# 8. Overview of Tectonic Setting, Fault Systems, and Seismic Hazards in the City of Alexandria, Virginia

by Tony Fleming, 2016

***Introduction***

Evaluating seismic risk is a multifaceted issue involving elements of *tectonics*, local and regional geologic history, the distributions of geologic materials with different engineering properties, and a host of cultural and institutional considerations. Tectonic setting determines the nature and intensity of crustal *strain* currently imposed on the local geologic framework, while geologic history greatly affects how that strain is manifested in local rocks and sediments. Boundary conditions produced by local discontinuities in the geologic framework, such as *faults*, fractures, and contacts between formations, typically determine where and how efficiently *seismic energy* is transmitted, while the physical properties of different rocks, sediments, and the soils developed on them determine whether seismic energy is amplified or attenuated in any given place. Poorly consolidated geologic materials with a shallow water table, for example, are susceptible to strong shaking and *liquefaction*, while a nearby area underlain by solid *bedrock* or well consolidated sediments will typically experience much less ground motion from the same amount of seismic energy. Finally, the nature of land use itself, and the design and engineering of the infrastructure present, are of utmost importance in determining whether a strong *earthquake*, or even a moderately strong one, is merely a temporary inconvenience or a truly devastating event. Neighborhoods dominated by old, unreinforced masonry structures built over artificial fill tend to experience exponentially more severe damage in any given seismic event than do newer structures built on firm native soil following modern building codes.

All of these issues are in play in the densely populated and geologically complex region along the mid-Atlantic seaboard, whose long history of European settlement overlain on a sometimes inscrutable geologic framework poses a variety of distinct challenges. To take just one example, assessing the potential for damaging earthquakes in this region is a complex issue that doesn't necessarily lend itself to unambiguous answers, at least not given our current understanding of the tectonic framework. It seems likely, for example, that the region has experienced strong prehistoric earthquakes, judging by observable faults that offset late *Tertiary* to early *Pleistocene* *Coastal Plain* strata, as well as river terraces arguably as young as late Pleistocene (figure 8-1). And it is equally clear that the entire regional landscape has been tilted from west to east, beginning in the early *Cretaceous* period and continuing up to the present, a process in which faults and earthquakes have undoubtedly played the major role. The eastward slope of the *bedrock surface* at greater than 100 feet/mile beneath Alexandria is a manifestation of that process.

On the other hand, the rather limited record of mid Atlantic earthquakes in historical times would seem to argue that such events may be very infrequent. After all, this isn't California, where moderate to strong historical temblors have occurred with sufficient regularity to enable scientists to forecast where earthquakes are likely to occur in the relatively near future, if not exactly when. The regular *seismicity* has also had another important consequence, in that it spurred intensive geologic mapping and exploration of the subsurface along the west coast, leading to the recognition of numerous faults, most of which are now at least reasonably well characterized in terms of age, style, location, and potential risk of generating earthquakes.

The same cannot be said of fault systems along the mid-Atlantic seaboard. This dichotomy is partly a function of geologic setting: the Appalachian Mountains have intrigued armies of geologists for well over a century, serving as the ultimate proving ground for a host of geologic theories, yet at the same time, this ancient range has also been long regarded as something that happened in the past—a geologically dormant and largely aseismic entity that is slowly eroding away, exposing the inner workings of tectonic events that occurred hundreds of millions of years ago. Although a few relatively young faults were recognized in the Washington area as far back as the 1890's (figure 8-1), it has only been relatively recently that the true extent of *Cenozoic* fault systems and their potential significance have become apparent. Prominent examples include the Brandywine fault zone of southern Maryland (Jacobeen, 1972), the Stafford fault system of northern Virginia (Mixon and Newell, 1976; 1977; 1978; Newell and others, 1976**;** Powars and others, 2015), the Mountain Run fault zone of central Virginia (Pavlides and others, 1983; Bobyarchick, 2015), and the Rock Creek shear zone in Washington, D.C. (Fleming and others, 1994; Fleming and Drake, 1998).

*Figure 8-1. Darton's fault, on Adams Mill Road by the National Zoo, Washington, D.C. The head of the hammer lies on the fault plane, along which banded Paleozoic mylonite of the Rock Creek shear zone (left) is thrust over terrace gravel of late Tertiary or Pleistocene age (right). This is the first of several relatively young faults that Darton recognized in the District; it is still exposed today in an enclosure erected by the Smithsonian Institution with the encouragement of the local geological community shortly after the photo was taken (Bassler, 1940). Photo by N.H. Darton, circa 1925, courtesy of the U.S. Geological Survey.*

For most of the past century, however, these relatively "young" faults were often regarded as curiosities by the geologic community, because no modern seismicity or compelling evidence of historical motion was associated with them. Compared to the large, active fault systems along the west coast and in the mid-continent region, the relatively small number of seemingly innocuous faults known from the Washington, D.C. area were largely perceived to lack much potential for generating damaging earthquakes. While this perception had begun to change in some circles by the late 20th century, the $M_w$ 5.8 (moment magnitude) Mineral, Virginia earthquake on August 23, 2011 was a watershed moment.

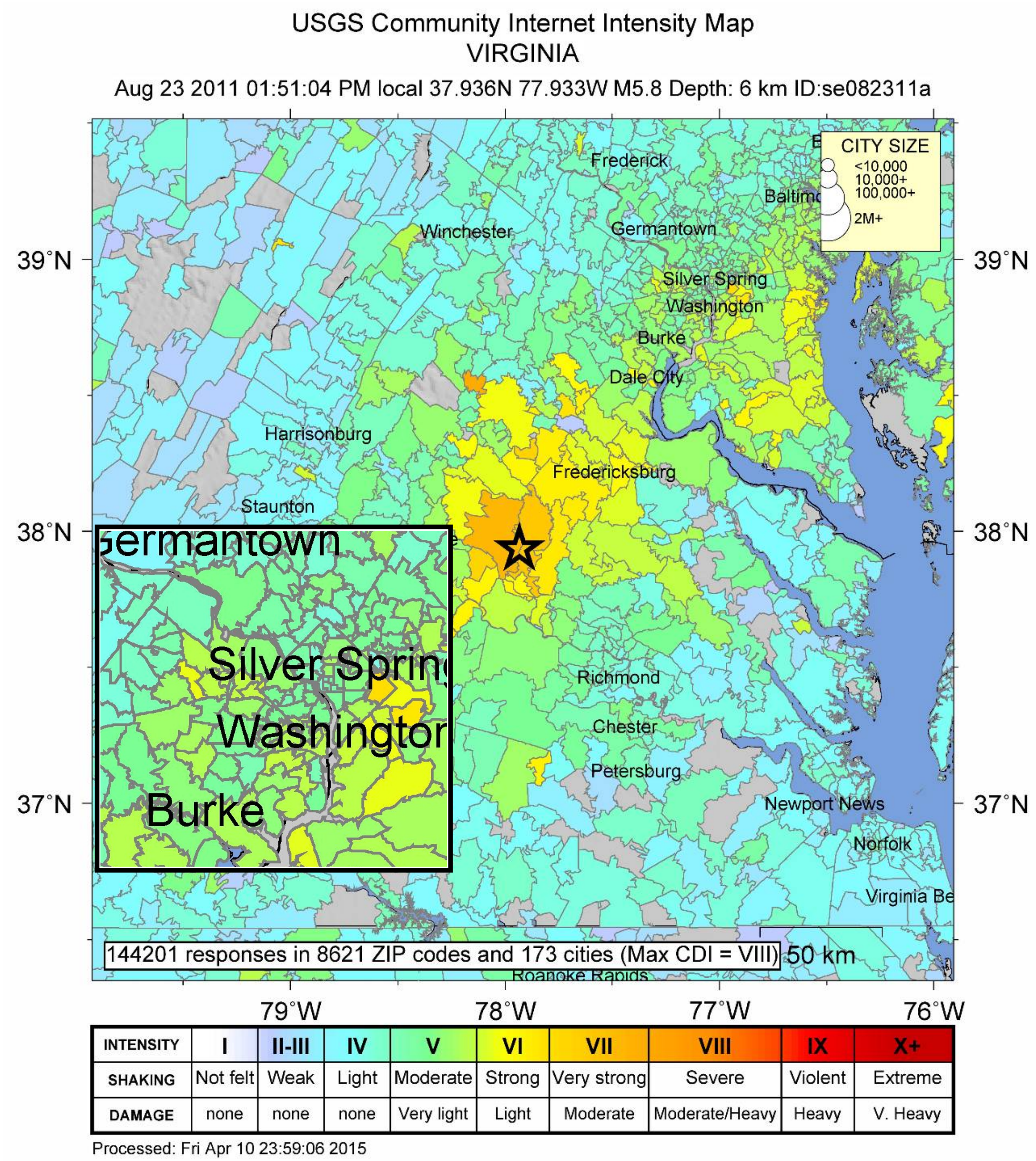


*Figure 8-2. Community Internet Intensity Map of the August 23, 2011 Mineral, Virginia earthquake (main shock) from the USGS "Did You Feel It?" website. Intensity levels are based on analysis of online questionnaires submitted by the public, located by zip code and detailing commonly observable effects of shaking. The Mineral earthquake generated the largest number of responses in the history of the program (Horton and others, 2015), with more than 1,000 of those coming from zip codes within the City of Alexandria. The felt intensity exhibits a strong directional component elongated in a northeast-southwest direction, parallel to regional tectonic structure (Hough, 2012). This anisotropy resulted in stronger felt intensity in parts of the DC area (inset map) than in adjacent areas, including several Alexandria zip codes (located behind the "sh" in "Washington).*

The Mineral earthquake was widely felt in the eastern US. Although centered about 80 miles (130 km) southwest of the Washington area, the quake was strongly felt in the region and caused a significant amount of damage to unreinforced masonry structures in the District (Horton and others, 2015). Some of the strongest shaking in the Washington area, as recorded by numerous USGS "Did You Feel It" *intensity* reports (USGS, 2011), occurred in zip codes that include parts of Alexandria (figure 8-2), where felt intensity ranged from M4.7 to M5.7, with an average value of 5.3 (moderate shaking). The earthquake served as a wake-up call that, while seemingly rare, damaging earthquakes in the densely populated mid-Atlantic region are indeed possible, and prompted a renewed interest in the faults and fault systems in the region, and the relatively poorly understood seismic hazards they pose.

This part of the Geologic Atlas of Alexandria presents a brief overview of the tectonic setting of the city; summarizes current knowledge regarding the potential risk of seismic events originating both nearby and on distant faults, such as in the Central Virginia Seismic Zone where the Mineral earthquake occurred; highlights places in the city that appear susceptible to strong shaking; and concludes with a catalog of known and likely faults in the city as well as other suspect structures that may merit further investigation.

It must be emphasized that assessments of seismic risk in the DC region are necessarily fraught, for a variety of reasons. Chief among these is the small number of historical earthquakes in the region, which *appears* to suggest that damaging quakes are low frequency events, yet have the potential for major impacts given the densely populated character of the area, the presence of much critical infrastructure, and the abundance of older structures not designed according to modern seismic standards. Another reason is that it is extremely difficult to identify young faults in the region, much less observe them directly or determine which ones are active. The information herein should thus be regarded as highly preliminary, and subject to change as more becomes known about the relationships of the fault systems in the region and the ages of the strata they cut. It is intended as a general guide for understanding seismic risk, and to serve as a starting point for subsequent investigations and discussion of the issues.

Finally, this section represents a highly abbreviated summary of a much larger body of work concerning the regional tectonic setting, earthquake risk in the eastern United States, and general seismic engineering principles. Readers interested in acquiring more information about these topics are encouraged to consult the references listed in the bibliography and to visit the websites of the U.S. Geological Survey, the Virginia Division of Geology and Mineral Resources, the American Society of Civil Engineers, and numerous universities and professional organizations in the State of California, where decades of experience has led to a wealth of practical and applied information, much of it readily available online.

### *Tectonic Setting*

The vast majority of earthquakes occur along boundaries of tectonic plates. The mid-Atlantic region, however, lies squarely within the North American plate, far from any active plate boundary. The ultimate causes of so-called "intraplate" earthquakes, such as the Mineral event, are poorly known, but they can generally be understood to represent the interaction of the modern stress field with favorably oriented structures left over from former plate boundaries, leading to the reactivation of old fault systems and the development of new, subsidiary structures. Since it is the rupture of faults that generates the release of seismic energy in earthquakes, faults are the main focus of this discussion.

Alexandria straddles the *Fall Zone* (figure 8-3), where poorly consolidated Coastal Plain sediments of Cretaceous through *Quaternary* age overlap *crystalline* Piedmont rocks of early *Paleozoic* age. The *Piedmont* is commonly referred to as the "basement", reflecting the fundamentally different character and history of the crystalline rocks, which participated in the folding, metamorphism, and uplift of the Appalachians before being beveled by erosion to form the platform upon which the much younger and largely *unconsolidated* Coastal Plain strata were deposited. The major "basement" *unconformity* at the base of the Coastal Plain is a fundamentally important and readily recognizable stratigraphic horizon, both regionally and in Alexandria specifically, and is discussed in the **expanded explanation of plate 3**.

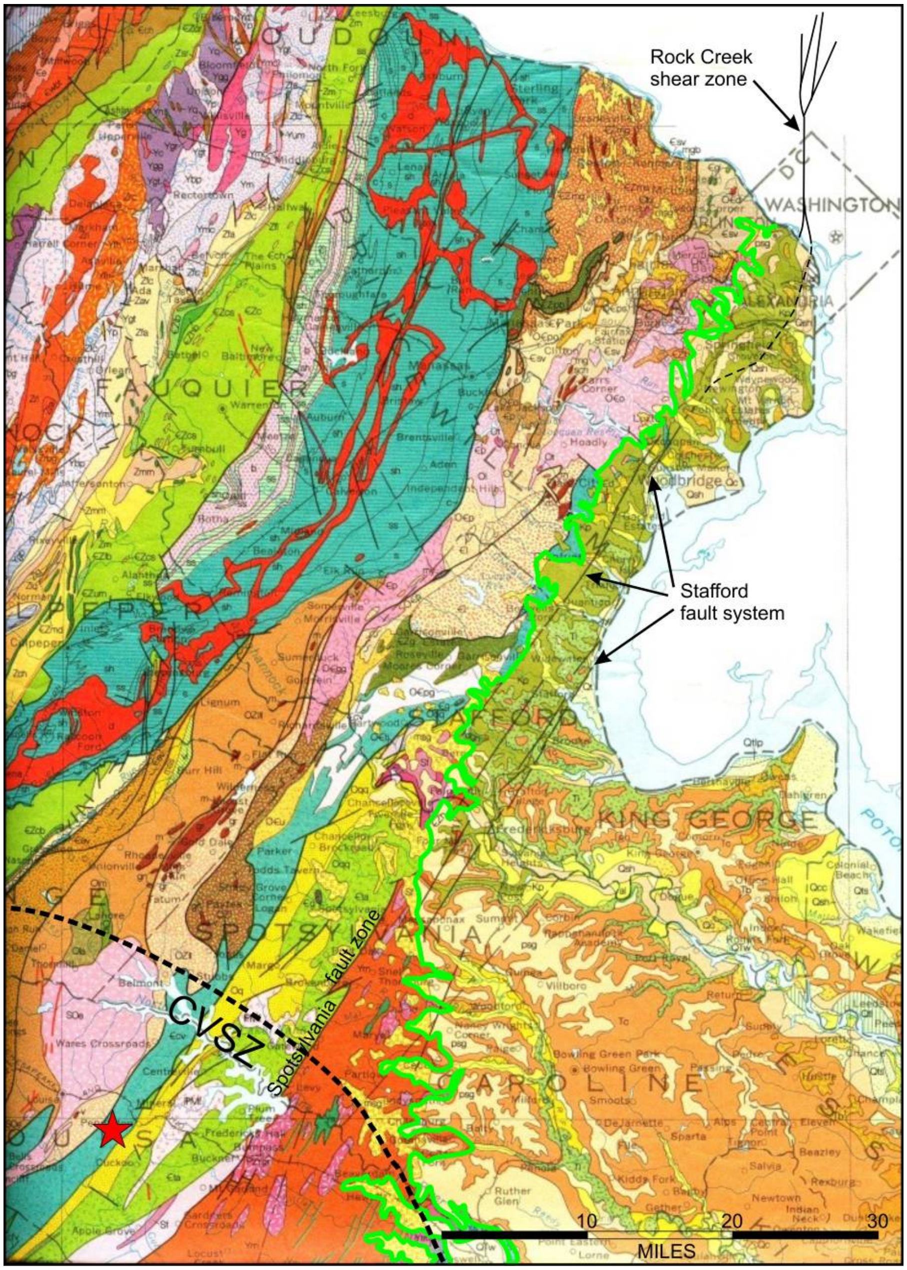


*Figure 8-3. Portion of the Geologic Map of Virginia (Virginia Division of Mineral Resources, 1993) showing northeastern Virginia. The green line is the approximate location of the Fall Zone, separating the Piedmont to the west and the Coastal Plain to the east. Heavy dark lines are faults; faults that project into Alexandria are labeled. The red star near the southwest corner is the epicenter of the 2011 Mineral earthquake, while the dashed line is the approximate northern edge of the Central Virginia Seismic Zone (CVSZ; Horton and others, 2015, and references therein), a distinct area of moderate historical seismicity. The pronounced northeast-to-southwest orientation of geologic structures likely facilitates preferential transmission of seismic energy in the same direction (Hough, 2012), and may explain why the 2011 Mineral earthquake was felt so strongly in the Washington, DC area.*

The Piedmont consists of a series of fault-bounded geologic *terranes* that differ from adjacent terranes in terms of age, origin, composition, and/or geologic history. Several major terranes, mostly of lower Paleozoic age, are recognized in the Piedmont in the greater Baltimore-Washington-northern Virginia region (Horton and others, 1989). These terranes and the fault zones that bound them exhibit a pronounced northeast-to-southwest-trending orientation, producing a strongly anisotropic regional *tectonic fabric* (figure 8-3).

Two such terranes underlie Alexandria: the Potomac terrane, which includes the rock units exposed at the surface in the western part of the city and is thought to have formed in a submarine trench adjacent to a lower Paleozoic volcanic arc; and the Chopawamsic terrane, which lies beneath Old Town and consists in large part of volcanic rocks formed in the arc itself. The fault zone that separates the two terranes is considered to be the southward extension of the Rock Creek shear zone (Fleming and Drake, 1998), discussed later in this section and in the expanded explanation of plate 3.

The fault zones that bound the Piedmont terranes originated as Paleozoic structures during the deformation and assembly of the Appalachian Mountains. Most have complex movement histories, involving one or more major episodes of motion that typically involved compression—something like a direct, head on collision between two blocks of rock—or a more oblique style of crustal motion referred to as transpression, akin to being sideswiped. Some were active as *thrust faults* when exotic terranes were emplaced onto North America, while many others are *strike slip faults* that laterally translocated adjacent blocks of rock by tens or possibly hundreds of miles. The Paleozoic faults in the Washington area are *ductile* structures, that is, the rock was hot and behaved plastically when it was deformed, not unlike kneading warm dough. They are distinguished by zones of *mylonite*—dense, fine grained *metamorphic rock* that was milled down and recrystallized at depth under high temperature and pressure (figure 8-4). A few faults were reactivated during the *Mesozoic*, under enormous extensional forces when North America rifted apart from the other continents, producing several Mesozoic basins (Culpepper, Gettysburg) in the Piedmont. Many of these old Appalachian faults, however, have remained dormant since the Paleozoic.

Figure 8-4. Spotted mylonite from the Rock Creek shear zone, Melvin Hazen Valley Park, Washington, DC. The dark colored part of the mylonite consists of ultra-fine grains that were severely reduced in size and welded together during fault motion, producing an almost glassy, appearance. The "spots" are remnants of original quartz and feldspar grains in the parent rock that survived the milling process; many are severely flattened and some are rotated. This mylonite formed at a temperature of about 550° C and a depth of several miles (Fleming and Drake, 1998). Photo by Tony Fleming.

Sizable faults also cut the Coastal Plain in both Virginia and southern Maryland, and clearly have a much younger history of motion. Most Coastal Plain faults have been recognized only in the last several decades due to the advent of deep exploratory drilling, high resolution seismic profiles, and other *geophysical* methods (the *aeromagnetic* survey shown in **figure 3-4** is an example). An interesting feature of many Coastal Plain faults is that the observed offset becomes progressively less the higher in the stratigraphic section one goes. For example, the offset along individual faults within the Stafford fault system is typically several tens of meters at the basement unconformity, diminishing to less than ten meters in middle Tertiary strata, and a meter or less where they cut late Tertiary to Pleistocene river terraces (Powars and others, 2015). Such a relationship indicates a prolonged, episodic history of motion, rather than a single large event. As a result, these faults are commonly termed "post-Cretaceous" faults, a reference to the early Cretaceous age of the *Potomac Formation*, which forms the base of the Coastal Plain in this region.

Unlike the Paleozoic faults, these post-Cretaceous faults are *brittle* structures, that is, fault motion took place at shallow depths when the rock or sediment was relatively cold and competent. They are distinguished by zones of *fault gouge*, *breccia*, rotated blocks of shattered material, and similar features (figure 8-5). Although offset of Coastal Plain strata and upland terraces is the gold standard for recognizing post-Cretaceous faults, the presence of brittle structures is extremely useful for distinguishing younger, more recently active faults from older, inactive Paleozoic faults in bedrock exposures where younger strata are absent.

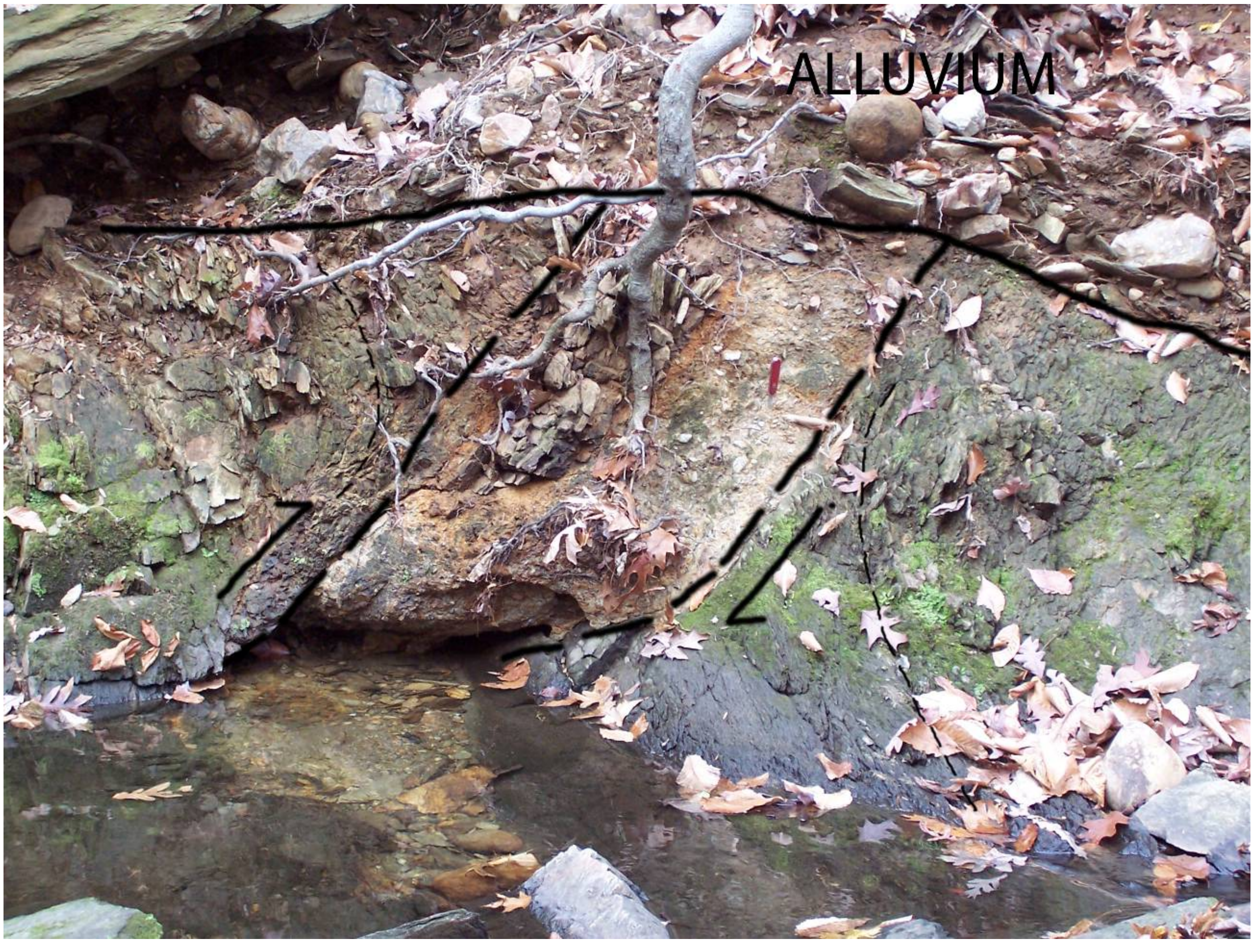


*Figure 8-5. Brittle fault cutting Paleozoic metamorphic rock along Broad Branch, Rock Creek Park, Washington, DC. The long-dashed lines outline the walls of the fault, arrows show sense of motion. The interior of the fault is composed of gouge and breccia. Gouge is fine, powdery or clayey material ground up by fault motion, while breccia consists of angular fragments of the surrounding rock. Rotation of the foliation in the wallrock adjacent to the fault (shown by small dashed lines) is known as "drag" and gives a clear indication of the direction of fault motion. Photo by Tony Fleming.*

In some places, post-Cretaceous faults occur within older, Paleozoic and(or) Mesozoic fault zones that have been reactivated. Darton's fault (fig. 8-1), located by the National Zoo and discovered in 1893, is a good example, and is still visible today (Darton, 1950). Other young faults have been recognized more recently within the Rock Creek shear zone (Fleming and Drake, 1998 and Fleming, unpublished data), and there are other examples from elsewhere in the region, such as the Everona fault (Bobyarchick, 2015) and potentially parts of the Stafford fault system (Mixon and Newell, 1977; 1982; Mixon and others, 2000). Powars and others (2015) summarize the regional evidence for this relationship.

One explanation for this "tectonic inheritance" is that the zones of damaged rocks along Paleozoic faults are mechanically more likely than undamaged rocks to rupture under the modern mid-Atlantic stress field, which currently is favorably oriented with respect to the trends of the older Paleozoic structures (Zoback, 1992). On the other hand, there are other examples of young faults in the region that do not appear to be associated with any known Paleozoic fault zones, a prominent example being the previously unknown fault that ruptured in 2011 to produce the Mineral, Virginia earthquake. The relationship between young, potentially earthquake-generating faults and older structures is thus ambiguous, and a subject of ongoing investigation (c.f., Horton and others, 2015, for a summary).

***Seismic Hazard***
Sources of Earthquakes: The *intensity* of shaking and associated damage from earthquakes is rated according to the Modified Mercalli Intensity (MMI) scale (table 8-1). The most recent National Seismic Hazard Maps published by the U.S. Geological Survey (Petersen and others, 2014) indicate Alexandria has a 2% chance of experiencing moderate shaking (MMI V) from an earthquake during the next 50 years, with light expected damage (figure 8-6).

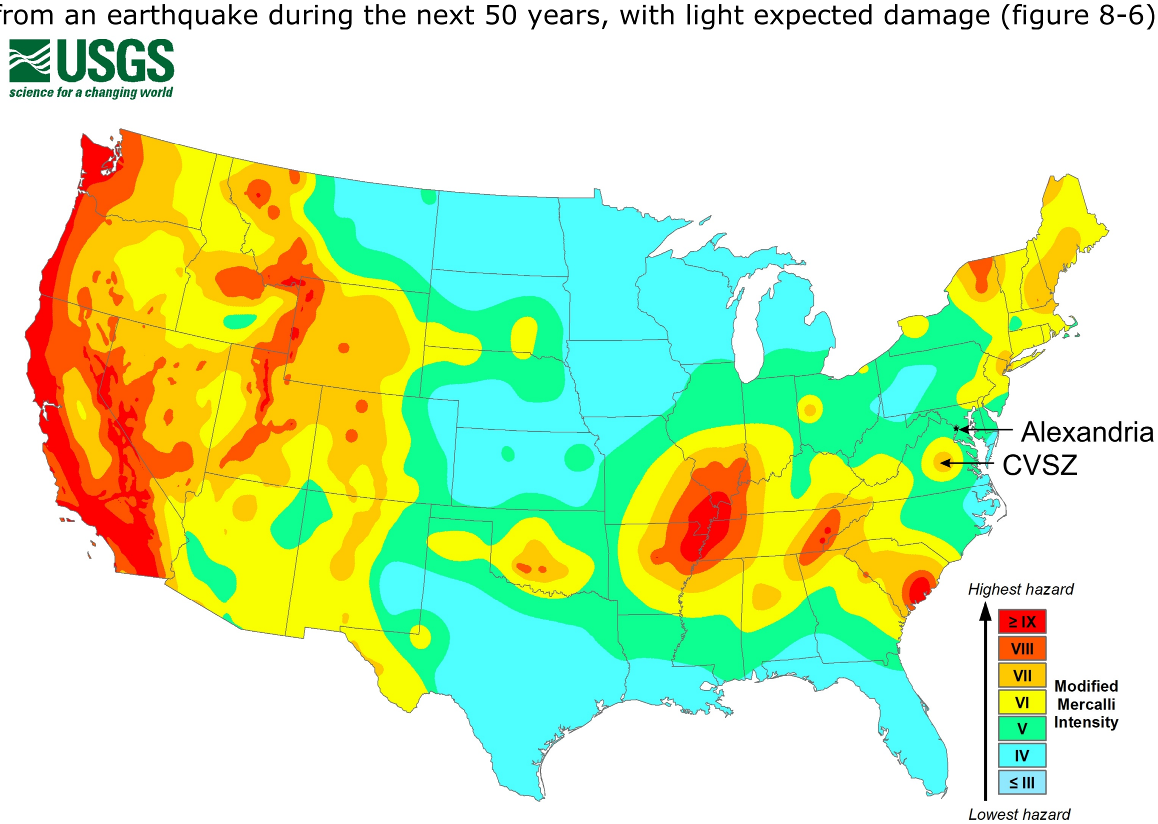


*Figure 8-6. USGS map showing the intensity of potential earthquake ground shaking that has a 2% chance of occurring in 50 years. CVSZ-Central Virginia Seismic Zone. Source: http://gallery.usgs.gov/images/wordpress/20150810/GroundShaking.jpg*

This rating is influenced by a combination of model inputs, including but not limited to the intensity of historical earthquakes and the presence of faults known to offset Quaternary (i.e., young) strata, and generally agrees well with the effects felt during the 2011 Mineral, Virginia earthquake.

| **Magnitude** | **Intensity** | **Shaking** | **Description of Effects and Damage** |
|---|---|---|---|
| 1.0-2.9 | I | Not felt | Not felt except by a very few under especially favorable conditions |
| 3.0-3.9 | II | Weak | Felt only by a few persons at rest, especially on upper floors of buildings |
| | III | Weak | Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated |
| 4.0-4.9 | IV | Light | Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably |
| | V | Moderate | Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop |
| 5.0-5.9 | VI | Strong | Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight |
| 6.0-6.9 | VII | Very strong | Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken |
| ≥7.0 | VIII | Severe | Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned |
| | IX | Violent | Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations |
| | X | Extreme | Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent |
| | XI | | Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly |
| | XII | | Damage total. Lines of sight and level are distorted. Objects thrown into the air |

*Table 8-1. Strength of shaking and associated effects as defined by the Modified Mercali Intensity scale.* Intensity *is defined by observed effects on people, structures, and the natural environment at a specific location and varies with distance from the earthquake epicenter. Magnitude, on the other hand, is measured by seismographs and indicates the amount of seismic energy released at the hypocenter. The relationship between magnitude and intensity is not exact and depends on depth, distance, local geology, and other factors. Adapted from USGS (1989) and other data on the USGS Earthquake Hazards website.*

The closest historical source of earthquakes strong enough to produce this level of shaking is the Central Virginia seismic zone (CVSZ), located about 75 miles south of the city. The CVSZ appears as the “bulls eye” in the middle of the state on figure 8-6, with a maximum MMI rating of VII in the center. Shaking intensity declines with increasing distance from the source—this relationship can be seen in figure 8-2 for the 2011 Mineral earthquake, where felt intensities were on the order of 2 to 3 intensity classes greater at the epicenter than they were in the city 75 miles to the north—hence, it would require a very large earthquake ($M_w$ 7 or more) in the CVSZ to generate even moderately damaging shaking in Alexandria. But as the distributions of felt intensities in figure 8-2 demonstrate, shaking in the Washington area was not evenly distributed during the Mineral earthquake, and should not be expected to be so in future temblors. Local variations in the underlying geology and attendant soil conditions (discussed below) along with the positions of strongly aligned geologic structures that preferentially transmit seismic energy relative to the source and receptor sites (figure 8-3) can greatly influence the local effects of any given quake.

Other fault systems located much closer to the city could also be potential sources of earthquakes, and an event the same size as the Mineral earthquake along one of these faults would produce significantly stronger local shaking due to the proximity of the source.

While none of these more local faults can definitively be shown to have been active within the *Holocene* (the last 11,000 years), or the latest part of the *Pleistocene* (say, the past 100,000 years), absence of evidence is not the same thing as absence of risk. As mentioned elsewhere, evaluating the hazard posed by a particular fault or fault system in the seismically quiescent mid Atlantic is rather challenging for various reasons, perhaps exceeded only by the difficulty and serendipitous nature of discovering them in the first place. Unlike the presumption of innocence employed by the court system, some of these structures, such as the Stafford fault system near Fredericksburg, Darton's fault in Washington, DC, and even the RCSZ below Alexandria, are best considered "suspect" unless and until better evidence emerges to exonerate them as potential seismic hazards.

Shaking and Other Effects: Ground shaking is either directly or indirectly responsible for the damage produced by earthquakes. Direct effects include damage or destruction of structures during the shaking, whereas indirect effects commonly involve catastrophic failure or alteration of the landscape via *landslides*, *liquefaction*, or *tsunamis*. Shaking is produced by the motion of several kinds of *seismic waves* travelling through the earth. In general, the greatest shaking and damage result from surface waves, which travel slowly in a two-dimensional, horizontal direction, producing strong vertical motion of the ground surface. Likewise, shallow earthquakes tend to produce greater shaking and damage than do deep-seated earthquakes of similar magnitude.

As noted in figure 8-2 and table 8-1, however, shaking is not uniformly distributed across the landscape: among sites located at the same distance from a seismic source, the intensity of shaking varies greatly according to local geologic conditions. Soft soils amplify shaking because they transmit seismic waves inefficiently, resulting in strong vertical motion as the waves pass. In contrast, solid bedrock and stiff, *overconsolidated* sediments like much of the Potomac Formation transmit seismic waves more efficiently, allowing them to pass quickly with less vertical acceleration at the surface. Saturated soils and places where the water table lies relatively close to the land surface are also prone to indirect damage via liquefaction: the motion of surface waves produces extreme changes in pore pressure that cause soil particles to move apart, resulting in catastrophic loss of strength.

Given the diverse surficial geology of Alexandria, it is reasonable to expect the intensity of shaking from a hypothetical earthquake to vary considerably from place to place. In this context, it is worth noting that the ground shaking intensity ratings in the seismic hazard map in figure 8-6 assume "average" soils (class C, see table 8-2), ergo, it is likely that some parts of Alexandria are susceptible to more intense shaking than the average value represented by the map. The internal sedimentary variability of many geologic units in Alexandria, however, makes predictions about shaking intensity problematic at anything but a fairly broad scale: more exacting estimates depend on site specific geology as well as the modifications to the site that have occurred since settlement.

As the foregoing statement implies, *artificial fill* presents a particular concern for seismic hazard assessment. Large areas underlain by artificial fill are widely understood to pose an elevated risk of damage to infrastructure from earthquakes: a clear example comes from San Francisco, where the most widespread damage from both the 1906 and 1989 earthquakes occurred in districts built on fill (USGS, 2015). Fill tends to be looser than native soils and is often composed of heterogeneous mixtures of material whose physical properties are highly variable in both the lateral and vertical dimension, making it difficult to characterize. The depth can vary widely over short distances, and multiple generations of fill are commonly present in areas that have been settled the longest. In addition, fill is commonly emplaced over formerly wet areas, adding the further disadvantage of a high water table. For all these reasons, seismologists and hazard planners typically rate artificial fill as among the worst categories of soil for seismic risk (c.f, Holzer and others, 2002; Hitchcock and others, 2008).

The National Earthquake Hazards Reduction Program (NEHRP) defined five soil types based on their *shear wave velocities* (Building Seismic Safety Council, 2000), and subsequently added a sixth, more problematic category (BSSC, 2003). They are listed in table 8-2.

| **Soil Type** | **Velocity (Vs) (ft/second)** | **Amplification Potential** | **Typical Lithologic Description** |
|---|---|---|---|
| A | Vs >5,000 | Negligible | Very hard unweathered granite |
| B | 2,500 < Vs ≤5,000 | None or very low | Moderately hard bedrock types |
| C | 1,200 < Vs ≤ 2,500 | Low | Soft weathered bedrock, very dense soil and unconsolidated sediments |
| D | 600 ≤Vs ≤ 1,200 | Moderate | Stiff soil and unconsolidated sediments |
| E | Vs < 600 | High | Soft muds, water saturated sediments, some artificial fill |
| F | Unknown | Potentially high | Soft or highly plastic clays, organic sediment, artificial fill. By definition, type F requires site specific evaluation |

*Table 8-2. NEHRP soil types. Shear wave velocity is related to the ability of a soil to amplify seismic waves and increase shaking. Amplification of surface waves becomes progressively stronger proceeding from type A to type E. In this classification, the term "soil" is used in a generic, engineering sense to refer to the substrate that underlies a building foundation.*

In practice, the NEHRP soil classification requires in-situ measurements of shear wave velocity in order to be applied effectively. It is typically used to characterize individual building sites where seismic velocities have been obtained or where other geotechnical data (e.g., blow count, plasticity index) are sufficiently well constrained to serve as a proxy.

The NEHRP soil rating system has also been adapted for the purpose of producing potential shaking intensity maps (sometimes referred to shaking amplification maps) based on local soil conditions, primarily in California and other high-seismic-risk locations (e.g., Holzer and others, 2002 and 2005; Haase and others, 2011a). The quantitative classification of map polygons under this scheme requires a combination of detailed geologic mapping and a relatively large body of empirical shear wave velocity data measured in the geological units present in the map area. The former is available for Alexandria (**plate 5**, this atlas), but shear wave velocities are poorly known, with measured velocities reported at just a handful of relatively recent geotechnical boring sites, mainly in Old Town. A significantly larger body of shear wave velocity data would be needed to generate a quantitative map of potential shaking intensity at the same scale as the other plates in this atlas.

Enough is understood about the distributions and general characteristics of the geologic units, however, to qualitatively rank the shaking potential of different parts of the city relative to one another, and to highlight certain subsurface characteristics that could be at least locally problematic during a seismic event (figure 8-7).

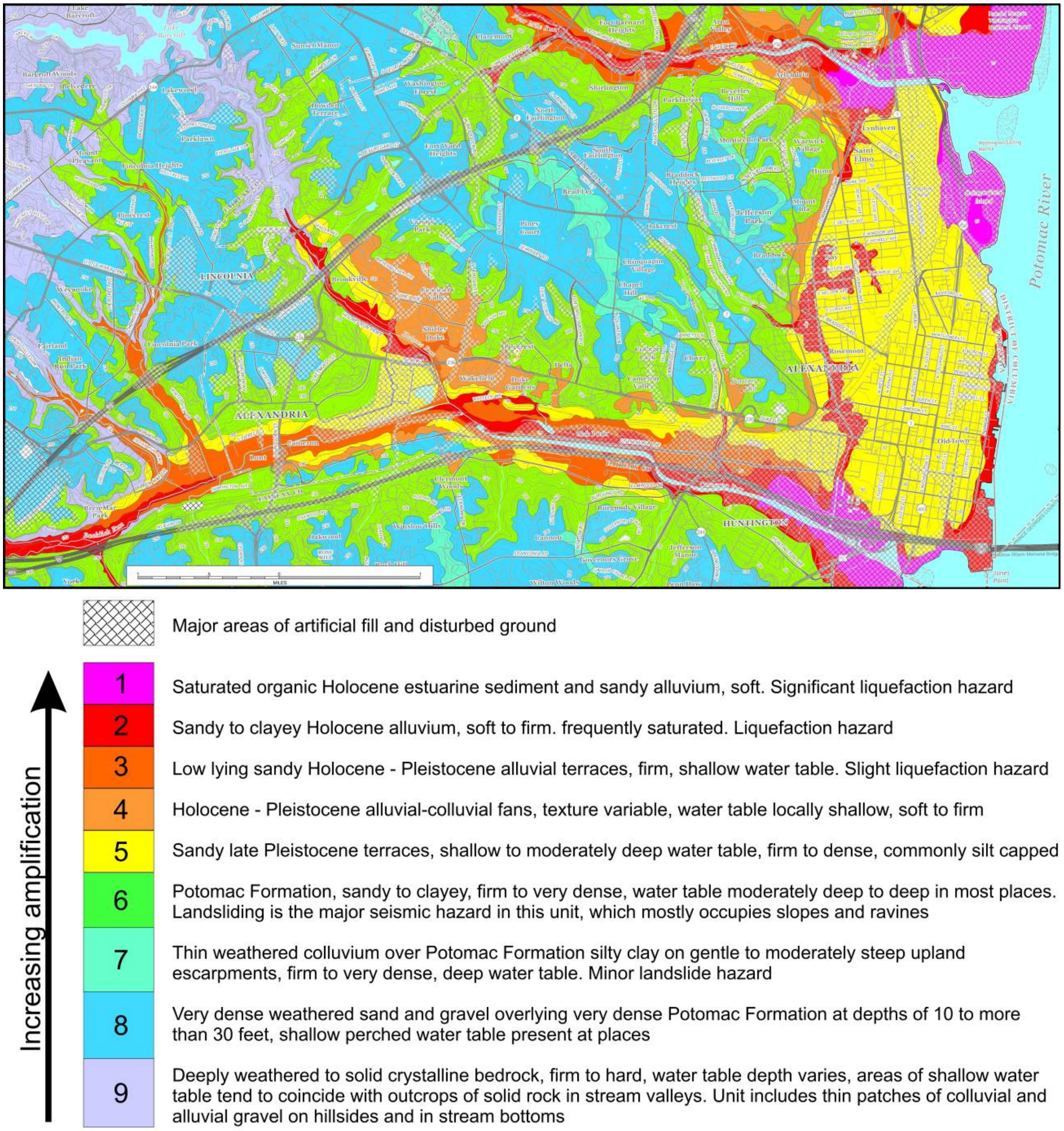


*Figure 8-7. Map showing estimated relative potential for amplification of seismic waves in relation to surficial geology. Major areas of artificial fill are indicated with an overlay and have the potential to rank at or near the top for amplification of earthquake shaking, depending on how well they were compacted when emplaced, water table depth, and other factors. Lack of in situ measured shear wave velocities precludes definitive assignments of seismic soil classes, but based on their geologic and geotechnical characteristics, units 1-2 probably fall into soil classes E-F, units 3-4 into class D, unit 5 into classes C-D, and units 6-7-8-9 into class C, with some areas of unweathered crystalline bedrock in unit 9 potentially in class B. Inclusions of more and/or less amplification-prone soils are likely within most of the map units because of the small scale of the map and the natural variability in lithology, weathering history, and water table depth within the underlying geologic units.*

### ***Identifying Faults and Geologically Recent Fault Motion in the Map Area***

As noted in figure 8-3, major fault systems project towards Alexandria from both the south (Stafford fault system/Spotsylvania fault) and the north (Rock Creek shear zone), and both systems consist of old *ductile* bedrock faults that have been reactivated by much younger faulting that cuts Coastal Plain strata and upland river terraces. Further, the large aeromagnetic lineament that defines part of the Rock Creek shear zone (RCSZ) continues southward through Alexandria (**plate 3**; figure 8-8); since aeromagnetic anomalies are caused by bedrock structures, it is virtually certain that the Paleozoic fault system of the RCSZ also continues southward beneath Alexandria. Daniels (1980) also interpreted this aeromagnetic feature as a fault zone, before the RCSZ even was recognized in the field.

Based on the trend of the aeromagnetic anomaly, Fleming and Drake (1998) postulated that the fault connects with another Paleozoic shear zone with similar characteristics exposed near the Town of Occoquon (Heimgartner, 1995; Davis and others, 2001), very close to the northernmost mapped extent of the Stafford fault system. Likewise, geologists have long speculated that the Stafford fault system projects into the Alexandria-Annandale area (Mixon and Newell, 1977; Drake and Froelich, 1986; Froelich, 1985), and Powars and others (2015) recently postulated a connection beneath Alexandria between it and the young faults associated with the RCSZ in DC. Considering the totality of the evidence, one or more post-Cretaceous fault zones seem highly likely beneath Alexandria. The question is, where?

For a variety of reasons, post-Cretaceous faults may not be readily apparent, either in the field or in subsurface data, and when they are found, it is usually very difficult to ascertain a precise age for the most recent movement. In the first instance, the soft, poorly consolidated Coastal Plain sediments where these young faults are most easily recognized tend to make fewer, smaller, and more ephemeral outcrops (relative to the crystalline bedrock). It is also difficult to recognize faults from subsurface data because reliable, continuous lithological markers are not regularly distributed, especially in the Potomac Formation, with its many abrupt *facies* changes. Moreover, most such data in the city consist of anecdotal accounts of decades-old water wells, or geotechnical borings where stratigraphic descriptions are not always specific because the objectives of drilling are different. Finally, the densely urbanized character of the map area obscures many geologic features. While urbanization can be both good and bad for geologic exploration—it creates many temporary exposures, assuming someone is available to document the geology—it has covered over many ravines in the city, where the best natural exposures typically occur. Therefore, it is highly unlikely that most Coastal Plain faults are going to be found, barring a fortuitous exposure. More often than not, faults end up being inferred from indirect evidence that ranges widely in character and quality. The catalog of faults and other features of interest in the following section gives a sense of that process.

But even when a young fault is seen in outcrop, documenting the movement history is challenging. For starters, most of the faults observed in outcrop in the map area are exposed in the bottoms of ravines. Ergo, usually all that can be seen is offset of the Paleozoic bedrock, the bedrock surface, and(or) the Potomac Formation. All that can be said in these places is that fault motion occurred sometime during the last ~131 million years.

In rare cases where a fault can be observed to cut one of the upland terraces (figure 8-1) or even inferred to, as is the case with the Fort Williams fault, lack of positive age control on these upland gravel deposits limits estimates of fault motion only to the last several million years—not helpful for getting a firm handle on the seismic hazard they pose. New methods of dating involving *cosmogenic isotopes* may eventually enable the ages of the upland terraces and lower terraces along modern streams to be determined, providing better time constraints on the evolution of the local landscape and the faults that cut it.

A more indirect, but equally effective method of relatively dating seismic activity is the presence of liquefaction structures in young sediments, such as modern *alluvium* or estuarine sediment along streams. Liquefaction typically occurs in saturated sediment with a high sand content when strong shaking (such as from surface seismic waves) compresses the water between the grains, causing pore pressures to rise so much that they exceed the frictional forces at the grain-to-grain contacts. At that point, the sediment behaves as a viscous liquid and flows, creating cross cutting dikes and other distinctive soft sediment structures, and sometimes erupting to the surface as sand volcanoes, or sand blows. The types of sediments commonly affected by liquefaction often contain organic matter that can be dated by radiocarbon methods, providing a maximum age for the seismic event.

While dating liquefaction structures doesn't pin down the age of motion on a specific fault, it does indicate the occurrence of strong local earthquakes in relatively recent geologic history—a magnitude greater than 6.5 is typically needed to trigger liquefaction in coarse-grained granular sediments—which is useful for estimating seismic hazards. In fact, the size of liquefaction structures, and the percentage of the ground surface they cover, are directly related to the intensity of shaking and can be used to infer the location and strength of large prehistorical earthquakes (Obermeier, 1996; 1998). With all of the construction activity in the Cameron and Four Mile Run Valleys and along the Potomac waterfront, it seems likely that liquefaction features will be uncovered in excavations—if they haven't already been—but the question is whether they will be recognized for what they are.

### *Catalog of Faults and Other Suspect Structures*

This section contains descriptions of faults, potential faults, and suspect structures that may signify nearby faults. The information is presented in catalog format, with a separate entry for each structure (22 in all) that consolidates and expands on information from other parts of the atlas as well as from other sources. Each entry includes: specific location of the feature; strata and/or landforms involved; type of fault-related fabric or structures, if present; where in this atlas (e.g., plates or cross sections) the structure appears, and, if recognized by previous workers, in what body of work; and a discussion of the potential significance of the feature.

The features described herein are numbered and indexed to the map in figure 8-8. Each feature is also assigned to one of several categories, listed in the header of each entry:
-Faults observed in the field: these are actual fault planes or fault zones observed in outcrop. Most were observed during fieldwork for the atlas, but a few were documented by previous workers and not found during the present study
-Inferred fault: there is only one in the catalog. Although no fault zone was observed in the field, other indirect evidence for a fault is very persuasive
-Aeromagnetic lineaments: these are manifested by sharp anomalies—usually pronounced gradients—on the regional aeromagnetic map. Such anomalies commonly coincide with major bedrock fault zones in places where bedrock is exposed, and one of the lineaments aligns directly with a major fault zone to the north of the map area
-Topographic lineaments: these were observed on the Alexandria digital elevation model or the topographic base map, and correspond to strongly aligned topographic features such as escarpments, bluffs, and drainages
-Features of interest: This is a broad category encompassing a wide range of structural, topographic, and borehole features that appear "suspect". To use a familiar analogue, "features of interest" are like "suspects of interest" at a crime scene: they seem to turn up in the wrong places and have sketchy alibis

All sites are within the City of Alexandria unless noted otherwise in the location description.

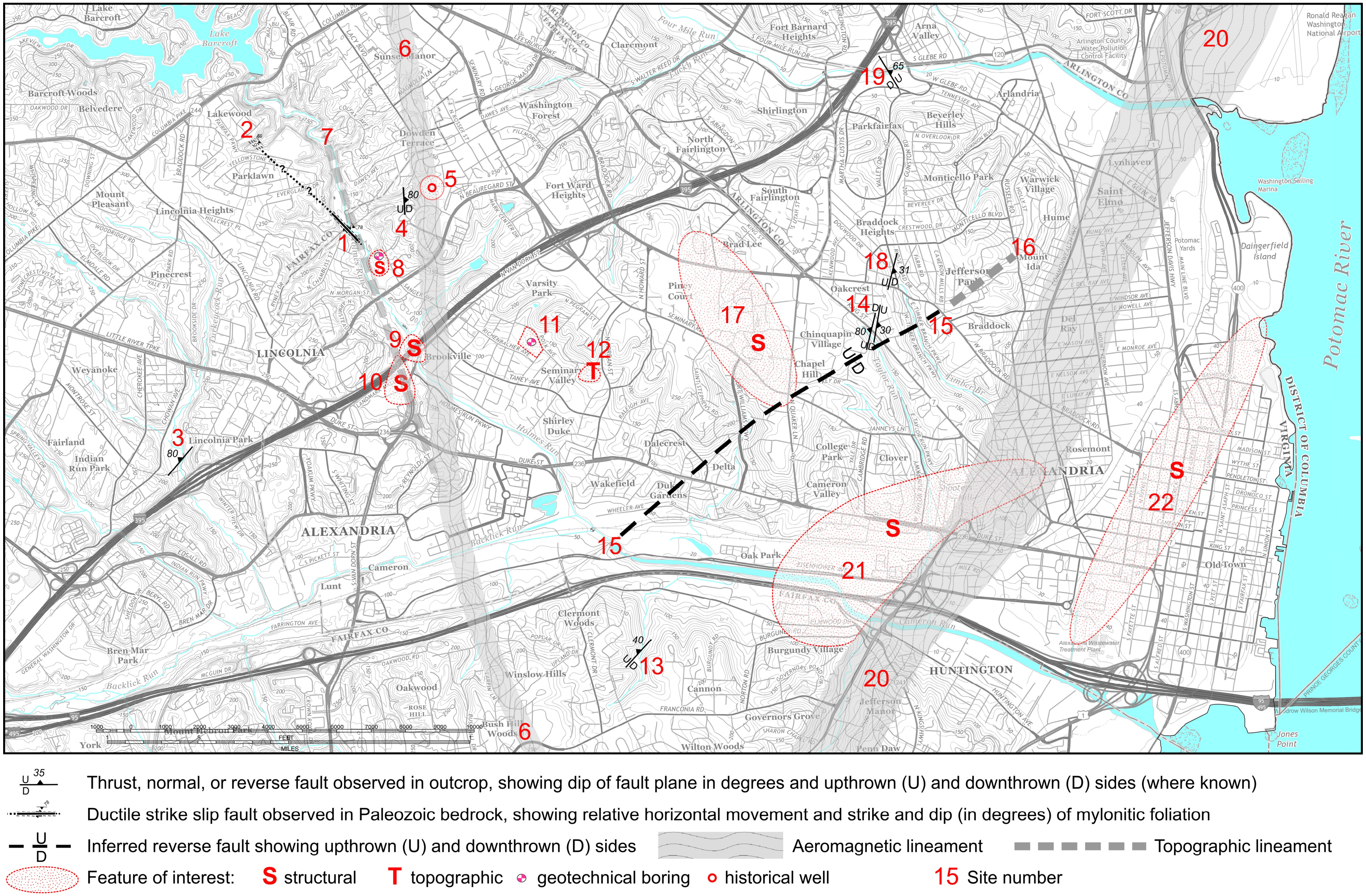


*Figure 8-8. Index map of faults, lineaments, and other features of interest discussed in this section.*

**Site: 1** **Category: Fault observed in outcrop**

Location: Holmes Run at Fairfax Co line (exposures 150-151)
Youngest strata affected: Occoquon Granite (Ordovician)
Fault fabric: ductile mylonite
Appears on: plates 3 and 5, cross section J-J'
Discussion: This fault comprises a narrow zone of *mylonite* with a maximum observed width of about 25 feet. It is exposed in a series of outcrops on the west bank of Holmes Run extending about 100 feet downstream from the mouth of Rynex ravine. The fault is primarily in Occoquon granite, except right at the mouth of the ravine, where it appears to juxtapose a narrow body of schist (west wall of fault) against granite (east wall). At least two mylonitic fabrics are present (see figure 3-12); the latest motion appears to have been oblique *dextral strike slip* with a west-side-up component. The *foliation* associated with this latest mylonitic fabric strikes about N45W and dips 78SW. No brittle structures have been observed along this fault and, as far as known, it is strictly a *Paleozoic* structure that does not deform any strata above the bedrock. It may be contiguous with the structure in #2. This fault lies directly on a strong topographic lineament (site 7), but the relationship is ambiguous because the orientations of these two features diverge by about 30 degrees.

**Site: 2** **Category: Fault observed in outcrop**

Location: Ravine below Glasgow School, Fairfax Co. (exposure 196)
Youngest strata affected: Falls Church Tonalite (Ordovician)
Fault fabric: ductile mylonite
Appears on: plates 3 and 5
Discussion: This fault is expressed by a narrow zone of variably sheared *tonalite* with a maximum observed width of about 75 feet. It is exposed in a series of mostly *saprolite* outcrops in the streambed, starting about 950 feet upstream of Holmes Run. Mylonitic foliation strikes about N50W and dips 80 SW. The core of the fault zone is intruded by a large body of massive quartz and several smaller ones (see figure 3-12). None of the quartz is shattered. The fault is entirely within Falls Church Tonalite; sparse fault fabric indicates late oblique dextral strike-slip motion, similar to the fault at site #1, with which it may be contiguous or related. Alluvium and colluvium are well exposed at several places above the bedrock along the streambanks in the fault zone; there is no evidence that the fault cuts anything other than tonalite, nor were any brittle structures observed that might suggest post-Paleozoic motion.

**Site: 3** **Category: Fault observed in outcrop**

Location: Turkeycock Run, approx. 500 feet upstream of Shirley Highway, Fairfax County
Youngest strata affected: Occoquon Granite (Ordovician)
Fault fabric: unknown
Appears on: plates 3 and 5
Discussion: This fault was mapped by Drake and Froelich (1986) on the Annandale Geologic Quadrangle. It is described as a "small fault seen in outcrop", with a strike of about N40E and dip of 80 NW. No other description is provided. This fault was not observed during the present study. Based on their map, it is presumed to be a bedrock fault of Paleozoic age.

**Site: 4** **Category: Fault observed in outcrop**

Location: Chambliss Park, 700 feet due south of Fairfax Co line (exposure 153)
Youngest strata affected: Base of Potomac Formation (early Cretaceous)
Fault fabric: brittle – breccia, folding, rotated blocks of bedrock in Potomac Formation
Appears on: plates 3, 4, and 5; cross section J-J'
Discussion: This fault is exposed in a steep natural cut on the south bank of the ravine that runs through Chambliss Park, about 10 feet downstream of the confluence of two forks of

the ravine. It is easy to miss: the exposure is frequently obscured by major slumping and undermining of streambank; quality of exposure depends on recent flooding to remove slumped material; manual cleaning of the outcrop is usually required. This is a small *reverse fault* with west-side-up motion that offsets the bedrock surface/base of the Potomac Formation by less than 5 feet. The fault strikes about N5W and dips about 80 E. Relations are somewhat confusing (figure 8-9) due to apparent blocks of bedrock floating in the fault zone, but the bedrock surface appears to be at least 2-3 feet higher on the west (upthrown) side. The lowermost several feet of the Potomac Formation on the east side of the fault consists of coarse, thoroughly weathered gravel interbedded with green silt; this basal gravel appears to be truncated at the east wall of the fault—whereas the overlying crossbedded sand appears on both sides of the fault—which might indicate that motion occurred during the early Cretaceous, as the Potomac Formation began being deposited.

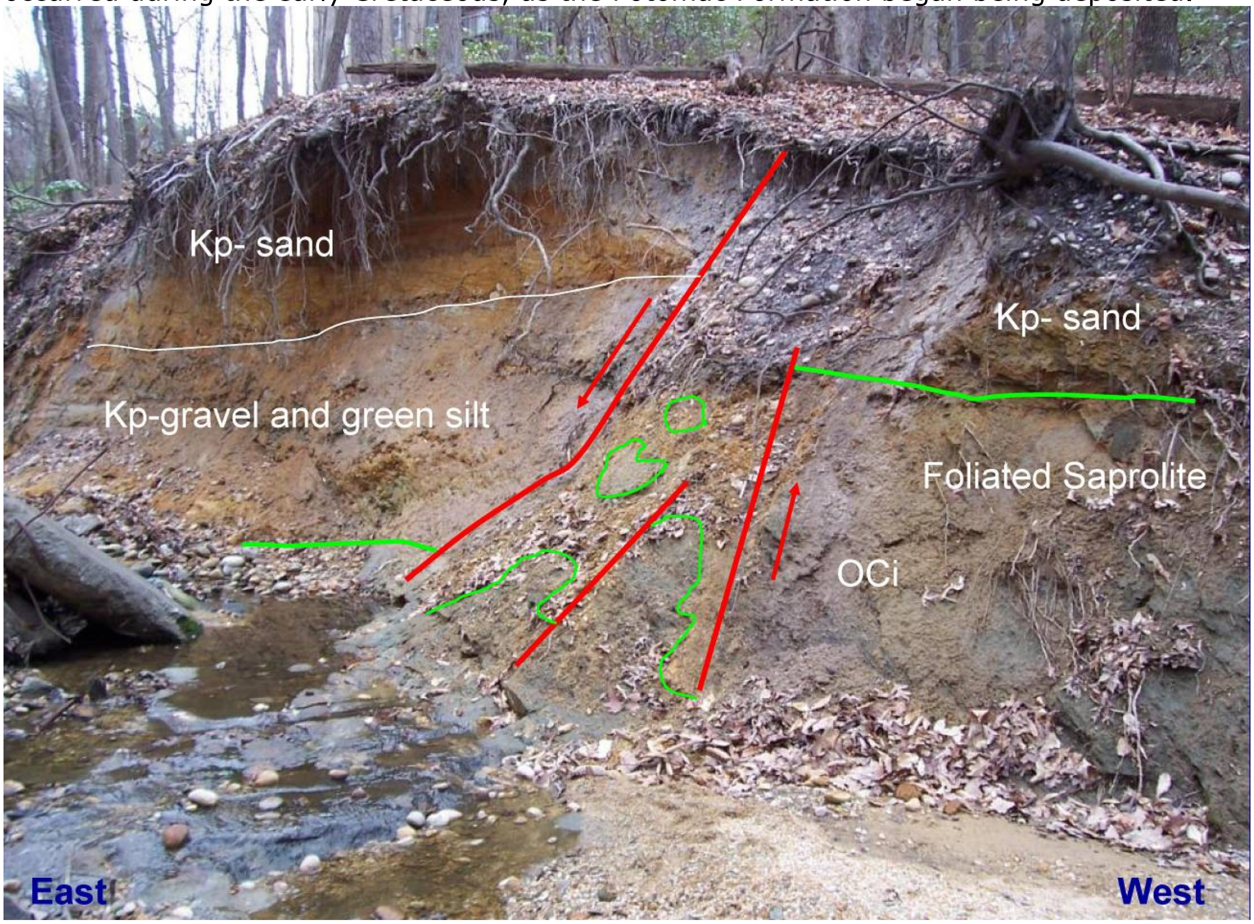


*Figure 8-9.The Chambliss Park fault. Red lines and arrows denote fault walls and sense of motion, respectively. Heavy green line denotes bedrock surface on the Indian Run Formation (OCi). The base of the Potomac Formation (Kp) on the east side of the fault consists of coarse gravel interbedded with green silt, whereas it is sand on the west side. The zone in the middle appears to consist of blocks of bedrock (outlined in green) floating in Potomac Formation sand (Kp). West is to the right. The gravel at the top of the cut is colluvium. Photo by Tony Fleming.*

The Chambliss Park fault is close to two other features of interest: it is less than 250 feet west of a prominent aeromagnetic lineament (site 6), and about 800 feet southwest of a historical water well (J-42; site 5). As illustrated in figure 8-10, the bedrock surface appears to slope sharply eastward between the Chambliss Park fault and well J-42.

**Site: 5** **Category: Feature of Interest**

Location: Dowden Terrace
Type of Feature: historical public water supply well catalogued by Johnston (1961)
Appears on: plate 1 (well #42); cross section J-J'; Johnston (1964); Froelich (1985)
Strata affected: lower Potomac Formation (early Cretaceous); bedrock surface (Ordovician)
Discussion: This well is reported to have encountered the bedrock surface at an elevation of 110 feet—some 60 feet lower than the bedrock elevation in outcrop at site 4 (Chambliss Park) about 800 feet to the southwest (figure 8-10). This translates to an unusually steep bedrock surface slope of almost 400 feet per mile between the two sites, nearly 4 times the regional average. In addition, the well penetrates the lower 110 feet of the Potomac Formation, which was interpreted by Froelich (1985; the basis of this interpretation is not stated) to contain "0% sand", in other words, all clay. If correct, this is also rather unusual, considering that the lower 100+ feet of the formation in this part of the map area is predominantly sand, as seen in exposures and described in other borings (c.f., cross sections **I-I'** and **J-J'**). The sharp bedrock surface gradient and near-complete change from sand to clay between sites 4 and 5 suggest the potential of a fault; alternately, the lithological differences may reflect a somewhat more gradual *facies* change, as shown in cross section J-J'. This site also lies within the aeromagnetic anomaly described at site 6.

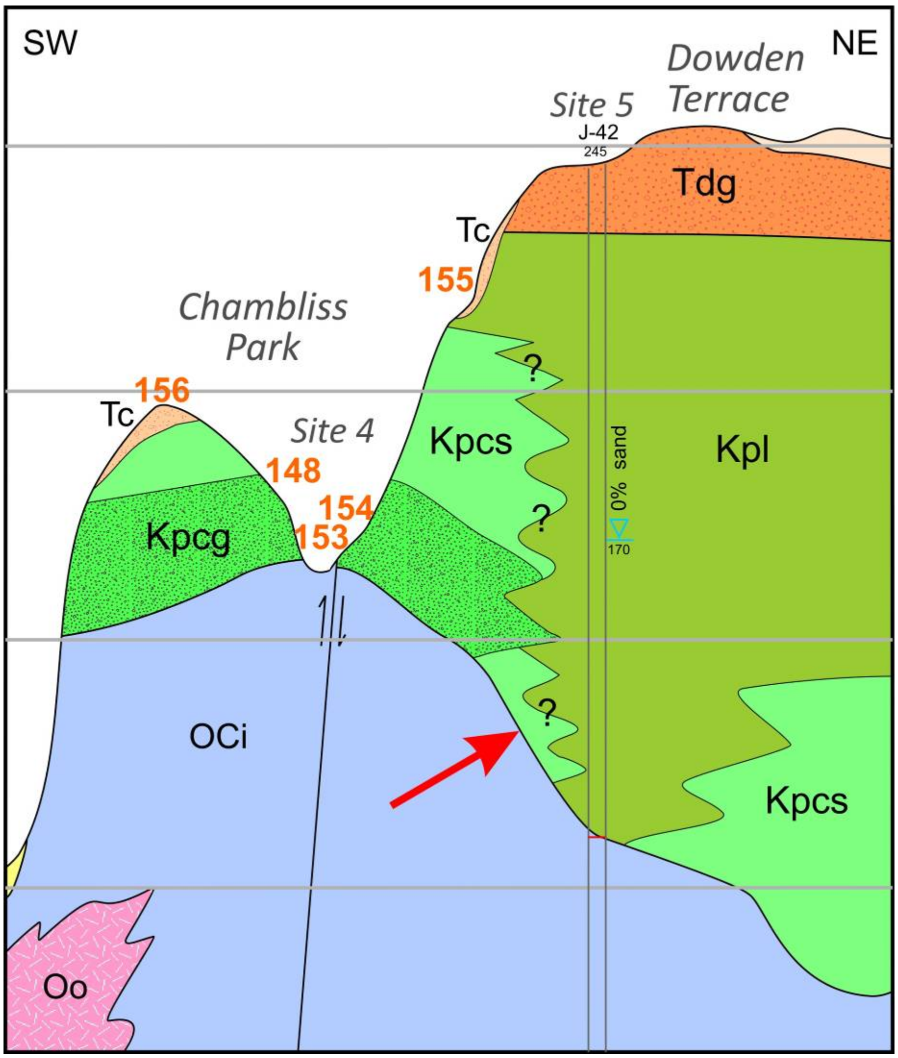


*Figure 8-10. Part of the Northwest cross section (**plate 2J**) illustrating apparent relations of the bedrock surface (red arrow) and Potomac Formation between sites 4 and 5. Light gray horizontal lines are 50-foot elevation reference lines. Orange numbers are outcrops. Geologic units are: Tc, Tdg – upland colluvium and terrace gravel; Kpcs, Kpcg – Potomac Fm, Cameron Valley sand member; Kpl – Potomac Fm, Lincolnia silty clay member; Oo – Occoquon granite; OCi - Indian Run Fm. Width of cross section: about 3,200 ft. The cross section in this figure has been modified to show the interval of Potomac Formation in well J-42 to contain "0% sand" as interpreted by Froelich (1985), an interpretation the author of this atlas is skeptical of for various reasons.*

**Site: 6** **Category: Aeromagnetic lineament - potential bedrock fault**

Location: Extends southward across the map area from near Baileys Crossroads to Bush Hill Woods in Fairfax County. Broadly parallels the east rim of Holmes Run Gorge in the northern part of map area, eventually merging with a much larger aeromagnetic lineament (feature #20) near Hybla Valley south of map area

Appears on: plate 3

Discussion: Moderately strong aeromagnetic gradient, parallels Holmes Run Gorge and continues south-southeastward across the Cameron Valley, following a series of linear topographic sags to its convergence with the RCSZ lineament near the northwest corner of Hybla Valley. The source of this anomaly is in the bedrock, but remains unclear because the feature largely lies outside of the area where bedrock crops out. The southern and central segments of the anomaly coincide in part with the contact of the Occoquon Granite, which is probably responsible for the strong gradient on the west side of the lineament, but the origin of the rest of the lineament cannot be related directly to any known geologic feature. Potentially represents a zone of damaged bedrock susceptible to hosting younger faults.

**Site: 7** **Category: Topographic lineament**

Location: Parallels Holmes Run for about 10,000 feet between Lincolnia (Duke x Reynolds Sts) and Glasgow School

Appears on: Annandale 7.5-minute topographic quadrangle and Alexandria DEM (fig. 8-11)

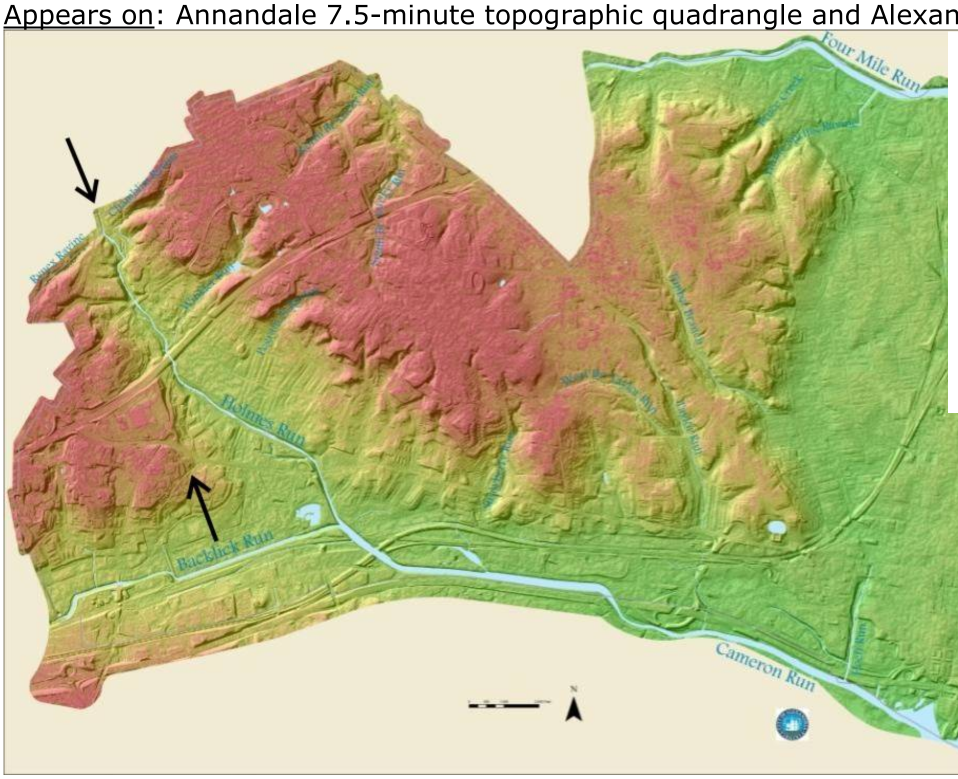


*Figure 8-11. Topographic lineament (between arrows) along Holmes Run Gorge, as seen on the Alexandria digital elevation model.*

Discussion: Strong, straight topographic lineament oriented at N18W trends slightly oblique to the walls of Holmes Run Gorge. Approximately the southern third of the lineament is defined by a series of sharp, straight bluffs on the west rim of the gorge, mostly developed on the Potomac Formation. The northern part is defined by the straight *thalweg* of the bedrock gorge. Upstream of about Beauregard Street, the walls of the gorge and its tributaries have numerous rectilinear aspects suggestive of fracture- or joint-controlled valley walls. The lineament is spatially associated with at least three places (sites 8, 9, and 10) characterized by short, steep gradients on the bedrock surface. None of these bedrock slopes are sufficiently tall to be evident at the scale and bedrock contour interval in plate 3. Instead, they are suggested by site specific data.

**Site: 8** **Category: Feature of Interest**

Location: Ramsay Elementary School/Ford Nature Center, 5750 Sanger Ave
Type of Feature: geotechnical boring site
Appears on: plate 1 (GTB #87); cross section I-I'
Strata affected: lower Potomac Formation (early Cretaceous); bedrock surface (Ordovician)
Discussion: Several geotechnical borings within a relatively compact site define a sharp, south-facing slope on the bedrock surface that appears almost scarp-like at the scale of cross section I-I' (figure 8-12). Precise identification of the bedrock surface is complicated in some of the borings by weathering that caused the consultant to confuse dense, tan-orange-gray, silty, micaceous sand at the base of the Potomac Formation with "bedrock residuum". Nevertheless, there is at least 24 feet of relief on the bedrock surface over a distance of no more than about 250 feet—considerably steeper than the regional average. No faults are known from the outcrops adjacent to the nature center, however, the site is sandwiched between the topographic lineament just to the south (site 7) and the aeromagnetic lineament to the north (site 6), is almost directly online with the bedrock fault mapped upstream (site 1), and is not far offline of the post-early Cretaceous fault in Chambliss Park (site 4). Ergo, a fault at this site would not be totally surprising. On the other hand, a considerable amount of local erosional relief is evident on the bedrock surface in this part of Holmes Run Gorge.

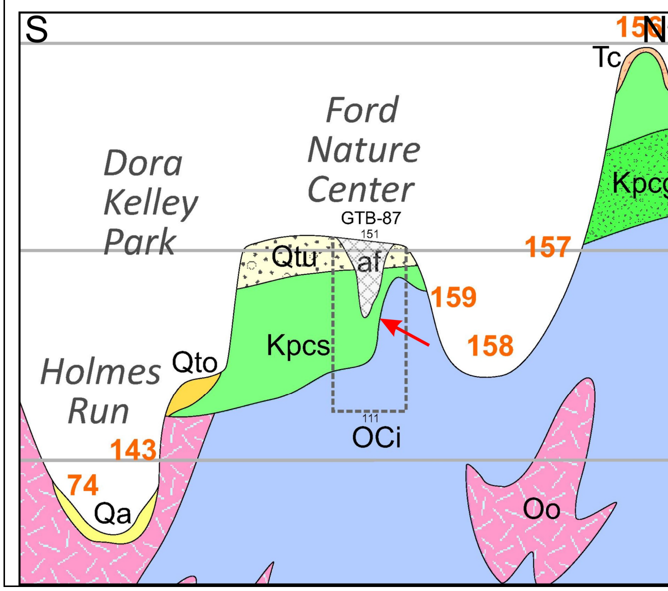


*Figure 8-12. Part of the Van Dorn St. cross section (plate 2I) illustrating the sharp bedrock surface slope (red arrow) beneath Ramsay Elementary School/Ford Nature Center (site GTB-87). Light gray horizontal lines are 50-foot elevation reference lines. Orange numbers are outcrops shown on plate 1. Geologic units are: af – artificial fill; Qa – modern alluvium; Qtu, Qto – late Pleistocene stream terraces; Tc – colluvium; Kpcs, Kpcg – Potomac Formation, Cameron Valley sand member; Oo – Occoquon granite; OCi - Indian Run Formation. Width of cross section: about 2,800 ft.*

**Site: 9** **Category: Feature of Interest**

Location: Holmes Run x Shirley Highway (Brookville)
Type of Feature: Outcrops and geomorphic evidence of steep bedrock surface slope
Appears on: plate 1; cross section L-L'
Strata affected: lower Potomac Formation (early Cretaceous); bedrock surface (Ordovician)
Discussion: Cross bedded sand at the base of the Potomac Formation overlying weathered Occoquon Granite was observed in exposure #35 in a bank behind an apartment building adjacent to Shirley Highway at 5400 N Morgan St. Here, the elevation of the *bedrock surface* is 125 feet (figure 8-13). Just a few hundred feet to the east, bedrock also crops out in the bed of Holmes Run between Shirley Highway and Paxton Street, at elevations ranging between 60 and 75 feet. The Potomac Formation crops out extensively around Paxton Street, where the elevation of the basement *unconformity* can reliably be measured at about 60 feet. The Potomac Formation is also inferred to lie just below the modern *alluvium* and *Quaternary* stream terraces at Brookvalley Park, closer to Shirley Highway, based on a

few small streambank exposures of dense, green-gray sand and silt. These relations indicate that the bedrock surface (i.e., sub-Cretaceous unconformity) slopes sharply northward, falling about 50 feet or more over a horizontal distance of less than 700 feet, or roughly 400 feet per mile. The same considerations discussed for site 8 apply to this site as regards the potential presence of faulting and its influence on bedrock surface structure.

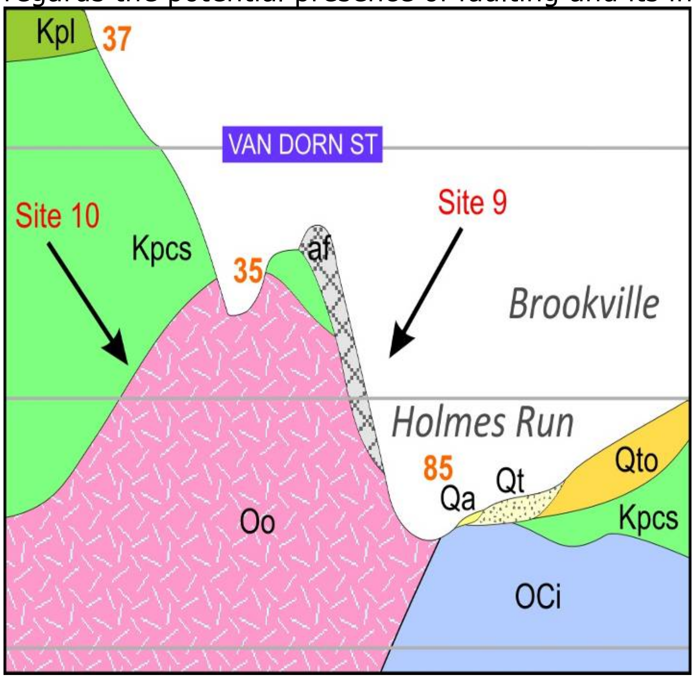


*Figure 8-13. Part of the Shirley Highway cross section (**plate 2L**) illustrating the relatively steep bedrock surface slopes (arrows) at Brookville (site 9) and beneath Landmark (site 10). North is to the right. Light gray horizontal lines are 50-foot elevation reference lines. Orange numbers are outcrops. Geologic units are: af – artificial fill; Qa – modern alluvium; Qt, Qto – late Pleistocene stream terraces; Kpcs – Potomac Formation, Cameron Valley sand member; Kpl –Potomac Formation, Lincolnia silty clay member; Oo – Occoquon granite; OCi - Indian Run Formation. Width of cross section: about 3,300 ft.*

**Site: 10** **Category: Feature of Interest**

Location: Below Landmark Mall (Shirley Hwy x Van Dorn St.)
Type of Feature: Cross section interpretation of bedrock surface
Appears on: plate 1; cross sections I-I' and L-L'
Strata affected: lower Potomac Formation (early Cretaceous); bedrock surface (Ordovician)
Discussion: The slope on the bedrock surface here does not appear to be as steep as at the two previous sites; however, both the existence and pitch of a bedrock slope at this site is largely a matter of interpretation, specifically involving the position of the bedrock valley shown on **plate 3** and cross sections **I-I'** and **L-L'**. The challenges associated with identifying the course of this valley through the heavily urbanized Landmark area are discussed in the **expanded explanation of plate 3**—the bedrock valley is well defined at Green Spring Garden Park (Pinecrest) in the western part of the map area, but becomes increasingly difficult to trace eastward—and it is possible no such feature exists at this location. Ergo, the evidence for an unusually steep bedrock surface slope and potential fault influence at site 10 is the weakest of the three sites (8, 9, and 10) along the topographic lineament (site 7).

**Site: 11** **Category: Feature of Interest**

Location: James Polk Elementary School, 5000 Polk Street
Type of Feature: geotechnical boring site showing abrupt lithological change
Appears on: plate 1 (GTB #82A and 82B); schematic diagrams of geotechnical boring sites
Strata affected: Potomac Formation (early Cretaceous)
Discussion: Two sets of boring logs from James Polk School show completely different lithologic characteristics in the same 30- to 45-foot thick interval of Potomac Formation. The two boring sets are less than 250 feet apart at their closest point. This site is interpreted to

lie very close to the contact between the Lincolnia silty clay and the underlying Cameron Valley sand members (see **plate 4**) based on the evidence from outcrops and geotechnical boring sites in this part of the city. As **discussed elsewhere**, this contact ranges from razor sharp to highly gradational with large-scale interbedding of the two lithofacies over tens of feet of vertical section. Thus, while it is more likely that the lithological differences between the two boring sets beneath Polk School simply represent a sharp local facies change, the possibility of a tectonic influence cannot be entirely discounted. Other evidence of faults is lacking from the immediate area, however, including local data on bedrock surface elevations which could help to sort out the possibilities, so this site does not rate very highly as a potential fault candidate.

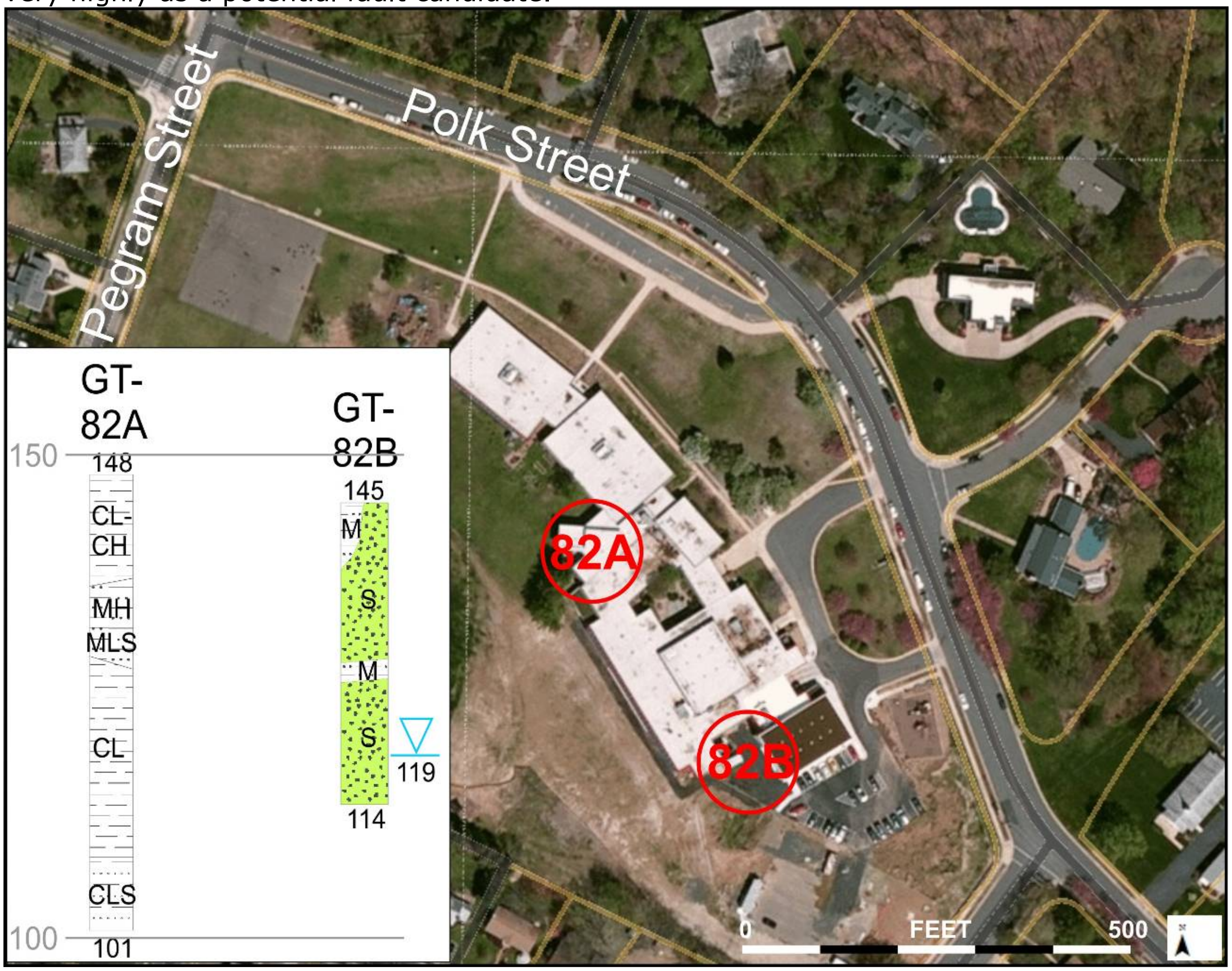


*Figure 8-14. Aerial photograph of James Polk Elementary School (GTB #82) showing the locations of the two sets of geotechnical borings, which are illustrated by the schematic summary diagrams in the inset. Site 82A includes 4 borings for the library addition, all of which consisted entirely of variably sandy silts (MH, MLS) and silty clays (CL, CH, CLS) typical of the Lincolnia silty clay member of the Potomac Formation. Site 82B consists of three ground water monitoring wells at a former UST site, all of which penetrated dense, green-gray sand (S) with minor sandy silt layers (M), presumably the Cameron Valley sand member. Light gray horizontal lines are the 100 and 150-foot elevation reference lines. Numbers above and below the boring logs represent the maximum surface elevation and lowest elevation penetrated, respectively, in each set. Aerial photo from City of Alexandria parcel viewer* ***http://geo.alexandriava.gov/Html5Viewer/Index.html?viewer=parcelviewer&run=initialSettings***

**Site: 12** **Category: Feature of Interest**

Location: Natural area directly behind Patrick Henry Elementary School, 4643 Taney Avenue
Type of Feature: Peculiar, isolated, gravel-covered hill with anomalous summit elevation
Appears on: Alexandria 7.5-minute topographic quadrangle; plate 5; cross section H-H'
Strata affected: Potomac Formation (early Cretaceous); gravel of uncertain age and origin
Discussion: This steep-sided, conical hill is enigmatic. Its gravel-covered summit stands at an elevation of a little over 200 feet, which does not match any other geomorphic surface along the Hospital *escarpment*. Gravel appears to have been at least prospected, if not mined, from a small, shallow (3-4 feet) borrow pit west of the summit that is now slumped over and overgrown. The thickness of the gravel is not known, and it may simply be old *colluvium*, or possibly the remnant of a very high, early *terrace* of Holmes Run. The hill is separated from the adjacent escarpment by a shallow (~20 feet), narrow divide that probably marks an abandoned drainage, which supports the idea that the hill is a former spur ridge—of which there are several further to the east along the escarpment—that has become isolated by erosion. On the other hand, the peculiar characteristics at least suggest the possibility of some kind of tectonic influence. Perhaps it is a giant slump block triggered by a large prehistorical earthquake, a theory that may not be as outrageous as it initially seems: as **discussed elsewhere**, abundant landslide scars and oversteepened slopes attest to the major role mass movement has played in the geomorphic evolution of the adjacent escarpment. In any case, the origin of the hill is an intriguing geomorphic problem.

**Site: 13** **Category: Fault observed in outcrop**

Location: Clermont Woods Park, Fairfax County (exposure 132)
Strata affected: Potomac Formation, silty clay (early Cretaceous)
Fault fabric: brittle – breccia, slickensides, rotation and folding of strata
Appears on: plates 4 and 5
Discussion: This *reverse fault* is exposed on the west bank of the main ravine, immediately below an old road grade that crosses the stream next to the confluence of a small tributary. The fault plane strikes N40E, dips 40 NW and is accompanied by a zone of breccia and rotated strata that give the sense of fault motion (figure 8-15). Slickensides on the fault plane point nearly straight down dip. The exposed part of the fault is entirely within silty clay of the Potomac Group that occurs at in the same interval and at about the same distance off the base of the formation as the Arell clay member on the north side of Cameron Run. Banded clay is thrust over massive olive green clay that is very similar in appearance to the Arell clay member. A profuse amount of ground water was seeping from the fault zone during every visit to the site made by the author. No distinctive marker beds are available to determine the amount of offset along the fault.

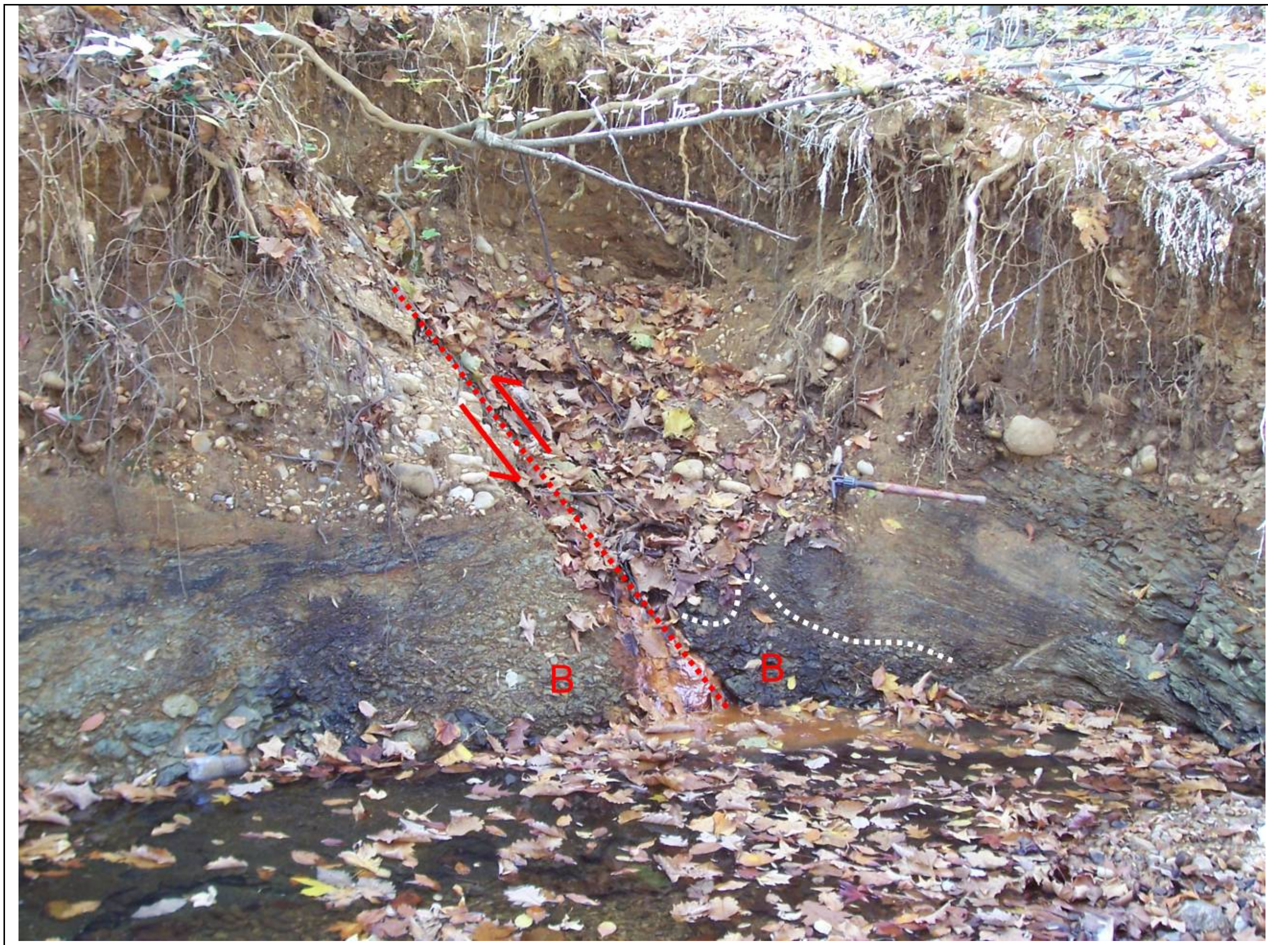


*Figure 8-15. Reverse fault in Potomac Formation silty clay at Clermont Woods Park, Fairfax County. The fault plane and sense of motion are indicated by the red dotted line and arrows. The clay adjacent to the fault is brecciated (B), with fragments commonly rotated by fault motion from their original positions. Contorted strata are visible to the right of the fault plane, with small recumbent folds (white dotted line) indicating the sense of motion. Photo by Tony Fleming.*

**Site: 14** **Category: Fault observed in outcrop**

Location: Chinquapin Hollow, Forest Park (Taylor Run) (exposure 125)
Strata affected: Chinquapin Hollow member of Potomac Fm (early Cretaceous)
Fault fabric: a few small slickensides; minor contortion of adjacent strata
Appears on: plates 4 and 5; Drake and others (1979); Froelich (1978; 1985)
Discussion: This site includes 3 small faults – two *thrust faults* and one *reverse fault*. The faults are exposed along a ~50-foot stretch of streambank in the bottom of the ravine, about 750 feet downstream of Chinquapin Recreation Center, in the upper part of a long, semi-continuous set of exposures of the Potomac Formation. Various types of faults have been mapped and/or described at this locality by previous workers. Maps by Drake and others (1979) and Froelich (1985) show a northwest dipping normal fault; Langer and Obermeier (1978) describe a "shear"; whereas Obermeier (1984) and Obermeier and Langer (1986) include a photograph (the same image in both publications) that appears to show a southeast dipping thrust fault, and is labeled as a thrust fault in the latter publication. Both Langer and Obermeier (1978) and Froelich (1978) posited that the structure(s) here may be related to the Stafford fault system.

This site was visited multiple times during fieldwork for the Alexandria Geologic Atlas. The two thrust faults are located within a few feet of each other on the northeast bank of the stream, where they cut the same heavily fractured lens of silty clay in the Chinquapin Hollow member. Both have similar attitudes, striking about N10E and dipping 30 E. Other than some mild contortion of adjacent strata and small slickensides, no compelling evidence of major brittle deformation – for example, fault *breccia* and rotation of blocks – was observed along either fault plane. The offset cannot be positively determined due to a lack of clear marker horizons, but appears to be very small, probably less than a foot or two as postulated by Obermeier (1984; p. 15). Both of these small faults could easily represent penecontemporaneous deformation produced during or shortly after deposition, instead of tectonic structures, as there are many structures produced by soft sediment deformation visible in the Potomac Formation in Chinquapin Hollow and elsewhere. Likewise, slickensides produced by expansion and contraction of *vertisols* are common along fractures in clayey Potomac sediments, and do not uniquely indicate a tectonic origin.

The reverse fault is exposed in the southwest stream bank, about 50 feet upstream of the thrust faults, and cuts fine sandy clay and clayey sand. The structure strikes about N15E and dips west between 75 and 80 degrees. Superficially, it resembles several other large joints in this exposure, but unlike the joints, it shows a very small displacement, with the west side up by about 2-3 inches based on offset of color variegations. No fabric was observed along or near the fault plane.

The lack of significant fabric and other unambiguous evidence of tectonic deformation along these structures indicates they could be related to soft-sediment deformation, paleosol development (vertisols in expandable parent material) or, if they are tectonic, they are probably very localized features. On the other hand, these exposures are close to the inferred trace of the Fort Williams fault (site 15), which appears to cut the nearby late Tertiary upland terraces. Ergo, it is also reasonable to think these structures may be related to the Fort Williams fault, which is covered in the next section.

**Site: 15** **Category: Inferred fault**

Location: Extends northeast across the central part of the map area from at least Duke Street on the south to at least King Street on the north. This structure is called the Fort Williams fault on the plates and cross sections
Strata affected: Seminary and Chinquapin Village terraces (Miocene? and Pliocene?); Potomac Formation (early Cretaceous); bedrock
Fault fabric: unknown
Appears on: plates 3, 4, 5; cross sections G-G’, M-M’, N-N’, O-O’
Discussion: Several independent lines of evidence strongly indicate the presence of a significant, northeast-trending fault or fault zone, minimally extending from southwest of Fort Williams Park to northeast of Chinquapin Hollow. At Fort Williams Park, medium-coarse grained, trough cross-bedded sand of the upper Cameron Valley member (Kpcv) crops out in a series of ledges along Strawberry Run extending approximately 1,100-1,200 feet upstream of Duke Street (exposure #’s 247-251, 298). The entire section is tilted sharply westward as much as 10-12 degrees, which is rather anomalous, considering that the whole Potomac Formation is tilted noticeably in the other direction in virtually every other outcrop in the city, including some exposures in Strawberry Run close to Duke Street. The strong tilting of these beds implies some sort of nearby fault or flexure. This belt of tilted exposures is aligned with a prominent linear topographic scarp on the upland to the north that separates distinctly higher and lower portions of two terraces (the Seminary and Chinquapin Village terraces), in which the southeasterly portion of each terrace appears to be downthrown some 20 or more feet relative to the northwest portion, based on observable differences in the base elevations of both terraces across the scarp. The small

faults observed in Chinquapin Hollow (site 14) also align with this trend. In addition, the map pattern in the vicinity of Duke Street suggests that Potomac strata to the southeast of the inferred fault trace are downthrown relative to strata to the northwest, with some 30 feet of offset of the contact between the Cameron Valley sand and the Arell clay members, a relation inferred from exposures and geotechnical borings in the immediate area. Further, the slope on the base of the Arell clay appears to abruptly increase across this zone: between Varsity Park and Fort Williams Park (a distance of 5,500 feet), it is about 62 feet/mile, but from Fort Williams Park to Wheeler Avenue (2,500 feet), it more than doubles to ~127 feet/mile. The inferred trace of the fault broadly parallels a wavy aeromagnetic gradient that defines the southeastern boundary of a deep aeromagnetic low interpreted as a buried granitoid body (see **figure 3-4**). Northeast of King Street, stratigraphic evidence for faulting is lacking (perhaps due to poor subsurface control), though the trace of the inferred fault projects into the northeast-trending part of the Jefferson Park escarpment, which forms a straight topographic lineament (site 16). All of the above features fall along a distinct alignment, and are collectively sufficient to postulate the northeast-trending fault zone shown on plates 3, 4 and 5, which is informally dubbed the Fort Williams fault.

**Site 16** **Category: Topographic lineament**

Location: Jefferson Park, between Braddock Road and Mount Ida
Appears on: Plate 5; Alexandria 7.5-minute topographic map and DEM (figure 8-16)
Discussion: The feature forms a strong, straight topographic lineament oriented about N50E. It coincides with the southeast-facing leg of the Jefferson Park escarpment, a river-cut scarp separating the Chinquapin Village and Beverly Hills terraces. The northeast end of the Fort Williams fault projects directly into the southeast end of the lineament, suggesting the possibility of a tectonic influence on the scarp. Subsurface data are sparse in this area, however, and other lines of evidence are lacking to support an extension of the fault northeastward into the scarp.

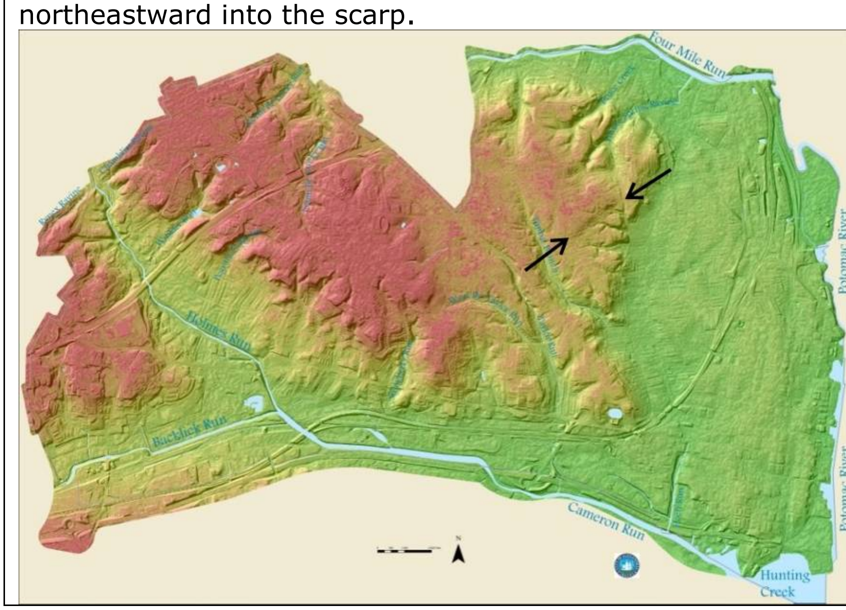


*Figure 8-16. Topographic lineament (between arrows) parallel to the Jefferson Park escarpment is prominent on the Alexandria DEM.*

**Site: 17** **Category: Feature of Interest**

Location: Below Episcopal Seminary and vicinity
Type of Feature: Historical water wells catalogued by Darton (1950) and Johnston (1961)
Appears on: plates 1 and 3; cross sections H-H' and M-M'; Powars et al (2015, their fig. 9)
Strata affected: bedrock surface (Ordovician); Potomac Formation (early Cretaceous)
Discussion: Historical water wells compiled by Darton (1950) and identified on **plate 1** as D-22 and D-23 indicate a significantly elevated area on the bedrock surface along Braddock

Road, just north of the seminary, while other wells just to the southeast (D-21, J-27, and others shown on plate 1) did not encounter bedrock even though they bottomed out at elevations some 135 to 150 feet lower than the Braddock Road wells. Some uncertainty exists because of the lack of formation logs and imprecise locations for these wells, nevertheless the apparent elevation differential on the bedrock surface between the two closest of these wells is minimally 135 feet over a horizontal distance of 1,500 feet, resulting in an apparent bedrock slope greater than 475 feet per mile.

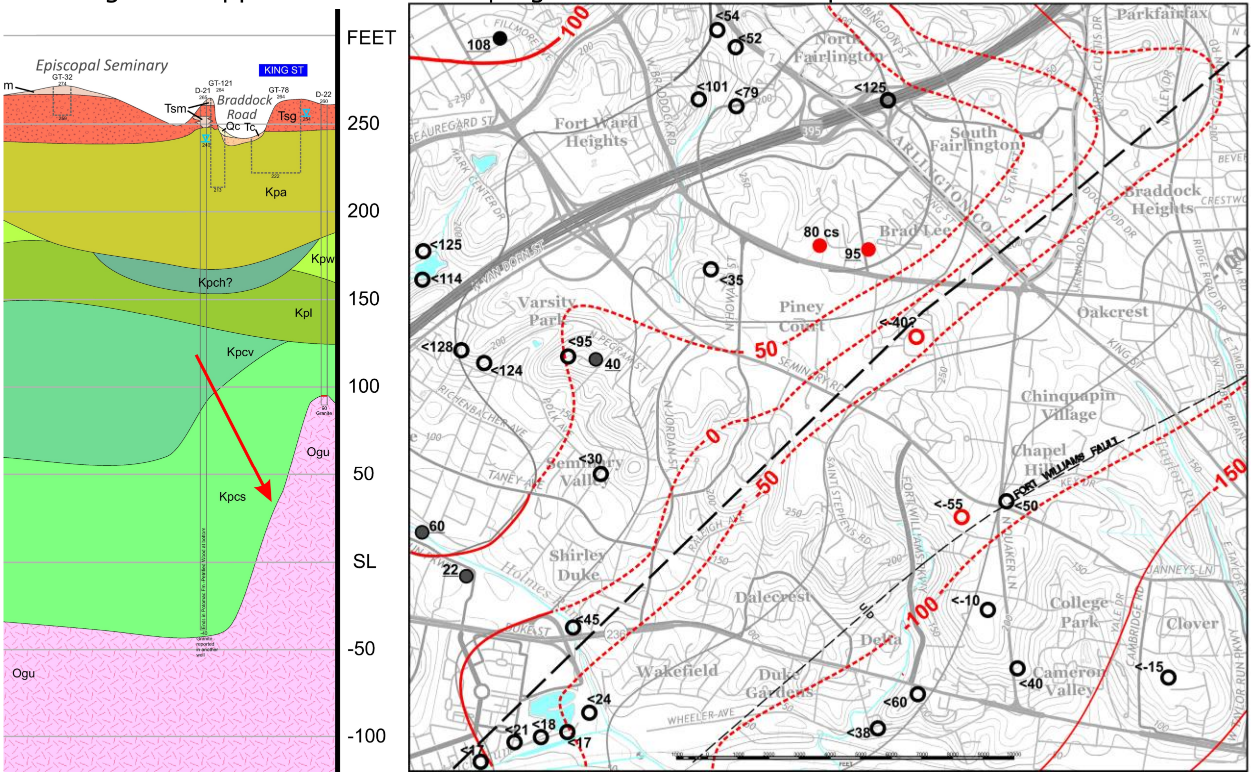


*Figure 8-17. Left: The abrupt change in elevation of the bedrock surface below the seminary appears as an almost scarp-like face (arrow) at the north end of the Hospital cross section (H-H'). Geologic units are: Ogu – undifferentiated granitic bedrock; Kpcs, Kpcv, Kpl, Kpw, Kpch, Kpa – Potomac Formation; Tsg, Tsm – Seminary terrace. Right: An alternative interpretation of bedrock topography (dashed red lines) in the central part of the map area if the sharp slope on the bedrock surface below the seminary is interpreted as a dissected fault scarp. Compare to* ***plate 3****. The hypothetical fault appears as a heavy dashed black line, roughly paralleling the Fort Williams fault. Solid dots and numbers are firm bedrock elevations at boreholes that reached the bedrock surface. Open circles and "less than" numbers represent the bottom elevations of boreholes that did not reach the bedrock surface. The well numbers mentioned in the text are shown in red.*

While the unusually steep bedrock topography at this site is certainly suggestive of a fault, it can be interpreted in more than one way. It could simply be an erosional feature produced by the early _Cretaceous_ river system that deposited the Potomac Formation—a remnant upland developed on resistant granitic rock, or a large _cut bank_ along a valley wall come to mind—similar in scale to features observable today in the modern Piedmont landscape. The contours on plate 3 suggest such an interpretation.

On the other hand, this part of the buried bedrock surface *appears* to be unique in the map area for its abrupt change of elevation and height of the corresponding slope, though such appearances could be an artifact of both the sparse distribution of borehole data in the map area that actually reach the bedrock surface, as well as the limitations of the contouring process. The extent and orientation of the feature are highly uncertain, given the limitations of the available data— the only place a major change in elevation of the bedrock surface can actually be defined is beneath the relatively limited confines of the seminary, with a handful of old boreholes whose characteristics are based mainly on anecdotal descriptions.

The feature is nonetheless tantalizing. Its proximity to the Fort Williams fault, together with the strong possibility that fault systems project into and through the map area from both the north and south, make this site one of the most suspect candidates for a fault in the map area. Powars et al (2015) suggested this structure is part of a proposed northward extension of the Dumfries fault zone, a major strand of the Stafford fault system. The contour map in figure 8-17 presents an alternate interpretation of bedrock topography (compared to plate 3) that assumes the slope beneath the Seminary is part of a longer, somewhat dissected fault scarp oriented in a northeast-southwest direction, broadly parallel to both the regional structural grain of the bedrock and the nearby Fort Williams fault.

**Site: 18** **Category: Fault observed in outcrop**

Location: Timber Branch, between near Monticello Blvd and Janneys Lane
Strata affected: Potomac Formation (early Cretaceous)
Fault fabric: unknown
Appears on: plates 4 and 5; Drake and others, 1979; Froelich, 1985
Discussion: This fault was mapped by Drake and others (1979) on the Preliminary Geologic Map of Fairfax County, and described as a "small fault seen in outcrop". Froelich (1985) shows the fault as a normal fault that strikes about N10E, dips 31 E, with the east side being downthrown. Langer and Obermeier (1978) briefly mentioned the structure, referring to it as a "shear zone" and postulated that it is connected to the thrust fault(s) in Chinquapin Park (site 14) based on their similar orientations and characteristics. This structure could not be located during the present study.

**Site: 19** **Category: Fault observed in outcrop**

Location: Shirley Hwy x Four Mile Run (S. Glebe Rd interchange), Arlington County
Strata affected: Potomac Formation (early Cretaceous)
Fault fabric: unknown
Appears on: plates 4 and 5; cross-section L-L'; Drake and others, 1979; Froelich, 1985
Discussion: This fault was mapped as a "small fault seen in outcrop" by Drake and others (1979) on the Preliminary Geologic Map of Fairfax County. Froelich (1985) shows the fault as a *reverse fault* that strikes about N20W and dips 65 NE, with the NE side up. No other description is available. This structure could not be located during the present study; it may have been exposed temporarily in the 1970's during a construction project on Shirley Highway, or in Four Mile Run prior to channelization and armoring of the streambanks.

*Geotechnical* borings at this interchange (site GTB-66) and at nearby bridges just to the south along Shirley Highway (sites GTB-67 and 69) are not incompatible with a fault zone, but they are scarcely definitive. Two features are noteworthy in this regard. First, the borings at the Glebe Road interchange penetrate a thick section of clayey silt, whereas in the other boring sets just south of Four Mile Run, this interval consists mostly of sand. Based on the bedrock topography in **plate 3**, this horizon lies within the lower 50-100 feet of the Potomac Formation, which is typically occupied by the Cameron Valley sand member (Kpcs, figure 8-18), which in turn consists nearly everywhere of sand and rarely contains such large bodies of silt and clay. Thus, the presence of such a thick mass of fine grained sediment in this interval is unusual. Second, the borings at the Glebe Road interchange indicate a fairly abrupt transition from all silt in the south and central parts of the site to a thicker basal sand unit in borings at the far north end of the site.

Interpretations are complicated by: 1) the Four Mile Run bedrock valley, which lies beneath the site and may contain complex cut-and-fill structures that result in abrupt lateral lithological changes, and 2) the fact that none of the borings along this part of Shirley Highway reach the bedrock surface, where fault offset is typically more readily recognizable between adjacent borings than in the more lithologically variable Potomac Formation.

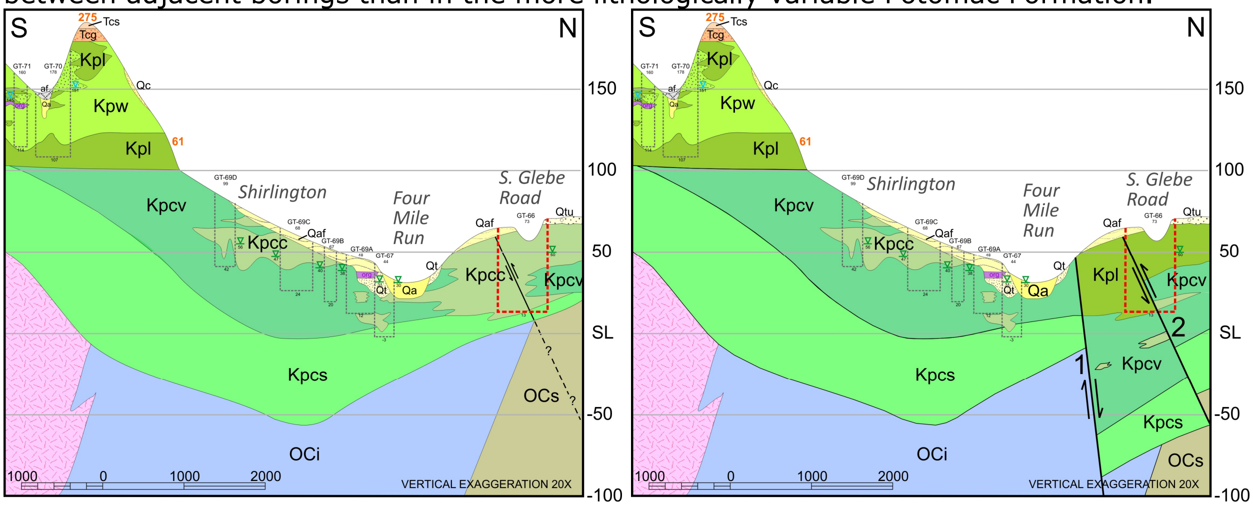


*Figure 8-18. Cross sections illustrating competing explanations of the geologic structure in the vicinity of Shirley Highway and Four Mile Run. In one interpretation (left), the large body of clayey silt on the north side of Four Mile Run (Kpcc) and the sands to the south (Kpcv) are in a lateral facies relationship: the silt is considered to be a fine-grained sedimentary facies deposited in a backswamp localized along the north margin of the Four Mile Run bedrock valley, whereas the thick sand units are developed over the thalweg of the bedrock valley. The "small fault seen in outcrop" by Drake et all (1979) is just that, with negligible offset of strata. In an alternate interpretation (right), the thick plug of silt represents a downthrown block of Lincolnia silty clay (Kpl)—a map unit prominent in the bluffs just to the south and west—which has been juxtaposed against stratigraphically lower sands (Kpcv) along a normal fault (1). In this model, the fault (2) mapped by Drake and others (1979) assumes greater importance and is responsible for the seemingly abrupt change from silt to sand in the lower part of the borings in the northern part of the S. Glebe Road interchange (GT-66, highlighted by the red dashed line), resulting in a small, graben-like structure between the two faults. In the absence of more definitive evidence, however, no major fault is currently postulated at this location, and the structural relations depicted on the maps and cross sections are as shown in the left hand diagram.*

**Site: 20** **Category: Aeromagnetic lineament, likely fault**

Location: Extends completely across the map area from National Airport to Telegraph Road, paralleling the Mount Ida escarpment
Strata affected: Ordovician bedrock; potentially contains faults cutting younger strata
Fault fabric: displays both ductile and brittle structures in Washington, DC
Appears on: plate 3, cross sections C-C′, D-D′, E-E′, F-F′, M-M′, N-N′, O-O′
Discussion: The feature in question is an intense aeromagnetic gradient up to a half mile wide. It was interpreted by Fleming and Drake (1998) as the southward continuation of the Rock Creek shear zone (RCSZ) from Washington, DC. The Spotsylvania fault (bedrock structure) and strands of the Stafford fault system (Coastal Plain structure) also project northward into this part of the map area from southern Fairfax County, according to Powars and others (2015). Hence, this major aeromagnetic lineament could well be the "missing link", or one of them, that connects fault systems to the north and south of the city.

The source of this intense aeromagnetic gradient is almost certainly a Paleozoic ductile fault that separates the Potomac terrane (Sykesville-Indian Run Formations) on the west from the Chopawamsic terrane (Chopawamsic Formation) on the east (Horton and others, 1989). In Rock Creek Park, the RCSZ is characterized by ductile mylonite formed during two major episodes of Paleozoic strike slip motion; it also contains numerous post-Paleozoic brittle faults, some of which cut strata potentially as young as Pleistocene. Likewise, the Stafford fault system is the quintessential Coastal Plain fault system in northern Virginia, with tens of feet of offset of Cretaceous and Tertiary strata. Therefore, this feature is judged to have a strong likelihood of containing post-Cretaceous faults in the map area and, based on current data, is the most credible candidate to pose a local seismic hazard, either as a potential source of earthquakes itself or by efficiently transmitting seismic energy from more distant places like the Central Virginia seismic zone. The striking parallelism of the lineament with the Mount Ida escarpment has been noted **elsewhere in this atlas**, but no direct evidence supporting a tectonic influence on the scarp has thus far been uncovered.

**Site: 21** **Category: Feature of Interest**

Location: Extends northeast from the Fairfax County line to Shooters Hill
Type of Feature: Changes in the slope of the bedrock surface and Potomac Formation strata, and potential repetition of the upper part of Cameron Valley sand member, are both inferred from geologic mapping and structural relations in cross sections
Appears on: plates 3 and 4; cross sections C-C′, F-F′, M-M′, O-O′
Strata affected: bedrock surface (Ordovician); Potomac Formation (early Cretaceous)
Discussion: The slope of the bedrock surface appears to steepen abruptly along a northeast-trending zone extending from the Capital Beltway west of Telegraph Road to King Street at the north side of Shooters Hill. Part of this structure is manifested on **plate 3** by a tightening of the bedrock contours along the north side of the Cameron bedrock valley just west of Telegraph Road. The structure generally parallels the west side of the Rock Creek shear zone (RCSZ), as defined by its aeromagnetic signature (site 20).

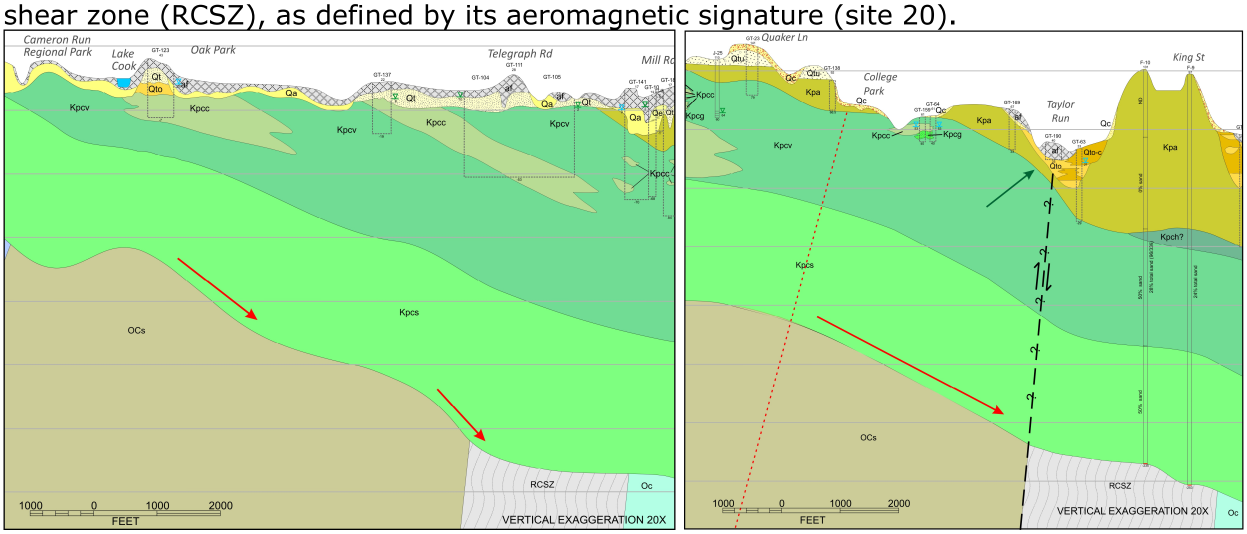


*Figure 8-19. Left: In the Eisenhower Valley, the slope of the bedrock surface appears to steepen (arrows) between Oak Park and Telegraph Road as the west wall of the RCSZ is approached. This feature coincides with an exceptionally thick section of the Cameron Valley sand member (Kpcs-Kpcv-Kpcc) — 250 to 300 feet – greater than anywhere else in the map area. Right: Further north, along Duke Street, the increased gradient of the bedrock surface (red arrow) and sharp changes in the thickness and base elevation of the Arell clay member (Kpa; green arrow) suggest the presence of a flexure (red dashed line) and fault zone in the Potomac Formation (queried black dashed line). Light gray horizontal lines are 50-foot elevation reference lines.*

The changes in the gradient of the bedrock surface are accompanied by other suspect structural-stratigraphic features in the Potomac Formation, which appear in cross sections that traverse this area (figure 8-19). For example, the changes in bedrock slope beneath Eisenhower Valley (**cross section F-F'**) coincide with an extraordinarily thick section of Cameron Valley sand, which suggests that parts of the Potomac Formation may be repeated by faulting. Further north, approximately coincident with College Park along Duke Street (**cross section O-O'**), the eastward dip of the bedrock surface and overlying Potomac Formation members appears to increase markedly from west to east. This suggests the hingeline of a flexure is located roughly coincident with Cambridge Street. The steep dip continues eastward to the mouth of Taylor Run at the west edge of the RCSZ. At that location, the thickness of the Arell clay, as interpreted from several geotechnical boring sites, appears to increase abruptly, while its base also declines tens of feet in elevation over a very short distance. Similar behavior of the Arell clay seen along King St (**cross section M-M'**) may be reflecting the same structural control.

Some, and maybe all, of these unusual features might be explained by relatively ordinary sedimentary processes. For example, the section along Eisenhower Valley is within the Cameron bedrock valley, which may explain both the great thickness of the Cameron Valley sand, and the apparent undulations of the bedrock surface as the cross section comes into and out of the thalweg of the valley. Likewise, the relations along Duke Street could be explained by an abrupt facies change in the Potomac Formation or a locally deeper part of the basin in which the Arell clay was deposited.

On the other hand, there are good reasons to suspect a tectonic influence. The coincidence of structures that appear to extend from the bedrock surface through virtually the entire Potomac Formation section is striking. The setting of this group of structures adjacent to the RCSZ — a major structure that may well connect young fault zones north and south of the map area — also is strongly suggestive. These relations are sufficient to show a hypothetical fault on the Duke Street (O-O') and King Street (M-M') cross sections, though the geometry and stratigraphic extent remains poorly defined. Better control on the altitude of both the bedrock surface and the boundaries between members in Potomac Formation are needed to help resolve the presence and nature of any tectonic structures in this area.

**Site: 22** **Category: Feature of Interest**

Location: Extends north-northeast beneath the western part of Old Town from the Capital Beltway towards Daingerfield Island
Type of Feature: Changes in slope of bedrock surface indicated by historical water wells
Appears on: plate 3; cross sections A-A', C-C', F-F', O-O'
Strata affected: bedrock surface (Ordovician); Potomac Formation? (early Cretaceous)
Discussion: Historical water wells catalogued by Johnson (1961), Darton (1950), and Froelich (1985) show a steepening of the bedrock surface gradient across a north to northeast trending zone below Old Town. On **plate 3**, the strongest part of this structure appears as a marked tightening of the -300, -350, and -400' bedrock surface contours centered on the NW part of Old Town and broadly parallel to N. Patrick Street between King and Montgomery Streets. Figure 8-20 highlights this area. The structure also appears on several cross sections beneath Old Town, being particularly strong on the **Beverley Hills section (C-C')**, which closely parallels the regional bedrock surface slope. As shown on the cross sections, the slope of the individual members within the Potomac Formation is generally assumed to parallel the bedrock surface slope, including in the region above the structure discussed here. As discussed **elsewhere**, however, the stratigraphy of Potomac Formation is very poorly known at depth under Old Town, due to a lack of high resolution data. Therefore, it is ultimately unclear whether and to what extent this structure is actually affecting the Potomac Formation.

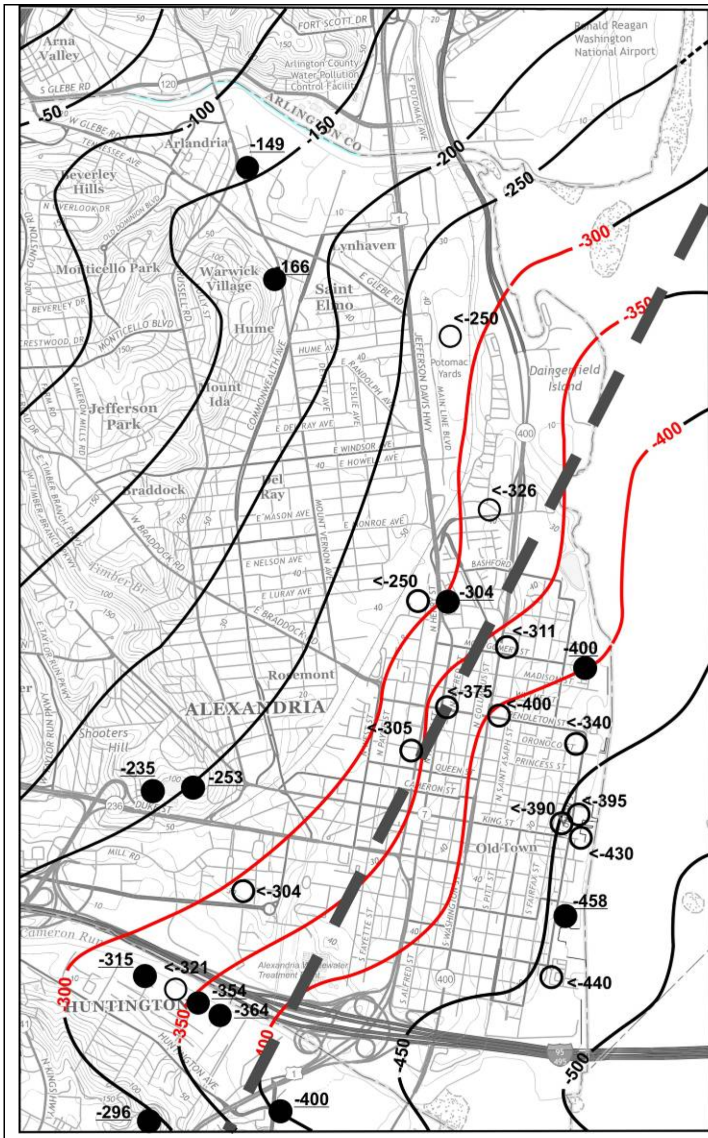


*Figure 8-20. Bedrock topography in the eastern part of the map area. Contour interval is 50 feet. Solid circles and numbers are firm bedrock elevations reported in wells that reached the bedrock surface. Open circles and "less than" numbers represent the bottom elevations of wells that did not reach the bedrock surface. The bedrock surface slope increases across a north to northeast trending zone indicated by the red contours. The steepest part of the structure appears to underlie the northwestern part of Old Town, where the contours are most tightly spaced, however, that could be an artifact of greater data density than elsewhere along the structure. The heavy dashed line marks the trend of a hypothetical fault.*

This structure lies about 1,000 - 1,200 ft east of the northeastward extension of the Brooke fault zone (BFS) proposed by Powars and others (2015). The BFZ is one of several well documented structures that make up the Stafford fault system south of the map area; the BFZ has at least 30 meters of cumulative vertical offset in Spotsylvania County (Powars and others, 2015), and potentially up to 60 meters at the Quantico Marine Base in Prince William County (Mixon and Newell, 1982). Seiders and Mixon (1981) and Powars and others (2015) have hypothesized that the trace of the BFS follows and controls the very straight, northeast-trending reach of the Potomac River between Quantico and Alexandria. If correct, then the structure beneath Old Town is a strong candidate for the continuation of the BFS, and would be expected to offset the Potomac Formation, and potentially parts of the overlying Old Town terrace.

### *References*


Bassler, R.S., 1940, Geological exhibits in the National Zoological Park: Smithsonian Annual Report-1939, Publication 3565, p. 265-279.

Bobyarchick, A.R., 2015, Structural analysis of the original Everona fault excavation and Cenozoic deformation in the Mountain Run fault zone, central Virginia, *in* Horton, J.W., Jr., Chapman, M.C., and Green, R.A., eds., The 2011 Mineral, Virginia, Earthquake and Its Significance for Seismic Hazards in Eastern North America: Geological Society of America Special Paper 509, p., 391-406, doi: 10.1130/2015.2509(22).
**http://specialpapers.gsapubs.org/content/509**

Building Seismic Safety Council, 2000, NEHRP recommended provisions for new buildings and other structures, FEMA 368. Washington, D.C., Fed. Emergency Management Agency.

Building Seismic Safety Council, 2003, NEHRP recommended provisions for new buildings and other structures, FEMA 450, ch. 3: Washington, D.C., Federal Emergency Management Agency.**http://c.ymcdn.com/sites/www.nibs.org/resource/resmgr/BSSC/nehrp2003_P3A.pdf**

Daniels, D.L., 1980, Geophysical-geological analysis of Fairfax County, VA: U.S. Geological Survey Open-File Report 80-1165, 64 p.

Darton, N.H., 1950, Configuration of the bedrock surface of the District of Columbia and vicinity: U.S. Geological Survey Professional Paper 217, 42 p. plus 4 plates.
**http://pubs.er.usgs.gov/publication/pp217**

Davis, A.M., Southworth, C.S., Reddy, J.E., and Schindler, J.S., 2001, Geologic map database of the Washington, D.C. area featuring data from three 30 x 60 minute quadrangles: Frederick, Washington West, and Fredericksburg: U.S. Geological Survey Open-File Report OF-2001-227. **http://ngmdb.usgs.gov/Prodesc/proddesc_51791.htm**

Drake, A.A., Jr., Nelson, A.E., Force, L.M., Froelich, A.J., and Lyttle, P.T., 1979, Preliminary Geologic Map of Fairfax County, Virginia: U.S. Geological Survey Open-File Report 79-398, scale 1:48,000. **http://pubs.er.usgs.gov/publication/ofr79398**

Drake, A.A., Jr., and Froelich, A.J., 1986, Geologic Map of the Annandale Quadrangle, Fairfax County, Virginia: U.S. Geological Survey Geologic Quadrangle Map GQ-1601, scale 1:24,000. **http://pubs.er.usgs.gov/publication/gq1601**

Fleming, A.H., and Drake, A.A., Jr., 1998, Structure, age, and tectonic setting of a multiply-reactivated shear zone in the Piedmont in Washington, D.C., and vicinity: Southeastern Geology, v. 37 (3), p. 115-140.

Fleming, A.H., Drake, A.A., Jr., and McCartan, L., 1994, Geologic Map of the Washington West Quadrangle, District of Columbia, Montgomery and Prince Georges Counties, Maryland, and Arlington and Fairfax Counties, Virginia: U.S. Geological Survey Geologic Quadrangle Map GQ-1748, scale 1:24,000. **http://ngmdb.usgs.gov/Prodesc/proddesc_277.htm**

Froelich, A.J., 1978, Map showing planar and linear features of Fairfax County, Virginia: U.S. Geological Survey Open-File Report 78-443, scale 1:48,000.
**https://pubs.er.usgs.gov/publication/ofr78443**

Froelich, A.J., 1985, Folio of geologic and hydrologic maps for land-use planning in the Coastal Plain of Fairfax County, Virginia, and vicinity: U.S. Geological Survey Miscellaneous Investigations Series Map (IMAP) I-1423, scale 1:100,000.
**http://pubs.er.usgs.gov/publication/i1423**

Haase, J.S., Nowack, R.L., Cramer, C.H., Boyd, O.S., and Bauer, R.A., 2011a, Earthquake scenario ground motions for the urban area of Evansville, Indiana: U.S. Geological Survey Open-File Report 2011–1260, 17 p. **https://pubs.er.usgs.gov/publication/ofr20111260**

Haase, J.S., Choi, Y.S., Nowack, R.L., Cramer, C.H., Boyd, O.S., and Bauer, R.A., 2011b, Liquefaction hazard for the region of Evansville, Indiana: U.S. Geological Survey Open-File Report 2011–1203, 37p. **https://pubs.er.usgs.gov/publication/ofr20111203**

Heimgartner, D., 1995, Geologic investigation of a ductile shear zone in the northern Piedmont of Virginia: Fairfax, Virginia, George Mason University, Department of Geography and Earth System Science, unpublished senior thesis, 23 p., plus 21 figures.

Hitchcock, C., Givler, R., De Pascale, G., and Dulberg, R., 2008, Detailed mapping of artificial fills, San Francisco Bay area, California: William Lettis Associates, Final Technical Report, National Earthquake Hazards Reduction Program, U.S. Geological Survey Award Number 07HQGR0078
**http://earthquake.usgs.gov/research/external/reports/07HQGR0078.pdf**

Holzer, T.L., Bennett, M.J., Noce, T.E., Padovani, A.C., and Tinsley, J.C., II, 2002, Liquefaction hazard and shaking amplification maps of Alameda, Berkeley, Emeryville, Oakland, and Piedmont, California: A digital database: U.S. Geological Survey Open-file Report 2002-296. **http://pubs.usgs.gov/of/2002/of02-296/of02-296_1.1.pdf**

Holzer, T.L., Padovani, A,C., Bennett, M.J., Noce, T.E., Tinsley, J.C., 2005, Mapping NEHRP VS30 Site Classes: Earthquake Spectra, Vol. 21, p. 353-370. doi:10.1193/1.1895726.
**http://earthquakespectra.org/doi/abs/10.1193/1.1895726**

Horton, J.W., Drake, A.A., Jr., and Rankin, D.W., 1989, Tectonostratigraphic terranes and their Paleozoic boundaries in the central and southern Appalachian, in Dallmeyer, R.D., ed., Terranes in the circum-Atlantic Paleozoic orogens: Geological Society of America Special Paper 230, p. 213-245. **http://specialpapers.gsapubs.org/content/230**

Horton, J.W., Jr., Chapman, M.C., and Green, R.A., 2015, The 2011 Mineral, Virginia, earthquake, and its significance for seismic hazards in eastern North America—Overview and Synthesis, *in* Horton, J.W., Jr., Chapman, M.C., and Green, R.A., eds., The 2011 Mineral, Virginia, Earthquake and Its Significance for Seismic Hazards in Eastern North America: Geological Society of America Special Paper 509, p., 1-25, doi: 10.1130/2015.2509(01). **http://specialpapers.gsapubs.org/content/509**

Hough, S.E., 2012, Initial assessment of the intensity distribution of the 2011 Mw 5.8 Mineral, Virginia, earthquake: Seismological Research Letters, v. 83, p. 649-657, doi:10.1785/0220110140. **http://srl.geoscienceworld.org/content/83/4/649**

Jacobeen, F.H., Jr., 1972, Seismic evidence for high-angle reverse faulting in the Coastal Plain of Prince Georges and Charles Counties, MD: Maryland Geological Survey Information Circular 13, 21 p.

Johnston, P.M., 1961, Geology and ground-water resources of Washington, D.C. and vicinity - well records and data tables: U.S. Geological Survey Open-File Report 61-79.

Johnston, P.M., 1964, Geology and ground-water resources of Washington, D.C. and vicinity: U.S. Geological Survey Water Supply Paper 1776, 98 p, scale 1:62,500.
**http://pubs.usgs.gov/wsp/1776/report.pdf**

Langer, W. H., and Obermeier, S.F., 1978, Relationship of landslides to fractures in Potomac Group deposits, Fairfax County, Virginia: U.S. Geological Survey Open-File Report 78-779, 37 p.

Mixon, R.B., and Newell, W.L., 1976, Preliminary investigation of faults and folds along the inner edge of the Coastal Plain in northeastern Virginia: U.S. Geological Survey Open-File Report 76-330. **http://pubs.er.usgs.gov/publication/ofr76330**

Mixon, R.B., and Newell, W.L., 1977, Stafford fault system: structures documenting Cretaceous and Tertiary deformation along the Fall Line in northeastern Virginia: Geology, v. 5, p. 437-440. **http://geology.gsapubs.org/content/5/7.toc**

Mixon, R.B., and Newell, W.L., 1978, The faulted Coastal Plain margin at Fredericksburg, VA: Reston, Virginia, Tenth Annual Virginia Geology Field Conference Guidebook, October 13-14, 1978, Virginia Academy of Sciences, 50 p.

Mixon, R.B., and Newell, W.L., 1982, Mesozoic and Cenozoic compressional faulting along the Atlantic Coastal Plain margin, Virginia, in Lyttle, P.T., ed., Central Appalachian Geology: Geological Society of America, Northeast and Southeast Sections Annual Meeting Field Trip Guidebook: Falls Church, Virginia, American Geological Institute, p. 29-54.

Mixon, R.B., Powars, D.S., and Daniels, D.L., 1992, Nature and timing of deformation of upper Mesozoic and Cenozoic deposits in the inner Atlantic Coastal Plain, Virginia and Maryland, *in* Gohn, G.S., ed., Proceedings of the 1988 U.S. Geological Survey Workshop on the Geology and Geohydrology of the Atlantic Coastal Plain: U.S. Geological Survey Circular 1059, p. 65-73. **https://pubs.er.usgs.gov/publication/cir1059**

Mixon, R.B., Pavlides, L., Powars, D.S., Froelich, A.J., Weems, R.E., Schindler, J.S., Newell, W.L., Edwards, L.E., and Ward, L.W., 2000, Geologic map of the Fredericksburg 30 x 60 minute quadrangle, Virginia and Maryland: U.S. Geological Survey Investigation Map I-2607, scale 1:100,000, 34 p. **https://pubs.er.usgs.gov/publication/i2607**

Newell, W.L., Prowell, D.C., and Mixon, R.B., 1976, Detailed investigation of a Coastal Plain-Piedmont fault contact in northeastern Virginia: U.S. Geological Survey Open-File Report 76-329.

Obermeier, S.F., 1984, Engineering geology and slope design of the Cretaceous Potomac deposits in Fairfax County and vicinity, Virginia: U.S. Geological Survey Bulletin 1556. 88 p. **http://pubs.er.usgs.gov/publication/b1556**

Obermeier, S.F., 1996, Use of liquefaction-induced features for paleoseismic analysis - An overview of how seismic liquefaction features can be distinguished from other features and how their regional distribution and properties of source sediment can be used to infer the location and strength of Holocene paleo-earthquakes: Engineering Geology, 44(1-4): 1-76. **http://www.sciencedirect.com/science/article/pii/S0013795296000403**

Obermeier, S.F., 1998, Liquefaction evidence for strong earthquakes of Holocene and latest Pleistocene ages in the states of Indiana and Illinois, USA: Engineering Geology, 50: 227-254. **http://www.sciencedirect.com/science/article/pii/S0013795298000325**

Obermeier, S.F., and Langer, W.H., 1986, Relationships between geology and engineering characteristics of soils and weathered rocks of Fairfax County and vicinity, Virginia: U.S. Geological Survey Professional Paper 1344, 30 p.
**https://pubs.er.usgs.gov/publication/pp1344**

Obermeier, S.F. et al., 1991, Evidence of Strong Earthquake Shaking in the Lower Wabash Valley from Prehistoric Liquefaction Features: Science, 251(4997): 1061-1063.

Pavlides, L., Bobyarchick, A.B., Newell, W.L., and Pavich, M.J., 1983, Late Cenozoic faulting along the Mountain Run fault zone, central Virginia Piedmont: Geological Society of America, abstracts with programs, v. 15, p. 55.

Petersen, M.D., Moschetti, M.P., Powers, P.M., Mueller, C.S., Haller, K.M., Frankel, A.D., Zeng, Yuehua, Rezaeian, Sanaz, Harmsen, S.C., Boyd, O.S., Field, Ned, Chen, Rui, Rukstales, K.S., Luco, Nico, Wheeler, R.L., Williams, R.A., and Olsen, A.H., 2014, Documentation for the 2014 update of the United States national seismic hazard maps: U.S. Geological Survey Open-File Report 2014–1091, 243 p., **http://dx.doi.org/10.3133/ofr20141091**.

Powars, D.S., Catchings, R.D., Horton, J.W., Jr., Schindler,l J.S., and Pavich, M.J., 2015, Stafford fault system: 120 million year fault movement history of northern Virginia, *in* Horton, J.W., Jr., Chapman, M.C., and Green, R.A., eds., The 2011 Mineral, Virginia, Earthquake and Its Significance for Seismic Hazards in Eastern North America: Geological Society of America Special Paper 509, p., 407-431, doi: 10.1130/2015.2509(23).
**http://specialpapers.gsapubs.org/content/509**

Seiders, V.M., and Mixon, R.B., 1981, Geologic map of the Occoquon Quadrangle and part of the Fort Belvoir Quadrangle, Prince William and Fairfax Counties, Virginia: U.S. Geological Survey Miscellaneous Investigations Map MI-1175, scale 1:24,000.
**http://ngmdb.usgs.gov/Prodesc/proddesc_9006.htm**

US Geological Survey, 1989, The severity of an earthquake - a U.S. Geological Survey General Interest Publication: U.S. GOVERNMENT PRINTING OFFICE: 1989-288-913.
**http://pubs.usgs.gov/gip/earthq4/severitygip.html**

US Geological Survey, 2011, Community Internet Intensity Map and Related Data of the August 23, 2011 Mineral, Virginia earthquake:
**http://earthquake.usgs.gov/earthquakes/dyfi/events/se/082311a/us/index.html**

U.S. Geological Survey, 2016, Earthquake hazards website: **http://earthquake.usgs.gov/**

Virginia Division of Mineral Resources, 1993, Geologic Map of Virginia: Charlottesville, VA, Division of Mineral Resources, scale 1:500,000.
**https://www.dmme.virginia.gov/commerce/ProductDetails.aspx?ProductID=1280**

Zoback, M.L., 1992, Stress field constraints on intraplate seismicity in eastern North America: Journal of Geophysical Research, v. 97, no. B8, p. 11,761-11,782.
**http://onlinelibrary.wiley.com/doi/10.1029/92JB00221/abstract**

**Return to Home Page**