GEOTECHNICAL RECONNAISSANCE OF THE DECEMBER 12, 2018 M4.4 DECATUR, TENNESSEE EARTHQUAKE

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Geotechnical Reconnaissance of the December 12, 2018 M4.4 Decatur, Tennessee Earthquake

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We acknowledge and thank Dr. Robert D. Hatcher Jr. of the University of Tennessee for meeting with us, providing reference material for our use in writing the sections on regional seismicity and geology, and reviewing our report.

EXECUTIVE SUMMARY

On December 12, 2018 at 4:14am EST, a moment magnitude (M_w) 4.4 earthquake occurred approximately 12 kilometers North-Northeast of Decatur, Tennessee (TN) (Latitude: 35.612°N Longitude: 84.732°W), which is roughly 240 kilometers southeast of Nashville, TN. Fifty-two instrumentation stations detected the earthquake ground motion as far as 485 kilometers away in Memphis, TN. The closest station (23 kilometers from the epicenter) at the Tennessee Technology Center in Athens, TN recorded a peak ground acceleration (PGA) of .0119g and a peak ground velocity (PGV) of 0.34cm/s. The highest recorded PGA was 0.0215g at the Dayton, TN station which is approximately 36 km from the epicenter. As of December 18, 2018, at least 21 aftershocks followed the December 12, 2018 earthquake.

On December 20, 2018, a Geotechnical Extreme Events Reconnaissance (GEER) investigator visited the area of the epicenter in search of any visible damage. The epicenter and surrounding area are located in a rural setting where the building stock is primarily widely spaced, single-story residences and, in particular, manufactured homes. The firsthand reconnaissance canvassed the accessible areas as best as possible through many of the private residences were posted with "No Trespassing" signs, which prohibited observation on private land. Overall, the GEER team reconnaissance did not encounter any firsthand evidence of earthquake-induced damage.

Several prominent organizations including the Tennessee Valley Authority (TVA), the Oak Ridge National Laboratory (ORNL), the Y-12 National Security Complex and Tennessee Department of Transportation (TDOT) reported that either there was no damage to their facilities or that their operations were unaffected due to earthquake.

INTRODUCTION

The moment magnitude 4.4 (M4.4) Decatur, TN earthquake occurred on December 12, 2018 at 4:14am local time (EST). The earthquake was the strongest earthquake in Tennessee within the last 46 years and sufficient to wake nearby residents. Some of those affected reported hearing "cracking sounds" from the walls during a sensation described as "like a heavy truck striking a building[1]".

The NSF-funded Geotechnical Extreme Events Reconnaissance (GEER) association organized a team under the supervision of Shideh Dashti (University of Colorado, Boulder), J. David Frost (Georgia Institute of Technology), Fangzhou A. Liu (Georgia Institute of Technology), and Jonathan P. Stewart (University of California, Los Angeles). The GEER team consisted of Timothy C. Siegel (Dan Brown and Associates PC), Glenn J. Rix (Geosyntec), Missy Setz (Geosyntec), and Shahram Pezeshk (University of Memphis). Alexia Leib and Mark Madgett, both with Dan Brown and Associates, assisted in the research and preparation of this report. Dr. Robert D. Hatcher Jr. of the University of Tennessee provided invaluable assistance in preparing the sections on regional seismicity and geology.

The main objectives of the GEER team were to identify, observe, and document the perishable data and assess general patterns of damage to better understand earthquake effects. This information is important for improving engineering design, informing planning efforts and reducing society's exposure to seismic risk. Our approach was to observe and document the damage in the vicinity of the earthquake epicenter and collect reports from nearby critical structures such as those owned and/or operated by the TVA, ORNL, Y-12 National Security Complex, and TDOT.

[1] https://www.knoxnews.com/story/weather/2018/12/12/earthquake-east-tennessee-knoxville-area-4-4-magnitude-quake-felt-far-atlanta/2286871002/

SUMMARY OF EARTHQUAKE

On the basis of the instrumentation data obtained from U.S. Geological Survey (USGS), the epicenter, shown on Figure 1, was located at the coordinates 35.612°N 84.732°W.

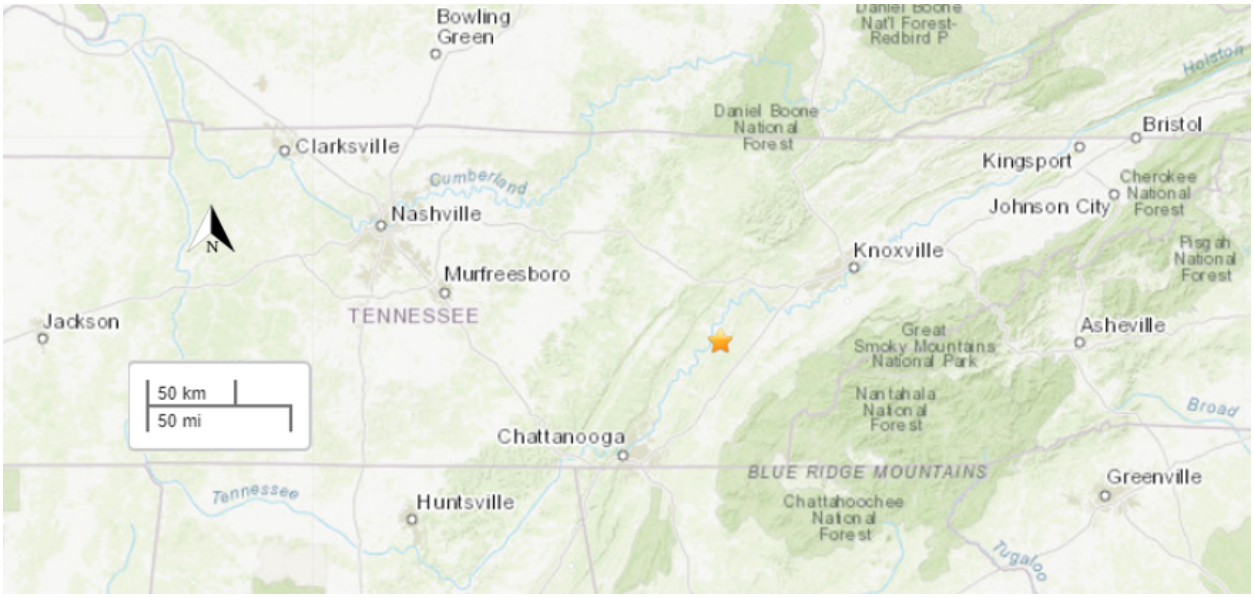

FIGURE 1. DECEMBER 12, 2018 EARTHQUAKE EPICENTER LOCATION.

Numerous reports[2] support that the southeastern United States felt intensity rates ranging from light (MMI IV) to violent shaking (MMI IX). Figure 2[3] shows the how strongly the community surrounding the epicenter reporting feeling the earthquake through the USGS "Did You Feel It?" survey.

[2] https://www.volcanodiscovery.com/earthquakes/quake-info/2197919/M5-Wed-12-Dec--EASTERN-TENNESSEE.html

[3] https://earthquake.usgs.gov/earthquakes/eventpage/se60247871/dyfi/intensity

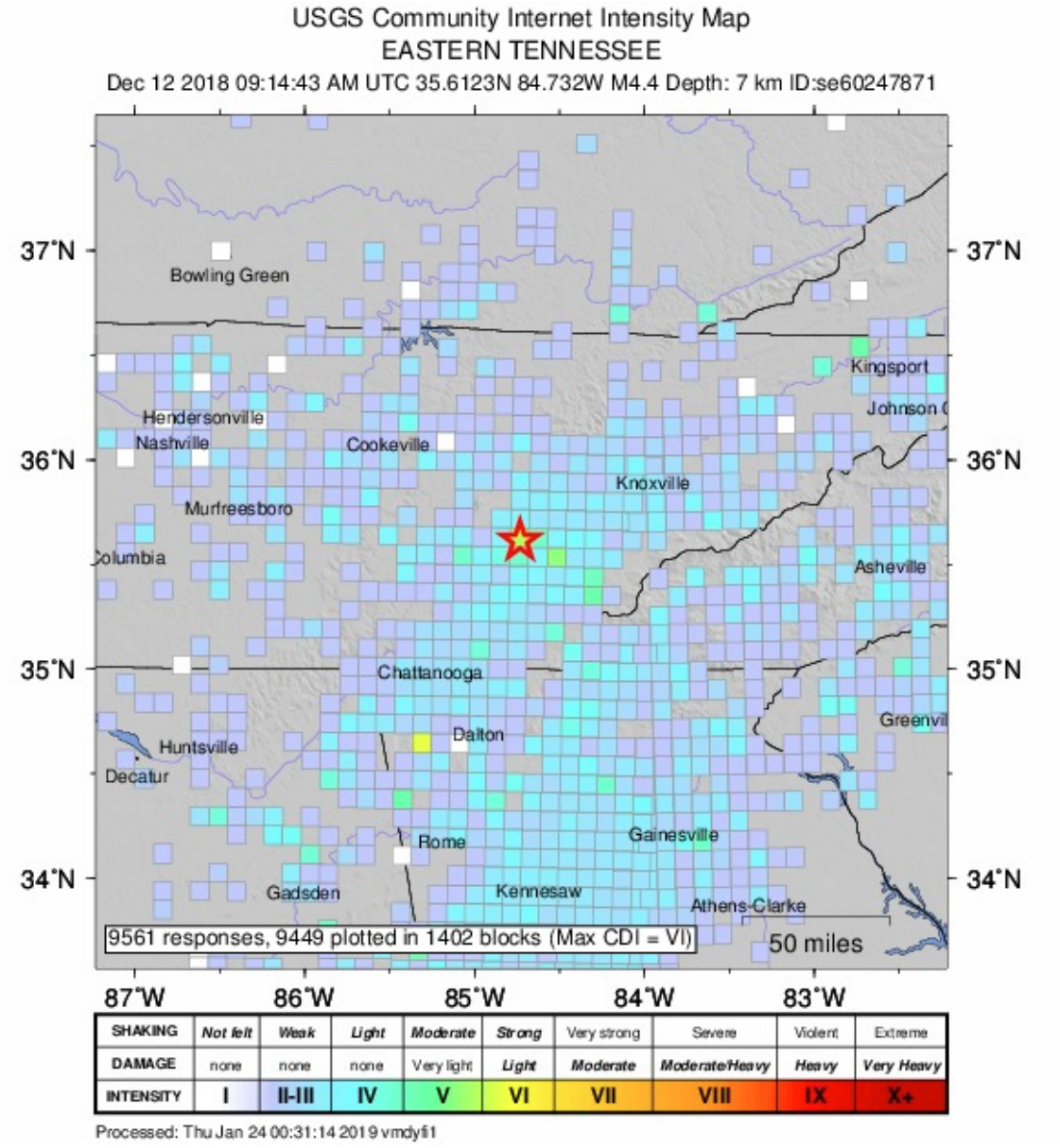

FIGURE 2. USGS COMMUNITY INTERNET INTENSITY MAP.

REGIONAL TECTONICS AND SEISMICITY

The contiguous United States can be seismically split into two divisions by the sources of stress that drive earthquake activity: (1) the Cordillera region, stretching from the eastern Rocky Mountain foothills to the Pacific Ocean, and (2) the central and eastern United States intraplate region, which includes everything east of the Rocky Mountains and western portions of the North Atlantic basin. Seismic activity in the western United States is driven by the interaction between the North American and Juan de Fuca plates. Unlike the western portion of North America, the driving mechanism of plate motion in the central and eastern United States intraplate region is believed to originate from ridge push forces of the North American plate[4]. Tectonic movement is not indicative of earthquake activity as the closest tectonic boundaries with the North American plate are in the Caribbean Sea and the Atlantic Ocean[5]. Intraplate earthquakes like the one that occurred on December 12, 2018 are not well understood because they do not occur on plate boundaries.

Within the central and eastern United States intraplate, three areas are well known to cause earthquakes in the Southeastern United States: the New Madrid seismic zone, the East Tennessee seismic zone, and the Charleston, South Carolina seismic zone as shown in Figure 3[6].

[4] Zoback, M.I., and Zoback, M.D. (1989). Tectonic stress field of the continental United States, in *Pakiser*, W.D. Mooney, Geophysical framework of the continental United States: Boulder, Colorado, Geological Society of America Memoir 172.

[5] https://earthquake.usgs.gov/earthquakes/eventpage/se60247871/executive

[6] https://www.usgs.gov/media/images/2014-usgs-national-seismic-hazard-map-0

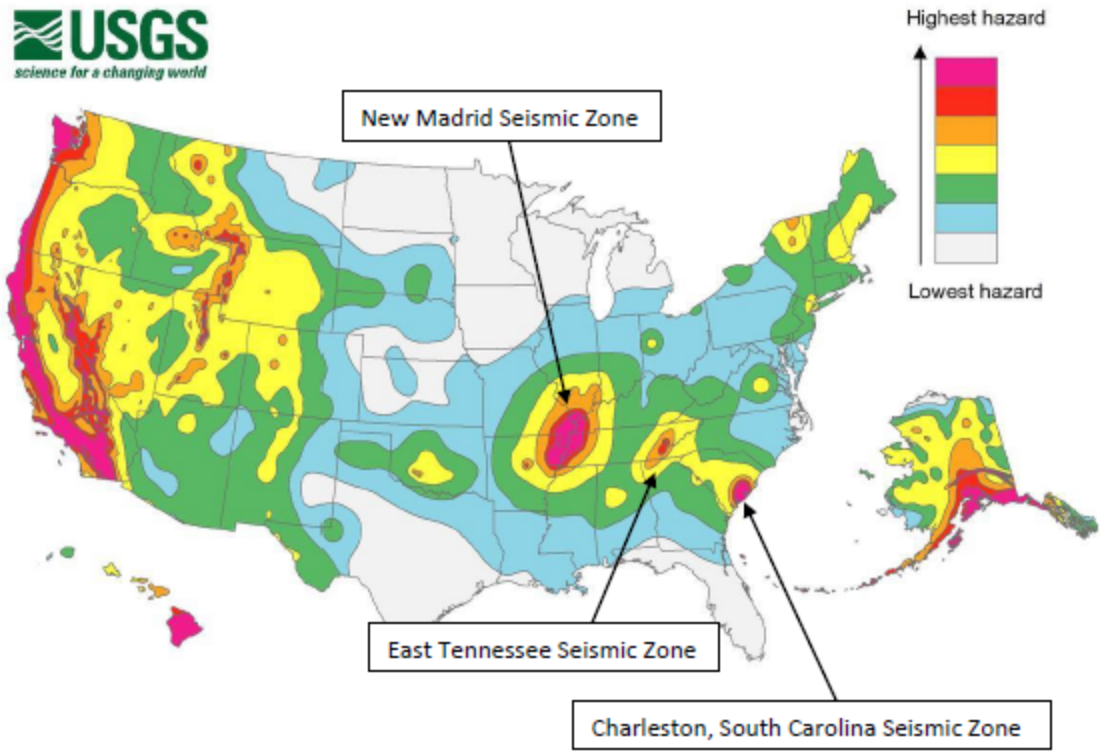

FIGURE 3. SEISMIC HAZARD MAP OF THE UNITED STATES.

The December 12, 2018 M4.4 earthquake occurred in the East Tennessee seismic zone (ETSZ). The ETSZ is the second most active in the eastern US; the New Madrid seismic zone (NMSZ) is first in terms of numbers of earthquakes, with an annual average of 200 earthquakes over M1.5[7]. Though the ETSZ is relatively active, an earthquake originating in this region has never been recorded over M4.8. Recent research has uncovered evidence to suggest that the ETSZ has produced at least three earthquakes greater than M6.5 in the last 10,000 years[8].

Numerous faults occur at the surface geology in the ETSZ but have been inactive for the past several hundred million years. The fold-thrust belt near the December 12, 2018 epicenter has been extensively mapped as seen in Figure 4. Faults that have been created more recently are considered to be coseismic features, meaning they do not cause seismic activity, rather they are the effect of activity that occurs much deeper in the Earth's crust[8].

[7] Williams, R.A., McCallister, N.S., and Dart, R.L. (2011). 20 cool facts about the New Madrid Seismic Zone – commemorating the bicentennial of the New Madrid earthquake sequence, December 1811-February 1812 [poster]: U.S. Geologic Survey General Information Product 134

[8] Warrell, K.F., Cox, R.T., Hatcher R.D. Jr., Vaughn, J.D., and Counts R. (2017). Paleoseismic evidence for multiple Mw ≥6 earthquakes in the eastern Tennessee seismic zone during the late quaternary, *Geol. Soc. Am. Bull.* **107**, 1610-1624

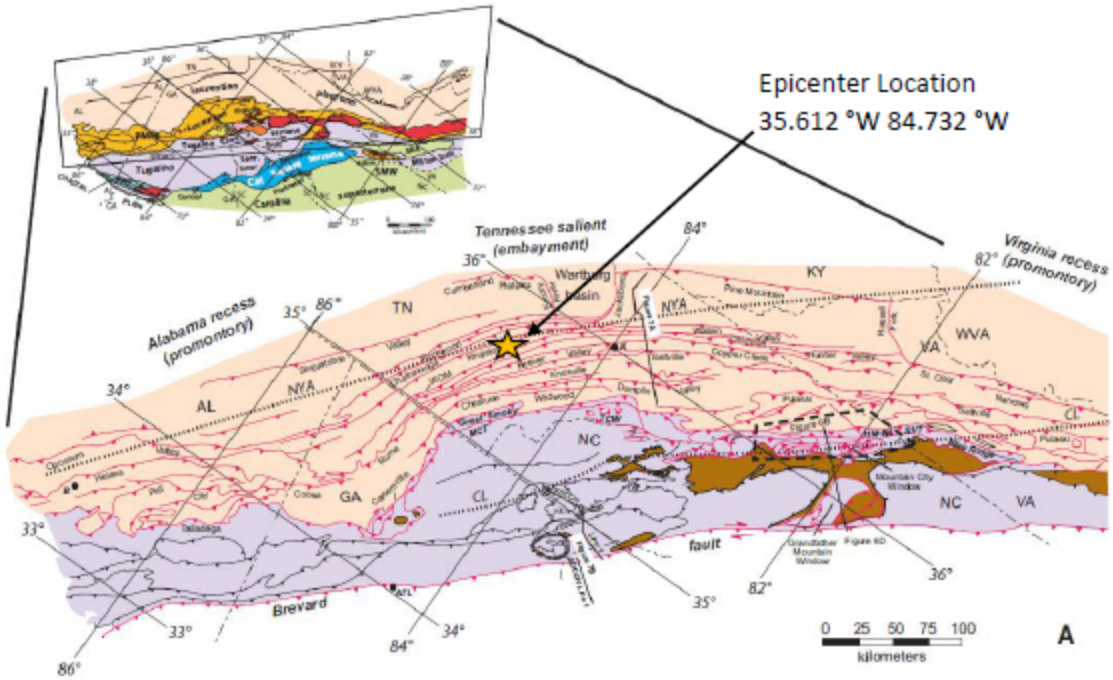

FIGURE 4. SIMPLIFIED TECTONIC MAP ILLUSTRATING THE DISTRIBUTION OF APPALACHIAN (>200 M.Y. OLD) FAULTS IN THE REGION AND THE LOCATION OF THE DECEMBER 12, 2018 EPICENTER.

With the current technology, it is very difficult to predict earthquake activity. Seismic activity in the ETSZ occurs five to twenty-six kilometers beneath the surface of the Earth[9]. New faults could develop or old faults become inactive without being detected. The earthquakes themselves are most telling about what is happening beneath the surface which marks the importance of studying and reporting seismic activity[10].

[9] Warrell, K.F., Cox, R.T., Hatcher R.D. Jr., Vaughn, J.D., and Counts R. (2017). Paleoseismic evidence for multiple Mw ≥6 earthquakes in the eastern Tennessee seismic zone during the late quaternary, *Geol. Soc. Am. Bull.* **107**, 1610-1624

[10] https://earthquake.usgs.gov/earthquakes/eventpage/se60247871/executive

REGIONAL GEOLOGY

The rocks that make up the geology of the eastern Tennessee, north Georgia, and the western Carolinas were formed from 750 to 280 million years ago when a supercontinent fragmented, and sediments accumulated in the resulting seas that formed. These became the sedimentary rocks of the foreland fold-thrust belt that were tilted and thrust faulted some 270 million years ago when Africa collided with North America. The collision produced a double-thickness crust that uplifted in the Appalachians. Today's Appalachian Mountains are the product of uplift in the past 5 million years.

The horizontal sedimentary rocks were deformed into the Appalachian foreland fold-thrust belt bounded by the Blue Ridge-Piedmont megathrust sheet indenter and the rigid basement as seen in Figure 5[11]. The displaced sedimentary rocks form an unconfined topographic free surface.

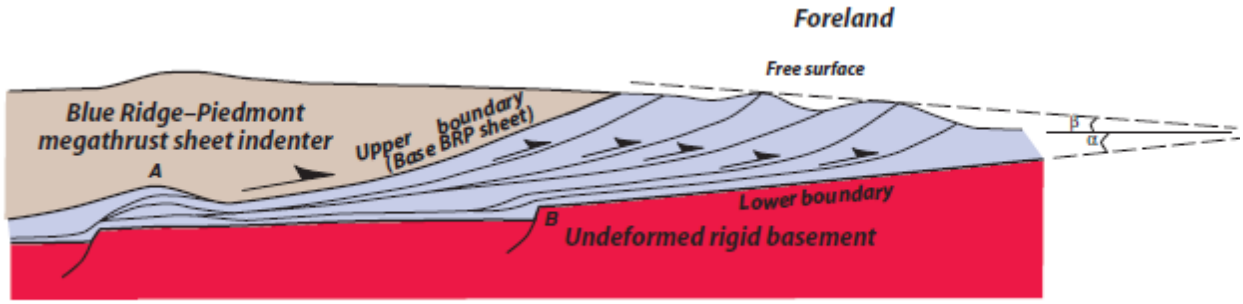

FIGURE 5. CARTOON OF THE FORMATION OF RIDGES IN A FOLD-THRUST BELT.

This is the form of the early Appalachian Mountains where some thrusts were rotated into an almost vertical position, as seen in Figure 6[11]. Gradually, some of the erodible rocks were degraded to the point that valleys formed between the harder ridge layers.

[11] Hatcher, R.D. Jr., Lemiszki, P.J., and Whisner, J.B. (2007). Character of rigid boundaries and internal deformation of the southern Appalachian foreland fold-thrust belt, *in* Sears, J.W. Harms, T.A., and Evenchick, C.A., eds., Whence the Mountains? Inquired into the Evolution of Orogenic Systems: A Volume in Honor of Raymond A. Price: Geological Society of America Special Paper 433, p. 243-276

FIGURE 6. EXPOSED THRUST INSIDE OF THE KNOXVILLE, TN CITY LIMITS ON BROADWAY ABOUT 100 YARDS NORTH OF THE I-640-BROADWAY EXIT.

The December 12, 2018 event was located in the Tennessee Valley and Ridge physiographic province. This province, within the Appalachian Mountains, is characterized by long ridges, with long continuous valleys between these ridges. Rock types in the area of the event are predominantly sedimentary rock types (shale, limestone, and sandstone) extending northeast to southwest in relatively long, narrow bands (Figure 7 and Figure 8[12]).

[12] Hardeman, W.D., Miller, R.A., and Swingle, G.D. (1966). Geologic Map of Tennessee. Tennessee Division of Geology

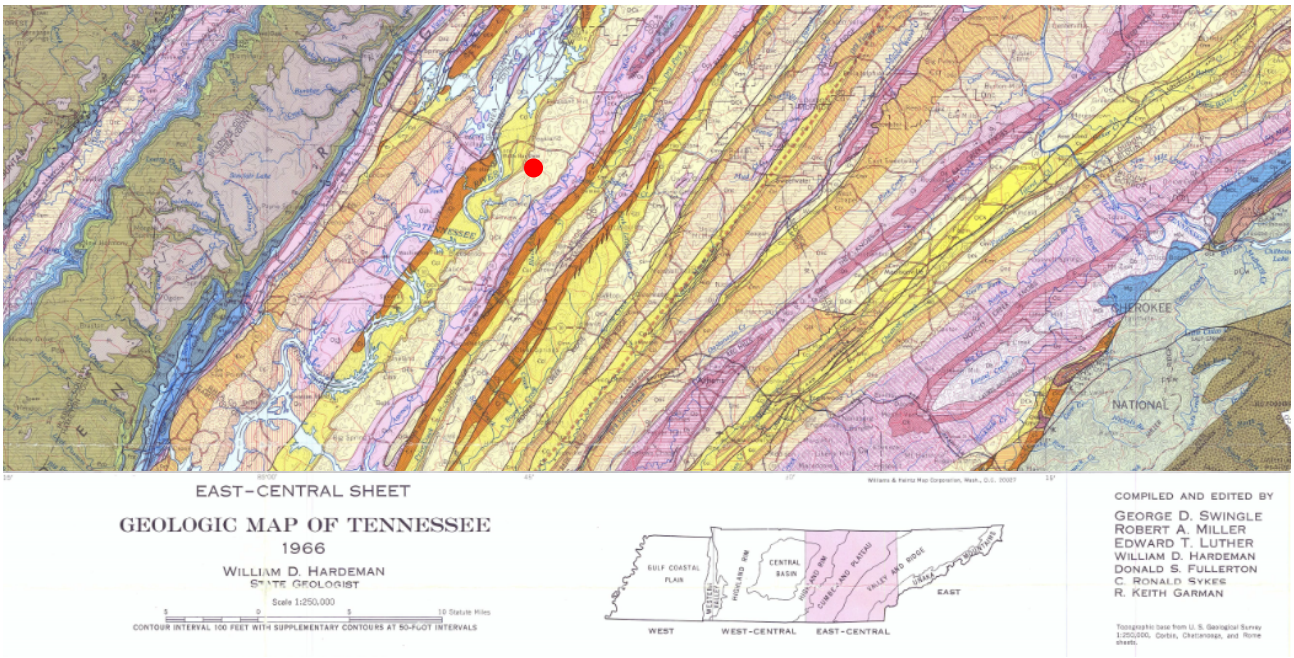

FIGURE 7. GENERAL GEOLOGIC CONFIGURATION MAP OF THE VALLEY AND RIDGE IN THE VICINITY OF THE DECEMBER 12, 2018 EPICENTER.

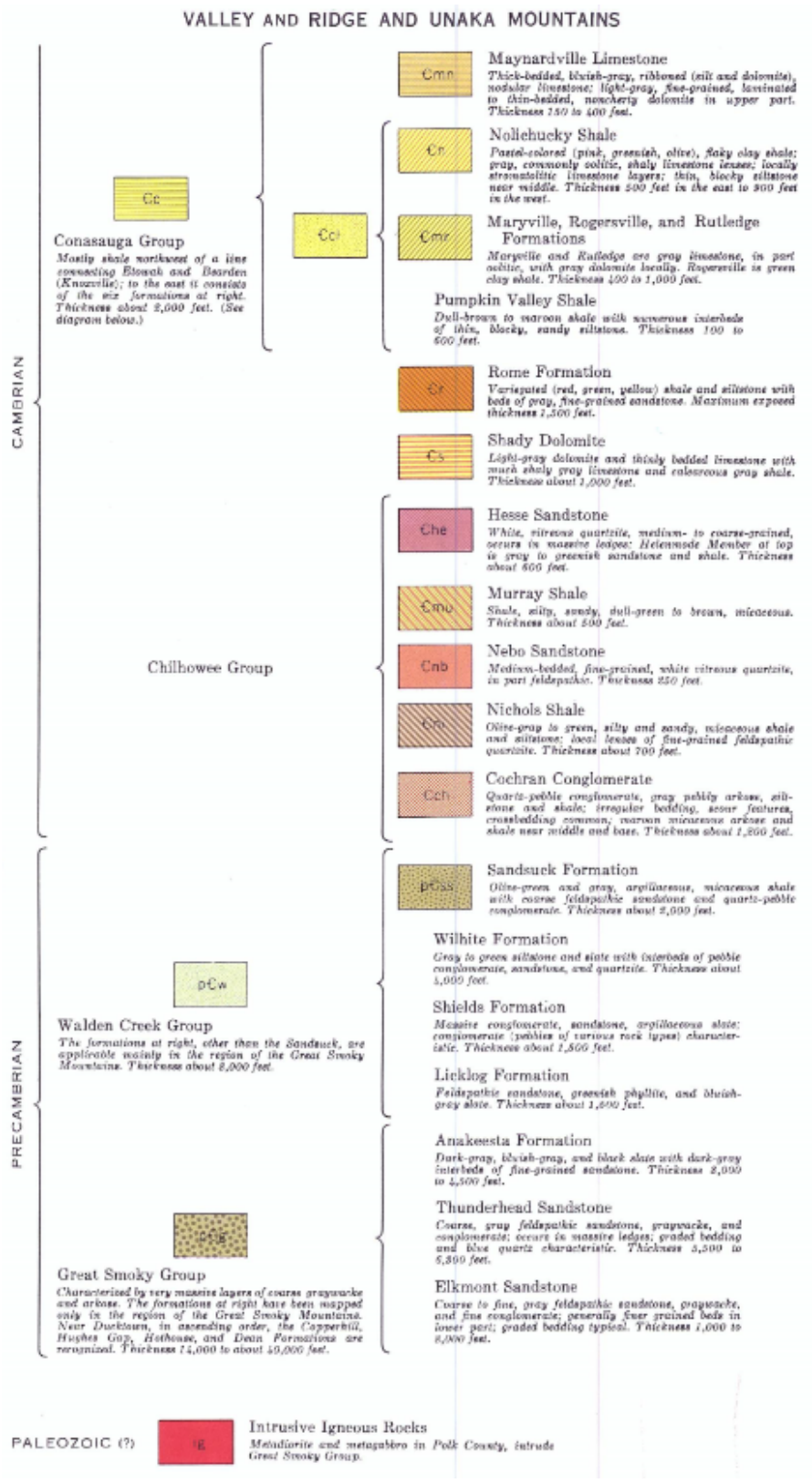

FIGURE 8. LEGEND OF ROCK TYPES FOR VALLEY AND RIDGE FORMATION.

GROUND MOTIONS

The details of the earthquake origin are summarized in Table 1.

TABLE 1. DETAILS OF EARTHQUAKE ORIGIN.

Magnitude	4.4M
Location Uncertainty	35.612°N 84.732°W +/- 0.2 km
Depth Uncertainty	7.9 km +/- 0.7 km
Origin Time	2018-12-12 09:14:43.610 UTC

Obtained from https://earthquake.usgs.gov/earthquakes/eventpage/se60247871/origin/detail

Figure 9 shows the waveform data for the Tuckaleechee Caverns, TN (TKL) recording station that is located at latitude and longitude of 35.66° N 83.77°W, about 47 miles from the epicenter, and a depth of zero.

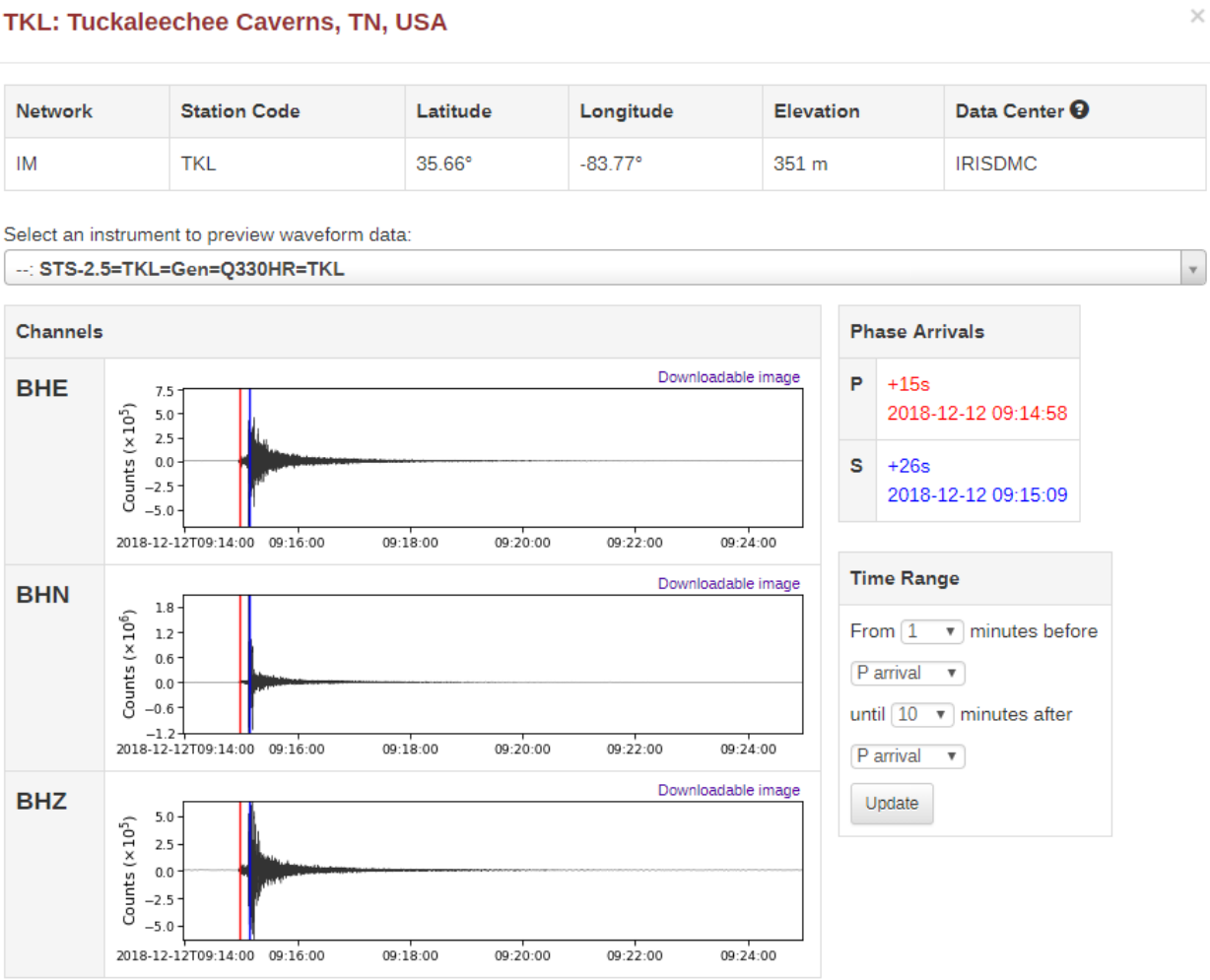

FIGURE 9. WAVEFORM DATA FROM TUCKALEECHEE CAVERNS, TN (TKL) RECORDING STATION.

GEER TEAM FIRST HAND RECONNAISSANCE

Siegel from the GEER team visited the area on December 20, 2018 to observe the conditions surrounding the epicenter. The approximate perimeter of observations is shown relative to the epicenter in Figure 10. The epicenter and surrounding area are in a rural setting where the buildings primarily consist of widely spaced, single-story residences, particularly manufactured homes. The firsthand reconnaissance canvassed the accessible areas as best as possible, though many of the private residences were posted with "No Trespassing" signs which prohibited observation on private land. Overall, the GEER team reconnaissance did not encounter any firsthand evidence of earthquake-induced damage.

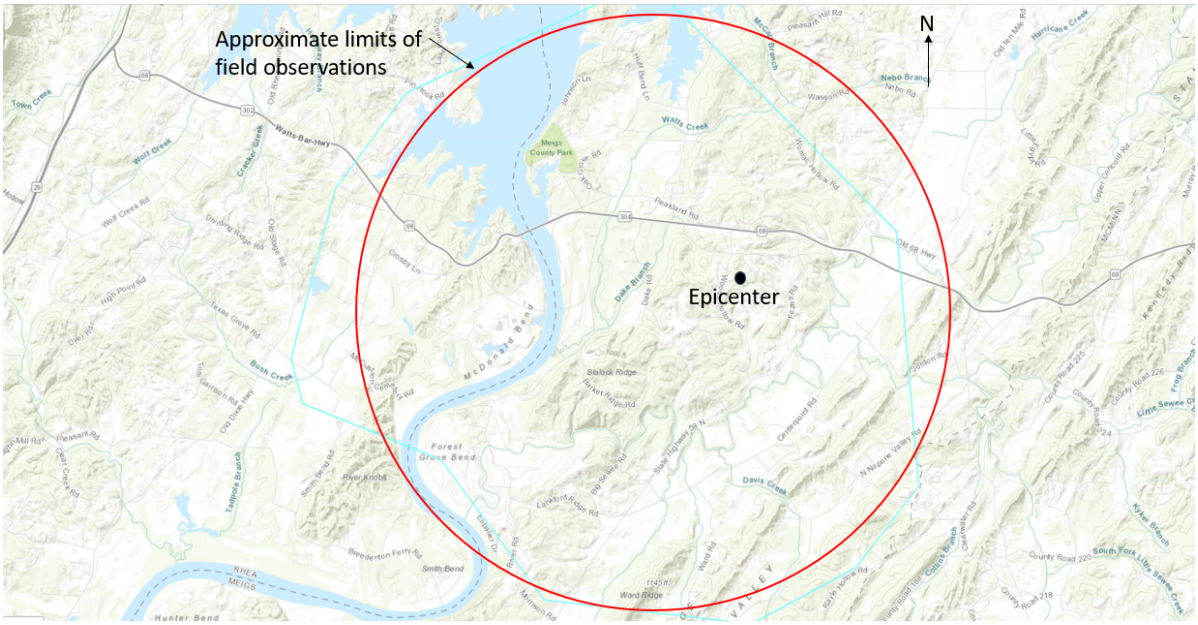

FIGURE 10. APPROXIMATE PERIMETER OF FIRSTHAND GEER OBSERVATIONS.

As part of the reconnaissance, Siegel photographed buildings, slopes, retaining structures, and surface items that would most likely be susceptible to earthquake-related damage. Figure 11 shows the locations where Figure 12 through Figure 15 were taken and the arrows point in the direction of the photographs. Figure 12 faces the location of the event epicenter when looking from the north.

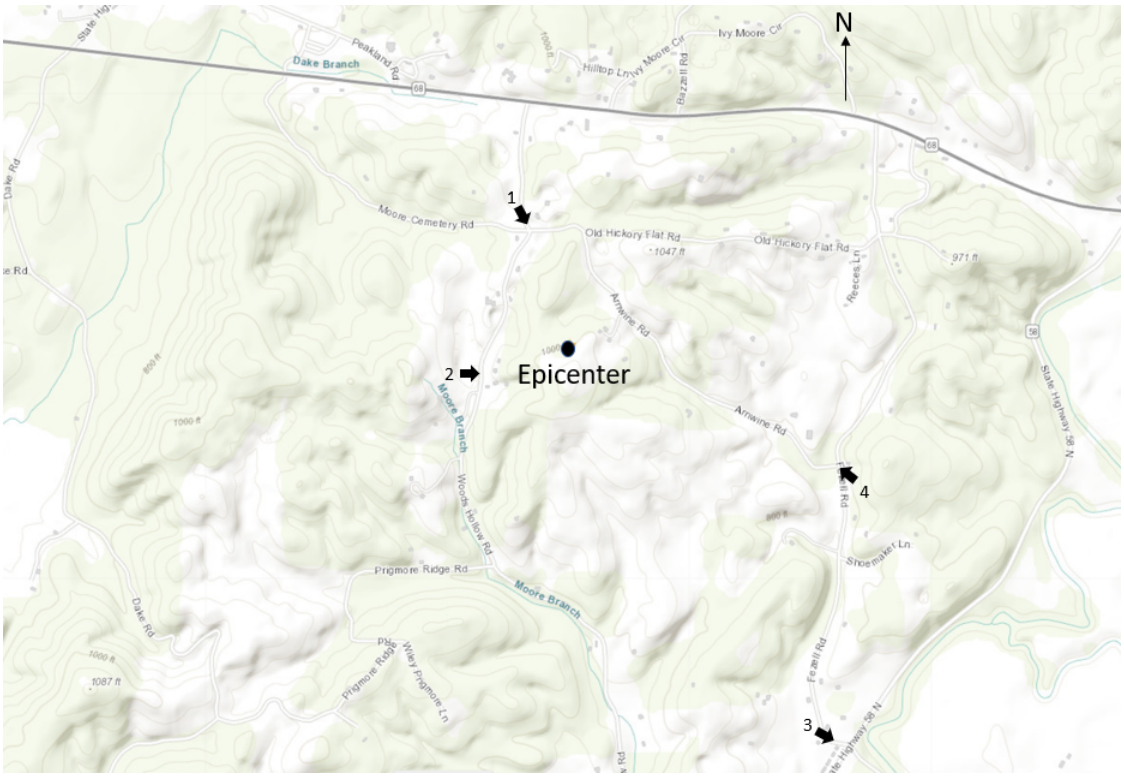

FIGURE 11. LOCATIONS OF PHOTOGRAPHS 1 THROUGH 4.

FIGURE 12. PHOTOGRAPH (1) ALONG WOODS HOLLOW ROAD LOOKING SOUTH TO EPICENTER (35.617 °N 84.734 °W).

Figure 13 shows a one-story single-family residence that has a stacked stone foundation wall. This house is very near the epicenter and would have been subjected to ground shaking from the December 12, 2018 earthquake. The stacked stone foundation does not appear to exhibit any recent damage and appears intact and in good shape.

FIGURE 13. PHOTOGRAPH (2) OF SINGLE-FAMILY RESIDENCE ALONG WOODS HOLLOW ROAD (35.611 °N 84.736 °W).

Figure 14 shows a stacked stone retaining wall on the southeast corner of the intersection of Tennessee Highway 58 and Fezzell Road. The wall is near vertical and a few feet in height. There were no indications that suggest that this small retaining wall experience earthquake-induced damage. Figure 15 faces the location of the event epicenter when looking from the southeast.

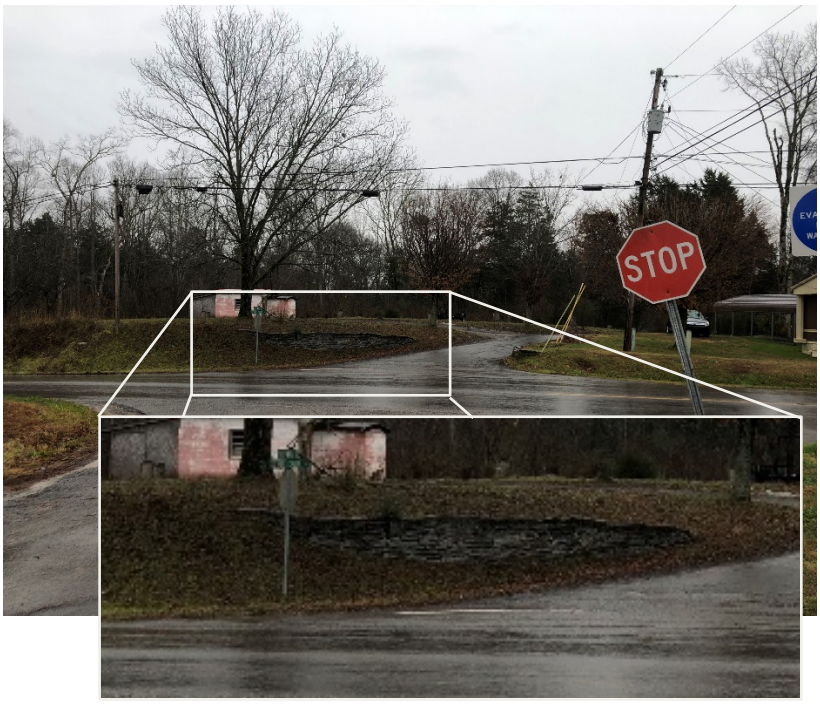

FIGURE 14. PHOTOGRAPH (3) STACKED STONE RETAINING WALL (35.598 °N 84.719 °W).

FIGURE 15. PHOTOGRAPH (4) ALONG FEZZELL ROAD (35.608 °N 84.197 °W).

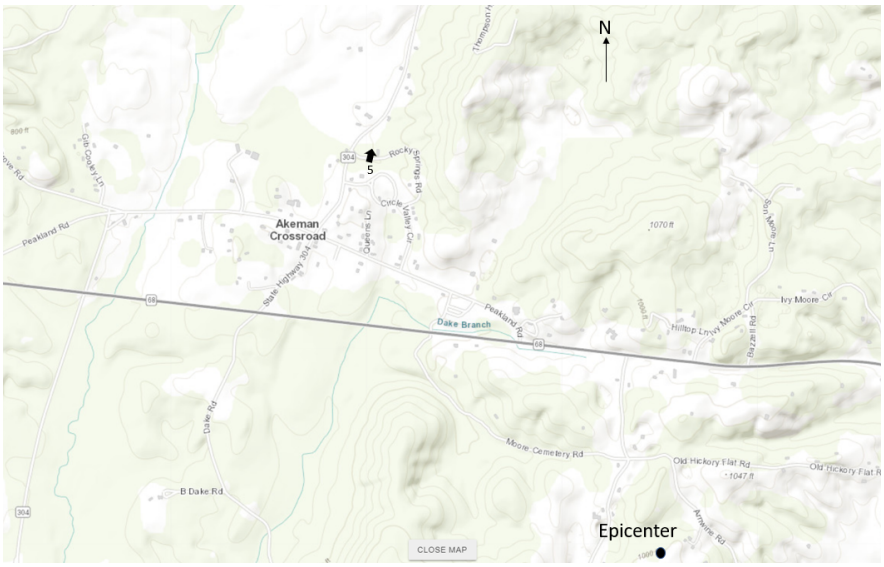

FIGURE 16. LOCATION OF PHOTOGRAPH 5.

Figure 16 shows the location where *Figure **17*** was taken and the arrow points in the direction of the photograph. Figure 17 is a photograph taken in a cemetery located northwest of the epicenter. The headstone in the foreground is dramatically tilted. Even in its fragile condition, it did not fall over as a result of the earthquake. Overall the headstones and other ornaments showed little or no damage from the December 12, 2018 earthquake.

FIGURE 17. PHOTOGRAPH (5) OF A LEANING HEADSTONE NORTH OF EPICENTER (35.631 °N 84.748 °W).

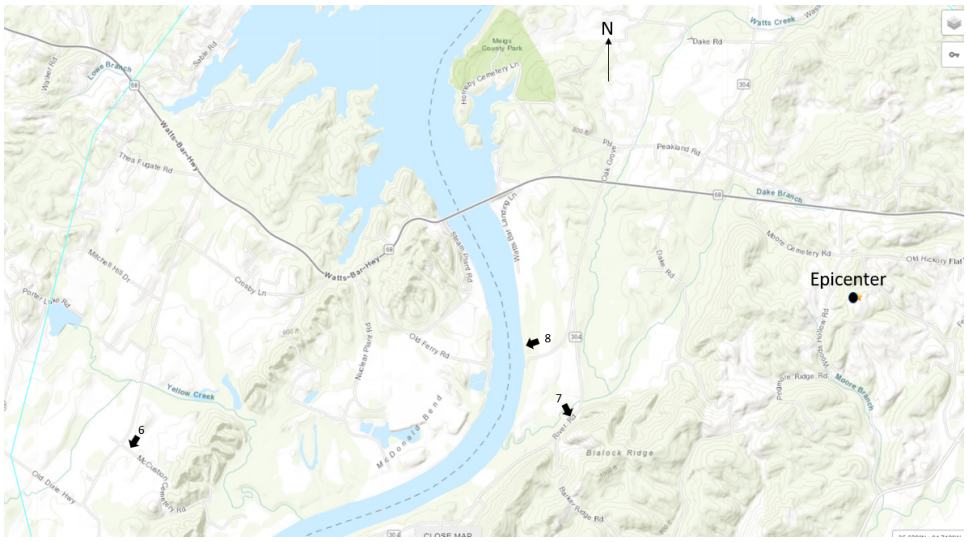

FIGURE 18. LOCATION OF PHOTOGRAPHS 6 THROUGH 8.

Figure 18 shows the locations where Figure 19 through Figure 21 were taken and the arrows point in the direction of the photographs. Figure 19 shows a single-story church building with the masonry foundation wall that is west of the epicenter. No cracks or other signs of distress were observed in the masonry wall or any other part of the church exterior. Figure 20 shows a slope along Tennessee Highway. The slope is covered with vegetation with some exposed rock debris but did not appear to have any instability, surficial or otherwise. The cooling towers of the Watts Bar Nuclear Plant are shown in the background of Figure 21 which was taken from Tennessee Highway 304 looking west. The nuclear plant is downstream of the Watts Bar dam which is one of the three priority dams inspected by TVA.

FIGURE 19. PHOTOGRAPH (6) OF UNDAMAGED MASONRY BLOCK FOUNDATION WALL (35.597 °N 84.826 °W).

FIGURE 20. PHOTOGRAPH (7) OF SLOPE ALONG HIGHWAY 304 WITH NO SIGNS OF RECENT INSTABILITY (35.601 °N 84.767 °W).

FIGURE 21. PHOTOGRAPH (8) WATTS BAR NUCLEAR PLANT DOWNSTREAM FROM DAM (35.605 °N 84.774 °W).

SECOND HAND RECONNAISSANCE

To the extent of the knowledge of the GEER team, there was little significant damage reported to local authorities and the news media. A statement released following the earthquake by TVA, who operates the Watts Bar Nuclear Plant near Spring City, TN and the Sequoyah Nuclear Plant just outside of Chattanooga, TN, stated that the two nuclear plants did not appear to be affected and were continuing to operate safely[13].

After the event, TVA dispatched staff to inspect 22 dams within their portfolio less than 24 hours after the earthquake. Because of their proximity to the epicenter, Watts Bar, Tellico, and Fort Loudon dams were priorities for TVA. No significant impacts were identified, but a couple of minor effects that may have been related to the earthquake were found. Minor cracking was observed in an ancillary, concrete-block structure as well as an isolated instance of minor cracking in the shallow foundation of an oxygenation facility at Watts Bar Dam.

Piezometers installed in and near the Watts Bar Dam embankment and one continuously monitored seepage location did not indicate any unusual readings after the earthquake. There were no signs of any ground deformation on or near the Watts Bar embankment.

The earthquake was recorded by seismic instrumentation at many of TVA's dams; the recordings will be used to inform selection of near-surface attenuation parameters (e.g. kappa) as part of an ongoing TVA effort to update probabilistic seismic hazard analyses for TVA's facilities. TVA installed a temporary seismic instrument at Watts Bar Dam that recorded approximately two dozen small aftershocks of the December 12, 2018 event.

Oak Ridge Environmental Management reported that the Oak Ridge Reservation's nuclear cleanup sites came through the earthquake undamaged[14]. Additionally, the National Nuclear Security Administration reported that the Y-12 National Security Complex (essentially adjacent to the Oak Ridge Reservation) was not impacted either.

Mr. Steve Hutchins, Regional Bridge Manager with Region 2 of TDOT, stated that their personnel performed inspections of bridges along State Route 58, 68, and 29 within a 5-mile radius of the epicenter. TDOT also inspected a few county-owned bridges along routes 302, 304, and 305. TDOT reported that no significant changes or damage were observed during their inspections.

Mr. Bhargav Patel, Transportation Project Specialist with Region 1 of TDOT, stated that their personnel inspected bridges along State Route 1 in Roane County as well as State Route 2 in Monroe County. They also inspected county-owned bridges along 304 in Roane County, 307 in

[13] https://wdef.com/2018/12/12/engineers-inspecting-watts-bar-nuclear-plant-earthquake/

[14] https://www.knoxnews.com/story/weather/2018/12/12/earthquake-east-tennessee-knoxville-area-4-4-magnitude-quake-felt-far-atlanta/2286871002/

Monroe County, and 322 in Roane, Loudon, and Monroe Counties. Additionally, TDOT inspected bridges along Interstate 75 from the Loudon County line to the Monroe County line. None of the bridges inspected showed visible impacts of the earthquake.