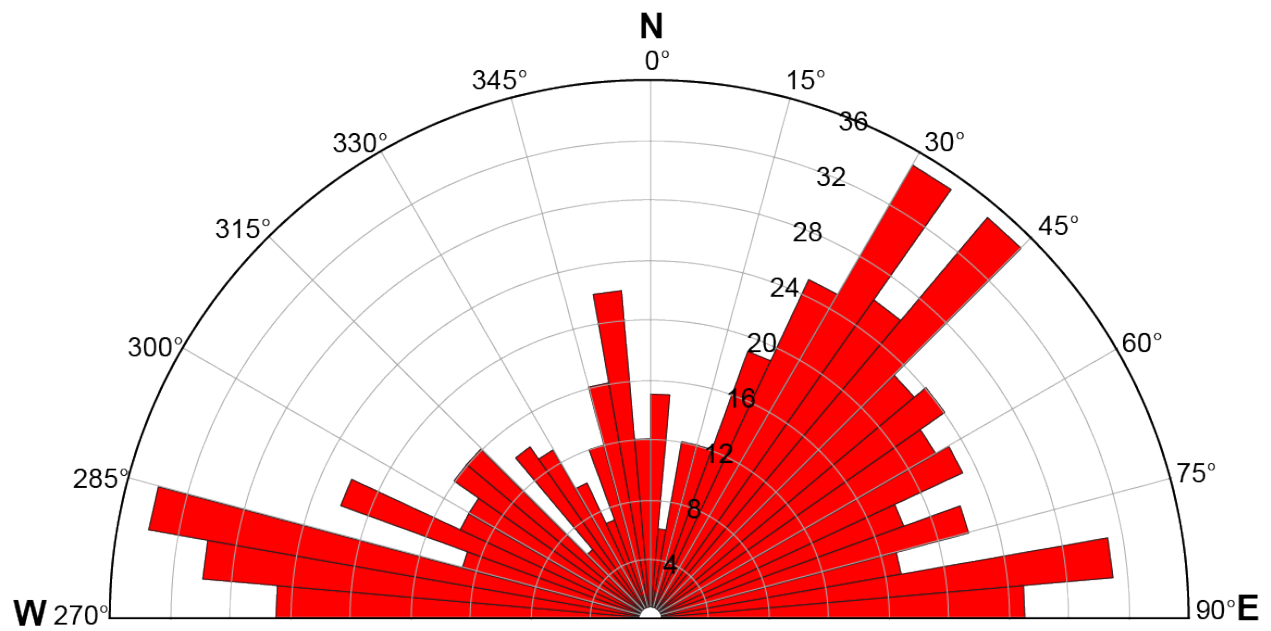


Figure 40: Rose diagram of fracture orientations measured in the Pulpit Arch (n = 686)

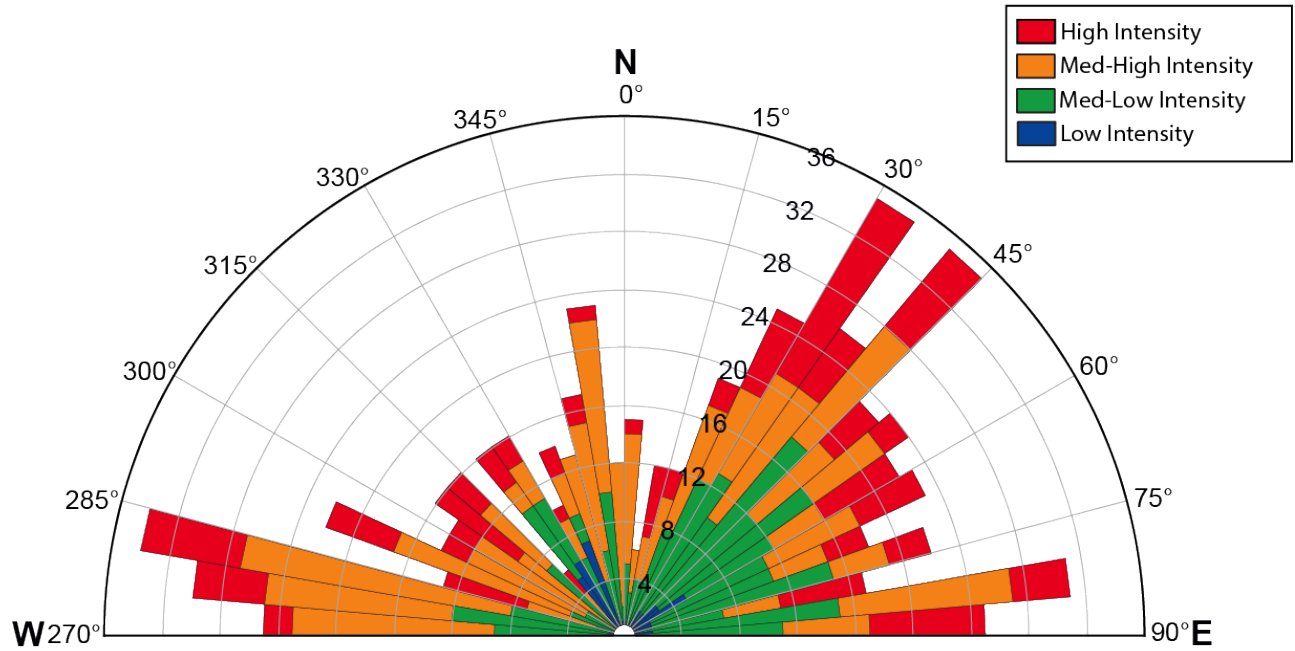


Figure 41: Rose diagram of all fracture orientations measured in the field, categorized by intensity. Colors correspond to those in Fig. 26. Bin size is 5°. (n = 701)

Both single and cluster deformation bands were common. 347 cluster deformation bands and 339 single deformation bands were recorded. 15 proto deformation bands were observed, and only at PA17, in the control area. Fracture lengths also varied across the Pulpit Arch, ranging from a minimum of 1 dm and maximum of 27 dm (Fig. 42). Fractures with length under 1 dm were not measured for this project. Longer fractures were generally more common at Low and Med-Low fracture stations, while shorter fractures were more common at High and Med-High stations. It is important to note, the max fracture length was effectively capped by the chose station size, 16 m².

Fracture termination style varied across the Pulpit Arch, with border terminations being the clear dominant style, accounting for ~68% of all terminations (Fig. 43). Border terminations were especially common in fractures of length 17 dm and greater. Truncation terminations were

most prevalent in shorter fractures, but some truncations were observed in fractures of relatively high lengths. End terminations were least common, and none were observed in fractures of length greater than 16 dm. Orientation and termination style did not seem to be related (Fig. 44). Finally, cross-cutting was almost non-existent. When cross-cutting was present, the magnitude of displacement averaged ~2 cm.

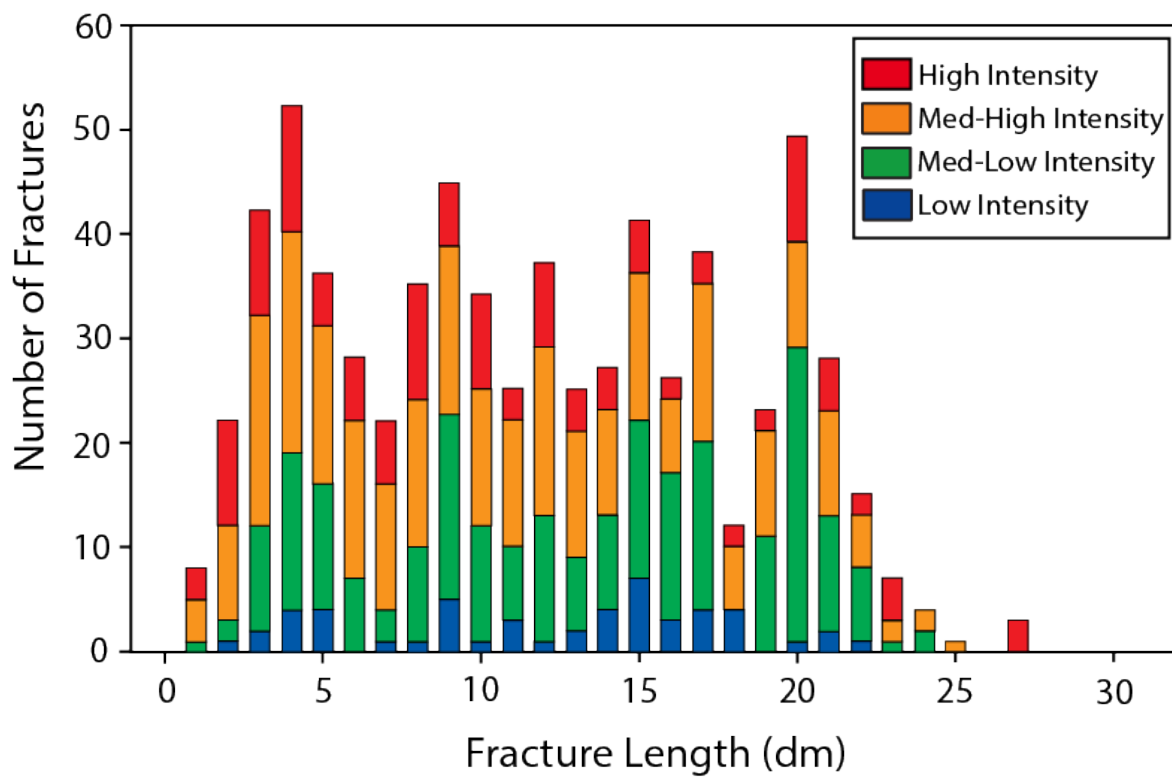


Figure 42: All fracture lengths measured in the field, categorized by intensity. Colors correspond to those in Fig. 26.

(n = 701)

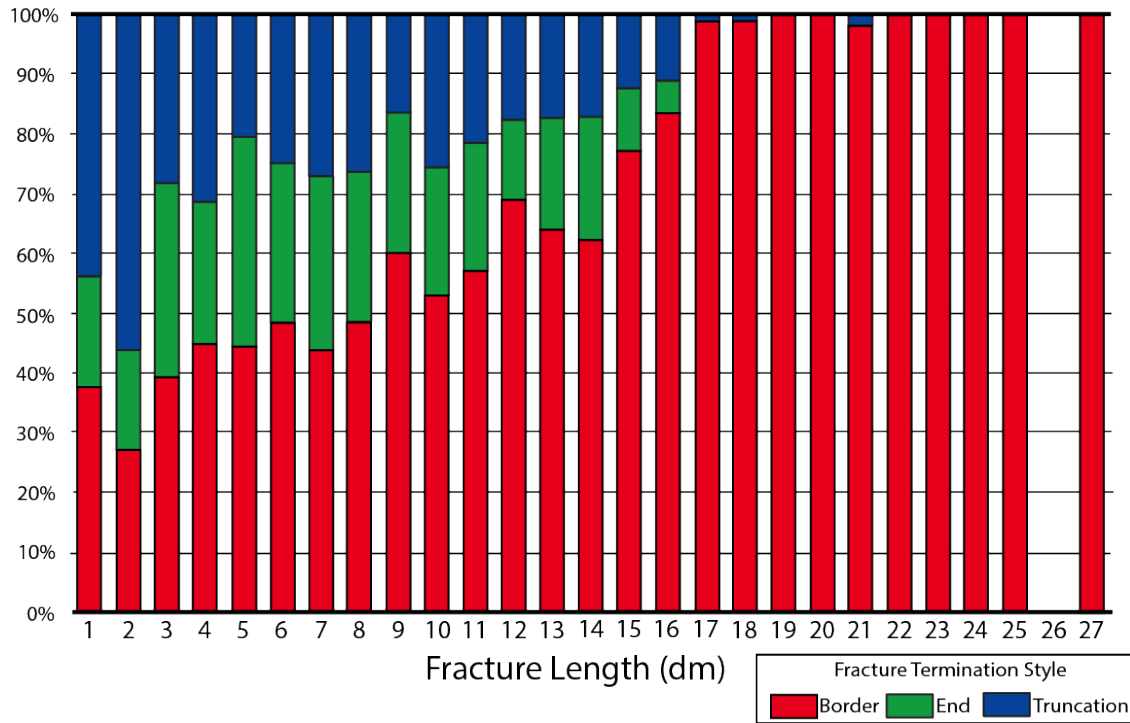


Figure 43: Fracture termination styles per fracture length. No fractures were observed with length 26 dm.

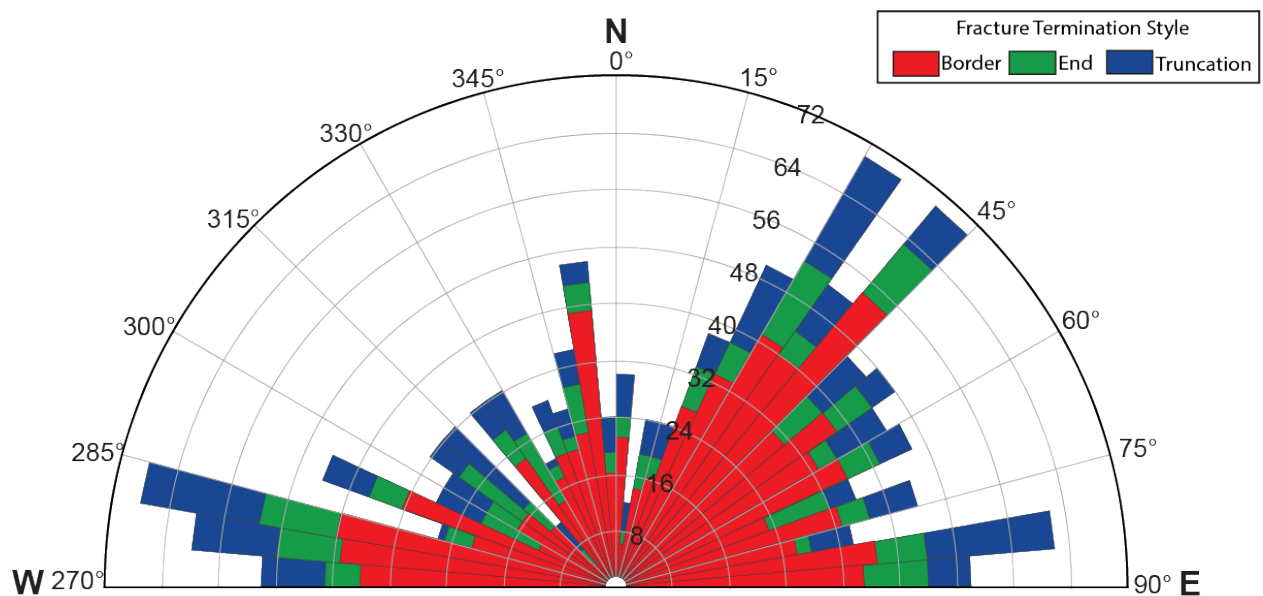


Figure 44: Fracture termination styles per fracture orientation. (n = 1402)

Three-dimensional fracture data was also analyzed. Stereonets created were corrected for bedding orientation using the average bedding values for each station. All stereonet can be found in Appendix C. Fracture dip magnitudes measured in the field were generally steep, with most measurements falling between $\sim 75^\circ$ and 90° (Fig. 45). Radial direction was compared to the dominant fracture set orientations at individual stations. The allowed for the distribution of radial and tangential fractures across stations, and subsequently the entire Navajo exposure of the Pulpit Arch, to be analyzed. Overall, 242 fractures were identified as radial and 241 fractures were identified as tangential. The remaining 203 fractures were not predominately radial or tangential, and were identified as “other”. Radial, tangential, and “other” fractures were separated by termination style to determine if there was any variation between fracture types (Fig. 46).

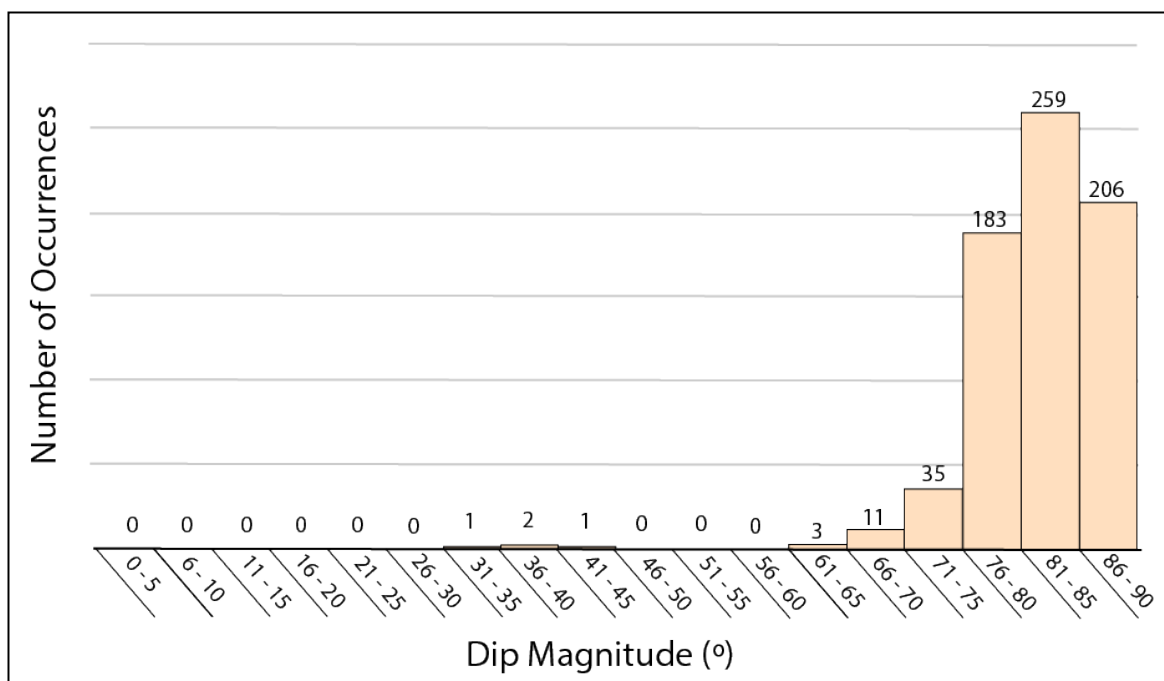


Figure 45: Dip magnitude for all fractures measured in the field. (n = 701)

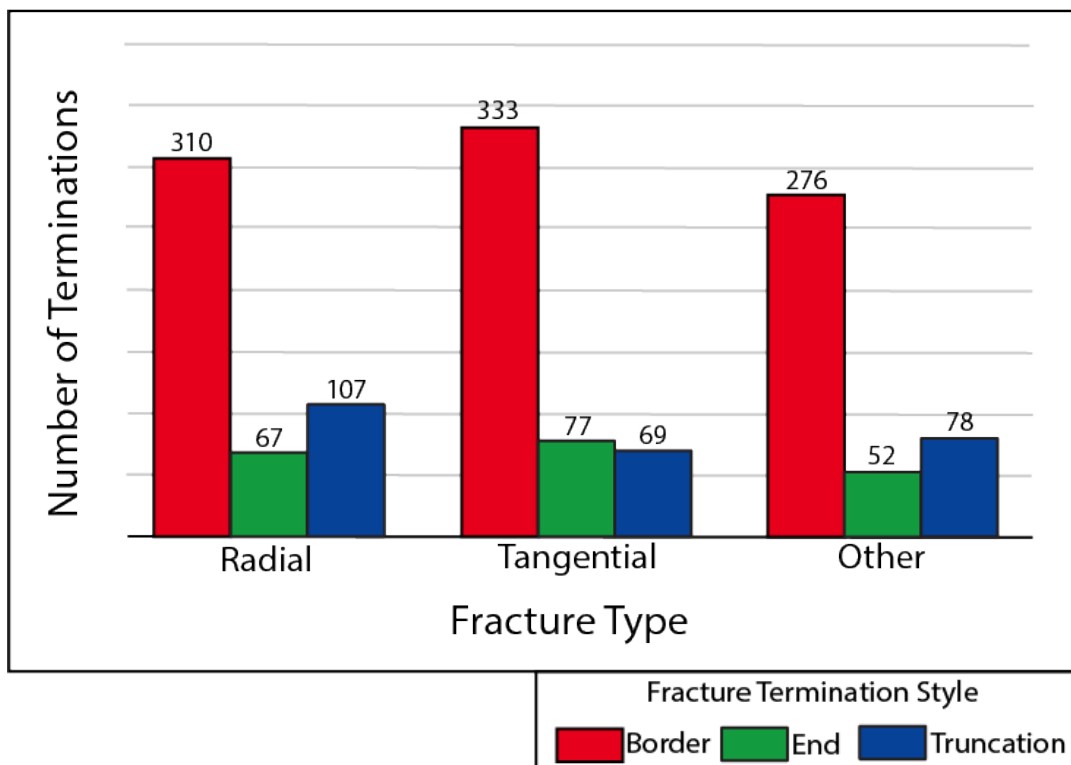


Figure 46: Radial, tangential, and “other” fractures per termination style.

Fracture Variation Across the Dome

Different maps of the Pulpit Arch were created by applying data collected in the field with pre-existing maps of the region. The dips of bedding collected at each fracture station were averaged to produce a single dip value for each station (Table 6). These values were plotted onto the geologic map of the area and resulted in a map of bedding across the crest of the Pulpit Arch (Fig. 47). Maximum and minimum dip magnitudes were $\sim 12^\circ$ and $\sim 1^\circ$, respectively, though these values varied across the dome. All sedimentary beds dipped away from the crest of the dome in the northwest portion of the field area, where the igneous body is interpreted to be

thickest. Bedding magnitudes were generally lower towards the western section of the Pulpit Arch and increased steadily towards the outer limits of the outcrop area of the Navajo Sandstone.

To describe the geometry of the dome prior to erosion of the Pulpit Arch, the geometry of the contact between the Navajo Sandstone and overlying Page Sandstone was reconstructed. Estimated stratigraphic position recorded in the field within the Navajo Sandstone was transferred into ArcGIS, and the elevation values of this contact were applied to each station, represented by points in ArcGIS. After the contact between the Navajo and the Page Sandstone was updated, a polyline was constructed along this contact. Points were distributed along this polyline every 100 m, and elevation values were extracted for those points. The ArcMap Kriging tool was used to fit a smoothed surface through the points. This created a raster surface approximating the elevation and geometry of the Navajo-Page contact prior to erosion. This raster was contoured in ArcMap, resulting in a structure contour map of the Pulpit Arch's original surface (Fig. 48). Topographically, the original Navajo-Page contact is higher in the west than in the east. The highest region of the area is to the northwest, where the intrusion was originally emplaced.

The structure contour map was converted into a curvature map of the dome's original surface (Fig. 48), using ArcMap's Curvature tool. A polyline was created approximately 50 m outside of the Navajo/Page contact. After the curvature map was created, the Extract by Mask tool in ArcMap was used to trim the curvature map to just the Navajo's exposure area.

The curvature map (Fig. 49) is a color intensity map, meaning that vibrant colors represent high curvature values, while muted colors represent lower curvature values. Increasing positive and negative curvature values indicate the surface is convex-up and concave-up, respectively. A cell size of 50 m was used, which allowed for curvature values to be extrapolated

to an appropriate area surrounding a fracture station. Larger cell sizes did not allow for sufficient extrapolation, leading to skewed curvature values across the entire map. Overall, the Navajo exposure in the Pulpit Arch appears to have a similar distribution of high and low curvature values. Values seem to be highest around the outer extent of the Navajo to the west (e.g. near PA26 and PA28), and lower towards the center and eastern side of the Navajo (e.g. near PA25, PA30, and PA39). Curvature values at fracture stations were extracted to determine if any clear relationship exists between curvature and fracture intensity (Fig. 50).

Station Number	Avg. Strike	Avg. Dip Magnitude	General Dip Direction
PA1	333	07	E
PA10	049	04	SE
PA11	068	10	SE
PA21	311	12	NE
PA22	319	12	NE
PA23	271	06	N
PA24	322	04	NE
PA25	303	09	NE
PA26	018	05	E
PA27	005	07	E
PA28	060	09	SE
PA30	019	08	E
PA31	326	11	NE
PA37	051	09	SE
PA38	042	06	SE
PA39	033	02	SE
PA40	064	05	SE
PA41	068	06	SE
PA42	054	08	SE
PA43	037	02	SE
PA44	036	03	SE
PA45	335	07	E
PA46	343	08	E

Table 6: Average bedding values for Pulpit Arch fracture stations.

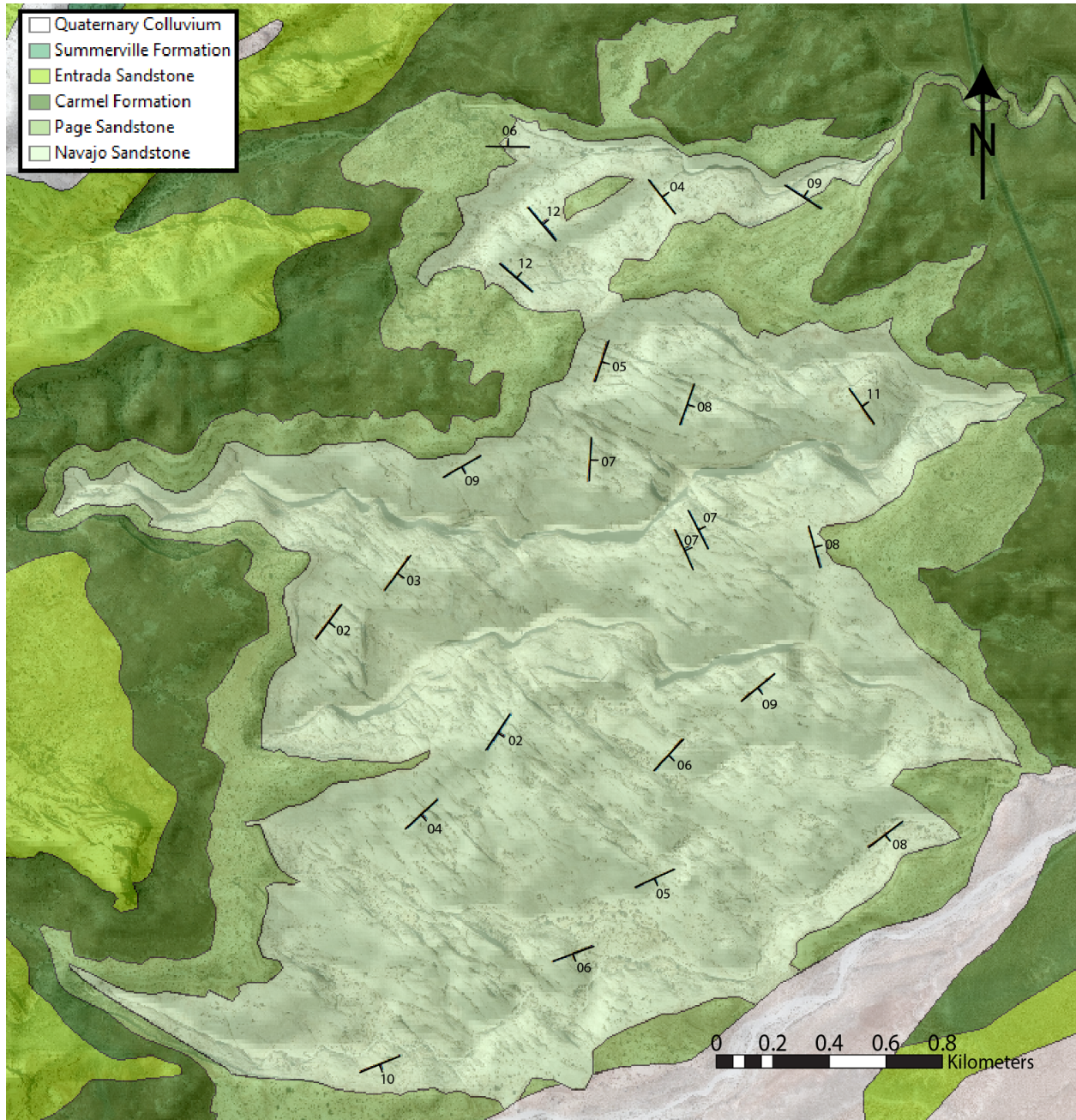


Figure 47: Map of bedding measurements across the Pulpit Arch.

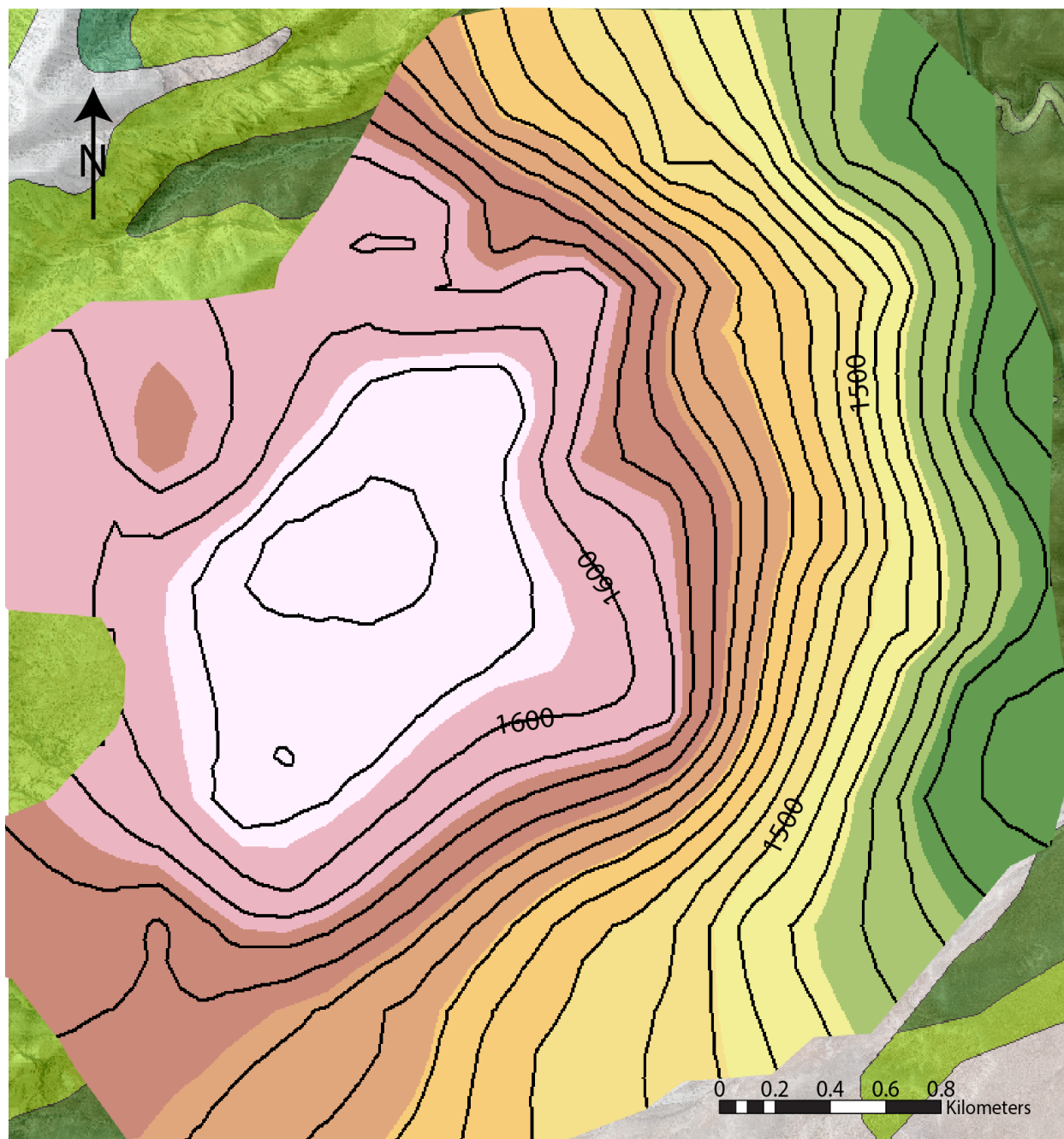


Figure 48: Structure contour map of the Navajo/Page contact in the Pulpit Arch. Contour interval is 10 m.

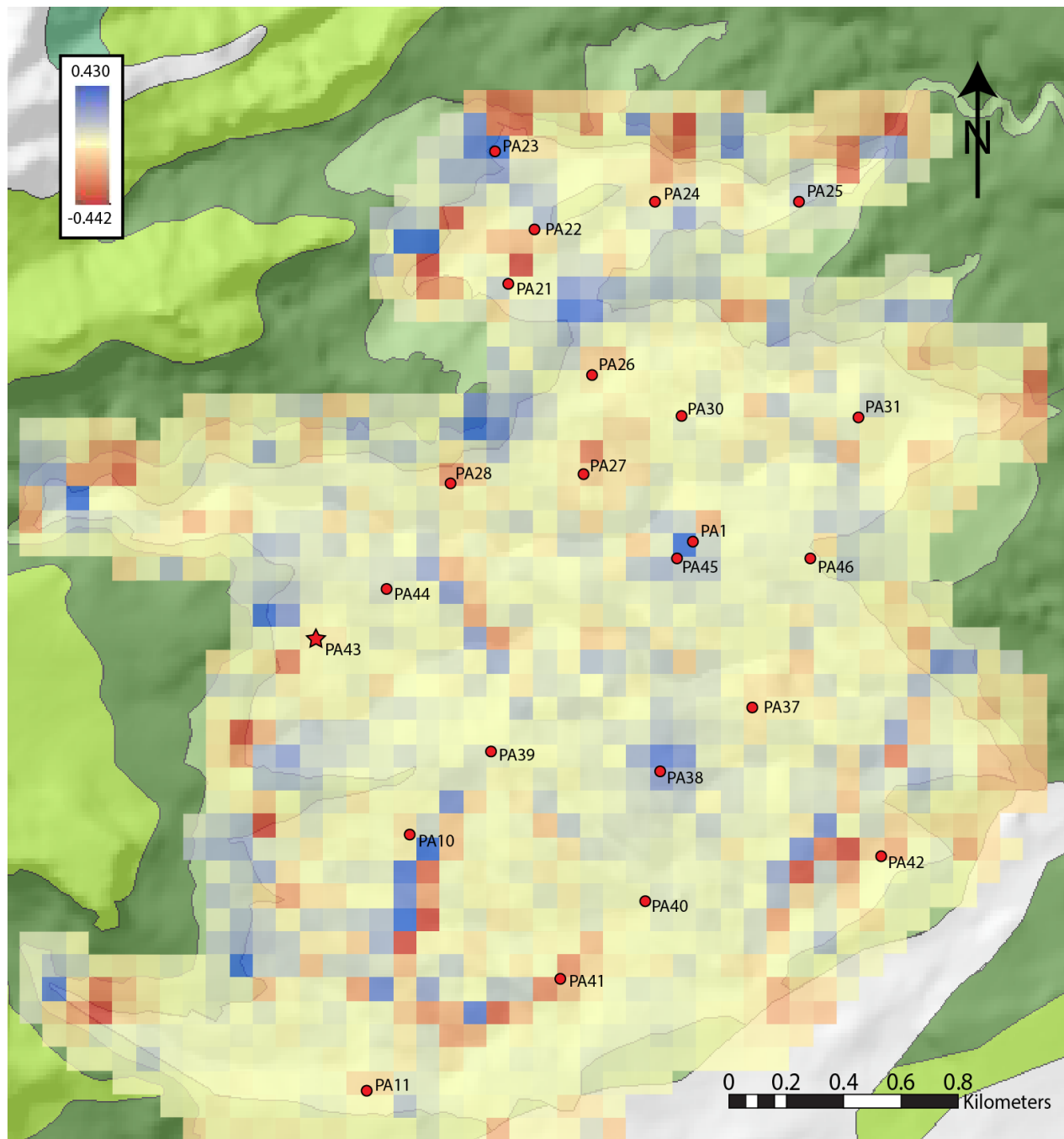


Figure 49: Curvature map of the Navajo Sandstone exposure in the Pulpit Arch area. Vibrant colors represent areas of relatively high curvature, muted colors represent areas of low curvature.

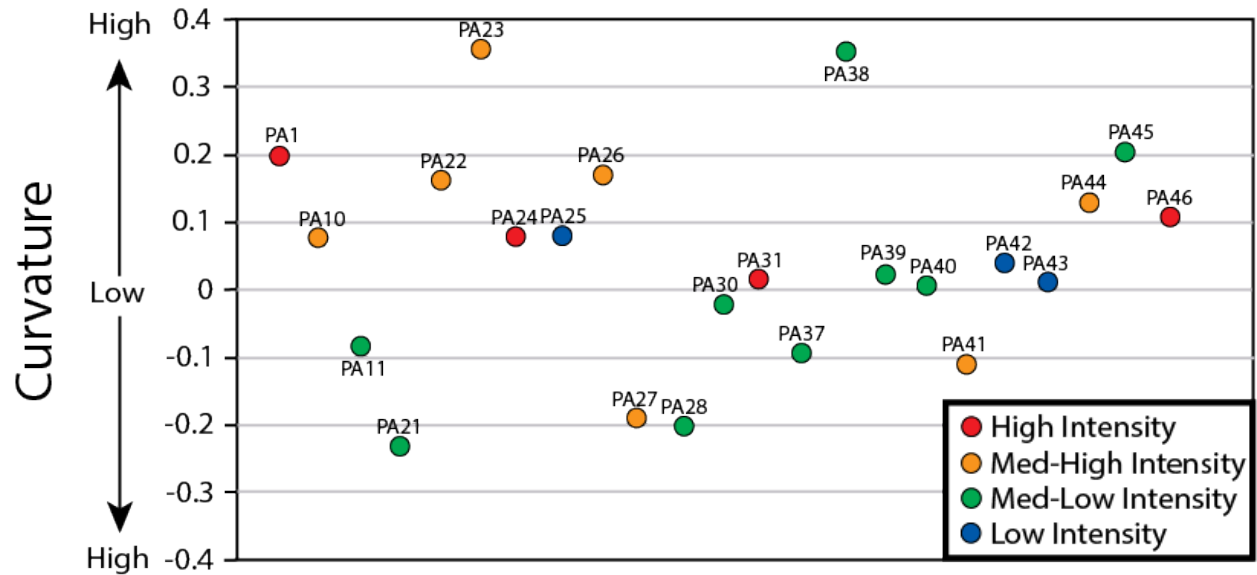


Figure 50: Curvature values at Pulpit Arch fracture stations.

Porosity Analysis

Overall, 56 photomicrographs were taken across the 10 thin sections. As previously described, 3 segments were isolated in each photomicrograph (Fig. 20). In undeformed samples, segments were chosen to provide as much coverage for the thin section, with little-to-no overlap between segments. Porosity values for deformed samples were measured by selecting segments away from deformation bands, if any were present in the thin section. Deformation band porosity was measured by selecting segments exclusively within the deformation band(s) present in the thin section. This prevented pore space around the deformation bands from skewing the measurements. For each micrograph, the average porosity of their respective segments was calculated to estimate the porosity of the entire photomicrograph. All thin sections and photomicrographs can be found in Appendix D.

The average porosity of all undeformed samples (Table 7) was 13.1%, with the porosity of individual segments (n=27) ranging from 11.7% to 14.5%. The average porosity value of deformed samples (Table 8) was 22.5%, with segments (n=78) ranging from 18.8% to 26.8%. Finally, the average porosity value of deformation bands (Table 9) was 2.2%, with segments (n=63) ranging from 0.6% to 3.5%. Porosity values for deformed, undeformed, and deformation band samples fall within the expected range for undeformed sandstone, deformed sandstone, and deformation bands, respectively (Uygur and Picard, 1980; Antonellini et al., 1993; Fossen, 2007; Fossen and Bale, 2007). In their study of deformation bands in Arches National Park, Antonellini et al. (1993) found coplanar patches (~0.5-5 cm in length) of host rock around a deformation band exhibited a porosity increase of ~9% due to grain rotation in deformation bands. This is a possible explanation for the higher porosity values measured in deformed samples compared to undeformed samples collected in this project.

Fracture Station #	1st PM Avg. (%)	2nd PM Avg. (%)	3rd PM Avg. (%)	4th PM Avg. (%)	5th PM Avg. (%)	Total Station Avg. (%)	Total Undeformed Sample Avg. (%)
PA13	14.5	12.9	13.6	13.7	11.9	13.3	13.1
PA15	18.6	13.3	12.2	13.5	-	12.9	

Table 7: Porosity values for undeformed samples. PM, photomicrograph.

Fracture Station #	1 st PM Avg. (%)	2 nd PM Avg. (%)	3 rd PM Avg. (%)	4 th PM Avg. (%)	Total Station Avg. (%)	Total Deformed Sample Avg. (%)
PA1	23.9	23.2	21.1	-	22.7	22.5
PA11	22.8	25.7	22.3	-	23.6	
PA23	24.3	18.8	20.3	21.0	21.1	
PA26	22.5	21.3	-	-	21.9	
PA30	26.8	20.9	20.3	-	22.7	
PA37	23.1	24.6	22.5	25.0	23.8	
PA41	21.9	20.6	23.6	22.0	22.0	
PA45	23.0	22.5	21.8	-	22.4	

Table 8: Porosity values for deformed samples outside of deformation bands. PM, photomicrograph.

Fracture Station #	1 st PM Avg. (%)	2 nd PM Avg. (%)	3 rd PM Avg. (%)	4 th PM Avg. (%)	Total Station Avg. (%)	Total Deformation Band Sample Avg. (%)
PA1	2.2	2.0	1.5	2.2	2.0	2.2
PA11	1.6	1.1	2.3	-	1.7	
PA23	2.7	3.2	1.5	-	2.5	
PA26	2.2	2.7	1.7	-	2.2	
PA30	1.7	2.9	1.2	2.2	2.0	
PA45	2.6	2.9	2.4	2.1	2.5	

Table 9: Porosity values for deformation bands in deformed samples. PM, Photomicrograph,

Discussion

Regional Fracture Systems

Observations of fractures within the Navajo Sandstone in the control area suggest there is a regional fracture set in the area. Fractures were observed in the control area only at station PA17. Comparison of the fractures seen in the Pulpit Arch and at PA17 reveal only one fracture orientation found in both areas: NW to SE. This orientation being present in the control area suggests that fractures with these orientations may have been influenced by events independent of the doming process. Fractures with NW to SE orientations within the Pulpit Arch may have developed prior to doming, then reactivated during the doming process. This may have caused NW to SE fractures to further develop, which could provide an explanation for the higher number of NW to SE fractures in the Pulpit Arch relative to the control area. The presence of the regional-scale joints (Fig. 14) may also indicate reactivation of slip surfaces, as these joints were not seen in the control area. However, NW to SE is not the dominant fracture orientation in the Pulpit Arch. This suggests any pre-existing fracture sets did not strongly influence later fracture development.

Previous work in the Colorado Plateau area (e.g. Kelley and Clinton, 1960; Jackson and Pollard, 1990; Bump and Davis, 2002) has also noted the presence of fractures trending NW to SE. Kelley and Clinton (1960) recorded the presence of extensive fracture sets trending NW to SE across the entirety of the Colorado Plateau. Jackson and Pollard (1990) recorded fracture characteristics at three of the Henry Mountains: Mt. Hillers, Mt. Holmes, and Mt. Ellsworth, and Bump and Davis (2002) studied fractures at several monoclines throughout the Colorado Plateau,

respectively. Jackson and Pollard (1990) and Bump and Davis (2002) both documented the presence of fractures trending NW to SE at their respective field sites.

Jackson and Pollard (1990) and Bump and Davis (2002) studied fractures at folded sites across the Colorado Plateau, which may indicate that NW to SE fractures are related to the folding of these sites. It seems unlikely that all of these chosen field areas would share deformation characteristics if the cause of deformation was unique to each specific site. Instead, the regionally extensive development of NW to SE fractures across the Colorado Plateau region may support their source being regional deformation.

Fractures in the Pulpit Arch

Fracture data recorded in the field generally agreed with predictive models such as those created by Cosgrove and Ameen (1999), who suggest fracture orientation in a dome is related to the slip direction along the bedding in the area, but tangential and radial fractures are common at the crest of a dome. Both types of fractures were observed in the Navajo Sandstone exposure in the Pulpit Arch and, overall, the distribution of tangential and radial fractures in the Pulpit Arch was generally uniform, (Fig. 46). This did seem to vary by station though, as some stations featured predominantly tangential fractures (Fig. 51) while others featured mostly radial fractures (Fig. 52).

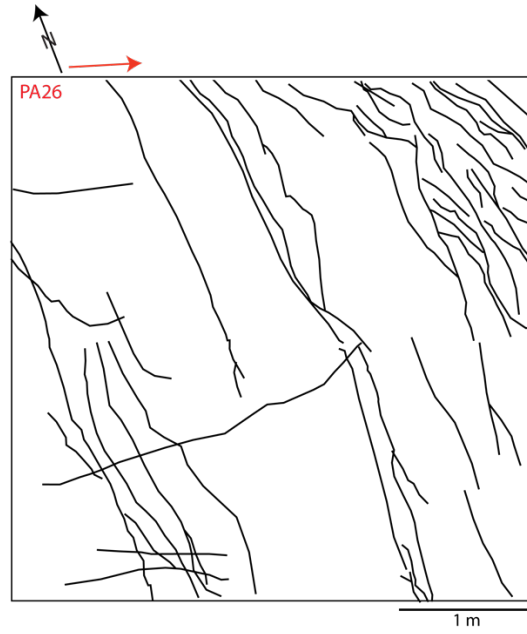


Figure 51: Fracture trace map for PA26, a station which exhibited predominately tangential fractures. Local Navajo bedding dip direction is indicated by the red arrow.

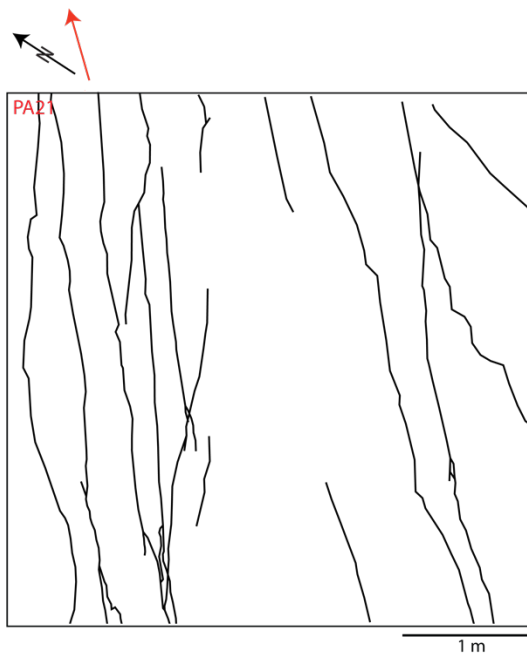


Figure 52: Fracture trace map for PA21, a station which exhibited predominately radial fractures. Local Navajo bedding dip direction is indicated by the red arrow.

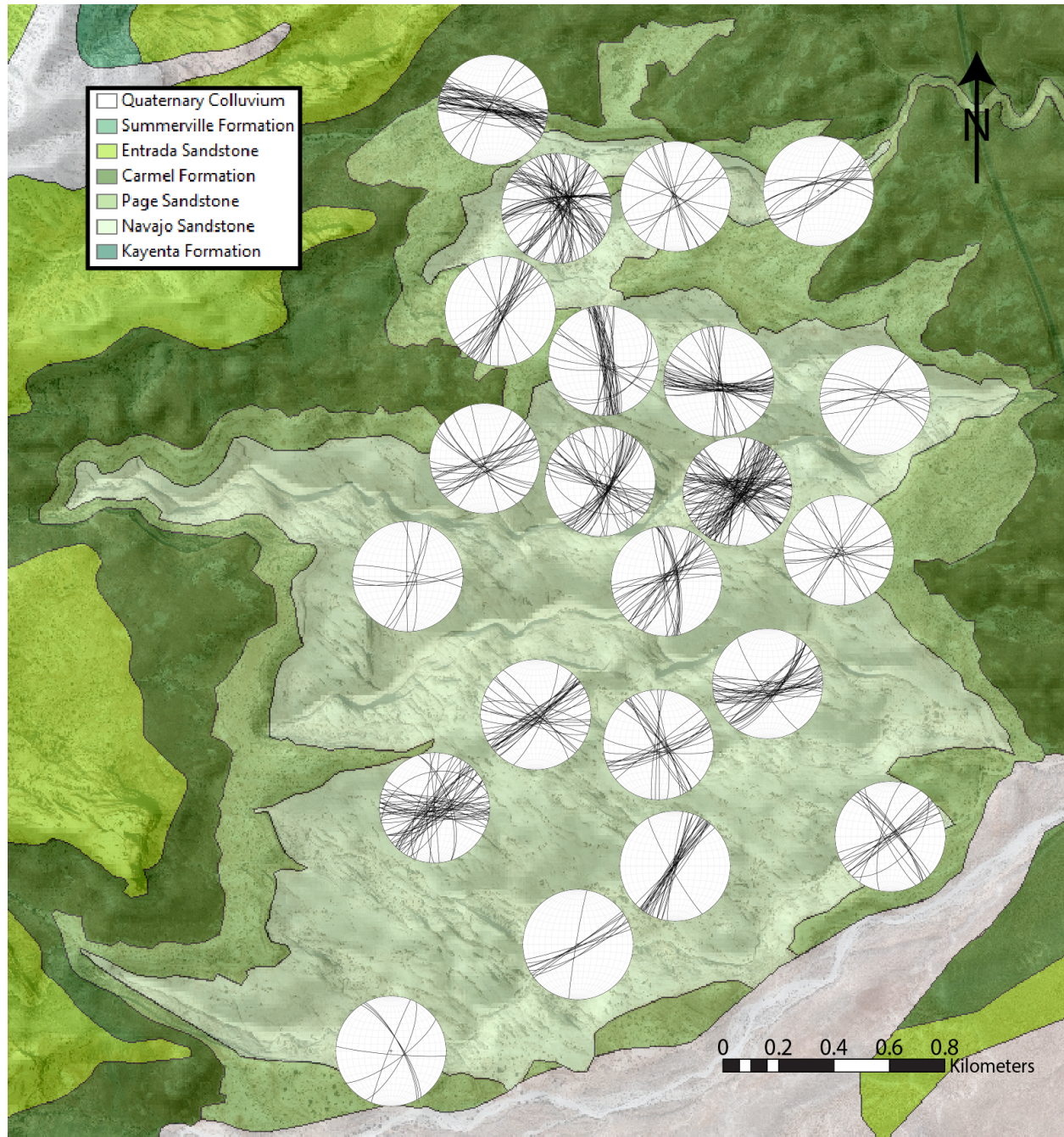


Figure 53: Stereonets for each fracture station at their respective locations.

Distinct fracture sets formed in the Pulpit Arch as a result of doming, and their characteristics vary throughout the dome (Fig.53). While stations with relatively complex fracture development featured both radial and tangential fractures, most relatively simple stations feature mostly tangential fractures. It is likely that early fractures that formed in the Pulpit Arch were primarily tangential, though significant fracturing allowed radial fractures to form (Jackson and Pollard, 1990).

It is important to note that no faults were found in the field area. As previously stated, as deformation band networks grow in complexity, they will eventually link and begin to act as slip surfaces, which may result in the formation of a fault (Aydin and Johnson, 1978; Pollard and Fletcher, 2005). The absence of faulting in the Navajo Sandstone of the Pulpit Arch suggests the deformation band systems are not advanced enough for appreciable offset to force fault development. By Jackson and Pollard's (1990) descriptions of early-, mid-, and late-stage domes, the Pulpit Arch would not have developed sufficiently to be considered even an early-stage dome. The lack of faulting and the relative simplicity of some of the fracture systems in this field area, compared to those studied in other literature, support this.

There appears to be some correlation between fracture termination style and fracture length. Border terminations were the clear dominant termination style, though that is likely due to the area of the field stations. Truncation-type and End-type terminations occurred more often with fractures of relatively low lengths. Lower mean fracture lengths were observed more commonly at stations with higher fracture intensities. This suggests that as areas experience deformation events, fractures will begin to develop more easily in areas that are already deformed, truncating against previously existing fractures. The introduction of new fractures near pre-existing ones may cause a transition from single fractures into clusters. No clusters of

deformation bands were seen in the control area, but were seen in the Pulpit Arch. High intensity fracture stations typically exhibited more clusters than low intensity stations. This suggests that clustering of deformation bands is a good indicator that a region has undergone more complex deformation and may help to explain deformation band evolution over time.

No clear correlation was found between curvature and fracture intensity (Fig. 50). Curvature values varied between fracture stations overall. Low-intensity stations did seem to favor areas of low curvature, though there may not be a large enough sample size for definitive conclusions. Due to the Navajo exposure likely lying entirely within the crest of the dome, curvature here should be relatively high compared to values on the limbs of the feature. It is also possible that the distribution of fracture stations across the Pulpit Arch may have resulted in curvature values being interpolated as low. More established stations would result in more complete coverage of the Pulpit Arch, and may provide more accurate curvature values in the area.

During early stages of deformation of porous sandstones, individual deformation bands may emerge and begin to grow. As the region undergoes more deformation, fracture systems begin to gain complexity, and old fracture surfaces may be reactivated. More individual bands may form near pre-existing bands, eventually resulting in clusters of deformation bands. As these clusters continue to grow in complexity, they may become interconnected networks, and may transition into larger fractures, such as faults or joints. (Fossen, 2007).

Cosgrove and Ameen (1999) suggested that fracture intensity increases with increasing curvature in a dome. In their model, the crest and the outer hinge of a dome have a relatively high fracture intensity, while the limbs of the dome have a relatively low fracture intensity. While fracture intensity varied between stations, the northern half of the field area had a larger

presence of Med-High and High intensity fracture stations. Furthermore, the lack of significant pattern in the distribution in fracture intensities across the Navajo exposure in the Pulpit Arch suggests that the Navajo lies entirely in the crest of the dome, and the dome extends under the nearby Carmel Formation or Entrada Sandstone. Increasing the number of fracture stations both in the Navajo Sandstone of the Pulpit Arch and surrounding units (Page Sandstone, Carmel Formation, etc.) would allow for an accurate location of the crest and hinges of the underlying intrusion.

Analogue to Other Domes

Average porosity values in Navajo Sandstone samples agree with those found by Uygun and Picard (1980), who found porosity values generally ranging from 7 to 35%. Porosity values in deformed Pulpit Arch samples had averages higher than the undeformed samples by ~9%. As previously stated, this may be due to the proximity to deformation bands that porosity measurements of deformed sandstones were measured (Antetollini et al., 1993). Deformation bands exhibited extremely low porosity values (1.1% to 2.9%), agreeing with their tendency to baffle fluid movement (Fossen, 2007; Fossen and Bale, 2007).

Extension values calculated for the Pulpit Arch (0.63% to 0.96%) were much lower than those calculated for other Henry Mountain domes by Jackson and Pollard (1990). Jackson and Pollard (1990) calculated values of 4% and 12% at Mount Holmes and Mount Ellsworth, respectively. The Pulpit Arch is an extremely early stage dome, and the comparison of extension values calculated for this project and published values by Jackson and Pollard (1990) reflect that.

Further application of similar methodology used in this project on other domes in the Henry Mountains would lead to further understanding on the range of dome development in the region.

Conclusions

It is likely that dominant fracture patterns observed in the Pulpit Arch are tied directly to doming of the area by a subsurface igneous intrusion. Relatively high fracture intensity in the Pulpit Arch compared to the control area suggests that while a regional fracture pattern likely does exist, further deformation causes fracture systems to grow in complexity. This may happen through reactivation of pre-existing slip surfaces. In the case of deformation bands, the only fracture type observed in the Navajo, this may lead to the development of faults. Though it may seem relatively developed, comparing extension values calculated in this project with those measured on other intrusion-fed domes nearby reveals the Pulpit Arch is in an extremely early stage of development.

Many fracture characteristics remained similar across the Pulpit Arch. As expected of aeolian sandstone, deformation bands were the only fracture type observed in the field. Fracture subtypes were fairly evenly distributed, with only a few more CDBs than SDBs. Border-type was the dominant termination style, though that is likely affected by the station area. Radial and tangential fractures were evenly distributed overall, with some stations favoring one type over the other.

Porosity values found in this project generally agree with previously found values for undeformed sandstone, deformed sandstone, and deformation bands, respectively. High porosity values calculated here in deformed sandstones may be a result from the close proximity of the measurement location to a deformation band. Porosity measurements reaffirm the Navajo Sandstone as a good reservoir analogue.

Based on the data collected in this project, there are fracture patterns that develop as a direct result of the doming process. However, it is likely the Pulpit Arch is in too early a stage of doming for any significant fracture patterns to form. With progressive deformation, fracture systems begin to self-organize, and more apparent patterns will develop in fracture characteristics. Despite no strong patterns present at the Pulpit Arch, the full coverage of sedimentary strata on the dome allows for data to be collected across the extent of the dome's crest.

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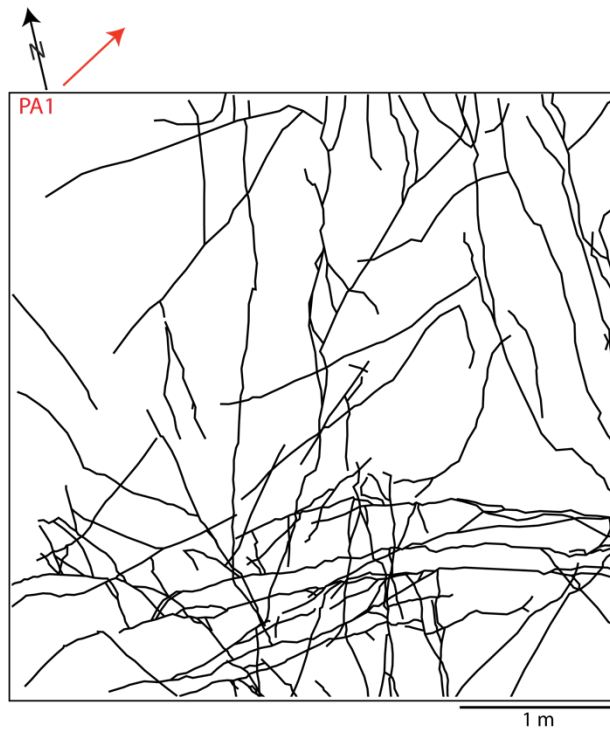
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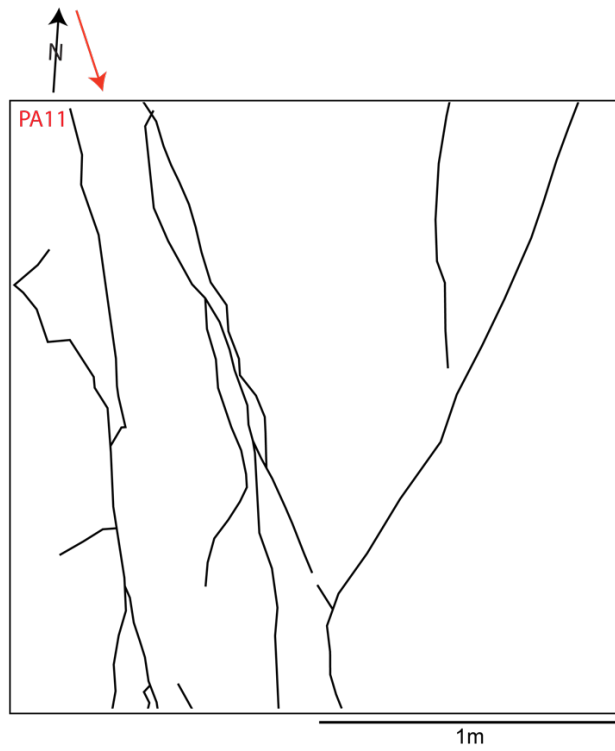
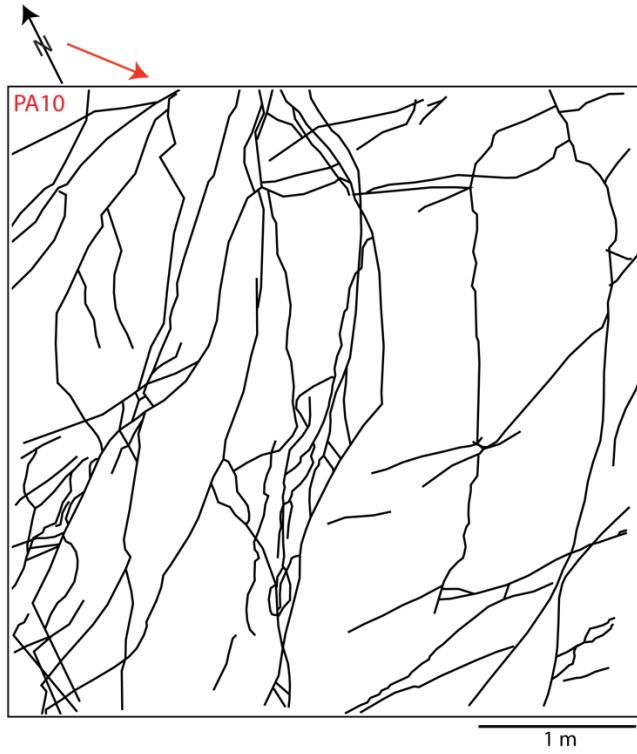
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Appendix A – Fracture Trace Data

Local Navajo bedding dip direction is indicated by the red arrow.

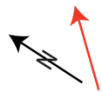




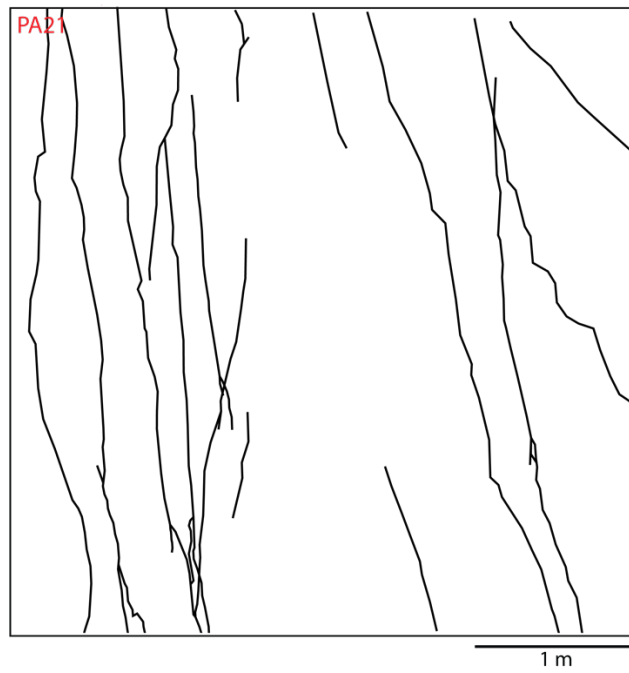


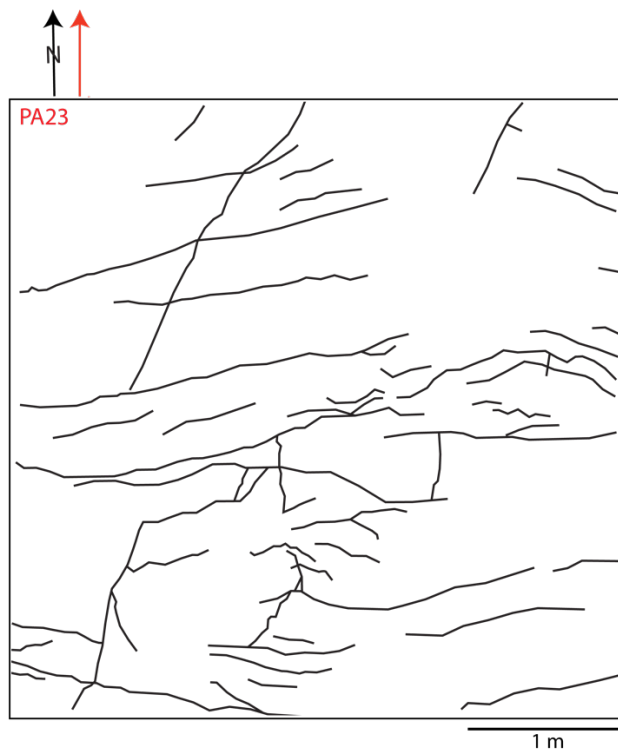
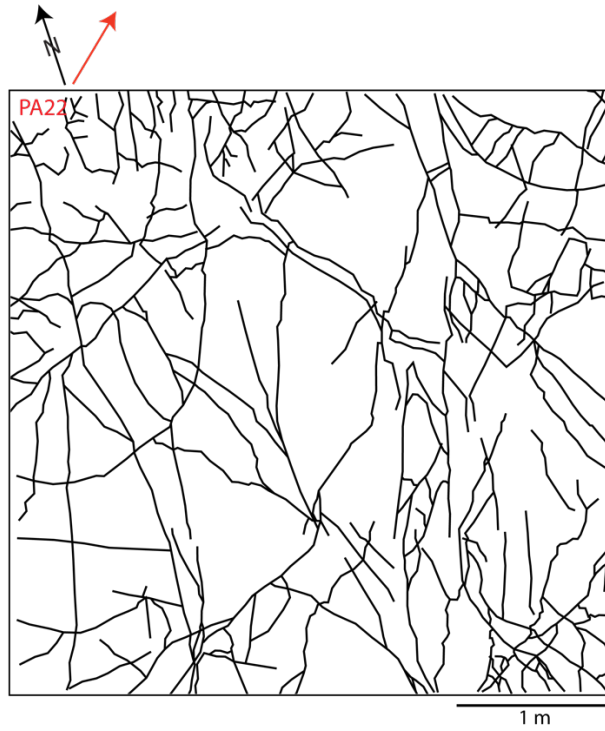
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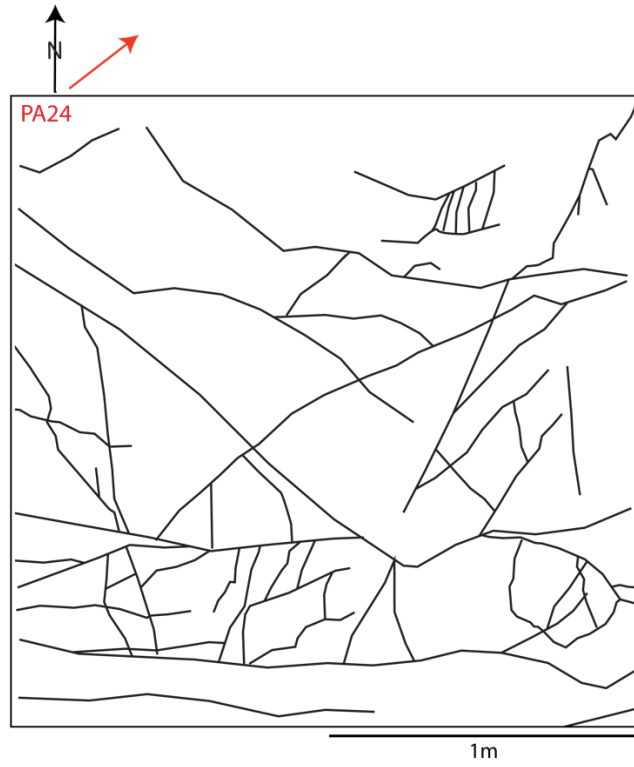
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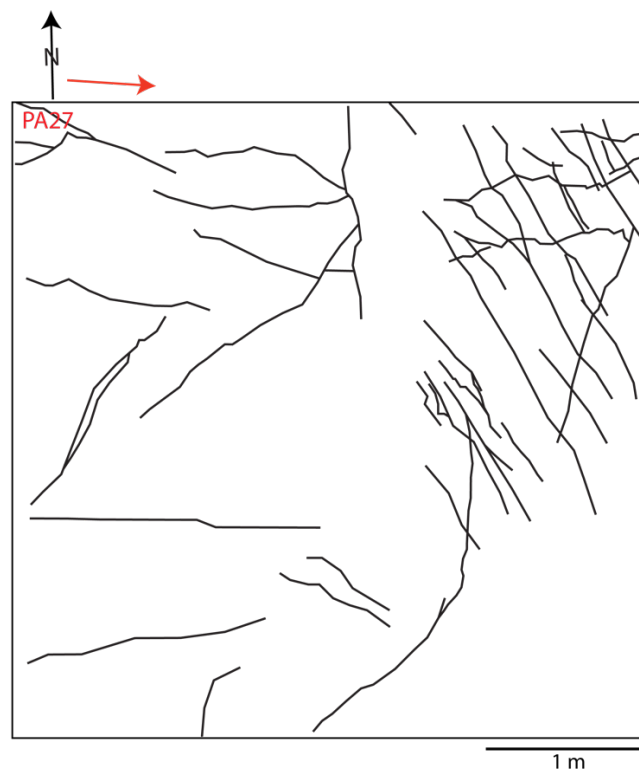
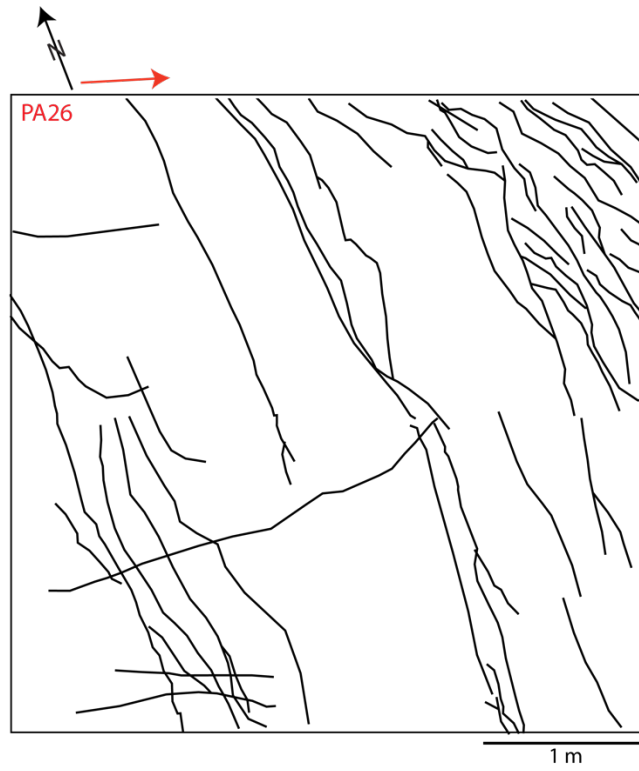


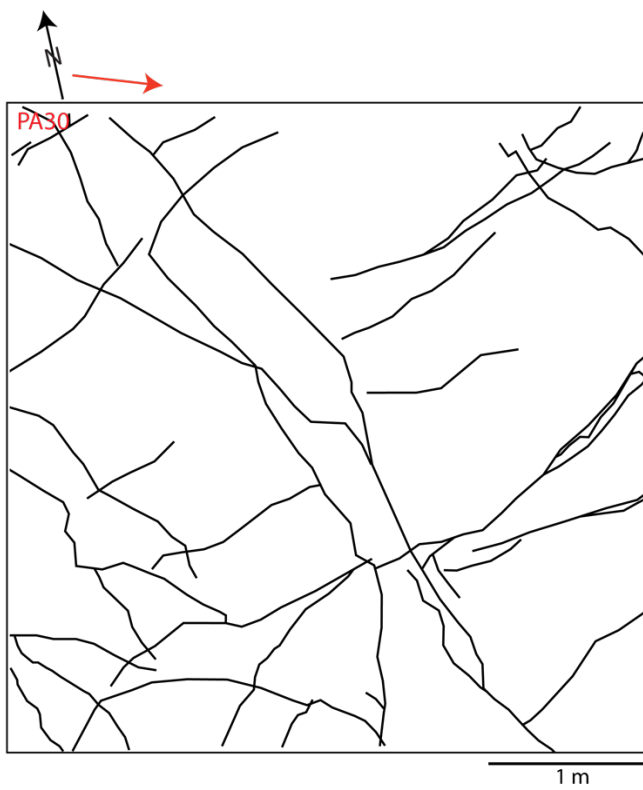
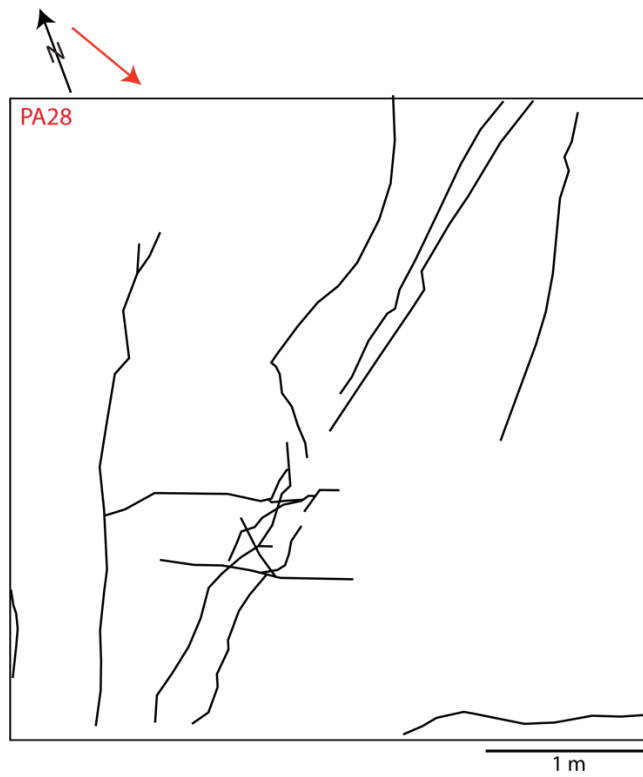
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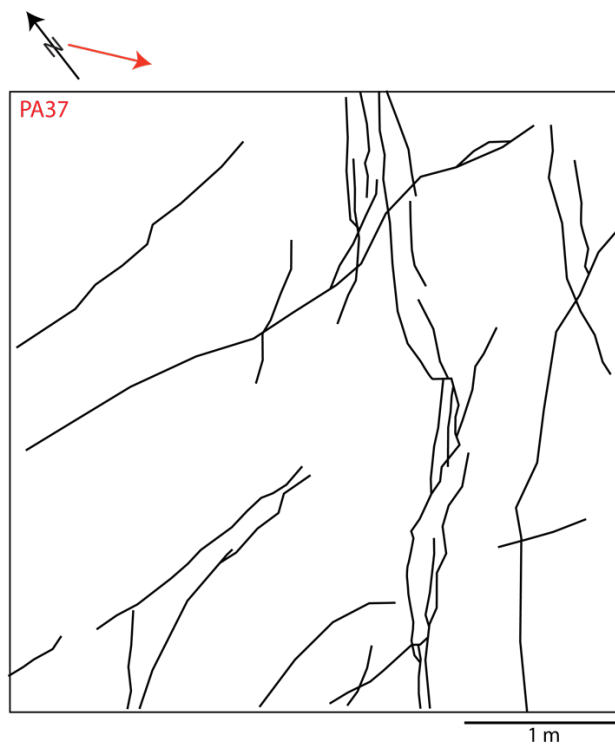
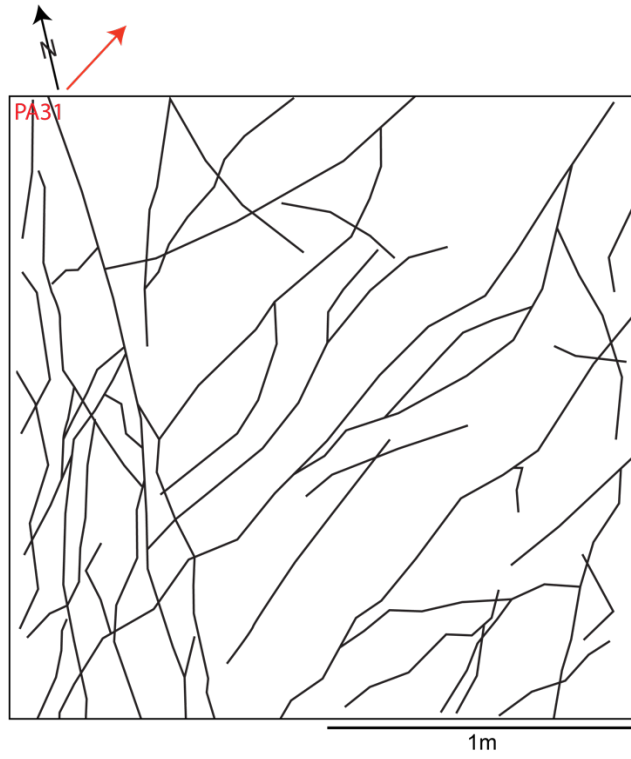


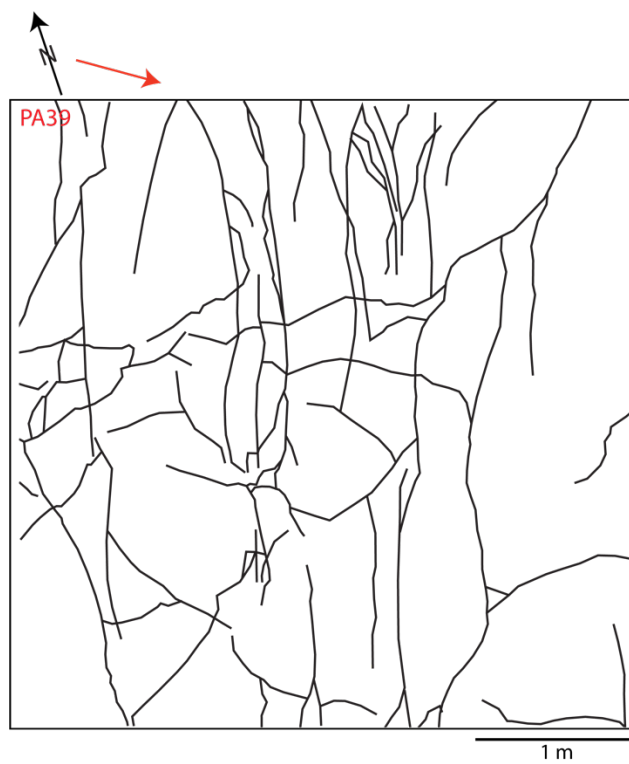
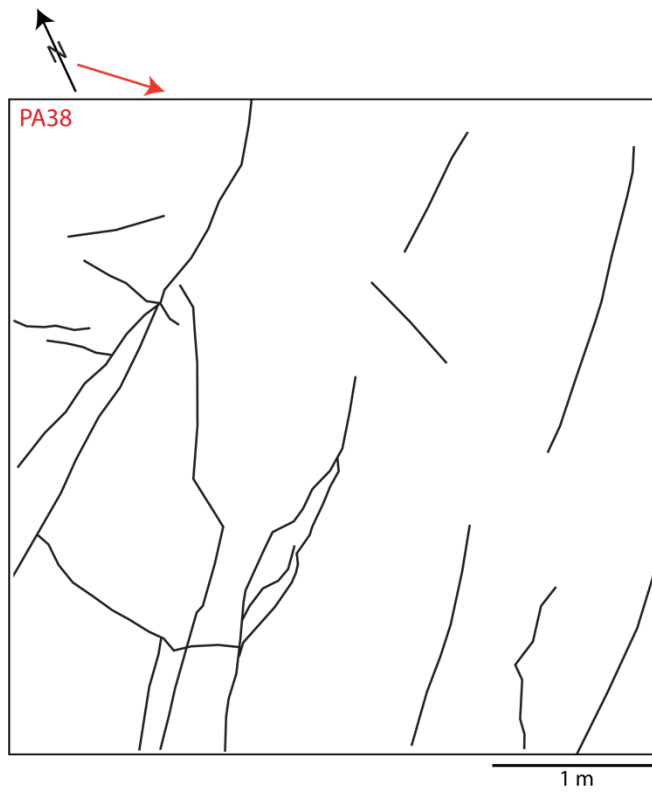


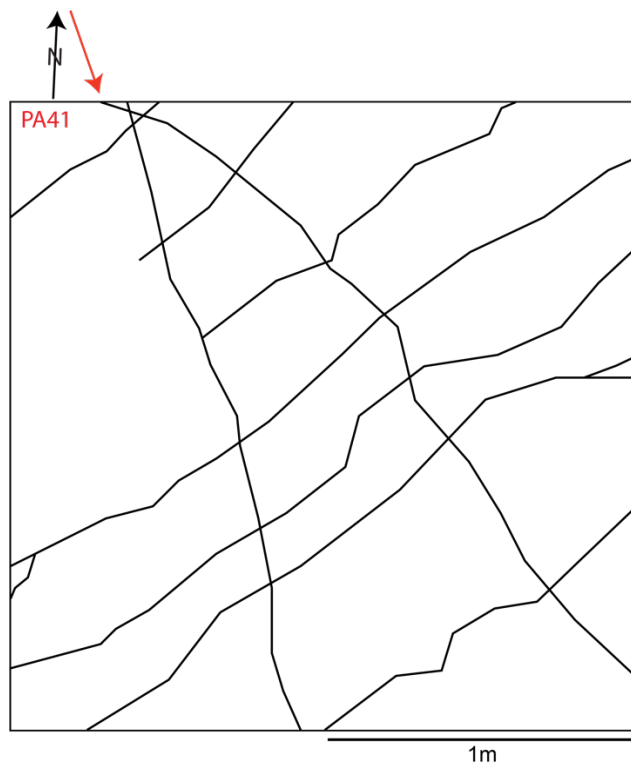
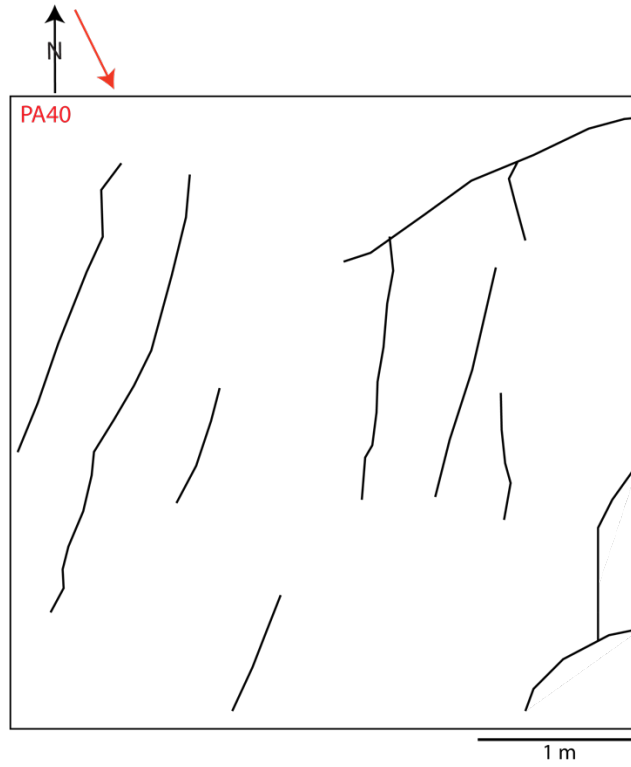


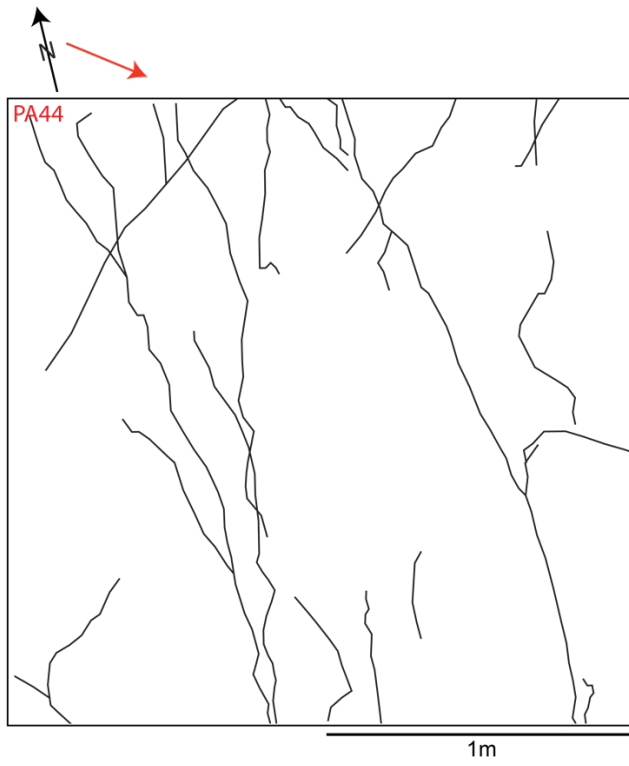
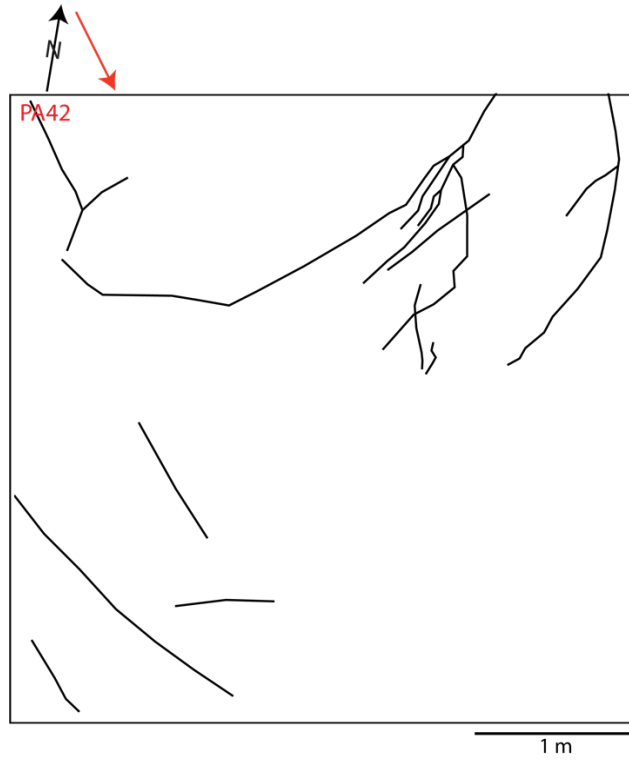


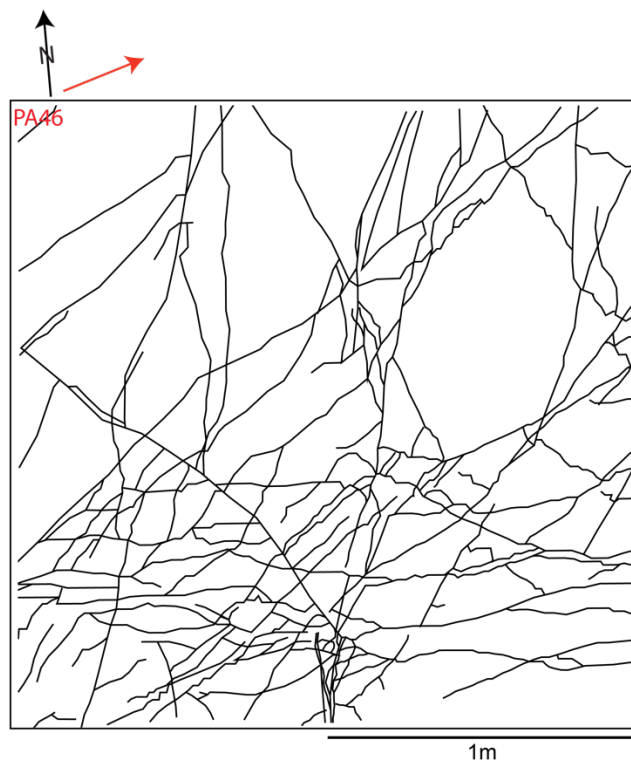
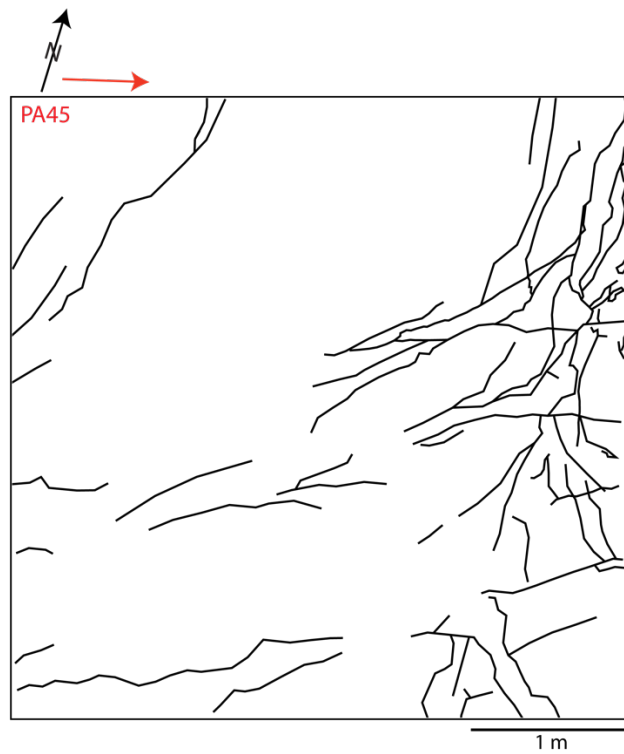












Appendix B – Raw Fracture Data

FT – Fracture Type

SDB – Single Deformation Band

CDB – Cluster Deformation Band

PDB – Proto Deformation Band

C – Clustering

P – Planarity

DM – Dip Magnitude

DD – Dip Direction

S – Strike

L – Length (dm)

T – Termination Style

B – Border Termination

E – End Termination

T/x – Truncation Termination/Set # fracture truncates into

Set # - Fracture Set Number

ISO – Isolated Fracture

X-C – Cross-Cutting

Y – Yes (offset in cm)

N – No

PA 1 (1/2):

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
A	SDB		1	86	107	17	9	B,T/2	1	N
A	SDB		1	82	136	46	2	B,T/2	1	N
A	SDB		2	68	324	234	20	B,B	1	N
A	CDB	3	2	88	138	48	20	B,B	1	N
A	CDB	2	2	88	125	35	5	B,T/2	1	N
A	SDB		1	89	147	57	6	B,E	2	N
A	SDB		1	84	165	75	27	B,B	2	N
A	SDB		1	83	166	76	6	B,B	2	N
A	CDB	1	1	82	196	106	16	B,B	3	N
A	SDB		2	79	18	288	8	B,E	3	N
A	SDB		1	74	358	268	4	B,B	3	N
A	SDB		2	84	44	314	4	T/2,E	ISO	N
B	SDB		2	88	122	32	23	B,B	1	N
B	SDB		2	88	120	30	22	B,B	1	N
B	SDB		2	84	120	30	21	B,B	1	N
B	SDB		3	80	106	16	6	B,T/1	1	N
B	SDB		1	80	121	31	3	B,T/ISO	1	N
B	CDB	1	2	82	132	42	7	B,T/2	1	N
B	SDB		2	86	300	210	4	E,T/2	1	N
B	SDB		1	84	91	1	2	T/1,T/2	1	N
B	SDB		2	87	115	25	3	B,T/3	1	N
B	SDB		2	88	211	121	12	T/2,T/1a	2	N
B	CDB	1	2	76	355	265	12	B,T/3	2	N
B	CDB	1	3	78	0	270	10	B,T/3	2	N
B	SDB		2	88	10	280	6	T/2,T/3	2	N
B	SDB		1	86	12	282	4	B,T/3	2	N
B	SDB		1	82	15	285	4	B,T/3	2	N
B	SDB		3	85	20	290	3	T/1,E	2	N
B	CDB	1	1	86	14	284	1	T/1,E	2	N
B	SDB		2	86	348	258	1	T/1,T/1	2	N
B	CDB	1	2	80	325	235	11	T/2,B	3	N
B	SDB		2	74	335	245	18	E,E	3	N
B	SDB		2	89	13	283	2	B,E	3	N
B	SDB		2	86	355	265	1	B,E	3	N
B	SDB		1	73	145	55	5	B,T/1	ISO	N
B	SDB		1	70	320	230	2	T/2,T/2	ISO	N
B	SDB		2	78	185	95	3	B,E	ISO	N
C	SDB		1	88	120	30	7	E,T/3	1	N
C	SDB		1	88	130	40	3	T/2,E	1	N
C	SDB		2	68	295	205	8	T/2a,T/2	1	N
C	CDB	1	2	88	295	205	10	B,T/2	1	N
C	SDB		1	70	133	43	10	B,E	1	N
C	SDB		1	70	308	218	10	B,T/ISO	1	N
C	SDB		2	80	295	205	10	B,T/ISO	1	N
C	CDB	3	2	80	290	200	20	B,B	1	N

PA 1 (2/2):

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
C	SDB		2	82	125	35	11	B,T/3	1	N
C	SDB		2	70	122	32	4	T/3,T/3	1	N
C	SDB		2	84	126	36	9	T/3,T/3	1	N
C	SDB		2	86	115	25	4	T/3,T/3	1	N
C	SDB		1	82	280	190	3	E,E	1	N
C	CDB	1	1	83	116	26	8	T/3,T/2	1	N
C	CDB	2	2	82	158	68	19	B,B	2	N
C	SDB		2	84	160	70	21	B,T/3	2	N
C	CDB	1	2	75	145	55	13	B,T/3	1	N
C	CDB	1	1	72	149	59	2	T/1,T/1	ISO(?)	N
C	SDB		2	74	153	63	10	B,E	2	N
C	SDB		2	78	335	245	3	E,T/3	2	N
C	SDB		1	76	350	260	2	T/1,T/3	2	N
C	SDB		2	76	153	63	3	T/3,T/3	2	N
C	CDB	1	2	88	218	128	22	B,B	3	N
C	SDB		1	89	37	307	3	T/2,T/2	3	N
C	CDB	1	3	86	220	130	13	T/2,T/3	3	N
C	CDB	2	2	82	231	141	23	B,B	3	N
C	SDB		3	84	200	110	17	B,B	3	N
C	CDB	2	2	87	196	106	13	B,B	3	N
C	CDB	2	1	88	200	110	17	B,B	3	N
C	CDB	1	2	84	290	200	8	B,T/3	1	N
C	SDB		2	78	10	280	16	B,T/3	ISO (2a)	N
C	CDB	2	2	78	225	135	8	B,T/3	ISO	N
C	SDB		2	80	280	190	4	T/3,T/3	ISO	N
D	SDB		1	83	355	265	15	E,E	1	N
D	CDB	1	2	83	334	244	5	B,B	1	N
D	SDB		2	80	355	265	12	B,T/2	1	N
D	SDB		2	80	7	277	14	B,T/2	1	N
D	SDB		2	86	355	265	2	B,E	1	N
D	SDB		2	81	186	96	4	T/2,E	1	N
D	SDB		1	72	170	80	2	T/2,T/2	1	N
D	SDB		1	81	215	125	8	E,T/1c	2	N
D	SDB		1	83	217	127	17	B,B	2	N
D	CDB	1	2	82	226	136	14	B,T/1	2	N
D	CDB	2	2	82	232	142	15	B,B	2	N
D	SDB		1	76	215	125	7	B,E	2	N
D	SDB		2	79	216	126	7	E,T/3	2	N
D	SDB		3	66	207	117	9	E,T/2	2	N
D	CDB	3	2	86	135	45	14	B,T/1	3	N
D	CDB	3	2	85	130	40	19	B,B	3	N
D	SDB		1	85	124	34	2	T/2,T/2	3	N
D	SDB		2	80	303	213	9	B,T/2	3	N
D	SDB		2	81	135	45	8	B,T/2	3	N
D	SDB		2	81	280	190	10	B,B	ISO	N
D	SDB		2	80	310	220	8	E,T/2	3	N

PA 10 (1/2):

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
A	SDB		3	72	120	30	21	B,B	1	N
A	CDB	1	2	84	290	200	22	B,B	1	N
A	SDB		2	88	124	34	10	T/2,T/2	1	N
A	SDB		2	86	275	185	3	T/2,E	1	N
A	SDB		3	88	265	175	4	T/2,T/2	1	N
A	CDB	3	2	82	312	222	21	B,B	2	N
A	SDB		1	87	141	51	21	B,B	2	N
A	SDB		3	89	307	217	19	B,B	2	N
A	SDB		2	81	323	233	19	B,B	2	N
A	SDB		2	83	150	60	5	T/1,E	2	N
A	SDB		3	82	310	220	5	T/2,B	2	N
A	SDB		1	84	164	74	13	T/1,B	3	N
A	CDB	1	2	72	10	280	11	T/2,B	3	N
A	SDB		1	76	14	284	4	T/2,T/2	3	N
A	SDB		3	78	186	96	5	T/1,T/2	3	N
A	SDB		2	75	180	90	5	T/1,T/2	3	N
A	SDB		2	76	270	180	5	T/2,E	ISO	N
B	SDB		3	74	118	28	20	B,B	1	N
B	SDB		3	80	300	210	24	B,B	1	N
B	SDB		1	89	180	90	5	T/1,B	2	N
B	SDB		1	89	167	77	4	T/1,B	2	N
B	SDB		2	88	175	85	2	T/1,B	2	N
B	SDB		2	88	335	245	11	T/3,B	2	N
B	SDB		2	86	14	284	9	T/2,B	3	N
B	SDB		3	85	200	110	17	T/1,B	3	N
B	SDB		2	89	209	119	10	T/1,B	3	N
B	SDB		2	89	173	83	14	B,B	3	N
B	SDB		2	78	0	270	10	B,B	3	N
B	SDB		2	80	190	100	5	B,E	3	N
B	SDB		3	80	20	290	6	T/1,B	3	N
C	SDB		3	62	290	200	6	B,T/2	1	N
C	SDB		2	66	74	344	4	T/2,T/2	1	N
C	SDB		2	70	74	344	6	T/2,T/2	1	N
C	SDB		3	81	140	50	6	B,E	2	N
C	CDB	2	3	78	315	225	21	B,B	2	N
C	SDB		2	78	135	45	15	B,T/2	2	N
C	SDB		2	78	150	60	20	B,B	2	N
C	CDB	3	3	72	310	220	21	B,B	2	N
C	SDB		2	72	150	60	7	B,T/2	2	N
C	SDB		2	80	5	275	6	B,T/1	ISO	N
D	CDB	2	2	79	150	60	13	B,B	1	N
D	SDB		1	81	130	40	21	B,B	1	N
D	SDB		2	80	295	205	15	B,E	1	N
D	CDB	1	2	86	315	225	4	B,E	1	N
D	SDB		2	87	5	275	17	B,E	2	N
D	SDB		2	86	185	95	9	B,E	2	N
D	SDB		1	79	350	260	4	T/1,T/1	2	N

PA 10 (2/2):

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
D	CDB	1	1	86	354	264	10	B,T/1	2	N
D	SDB		2	32	348	258	10	B,T/1	2	N
D	SDB		1	76	315	225	1	T/2,T/2	1	N
D	SDB		2	80	180	90	7	B,T/1	2	N
D	CDB	3	2	80	180	90	4	B,E	2	N
D	SDB		1	81	185	95	2	B,E	2	N

PA 11:

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
ONLY	SDB		2	74	90	360	10	B,T/ISO	1	N
ONLY	CDB	1	1	74	65	335	21	B,B	1	N
ONLY	CDB	1	2	72	60	330	22	B,B	1	N
ONLY	CDB	1	2	73	63	333	21	B,B	1	N
ONLY	SDB		1	80	290	200	18	B,T/1	ISO	N
ONLY	SDB		2	79	119	29	5	B,E	ISO	N
ONLY	SDB		3	84	145	55	7	B,T/1	ISO	N
ONLY	SDB		2	86	5	275	9	B,T/1	ISO	N

PA 13:

No Fractures Present

PA 15:

No Fractures Present

PA 17:

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C	
A	PDB		1	88	66	336	18	B,B	1	N	
A	PDB		2	84	52	322	18	B,B	1	Y	8
A	PDB		2	83	65	335	4	B,B	1	N	
B	PDB		2	83	65	335	18	B,B	1	N	
B	PDB		2	84	52	322	15	B,E	1	Y	8
B	PDB		2	82	65	335	16	B,B	1	Y	6
C	PDB		1	88	67	337	16	B,B	1	N	
C	PDB		2	80	66	336	11	B,B	1	N	
C	PDB		1	80	68	338	20	B,B	1	N	
C	PDB		1	86	76	346	4	B,E	1	N	
C	PDB		1	86	80	350	7	B,E	1	N	
D	PDB		2	83	57	327	4	B,B	1	N	
D	PDB		2	86	56	326	13	E,E	1	N	
D	PDB		1	89	59	329	9	B,E	1	N	
D	PDB		1	83	70	340	10	B,E	1	N	

PA 18:

No Fractures Present

PA 21:

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
A	SDB		2	83	302	212	8	B,E	1	N
A	CDB	2	3	82	311	221	20	B,B	1	N
A	CDB	3	3	81	123	33	20	B,B	1	N
A	SDB		3	85	115	25	20	B,B	1	N
A	SDB		3	84	119	29	21	B,B	1	N
A	CDB	2	3	82	125	35	19	B,B	1	N
B	CDB	1	2	87	307	217	20	B,B	1	N
B	CDB	2	3	86	115	25	21	B,B	1	N
B	SDB		1	86	111	21	9	B,B	1	N
B	SDB		3	81	273	183	14	B,B	ISO	N
B	CDB	3	2	78	282	192	14	B,T/1	ISO	N
B	SDB		2	77	234	144	10	E,T/1	ISO	N
C	CDB	1	3	88	329	239	18	B,B	1	N
C	SDB		3	84	138	48	16	B,B	1	N
C	CDB	2	1	87	134	44	17	B,B	1	N
C	CDB	3	3	88	124	34	17	B,B	1	N
C	SDB		3	89	109	19	14	B,E	1	N
D	CDB	2	2	86	302	212	16	B,B	1	N
D	CDB	1	3	78	140	50	19	B,B	2	N
D	SDB		2	88	293	203	12	B,E	1	N
D	CDB	3	3	88	110	20	17	B,B	2	N
D	SDB		3	79	253	163	4	B,B	ISO	N

PA 22 (1/2):

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
A	SDB		3	84	118	28	7	B,T/3	1	N
A	CDB	2	3	82	77	347	6	B,T/2	1	N
A	SDB		2	84	87	357	7	B,T/2	1	N
A	SDB		3	85	285	195	7	T/3,T/3	1	N
A	SDB		3	83	264	174	12	B,B	1	N
A	SDB		2	82	109	19	3	B,T/2	1	N
A	SDB		2	84	125	35	9	B,B	1	N
A	CDB	3	3	84	253	163	12	B,B	1	N
A	CDB	3	3	83	254	164	8	B,B	1	N
A	SDB		1	82	249	159	2	E,E	1	N
A	SDB		3	81	79	349	7	E,E	1	N
A	CDB	2	3	80	90	360	5	B,E	1	N
A	CDB	2	3	88	164	74	11	B,E	2	N
A	SDB		2	86	190	100	3	B,E	2	N
A	CDB	2	3	72	21	291	14	B,B	2	N
A	SDB		3	80	354	264	11	B,B	2	N
A	CDB	1	3	80	0	270	4	B,B	2	N
A	SDB		3	82	350	260	2	T/1,T/1	2	N
A	CDB	3	3	80	228	138	4	E,E	3	N
A	CDB	1	2	82	30	300	11	B,B	3	N
A	CDB	3	3	82	220	130	3	T/1,T/1	3	N
A	SDB		2	82	42	312	4	B,T/1	3	N
A	SDB		1	81	44	314	2	B,T/2	3	N
A	SDB		3	82	211	121	3	B,E	3	N
A	SDB		3	83	209	119	4	T/1,T/1	3	N
B	CDB	3	3	72	272	182	17	B,B	1	N
B	CDB	2	3	76	265	175	7	B,E	1	N
B	SDB		3	86	263	173	15	B,B	1	N
B	SDB		2	80	76	346	4	B,E	1	N
B	SDB		3	80	88	358	9	B,B	1	N
B	SDB		3	86	60	330	8	B,B	1	N
B	SDB		1	76	84	354	1	B,B	1	N
B	CDB	3	3	80	172	82	8	B,B	2	N
B	CDB	1	2	80	355	265	10	B,B	2	N
B	CDB	1	3	84	350	260	5	B,T/1	2	N
B	SDB		3	86	246	156	3	B,T/1	2	N
B	CDB	1	3	84	349	259	9	B,E	2	N
B	CDB	2	2	84	351	261	14	B,T/1	2	N
B	SDB		2	82	350	260	3	B,E	2	N
B	CDB	2	3	81	352	262	9	B,E	2	N
B	SDB		2	80	35	305	3	B,E	ISO	N
C	CDB	3	2	88	308	218	12	B,B	1	N
C	SDB		1	87	306	216	8	E,E	1	N
C	SDB		3	86	134	44	5	E,E	1	N
C	SDB		1	87	126	36	12	B,B	1	N
C	SDB		3	86	304	214	4	T/2,T/2	1	N

PA 22 (2/2):

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
C	SDB		3	86	126	36	2	T/2,T/2	1	N
C	CDB	1	3	85	60	330	12	B,B	2	N
C	SDB		2	85	124	34	4	B,E	2	N
C	SDB		2	86	216	126	6	B,E	2	N
C	CDB	2	1	86	35	305	6	B,E	2	N
C	SDB		3	85	223	133	3	B,E	2	N
C	CDB	1	3	80	0	270	9	B,B	2	N
C	SDB		2	76	49	319	4	T/1,T/1	2	N
C	SDB		3	86	235	145	8	B,T/1	2	N
C	CDB	3	2	78	29	299	6	B,E	2	N
D	CDB	2	3	84	346	256	9	B,B	1	N
D	CDB	1	3	82	333	243	12	B,B	1	N
D	SDB		2	82	317	227	12	B,B	1	N
D	CDB	1	3	81	134	44	16	B,B	1	N
D	CDB	1	3	74	135	45	12	B,B	1	N
D	CDB	2	3	74	305	215	12	B,B	1	N
D	CDB	1	3	80	112	22	13	B,B	1	N
D	SDB		1	83	110	20	9	B,B	1	N
D	CDB	1	3	82	107	17	6	B,E	1	N
D	CDB	1	2	76	40	310	14	B,B	2	N
D	SDB		2	78	226	136	3	B,T/2	2	N
D	CDB	2	2	79	39	309	3	B,T/2	2	N
D	CDB	2	2	77	31	301	8	B,T/1	2	N
D	SDB		2	80	354	264	2	T/1,T/1	ISO	N
D	CDB	2	2	81	355	265	2	T/1,T/1	ISO	N

PA 23:

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
A	CDB	2	2	77	192	102	15	B,B	1	N
A	SDB		3	82	188	98	12	B,E	1	N
A	CDB	2	2	82	193	103	15	B,B	1	N
A	CDB	1	2	82	21	291	12	B,E	1	N
A	CDB	2	2	78	21	291	17	B,B	1	N
A	SDB		2	82	182	92	8	E,E	1	N
A	CDB	2	2	85	187	97	16	B,B	1	N
A	CDB	3	3	84	189	99	17	B,B	1	N
A	SDB		3	88	322	232	17	B,B	ISO	N
B	CDB	2	3	81	190	100	19	B,B	1	N
B	CDB	2	3	81	198	108	19	B,B	1	N
B	CDB	2	3	82	190	100	20	B,B	1	N
B	SDB		2	78	20	290	10	B,E	1	N
B	CDB	1	3	79	200	110	20	B,B	1	N
B	CDB	1	3	80	183	93	21	B,B	1	N
B	CDB	2	2	88	180	90	19	B,B	1	N
B	CDB	2	2	86	26	296	8	T/1,T/1	1	N
B	SDB		2	75	27	297	7	B,E	1	N
B	SDB		3	84	211	121	7	B,E	1	N
B	CDB	1	3	86	37	307	5	B,E	1	N
B	CDB	1	3	85	215	125	4	B,E	1	N
B	SDB		2	89	200	110	3	B,T/1	1	N
B	CDB	2	2	87	205	115	1	B,T/1	1	N
C	CDB	3	2	80	20	290	13	B,T/1	1	N
C	CDB	1	2	82	208	118	10	B,E	1	N
C	CDB	1	3	83	190	100	15	B,E	1	N
C	CDB	1	2	86	12	282	7	B,E	1	N
C	CDB	1	2	82	210	120	14	B,E	1	N
C	CDB	2	3	84	188	98	17	B,B	1	N
C	CDB	1	2	81	5	275	10	B,E	1	N
C	CDB	1	2	84	195	105	11	B,E	1	Y
C	CDB	1	2	86	13	283	11	B,E	1	N
C	CDB	3	2	86	13	283	15	B,B	1	N
C	CDB	2	3	87	306	216	19	B,B	ISO	N
D	CDB	3	2	86	11	281	4	B,B	1	Y
D	CDB	3	2	84	183	93	6	B,B	1	N
D	CDB	3	1	72	183	93	9	B,B	1	N
D	CDB	3	2	76	5	275	10	B,E	1	N
D	CDB	3	2	76	180	90	13	B,B	1	N
D	CDB	3	2	62	192	102	16	B,B	1	N
D	CDB	3	2	83	156	66	17	B,B	1	N
D	CDB	1	1	82	9	279	17	B,B	1	N
D	CDB	3	3	81	195	105	18	B,B	1	N
D	SDB		1	86	25	295	9	B,E	1	N
D	SDB		2	86	19	289	2	B,E	1	N
D	SDB		3	86	295	205	18	B,B	ISO	N

PA 24:

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
ONLY	CDB	3	1	85	198	108	20	B,B	1	N
ONLY	CDB	3	1	85	194	104	20	B,B	1	N
ONLY	CDB	3	3	87	220	130	20	B,B	1	N
ONLY	CDB	2	2	88	216	126	10	B,B	1	N
ONLY	CDB	3	1	82	245	155	15	B,T/1	2	N
ONLY	CDB	1	2	83	256	166	4	T/3,T/3	2	N
ONLY	CDB	1	2	85	246	156	12	E,T/1	2	N
ONLY	CDB	1	3	87	256	166	8	B,B	2	N
ONLY	SDB		2	84	237	147	3	E,T/3	2	N
ONLY	CDB	1	2	76	147	57	6	E,T/1	3	N
ONLY	CDB	2	2	76	153	63	9	B,T/ISO	3	N
ONLY	CDB	2	2	77	342	252	15	T/1,T/1	3	N
ONLY	CDB	1	1	84	134	44	9	T/1,T/1	ISO	N
ONLY	SDB		1	85	304	214	5	E,T/1	ISO	N
ONLY	CDB	2	2	83	283	193	10	T/1,T/1	ISO	N

PA 25:

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
A	CDB	3	2	78	124	34	15	B,B	1	N
A	CDB	3	3	80	137	47	14	B,T/2	1	N
A	CDB	1	2	82	145	55	15	B,T/2	1	N
A	CDB	3	2	86	350	260	11	B,B	2	N
A	CDB	2	2	78	5	275	9	B,B	2	N
A	CDB	3	2	80	295	205	17	B,B	2	N
B	CDB	2	3	80	340	250	15	B,B	1	N
B	CDB	1	2	80	335	245	15	B,B	1	N
B	CDB	1	2	84	349	259	17	B,B	1	N
B	CDB	2	1	85	350	260	14	B,B	1	N
B	CDB	2	2	86	10	280	17	B,B	2	N
C	CDB	3	2	72	140	50	21	B,B	ISO	N
D	CDB	3	2	72	147	57	8	B,B	1	N
D	CDB	1	2	74	146	56	9	B,E	1	N
D	CDB	3	2	74	152	62	11	B,E	1	N

PA 26:

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
A	SDB		3	79	274	184	4	B,B	1	N
A	SDB		2	89	100	10	12	B,B	1	N
A	CDB	3	2	87	101	11	13	B,B	1	N
A	SDB		3	80	92	2	20	B,B	1	N
A	SDB		3	83	265	175	8	B,B	1	N
A	SDB		2	86	85	355	3	B,E	1	N
A	SDB		2	81	275	185	3	B,T/ISO	1	N
A	CDB	2	2	84	263	173	9	B,B	1	N
A	CDB	2	2	82	213	123	10	B,T/1	ISO	N
A	SDB		2	82	201	111	18	B,T/1	ISO	N
B	CDB	2	2	80	78	348	5	B,B	1	N
B	CDB	3	2	80	254	164	8	B,B	1	N
B	CDB	3	3	82	74	344	12	B,B	1	N
B	SDB		3	83	76	346	14	B,B	1	N
B	SDB		3	87	255	165	15	B,B	1	N
B	CDB	3	2	89	260	170	20	B,B	1	N
B	SDB		3	87	270	180	21	B,B	2	N
B	SDB		3	85	80	350	22	B,B	2	N
B	SDB		3	87	261	171	19	B,B	2	N
B	SDB		3	80	72	342	13	B,B	2	N
B	SDB		2	80	80	350	12	B,B	2	N
B	CDB	1	3	40	145	55	20	B,B	ISO	N
C	CDB	1	3	88	84	354	7	B,B	1	N
C	SDB		3	87	266	176	15	B,B	1	N
C	SDB		2	87	78	348	17	B,B	1	N
C	CDB	2	3	86	260	170	17	B,B	1	N
C	CDB	3	3	89	260	170	18	B,B	1	N
C	SDB		2	87	30	300	9	B,E	2	N
C	CDB	2	2	86	216	126	12	B,E	2	N
C	CDB	2	2	83	184	94	17	B,B	2	N
D	SDB		2	80	90	360	5	B,T/ISO	1	N
D	SDB		2	83	259	169	13	B,T/ISO	1	N
D	SDB		2	80	254	164	19	B,E	1	N
D	CDB	2	3	85	259	169	19	B,B	1	N
D	SDB		2	89	74	344	21	B,B	1	N
D	CDB	1	3	40	134	44	21	B,B	ISO	N
D	CDB	2	3	78	175	85	19	B,B	ISO	N

PA 27:

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
A	CDB	2	2	80	86	356	4	B,B	1	N
A	CDB	1	3	81	61	331	16	B,T/ISO	1	N
A	CDB	3	2	78	232	142	16	B,T/ISO	1	N
A	CDB	3	3	74	234	144	15	B,T/ISO	1	N
A	CDB	1	3	74	239	149	7	B,T/ISO	1	N
A	CDB	1	2	42	190	100	10	B,B	ISO	N
B	CDB	2	2	82	90	360	6	B,B	1	N
B	CDB	3	3	78	265	175	8	B,B	1	N
B	SDB		3	76	140	50	12	B,B	1	N
B	SDB		3	80	300	210	4	E,T/ISO	1	N
B	CDB	3	2	82	126	36	15	B,B	1	N
B	CDB	3	2	81	132	42	16	B,B	1	N
B	CDB	2	3	78	118	28	20	B,B	1	N
B	CDB	1	3	78	125	35	18	B,B	1	N
B	CDB	2	2	80	114	24	13	B,B	1	N
B	SDB		2	79	105	15	3	B,E	1	N
B	CDB	2	3	79	115	25	3	B,E	1	N
B	CDB	2	2	72	56	326	15	B,B	ISO	N
B	CDB	1	2	76	215	125	13	B,B	ISO	N
B	CDB	1	2	80	214	124	11	B,B	ISO	N
C	SDB		2	82	20	290	3	B,B	1	N
C	SDB		3	84	204	114	15	B,E	1	N
C	CDB	3	3	84	220	130	17	B,B	1	N
C	SDB		3	86	212	122	14	B,E	1	N
C	SDB		2	80	215	125	11	E,E	1	N
C	CDB	1	3	80	205	115	9	E,E	1	N
C	CDB	3	2	81	193	103	15	B,B	1	N
C	CDB	1	1	85	103	13	1	B,E	ISO	N
D	CDB	1	2	86	130	40	3	B,B	1	N
D	CDB	1	2	79	129	39	5	B,B	1	N
D	CDB	2	2	79	130	40	9	B,E	1	N
D	CDB	2	3	80	124	34	13	B,E	1	N
D	CDB	3	2	81	114	24	14	B,T/2	1	N
D	CDB	3	2	80	121	31	17	B,E	1	N
D	CDB	2	3	82	114	24	14	E,E	1	N
D	SDB		2	81	111	21	3	E,T/2	1	N
D	SDB		3	82	136	46	5	E,T/2	1	N
D	CDB	3	2	83	187	97	18	B,B	2	N
D	SDB		3	86	204	114	23	B,B	2	N
D	CDB	3	2	87	199	109	23	B,B	2	N
D	SDB		3	86	193	103	6	E,E	2	N
D	SDB		2	88	84	354	10	B,T/2	ISO	N
D	SDB		1	84	248	158	6	B,E	ISO	N

PA 28:

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
A	SDB		3	80	170	80	10	B,B	1	N
A	CDB	2	3	81	145	55	17	B,B	1	N
A	SDB		3	81	154	64	16	B,B	1	N
A	SDB		2	85	140	50	12	B,E	1	N
A	SDB		3	86	255	165	8	E,T/1	ISO	N
B	SDB		3	79	146	56	12	B,B	1	N
B	SDB		2	78	340	250	17	B,B	1	N
B	CDB	2	3	89	346	256	20	B,B	1	N
B	CDB	2	2	88	326	236	18	B,B	1	N
B	SDB		1	86	299	209	2	T/1,T/1	ISO	N
C	SDB		2	79	170	80	7	E,T/2	1	N
C	CDB	3	3	88	350	260	19	B,B	1	N
C	CDB	3	3	86	177	87	20	B,B	1	N
C	CDB	2	2	85	317	227	17	B,B	1	N
C	SDB		1	87	315	225	5	B,E	1	N
C	SDB		2	80	211	121	16	B,T/1	2	N
C	SDB		2	78	221	131	14	B,E	2	N
C	SDB		2	78	220	130	9	E,E	2	N
D	SDB		2	80	339	249	10	B,E	1	N
D	SDB		3	81	338	248	3	E,E	1	N
D	SDB		2	80	158	68	8	E,T/2	1	N
D	CDB	2	3	84	234	144	15	B,B	2	N
D	SDB		3	83	205	115	9	B,E	2	N
D	SDB		2	84	208	118	19	B,B	2	N

PA 30:

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
A	CDB	1	2	72	188	98	4	B,B	1	N
A	SDB		3	80	177	87	10	B,E	1	N
A	SDB		2	82	165	75	13	B,T/2	1	N
A	SDB		3	84	165	75	9	B,T/2	1	N
A	SDB		3	85	183	93	11	B,T/2	1	N
A	SDB		3	88	175	85	12	B,T/2	1	N
A	CDB	2	2	86	190	100	18	B,B	1	N
A	SDB		3	80	184	94	11	B,E	1	N
A	CDB	3	2	79	200	110	5	B,B	1	N
A	SDB		2	86	175	85	5	B,E	1	N
A	SDB		2	82	172	82	3	B,E	1	N
A	CDB	2	2	87	258	168	15	B,B	2	N
A	CDB	2	3	87	263	173	17	B,B	2	N
A	CDB	1	2	86	252	162	20	B,B	2	N
B	CDB	3	2	89	176	86	4	B,B	1	N
B	SDB		2	86	208	118	15	B,E	1	N
B	CDB	1	2	88	192	102	12	B,E	1	N
B	CDB	2	2	89	18	288	16	B,E	1	N
B	SDB		3	89	194	104	13	B,T/2	1	N
B	SDB		3	78	180	90	4	B,T/2	1	N
B	SDB		2	80	173	83	3	B,T/2	1	N
B	CDB	1	3	74	260	170	12	B,B	2	N
B	CDB	1	3	82	272	182	15	B,B	2	N
C	CDB	1	3	80	178	88	5	B,B	1	N
C	CDB	3	2	80	180	90	13	B,B	1	N
C	SDB		2	78	185	95	4	E,T/2	1	N
C	SDB		3	78	190	100	11	T/2, T/2	1	N
C	CDB	2	3	79	184	94	6	B,E	1	N
C	SDB		1	89	180	90	1	B,T/2	1	N
C	CDB	3	2	86	240	150	21	B,B	2	N
C	CDB	1	3	80	250	160	10	B,B	2	N
D	CDB	3	3	81	187	97	16	B,B	1	N
D	SDB		1	79	201	111	14	B,E	1	N
D	SDB		3	86	182	92	13	B,B	1	N
D	CDB	2	3	87	189	99	9	B,B	1	N
D	CDB	1	1	88	185	95	3	B,B	1	N
D	CDB	3	2	87	264	174	24	B,B	ISO	N
D	CDB	1	3	81	276	186	15	B,B	ISO	N
D	CDB	3	3	86	210	120	10	B,T/ISO	ISO	N
D	SDB		3	87	220	130	6	T/ISO,T/ISC	ISO	N

PA 31:

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
ONLY	CDB	3	2	84	120	30	21	B,B	1	N
ONLY	CDB	3	3	82	310	220	7	B,T/2	1	N
ONLY	CDB	2	3	87	304	214	12	B,T/2	1	N
ONLY	CDB	3	3	84	30	300	20	B,B	2	N
ONLY	CDB	3	2	86	24	294	23	B,B	2	N
ONLY	CDB	3	3	86	352	262	27	B,B	2	N
ONLY	CDB	3	2	87	177	87	27	B,B	2	N
ONLY	CDB	3	2	85	350	260	23	B,B	2	N
ONLY	CDB	2	3	80	164	74	18	B,B	2	N
ONLY	CDB	2	3	90	13	283	12	B,T/2	2	N
ONLY	CDB	2	2	80	5	275	4	B,T/1	2	N
ONLY	CDB	2	3	83	8	278	6	B,T/1	2	N

PA 37:

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C	
A	CDB	2	2	86	18	288	20	B,B	1	Y	3
A	SDB		3	87	4	274	22	B,B	1	N	
A	SDB		3	82	9	279	3	B,T/ISO	1	N	
A	SDB		3	84	163	73	9	E,E	ISO	N	
A	CDB	1	3	85	142	52	10	B,E	ISO	N	
B	SDB		2	82	133	43	8	B,E	1	N	
B	CDB	2	2	81	125	35	21	B,B	1	N	
B	CDB	2	2	86	134	44	12	B,E	1	N	
B	SDB		2	82	130	40	7	B,E	1	N	
B	CDB	1	3	84	340	250	15	B,B	2	N	
B	SDB		3	80	160	70	8	T/1,T/ISO	2	N	
B	SDB		1	81	170	80	4	B,E	2	N	
B	CDB	3	2	86	173	83	15	B,T/1	2	N	
B	CDB	1	3	83	352	262	17	B,B	2	N	
B	CDB	1	2	88	176	86	5	B,E	2	N	
B	SDB		2	84	167	77	3	B,E	2	N	
B	SDB		2	79	164	74	12	B,T/1	2	N	
B	SDB		1	82	190	100	5	E,T/1	2	N	
B	SDB		2	80	180	90	14	B,T/1	2	N	
B	SDB		2	70	173	83	11	T/1,T/1	2	N	
B	SDB		2	80	235	145	3	T/1,T/1	ISO	N	
C	SDB		2	76	324	234	13	B,T/2	1	N	
C	CDB	2	2	79	123	33	5	B,E	1	N	
C	SDB		3	84	134	44	19	B,B	1	N	
C	CDB	1	2	84	179	89	4	B,B	2	N	
C	SDB		2	88	330	240	6	B,B	2	N	
C	SDB		2	86	174	84	13	B,E	2	N	
C	CDB	1	3	81	161	71	23	B,B	2	N	
C	CDB	1	2	81	341	251	22	B,B	2	N	
C	SDB		1	87	176	86	21	B,B	2	N	
D	CDB	1	3	80	315	225	10	B,E	1	N	
D	CDB	3	3	82	315	225	20	B,B	1	N	
D	CDB	3	2	81	133	43	20	B,B	1	N	
D	SDB		3	80	6	276	9	B,T/1	ISO	N	
D	SDB		1	87	340	250	3	B,E	ISO	N	
D	SDB		2	87	134	44	4	B,B	ISO	N	

PA 38:

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
A	CDB	3	3	88	174	84	18	B,B	ISO	N
A	SDB		2	82	82	352	4	B,E	1	N
A	SDB		2	86	53	323	10	B,E	1	N
A	SDB		2	82	64	334	8	B,E	1	N
A	SDB		3	81	239	149	9	B,E	1	N
A	SDB		2	83	237	147	5	B,E	1	N
A	SDB		2	81	55	325	4	E,T/ISO	1	N
A	CDB	2	3	83	321	231	9	B,E	ISO	N
B	CDB	3	3	83	186	96	17	B,B	1	N
B	SDB		1	84	172	82	18	B,B	1	N
B	CDB	2	2	78	153	63	19	B,B	1	N
B	SDB		2	80	68	338	4	B,T/1	2	N
B	SDB		2	87	58	328	4	E,T/1	2	N
B	SDB		2	86	53	323	15	B,E	2	N
B	CDB	3	3	85	54	324	12	B,T/1	2	N
B	CDB	3	2	83	42	312	5	B,T/1	2	N
C	CDB	1	3	87	269	179	15	T/2,T/2	1	N
C	SDB		3	80	277	187	10	T/2,T/2	1	N
C	SDB		3	84	273	183	9	B,T/2	1	N
C	CDB	2	1	83	337	247	4	B,B	2	N
C	CDB	1	3	89	150	60	15	B,B	2	N
C	CDB	3	2	89	161	71	18	B,B	2	N
D	CDB	2	2	88	160	70	20	B,B	1	N
D	CDB	1	2	84	156	66	20	B,B	1	N
D	CDB	1	3	79	158	68	20	B,B	1	N
D	CDB	1	1	82	163	73	16	B,B	1	N

PA 39:

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
A	CDB	2	3	86	151	61	20	B,B	1	N
A	CDB	3	3	88	144	54	20	B,B	1	N
A	CDB	2	3	81	326	236	20	B,B	1	N
A	CDB	2	3	87	337	247	14	B,T/ISO	1	N
A	SDB		2	89	142	52	18	B,B	2	N
A	CDB	2	3	86	165	75	15	B,B	2	N
A	SDB		3	86	331	241	18	B,B	2	N
A	CDB	3	3	87	200	110	16	B,T/1	ISO	N
A	CDB	3	2	83	224	134	3	B,T/1	ISO	N
B	SDB		3	87	151	61	15	B,B	1	N
B	SDB		2	84	139	49	11	B,E	1	N
B	CDB	2	3	86	143	53	17	B,B	1	N
B	CDB	2	3	80	152	62	18	B,B	1	N
B	SDB		3	81	139	49	18	B,B	1	N
B	SDB		3	77	175	85	6	B,B	2	N
B	SDB		3	82	186	96	9	B,B	2	N
B	CDB	1	3	74	200	110	18	B,B	2	N
C	CDB	1	3	80	114	24	16	B,B	1	N
C	SDB		1	89	143	53	18	B,B	1	N
C	CDB	2	2	82	324	234	17	B,B	1	N
C	CDB	2	3	84	132	42	19	B,B	1	N
C	SDB		3	76	13	283	3	B,T/1	ISO	N
C	SDB		3	89	40	310	8	T/1,T/1	ISO	N
C	SDB		2	88	42	312	6	T/1,T/1	ISO	N
C	SDB		3	80	190	100	15	T/1,T/1	ISO	N
D	SDB		2	88	143	53	17	B,B	1	N
D	CDB	2	2	87	317	227	17	B,B	1	N
D	SDB		2	79	160	70	17	B,B	1	N
D	CDB	1	3	85	320	230	20	B,B	1	N
D	SDB		3	85	131	41	9	B,B	1	N
D	SDB		3	81	54	324	8	B,E	ISO	N
D	SDB		3	84	210	120	9	B,T/1	ISO	N
D	SDB		3	86	185	95	12	B,T/1	ISO	N

PA 40:

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
A	CDB	2	3	80	295	205	8	B,B	1	N
A	CDB	1	2	88	297	207	14	B,E	1	N
A	CDB	3	2	83	289	199	20	B,B	1	N
A	CDB	3	2	85	310	220	20	B,B	1	N
A	SDB		2	84	309	219	12	E,E	1	N
A	CDB	3	2	84	316	226	22	B,B	1	N
B	CDB	3	2	80	308	218	14	B,B	1	N
B	SDB		2	89	284	194	20	B,B	1	N
B	CDB	3	2	83	304	214	21	B,B	1	N
B	CDB	3	2	88	289	199	22	B,B	1	N
B	CDB	2	2	84	278	188	9	B,B	1	N
C	CDB	3	3	90	307	217	18	B,B	1	N
C	CDB	3	2	84	306	216	21	B,B	1	N
C	CDB	3	2	85	305	215	22	B,B	1	N
C	CDB	2	2	85	126	36	16	B,B	1	N
C	CDB	2	3	83	299	209	16	B,B	1	N
C	CDB	3	3	84	240	150	19	B,B	ISO	N
D	CDB	3	3	84	298	208	16	B,B	1	N
D	CDB	2	3	87	284	194	18	B,B	1	N
D	CDB	3	3	86	308	218	19	B,B	1	N
D	CDB	2	2	84	289	199	20	B,B	1	N
D	CDB	3	2	81	294	204	20	B,B	1	N
D	CDB	3	3	78	302	212	19	B,B	1	N
D	CDB	1	1	80	301	211	2	B,B	1	N

PA 41:

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
ONLY	CDB	1	2	87	332	242	9	B,B	1	N
ONLY	CDB	2	3	88	160	70	11	B,B	1	N
ONLY	SDB		2	81	152	62	6	B,E	1	N
ONLY	SDB		2	82	146	56	16	B,B	1	N
ONLY	CDB	1	1	84	328	238	20	B,B	1	N
ONLY	CDB	1	2	84	326	236	22	B,B	1	N
ONLY	CDB	2	3	85	323	233	11	B,T/ISO	1	N
ONLY	CDB	3	2	88	336	246	25	B,B	1	N
ONLY	CDB	1	1	87	335	245	13	B,E	1	N
ONLY	SDB		2	86	344	254	11	B,B	1	N
ONLY	CDB	1	3	84	279	189	8	B,E	ISO	N

PA 42:

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
A	SDB		2	90	232	142	15	B,B	1	N
A	SDB		2	78	55	325	5	B,E	1	N
A	SDB		2	78	58	328	2	B,E	1	N
A	SDB		2	80	45	315	5	B,E	1	N
A	SDB		3	80	319	229	4	B,B	2	N
A	SDB		2	82	328	238	12	B,B	2	N
A	CDB	2	3	86	334	244	18	B,B	2	N
A	CDB	3	2	86	320	230	3	B,E	2	N
B	CDB	3	3	86	234	144	22	B,B	1	N
B	SDB		2	70	280	190	13	E,E	2	N
B	CDB	1	3	64	134	44	17	B,B	2	N
B	SDB		3	72	303	213	5	E,E	2	N
B	SDB		2	80	319	229	3	E,E	2	N
B	CDB	3	2	80	325	235	14	B,B	2	N
B	CDB	2	3	83	314	224	16	B,B	2	N
C	SDB		2	80	241	151	9	B,B	1	N
C	CDB	1	2	82	50	320	21	B,B	1	N
C	SDB		2	78	335	245	14	B,E	2	N
C	SDB		3	82	343	253	15	B,B	2	N
D	SDB		3	80	55	325	5	B,E	1	N
D	SDB		3	89	321	231	9	B,E	2	N

PA 43:

No Fractures Present

PA 44:

Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
ONLY	CDB	2	2	86	105	15	24	B,B	1	N
ONLY	CDB	3	3	89	115	25	20	B,B	1	N
ONLY	CDB	3	3	84	106	16	22	B,B	1	N
ONLY	SDB		3	80	112	22	8	E,E	1	N
ONLY	SDB		2	86	270	180	8	B,E	1	N
ONLY	SDB		2	80	85	355	3	B,B	1	N
ONLY	SDB		3	79	175	85	22	B,B	2	N
ONLY	CDB	3	2	83	179	89	17	B,E	2	N
ONLY	CDB	2	2	84	171	81	14	B,E	2	N
ONLY	CDB	1	2	82	12	282	4	B,B	2	N

PA 45:

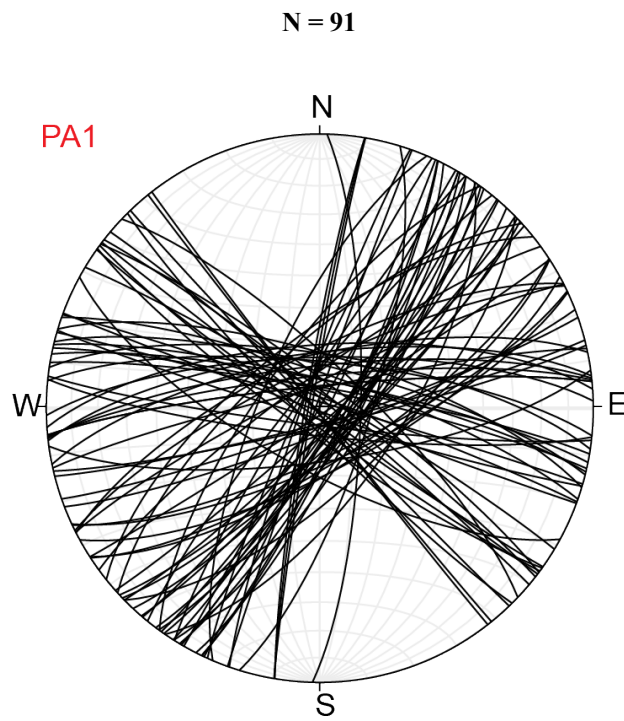
Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
A	CDB	3	3	80	294	204	17	B,B	1	N
A	CDB	3	3	83	296	206	21	B,B	1	N
A	CDB	1	2	89	302	212	22	B,B	1	N
A	SDB		2	88	304	214	9	B,E	1	N
A	CDB	1	3	84	124	34	4	B,B	1	N
A	SDB		3	85	114	24	6	B,B	1	N
B	CDB	3	3	80	90	360	20	B,B	1	N
B	CDB	3	2	83	261	171	20	B,B	1	N
B	CDB	3	2	81	79	349	21	B,B	1	N
B	CDB	3	2	80	80	350	20	B,B	1	N
B	CDB	2	3	79	82	352	20	B,B	1	N
B	SDB		3	80	269	179	11	B,E	1	N
B	SDB		3	80	84	354	16	E,T/ISO	1	N
B	CDB	3	3	88	172	82	15	B,B	ISO	N
C	SDB		2	80	348	258	20	B,B	1	N
C	SDB		1	81	332	242	11	B,E	1	N
C	SDB		3	84	356	266	13	B,E	1	N
C	CDB	3	2	89	322	232	19	B,B	1	N
C	CDB	2	2	83	314	224	18	B,B	1	N
C	SDB		3	84	311	221	17	B,B	1	N
C	SDB		3	82	311	221	16	B,B	1	N
C	SDB		2	80	116	26	6	B,E	1	N
C	SDB		3	78	255	165	5	E,E	ISO	N
C	SDB		3	83	80	350	4	E,T/1	ISO	N
D	SDB		3	84	339	249	9	B,B	1	N
D	SDB		3	80	314	224	9	B,B	1	N
D	CDB	2	2	85	341	251	15	B,B	1	N
D	CDB	3	3	85	326	236	12	B,B	1	N
D	CDB	3	3	80	336	246	24	B,B	1	N
D	CDB	1	3	78	133	43	5	B,B	1	N
D	CDB	3	3	78	78	348	20	B,B	ISO	N

PA 46:

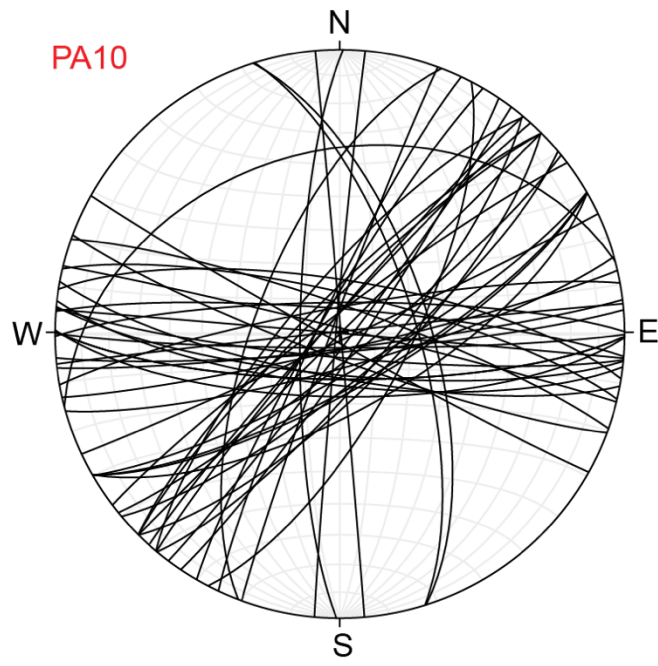
Quadrant	FT	C	P	DM	DD	S	L	T	Set #	X-C
ONLY	CDB	2	3	84	281	191	8	B,B	N/O	N
ONLY	SDB		2	87	307	217	12	B,T	N/O	N
ONLY	CDB	3	2	88	357	267	21	B,B	N/O	N
ONLY	CDB	3	2	88	264	174	21	B,B	N/O	N
ONLY	SDB		2	79	303	213	12	B,T	N/O	N
ONLY	SDB		2	85	302	212	14	B,T	N/O	N
ONLY	SDB		1	81	169	79	8	B,B	N/O	N
ONLY	SDB		1	84	167	77	5	B,B	N/O	N
ONLY	SDB		1	81	165	75	2	B,B	N/O	N
ONLY	CDB	1	3	76	239	149	15	B,B	N/O	N
ONLY	CDB	3	2	72	209	119	20	B,B	N/O	N
ONLY	CDB	2	3	80	199	109	20	B,B	N/O	N
ONLY	CDB	1	2	83	241	151	13	B,E	N/O	N
ONLY	SDB		2	88	234	144	11	B,T	N/O	N
ONLY	CDB	2	3	86	201	111	20	B,B	N/O	N
ONLY	SDB		1	88	150	60	4	B,B	N/O	N
ONLY	SDB		3	82	184	94	7	B,B	N/O	N

Appendix C – Stereonets

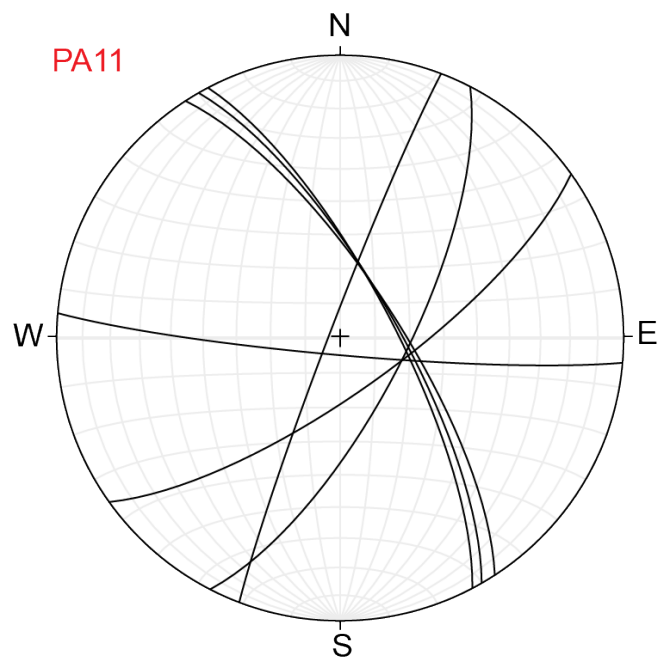
All orientations have been corrected for bedding orientation.



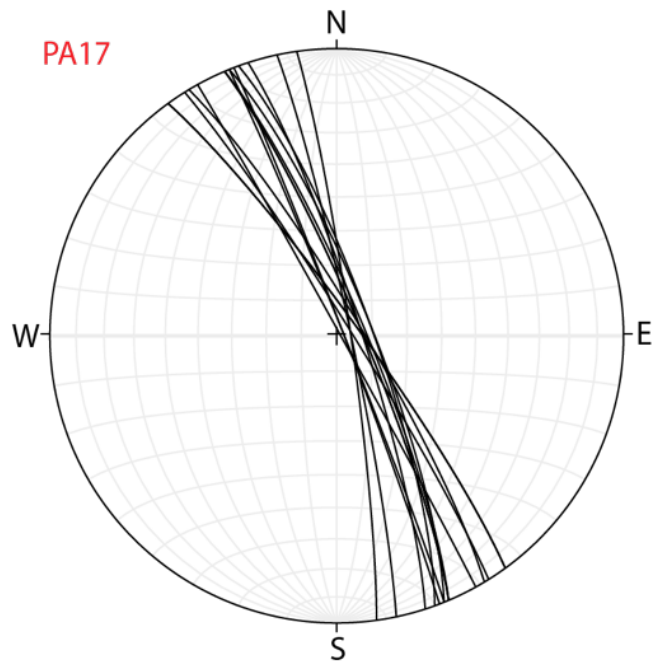
N = 53



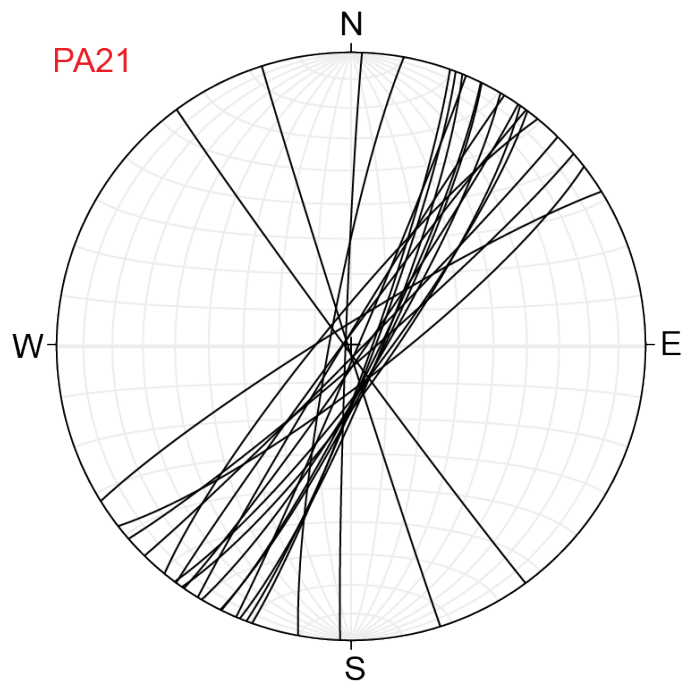
N = 8



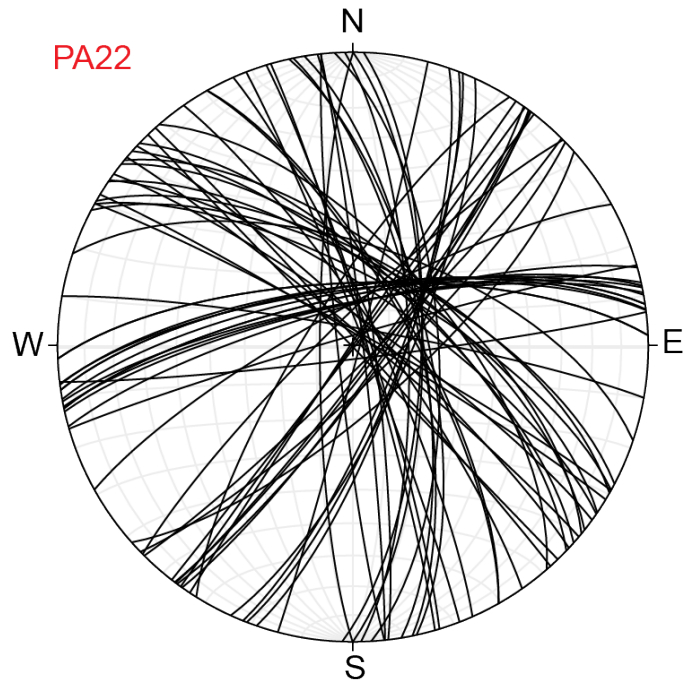
N = 15



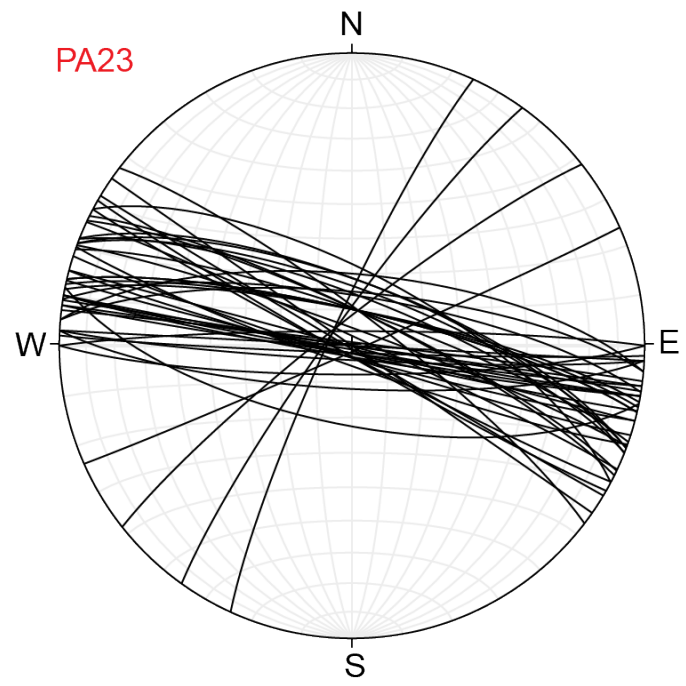
N = 22



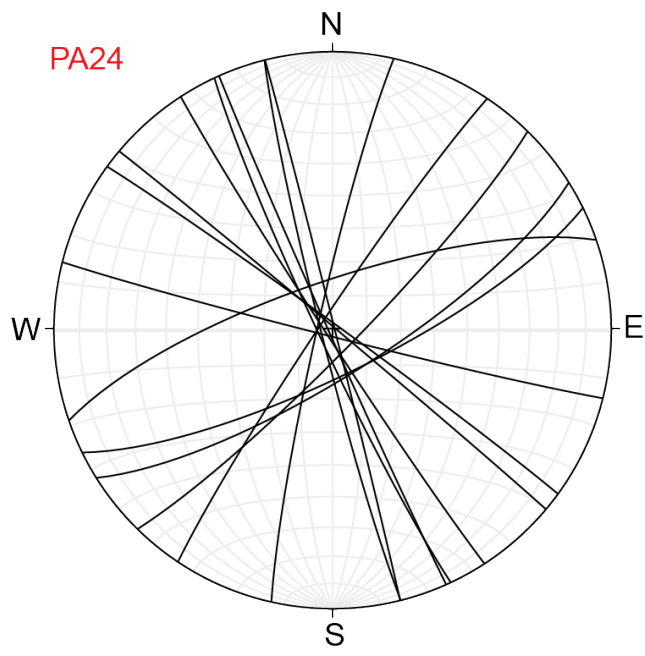
N = 71



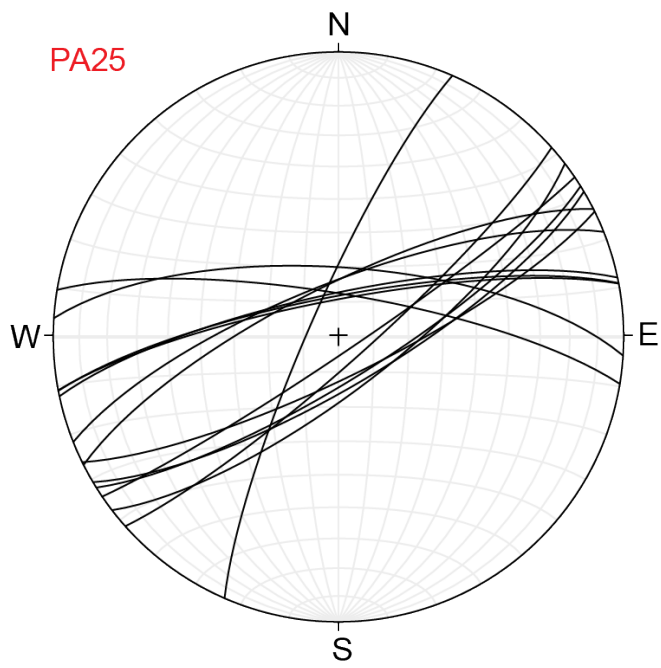
N = 46



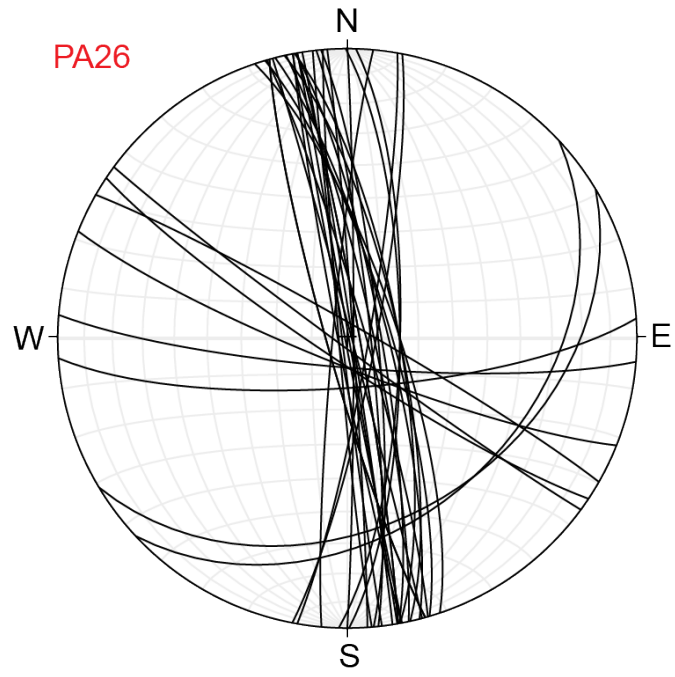
N = 15



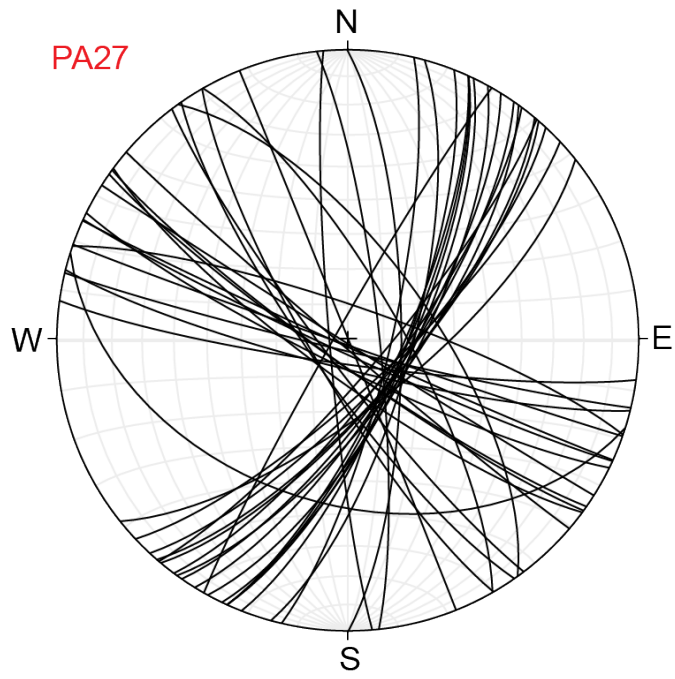
N = 15



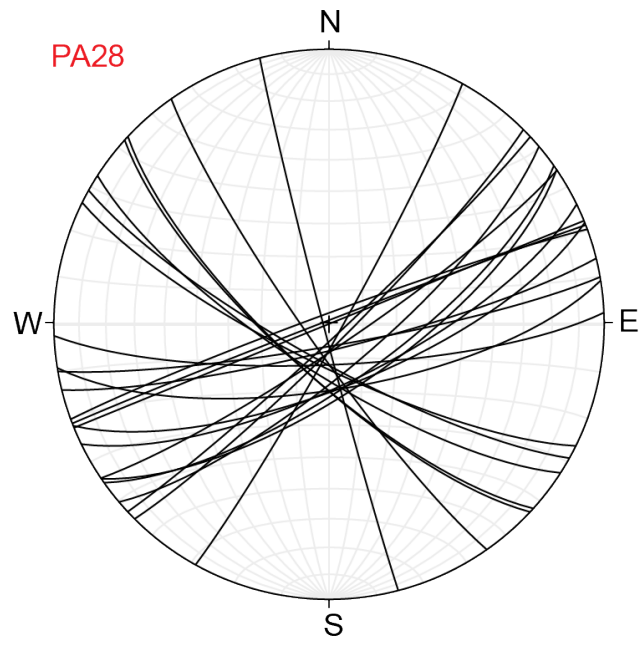
N = 37



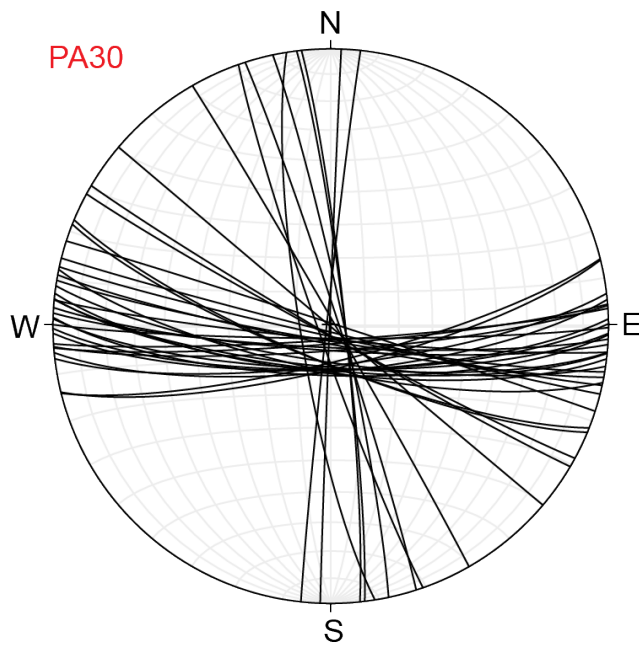
N = 43



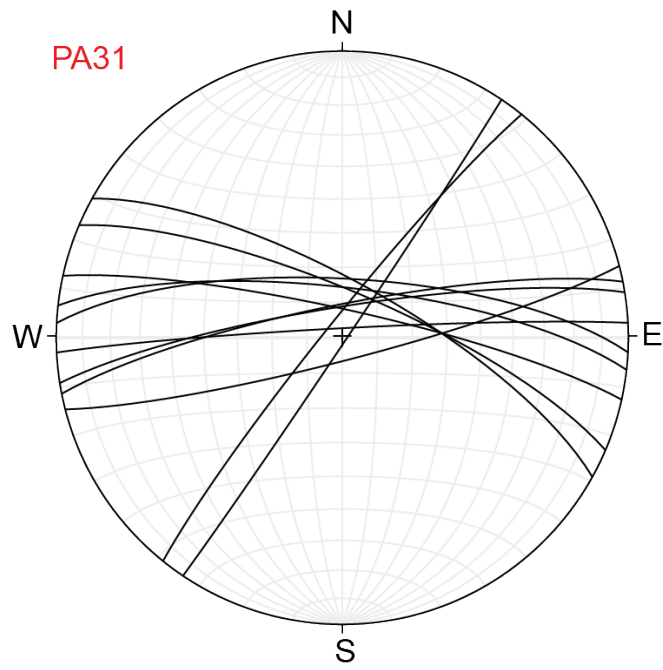
N = 24



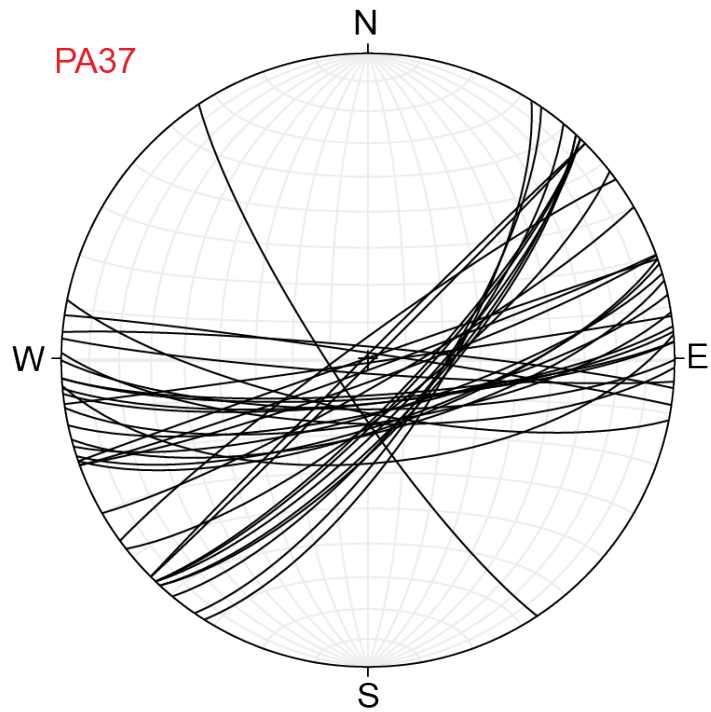
N = 40



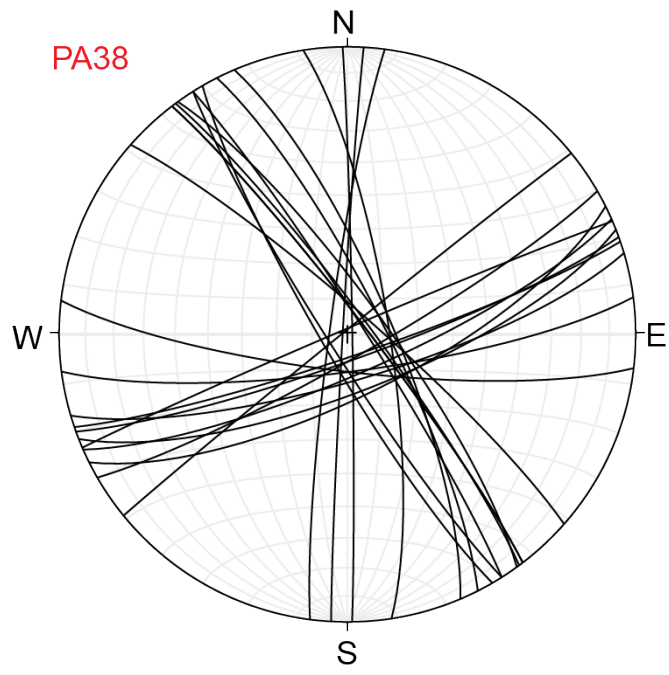
N = 12



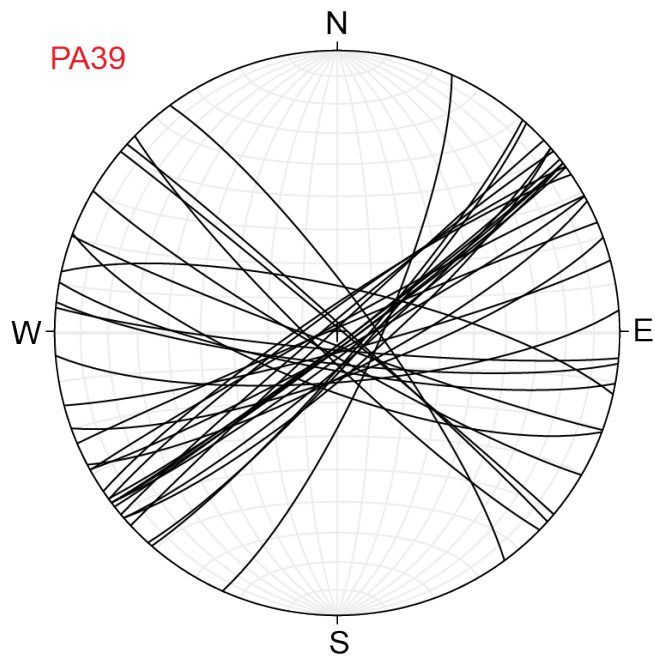
N = 36



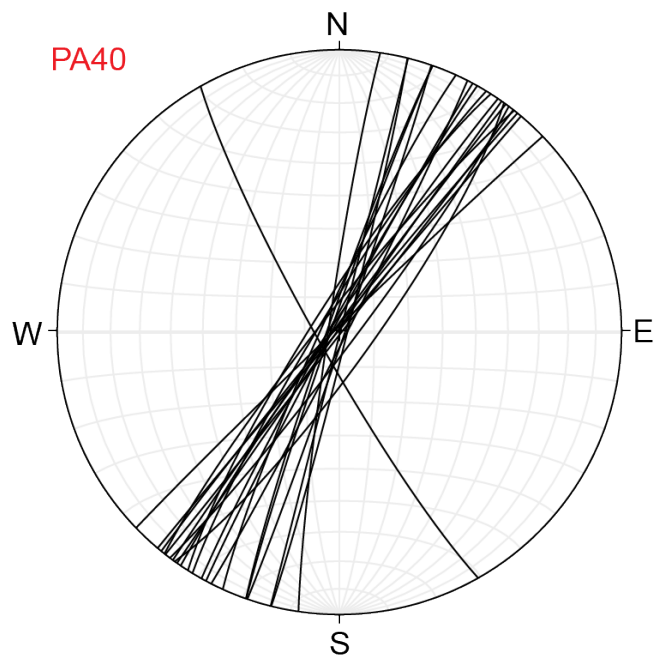
N = 26



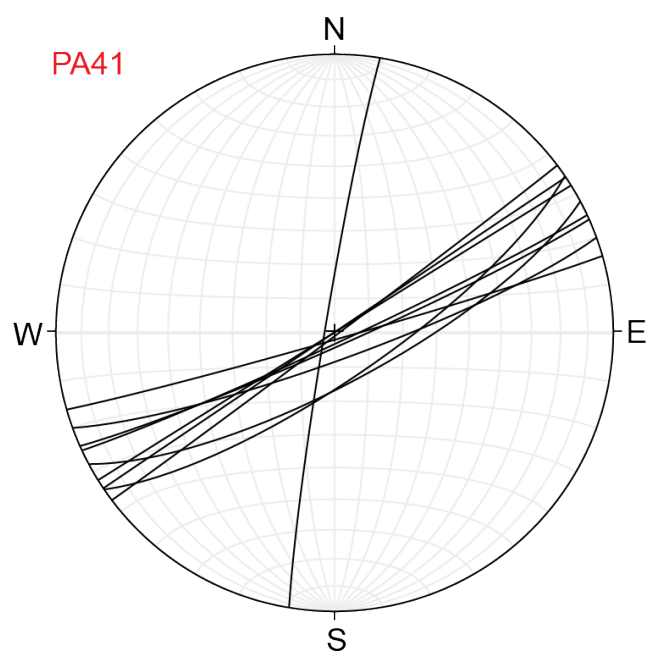
N = 33



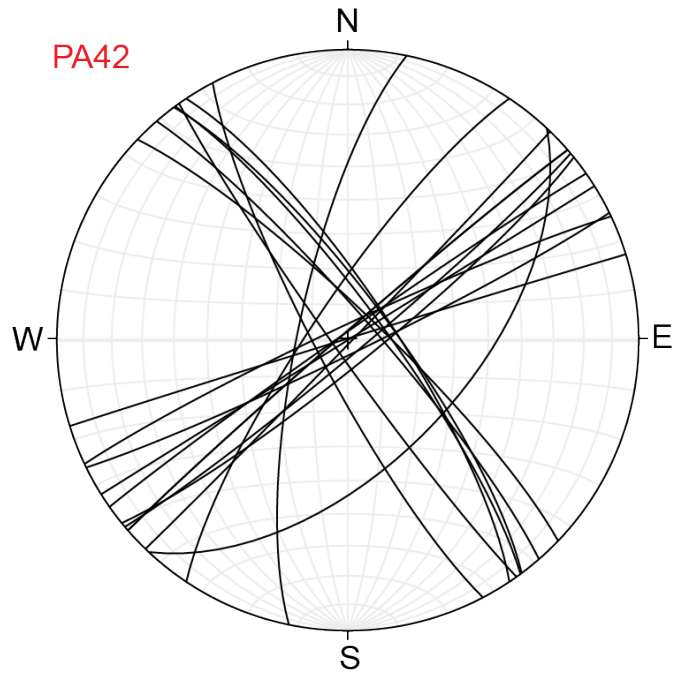
N = 24



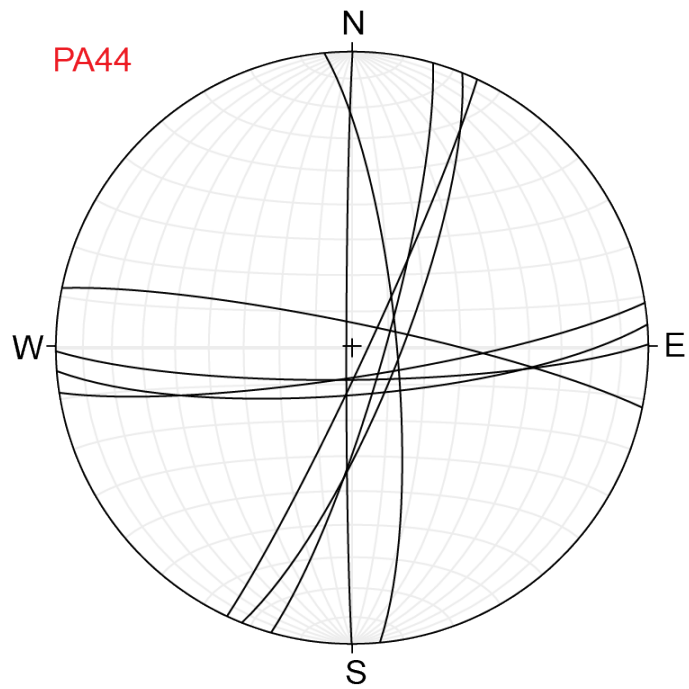
N = 11



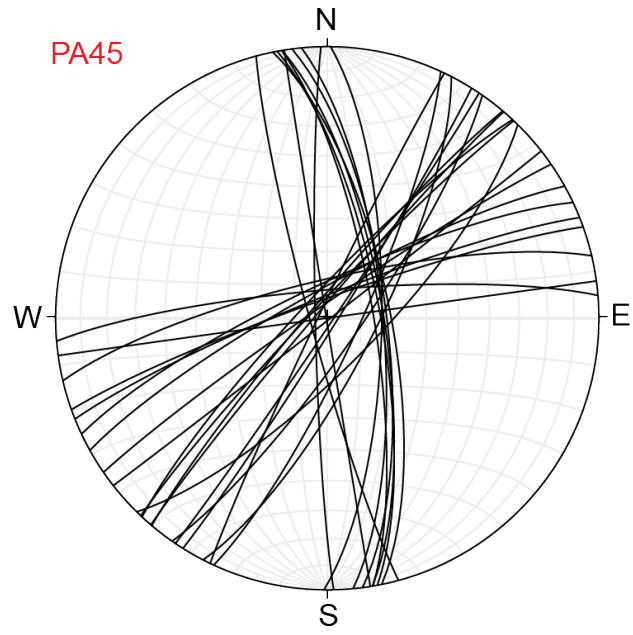
N = 21



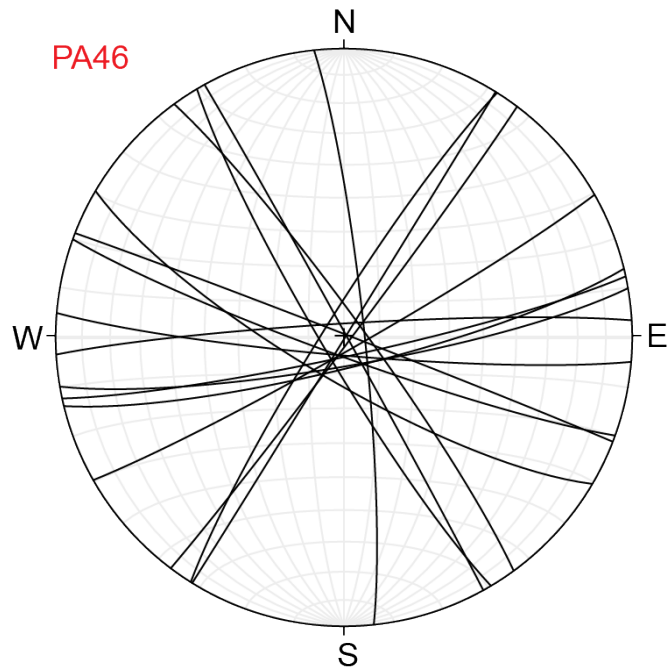
N = 10



N = 31



N = 17



Appendix D – Thin Section Photographs

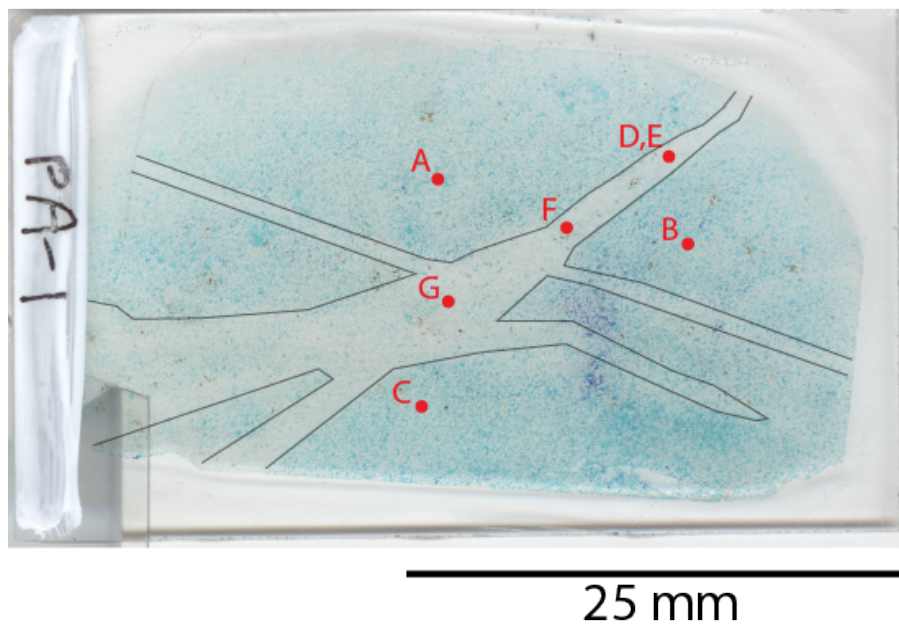
Any deformation bands present in the thin sections have been highlighted.

2x – 2x Magnification

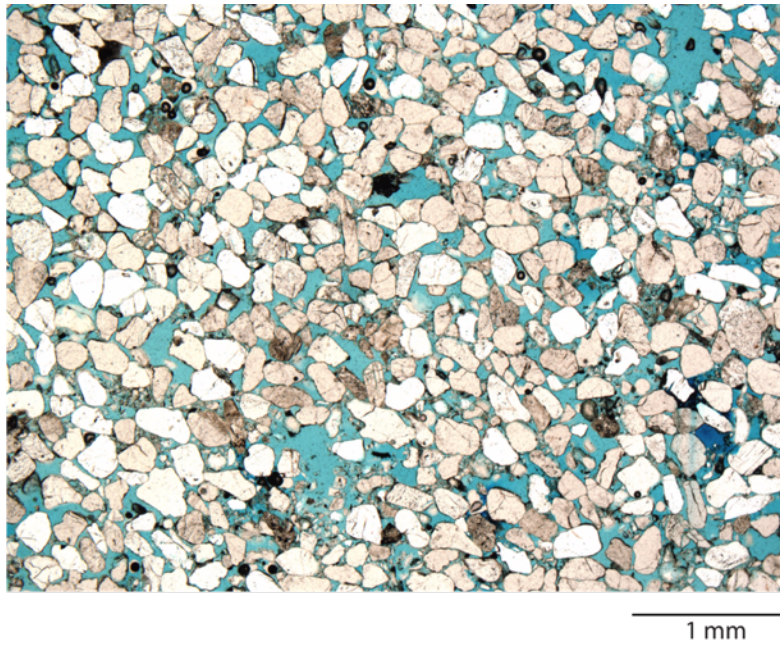
4x – 4x Magnification

PA 1:

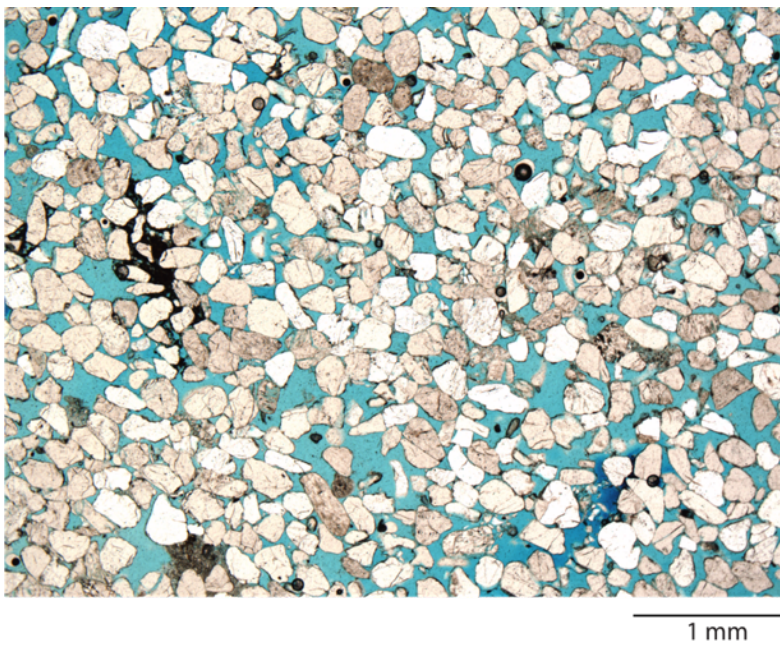
Thin Section:



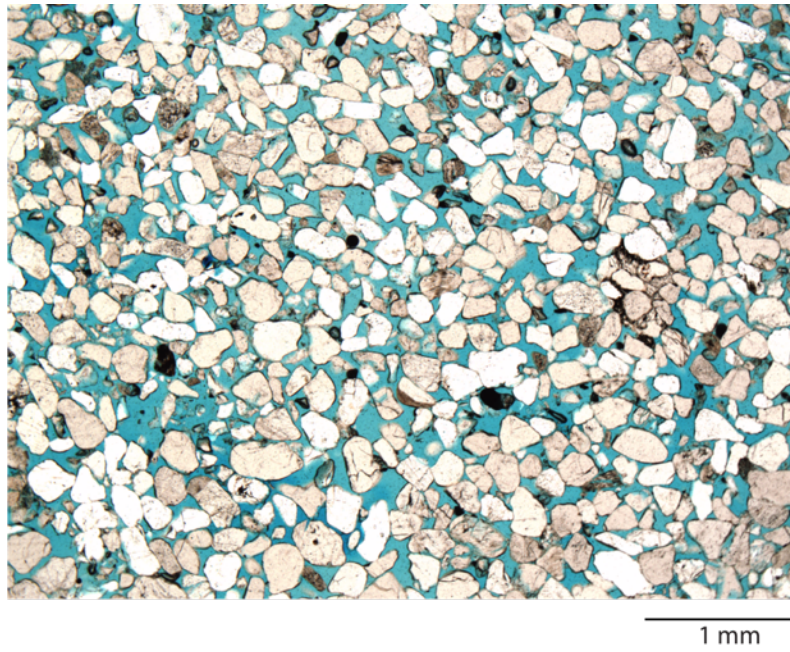
PA1 Photomicrograph A – 4x:



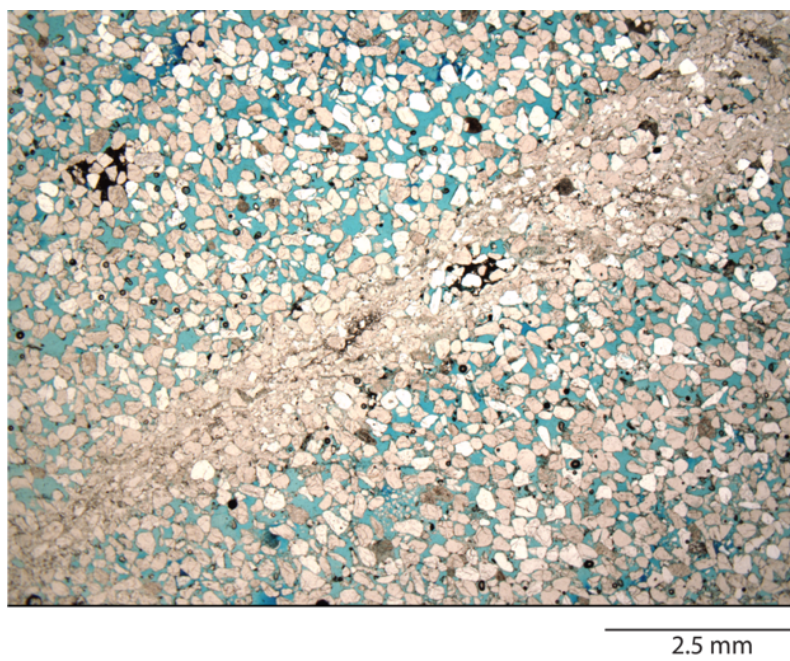
PA1 Photomicrograph B – 4x:



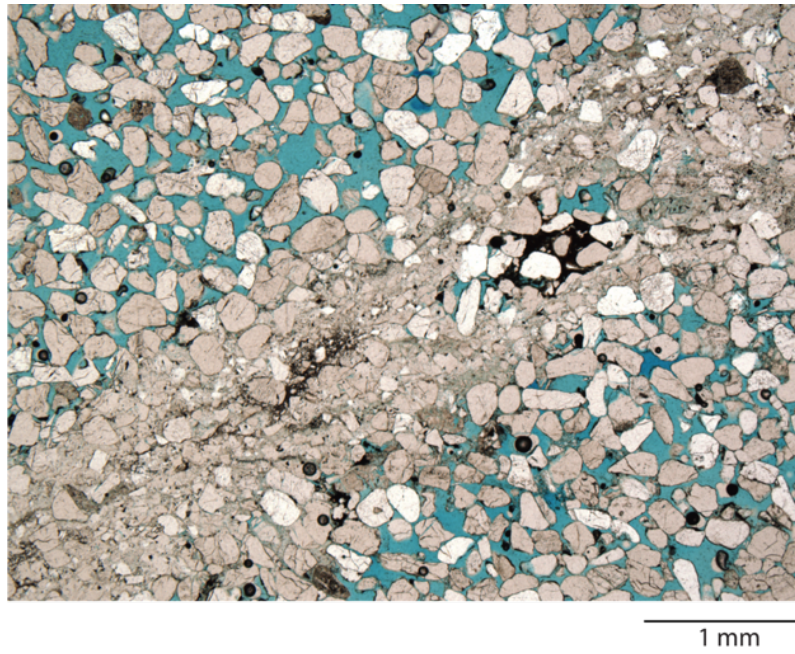
PA1 Photomicrograph C – 4x:



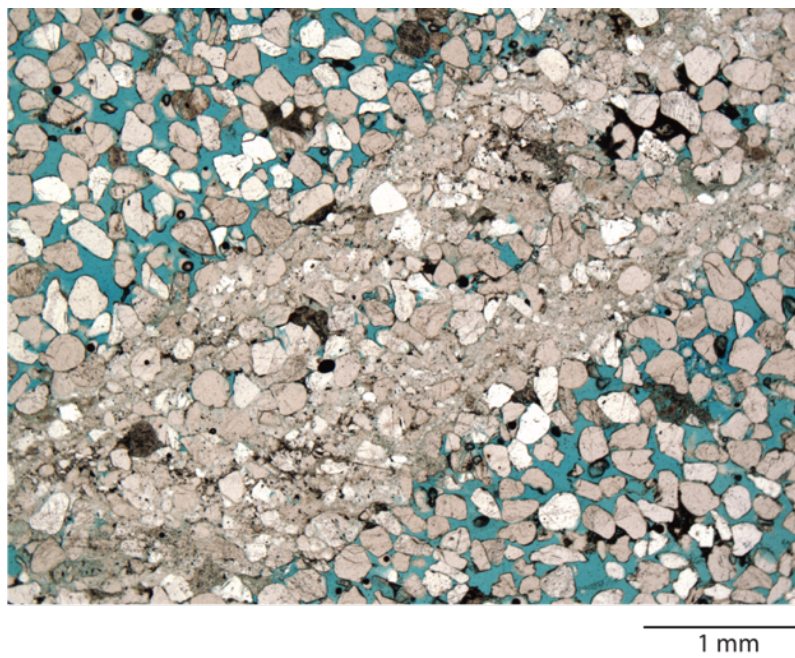
PA1 Photomicrograph D – 2x:



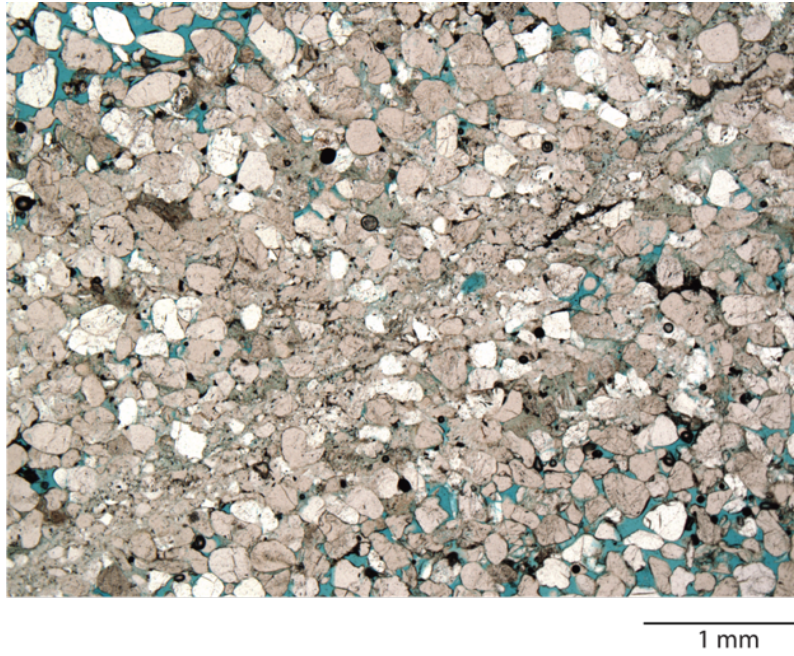
PA1 Photomicrograph E – 4x:



PA1 Photomicrograph F – 4x:

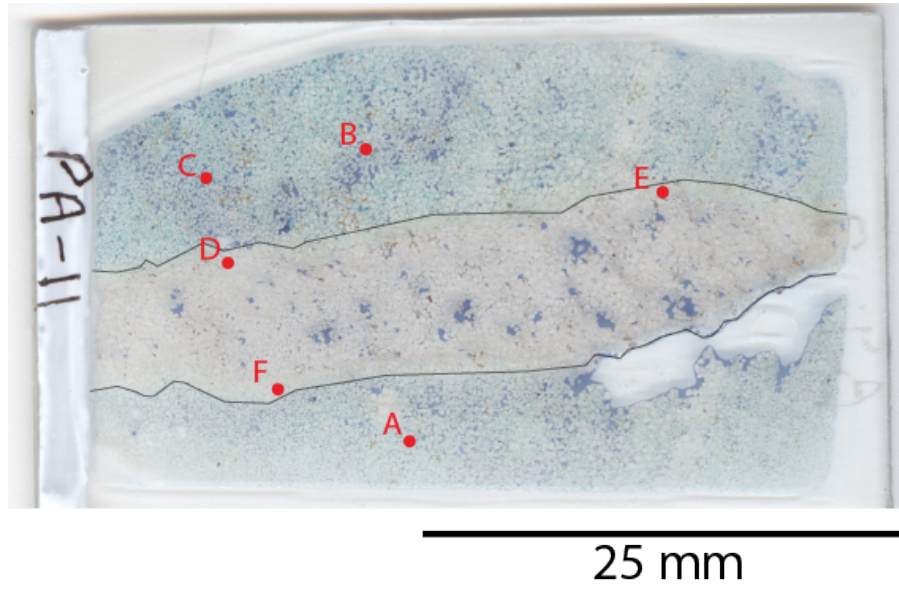


PA1 Photomicrograph G – 4x:

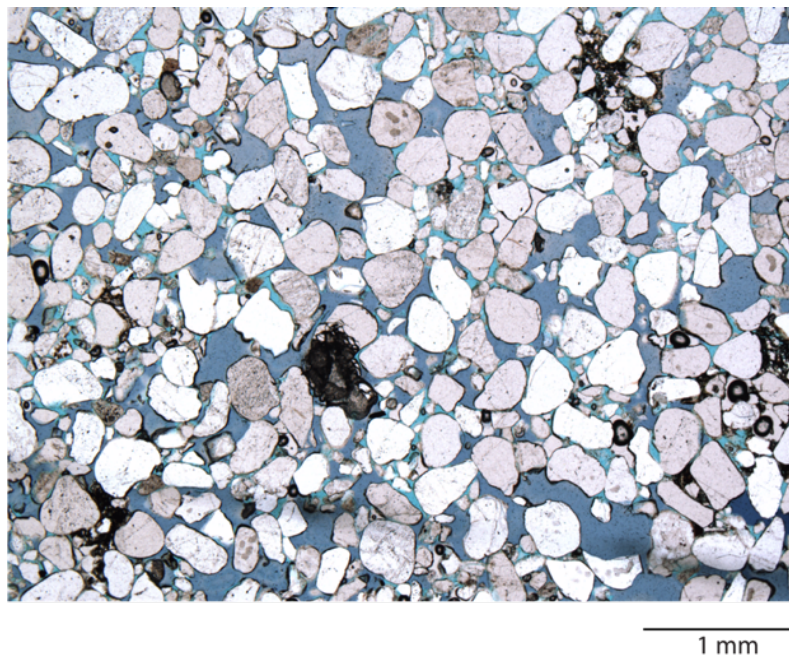


PA 11:

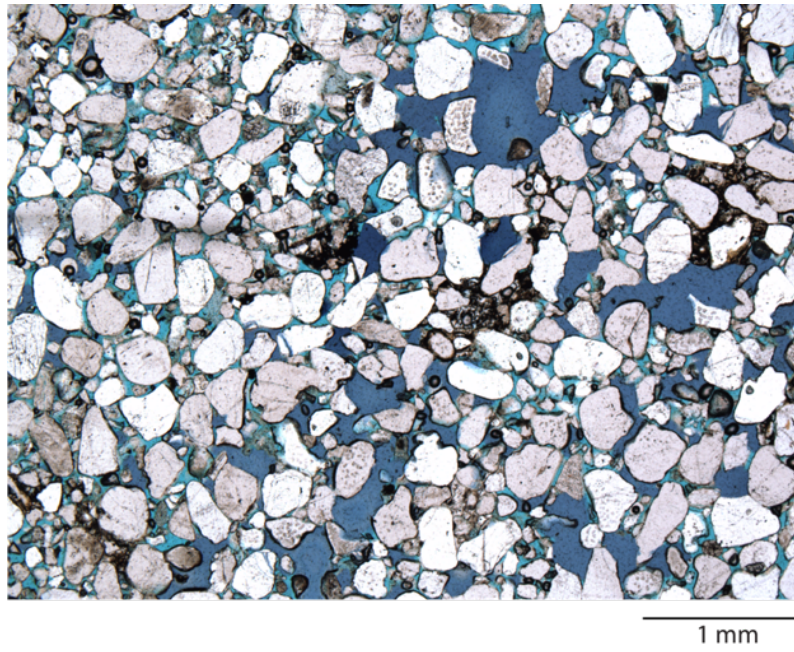
Thin Section:



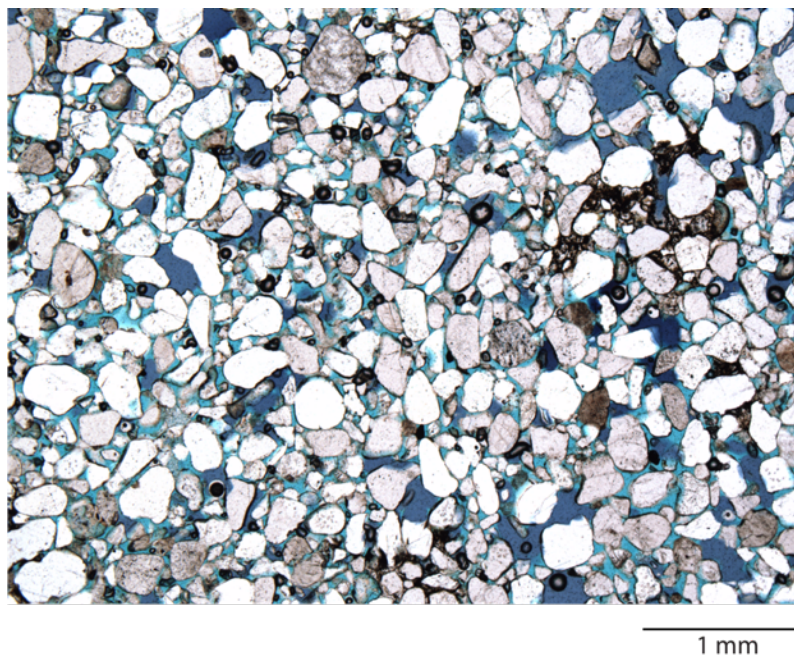
PA11 Photomicrograph A – 4x:



PA11 Photomicrograph B – 4x:



PA11 Photomicrograph C – 4x:



PA11 Photomicrograph D – 2x:



PA11 Photomicrograph E – 2x:



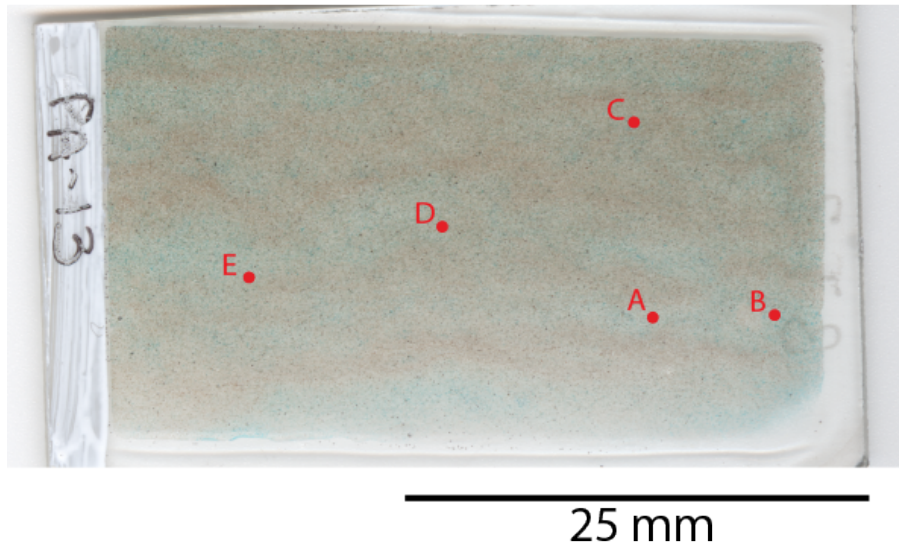
PA11 Photomicrograph F – 2x:



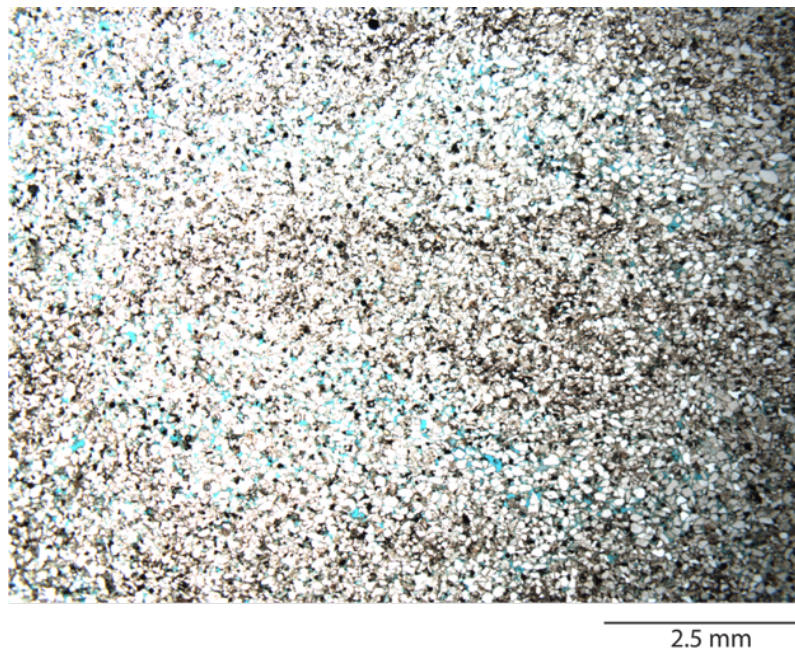
2.5 mm

PA 13:

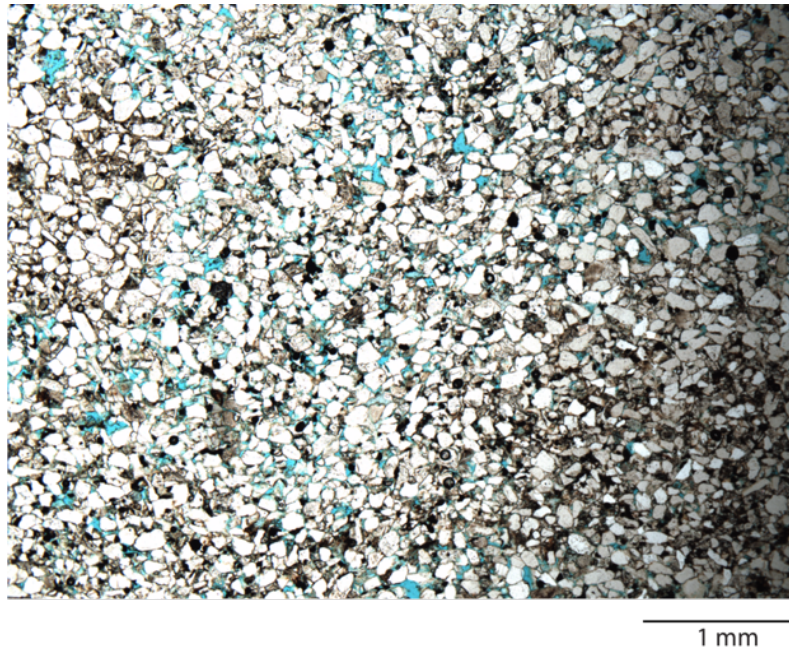
Thin Section:



PA13 Photomicrograph A – 2x:



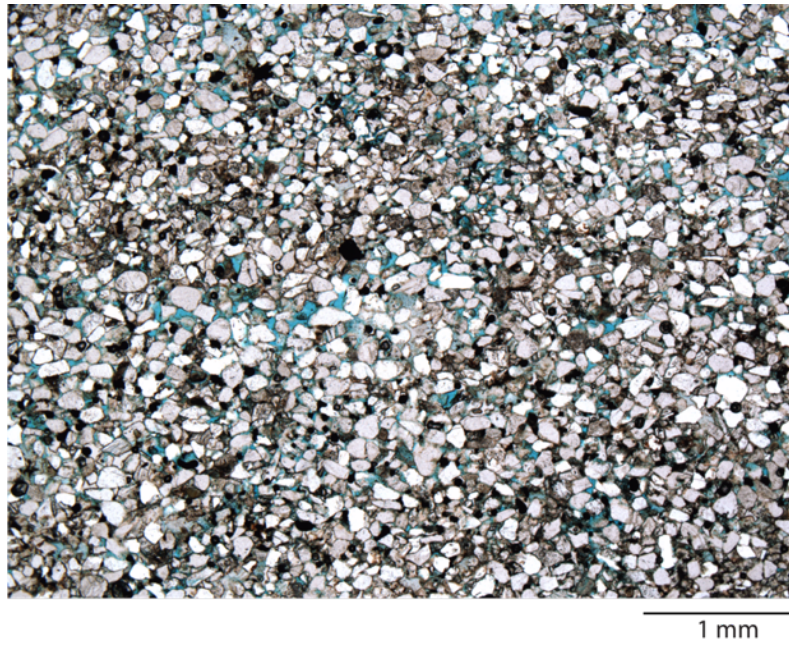
PA13 Photomicrograph B – 4x:



PA13 Photomicrograph C – 4x:



PA13 Photomicrograph D – 4x:

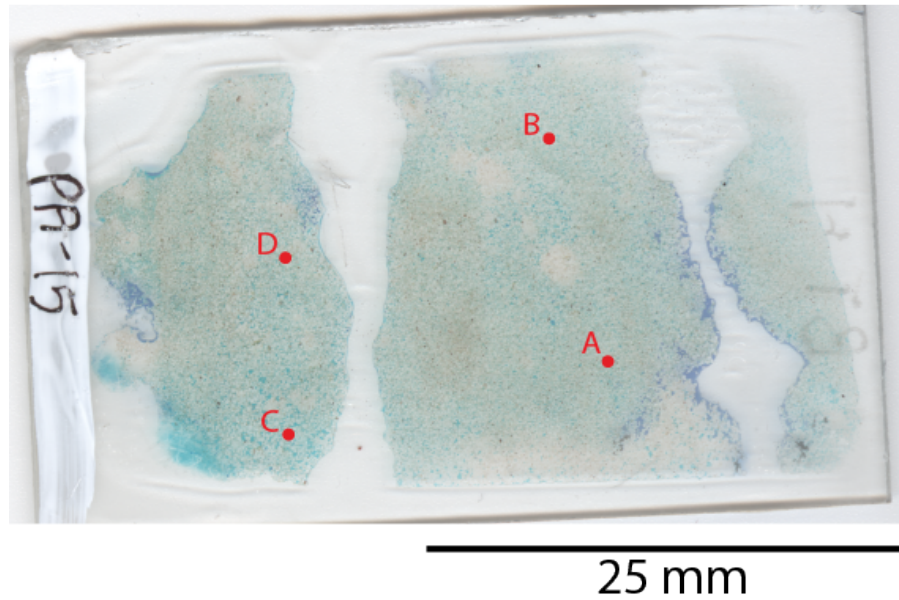


PA13 Photomicrograph E – 4x:

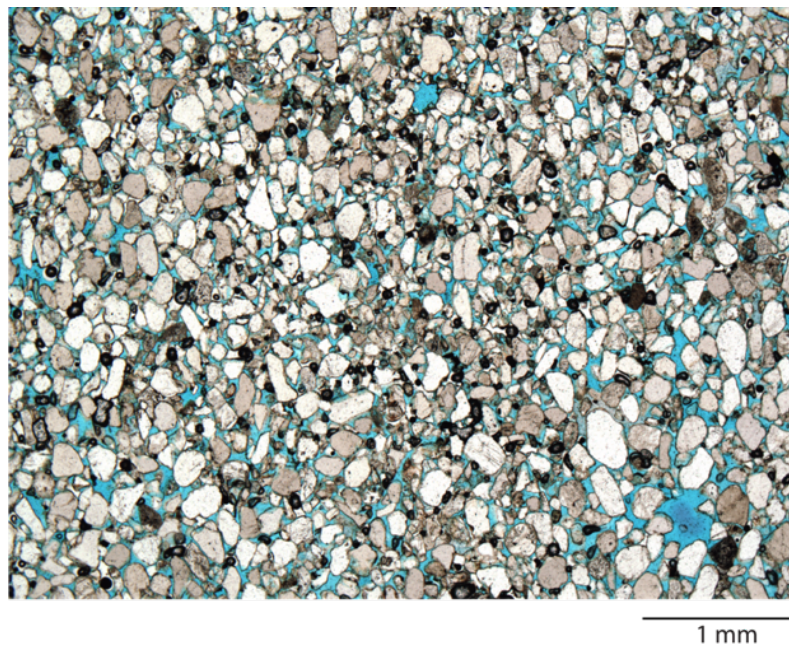


PA 15:

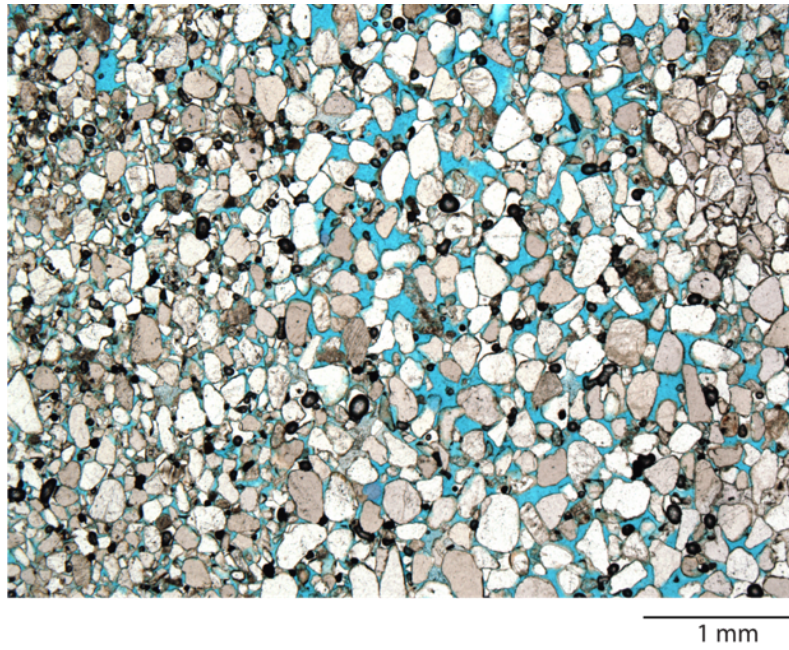
Thin Section:



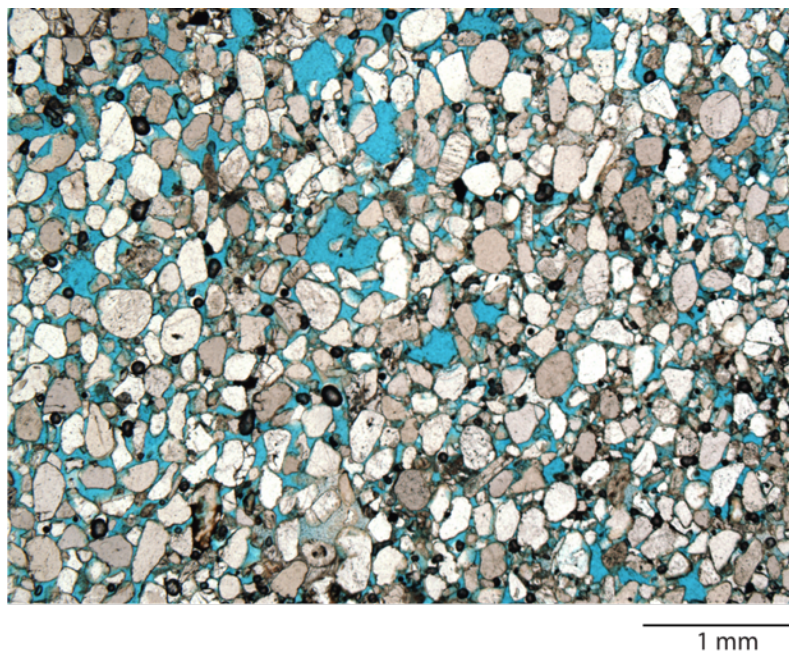
PA15 Photomicrograph A – 4x:



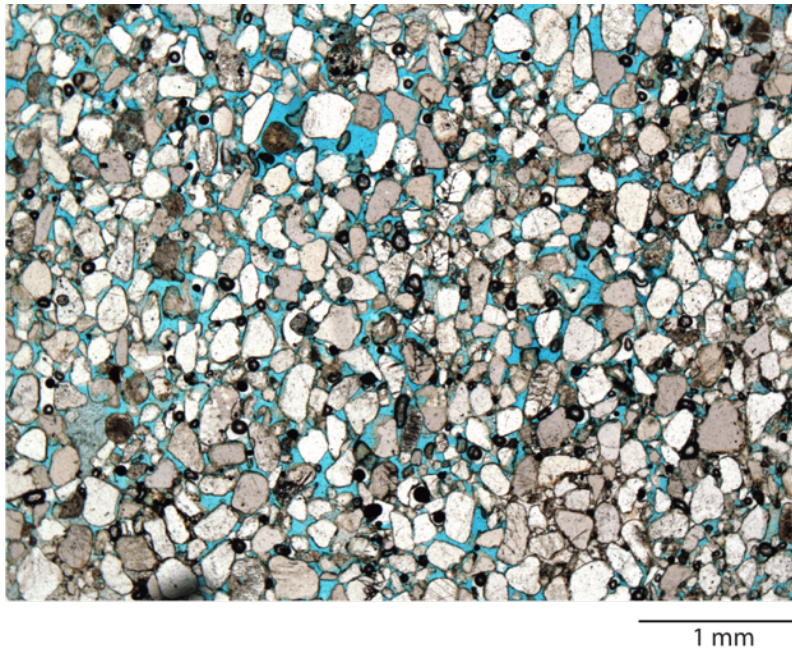
PA15 Photomicrograph B – 4x:



PA15 Photomicrograph C – 4x:

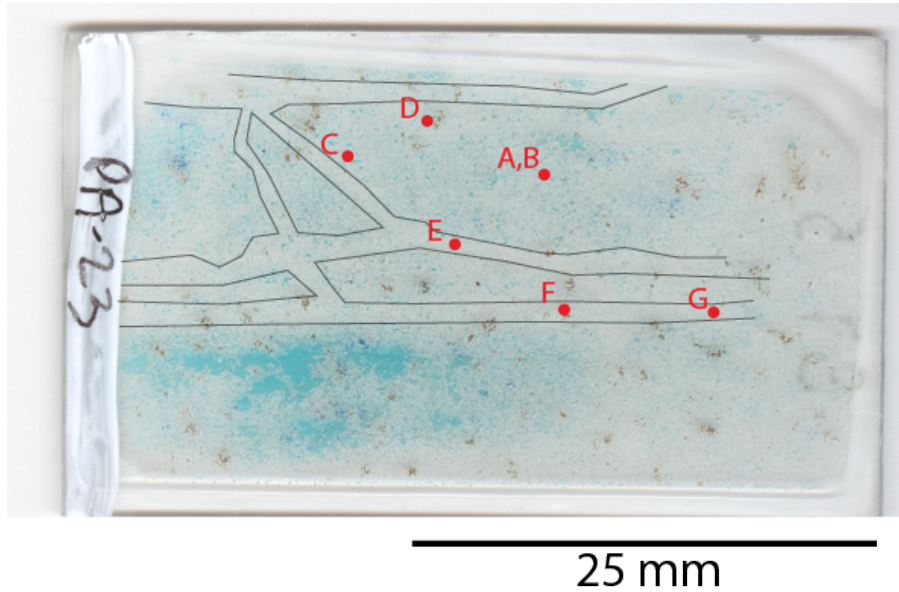


PA15 Photomicrograph D – 4x:

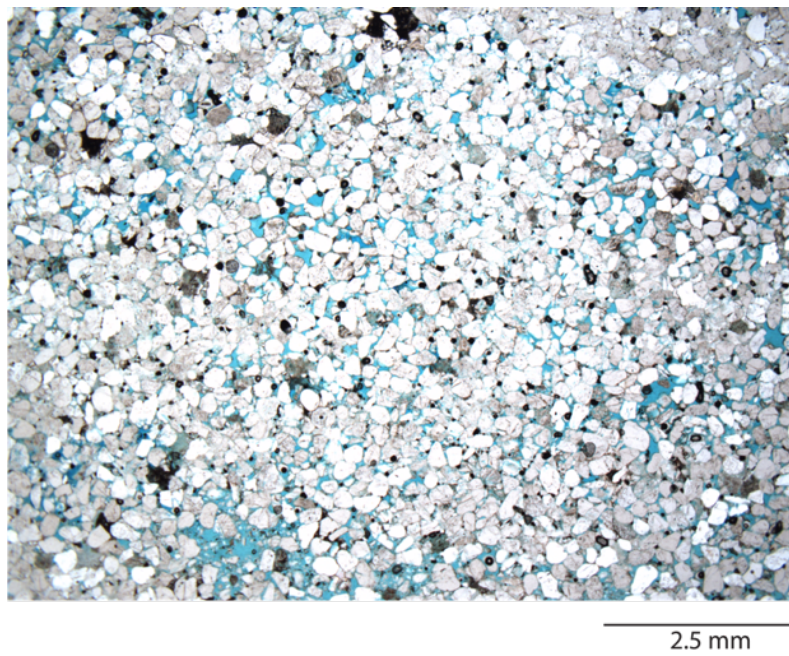


PA 23:

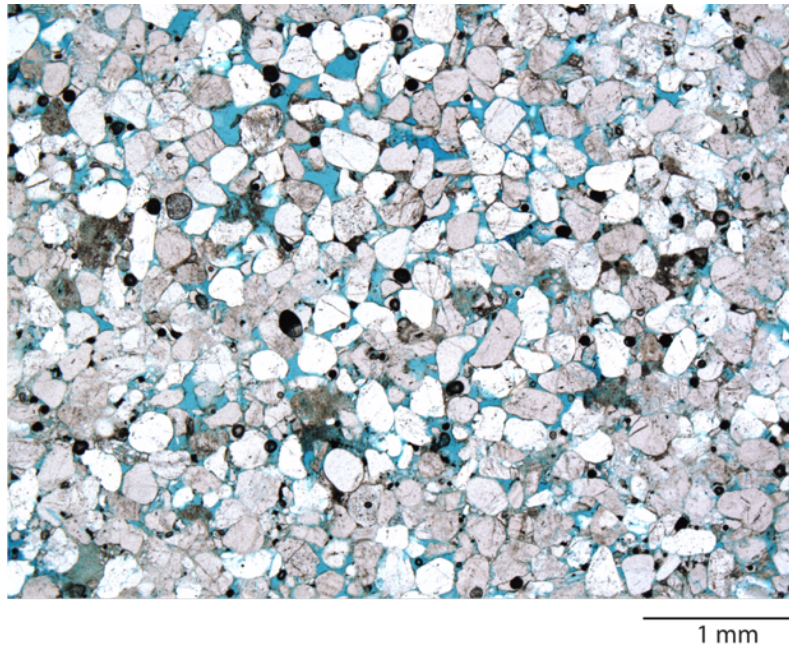
Thin Section:



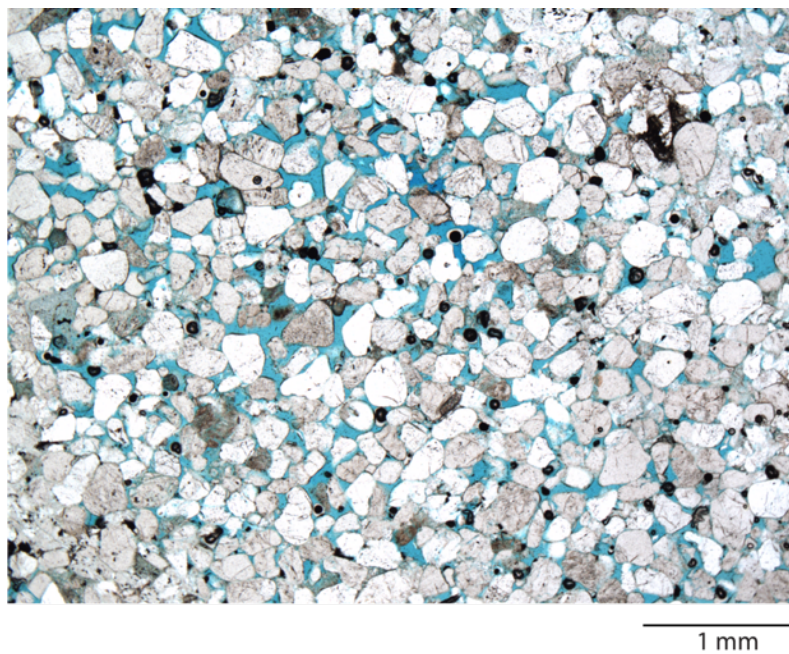
PA23 Photomicrograph A – 2x:



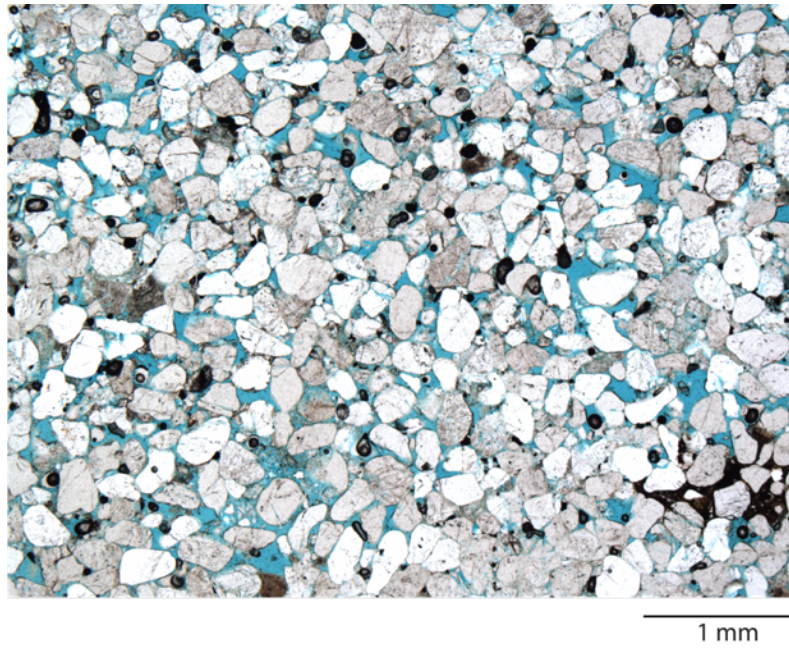
PA23 Photomicrograph B – 4x:



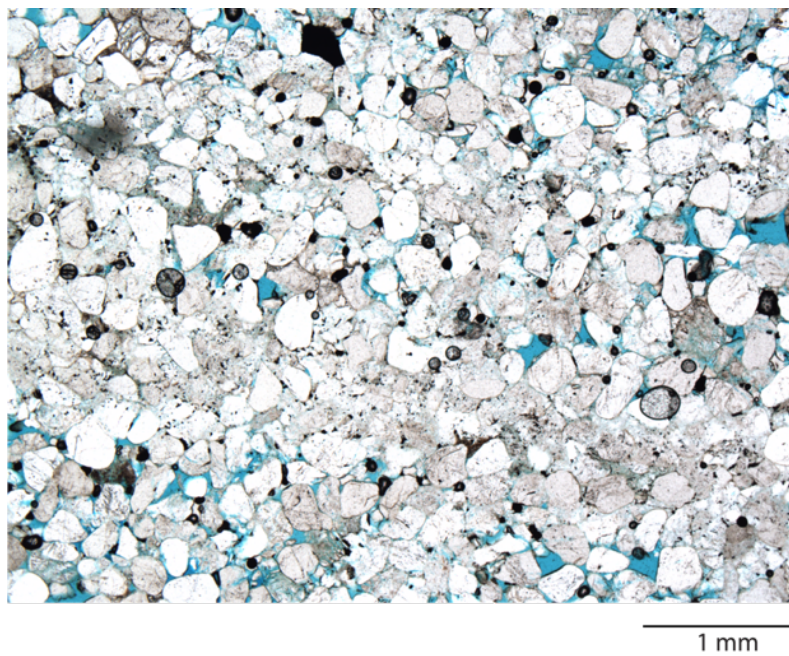
PA23 Photomicrograph C – 4x:



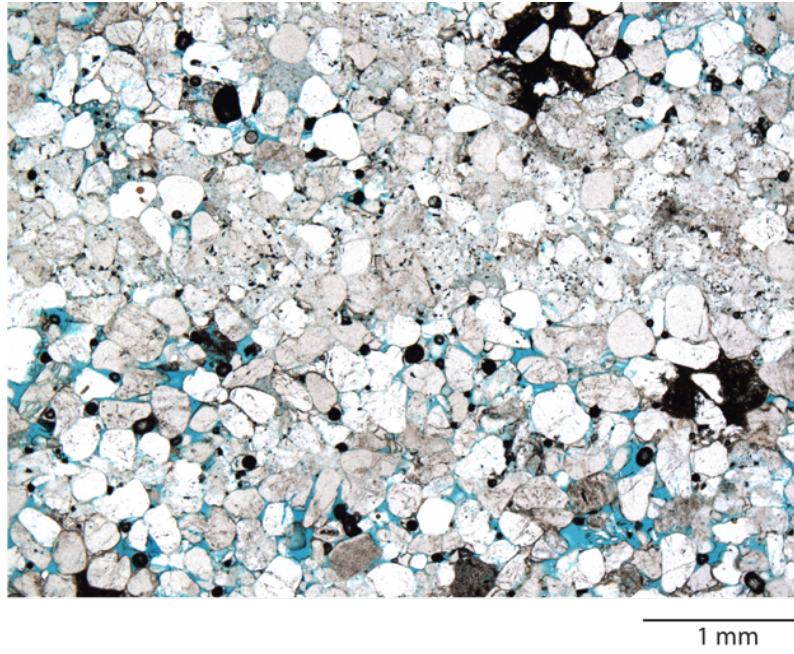
PA23 Photomicrograph D – 4x:



PA23 Photomicrograph E – 4x:

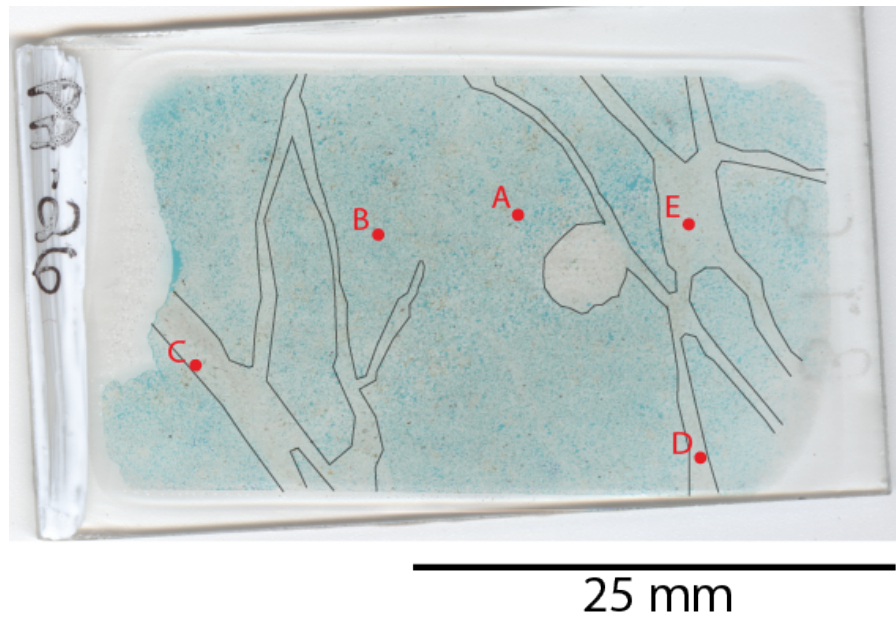


PA23 Photomicrograph F – 4x:

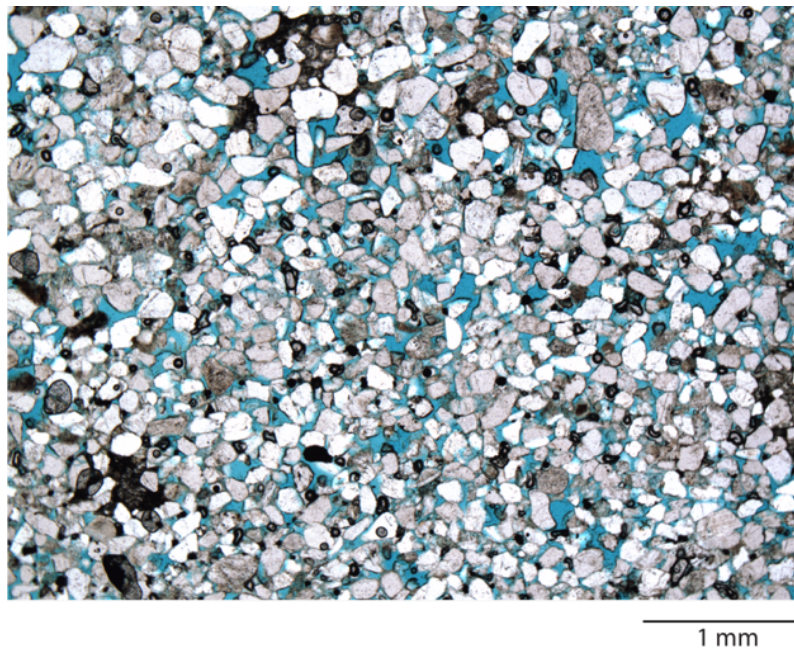


PA 26:

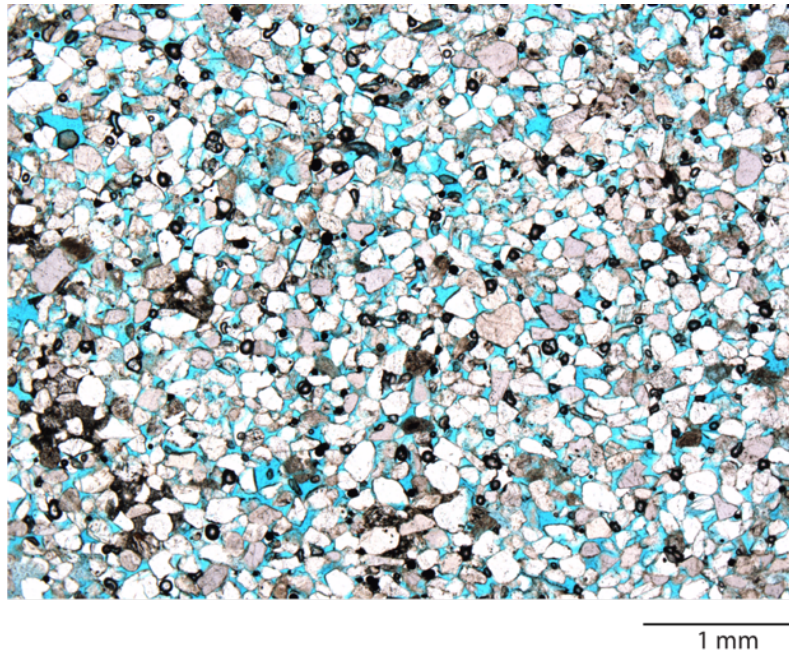
Thin Section:



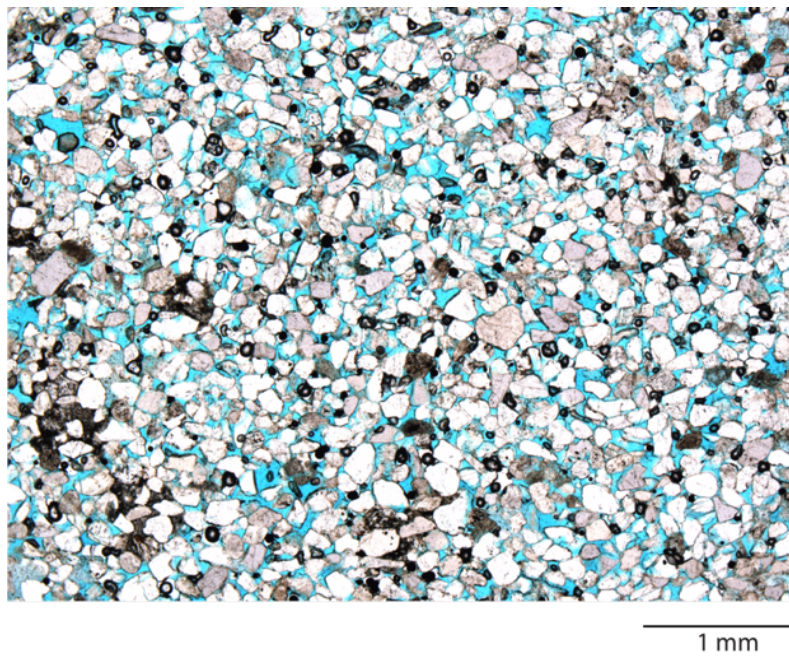
PA26 Photomicrograph A – 4x:



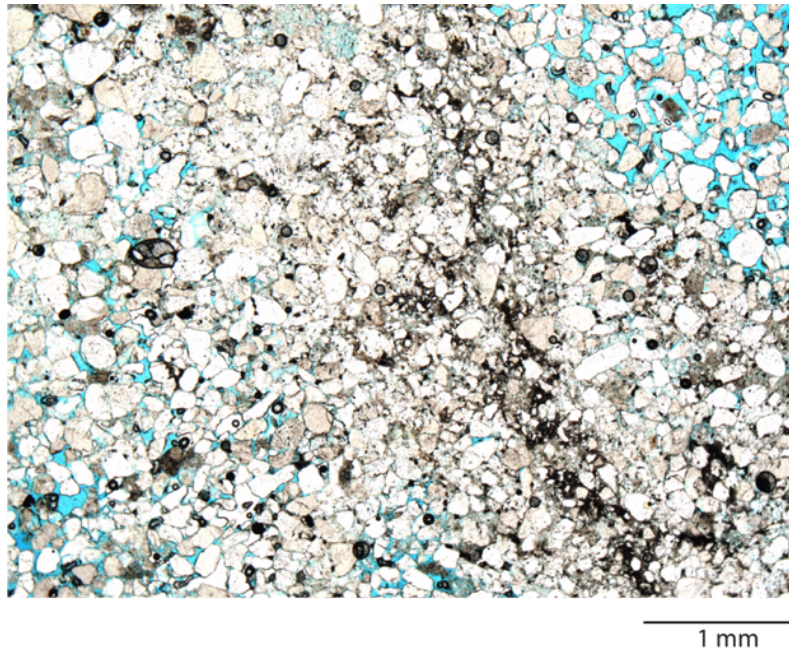
PA26 Photomicrograph A – 4x:



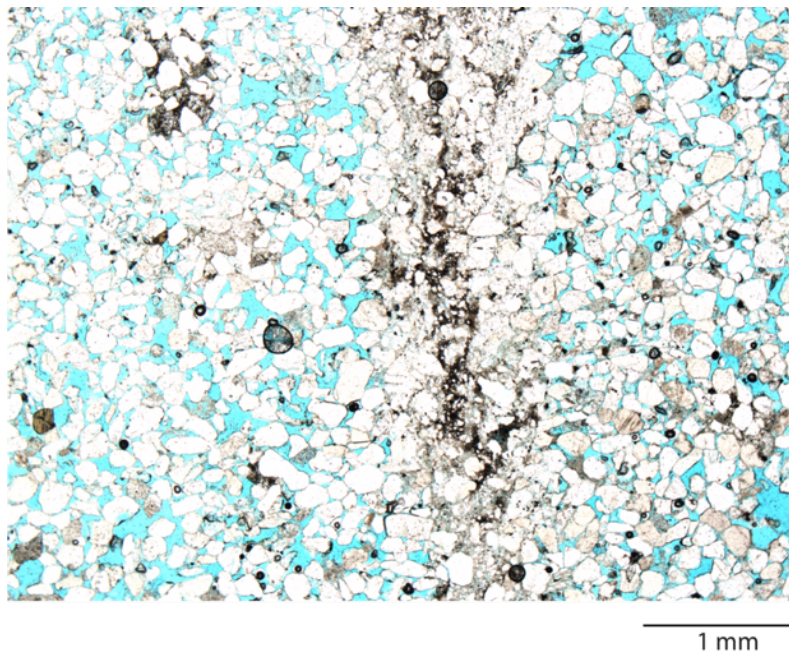
PA26 Photomicrograph B – 4x:



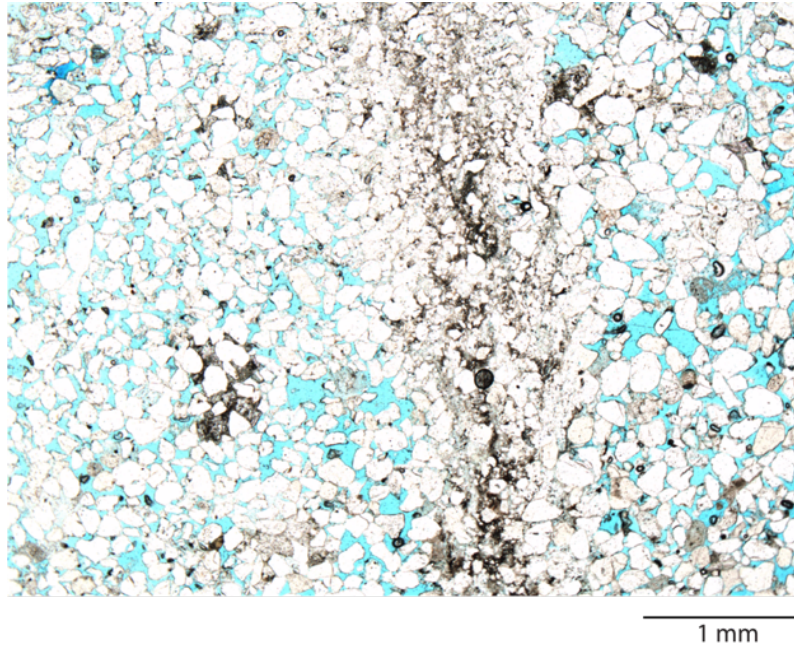
PA26 Photomicrograph C – 4x:



PA26 Photomicrograph D – 4x:

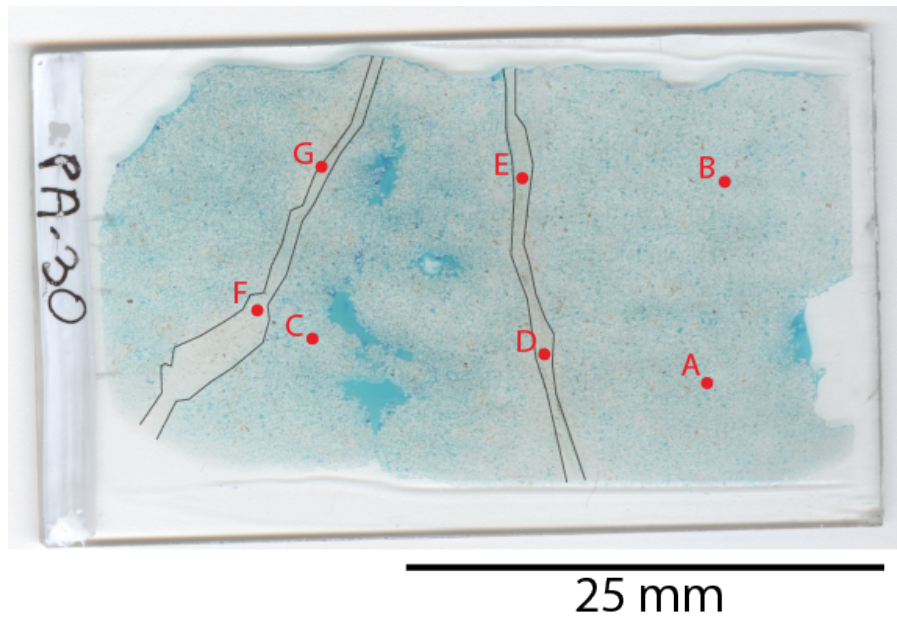


PA26 Photomicrograph E – 4x:

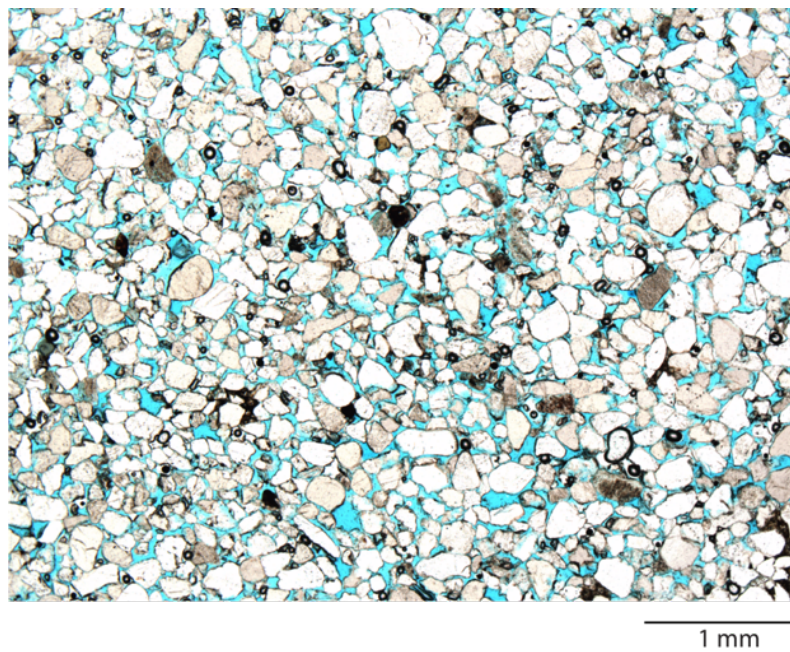


PA 30:

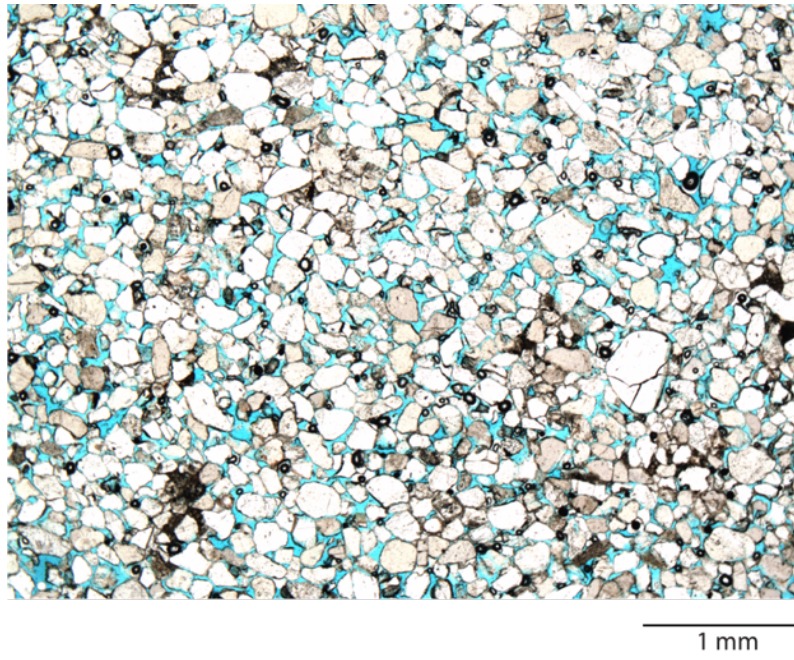
Thin Section:



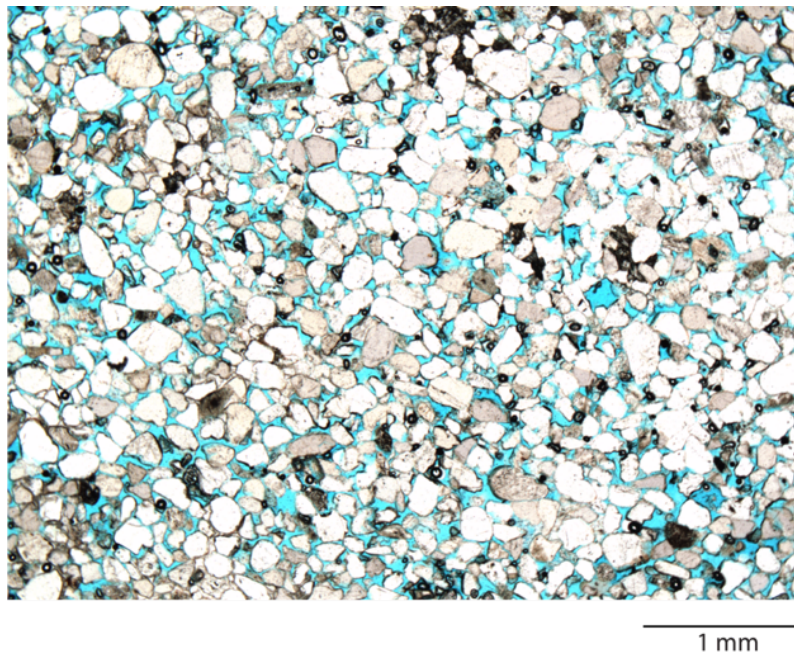
PA30 Photomicrograph A – 4x:



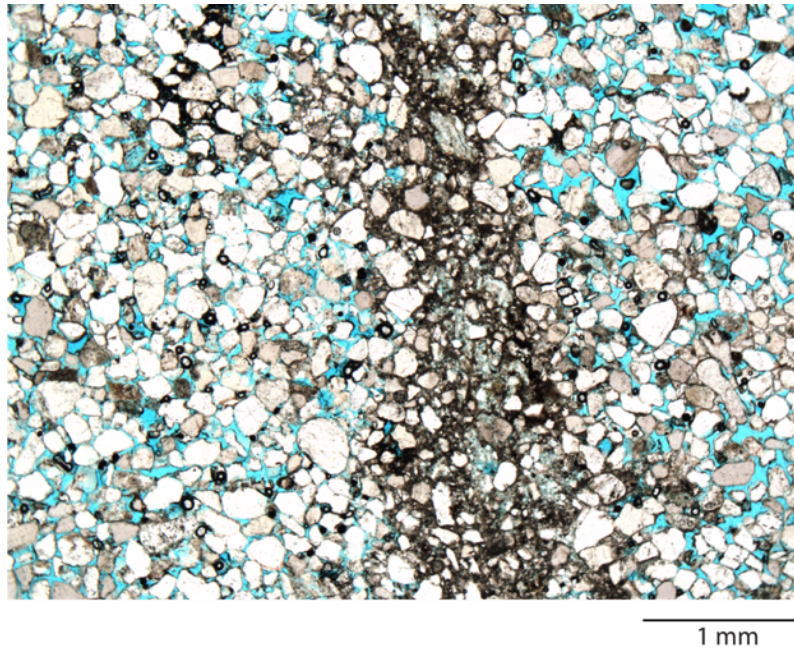
PA30 Photomicrograph B – 4x:



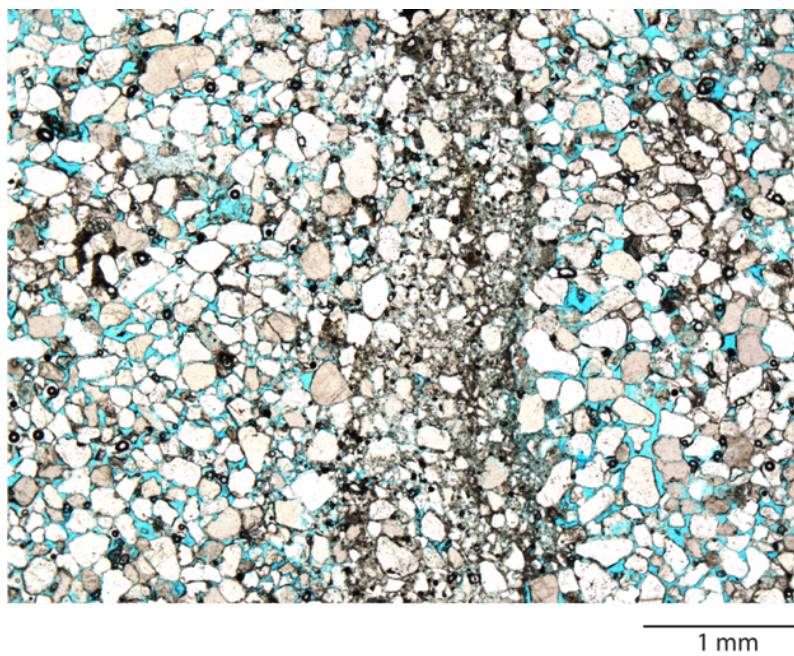
PA30 Photomicrograph C – 4x:



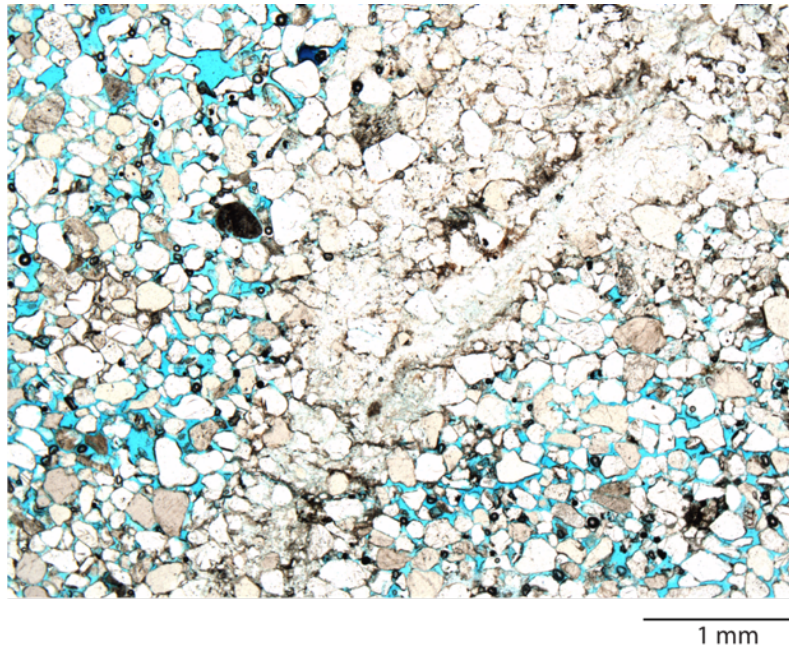
PA30 Photomicrograph D – 4x:



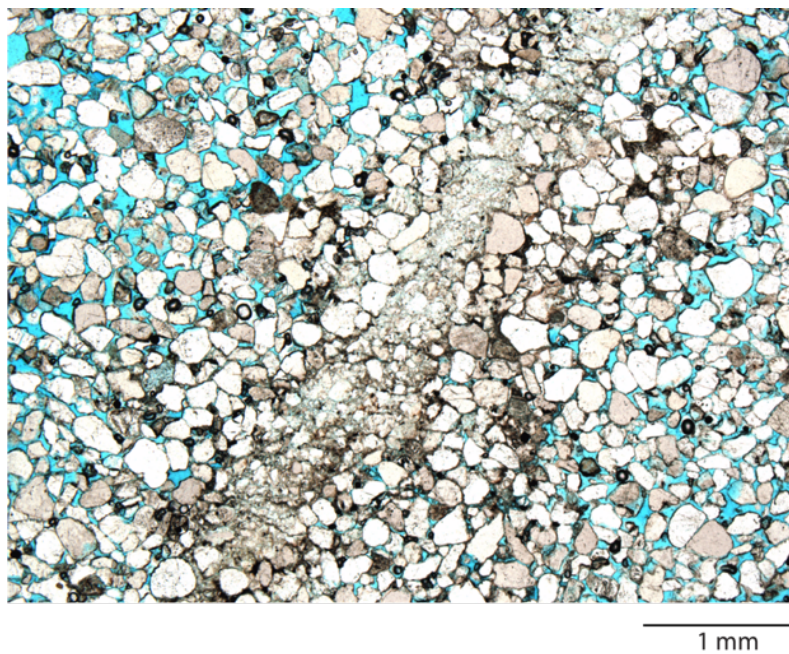
PA30 Photomicrograph E – 4x:



PA30 Photomicrograph F – 4x:

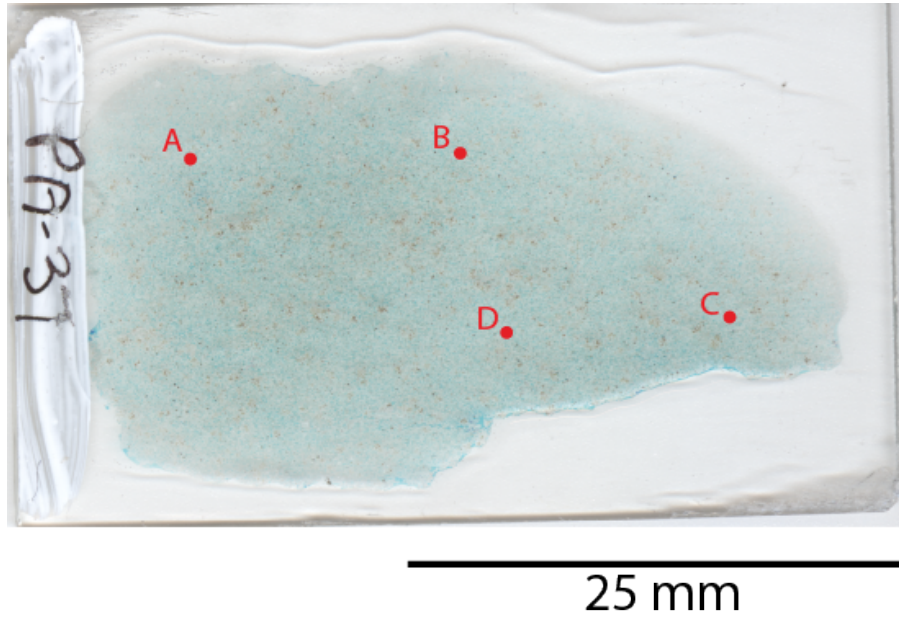


PA30 Photomicrograph G – 4x:

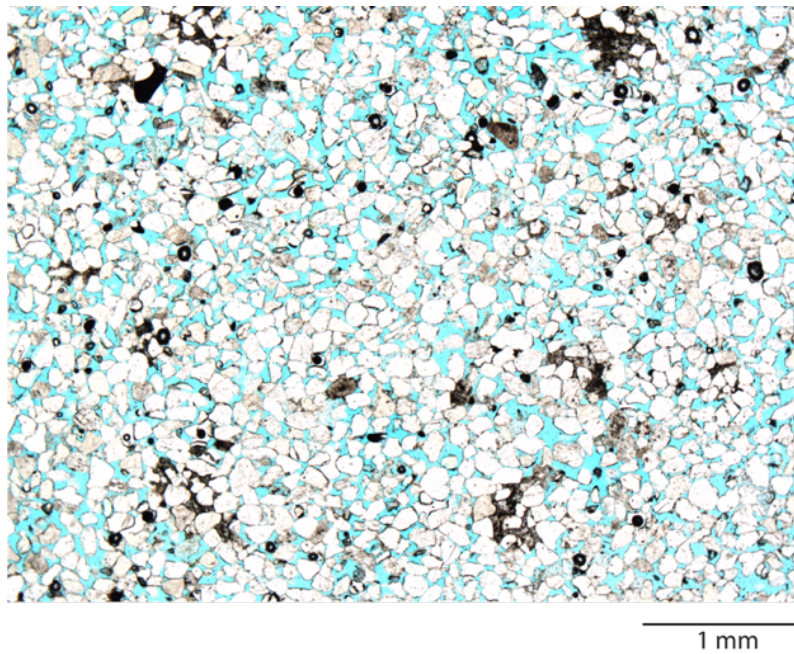


PA 37:

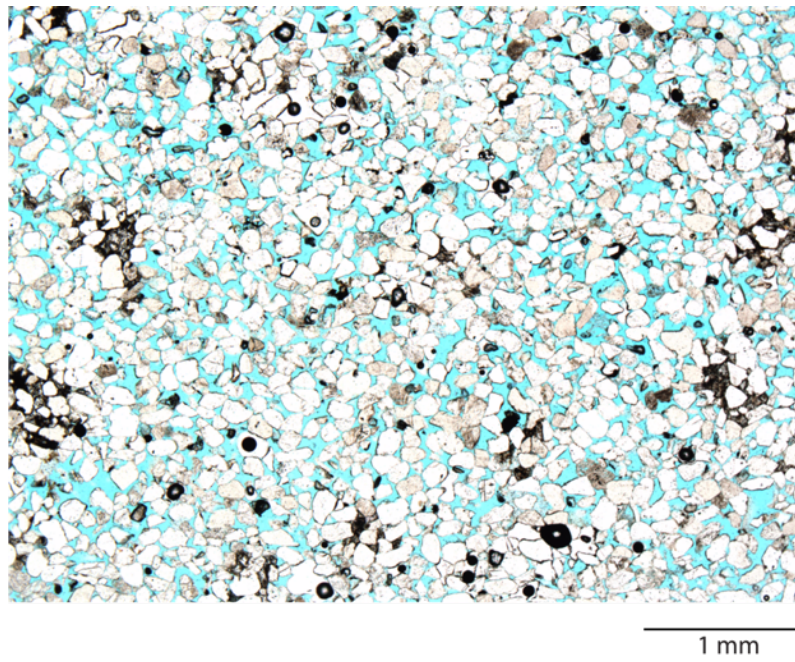
Thin Section:



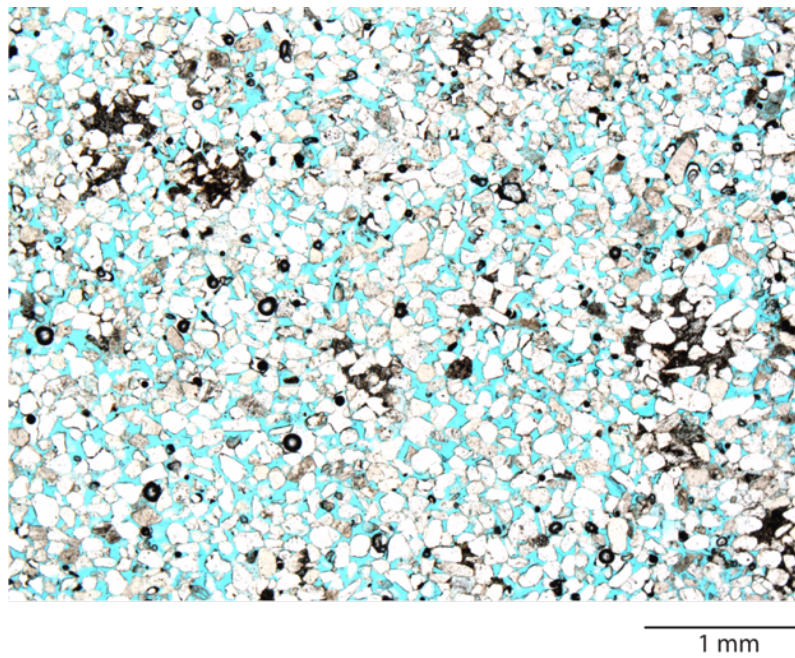
PA37 Photomicrograph A – 4x:



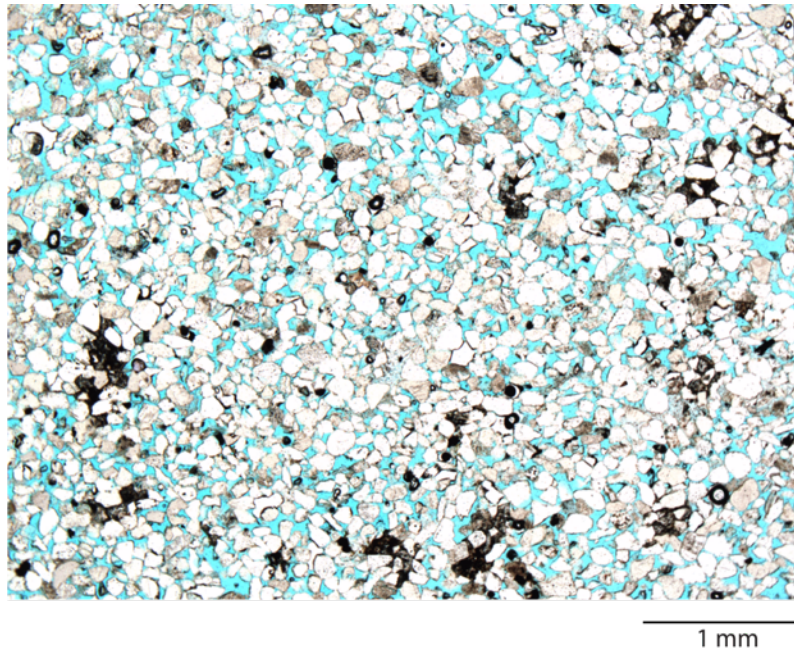
PA37 Photomicrograph B – 4x:



PA37 Photomicrograph C – 4x:

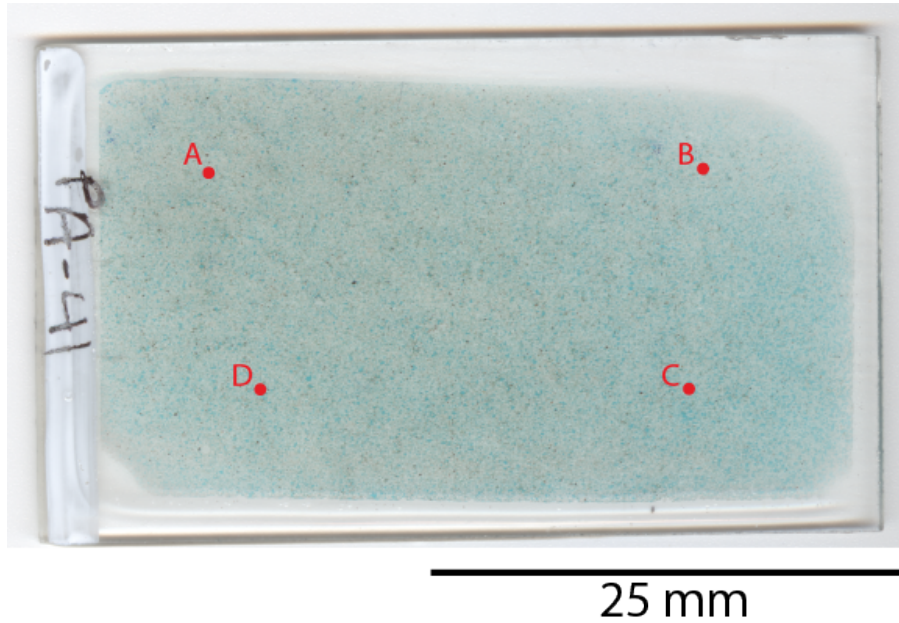


PA37 Photomicrograph D – 4x:



PA 41:

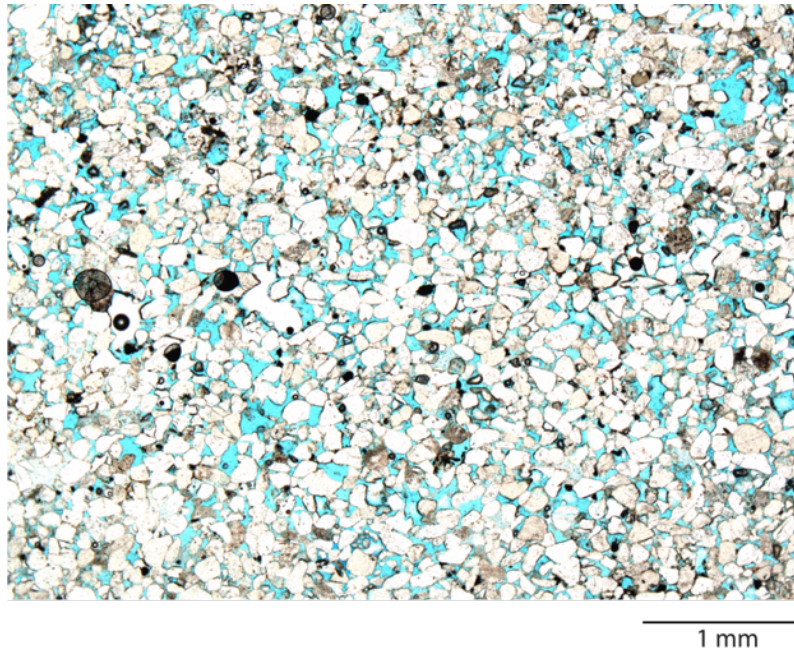
Thin Section:



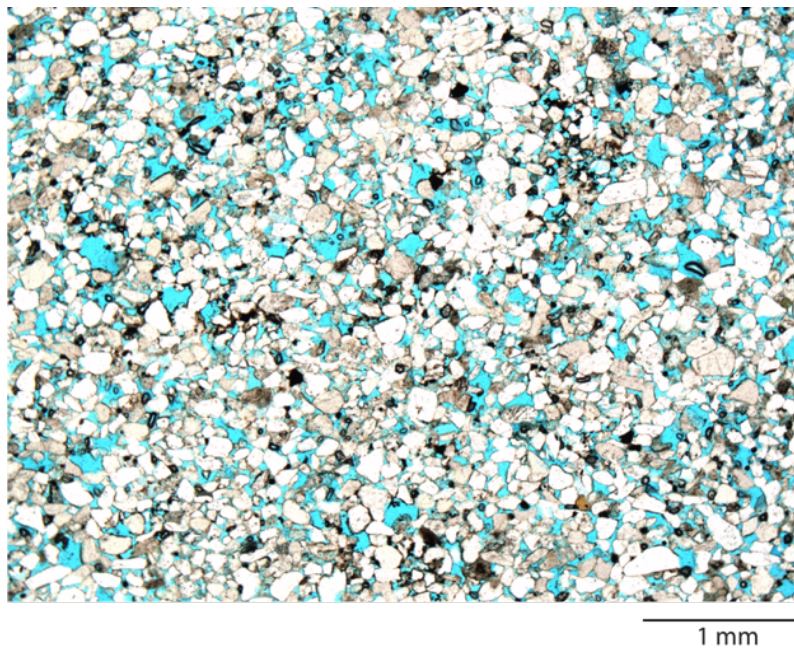
PA41 Photomicrograph A – 4x:



PA41 Photomicrograph B – 4x:



PA41 Photomicrograph C – 4x:

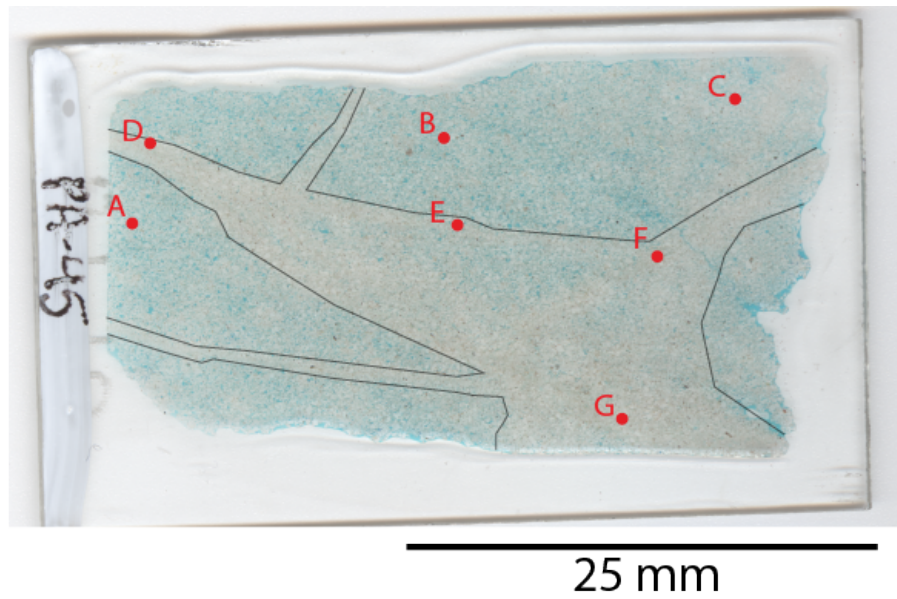


PA41 Photomicrograph D – 4x:

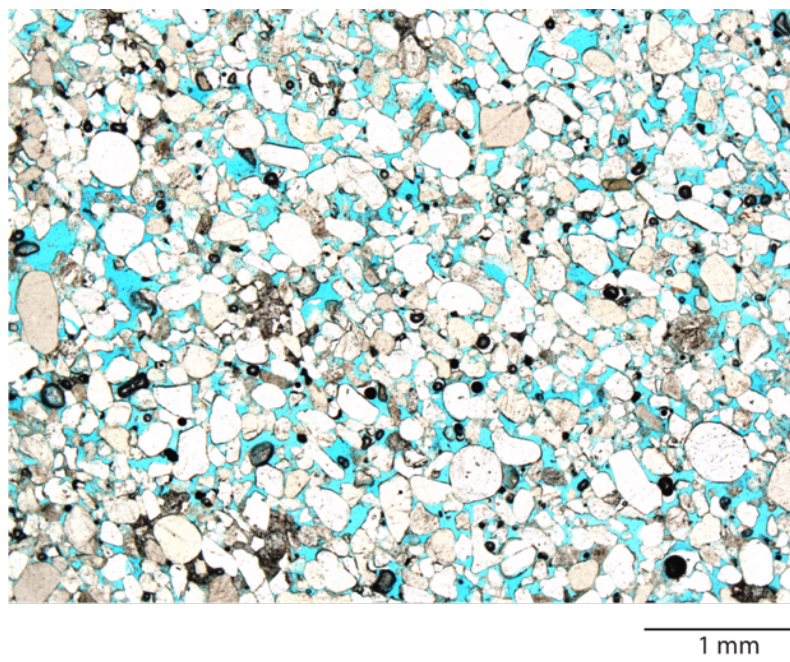


PA 45:

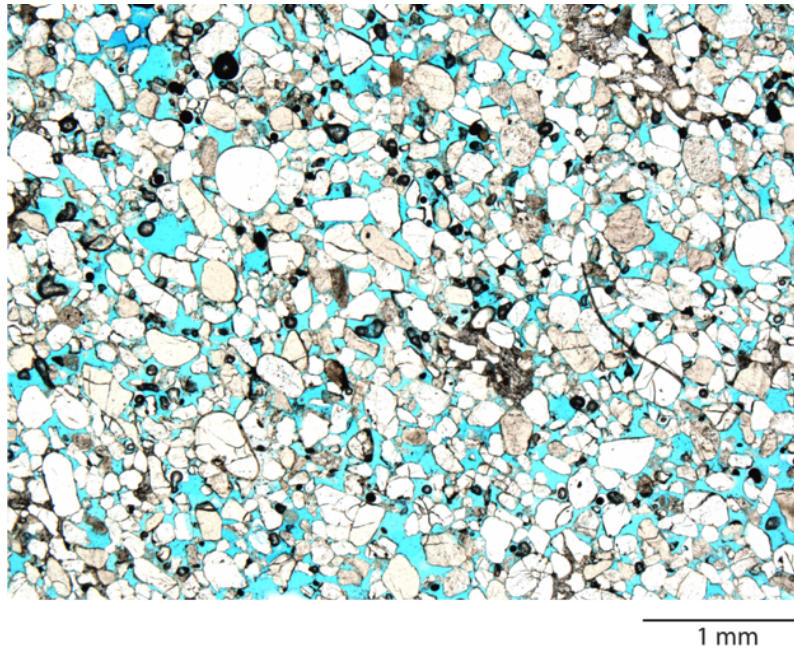
Thin Section:



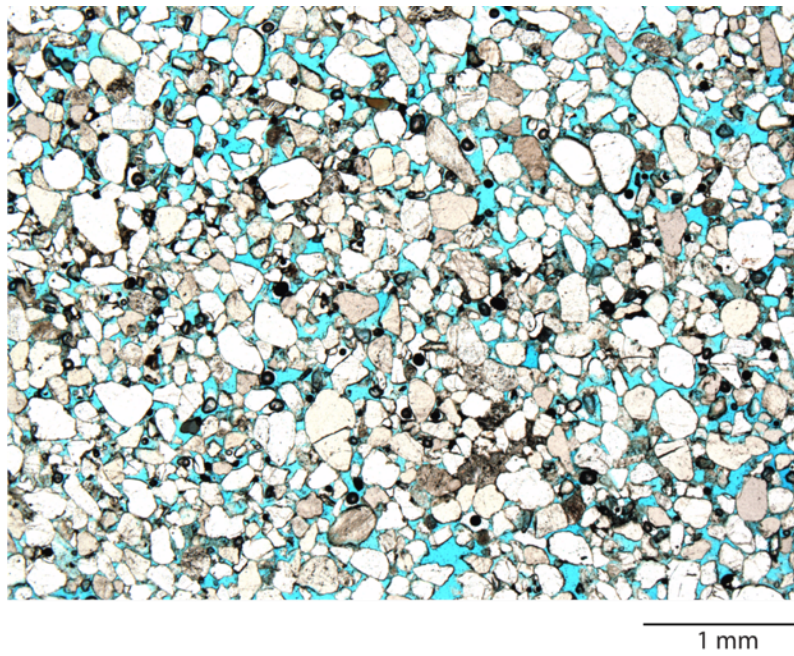
PA45 Photomicrograph A – 4x:



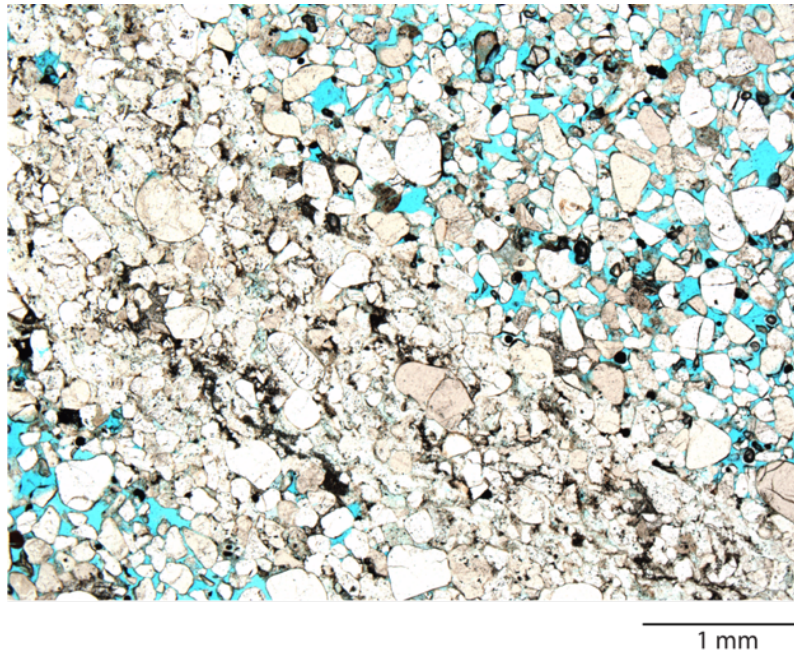
PA45 Photomicrograph B – 4x:



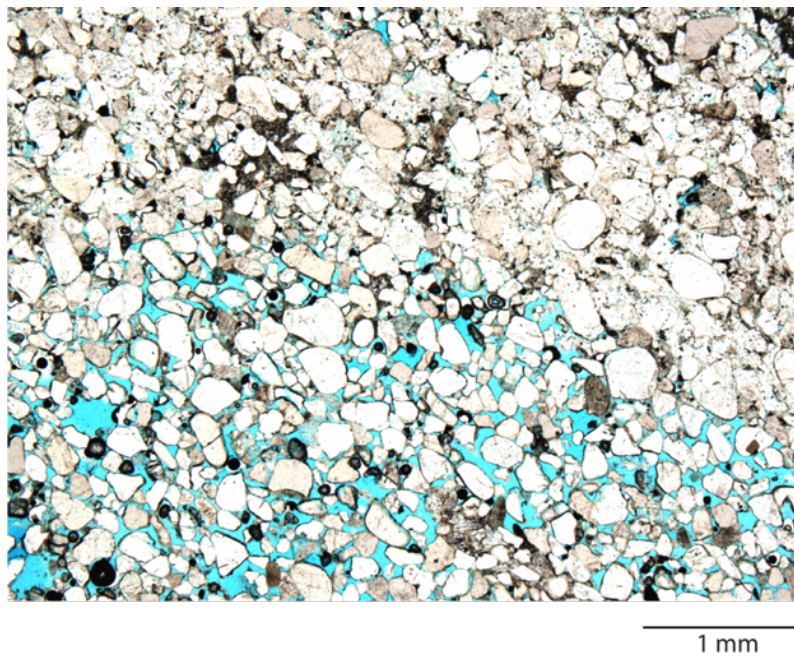
PA45 Photomicrograph C – 4x:



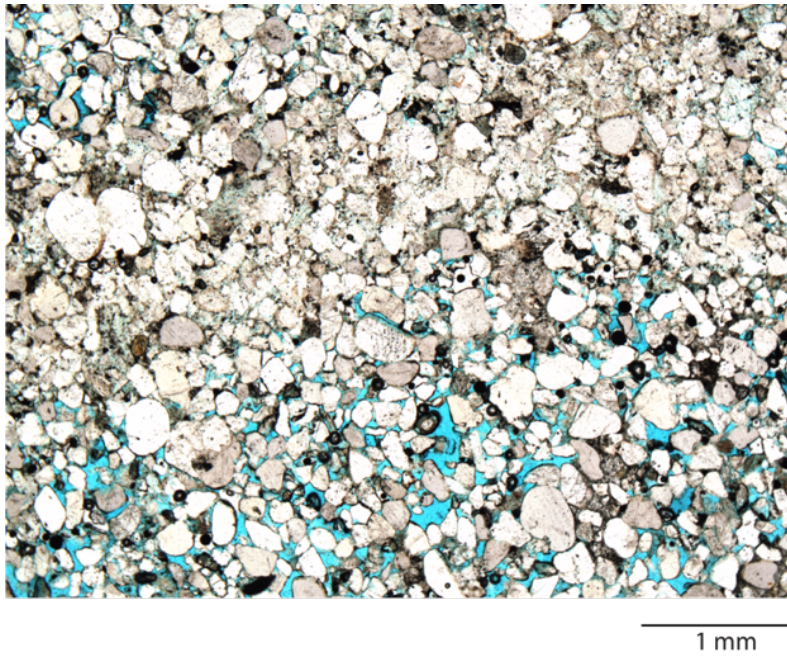
PA45 Photomicrograph D – 4x:



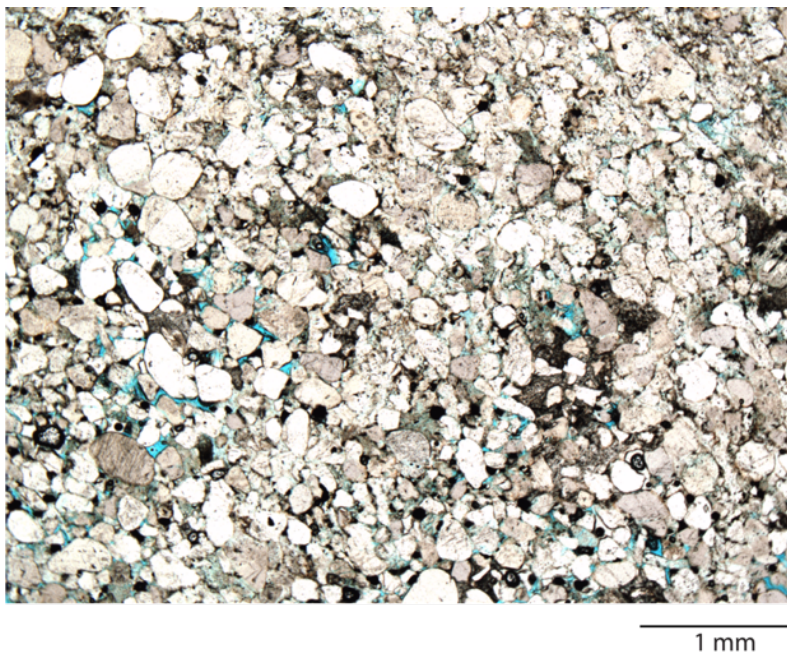
PA45 Photomicrograph E – 4x:



PA45 Photomicrograph F – 4x:



PA45 Photomicrograph G – 4x:



Appendix E – UTM Coordinates for Stations

All coordinates are located in UTM zone 12N.

* - Control area station

** - Station taken in Page Sandstone

Station Number	Station Type	Easting	Northing
PA1	Fracture	536982	4193912
PA2	Bedding	539064	4194011
PA3	Bedding	537285	4194009
PA4	Bedding/Contact	537335	4193945
PA5	Bedding/Contact	537345	4193904
PA6	Bedding	535218	4194140
PA7	Bedding	535014	4193716
PA8	Bedding	535026	4193158
PA9	Bedding	535909	4193205
PA10	Fracture	536479	4193409
PA11	Fracture	536297	4192706
PA12	Bedding	536338	4192688
PA13*	Fracture	541257	4194757
PA14*	Bedding	541063	4194833
PA15*	Fracture	541093	4194956
PA16*	Bedding	541024	4194998
PA17*	Fracture	540497	4194975
PA18*	Fracture/Contact	540519	4195649
PA19*	Bedding	537961	4195537
PA20**	Fracture	526969	4209632
PA21	Fracture	536593	4194462

PA22	Fracture	536653	4194594
PA23	Fracture	536561	4194772
PA24	Fracture	536919	4194660
PA25	Fracture	537228	4194662
PA26	Fracture	536770	4194284
PA27	Fracture	526741	4194065
PA28	Fracture	536466	4194048
PA29	Contact	536567	4194125
PA30	Fracture	536969	4194190
PA31	Fracture	537357	4194191
PA32	Bedding	534302	4193342
PA33	Bedding	534226	4193125
PA34	Bedding	534129	4192970
PA35	Bedding	535353	4195275
PA36	Bedding	535596	4196416
PA37	Fracture	537121	4193544
PA38	Fracture	536926	4193493
PA39	Fracture	536545	4193454
PA40	Fracture	536885	4193126
PA41	Fracture	536717	4192969
PA42	Fracture	537415	4193226
PA43	Fracture	536162	4193699
PA44	Fracture	536311	4193814
PA45	Fracture	536958	4193878
PA46	Fracture	537245	4193873

