Investigation of Fault Control at Mather Gorge and Petrographic Analysis of Lamprophyre Dikes

Casey Soneira
Advisor: Dr. Aaron Martin
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Abstract

Mather Gorge is a deeply incised, very straight reach of the Potomac River. Runoff and groundwater en route to the Atlantic Ocean flow through the gorge between its steep, schistose cliff walls that have been eroding for thirty-five thousand years. Five lamprophyre dikes intrude the Mather Gorge formation, and four of these outcrop within the gorge. The latter four dikes show ~25 meters of dextral offset, which is speculated by others including Reed et al. (1970) to be the cause of slip on a strike-slip fault trending through Mather Gorge. The primary objective of this paper was to measure the dikes to determine whether they are tabular slabs or curved bodies with variable thickness. Offset of tabular dikes suggests slip on a fault, whereas no fault is needed to explain apparent offset of irregularly shaped dikes. It was found that the dikes are not tabular, and that they infill the joint set (average orientation 102°/76°±2°NE) with a moderate degree of variability, resulting in their non-uniform appearance from one side of the river to the other. This conclusion leads to the exclusion of the lamprophyre dikes as indicators of offset. In spite of the convenience of the dikes as offset indicators, the Rocky Islands to the north are places where a fault should have left indications of movement. Upon inspection of these islands there was no fracture that matched the alignment of the gorge well enough to explain its straight trend.

To better understand the internal behavior of the dikes themselves, a petrographic and microstructural analysis is needed. Nine thin sections were analyzed using a petrographic microscope. It was found that there are at least two generations of biotite defined principally by differences in size (specifically aspect ratio) and extent of alteration. Samples from the first generation mineral separates could be dated and contribute to the igneous history of the region. For example, using dates in conjunction with other information, crystallization or denudation rates can be calculated. These new data could be applied to other instances where lamprophyre material has a major role in a discovery, for example the dike swarms associated with the Acadian Orogeny.

Introduction

The ability of water to incise a channel through bedrock has yielded spectacular geological features across the planet. The goosenecks of the San Juan River in Utah feature a deeply incised, narrow meander (fig. 1). In contrast, the Channeled Scablands in eastern Washington are characterized by much wider, deep gorges incised into basaltic bedrock from massive periodic glacial floods (fig. 2). Just west of Washington, D.C., the Potomac River deeply and narrowly incises schistose bedrock of the Mather Gorge Formation to create Mather Gorge (fig. 3). The power of water carved these striking features, but what caused the river to incise a narrow path in one case and a broad path in others? This paper aims to help answer that question, and in so doing, contribute to the more over-arching question of how rivers evolve.

The Potomac River is the second largest tributary to the Chesapeake Bay, trailing only the Susquehanna River. The Potomac is a natural resource, tourist attraction, tool of commerce, and a subject of interest for many scientific studies, especially in the realms of biology, hydrology, and geology. It boasts two national parks: Great Falls National Park in Virginia and Chesapeake and Ohio Canal (C&O Canal) National Historical Park in Maryland. Meandering southeast through the Valley and Ridge, Blue Ridge, Piedmont, and Coastal Plain terrains, the Potomac defines the boundary between Virginia and

Maryland, and the southern boundary of Washington, D.C. (www.nps.gov). The transition from durable Piedmont metasedimentary and igneous rock to weaker Coastal Plain sedimentary rock causes Atlantic-bound rivers and streams to experience falls or rapids (Schmidt, 1993). By connecting the eastern-most rapids of each river that crosses the transition, the "fall line" is defined (fig. 4). European settlers traveling by boat experienced their first set of major rapids in the fall zone and had to stop. This is how many major cities on the east coast came to be located at the terrain transition, and Washington, D.C. is no exception (Schmidt, 1993). As the power of the water causes the stream channel to erode and falls to migrate upstream, the fall line turns into a more appropriately named "fall zone."

Comprising a drop of 15 meters across a distance of about 150 meters, Great Falls marks the present day fall zone for the Potomac River, having migrated upstream over the course of about thirty thousand years (Bierman et al., 2004; Reusser, 2002). Just downstream of the falls, the Potomac flows through Mather Gorge (fig. 5). The gorge is very deeply incised as much as 21 meters to the submerged floor, (Bierman et al., 2004). It is also uncharacteristically straight with respect to the rest of the Potomac. The walls of the gorge display some of the best views of the geology that the river has to offer (fig. 6). Nested within steeply dipping joint sets of highly metamorphosed schist, lamprophyre dikes are visible on both sides of the river. According to Bierman et al., (2004), these dikes show dextral offset across the river of 25 meters, which many believe is due to a fault trending parallel to and located within Mather Gorge (Gilbert, 1905; Reed, 1980; Schmidt, 1993; Southworth et al., 2002; Bierman et al., 2004

Water coursing through the Potomac incised the gorge channel, but what caused the river to incise? Bedrock incision is influenced by hydrologic events and channel sensitivity (Whipple et al., 2000). For example, channel walls comprised of sediments or weak rocks respond more dramatically to the forces of weathering. Reusser et al. (2004) offers the effects of glacial melt beginning 37 thousand years ago during the Pleistocene ice ages, as the source of excess water. The incision rate of a rock terrace about midway up the gorge wall was calculated to be 0.8m/kyr, but a sample collected from a terrace just above the gorge yields a much slower rate of incision (using model ^{10}Be ages), which suggests that the course of the Potomac had already been determined (Reusser et al., 2004). In an earlier paper, Reusser (2002) claims that incision was coincident with a major drop in eustatic sea level as water was frozen into glaciers. Both a base level decrease and increased discharge are contributing factors to enhanced river incision (Hetzel et al., 2006), so it is quite likely that fluctuating and periodic glacial cycles in the Pleistocene were the primary sources of incision energy. In a recent study investigating the effects of erosive energy on knickpoint migration in the Appalachians, it was found that the energy causes abrasion, plucking, and pothole formation which contributes to the upstream retreat and vertical down-wearing of said knickpoint (Frankel et al., 2007). But how was the incision path determined?

The main objective of this study is to find an answer to the above question through the quantitative analysis of the aforementioned dikes, as the diagnostic feature of offset by a fault. Incision and pathway control at Mather Gorge could be explained by the presence of a fault. By studying the dikes' large-scale three-dimensional characteristics, as well as their petrology and microstructure, a better understanding of the processes that control channel shape and incision are gained. More specifically, this study will contribute to the hydraulic and lithologic histories of Great Falls and the C&O Canal National Parks.

It should be noted that the presence or absence of offset on the dikes does not necessarily implicate a fault as the controlling factor of the trend of Mather Gorge. A strike-slip fault through the gorge is the simple explanation for the deep, narrow incision; however, there are several more complicated reasons that have been recognized.

Geologic Setting

The Appalachian Piedmont consists of three fault-bounded domains. From west to east they are the Westminster, Potomac, and Baltimore terrains, as defined by Kunk et al., 2004. The Pleasant Grove Fault separates the Westminster and Potomac terranes; the fault trends to the northeast with dextral strike-slip motion (Kunk et al., 2004) (fig. 7). The Potomac terrane is further divided into three metasedimentary units, which are also distinguished by faults: the Mather Gorge, Sykesville, and Laurel Formations (fig. 7) (Kunk et al., 2004; Kunk et al., 2005). The Mather Gorge Formation consists of highly metamorphosed granofelsic metagraywackes and quartz-mica schists. There is a chlorite to sillimanite-grade Barrovian sequence near Great Falls, with migmatitic rocks in a one kilometer wide belt at the falls (Kunk et al., 2005).

The Mather Gorge Formation can be further subdivided into three more domains. From west to east, they are Blockhouse Point, Bear Island, and Stubblefield Falls domains (see fig. 7) (Kunk et al., 2004; field trip guide). Mather Gorge lies within the Bear Island domain, and the study area is therefore tentatively limited to it. Rocks characteristic of this domain are Neoproterozoic to early Cambrian well-bedded metagraywackes, migmatite, granodiorite, pegmatite, and the lamprophyre dikes.

The study area is relatively compact, encompassing the area between the four southernmost dikes on either side of the river, to the northernmost dike, found on the Virginia side, just meters south of the falls. The area extends away from the river only as far as the dikes can be traced, a few tens of meters.

Objectives

The objectives of this research apply to numerous levels and realms of geology. Though the study area is physically constrained to a small section of land, it is attempting to contribute to the larger, global questions of how rivers incise bedrock, and the even larger matter of how a river determines its path. Mather Gorge is just one example of how a river eroded rock, but other examples, such as the Goosenecks of the San Juan River in Utah (fig. 1) and the Channeled Scablands in eastern Washington (fig. 2) show the diverse impacts that water can have on the landscape.

A backbone of structural geology is the recognition that a fault may cause features to be offset, if there are observable features available in the rock. It is harder to recognize faulting through texturally and compositionally mature and homogenous sandstone than through a formation with lineations or connectable elements, for example. Conveniently, the Mather Gorge Formation houses approximately five lamprophyre dikes that strike northeast almost perpendicular to the river. The perpendicular position is critical because offset parallel to and between the dikes is not necessarily noticeable. With the exception of the northernmost dike which only outcrops on the Virginia cliff face, the dikes outcrop superbly on both Maryland and Virginia cliff faces. Speculation that the cause of dike offset is due to faulting is completely reasonable; however these features cannot be taken at face value. The nature and configuration of the dikes must be taken into consideration.

I hypothesize that the trend of Mather Gorge is not controlled by a fault. There are multiple explanations as to why there is a projected ~25 meter offset between the Maryland and Virginia sides of the Potomac River (Bierman et al., 2004). One possible explanation that was recognized by Bierman et al. (2004) is that the dikes are not completely tabular features. They may pinch and swell, infilling different fractures and joints. This possibility has huge implications as to whether it is necessary to place a fault through Mather Gorge. The misalignment between the Maryland and Virginia dikes may be due to a dextral jog that the dikes took during intrusion that has subsequently been eroded away by the river (fig. 8b). Another possible reason is due to a region of spreading perpendicular to the trend of the gorge. This spreading may also explain the intrusion of the dikes themselves, although this hypothesis has not been fully explored (Zen, 2006)

The goal of my research is to determine which case best fits the Mather Gorge scenario through careful three-dimensional mapping. The hypothesis that the trend of Mather Gorge is not fault controlled can be falsified if evidence of motion on a fault is found. This evidence includes criteria such as slickensides, deflection of foliation, or offset markers.

Further goals of my research involve petrographic and microstructural analysis of the lamprophyre dikes. This analysis allows me to characterize the intrusion history of the ultramafic material; whether it intruded in one event or if there were multiple injections or a metamorphic overprint from differential stress. Additionally, thin section analysis may provide insight as to why there are magnetic lows at the dike margins. These lows were detected by Reed et al. (1970) as well as myself during field work. I hypothesize that there are multiple generations of biotite growth within the dikes. This can be concluded by crystal analysis in thin section. Multiple generations of biotite might show different growth directions, which may suggest multiple injections or a partial melt and recrystallization. Additionally, thin section analysis may show why the dikes have magnetic lows at their margins.

The information gathered from thin section analysis can be used in later studies to more accurately date the dikes. Although this dating process is not included within the scope of my research, accurate dating of the oldest mineral generation will be useful in further studies of the igneous activity in the area, and in studies involving lamprophyre. If biotite samples are not obtained carefully, more than one generation may be dated, resulting in an average age of all the biotite within the sample rather than the oldest age. Reed et al. (1970) placed age constraints on the lamprophyre using K/Ar techniques, which were determined to be 360±13 Ma, during the mid- to late-Devonian.

Hypotheses

1. The trend of Mather Gorge is not controlled by a fault.
2. There are multiple generations of biotite growth in the lamprophyre dikes at Mather Gorge.

Tests
Hypothesis 1:
a. Map and measure the dikes in the vertical dimension using photographs.
b. Map and measure the dikes on a topographic map.
c. Search for evidence of motion and fault manifestation on the Rocky Islands.
Hypothesis 2:
a. Inspect thin sections for biotite grains oriented in different directions.

Methods

Dike Analysis

In order to determine how tabular the dikes are, all of the dikes on both sides of the river were mapped in three dimensions using topographic maps (fig. 9) and photos (fig. 10 and fig. 11).

1. Horizontal Extent

Mapping the dikes on a 2- to 5-foot contour interval topographic map provides the comprehensive location data needed to interpret the regional structure. If the dikes on both sides of the Potomac are consistently spaced from one another and follow a straight path away from the river, a fault would be a valid explanation for their offset (fig. 8a). Conversely, dikes that pinch and swell in the measured dimensions will show up as non-linear features on the map, not necessarily holding a fault responsible for their offset (fig. 8b).

Methods employed to map the dikes include detecting recessions in joints, followed by identification of lamprophyre material within that recession. Once positively identified, the width and orientation are measured at various points along the recession, using a tape measure and Brunton compass (adjusted for declination at approximately 11.5°W), respectively (appendix A).

Human development along the river, seasonal changes, and normal weathering processes make the identification of the total extent of a dike a challenge, especially because the dikes weather recessively compared to the schist wall rock. Dike mapping in the heavily wooded, highly weathered terrain is propelled by observation-based predictions which are not necessarily correct all of the time. Because of this complexity of finding dikes to map, a proton precession magnetometer[1] was used to locate dikes where they do not outcrop. Although preliminary field work with this instrument was

[1] The magnetometer functions using decane, a high proton concentration fluid, to measure the magnetic field difference between the Earth and the area or material being tested. Lamprophyre is an ultramafic, ultrapotassic rock characterized by porphyroblasts which may be feldspar or biotite. The magnetometer is calibrated for the magnetic field of the region which is approximately fifty-four thousand gammas, or 0.54 Gauss (using the conversion of $1\gamma=10^{-5}$ Gauss). When taking a reading, the protons in the decane briefly align themselves with the magnetic field of the mineral. This field difference is detected by a metal coil which then calculates the vector difference between the magnetic field of the Earth and that of the mineral, which is displayed in quantum units, gamma. These units can be converted to Gauss, Oersted, Webers/m^2, or Tesla for ease of analysis.

ineffective, further trips to the field and refining the methodology resulted in better data (appendix B).

Initially the sensor head was about three meters off the ground and unable to detect the differences in magnetic field over the small range that I was attempting to detect. After several trials with the head at different heights, I was able to resolve significant differences in magnetic field when the head was attached to a one-meter pole, held upside-down, and hovering immediately above the dike (not more than a few centimeters). These low magnetic readings were identified only in certain locations. That is, while the lows were resolvable, they were only resolvable when the sensor head was positioned exactly above the lamprophyre in question. Unfortunately this position could only be roughly approximated. For example, sometimes the sensor would be positioned over a dike margin and would give a low reading, other times it would give a high reading. A source of these conflicting readings may have been due to the sensor's proximity to the wall rock when the reading was taken. Although the magnetometer based work produced somewhat inconsistent data, the data that it did produce was useful in constraining the horizontal character and extent of the dikes at specific locations.

<u>2. Vertical Character and Width</u>

The dike outcrops in the vertical dimension is more elaborate than large-scale photos may suggest. At least two scales of photos, as seen in figures 10 and 11, are needed to accurately capture the intricacies of the dikes as they outcrop on the cliff faces of Mather Gorge. The best way to evaluate and obtain photos of the outcrops on the cliff faces is to examine them close up; it can be difficult to differentiate between schist and muddy lamprophyre without looking at a fresh surface. During the summer when the discharge is at its lowest, the Virginia cliff face is accessible by walking next to the river, along a narrow patch of exposed beach. When discharge rates are higher, the only ways to safely access the Virginia dikes is to rappel from over the cliff or paddle in a kayak or other aquatic conveyance. The cliffs on the Maryland side of Mather Gorge are decidedly less steep; however, the lower reaches of them are also inaccessible during periods of moderately high discharge. These seasonal changes restrict the vertical scope of research to the topographically higher areas during much of the year.

The tools used for orientation and width measurements were the Brunton compass and the tape measure, respectively. Measurements of width on each of the dikes were taken at several points along each vertical surface accessible by safe climbing (appendix A). In some cases the width of the dike was difficult to discern due to weathering differences that produced variability of the boundary. That is, the dike-wall rock boundary was weathered to the extent that discerning a boundary was sometimes a challenge in itself. From topographic top to bottom, the dikes show a variation in thickness on the order of tens of centimeters.

The vertical dike characteristics are important for more than just getting a better idea of what pinches and swells; they may additionally illustrate the subsurface behavior of a dike that also outcrops on a terrace. For example, a dike which forks into two arms may appear at the surface as two separate dikes (fig. 12).

Locating a Fault

The Rocky Islands to the north of the gorge are geographically relevant candidates for the extension of a fault through the gorge onto land. Bierman et al. (2004) points out that a fault trending through Mather Gorge would manifest itself somewhere on the Rocky Islands, directly northeast of the gorge. I searched for signs of a fault that may have passed through the jointed cliffs of the Islands (fig. 13). Indications of a strike-slip fault include slickensides and slickenlines, fault breccias, deflection of foliation, and offset markers. Alone, these indicators reflect movement; however, their presence in alignment with the gorge could implicate a fault striking through the gorge. This alignment was another necessary criterion for fault location. Although the presence of indicators on the Islands may reflect movement, they would not necessarily point to a fault trending through Mather Gorge.

Thin Section Analysis

Fist size samples of lamprophyre dike material were taken from Great Falls and C&O Canal State Parks with written permission of the National Park Service (appendix D). The orientation of the samples was measured and recorded on the in situ specimen and carefully preserved. Using this information along with the relative position of the sample within the dike (which side was up and which was down) I cut oriented billets for thin section. The thin sections show a slice of the rock oriented to show which way is up. This orientation makes spatial analysis much easier because direction can be considered. Orientation is useful for comparing potential metamorphic features within the lamprophyre to the substantial amount of metamorphism in the surrounding wall rocks. If the two types of rock show strain in the same planes, it is possible that they bore stress from the same event or events. From these oriented thin sections, I will be able to study the microstructures and petrology of the lamprophyre material, identify generations of biotite, and compare signs of strain to schist wall rock.

Observations

Dike Analysis

1. Horizontal Extent

The horizontal extents of the dikes were traced using visual cues from recessive weathering and a magnetometer. The dikes on each side of the river were investigated on separate days due to the time constraint logistics involved with driving.

Beginning at the top of the Maryland side cliff face and walking east toward the C&O Canal, I was first able to find the magnetic low of the dike margin. This low is detectable when the magnetometer's sensor head is pointed north and a reading is taken above a margin that is only mildly buried. These data were used to compile a topographic map with the dikes mapped with as much detail as possible (fig. 14a). As seen in the map of the Maryland side (fig. 14b), even using such a sophisticated piece of equipment, I was still only able to map the dikes at a minimal level. The clearest evidence for non-tabular dikes on the Maryland side is shown through photographic evidence from the cliff face and discussed in the next section.

Moving across the river to the Virginia side cliff face, four distinct dikes strike nearly due east and dip steeply to the northeast. Standing at the top of the cliff, the dikes are more difficult to trace due to the foliage and weathering of the surface. At the cliff-surface interface the dikes are easily visible, but moving farther inland, away from the river just a few meters, renders the dikes nearly undetectable. Walking inland along the developed path and across the pedestrian bridge, five dikes outcrop along a channel carved by a small tributary. These dikes, too, mainly outcrop in the vertical dimension; however they provide landmarks to that are useful for mapping.

Using the cliff face outcrops and the tributary outcrops as guides, I used the magnetometer to detect lamprophyre material between the two, where it was not visible. Like on the Maryland side, this method provided results some of the time, but it was hard to get consistent readings due to the proximity of other rocks, buried lamprophyre, and limited range for which there was a magnetic variation. The latter is the main reason that the magnetometer was such a challenge to use; only the dike margins have a detectable magnetic difference compared to the wall rock, which means that I had to hold the magnetometer directly over a dike margin that was not heavily covered in sediment in order to confirm the presence of lamprophyre. I was able to trace short lengths of the dikes far enough to characterize them as straight or bent. One of the bending dikes, the fifth from the north, changes direction from trending southeast/northwest to trending almost due north. This dike is seen in figure 15.

The topographic map (fig. 14a) and close ups of the Virginia and Maryland sides (figs. 14b and 14c) show that the dikes are not tabular in the extent of a map view. Although the dikes certainly infill the same joint set, they clearly do not infill the same joint as they outcrop away from the river on both sides. With these data I can conclude that the dikes are not tabular in the horizontal, or map view, dimension.

2. <u>Vertical Character and Width</u>

Using photographs and observations from the cliff faces and the small tributary outcrops, along with the map, the character of the dike set is clearer. Perhaps the most convincing evidence for non-tabular dikes comes from the photographic evidence of the cliff faces (figs. 10 and 16).

Comparing the photograph of the Maryland side to the photo from the Virginia side, a first order observation can be made that the sides do not match. That is, if the two sides of the river were to be put back together, the dikes would not have a corresponding counterpart on the other side. The nearly straight, vertical dikes of the Virginia side and the pinching and swelling dikes of the Maryland side are obviously mismatched. In a close-up picture of a dike on the Maryland side (fig.11), a jog to the right demonstrates how non-tabular they are. That is not to say that the Virginia dikes are tabular and the Maryland ones are not. The distinction is that the Maryland dikes are decidedly less tabular than the Virginia dikes.

On the Virginia side there are three distinct locations where the dikes outcrop vertically. These locations can be seen on the topographic map (fig. 14c) at the cliff face outcrops and the inland dikes. Photos show that these have relatively consistent vertical character (figs. 17 and 18), in contrast with the dikes on the Maryland side which pinch and swell quite drastically as they outcrop up the cliff face. Although the individual dikes outcropping inland have more consistent widths, the widths vary from one dike to another. In figure 17 the three dikes are narrow, but just to the south the dikes in figure 18 are wide with larger spacing between them.

Locating a Fault

I found a linear feature that spanned the length of the western Rocky Island. This feature is of particular interest because it is a long fracture that outcrops for nearly the entire length of the island, in contrast to the many other fractures which taper out, or get truncated by other fractures (fig. 13). The fracture shows evidence of both brittle and ductile motion via a region of possible fault breccia (fig. 19), and possible abrupt change of foliation (fig 20) respectively.

The orientation along this fracture was measured at multiple locations and was determined to be N4°E/81° ±2° NW (fig 21). This orientation is not aligned with Mather Gorge which trends approximately N17°W (fig 22).

Thin Section Analysis

Prior to cutting billets I examined the hand samples for foliation. Several samples showed signs of preferential weathering which led me to believe that they may have foliation, and were cut according to those observations and conventional orientation[2].

I analyzed seven lamprophyre and two schist thin sections for a total of nine samples. The lamprophyre was sampled from five different dikes, two on the Virginia side, three on the Maryland side. There is no distinction between the petrology of the two sides of the Potomac River. However, the lamprophyre thin sections as a group are not entirely identical (appendix C). Although these differences are not immediately apparent, close inspection shows observable differences in grain size, mineral abundance, and level of foliation

The lamprophyre samples (L-02 through L-06) are biotite-rich, ultramafic, ultrapotassic rocks. The first generation minerals identified include biotite (or phlogopite), pyroxene, olivine, and a few accessory phases. These primary minerals are mostly phenocrysts, though the biotite ranges dramatically in size, shape, and level of alteration. The deuteric or replacement minerals are chlorite, calcite (fig. 23), actinolite, and quartz. The chlorite and calcite are relatively abundant, in some cases entirely replacing pyroxene crystals, whereas the quartz and actinolite are much more fine-grained (<0.5mm) and less abundant.

Igneous texture is pervasive throughout as seen in the glomerocryst in figure 24, though metamorphism is poorly expressed through weakly aligned biotite crystals. The level of alignment of biotite crystals varies from slide to slide as seen comparing figures 24 and 25. In the prior, the biotite grains are part of a glomerocryst and are oriented in a radial pattern. Comparing the prior to the latter, the grains have a greater extent of alignment, especially in 25a relative to 25b. Figure 25 also shows the two grain sizes of biotite. The best example of this size dichotomy is in figure 25b, where the two larger crystals represent one generation and the smaller, more narrow and altered ones represent a different generation. The variability in the biotite crystals will be discussed in more depth in the interpretations section.

[2] Rock samples being prepared for thin section are generally cut in planes perpendicular to foliation and parallel to lineation. This orientation shows the planes of the maximum and minimum strain on the rock, (Passchier and Trouw, 1996).

Interpretations and Discussion

Dike Analysis

Horizontal and Vertical Planes

Using the compiled topographic maps seen in figures 14a, b, and c, as well as field observations, it is clear that the dikes are not tabular in the horizontal plane (map view). When mapped, the dikes are neither aligned from bank to bank, nor are they aligned from the bank (cliff face) farther inland.

In order to classify the dikes as being either tabular or sinuous, all three dimensions must be taken into consideration. In this section, the width and consistency of verticality will be discussed. Comparing the Maryland cliff face with the Virginia cliff face may be the most compelling evidence of heterogeneity in the vertical infilling of the joint sets. In addition to the difference in cliff faces, comparing the straight, aligned, inland Virginia dikes (figs. 17 and 18) with the Maryland dikes shows that there is inconsistency in the general character on either side, that is, the Maryland dikes tend to be generally more sinuous than the Virginia dikes. There observation can be explained by the dikes jogging and alternating between joints. This means that the Maryland and Virginia side never had to match to explain their offset. Alternatively, if they used to be connected with analogs on the opposite bank, river processes have since eroded away evidence of those connections.

The photographic evidence makes a strong case for the sinuosity of the dikes in the vertical dimension. First, the dikes on the Maryland and the Virginia cliff faces do not correspond with spacing, width, or degree of sinuosity. Second, the dikes farther inland on the Virginia side (figs. 17 and 18) are not aligned with the dikes outcropping on the cliff face. Lastly, the individual dikes, especially evident on the Maryland side, are simply not tabular. I conclude that while there is offset of the lamprophyre dikes on either side of the river, they cannot be used as offset markers of a fault trending through Mather Gorge.

Locating a Fault

Investigation of the Rocky Islands led to the discovery of a fracture that shows evidence of movement but is not aligned with the gorge. Although this is a unique fracture in extent and it shows signs of motion, the orientation is not aligned with Mather Gorge. The two signs of different kinds of motion noted in the observations section above also complicate the interpretation of this fracture. On the southern side of the island the possible breccia indicates brittle deformation, while on the northern side of the island, approximately six meters away, there are signs of ductile deformation. It is possible that if this fracture experienced motion on more than one occasion the rocks reacted differently. This is a valid explanation only for the observations made about motion on the island. The misalignment with Mather Gorge must be considered when trying to classify the fracture as the trend-controlling fault.

If indeed the fracture in question is a fault, which I suspect that it is based on evidence of movement, its orientation fails to cleanly explain the trend of Mather Gorge. There is the possibility that a fault through the gorge may have bent; however this bend would have had to occur in the rock under the river which is, unfortunately, inaccessible. The fracture shows signs of movement as seen in figures 19 and 20. In spite of this suspected episodic movement, the orientation is not in line with the gorge and, without more data, is an unfounded, simple interpretation as the fault controlling the trend of Mather Gorge.

Thin Sections

Upon microscopic analysis I found that the apparent macroscopic foliation did not permeate throughout the rock, and was therefore only a weathering feature. The presence of replacement minerals such as calcite, chlorite, and actinolite imply a certain degree of metamorphism. I was not expecting to see such a high abundance of calcite in such an ultramafic rock; however, according to Armstrong et al. (2004) carbonates are not uncommon in ultramafic rock suites, and were present in the komatiites that he studied. Quartz is another unexpected mineral, but its presence suggests an outside source providing silica to the lamprophyre. Further investigation into these deuteric minerals could lead to clues about the intrusion history and metamorphic activity in the area.

Based on observations of the biotite crystals, there are at least two generations of biotite within the lamprophyre dikes. These conclusions are based on four consistent dissimilarities noticeable in each sample: the difference in size, aspect ratio, extent of alteration, and orientation, in some cases. Multiple generations or growing regimes of biotite in an igneous rock implicate a secondary event which brought energy to the system.

Conclusions

Based on the elimination of dikes as offset markers and lack of a suitable fault on the Rocky Islands, I conclude that the trend of Mather Gorge is not controlled by a straight fault. My conclusions are not meant to imply that there is not a fault or multiple faults present, but that there may be a more complicated suite of scenarios waiting to be uncovered.

The petrographic analysis shows that there are at least two identifiable generations of biotite growing within the dikes. These generations can be distinguished visually and probed for more accurate age data.

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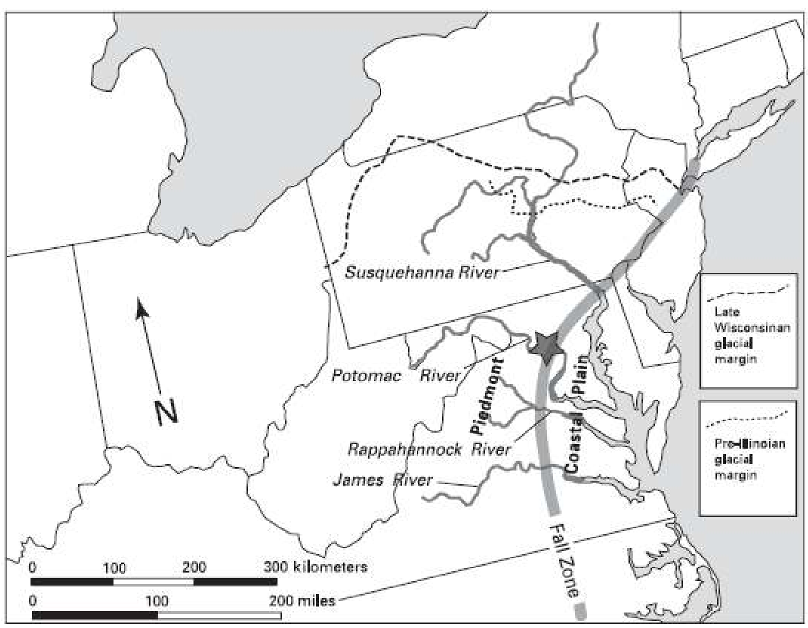
Dr. E-An Zen, personal communication; University of Maryland, November, 2006.

Figures

Figure 1. Water meandering through the goosenecks of the San Juan River, Utah, cuts deep into the layers of rock exposing millions of years of strata. The goosenecks are a prime demonstration of one of the many products of bedrock incision. (Photograph by Michael Rissi).

Figure 2. The Channeled Scablands in eastern Washington are Columbia River Basalts that have been scoured out by periodic massive glacial flooding. This deep, wide canyon shows another result of erosive power.

Figure 3 is an aerial photograph of Mather Gorge looking north. Note how straight the gorge is with respect to the river channel immediately to the north and south of it. From http://www.esm.versar.com.



A

Figure 4. . Map showing the Fall Zone which traces the Piedmont/Coastal Plain transition zone along the east coast. The star indicates the location of Washington, D.C. From Bierman et al., 2004.

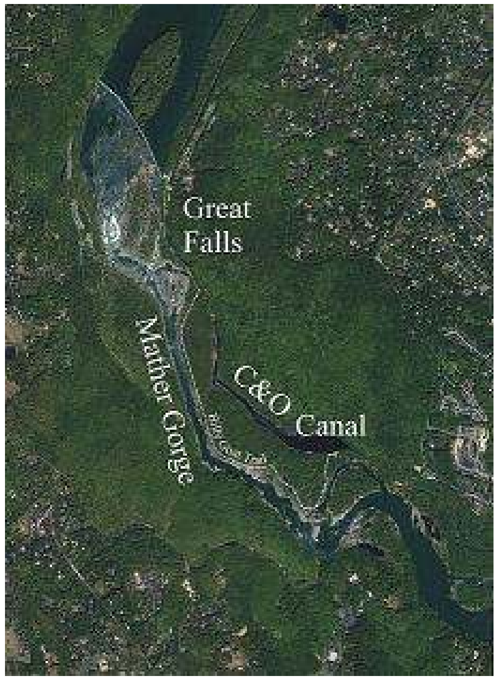


Figure 5. Satellite view of Mather Gorge and the surrounding area. The change in sinuosity between the channels to the north and south and the Gorge is striking. http://earthobservatory.nasa.gov/Newsroom/NewImages.

Figure 6. Photo taken looking downstream (south) through Mather Gorge. Notice how steep the walls are indicating high incision rate. This photo was taken when the river discharge was low. (Photo from Burgy, 2006).

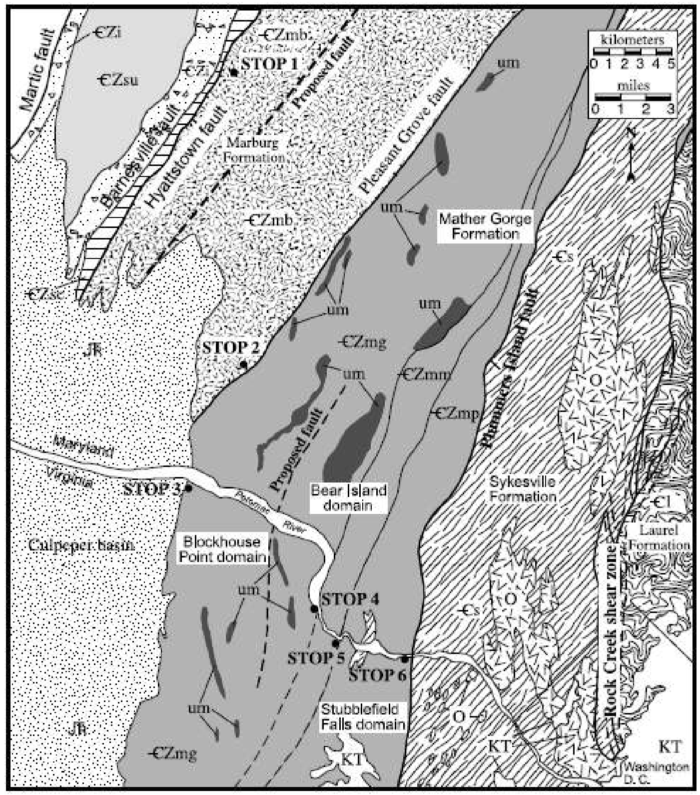


Figure 7. Map showing the three domains within the Mather Gorge Formation (in medium gray): Blockhouse Point domain, Bear Island domain, and Stubblefield Falls domain. Mather Gorge and the study area fall within the Mather Gorge Formation. From Kunk et al., 2004.

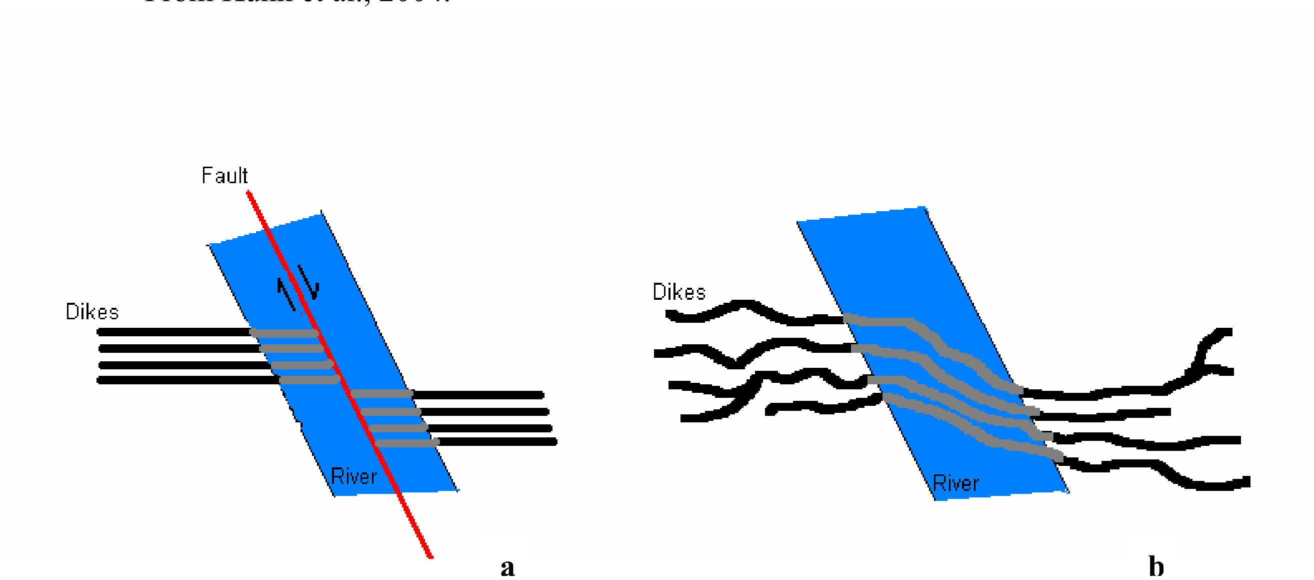


Figure 8. Schematic of possible reasons for the offset of the dikes across the Potomac River. (a) Tabular dikes with offset from a fault. (b) Pinching and swelling dikes whose offset is caused by orientation. This option does not require a fault to explain the offset.

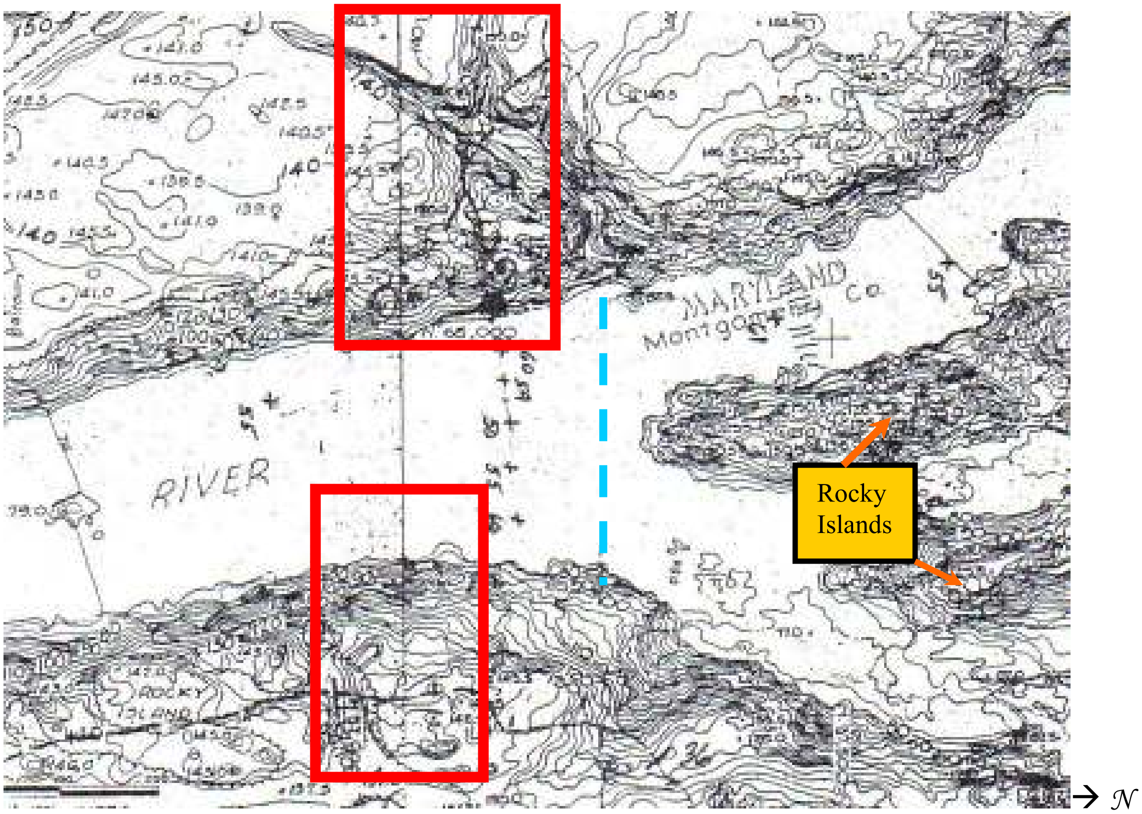


Figure 9. Topographic map of the southern end of the Rocky Islands, dike mapping area (red boxes), and beginning of Mather Gorge (dashed blue line).

Figure 10. Photograph of the Maryland side cliff face. The dikes have been traced in yellow. Notice the two dikes in the middle that come together to form an X-shape. These dikes do not have an X-shaped counterpart on the Virginia side pointing to the conclusion that the two sides did not need to fit together. Also notice that the two dikes on the right (to the south) pinch out at the top, but the two to the left continue to the surface.

Figure 11. This photograph is a close-up of the southernmost Maryland side dike on the cliff face. The dike is outlined in pale yellow and shows an example of the non-tabular nature in this dimension. In this case, the dike infilling the joint shows dextral offset that is not caused by slip. Careful inspection shows that the lamprophyre material is continuous as it in-fills to the right.

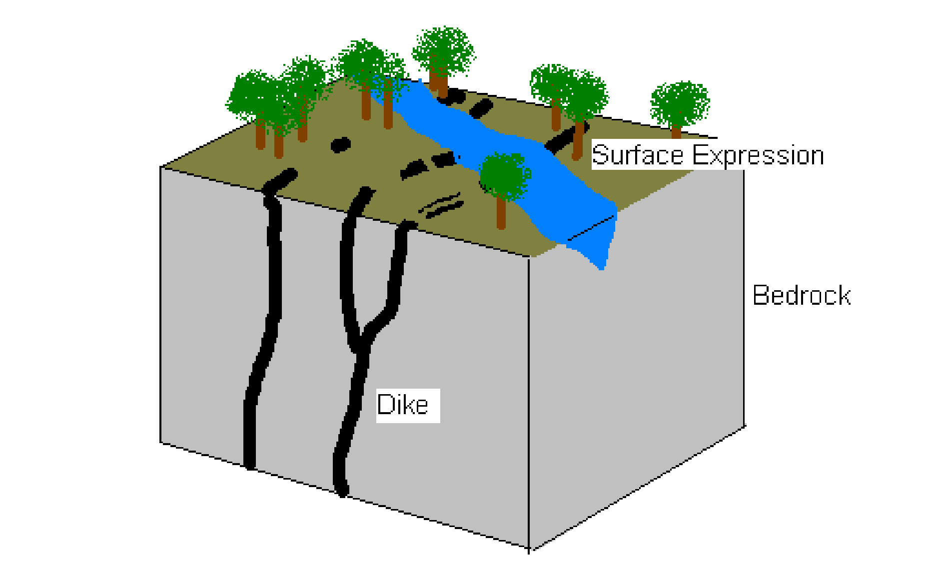


Figure 12. This is a schematic of generic dikes intruding through bedrock. Notice that although the dikes are traceable in the vertical dimension, they are more difficult to trace at the surface. Additionally, they might not behave as one would expect them to based on observations and predictions made from another dimension.

→N

Figure 13. This is a topographic map of the Rocky Islands. The western island is where I attempted to locate the manifestation of a fault on land.

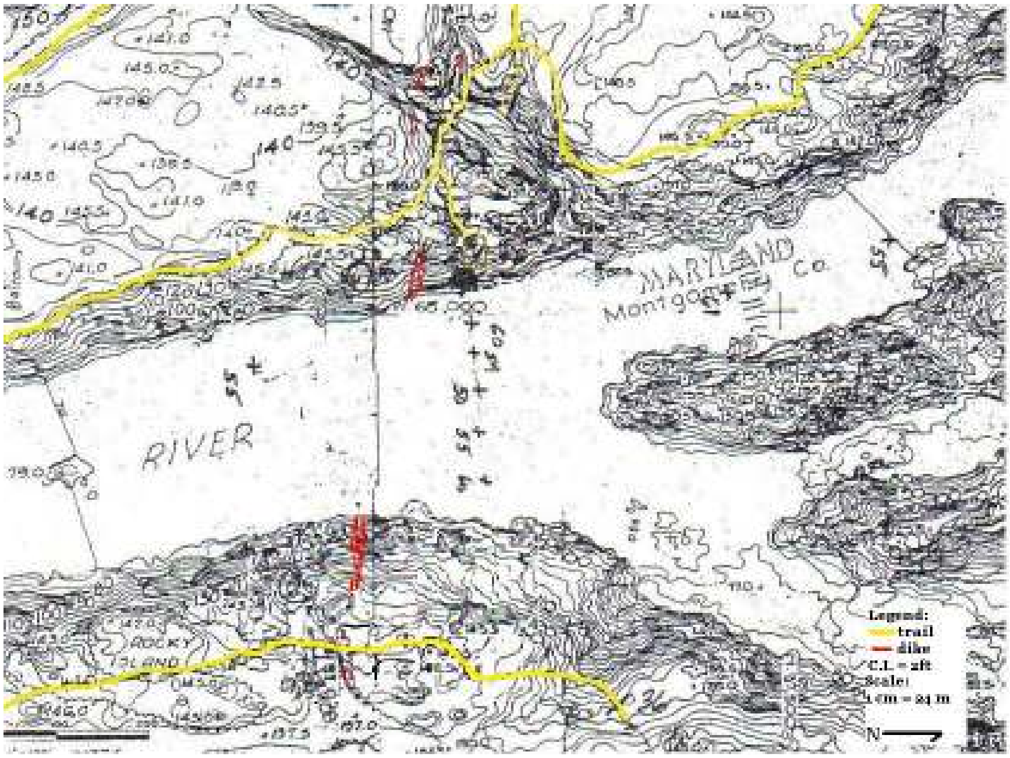


Figure 14a. This is a topographic map with the traced dikes overlain. The dikes are represented by red lines and two popular trails are highlighted in yellow.

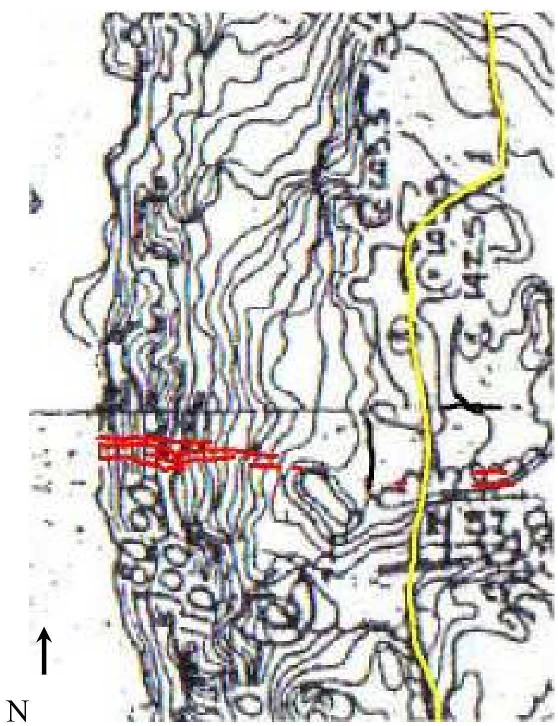


Figure 14b. This is a topographic map of the Maryland side with the dikes drawn in red. They are discontinuous and pinch and swell.

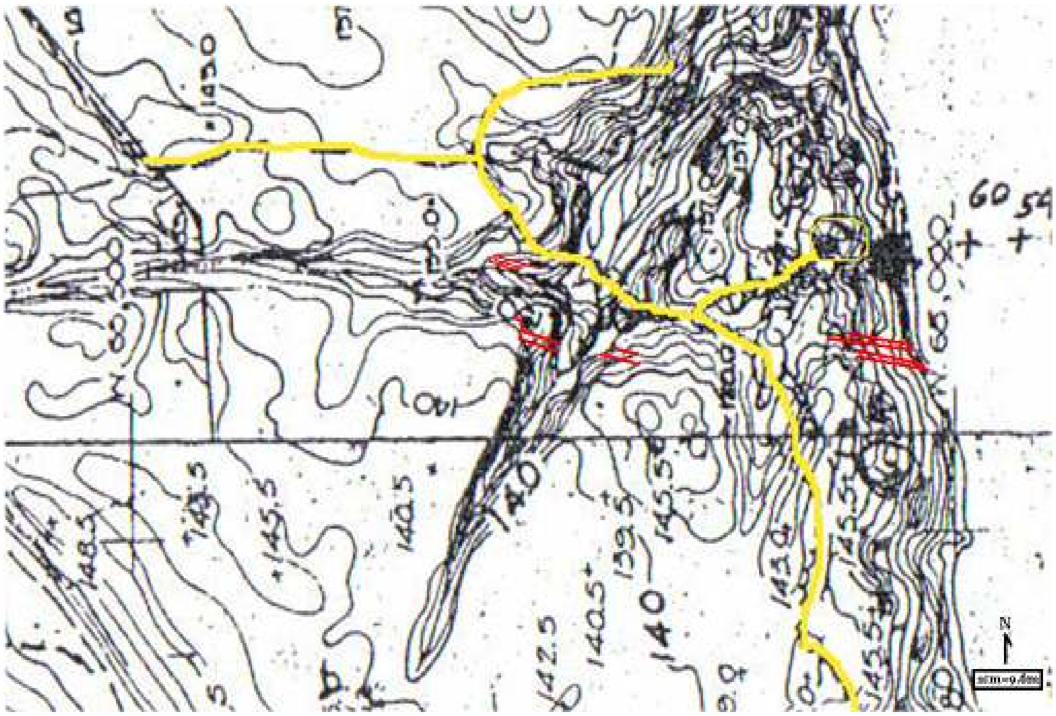


Figure 14c. This is a topographic map of the Virginia side dikes drawn in red. Notice that even at such a large scale, the dikes are so narrow that they are difficult to distinguish from one another.

Figure 15. This is a photograph of an inland dike on the Virginia side covered with sediment and foliage. The magnetometer was able to resolve a magnetic low at several places which allowed me to trace a dextral bend to the north in it, pictured here by the corner of the schist under the north arrow.

→ N

Figure 16. This is a photograph of the dikes on the Virginia cliff face. Although they are not completely tabular, they show it to a much greater degree than the dikes on the Maryland side cliff face which are decidedly less straight.

Figure 17. This is a photograph of the northern Virginia side dikes. Notice that they are relatively straight and not particularly wide, especially compared to those in figure 18.

→N

Figure 18. These are the two southernmost inland dikes on the Virginia side. Notice how straight these are, as well as their thicker width. There are no similar outcrops on the Maryland side.

→N

Figure 19. This is a close up photograph of a possible fault breccia found in a continuous fracture on the Rocky Island. The arrow is pointing to the dark region that may be breccia. The photograph was taken facing upstream.

Figure 20. In this photograph the evidence of possible foliation change has been traced in red marker. To the left the foliation is more organized than to the right, where several boudins have been traced and the foliation is vertical.

Figure 21. This is a photograph taken standing in the fracture. The suspected fault (assuming that it does not bend) would project across the river onto the patch of sunlit rocks.

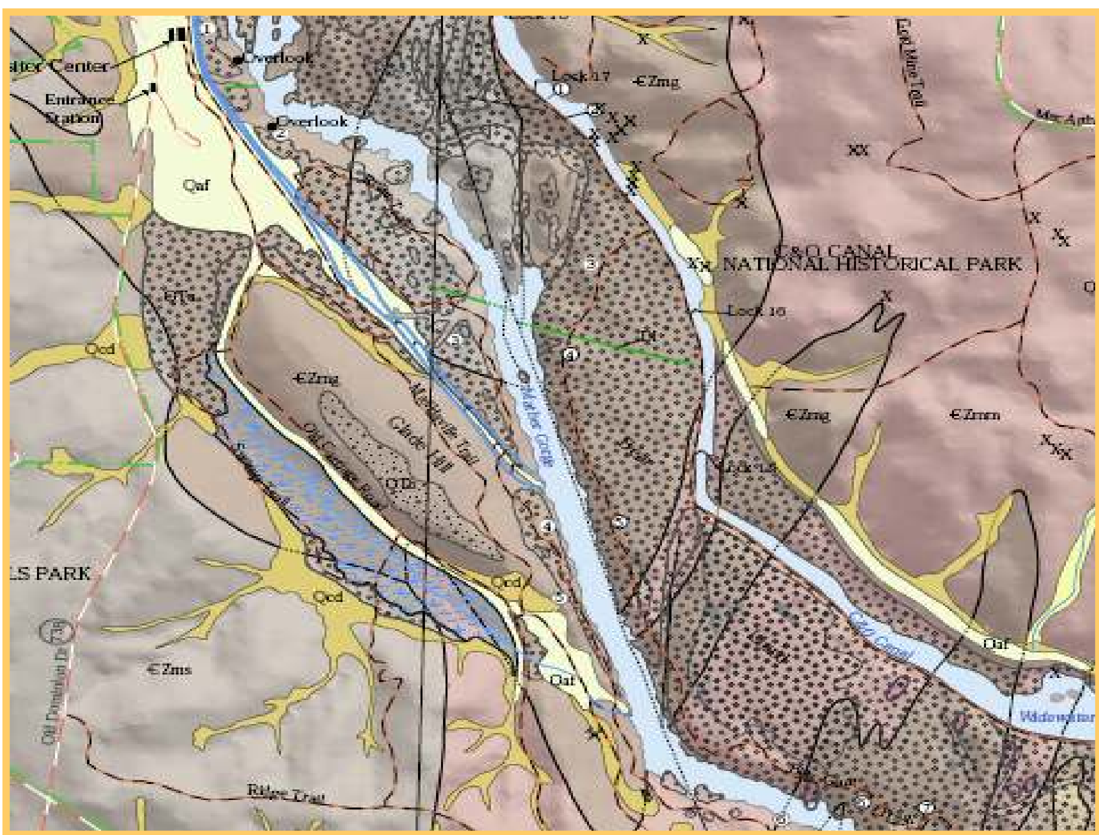


Figure 22. This is a geologic map of the Great Falls/Mather Gorge area. From Scott Southworth and Carrie Fingeret, 2000.

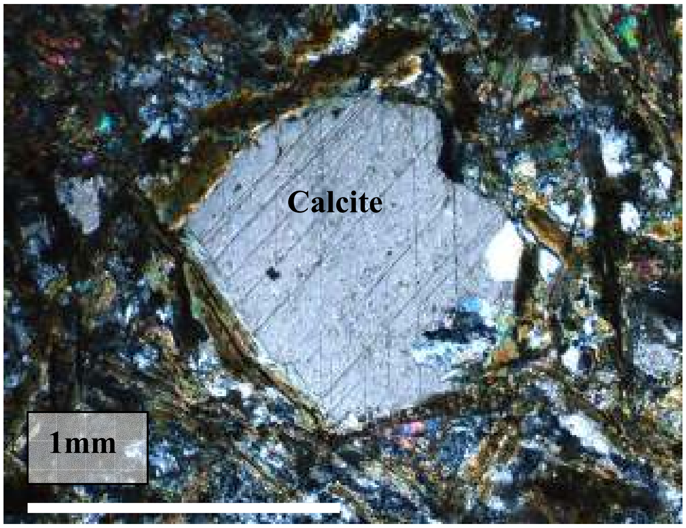
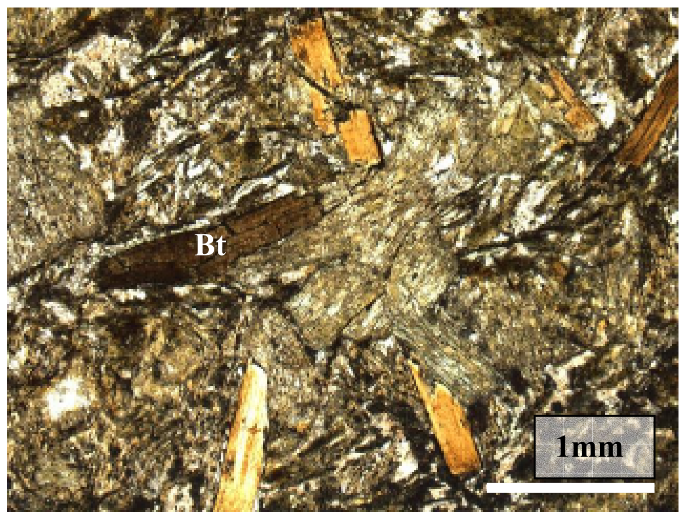


Figure 23 (left) is a photograph of a deuteric calcite grain in L-02b. Calcite is pervasive as an alteration mineral of both clinopyroxene and olivine in these samples. It is seen as well formed crystals, as above, and as smaller alteration components.

Figure 24 (right) is a photograph of a clinopyroxene/biotite glomerocryst. The pyroxene portion in the center has four elongate biotite crystals extending radially outwards from its edges. The clinopyroxene has been almost entirely replaced by chlorite in this photograph.



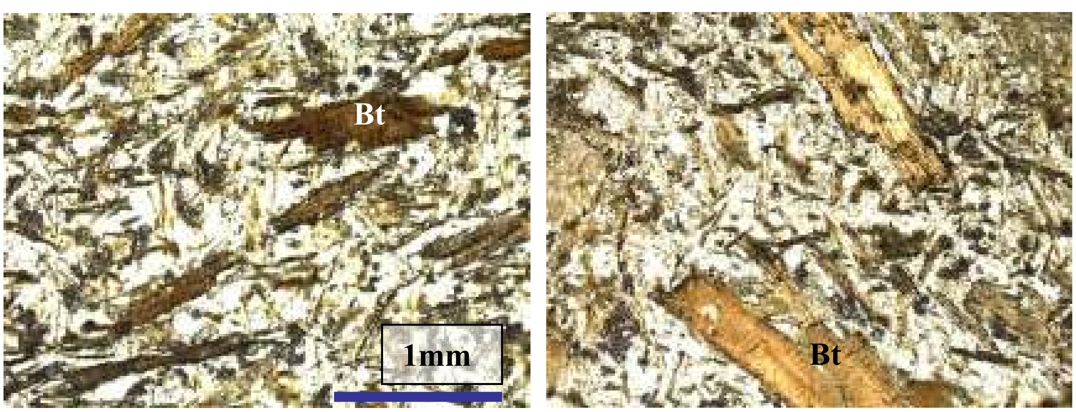


Figure 25. These photographs show two generations of biotite and alignment of the crystals in sub-foliation. Both photos were taken at 5x magnification and have aligned biotite phenocrysts.

Appendix A

Chart of dikes on the Maryland (MD#) and Virginia (VA#) sides with measurements orientation and width. Multiple locations indicate that the dike was measured on more than one occasion.

Location	Orientation (strike/dip)	Width (cm)
VA2	108°/77°NE	68
VA2	118°/80°NE	21
VA2		10
VA2	105°/71°NE	28
VA3		32
VA3	95°/75°NE	29
VA4	95°/73°NE	61
VA4	97°/78°NE	16
VA4		45
VA4		68
VA4		70
VA5	97°/80°NE	
VA5		32
MD2	97°/74°NE	
MD3	93°/70°NE	42
MD3	95°/75°NE	
MD3	97°/70°NE	43
MD4	100°/78°NE	
MD4	103°/79°NE	59
MD4	104°/78°NE	
MD4		59
MD5	110°/84°NE	44
MD5		31

Appendix B

Table of gamma values (see footnote 1) collected from the magnetometer. These values correspond to the strength of the magnetic field at the immediate location of the reading.

No.	Output (γ)	Notes	No.	Output (γ)	Notes
1	51781	Readings 1-36 are measurements taken on the Virginia side.	36	54150	36-44 are readings taken along the toe path in a dike-free environment to get a standard regional reading.
2	53335	We started at the cliff face and walked our way west, taking measurements along strike of the VA4 dike, then the VA5 dike to try to get a standard by which to identify the lamprophyre material.	37	58547	These readings have a higher average than the "dike present" readings.
3	53075		38	53225	The schist may have a slightly higher magnetic pull than the lamprophyre.
4	51730		39	58487	
5	51738		40	58480	
6	58484	high	41	53736	
7	53612		42	55270	
8	52531		43	54554	
9	51132		44	53225	
10	51436		45	53196	Begin readings taken on MD side.
11	51972		46	53136	Walking along strike of a known outcrop, we got readings 45-69
12	58552	high	47	52798	
13	52137		48	53057	
14	52481		49	53496	
15	52103		50	52281	
16	52330		51	51774	
17	51959		52	51530	
18	52014		53	52123	
19	52022		54	52597	
20	51982		55	52181	
21	55968		56	8747	These low readings are representative of two recessions in schist that are aligned with the known lamprophyre outcrops.
22	53027		57	7147	These were mostly detected near the margins of the dikes.
23	52066		58	9771	Margin

24	49388	low?	59	8954	Margin
25	52757		60	8877	Margin (MD4 or MD5)
26	52700		61	11531	
27	52071		62	7888	
28	52584		63	11302	Center of a recession
29	51623		64	11689	
30	52023		65	9885	Near edge of a dike
31	51513		66	7383	
32	51964		67	7060	
33	52236		68	2030	
34	52557		69	8160	
35	51962				

Appendix C

Table of rock samples and thin sections. "Location" is a description of where the rock was sampled from. Notes correspond to the thin sections and microscopic analysis. The samples are named in the order with which they were removed, "S-" for schist and "L-" for lamprophyre.

Sample	Orientation	Location	Notes
S-01	N0°E/73°E	Taken from an outcrop between the river trail and the gravel trail in Great Falls.	Well developed foliation. Contains mainly quartz and biotite.
		5°E of S, ~75ft from hill above small tributary confluence near the pedestrian bridge.	
L-02a	N68°W/76°NE	Sample taken from VA-2 on south side of pedestrian bridge. Dislodged with a sledge hammer from the outcrop ~6ft above stream bed.	Many mineral phases are highly altered. Groundmass consists of long, narrow biotite crystals, actinolite, quartz, calcite, chlorite. ~2mm biotite phenocrysts less altered than groundmass. Euhedral to subhedral olivine and cpx almost completely altered to chlorite.
			Rock only slightly deformed- alteration is more pervasive than any notable foliation, though some regions show more mineral alignment than others.
L-02b	N68°W/76°NE	Thin section cut from the same sample as L-02 but with a cross section of margin to interior rather than traditional orientation.	Larger biotite phenocrysts and more abundant cpx than L-02a. Generally the same composition as L-02a but with more calcite phenocrysts.

L-03a	N95°E/75°NE	Sample taken from southern margin of VA-3, ~4ft above stream bed. Sample is dry and out of reach of the waterfall.	Billet cut from an interior piece of the rock. Pyroxenes maintain habit but are almost completely altered to chlorite. Calcite is pervasive as a secondary mineral also replacing cpx. Two distinct biotite behaviors: one has higher aspect ratio and makes up the groundmass, the other is less altered and bigger.
			~2mm cpx with radial biotite glomerocryst. Good example of igneous texture.
L-03b	N95°E/75°NE	Same as L-03a.	Groundmass biotite is finer but sample is otherwise the same as L-03a.
L-04	N100°E/78°NE	Taken from just above where MD-3 and MD-4 intersect. Sample has lichen on it (look for alteration) but was in a relatively dry area.	Biotite grains are more preferentially aligned than in other samples, but no definite strain. Alteration is heavy in pyroxenes, with chlorite, calcite, and very fine quartz grains present as replacement.
L-05	N95°E/75°NE	Sample taken from north side of margin on MD-3 on cliff face.	Larger bioite grains are more aligned than other samples. Also, groundmass is not as biotite-rich, causing it to have an overall lighter color.
L-06	N97°E/74°NE	Sample taken from MD-2 on cliff face.	Most notable is an alteration front along the length of the slide. One half is much more altered than the other. Larger biotite phenocrysts are somewhat smaller than the other samples.
			Moderate foliation in top (altered) section.
S-07	N8°E/82°SE	Sample taken from outcrop just off the Billy Goat trail, atop a cliff overlooking the tip of the western Rocky Island. ~30°SE, 300ft from the island's southern tip.	Well foliated schist. Contains multiple microlithon and cleavage domains. Primary constituents are biotite and quartz. One generation of metamorphism.

Appendix D

C&O Canal and Great Falls National Parks collection permits.

SCIENTIFIC RESEARCH AND COLLECTING PERMIT

Grants permission in accordance with the attached general and special conditions

United States Department of the Interior
National Park Service

Chesapeake & Ohio Canal NHP

Study#: CHOH-00072
Permit#: CHOH-2007-SCI-0002
Start Date: Mar 01, 2007
Expiration Date: Jul 31, 2007
Coop Agreement#: n/a
Optional Park Code: n/a

Name of principal investigator:

Name: Aaron Martin **Phone:** 301-405-5352 **Email:** martinaj@geol.umd.edu

Name of institution represented:

University of Maryland

Co-Investigators:

No co-investigators

Project title:

The geologic significance of lamprophyre dikes in the Mather Gorge Formation, Great Falls, Maryland

Purpose of study:

In this proposal I seek permission to collect seven oriented rock samples from the outcrops near Great Falls and Mather Gorge, Maryland. Analysis of the samples and interpretation of results will form the basis of several undergraduate theses to be completed at the University of Maryland under my direction. My students and I will use the samples and associated field data to better understand the tectonic development of the Appalachian Mountains prior to ~300 million years ago.

Subject/Discipline:

Geology / General

Locations authorized:

I propose to collect samples from just below Great Falls and south through Mather Gorge along the Potomac River in Chesapeake and Ohio National Historical Park, Maryland.

Transportation method to research site(s):

I will access the sample sites on foot via established trails leading from the visitor's parking lot.

Collection of the following specimens or materials, quantities, and any limitations on collecting:

n/a

Name of repository for specimens or sample materials if applicable:

Repository type: Will be destroyed through analysis or discarded after analysis
Objects collected:
I will collect 7 fist-sized oriented rock samples from several locations in the park. I will collect 1 sample of each lamprophyre dike (total of 5) and 2 samples of the wallrock into which the dikes intrude. I will take care to collect samples only from outcrops not visible from trails and scenic overlooks to reduce the visible impact to park visitors. Because the trails and overlooks are mostly 10-15 meters above the river, I plan to collect samples near the river, far from the established trails. Most visitors never venture off the trails and onto the rocks near the river, so most visitors will never see my sampling sites. In my experience, even people who do see sampling sites usually do not notice that a small rock was removed from the outcrop. To the best of my knowledge, no permanent collections of oriented samples exist. Oriented samples are necessary for determining directions of shear during deformation. I also do not know of any existing samples that could be crushed and powdered for the isotopic and element abundance analyses.

Specific conditions or restrictions (also see attached conditions):

1. All work will proceed on weekdays during daylight hours only, unless otherwise authorized in the Scientific Research and Collecting permit. No work will proceed on Federal holidays unless previously authorized.

Permit:CHOH-2007-SCI-0002 - Page 1 of 3

SCIENTIFIC RESEARCH AND COLLECTING PERMIT

Grants permission in accordance with the attached general and special conditions

United States Department of the Interior
National Park Service
George Washington Memorial PKWY

Study#: GWMP-00063
Permit#: GWMP-2007-SCI-0003
Start Date: Feb 15, 2007
Expiration Date: Jul 31, 2007
Coop Agreement#: n/a
Optional Park Code: n/a

Name of principal investigator:

Name: Aaron Martin **Phone:** 301-405-5352 **Email:** martinaj@geol.umd.edu

Name of institution represented:

University of Maryland

Co-Investigators:

No co-investigators

Project title:

The geologic significance of lamprophyre dikes in the Mather Gorge Formation, Great Falls, Virginia

Purpose of study:

In this proposal I seek permission to collect seven oriented rock samples from the outcrops near Great Falls and Mather Gorge, Virginia. Analysis of the samples and interpretation of results will form the basis of several undergraduate theses to be completed at the University of Maryland under my direction. My students and I will use the samples and associated field data to better understand the tectonic development of the Appalachian Mountains prior to ~300 million years ago.

Subject/Discipline:

Geology / General

Locations authorized:

We propose to collect samples from just below Great Falls and south through Mather Gorge along the Potomac River in Great Falls National Park, George Washington Memorial Parkway, Virginia.

Transportation method to research site(s):

We will access the sample sites on foot via established trails leading from the visitor's parking lot.

Collection of the following specimens or materials, quantities, and any limitations on collecting:

n/a

Name of repository for specimens or sample materials if applicable:

Repository type: Will be destroyed through analysis or discarded after analysis
Objects collected:
We will collect 7 fist-sized oriented rock samples from several locations in the park. We will collect 1 sample of each lamprophyre dike in the park (total of 5) and 2 samples of the wallrock into which the dikes intrude. We will take care to collect samples only from outcrops not visible from trails and scenic overlooks to reduce the visible impact to park visitors. Because the trails and overlooks are mostly 10-15 meters above the river, we plan to collect samples near the river, far from the established trails. Most visitors never venture off the trails and onto the rocks near the river, so most visitors will never see our sampling sites. In my experience, even people who do see sampling sites usually do not notice that a small rock was removed from the outcrop. To the best of my knowledge, no permanent collections of oriented samples exist. Oriented samples are necessary for determining directions of shear during deformation. I also do not know of any existing samples that could be crushed and powdered for the isotopic and element abundance analyses.

Specific conditions or restrictions (also see attached conditions):

1. Permittee will notify Natural Resource Specialist Melissa Kangas (703-289-2542; melissa_kangas@nps.gov) 24 hours prior to arrival onsite to conduct field work. Kangas will notify U.S. Park Police and NPS site staff of specific permit