INTRODUCTION

The Virginia Tech seismic network operates in conjunction with other regional networks in the ANSS mid-America region to collect high-quality seismic data in Virginia and adjacent parts of the Appalachian region. Research objectives include earthquake monitoring to maintain continuity of earthquake catalogs for seismic hazard assessment, studies of the seismotectonics of the region, earthquake source studies, wave propagation, and the temporal/spatial behavior of seismicity. Outreach objectives include development and maintenance of regional earthquake catalogs; and dissemination of information to federal/state/local governments, the engineering community and the general public.

NETWORK OPERATION AND RESEARCH

Stations in operation in Virginia and the adjacent area during the project period are shown in Figure 1. Stations WMV, PWV, FWV, ELN, BLA and VWCC are 3 component, short-period with 24-bit digitization. Station WMV was decommissioned during 2004 and reinstalled as station VWCC in 2005. Stations PWV and FWV were decommissioned during 2006 and are to be re-installed in central Virginia in 2007. Broadband station URVA became operational in February, 2006. That station is a collaboration between Virginia Tech, the University of Richmond and the City of Richmond. The city of Richmond purchased the equipment (Geotech Instruments SMART-24D digitizer and KS-2000 broadband sensor). University of Richmond provides the site, and internet connection, and Va Tech provides maintenance, technical support and analysis of the data. Telemetry for station ELN is by digital duplex radio. Telemetry of URVA and VWCC is by a combination of local UHF digital radio and Internet.

The digital network data are ported to an EARTHWORM system and are exported to USGS NEIC in Golden, Co, and CERI (University of Memphis). Virginia Tech and other collaborative institutions forming the Mid-America region of ANSS are committed to efficient data acquisition, analysis and dissemination under the auspices of the Advanced National Seismic System (see the ANSS-MA website at **http://www.anss-ma.org**).

In addition to the data dissemination via EARTHWORM, Va Tech maintains an anonymous ftp site containing waveform data from selected regional events. This is accessible via web browsers at **ftp://vtso.geol.vt.edu/events**. The worldwide web site **http://www.geol.vt.edu/outreach/vtso**/ contains information on how to access the waveform data, as well as the other products of this project, which include a regional seismicity bulletin and historical earthquake catalog for the southeastern U.S. region. In addition, the website includes twelve hour digital Helicorder trace data from all components of the network.

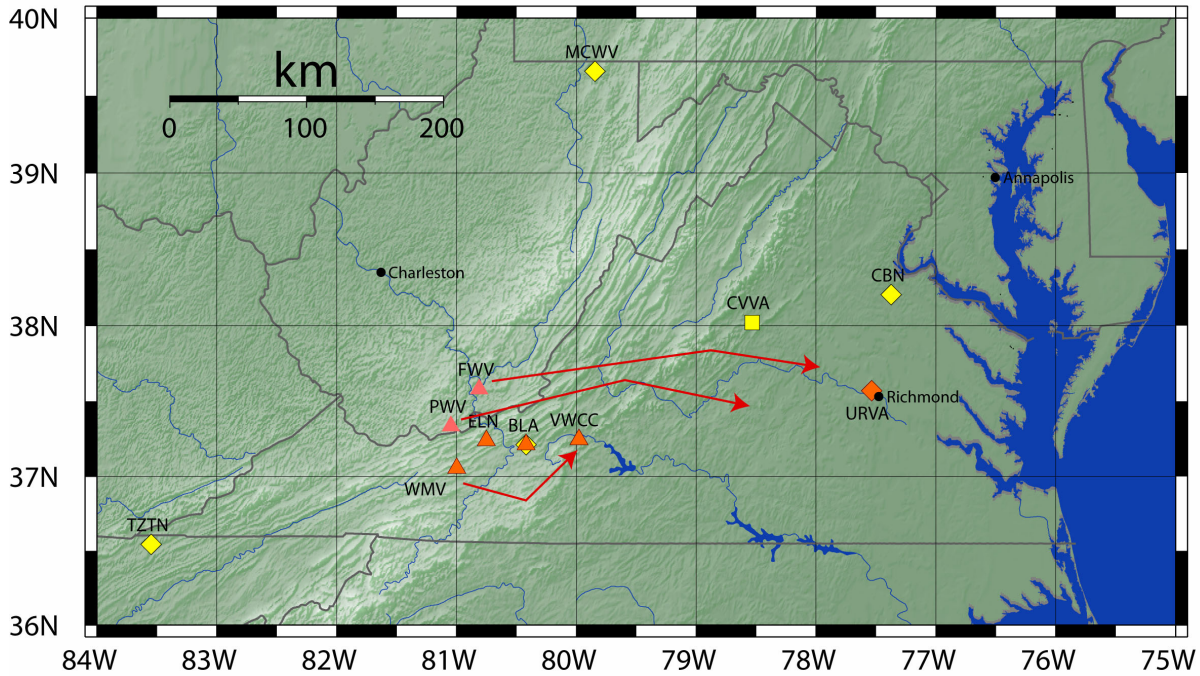

Figure 1. Stations operated by Virginia Tech during 2004-2006 are shown by the orange triangles and the orange diamond. Yellow diamonds are ANSS broadband backbone stations. The yellow square is an ANSS strong motion station. Station URVA is a broadband station operated jointly by Va Tech, the University of Richmond and the City of Richmond. Station WMV was decommissioned during 2004 and re-installed as station VWCC during 2005. Stations PWV and FWV were decommissioned during 2006 and are to be re-installed in central Virginia in 2007.

Seismicity in the Vicinity of the Virginia Tech Network During the Project Period

Seismicity during 2004

Figure 2 shows earthquakes occurring in the southeastern U.S. during 2004, as reported in Southeastern U.S. Seismic Network Bulletin No. 39 . There were 48 events with magnitudes exceeding 2.0. The largest earthquake reported during the year was mb(Lg) = 4.4, occurring on November 7, 2004, near Union, Alabama (See Figure 7).

After a rousing demonstration of seismicity in 2003, Virginia calmed down in 2004. Only one shock was located by the Va Tech Network within the state during 2004. This was a magnitude 2.5 shock on December 3, 2004. The epicenter is in central Virginia, approximately 5 km to the northeast of the epicenter of the December 9, 2003 shocks. This event was reported to the USGS community internet intensity map with at least 19 responses in 11 zip code areas (Figure 3). The maximum intensity was IV MM. The epicenter of this event is uncertain (ERH 13 km) therefore, geological interpretation of the

event is impossible. However, this shock, as well as those of 2003, are in proximity of a major brittle/ductile zone of deformation (Spotsylvania zone). Figure 4 shows seismograms recorded by the short-period stations of the Va Tech network for this event.

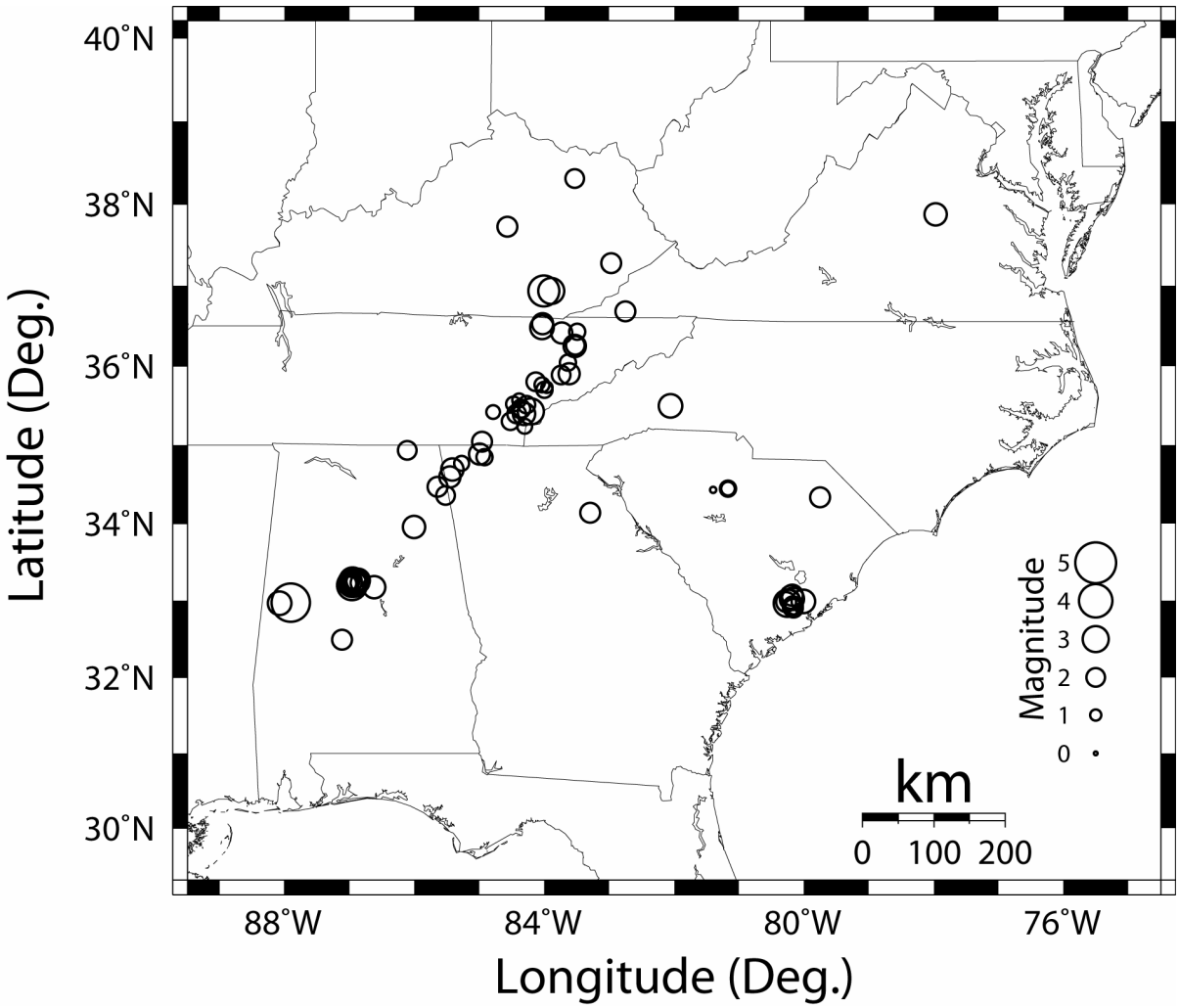

Figure 2. Epicenters of earthquakes, M>0.0, occurring during 2004 and contained in the Southeastern U.S. Seismic Network Bulletin No. 39. The largest event was on 11/7/04, near Union, Alabama (seismograms are shown in Figure 7).

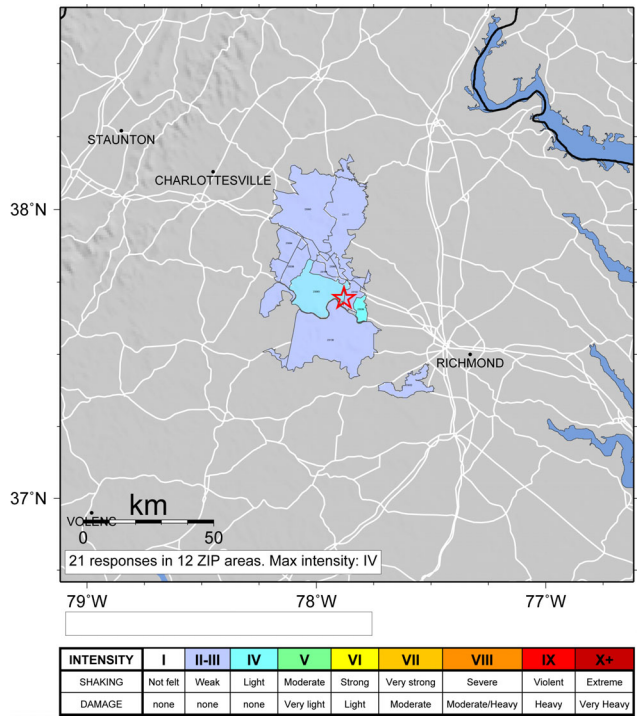

Figure 3. USGS community internet intensity map for the December 3, 2004 M 2.5 shock in central Virginia.

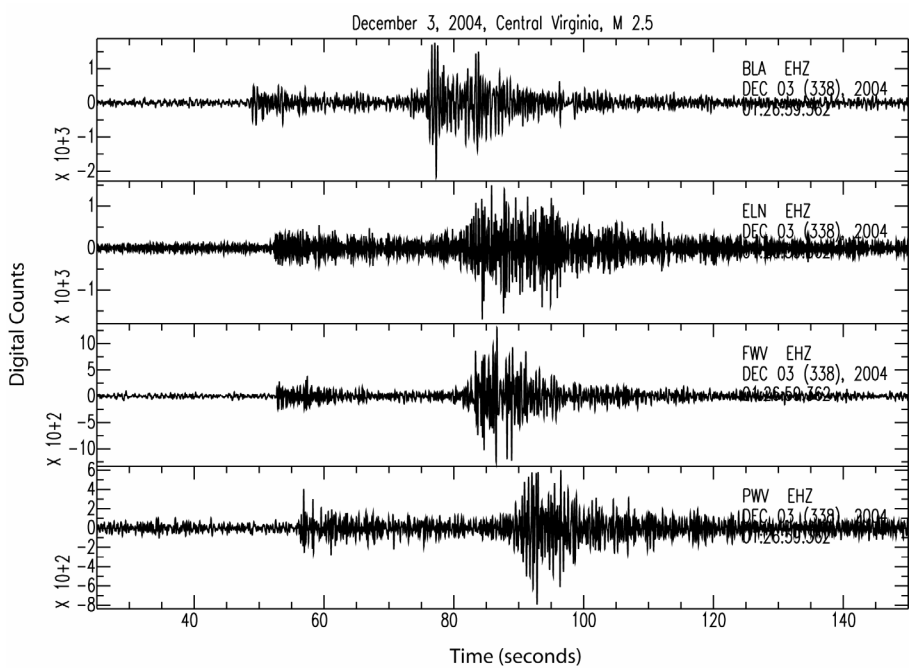

Figure 4. Seismograms from the Virginia Tech short-period stations for the 12/3/2004 earthquake in central Virginia.

Regional Seismicity, 2004

Figures 5 through 7 show seismograms recorded by the Virginia Tech network from other notable earthquakes occurring in eastern North America during 2004.

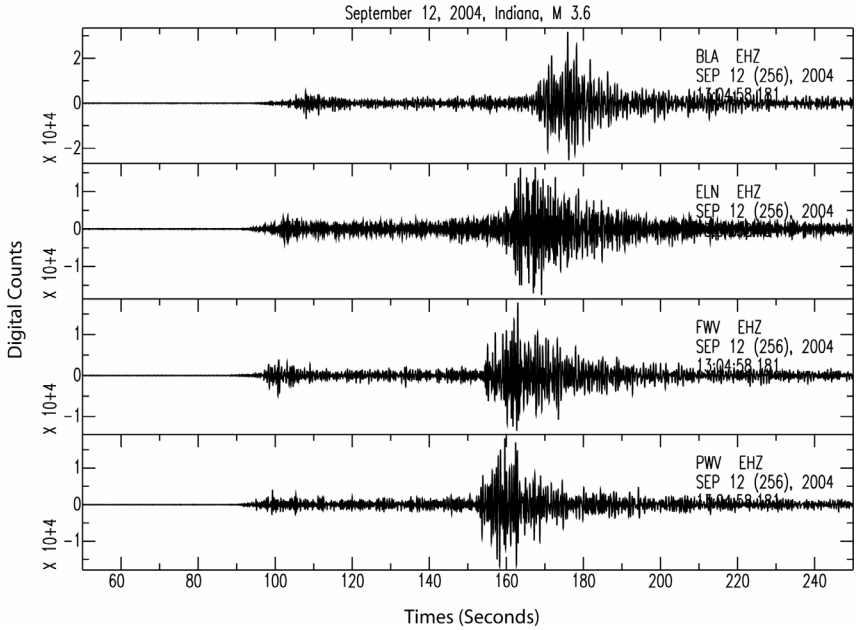

Figure 5. Seismograms from the Virginia Tech short-period stations for the 9/12/2004 earthquake in southern Indiana.

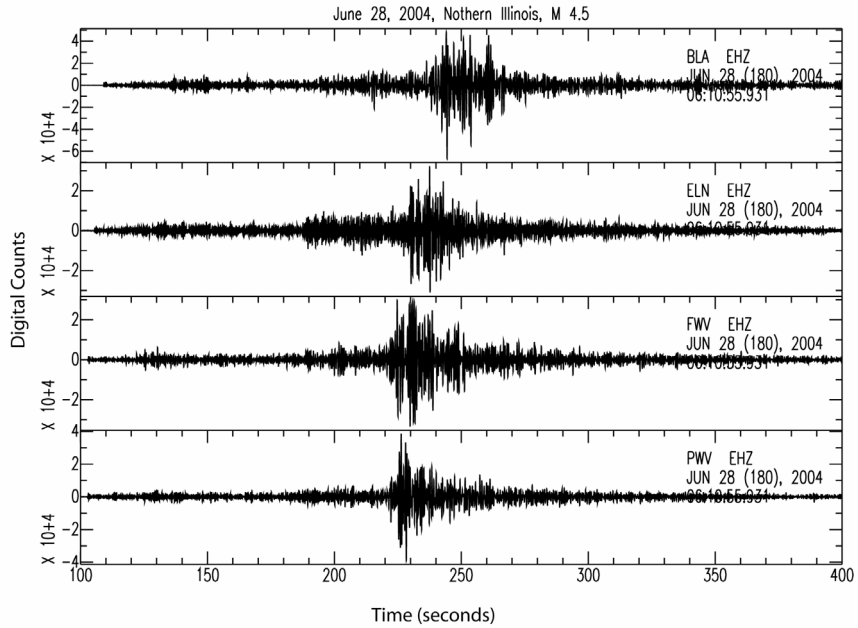

Figure 6. Seismograms from the Virginia Tech short-period stations for the 6/28/2004 earthquake in northern Illinois.

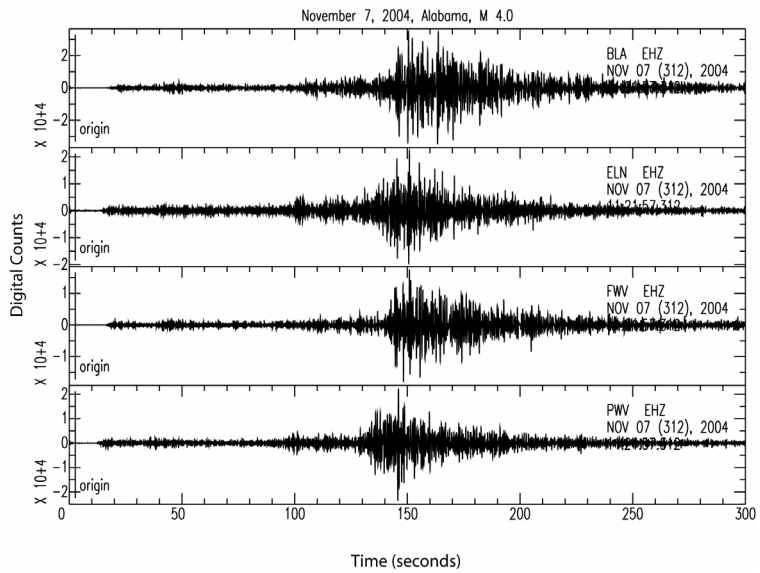

Figure 7. Seismograms from the Virginia Tech short-period stations for the 11/7/2004 earthquake in Alabama.

Seismicity during 2005

Figure 8 shows the epicenters of earthquakes occurring during 2005, reported in the Southeastern U.S. Seismic Network Bulletin No. 40. The largest shock occurred on August 25, 2005 (mb(Lg) = 3.7) near Hot Springs, North Carolina.

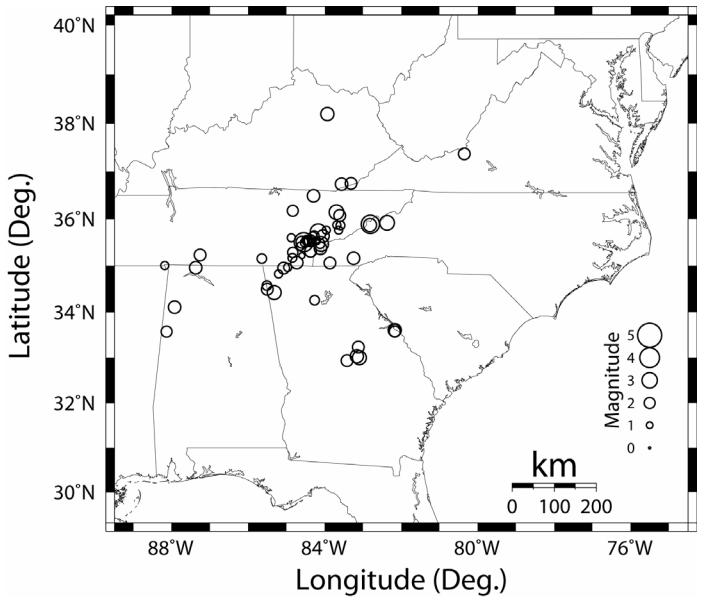

Figure 8. Epicenters of earthquakes, M>0.0, occurring during 2005 and contained in the Southeastern U.S. Seismic Network Bulletin No. 40.

Only one natural event was detected near the Virginia Tech network stations in 2005. Unlike 2003 and 2004, central Virginia remained quite. On December 30, 2005, a small (M 2.2) shock occurred near

Catawba, Virginia, some miles northeast of the historically active Giles County area. No felt reports were received. The seismograms from the VTSO short period stations are shown in Figure 9.

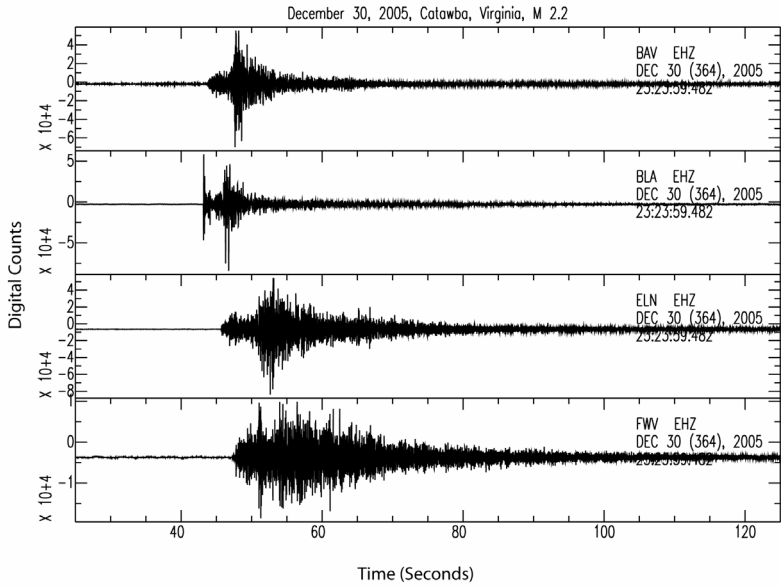

Figure 9. Seismograms from the Virginia Tech short-period stations for the 12/30/05 earthquake in western Virginia.

Regional Seismicity, 2005

The August 25, 2005 shock near Hot Springs, NC

The August 25, 2005 Hot Springs Earthquake is of special interest because it represents the first significant earthquake to occur in the Blue Ridge province of western North Carolina in several decades. Figure 10 shows the USGS internet intensity map. The epicenter, determined by the author using P and S arrival time data at 47 stations is 35.887N, 82.803W, depth 6.0 km and origin time 03hr. 09min. 41.7 sec. The nearest station distance was 78 km, and the azimuthal gap was 138 degrees. The velocity model used is that developed for the eastern Tennessee seismic zone by Vlahovic et al., (1998). HYPOELLIPSE horizontal and vertical error estimates are 1.1 km (seh max) and 1.6 km (sez).

Figure 11 shows the focal mechanism determined by the author using first-motion polarity data from 31 stations. It indicates predominately normal faulting on East-West trending nodal planes (nodal plane 1: strike N117E; dip 44 deg; rake -60 deg: nodal plane 2: strike N259E; dip 53 deg.; rake -115 deg.). The trend and plunge of the P axis is N109E, 69 deg: trend and plunge of the T axis is N7E, 5 deg. This first motion mechanism is similar to that determined from an inversion of broadband waveform data by Dr. Robert Herrmann at St. Louis University (personal comm. 2005). His preferred mechanism is (nodal plane 1: strike N90E; dip 60 deg; rake -60 deg; nodal plane 2: strike N221E ; dip 41 deg.; rake -131 deg). Herrmann finds Mw=3.65 and best fitting focal depth 8 km.

Because this event was well-recorded at many stations at both regional and local distances, the author examined the waveforms for possible depth phases. Surface reflections pPmP, sPmP, pPn and sPn were identified on some recordings at distances greater than 115 km. A least-squares fit to the phase arrival time differences indicates a focal depth of 5.5 km.

The shallow focal depth and subhorizontal T axis of this earthquake are in marked contrast to findings obtained from earthquakes in the eastern Tennessee seismic zone (ETSZ) to the west (Figure 12). Shocks in the ETSZ usually occur at depths in the range 5 to 22 km, and feature subhorizontal P axes (predominately strike-slip mechanisms).

The epicenter is only 2 km east of Hot Springs, a small resort town noted for thermal springs. The town is in a water gap cut by the French Broad river as it traverses the Blue Ridge mountains flowing in a general SE to NW direction. The surface geology is extremely complex. The epicenter of the shock plots on a mapped east-west trending fault, interpreted as part of a complicated thrust window (Oriel, 1950). The estimated thickness of the Precambrian and Paleozoic rocks of the Appalachian detachment at this location is 8 km, based on seismic reflection profiling. This places the 2005 shock within the detached rocks, a situation in marked contrast to earthquakes occurring to the west, in the Tennessee valley (ETSZ), but consistent with results for earthquakes in the central Virginia seismic zone (see, e.g., Kim and Chapman, 2005). Figure 13 shows the short-period recordings from the Va Tech network for this earthquake.

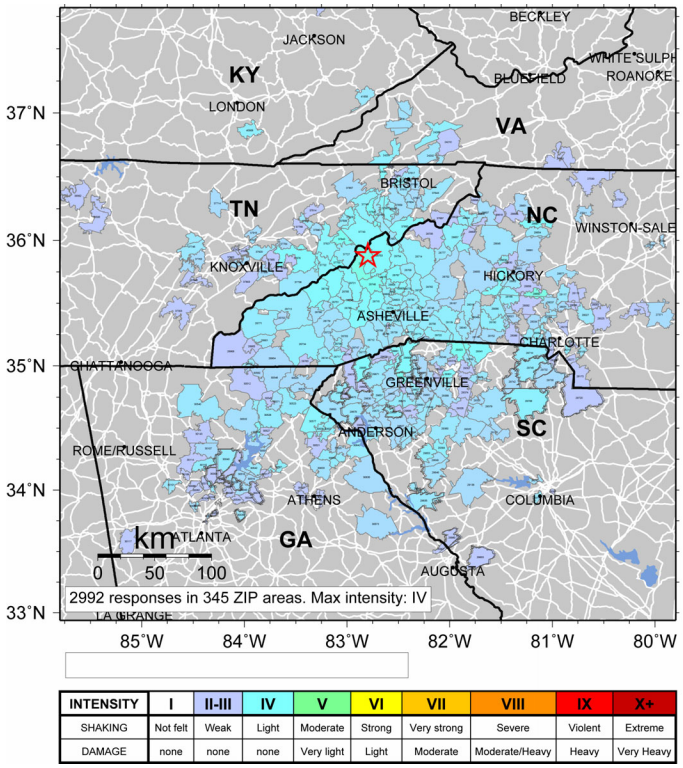

Figure 10. USGS Community internet intensity map of the August 25, 2005 Hot Springs, North Carolina earthquake.

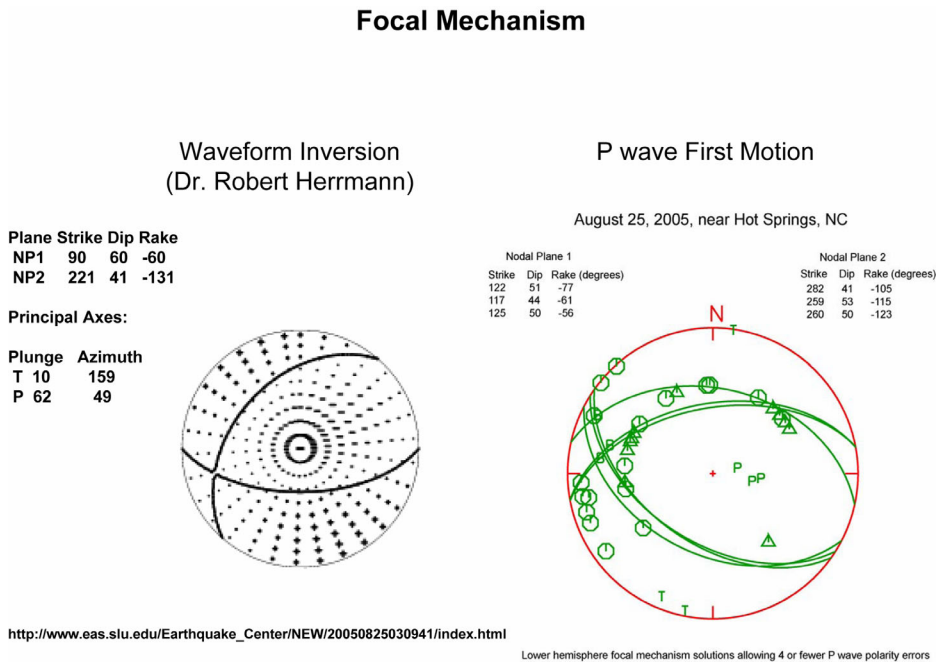

Figure 11. Left: focal mechanism for the 8/25/05 Hot Springs earthquake determined by Dr. Robert Herrmann (personal communication, 2005). Right: Focal mechanism determined by M. Chapman from P wave polarities.

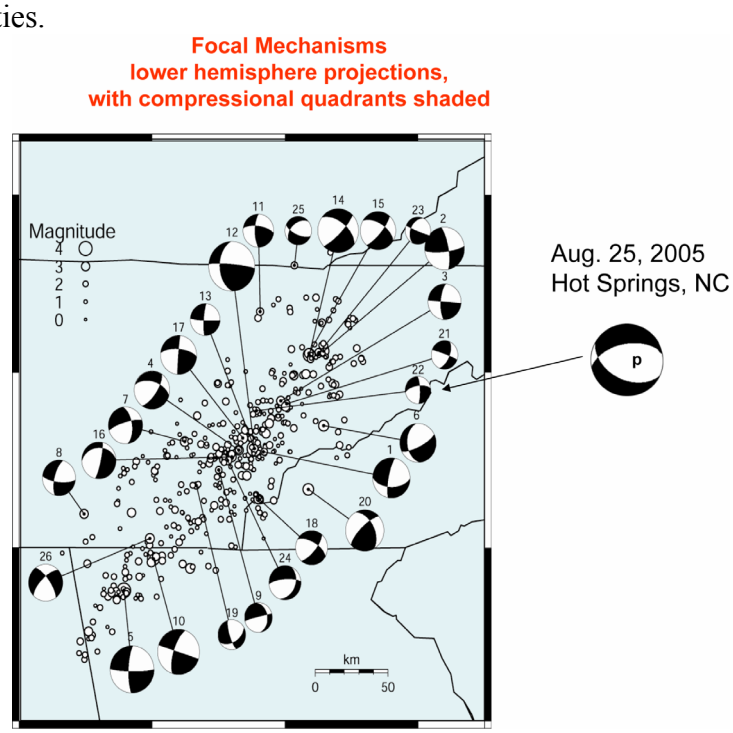

Figure 12. Focal mechanisms in the eastern Tennessee seismic zone, and the 2005 Hot Springs, NC earthquake. (from Chapman et al., 1997).

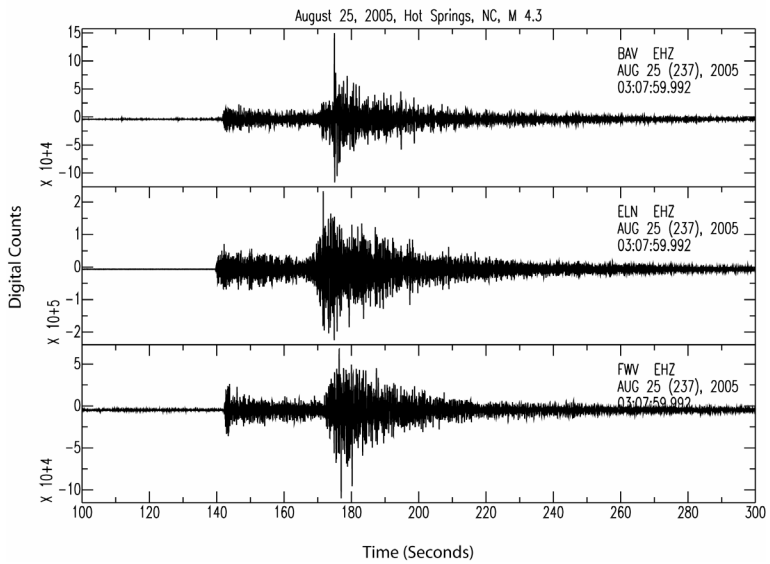

Figure 13. Seismograms from the Virginia Tech short-period stations for the 8/25/05 earthquake at Hot Springs, North Carolina.

The October 12, 2005 event near Niota, Tennessee, M 3.6

On October 12, 2005 a magnitude 3.6 earthquake occurred near Niota, Tennessee in the eastern Tennessee seismic zone. Figure 14 shows the seismograms recorded by the Va Tech network short-period stations.

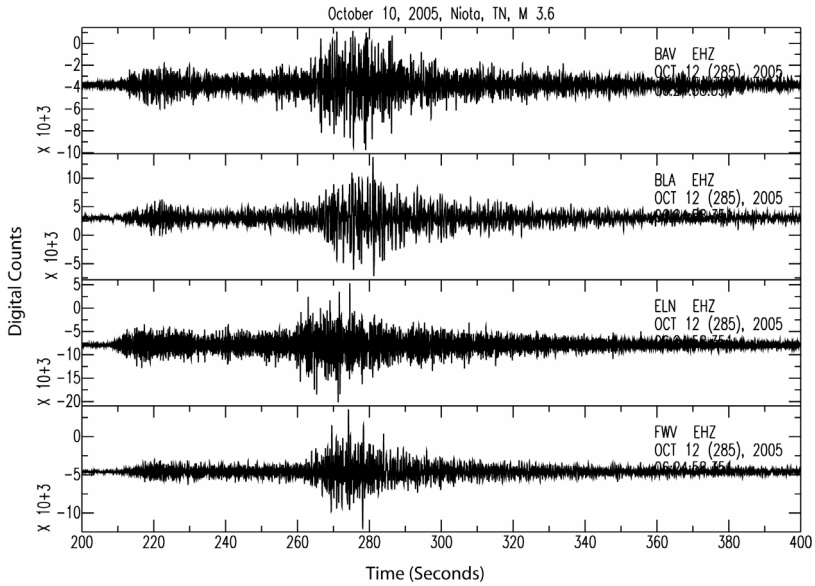

Figure 14. Seismograms from the Virginia Tech short-period stations for the 10/12/05 earthquake near Niota, Tennessee.

The December 7, 2005 event near Burnsville, North Carolina, M 2.8

On December 7, 2005, a magnitude 2.8 shock occurred near Burnsville, in western North Carolina. Figure 15 shows the seismograms recorded by the short-period stations in the Va Tech network. This earthquake is important because it may be related to the August 25, 2005 Hot Springs, NC event. Figure 16 shows the seismicity of western North Carolina. A prominent east-west trending topographic lineament is apparent in Figure 16 extending from Spruce Pine, NC on the east to Hot Springs, NC on the west. This feature is known as the Laurel Creek Lineament. The geologic nature of the feature is poorly understood. Burnsville is a small town, located on this feature. The two felt shocks in North Carolina during 2005 both occurred on the Laurel Creek lineament. In addition, the focal mechanism of the Hot Springs earthquake (Figure 11) shows nodal planes sub-parallel to the east-west trending topographic feature. Unfortunately, a focal mechanism could not be resolved for the December 7, 2005 Burnsville event.

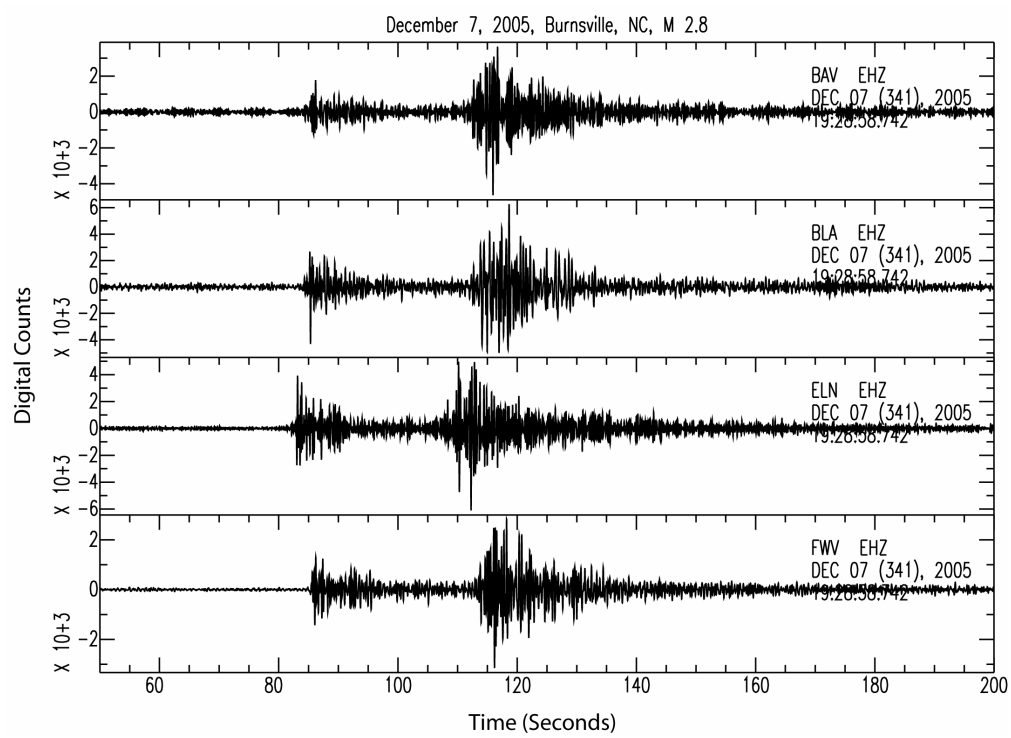

Figure 15. Seismograms from the Virginia Tech short-period stations for the 12/5/05 earthquake near Burnsville, North Carolina.

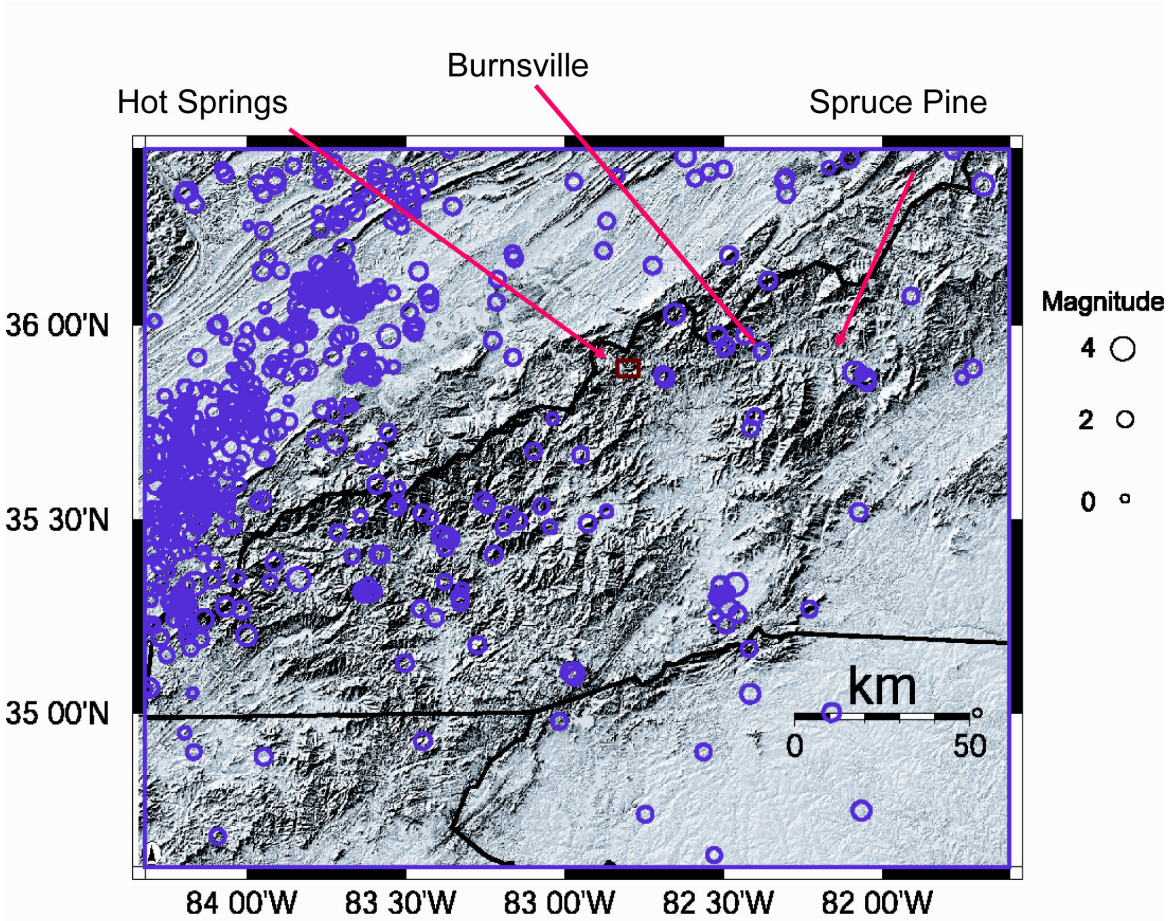

Figure 16. Instrumental seismicity in western North Carolina, 1983-2006. The locations of Hot Springs, Burnsville and Spruce Pine, North Carolina are indicated. The three localities lie along the Laurel Creek Lineament, the prominent east-west trending topographic valley apparent in the figure.

Seismicity during 2006

Figure 17 shows the epicenters of earthquakes occurring during 2006 in the southeastern U.S. region, to be reported in the Southeastern U.S. Seismic Network Bulletin No. 41, now in preparation.

The largest shock during 2006 occurred on September 25 (mb(Lg) = 3.7) near Florence, South Carolina.

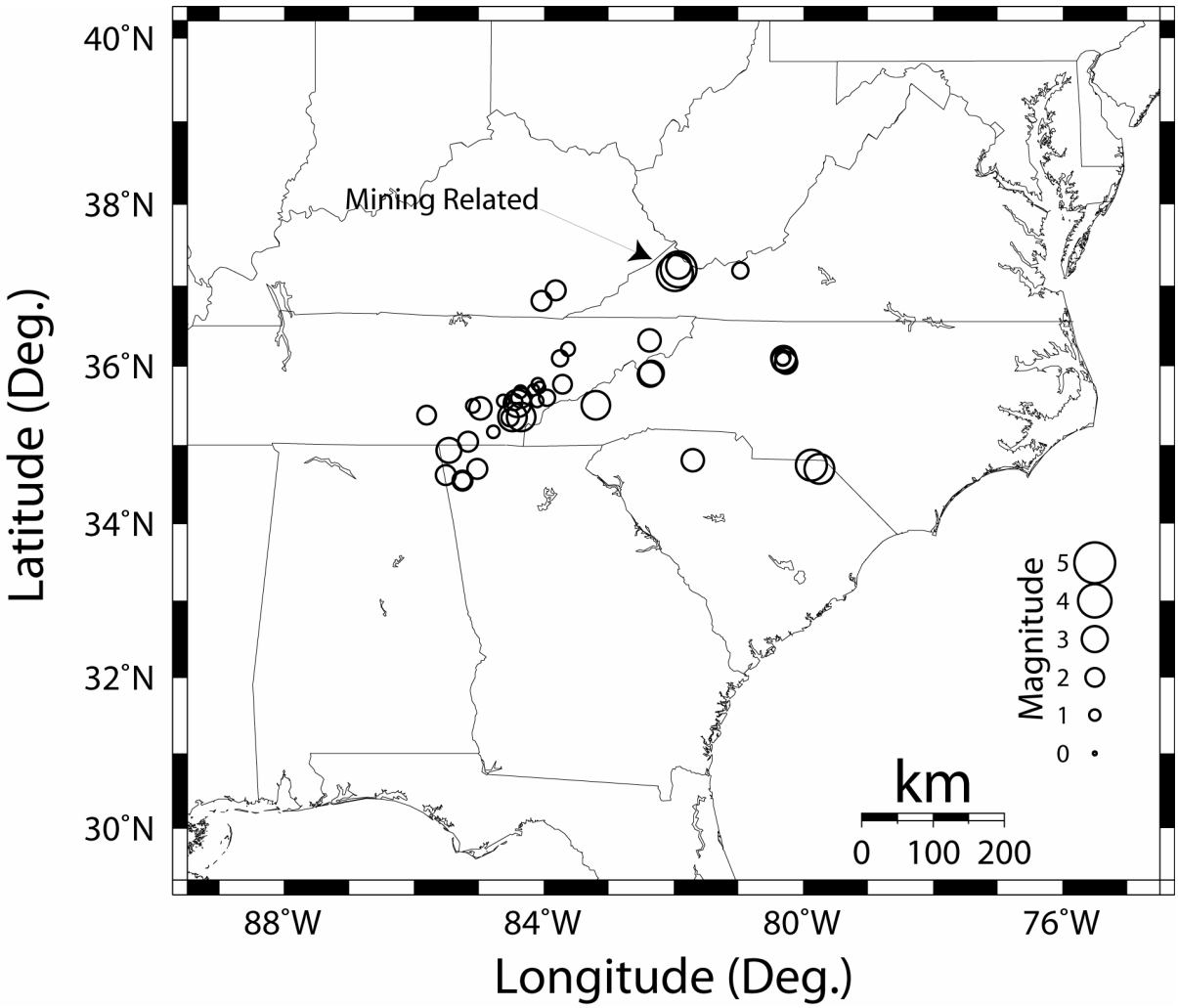

Figure 17. Epicenters of earthquakes, M>0.0, occurring during 2006 to be contained in the Southeastern U.S. Seismic Network Bulletin No. 41. The large events in southwestern Virginia are mining induced events related to long-wall coal mining operations in Buchanan County, Virginia. The events in central North Carolina are a series of felt events located by VTSO within the city limits of Winston-Salem, NC.

The only natural earthquake detected in Virginia during 2006 occurred on July 2, 2006. The magnitude was mb(Lg) 1.7. The epicenter was on Gauley Ridge, near Mechanicsburg, Virginia.

Regional Seismicity in 2006

June 16, 2006 earthquake near Ravensford, NC, M 3.5

On June 16, 2006 a M 3.5 event occurred near Ravensford, North Carolina, near the southern boundary of the Great Smokey Mountains Park. The hypocenter location derived by the author using 21 P and S arrival times is

Latitude: 35.5154N 83.2291W
Depth: 4.7 km
00hr 57min 27.71sec UTC, June 16, 2006
Gap: 103, Dmin 47km
Hypoellipse SEH: 1.4km, SEZ: 5.5km.

Figure 18 shows the short-period seismograms from the Virginia Tech seismic network. Figure 19 shows the focal mechanism derived by the author using P wave first motion polarities. Although the solution is well-constrained, it is ambiguous, because the B and T axes are interchangeable. One possibility is N-S or E-W strike slip, similar to the prevailing situation in the eastern Tennessee seismic zone to the west. The other possibility is thrusting on NW-SE striking nodal planes.

The June 16, 2006 earthquake, like the Burnsville and Hot Springs earthquakes of 2005, occurred on one of the major topographic lineaments of the Blue Ridge province in North Carolina. In this case, the Ravensford event is located upon the Swananoa lineament (Figure 20).

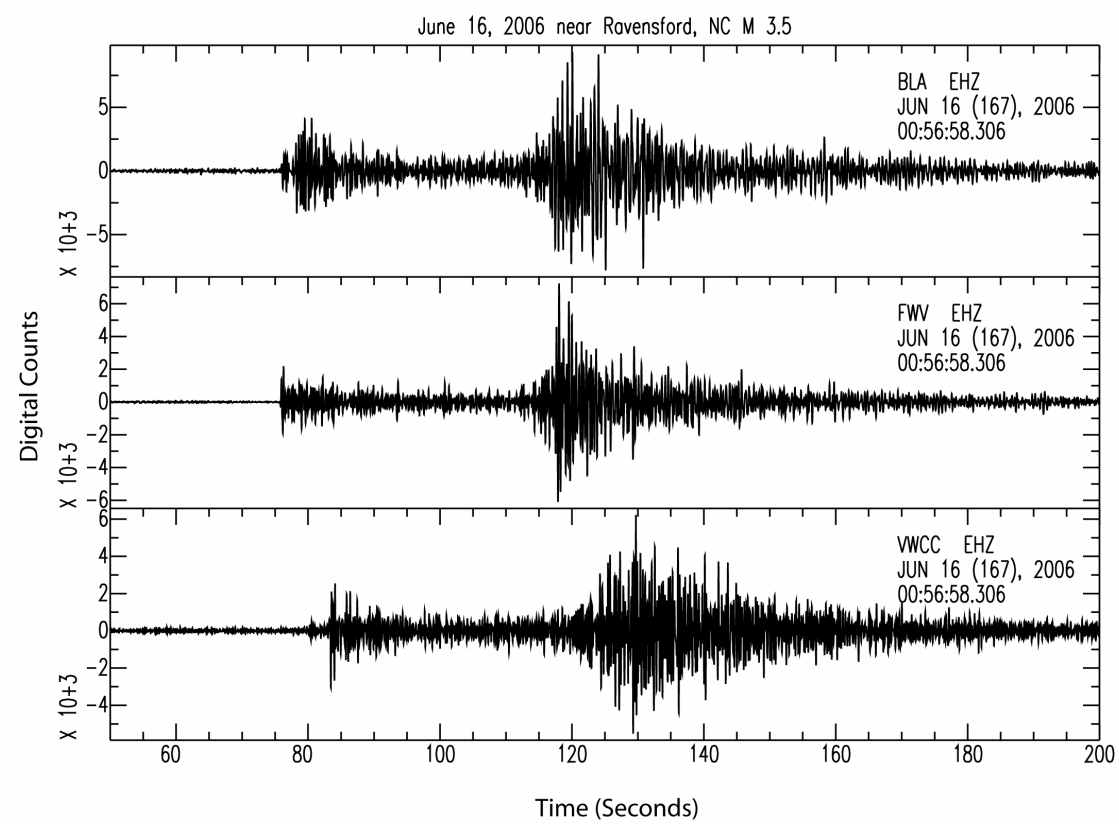

Figure 18. Seismograms from the Virginia Tech short-period stations for the 6/16/06 earthquake near Ravensford, North Carolina.

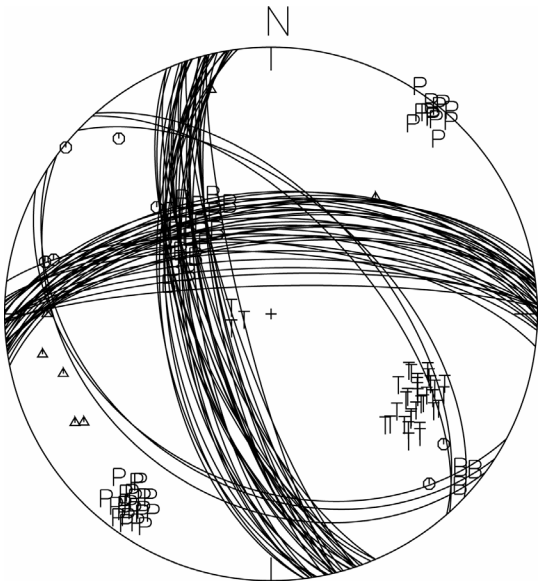

Figure 19. Lower hemisphere focal mechanism solution for the June 16, 2006 earthquake near Ravensford, North Carolina. P-wave compressions are shown as circles, dilatations are shown as triangles. P, T and B axes are indicated.

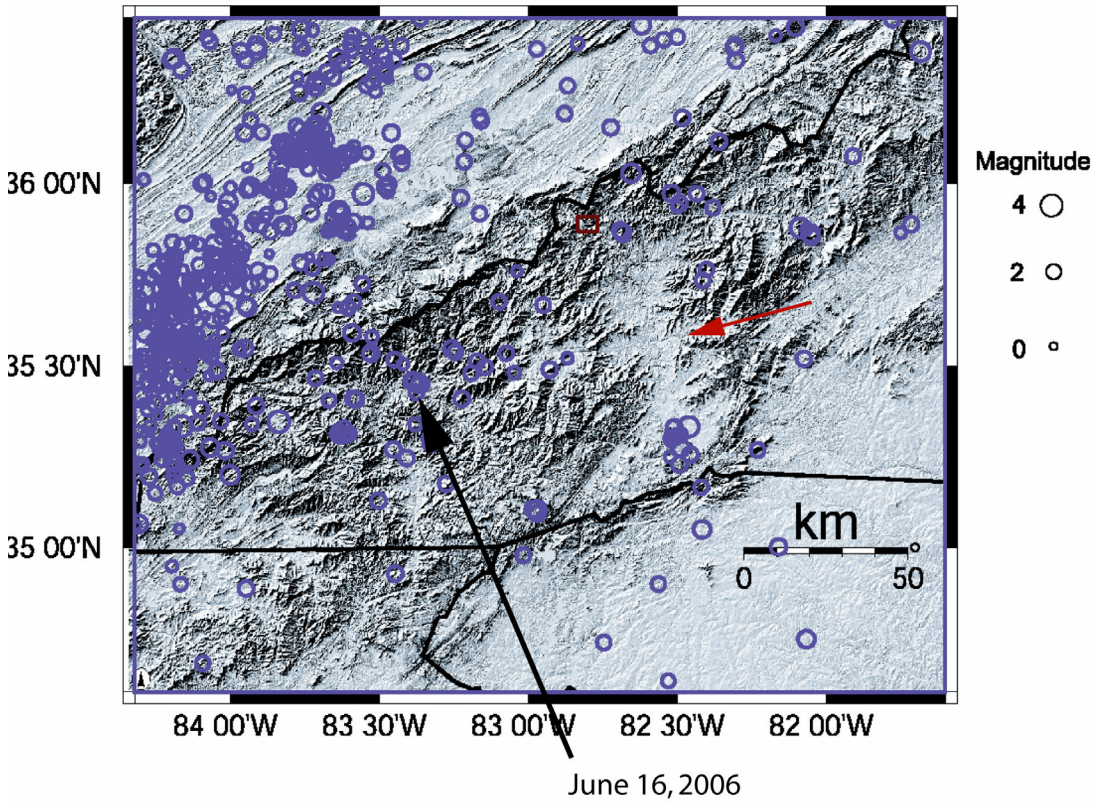

Figure 20. Epicenters of earthquakes in western North Carolina and southeastern Tennessee, 1983-2006. The black arrow indicates the epicenter of the June 16, 2006 event near Ravensford, NC. The red arrow indicates the E-W trending topographic valley known as the Swananoa lineament.

September 22 and September 25, 2006 events near Florence, South Carolina

On September 22 and 25, 2006, events of magnitude 3.5 and 3.7, respectively, occurred in northeastern South Carolina. Figure 21 shows the short-period recordings from the Va Tech Network. The events are notable for the unusual distribution of the felt reports. In both cases, the felt area appears skewed to the northwest of the epicenter. Figures 22 and 23 show the USGS community internet intensity maps for these two earthquakes. It is the author's opinion that the distribution of felt reports reflects the site response characteristics of the Cretaceous sands that are prevalent in the upper Coastal Plain in this area (Figure 24). Areas immediately to the northwest of the epicenter are underlain by relatively thin deposits of Cretaceous age, whereas areas to the southeast of the epicenters are underlain by much thicker deposits of younger sediments. It is likely that the younger (and thicker) deposits tend to amplify high-frequency motions somewhat less than the thinner Cretaceous sediments to the northwest.

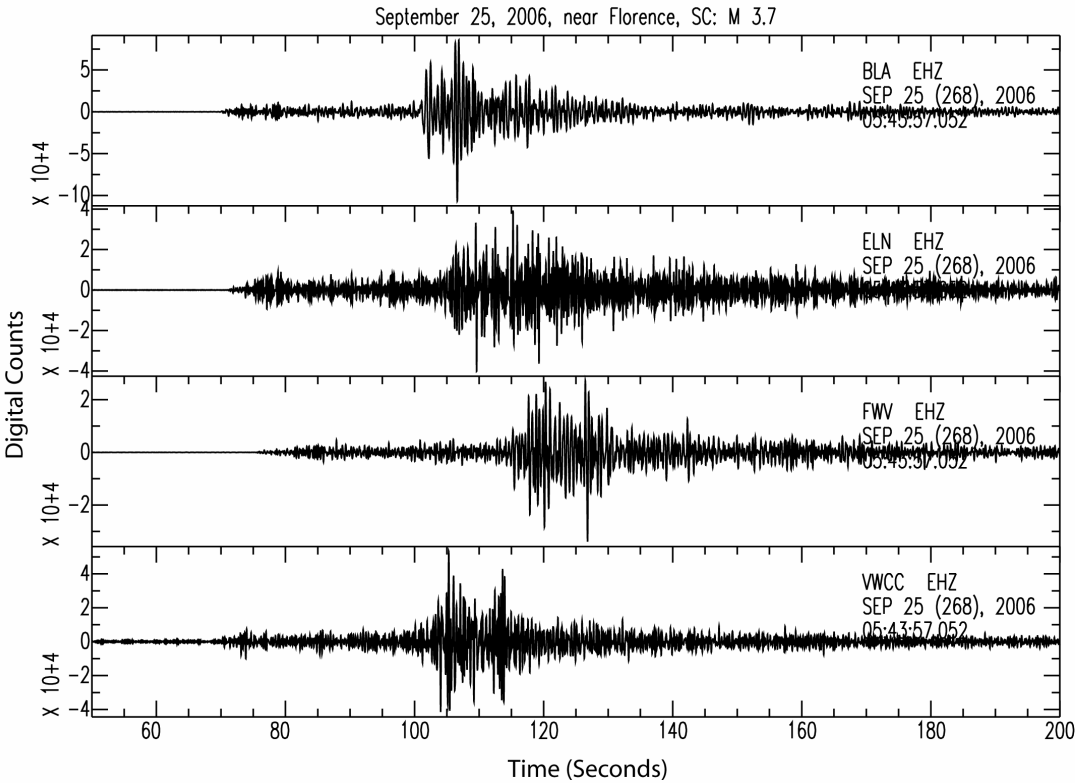

Figure 21. Seismograms from the Virginia Tech short-period stations for the 9/25/06 earthquake near Florence, South Carolina.

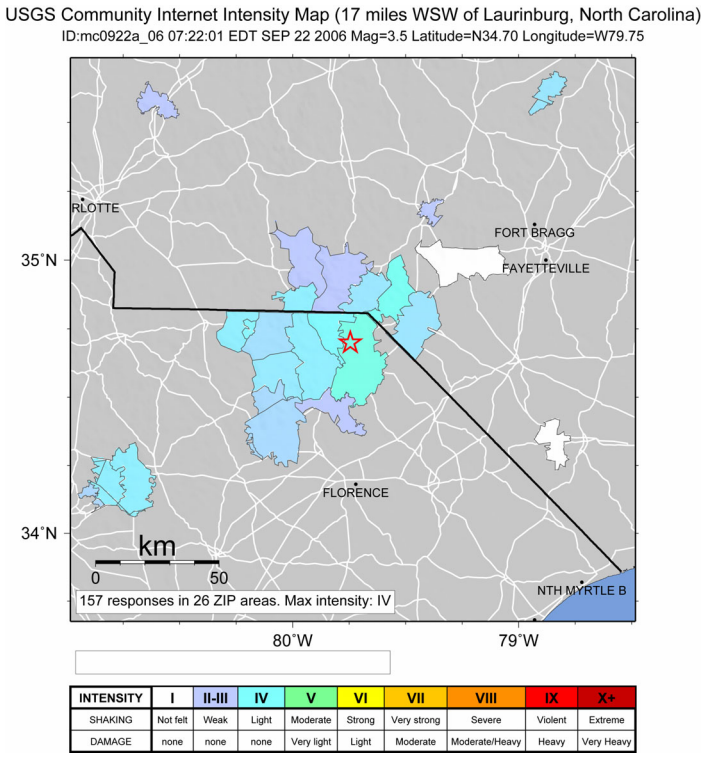

Figure 22. USGS community internet intensity map for the September 22, 2006 event in northeastern South Carolina.

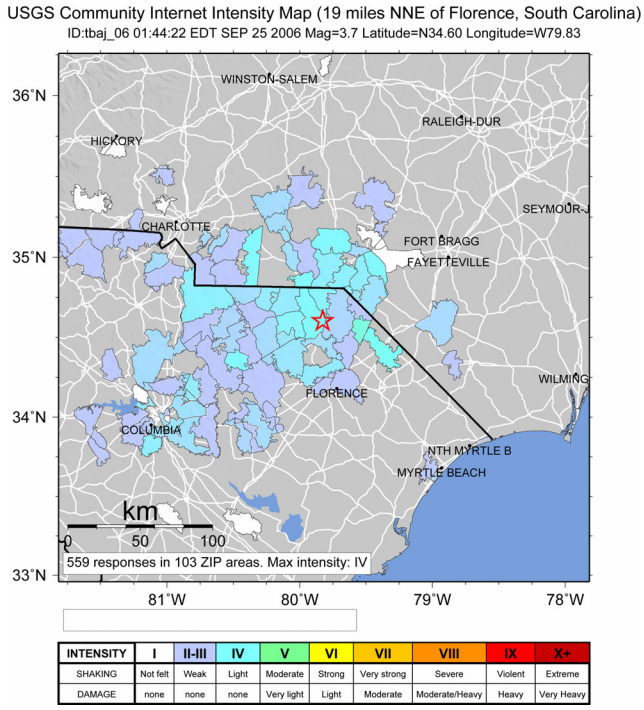

Figure 23. USGS community internet intensity map for the September 25, 2006 event in northeastern South Carolina.

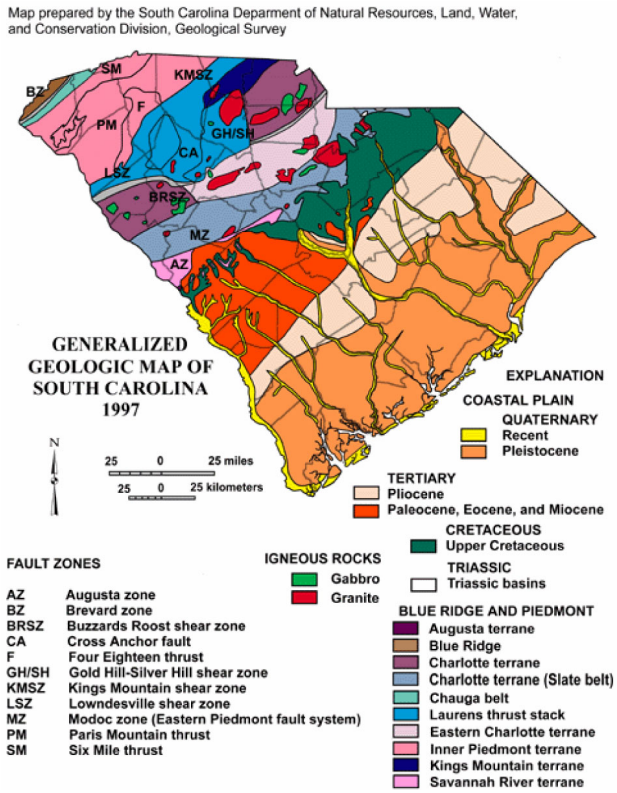

Figure 24. Generalized geologic map of South Carolina. Note that the area shown in dark green (Upper Cretaceous) corresponds to the area of maximum shaking intensity shown in Figures 22 and 23 above, for the September 22 and 25, 2006 events in northeastern South Carolina.

December 18, 2006 earthquake near Tellico Plains, TN, M 3.3

A magnitude 3.3 shock occurred in southeastern Tennessee (eastern Tennessee seismic zone) near the town of Tellico Plains on December 18, 2006. The following is the hypocenter determined by the author, using all available phase data, including arrival times from two nearby TVA strong motion stations (Blue Ridge Dam abutment, and Tellico Dam abutment).

Latitude: 35.3565N Longitude: 84.3470W depth: 14.91 km
08hr 34min 26.63sec UTC, December 18, 2006
Gap: 70 deg. , Dmin 10km
Hypoellipse SEH: 0.7km, SEZ: 1.5km.

Figure 25 shows the short-period recordings of this earthquake at the Va Tech seismic network. Figure 26 shows the focal mechanism derived by the author using P-wave first motion polarities. The mechanism is very well constrained, and indicates either right-normal oblique motion on a north-northeasterly striking plane or left-normal oblique motion on a west-striking plane. E-W and N-S trending nodal planes with strike-slip motion are frequently observed in the eastern Tennessee seismic zone (Chapman et al., 1997). In this case, however, there is a larger-than-usual component of normal slip.

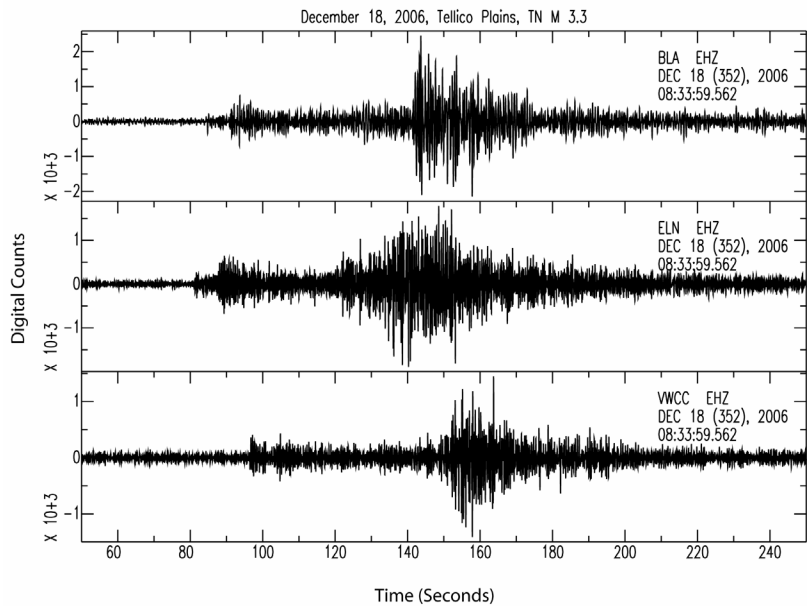

Figure 25. Short-period recordings from the Virginia Tech seismic network for the December 18, 2006, M 3.3 shock near Tellico Plains, TN.

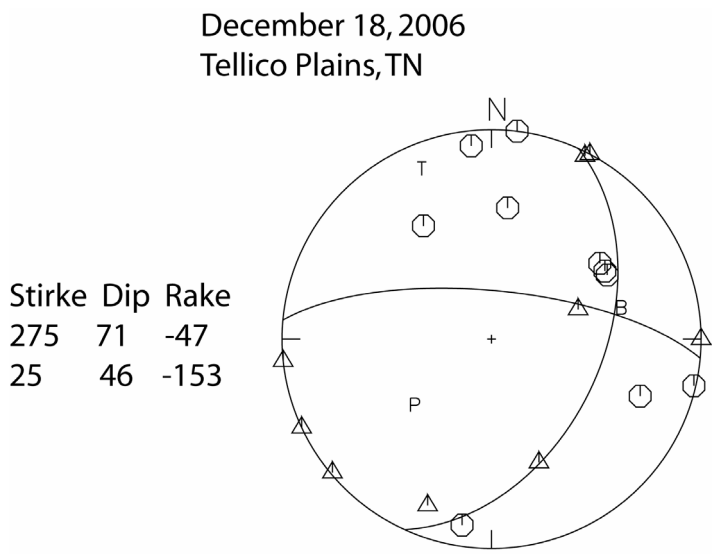

Figure 26. Focal mechanism for the December 18, 2006 Tellico Plains, TN earthquake derived using P-wave first motion polarities.

Earthquakes in Winston-Salem, North Carolina during 2006

A series of small earthquakes were experienced in Winston-Salem, North Carolina during 2006. The events apparently began in October, 2006 and continued until early November, 2006. The Va Tech network stations are the closest stations to the epicenters. This series of events is similar in all respects to those that have occurred on two different occasions in Richmond, Virginia. The events are apparently very shallow in this case, as indicated by prominent Raleigh wave arrivals. The following Table 1 gives

a listing of hypocenter coordinates determined by the author using all available data from all stations in the region.

Table 1
Hypocenters for the October-November, 2006 Earthquake Sequence
in Winston-Salem, NC

Date	hr m s	Lat N	Lon W	depth	#ph	Dmin	gap	seh	sez	Md
20061017	08:56:30.1	36.074	-80.290	2.4	20	127	83	1.7	2.5	2.9
20061017	23:54:49.8	36.102	-80.308	1.2	18	124	100	1.9	3.3	1.7
20061018	01:11:00.5	36.101	-80.303	2.0	18	124	100	1.1	1.8	3.1
20061018	15:47:29.0	36.104	-80.306	2.8	16	123	181	2.7	3.1	2.2
20061103	15:48:36.2	36.042	-80.258	2.1	11	122	181	1.4	2.4	2.5

All times UTC
depth in km: Dmin in km: gap in degrees: seh and sez in km, Md duration magnitude

Figure 27 shows the short-period recordings of the Va Tech network for the October 18, 01:11 UTC event.

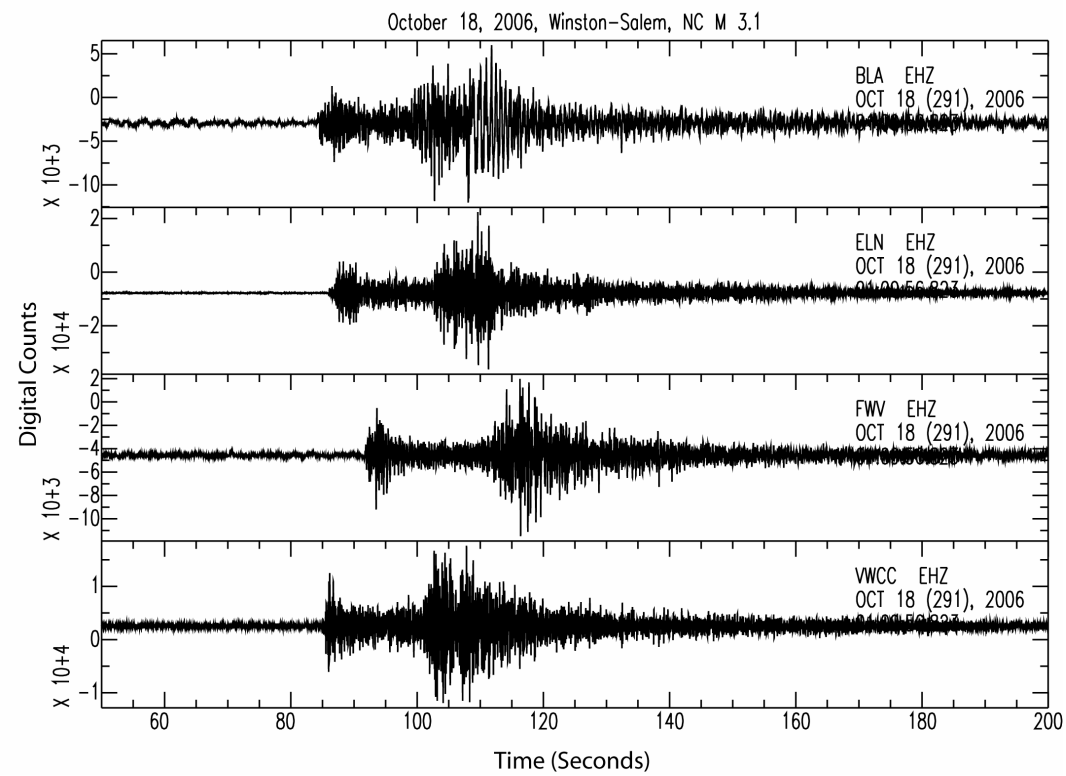

Figure 27. Short-period recordings from the Virginia Tech seismic network for the October 18, 2006, M 3.1 shock in Winston-Salem, NC. Note the Raleigh wave arrivals that are prominent on BLA. This indicates a very shallow focal depth.

Mining Induced Events During the Report Period

Mining Induced Events in Buchanan County, Southwestern Virginia

Several large mining induced events occurred in Buchanan County, Virginia during 2005 and 2006. They happen in response to extensive underground mining operations at the Consolidation Coal, Inc. Buchanan no. 1 mine, located in the Oakwood - Keen Mountain area of Buchanan County, Virginia. These events are NOT natural earthquakes, but somehow they have found their way as such into the ANSS catalog. The events also appear in the NEIC webpage listings as natural events. Table 2 below lists these events in chronological order.

Table 2
Mining Related Events During 2005-2006
Epicenter: 37.22N -81.90W

Date	Time (UTC)	mb(Lg)
February 8, 2005	11hr: 43min	2.6
February 14, 2005	21hr:16min	3.3
February 15, 2005	02hr:37min	3.4
February 15,2005	04hr:17min	2.3
October 31,2006	00hr:25min	2.6
November 2, 2006	17hr:53min	4.0
November 12, 2006	14hr:44min	
November 15, 2006	20hr:25min	
November 23, 2006	10:hr:42min	4.2

Seismic Event Associated with the January 2, 2006 Incident at Sago, WV

The author examined regional seismic network recordings for the time interval around 6:30 AM, EST January 2, 2006 to determine if the unfortunate event at the Sago mine was seismically recorded.

A small amplitude signal was identified on records at ANSS broadband station MCWV, near Mont Chateau, WV, the nearest seismic station to the mine. The signal was also recorded at larger distances by three Va Tech network stations to the south: FWV, ELN and BLA.

Figures 28 through 31 show the data recorded at stations MCWV, FWV, ELN and BLA respectively. The signals have been bandpass-filtered using a 3 pole Butterworth prototype with corner frequencies 1.0 and 5.0 Hz. The signal/noise ratios of these data are small, however, measurement of arrival times for P and S waves was possible. The estimated arrival times are given below in Table 3, *in Eastern Standard Time*.

Figure 32 shows the epicenter estimated using the arrival time data in Table 3. The locations were determined using the velocity model in Table 4, in conjunction with the computer program **Hypoellipse**. Table 5 gives hypocenter and origin time estimates for 3 cases.

The first case assumes that the focal depth of the source is near the ground surface, consistent with a mining-related source, but not necessarily located near the Sago mine. Latitude, longitude and origin time are treated as unknowns to be determined from the arrival time data. The origin time estimate in this case is 06:26:38.29 EST with standard error 1.65 seconds. The 68% confidence ellipse for the epicenter determined from the seismic data includes the Sago mine location (Figure 32). A 68% confidence interval for the origin time is 06:26:36.60 to 06:26:39.94 EST, assuming no systematic bias due to uncertainty associated with the velocity model in Table 4 or in phase arrival time measurement.

The second case is a completely un-constrained location, in which the latitude, longitude, focal depth and origin time are treated as unknowns to be determined. The computed epicenter is very near the Sago Mine location in this case (Figure 32). The estimated focal depth is shallow (2.5 km) but very poorly determined (68% confidence: 0 to 34 km). The 68% confidence interval for the origin time is 06:26:35.35 - 06:26:41.21 EST.

The third case assumes that the source occurred at the Sago mine, (Latitude 38.9407°N; Longitude 80.2030°W) with zero focal depth. The only free parameter to be determined is the origin time. The 68% confidence interval for the origin time is 06:26:36.46 - 06:26:40.00 EST.

Summary

The seismic signal recorded on January 2, 2006 at approximately 06:26 EST was caused by an underground disturbance at or near the Sago mine. Assuming that the source was at the Sago mine, a 68% confidence interval for the origin time is 06:26:36.46 - 06:26:40.00 EST. Simply put, the event most likely occurred within a 4 second interval centered at 06:26:38.2 AM. This estimate assumes no systematic error in phase arrival time determination, and/or bias in the seismic wave velocity model used for analysis. It is possible that the origin time estimate is slightly late, due to the very emergent nature of the P and S wave arrivals because of low signal/noise ratios at all the recording stations.

Table 3

Station	P arrival*			S arrival*		
	Hour	Minute	Second	Hour	Minute	Second
MCWV	06	26	52.6	06	27	3.5
FWV	06	27	5.1	06	27	24.1
ELN	06	27	9.0	06	27	32.7
BLA	06	27	9.7	06	27	32.2

*** All times are Eastern Standard Time.**

Table 4

P wave velocity (km/sec)	S wave velocity (km/sec)	Layer thickness (km)
5.63	3.43	5.7
6.05	3.52	9.0
6.53	3.84	36.0
8.18	4.78	–

Table 5

	Latitude	Longitude	Focal Depth	Origin Time*	Standard Error of Origin Time	Azimuth of Error Ellipse Semi-Major Axis	Major Axis Length	Minor Axis Length
Depth constrained	38.9243°N	80.1169°W	0 km (fixed)	06:26:38.29	1.65 s	286°	23 km	4.4 km
Depth unconstrained	38.9465°N	80.1920°W	2.45 km	06:26:38.28	2.93 s	289°	23 km	4.0 km
Depth and location constrained	38.9407°N (fixed)	80.2030°W (fixed)	0 km (fixed)	06:26:38.23	1.77 s			

*** All times are Eastern Standard Time.**

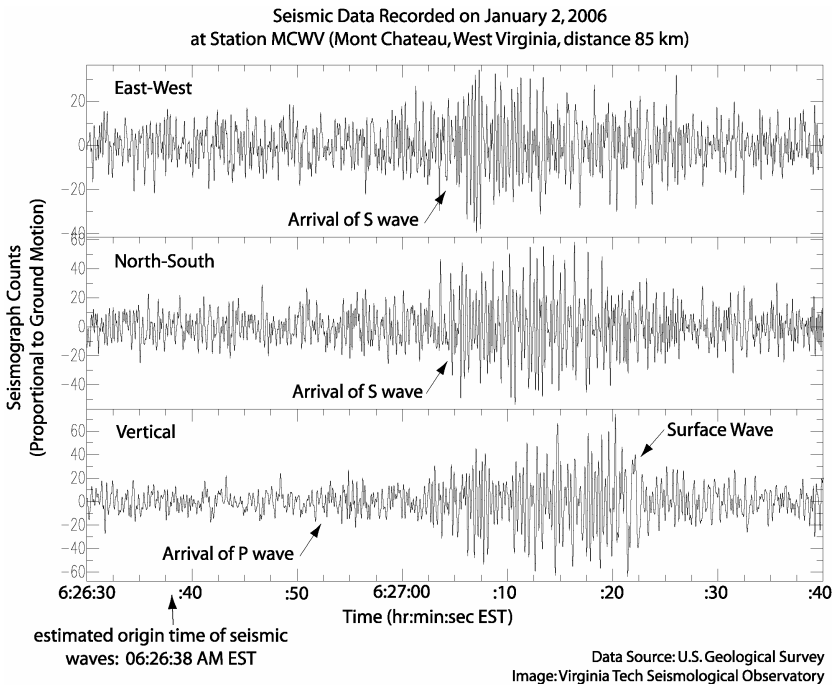

Figure 28. Waveforms recorded at station MCWV, 85.4 km from the assumed epicenter at 38.94065 degrees N, 80.20295 degrees W.

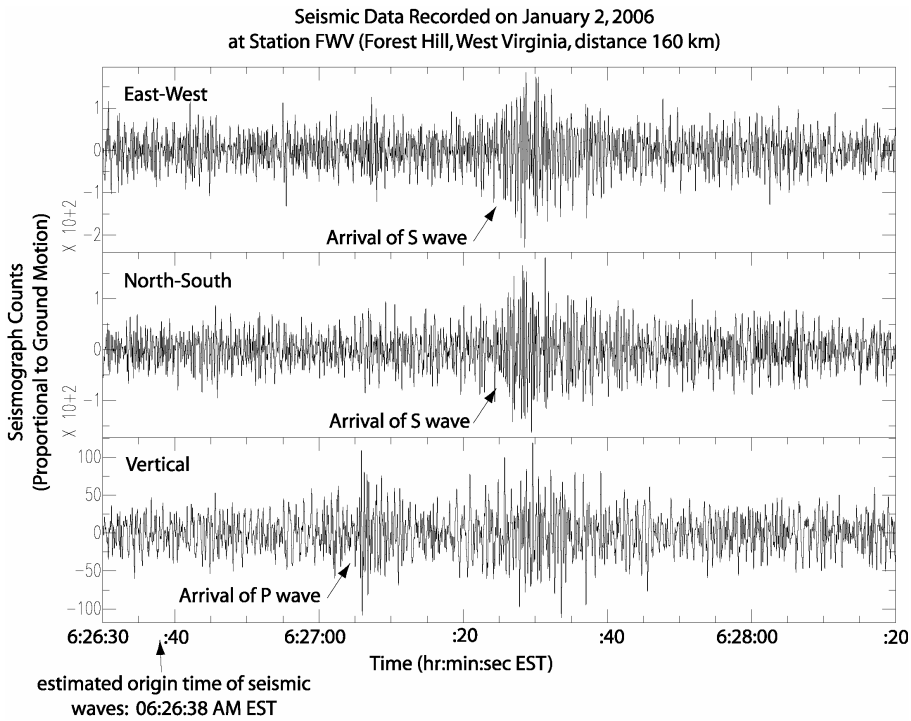

Figure 29. Waveforms recorded at station FWV, 160.1 km from the assumed epicenter at 38.94065 degrees N, 80.20295 degrees W.

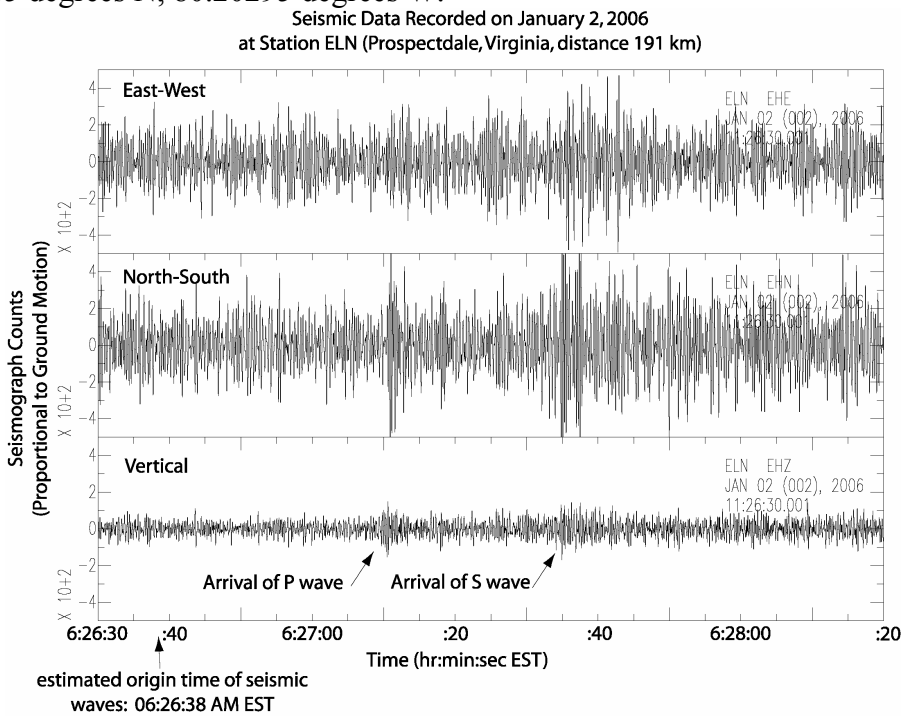

Figure 30. Waveforms recorded at station ELN, 190.5 km from the assumed epicenter at 38.94065 degrees N, 80.20295 degrees W.

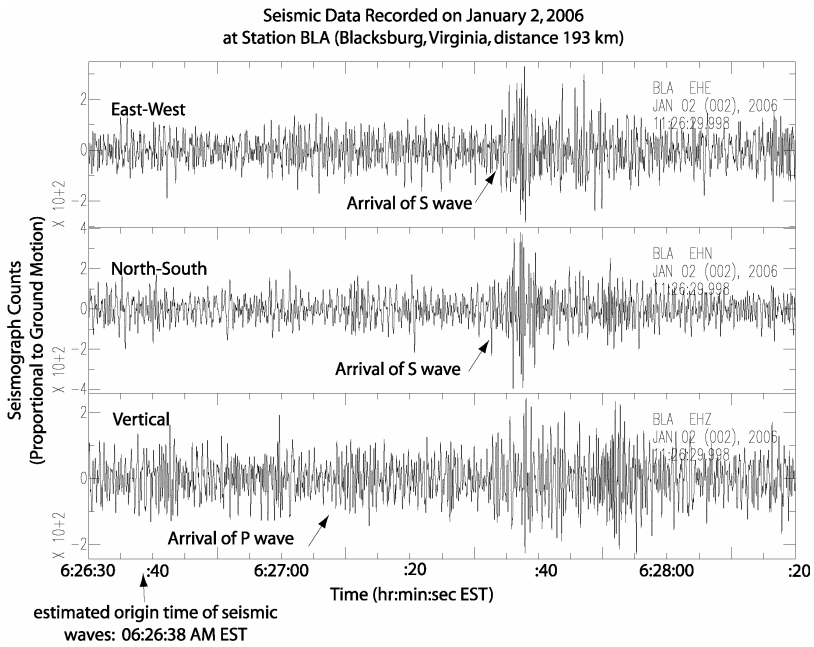

Figure 31. Waveforms recorded at station BLA, 192.9 km from the assumed epicenter at 38.94065 degrees N, 80.20295 degrees W.

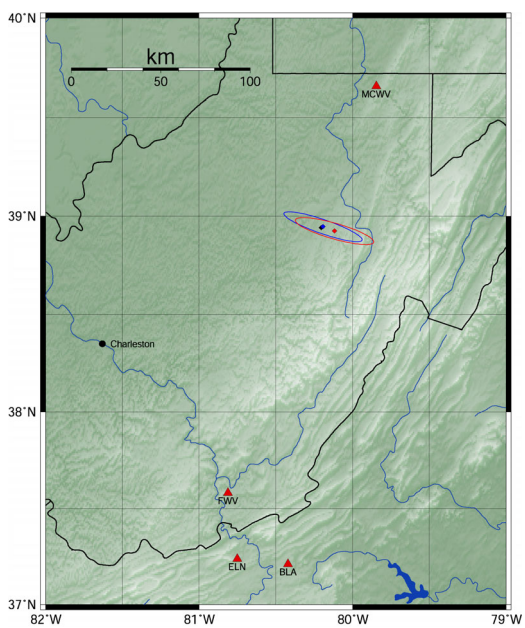

Figure 32. Map showing as a black diamond the assumed location of the Sago mine event (38.94065 degrees N, 80.20295 degrees W). The red diamond shows the epicenter determined using the arrival time data in Table 1 with focal depth fixed at the ground surface. The red line indicates 68% confidence ellipse for the epicenter location. The blue diamond is the epicenter estimated with the depth unconstrained. The blue line shows the corresponding 68% confidence ellipse. Seismic stations used in the location are indicated by the red triangles.

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