GIS Fault Mapping of Virginia Seismic Zones

Completed in Accordance with

Grant Agreement HGMP 4042-000-014

Virginia Department of Mines, Minerals and Energy
Division of Geology and Mineral Resources

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INTRODUCTION

On August 23rd 2011, a magnitude 5.8 earthquake shook central Virginia and was widely felt across the eastern United States. This event caused considerable property damage near the epicenter and scattered damage across central and northern Virginia. In response to the earthquake, the Federal Emergency Management Agency (FEMA) issued a major disaster declaration (DR-4042) and offered assistance to affected residents, businesses, and communities. In addition, FEMA also provided funding through the Virginia Department of Emergency Management (VDEM) Hazard Mitigation Grant program to reduce the impact of future earthquakes. The Virginia Department of Mines, Minerals, and Energy (VDMME) Division of Geology and Mineral Resources (DGMR) applied for and received a grant (HGMP-4042-000-014) to: 1) compile information about past damaging earthquakes in Virginia into a report with a map of documented events, 2) review existing geologic maps and compile identified faults into an ArcGIS geodatabase, 3) verify and classify identified faults through geological field studies, 4) use LiDAR data within the epicentral area of the 2011 earthquake to help identify possible faults, 5) use GIS analysis to identify communities and infrastructure at greatest risk of future earthquake damage, and 6) present maps, reports, and digital data to planning and emergency management personnel and agencies in the affected communities. For task 1, the scope was statewide. Tasks 2, 3, 5, and 6 focused on recognized areas of elevated seismic activity in the Commonwealth. For task 4, the scope was limited to the epicentral area of the August 23, 2011 Mineral earthquake.

ACKNOWLEDGEMENTS

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Martin Chapman and Bill Henika of Virginia Tech and Chuck Bailey of the College of William and Mary worked as consultants on this project and assisted with project design, the collection of earthquake and fault information, and the review of the final deliverable products. Mike Enomoto, Marques Hatfield, William Swanger, Marcie Occhi, and Aaron Cross of DGMR completed specific tasks for the project. Christy Straight of the New River Valley Planning District provided assistance in arranging a meeting with local agencies in the Giles County Seismic Zone. Amy Howard of VDEM served as grant coordinator.

PROJECT TASKS

Task 1. Compile information about past damaging earthquakes in Virginia into a report with a map of documented events

Relevant data about past earthquakes in Virginia is available from a variety of academic and governmental sources. Seismic catalogs provide information about the location and magnitude of modern and historic earthquakes. Modern earthquakes are considered to be those that have precise locations recorded by a regional network of seismometers in place since the late 1970s. Historic earthquakes include those that are approximately-to-arbitrarily located based on a town or region where shaking occurred, and whose magnitude was estimated based on felt reports. Catalogs utilized for this grant are maintained by the Advanced National Seismic System (ANSS), Center for Earthquake Research and Information (CERI), International Seismological Centre (ISC), National Center for Earthquake Engineering Research (NCEER), National Earthquake Information Center (NEIC), U.S. Geological Survey (USGS), and Virginia Tech Seismological Observatory (VTSO). With guidance from Dr. Martin Chapman of the VTSO, DGMR staff compiled the best information available from each of these catalogs.

In addition to the seismic catalogs listed above, DGMR also located and reviewed reports of historical earthquakes that occurred between 1774 TO the late 1970s. Many of these events are described in existing compilations of historic earthquakes. A bibliography of reviewed earthquake compilations is included in Appendix A. In addition, DGMR obtained an online account to Newspapers.com, reviewed hundreds of newspaper articles, and identified more than 180 newspaper articles that provided additional details about historical earthquakes in Virginia. These articles have been compiled into a chronological bibliography that is included as an appendix to a separate report, "Seismic History of Virginia" (Kelly and others, 2017).

The initial compilation of earthquakes contained approximately 360 modern earthquakes and 200 historic earthquakes. Following review of the data, approximately 84 events were removed. The most common reasons for removal were: 1) the epicenter was determined to be outside Virginia, 2) the event was determined to be mining-related or have another anthropogenic cause, 3) the event was determined be a duplicate of an existing event, or 4) insufficient data on location, or date. The final compilation, consisting of 313 modern earthquakes and 163 historical earthquakes is included as an appendix in a separate report, "Seismic History of Virginia" (Kelly and others, 2017) and includes basic information about each earthquake including the data and time, magnitude, and catalogs where the information was derived.

Historic and modern earthquake epicenters are also available as a point feature class within the project geodatabase in Appendix B. Each earthquake has been located geographically with the available latitude and longitude in decimal degrees, and contains similar data (time, magnitude, etc.) as the compilation in the "Seismic History of Virginia." Each epicenter also has an attribute describing the quality of the location data in a field called "Location_Quality". This field describes whether the latitude and longitude location was derived based on seismometers (precise) or if the location is only as accurate as the reported town (approximate) or region (arbitrary).

Since the early 1970's, geologists have recognized that three areas of the Commonwealth are more likely to have earthquakes, but the boundaries of these areas have not been well-defined. Since all of the known damaging earthquakes in Virginia have occurred generally within these three seismic zones, DGMR determined that it was important to define boundaries in order to target fault compilation and outreach efforts. The earthquake epicenter database developed during Task 1 and earthquake data from adjacent states were utilized to delineate the boundaries of these zones based on earthquake frequency.

Earthquake point locations were entered into the “Kernel Density” Tool in the ArcGIS Spatial Analyst Toolbox. This tool determines how many features are identified within a determined search radius. The output is a raster file where each pixel is equal to the number of features (in this case epicenters) are found within the selected search radius (30 square miles). This raster was then symbolized using an 8-class Quantile Classification scheme, where each class has the same number of values. Since there are so few epicenters for the study area, this helped identify where there were greater concentrations of earthquake epicenters and thus define, generally, the boundaries of the seismic zones (Figure 1). Of course, the boundaries of the seismic zones are diffuse and earthquakes will certainly occur outside of these boundaries. To that end, these seismic zones should not be used to identify or assess seismic hazard. These boundaries merely identify where there has historically been a greater frequency of earthquakes based on the DGMR earthquake catalog. To assess seismic risk and hazard, users should refer to the seismic hazard maps recently updated by the U.S. Geologic Survey in 2014 (Peterson and others, 2014).

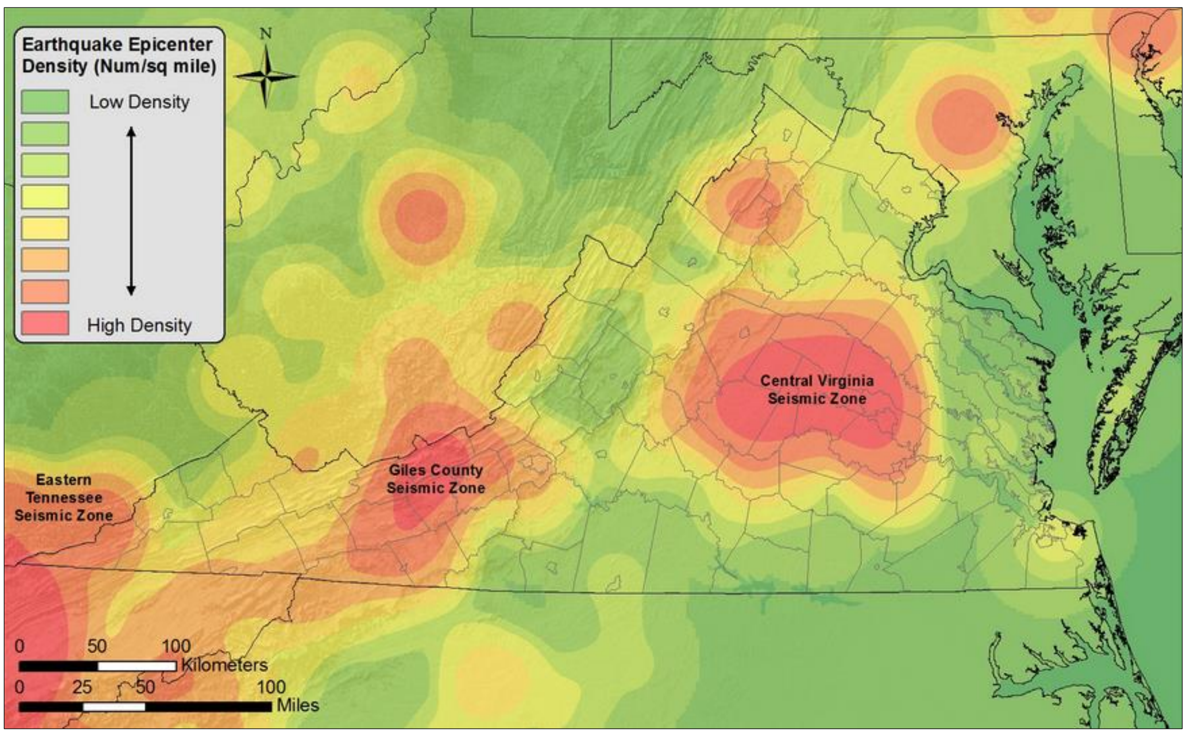

Figure 1. Virginia’s seismic zones, defined by areas of elevated earthquake density.

Task 2. Review existing geologic maps and compile identified faults into an ArcGIS geodatabase

At the beginning of the project, DGMR developed an ESRI ArcGIS geodatabase containing multiple point, line, and polygon feature classes and associated tables for the compilation of fault data and other project-related information. Fault data (Significant_Faults) is captured in a line feature class and includes information about the location, movement type, fault name (if known), and data source of each fault segment. The symbology used for faults is shown in Figure 3. Fault-related information is entered through a series of pull-down menus to standardize data entry. In addition to faults, the geodatabase structure allows for the collection of new geologic field data and earthquake epicenters.

Geologic structural zones (Structural_Zones) are captured in a polygon feature class. These areas identify zones of deformation, where ductile and/or brittle shearing of rock has occurred and represent an area of weakness in the crust. This feature class includes a variety of geological structures including fault breccias, fault gouge, shear zones, and mylonitic rock. In addition, Mesozoic basins (Mesozoic_Basins) were also included as a polygon feature class and digitized from existing geologic mapping. These sediment-filled depositional basins were formed during the breakup of Pangea and are typically fault-bounded. The symbology used for faults, structural zones, and Mesozoic basins is shown in Figure 3. A non-spatial table containing data sources for each geologic map was also created and associated with each line segment and polygon in the various feature classes using a unique data source ID number. This allows the user to click on a line or polygon feature and easily identify the geologic map reference for the feature.

Name	Type
Compiled_Faults	File Geodatabase Feature Class
Earthquake_EpicentersAnno	File Geodatabase Feature Class
Epicenters	File Geodatabase Feature Class
Mesozoic_Basins	File Geodatabase Feature Class
Mesozoic_BasinsAnno	File Geodatabase Feature Class
Seismic_Zones	File Geodatabase Feature Class
Significant_Faults	File Geodatabase Feature Class
Significant_FaultsAnno	File Geodatabase Feature Class
Structural_Zones	File Geodatabase Feature Class
Structural_ZonesAnno	File Geodatabase Feature Class
VA_COUNTY	File Geodatabase Feature Class
VA_STATE	File Geodatabase Feature Class
DataSources	File Geodatabase Table

Figure 2. Structure of earthquake project geodatabase.

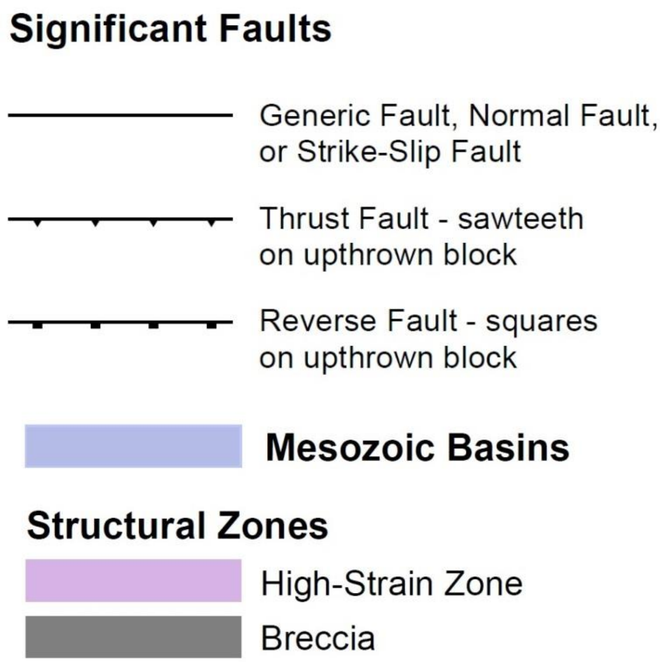

Figure 3. Symbology used for faults, structural zones, and Mesozoic basins.

After the geodatabase framework was developed, DGMR began identifying geologic maps containing fault data within the three identified areas of elevated seismic activity in Virginia, as delineated by the earthquake frequency mapping of Task 1. These geologic maps included published and unpublished data from DGMR, the U.S. Geological Survey, academic institutions, unpublished field, thesis, dissertation, and transfer geologic maps, and geologic maps from field trip guidebooks. Unpublished maps that were not already available in GIS were scanned, georeferenced, and digitized. Since fault line work varied by map, several duplicative fault line feature classes were developed to compile data from various map scales: 1:500,000, 1:250,000, 1:100,000, 1:62,000, 1:24,000, an “Other” feature for non-standardized map scales, “County” scale maps, and a “Thesis” feature class for thesis and dissertation maps. Dividing the maps by scale allowed multiple workers to digitize at once, and allowed for better organization of the data. A similar process was completed for structural zone data. In total, more than 200 maps at scales ranging from 1:12,000 to 1:500,000 were identified and entered into the database.

Task 3. Verify and classify identified faults through geological field studies

After Task 2 was completed, a review of the raw feature class data was performed and several types of QA/QC issues were identified. The most common issues were: 1) the same fault segment was depicted on several geologic maps, but the location or trace of the fault varied between maps; 2) the type, width, orientation, character (ductile vs. brittle), depiction (single line fault vs. broad high strain zone), or age of a fault segment was shown differently on different maps; 3) the locations of fault segments on adjacent maps did not line up with each another; 4) a fault was shown to extend to the boundary of one map, but did not continue into the adjacent map area; and 5) a geologic map was not available in an area where a fault appears to exist based on smaller-scale geologic mapping or maps in adjacent areas.

To address issues of type 1 and 2, DGMR developed a methodology, documented in the flow-chart in Figure 4, to select the best fault segment to use in each area, and to determine the best way to depict that particular fault. To address issues of type 3, DGMR first reviewed the offset in the context of the source geologic maps and any available geologic data from other sources. If the offset was small, and within the uncertainty of the available data, DGMR adjusted one or both fault segments to eliminate the offset. If the conflict was large and could not be resolved, DGMR next attempted to contact the authors of the maps involved to see if additional information was available. If the authors were not available or the issue could not be resolved with this information, the conflict was flagged for field review and assigned a high or low priority. An attempt was made to resolve all high priority conflicts and some low priority conflicts by making new field observations in the area of concern.

To address issues of type 4 and 5, DGMR contacted geologists who may have completed field work in the area of concern to determine if additional information existed that could be used to extend faults into unmapped or more coarsely mapped areas. If not, field work was completed in prioritized areas to connect or extend faults into unmapped areas, with a focus on significant regional faults. New geologic mapping of large areas was beyond the scope of this project. It is anticipated that faults will be extended into new areas as detailed geologic mapping continues in Virginia.

Fault segments and structural zones verified by the QA/QC process were compiled into a new feature class, "Compiled_faults" that retained all of the attributes of the raw fault feature classes. Fault segments that were added or changed during this process were attributed to reflect a modification by DGMR staff. This inferred or modified line work is attributed as "Inferred by DGMR" in the "IdentificationMethod" field to distinguish it from those that were digitized directly from the source mapping. The result of this work is a compilation that contains the best available mapped fault locations within seismically active areas of Virginia. The compilation feature classes for faults (Compiled_Faults) and Structural Zones (Structural_Zones) are included in the geodatabase in Appendix B.

A review of this compilation of fault locations was subsequently completed, and DGMR decided that while accurately reflecting the current status of geologic mapping, the compilation was overly complex and inconsistent in some areas and could be confusing to end users. After some discussion, it was decided to create a refined compilation focusing on significant faults. These features where simplified into a single line or polygon with a consistent name (if known) and movement type (thrust, normal, reverse, etc). These features are represented using standard

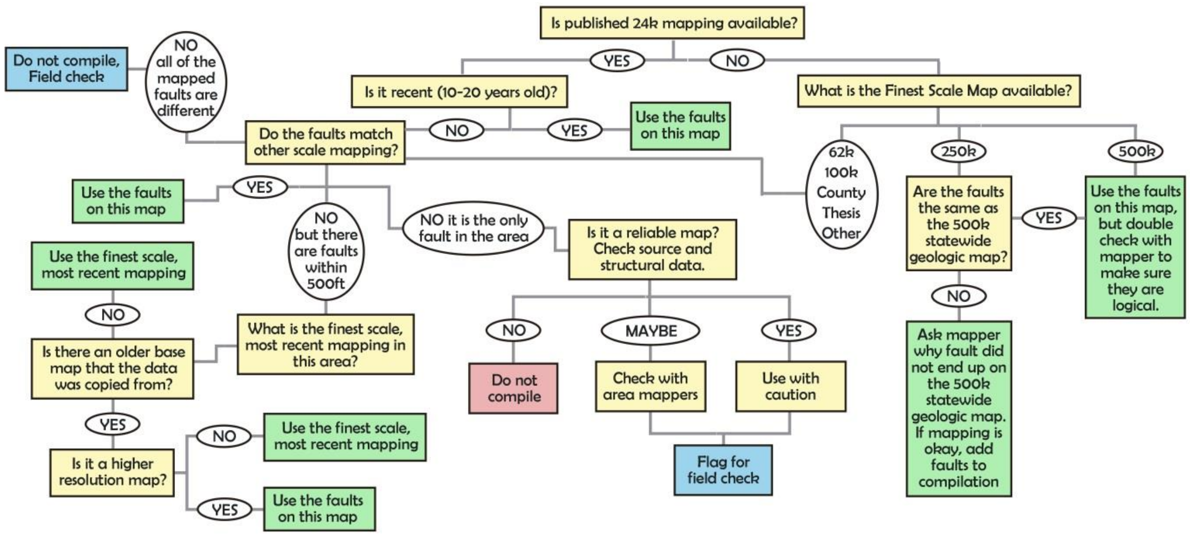

Figure 4. Flow-chart used to select the appropriate fault to include in the GIS geodatabase.

geologic map symbology. This simplified compilation feature class is referred to as "Significant_Faults" and is included in the geodatabase in Appendix B. It is recommended that the Significant_Faults feature class be the primary source of fault information for non-specialists such as land use planners and the general public

Geodatabase metadata describes each feature class, table, and attribute in detail and is contained in Appendix B. Four ESRI map document (.mxd) files are also provided in Appendix B to allow for convenient viewing of the GIS fault data for the Central Virginia Seismic Zone (CVSZ), Giles County Seismic Zone (GCSZ), Eastern Tennessee Seismic Zone (ETSZ), and the locations of historic and modern earthquake epicenters. These map documents also provide the basis for Plates 1-4 of this report.

Task 4. Use LiDAR data within the epicentral area of the 2011 earthquake to identify possible faults

Following the August 23, 2011 Mineral, Virginia earthquake, high-resolution, QL1 (post-spacing 0.33 m) airborne LiDAR data was collected over a 1300 km^2 area in the epicentral region. VDMME worked cooperatively with the USGS to analyze these data to identify any linear features (lineaments) potentially associated with neotectonic faulting in the CVSZ or to identify modern fault scarps.

Bare-earth point cloud data was converted to a 1-meter pixel resolution digital elevation raster and used to create three derivative raster files (hillshade, slope, and aspect) using the ArcGIS suite of Spatial Analyst Tools. Each raster was then analyzed independently by two different geologists to identify linear features, such as fracture or joint sets, foliation-parallel fractures, weathered geologic contacts or other geologic discontinuities. The inspection was repeated twice for each raster dataset as a "double blind" test.

After the manual lineament identification was completed, several automated steps prepared the data and compared the individual datasets to identify coincident line segments between the two observers. Two ArcGIS geoprocessing workflows were created in ModelBuilder, one to detect and remove digitizing errors in the manual dataset and the other to detect and report coincident line segments. The resulting files were then joined by a common field in the attribute table. Individual sets of coincident line segments were compared, selecting for the longest line length. These lines were then output to a new line file.

Over 90,000 lineaments were digitized from the 10 initial datasets identified by the two geologists, but only 438 lines were recognized as coincident across all three raster datasets, indicating that only 0.5% of mapped lineaments were coincident between the observers. Even within this limited dataset (n=438) regional structural trends (NW/NE) are still evident. Generally, lineament reproducibility by the individual geologist was good: 34−58%. This is within the range of percent reproducibility found by Mabee and others (1994) for a similar exercise.

This analysis suggests that lineaments in the 2011 epicentral area are strongly controlled by lithologic contacts and regional joint sets. Surface weathering, stream incision and neotectonic uplift in the seismic zone have all contributed to the topographic expression of these lineaments. Apparent changes in joint set density and spacing occur within major rock units. Although no linear features have yet been conclusively associated with recent faulting in the CVSZ, there is a potential that these lithologic bedding, joint, or foliation planes could have acted as planes of movement in the geologic past, or could be a focus for future rupture.

Recent work by Horton and others (2017) indicates that NNW-striking lineaments identified on the LiDAR by this study are associated with preexisting joint orientations parallel to Jurassic diabase dikes. These dikes where formed by extensional stresses during the rifting of Pangea approximately 200 million years ago. The trend of these lineaments also parallels the focal mechanisms of a cluster of shallow aftershocks associated with the 2011 earthquake, just NE of the main shock. This evidence may suggest that these aftershocks are reactivating along zones of weakness parallel to these NNW-trending features.

Task 5. GIS Analysis to identify communities and infrastructure at greatest risk

The United States National Seismic Hazard Map (Petersen and others, 2014; Figure 5) was used to assess risk to infrastructure. GIS analysis was performed to examine key infrastructure and critical facilities within each seismic zone (Figures 6 and 7). Tables 1-3 show the total number of types of infrastructure and critical facilities that could be potentially damaged by earthquake shaking in Virginia based on their location on the 2014 USGS 2% probability of exceedance in 50 years peak ground acceleration (PGA) maps (or 0.04% probability in any given year). Potential damage designations (Moderate, Light, Very Light, None) are based on the table of Modified Mercalli Intensity to PGA equivalents in the 2013 Commonwealth of Virginia Hazard Mitigation Plan (Table 3.13-3).

The design and existing condition of structures appeared to be an important factor in damage during the 2011 Mineral earthquake (Earthquake Engineering Research Institute, 2011; Heller and Carter, 2015). It is recommended that key infrastructure and critical facilities be evaluated and repaired or upgraded as needed in order to minimize damage from future events. It is also recommended the siting and design of new key infrastructure and critical facilities consider risk from earthquakes.

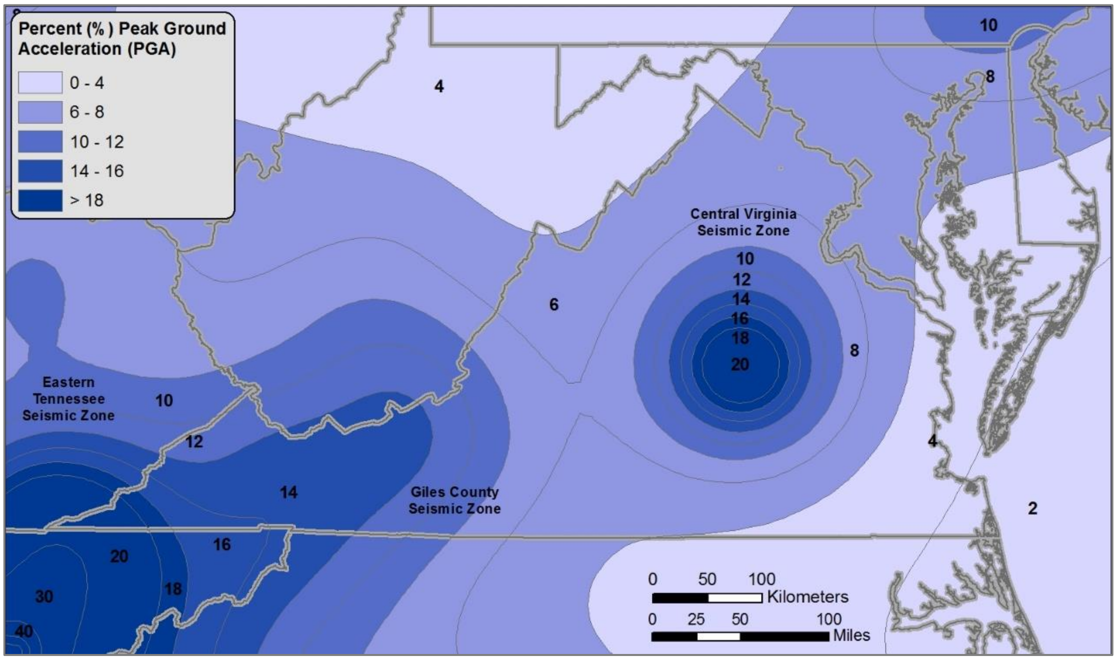

Figure 5. Statewide map showing U.S. Geological Survey Percent Peak Ground Acceleration for a 2% probability of exceedance in a 50 year period (modified from Peterson and others, 2014).

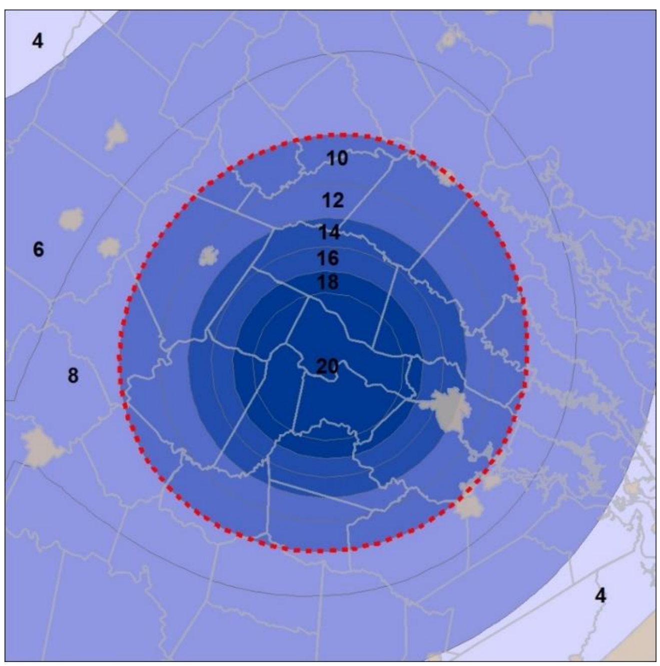

Figure 6. The location of the Central Virginia Seismic Zone (red dashed outline) as derived from the 2014 U.S. Geological Survey 2% probability of exceedance in 50 years peak ground acceleration (PGA) map. The CVSZ has potential minimum PGA values which range from 10% g to 20% g, indicating that these areas have an elevated risk for earthquake damage.

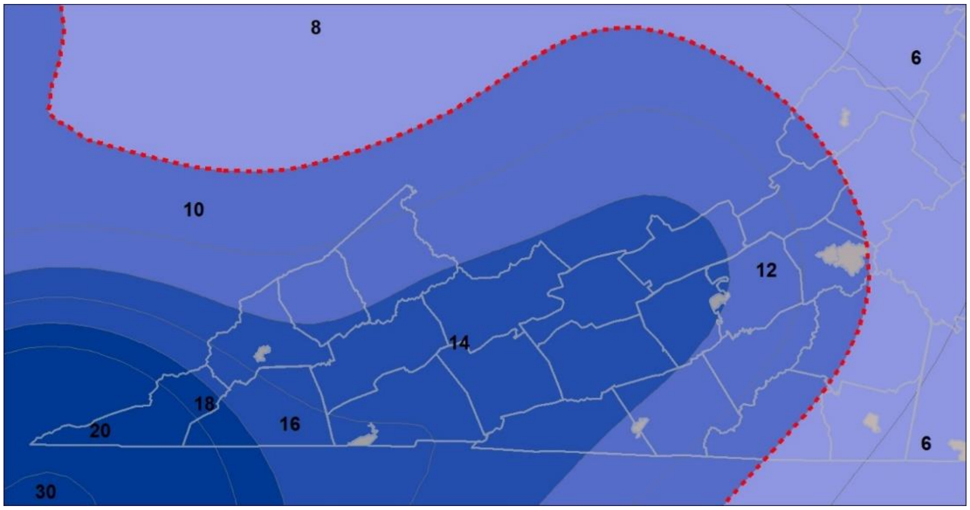

Figure 7. The approximate extent of the Giles County Seismic Zone and Eastern Tennessee Seismic Zone in southwestern Virginia (red dashed outline) as derived from the 2014 U.S. Geological Survey 2% probability of exceedance in 50 years peak ground acceleration (PGA) map.

Table 1. Statewide assessment of infrastructure at risk for damage from earthquakes, based on the United States National Seismic Hazard Map (Petersen and others, 2014).

Infrastructure Type	Total Number	Moderate (≥18%)	Light (16%-10%)	Very Light (8%-6%)	None (≤4%)
Schools K-12[1]	2359	60	715	1112	472
Colleges and Universities[1]	156	0	53	65	38
State Police Headquarters[1]	7	0	3	3	1
State Police Offices[1]	62	2	22	29	9
Police Stations[1]	382	6	126	173	77
Fire Stations[1]	1001	40	325	474	162
Hospitals[1]	155	1	62	54	38
Federal and State Prisons[1]	84	9	33	31	11
National Guard Armories[1]	46	1	17	20	8
State Designated Shelters[1]	37	0	16	17	4
Water Treatment Facilities[2]	2882	92	912	1432	446
Dams (Earthen and Concrete)[3]	3286	358	1093	1618	217
Hazard Potential - High	416	16	122	247	31
Hazard Potential - Significant	310	13	94	197	6
Hazard Potential - Low	1152	89	414	547	102
Hazard Potential - Unknown	1408	240	463	627	78
Power Plants[2]	102	3	25	55	19
Petroleum Bulk Storage Facilities[4]	22	0	11	5	6
Underground Storage Tanks (Inactive and Active)[4]	21022	394	6922	9559	4147
Bridges[5]	13856	477	4975	7016	1388
Condition - Good	4833	165	1441	2819	408
Condition - Fair	8142	278	3158	3802	904
Condition - Poor	881	34	376	395	76
Railroad Bridges[6]	47	2	11	22	12

Table 2. Assessment of infrastructure at risk for damage from earthquakes in the CVSZ based on the United States National Seismic Hazard Map (Petersen and others, 2014).

Infrastructure Type	Total Number	Moderate (≥18%)	Light	
			(16%-14%)	(12%-10%)
Schools K-12 – All[1]	444	47	152	245
Colleges and Universities[1]	28	0	20	8
State Police Headquarters[1]	1	0	1	0
State Police Offices[1]	12	2	5	5
Police Stations[1]	53	4	15	34
Fire Stations[1]	165	27	56	82
Hospitals[1]	34	0	20	14
Federal and State Prisons[1]	29	7	7	15
National Guard Armories[1]	12	1	1	10
State Designated Shelters[1]	12	0	3	9
Water Treatment Facilities[2]	526	76	134	316
Dams (Earthen and Concrete)[3]	1135	349	271	515
Hazard Potential - High	61	12	17	32
Hazard Potential - Significant	75	13	20	42
Hazard Potential - Low	312	84	93	135
Hazard Potential - Unknown	687	240	141	306
Power Plants[2]	16	3	6	7
Petroleum Bulk Storage Facilities[4]	1	0	0	1
Underground Storage Tanks (Inactive and Active)[4]	4121	300	1649	2172
Bridges[5]	2169	302	671	1196
Condition - Good	685	120	188	377
Condition - Fair	1303	167	427	709
Condition - Poor	181	15	56	110
Railroad Bridges[6]	4	1	2	1

Table 3. Assessment of infrastructure at risk for damage from earthquakes in the GCSZ and ETSZ, based on the United States National Seismic Hazard Map (Petersen and others, 2014). The two seismic zones were combined for this analysis because the scale of the National Seismic Hazard Map did not allow for separation into distinct zones.

Infrastructure Type	Total Number	Moderate (≥18%)	Light	
			(16%-14%)	(12%-10%)
Schools K-12 – All[1]	331	13	170	148
Colleges and Universities[1]	25	0	12	13
State Police Headquarters[1]	2	0	1	1
State Police Offices[1]	12	0	7	5
Police Stations[1]	79	2	49	28
Fire Stations[1]	200	13	114	73
Hospitals[1]	29	1	12	16
Federal and State Prisons[1]	13	2	9	2
National Guard Armories[1]	6	0	5	1
State Designated Shelters[1]	4	0	0	4
Water Treatment Facilities[2]	478	16	276	186
Dams (Earthen and Concrete)[3]	316	9	165	142
Hazard Potential - High	77	4	44	29
Hazard Potential - Significant	32	0	20	12
Hazard Potential - Low	191	5	92	94
Hazard Potential - Unknown	16	0	9	7
Power Plants[2]	12	0	6	6
Petroleum Bulk Storage Facilities[4]	10	0	6	4
Underground Storage Tanks (Inactive and Active)[4]	3195	94	1497	1604
Bridges[5]	3282	175	1683	1424
Condition - Good	920	45	401	474
Condition - Fair	2133	111	1142	880
Condition - Poor	229	19	140	70
Railroad Bridges[6]	9	1	8	0

Damage Descriptions for Tables 1-3:

Moderate Damage (≥18%): Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.

Light Damage (10%-16%): Some heavy furniture moved; a few instances of fallen plaster. Reported damage is slight.

Very Light Damage (6%-8%): Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop. Generally, little to no damage is reported.

Data Sources for Tables 1-3:

[1]Virginia Department of Emergency Management ArcGIS REST Service

[2]Environmental Protection Agency Facility Registry Service

[3]Virginia Department of Conservation and Recreation ArcGIS REST Service
Dams are classified based on the potential for loss of life or property damage if the dam were to fail and inundate the area downstream. The classification is unrelated to the physical condition of the dam or the probability of failure. The hazard classification used by VA DCR and in this analysis is as follows:

High: Dams that would cause loss of life or serious economic damage upon failure
Significant: Dams that may cause loss of life or economic damage upon failure
Low: Dams that would lead to no expected loss of life or property damage upon failure
Unknown: The dam has not been classified by DCR.

[4]Virginia Department of Environmental Quality – Environmental Geographic Information Systems Datasets

[5]U.S. Department of Transportation, Federal Highway Administration, National Bridge Inventory
Bridges are rated based on their existing in-place condition, compared to the as-built condition. They are evaluated based on the physical condition of the bridge components including the deck, superstructure and substructure. The following classification is used by the NBI to indicate bridge condition:

Good: Some minor problems may be noted, but the bridge is in otherwise good condition.
Fair: All primary structural elements are sound, but there may be section loss, spalling or scour of the bridge components.
Poor: Advanced section loss, deterioration or scour of the bridge components is occurring.

[6]U.S. Department of Transportation, Bureau of Transportation Statistics, National Transportation Atlas Database 2013

Task 6. Present maps, reports, and digital data to planning and emergency management personnel and agencies in affected communities

During the project, DGMR compiled existing digital and hard copy informational and educational materials related to seismic hazards that would be useful to local and state agencies and organizations. It was recognized early in the project that most of the existing materials were broad in scope and that information specific to seismic hazards in Virginia was lacking. In response, DGMR:

- Improved earthquake-related content on the VDMME web site,
- Developed a project page on the VDMME web site where project deliverables could be accessed online,
- Wrote and published an article for the Virginia Newsletter, a publication of the UVA Weldon Cooper Center for Public Service (Kelly and Witt, 2015) describing Virginia's earthquake history.
- Updated an existing DGMR fact sheet about earthquakes in Virginia
- Developed a new DGMR fact sheet about earthquake hazards in Virginia specific to the Central Virginia and Giles County Seismic Zones
- Developed a new online document related to living in a Virginia Seismic Zone
- Developed presentations describing the project, Virginia's earthquake history, the earthquake geodatabase, earthquake hazards and emergency preparedness
- Developed recommendations for localities updating hazard mitigation plans.

At the beginning of the project, DGMR made contact with the eleven planning districts that overlap Virginia's seismic zones (Figure 8) to describe the project, seek input, and offer assistance during the project period.

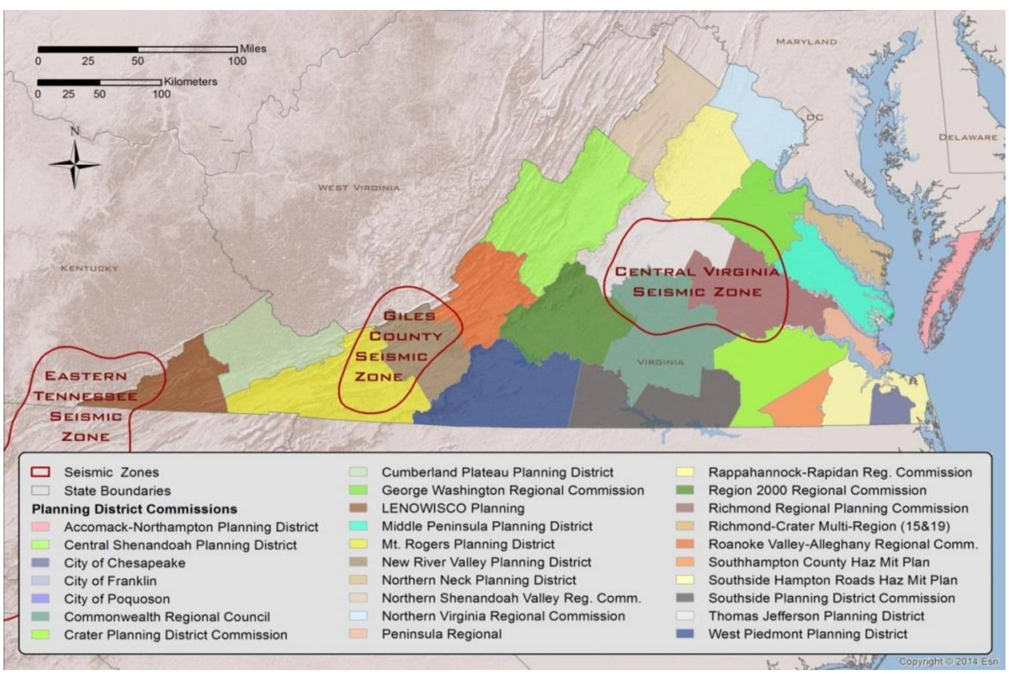

Figure 8. Virginia Planning Districts within seismic zones defined by earthquake frequency.

Near the end of the project, DGMR scheduled meetings in each seismic zone to present the project deliverables to representatives of local and state organizations. In addition, DGMR was invited to give project overviews to the Commonwealth Planning District on February 14, 2017 and the Central Virginia Emergency Management Alliance on February 16, 2017.

On February 23, 2017, the DGMR hosted an informative meeting for the Central Virginia Seismic Zone where representatives from 7 different counties, 4 state and federal agencies, 3 universities, 3 different Planning District Commissions, and 8 additional organizations were in attendance. A second, similar meeting was held on March 10, 2017 for the Giles County Seismic Zone in which representatives from 3 counties, 3 towns, 2 Planning District Commissions, 1 university, and 1 state agency were in attendance. A third meeting for the Eastern Tennessee Seismic Zone occurred on April 5, 2017 during which representatives from three counties (Scott, Lee, and Wise), the LENOWISCO Planning District, DMME, and VDEM were in attendance.

Each meeting consisted of several presentations reviewing the project and derivative products, including an overview of the seismic history of Virginia, methodology of the fault geodatabase compilation, and earthquake emergency preparedness and recommendations for planning. For the Central Virginia meeting, additional presentations were provided by VDEM representatives concerning local perspectives on the 2011 earthquake and available resources in case another damaging earthquake were to occur. Leading seismicity experts from Virginia Tech and the U.S. Geological Survey provided an overview of the geology of the Central Virginia Seismic Zone, and discussed resources available to planners and citizens. In addition to informative presentations, meeting attendees also received a packet of educational digital resources including earthquake emergency preparedness guides for citizens and planners, fact sheets, and the USGS 2014 hazard map.

Key Findings

Based on the review of available information about past earthquakes and recent scientific advances in understanding the Virginia seismic zones, the knowledge gained by compiling known faults in Virginia, and the results of the GIS analysis within each seismic zone, DGMR can make the following observations.

1. Earthquakes are common and widespread in Virginia. Since 1774, 476 earthquakes have been reported. 56 of 95 Virginia counties contain an earthquake epicenter. Earthquakes have occurred in 21 of 27 of Virginia's planning districts.

2. Earthquakes are more common in some parts of Virginia. Since 1774, approximately 90% of seismic events have been spatially associated with the CVSZ, ETSZ, or GCSZ. In Virginia, the CVSZ is the most active seismic zone historically, with approximately 300 reported earthquakes since 1774. Approximately 220 earthquakes in the CVSZ have occurred since 1978 including approximately 80 events that are likely aftershocks to the 2011 Mineral, Virginia Earthquake. Within the GCSZ and ETSZ, approximately 130 earthquakes have occurred since 1774, including 87 since 1978.

3. Damaging earthquakes are rare in Virginia. Since 1774, 26 earthquakes with a Modified Mercalli intensity of VI or greater (damaging) have been reported. Most of these events caused localized or minor damage. Five earthquakes with an intensity of VII or greater,

including a foreshock of the intensity VIII 1897 Giles County earthquake and an aftershock of the intensity VIII 2011 Mineral Earthquake, have occurred.

4. Many thousands of faults exist in Virginia. Many more faults are unrecognized or exist in areas that have not been mapped in sufficient detail within the seismic zones.

5. Most of the faults in Virginia are geologically very old and are not active. Within the CVSZ, ETSZ, and GCSZ all known, mapped faults are associated with periods of mountain building and rifting activity during the Paleozoic or Mesozoic eras. Movement along faults during the Cenozoic era has been documented in other parts of Virginia, including the Coastal Plain and Northern Virginia. Ongoing research suggests there are measurable changes in channel sinuosity and incision rates along terraces of the South Anna River in the vicinity of the 2011 Mineral earthquake. These geomorphological changes suggest ongoing uplift along one or more faults in that area (Berti and others, 2014).

6. Mapped fault locations at the surface of the Earth do not correlate well with historic epicenter locations in Virginia. Within the ETSZ and GCSZ, most earthquakes appear to be related to movement along faults within basement rocks beneath a major discontinuity several kilometers within the earth's crust. Within the CVSZ, some earthquakes do appear to be related to faults that extend, or may extend, to the earth's surface. In many other cases, earthquake epicenters in the CVSZ do not align with mapped faults. In light of this information, it is not appropriate to use the locations of mapped faults to assign seismic hazard or risk.

Preparing for Future Earthquakes

Each year, hundreds of lives are lost and billions of dollars in damages occur in the United States due to natural hazards (Gall and others, 2011). While geological hazards like earthquakes, tsunamis, and volcanic eruptions account for only 10 percent of the monetary losses from all types of natural hazards, their impacts can be catastrophic and economically overwhelming to individual communities (Gall and others, 2011). Unlike hurricanes and floods, where we may have days of warning and preparation time, earthquakes are unpredictable and can occur without warning at any time of the year, day or night.

When a 5.8 magnitude earthquake shocked central Virginia in August of 2011, it drew new attention to seismic hazard preparedness in what are commonly considered less seismically active areas of the United States. Although most people would not consider earthquakes a common occurrence in Virginia, small earthquakes have occurred regularly throughout recorded history and will continue to occur into the future. Earthquakes will pose an even greater risk as population density and development continue to increase. Developing resources to improve our understanding of earthquake dynamics, frequency, and intensity will ultimately improve our ability to mitigate losses from earthquake hazards and may eventually lead to earthquake prediction.

The more residents do to prepare for an earthquake, the less at risk they will feel from a potential future event (Joffe and others, 2013). Planning districts can provide critical information and disseminate outreach materials to the public with recommendations for improving residential safety and prevent property damage. This will serve to educate and empower residents within seismic zones to take action to modify their homes so that they are actively and effectively reducing risk.

DGMR has produced such outreach materials with the aim of raising awareness of seismic potential in Virginia and helping to increase preparation in seismically active areas. These materials help residents consider factors that would be critical before or during a high magnitude earthquake event. For example, residents can ensure that their home is as resistant to earthquake damage as possible by assessing how it was built. Earthquake risk to homes varies depending on the age, size, and height of the structure, the building materials used, the type of soil underneath the building (certain soil types may be prone to liquefaction), and whether or not a home is located in an area of historic seismicity.

Residents can also make homes more resistant to earthquake damage by assessing what is inside. Securing any objects that can move, break, or fall, looking for and securing heavy items (such as bookcases, or items that hang from the walls or ceilings), and moving any items that could fall on residents away from beds or tables and away from escape routes. Other methods to reduce risk could include learning how to turn off the gas line, securing water heaters with nylon or metal straps, relocating items to lower shelves or cabinets with latched doors, installing flexible connectors on gas appliances, putting together and stashing emergency supplies such as food, water, medicine, and a communication device, and even identifying local evacuation routes. Finally, simply following safe building guidelines is a great way to ensure increased safety. New structures within areas of known increased seismic occurrence may also be designed and built using the seismic provisions of United States model building codes (https://www.fema.gov/media-library/assets/documents/6015). Although we can never eliminate earthquake hazards, preparedness may help reduce our exposure to conditions that cause economic loss or loss of life.

The compilation of best available fault, epicenter locations, and related geological data are included as feature classes within the Fault Mapping geodatabase in Appendix B. It is hoped that this data will be a useful tool for land use planners and emergency management officials. Although earthquake epicenters in Virginia do not align well with near surface faults, these areas still indicate zones of weakness in the crust and may help later define the stress regimes which lead to earthquakes. In addition, this data can serve as a foundation upon which additional geological mapping data can be added, ultimately expanding the fault compilation database across the entire Commonwealth as funding allows. The database may eventually help reveal patterns in seismicity, and assist geologists in identifying active geologic faults, and more accurately link earthquakes to causative faults.

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