

## Geotechnical Quick Report on the Affected Region of the 23 August 2011 M5.8 Central Virginia Earthquake near Mineral, Virginia



Photo: damage from unreinforced masonry wall collapse in the Washington DC area.

*Credit: adapted from MSNBC*

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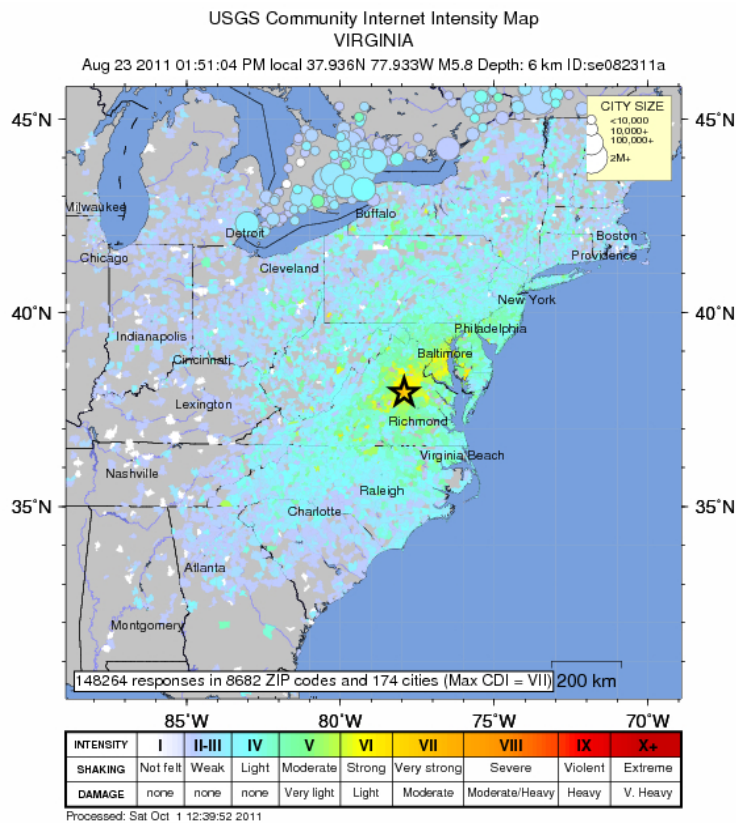
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# INTRODUCTION

The 2011 Virginia Earthquake occurred on August 23, 2011, at 1:51 pm EDT (17:51 UTC) in the Piedmont region of central Virginia. The epicenter was in Louisa County near the small town of Mineral, about 50 km east of Charlottesville, 60 km northwest of Richmond, and 130 km southwest of Washington, DC. The event occurred as reverse faulting on a north or northeast-striking plane within the Central Virginia Seismic Zone, a region long associated with frequent felt earthquakes. The 23 August earthquake, the largest historical earthquake in the region, was magnitude 5.8 with a maximum perceived intensity of VII on the Modified Mercalli Intensity scale; see Figure 1. The hypocentral depth was about 6 km. Several aftershocks, ranging up to M 4.5 occurred after the main tremor.

The main shock was felt along most of the eastern seaboard, reaching from Georgia to Canada. The large felt area coupled with the high population density along the coast meant that this was the most felt earthquake in US history. There were no reported fatalities or serious injuries, but minor damage to buildings was widespread. Unreinforced masonry walls, gable walls, and chimney collapses were the most common failures. In the sparsely populated epicentral region, tens of private residences, especially unreinforced masonry structures, were severely damaged and several were partially collapsed. Across the state, 33 residences were destroyed and 180 suffered major damage. Two public schools were damaged seriously enough that they will be closed for the entire school year. Current damage estimates are more than \$90 million in Virginia, and \$200 million to \$300 million overall.



**Figure 1 – Intensity map showing affected region of the 23 August M5.8 Earthquake**

The earthquake resulted in the shutdown of the nuclear reactors at the North Anna Power Plant (NPP), 18 km from epicenter, which used backup generators to keep spent nuclear fuel cooled and to remove residual heat from the reactor. In-structure foundation level recordings in the reactor containment, founded on hard rock, indicated a PGA of 0.26g. The recorded response spectrum exceeded the Design Basis Ground motion of the reactor, but did not result in apparent damage to the safety related systems. The NPP record is the best and closest available strong motion recording of the M5.8 main shock.

Toward the east in the Richmond area, minor damages occurred to unreinforced masonry structures especially in the form of broken chimneys. To the northeast in Washington, DC, southern Maryland and Delaware, more than 130 km away, there was a marked uptick in damages relative to other locations closer to the epicenter. This was especially apparent for sites on Coastal Plain sediments overlying hard rock. Damages, some of which were quite significant, occurred to a variety of structures, including buildings, bridges, and monuments and institutions.

The earthquake tied up phone and internet connections, disrupted rail lines, and caused extensive traffic delays and business disruptions as far away as New York City. Minor damages were reported as far away as New Jersey and New York more than 450 km to the northeast, and as far as Charleston, SC 600 km to the southwest. The earthquake caused widespread confusion between the public and emergency personnel on how to respond.

### **GEER Reconnaissance**

In the hours following the earthquake engineering and seismology faculty members and graduate students from Virginia Tech, along with local United States Geological Survey (USGS) and Virginia Department of Mines, Minerals, and Energy (VA DMME) personnel, mobilized to the epicentral area for field reconnaissance. Several of the early arrivers included would-be GEER team members.

The initial core GEER team was formed two days after the event and was focused on collecting geotechnical data as rapidly as possible, building on the efforts of those that mobilized to the affected area immediately after the earthquake. The most pressing issue was collecting perishable data ahead of Hurricane Irene which struck the area a few days after the earthquake.

In this effort, the GEER team successfully leveraged the assistance of many geotechnical engineering firms and relevant contacts throughout the region. We coordinated with key agencies and organizations such as EERI, USGS, the VA DMME, Departments of Transportation in Virginia, Maryland, and Washington, among other groups.

Current GEER team members and their primary areas of responsibility are:

- Professor James Martin, Civil and Environmental Engineering, Virginia Tech – team leader
- Mr. Carl Benson, P.E., P.G. VDOT Geotechnical Engineering Program Manager – geotechnical findings in Richmond and eastern VA, and performance of VA bridges
- Mark W. Carter, Research Geologist, U.S. Geological Survey– geology of the epicentral region

- Dr. Martin Chapman, Director, Virginia Tech Seismological Observatory- seismology issues and recorded ground motions, NPP seismic instrumentation
- Mr. Morgan Eddy, P.E., Geotechnical Engineering Contractor, Steele Foundation, and PhD Candidate, Virginia Tech – epicentral region and Washington, DC area geotechnical issues
- Assoc. Professor Russell Green, P.E., Civil Engineering, Virginia Tech - epicentral area geotechnical issues and structural failures; NPP facility and Lake Anna Dam
- Dr. Anne Kammerer, P.E, US Nuclear Regulatory Commission, Rockville, MD - geotechnical observations in National Capital Region; regulatory issues associated with NPP
- Mr. Sam Lasley, Geotechnical Engineering Ph.D. candidate, Virginia Tech - epicentral area geotechnical issues and structural failures
- Dr. Carlos Lazarte, P.E., Senior Associate, Schnabel Engineering –Washington, DC and Maryland area geological and geotechnical issues
- Dr. Sissy Nikolaou, P.E., Head Geo-Seismic Department, Mueser Rutledge Consulting- Geo-seismic issues, geological and geotechnical information for distant damages in DC and NY
- Asst. Professor Burak Tanyu, P.E., Civil Engineering, George Mason University - geologic and geotechnical issues in northern VA and DC area
- Dr. Martitia Tuttle, Director and Principal Investigator, M. Tuttle & Associates - liquefaction evidence along streams in the epicentral region, National Capital Region, and Eastern VA

As expected, given the proximity of this moderate earthquake, the team is dominated by participants based in the region. Most team members have a strong regional network of contacts at private engineering firms companies and state and federal agencies. Since costs are relatively low for reconnaissance in the affected area for participants based close by, there was little downside to adding as many willing contributors who wanted to take part.

Geotechnical reconnaissance was organized into four regions, including the epicentral area, Richmond and Eastern Virginia, the National Capital region, and distant sites. Findings are grouped and presented in this manner. We focused on documenting ground failure, such as liquefaction, along with the performance of bridges and other lifelines, dams and embankments, building foundations, landfills, and critical facilities within each region. Although few ground failures were suspected, our philosophy is that it is of equal significance to study sites where failure did not occur, especially in the epicentral region where PGAs were relatively high. Careful documentation of this earthquake is of added importance due to the sparseness of recorded motions and modern documentation of seismic performance in the eastern US.

In the epicentral region careful searches were conducted along rivers, creeks, and Lake Anna where we focused on vulnerable soils areas such as boat ramps, small marinas, creeks and inlets, retaining structures, man-made beaches, railroad and highway embankments, and slopes and dams. We were especially interested in the performance of the North Anna Nuclear Power Plant and the 30-m high embankment dam on Lake Anna. In Richmond and eastern Virginia, we focused mainly on soft Coastal Plain deposits and major waterways such as the James River. In the Washington, DC area careful searches were made along major waterways, at waterfront structures, at critical facilities such as dams and airports, and at sites where damage occurred to



monuments and institutions. At distant sites, such as New York, we focused mainly on documenting isolated sites of minor damage.

There were few instances of ground failure produced by this earthquake. We found minor liquefaction and slumping along some streams, minor separation of approach abutments from bridge bents, rockfalls, and slope movements in marginally stable slopes. Most of these observations were in the epicentral region. Although there were few sites of ground failure, there were observations important to the geotechnical engineering community. Of particular significance, we saw a clear correlation between geotechnical conditions and damages from this event, especially in the National Capital Region. It was clear that soil amplification in soft sediments overlying hard rock influenced damage and shaking intensity patterns, as did the underlying geologic structure associated with the Appalachian Mountains and the strike of regional geologic faulting. There will also be instructive findings related to regional ground motion attenuation, topographical effects, unique site conditions not fully captured by current IBC/ASCE7 soil amplification factors, and seismic hazard assessment.

From a seismological standpoint, it was unfortunate that the M5.8 event was not well recorded, although several of the larger aftershocks were very well recorded. Only a few strong motion instruments were located within 200 km of the epicenter at the time of the main shock. This will limit the ultimate amount of seismological and engineering knowledge that can be gained; nevertheless, there will be valuable lessons. Among these include a complex fault rupture process, which may be found to be characteristic of central and eastern North American (CENA) earthquakes, and a pronounced directivity of maximum radiated shaking. Both issues increase uncertainties associated with ground motion prediction and seismic hazard for CENA. The event has important implications for current efforts such as the New Generation Attenuation (NGA) East program charged with developing a new set of comprehensive and broadly accepted attenuation models for CENA. Finally, beyond engineering and seismological findings, the event can teach us much about the need for improved preparedness for and better awareness of eastern US earthquake hazards.

This report presents findings from the reconnaissance efforts to date. It is preliminary in scope and inevitably incomplete, and presented mainly for timely dissemination of observations to the engineering community and relevant stakeholders. Analyses are being conducted that will allow refined assessments. A subsequent report, more comprehensive in scope, will be issued in the next few months.

In addition to Section 1, presented here, Sections 2 and 3 present a summary of Central Virginia Zone seismicity and regional geological structure. Seismological findings are presented in Section 4. Sections 5, 6, and 7 present findings from the epicentral region, Richmond and eastern Virginia, and the National Capital region, respectively. Section 8 presents possible research topics associated with this event.

Any opinions, findings, and conclusions or recommendations expressed in this report are those of the authors and do not necessarily reflect the views of the associated organizations and funding agencies.

## **Acknowledgements**

Team members gratefully acknowledge generous support from numerous individuals, firms, organizations, agencies and institutions: **DC Department of Transportation (DDOT), Earthquake Engineering Research Institute (EERI), Fugro Consultants, Maryland Department of Transportation (MDOT), Mueser Rutledge Consulting Engineers, PSI, Schnabel Engineering, Smithsonian Institution, Steele Foundations, Virginia Department of Mines, Minerals, and Energy (DMME), United States Geological Survey (USGS), Virginia Department of Transportation (VDOT), the Virginia Tech Seismological Observatory (VTSO), Dr. Deborah Pettit, Superintendent of Louisa County Schools, and residents of the affected area.**

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## 2. REGIONAL SEISMICITY AND GEOLOGY

### Regional Tectonic Setting and Southeastern US Seismicity

The tectonic regime in the eastern US involves compression of the Atlantic Coast region presumably due to ridge-push from the Mid-Atlantic Ridge, and/or the formation of the Appalachian Mountains due to collision between North America and Africa about 300 million years ago (Zoback and Zoback, 1980; USGS, 2011a). Principal compressive stresses are oriented in the west-northwest to east-southeast direction, as depicted in Figure 2-1. As discussed below, moment tensor solutions from the M5.8 earthquake indicate thrust faulting with the direction of compressive stresses consistent with the regional stress field. A more thorough discussion of regional tectonics and crustal stress states is presented in Zoback and Zoback (1980).

As shown in Figure 2-2, the eastern US is an area of diffuse low-level seismicity with concentrations of activity both parallel and normal to the northeasterly structural trend of the Appalachian Mountains. The largest historical earthquake in the region was the 1886 Charleston, SC Earthquake estimated at M7.3. The previous largest historical earthquake in Virginia was the Giles County Earthquake of 1897, estimated at M5.9.

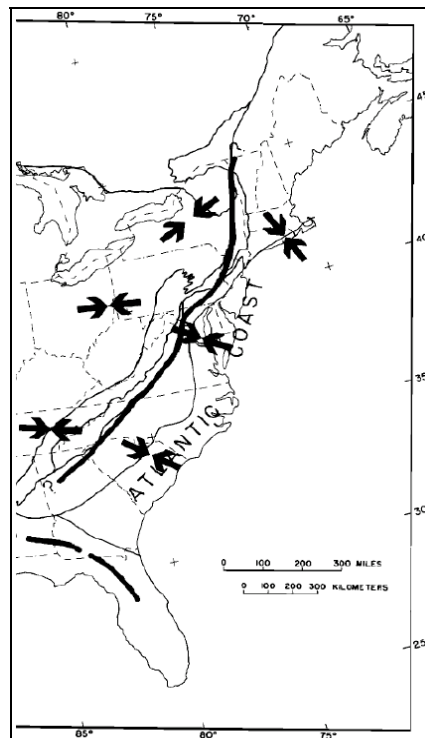
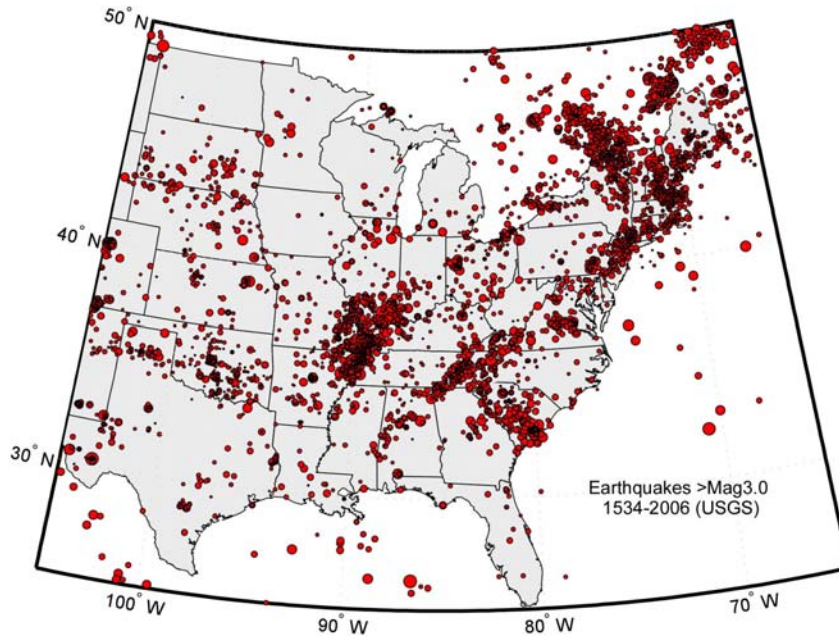


Figure 2-1 – Orientation of regional stress field along the Atlantic Coast (adapted from Zoback and Zoback, 1980).



**Figure 2-2 – Eastern and central US seismicity for M>3 since the mid-16<sup>th</sup> century (USGS)  
Central Virginia Seismicity.**

The epicenter of the August 2011 M5.8 earthquake and its aftershocks fall within the Central Virginia Seismic Zone (CVSZ), a cluster of earthquakes centered about halfway between Richmond and Charlottesville, Virginia. The CVSZ can be seen in Figure 2-3, delineated by earthquakes located by the Virginia Tech Seismological Observatory (VTSO). The region is well-known for frequent small-to-moderate shocks that have occurred since at least 1774. Small earthquakes that cause little to no damage are felt about once a year. USGS catalogs indicate more than 175 felt events over the past 235 years. The previous largest historical CVSZ earthquake occurred in 1875. This shock is estimated at M4.8 based on felt area. The earthquake shook bricks from chimneys, broke plaster and windows, and overturned furniture at several locations. More recently, an M4.5 earthquake occurred in December 2003, causing minor damage. This event was located about 20 km southwest of the M5.8 shock.

The CVSZ has been of particular interest to regional seismologists, especially VTSO researchers who have instrumentally recorded seismicity there since 1978. Data from their studies, along with historical accounts, have been used for regional seismic hazard assessments. The higher rate of seismicity relative to other mid-Atlantic locations is reflected in national seismic hazard maps, such as that shown in Figure 2-4. Seismicity data from VTSO is available at:

<http://www.geol.vt.edu/outreach/vtso/>.

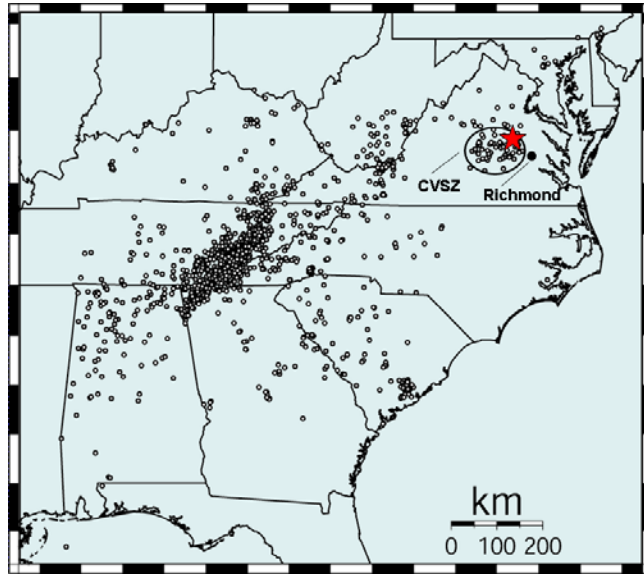


Figure 2-3 – Southeastern seismicity recorded by VTSO from 1977-1999 for  $M > 0.0$ ; CVSZ shown along with M5.8 epicenter (red star).

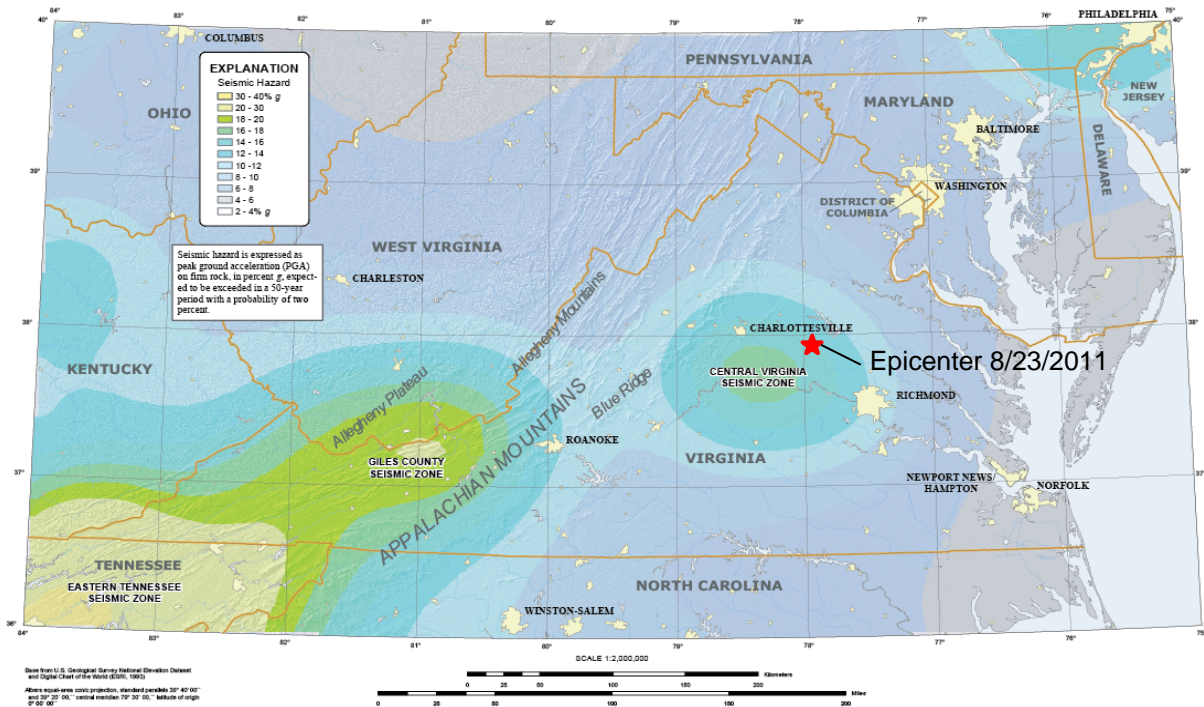
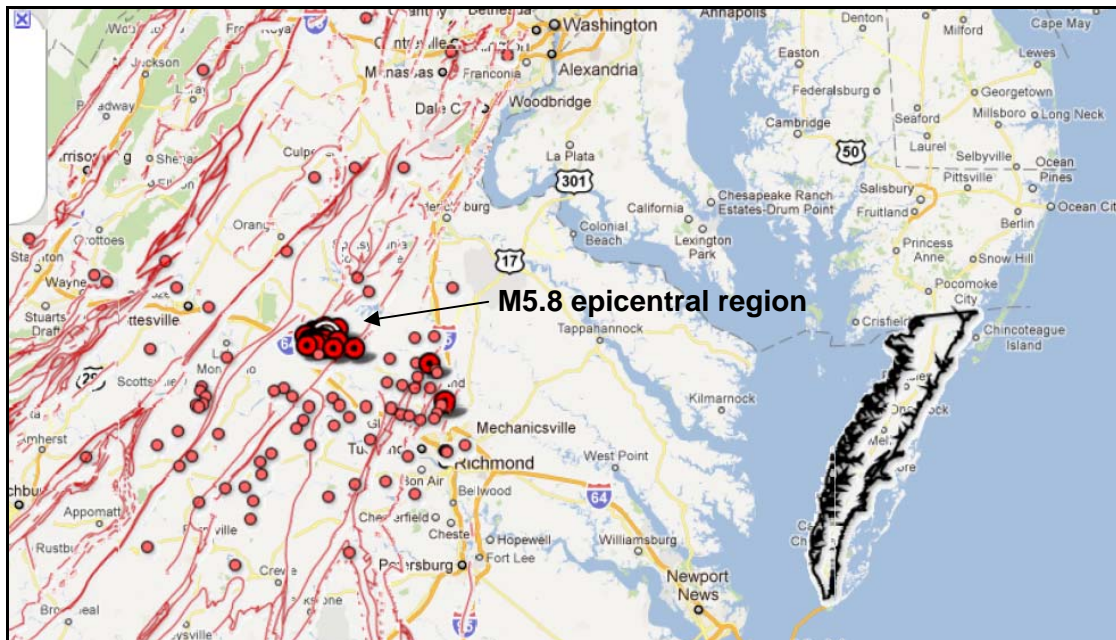


Figure 2-4 - National seismic hazard map showing the higher hazard of the CVSZ (figure adapted from USGS).



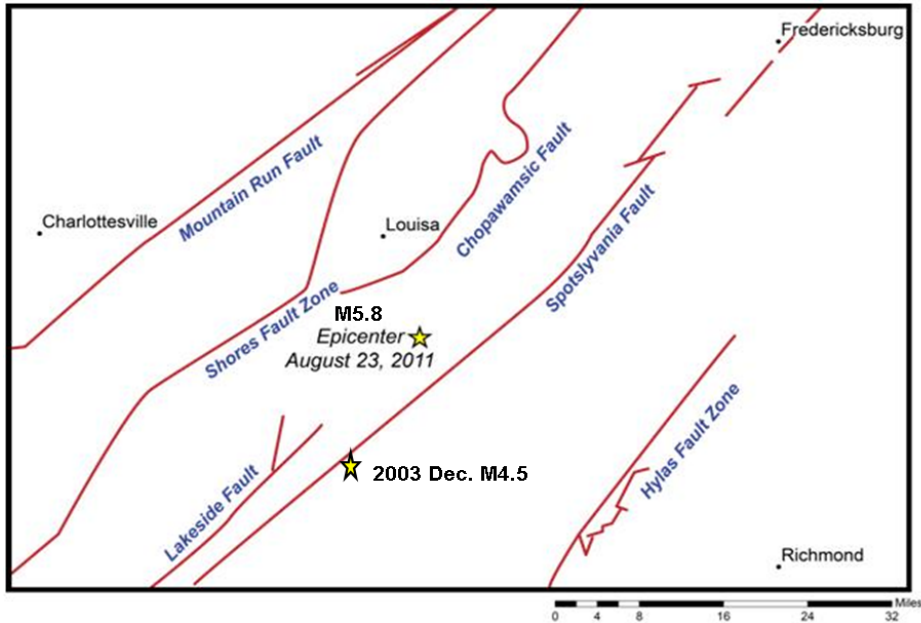
## Regional Geologic Structure

The regional geologic structure in central Virginia is oriented mainly southwest-northeast, along the strike of the Appalachian Mountains. A map showing known faults in Virginia, adapted from the State Geologic Map of Virginia (VDMR, 1993), is presented in Figure 2-5. Numerous faults in this region have been well mapped, although numerous smaller and/or deeply-buried faults remain undetected. Moreover, mapped faults are typically poorly located at earthquake depths. Few, if any, earthquakes in the CVSZ can be linked to named faults, meaning that regional seismic hazard assessments are based primarily on the locations of the earthquakes themselves (a commonly encountered situation east of the Rockies).



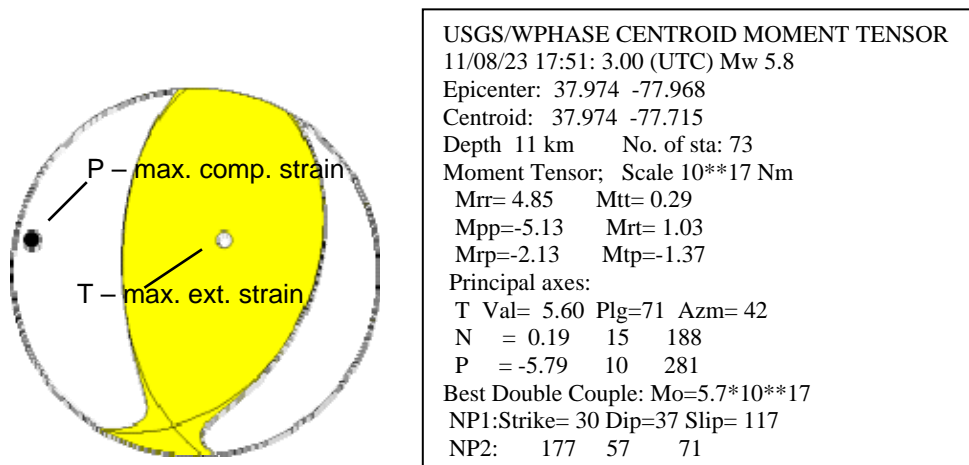
**Figure 2-5 – Known faults in Virginia and locations of regional earthquakes (adapted from VDMR, 1993).**

In the vicinity of the M5.8 epicenter near Mineral, VA, there are several well-known faults including the Chopawamsic Fault, the Lakeside Fault, and the Spotsylvania Shear Zone, as shown in Figure 2-6. These faults, like those throughout most of the state, are very old and related to tectonic events that assembled Pangea more than 300 million years ago. Even though these faults are old, and most are considered inactive, occasional earthquakes continue to occur in the region.



**Figure 2-6 – Known faults in the epicentral region of the 2011 M5.8 and 2003 M4.5 Earthquakes (adapted from VA DMME, 2011).**

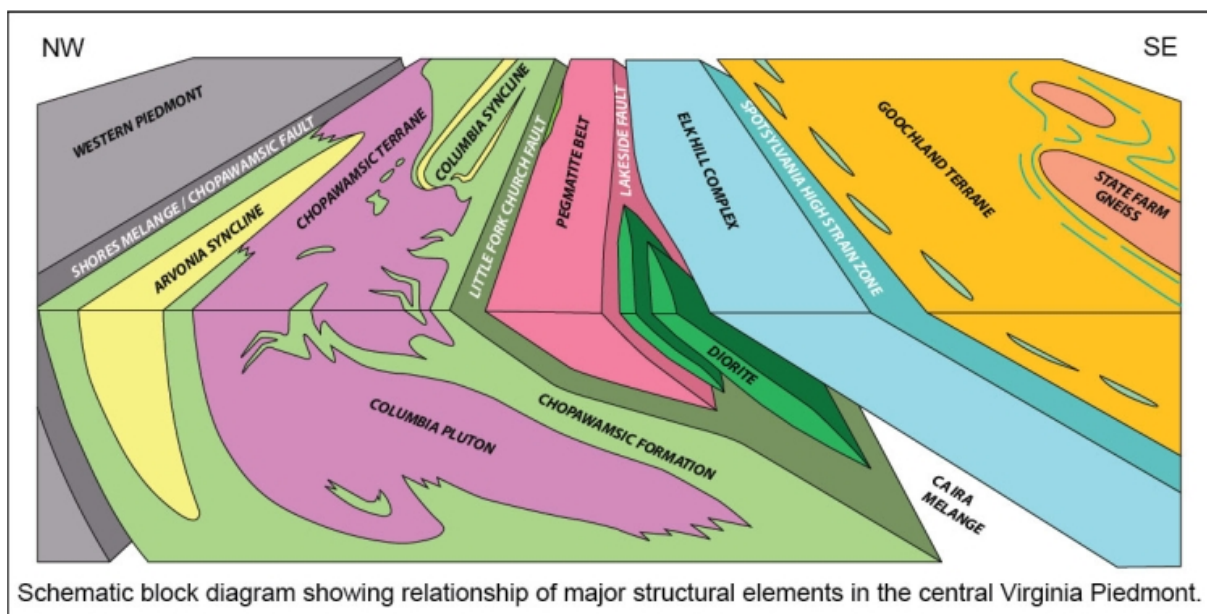
As shown in Figure 2-7, moment tensor solutions developed by the USGS (2011b) indicate the M5.8 earthquake occurred due to reverse faulting on a north or northeast-striking plane, but neither this event nor previous earthquakes have been causally associated with mapped faults. Previous, smaller instrumentally-recorded earthquakes from the CVSZ have had shallow focal depths occurring at an average depth of about 8 km. These events have had diverse focal mechanisms and have occurred over an area with a length and width of approximately 120 km. They have not been aligned in a pattern that might suggest they occurred on a single causative fault.



**Figure 2-7 – Moment tensor solution of the M5.8 Earthquake indicating reverse faulting (USGS, 2011b). The shaded areas show quadrants of the focal sphere in which the first P-wave motions were away from the source. The black and white dots represent the maximum and compressive and extensional strain, respectively.**

Individual earthquakes within the CVSZ occur as the result of slip on faults that are much smaller than the overall dimensions of the zone (USGS, 2011a). The dimensions of the fault that produced the M5.8 August 2011 earthquake will not be known until longer-term studies (ongoing) are completed; however, the spatial distribution of recorded aftershocks suggest a fault rupture plane approximately 10 km long by 6 - 7 km wide (USGS, 2011a; M. Chapman, personal communication).

A block diagram showing the main geologic structures within the CVSZ is shown in Figure 2-8. A detailed discussion of epicentral-area geologic structure, especially as it pertains to the M5.8 event and other recent earthquakes, is provided by Harrison et al. (2011), Bailey (2004), and Spears et al. (2004), among others. A description of the bedrock geology of the epicentral region (Ferncliff, VA 7.5-minute Quadrangle) is also presented in Appendix A of this report.



**Figure 2-8 Geologic structures within the CVSZ (adapted from Spears at DMME 2011).**

In previous efforts to better understand the underlying faulting structure, a deep seismic profile was run along Interstate 64 from the Valley and Ridge to the Coastal Plain (Harris et al., 1986). As shown in Figure 2-9, the I-64 seismic profile is only about 5.5 km southwest along strike of the M5.8 hypocentral area and provides at least some insight into the faulting structure. The highlighted box in Figure 2-10 indicates the approximate position of the M5.8 hypocenter within the profile 5.5 km southwest along strike from the event.



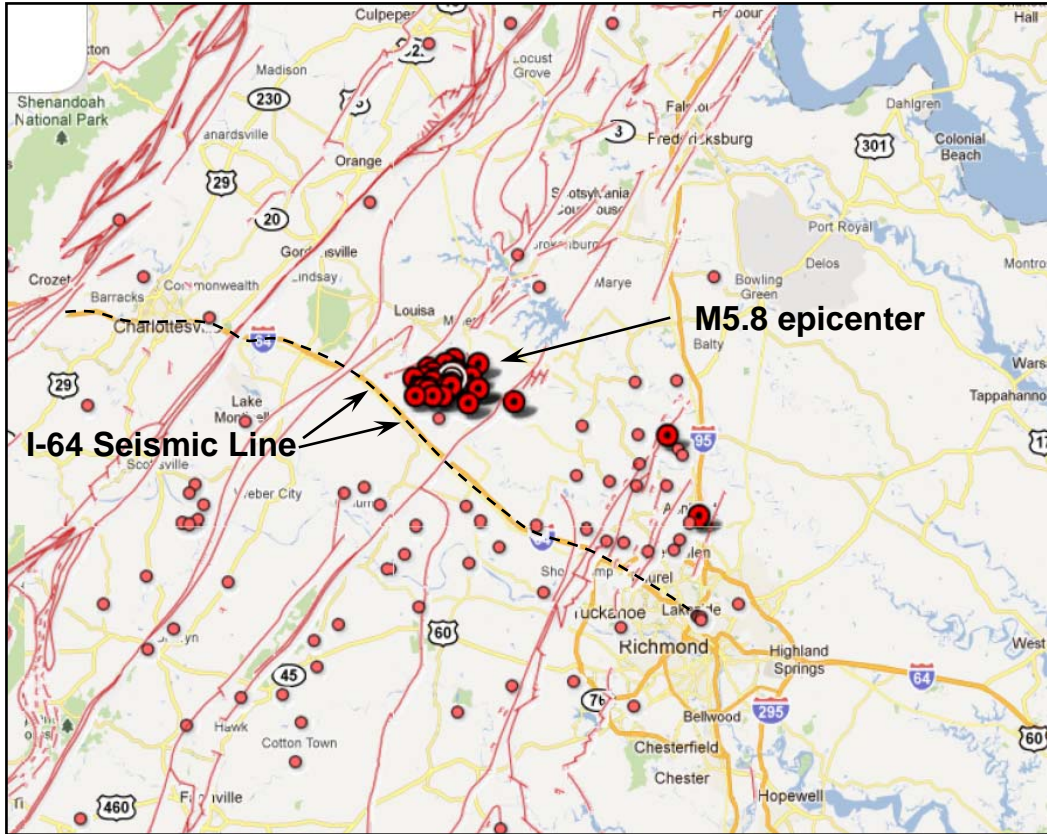


Figure 2-9 - Location of 1986 seismic line run along I-64 ~ 5.5 km SW of the M5.8 EQ (adapted from VDMR, 1993).

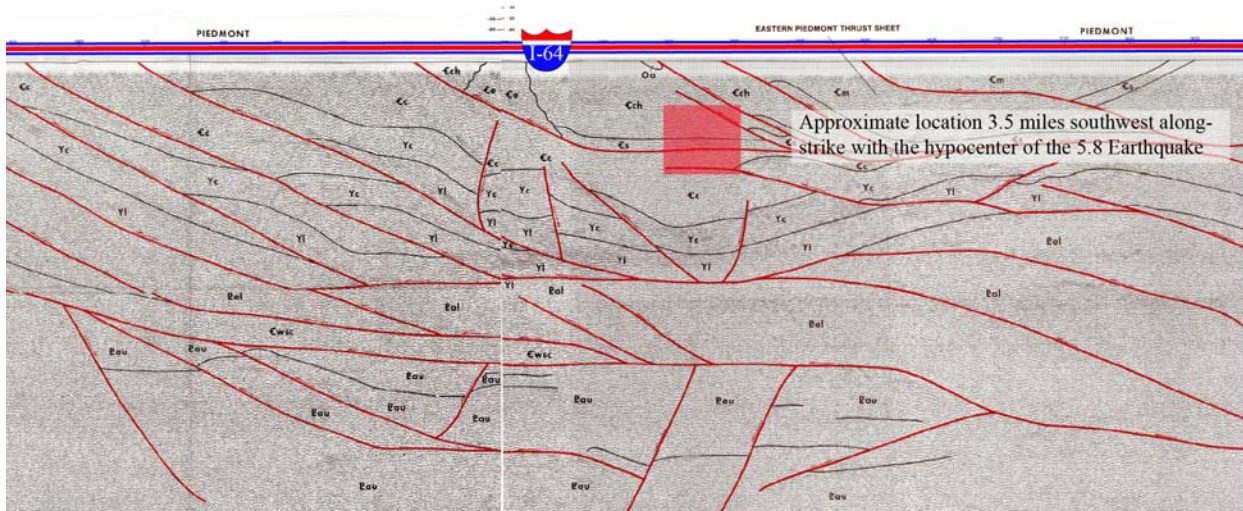


Figure 2-10 Seismic profile along I-64 showing structure beneath the CVSZ 5.5 km (3.5 mi.) SW of the M5.8 Earthquake (adapted from Harris et al., 1986 and VA DMME, 2011).

## **Surface Geology of the Epicentral Region (from M. Carter, personal communication)**

The epicentral area is drained by the South Anna River and its major, secondary, and tertiary tributaries. Alluvium in the form of unconsolidated clay, silt, sand, and gravel of Tertiary to Quaternary age, occurs along portions of these streams, typically at leeward-side point bars and horseshoe bend cut-offs. Alluvium thickness in these areas ranges from a few meters to tens of meters.

Topographic sideslopes and hilltops are typically underlain by saprolite (decomposed bedrock chemically weathered in-place) beneath soil horizons. Saprolite typically ranges from a few meters to tens of meters thick.

These topographic settings are also typically mantled by thin deposits (typically less than a 0.5-meter thick) of gravel-, cobble- and boulder-size polycrystalline vein quartz. (Thin veins of quartz, in this region locally gold-bearing, are likely Paleozoic in age, and cross-cut metavolcanic, metaplutonic, and metavolcaniclastic rocks throughout the region). These vein quartz deposits may have accumulated in-situ from weathering of surrounding bedrock, but more likely are colluvial, having been transported and concentrated down-slope, albeit locally, via Cenozoic erosional processes.

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USGS (2011a) U.S. Geological Survey (2011); viewed 21 September 2011  
[http://earthquake.usgs.gov/earthquakes/eqarchives/fm/neic\\_c0005ild\\_wmt.php](http://earthquake.usgs.gov/earthquakes/eqarchives/fm/neic_c0005ild_wmt.php)

USGS (2011b) U.S Geological Survey (2011); viewed 21 September 2011  
<http://earthquake.usgs.gov/earthquakes/recenteqsww/Quakes/se082311a.php#summary>



VA DMME (2011) Virginia Department of Mines, Minerals, and Energy,  
viewed 21 Sept. 2011 [http://www.dmme.virginia.gov/DMR3/va\\_5.8\\_earthquake.shtml](http://www.dmme.virginia.gov/DMR3/va_5.8_earthquake.shtml)

VDMR (1993) - Virginia Division of Mineral Resources (1993), *Geologic Map of Virginia*,  
Department of Mines, Minerals, and Energy, Division of Mineral Resources, Charlottesville,  
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Zoback M. L. and Zoback, M. (1980), “ State of Stress in the Conterminous United States,”  
*Journal of Geophysical Research*, v. 85, p. 6113-6156, 1980.

### 3. EPICENTRAL REGION

This chapter summarizes the observations made by GEER Team members on the geotechnical/geological aspects of the  $M_w$ 5.8 Mineral, Virginia earthquake of 23 August 2011 in the epicentral region. Within hours of the event, members of the team arrived in the epicentral region (i.e., Louisa County, Virginia) to document perishable data that potentially could be used to advance the geo-engineering profession's understanding of the geotechnical/geological aspects of earthquakes in general, and of intra-plate earthquakes more specifically. The team focused on documenting tectonically/seismically-induced ground deformations, evidence of liquefaction and lateral spreading, land/rock slides, ground subsidence, performance of earthen dams, damage to building foundations, and damage to public infrastructure and lifelines, among other effects of the earthquake. The team began collecting data on the night of the main shock (i.e., 23 August 2011) and continued for several months thereafter, with the majority of effort being concentrated in the few days immediately following the main shock. The documentation of the data following the event was time critical because of the heavy rains and river flooding associated with Hurricane Irene that was forecast to impact the area on 27 August 2011, with the rains and flooding having the potential to significantly modify or destroy the geotechnical/geological effects of the earthquake. To maximize the efficiency of the team's efforts, team members met several times with the personnel staffing the Emergency Operations Center (EOC) in Louisa to obtain damage reports which were used to coordinate the team's field surveys.

The Team's observations are organized in the following categories: Ground Failures (liquefaction, river bank slumps, subsidence, and rockfalls); Lifelines (bridges, power, water, and railroad); Dams, Landfill, Schools, and Foundations/Buildings.

#### **Ground Failures**

##### ***Liquefaction***

The soils in Louisa County are largely residual clay, so it was not expected that liquefaction would be pervasive during this event. However, the Team did search in low lying areas where the ground water table was expected to be high and where there was a possibility of the presence of liquefiable deposits (e.g., floodplains). In total, four small liquefaction sand boils were found at the locations marked in Figure 1, with photos of the features shown in Figure 2 (Note that the two features in the S. Anna River bed were found by Jeff Munsey, TVA, and the nearby feature on the roadside was found by Ed Harp, USGS). Also shown in Figure 1 are the epicentral locations of the main shock and aftershocks that were greater than  $M_w$ 3.0 that occurred within two days of the main shock. Assuming that these epicenters define the general location/orientation of the rupture plane of the main shock, it can be inferred from Figure 1 that the liquefaction features lie approximately above the rupture plane. It is possible that liquefaction occurred in other areas, but the undergrowth in the region is so thick and

sand deposits so sparse, no other features were found despite an extensive search along streams and in floodplains in the epicentral region. Also, there were several heavy rains in the days and weeks after the main shock that resulted in high river levels, which likely washed away any features in the river and creek beds.

The liquefied soil was coarse sand, with the feature in the drainage channel containing some plasticity. No feeder dikes could be found for the features in the S. Anna River riverbed (Figure 2b), but the riverbed was very gravelly and the water table was only an inch or two below the ground surface. As a result, a clean cut could not be made vertically through the feature and the cut quickly filled with water. The features on the roadside (Figures 2c,d) and the feature in the drainage channel in the woods (Figures 2e,f) both appeared to have vented through existing animal holes or burrows.

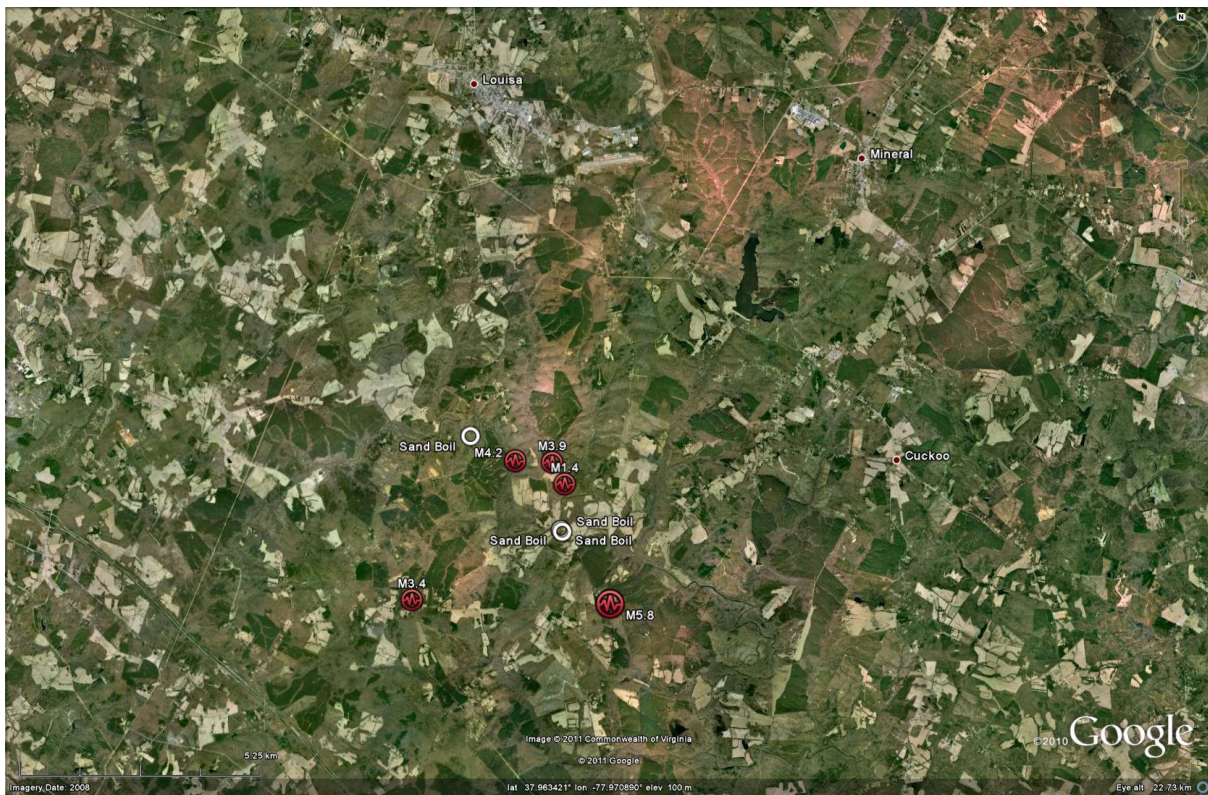


Figure 1. Aerial image of the epicentral region showing locations of observed liquefaction sand boils. Also shown in this image are the epicenters of the main shock and aftershocks that occurred within two days of the main shock that had magnitudes greater than 3.0.





(a) (source: Mark Carter, USGS)



(b)





(c)



(d)





(e)



(f)

Figure 2. Liquefaction sand boils found in the epicentral region: (a) two sand boils in the S. Anna River riverbed near Yancy Mill (features found by Jeff Munsey, TVA) (37.93839, 77.98269); (b) cross-sectional cut through one of the sand boils in the S. Anna River riverbed. The trowel points to a layer of leaves, indicating that the blow material was recently placed; (c) sand boil found across the road from the features in the riverbed (feature found by Ed Harp, USGS) (37.93807, -77.98238); (d) horizontal cut through the roadside feature showing a plan view of the feeder dike; (e) sand boil found in a drainage channel in the woods of Bend



of River Rd (37.95668, -78.00502); (f) horizontal and vertical cut through the drainage channel feature.

On 25 August 2012, geologists F. Syms and R. Cumbest, Fugro Consultants, Inc., conducted a low altitude over flight of the epicentral region. As shown in Figure 3, the flight path originated in Chesterfield, VA (just south of Richmond) and included the James and Rivanna Rivers, epicentral region, and the western edge of Lake Anna. No evidence of surface deformation in the epicentral and surrounding region was noted. Numerous point bars (e.g., Figure 4), river and lake banks, open crop fields, were observed with no signs of liquefaction, lateral spread or surface offset. The vegetation over smaller creeks prevented any observations.

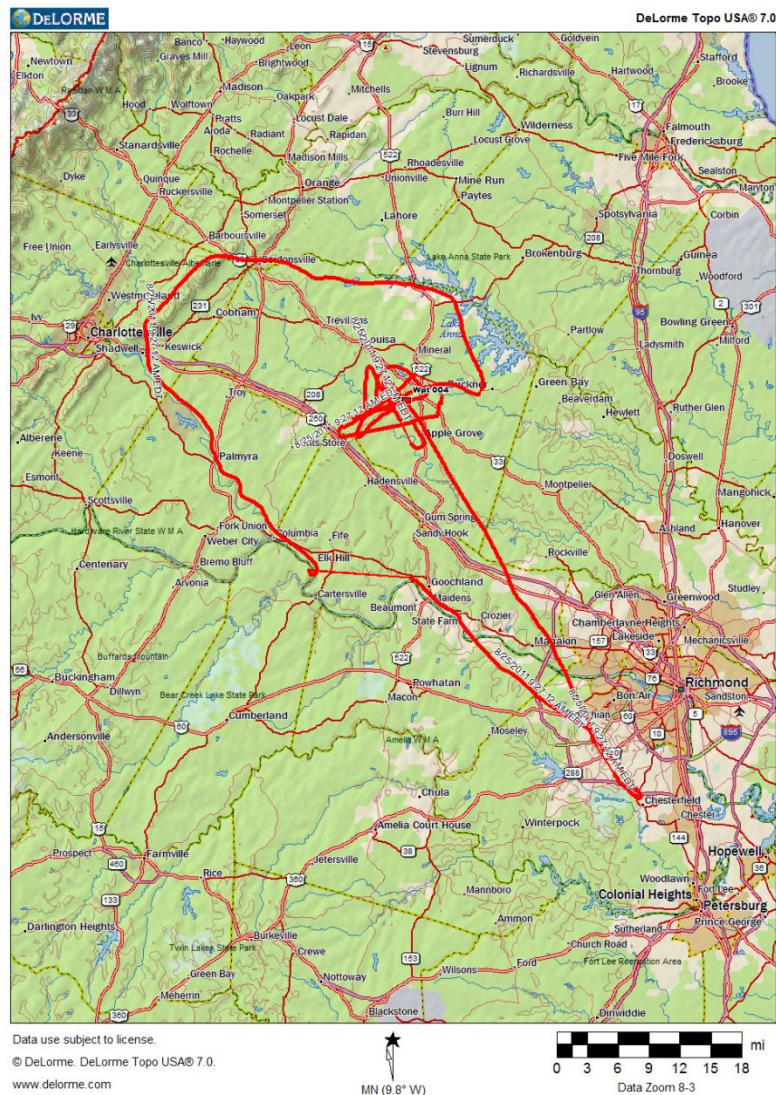
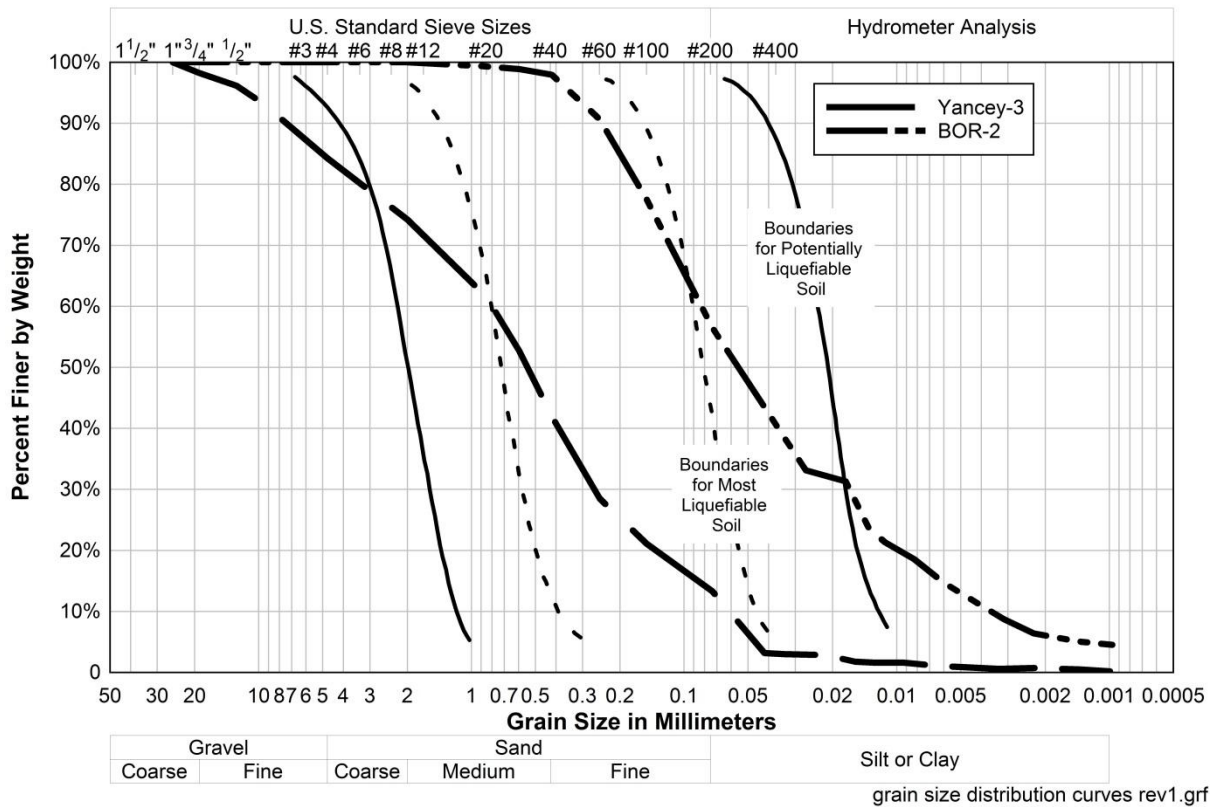


Figure 3. Low altitude flight path of geologists F. Syms and R. Cumbest conducted on the morning of 25 August 2012. (courtesy of F. Syms)



Figure 4. Aerial photo of point bar along Rivanna River near Palmrya, VA, approximately 27 km from the epicenter. No evidence of liquefaction or lateral spreading was observed. (courtesy of F. Syms)

Samples of liquefaction ejecta were collected from both liquefaction sites for grain size analyses. Figure 5 shows the grain size distribution curves for the samples. The ejecta from the features at the Yanceyville mill site (Yancey-3) classified as SW-SM: Well-graded Sand with Silt and Gravel per the ASTM-2487 soil classification system (ASTM 2011). Because the ground surface layer at this site was very gravelly and the water-table was only several centimeters below ground surface, a clean cut could not be made vertically through the feature and the cut that was made quickly filled with water. As a result, feeder dikes for the features could not be found (Figure 2a,b). The ejecta sample from the Bend of the River site (BOR-2) was much finer than that from the Yancey-3 site and classified as ML: Silt per the ASTM-2487 soil classification system (ASTM 2011). The feature at the Bend of River site (Figures 2e,f) appeared to have vented through an existing animal or root hole, and it is likely that the feature would not have manifested on the ground surface in the absence of the pre-existing hole. Finally, superimposed on the grain distribution plot are the bounds proposed by Tsuchida (1970) for the grain size ranges for soils that are “most susceptible to liquefaction” and “potentially susceptible to liquefaction”. While grain size distribution is only one aspect influencing the liquefaction susceptibility of a soil stratum, it can be seen that the samples from the Yancey-3 and BOR-2 sites generally fall outside the “most susceptible to liquefaction” boundaries, but do generally fall within the boundaries for “potentially susceptible to liquefaction”.



**Figure 5.** Grain size distribution curves for the liquefaction ejecta samples. Superimposed on the grain distribution plot are the bounds proposed by Tsuchida (1970) for the grain size ranges for soils that are “most susceptible to liquefaction” and “potentially susceptible to liquefaction”.

In addition to grain size analyses, dynamic cone penetration (DCP) tests were performed at the two liquefaction sites. The DCP used for this study was designed by Professor George Sowers (Sowers and Hedges, 1966) and is shown in Figure 6. In addition to this earthquake, the Sowers DCP has been used on several other recent post-earthquake investigations to evaluate deposits that liquefied (e.g., the 2008,  $M_w$ 6.3 Olfus, Iceland earthquake, the 2010,  $M_w$ 7.0 Haiti earthquake, the 2010  $M_w$ 7.1 Darfield, New Zealand earthquake, the 2010,  $M_w$ 8.8 Maule, Chile earthquake, and the 2011,  $M_w$ 6.2 Christchurch, New Zealand earthquake). This system utilizes a 6.8 kg mass (15-lb drop weight) on an E-rod slide drive to penetrate an oversized 45° apex angle cone. The cone is oversized to reduce rod friction behind the tip. The DCP tests consists of counting the number of drops of the 6.8 kg mass that is required to advance the cone ~4.5 cm (1.75 inches), with the number of drops, or blow count, referred to as the DCP N-value or  $N_{DCPT}$ .  $N_{DCPT}$  is approximately equal to the Standard Penetration Test (SPT) blow count up to an N-value of about 10 (Sowers and Hedges, 1966; Green et al., 2011a,b). However, beyond an N-value of 10, the relationship becomes non-linear. The correlation relating SPT and DCP N-values used in this study is the same one used by Green et al. (2011a,b), which is a slightly modified version of the correlation proposed by Sowers and Hedges (1966).





**Figure 6.** Sowers Dynamic Cone Penetrometer (DCP). Used to measure in-situ properties at the Yancey-3 and BOR-2 liquefaction sites.

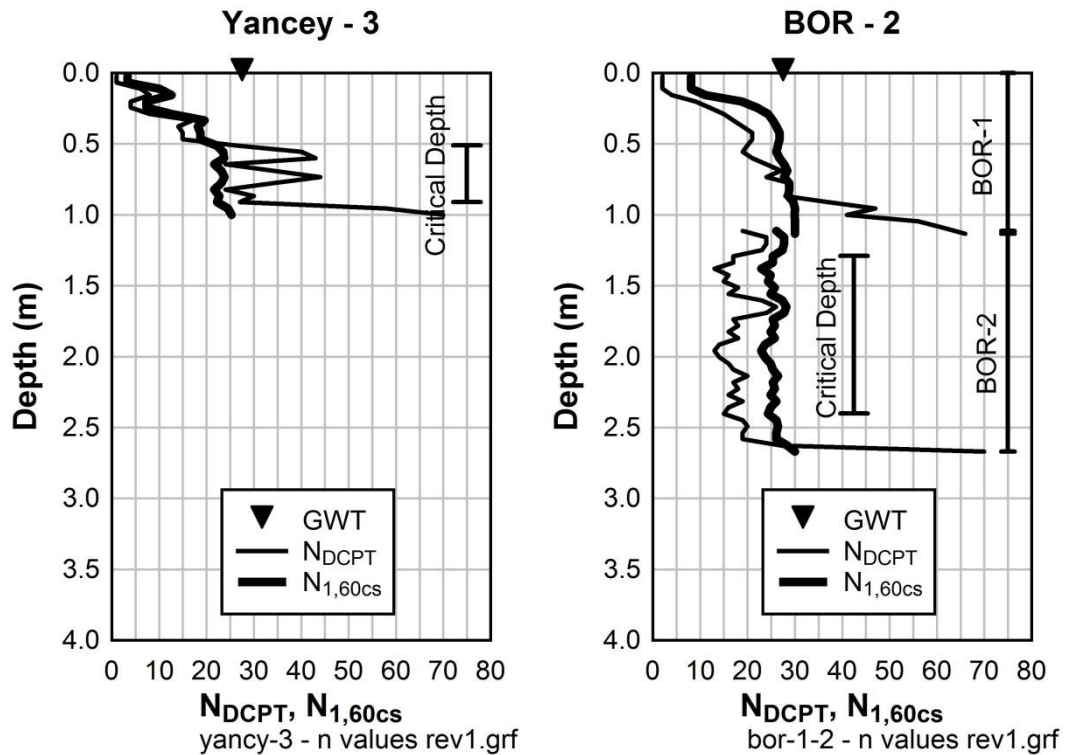
Following the procedure outlined in Olson et al. (2011), the SPT equivalent N-values ( $N_{SPT\text{equiv}}$ ) values were normalized for effective overburden stress and hammer energy using the following relationship:

$$N_{1,60\text{-SPT}\text{equiv}} \approx N_{SPT\text{equiv}}(N_{DCPT}) \cdot \left( \frac{P_a}{\sigma'_{vo}} \right)^{0.5} \frac{ER}{60\%} \quad (1)$$

where  $N_{SPT\text{equiv}}(N_{DCPT})$  is the functional relationship between  $N_{SPT}$  and  $N_{DCPT}$  mentioned above (Green et al., 2011a,b),  $P_a$  is atmospheric pressure (i.e., 101.3 kPa),  $\sigma'_{vo}$  is initial vertical effective stress (in the same units as  $P_a$ ), and ER is energy ratio. This relationship uses the effective stress and hammer energy normalization schemes outlined in Youd et al. (2001). Although the energy ratio for the system was not measured, the DCP hammer is similar to the donut hammer used for the SPT. Skempton (1986) and Seed et al. (1984) suggested that the energy ratio for an SPT donut hammer system ranges from about 30 to 60%. However, because the DCP system does not have pulleys, a cathead, etc., we anticipate that the energy ratio for the DCP is likely to be near the upper end of this range. Therefore, we assumed an ER = 60% for our calculations.

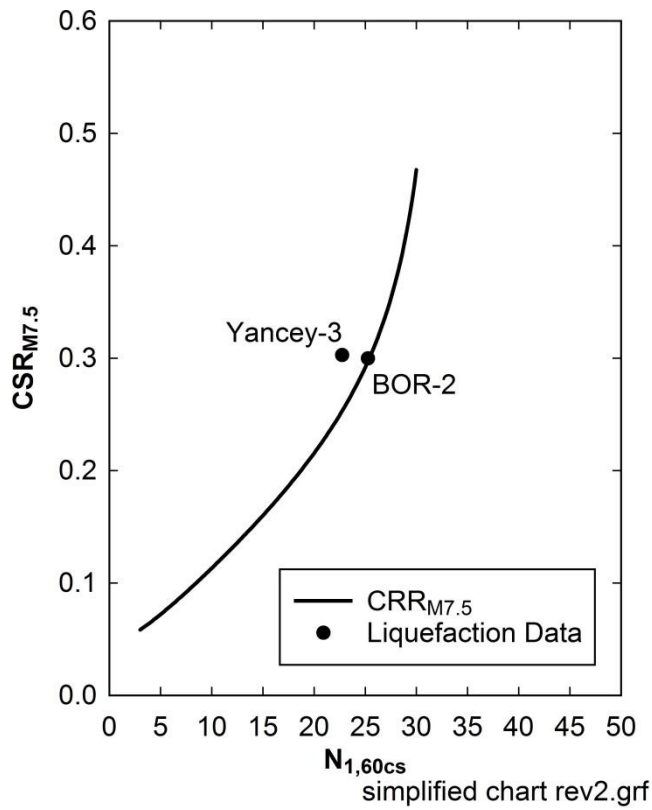
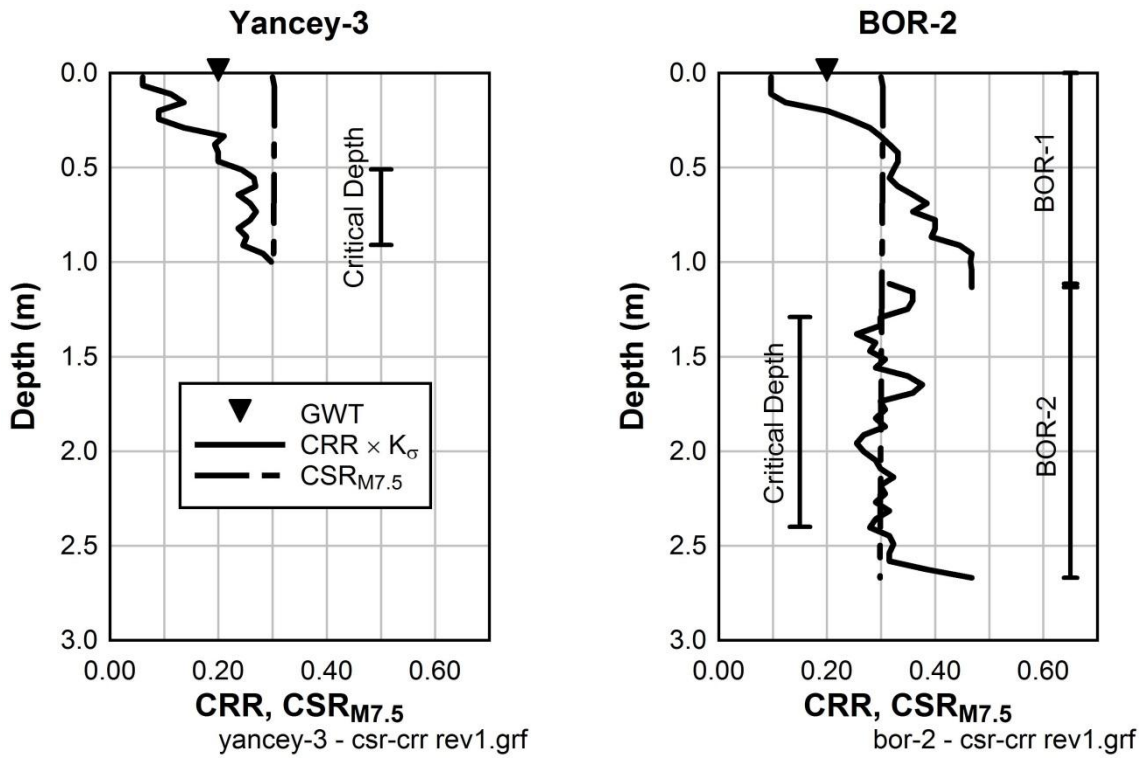
In addition to the effective stress and hammer energy corrections, the  $N_{SPT\text{equiv}}$  values were also corrected for fines content following the procedure proposed in Youd et al. (2001), where the fines contents were determined from the grain size distribution curves shown in Figure 5. Figure 7 shows a plot of  $N_{DCPT}$  and  $N_{1,60\text{cs-SPT}\text{equiv}}$  for the two liquefaction sites identified by the ground reconnaissance team.





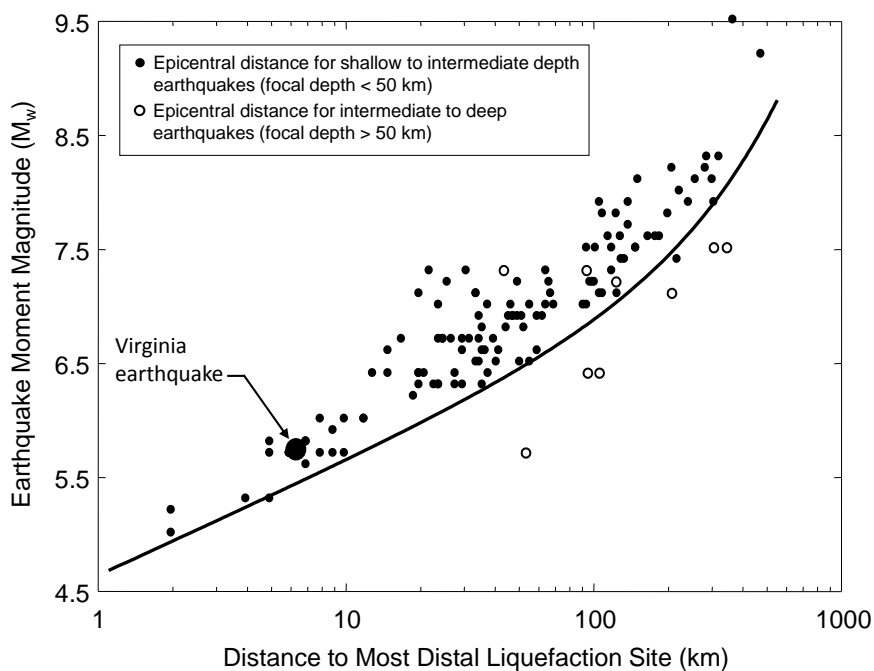
**Figure 7.**  $N_{DCPT}$  and  $N_{1,60cs-SPT_{equiv}}$  for the two liquefaction sites identified by the ground reconnaissance team (Yancey-3 and BOR-2).

The cyclic stress ratios (CSRs) at the DCP test sites were calculated following the methodology outlined in Youd et al. (2001), assuming the peak ground accelerations (PGA) at both sites were 0.5 g (Chapman, 2012b). The average of the recommended range of magnitude scaling factors (MSFs) proposed in Youd et al. (2001) was used to compute  $CSR_{M7.5}$  at the sites. Using the  $N_{1,60cs-SPT_{equiv}}$  described above, the correlation proposed by Youd et al. (2001) was used to estimate the cyclic resistance ratio for a  $M_w7.5$  event (i.e.,  $CRR_{M7.5}$ ). Comparisons of the computed  $CSR_{M7.5}$  and  $CRR_{M7.5}$  for both sites are shown in Figure 8. As shown in this figure, liquefaction is predicted to have occurred at both sites (i.e.,  $CSR_{M7.5} > CRR_{M7.5}$ ). However, the factors of safety against liquefaction ( $FS = CRR_{M7.5}/CSR_{M7.5}$ ) are very close to 1.0 and the thicknesses of the liquefied layers are predicted to be relatively thin. These predictions are consistent with the small sand boils found at the sites. Furthermore, these analyses show that the stark contrast in the paucity of features produced by the Mineral earthquake compared to the widespread liquefaction that was caused by similar magnitude events in Christchurch, New Zealand in June 2011 is most likely due to the differences in the liquefaction susceptibility of soils in the two regions, rather than the difference in the characteristics of the ground shaking (Green and Lasley, 2012).



**Figure 8.** Results from simplified liquefaction evaluations of Yancey-3 and BOR-2 liquefaction sites.

Finally, from an engineering perspective, the observed liquefaction during the Mineral, Virginia earthquake is not significant in itself. However, it adds to the relatively limited database of earthquake-induced liquefaction in stable continental regions and is valuable in validating relationships used to estimate the magnitude of pre-instrumental and/or paleoearthquakes in the region. Towards this end, the most distal liquefaction feature from the epicenter for this event is BOR-2 site, which is ~6.25 km from the main shock epicenter. This distance is plotted in Figure 9, along with data from worldwide earthquakes compiled by Ambraseys (1988). As may be observed from this figure, the epicentral distance falls close to, but within, the boundary for maximum distance.



**Figure 9.** Comparison of the most distal liquefaction feature from the Mineral, Virginia earthquake of 23 August 2011 with worldwide earthquake data collected by Ambraseys (1988).

### ***Riverbank Slumps***

Mark Carter, USGS, searched the South Anna River for slumps in the banks. One small slump was found very close to the liquefaction features shown in Figure 2a, which again is likely located approximately over the rupture plane. This slump is shown in Figure 10. Heavy rains from Hurricane Irene started on 27 August and made it impossible to definitively attribute slumps found subsequently to earthquake shaking.





Figure 10. Slump in the bank of the S. Anna River near the Yancy Mill (37.938495, -77.983203).

### ***Subsidence***

Mark Carter, USGS, found what is believed to be earthquake-induced subsidence of an abandoned gold mine. The location of the subsidence is shown in Figure 11. A photograph of the subsidence is shown in Figure 12.

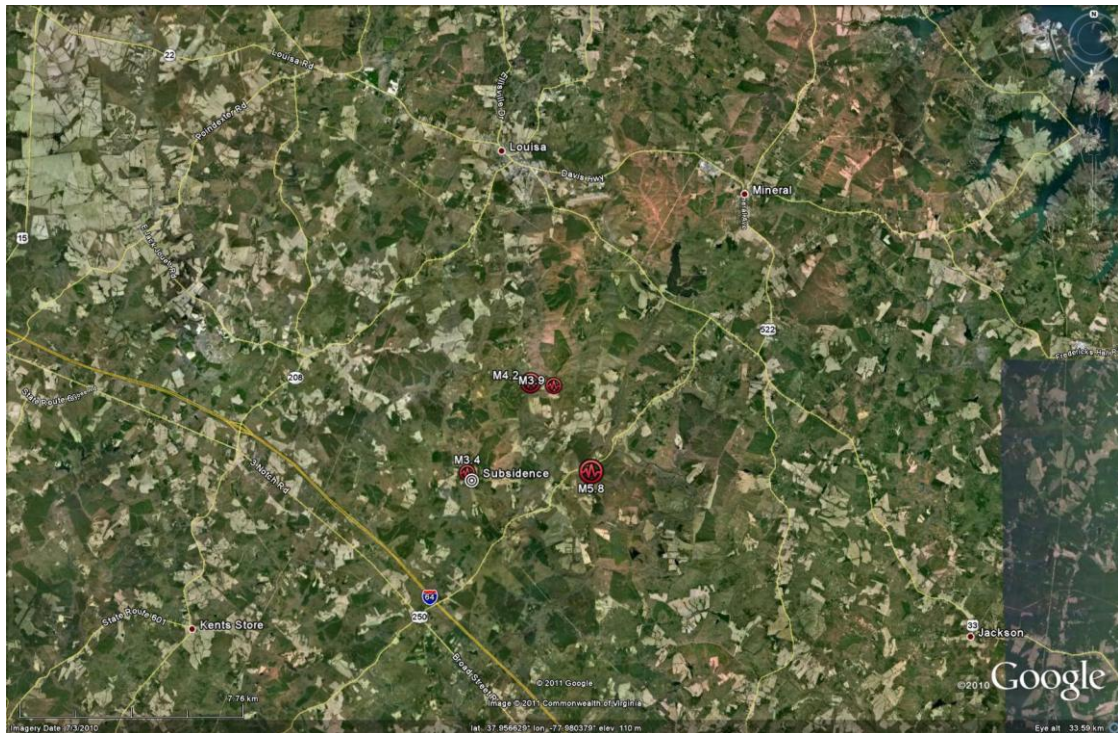


Figure 11. Aerial image showing the location of where it is believed the earthquake-caused subsidence of the ground surface above an abandoned gold mine.



(a)



(b)

Figure 12. Photograph of the area that subsided (Photo by Mark Carter) (37.9229, -78.0176).

### ***Rockfalls***

Mark Carter and Ed Harp, both of the USGS, identified four minor rock falls in the epicentral region, two along the banks of the South Anna River and two in road cuts. The locations of these rock falls are shown in Figure 13, with photographs of two of these rock falls shown in Figure 14.



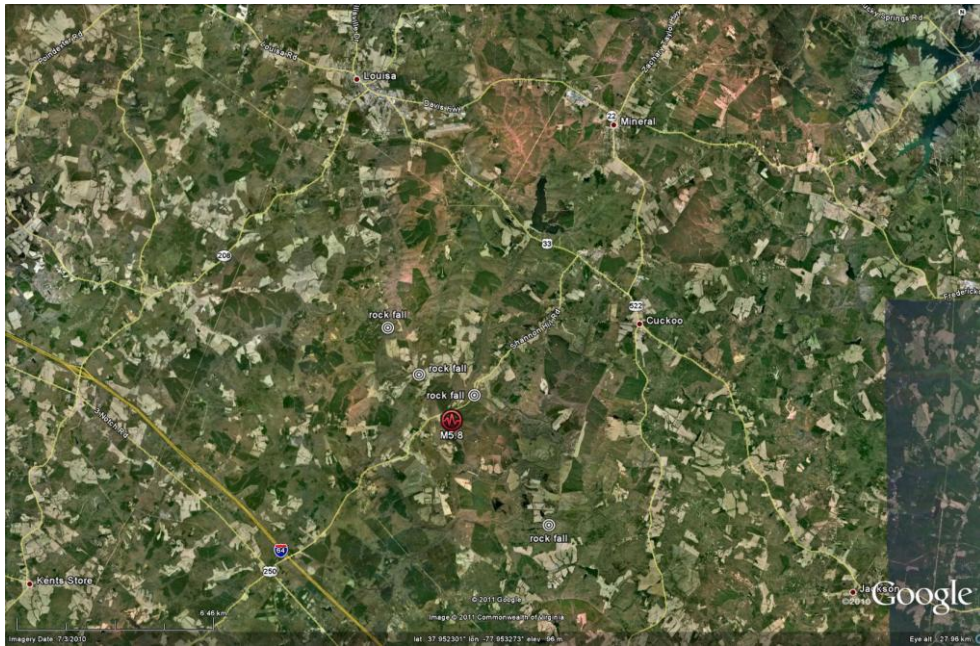
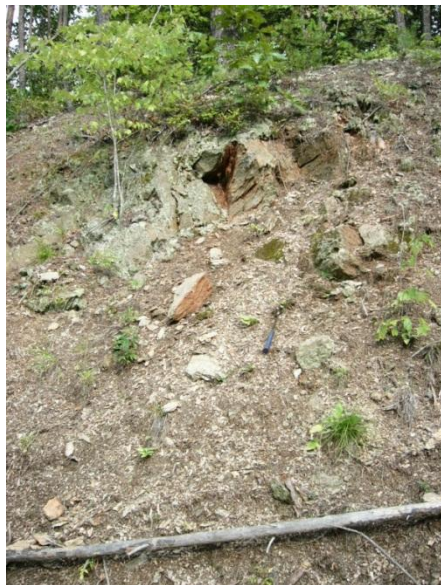


Figure 13. Locations of rock falls found in the epicentral region along the S. Anna River and road cuts.



(a)



(b)

Figure 14. Rock falls found in the epicentral region (source: Mark Carter): (a) rockfall along Shannon Hill Rd (37.93174, -77.96190); and (b) rockfall along Vigor Rd, near the intersection with Yanceyville Rd (37.93802, -77.98245).

Ed Harp and Randy Jibson, both from the USGS, determined the areal extents of rockfalls to be just north of Harper's Ferry to the north, the Virginia - West Virginia border to the west, and about 10 miles north of the North Carolina border along the Blue Ridge Parkway to the



southwest. They were not able to determine the eastern limit. The determined limits are shown in Figure 15.

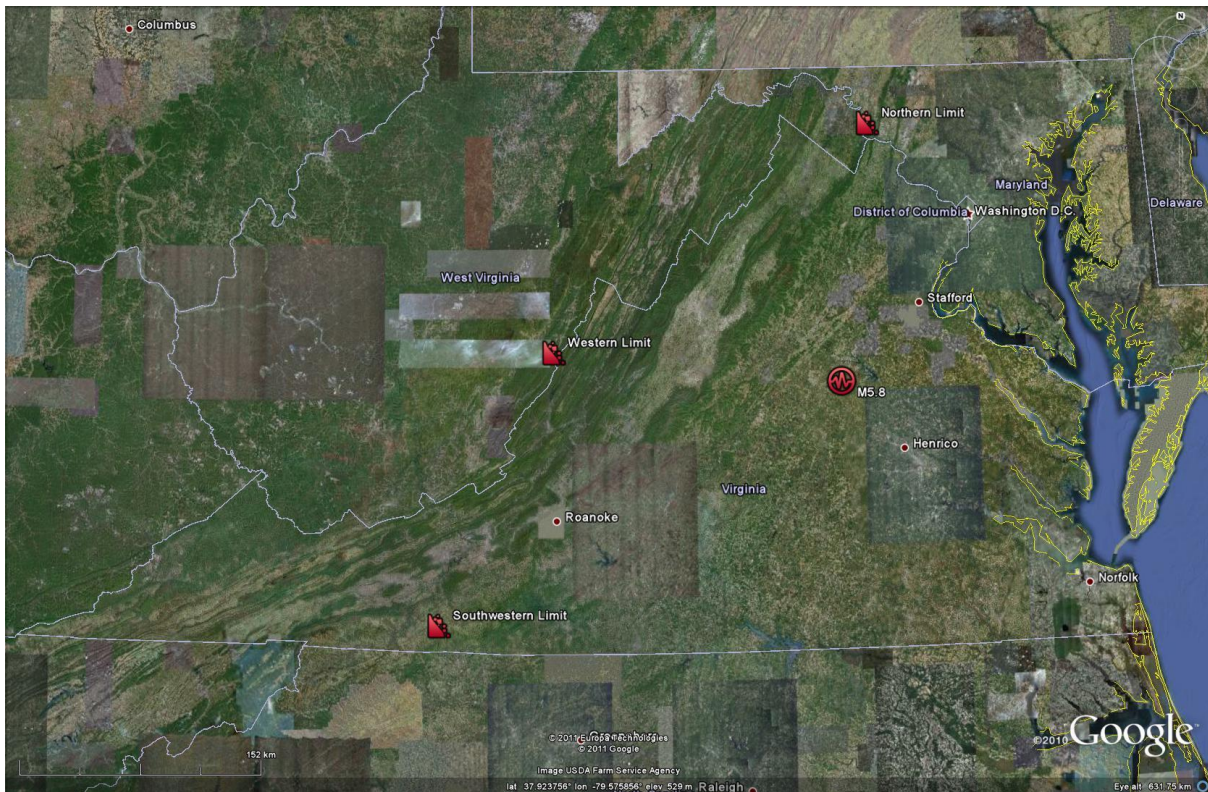


Figure 15. Aerial image showing the areal extent of rock falls to the North, West, and South of the epicenter; the eastern extent could not be determined.

## **Lifelines**

### ***Bridges***

Numerous bridges in the epicentral region were given rapid inspections, with two bridges inspected in detail. The locations of the two bridges are shown in Figure 16. The first is the Yancyville Rd bridge, which is ~40 m long and crosses the S. Anna River in the NW-SE direction. We inspected this bridge in detail because it is very near where the liquefaction features were found in the riverbed and along the roadside. Photos of the bridge are shown in Figure 17. The bridge has a two lane concrete deck that sits on two bents, in addition to the NW and SE abutments. The only effects of the earthquake that could be found was ~2.5 cm gap between the soil and the SE pier (Figure 17b). The gap is shown in Figure 17c and was on the river side of the piers. It is uncertain whether the gap was due to movement of the pier due to earthquake shaking (i.e., movement of the bridge in the NW direction relative to the ground) or due to slumping of the river bank. No other evidence of slumping of the river bank near the bridge was observed



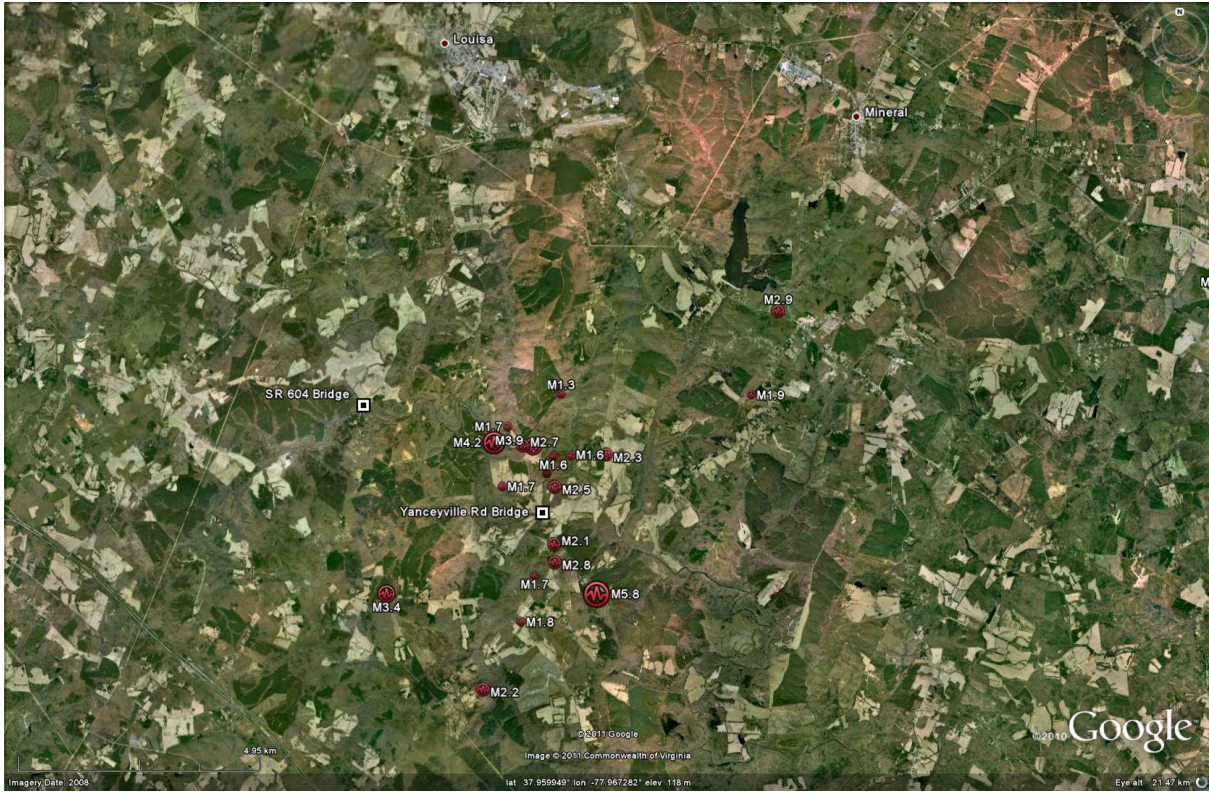


Figure 16. Aerial image showing the locations of the two bridges that were inspected in detail.



(a)





(b)



(c)

Figure 17. Yanceyville Rd Bridge (37.93898, -77.98269): (a) photo of the bridge looking to the NW; (b) photo of the SE bridge bent; and (c) photo of ~2.5 cm gap between one of the SE piers and soil (riverside only).

The second bridge that was inspected in detail was the SR 604 bridge, the location of which is shown in Figure 16. This bridge is ~36 m long and crosses the S. Anna River in the NE-SW direction. We inspected this bridge in detail because some of the local residents reported that “bumps” in the road surface of the abutment approaches worsened as a result of the main shock and aftershocks. Photos of the bridge are shown in Figure 18. As with the Yanceyville Rd bridge, this bridge has a two lane concrete deck that sits on two piers, in addition to the NE and SW abutments. Drawings obtained by Mark Carter, USGS, from the VDOT show that the abutments are founded on ~2.75 m (9 ft) of brown sandy silt with an SPT N-values of 5-7 blws/ft. Team members inspected the bridge on 24 August, the day after the main shock, but did not notice any obvious slumping of the abutments or evidence of seismic compression in the approaches (Figure 18a). However, after hearing from additional local residents that the bumps in the abutment approaches had gotten worse as a result of the main shock and aftershock, the bridge was revisited on 2 September, and it was found that the approaches already had been levelled and resurfaced (Figure 18b). Although heavy rains had fallen as a result of hurricane Irene, there was still evidence of a ~2.5 cm gap between SW pier and the soil on the riverside, shown in Figure 18f. As with the Yanceyville Rd bridge, it is uncertain whether the gap was due to movement of the pier due to earthquake shaking (i.e., movement of the bridge in the NE direction relative to the ground) or due to slumping of the river bank. Also, there was ~2.5 cm gap between the bridge deck and the SW abutment, shown in Figure 18e. It is likely that this existed prior to the earthquake to allow thermal expansion of the bridge deck.



(a)





(b)



(c)





(d)



(e)



(f)

Figure 18. SR 604 bridge (37.95915, -77.98269): (a) small bump in the approach to the bridge possibly due to seismic compression; (b) approach after relevelling and resurfacing of the bridge; (c) side view of bridge; (d) bridge abutment; (e) ~2.5 cm gap between bridge deck and the SW abutment; and (e) ~2.5 cm gap between the SW pier and soil (riverside only).

## Power

Approximately 3000 customers lost power as a result of the main shock. However, virtually all the power was restored within 4 hrs after the event. Team members inspected the Cuckoo Substation on Jefferson Hwy, the location of which is shown in Figure 19 and photo of the substation shown in Figure 20a. The only evidence of the earthquake shaking on the substation was that a green metal equipment box slid ~2.5 cm to the north, as shown in Figures 20b,c. The box was not anchored to the concrete base slab.



Figure 19. Aerial image of the epicentral region showing the location of the Cuckoo Substation, as well as the locations of the epicenters of the mainshock and aftershocks that occurred within two days of the mainshock.





(a)



(b)



(c)

Figure 20. Cuckoo Substation (37.97058, -77.91917): (a) photo of substation; (b) photo showing ~2.5 cm movement of green metal equipment box to the North; and (c) photo showing ~2.5 cm movement of the green metal equipment box to the North.

### ***Pipelines***

There were no reported gas leaks as a result of the earthquake. However, a 5 cm dia. water main in Mineral broke as a result of the earthquake, the location of which is shown in Figure 21. A photo of the excavated trench used to access the broken main is shown in Figure 22a. As may be observed in Figure 22b, the valve was heavily corroded and would have likely eventually failed even without the occurrence of the earthquake.





Figure 21. Aerial image of Mineral showing the location of the water main that broke during the earthquake.



(a)





(b)

Figure 22. Water main break in Mineral (38.01215, -77.90903): (a) trench showing broken water main; and (b) corroded water main valve with a crack that was caused by the earthquake.

### ***Railroad***

Team members talked with a crew on 24 August who were replacing ties on the railroad tracks in Louisa (Figure 23). The crew chief said that coal trains run about every two hours but were suspended after the main shock until the tracks could be inspected. He said that no damage was found and the ties were being replaced due to age, not due to earthquake damage.

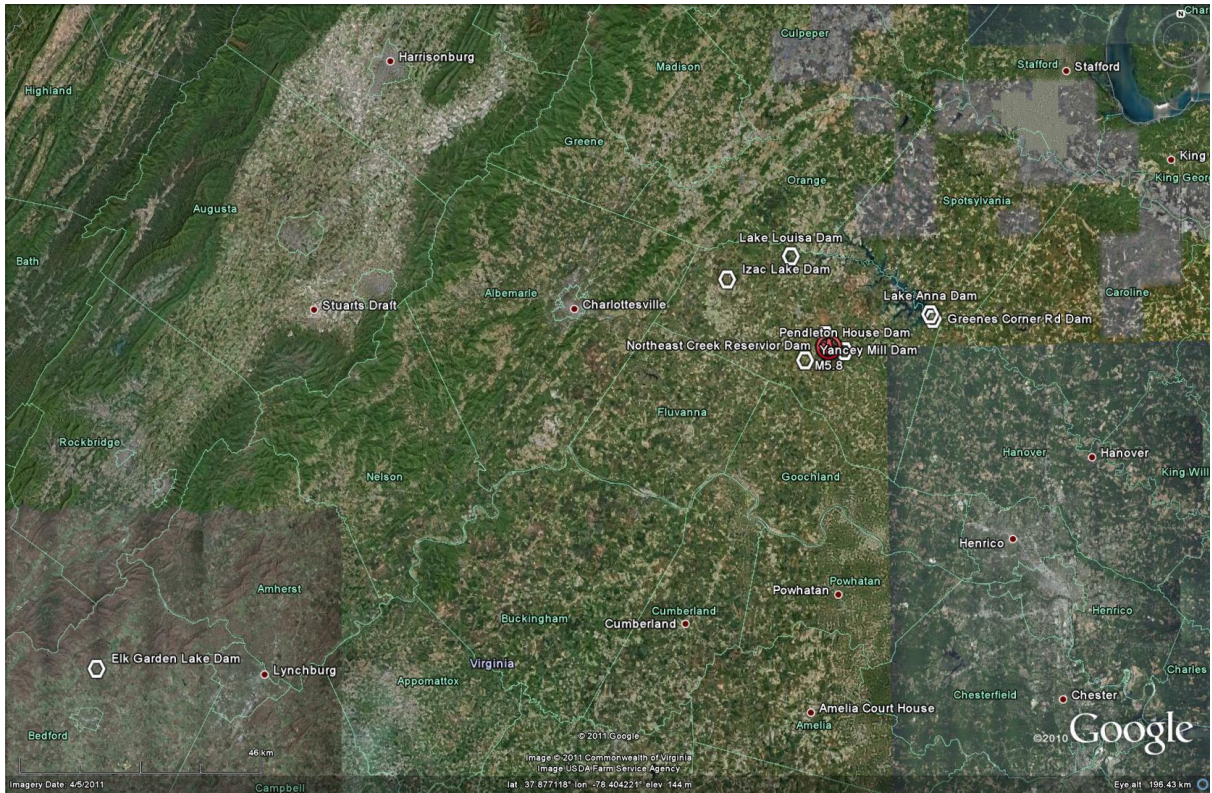


Figure 23. Crew replacing railroad old ties (38.019538, -77.978724).

## Dams

Team members inspected seven dams in the epicentral region and an eighth dam in Bedford County, which is located ~150 km from the epicenter of the main shock. The locations of the dams are shown in Figure 24. The dams ranged widely in size, with the largest being the Lake Anna dam, which is a large dam with a small hydroelectric plant, and the smallest being the Pendleton House dam, which impounds a small pond. Photos/drawings of the inspected dams are shown in Figures 25-34, but only the Yancey Mill Dam and the Elk Lake Dam showed damage. With the exception of the Lake Anna Dam, no commentary is given in this report on the dams that didn't sustain any damage, rather only photos are shown.





(a)



(b)

Figure 24. Aerial images showing dams that were inspected: (a) all dams inspected; and (b) dams inspected in the epicentral region.



## *Lake Anna Dam*

The North Anna Dam was built in conjunction with the North Anna [Nuclear] Power Station (NAPS) and is jointly owned by Dominion Resources, Inc. and Old Dominion Electric Cooperative. The main dam is ~1,524 m (~5,000 ft) long and ~27 m (~90 ft) high and impounds Lake Anna, which is approximately 13,000 acres in surface area and approximately seventeen miles long. The main dam consists of a compacted earthen embankment, a concrete spillway, and two hydroelectric units, 220 kW and 740 kW, where the two hydroelectric units were added ~15 years after the completion of the dam. (Dominion, 2011)

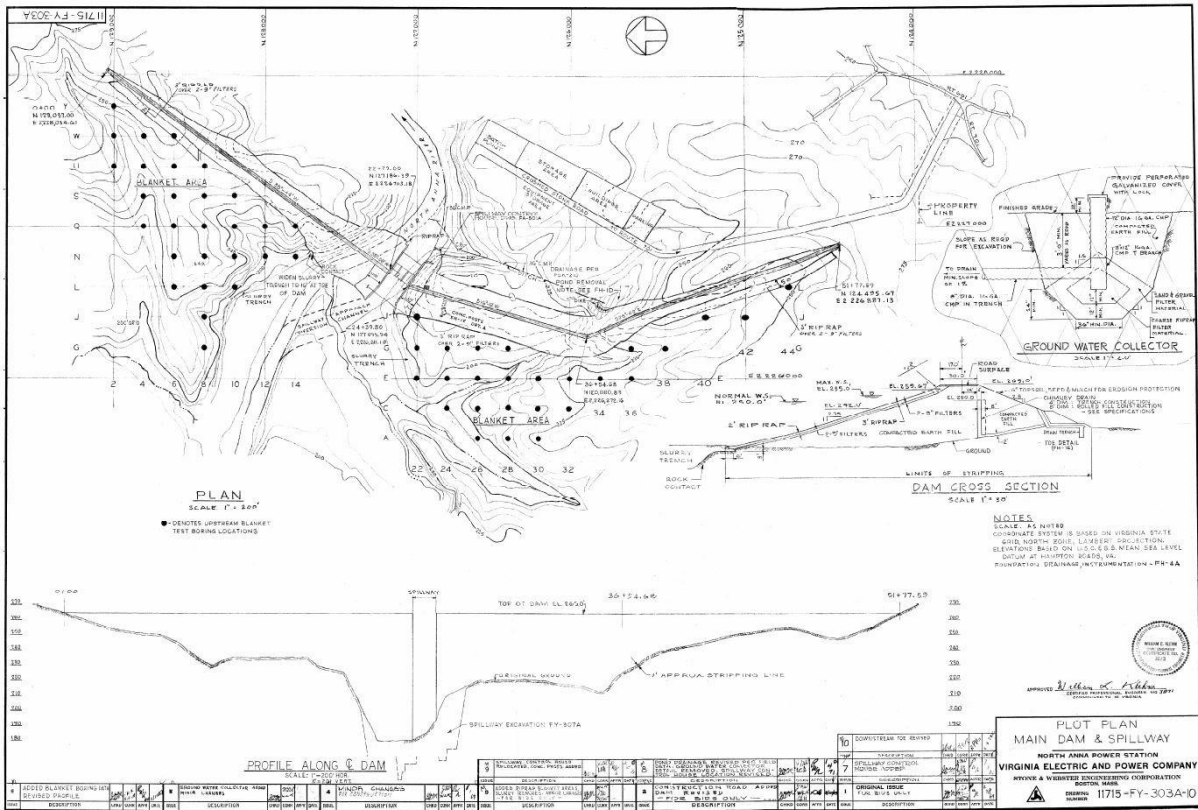
Site selection and the design of the dam were completed in 1969, with construction of the dam beginning in late 1969 and completed in late 1972. Because Lake Anna serves as a secondary source of cooling water for the NAPS, the US Nuclear Regulatory Commission (NRC) served as the regulator for the design and construction of the dam. Accordingly, a relatively rigorous quality control/quality assurance (QC/QA) process was established during the design and construction of the dam. Plan and cross-sectional views of the dam are shown in Figure 25, where the cross-sectional view is for Sta. 22+00 which is the highest portion of the dam, as measured from baserock. (Dominion, 2011)

Because the Lake Anna serves as a secondary source for cooling water for the NAPS, the dam was designed to the same Design Basis Earthquake (DBE) as the NAPS. The DBE for the NAPS was assumed equal to the largest shock associated with the Arvonian Syncline, only with the epicenter of this event occurring at the site of the NAPS. The largest event associated with the Arvonian Syncline occurred on 22 December 1875 just west of Richmond, Virginia, had a maximum Modified Mercalli Intensity (MMI) of VII (Figure 26a), and had an estimated magnitude of 4.5. The peak horizontal ground acceleration (PGA) for rock sites was estimated to be less than 0.12 g. Accordingly, the PGA for the DBE for rock sites was assumed to be 0.12 g. To define the entire response spectrum for the DBE, an envelope was taken of the response spectra for the east-west and north-south components of the  $M_w6.0$ , 31 October 1935 (18:38) Helena, Montana earthquake and the south-east component of the Golden Gate record of the  $M_w5.28$ , 22 March 1957 San Francisco, California earthquake scaled to 0.12 g. The resulting 5% damped DBE response spectrum is shown in Figure 26b. However, although the response spectrum for the DBE was developed from motions recorded during the 1935 Helena and 1957 San Francisco earthquakes, time history analyses of the North Anna Dam were performed using the north-south component of the  $M_w6.95$ , 19 May 1940 Imperial Valley (El Centro) earthquake scaled to 0.12 g. The 5% damped response spectrum for this latter event is also shown in Figure 26b. (Dominion, 2009, 2011)

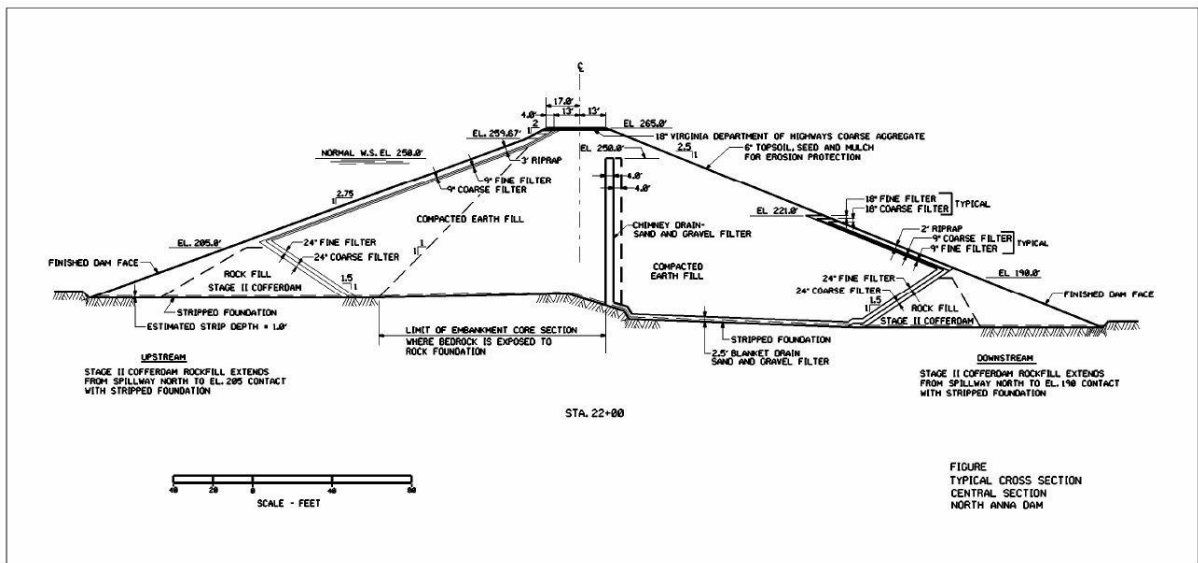
Motions from the 2011 Mineral, Virginia earthquake were recorded by a seismograph located on the basemat of the containment structure for Unit 1 of the NAPS, where the basemat is founded on rock. This seismograph is ~23 km from the epicenter of the event and ~8.5 km NW of the North Anna Dam; the dam is ~26 km from the epicenter. Assuming that the motions recorded at the NAPS were similar to those experienced at the North Anna Dam, the authors rotated the recorded motions to obtain motions that were oriented transverse to the longitudinal axis of the dam. The 5% damped response spectrum for these motions are shown



in Figure 26b. As may be observed from this figure, the motions from the Mineral earthquake exceed those of the DBE for oscillator frequencies greater than ~1.2 sec. Despite the DBE being exceeded over a wide range of frequencies, the team inspected the dam on 2 September 2011 and could not see any evidence of distress to the dam from the earthquake (Figure 27).



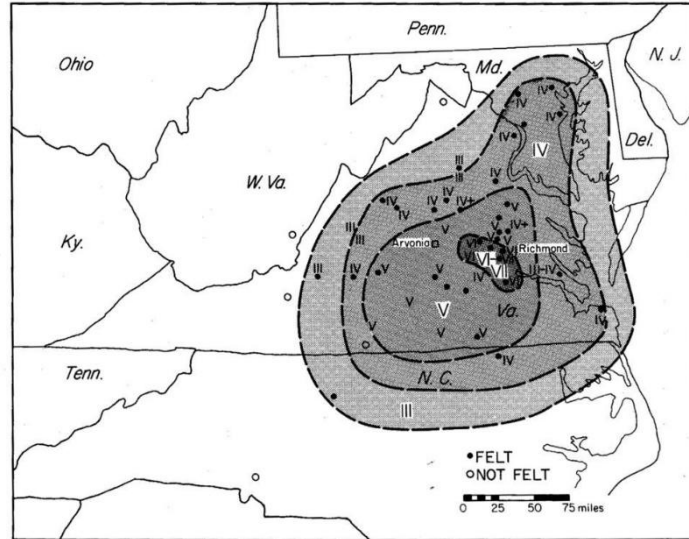
(a)



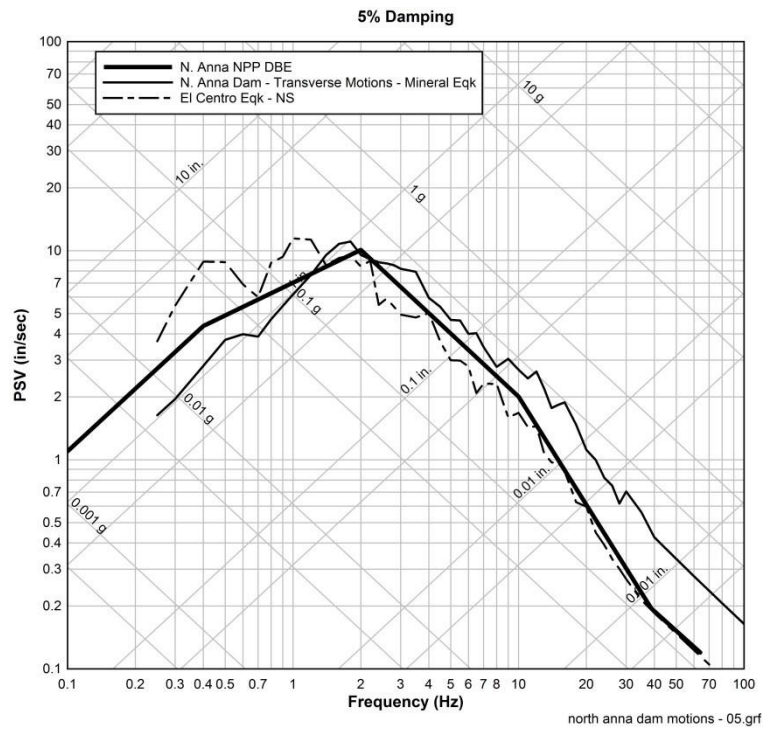
(b)

**Figure 25.** North Anna Dam: (a) plane view of dam layout; and (b) sectional view of the highest section of the dam, relative to baserock. (Dominion, 2011)





(a)



(b)

**Figure 26.** Design Basis Earthquake (DBE) for the North Anna Dam: (a)  $\sim M_w 4.5$ , 22 December 1875 earthquake, which is the largest historic event associated with the Arvonian Syncline (Chapman, 2012b); and (b) DBE, response spectrum for the 1940 El Centro N-S component scaled to 0.12 g, and response spectrum for the 2011 Mineral earthquake oriented in the transverse direction to the longitudinal axis of the dam.



(a)



(b)





(c)



(d)



(e)





(f)



(g)

Figure 27. Lake Anna hydroelectric dam. (a) 38.00621, -77.71210. (b) 38.01739, -77.70918. (c)(d)(e)(f) 38.01315, -77.71297. (g) 38.01259, -77.71347.

*Northeast Creek Reservoir Dam*



(a)



(b)





(c)

Figure 28. Northeast Creek Reservoir Dam (37.98087, -77.93952).

*Lake Louisa Dam*



(a)



(b)





(c)



(d)





(e)

Figure 29. Lake Louisa dam and outflow (38.11439, -78.01041).

*Izac Lake Dam*



(a)





(b)



(c)





(d)



(e)





(f)

Figure 30. Izac Lake dam (38.07649, -78.14759).

***Greenes Corner Road Dam***



(a)





(b)



(c)





(d)

Figure 31. Greenes Corner Road Dam (38.00511, -77.70724).

*Pendleton House Dam*



(a)



(b)

Figure 32. Pendleton House Dam (37.95283, -77.89812).

### ***Yancey Mill Dam***

The Yancey Mill Dam is on the S. Anna River and is a few meters upstream of the earthquake-induced sand boils found in the riverbed and nearby roadside ditch. The dam is ~1.5 m high. A photo of the dam is shown in Figure 33, and as shown in this photo, the dam is comprised of log cribs filled with rubble. A few of the cribs on the downstream face of the dam were broken and rubble spilled out. It is uncertain whether this damage was caused by the earthquake or not. A team member contacted the owner of the dam, and he said he wasn't aware of any pre-earthquake damage to the dam.





Figure 33. Yancy Mill Dam. It is unknown whether the damage shown in this photo resulted from the earthquake, but the owner was not aware of any pre-earthquake damage to the dam (37.93825, -77.98300).

### ***Elk Garden Lake Dam***

The Elk Garden Lake Dam is located in Bedford County, ~150 km from the epicenter of the main event. The dam is 9.1 m high and has a normal pool capacity of 66 acre feet. One of the homeowners near the dam was weed eating the downstream toe of the dam before the earthquake occurred. He noticed that a scarp started to form on the downstream face of the dam, near the crest. As a result, he stopped weed eating and went home, at which time the earthquake occurred. When he returned to the dam, the scarp had gotten bigger. The shallow slide is oval shaped and is ~6.4 m wide (running along the long axis of the dam) and ~9.1 m long (running down the downstream face of the dam). After the earthquake, the head scarp was ~17.8 cm high. There are no cracks visible at the top of the dam. The center of the slip is ~6.1 m to the left of the principal spillway pipe, looking downstream.

A team member met with W. Gray, the president of the homeowners association that owns the dam, on 9 September and inspected the dam. W. Gray said that 3 days before the earthquake they had 17.8 cm of rain in 12 hours. The saturated ground conditions likely triggered the initiation of the slide that occurred while the homeowner was weed eating, with the earthquake shaking making the slide worse. W. Gray said they covered the slide shortly after the earthquake with a plastic sheet to prevent water from flowing into the scarp. Photos of the slide taken both before and after it was covered with the plastic sheet are shown in Figure 34.



(a)



(b)





(c)



(d)



(e)



(f)





(g)

Figure 34. Shallow slide in the Elk Garden Lake Dam (37.4223, -79.5009): (a) photo of the shallow slide on the downstream face of the dam; (b) closer view of the shallow slide on the downstream face of the dam; (c) photo of head scarp of slide; (d) photo of slide taken from downstream toe of the dam; (e) photo showing head scarp covered with plastic sheet; (f) closer view of plastic sheet covering the head scarp; and (g) photo of plastic sheet taken from downstream toe of dam.

### **Landfill**

The Louisa County landfill was inspected on 9 September. It is located ~10 km from the epicenter of the main shock as shown in Figure 35. A team member talked with R. Petty, who is the operations manager for the landfill and who was present at the landfill during the earthquake. R. Petty said he noticed a small crack on the front slope of the landfill immediately after the earthquake. The crack was ~2.5 cm wide, but R. Petty was uncertain whether it was there prior to the earthquake. Photos of the front slope of the landfill are shown in Figure 36. By the time R. Green visited the landfill, the crack had largely filled in as a result of the heavy rains from hurricane Irene. However, the crack looked like it was the scarp of a shallow slide in the temporary clay cover; remnants of the crack are shown in Figure 37.

R. Petty said he was checking a leachate monitoring well on the side of the landfill when the earthquake occurred and that the shaking caused the ground to soften considerably, to the point that he thought he was going to sink into the ground. A photo of the leachate monitoring well is shown in Figure 38. The ground around the well is soft clay.

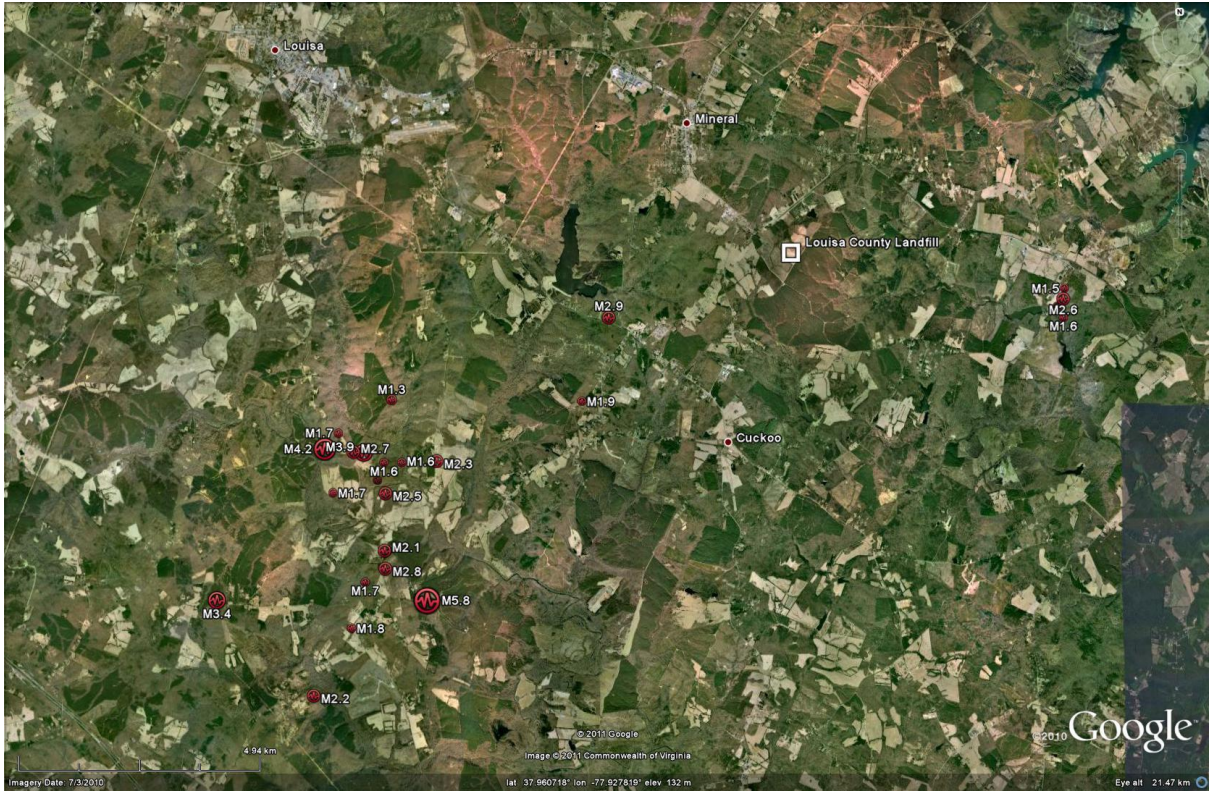


Figure 35. Aerial image showing the location of the Louisa County landfill.



(a)





(b)

Figure 36. Photos of the front slope of the Louisa County landfill (37.98670, -77.88474).



(a)





(b)

Figure 37. Photos showing the remnants of a crack in the front slope of the landfill that might have formed as a result of the earthquake shaking.



Figure 38. Leachate monitoring well where R. Petty was standing during the earthquake. The soft clay around the well got softer as a result of the earthquake shaking.

### **Public Buildings**

Several public buildings in Louisa County were inspected on 23 and 24 August. The buildings included the Louisa Town Hall, Louisa County High School, Mineral Town Hall, US Post Office, Mineral, and Thomas Jefferson Elementary School. The locations of these buildings are shown in Figure 39. Also shown in this figure are contours developed by M. Heller, VA Department of Mines, Minerals, and Energy (DMME), and M. Carter (USGS) of severity of earthquake damage. The green contour shows the extent of minor damage, the







(a)



(b)



(c)



Figure 40. Typical damage to internal contents of offices in the Louisa County Public School Administration Building (38.02066, -77.92373).

The Louisa County High School building was built in sections over a period of several decades. The most severe damage to the building was in a portion that had a steel frame with concrete block infill walls and a brick façade; it is uncertain whether this same type of structural system was used in all sections of the building. The observed damage included cracks in the infill block walls, with blocks from the top of the walls falling through the dropped ceiling in places. Additionally, in many rooms ceiling tiles along opposite walls fell, indicating a pronounced direction of shaking; unfortunately, the orientations of the walls were not determined. As with the Administration building, the internal contents in many rooms were in disarray. Photos showing some of the damage in the High School building are shown in Figure 41.



(a)



(b)



(c)



(d)

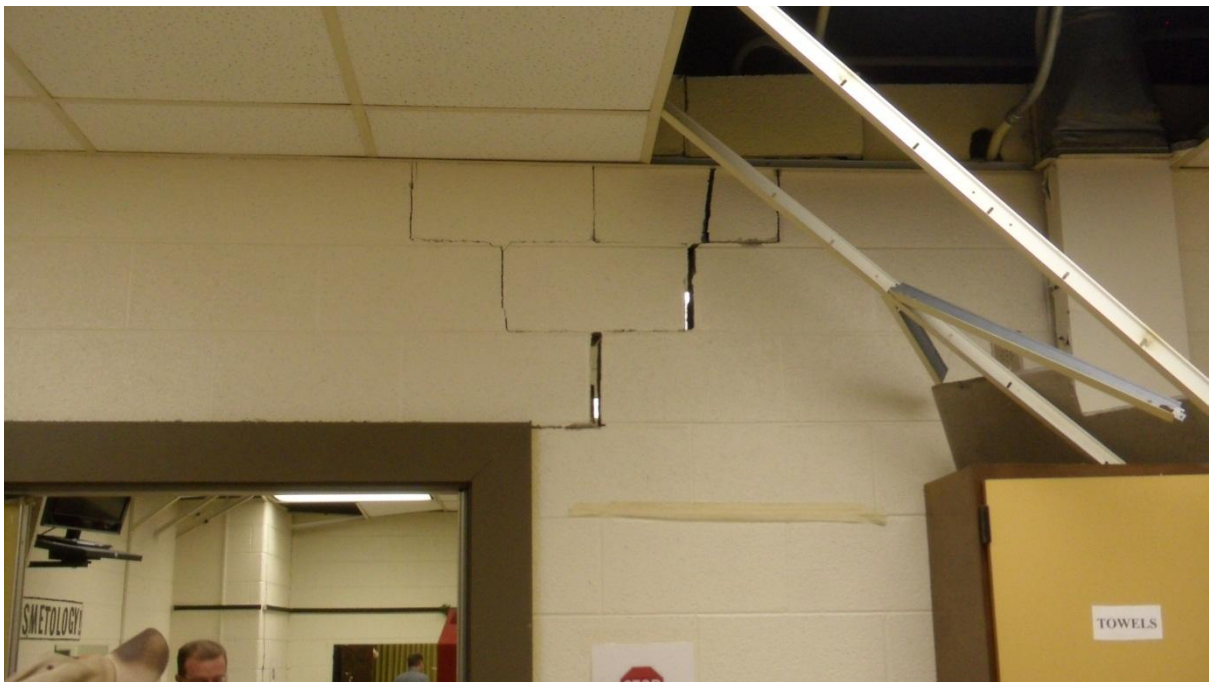




(e)



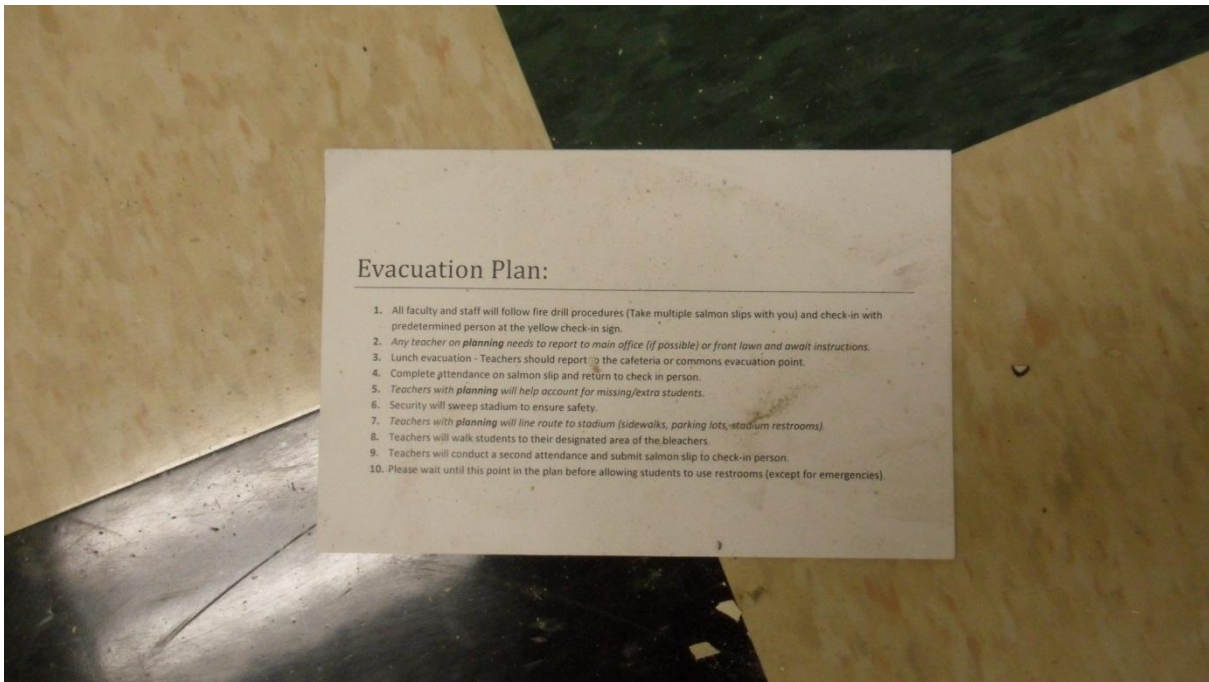
(f)



(g)



(h)



(i)





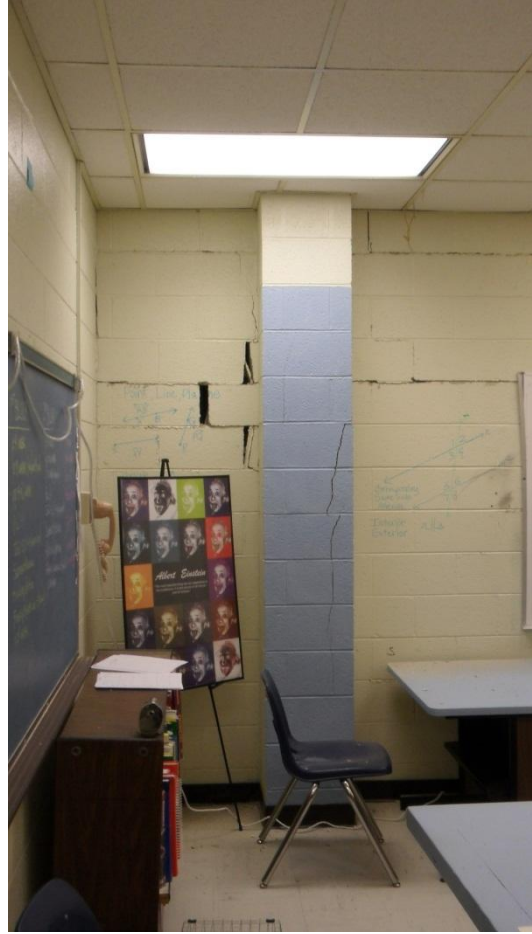
(j)



(k)



(l)



(m)



(n)

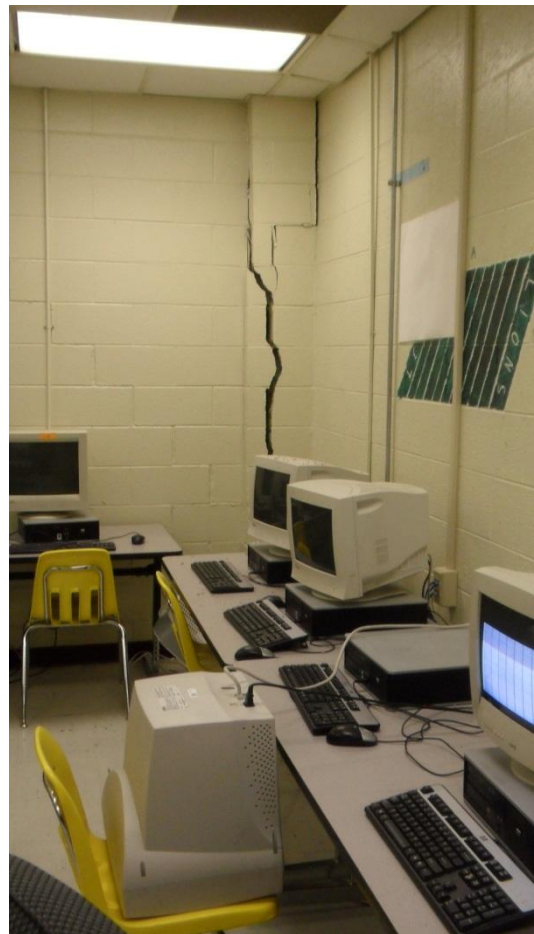




(o)



(p)



(q)



(r)



(s)





(t)

Figure 41. Typical damage to the Louisa County High School Building (38.01764, -77.92107).

*Thomas Jefferson Elementary School*

Team members visited Thomas Jefferson Elementary School on 24 August, but were only able to photograph the outside of the building. In addition to the Louisa County High School, this building was also severely damaged by the earthquake. A photo of the outside of this building is shown in Figure 42.



Figure 42. Photo of the outside of Thomas Jefferson Elementary School (37.99468, -77.96233). Along with the LCHS, this building was severely damaged by the earthquake.

## ***Town Halls***

### *Louisa Town Hall*

We had received reports on the night of the earthquake that the Louisa Town Hall (Figure 43) had a partial roof collapse. This prompted an inspection of the building on 24 August, the morning after the main shock. The building was constructed in 1907 (Figure 44a) and was damaged by fire in 1924 (Figure 44b); sometime between 1907 and 1924 a second story was added. The reports of damage were grossly exaggerated and most of the damage was cosmetic (e.g., fallen ceiling tiles, cracked plaster); photos of some of the damage are shown in Figure 45. The only structural damage was that the front wall of the building was slightly bowed outward as a result of the earthquake shaking.





Figure 43. Louisa Town Hall (38.02512, -77.99781) the morning after the earthquake.



(a)



(b)

Figure 44. Old photos of the town hall: (a) photo circa 1907 taken shortly after the building was constructed; and (b) photo circa 1924 taken after a fire gutted the structure.





(a)



(b)



(c)



(d)



(e)



(f)





(g)



(h)

Figure 45. Photos showing examples of damage to the Louisa Town Hall.

### *Mineral Town Hall*

We had received reports on the night of the earthquake that the Mineral Town Hall had completely collapsed during the earthquake. This prompted team members to inspect the building on 24 August, the morning after the main shock. As with the Louisa Town Hall, the initial damage reports for the Mineral Town Hall were grossly exaggerated. A photo obtained from the internet believed to have been taken within hours after the earthquake on 23 August is shown in Figure 46. As shown in this figure, the damage was mainly limited to the brick parapet towards the back of the building. Photos taken by a team member on 24 August are shown in Figure 47. We did not inspect the inside of the building.



Figure 46. Photo of the Mineral Town Hall (38.01090, -77.90848) believed to have been taken within hours after the earthquake (source: internet).





(a)



(b)



(c)

Figure 47. Damage to the Mineral Town Hall (38.01090, -77.90848).

*US Post Office, Mineral, VA*

Team members inspected the US Post Office in Mineral on 24 August, the morning after the main shock. The post office was open when we visited, but the main entrance and foyer were closed and residents had to use the backdoor to pick up their mail. Figure 48 shows the damage to the brick façade to the main entrance to the building. As with the Louisa County High School, ceiling tiles along opposite walls fell in the Mineral Post Office. In this case the tiles along the North and South walls fell (Figure 49), indicating a pronounced N-S direction of shaking.





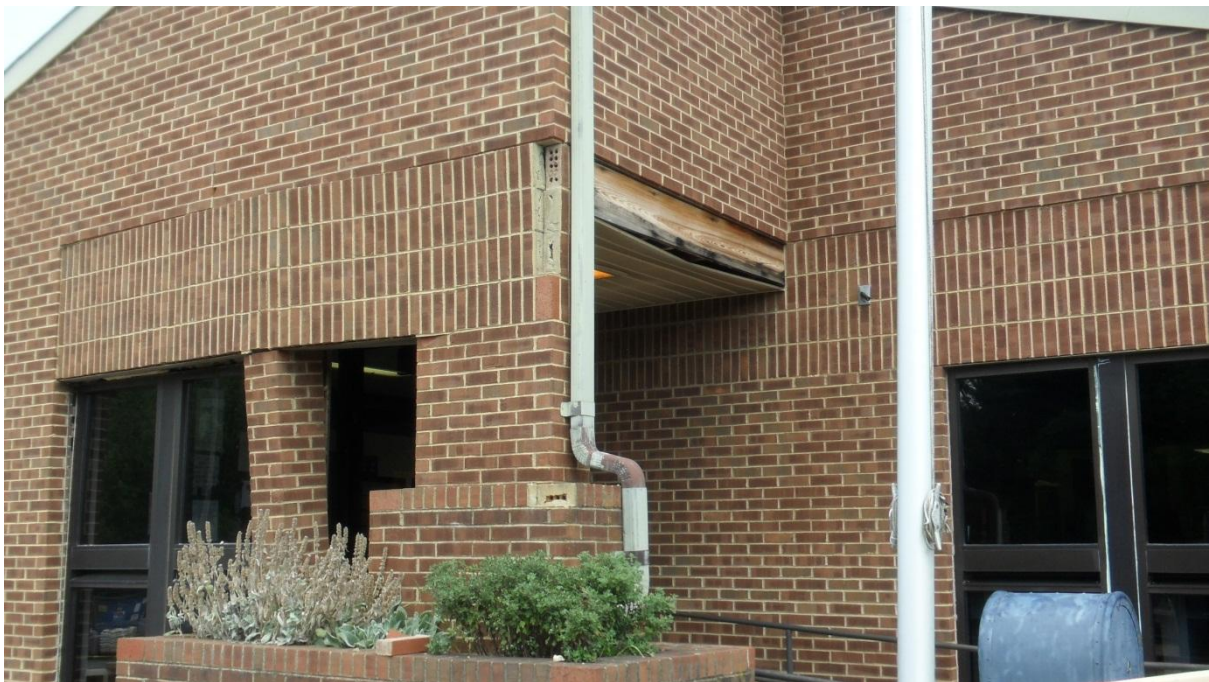
(a)



(b)



(c)



(d)





(e)

Figure 48. Damage to the main entrance of the Mineral Post Office (38.00669, -77.90859).



Figure 49. Ceiling tiles that fell along the North wall in the Mineral Post Office (38.00669, -77.90859).

### **Residential Structures**

With M. Carter (USGS), team members inspected residential structures throughout the epicentral region. Most of the structural damage was constrained to unreinforced masonry, to include brick/block buildings and chimneys, block foundation walls, and brick façades. Figure 50 shows contours developed by M. Heller (DMME) and M. Carter (USGS) of damage severity in the epicentral region. The green contour shows the extent of minor damage, the yellow contour shows the extent of minor-to-moderate damage, the orange contour shows the extent of moderate damage, the salmon contour shows the extent of moderate-to-major damage, and the red contour shows the extent of severe damage. M. Carter noted that houses oriented with their long-axes close to either N-S or E-W sustained more damage than those oriented NE-SW/NW-SE. He also noted that structures on the sides of hills sustained more damage than those on the top of the hills, and structures at base of hills sustained even less damage. Figure 50 also shows the locations of several of the residential structures that we inspected.



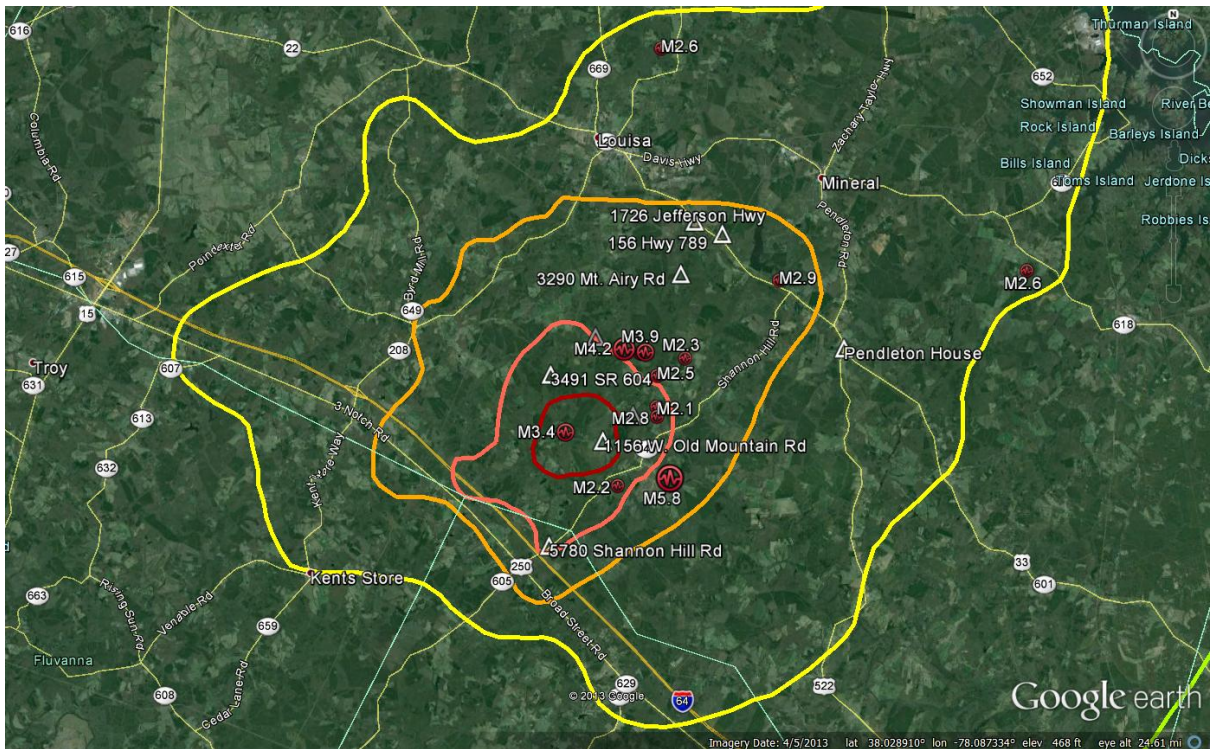


Figure 50. Aerial image of the epicentral region with contours of damage severity and the locations of residential structures that we inspected (after Heller and Carter, 2014).

**3290 Mt. Airy Rd, Louisa**



Figure 51. Typical damage to block foundation walls (37.9790, -77.9692).



*1726 Jefferson Hwy, Louisa*



Figure 52. Typical damage to brick chimneys (37.9966, -77.9631).

*156 Hwy 789, Mineral*



(a)





(b)



(c)

Figure 53. Representative severe damage to brick façade and block foundation walls (37.9923, -77.9513).

*1156 W. Old Mountain Rd, Louisa*



(a)

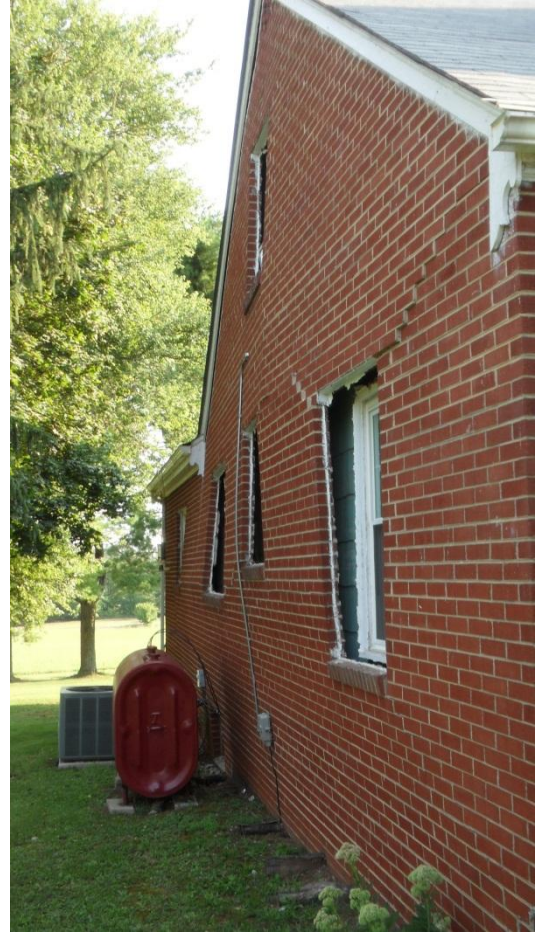


(b)





(c)



(d)



(e)

Figure 54. Representative severe damage to brick façade (37.9229, -78.0033).

3491 SR 604, Louisa



(a)



(b)

Figure 55. Typical damage to block foundation (37.9455, -78.0253).



*5780 Shannon Hill Rd, Louisa*



Figure 56. Representative severe damage to brick façade (37.8878, -78.0267).

*Twin Oaks Commune*



(a)





(b)



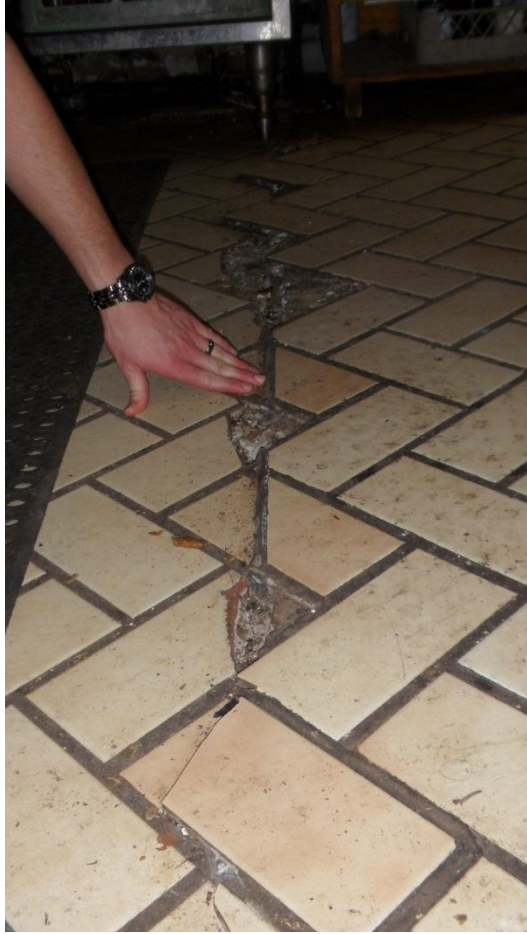
(c)



(d)

Figure 57. Damage to an unreinforced block garage structure (37.9314, -77.9903).





(a)



(b)



(c)

Figure 58. Damage to floor in dining facility (37.9306, -77.9898) caused by damage to unreinforced block foundation wall: (a) Crack in the tiled floor; (b) foundation wall below the crack in the tiled floor (note the broken block supporting the sill beam); (c) gap between sill beam and concrete block formed due to rotation of the sill beam resulting from the broken block supporting the sill beam.

### ***Bend of River Rd***

Team members inspected several houses on Bend of River Rd. The house shown in Figure 59 had a Superior Walls foundation system. The system consists of precast panels that are bolted together onsite. The owners of the house were home at the time of the earthquake and described the level of shaking as very intense. However, we could not find any damage to the foundation system.





(a)



(b)



(c)

Figure 59. Small house with a Superior Walls foundation system. We found no damage to the foundation system despite intense shaking. (37.95806, -78.00606)

### *Pendleton House*

The Pendleton House was inspected on 26 August. The Pendleton House was completed in 1818 and is listed in the National Registry of Historic Places. Figure 60a is a photo obtained from the internet showing the house before the earthquake. The subsequent photos were taken on 26 August, after the earthquake. As may be observed from these photos, the brick chimneys and walls on both sides of the walls suffered significant damage. Team members were unable to inspect the inside of the house.





(a) (source: internet)



(b)





(c)



(d)





(e)



(f)



(g)



(h)

Figure 60. Pendleton House (37.95327, -77.89987), which is listed in the National Registry of Historic Places.

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## **5. RICHMOND AND EASTERN VIRGINIA REGION**

The M5.8 earthquake on 27 August 2011 was strongly felt in the City of Richmond, located about 65 km southeast of the epicenter, and across most of Eastern Virginia. Throughout Tidewater, Williamsburg, Richmond, and surrounding counties, the average citizen reported audible sound, felt motion, fallen items from table-tops, and/or wall hangings out of kilter. However, little structural damage was reported anywhere in the region.

Where distress was noted, such distress was primarily related to architectural finishes (i.e., drywall or exterior cladding). In Goochland County, some measure of structural damage was observed. This was typically in the form of cracked foundation walls, which typically did not affect the use of the structure. In one instance, the structural damage resulted in a beam that needs to be fixed prior to occupancy.

Unfortunately, there were no M5.8 ground motions recorded in Richmond or Eastern Virginia. Reported intensities in Richmond were IV to V, much lighter than the VII to VIII that occurred in areas to the northeast, such as Washington, DC which is located twice as far from the epicenter. The relative lack of damage in Richmond and Eastern Virginia stands in contrast to the more significant damage seen in the epicentral region and parts of the Washington, DC area.

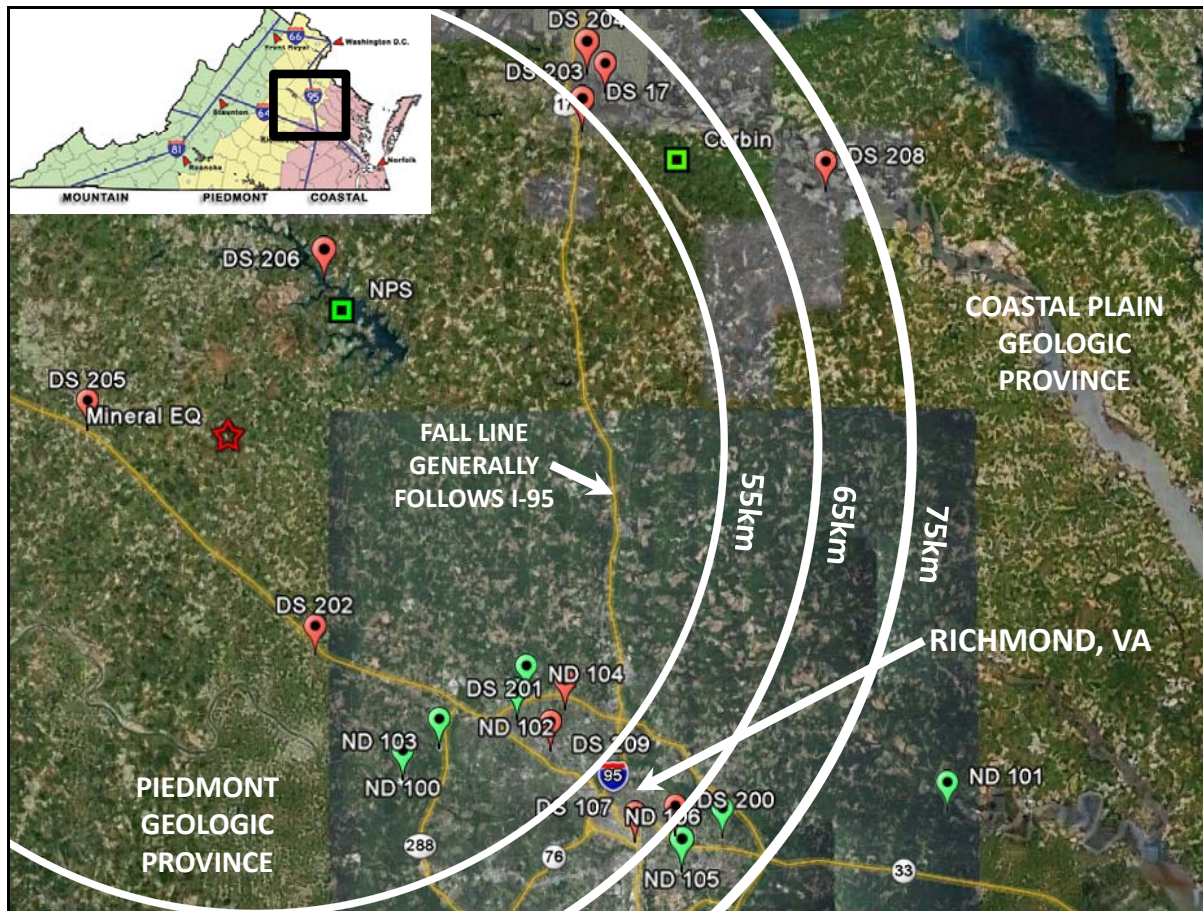
Regional reconnaissance involved limited site inspections by GEER team members guided largely by the observations of tens of other engineering professionals who reported very little in the way of ground failures. Primary attention was given to poor soil areas such as young alluvial deposits along rivers, creeks, and streams, including the James River. A summary of investigated sites is presented in Figure 5-1. Additional data for each site are available via the .kmz file on the GEER website.

### **Surficial Geology**

Regional geology likely affected ground motion and amplification of seismic energy. A map showing the major geologic provinces overlain by the GEER study sites is provided in Figure 5-2. The metropolitan Richmond area is located on a southeastward azimuth from the M5.8 epicenter, a direction roughly perpendicular to the orientation of regional geologic structure and thrust faulting. This is in contrast to the Washington, DC area which is located on an azimuth parallel to these same structures. Heading toward Richmond from the Mineral area, the Piedmont residuum becomes covered by a mantle of “terrace deposits” prior to the eastward thickening of Coastal Plain deposits, which begin to appear in Richmond. Additionally the Piedmont between the epicenter and Richmond includes exposed Triassic-aged basins (lateral grabens) of sedimentary rocks.



The James River falls from non-tidal to tidal influence in the City of Richmond, approximately at the location of Interstate I-95. To the west of Interstate I-95, the stream bottom of the James River is typically bedrock – to the east the stream bottom is unconsolidated sediments of the Coastal Plain. Heading east from Richmond, the depth to bedrock increases by about 6 m/km (300 m in 50 km).



**Figure 5-1 – Minor damage sites investigated by GEER in Richmond and Eastern Virginia.**

Unconsolidated Coastal Plain sediments between the “Fall Zone” (i.e., approximately along Interstate I-95) and the Surry Scarp (i.e., a paleoshoreline in proximity to Williamsburg) typically include a transgressive and regressive sequence of overconsolidated clay and compact sand. The Miocene-age Calvert formation (sensitive marine clay) is widely present in Richmond and is widely used for belled caisson support of multi-story buildings (i.e., there is rarely the need to use the much deeper bedrock for foundation support within the city). The Bacon’s Castle formation (gravel grading upward into sand and sandy clayey silt) is widely present to the east of Richmond and atop the sensitive marine clay of the Calvert formation.

Normally consolidated clays, organic silt, and peat with interlayered very loose sands are typically found to the east of Williamsburg (i.e., east of the Surry Scarp). The lack of soft and loose Coastal Plain sediments in proximity to the earthquake’s epicenter and the thickening of the sediments toward the east are thought to be factors in limiting seismic damage in this region.

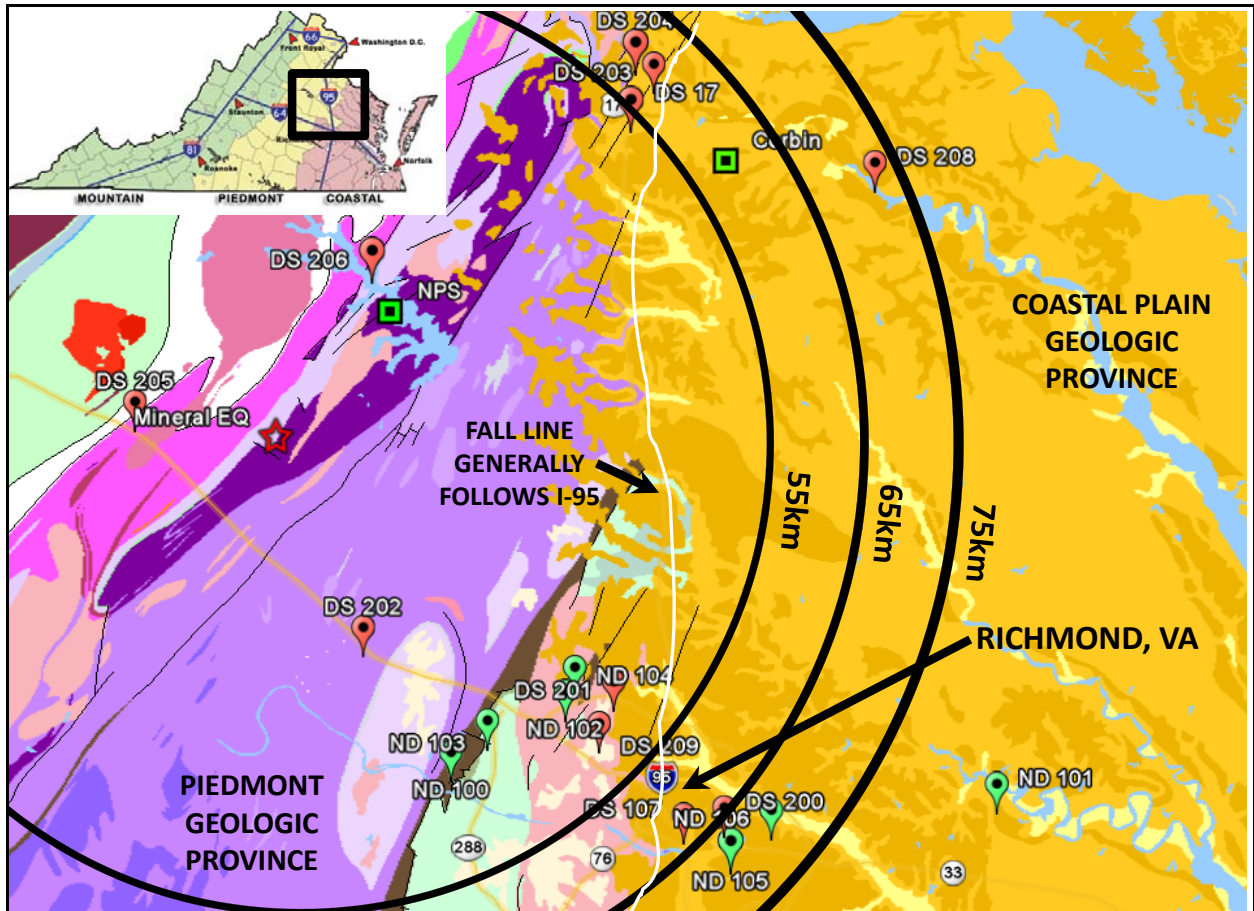


Figure 5-2 – Surficial geology overlain by GEER study sites in Richmond and Eastern Virginia.

### Liquefaction

There were no reports of sand boils in the Richmond and Eastern Virginia Region, although it is possible that small features may have been overlooked. Field observations of saturated, loose sand along the Pamunkey River (in the vicinity of White House Landing, New Kent County, Virginia – 37.5640, -77.0462) did not result in findings of sand boils. Luck Stone Corporation (prominent aggregate supplier) owns a ~700 acre environmental banking facility in this vicinity and the geologic professional that measures ground water levels (i.e., who transects the site on a regular basis) did not identify the presence of sand boils. Additionally, calls to WSSI (Wetland Studies and Solutions, Inc., Gainesville, Virginia) alerted their staff to look for sand boil features on their wetland banks. Their wetland banks are primarily in the Piedmont (i.e., where loose



sand is confined to riparian alluvium) and their field staff did not observe sand boils during their ongoing field work.

### **River Bank Slumps**

Through conversations with the staff of the James River Park System, no observations of river bank slumps or sand boils were noted in Richmond or to the east.

### **Rockfalls**

The study area of Richmond and Eastern Virginia includes a few rock outcrops and rock cuts. No rock falls were associated with the earthquake within this region.

Luck Stone Corporation did not report loss of support within their pits or other geologic hazards stemming from the earthquake. Luck Stone did report that the earthquake triggered their monitoring systems used to monitor blasting-induced vibrations. Luck Stone uses a third party to perform seismic monitoring and their consultant has assembled the results from about ~200 monitoring stations triggered by the event. Such monitoring stations are located in quarry sites owned by various aggregate producers and will be available to the GEER team when compiled.

### **Bridges**

Following the earthquake, Virginia Department of Transportation (VDOT) mobilized over 300 personnel to perform inspections on eight tunnels and over 700 bridges. The VDOT inspection program included the 238 structures that were identified in a 1994 study of earthquake-sensitive structures. The initial VDOT inspection program included an assessment of unusual orientation/movement (i.e., variation in sight-lines at deck joints or along the length of the structure); bearings at abutments and piers; signs of distress to the structure or substructure; and, utilities attached to the structure. From this initial review, four structures were identified for in-depth inspections. While no bridges were found to be structurally unfit for continued use, VDOT noted the following:

- Courthouse Road (Route 208) over South Anna River (37.98064, -78.04818) – Slight longitudinal movements;
- Courthouse Road (Route 208) over Interstate I-64 (37.94017, -78.10846) – Slight longitudinal movements;
- Parish Road (Route 683) over Interstate I-64 (37.89477, -78.04297) – Concrete spalling of barrier end wall;
- Courthouse Road (Route 1) over Hazel Run (38.28778, -77.48687) – Pier column cracking up to 15 mm wide (this is a City of Fredericksburg bridge).

Figures 5-3 through 5-7 show representative observations from VDOT bridge inspections.



**Figure 5-3 Courthouse Road over South Anna River - displacement of railing (37.98064, -78.04818).**



**Figure 5-4 Courthouse Road over South Anna River - bearing displacement (37.98064, -78.04818).**





**Figure 5-5 Parish Road over Interstate I-64 –spalling (37.89477, -78.04297).**



**Figure 5-6 Route 1 over Hazel Run- horizontal cracks at Column 4, Pier 1 (38.28778, -77.48687).**



**Figure 5-7 Route 1 over Hazel Run – horizontal crack at Column 3, Pier 1.**

**Power**

There was no reported loss of power within the Richmond and Eastern Virginia Region as a result of the earthquake.

**Water**

There was no reported loss of water within Richmond and Eastern Virginia Region as a result of the earthquake.

**Railroad**

There were no reports of railroad damage within the Richmond and Eastern Virginia Region as a result of the earthquake.



## **Dams**

There were no reports of damage to embankment dams within the Richmond and Eastern Virginia Region as a result of the earthquake.

## **Slopes**

There were no reports of slope movements or failures within the Richmond and Eastern Virginia Region as a result of the earthquake.

## **Landfills**

Calls to Allied Waste (owners and operators of the Old Dominion Landfill at 37.5077, -77.3744) indicate that there were no observations of distress or unusual effects stemming from the earthquake. This facility was designed in accordance with current regulations, which include considerations for seismic events.

Calls to Henrico County (owners of their own landfill facility at 37.6807, -77.5652) indicate that there were no observations of distress or unusual affects stemming from the earthquake. This facility was also designed in accordance with the current regulations.

## **Buildings and Foundations**

Limited structural damage was observed in buildings of the Richmond and Eastern Virginia region. In preparation of this brief summary, calls to the Virginia Department of General Services show that structural damage was not noted in any of their buildings. There was one observation of distress in an architectural item – the exterior cladding of the State Corporation Commission building (37.5366, -77.4322) realized minor cracking. This is a non-structural building component that may have become compressed against the stair well of the building during ground motion. Calls to local consulting structural engineers and building owners show that multiple building condition surveys did not disclose structural damage as a result of the earthquake. These building condition surveys include areas west of Richmond, such as “West Creek” (37.6281, -77.6613) and “Innsbrook” (37.6556, -77.5821) office parks. In some instances, minor drywall cracking was noted. One such observation was noted at a warehouse building in Fredericksburg, Virginia (38.2723, -77.4619) where drywall cracking was noticed at the mezzanine level.

In Port Royal, Virginia, the St. Peter's Church experienced some measure of distress from the earthquake. Discussions with local structural engineers indicate that minor cracking was noted on the parapet wall.

#### Goochland County

Goochland County completed inspections of 28 properties, including private residences, cell phone towers, churches and commercial buildings. For the case of residences, there were typical reports of foundation and stress cracks. There was only one instance (5735 Broad Street Road, Maidens, Virginia at 37.7201, -77.8259) where the residence was deemed "do not occupy" owing to chimney shifting, concern about brick veneer failure and loss of support in a basement beam.

#### Henrico County

Henrico County completed inspections of 13 residential properties, based on citizen concerns. Typical findings include, "possible aggravation of existing foundation issues," blockwork cracking, brick veneer cracks and in one instance a slab-on-grade crack that resulted in in-slab water-line leakage (37.6664, -77.5173). At the location of 3245 Gurley Road (37.6259, -77.5356) the inspection report notes cracking in concrete masonry unit and/or brick basement walls and chimneys.

Henrico County officials also completed inspections of their public office and school buildings. Of these self-performed inspections, some apparent cracking was noted in the masonry walls at the Technical Center of Highland Springs High School (37.5402, -77.3241). Some of these cracks appeared to be possibly earthquake related while many appeared to be related to settlement and temperature cracking. County inspectors also noted some masonry cracks in each of the three stairwells of the Eastern Henrico School Administration Building (37.5544, -77.3829). All of these masonry cracks were minor in nature and require raking out the mortar joint and re-pointing as a repair procedure.

#### City of Richmond

The City of Richmond responded to calls from citizens in the aftermath of the earthquake. The City has not provided a listing of their inspections; however, of those inspections the extent of damage was slight, and no homes were deemed unsafe to occupy.



## 8. POSSIBLE RESEARCH TOPICS

There were no significant ground failures from the 23 August 2011 M5.8 earthquake, and structural failures were minor throughout most of the affected region; however, as discussed in this report, there are important lessons for stakeholders and decision makers in the engineering and scientific communities and beyond. The rarity of a damaging earthquake in Central and Eastern North America (CENA) means that we have few opportunities to assess issues ranging from the seismic performance of constructed facilities and lifelines to regional earthquake hazard preparedness. Perhaps the most important lesson to take away is that CENA earthquakes as large as the M5.8 event (and possibly larger) will occur in the future, possibly closer to densely populated urban areas. This makes it imperative to glean as much data as we can from each occurrence of a rare event like the Virginia shock. Efforts such as the current NGA East Program, developed to provide a new generation of CENA ground motion models for seismic hazard assessment, require instrumental ground motion data in order to be meaningful. The seismological data set for the eastern United States is so sparse that empirical ground motion prediction models cannot be constructed and validated. This situation could have been improved to a significant degree if the M5.8 mainshock had been better recorded. The event was recorded on-scale by only three stations in the critical distance range for earthquake engineering, inside 100 km from the epicenter. Essential structures, such as the seismically-isolated Woodrow Wilson Bridge, were not instrumented to provide insight into their seismic response. Seismographic recording in central Virginia and elsewhere in the region was, and remains, inadequate to address scientific and engineering problems related to earthquake hazards. Despite this missed opportunity, much can be learned from the data in hand, and still more can be gleaned from future research.

Preliminary ideas on possible research topics are outlined below:

- **Seismological data requirements** – Supplementing the seismological data obtained from the few near-field recordings of the M5.8 mainshock, the aftershock data are also providing valuable information. The aftershock sequence is illuminating the fault plane responsible for the mainshock and helping to constrain the size and orientation of the likely rupture surface. This gives further insight into the M5.8 rupture process (e.g., stress orientation, stress drop, rupture velocity) and the geological nature of the causative fault. The aftershocks may also help us to better understand stress transfer mechanisms and possible triggering of subsequent earthquakes on nearby faults. An adequate density of seismic stations should remain operational in the epicentral area to provide baseline data going forward to quantitatively study the evolution of this important aftershock sequence. To provide the data necessary for a variety of research topics, instrumental monitoring of the Central Virginia Seismic Zone (CVSZ) must be a high priority. This will require a long-term commitment from agencies responsible for and institutions involved in earthquake monitoring in the United States.
- **Fault rupture mechanics of CENA earthquakes** – recordings near the source region suggest a complex fault rupture process for the M5.8 with two sub-events; this may be a common characteristic of CENA earthquakes and should be further studied.

- **Finite fault modeling studies** – For the first time, an aftershock sequence for an eastern earthquake can be used to provide good constraint on the geometry and extent of the fault rupture surface. This information can be used to develop improved models of the seismic source for strong motion simulation.
- **Wave propagation effects** – intensity of shaking from this event reported by the populace was more pronounced in the north-east/south-west direction. Although seismographic data are very limited, they must be used to study the cause of this observation, which in principle can be due to source (e.g., directivity) and/or path effects (e.g., high Q and low scattering parallel to the Appalachian structural trend).
- **Site characterization of seismic recording stations** – much insight and valuable data will be gained by characterization of sites where motions were recorded, many of which were on soil and indicate significant site effects. As of this writing, the USGS and others have efforts underway to measure velocity profiles at recording sites. This information will be valuable in trying to understand not only soil response, but the actually rock input shaking.
- **CENA ground motion attenuation** – the M5.8 event, although poorly recorded, has significant implications for development of CENA attenuation models, and is particularly relevant to ongoing NGA East efforts.
- **Seismic hazard assessment** – The event also has important implications for seismic hazard assessment, as complicated fault rupture, strong azimuthal variation of intensity and other regional factors seem to suggest increased uncertainties in prediction of CENA ground motions. The most common approach of PSHA modeling with areal seismic sources should be verified for this event.
- **Implications of unique geological and soil conditions on ground motions** – selective shaking intensity and damage patterns were correlated with regional geology and local soil conditions. Preliminary analyses indicate that soil amplification occurred in soft sediments overlying hard rock. A more detailed study of damage pattern and site conditions is needed to evaluate the cause and degree of amplification.
- **Development of region-specific soil amplification factors** – observations and preliminary site response analyses suggest that current simplified soil amplification factors, such as those used in IBC/ASCE7 and developed largely using WUS datasets, may not adequately capture the seismic response of certain CENA sites. Of particular concern are cases where very hard rock is relatively close to the ground surface such as along the Fall Line.
- **Building code assessments for CENA** – the adequacy of current design provision being used for constructed facilities and lifelines such as IBC/ ASCE7 should be evaluated, as currently the only CENA-based adjustments are the base hazard maps. Other parameters such as site factors should become region-specific.
- **Topographical effects**- there were observations in the epicentral region that suggested higher shaking intensities on hilltops and hillslopes relative to low-lying flat areas. Such effects for CENA-type ground motion characteristics should be studied.
- **Paleoliquefaction studies**- the event produced only minor liquefaction features in the epicentral area where PGAs were at least 0.26g. However, this may be due in part to the limited distribution of liquefiable sediments in the area. Additional reconnaissance for



liquefaction features is planned in the meizoseismal area along portions of rivers and streams where liquefiable sediments are likely to occur. In addition, liquefaction features that formed during the M5.8 event will be compared to paleoliquefaction features previously found in the CVSZ. The results of ongoing liquefaction studies may have implications for the back calculation of magnitude using paleoliquefaction evidence associated with CENA events and for the location and magnitude of paleoearthquakes in the CVSZ.

- **Performance of critical facilities such as nuclear power plants** – of particular interest is the performance of the North Anna Nuclear Power Station constructed in 1968. There will be many discussions on the seismic design and performance of nuclear facilities constructed during this generation.
- **Regional preparedness and awareness** – the affected region, in particular metropolitan areas such as Washington, DC, are unprepared to deal with even a moderate earthquake, particularly with respect to communications, evacuation, and transportation. There is relatively little earthquake awareness and preparedness planning in CENA relative to other US regions. Earthquakes can be integrated into preparedness planning efforts for hazards that communities in the region are more familiar with, such as hurricanes, terrorism, and fire.
- **Educational impacts** – efforts to incorporate earthquake basics in K-12 curricula and reach out to families and communities for preparation in the event of an earthquake. The latter should be developed specifically for CENA metropolitan areas that rely heavily on their (aged) infrastructure and lifeline systems.
- **Social and economic impacts** – the moderate M5.8 earthquake caused disruptions to communication, transportation, and business networks as far away as New York City, underscoring the vulnerability of the CENA and heightening the concern for the major impacts that a larger earthquake could have in this region. Additional studies are needed to further identify the vulnerabilities, assess the social and economic impacts, and evaluate regional resilience.