The Measurement of Small-Scale Structures to Determine Their Influence on the Orientation of the Mather Gorge of the Potomac River, Maryland and Virginia, USA

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Abstract

The Mather Gorge of the Potomac River is a 1.25 km-long, incised, linear reach of the Potomac River found within the Potomac Terrane of the Central Appalachian Piedmont of Maryland and Virginia, just west of Washington, D. C. Numerous studies constrain the geologic history of the rocks and river in the study area; however, they do not address in a systematic way why the gorge has its present orientation and what structures may influence the incision of the gorge. For this study, I measured the orientations of joints, foliations, and lineations to determine their influence upon the orientation of the gorge itself. The data indicate that these small-scale structures do not coincide with the trend of the river through Mather Gorge, and most likely do not control the gorge orientation. Alternatively, the data may support fault control of the orientation of the gorge. This research fits into a broader picture for geologists seeking to address unanswered questions about the formational processes and controls on river incision around the world.

I. Introduction

Incised river channels are found throughout the United States and the world. Well known examples include the Grand Canyon of the Colorado River, the Three Gorges of the Yangtze River, and Victoria Falls of the Zambezi River (Figures 1.1 - 1.3). All of these rivers spectacularly incise their channels in sinuous or linear fashions, and lead geologists to ask a number of questions including: How do rivers incise their channels and what controls the orientation of the incision? Comprehending the processes of and influences on river incision should lead to better geomorphologic understanding of river formation in regions of similar topography around the world and could be further extrapolated to other planets in our solar system. This study attempts to constrain the controls on orientation of Mather Gorge, a linearly incised stretch of the Potomac River in the Central Appalachian Piedmont just west of Washington, D.C.

Long before European geologists discovered the Great Falls of the Potomac River, Native Americans met above the falls to honor the spirit of the “Roaring Waters”. By 1608, the English explorer John Smith had arrived and he was soon followed by early European settlers (Reed et al., 1980). In 1754, George Washington envisioned the Potomac River as an “avenue of trade” and encouraged plans to build canals around the falls to foster the exchange of materials between the Chesapeake Bay and western portions of Maryland and Virginia (Reed et al., 1980). Plans to build a canal were necessary for trade because Great Falls was and is a formidable obstruction to navigation, with an estimated 9.5 trillion liters of water passing over the 15 m (50 ft.) falls each year, carrying with it 1.45 million metric tons of sediment and 1 million metric tons of dissolved material (Figure 1.4; Reed et al., 1980, Bierman et al., 2004).

As the Potomac River incises its channel, it provides modern day geologists, hikers, and tourists alike with especially good exposures of the highly metamorphosed and deformed rocks that make up the Appalachian Piedmont (Figures 1.5 and 1.6). Nowhere along its course does the Potomac River provide such an unobstructed glimpse of these rocks as in the scenic 1.25 km-long Mather Gorge, directly downriver of Great Falls (Figure 1.7). This exceptionally straight gorge and surrounding area has been the subject of numerous studies in a variety of disciplines including hydrology (Zen and Prestegaard, 1994; Bierman et al., 2004), geomorphology (Reed, 1981; Reusser et al., 2004), structure (Fisher, 1963; Fleming and Drake, 1998), and petrology (Reed and Jolly, 1963; Muth et al., 1979; Kunk et al., 2004; Kunk et al., 2005).

Previous work focuses mostly on constraining the timing of deformation and cooling in the region, as well as describing the paleo-Potomac's course and mechanisms for channel formation. Researchers have tentatively subdivided the rocks of Mather Gorge into several domains based on lithology and cooling ages. However, relatively little research has addressed why the Mather Gorge of the Potomac is such a linear feature while nearby reaches of the river appear rather sinuous in nature. In and near the gorge there are several prominent small-scale structures, including five identifiable joint sets, nearly vertical foliations, and mineral lineations, that might provide an explanation for the nearly straight course of the Potomac River through the gorge.

The study objective was to map and measure the small-scale structures to determine if they were a controlling factor in the orientation of the gorge. My null hypothesis was that the presence of joint sets, foliations, and/or lineations in the rocks in and along Mather Gorge influence the present course of the Potomac River through the gorge. Collected data indicate that this hypothesis is incorrect. The invalidation of this hypothesis could have several important consequences. It potentially eliminates small-scale structures from consideration as controlling factors in the formation of the gorge, and in doing so it may support alternative theories of formation and orientation control, such as those proposed by Reed et al. (1970), Reed et al. (1980), Bierman et al., (2004), Reusser et al., (2004), and Southworth et al., (2000).

II. Geologic Setting

A. Location and Extent

The Appalachian Mountains are divided into 5 physiographic provinces. From east to west, the provinces are the Coastal Plain, Piedmont, Blue Ridge, Valley and Ridge, and Appalachian Plateau (Schmidt, 1993). The study area is located within the Central Appalachian Piedmont (Figure 2.1) of Maryland and Virginia, just west of Washington, D.C.

The Piedmont province is divided into several tectonostratigraphic terranes that are mainly separated by west-vergent thrust faults. The study area is contained within the Potomac Terrane. To the east of the study area lies the Chopawamsic Terrane, which is thrust onto the Potomac Terrane, which is itself thrust onto the Westminster Terrane along the Pleasant Grove Fault. The fault zone is described as a 1-2 km wide belt of fine grained schist and quartzite (Figure 2.2; Muller et al., 1989; Kunk et al., 2004).

The Potomac Terrane, currently exposed in southern Maryland, northern Virginia, and Washington D.C., is further subdivided into three distinct lithologic units. From east to west, these units are the Laurel, Sykesville, and Mather Gorge Formations (Figure 2.3) (Drake and Froelich, 1997; Kunk, 2004). These formations are delineated on the basis of lithology and are separated by faults: the Rock Creek Shear Zone dextrally separates the Laurel and Sykesville Formations, and the Plummer's Island Thrust Fault places the Sykesville Formation on the Mather Gorge Formation (Kunk et al., 2004).

Mather Gorge of the Potomac cuts through the Mather Gorge Formation, previously labeled the Wissahickon Formation by Cloos and Cooke (1953) and the Morgan Run Formation by Muller et al. (1989). The Mather Gorge Formation trends north/northeast and is roughly subdivided into three domains based on lithology, metamorphic history, structure, and geochronology. From east to west, these domains are the Stubblefield Falls, Bear Island, and Blockhouse Point Domains (Figure 2.3; Kunk, 2004).

Southworth and Fingeret (2000) depict Mather Gorge completely within the Bear Island Domain, which is predominantly composed of garnet to sillimanite grade schist (Figure 2.4). The schist is often migmatitic, especially in the eastern part of the domain, and was intruded by ultramafic and granodiorite stocks and lamprophyre dikes (Kunk et al., 2004). Hopson (1964) identified an east to southeast trending increase in metamorphic gradient in the western Wissahickon formation, as well as a node of high grade metamorphism centered on Bear Island. The earliest metamorphic assemblage most likely consisted of cordierite-andalusite-sillimanite schist (Hopson, 1964). Zen (2006) theorizes this would have been possible at P<4 kbar and with a geothermal gradient of greater than or equal to 60 degrees C per km. The early mineral assemblages are now mostly obscured by strong retrograde metamorphism.

B. Geologic History and Age Constraints

The accretion of tectonostratigraphic terranes over some 250 Ma produced the present day Appalachian Mountains. The concept of tectonostratigraphic terranes forming separately and being accreted together over time was first developed in the Cordillera of the western United States, and may be applicable to the circum-Atlantic regions as well (Horton et al., 1989). A tectonostratigraphic terrane is defined as a fault-bounded entity of regional extent, with internally coherent stratigraphy and a geologic history that, within the specified time span, is different from that of contiguous terranes (Horton et al., 1989). The terranes may be fragments of continents, ocean basins, volcanic arcs, or continental margin basins (Howell et al., 1985).

The Potomac Terrane accreted to Laurentia during the Penobscottian Orogeny (500-490 Ma) (Kunk et al., 2005). The cross-cutting Occoquan Granite, emplaced approximately 494 $\pm$ 4 Ma and dated using Rb/Sr whole rock isochrons by Mose and Nagel (1982), constrains this age. The protoliths of the Potomac Terrane are thought to be distal slope deposits and olistrosomes. In particular, the Mather Gorge Formation consists of thick sequences of deep water turbidites (Drake, 1989). Muller et al. concur with this assertion and suggest a trench floor or slope-basin depositional environment. Based on available evidence the origin of the formation is interpreted to be a subduction complex (1989).

Subsequent orogenic events including the Taconian (470-440 Ma), Acadian (400-380 Ma), and Alleghanian (330-270 Ma) deformed the accreted terranes of proto-Appalachia, as seen in Figure 2.5 (Horton et al., 1989). During the Ordovician Taconian orogeny, the Potomac Terrane was thrust along the Pleasant Grove Fault onto the more westerly Westminster Terrane (Figure 2.3). The Pleasant Grove Fault is the Taconian suture between the two terranes (Horton et al., 1989). The Bear Island granodiorite, pictured in Figures 2.6 and 2.7, intruded the Mather Gorge Formation and cooled through 500 degrees C during this time. Muscovites from the Bear Island granodiorite have been Rb/Sr dated to 469 $\pm$ 20 and 469 $\pm$ 12 Ma (2σ) (Muth et al., 1979). $^{40}Ar/^{39}Ar$ dating of amphiboles from the Bear Island Domain ultramafics yield an age of 455 $\pm$ 23 Ma (Kunk et al., 2004).

The Devonian Acadian orogeny mostly did not extend into the central and southern Appalachians, thus the Potomac Terrane was only marginally affected by the orogeny (Horton et al., 1989). A biotite $^{40}Ar/^{39}Ar$ age of 364 $\pm$ 2 Ma indicates cooling of the Bear Island granodiorite and surrounding rocks through 300 degrees C during the

Mid-Devonian (Kunk et al., 2004). Lamprophyre dikes found south and east of Great Falls in the Bear Island Domain yield K/Ar ages of 360 $\pm$ 13 and 363 $\pm$ 13 Ma (2σ), demonstrating probable emplacement no later than Middle Devonian time (Reed et al., 1970). Thin sections of the lamprophyres can be seen in Figures 2.8 and 2.9.

The importance of the Carboniferous-Permian Alleghanian orogeny for deformation in the central and southern Appalachians, as well as in the Mather Gorge Formation, is unclear. However, the Alleghanian orogeny may be responsible for the dextral sense of shear along strike-slip faults in the central and southern Appalachians (Horton et al., 1989). Cooling curves for the Bear Island Domain of the Mather Gorge Formation and the Sykesville Formation summarize this geochronology (Figure 2.10; Kunk et al. 2004).

At least two episodes of regional metamorphism are described in the study area (Reed and Jolly, 1963). Both episodes must have occurred prior to the emplacement of the lamprophyre dikes during the Middle Devonian, as the dikes are not metamorphosed. Two distinct foliations can also be seen in the fabric of the thin sections of the Bear Island granodiorite (Figures 2.6 and 2.7) and were designated S_1 and S_2. The correlation between the foliations and the individual orogenic events remains uncertain (Kunk et. al., 2005).

Rifting of North America away from northern Africa during the Jurassic led to the formation of the Atlantic Ocean basin. Moderate erosion occurred as the rocks of the Mather Gorge Formation were exposed and cut into by the paleo-Potomac River (Reed et al., 1980). The earliest evidence of the Potomac Valley's formation is an unconformity between saprolitic Piedmont schist and overlying lacustrine/fluvial deposits dated to 5 Ma (Zen, 1997; Zen, 2006). Numerous hydrologic studies (e.g. Reed, 1981; Zen and Prestegaard, 1994; Reusser et al., 2004) suggest that the Potomac River had carved out its approximate present-day valley by 2 Ma. During the last (Wisconsinian) Pleistocene glaciation at 35 Ka, major hydrological regime changes combined with vegetation changes most likely gave rise to accelerated headward erosion leading to the formation of the inner Mather Gorge (Figure 2.11; Reusser et al., 2004; Zen, 2006). Differential uplift of the Piedmont relative to the Coastal Plain, occurring near a zone of flexure located on or near the boundary between the two provinces, is another proposed cause of incision (Reed, 1981).

III. Methods

A. Mapping Area and Procedures

The study area stretches from the southernmost tip of Rocky Island to a point 0.5 km downriver (Figure 3.1). It is constrained on the Maryland side of the Potomac River by the Billy Goat Trail and on the Virginia side by the River Trail. The study area is subdivided on each side of the river into eleven measurement stations spaced approximately 50 m apart. An additional station on the southern tip of Rocky Island is included in the study area. Three stations outside of the main study area were also included for comparison (Figure 3.2).

At each designated station latitude and longitude, two measurements of strike and dip for each of the five identified joint sets, two measurements of the strike and dip of foliation, and the plunge and trend of a penetrative mineral lineation contained in the plane of foliation are recorded. This is accomplished through the use of a Global Positioning System (GPS), Brunton compass, and protractor. The station positions are then placed on a 1:2,400 ft. scale, 2-ft. contour interval topographic map developed by the National Park Service and provided by Dr. E-an Zen. Lamprophyre dikes that cut obliquely across the river in the northern part of the study area are also marked on the topographic map. Additionally, station locations are placed onto photographic panoramas of both sides of the river.

B. Calibration of Instruments

The Brunton compass requires correction for magnetic declination, which is the difference between true north and magnetic north. In the Washington, D.C. area this declination has been calculated to be 10° 37' W, and this correction has been taken into account for all measurements (Figure 3.3; NGDC, 2004). The Global Positioning System is an eTrex Legend model developed by Garmin International Inc. It has a horizontal position accuracy of 3-5 m with a continuous update rate of 1 per second (Garmin International Inc., 2001).

C. Analysis of Measurements

Collected data for the joint sets, foliations, and lineations are entered into the stereographic projection program Geoplot 1.2, developed by Steve Ahlgren of the Department of Geosciences at the University of Arizona, Tucson. This program produces an equal area, lower hemisphere stereograph, two dimensional projection of the three dimensional structure, of each joint set, foliation, and lineation. The mean and one standard deviation for each set of measurements are also calculated.

Error analysis is accomplished through the use of a test outcrop in Great Falls National Park (Virginia side) as seen in Figure 3.4. On each field excursion several measurements are taken at the test outcrop before proceeding to the measurement stations downriver. To calculate the repeatability of the measurements, the same planes in several joint sets, a foliation, and a lineation on the outcrop are measured, and the mean and standard deviation for each set of measurements is computed. Actual variability of the small-scale structures was determined by measuring different planes in several joint sets, foliations, and lineations on the test outcrop and the mean and one standard deviation calculated. To estimate the total error, we compared the repeatability measurements and variability within the test outcrop to the variability in the rocks found within the study area.

D. Invalidation of Hypothesis

Before conducting the study we considered several possible outcomes that we might expect to find and their significance for either supporting or invalidating the hypothesis. We concluded that there could be several positive (or hypothesis supporting) results (Figure 3.5).

The first possibility is that the orientation of the small scale structures and river coincide both inside and beyond the gorge. If so, one might question whether the correlation found between the river orientation and gorge orientation indicates a causal relation, or merely a coincidence. In this line of thought, the other positive outcomes might suggest a coincidental conclusion. We also considered another outcome that would negate the null hypothesis: the orientation of the structures does not coincide with the orientation of the river. Our research supports this latter outcome.

IV. Observations

A. Station Measurements Within Study Area

Five joint sets have been identified within the study area including a nearly vertical dipping set, a moderately north dipping set, a moderately south dipping set, a gently east dipping set, and a gently west dipping set (Figures 4.1 - 4.3). Foliations in the study area strike northeast-northwest and are nearly vertical (Figure 4.4). Penetrative mineral lineations have fairly steep plunges and are found in the planes of the nearly vertical foliations.

At the beginning of this study, we hypothesized that the prominent north-northeast striking, nearly vertical joint set was the most likely control on the trend of the gorge (Figure 4.1). However, measurements show that the strike of the joint set does not align with the trend of the river, which has an azimuthal orientation of 342 degrees (Figure 4.5). The joints instead strike an average of 13 degrees with a standard deviation of 28 degrees (Figure 4.6; Appendix A). The nearly vertical joint set has an average dip of 81 degrees east with a standard deviation of 7 degrees.

The second joint set (Figure 4.7), dips to the north with an average strike of 278 degrees and a standard deviation of 14 degrees. It has an average dip of 66 degrees north with a standard deviation of 17 degrees (Appendix B). This set is most prominent in the northern section of Mather Gorge. The moderately south dipping joint set (Figure 4.8) has an average strike of 290 degrees with a standard deviation of 25 degrees. It has an average dip of 54 degrees south with a standard deviation of 23 degrees (Appendix C).

The gently east dipping joint set (Figure 4.9) has an average strike of 355 degrees with a standard deviation of 38 degrees. It has an average dip of 16 degrees east and a standard deviation of 8 degrees (Appendix D). The gently west dipping joint set (Figure 4.10) has an average strike of 13 degrees with a standard deviation of 42 degrees and on average dips 17 degrees west with a standard deviation of 8 degrees (Appendix E). This joint set has the largest standard deviation of strike of all five sets.

Foliation measurements (Figure 4.11) have an average strike of 9 degrees and a standard deviation of 10 degrees (Appendix F). Foliation dips fairly steeply, with a mean of 82 degrees east or west with a standard deviation of 7 degrees. Penetrative mineral lineations are found in the planes of the fairly steep east-west dipping foliations (Figure 4.12). They have an average plunge of 54 degrees south with a standard deviation of 18 degrees and an average trend of 175 degrees with a standard deviation of 41 degrees (Appendix G).

B. Station Measurements Outside of Study Area

Our research included three measurement stations outside of the main study at the northern and southern ends of the gorge for comparison with stations in the actual study area (Figure 3.2). We found no significant difference in the orientation of small scale structures at the stations outside of the study area or evidence of additional structures not seen in the gorge.

C. Error Analysis Measurements

Using a designated test outcrop on the Virginia side of the Potomac River, numerous measurements were taken to determine the repeatability of the measurements and the true variability of the structures in the rocks. The purpose of the test outcrop is to separate the two sources of variation found in any measurement. Variability can result from measurement error or from actual variations in the structures in the rock. By taking numerous measurements of the same structures, it is possible to determine how repeatable the measurements are, or how much human error is included in the taking of a measurement. The variability in the structures themselves can be determined by measuring different planes within a given joint set, foliation, or lineation.

To determine the repeatability of measurements, the same small-scale structures were measured on each visit to the field site (Figure 4.13). Measurements of a single, nearly vertical joint surface had a standard deviation of 2 degrees for strike and 1 degree for dip. Measurements of a single north dipping joint surface had a standard deviation of 1 degree for strike and 1 degree for dip, and measurements of a single, south dipping joint surface yielded a standard deviation of 3 degrees for strike and 5 degrees for dip. Foliation surface measurements had a 4 degree standard deviation for strike and a 2 degree standard deviation of dip (Figure 4.13). The repeatability measurements for lineations had a standard deviation of 12 degrees south for plunge and 11 degrees for trend. (Appendix H).

Variability of the structures in the rocks was determined by measuring different joints, foliations, and lineations of the same chosen structures in the same test outcrop. As seen in Figure 4.14, one of the joint sets has a much greater variability than the others. This is a moderately south-dipping joint set, which appears to have the greatest variation of all identified joint sets on the test outcrop and downriver as well. We recognize that the high degree of variability within the south-dipping joint set may not be representative of the amount of variation found within the other four joint sets. Consequently, we measured additional joint sets at the test outcrop for comparison. The strike of the nearly vertical joint set had a variability of 0 degrees and a variability of dip of 1 degree at one standard deviation. The moderately north dipping joint set had a variability of 3 degrees for strike and 2 degrees for dip. The moderately south dipping joint set had a variability of 18 degrees for strike and 11 degrees for dip. The foliation measurements had a variability of 2 degrees for strike and 5 degrees for dip. Measurement of lineations indicate a variability of 11 degrees south for plunge and 22 degrees for trend (Appendix I).

The repeatability error and the variability measurements for the rocks at the test outcrop can then be compared to the variability measured in the study area. This comparison is useful for recognizing if individual station measurements of structures are within a reasonable range of error. If the structures are not, it indicates a need for another explanation of error. Our findings indicate that the variability found in the rocks within the study area is much greater than the repeatability error or the variability seen in the test outcrop (Table 4.1).

V. Interpretations

None of the aforementioned structures exactly match the orientation of the Potomac River through Mather Gorge, though two joint sets come close. With an average strike of 355 degrees, the east dipping joint set is within one standard deviation of the trend of the river (Figure 4.9). However, this orientation remains a substantial 13 degrees from the trend of the river, and is thus unlikely to be controlling the orientation of incision. Similarly, the west dipping joint set strikes an average 13 degrees, which is within one standard deviation of the trend of the river as well, but remains a considerable 31 degrees from the actual trend (Figure 4.10). Although the mean trend of lineations is within one standard deviation of the mean trend of the river, the mean plunge of the lineations is not within the estimated plunge of the river bed and thus we eliminate these structures as potential controls on gorge orientation.

Our findings indicate that the trend of Mather Gorge is not structurally controlled by joint sets, foliations, or lineations. The measured trend of the Potomac River through Mather Gorge is 342 degrees (Figure 4.5). This trend does not coincide with the nearly vertical dipping joint set, the moderately north or south dipping joint sets, foliations, or lineations. The two joint sets that are within one standard deviation of the trend of the river include the gently east and gently west dipping sets. However, the standard deviations of the sets remain so large that the joint sets are unlikely controls of gorge orientation.

The error analysis demonstrates that both the repeatability error and variability found in the rocks of the test outcrop are less than the total variability measurements in the rocks in the study area. The repeatability measurements are less than the measured variability of all small scale structures except for the strike measurements of the nearly vertical joint set, the strike of the foliation, and the plunge of the lineation measurement. These findings could be explained by the small number of measurements taken for each structure, although all of the repeatability measurements that are larger than test outcrop variability measurements differ by 2 degrees or less. We expect the variability of the test outcrop to be less than the total variability of the rocks in the study area based on the sample size. The test outcrop describes an extremely small sample area that may not be representative of the variability of the study area as a whole.

VI. Discussion and Implications

Our observations do not support the hypothesis that the trend of Mather Gorge is structurally controlled by joints, foliations, or lineations. The trend of the river is 342 degrees (Figure 4.5). This conclusion potentially eliminates small-scale structural elements as the controlling factors in the gorge formation. This leads us to ask: If the gorge is not controlled by small-scale structures such as joints, lineations, and foliations, what other explanations are there for its apparent straightness?

Joint intersections have been proposed as one alternative control on the river orientation. To test this suggestion we plotted the average strike and dip of each joint set identified and marked the four intersections most likely to align with the present course of the river through Mather Gorge (Figure 6.1). After estimating the plunge and trend of the river to be 0.5 degrees southeast and 162 degrees, the only joint intersection which remained as a possible candidate for the gorge control was the nearly vertical east dipping joint set and the moderately south dipping joint set, which had a plunge and trend of 52 degrees southeast and 181 degrees. This orientation results in a 19 degree difference from the trend of the river and thus we discounted it as a possible control of the gorge.

Another theory, that a fault of undetermined geometry underlies the Potomac River through Mather Gorge and is responsible for its present day orientation, is proposed by Fisher (1963) and supported by Reed et al. (1970, 1980). Fisher (1963) projected the fault cutting along the western edge of Rocky Island and diagonally across Olmstead Island, directly east of Great Falls (Figure 6.2). Exposures on Olmstead Island display a 7.6-10.1 cm (3-4 in.) wide gouge zone that dips approximately 80 degrees southwest (Reed et al., 1970).

As the average depth of the Potomac River in Mather Gorge is 8 m, mapping of the proposed fault in the gorge itself has necessarily not been pursued. Instead, the offset swarm of lamprophyre dikes (Figure 6.3) found within Mather Gorge have been cited as additional evidence of a fault underlying the Potomac.

The dikes were first mapped using exposed outcrops and a ground magnetometer by Fisher (1963). He determined the along-strike extent of the dikes on the Maryland side to be greater than 300 m (1,000 ft.) and followed the dikes on the Virginia side for at least 90 m (300 ft.). Reed et al. (1970) mapped three distinct dikes across the Potomac River in both Maryland and Virginia, striking 80 degrees west of north, dipping 75-85 degrees north, and with an apparent right lateral sense of offset of approximately 24.4 -30.5 m (80-100 ft) with the Maryland side downriver. In later publications, Reed also agrees with these assertions (1980).

Our independent observations provide one new piece of information concerning the dikes and also confirm the previous work of Fisher and Reed. We identified four lamprophyre dikes ranging from 22.9-53.3 cm in width, on both the Maryland and Virginia sides of the gorge, one more than previously mapped. The dikes are mappable for several hundred feet away from the river. Our measurements of strike (275-281 degrees or 79-85 degrees west of north) and dip (71-84 degrees northeast) agree with those of Reed et al. (1970). Sighting across the river from the Maryland side, we estimate an offset for the dikes of approximately 30.5 m with a dextral sense of motion.

Although the offset of the dikes is used as evidence for a fault, Zen, in Bierman et al. (2004) points out that the dikes may be exploiting pre-existing fractures that deflect them to the north (VA) and south (MD), and thus are not offset at all. The apparent pinching out of two of the dikes may support this interpretation. Bierman et al. (2004) were also unable to identify the fault mapped by Reed et al. in 1970. However, we note that the dikes would require a joint set oriented at an angle not found in the field in order to be placed or deflected into their present offset position. This consideration would perhaps support the fault theory. Zen (2006) alternatively suggests the measurement variation may be accountable for the apparent offset. However, should the offset exist, it could result from variability in dike attitude, pinching or swelling or local extension due to transform motion on foliation planes. Further mapping will help to make a more definitive assertion.

Other researchers (Bierman et al., 2004; Reusser et al., 2004) support theories that explain the river incision as a combination of flexural uplift and isostatic rebound after Pleistocene glaciations, but our data cannot address why the river incised. However, our data could support answers to the questions of how the river incises a channel and what fluvial processes are involved. Close examination of the Potomac River in Mather Gorge reveals possible methods for river incision, including plucking of bedrock parcels separated from surrounding rocks due to preexisting weaknesses caused by joints or other small scale structures (Figure 6.4), potholing created by water vortexes at flood stages (Figure 6.5), or some combination of causes. These ideas are investigated more thoroughly by several researchers including Zen and Prestegaard, 1994; Whipple et al., 2000; and Bierman et al., 2004.

VII. Conclusions

Previous research has elucidated the accretional and deformational history of the Potomac Terrane, as well as the geologic history of the Potomac River throughout the study area. However, the lack of detailed small scale structural analysis allowed for somewhat unsubstantiated speculation about the orientation of the Potomac River incision in Mather Gorge. Our hypothesis that small scale structures such as joints, foliations, and lineations control the orientation of the river through the gorge is not supported by the data collected; rather, the data suggest that there may be other controls on the gorge orientation. Further mapping and research are necessary to determine if any other controls, such as a fault, may exist. This research places the Potomac River into a larger, worldwide context of river incisions that are not controlled by small scale structures and may reveal answers to questions about the fundamental mechanisms of river incision. Rivers found in similar topographic or lithologic regions may be evaluated and compared to the Potomac so that similar incision patterns or mechanisms may be identified.

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Figure Captions

Figure 1.1 - Spectacular example of an incised river, Mather Point of the Grand Canyon, AZ (Thayer, D., 2003; http://www.canyondave.com/GCWebPhotos.html).

Figure 1.2 - Another spectacular example of an incised river the Three Gorges, Yangtze River, China (http://www.chinadiscoverytours.com/image/2005Yangtze-river-1_lg.jpg).

Figure 1.3 - Example of incised river the Victoria Falls & Zambezi River, Zambia and Zimbabwe, Africa (http://www.zambiatourism.com/travel/places/victoria.htm).

Figure 1.4 - Great Falls of the Potomac River viewed from the Virginia side during a low stand 2005 (Burgy, 2005).

Figure 1.5 - The Atlantic passive margin (Colton, 1970).

Figure 1.6 - Highly deformed rocks of Great Falls, Appalachian Piedmont (Burgy, 2005).

Figure 1.7 - The 1.25 km-long Mather Gorge (Burgy, 2005).

Figure 2.1 - The physiographic provinces (Schmidt, 1993).

Figure 2.2 - The Piedmont province and terranes of study area, including the Potomac Terrane (Kunk et al., 2004).

Figure 2.3 - The lithologic units of the Potomac Terrane, from east to west, the Laurel, Sykesville, and Mather Gorge Formations. Mather Gorge is depicted between Stops 4 and 5. €zmg – Mather Gorge Formation, €mm – migmatitic Mather Gorge Formation, €mp – chlorite-sericite phyllonite of the Mather Gorge Formation, €mb – Marburg Formation, €s – Sykesville Formation, €l – Laurel Formation, um - ultramafics (Kunk et al., 2004).

Figure 2.4 - Lithologic units of Mather Gorge as mapped by Southworth and Fingeret, scale 1:10,000 (2000).

Figure 2.5 - A summary of the accretionary history of the central and southern Appalachians (Horton et al., 1989).

Figure 2.6 - Photomicrograph of Bear Island Granodiorite with two distinct foliations S_1 and S_2 in Quartz-Muscovite schist (Kunk et al., 2005).

Figure 2.7 - Photomicrograph of Bear Island Granodiorite with two distinct foliations S_1 and S_2 in Muscovite mica phyllonite (Kunk et al., 2005).

Figure 2.8 - Thin section of lamprophyre dikes collected by J.C. Reed Jr., PPL 4X magnification, field of view=3mm (Burgy, 2005).

Figure 2.9 - Thin section of lamprophyre dikes collected by J.C. Reed Jr., XPL 4X magnification, field of view=3mm (Burgy, 2005).

Figure 4.11 - Equal area stereoplot of nearly vertical planes of foliation. The purple dot on the outer edge of the stereoplot represents the trend of the river (Burgy, 2005).

Figure 4.12 - Equal area stereoplot of penetrative mineral lineations found within the plane of foliation. The purple dot on the outer edge of the stereoplot represents the trend of the river (Burgy, 2005).

Figure 4.13 - Equal area stereoplot of repeatability measurements. The green color represents joints, the blue color represents foliations, and the red dots indicate the plunge and trend of lineations (Burgy, 2005).

Figure 4.14 - Equal area stereoplot of variability measurements. The green color represents joints, the blue color represents foliations, and the red dots indicate the plunge and trend of lineations (Burgy, 2005).

Table 4.1 - Comparison of repeatability and variability measurements in the test outcrop to variability of structures in the rocks in the study area (Burgy, 2005).

Figure 6.1 - Equal area stereoplot of joint surfaces and intersections. Joint intersections and river trend marked in purple (Burgy, 2005).

Figure 6.2 - Map and explanation of general study area with lamprophyre dikes and fault surface marked (Reed et al., 1970).

Figure 6.3 - Lamprophyre dikes on Virginia side, viewed from Maryland side dikes (Burgy, 2005).

Figure 6.4 - Jointed rock blocks on Rocky Island are exposed during a low stand of the river and await plucking (Burgy, 2005).

Figure 6.5 - Horizontal pothole caused by abrasion near the tip of Rocky Island (Burgy, 2005).

Figure 1.1

Figure 1.2

Figure 1.3

Figure 1.4

Figure 1.5

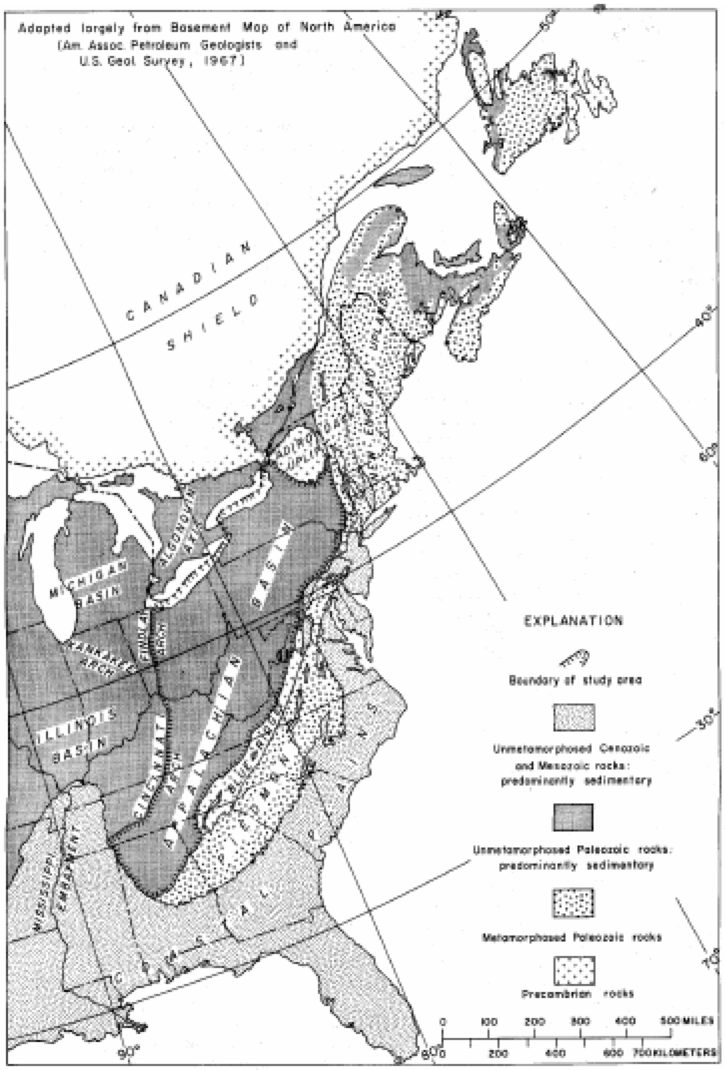

Adapted largely from Basement Map of North America
(Am. Assoc. Petroleum Geologists and
U.S. Geol. Survey, 1967)
CANADIAN
SHIELD
MICHIGAN
BASIN
KANKAKEE
ARCH
ILLINOIS
BASIN
ADIRONDACK
UPLIFT
BASIN
APPALACHIAN
PIEDMONT
MISSISSIPPI
EMBAYMENT
EXPLANATION
Boundary of study area
Unmetamorphosed Cenozoic
and Mesozoic rocks:
predominantly sedimentary
Unmetamorphosed Paleozoic rocks:
predominantly sedimentary
Metamorphosed Paleozoic rocks
Precambrian rocks
0 100 200 300 400 500 MILES
0 200 400 600 700 KILOMETERS
90°
80°
70°
60°
50°
40°
30°

Figure 1.6

Figure 1.7

Figure 2.1

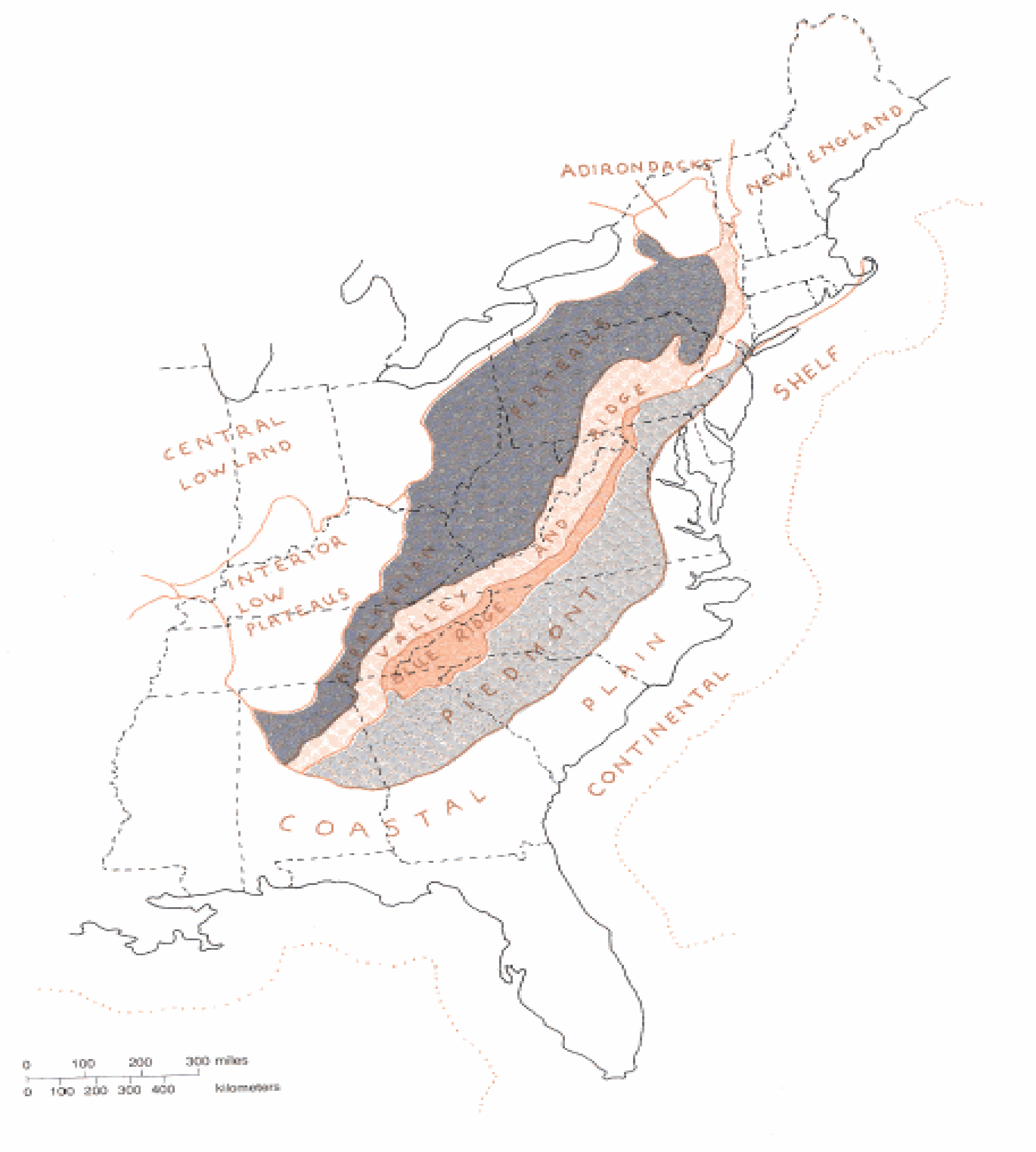

ADIRONDACKS
NEW ENGLAND
CENTRAL LOWLAND
INTERIOR LOW PLATEAUS
APPALACHIAN
PLATEAUS
VALLEY
AND
RIDGE
BLUE RIDGE
PIEDMONT
SHELF
COASTAL
PLAIN
CONTINENTAL
0 100 200 300 miles
0 100 200 300 400 kilometers

Figure 2.2

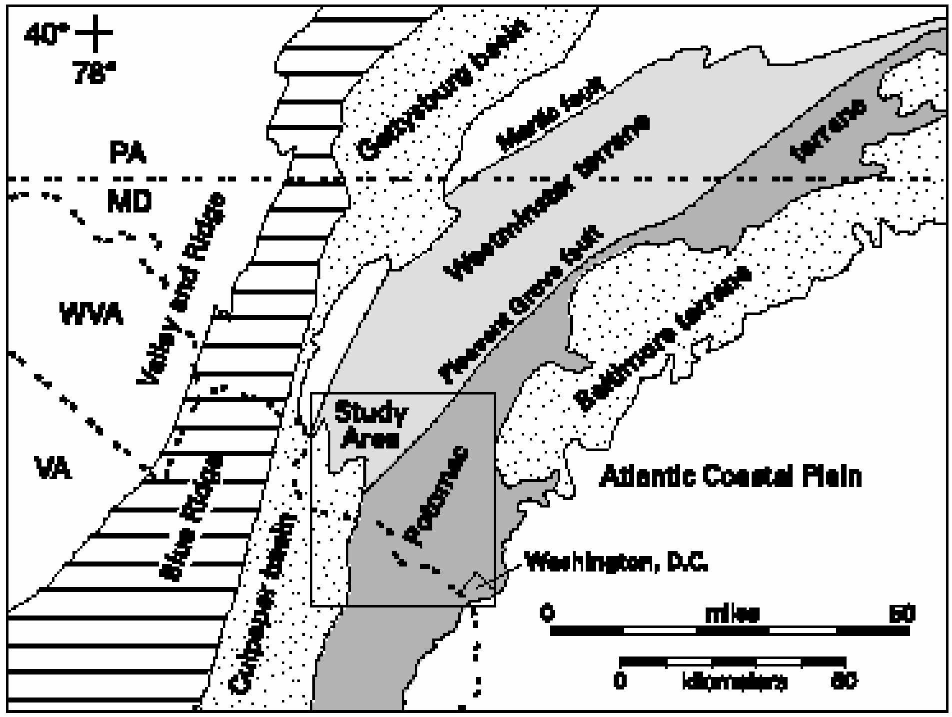


Figure 1. Terrane map of the south-central Appalachians. Box indicates the area of figures 2 and 6. Modified from Horton and others (1991).

Figure 2.3

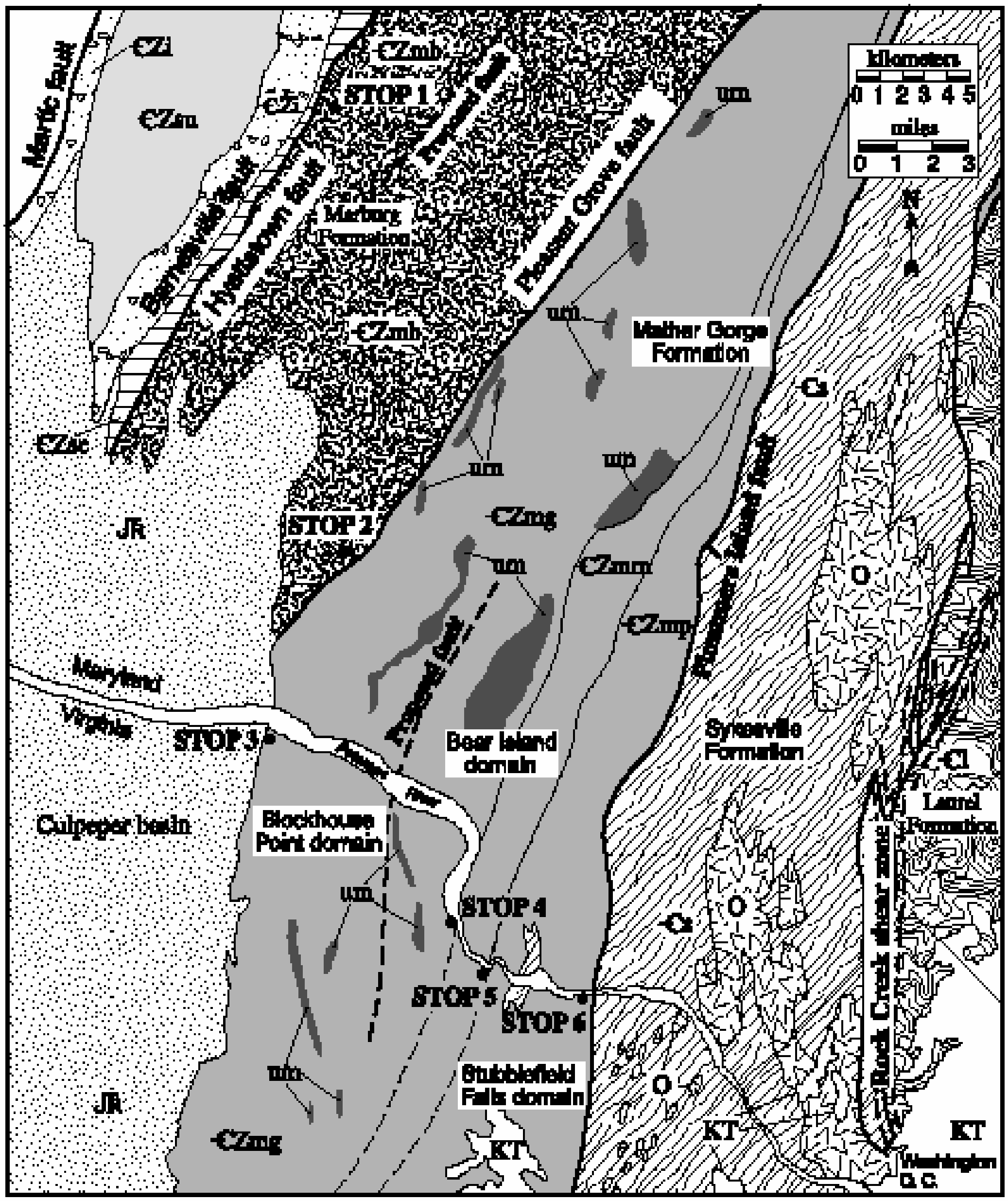
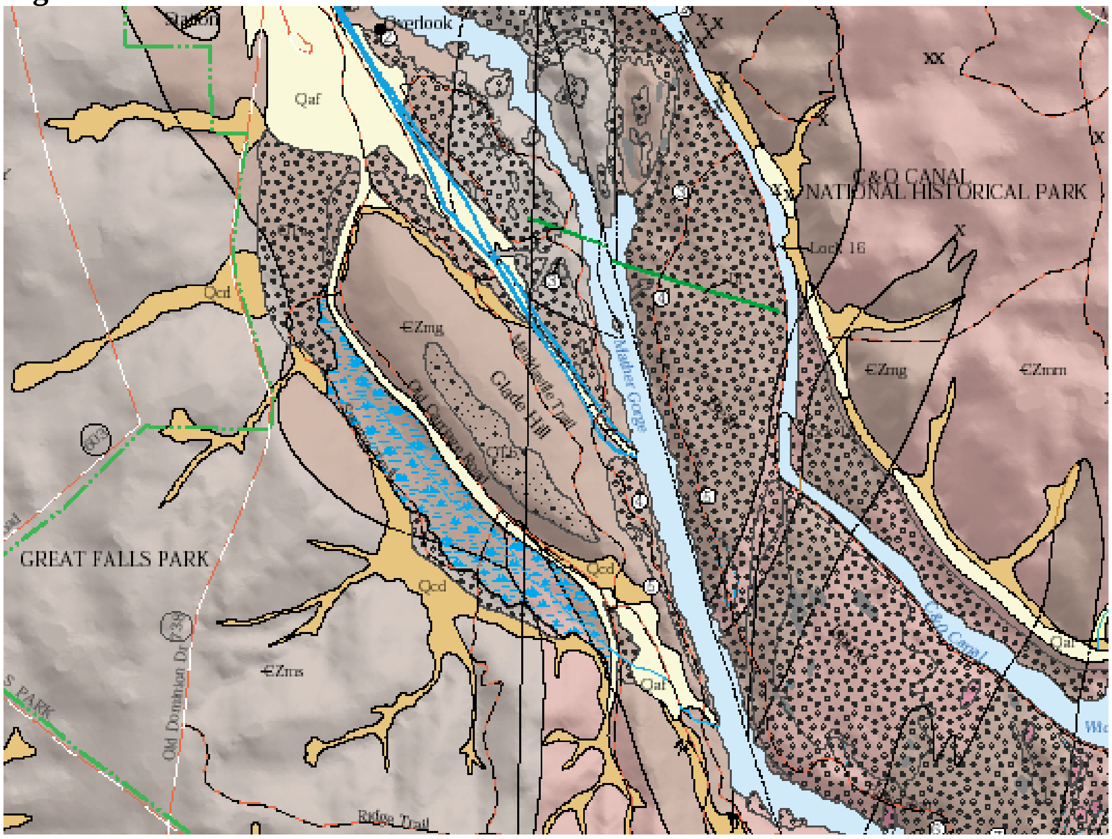


Figure 2. Geologic map of parts of the Westminster and Potomac terranes, Maryland, Virginia, and Washington, D.C. The Pleasant Grove fault separates the Westminster terrane on the west from the Potomac terrane on the east. Geologic map-unit symbols are as follows: ꞒZmg, Mather Gorge Formation; ꞒZmp, chlorite-sericite phyllonite of the Mather Gorge Formation; ꞒZmm, migmatitic Mather Gorge Formation; ꞒZi, Ijamsville Phyllite; ꞒZmb, Marburg Formation; ꞒZsc, Sams Creek Formation; ꞒZsu, undifferentiated metasiltstone, phyllite, quartzite, and metagraywacke; Ꞓs, Sykesville Formation; ꞒI, Laurel Formation; O, Ordovician plutons; um, ultramafics; JTR, Late Triassic and Early Jurassic rocks; KT, Cretaceous and Tertiary Coastal Plain deposits. Faults are as indicated and are dashed where inferred. Modified from Davis and others (2002).

Figure 2.4



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
€a	**Amphibolite sills (Early Cambrian-about 540 million years old)**—Dark-colored, hornblende-rich tabular intrusions, emplaced parallel to the bedding of the surrounding rock

METAMORPHOSED SEDIMENTARY ROCKS (Lower Cambrian and (or) Late Proterozoic—about 600 million years old)

Sykesville Formation

€Zs	**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

Mather Gorge Formation

€Zms	**Quartz-rich schist and mica gneiss**—Greenish-gray rocks with different textures; schist is finer grained, more planar, and less massive than gneiss
€Zmg	**Metagraywacke and metasiltstone schist**—Well-bedded, gray, dirty sandstone interbedded with siltstone; originally deposited in submarine turbidity currents on the ocean floor
€Zmm	**Migmatite**—Complex, light- and dark-gray rock formed when rocks of different ages were melted together
€Zmp	**Phyllonite with vein quartz**—Shiny, greenish-gray, fine-grained sheared rock with pods and veins of white quartz

OLDER IGNEOUS ROCKS

€Zu	**Ultramafic rocks**—Dark-green igneous rocks consisting of serpentinite, soapstone, and talc schist; occur as sedimentary blocks and fragments in the Mather Gorge Formation

Figure 2.5

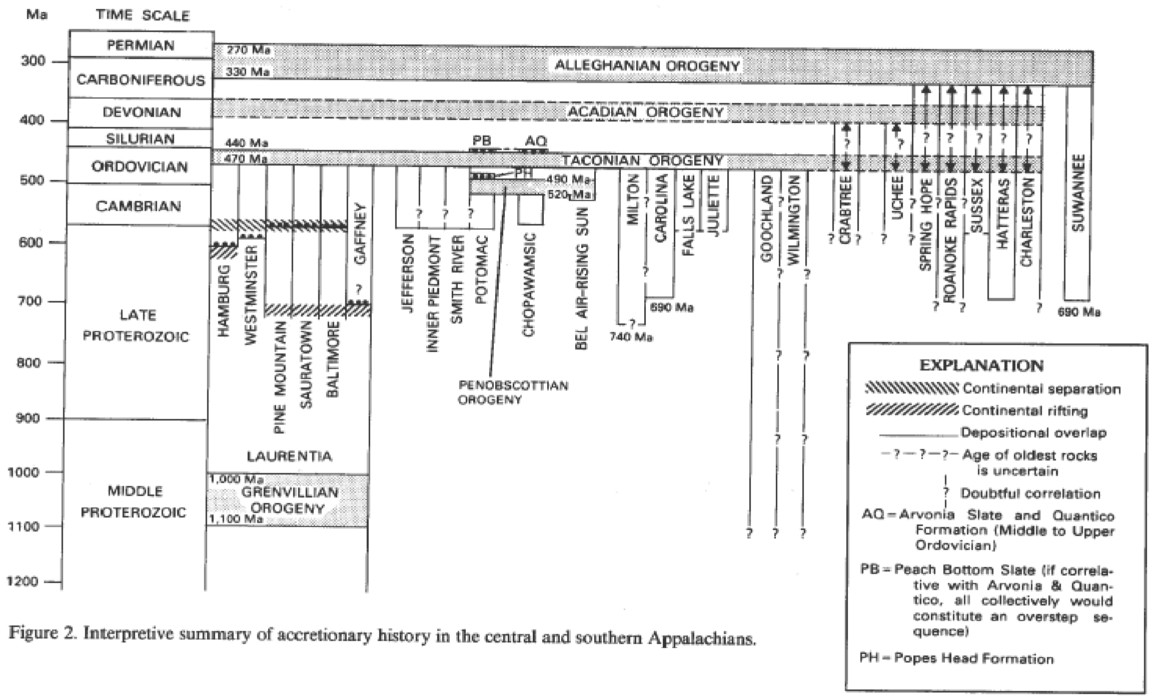


Figure 2. Interpretive summary of accretionary history in the central and southern Appalachians.

Figure 2.6

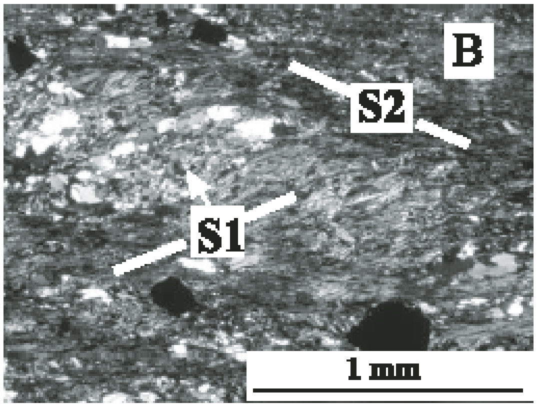


Figure 2.7

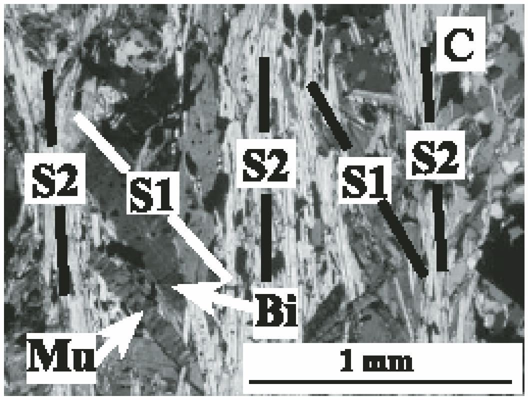
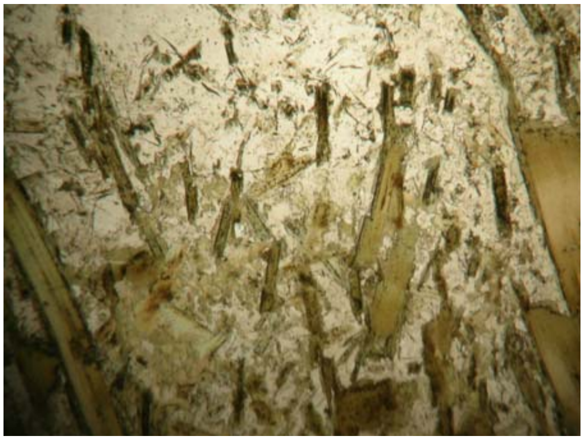


Figure 2.8



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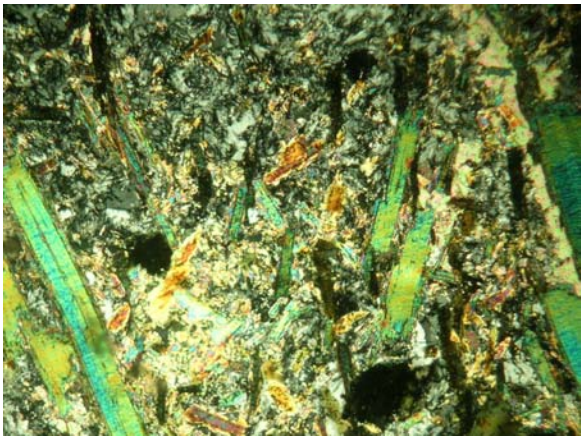


Figure 2.10

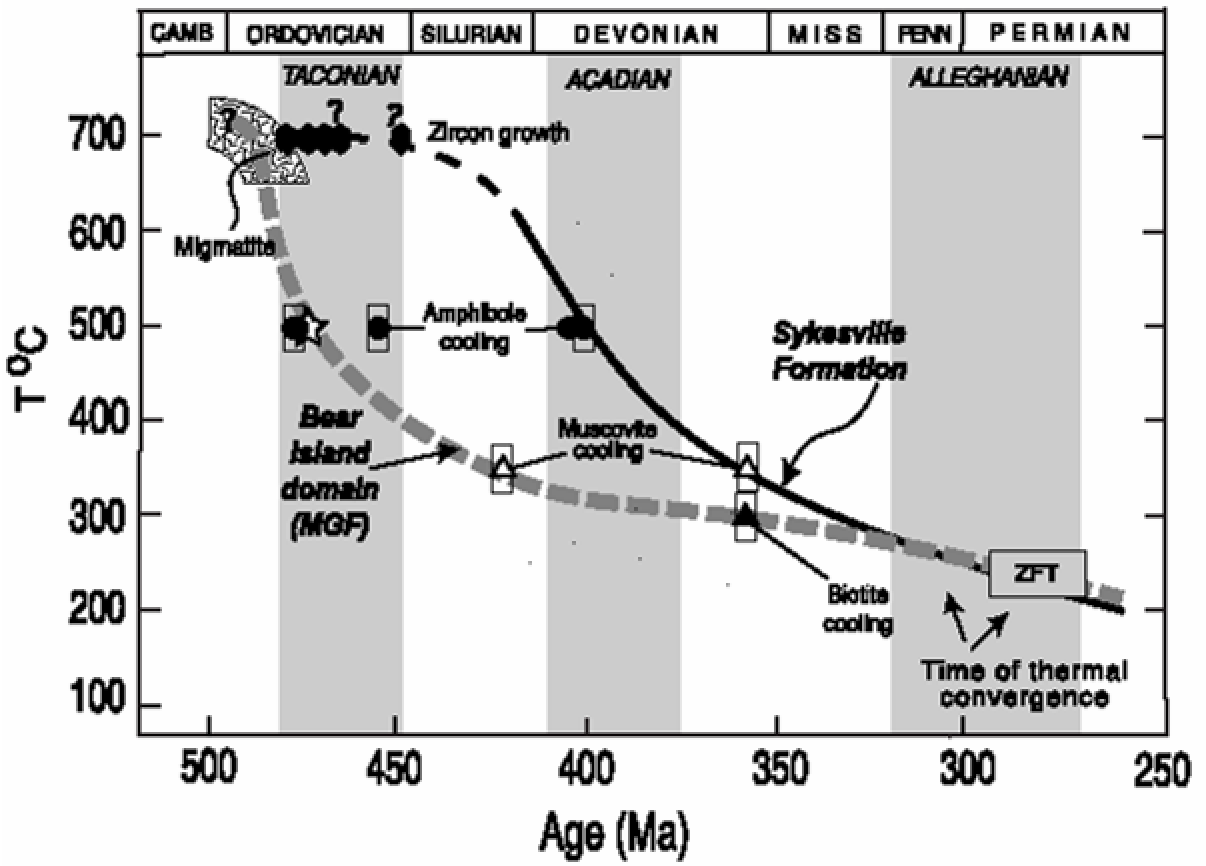

CAMB
ORDOVICIAN
SILURIAN
DEVONIAN
MISS
PENN
PERMIAN
TACONIAN
ACADIAN
ALLEGHANIAN
Zircon growth
Migmatite
Amphibole cooling
Sykesville Formation
Bear Island domain (MGF)
Muscovite cooling
Biotite cooling
ZFT
Time of thermal convergence
T °C
700
600
500
400
300
200
100
500
450
400
350
300
250
Age (Ma)

Figure 2.11

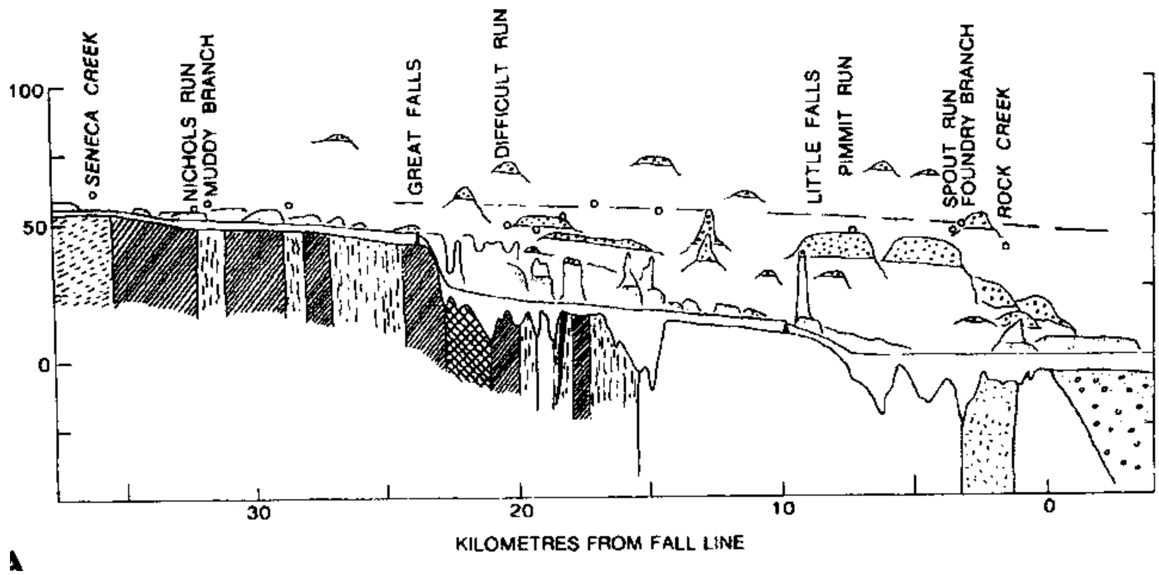

SENECA CREEK
NICHOLS RUN
MUDDY BRANCH
GREAT FALLS
DIFFICULT RUN
LITTLE FALLS
PIMMIT RUN
SPOUT RUN
FOUNDRY BRANCH
ROCK CREEK
100
50
0
30
20
10
0
KILOMETRES FROM FALL LINE

Figure 3.1

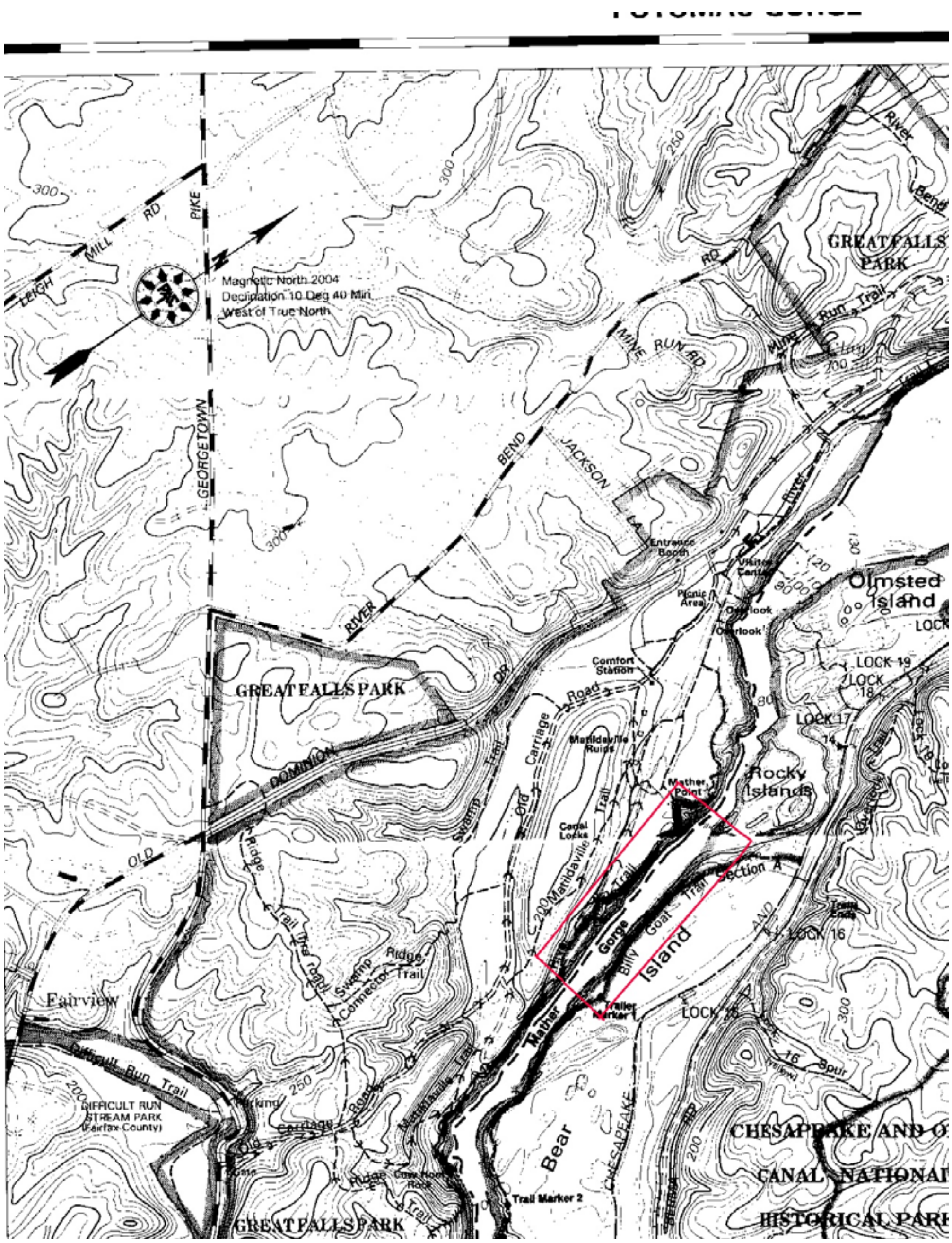

GREAT FALLS PARK
Magnetic North 2004
Declination 10 Deg 40 Min
West of True North
GEORGETOWN
PIKE
MINE RUN RD
BEND
JACKSON
RIVER
DOMINION
DR
OLD
Entrance Booth
Visitor Center
Picnic Area
Overlook
Comfort Station
Carriage Road
Matildaville Ruins
Canal Locks
Mather Point
Olmsted Island
LOCK 19
LOCK 18
LOCK 17
LOCK 16
LOCK 15
Rocky Islands
Section A
Billy Goat Trail
Gorge
Island
Bear
Fairview
Difficult Run Trail
DIFFICULT RUN STREAM PARK (Fairfax County)
Trail Marker 2
CHESAPEAKE AND O
CANAL NATIONAL
HISTORICAL PARK

Figure 3.2

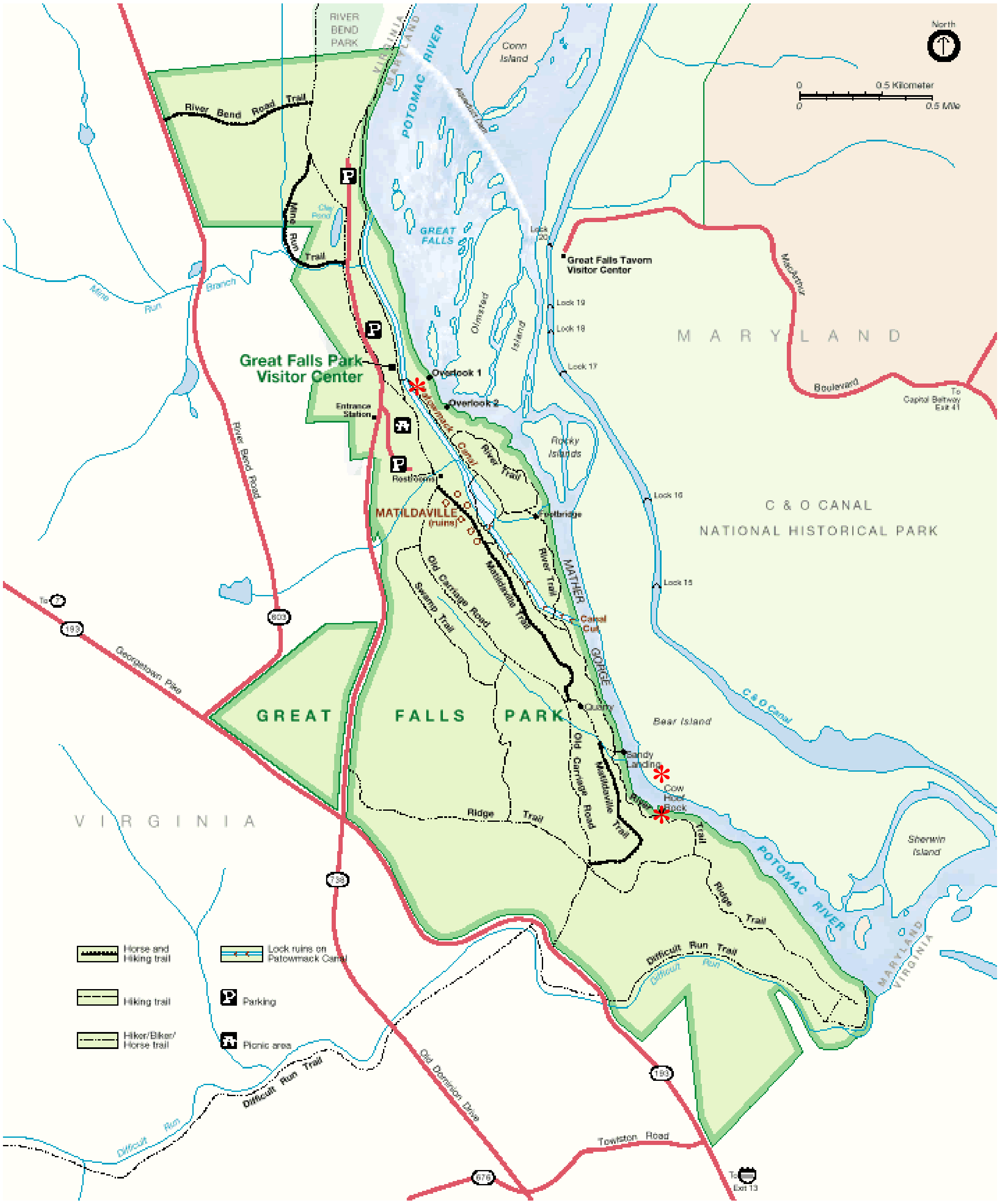

North
0 0.5 Kilometer
0 0.5 Mile
RIVER BEND PARK
POTOMAC RIVER
Conn Island
GREAT FALLS
Great Falls Tavern Visitor Center
MARYLAND
Great Falls Park Visitor Center
Entrance Station
Overlook 1
Overlook 2
Rocky Islands
MATILDAVILLE (ruins)
C & O CANAL NATIONAL HISTORICAL PARK
MATHER GORGE
Canal Cut
GREAT FALLS PARK
VIRGINIA
Bear Island
Sandy Landing
Cow Hoof Rock
Sherwin Island
Georgetown Pike
Old Dominion Drive
Towlston Road
River Bend Road
Ridge Trail
Old Carriage Road
Matildaville Trail
Swamp Trail
River Trail
Difficult Run Trail
Horse and Hiking trail
Lock ruins on Patowmack Canal
Hiking trail
Parking
Hiker/Biker/Horse trail
Picnic area

Figure 3.3

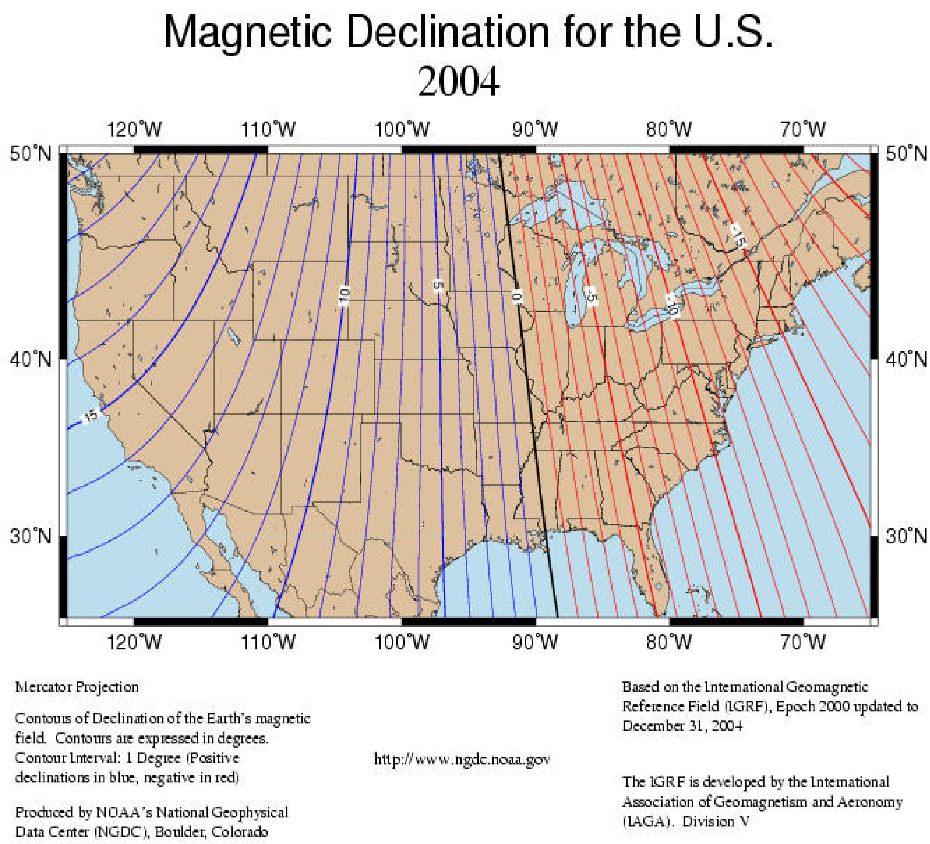

Magnetic Declination for the U.S.
2004
120°W
110°W
100°W
90°W
80°W
70°W
50°N
40°N
30°N
15
10
5
0
-5
-10
-15
Mercator Projection
Contours of Declination of the Earth's magnetic field. Contours are expressed in degrees. Contour Interval: 1 Degree (Positive declinations in blue, negative in red)
Produced by NOAA's National Geophysical Data Center (NGDC), Boulder, Colorado
http://www.ngdc.noaa.gov
Based on the International Geomagnetic Reference Field (IGRF), Epoch 2000 updated to December 31, 2004
The IGRF is developed by the International Association of Geomagnetism and Aeronomy (IAGA). Division V

Figure 3.4

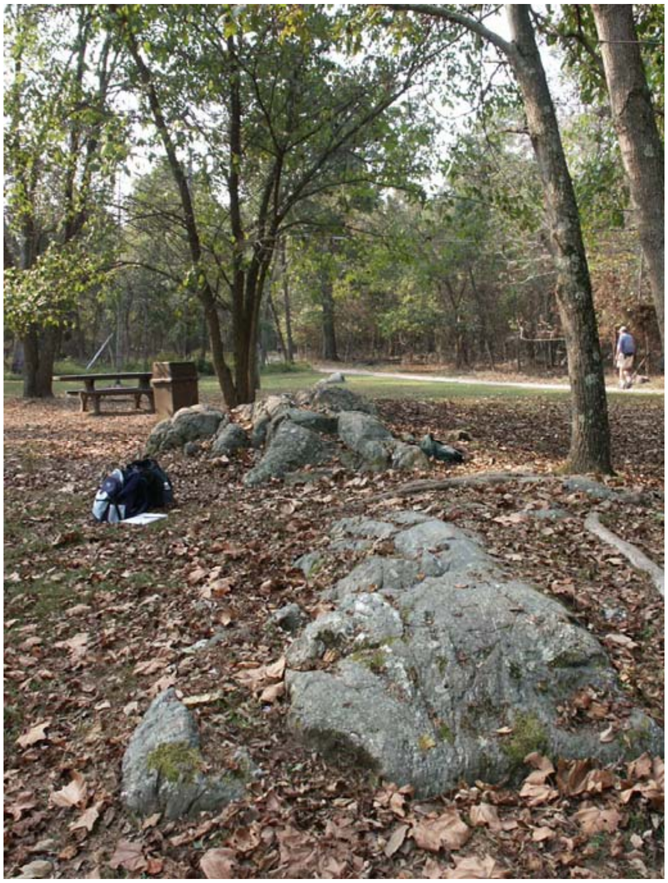


Figure 3.5

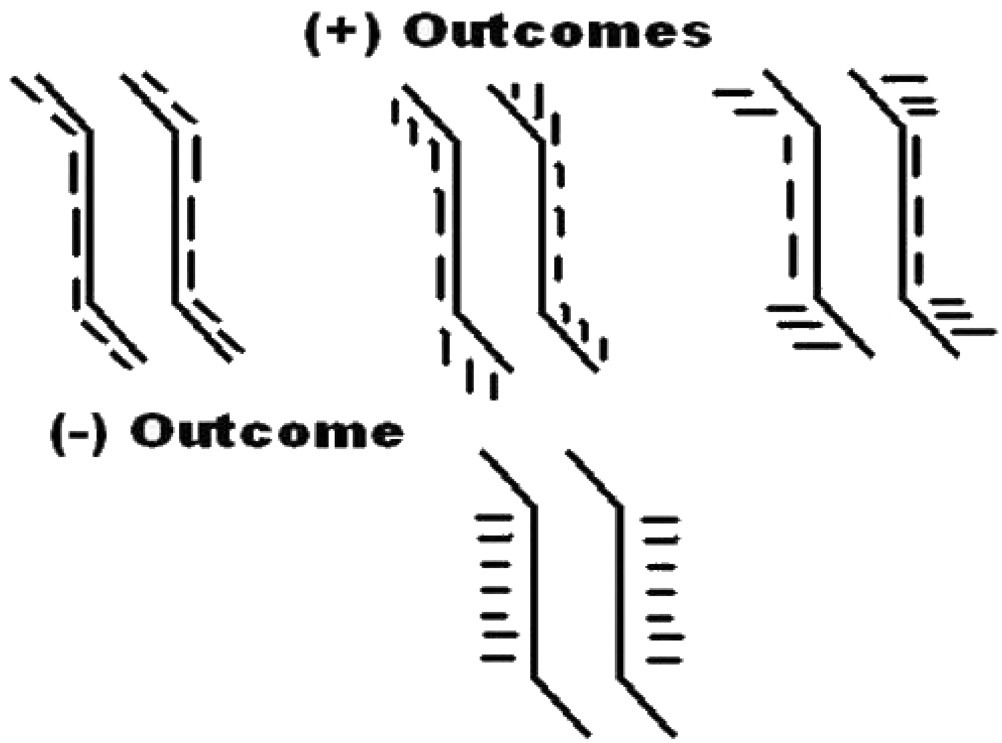


Figure 4.1

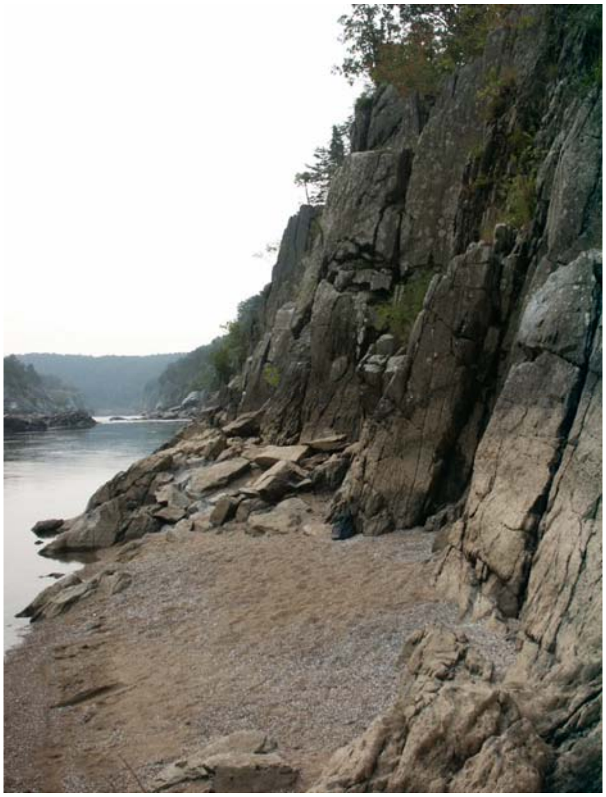


Figure 4.2

Figure 4.3

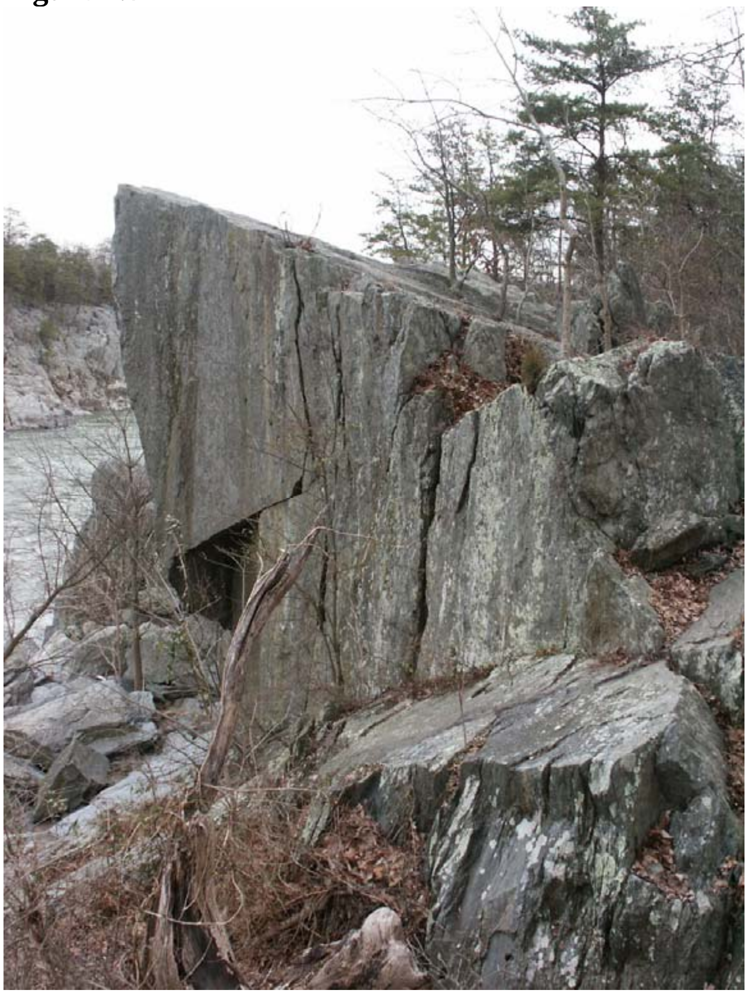


Figure 4.4

Figure 4.5

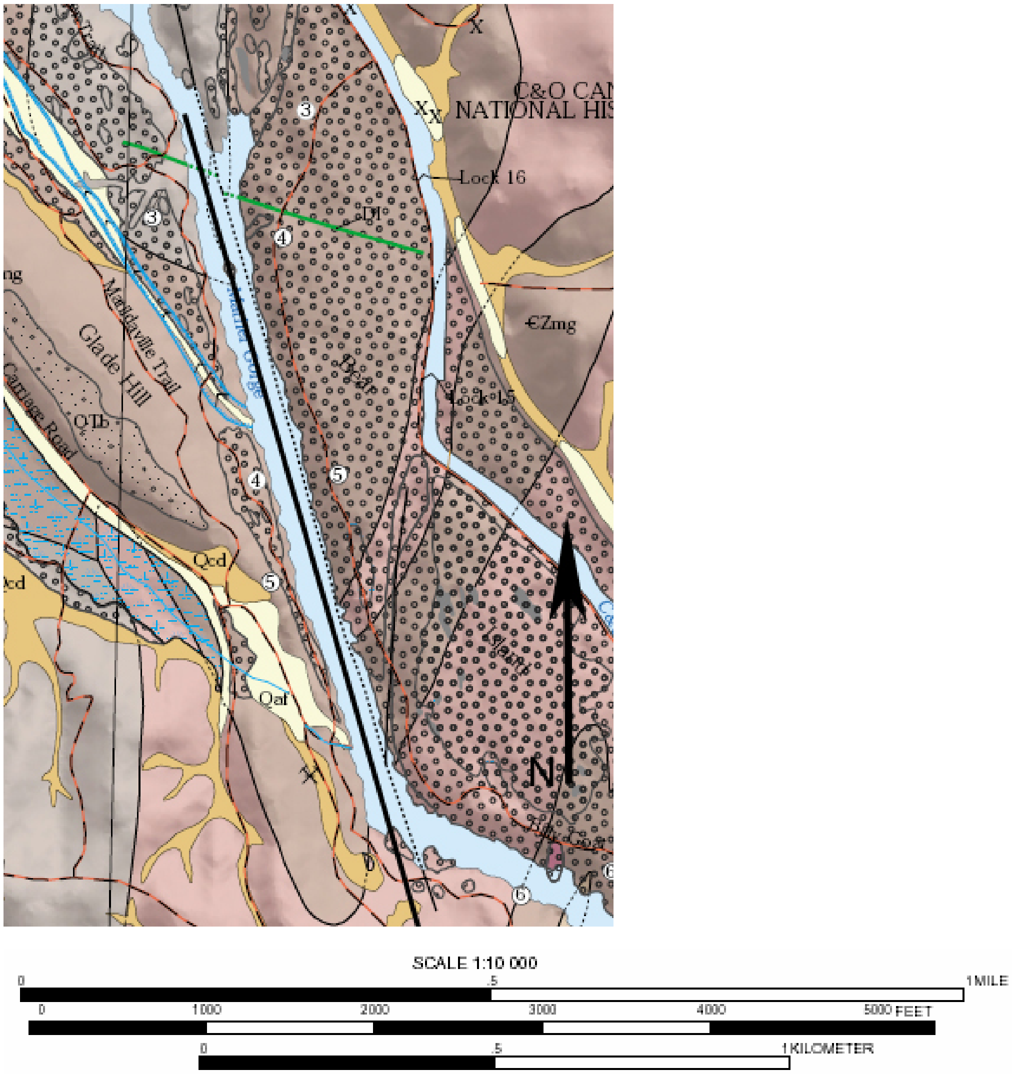

C&O CAN
NATIONAL HIS
Lock 16
€Zmg
Lock 15
Glade Hill
Carriage Road
QTb
Qcd
Qaf
N
SCALE 1:10 000
0
.5
1 MILE
0
1000
2000
3000
4000
5000 FEET
0
.5
1 KILOMETER

Figure 4.6

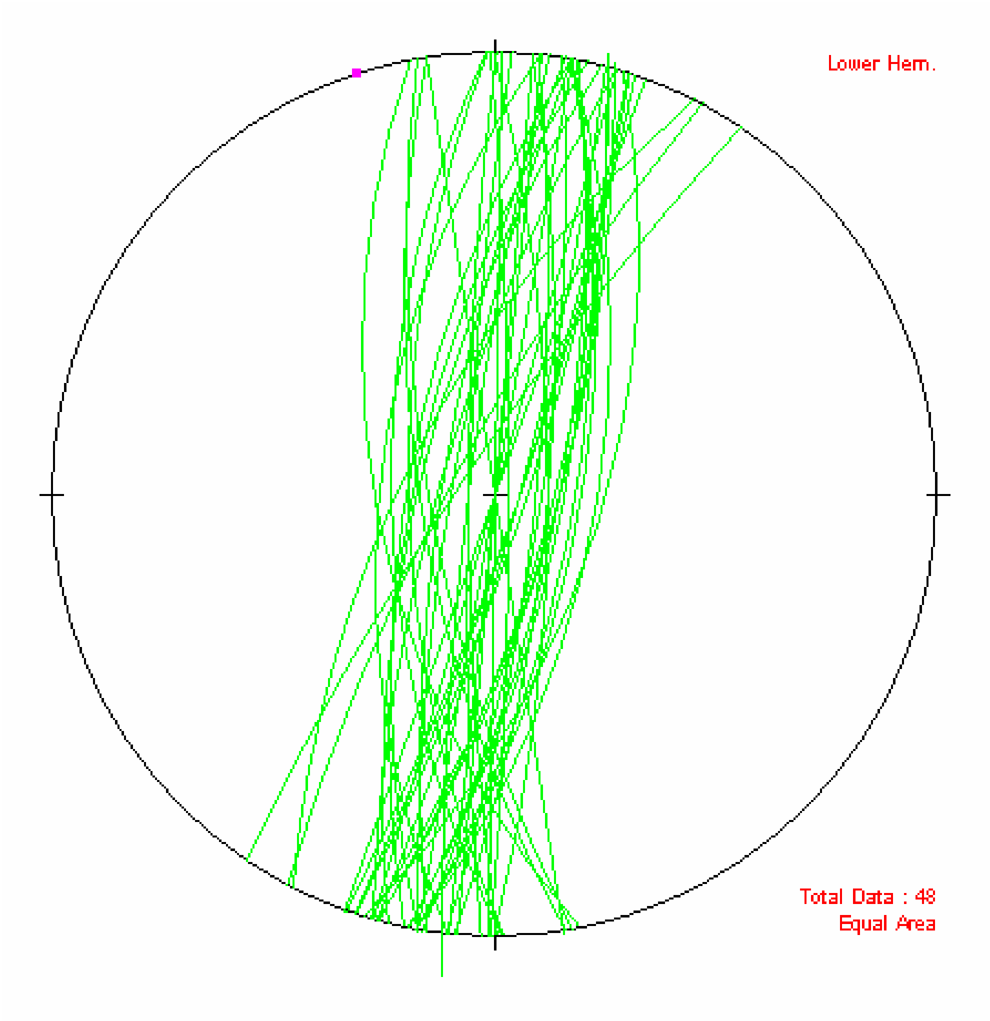
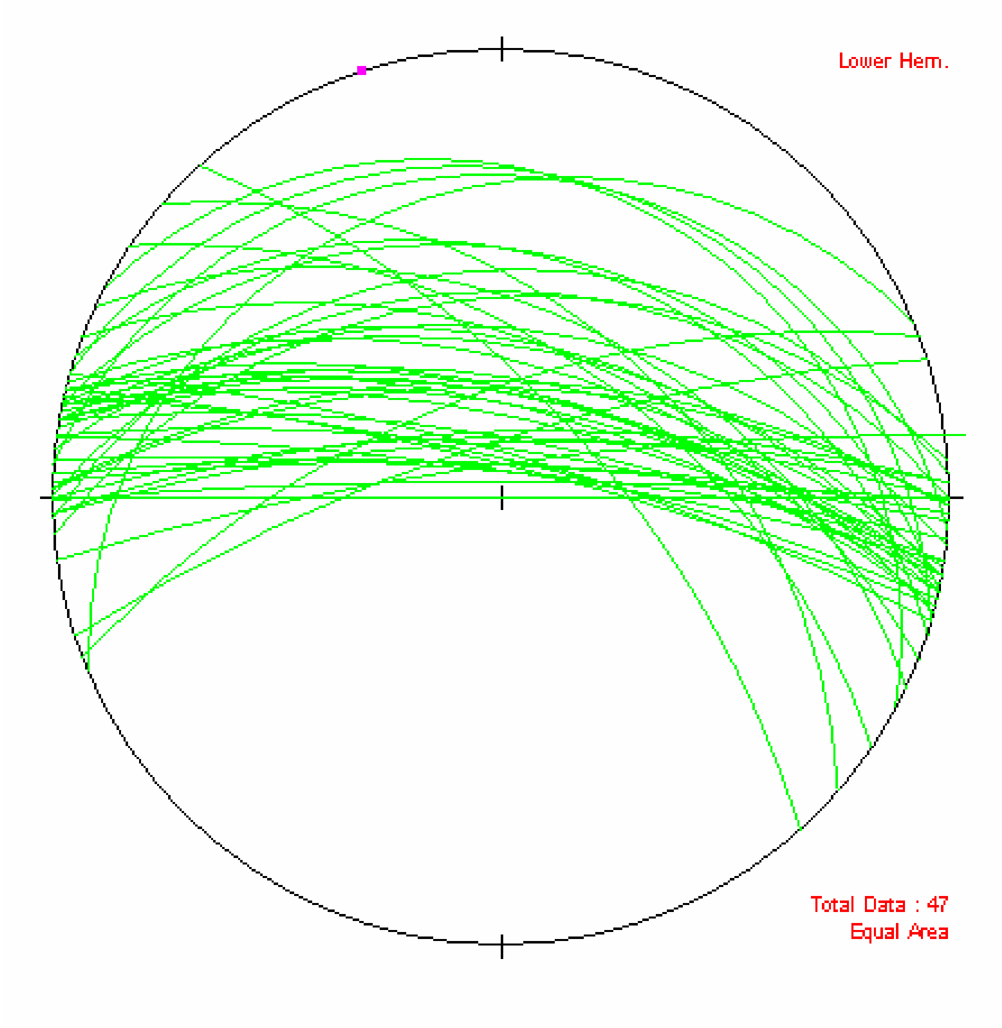


Figure 4.7



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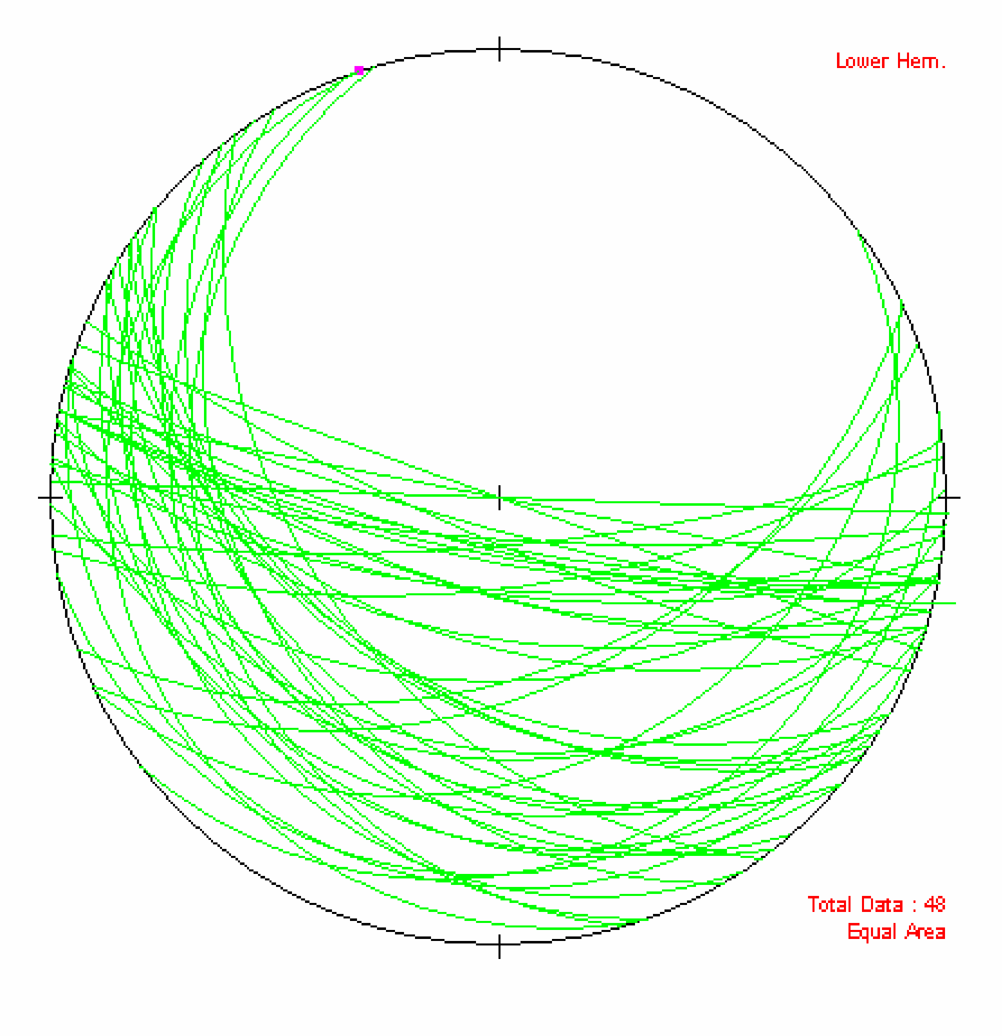

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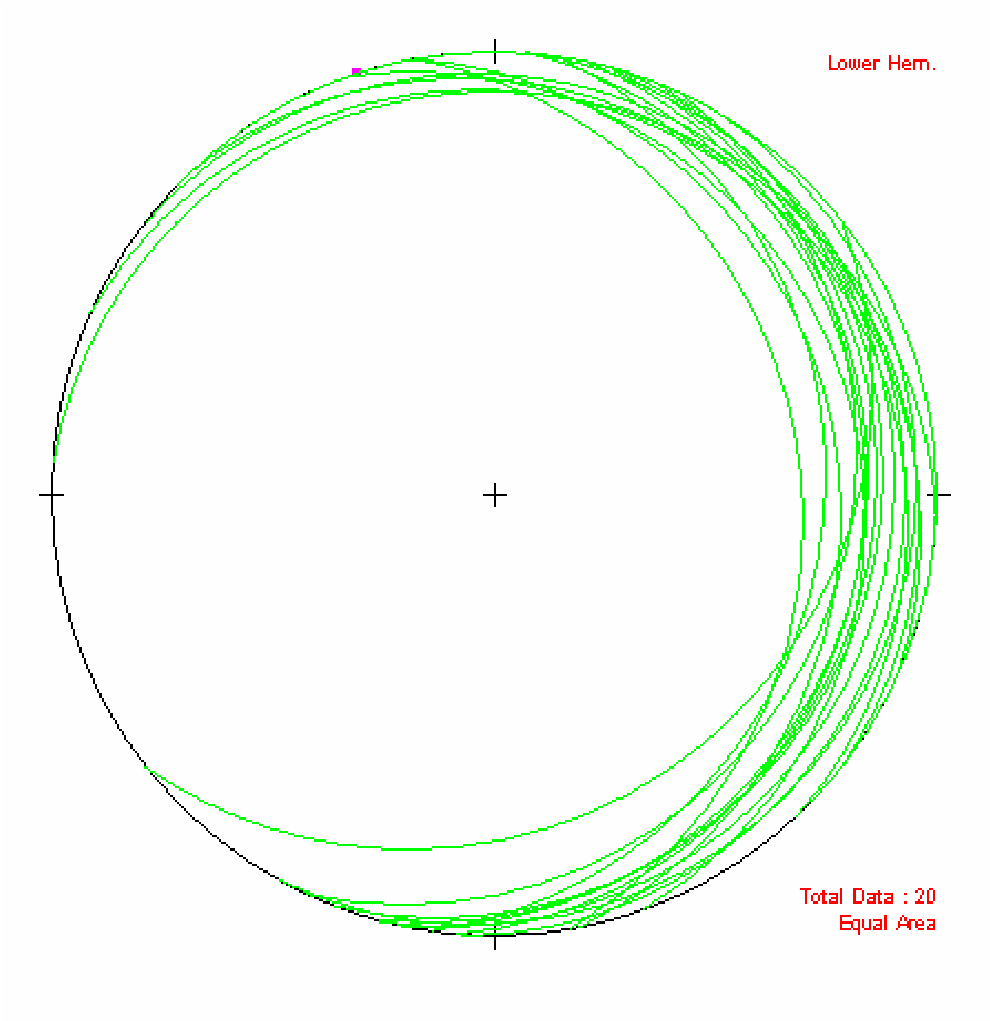


Figure 4.10

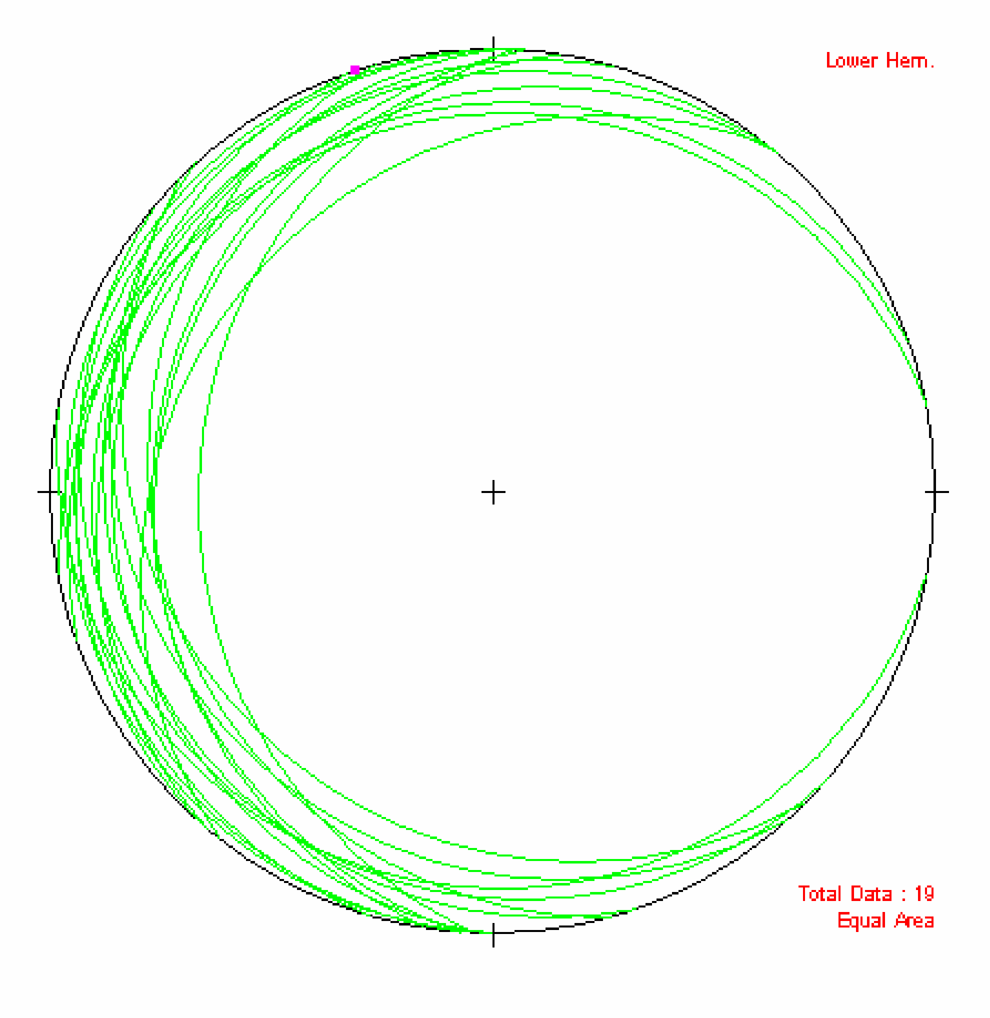
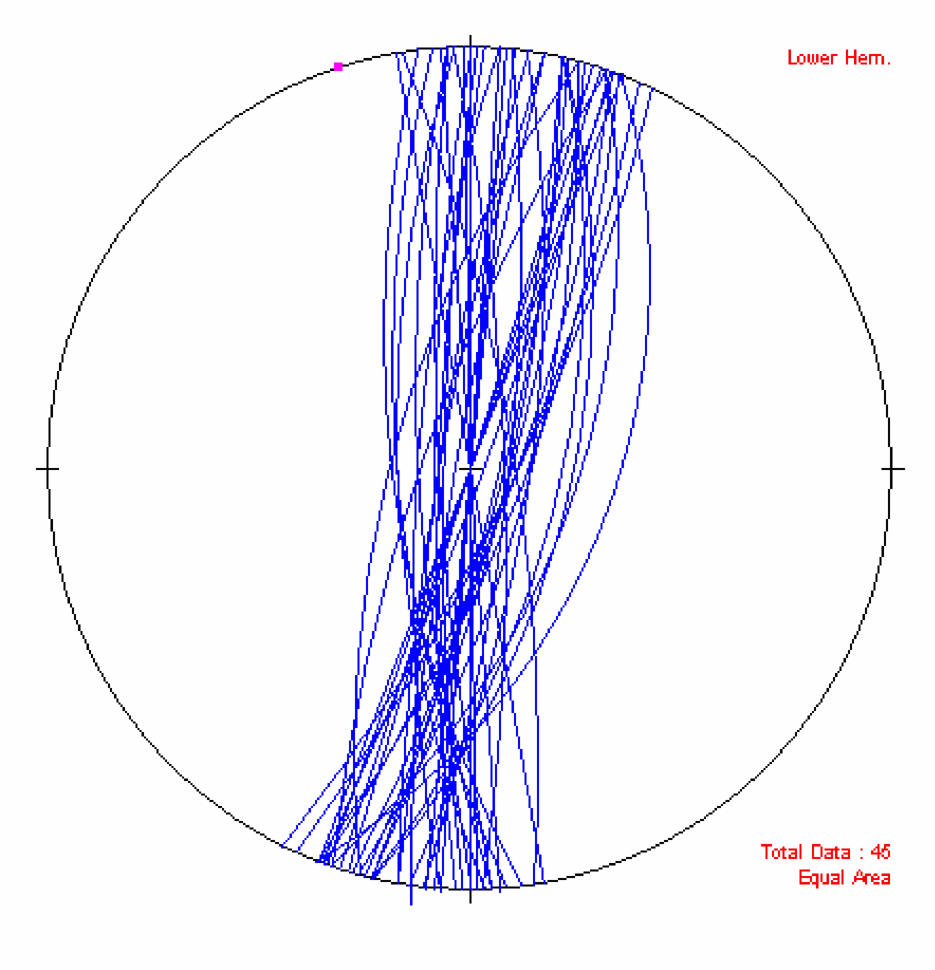


Figure 4.11



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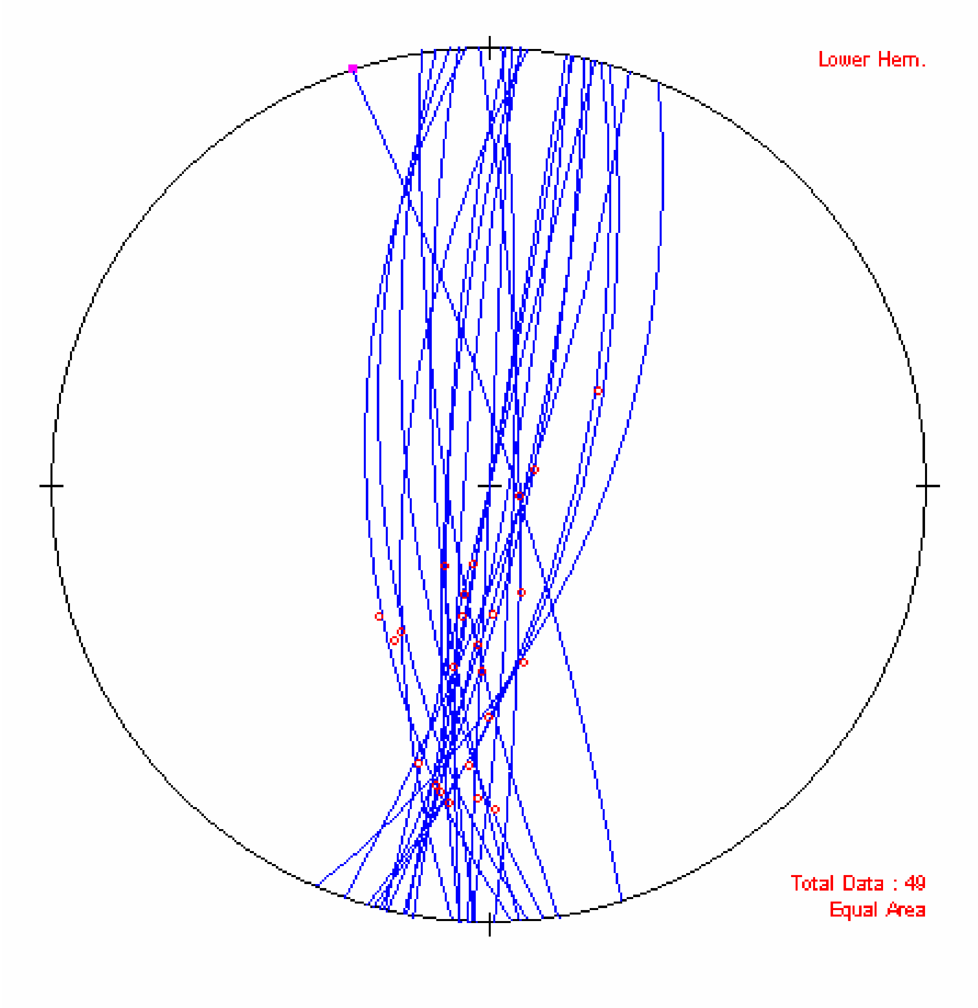

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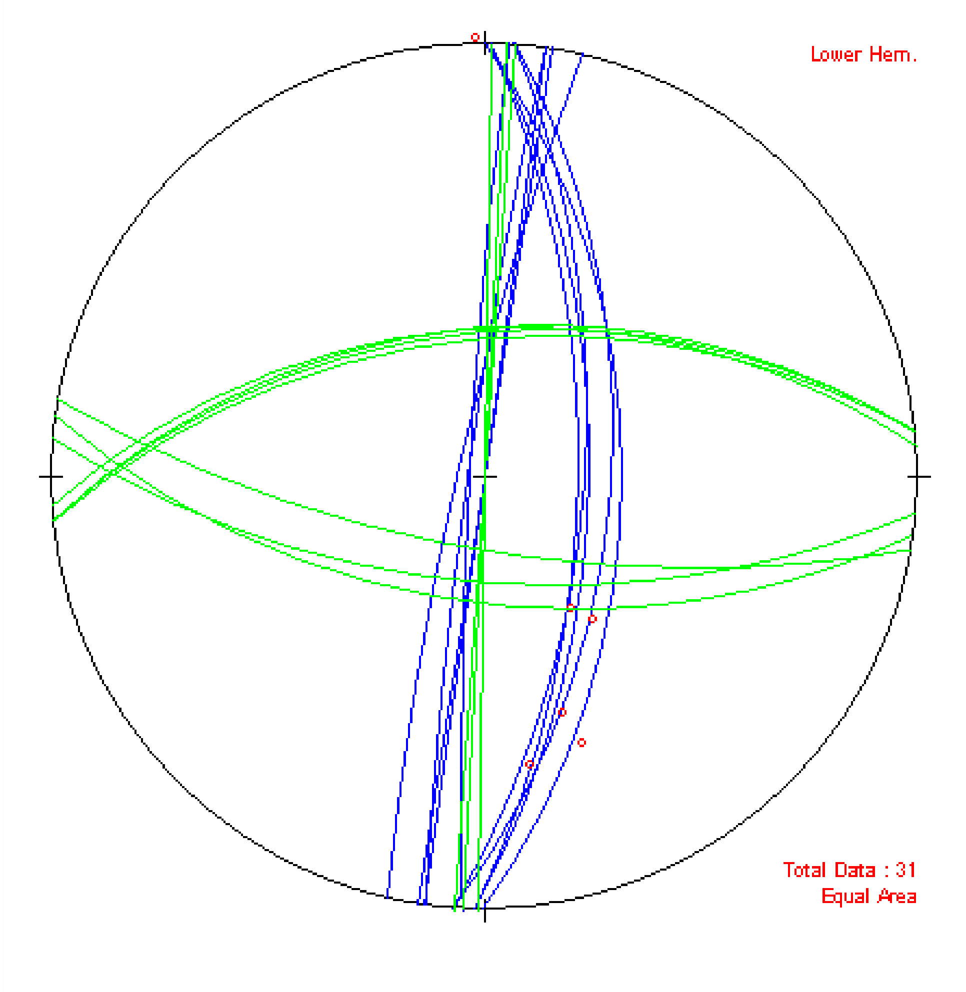

Figure 4.14

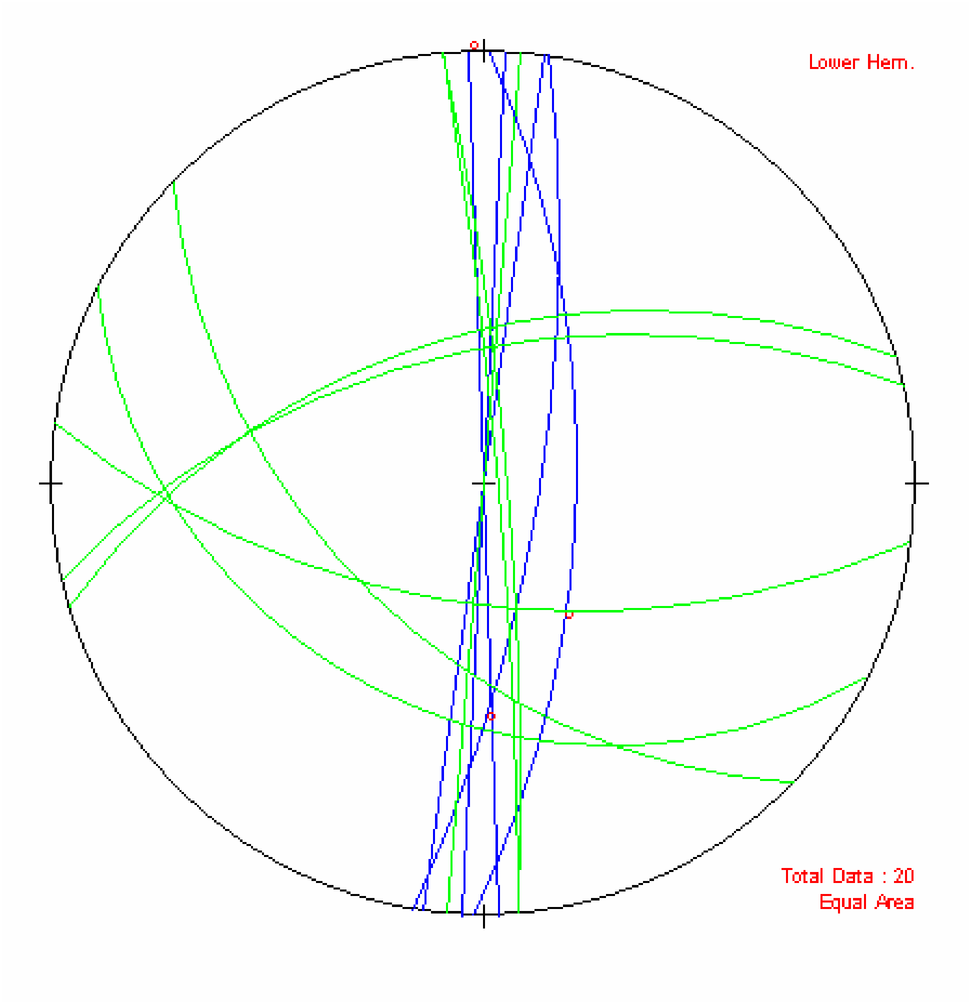

Table 4.1

Structure		Test Outcrop Data		Measured Study Area Variability
		Repeatability Error	Structure Variability	
Vertical Joint Set		(Degrees)	(Degrees)	(Degrees)
	Strike	2	0	28
	Dip	1	1	7
Upriver Joint Set				
	Strike	1	3	14
	Dip	1	2	17
Downriver Joint Set				
	Strike	3	18	25
	Dip	5	11	23
Gentle East Joint Set		used upriver data for gently dipping sets		
	Strike	1	3	38
	Dip	1	2	8
Gentle West Joint Set				
	Strike	1	3	42
	Dip	1	2	8
Foliation				
	Strike	4	2	10
	Dip	2	5	7
Lineation				
	Trend	11	22	18
	Plunge	12	11	41

Figure 6.1

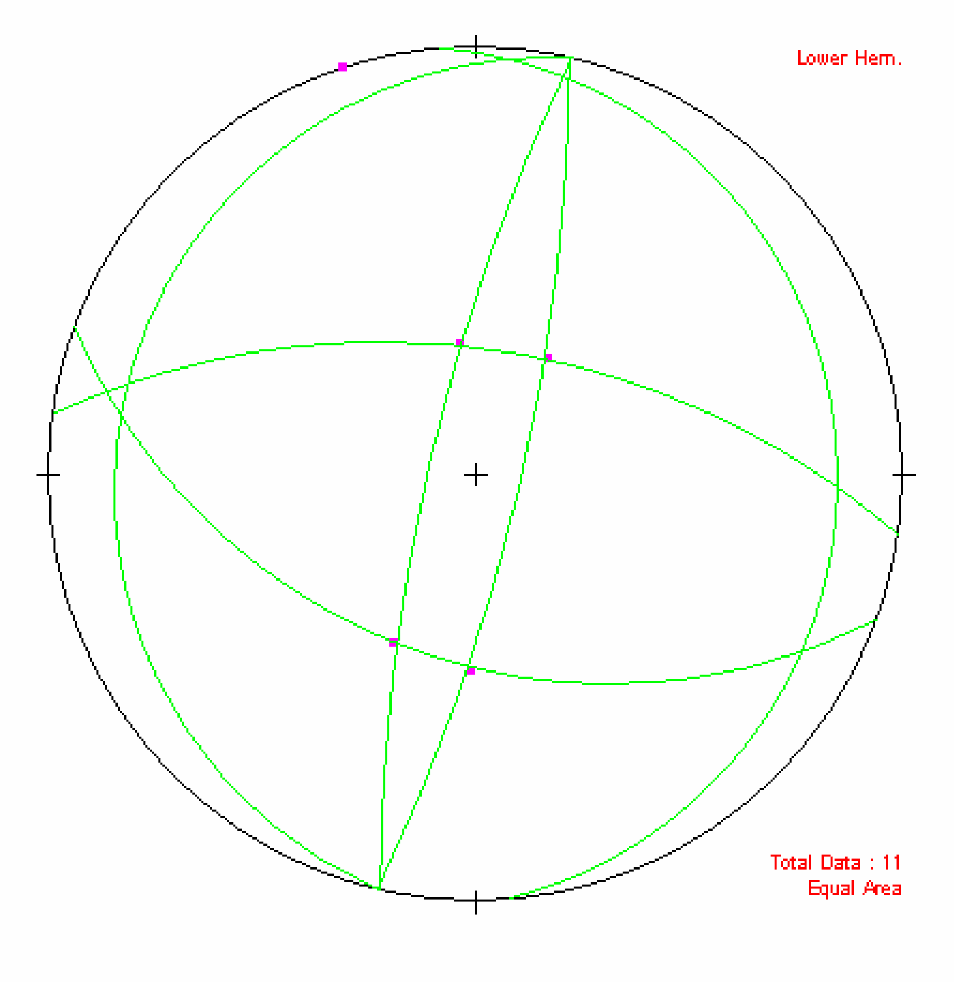

Figure 6.2

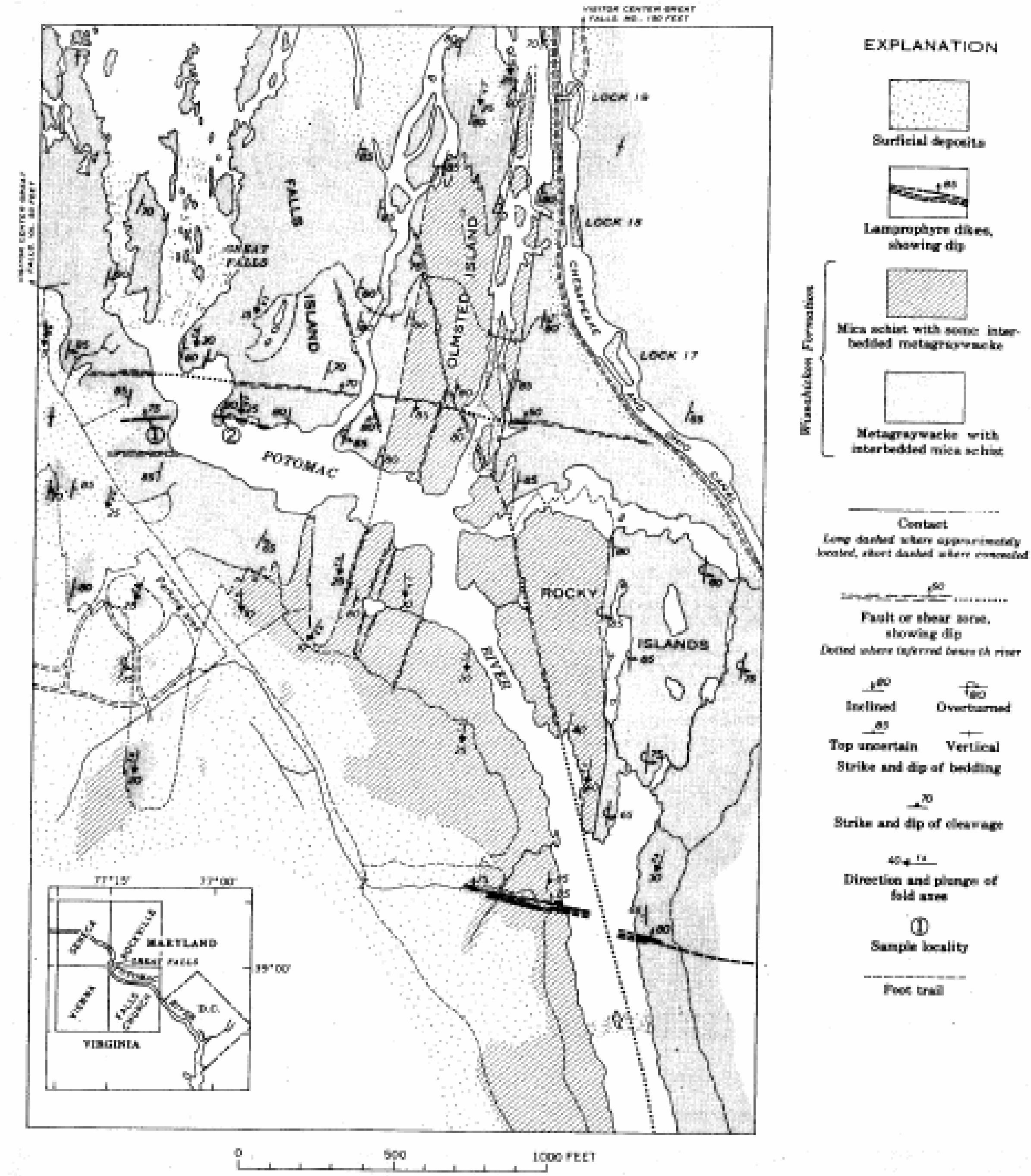
EXPLANATION
Surficial deposits
Lamprophyre dikes, showing dip
Wissahickon Formation
Mica schist with some interbedded metagraywacke
Metagraywacke with interbedded mica schist
Contact
Fault or shear zone, showing dip
Inclined
Overturned
Top uncertain
Vertical
Strike and dip of bedding
Strike and dip of cleavage
Direction and plunge of fold axes
Sample locality
Foot trail
LOCK 19
LOCK 18
LOCK 17
GREAT FALLS
FALLS ISLAND
OLMSTED ISLAND
POTOMAC
RIVER
ROCKY ISLANDS
MARYLAND
VIRGINIA
D.C.
0
500
1000 FEET

Figure 6.3

Figure 6.4

Figure 6.5

Appendix A – Nearly Vertical Dipping Joint Set Data

Strike (degrees)	Modified Strike (degrees)		Dip (degrees)
10	10		74
11	11		78
10	10		71
15	15		79
17	17		70
16	16		78
11	11		77
10	10		82
9	9		80
2	2		85
1	1		90
196	16		80
180	0		80
19	19		85
12	12		75
194	14		76
359	-1		71
16	16		90
15	15		85
10	10		74
351	-9		76
0	0		85
27	27		74
190	10		90
10	10		90
15	15		78
20	20		89
18	18		85
198	18		84
10	10		90
190	10		90
6	6		88
180	0		87
169	-11		68
9	9		81
170	-10		78
5	5		90
359	-1		74
7	7		85
214	34		84
186	6		69
10	10		88
5	5		80
190	190		75
171	-9		90
28	28		82
6	6		82
Mean Strike	**13**	**Mean Dip**	**81**
SD of Strike	**28**	**SD of Dip**	**7**

Appendix B – Moderately North Dipping Joint Set Data

Strike (degrees)	Modified Strike (degrees)		Dip (degrees)
281	281		71
282	282		70
279	279		68
280	280		71
272	272		84
282	282		75
270	270		52
282	282		44
282	282		61
291	291		61
280	280		79
94	274		29
104	284		73
270	270		79
88	268		80
88	268		78
265	265		53
105	285		65
100	280		62
98	275		81
96	276		59
280	280		73
69	249		71
104	284		70
131	311		55
286	286		82
91	271		69
72	252		80
90	270		87
108	288		45
247	247		32
82	262		84
283	283		83
124	304		62
106	286		28
295	295		55
104	284		84
275	275		85
318	318		72
298	298		29
91	271		70
278	278		85
270	270		90
267	267		48
247	247		32
93	273		84
Mean Strike	**278**	**Mean Dip**	**66**
SD of Strike	**14**	**SD of Dip**	**17**

Appendix C – Moderately South Dipping Joint Set Data

Strike (degrees)	Modified Strike (degrees)		Dip (degrees)
310	310		44
287	287		31
324	324		54
330	330		41
287	287		63
310	310		28
322	322		42
341	341		29
342	342		14
94	274		41
280	280		43
302	302		52
299	299		54
327	327		23
288	288		14
80	260		17
121	301		26
285	285		84
85	265		81
284	284		80
101	281		81
83	263		73
281	281		78
95	275		73
293	293		82
299	299		37
293	293		82
299	299		37
306	306		54
344	344		33
280	280		64
98	278		72
110	290		90
92	272		89
304	304		53
125	305		38
139	319		36
105	285		72
245	245		54
274	274		82
281	281		88
70	250		57
53	233		20
101	281		79
107	287		72
89	269		56
64	244		38
Mean Strike	**290**	**Mean Dip**	**54**
SD of Strike	**25**	**SD of Dip**	**23**

Appendix D – Gently East Dipping Joint Set Data

Strike (degrees)	Modified Strike (degrees)		Dip (degrees)
15	195		15
5	185		17
8	188		26
12	192		17
308	128		7
340	160		18
195	195		11
25	205		21
114	114		10
209	209		6
317	137		10
349	169		23
350	170		31
201	201		14
274	94		10
4	184		8
232	232		27
134	134		0
232	232		27
Mean Strike	**175 (or 355)**	**Mean Dip**	**16**
SD of Strike	**38**	**SD Dip**	**8**

Appendix E – Gently West Dipping Joint Set Data

Strike (degrees)	Modified Strike (degrees)		Dip (degrees)
250	250		14
1	181		15
345	165		24
130	130		11
38	218		28
180	180		4
101	281		11
318	138		20
220	220		9
184	184		24
196	196		11
220	220		15
259	259		16
184	184		6
3	183		34
189	189		25
315	135		25
161	161		14
Mean Strike	**193 (or 13)**	**Mean Dip**	**17**
SD of Strike	**42**	**SD of Dip**	**8**

Appendix F – Foliation Data

Strike	Mod Strike		Dip
0	0		90
4	4		80
14	14		83
1	1		85
10	10		87
8	8		84
356	-4		89
359	-1		90
173	-7		75
8	8		78
20	20		81
199	19		81
10	10		84
355	-5		76
20	20		90
350	-10		90
6	6		82
21	21		90
18	18		90
171	-9		81
186	6		90
204	24		81
20	20		87
184	4		90
357	-3		84
358	-2		83
13	13		84
26	26		81
177	-3		80
185	5		90
15	15		78
5	5		90
13	13		70
2	2		84
0	0		83
358	-2		76
15	15		75
13	13		72
21	21		79
16	16		82
17	17		90
19	19		69
13	13		82
21	21		62
Mean Strike	**9**	**Mean Dip**	**82**
SD of Strike	**10**	**SD of Dip**	**7**

Appendix G – Lineation Data

	Trend (degrees)		Plunge (degrees)
	180		46
	49		63
	71		81
	163		69
	187		28
	189		30
	179		27
	182		55
	191		65
	182		29
	194		35
	178		66
	184		36
	190		31
	111		84
	220		58
	169		56
	191		75
	211		56
	191		55
	184		60
	192		69
	209		73
	211		58
Avg. Trend	**175**	**Avg. Plunge**	**54**
SD of Trend	**41**	**SD of Plunge**	**18**

Appendix H – Test Outcrop Repeatability Data

Joint Set - North Dipping			
	Strike		**Dip**
	264		64
	266		62
	264		63
	264		63
	264		62
Mean Strike	**264**	**Mean Dip**	**63**
SD of Strike	**1**	**SD of Dip**	**1**

Joint Set - Vertical			
	Strike		**Dip**
	3		90
	1		88
	4		89
Mean Strike	**3**	**Mean Dip**	**89**
SD of Strike	**2**	**SD of Dip**	**1**

Joint Set - South Dipping			
	Strike		**Dip**
	275		70
	280		76
	278		66
Mean Strike	**278**	**Mean Dip**	**71**
SD of Strike	**3**	**SD of Dip**	**5**

Foliations			
	Strike		**Dip**
	9		90
	8		88
	13		85
	8		87
	3		87
Mean Strike	**8**	**Mean Dip**	**87**
SD of Strike	**4**	**SD of Dip**	**2**

Lineations	**Strike**		**Dip**	**Rake**		**Trend**		**Plunge**
	4		66	115		143		56
	0		64	140		160		35
	4		71	145		171		33
	1		72	115		147		60
	1		70	135		162		42
Mean Strike	**2**	**Mean Dip**	**69**		**Mean Trend**	**157**	**Mean Plunge**	**45**
SD of Strike	**2**	**SD of Dip**	**3**		**SD of Trend**	**11**	**SD of Plunge**	**12**

Appendix I – Test Outcrop Variability Data

Joint Set - South Dipping			
	Strike		**Dip**
	278		67
	314		60
	297		45
Mean Strike	**296**	**Mean Dip**	**57**
SD of Strike	**18**	**SD of Dip**	**11**

Joint Set - Vertical			
	Strike		**Dip**
	175		87
	175		85
Mean Strike	**175**	**Mean Dip**	**86**
SD of Strike	**0**	**SD of Dip**	**1**

Joint Set - North Dipping			
	Strike		**Dip**
	73		62
	77		65
Mean Strike	**75**	**Mean Dip**	**64**
SD of Strike	**3**	**SD of Dip**	**2**

Foliations			
	Strike		**Dip**
	8		90
	9		79
	3		90
	5		90
	5		90
Mean Strike	**6**	**Mean Dip**	**88**
SD of Strike	**2**	**SD of Dip**	**5**

Lineations	**Strike**		**Dip**		**Rake from N**		**Trend**		**Plunge**
	-2		90		135		178		45
	1		72		115		147		60
Mean Strike	**-1**	**Mean Dip**	**81**	**Mean Rake**	**125**	**Avg Trend**	**163**	**Avg Plunge**	**53**
SD of Strike	**2**	**SD of Dip**	**13**	**SD OF Rake**	**14**	**SD of Trend**	**22**	**SD of Plunge**	**11**