Impact of Geologic Structures on the Orientation of Potomac River Flow Near Great Falls, Maryland and Virginia

(Rocky Island, C&O National Historic Park, looking east)

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Table of Contents

Abstract

Many previous geologic studies of the Potomac Gorge region of Maryland and Virginia conclude that secondary structures within the bedrock affect river orientation; however, a recent research project in the Potomac Gorge region did not find a relationship between the physical evidence of structures and river orientation. This study addresses that contradiction. Rocks in this region are metasedimentary rocks which have been ductilely deformed leading to the formation of secondary structures. The Potomac River cut into these rocks by drilling and quarrying creating the channel we see today. Field data provides evidence that there are eight joint sets in the study area. The study area contains eight different orientations of flow for the Potomac River. Strike orientations of the joint sets demonstrate that secondary structures within the bedrock from Conn Island south to Rocky Island may influence the Potomac River's orientation.

I. Introduction

It is said that there are two things people can not help but watch - flames from a campfire and water flowing down a stream - but how many of us have wondered why the water travels a particular path? At Great Falls of the Potomac River the water rushes past with all its twists and turns, but why does the water flow in a particular direction (Figure 1)? The commonly accepted answer lies in the concept that geologic structures within the bedrock determine water flow orientation. For example, water might travel in a certain direction over rock because there exists a favorably oriented joint weakening the rock and allowing water to flow in a similar direction. Most of the studies completed in the Potomac Gorge region accept this explanation even though supporting evidence is rarely offered.

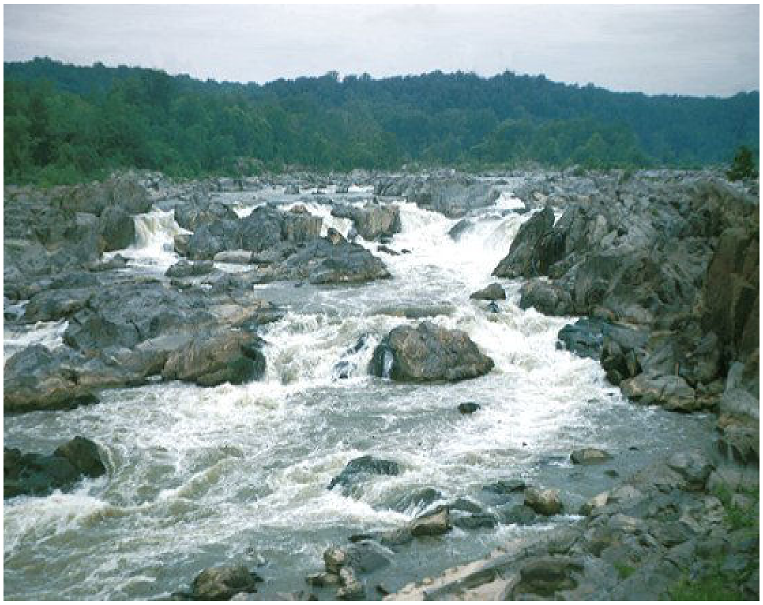


Figure 1 - Potomac River rushing through Great Falls of Potomac Gorge looking north from the Maryland Overlook.

The very nature of geologic structures points to a possible correlation between water and structure orientations. The geologic structures referred to here and throughout this study are secondary structures (faults, joints, fractures, folds, lineations etc.), which form after lithification for sedimentary and igneous rocks and during or after any metamorphism. These structures are the result of stresses exceeding rock strength. Fractures grow when propagation energy exceeds critical values (Tuncay et al 2000). Examples of critical values include compressive strength, fluid pressure and tensile strength. The largest favorably oriented flaw generally experiences the greatest stress (Lockner, 1995). In the case of a river providing stress, the flaw may orient with flow direction. If this stress exceeds the rocks resistance to fail, the flaw grows. The growth of cracks can increase stress intensity producing more growth until the rock is fractured (Lockner, 1995). The most direct control of fluvial erosion to bedrock is at joint spacing and fractures (Whipple et al, 2000). Water need not provide a large source of stress if orientation of flow aligns with orientation of a joint set because previously fractured rock has no cohesive strength, the only force necessary to move the bedrock is that required to overcome frictional resistance. Molnar et al. (2007) points out that fractures provide opportunity for water flow which enhances weathering and allows for the extraction of the rock by surface processes.

Southworth and Fingeret (2000) completed a survey of the Potomac Gorge area for the U.S. Geologic Society (USGS). The resultant geological map states in the legend under the title Landscape Evolution that “the river follows the trend of joints and faults.” Burgy (2006) completed research in Mather Gorge of the Potomac Gorge region and concluded that there is no correlation between identified geologic structures and Potomac River orientation. This contradiction is the stimulus behind my work.

This project extends the concept of structure and river flow orientation beyond Mather Gorge to demonstrate that stress from water flow orientation can exploit structures within bedrock (Figure 2). This project considers previously collected information, but focuses on field measurements to show a correlation between structure and river orientations. The objective of this study is to test whether the orientation of geologic structures in the bedrock along the Potomac River from Conn Island south to Rocky Islands impacts orientation of the river.

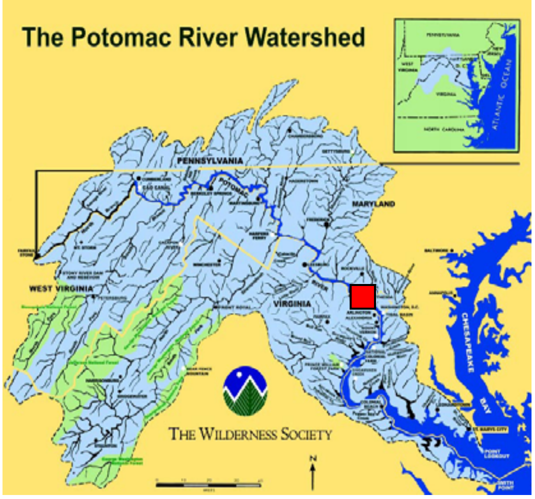


Figure 2 - The Potomac River Watershed. Note the scale and the many changes to orientation of flow seen as the river flows generally northwest to southeast. A red block indicates the study area. (Wilderness, 2007)

II. Geologic Setting

The Potomac River Valley cuts through five physiographic provinces (Figure 3). Great Falls region rocks are part of the Mather Gorge and Sykesville Formations with protoliths consisting of muddy sandstone, shale, mudstone, and basalt. Original deposition was likely an ancient ocean trough with slurries of mud and sand moving down slope to create the muddy sandstones of the Great Falls region, whereas the shale represents quieter waters that allow silt and clay sized particles to settle (Reed et al, 2005). After deposition, magma formed sills of basalt (Reed et al, 2005). Metamorphism of these rocks within the Potomac Gorge region led to development of mica schist, metagraywacke, and amphibolites. Granites and lamprophyre intruded during the Devonian (Kunk et al, 2004) (Figure 4). Further explanation of deposition and metamorphism tells the tectonic history of this area.

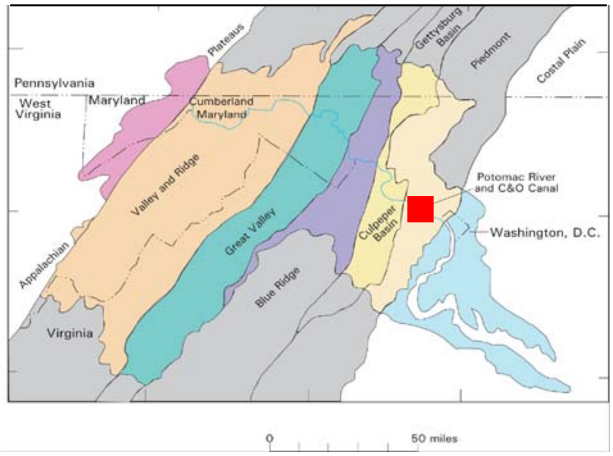


Figure 3 - The Potomac River watershed and physiographic regions. Study area shown as a red square. (Southworth et al, 2001)

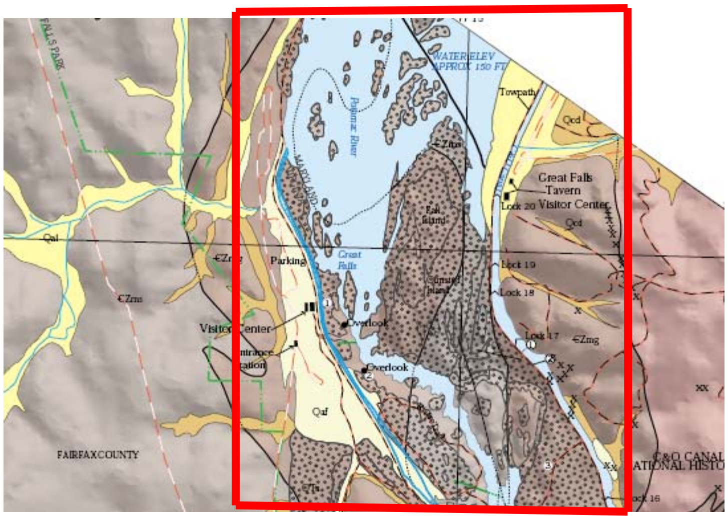


Figure 4 - Portion of geologic map of Potomac Gorge showing locations of rock types. Study region outlined in red. Legend information in Appendix A. (Southworth et al, 2000)

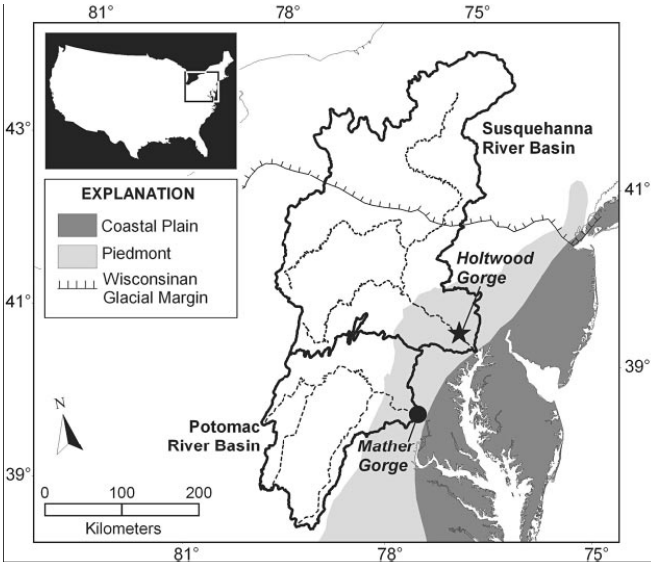
A. Geologic History

Approximately 525 million years ago (Ma), during the Cambrian and Ordovician, the area west of present day Great Falls was a region of passive continental margin with shelf development. The area east of the region was ocean basin (Southworth et al, 2001). In the middle and late Ordovician the Iapetus Ocean constricted, eventually leading to a subduction zone creating an island arc. This island arc would impact the region with resultant forces leading to the Taconic orogeny and thrusting oceanic sediments onto deep water sediments of the Piedmont. The region went through a time of erosion and deposition until the Alleghanian orogeny during the Carboniferous Period formation of Pangaea. The African plate rose over the margin of the America plate producing the Appalachian orogeny. Deformation created folds and faults in the anitclinoria and synclinoria of the Piedmont region. The resultant terrane is comprised of older rocks on younger interior rocks. Fractures preceded the movement of molten basalt, creating the lamprophyre dikes dated 360 Ma (Reed et al, 2005). At approximately 230-220 Ma, the super-continent began to break up with formation of the Atlantic Ocean. Alluvial fans and streams moved sediment from the uplifted regions for deposit downstream, becoming part of the coastal plains. This time of erosion and subsequent uplift continues today. (Appendix B)

B. Potomac River History

The Great Falls region is more than a story of rock; however, there must also be an understanding of the river and subsequent incision into the bedrock. The Potomac River is estimated at 616 km long with a watershed area approximately 37,995 square km of four states; Maryland, Virginia, West Virginia and Pennsylvania. Approximately 10 to 20 Ma, rivers along the Atlantic margin drained through wide valleys. Nearly 2 Ma the Potomac River settled into its current channel (Reed et al, 2005). Long-term lowering of the Potomac River valley is set at approximately .01 to .02 meters per thousand years (m/ky) (Reusser et al, 2004). Factors influencing this rate include flexural uplift, isostatic uplift from removal of sediment, and Cenozoic sea level fall. Using cosmogenic ^{10}Be samples from Mather Gorge, Reusser et al. (2004) show that a major increase in river downcutting occurred between 37 thousand years ago (ka) and 13 ka with a rate of approximately .8 m/ky. Causes for the downcutting rate are not clear but tend towards ice sheet growth and resulting eustatic ocean level decrease, uplift at the edge of the ice sheet caused by tilting of the lithosphere, and flooding (Reusser et al, 2004) (Figure 5). Estimates indicate that 65 percent of the 25 largest floods in the Potomac occurred over the past 75 years (Reusser et al, 2004). Possible modes of downcutting include abrasion, quarrying and drilling (Beirman et al, 2000). Today the Potomac River from the top of Great Falls to tidewater has a sinuosity of 1.2 and drops 43.89m with a gradient of 0.2 % (Zen, 1997) (Figures 6 & 2). Current age estimation for the channel we see today is 6 ka (Bierman et al, 2002).

Figure 5 - Diagram showing placement of Pleistocene Epoch ice sheet relative to the Potomac Gorge. (Reusser et al, 2004)



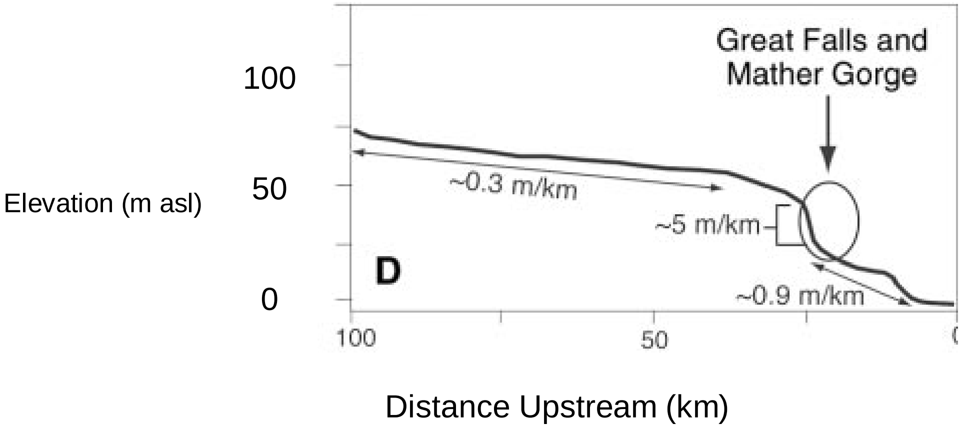


Figure 6 - Potomac River profile. (Adapted from Reusser et al, 2004)

III. Methods

The study area is shown in Figure 7. The area is approximately 2 km by 3 km. It comprises the C&O Canal Historical Park (Maryland), the Great Falls National Park (Virginia), and the Potomac River. The area contains several islands; from north to south the islands are Conn Island, Olmsted Island, and Rocky Islands. Conn Island marks the northern end of the area with the southern tip of the western Rocky Islands marking the southern end. The river is dissected by the Washington Aqueduct Dam just south of Conn Island. Selection of this area is due to the changing river flow orientations, river shoreline for access to bedrock, and land on the “mainland” to increase bedrock sources and reduce bias in the data.

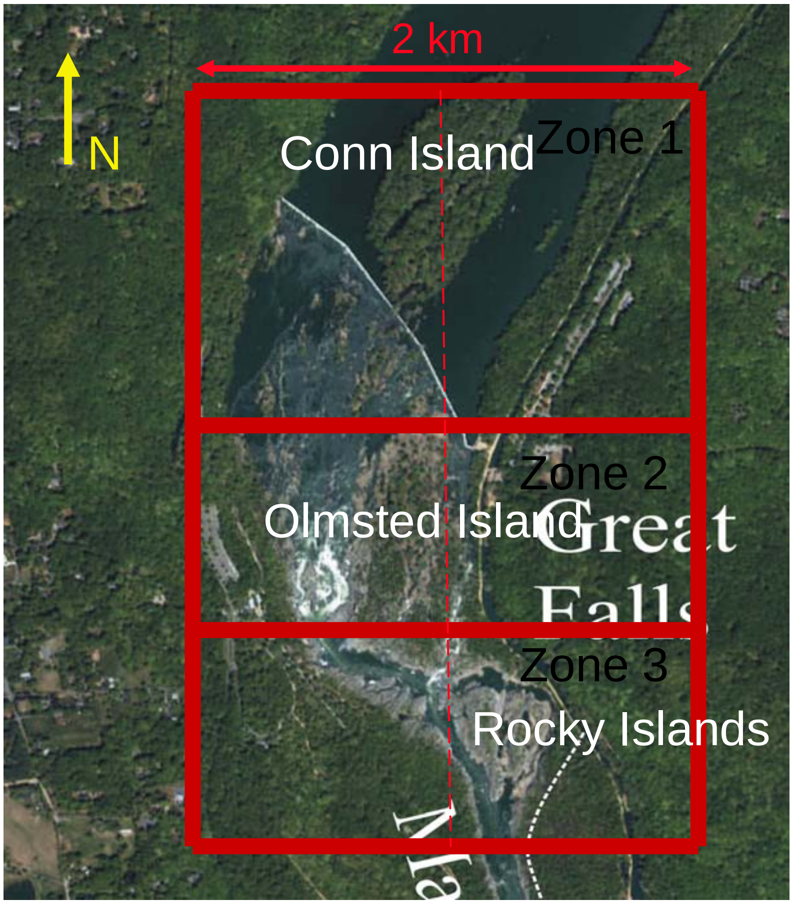


Figure 7 – Zones within the study area. Each zone contains a portion of the river with a different orientation of river flow (Adapted from Earthobservatory, 2007).

The study area is split into zones representing regions of modified river flow orientation. There are three zones within the region numbered from north to south and a dividing line to assist in evaluating distribution of data (Figure 7). Within each zone, I selected stations based on availability of bedrock, and the ability to locate and measure structures. Data were collected at as evenly spaced intervals as possible. Each station is identified using a Global Positioning Satellite (GPS) receiver, confirmed on a field map, labeled, and recorded. After identifying a station I examined the area up to approximately 10m in diameter around the station.

The initial stage of this study was completing reconnaissance. Maps for reconnaissance included the Great Falls and Mather Gorge visitor map from the National Park Service, TOPO! Outdoor Recreation Mapping Software topographic maps from National Geographic, Geologic Map of the Potomac River Gorge (Southworth et al, 2000) and 1:2400 scale 2 or 5 foot contour interval maps from the U.S Geologic Survey (Zen, 1997). Next, preliminary examination of the region provided an understanding of the terrain and accuracy of map reconnaissance. This work highlighted that topography within the study area influences the ability to access bedrock, especially during high water events (Figure 8).

Figure 8 – The area in between the Rocky Islands looking north showing bedrock access and area inaccessible during high water events.

A benchmark for determining reproducibility was established before any measurements of structures occurred. This benchmark has two planer structures of varying dip, one greater than 45°, and the other less than 30°. I used a permanent marker to place a line on each plane along strike and measured these lines with each visit to the region.

I used two different methods for locating structures. Both methods start with inspecting the station for all structures present. If structures were clear and measurable, I used the selection method with emphasis on joint sets. If however, there were a large amount of structures I used the inventory method. This method sets a limit to the size of the station then all identified structures are measured. The data are then combined by using similar strike/trend orientations. Similar orientations are those within 15° in strike/trend. Fifteen degrees is used as a guide due to the range for conjugate planer features of 15° to 90° (Martin, 2006).

My primary tool for measurements was a Brunton Transit Classic™. Declination for the Brunton was set at 11° W for Great Falls (Southworth et al, 2000). This measurement was confirmed by the National Geophysical Data Center (2004) using the declination of 10° 41´ W for zip code 20852. Procedures for measurements follow:

Plunge and trend for linear structures. Plunge is the angle between horizontal and the inclined line. Determine plunge by setting the transit's side along the linear element and adjust the clinometer until the tube level centers, and then read the angle from the inside scale. Trend is the azimuth or bearing of the line measured in the horizontal by using the bull's eye level and reading the directional needle.

Strike and dip of planer structures. Strike is the trend of a horizontal line in the plane recorded as the azimuth or bearing using the "Right Hand Rule". Determine azimuth by placing the side or edge of the transit flush against the plane or extension of the plane using a field notebook. Rotate the transit to center the bull's eye level and read the azimuth. Dip is the inclination of a line perpendicular to strike, recorded as the inclination angle and direction. Dip is ascertained by placing the transit side on the inclined plane so that the transit is in the direction of dip then rotate the clinometer until the tube level centers and read the angle.

After all data was gathered, structure measurements were recorded and entered into an equal area, lower half stereonet using StereoWinFull 120 (Allmindinger, 2002).

IV. Error Analysis

This project contains two forms of quantifiable error – random (indeterminate) and systematic (determinate). Random errors affect precision through limitations in the equipment or techniques, and are the errors we tend to think we assess by repeating measurements. Systematic errors limit accuracy and reflect an imperfection in the equipment being used or are from mistakes the individual makes while taking the measurements. To increase reliability of data, a goal within this project is to reduce errors.

Establishment of the benchmark helps determine random error for the Brunton Transit. There are two planes of measurement at the benchmark, one moderate dip greater than 45°, one gentle dip less than 30°. The shallower plane is in general harder to measure and therefore the primary data set for determining error. The steeper plane allows for verification. After establishing the benchmark, each day started with measurements of both planes. Upon completion of data collection for this project, a data set exists of just the benchmark planes. These data determine a numerical mean and standard deviation using the equation below (Figure 9).

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \overline{x})^2}$$

Figure 9 - Equation for Standard Devation

Additional reduction of random error in reference to the Brunton Transit is through intrinsic limitations. Accuracy of the Brunton Transit is set at azimuth +/- 0.5° and inclination +/- 1° (Brunton, 2000). Examination of the scale size on the actual compass, and experience in the field at hard to access areas, demonstrates that numbers of 0.5° can be difficult to determine (Figure 10). With the higher accuracy range set at +/- 1° for inclination, this becomes the inherent error of the Brunton Transit for both azimuth and inclination.

Figure 10 – Face of a Brunton Transit. Note the inner and outer scales. (Brunton, 2006)

Another control for systematic error is through verification of the transit used for this project using a separate or support transit. I set the support transit to the appropriate declination and established a fixed angle to measure (the benchmark angles). I measured the plane with both transits to compare readings. These two measurements fell within two degrees difference for dip and strike. The two transits measured data for one day at a field site verifying accuracy of the primary transit used in this project.

Error for location of stations using the Garmin GPSmap 60CSx is set by the number of satellites available, satellite signal strength, and conditions at the actual site (Garmin, 2006). To monitor this error, information concerning position of stations includes accuracy of the receiver at the time of recording.

The same structure can have varying measurements at the same station. Improvement of precision for orientation of located structures is through the statistical Law of Large Numbers. This law conveys the concept that the more units of something measured, the closer that sample's mean will be to the true average of the item measured. In practical terms for this project, this law equates to the idea that accuracy of the measurements is important and there is an aditional requirment to select sufficient stations so that each identifed structure has an adequate number of measurements to improve precision.

V. Results

Benchmark data includes one plane with a strike of 340° and a standard deviation (±) 2° and east dip of 23° ± 1° and one plane with a strike of 302° ± 1° with a south dip of 52° ± 1°. Verification of the primary Brunton transit readings all fell within two degrees (Appendix C).

There are eight joints sets in this region; two sets dip east, two sets dip west, two sets dip towards the north, and two sets dip south (Table 1). Additionally, foliation was identified in the study area and measured at 17 locations resulting in strike of 002° ± 12° and dip at 85° ± 5°. (Appendixes D & M)

Joint Set Dip Direction	Strike	Dip	Number Measurements	Appendixes
Steep East	193º ± 10	74 ± 9	47	E & N
Gentle East	194 ± 19	25 ± 8	24	F & O
Steep West	001 ± 14	74 ± 5	13	G & P
Gentle West	001 ± 23	28 ± 11	24	H & Q
Steep North	104 ± 10	72 ± 11	36	I & R
Gentle North	107 ± 22	26 ± 15	13	J & S
Moderate South	287 ± 21	58 ± 10	27	K & T
Gentle South	296 ± 16	24 ± 9	11	L & U

Table 1 – Joint sets measured in the study area.

River flow orientation through the study area varies. Starting from north to south and providing the water flow direction first followed by the reciprocal heading: Zone 1 near Conn Island shows a trend of 203/023° (a - Figure 11). Zone 2 west of Olmsted

Island the river flows 178/358° (b – Figure 11) and through Olmsted Island 198/018° (c – Figure 11). The eastern most flow through Olmsted Island was not used for this study due to man-made walls constraining and modifying the channel (d – Figure 11). In Zone 3 just south of Olmsted Island the flow orients 117/297° (e – Figure 11). The river flows north of the Rocky Islands 110/290° (f – Figure 11), and through the Rocky Islands 156/336° (g – Figure 11), 001/189° (h – Figure 11), and 191/011° (i – Figure 11). These three channels merge to enter Mather Gorge.

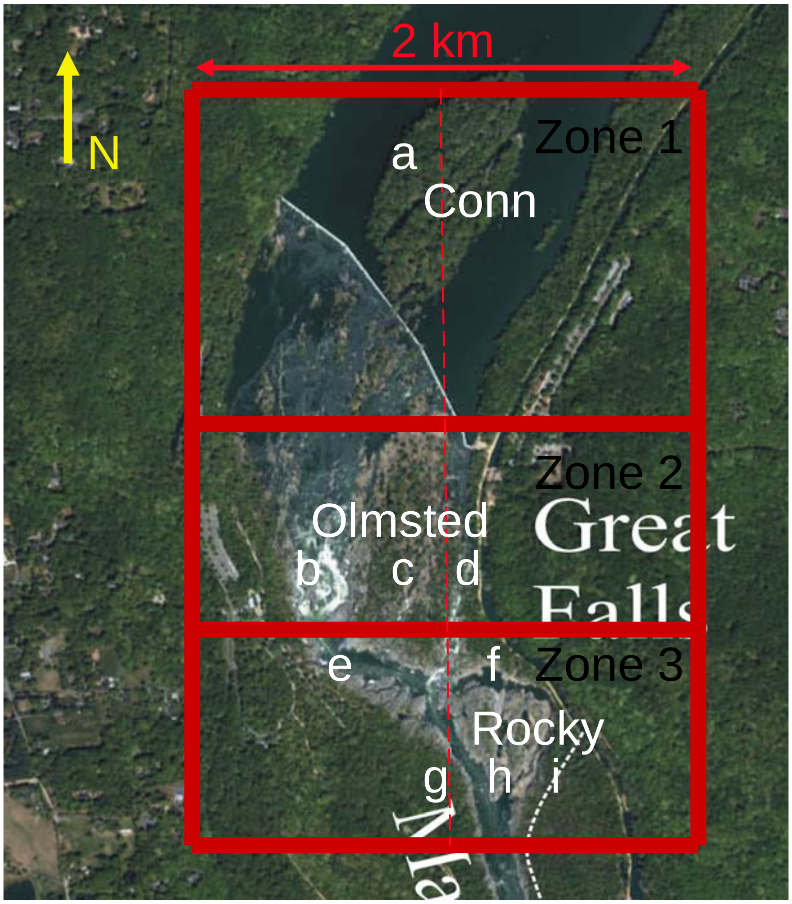


Figure 11 – Lower case letters designate different river flow orientations. (Adapted from Earthobservatory, 2007)

Previous research in the study area indicates that a fault at Mather Gorge may impact river orientation. Kunk et al (2005) point out the existence of two separate thermal domains with a tectonic boundary and thrusting dated by ^{40}Ar/^{39}Ar as Devonian. A possible major structure impacting river orientation in the vicinity of Rocky Islands requires examination of the islands and areas extending north however; in my study area no clear, readily available physical evidence of a fault was found.

VI. Discussion/Observation

The benchmark's two planes help establish reproducibility of measurements. The standard deviation for the gentle dipping plane was strike 2° and dip deviation at 1°. As predicted the steeper plane has smaller deviations but support the statement that error from measuring the various planes was approximately 2° strike and 1° dip (Appendix C). These errors combined with the inherent error using the Brunton (page 14), establishes reproducibility of measurements of 3° strike and 2° dip.

Eight different joint sets were first observed by collocating data. Once noticed that eight joint sets may exist, two dipping in generally each of the compass cardinal headings, I created the physical confirmation criteria that a minimum of one station must show both of the same general dipping direction sets. All joint sets satisfy this standard: for the north dipping sets stations 013 and 026, south dipping at stations 022 and 034, east dipping at stations 003 and 023, and west dipping at stations 004 and 020 (Appendixes V & W). Due to the close strike of the steep east and steep west dipping sets, combined with the few steep west dipping measurements, there was the possibility that east steep and west steep sets were the same and the dip had gone past 90 degrees; however, there is a station with steep east, steep west and gentle west identified (station 004).

In all cases the gentle dipping set of the two sets has the higher standard deviation of strike. Except for the west oriented sets, the gentle set occurred with less frequency. The west and north dipping sets have higher standard deviation for dip in the gentle set, while the opposite holds true for east and south sets. In all similar oriented joint sets the strike of the two sets fall within one standard deviation of the other measured strike.

Reproducibility of measurements falls to within 3° strike and 2° dip; however, with standard deviation for joint sets ranging from strike of 10°-23° and dip of 5°-15°, we notice that variability of measurements is large and therefore spread out away from the mean. Reproducibility then is not the key in duplicating measurements, but understanding variability in the measuring of structures is.

Within the study area, physical characteristics of the Potomac River support the findings of Finnegan et al. (2004, 2007) that the channel varies based on the material the river flows over. North of the Washington Aqueduct Dam more abundant alluvial deposits seem to produce a river type with higher width to depth ratio then below the dam where deposits are less likely (Finnegan et al 2007). With more bedrock exposed south of the dam, the channel becomes narrower and deeper.

The two abrupt river orientation changes from 358° to 297° south of Olmsted Island and 290° to 001° at the Rocky Islands have a physically noticeable similar trait. In both cases a steep joint set creates a wall the river flows along. Measured at station 026 the wall that forms the mainland of Virginia is 096° with dip of 87° (Figure 12). This is the steep north dipping joint set, dipping into the river flow. The walls making up the Rocky Islands, measured from west to east from stations 37-40, dip east and align with east steep dipping joint set (strike/dip 185°/84°, 194°/74°, 170°/86° and 193°/74° respectively).

Data is biased towards the south of the study area. Due to fluvial deposits covering bedrock, stations in Zone 1 are less abundant. There is an increase in stations in Zone 2; however, the zone has forested hills in the east and bedrock is again limited. Zone 3 provided the highest availability of bedrock. (Appendix W)

Figure 12 – Steep north dipping joint set at the change of river orientation south of Olmsted Island. (e in Figure 11)

Conclusion

There are eight different river orientations within the study area. For all but one of these orientations there is a joint set orientation within one standard deviation of the river flow or its reciprocal heading. The east dipping joint set's strikes of 193° ± 10° and 194° ± 19° account for the area north of Washington Aqueduct Dam with river measurement at 023°/203°, through Olmsted Island at 018°/198°, through Rocky Island at 001°/189°, and east of Rocky Island at 011°/191°. The north dipping sets at 104° ± 10° and 107° ± 22° account for the orientations south of Olmsted Island with the river at 297°/117° and north of the Rocky Islands at 290°/110°. West of Olmsted Island the river orientation is 358°/178° and the west dipping joint sets are at 001° ± 23° and 001° ± 14°. The area west of the Rocky Islands has the river at 336°/156°. This orientation does not fall within the standard deviation of a joint set; however it is two degrees outside of one standard deviation from the orientation of the west dipping joints sets. Evidence supports the hypothesis that secondary structures in the form of joint sets correlate to the Potomac River's orientation of flow from Conn Island to Mather Gorge.

Implications

Water is one of Earth's greatest resources. Life itself is dependent on access to water. As the earth and its environment changes we witness movement of water from being abundant to rare in some locations. Studying water and how it travels over the surface of Earth is and will become even more important.

This study contradicts the statement that the Potomac River does not follow secondary structures. The limited size of the study area reduces the scope of the conclusion and a study covering larger extents of the Potomac River is needed before determining characteristics of the river as a whole. For other rivers in this region with similar rock composition of the bedrock, structure orientation may impact flow orientation. This study may provide information for others researching river morphology with exposure of bedrock along the channel.

Acknowledgements

Thank you to Professor Martin for taking me on as a project and to Professor Zen for reliable backup. Thank you to Professor Prestegaard for trying to educate me reference the river processes. Thank you to Professor McDonough for your insight. Thank you to everyone who asked questions during this project and therefore kept me learning. There is not enough time or words to thank my wife, Tina, and daughters, Rochelle and Jacqueline, for allowing me time to finish and not going too crazy every time I stop to look at rocks.

Figures/Tables

Cover - From between the Rocky Islands, C&O National Historic Park, looking east at steep north, south and gentle south fracture sets. (Streker, 2007)

Figure 1 - Potomac River rushing through Great Falls of Potomac Gorge looking north from the Maryland Overlook. (Streker, 2006)

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Figure 4 - Portion of geologic map of Potomac Gorge showing locations of rock types. Study region outlined in red. Legend information in Appendix A. (Southworth et al, 2000)

Figure 5 - Diagram showing placement of Pleistocene Epoch ice sheet relative to the Potomac Gorge. (Reusser et al, 2004)

Figure 6 - Potomac River profile. (Adapted from Reusser et al, 2004)

Figure 7 - Zones within the study area. Each zone contains a portion of the river with a different orientation of river flow. (Earthobservatory, 2007)

Figure 8 - The area in between the Rocky Islands looking north showing bedrock access and area inaccessible during high water events. (Streker, 2006)

Figure 9 - Equation for Standard Devation. (Streker, 2006)

Figure 10 - Face of a Brunton Transit. Note the inner and outer scales. (Brunton, 2006)

Table 1 – Joint set data in study area. (Streker, 2007)

Figure 11 - Lower case letters designate different river flow orientations. (Earthobservatory, 2007)

Figure 12 - Steep north dipping joint set at the change of river orientation south of Olmsted Island (e from Figure 11). (Streker, 2007)

Figure 13 - Description of map units. (Adapted from Southworth et al, 2000)

Figure 14 - Additional information reference the geologic development of the Potomac Gorge region. (Southworth et al, 2001)

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Appendix A

Figure 13 – Description of map Units

Surficial Deposits

Qaf	**Artificial fill and ground disturbed by construction**
Qal	**Alluvium (Holocene—present to 10,000 years old)**— Unconsolidated clay, silt, sand, gravel, and cobbles in valley bottoms
Og	**Alluvial gravel-bar deposits along Difficult Run (Holocene and late Pleistocene—present to 100,000 years old)**
Qcd	**Colluvium (Holocene and late Pleistocene—present to 100,000 years old)**—Cobbles, boulders, and debris in slope hollows

Older Igneous Rocks

Dl	**Lamprophyre dikes (Late Devonian-about 360 million years old)**—Dark-colored, biotite mica-rich tabular intrusions that cut across the surrounding rock
Ob	**Bear Island Granodiorite and pegmatite bodies (Ordovician-about 470 million years old)**—Light-colored, muscovite mica-rich, elliptical intrusive bodies and small tabular intrusions
Ca	**Amphibolite sills (Early Cambrian-about 540 million years old)**—Dark-colored, hornblende-rich tabular intrusions, emplaced parallel to the bedding of the surrounding rock
ЄZu	**Ultramafic rocks**—Dark-green igneous rocks consisting of serpentinite, soapstone, and talc schist; occur as sedimentary blocks and fragments in the Mather Gorge Formation

Metamorphosed Sedimentary Rocks

ЄZms	**Quartz-rich schist and mica gneiss**—Greenish-gray rocks with different textures; schist is finer grained, more planar, and less massive than gneiss
ЄZmg	**Metagraywacke and metasiltstone schist**—Well-bedded, gray, dirty sandstone interbedded with siltstone; originally deposited in submarine turbidity currents on the ocean floor
ЄZmm	**Migmatite**—Complex, light- and dark-gray rock formed when rocks of different ages were melted together
Єzmp	**Phyllonite with vein quartz**—Shiny, greenish-gray, fine-grained sheared rock with pods and veins of white quartz
Єzs	**Melange**—Gray, fine-grained mixture of quartz and feldspar, with pebbles of white quartz and blocks of greenish-gray phyllonite; originally deposited on the ocean floor

(Adapted from Southworth et al, 2000)

Appendix B

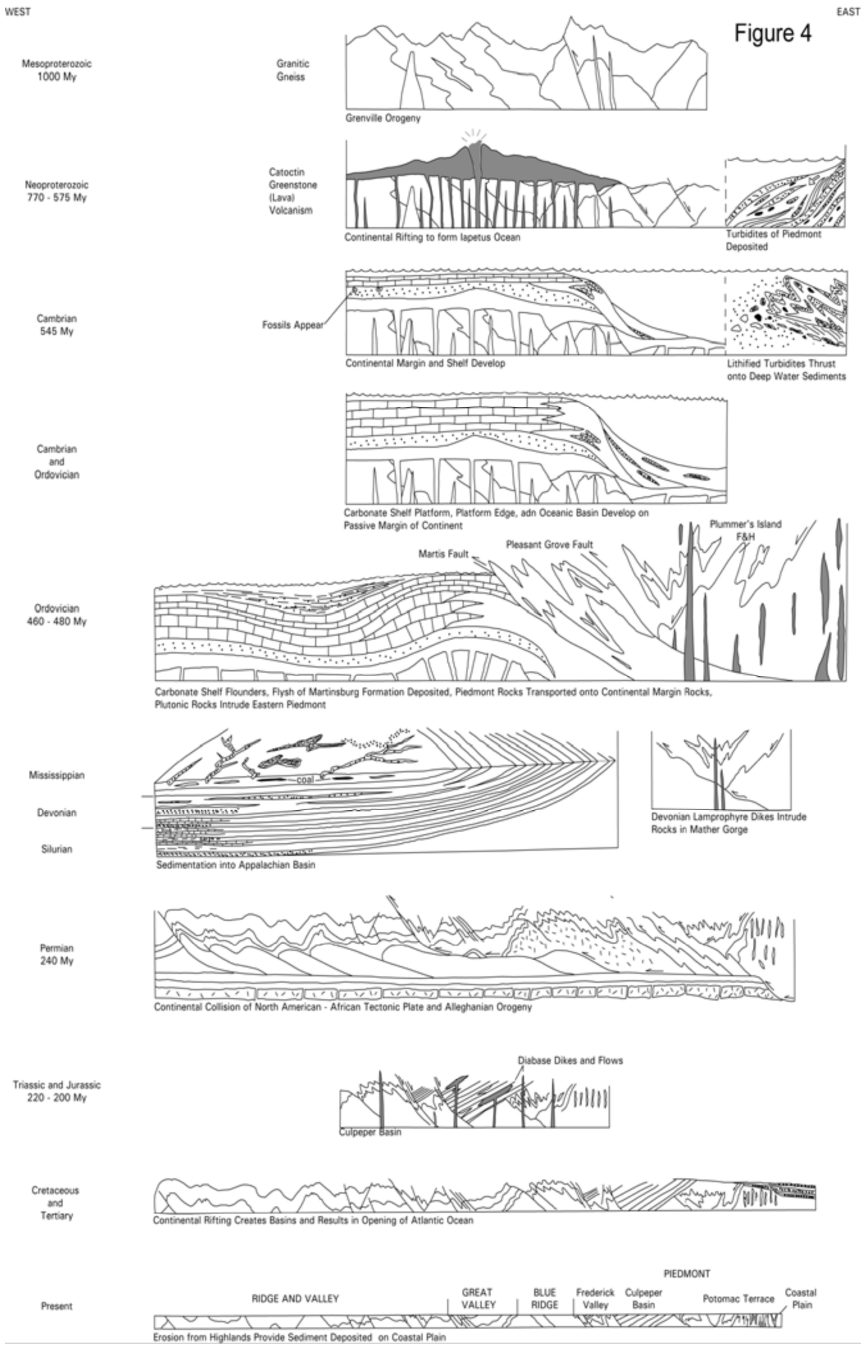


Figure 14 - Additional Information reference the geologic development of the Potomac Gorge region (Southworth et al, 2001).

Appendix C –
Figure 15 - Benchmark Data

Plane <30°

Azimuth	Dip
337	24
*338**	*24*
340	23
337	25
340	24
341	22
341	22
340	22
341	24
341	22
341	22
342	22

	Strike (°)	Dip (°)
Mean	340	23
Standard Deviation	2	1

Plane >45°

Azimuth	Dip
303	54
*303**	*52*
303	54
301	52
301	51
301	51
301	51
301	52
302	52
301	51
302	51
301	51

	Strike (°)	Dip (°)
Mean	302	52
Standard Deviation	1	1

*** Italics measurements from verification Brunton used the first day.**

Appendix D –
Figure 16 – Foliation east dipping

*** Table designed to show joint set measurements from north (top) to south (bottom) in study region and river flow between tables**

Virginia

Strike (degrees)	Dip (degrees)
000	87
356	78
021	82
004	90
347	76
349	85
020	83
359	90
006	84

Maryland

Strike (degrees)	Dip (degrees)
348	90
011	86
007	74
014	79
017	87
350	85
000	78
348	81

	Strike(°)	Dip (°)
Mean	002	85
Standard Deviation	12	5

17 measurements

Appendix E –
Figure 17 - Steep East Dipping Joint Set

*** Some strikes modified to satisfy "right hand rule"**
*** Table designed to show joint set measurements from north (top) to south (bottom) in study region and river flow between tables.**

Virginia

Strike (degrees)	Dip (degrees)
191	57
212	75
182	78
182	86
169	82
187	88
189	72
187	55
198	64
198	61
191	88
194	78
208	67
211	84
181	62
191	69
192	86
212	76
184	55
182	80
191	87
207	64
199	79
182	69

Maryland

Strike (degrees)	Dip (degrees)
196	84
194	60
185	84
194	74
170	86
193	74
197	67
210	74
192	90
181	77
195	72
174	84
189	64
216	68
184	69
184	67
197	75
189	74
192	74
201	77
204	64
189	74
197	77

	Strike (°)	Dip (°)
Mean	193	74
Standard Deviation	10	9

47 measurements

Appendix F –

Figure 18 – Gentle East Dipping Joint Set

*** Some strikes modified to satisfy "right hand rule"**
*** Table designed to show joint set measurements from north (top) to south (bottom) in study region and river flow between tables**

Virginia

Strike (degrees)	Dip (degrees)
159	18
213	16
196	23
206	14
198	19
204	27
213	16
194	38
192	15
206	14
184	37

Maryland

Strike (degrees)	Dip (degrees)
211	32
204	28
185	25
164	22
156	26
166	24
229	26
199	36
204	40
169	26
192	28
206	15
196	26

	Strike (°)	Dip (°)
Mean	194	25
Standard Deviation	19	8

24 measurements

Appendix G –
Figure 19 – Steep West Dipping Joint Set

*** Some strikes modified to satisfy "right hand rule"**
*** Table designed to show joint set measurements from north (top) to south (bottom) in study region and river flow between tables.**

Virginia

Strike (degrees)	Dip (degrees)
350	77
356	74
354	75
024	69
011	67

Maryland

Strike (degrees)	Dip (degrees)
353	78
006	66
020	72
348	77
009	82
015	77
347	76
337	72

	Strike (°)	Dip (°)
Mean	361	74
Standard Deviation	14	5

13 measurements

Appendix H –
Figure 20 – Gentle West Dipping Joint Set

*** Some strikes modified to satisfy "right hand rule"**
*** Table designed to show joint set measurements from north (top) to south (bottom) in study region and river flow between tables and river flow between tables**

Virginia

Strike (degrees)	Dip (degrees)
339	18
017	18
028	14
359	34
032	21
344	22
017	14
031	23
323	38
002	18
019	29
324	33
021	48

Maryland

Strike (degrees)	Dip (degrees)
324	48
331	44
015	32
340	43
351	32
350	31
015	28
350	10
024	28
015	19
010	17

	Strike (°)	Dip (°)
Mean	001	28
Standard Deviation	23	11

24 measurements

Appendix I –
Figure 21 - Steep North Dipping Joint Set

*** Some strikes modified to satisfy "right hand rule"**
*** Table designed to show joint set measurements from north (top) to south (bottom) in study region and river flow between tables**

Virginia

Strike (degrees)	Dip (degrees)
114	50
102	57
130	63
120	90
098	90
112	90
101	77
101	69
118	90
106	56
103	68
117	88
096	87
093	72
102	66
111	68
094	68
104	71
090	83
101	77

Maryland

Strike (degrees)	Dip (degrees)
106	74
102	65
116	78
087	65
109	50
112	65
087	59
110	71
099	75
099	76
095	76
100	74
110	65
106	74
106	64
092	69

	Strike (°)	Dip (°)
Mean	104	72
Standard Deviation	10	11

36 measurements

Appendix J –
Figure 22 – Gentle North Dipping Joint Set

*** Some strikes modified to satisfy "right hand rule"**
*** Table designed to show joint set measurements from north (top) to south (bottom) in study region and river flow between tables**

Virginia

Strike (degrees)	Dip (degrees)
082	21
120	44
081	15
131	34
111	44

Maryland

Strike (degrees)	Dip (degrees)
101	49
095	06
083	11
112	21
106	24
087	07
154	38
131	29

	Strike (°)	Dip (°)
Mean	107	26
Standard Deviation	22	15

13 measurements

Appendix K –
Figure 23 - Moderate South Dipping Joint Set

*** Some strikes modified to satisfy "right hand rule"**
*** Table designed to show joint set measurements from north (top) to south (bottom) in study region and river flow between tables**

Virginia

Strike (degrees)	Dip (degrees)
294	46
322	52
291	56
297	79
281	74
260	54
306	44
268	56
262	72
318	54
304	58
267	72
306	56
312	57

Maryland

Strike (degrees)	Dip (degrees)
281	49
290	57
265	46
300	52
254	64
272	77
317	72
262	47
313	56
263	64
308	55
282	43

	Strike (°)	Dip (°)
Mean	287	58
Standard Deviation	21	10

27 measurements

Appendix L –
Figure 24 – Gentle South Dipping Joint Set

*** Some strikes modified to satisfy "right hand rule"**
*** Table designed to show joint set measurements from north (top) to south (bottom) in study region and river flow between tables**

Virginia

Strike (degrees)	Dip (degrees)
291	18
273	11
273	11
295	35
300	20
310	34

Maryland

Strike (degrees)	Dip (degrees)
320	28
321	34
297	24
286	34
291	18

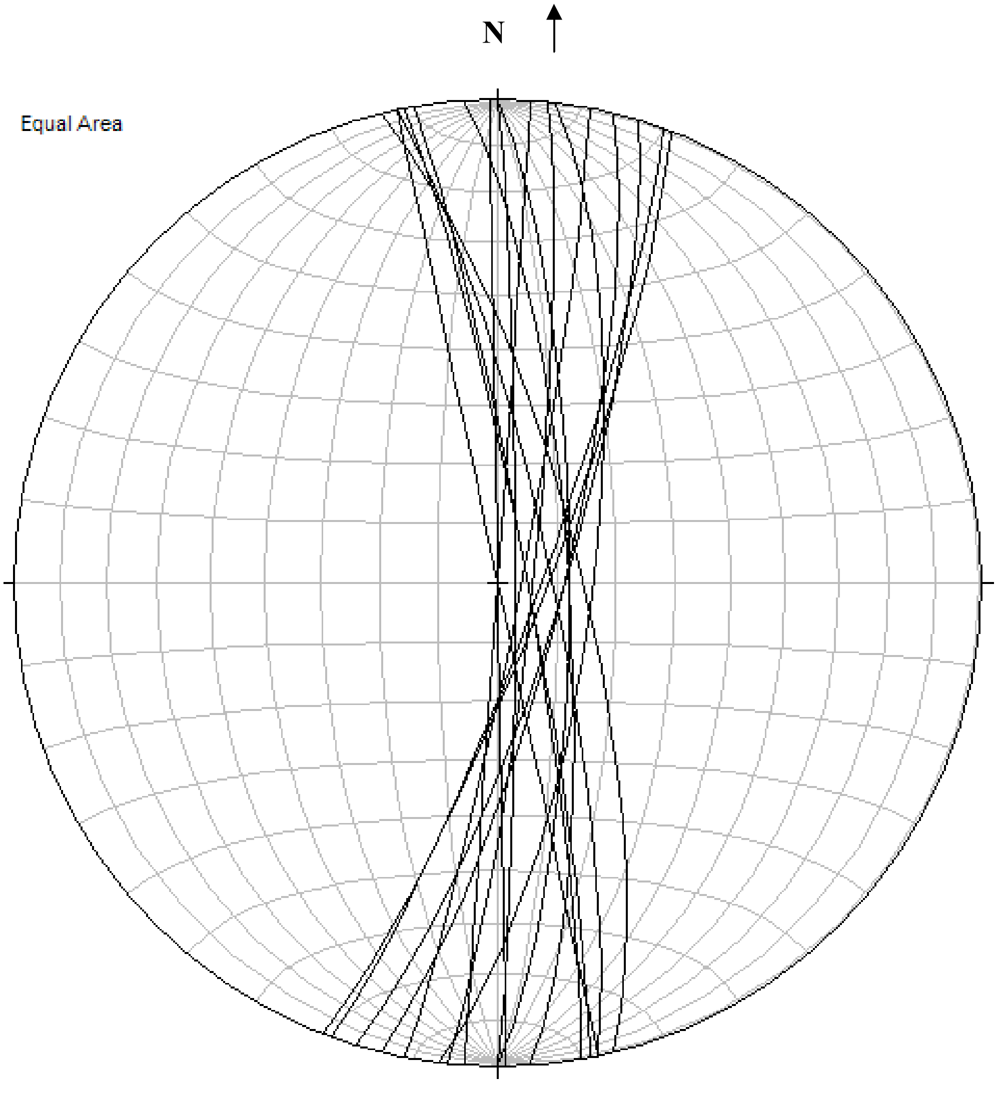
	Strike (°)	Dip (°)
Mean	296	24
Standard Deviation	16	9

11 measurements

Appendix M –

Figure 25 – Foliation

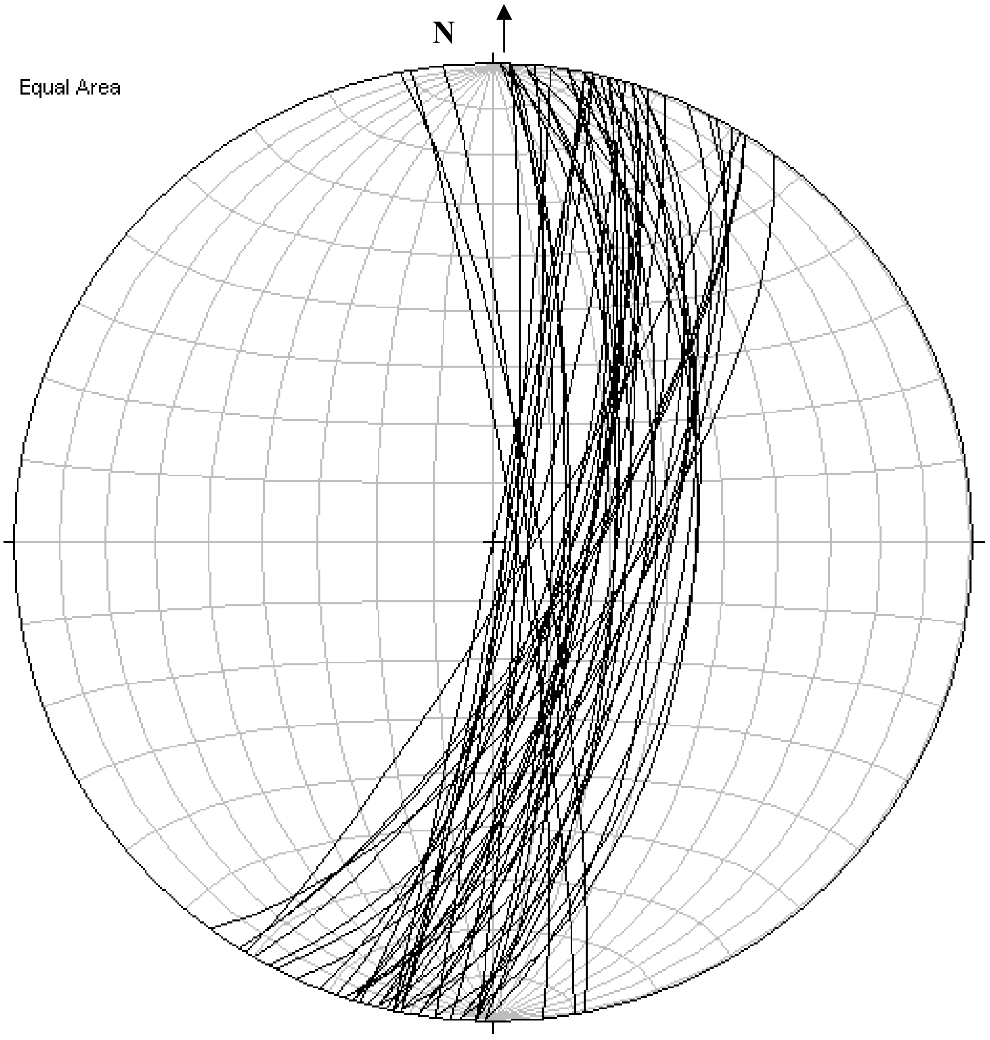
Lower Hemisphere



Appendix N –

Figure 26 - Steep East Dipping Joint Set

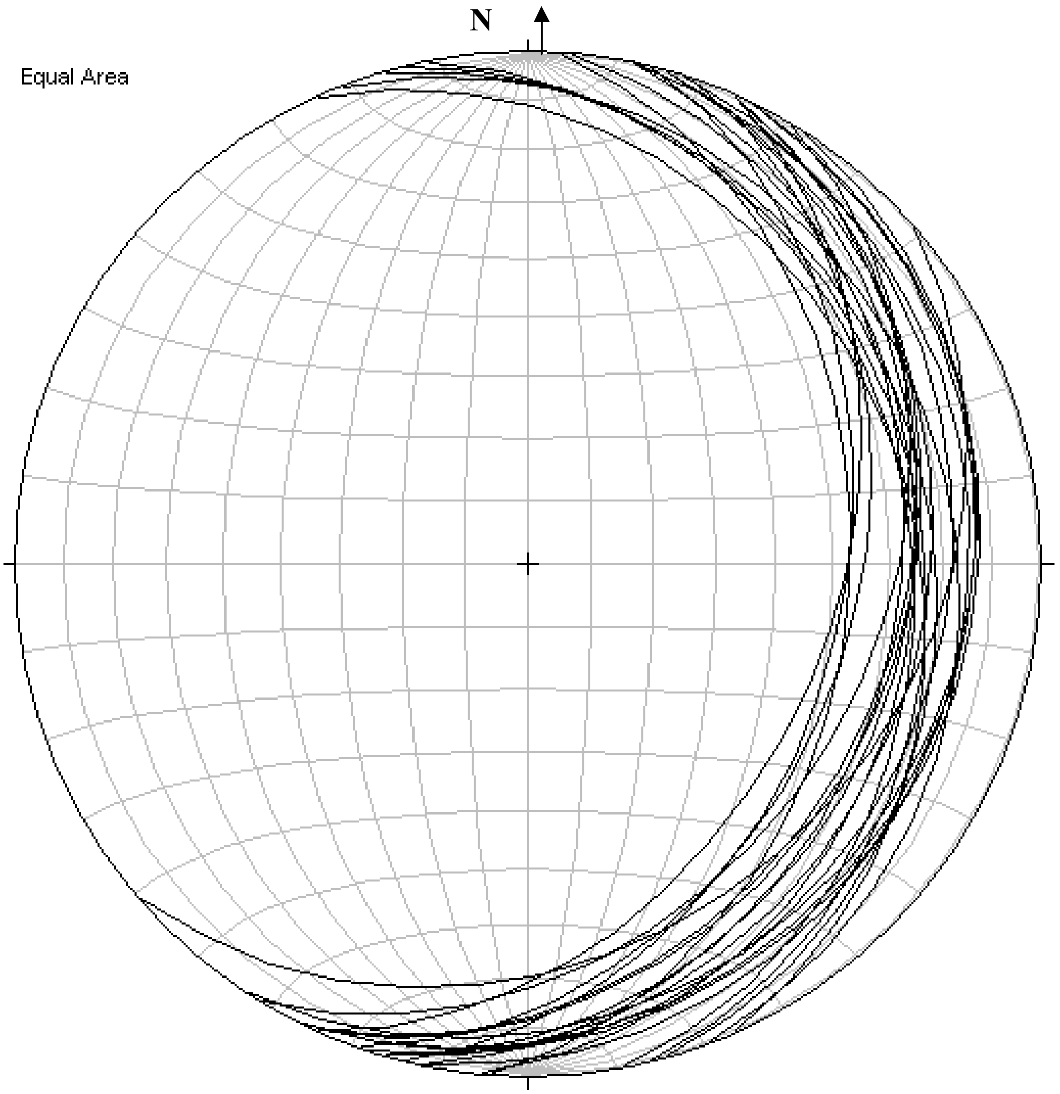
Lower Hemisphere



Appendix O –

Figure 27 - Gentle East Dipping Joint Set

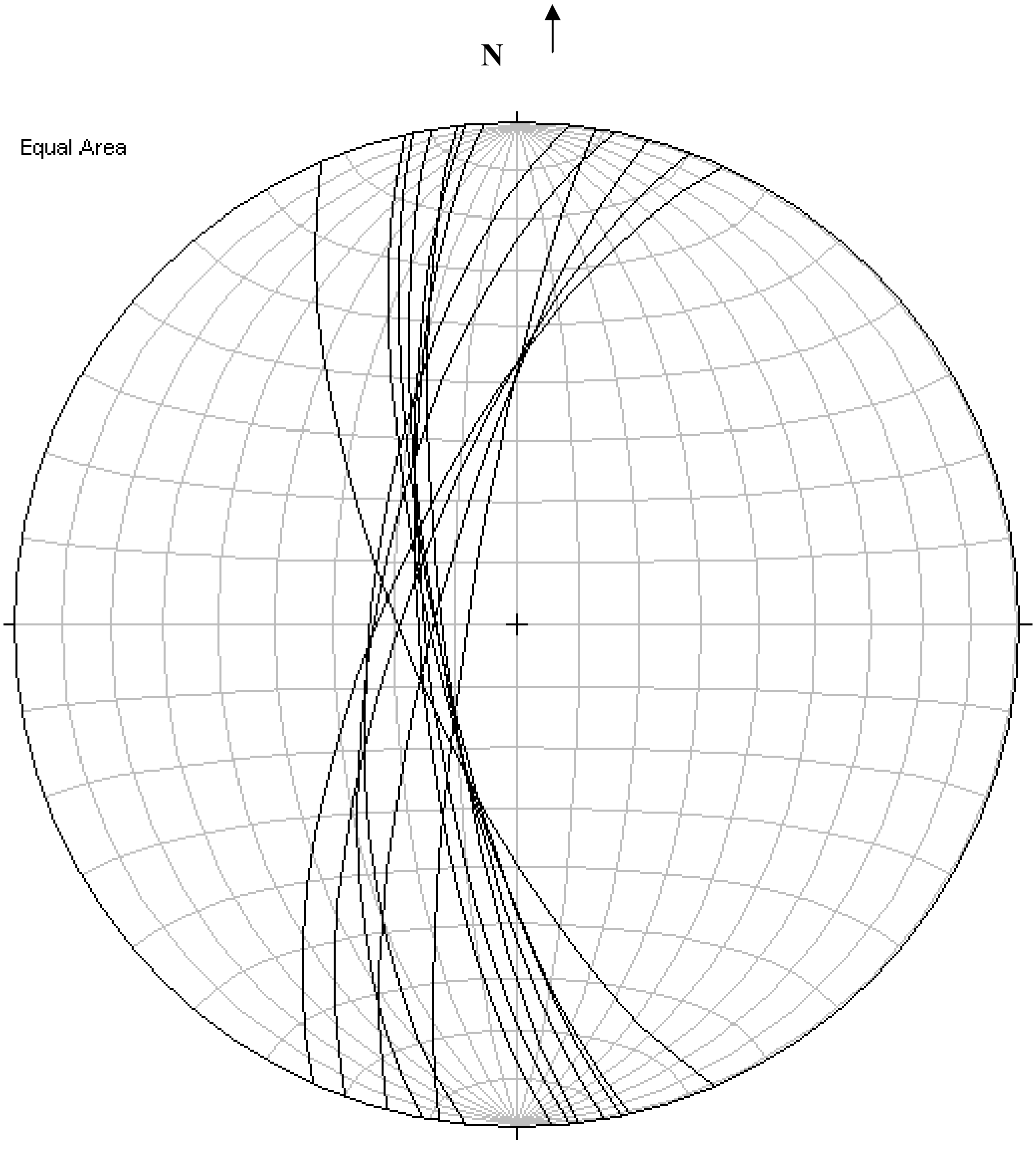
Lower Hemisphere



Appendix P –

Figure 28 - Steep West Dipping Joint Set

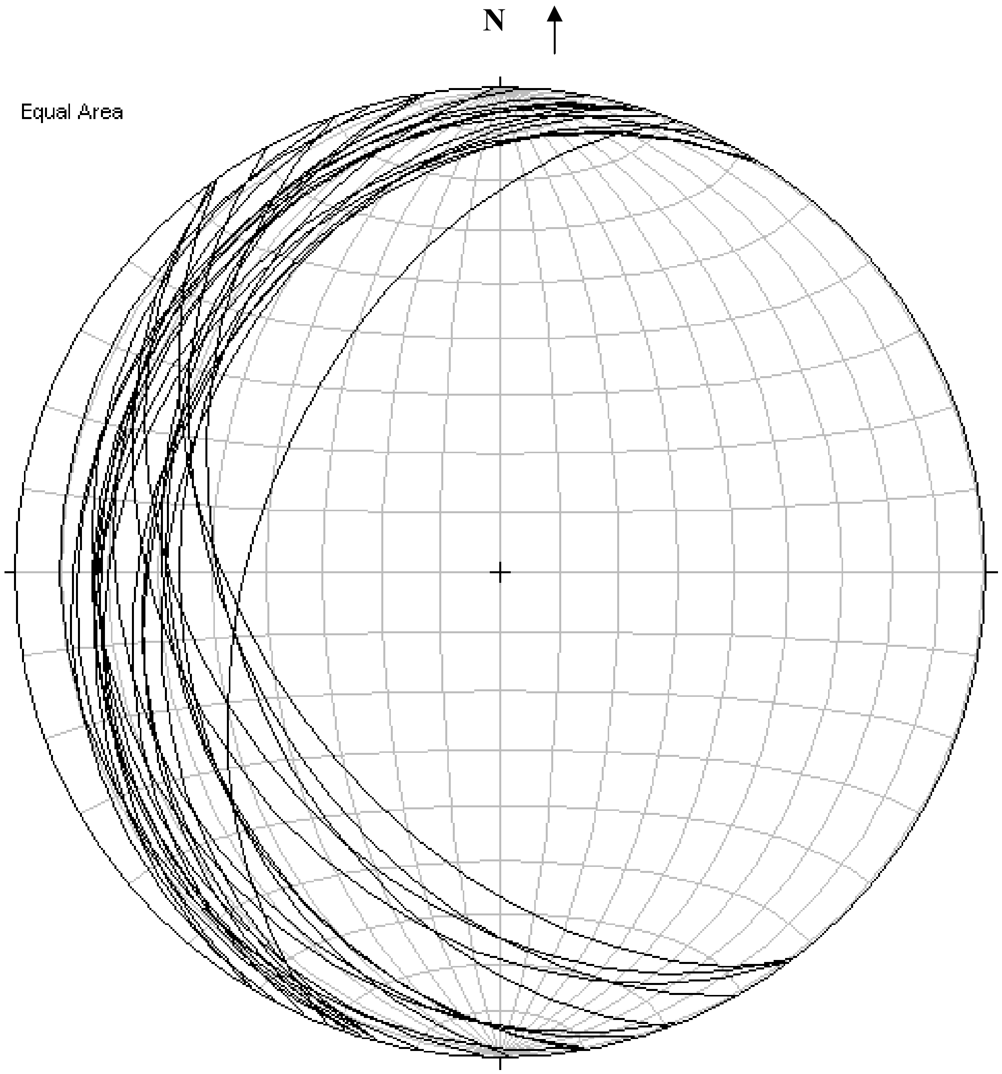
Lower Hemisphere



Appendix Q –

Figure 29 - Gentle West Dipping Joint Set

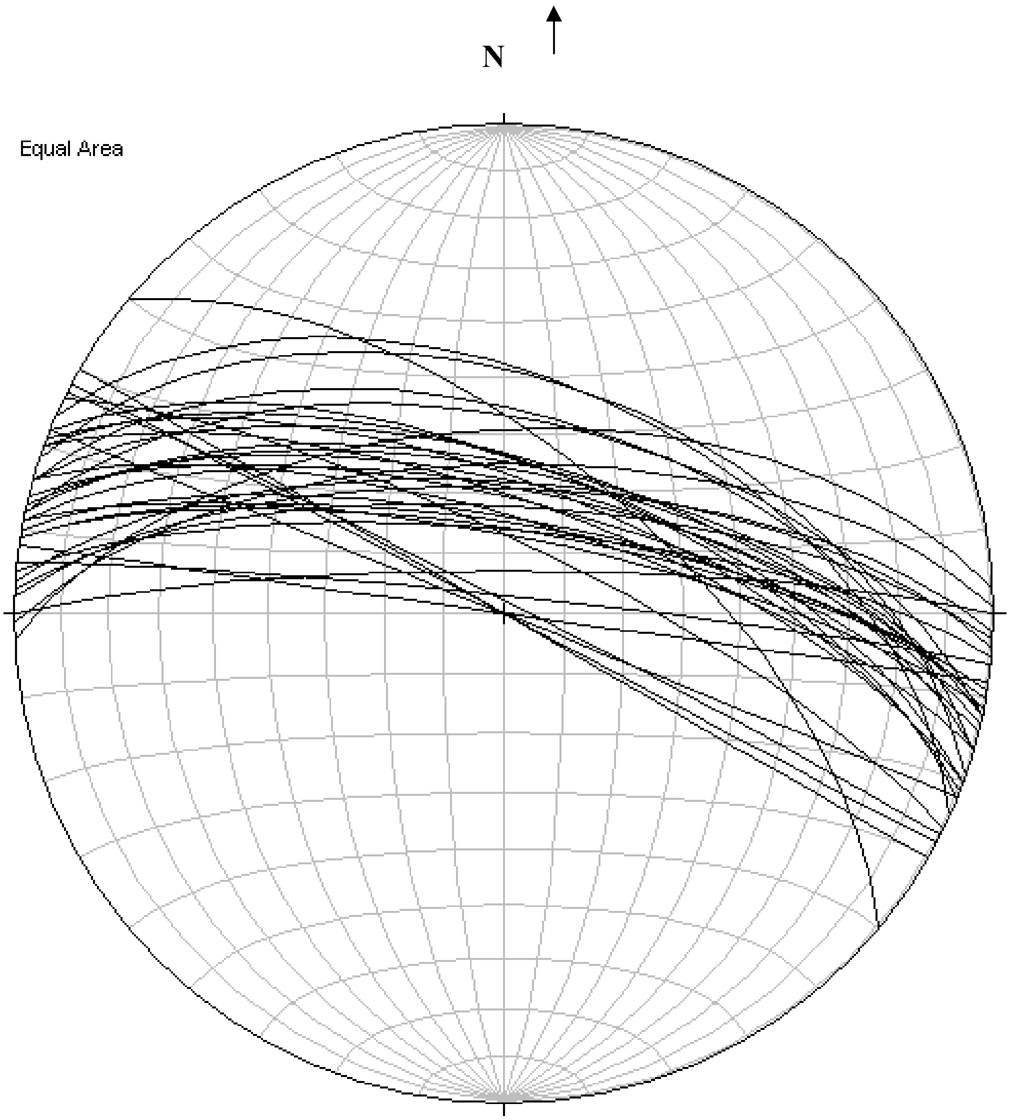
Lower Hemisphere



Appendix R –

Figure 30 - Steep North Dipping Joint Set

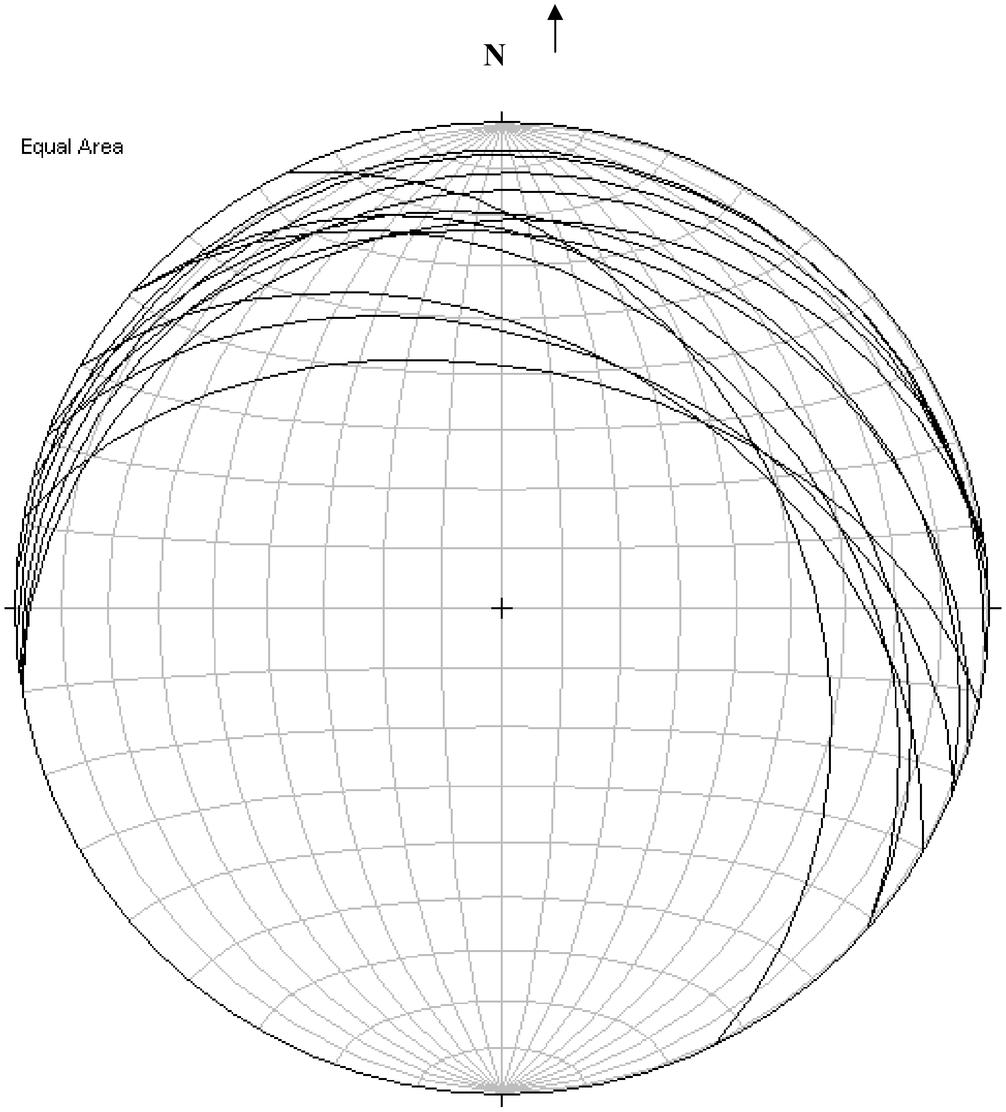
Lower Hemisphere



Appendix S –

Figure 31 - Gentle North Dipping Joint Set

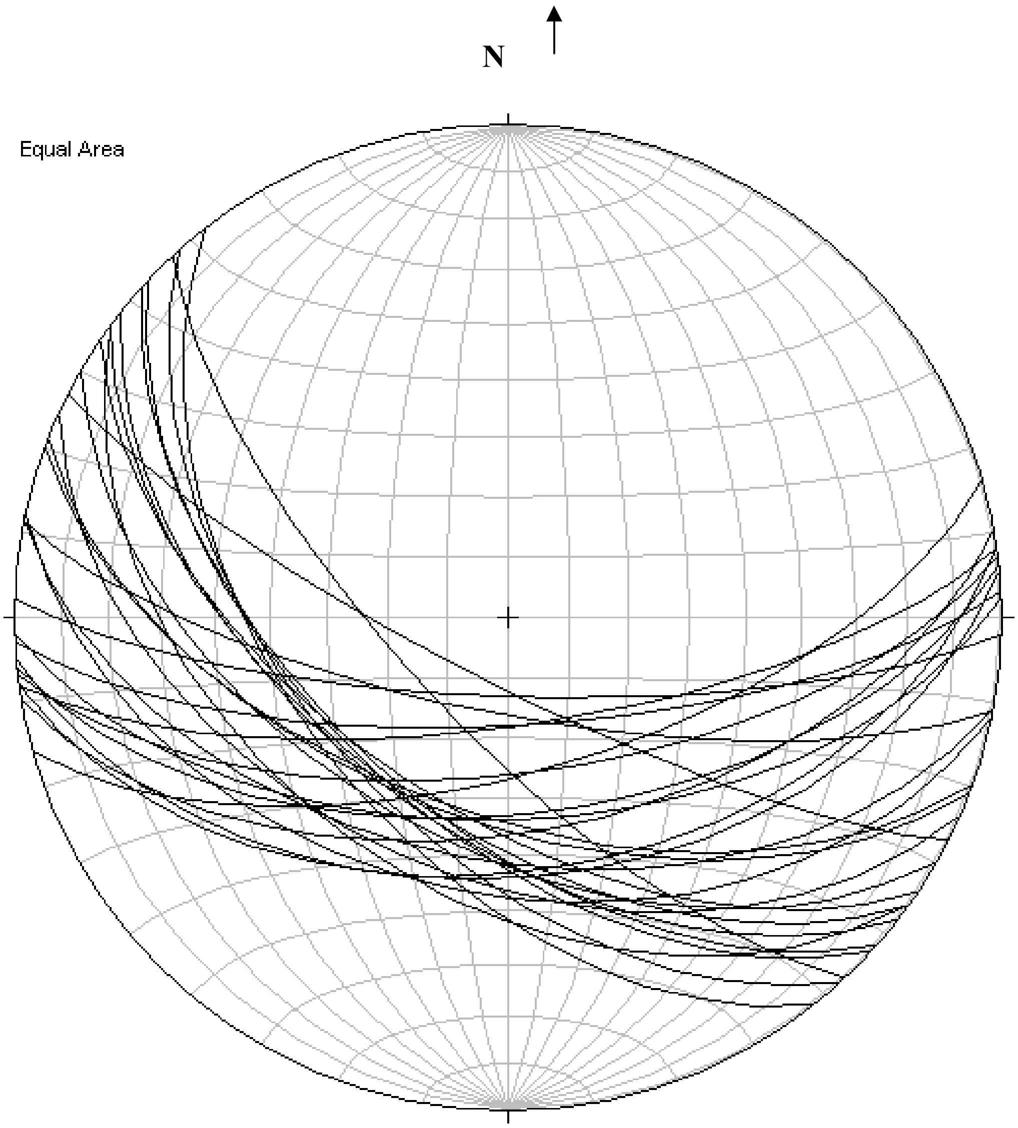
Lower Hemisphere



Appendix T–

Figure 32 - Moderate South Dipping Joint Set

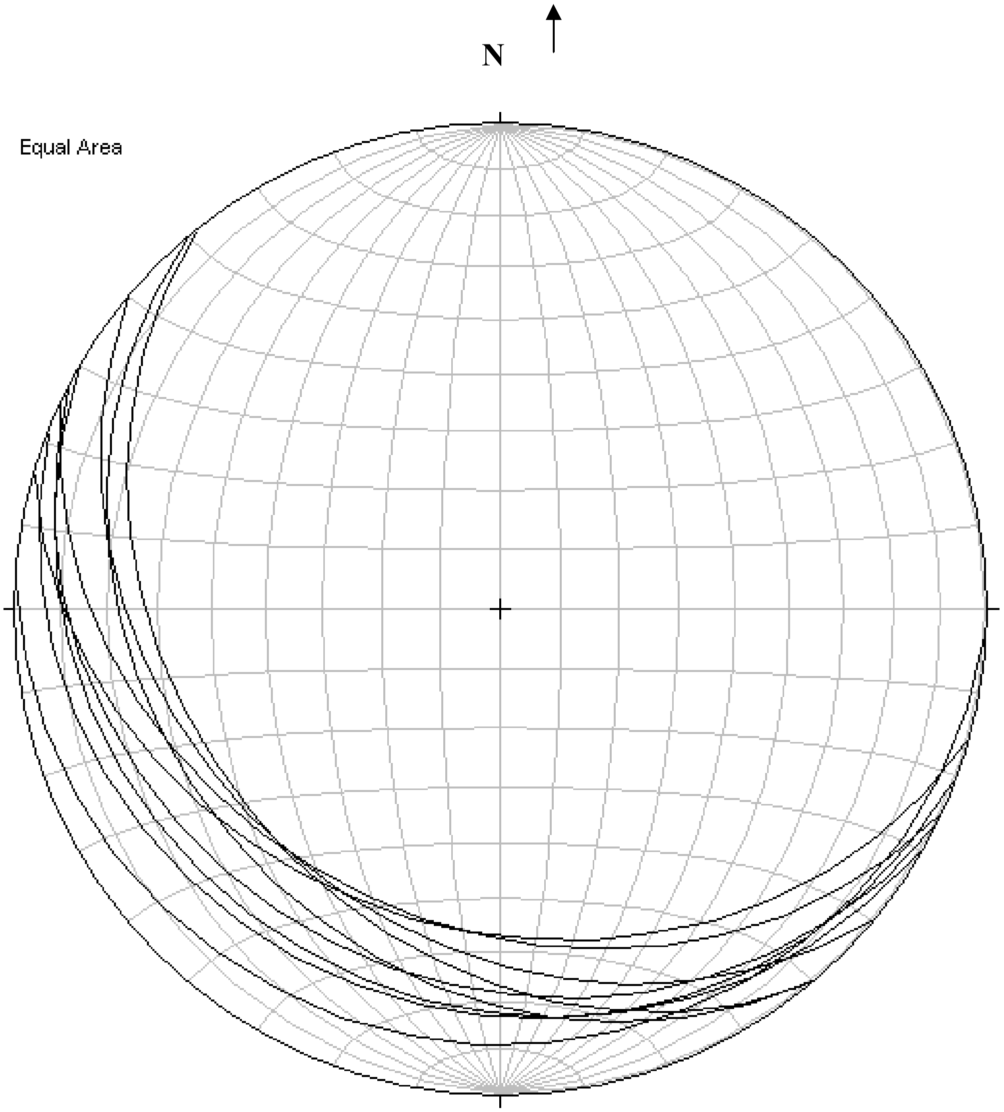
Lower Hemisphere



Appendix U –

Figure 33 - Gentle South Dipping Joint Set

Lower Hemisphere



Appendix V –

Figure 34 - Station Locations in Study Area

Station #	WGS 84 Datum	Error (ft)
001	N38.997W077.249	+/- 14
002	N38.993W077.247	+/- 13
003	N38.992W077.248	+/- 15
004	N38.994W077.249	+/- 14
005	N38.995W077.249	+/- 16
006	N38.995W077.248	+/- 14
007	N38.995W077.248	+/- 14
008	N38.995W077.250	+/- 19
009	N38996W077.252	+/- 25
010	N38.997W077.252	+/- 15
011	N38.998W077.252	+/- 14
012 *	N38.999W077.252	+/- 20
013	N39.001W077.251	+/- 14
014	N39.011W077.252	+/- 23
015	N39.001W077.253	+/- 24
016	N39.007W077.255	+/- 26
017	N39.006W077.255	+/- 15
018	N39.005W077.256	+/- 19
019	N39.001W077.255	+/- 13
020	N39.000W077.255	+/- 15
021	N38.999W077.254	+/- 12
022	N38.998W077.254	+/- 18
023	N38.997W077.254	+/- 20
024	N38.996W077.253	+/- 18
025	N38.995W077,252	+/- 12
026	N38.995W077.251	+/- 13
027	N39.995W077.251	+/- 13
028	N39.994W077.250	+/- 12
029	N38.993W077.249	+/- 15
030	N38.992W077.249	+/- 21
031	N39.010W077.248	+/- 19
032	N39.007W077.248	+/- 11
033	N38.998W077.248	+/- 20
034	N38.996W077.247	+/- 18
035	N38.994W077.245	+/- 21
036	N39.000W077.248	+/- 18
037 *	N38.993W077.249	+/- 14
038 *	N38.994W077.248	+/- 16
039 *	N38.994W077.248	+/- 14
040 *	N38.994W077.247	+/- 18
041	N38.992W077.254	+/- 19
042	N38.992W077.250	+/- 17
043	N38.996W077.250	+/- 13
044	N38.993W077.252	+/- 21
045	N39.000W077.252	+/- 18

Note – Entries that appear to be duplicates have been checked and verified to be different waypoints. Error of the GPS, distance traveled, and round-off of entries for recording combine to give the impression that there was no distance change.

*** Only one joint set measured at these stations**

Appendix W -

Figure 35 - Station Locations

Legend – Yellow circle represents a station with more then one joint set measurement. The waning crescent shape stations have measurement for one joint set only. Teal circle is the benchmark.