VIRGINIA DIVISION OF GEOLOGY AND MINERAL RESOURCES

PUBLICATION 185

SEISMIC HISTORY OF VIRGINIA

Wendy S. Kelly[1], Anne C. Witt[1], Matthew J. Heller[1], and Martin C. Chapman[2]

[1]*Department of Mines, Minerals and Energy*
[2]*Virginia Tech Seismological Observatory*

COMMONWEALTH OF VIRGINIA
DEPARTMENT OF MINES, MINERAL AND ENERGY
DIVISION OF GEOLOGY AND MINERAL RESOURCES

CHARLOTTESVILLE, VIRGINIA
2017

VIRGINIA DEPARTMENT OF MINES, MINERALS AND ENERGY
RICHMOND, VIRGINIA

John W. Warren, Director

DIVISION OF GEOLOGY AND MINERAL RESOURCES
CHARLOTTESVILLE, VIRGINIA

David B. Spears
Director and State Geologist

This report documents the results of a three-year project funded by FEMA through VDEM and by the VDMME via Grant Agreement Number HMGP-DR-4042-000-014 for $548,969.

Front Cover: Portion of a colonial map of present day United States, Carte de Louisiane et du cours du Mississipi (L'Isle, 1718). The map shows a portion of the Piedmont as "terre tremblante" or "trembling earth."

CONTENTS

ILLUSTRATIONS

INTRODUCTION

Earthquakes are widely recognized as common occurrences in the western United States, but are not typically associated with eastern U.S. states like Virginia. However, when a 5.8 magnitude earthquake caused hundreds of millions of dollars in damages to the Commonwealth of Virginia in 2011, the Federal Emergency Management Agency (FEMA) issued a major disaster declaration (DR-4042) and offered assistance to affected businesses and residents. FEMA also provided funding for planning projects to reduce the impact of seismic hazards in the eastern United States.

Although damaging earthquakes do not occur frequently in Virginia, modern seismic catalogs, historic documents, and paleoseismic evidence document persistent seismicity in the region. The information from these sources has been compiled in this report and an accompanying database by the Virginia Department of Mines, Minerals and Energy (VDMME), Division of Geology and Mineral Resources (DGMR). This report also provides background about earthquakes and summarizes the greatest magnitude events from that database (earthquakes greater than 4.5 magnitude). It is one of the products of a three-year project funded by FEMA through the Virginia Department of Emergency Management and by the VDMME via Grant Agreement Number HMGP-DR-4042-000-014 for $548,969.

BACKGROUND

The Earth is a dynamic planet. The tectonic plates that make up the rigid outer crust of our planet are in constant motion. The slow movement of these plates results in the transfer and accumulation of stress in the crust. When a sudden release of accumulated stress occurs along a geologic fault, an earthquake occurs (Figure 1). The point within the Earth where this rupture occurs is called the earthquake hypocenter. The point on the ground surface directly above the hypocenter

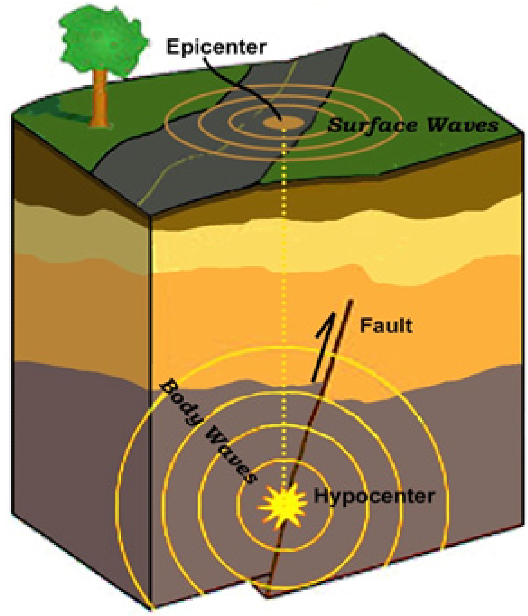


Figure 1. Anatomy of an Earthquake. Modified from U.S. Geological Survey (2017a).

is called the epicenter. The depth to the hypocenter is called the focal depth. Globally, earthquake focal depths can range from essentially zero (the Earth's surface) down to 660 kilometers. However, in plate interior settings, like Virginia, earthquake focal depths are confined to the upper and middle part of the Earth's crust, from near surface to depths of about 30 kilometers.

Earthquakes are usually the result of sudden movement along a pre-existing plane of weakness called a fault. The movement along the fault rapidly releases some of the accumulated energy as seismic waves. When an earthquake occurs, there are two kinds of seismic waves that travel away from the hypocenter and through the interior of the Earth. The fastest seismic wave is the P-wave (or "compressional" wave), which is analogous to an acoustic (sound) wave in air or water. The S-wave (or "shear" wave) travels slower than the P-wave, but is much larger and more damaging.

When these waves reach the ground surface, they generate other kinds of seismic waves that are confined to shallow depths. These "surface waves" travel slightly slower than the S-wave, but travel away from the epicenter with relatively little loss of amplitude as distance increases, compared to the P and S-waves. There are two kinds of surface waves. Rayleigh waves cause the ground to move in a rolling nature, similar to a wave on the ocean. Love waves cause the ground to move horizontally. Both types of seismic surface wave are created by interaction of the P and S-waves with the free surface of the ground. The shaking caused by surface waves is what many people experience as an "earthquake".

EARTHQUAKE MAGNITUDE

The "size" of an earthquake depends on three things. The first factor is the area of the fault that slips during the earthquake. The second factor is the average displacement across the fault. The third factor is the strength of the rocks on either side of the fault. The mathematical product of those three factors is called the seismic moment. Although it has physical units of energy, it is only correct to think about it as a force times a distance (i.e., moment). Big earthquakes result from large amounts of slip on large faults whereas little earthquakes are caused by small slips on little faults.

Many people are familiar with the terms "earthquake magnitude" or "Richter magnitude", but the concept is often misunderstood. Unlike seismic moment, magnitude is not a simple measurement of earthquake size. Charles Richter developed the earthquake magnitude scale in the 1930s as an easily calculated measure of relative earthquake size (Richter, 1935). Richter's magnitude is based on a logarithmic scale and is calculated by measuring the amplitude of ground motion caused by an earthquake and recorded by a seismograph at some distance from the epicenter, and then mathematically correcting that measurement back to what it would have been at the earthquake epicenter. Next, that result is divided by the amplitude of ground motion that an arbitrarily chosen "standard" earthquake (one with zero magnitude) would have at the epicenter. The magnitude of the earthquake of interest is simply the base-10 logarithm of that ratio, expressed as a dimensionless whole number and decimal fractions.

Magnitude quantifies the relative size of an earthquake to that of the arbitrary standard earthquake. Since the scale is logarithmic, the ground motion at all distances caused by a magnitude 1.0 earthquake is 10 times greater than that caused by the standard. An earthquake of magnitude 6.0 would cause one million times more ground motion amplitude at all distances, compared to a zero magnitude earthquake. Richter wisely chose his standard earthquake to be very small, too small for people to feel. Modern seismographs can detect earthquakes with negative magnitudes (much smaller than Richter's standard earthquake).

Recently, seismic moment has become a routine seismological measurement, even for small shocks in eastern North America. Traditional magnitude scales, like Richter's original scale described above, are being superseded by moment magnitude, abbreviated as Mw. The reason for this is primarily due to public familiarity with the concept of magnitude. Since about the year 2000, Mw has gradually replaced an older magnitude scale (abbreviated by mbLg) that was formerly used in eastern North America (Nuttli, 1973). Mw and mbLg are not exactly equivalent. For a given earthquake in eastern North America, the moment magnitude (Mw) is usually significantly smaller than the mbLg magnitude. As the DGMR earthquake catalog compiles events dating back through the 18th century, both measurement types, as well as other measurements including local magnitude (Ml) and body magnitude (Mb) are included.

EARTHQUAKE INTENSITY

Seismographs were invented in the late 19th century. Prior to that time, and for many decades thereafter, ground motion from earthquakes was "measured" in terms of the effects that the motion had on people, other objects of nature and

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

Figure 2. Earthquake magnitude and typical correlated intensity. Modified from U.S. Geological Survey (2017b).

structures. A scale of measurement was devised wherein a given degree of shaking intensity is correlated with a specific set of observable effects to humans and man-made structures. The 10-degree Rossi-Forel scale was used prior to the late 19th century, when Italian vulcanologist Giuseppe Mercalli revised it (Mercalli, 1902). The Mercalli scale was expanded to 12 degrees of intensity in the early 20th century by Italian physicist Adolfo Cancani (Cancani, 1904). Shortly thereafter, German geophysicist August Sieberg contributed further revisions (Sieberg, 1923). That was known as the Mercalli-Cancani-Sieberg Intensity Scale (MCS). Americans Harry Wood and Frank Neumann revised the MCS scale and published the result in English (Wood and Neumann, 1931). That was known as the Mercalli-Wood-Neumann Intensity Scale. A few years later, Charles Richter made minor improvements. That result is still in use, and is referred to simply as the Modified Mercalli Intensity (MMI) Scale (Figure 2).

Study of earthquakes prior to the widespread distribution of seismographs focused on collecting intensity information and constructing maps of the shaking intensity. The various degrees of intensity were contoured, creating what are known as felt area, or "isoseismal" maps. Intensity decreases generally decreases away from the earthquake, with the greatest intensities being near the epicentral region. The isoseismals (contours of equal intensity) increase in area as the size of the earthquake increases. However, the intensity of shaking at a given distance from a particular earthquake is highly variable, being affected by many factors, including the local geology. For example, locations underlain by soft soils typically experience higher intensity shaking than sites on bedrock.

With the development and deployment of seismometers in the late 20th century, it became possible to correlate intensity measures, such as the maximum intensity and felt area, with the earthquake magnitude. In addition, it was found that the center of the isoseismal enclosing the maximum shaking intensity often gives an idea of where the epicenter is located. Thus, it is possible to use intensity information, particularly isoseismal maps, to estimate the epicenter locations and magnitudes of older earthquakes that occurred prior to the existence of seismograph networks. This observation is very important for the development of historical earthquake catalogs, and studies such as this report.

VIRGINIA'S TECTONIC SETTING

Although the majority of earthquakes occur within active tectonic settings, such as at plate boundaries where strain rates are greater (Figure 3), earthquake hazards also exist within intraplate settings, such as in eastern North America (Figure 4). Although a great deal has been learned about earthquakes in active tectonic settings, much remains to be understood about intraplate earthquakes and seismicity in the eastern United States.

Virginia currently rests within the relatively stable North American tectonic plate. Even so, earthquakes are nothing new to Virginia. The same processes that built the Appalachian Mountains and opened the Atlantic Ocean have left Virginia laced with thousands of geologic faults. Some of these faults may be zones of weakness and present a path of least resistance for the accommodation of new strain in the earth's crust.

Within intraplate settings, tectonic strain is more diffuse than along plate boundaries (Zoback, 1992). In general, the dominant regional tectonic strain-rate in the central eastern United States is compressive along a NE-SW axis (Zoback, 1992). This strain is primarily due to plate motion originating from the Mid-Atlantic Ridge, which is causing the North American plate to move away from the Eurasian plate, slowly widening the Atlantic Ocean basin. This tectonic process results in a slow deformation of the North American intraplate region.

The long and varied tectonic history of eastern North America has also resulted in a complex

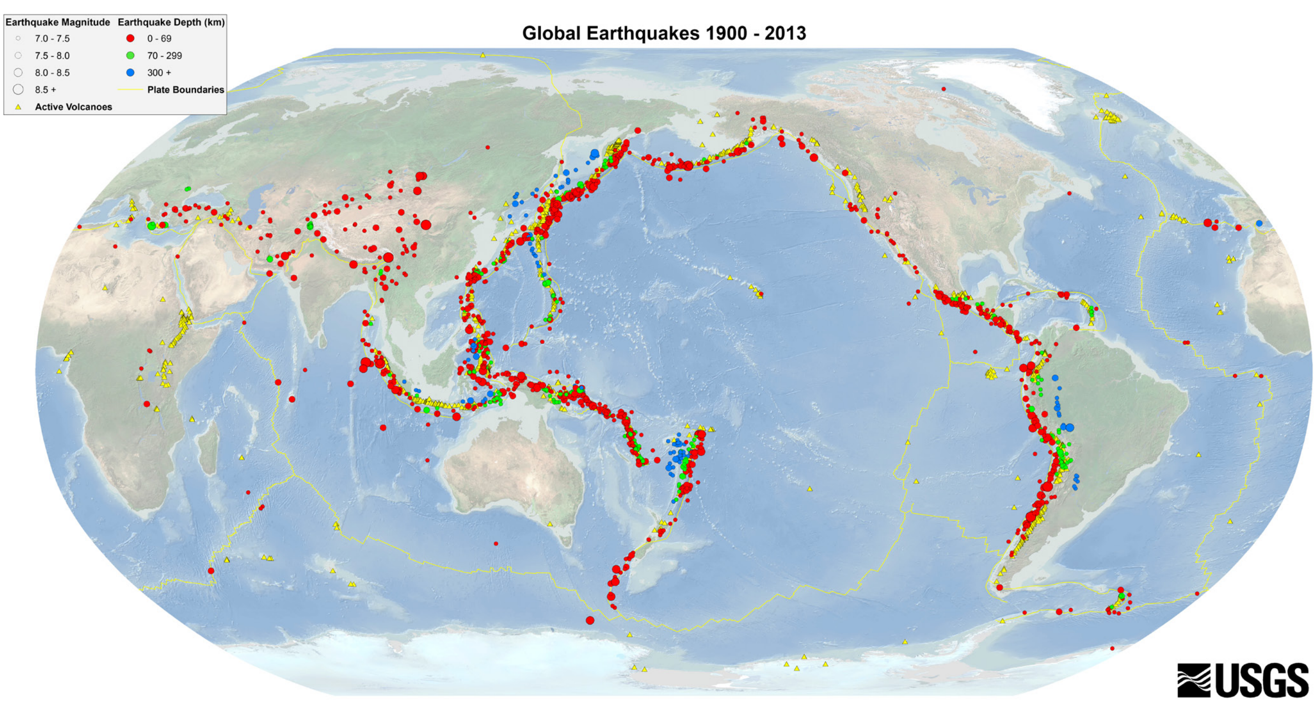


Figure 3. Map showing the locations and depths of earthquakes with magnitudes of at least 7.0, from 1900 - 2013 (U.S. Geological Survey, 2017c).

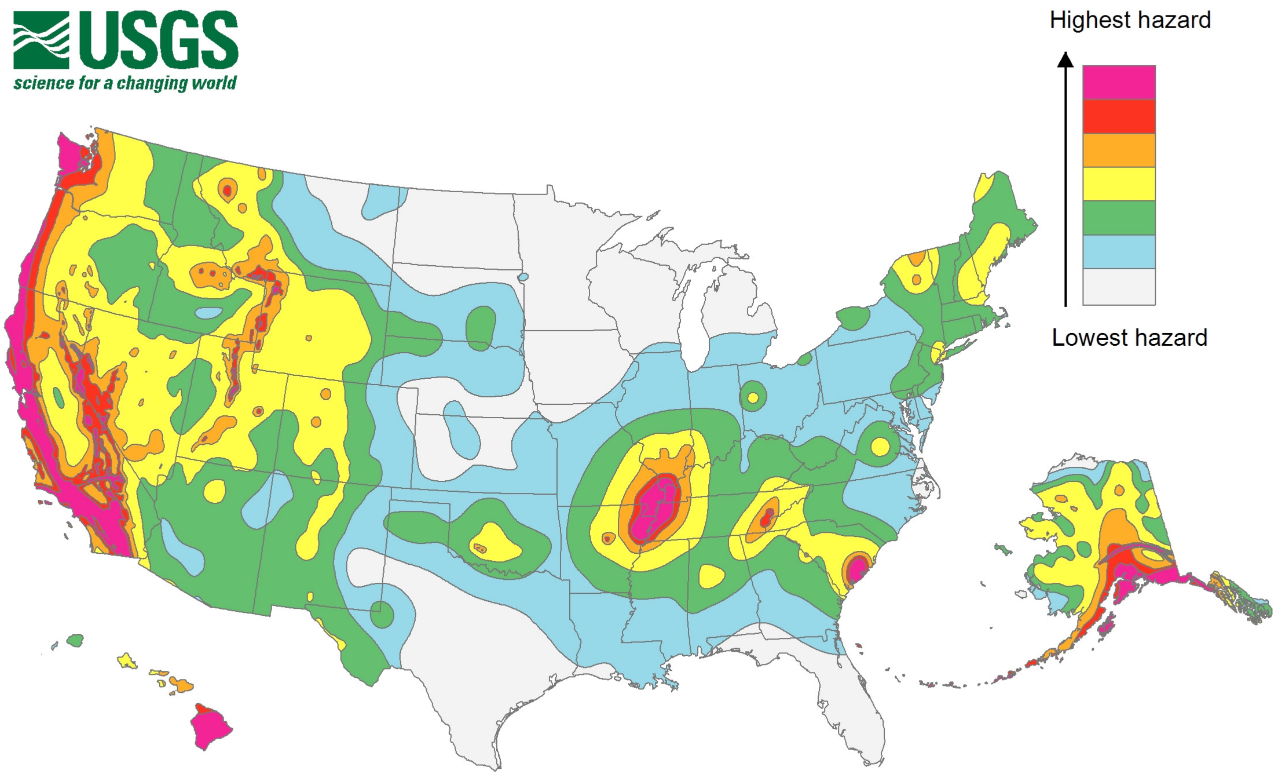


Figure 4. Simplified earthquake hazard map for the United States (Petersen and others, 2014).

crust of variable thickness. This may allow for variability in strain accumulation across the region (Biryol and others, 2016; Soto-Cordero and others, 2016). Areas of concentrated strain or areas of weaker crust may be the cause of localized seismicity (Gangopadhyay and Talwani, 2003). A few researchers have also suggested that changes in ground-water storage in underground fractures may play a role in triggering earthquakes (Bollinger and Costain, 1988; Costain, 2015).

Human activity can also cause seismicity. The collapses of underground mines, large controlled blasts, and accidental mine explosions have all been recorded by regional seismic networks in the eastern United States. Earthquakes can also be triggered by changes in storage in water reservoirs, and by the deep injection of water. In Virginia, no instances of seismicity related to reservoirs or water injection have been reported to date. Mining-related seismicity in Virginia has been attributed to either blasting or the collapse of underground mines, mostly in the coal fields of southwestern Virginia. Induced earthquakes (primarily mining related) were removed from the final earthquake database (Appendix A) and were not considered when mapping earthquake density or identifying areas of elevated seismicity for this report (Figure 5).

AREAS WITH ELEVATED SEISMIC ACTIVITY IN VIRGINIA

The U.S. Geological Survey defines a seismic zone as “an area of seismicity probably sharing a common cause.” In Virginia, three seismic zones are recognized by most geoscientists: Central Virginia, Giles County, and Eastern Tennessee (Figure 5). Significant earthquakes in Virginia have occurred outside of these areas, most notably in northern Virginia. Bollinger (1973) has suggested that these earthquakes are part of a more diffuse zone of seismic activity, which he referred to as the Northern Virginia – Maryland Seismic Zone.

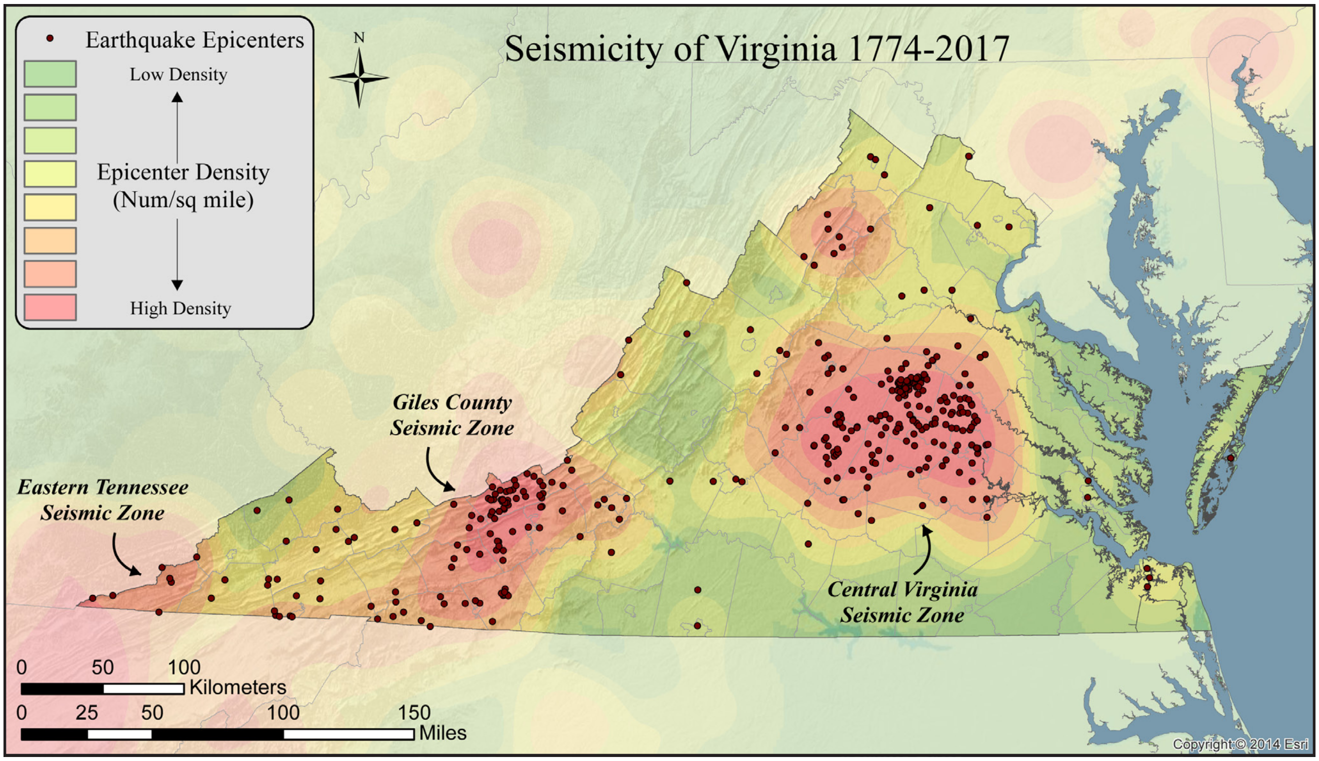


Figure 5. Virginia's seismic zones, defined by areas of increased earthquake density.

CENTRAL VIRGINIA SEISMIC ZONE

The Central Virginia Seismic Zone (CVSZ) stretches from Richmond to Charlottesville and has long been recognized as an area of long-term, low-magnitude seismic activity (Bollinger and Sibol, 1985; Bollinger and others, 1989). The largest historical earthquake within the CVSZ was the August 23, 2011 Mineral earthquake, which had a reported moment magnitude (Mw) of 5.8 (Horton and others, 2015; Chapman, 2015). The Mineral earthquake is the largest earthquake to have occurred in Virginia in historical time.

The CVSZ is primarily in the Piedmont geologic province, which is mostly composed of crystalline metamorphic and igneous rocks that were accreted to eastern North America during the Paleozoic Era. These rocks are assigned to geologic terranes including the Western Piedmont, Chopawamsic and Goochland terranes, which are sutured together along ductile faults known as high strain zones (Figure 6). Several Mesozoic rift basins overlie the crystalline rocks and are bounded on one or both sides by northeast-striking normal faults. These faults are brittle in nature and commonly coincide with high strain zones, suggesting reactivation of the older structures. Seismic reflection data suggests variability in thickness of the crust in this region and the presence of significant structures, such as faults, in the subsurface (Coruh and others, 1988; Pratt and others, 1988; Pratt and others, 2015).

Seismic events in the CVSZ occur in the upper crust in crystalline rocks of Paleozoic age. Well-constrained hypocenter depths range from near-surface to approximately 12 kilometers, with an average depth of 8 kilometers (Bollinger and others 1985; Bollinger and others, 1991). Based on compiled event data, the CVSZ is elongate in an east-west orientation and is not aligned with the north-northeast regional strike of bedrock in this part of the Appalachians.

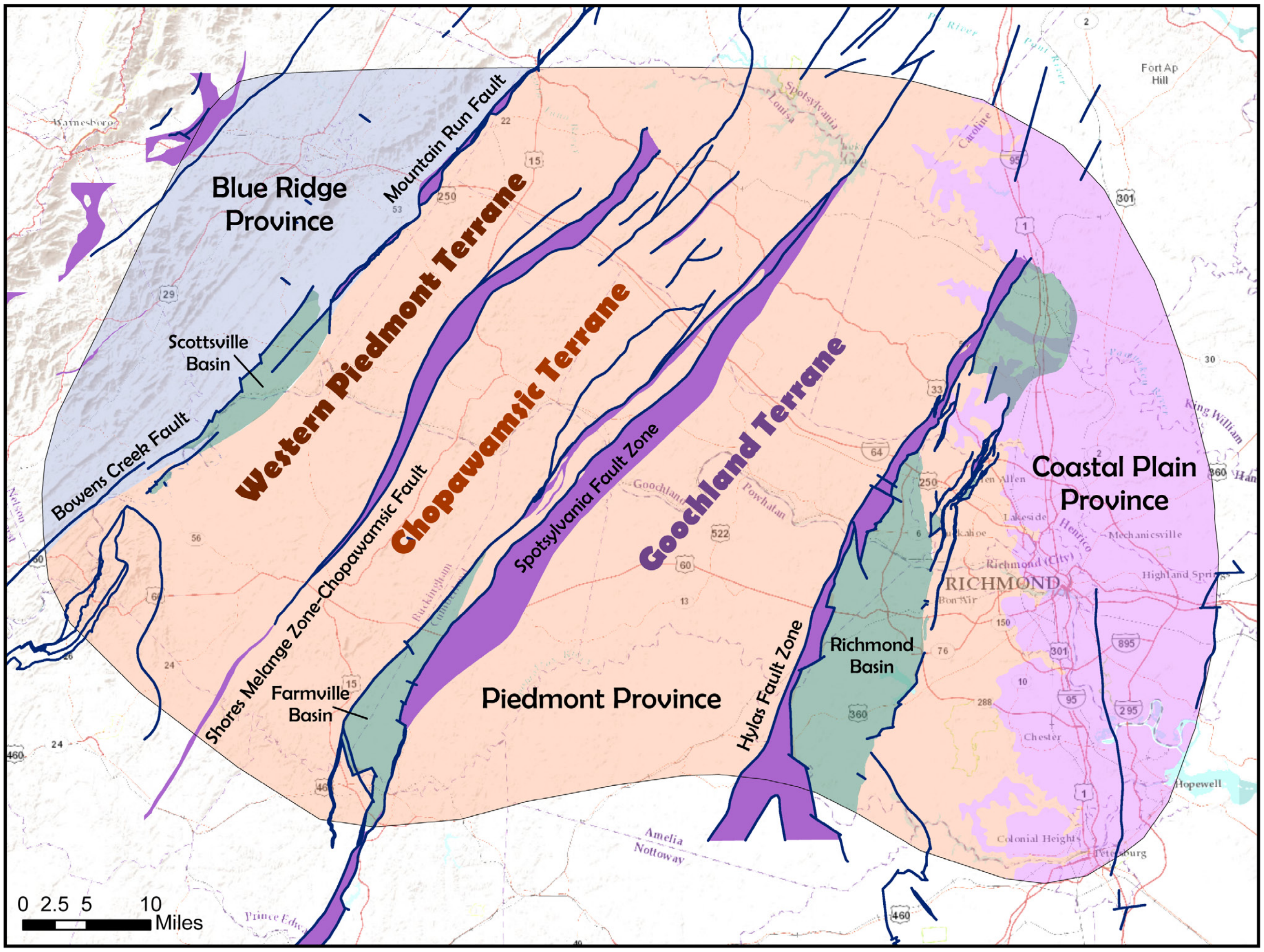


Figure 6. Major faults and tectonic terranes within the Central Virginia Seismic Zone. Geology modified from the 1993 Geologic Map of Virginia.

EASTERN TENNESSEE SEISMIC ZONE

The Eastern Tennessee Seismic Zone (ETSZ) is an approximately 300 kilometers long and 50 kilometers wide area of elevated seismicity centered in southeastern Tennessee (Chapman and others, 1997; Dunn and Chapman, 2006). The ETSZ extends into the southwestern tip of Virginia (Figure 5) and is the second most active seismic area in the eastern United States (Powell and others, 1994). Within the ETSZ, hypocenter depths of 5 to 26 kilometers have been reported (Chapman and others, 1997; Vlahovic and others, 1998). The largest historical earthquake within the ETSZ occurred outside of Virginia and had an estimated magnitude of 4.6 (Bollinger, 1973). Focal mechanism solutions for earthquakes within the ETSZ suggest strike-slip movement along steep north- or east-trending faults (Johnston and others, 1985; Chapman and others, 1997). Based on the depth of the hypocenters, these faults are likely in underlying igneous and/or metamorphic basement rocks and may not be related to faults in the overlying sedimentary rocks that intersect the surface (Figure 7; Johnston and others, 1985; Powell and others, 1994).

Many earthquakes within the ETSZ are spatially associated with an aeromagnetic anomaly known as the New York – Alabama lineament, which may represent a buried boundary between two crustal blocks (Powell and others, 1994). This lineament roughly parallels the regional strike of bedrock in this region.

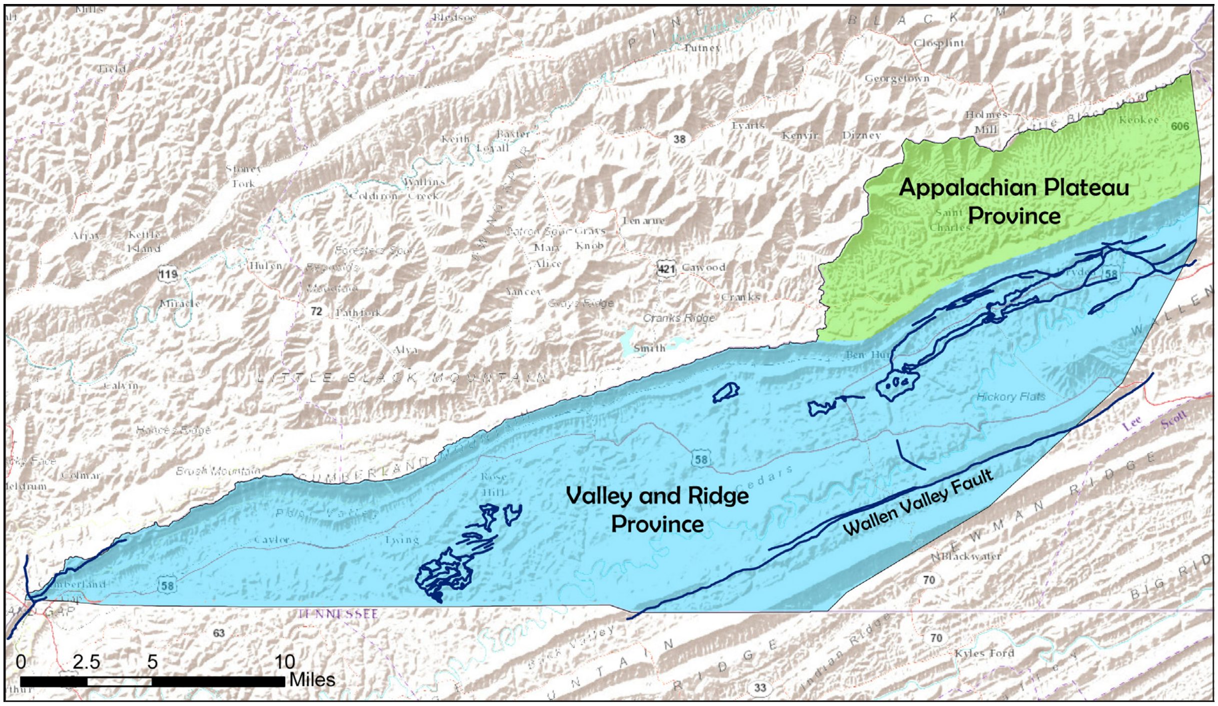


Figure 7. The Eastern Tennessee Seismic Zone in Virginia includes portions of both the Valley and Ridge and Appalachian Plateaus provinces.

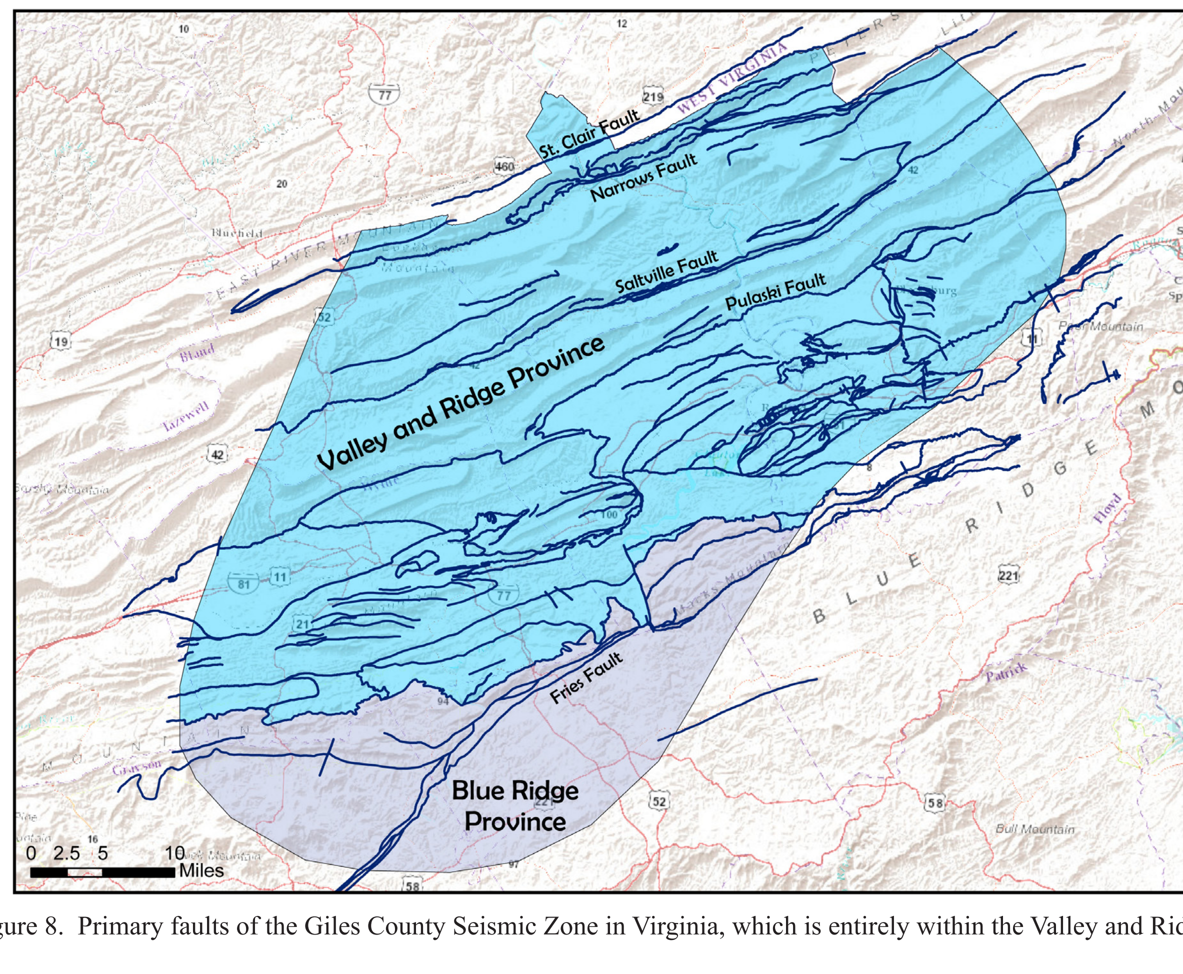


Figure 8. Primary faults of the Giles County Seismic Zone in Virginia, which is entirely within the Valley and Ridge

GILES COUNTY SEISMIC ZONE

The Giles County Seismic Zone (GCSZ) is an area of elevated seismicity centered in the New River Valley of Virginia (Bollinger, 1973; Bollinger and Wheeler, 1988). Most geoscientists consider the GCSZ to be geographically separate from the larger Eastern Tennessee Seismic Zone (ETSZ) to the southwest (Figure 5). The largest shock in the GCSZ occurred on May 31, 1897, estimated at 5.8 (Mblg) on the basis of intensity reports (Nuttli and others, 1979). A recent estimate of the moment magnitude (Mw) of the 1897 shock is 5.5 (Hough, 2012). This earthquake was the largest historical shock in Virginia, and the second largest shock to have occurred in the entire southeastern United States, until the occurrence of the Mw 5.8 (mbLg 6.3) Mineral, Virginia earthquake on August 23, 2011.

The GCSZ is within the Valley and Ridge physiographic province of Virginia, which consists of linear ridges and valleys underlain by Paleozoic sandstone, siltstone, shale, and limestone (Figure 8). Structurally, the Valley and Ridge is composed of several overlapping bedrock layers separated by thrust faults (McDowell and Schultz, 1990). Geophysical data suggest that these sedimentary rocks are underlain by igneous and/or metamorphic basement rocks at a depth of 3 to 6 kilometers (Bollinger and Wheeler, 1988). Historic seismic hypocenters have been concentrated within these underlying rocks (Bollinger and Wheeler, 1988), potentially along faults that either have not been mapped or may not intersect the ground surface. Some earthquakes within the GCSZ are spatially associated with the Clingman magnetic lineament, which may represent a buried boundary between two distinct crustal blocks (Powell and others, 1994). Based on compiled data of this report, the GCSZ is elongate in a north-northeast orientation and is not aligned with the regional east-northeast strike of bedrock in this part of the Appalachians.

PAST EARTHQUAKES IN VIRGINIA

In order to understand Virginia's seismic history, and to evaluate modern risks posed by earthquakes, it is important that prehistoric and historic evidence for earthquakes be considered in addition to more readily available data recorded for modern earthquakes.

PREHISTORIC EARTHQUAKES

European colonists may have been aware of earthquake activity in Virginia during the early 18th century (Figure 9). It is likely that Native Americans were aware of the potential for ground shaking before the colonists arrived. However, compiling a record of seismic events prior to the arrival of European colonists presents significant challenges. With no written record, evidence for pre-contact earthquakes requires an investigation of Virginia's paleoseismicity.

For example, if an earthquake of significant magnitude occurred in the pre-historic past, it may have caused disruption on the surface or in the shallow subsurface that is still preserved and can be identified today (Figure 10). A surface rupture for example, may still be observable as a scarp

Figure 9. Portion of a colonial map of present day United States, Carte de Louisiane et du cours du Mississipi (L'Isle, 1718). This map shows a portion of the Piedmont as "terre tremblante" or "trembling earth."

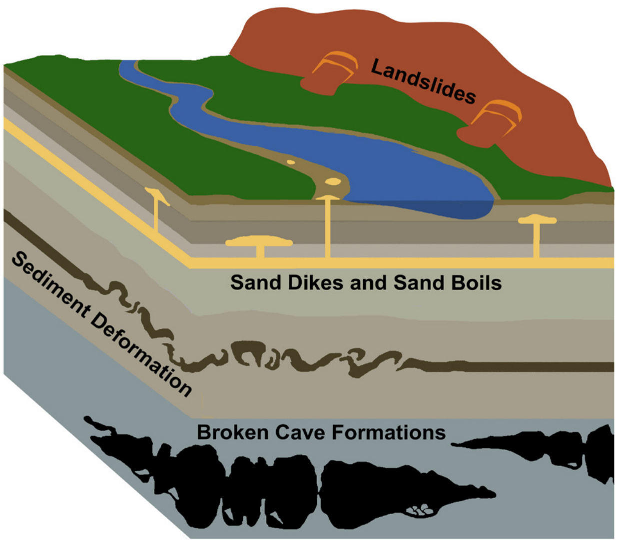


Figure 10. Illustration of earthquake-induced deformation.

or a visible offset of a landform. Landslides of a similar age may have formed in response to a large seismic event. Past liquefaction of soil related to shaking of wet sediments during an earthquake may be observed today as sand dikes within alluvial deposits along modern streams. Large breakdowns of formations within caves could also be related to earthquake activity.

Examples of these types of paleoseismic features have been identified in the GCSZ, CVSZ, and ETSZ. Schultz and Southworth (1989) observed several large landslides interpreted to be Quaternary in age (~10-25 ka) that may have been triggered by seismicity in the GCSZ. Hatcher and others (2012) reported faults offsetting bedrock and younger alluvium, and paleoliquifaction features including sand dikes, within the ETSZ in Tennessee. Age-dating of these deformed sediments suggests a maximum age of 73,000 to 112,000 years before present, with evidence for at least two subsequent events. Obermeier and McNulty (1998) and Tuttle (2015) report isolated paleoliquification features within late Holocene alluvium along major rivers within the CVSZ. The sinuosity of rivers in the CVSZ also appears to be distinct from rivers outside of the seismic zone, suggesting that these rivers may have responded to crustal deformation related to large earthquakes in the more distant past (Carnes and others, 2016).

Within caves, caverns, or karst, features such as stalactites or stalagmites (called speleothems) may preserve evidence for past seismic activity. Speleothems in the New River Cave and Tawny's Cave, located near Blacksburg in the GCSZ, may have formed in response to three separate prehistoric earthquakes (EBASCO, 1993). Within the New River Cave, rock falls, fractured column formations, and breakdown of stalactites are observed with regrowth, suggesting a period of abrupt and damaging shaking followed by quiescence, during which regular cave formation growth resumed (EBASCO, 1993). Regrowth within New River Cave has been age dated, suggesting the oldest event took place approximately 12,130 (+/- 80) years ago, with a second event following at 1,450 (+/- 60) years ago (EBASCO, 1993). Nearby, similar karst disturbance is also observed in Tawny's Cave, with bedrock block and stalactite breakdown, and fracture and offset of column formations (EBASCO, 1993). The event magnitudes for these earthquakes are unknown, but it is likely they were relatively significant based on the damage caused.

HISTORIC EARTHQUAKES

Prior to 1963, documents such as newspapers and journal articles provide the best historical record of earthquakes in Virginia. The observations recorded in these documents have helped researchers determine earthquake intensities and the locations of epicenters, and estimate magnitudes for previous events (Figure 11). A chronological listing of documented historical earthquakes, as well as modern earthquakes, is provided in Appendix A. The distribution of these earthquakes is shown on Plate 1. A comparison of historical and modern earthquake data (Figure 12) suggests that only a subset of historical earthquakes, generally those with magnitudes greater than 2.5, have been recorded. Many of the recorded earthquakes caused alarm, but no damage. Larger

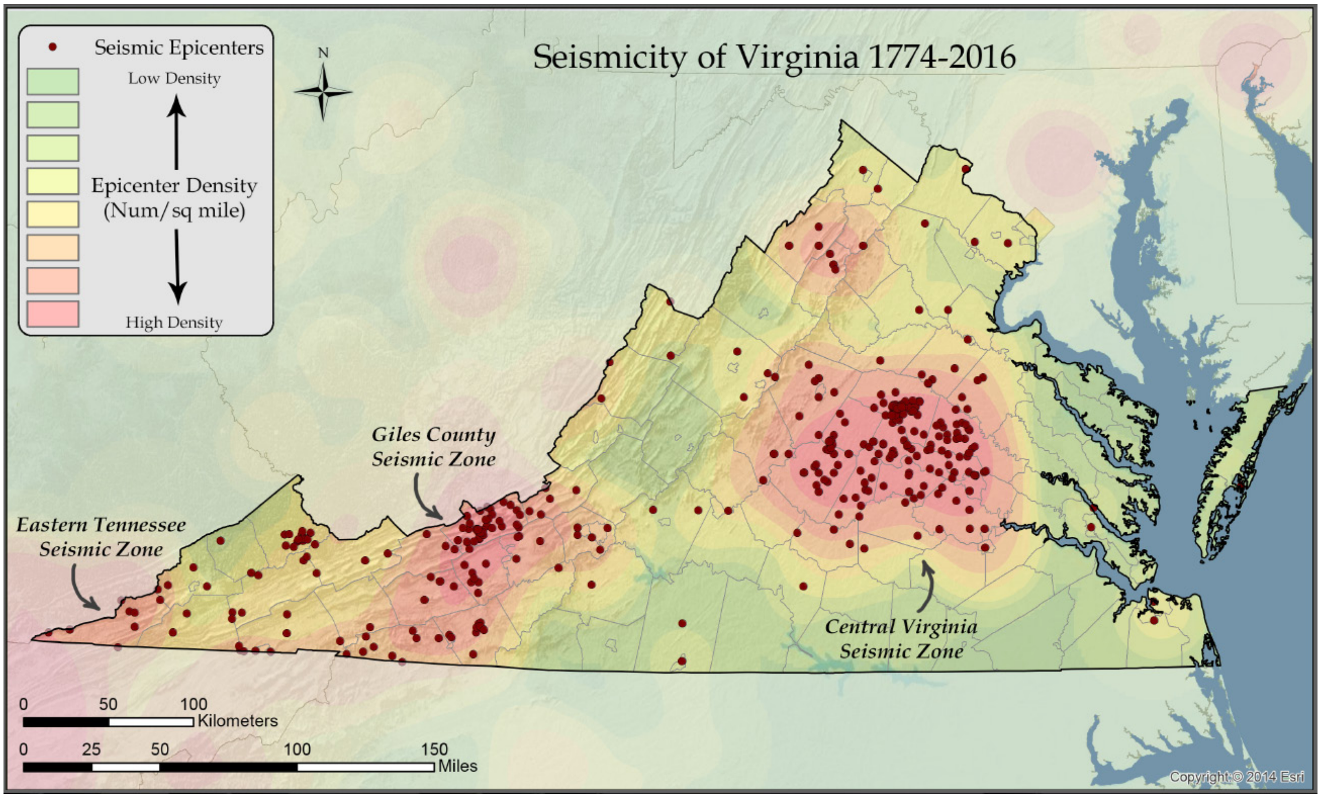


Figure 11. Seismic events documented in Virginia, 1774 through 2016.

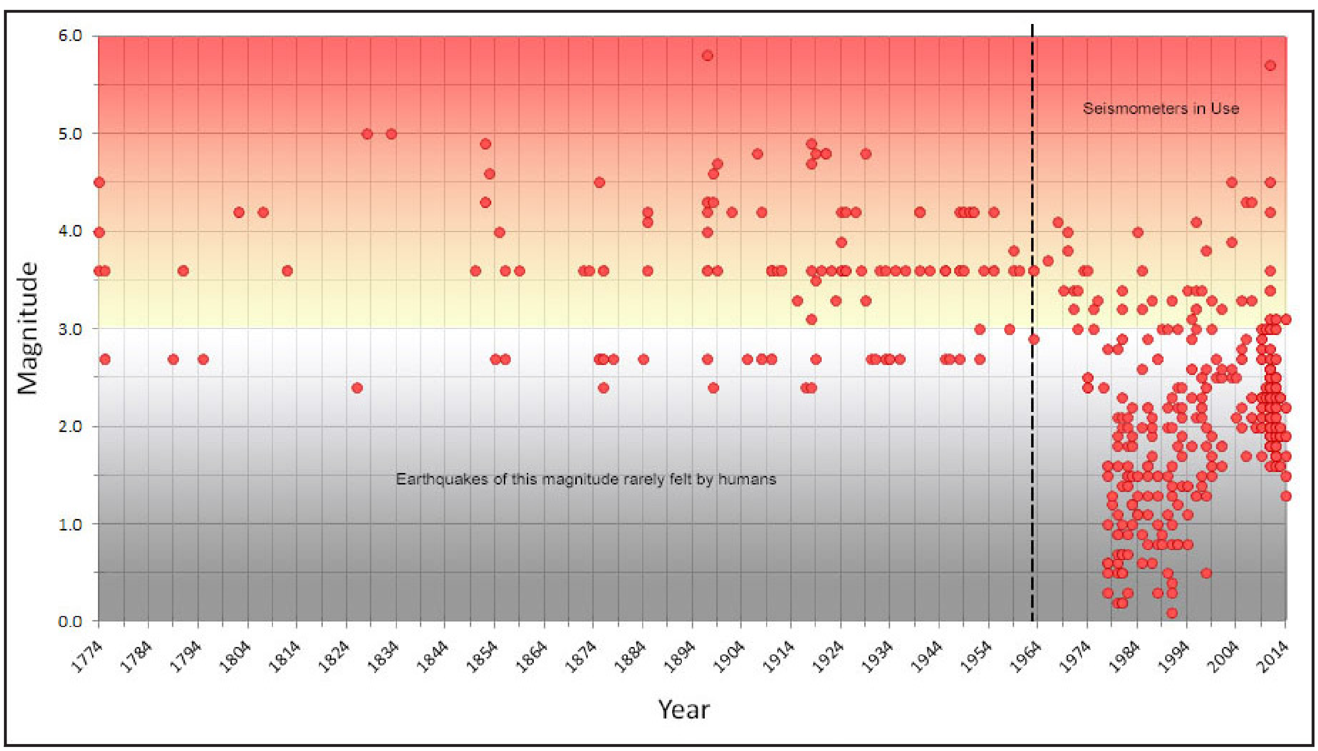


Figure 12. Magnitudes of historical and instrument-recorded earthquakes in Virginia. Magnitude increases as shading transitions from grey to red.

magnitude earthquakes occurred less frequently, and stand out in documentation as memorable and sometimes damaging. A chronological bibliography of all earthquake news reports is included in Appendix B. Significant earthquakes, with magnitudes greater than 4.5, are described below.

February 21st 1774
(estimated magnitude Mb 4.5)

The earliest documented written account of an earthquake in Virginia is found in Thomas Jefferson's personal account book. During the afternoon of February 21, 1774 at Monticello, an earthquake "shook the houses so sensibly that every body [sic] run out of doors" (Bear and Stanton, 1997). In Fredericksburg, buildings shook and glasses rattled; at Westover Plantation in Charles City County the earthquake reportedly "shook the Dwelling-House very much" and; in Richmond the earthquake was accompanied by "a loud noise like thunder" (The Virginia Gazette, 1774). Aside from causing a general panic, the 1774 earthquake reportedly resulted in serious structural damage closer to the probable epicenter. In the towns of both Petersburg and nearby Blandford, houses were physically dislodged from their foundations (The Virginia Gazette, 1774). Store bells as far away as Winston-Salem, North Carolina chimed (MacCarthy, 1957; Stover and Coffman, 1993). It is estimated that people within 130,000 square kilometers of the 1774 earthquake reported feeling the event (Hopper and Bollinger, 1971) (Figure 13). Aftershocks were reported in Charlottesville on February 22 (MacCarthy, 1964) and in Williamsburg on February 23 (The Virginia Gazette, 1774).

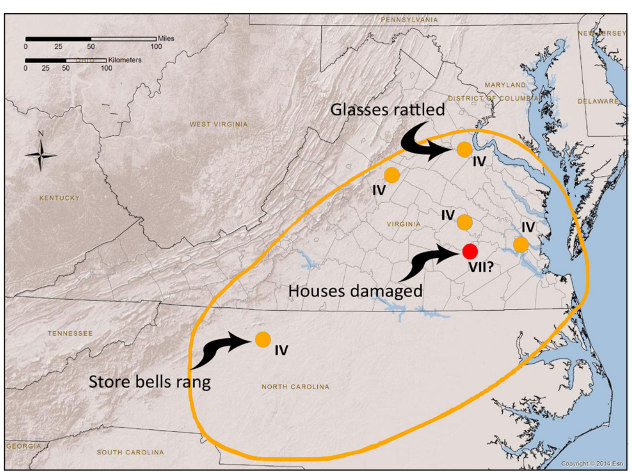


Figure 13. Generalized felt area with intensities for the February 21, 1774 earthquake. Modified from Hopper and Bollinger (1971).

March 9th 1828
(estimated magnitude Mb 5.0)

A significant earthquake occurred on March 9th of 1828. This event was felt across a broad area of more than 500,000 square kilometers (Bollinger, 1969), startling residents from Pennsylvania to Ohio and Kentucky, and south into South Carolina (MacCarthy 1963, 1964; Figure 14). In Washington, D.C., president John Quincy Adams recorded his experience as being similar to "…the heaving of a ship at sea" (Adams, 1875 via MacCarthy, 1964). The shock was apparently also accompanied by a loud rumbling "not unlike that produced by the rapid passage of many carriages over a pavement" (The Susquehanna Democrat, 1828). Although reports of rattling dishes, windows, and doors were common within the felt area, the maximum MMI was not greater than V (MacCarthy, 1964). The epicenter is believed to have been in southwestern Virginia (MacCarthy, 1964).

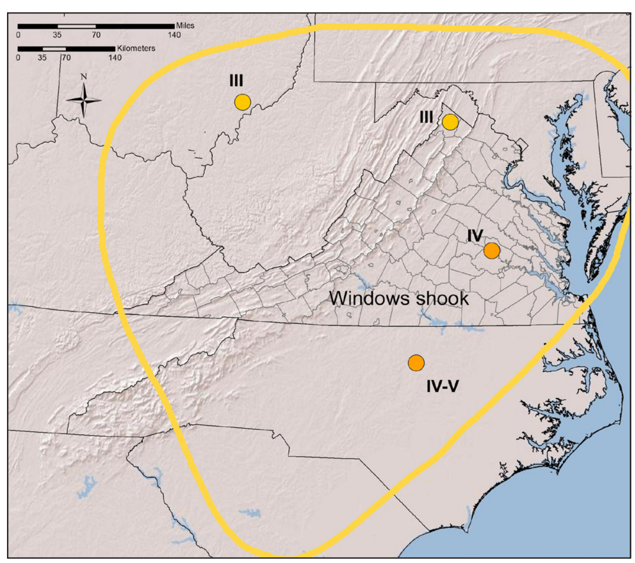


Figure 14. Generalized felt area with intensities for the March 9, 1828 earthquake. Modified from Hopper and Bollinger (1971).

August 27th 1833
(estimated magnitude Mb 5.0)

A maximum MMI VI event was felt on August 27th, 1833, in the Richmond and Charlottesville area, but also as far south as Raleigh, North Carolina and north to Baltimore, Maryland. This event was reportedly accompanied by a loud rumbling sound. Two coal miners were killed on the job due to the panic caused by the earthquake (MacCarthy, 1957). Individuals witnessed the shaking of fences near Louisa, and of buildings and windows in Lynchburg (Stover and Coffman, 1993), although no damage was reported (MacCarthy, 1964). The felt area of this earthquake was approximately 150,000 square kilometers (Hopper and Bollinger, 1971).

April 29th 1852
(estimated magnitude mbLg 4.9)

A damaging earthquake occurred on April 29th 1852. With a felt area of 490,000 square kilometers (Figure 15; MacCarthy, 1964), this event was felt as two separate shocks in Washington, D.C. It was also felt in the towns of Lynchburg and Staunton at 12:45 p.m., and throughout parts of Maryland, North Carolina, Ohio, Pennsylvania, and Tennessee (MacCarthy, 1964). With a maximum MMI of VI, this mbLg 4.9 event damaged brick chimneys in the possible epicentral town of Wytheville, in areas south of Charlottesville, and also in Davie County, North Carolina. The city of Staunton was also violently shaken (Stover and Coffman, 1993).

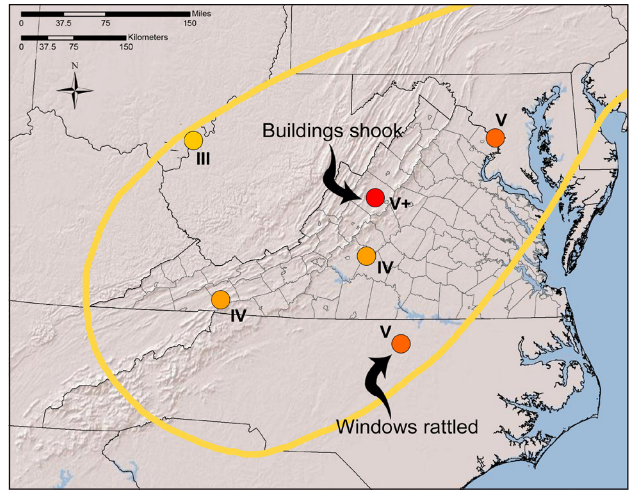


Figure 15. Generalized felt area with intensities for the April 29, 1852 earthquake. Modified from Hopper and Bollinger (1971).

May 2nd 1853
(estimated magnitude Mb 4.6)

Felt as far away as Ohio, the earthquake of May 2nd, 1853, may have been a double event (MacCarthy, 1964). With a possible epicentral area west of the Central Virginia Seismic Zone, the shaking caused by this event frightened Bedford County students out of their classrooms in the town of Liberty (Richmond Semi-weekly Examiner in MacCarthy, 1964). Although the event caused no reported damage, it was felt over an area of up to 190,000 square kilometers and had a maximum MMI of VI (Stover and Coffman, 1993; MacCarthy, 1964).

December 22nd 1875
(estimated magnitude mbLg 4.5)

An earthquake on December 22, 1875 was the most damaging seismic event within the CVSZ prior to the August 23, 2011 earthquake. This earthquake was felt over 130,000 square kilometers from Baltimore to Greensboro, North Carolina, and from West Virginia to the coast of Virginia (Figure 16; Bollinger and Sibol, 1985). With a magnitude of mbLg 4.5, the epicenter of this event was most likely near the town of Arvonia, approximately 50 miles northwest of Richmond, where a maximum MMI of VII is determined based on the degree of damage (Eppley, 1965). In Richmond, people were awakened at approximately 11:45 p.m. and ran out into the streets as their crockery and china fell, windows rattled, and furniture jumped (New York Times, 1875). The greatest damage seemed to be concentrated along the James River, especially in Richmond where chimney bricks fell and windows broke (Oaks and Bollinger, 1986; Stover and Coffman, 1993).

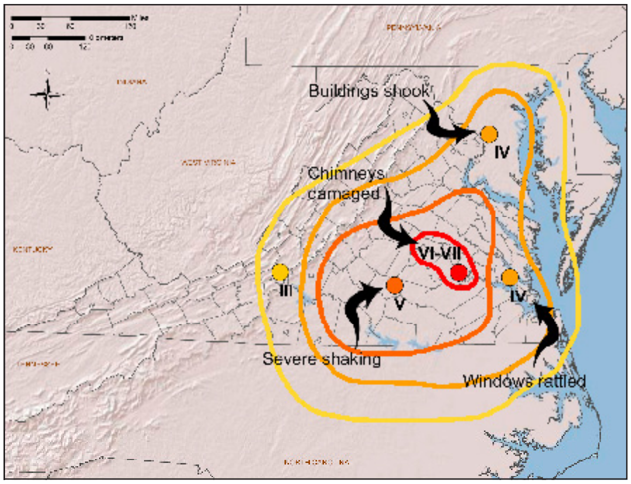


Figure 16. Generalized felt area with intensities for the December 22, 1875 earthquake. Modified from Hopper and Bollinger (1971).

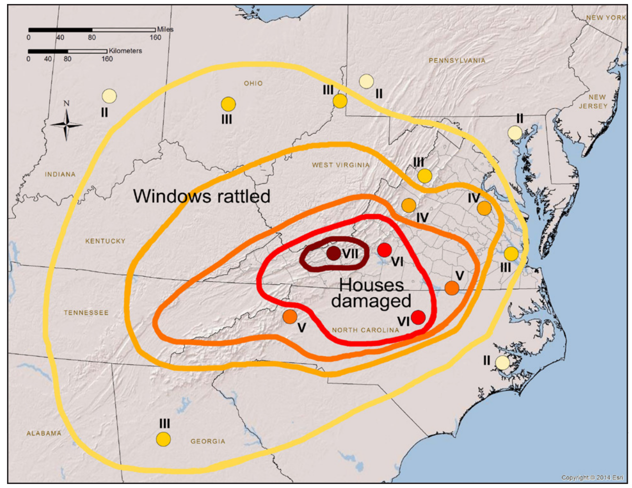


Figure 17. Generalized felt area with intensities for the May 31, 1897 earthquake. Modified from Hopper and Bollinger (1971) and from Hough (2012).

May 31st 1897
(estimated magnitude Mw 5.5)

One of Virginia's largest earthquakes occurred in Giles County on May 31, 1897. Newspaper reports suggest that this event was felt over an area of 780,000 square kilometers from Georgia to Pennsylvania, and as far west as Indiana (Figure 17; Bollinger and Stover, 1978). This Mw 5.5 magnitude event caused the greatest damage in the towns of Narrows and Pearisburg, which were closest to the epicenter. Brick homes and chimneys were damaged (cracked, shifted, or toppled) in a wide area around the epicenter from Knoxville, Tennessee and Bluefield, West Virginia to Raleigh, North Carolina (Coffman and von Hake, 1982). Springs are reported to have been disturbed and landslides triggered (Campbell, 1898).

On May 3, 1897 a MMI VII foreshock caused plaster and chimney damage in the towns of Radford, Pulaski, and Roanoke, and was felt in several North Carolina towns (Heck, 1928; Coffman and von Hake, 1982). The 1897 main shock was also followed by a series of aftershocks that lasted throughout the remainder of the year (Campbell, 1898). On June 28, an aftershock was felt from Lexington to Wytheville, causing a general disturbance and rattling kitchenware and windows in Roanoke (Hopper and Bollinger, 1971). Another pronounced aftershock occurred in Pearisburg on September 3, and a third in Wytheville on October 20 (Hopper and Bollinger, 1971). Although none of these aftershocks caused significant damage, they were described in local newspapers as "distinct."

February 13th 1899
(estimated magnitude Mb 4.7)

On February 13, 1899, residents from Lynchburg to Wytheville were awakened at 4:30 a.m. as furniture "jumped" and buildings shook (MacCarthy, 1964; Coffman and von Hake, 1982). This southwestern Virginia earthquake was felt across at least 80,000 square kilometers (Figure 18; Hopper and Bollinger, 1971). A maximum MMI of V was recorded in the epicentral area near Wytheville (MacCarthy, 1964). Possibly a compound event, reports suggest as many as four separate shocks were felt, two shocks noted in Salem, and three in Danville (MacCarthy, 1964). This earthquake was felt as far west as Chillicothe, Ohio, as a slight vibratory shock. The earthquake awakened people and caused confusion in Christiansburg (Hopper and Bollinger 1971), moved furniture in Lynchburg, was accompanied by a 'heavy rumbling noise" in Floyd (Hopper and Bollinger 1971), and awakened many in Wytheville, Danville, Dublin, East Radford, Lynchburg, and Pulaski (MacCarthy, 1964; Coffman and von Hake, 1982). Although this event is described as a 'shock of considerable violence', no real damage was reported.

April 9th 1918
(estimated magnitude Ml 4.6)

On April 9, 1918, residents in central Virginia were surprised by a 4.9 Ml magnitude earthquake that broke windows and cracked plaster across the Shenandoah Valley (MacCarthy, 1964). Damage was confined to the epicentral area of this earthquake (near the town of Luray; Figure 19), where the MMI is estimated to be VI based on ceilings that cracked "badly" (MacCarthy, 1964). The felt area of this event was at least 180,000 square kilometers, and included reports from residents as far away as Pennsylvania (Hopper and Bollinger, 1971). Three shocks were reported in Richmond and Culpeper, and two in the Shenandoah Valley. This event was also captured by several of the earliest eastern seismometers, including instruments at Georgetown University in Washington, D.C., Cornell University in Ithaca, NY, and Harvard University in Cambridge, MA (The Washington Times, 1918; Figure 20). Several aftershocks were reported (MacCarthy, 1964).

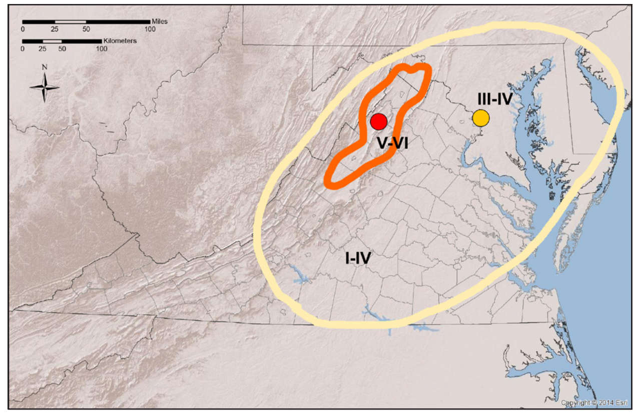


Figure 19. Generalized felt area with intensities for the April 9, 1918 earthquake. Modified from Bollinger (1973).

MODERN EARTHQUAKES

Since 1963, networks of seismometers have been installed across the eastern United States to detect earthquakes. Such highly sensitive seismic networks help scientists accurately pinpoint earthquake epicenters and measure magnitudes for even the lowest magnitude events (Figure 12). In 1963, the first seismic station in Virginia went online (Virginia Tech Seismological Observatory, 2017). By 1978, a seismic network of nine stations was assembled across central Virginia and recorded events until 1996 (Bollinger and Sibol, 1985). Since 1996, additional seismome-

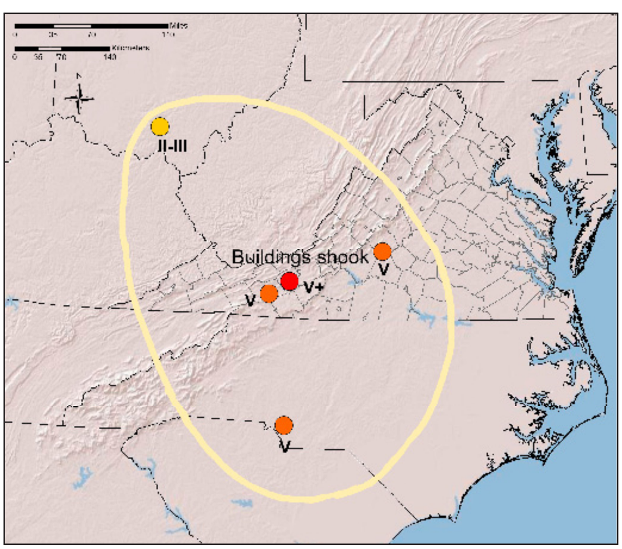
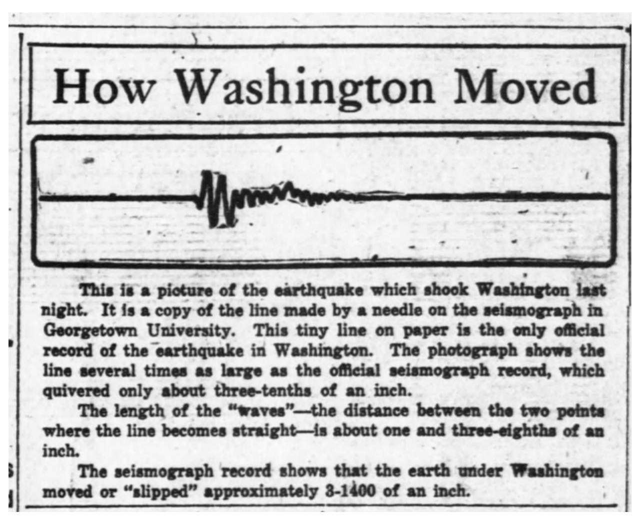


Figure 18. Generalized felt area with intensities for the February 13, 1899 earthquake. Modified from Hopper and Bollinger (1971).



How Washington Moved

This is a picture of the earthquake which shook Washington last night. It is a copy of the line made by a needle on the seismograph in Georgetown University. This tiny line on paper is the only official record of the earthquake in Washington. The photograph shows the line several times as large as the official seismograph record, which quivered only about three-tenths of an inch.

The length of the "waves"—the distance between the two points where the line becomes straight—is about one and three-eighths of an inch.

The seismograph record shows that the earth under Washington moved or "slipped" approximately 3-1400 of an inch.

Figure 20. An early seismograph from Georgetown University, which recorded the April 9, 1918 earthquake of Luray, Virginia (The Washington Times, 1918).

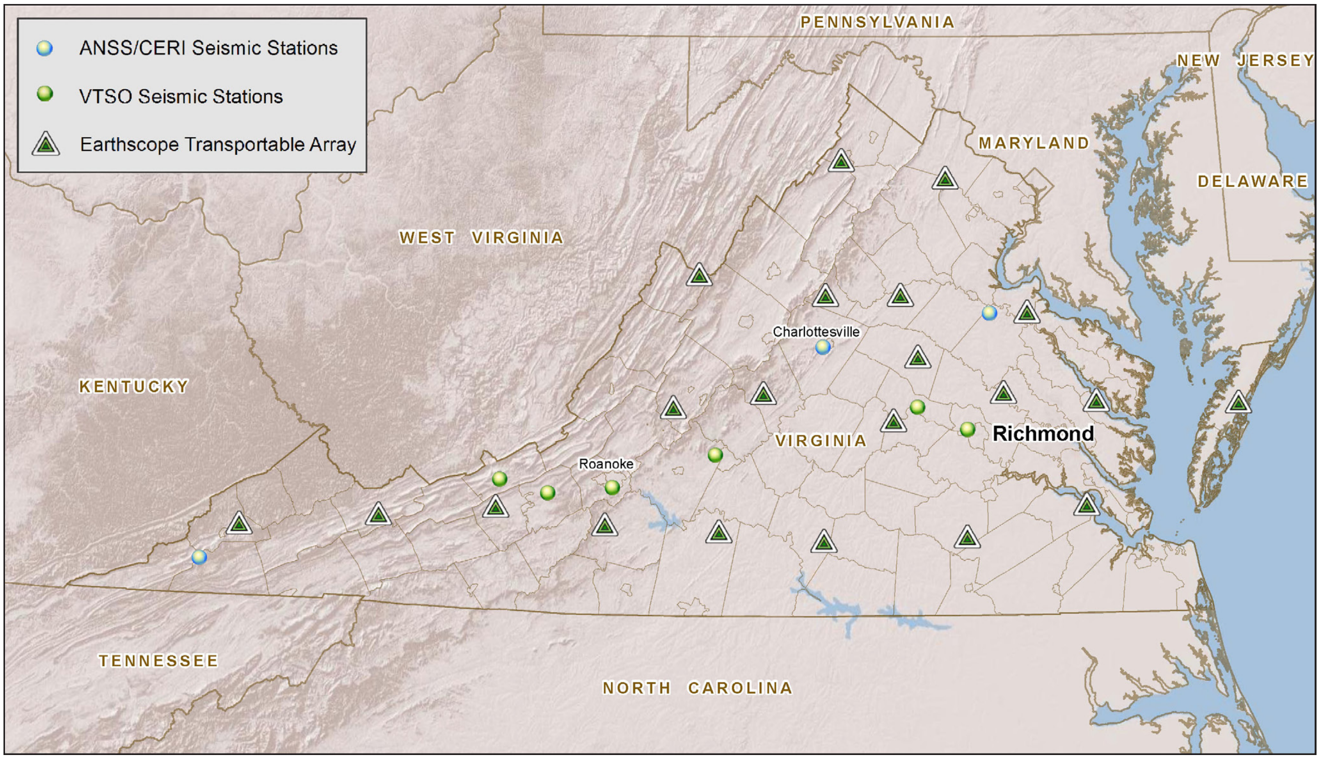


Figure 21. Virginia's seismic monitoring network.

ters have been set up to record data, including the most recent National Science Foundation funded EarthScope transportable array. EarthScope has moved 400 monitoring stations eastward across the United States since 2004 in order to obtain additional seismic insights about North America (Witze, 2013). Upon reaching Virginia in 2012, approximately twenty transportable stations were temporarily installed until 2013. Five legacy stations were left behind to continue collecting data. At present, approximately 30 seismometers are recording seismic data throughout the state of Virginia (Figure 21).

December 9th 2003 (magnitude 4.5 mbLg)

Seismometers recorded a significant event on the afternoon of December 9th, 2003. The earthquake epicenter was located near the community of Fife, about 60 kilometers west of Richmond, with a focal depth of 10 kilometers (U.S. Geological Survey, 2003a; Kim and Chapman, 2005). The earthquake had a maximum MMI of VI, and was felt strongly over most of Virginia. Although no structural damage occurred during the event, the U.S. Geological Survey (2003a) reported that the trembling was widely felt in parts of North Carolina, Maryland, Pennsylvania, and

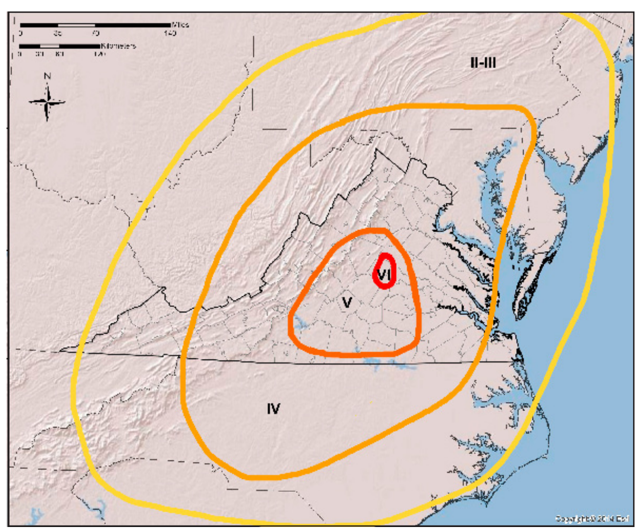


Figure 22. Generalized felt area with intensities for the December 9, 2003 earthquake. Based on USGS "Did you feel it" data (http://earthquake.usgs.gov/data/dyfi/).

West Virginia (Figure 22). Shaking was such that state government buildings were evacuated and inspected for damage. It had been preceded on May 5, 2003 by a 3.6 event whose epicenter was just a few kilometers away (U.S. Geological Survey, 2003b).

Seismometers confirmed that this earthquake consisted of two 4.5 magnitude shocks occurring approximately twelve seconds apart in time and 300 meters apart in space. Both shocks may have occurred on the same fault plane (Kim and Chapman, 2005). This earthquake is spatially associated with the Lakeside Fault, a prominent older ductile fault that was reactivated as part of an ancient fault-bounded basin formed by the rifting of Pangaea and opening of the Atlantic Ocean (Spears, 2011).

August 23rd 2011 (magnitude Mw 5.8)

On August 23rd 2011, the most damaging earthquake ever felt in Virginia was recorded. Approximately 150,000 individuals reported feeling the earthquake through the U.S. Geological Survey Earthquake Hazard Program, "Did You Feel It?" website (https://earthquake.usgs.gov/data/dyfi/). The earthquake was felt over the entire eastern

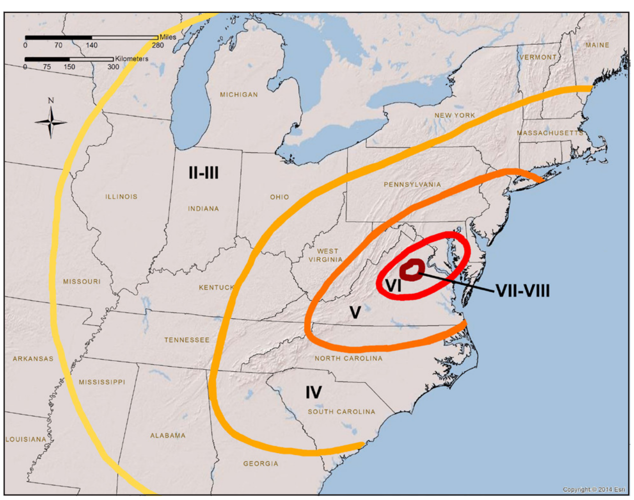


Figure 23. Generalized felt area with intensities for the August 23, 2011 earthquake. Based on Hough, 2012 and USGS "did you feel it" data (http://earthquake.usgs.gov/data/dyfi/).

United States and into Canada, potentially making it the earthquake felt by more people than any other in United States history (Figure 23; Horton and Williams, 2012).

The Mw 5.8 earthquake (6.4 mbLg) shocked residents of Central Virginia. Chapman (2013 and 2015) determined that this was a complex earthquake comprised of three subevents (distinct faulting episodes). The faulting initiated at 8 kilometers depth and progressed to the northeast and to shallower depth. Most of the slip on the fault occurred at approximately 7 kilometers.

The northeastward progression of rupture may account for the fact that ground motions were much stronger to the northeast, toward the Washington, D.C. area, as compared to shaking experienced in other directions from the epicenter. Some homes in the epicentral were shifted off of their foundations, had chimneys that toppled, and sustained damage to exterior and interior walls and framing (Figure 24).

Total damages resulting from the 2011 earthquake reached at least $300 million (Martin and others, 2011). Eight counties in Central Virginia were included in the federally-declared disaster area; Louisa County alone received almost 1,500 damage reports from residents (Heller and Carter, 2015). The entire Louisa County school system closed down for weeks following the earthquake, and two schools were considered damaged beyond repair (Heller and Carter, 2015).

Only 11 miles from the epicenter, the North Anna Nuclear Generating Station experienced an automatic shutdown, the first safe automatic shutdown of a nuclear power plant in United States history (Fenster and Walsh, 2011). Although ground motion from the earthquake exceeded plant seismic design levels, the station experienced only minor structural damage and no critical structures were affected (Li and others, 2015).

The earthquake damaged two small dams, contributed to the failure of a water main in the town

Figure 24. Property damage near the 2011 Mineral earthquake epicenter (left) and the steeple of the National Cathedral in Washington, D.C. that was displaced (right). Photos by Francis Ashland, U.S. Geological Survey.

of Mineral, and left 3,000 people without power (Green and others, 2015). While the greatest damage occurred in Central Virginia, damage was reported in Northern Virginia, Maryland, and Washington, D.C. Monitoring of water wells revealed a disturbance in groundwater levels as far as 350 miles away (Horton and Williams, 2012; Roeloffs and others, 2015). In Washington, D.C., several of the Smithsonian Museum of Natural History's specimen jars fell to the floor, the Washington Monument developed several cracks, and the National Cathedral was significantly damaged (Figure 24; Wells and others, 2015).

Following the main shock, temporary seismic networks recorded a series of over 500 aftershocks with a magnitude greater than Mw 1.0 (Fenster and Walsh, 2011; Horton and others, 2015a). The aftershock sequence of the Mineral earthquake was the best recorded to date in eastern North America and helped to reveal the location of a previously undiscovered fault, suggesting that there are other potentially active faults within the area (Horton and others, 2015b).

Not only did the 2011 earthquake cause structural damage, but it also left its mark in the geologic record. Soft sediment deformation such as sand boils and sand dikes were identified within the epicentral area following the earthquake (Figure 25; Green and others, 2015). Although the surface evidence of these features was quickly washed away by Hurricane Irene a few days later, geologists continue to search for related subsurface deformation.

Figure 25. Sand boils near the 2011 Earthquake epicenter. Photo by Mark Carter, U.S. Geological Survey.

CONNECTING FAULTS AND EARTHQUAKES

Most of the mapped faults in Virginia are millions of years old. The movement that created these faults was related to stresses that existed when Virginia was much closer to active tectonic plate boundaries. The relationship between these faults and modern earthquakes is uncertain, as no historic earthquakes in Virginia have been directly tied to a fault mapped at the surface. Within the ETSZ and GCSZ, research to date suggests that deeper faults below a major decollement and within older basement rocks are responsible for observed seismicity (Johnston and others, 1985; Bollinger and others, 1991; Powell and others, 1994; Kim and Chapman, 2005). It is unclear if any of these faults extend upward into the overlying sedimentary bedrock that is exposed at the surface. Within the CVSZ, historic earthquakes do not correlate with faults mapped at the Earth's surface and are not aligned with the regional bedrock structural trend. Bollinger and Sibol (1985) and Coruh and others (1988) did suggest a correlation between some historic earthquake hypocenters and a deep gently west-dipping discontinuity interpreted to be a major decollement on a seismic profile along I-64. However, this discontinuity does not appear to intersect the surface. An analysis of the same profile did not identify any faults or discontinuities along strike with the August 23, 2011 Mineral, Virginia, earthquake or its aftershocks (Pratt and others, 2015).

Although there does not appear to be strong evidence to connect historic earthquakes to faults mapped at the surface, it is reasonable to expect that many existing faults are zones of relative weakness in the earth's crust. Thus, they may be preferential places for movement to occur if they are favorably oriented relative to regional stresses. Bedding and foliation planes, joint surfaces, and geologic contacts between rocks of different competence may also behave in a similar way. It should be noted that within and near the CVSZ, many faults resulted from ductile deformation, sometimes associated with silicification or the intrusion of igneous magma. As a result, the bedrock within these fault zones may be more competent than the surrounding country rock.

The presence of a regional seismic monitoring network may improve our ability to assign modern events to specific geologic faults. Detailed aftershock sequences can be recorded and may help delineate the fault that produced the main shock. For example, many of the aftershocks of the 2011 Mineral earthquake lie in a northeast striking, southeast dipping tabular zone. This aftershock cluster was initially interpreted to define a previously unmapped fault zone, the Quail Fault (Horton and others, 2015b). Later work, using a much larger set of hypocenter locations and focal mechanisms, indicates that most of the aftershocks in the tabular zone are actually occurring on minor faults with strikes and dips different from the overall trend of the proposed Quail Fault (Wu and others, 2015). The actual zone of fault rupture in the Mineral earthquake is revealed to be a gap in the aftershock cluster that extends from 8 kilometers upward to 6 kilometers in depth, with the aftershocks forming a semi-circular halo above the rupture zone. The spatial orientation of the shallower aftershocks probably represents the geometry of the stress field perturbation induced by the mainshock, rather than a single, coherent fault zone (Wu and others, 2015). Only future data collection and research can further address this important issue.

CONCLUSIONS

Earthquakes are a significant geologic hazard in the United States. Although much research has focused on the active tectonic setting of the western United States, seismicity in the eastern United States is not as well understood. Although severe earthquakes are relatively infrequent, they have occasionally surprised Virginia residents with their destructive power. The 2011 event in central Virginia was a reminder of that potential. As Virginia's population and infrastructure continue to grow, so too will seismic-related risk. Studying Virginia's seismic history and encouraging the development of real-time monitoring of modern earthquakes through a permanent and growing eastern seismic network will help scientists better understand regional seismicity. Such information will enable planning district commissions to improve Hazard Mitigation Plans and increase education and preparedness for future seismicity in the Commonwealth.

ACKNOWLEDGEMENTS

Marques Hatfield and William Swanger assisted in compiling historic earthquake and epicenter information. Michael Smith and David Spears reviewed the manuscript and provided helpful suggestions that improved the final product.

REFERENCES CITED

Bear, J.A., Jr., and Stanton, L.C., eds., 1997, Jefferson's Memorandum Books: Accounts, with Legal Records and Miscellany, 1767-1826: Princeton University Press, 1624 p.

Biryol, C.B., Wagner, L.S., Fischer, K.M., and Hawman, R.B., 2016, Relationship between observed upper mantle structures and recent tectonic activity across the Southeastern United States: Journal of Geophysical Research: Solid Earth, v. 121, p. 3393–3414.

Bollinger, G.A., 1969, Seismicity of the central Appalachian states of Virginia, West Virginia, and Maryland – 1758 through 1968: Bulletin of the Seismological Society of America, v. 59, p. 2103–2111.

Bollinger, G.A., 1973, Seismicity of the southeastern United States: Bulletin of the Seismological Society of America, v. 63, p. 1786–1808.

Bollinger, G.A. and Costain, J.K., 1988, Long-term cyclicities in earthquake energy release and major river flow volumes in Virginia and Missouri seismic zones: Seismological Research Letters, v. 59, no. 4, p. 279–283.

Bollinger, G.A. and Sibol, M.S., 1985, Seismicity, seismic reflection studies, gravity and geology of the central Virginia seismic zone: Part I. Seismicity: Geological Society of America Bulletin, v. 96, p. 49–57.

Bollinger, G.A., and Stover, C.W., 1978, List of intensities, epicentral distances, and azimuths for the 1897 Giles County, Virginia, earthquake and the 1969 Elgood, West Virginia, earthquake: U.S. Geological Survey Open-File Report 78-1017.

Bollinger, G.A. and Wheeler, R.L., 1988, The Giles County, Virginia, Seismic Zone – seismological results and geological interpretations: U.S. Geological Survey Professional Paper 1355.

Bollinger, G.A., Chapman, M.C., Sibol, M.S., and Costain, J.K., 1985. An analysis of earthquake focal depths in the southeastern U.S., Geophysical Research Letters, 12, 785-788.

Bollinger, G.A., Johnston, A.C., Talwani, P., Long, L.T., Shedlock, K.M., Sibol, M.S., and Chapman, M.C. 1991. Seismicity of the southeastern United States; 1698 to 1986, in Neotectonics of North America, D. B. Slemmons, E.R. Engdahl, M.D. Zoback, and D.D. Blackwell (Editors), Geological Society of America, 291-308.

Bollinger, G.A., Snoke, J.A., Chapman, M.C. and Sibol, M.S., 1989, Estimates of the occurrence and resulting effects of damaging earthquakes in Virginia: Virginia Minerals, v. 35, no. 3, p. 17-23.

Campbell, M.R., 1898. Earthquake shocks in Giles County, Virginia: Science, v. 7, no. 164, p. 233–235.

Cancani, A., 1904, Sur l'emploi d'une double echelle sismique des intensitès, empirique et absolue: Gerlands Beitr. Geophys., v.2, p. 281–283.

Carnes, L., Pazzaglia, F.J., and Kodama, K., 2016, River sinuosity response to central and eastern US (CEUS) intraplate seismicity with a focus in the central Virginia and Charleston seismic zones: Geological Society of America Abstracts with Programs, v. 48, no. 7.

Chapman, M.C., Powell, C.A., Vlahovic, G., and Sibol, M.S., 1997, A statistical analysis of focal mechanisms and epicenter locations in the Eastern Tennessee Seismic Zone: Bulletin of the Seismological Society of America, v. 87, no. 6, p. 1522–1536.

Chapman, M.C. 2013, On the rupture process of the 23 August 2011 Virginia earthquake, Bulletin of the Seismological Society of America, vol. 103, no. 2A, p. 613-628.

Chapman, M.C. (2015) Magnitude, recurrence interval, and near-source ground-motion modeling of the Mineral, Virginia, earthquake of 23 August, 2011, Geological Society of America Special Papers, 2015, vol. 509, p. 27-45, doi: 10.1130/2015.2509(02)

Coffman, J.L. and von Hake, C.A, 1982, Earthquake history of the United States: U.S. Department of Commerce, NOAA and U.S. Geological Survey, Publication 41-1.

Coruh, C., Bollinger, G.A., and Costain, J.K., 1988, Seismogenic structures in the Central Virginia Seismic Zone: Geology, v. 16, p. 748–751.

Costain, J.K., 2015, Finite element simulation of an intraplate earthquake setting – implications for the Virginia earthquake of 23 August 2011: in Horton, J.W., Jr., Chapman, M.C., and Green, R.A. eds., The 2011 Mineral, Virginia, Earthquake, and its significance for seismic hazards in eastern North America: Geological Society of America Special Paper 50, p. 137–150.

Dunn, M.M. and Chapman, M.C., 2006, Fault Orientation in the Eastern Tennessee Seismic Zone: A study using the double-difference earthquake location algorithm: Seismological Research Letters, v. 77, p. 494–504.

EBASCO, 1993. Studies of speleothem deposits in the Giles County, Virginia, seismic zone, progress report for April and May, 1993: Unpublished report to Nuclear Regulatory Commission, Contract Number NRC–04–90–099, 79 p.

Eppley, R.A., 1965, Earthquake history of the United States, Part I: stronger earthquakes of the United States: U.S. Coast and Geodetic Survey, Washington, D.C., 120 p.

Fenster, D.F. and Walsh, L.S., 2011, Preliminary information on the Mw 5.8 Mineral, Virginia, earth¬quake: AEG News, v. 54, no.4, p. 26–30.

Gangopadhyay, A. and Talwani, P., 2003, Symptomatic features of intraplate earthquakes: Seismological Research Letters, v. 74, no. 6, p. 863–883.

Green, R.A., Lasley, S., Carter, M.W., Munsey, J.W., Maurer, B.W., and Tuttle, M.P., 2015, Geotechnical aspects in the epicentral region of the 2011 Mw5.8 Mineral, Virginia, earthquake: Geological Society of America Special Paper 509, p. 151–172.

Hatcher, R.D., Jr., Vaughn, J.D., and Obermeier, S.F., 2012, Large earthquake paleoseismology in the east Tennessee seismic zone: results of an 18-month pilot study: in Cox, R.T, Tuttle, M.P., Boyd, O.S., and Locat, J., eds, Recent advances in North American Paleoseismology and neotectonics east of the Rockies: Geological Society of America Special Paper 493, p. 111–142.

Heck, N. H., 1928, Earthquake history of the United States: Department of Commerce, U.S. Coast and Geodetic Survey Special Publication No. 149.

Heller, M.J. and Carter, A.M., 2015, Residential property damage in the epicentral area of the Mineral, Virginia, earthquake of 23 August 2011: Geological Society of America Special Paper 509, p. 173–187.

Hopper, M.G. and Bollinger, G.A., 1971, The earthquake history of Virginia, 1774 to 1900: Virginia Polytechnic Institute and State University, Blacksburg, Virginia.

Horton, J.W., Jr., and Williams, R.A., 2012, The 2011 Virginia earthquake: What are scientists learning?: EOS, v. 93, no. 33, p. 317–318.

Horton, J.W., Jr., Chapman, M.C., and Green, R.A., 2015a, The 2011 Mineral, Virginia, earthquake, and its significance for seismic hazards in Eastern North America - an overview and synthesis: Geological Society of America Special Paper 509, p. 1–25.

Horton J.W., Jr., Shah, A.E., McNamara, A.K., Snyder, D.E., and Carter, S.L.., 2015b, Aftershocks illuminate the 2011 Mineral, Virginia, earthquake causative fault zone and nearby active faults: Geological Society of America Special Paper 509, p. 253–271.

Hough, S.E., 2012, Initial assessment of the intensity distribution of the 2011 MW 5.8 Mineral, Virginia earthquake: Seismological Research Letters, v. 83, no. 4, p. 649–57.

Johnston, A.C., Reinbold, D.J., and Brewer, S.I., 1985, Seismotectonics of the Southern Appalachians: Bulletin of the Seismological Society of America, v. 75, n. 1, p. 291–312.

Kim, W.Y. and Chapman, M., 2005, The 9 December 2003 central Virginia earthquake sequence: A compound earthquake in the Central Virginia Seismic Zone: Bulletin of the Seismological Society of America, v. 95, no. 6, p. 2428–2445.

Li, Y., Stirewalt, G.L., and Monoly, K.A., 2015, Overview of performance of the North Anna Nuclear Power Station during the 2011 Mineral, Virginia, earthquake and continued seismic evaluations: Geological Society of America Special Paper 509, p. 189–198.

L'Isle, Guillaume de, 1718, Carte de la Louisiana et du cours du Mississippi: Paris.

MacCarthy, G.R., 1957, An annotated list of North Carolina earthquakes: Journal of the Elisha Mitchell Scientific Society, v. 73, p. 84–100.

MacCarthy, G.R., 1963, Three forgotten earthquakes: Bulletin of the Seismological Society of America, v. 53, p. 687-692.

MacCarthy, G.R., 1964, A descriptive list of Virginia earthquakes through 1960: Journal of the Elisha Mitchell Scientific Society, v. 80, p. 95–114.

McDowell, R.C. and Schultz, A.P., 1990, Structural and stratigraphic framework of the Giles County area, a part of the Appalachian Basin of Virginia and West Virginia: U.S. Geological Survey 1839–E, 24 p.

Martin, J.R., Benson, C., Chapman, M., Eddy, M., Green, R., Kammerer, A., Lasley, S., Lazarte, C., Nikolaou, S., Tanyu, B., and Tuttle, M., 2011, Geotechnical quick report on the affected region of the 23 August 2011 M5.8 central Virginia earthquake near Mineral, Virginia: GEER Association Report No. GEER-026, 123 p.

Mercalli, Giuseppe, 1902, Sulle modificazioni proposte alla scala sismica De Rossi-Forel: Boll. Soc. Sismol. Ital., v. 8, p. 184–191.

Nuttli, O.W., 1973, Seismic wave attenuation and magnitude relations for eastern North America, Journal of Geophysical Research, vol. 78, no. 5, p. 876-885

Nuttli, O.W., Bollinger, G.A., and Griffiths, D.W., 1979. On the relation between Modified Mercalli Intensity and body-wave magnitude, Bulletin of the Seismological Society of America, v. 69, no. 3, pp. 893-909.

The New York Times, "An Unpleasant Visitor," December 25, 1875: New York, NY., p. 4.

Oaks, S.D. and Bollinger, G.A., 1986, The Epicenter of the mb 5, December 22, 1875 Virginia earthquake: New findings from documentary sources: Seismological Research Letters, v. 57, no. 3, p. 65–75.

Obermeier, S.F. and McNulty, W.E., 1998, Paleoliquefaction evidence for seismic quiescence in central Virginia during Late and Middle Holocene Time: EOS, Transactions of the American Geophysical Union, v. 79, no. 17, Spring Meeting Supplement, Abstract T41A–9.

Petersen, M.D., Moschetti, M.P., Powers, P.M., Mueller, C.S., Haller, K.M., Frankel, A.D., Zeng, Y., Rezaeian, S., Harmsen, S.C., Boyd, O.S., Field, N., Chen, R., Rukstales, K.S., Luco, N., Wheeler, R.L., Williams, R.A., and Olsen, A.H., 2014, Documentation for the 2014 update of the United States National Seismic Hazard Maps: U.S. Geological Survey Open-File Report 2014-1091.

Powell, C.A., Bollinger, G.A., Chapman, M.C., Sibol, M.S., Johnston, A.C., and Wheeler, R.L., 1994, A seismotectonic model for the 300-kilometer-long eastern Tennessee seismic zone: Science, v. 264, p. 686–688.

Pratt, T.L., Coruh, C., and Costain, J.K., 1988, A geophysical study of the earth's crust in central Virginia: Implications for Appalachian crustal structure: Journal of Geophysical Research, v. 93, no. B6, p. 6649–6667.

Pratt, T.L., Horton, J.W. Jr., Spears, D.B., Gilmer, A.K., and McNamara, D.E., 2015, The 2011 Virginia Mw 5.8 earthquake: Insights from seismic reflection imaging into the influence of older structures on eastern U.S. seismicity: in Horton, J.W., Jr., Chapman, M.C., and Green, R.A. eds., The 2011 Mineral, Virginia, earthquake, and its significance for seismic hazards in eastern North America: Geological Society of America Special Paper 50, p. 285–294.

Richter, C.F., 1935, An instrumental earthquake magnitude scale: Bulletin of the Seismological Society of America, v. 25, n. 1-2, p. 1–32.

Roeloffs, E.A., Nelms D.L., and Sheets R.A., 2015, Widespread groundwater-level offsets caused by the Mw 5.8 Mineral, Virginia, earthquake of 23 August 2011: in Horton, J.W., Jr., Chapman, M.C., and Green, R.A. eds, The 2011 Mineral, Virginia, earthquake, and its significance for seismic hazards in eastern North America: Geological Society of America Special Paper 50, p. 117–136.

Schultz, A.P., and Southworth, C.S., 1989, Large bedrock landslides of the Appalachian Valley and Ridge province of Eastern North America: Geological Society of America Special Paper 236, p. 57-74.

Sieberg, A., 1923, Erdbebenkunde: Gustav Fischer, Jena, 572 p.

Soto-Cordero, L., Meltzer, A.S., and Stachnik, J., 2016, Intraplate seismicity in the Mid-Atlantic U.S.: Geological Society of America Abstracts with Programs, v. 48, n. 7.

Spears, D.B., 2011, Geology of the Lakeside Village quadrangle: Virginia Division of Geology and Mineral Resources Publication 177, 19 p.

Stover, C.W. and Coffman, J.L., 1993, Seismicity of the United States, 1568–1989 (Revised): USGS Professional Paper 1527.

The Susquehanna Democrat, "Earthquake," March 28, 1828: Wilkes-Barre, Pennsylvania, p. 6.

Tuttle, M.P., 2015, Earthquake potential of the central Virginia seismic zone: U.S. Geological Survey External report G13AP00045, 32 p.

U.S. Geological Survey, 2003a, M 4.5 – 16kilometers E of Weber City, Virginia: http://earthquake.usgs.gov/earthquakes/eventpage/se605386#map, Accessed 8 February 2017.

U.S. Geological Survey, 2003b, M 3.6 – 8kilometers SW of Goochland, Virginia: http://earthquake.usgs.gov/earthquakes/eventpage/se605353#executive, Accessed 8 February 2017.

U.S. Geological Survey, 2017a, Blind Thrust Fault: https://earthquake.usgs.gov/learn/animations/blindthrustfault.php, Accessed 8 February 2017.

U.S. Geological Survey, 2017b, Magnitude/intensity comparison: https://earthquake.usgs.gov/learn/topics/mag_vs_int.php, Accessed 25 January 2017.

U.S. Geological Survey, 2017, Earthquake information by region: https://earthquake.usgs.gov/earthquakes/byregion/, Accessed 8 February 2017.

U.S. Geological Survey, Earthquakes Hazard Program, Did You Feel It website, http://earthquake.usgs.gov/data/dyfi/, Accessed 25 January 2017.

The Virginia Gazette, "Extract of a letter from Fredericksburg," February 24, 1774: Williamsburg, Virginia, p. 3.

Virginia General Assembly Legislative Information System, Code of Virginia 15.2-4207 (https://leg1.state.va.us/cgi-bin/legp504.exe?000+cod+15.2-4207)

Virginia Tech Seismological Observatory, 2017, History of VTSO, http://www.magma.geos.vt.edu/vtso/about.html. Accessed 5 February 2017.

Vlahovic, G., Powell, C.A., Chapman, M.C. and Sibol, M., 1998, ET1D: New one dimensional P- and S-wave velocity models for the eastern Tennessee Seismic Zone: Seismological Research Letters, v. 69, n. 5, p. 441-449.

The Washington Times, "How Washington Moved," April 10, 1918: Washington, DC., p. 1.

Witze, A., 2013, US seismic array eyes its final frontier: Nature, v. 503, p.16–17.

Wells, D., Egan, J.A., Murphy, D.G., and Paret, T., 2015, Ground shaking and structural response of the Washington Monument during the 2011 Mineral, Virginia, earthquake: Geological Society of America Special Paper 509, p. 199–233.

Wood, H.O. and Neumann, F., 1931, Modified Mercalli intensity scale of 1931: Bulletin of the Seismological Society of America, Seismological Society of America, v. 21, p. 277–283.

Wu, Qimin, Chapman, M.C., and Beale, J.N., 2015, The aftershock sequence of the 2011 Mineral, Virginia, earthquake: Temporal and spatial distribution, focal mechanisms, regional stress, and the role of Coulomb stress transfer, Bulletin of the Seismological Society of America, v. 105, no. 5, p. 2521-2537.

Zoback, M.L., 1992. Stress field constraints on intraplate seismicity in eastern North America: Journal of Geophysical Research, v. 97, no. B8, p. 11.