**Award Number 01HQAG0016**

# COOPERATIVE CENTRAL AND SOUTHEASTERN US INTEGRATED SEISMIC NETWORK-VPI&SU

**Final Report**

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## ABSTRACT

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 via publication of seismicity bulletins and an internet website: *(http://www.geol.vt.edu/outreach/vtso/).*

Five high-dynamic range, short period stations were operated during the 3 year project period in western Virginia and southern West Virginia. The data were ported to an EARTHWORM and exported to ANSS mid-America network operators and the U.S. Geological Survey NEIC. Three volumes of the Southeastern United States Seismic Network Bulletin were assembled and distributed. Twelve earthquakes local to the Virginia Tech seismic network were located during 2001 through 2003. Four of these events were reported felt. The largest occurred on December 9, 2003 in Goochland County, central Virginia. The magnitude was 4.5 (mblg). It was felt from southern North Carolina to Pennsylvania (approximately 200,000 sq km felt area). The shock was comprised of two nearly identical sub-events separated in time by 12 seconds. Only minor damage, amounting to cracks in plaster walls and broken windows, was reported (maximum Modified Mercalli intensity VI). The December 9, 2003 shock occurred in the most active part of the central Virginia seismic zone, near the mapped Lakeside fault. It is the largest shock instrumentally recorded in central Virginia, and may be the second largest shock in the historical record for that part of Virginia.

## 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 during the project period are shown in Figure 1. The stations are 3 component, short-period with 24-bit digitization. Telemetry to the central recording facility on-campus is by duplex digital VHF radio. Strong motion ANSS station CVVA in Charlottesville, VA became operational in late September, 2002, and is providing data for earthquake engineering applications, as well as helping to monitor the central Virginia area.

The digital network data are ported to an EARTHWORM system and are being exported to USGS NEIC in Golden, Co, CERI (University of Memphis), JIEE-TVA in Knoxville, TN and to the University of South Carolina in Columbia. Along with Virginia Tech, these institutions take advantage of the greatly increased efficiency provided by the EARTHWORM system. Virginia Tech and other collaborative institutions are committed to efficient data acquisition, analysis and dissemination under the auspices of the mid-America region 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 vertical components of the network.

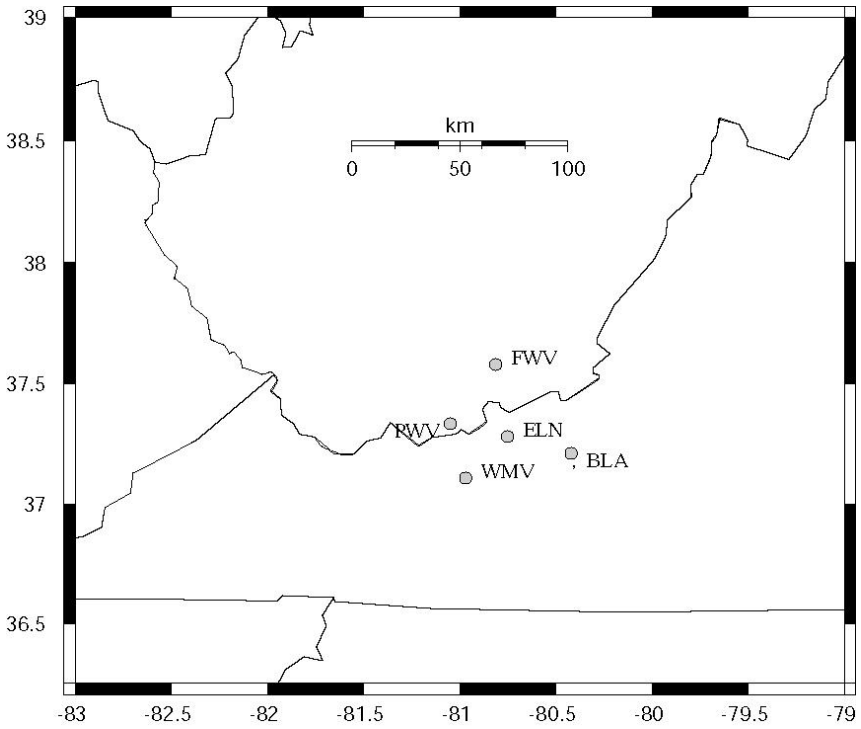



Figure 1. Circles show seismic stations operated by Virginia Tech.

**Seismicity in the vicinity of the Virginia Tech Network During the Project Period**

Figures 2 through 4 show the epicenters of earthquakes in the Southeastern U.S. region reported in volumes 36 through 38 of the Southeastern United Stated Seismic Network Bulletin, for 2001 - 2003.

*Local seismicity during 2001*

Table 1 lists the hypocenter locations and magnitudes of local shocks detected and located by this project during the three year report period. Virginia earthquakes during 2001 include a magnitude 2.5 shock on March 28, 2001 near the town of Narrows, in Giles County, western Virginia, a magnitude 2.5 shock near Culpeper, Virginia on June 25, 2001 that was felt locally, two small shocks (the largest, M 2.8) near Cumberland, Virginia on September 3, 2001 (neither were felt), a magnitude 3.2 shock IN Charlottesville, VA on September 22, 2001 (maximum intensity IV MM) that caused considerable consternation, confusion and disbelief on the eastern side of town. A magnitude 1.8 event occurred on October 1, 2001 near Roanoke, VA that was not reported felt. On November 8, 2001 a magnitude 1.8 event occurred 8 km northwest of Pulaski, VA and was not reported felt. This was followed on November 18, 2001 by a magnitude 1.6 shock near Blacksburg, VA that was not felt. A magnitude 3.1 (mblg) shock occurred near Forrest Hill, West Virginia on December 4, 2001. This latter event was large enough to have been felt but no reports were received. It occurred near the northernmost station FWV, (figure 1) in a sparsely populated area. The seismicity in western Virginia - southern West Virginia has been monitored by Virginia Tech since 1977 and is beginning to show a marked North-South alignment of epicenters. The December 4, 2001 event is one of the larger shocks to occur on this trend.

The September 22, 2001 Charlottesville, VA earthquake was notable for its shallow focal depth and location: it probably occurred within the eastern city limits. Most residents on the eastern side of Charlottesville both felt and heard the shock, and many called the local officials. Initially, the sheriff's department reported that the cause of the event was unknown, but possibly a sonic boom. The author was able to confirm the fact that the event was an earthquake, and distributed that information to the local authorities, press and public.

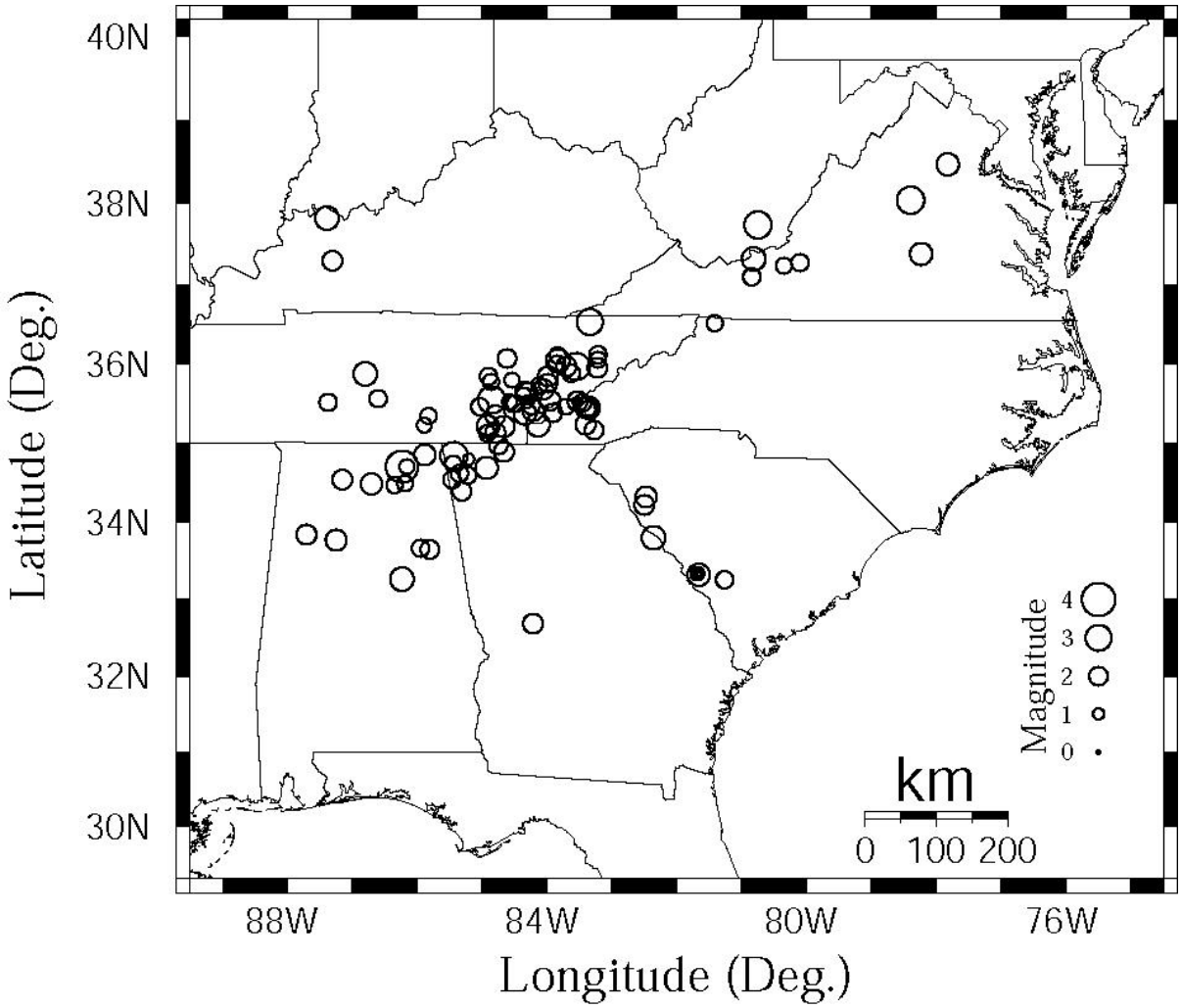



Figure 2. Epicenters of earthquakes occurring during 2001 and contained in the Southeastern U.S. Seismic Network Bulletin No. 36.

*Local seismicity during 2002*

2002 was an unusual year in terms of seismicity near the Virginia Tech network stations. No local shocks were detected, although eastern Tennessee remained active at average levels (Figure 3).

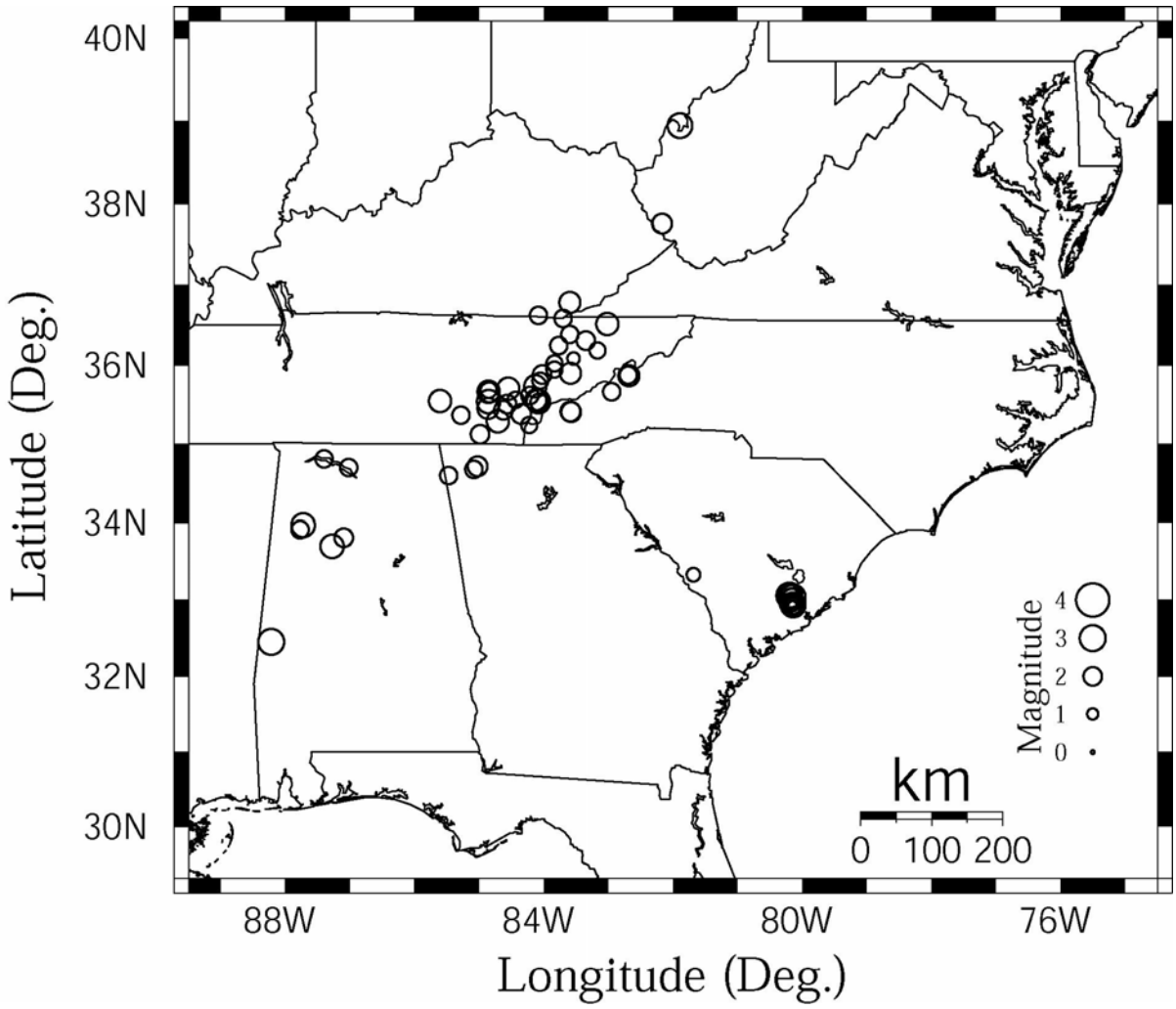



Figure 3. Epicenters of earthquakes occurring during 2002 and contained in the Southeastern U.S. Seismic Network Bulletin No. 37.

*Local seismicity during 2003*

Three earthquakes occurred in central Virginia in 2003 (Table 1). Figure 4 shows the seismicity of the southeastern U.S. region for 2003.

On May 5, 2003 a magnitude 3.9 (mblg) shock occurred near Cartersville, Virginia, in the central Virginia seismic zone. It was felt in several counties in central Virginia. Figure 5 shows the USGS community internet intensity map of the event. Maximum intensity was IV-V MM. No damage was reported. The nearest station distance was 86 km, so the depth of the shock is highly uncertain. It occurred in the most active part of the central Virginia seismic zone, which is along the James River, and includes the counties of Fluvanna, Buckingham, Cumberland, Goochland and Powhatan. Robert Herrmann (personal communication) derived a focal mechanism solution.

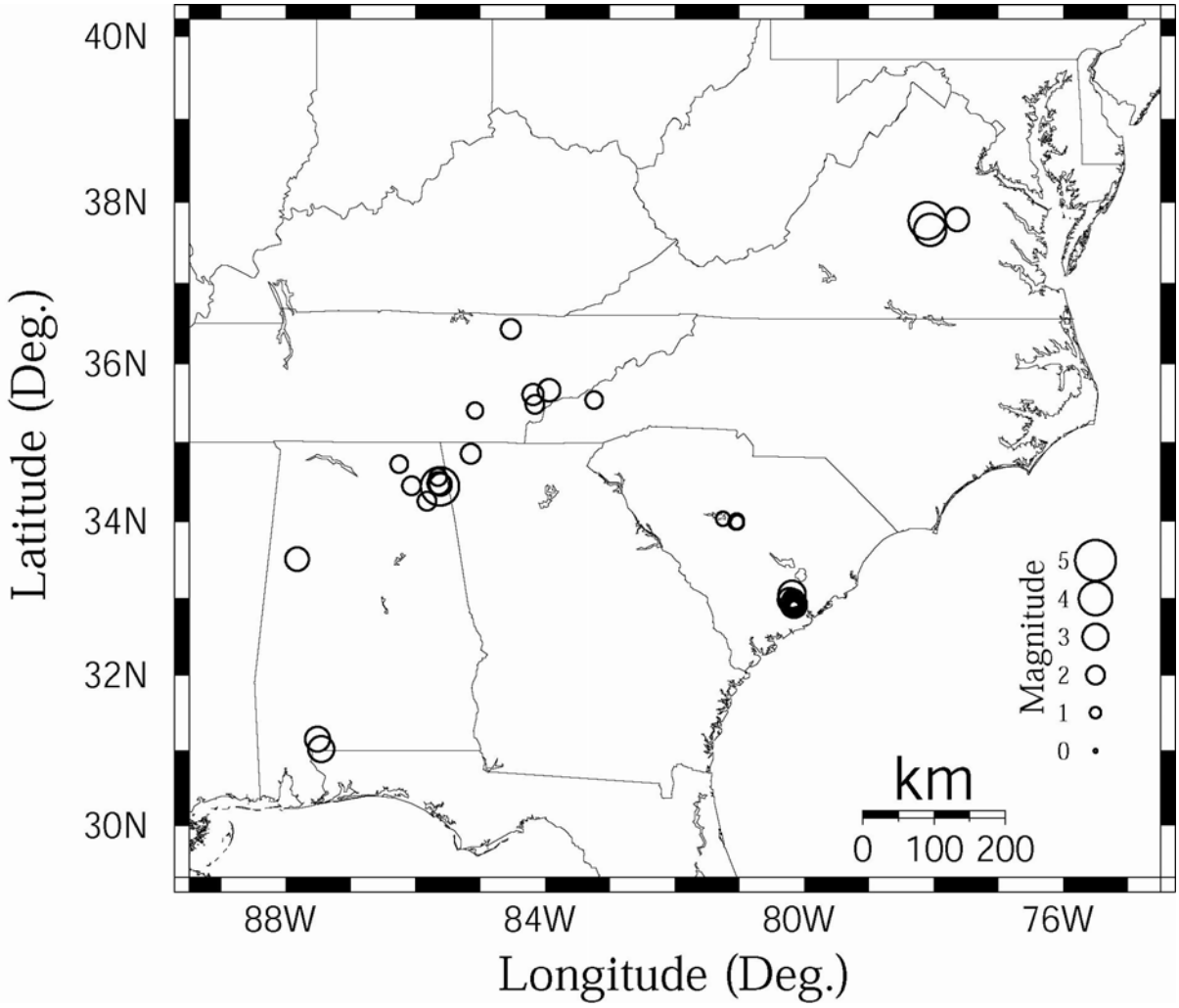
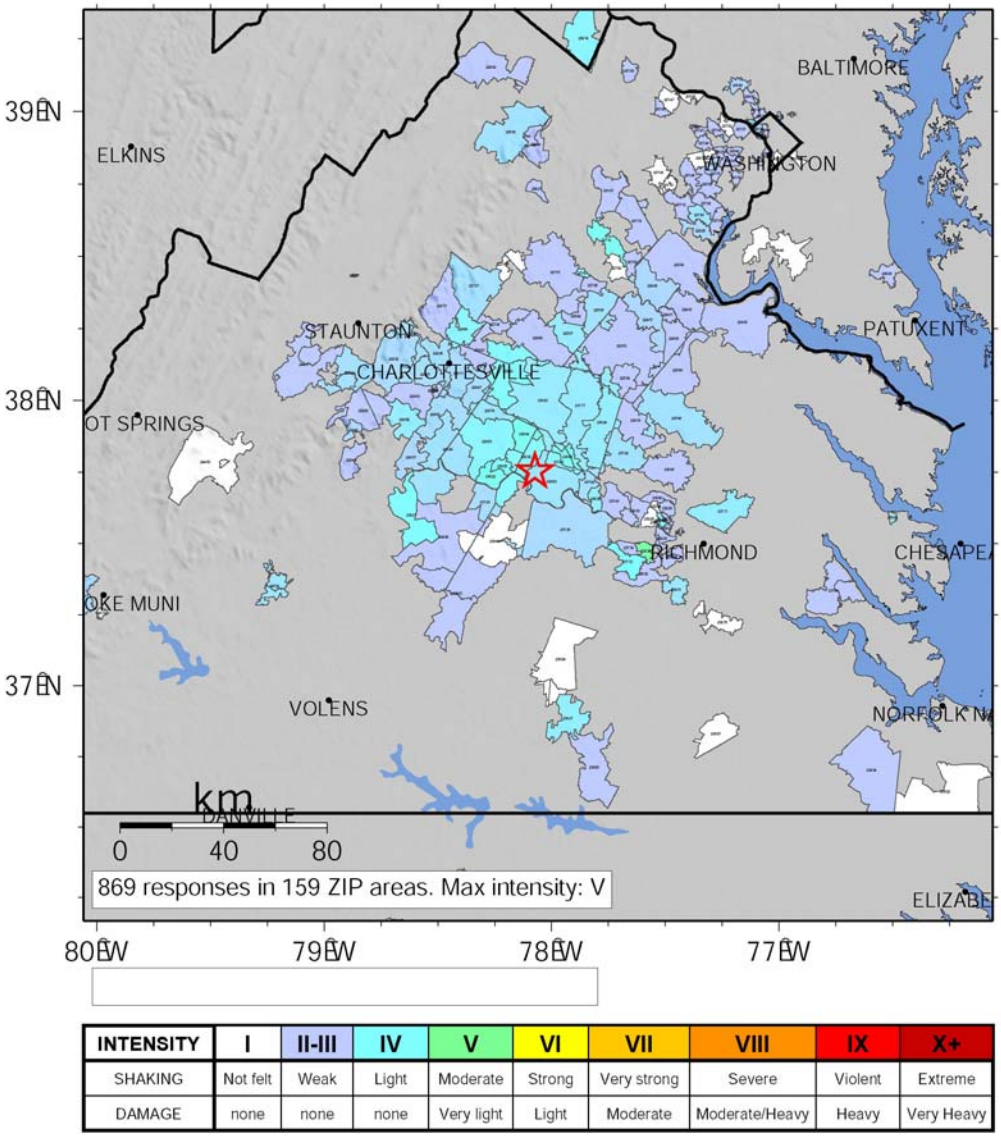



Figure 4. Epicenters of earthquakes occurring during 2003 and contained in the Southeastern U.S. Seismic Network Bulletin No. 38.

The strike, dip and rake (in degrees) for the May 5, 2003 central Virginia earthquake (derived by Robert Hermann) are as follows:

nodal plane 1:
strike: 3, dip: 71 rake: 158

nodal plane 2:
strike: 100, dip: 70 rake: 20.




| INTENSITY | I | II-III | IV | V | VI | VII | VIII | IX | X+ |
|---|---|---|---|---|---|---|---|---|---|
| SHAKING | Not felt | Weak | Light | Moderate | Strong | Very strong | Severe | Violent | Extreme |
| DAMAGE | none | none | none | Very light | Light | Moderate | Moderate/Heavy | Heavy | Very Heavy |

Figure 5. U.S. Geological Survey community internet intensity map for the May 5, 2003 central Virginia earthquake. Maximum intensity was IV to V.

Figure 6 shows the instrumentally located seismicity of central Virginia (from 1978 to date). Figure 7 shows all focal mechanism solutions for shocks in central Virginia. The mechanism for the May 5, 2003 shock derived by Robert Herrmann indicates primarily right-lateral strike-slip on the northerly striking plane or left-lateral motion on the easterly striking plane.

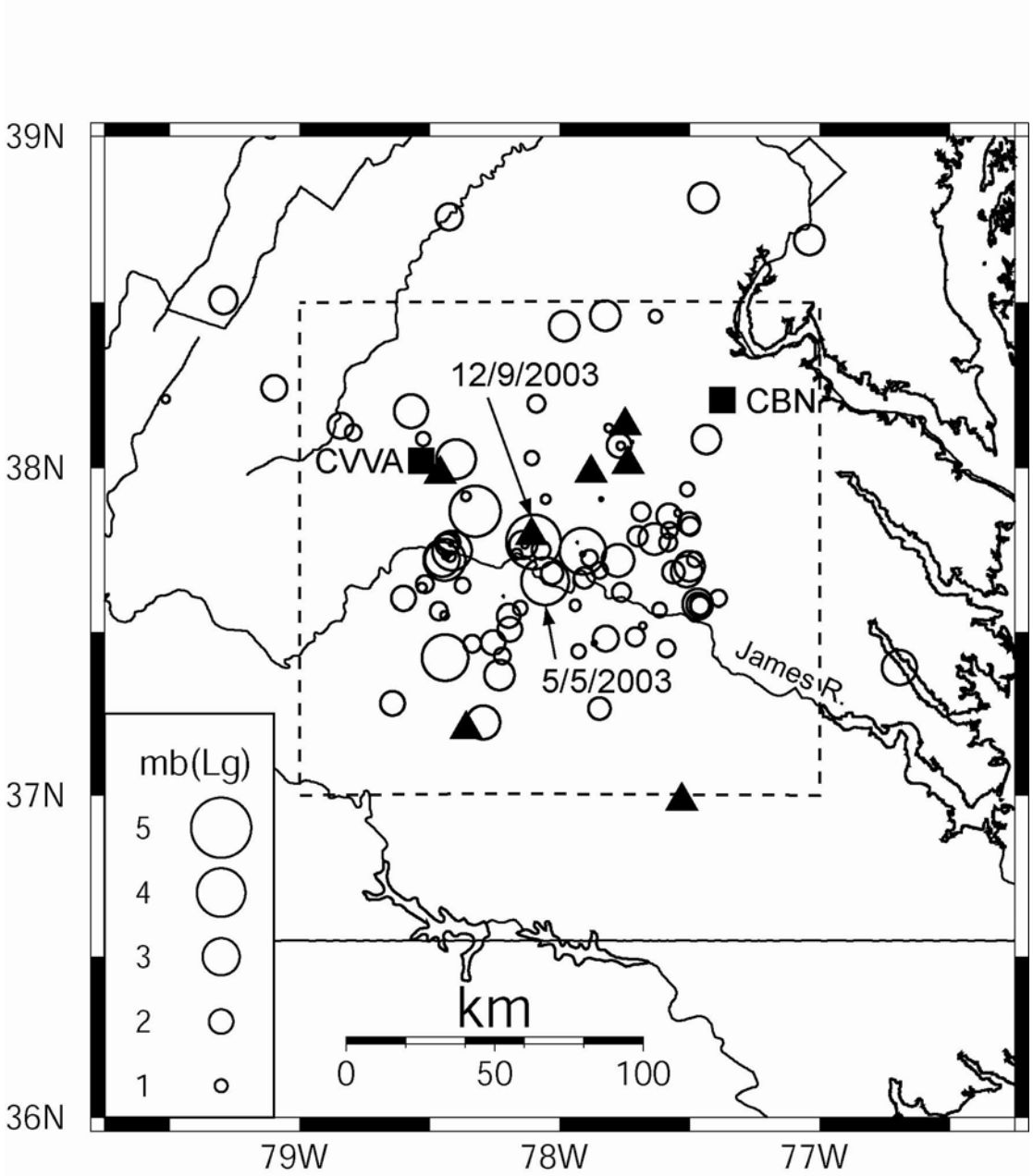



Figure 6. Epicenters of earthquakes instrumentally located in central Virginia from 1978 to Present. The triangles show the locations of Va Tech seismic network stations operational in the area through 1996. The squares show the locations of stations CVVA (an ANSS strong motion station installed in 2002), and CBN (an ANSS broadband station) that are currently operational in the central Virginia area. Epicenters of the May 5 and December 9, 2003 shocks are indicated.

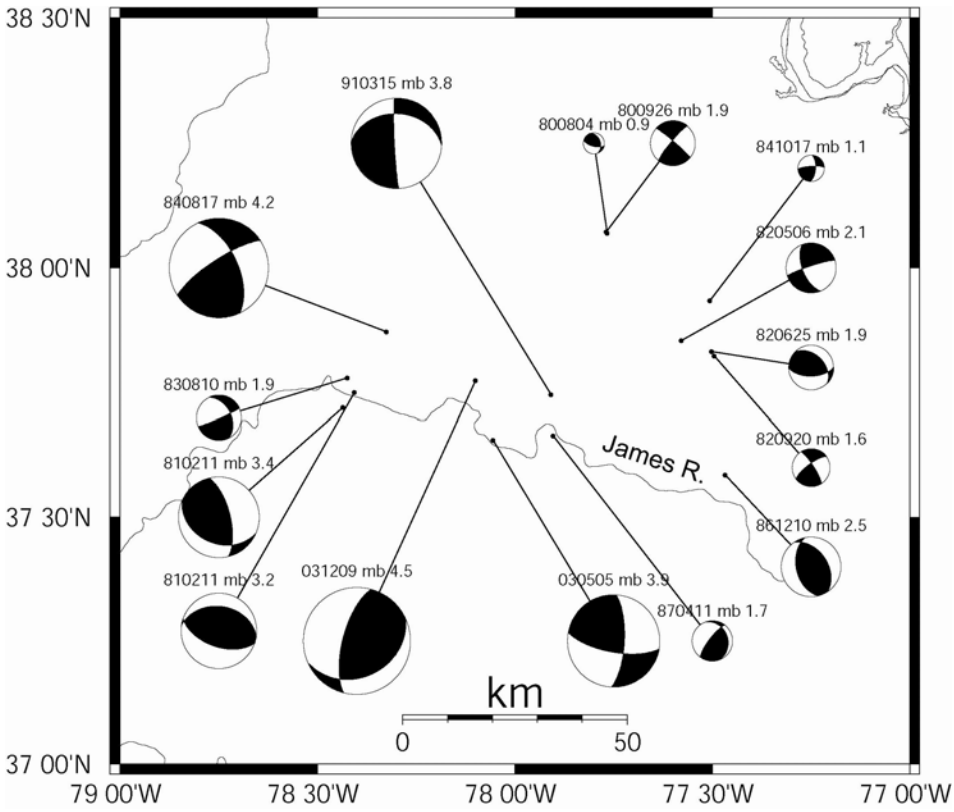
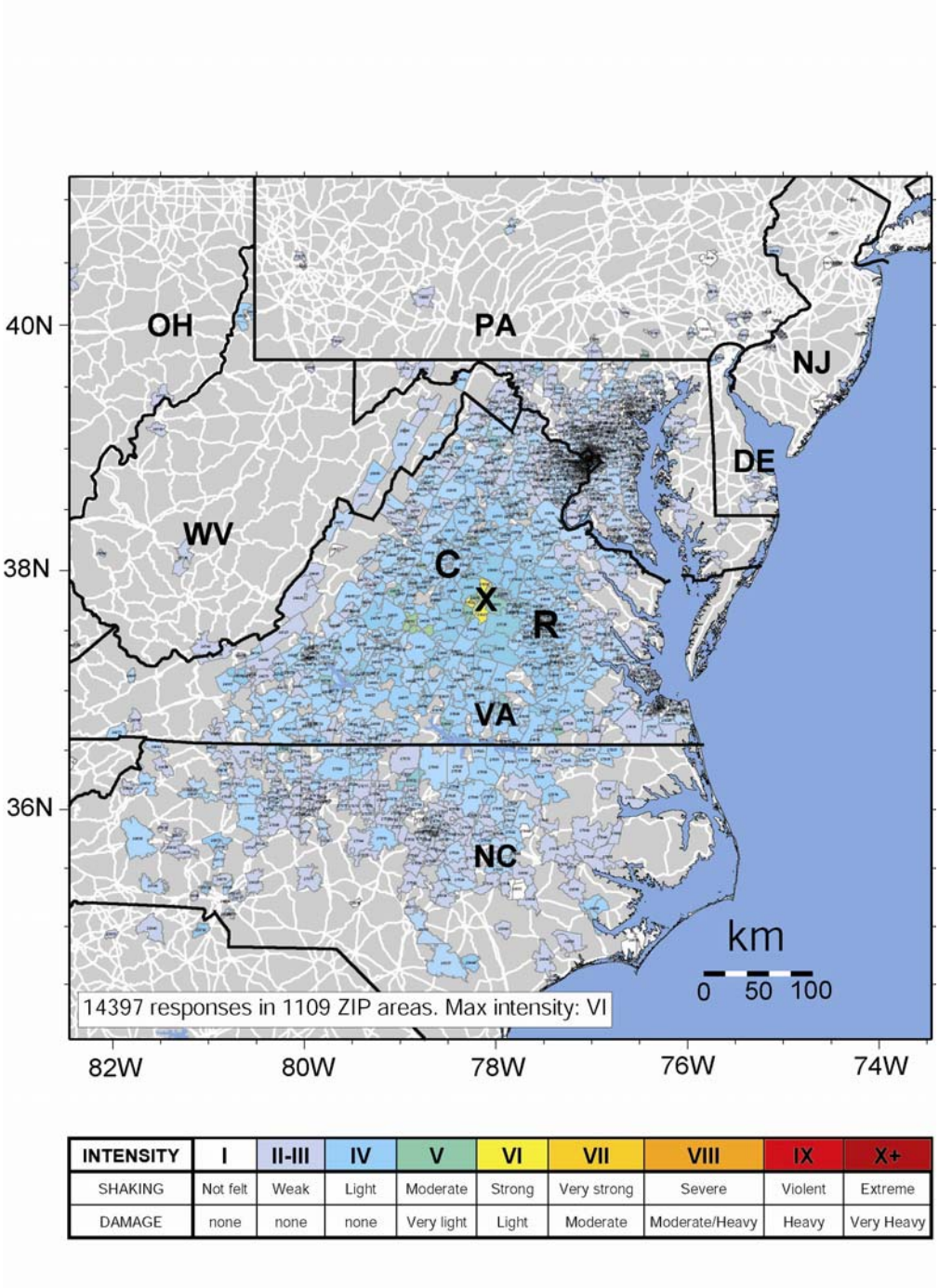



Figure 7. The focal mechanisms of earthquakes obtained to date in the central Virginia seismic zone. The two mechanisms obtained during the report period are for the mblg 3.9 shock on May 5, 2003 (030505) and December 9, 2003 (031209, mb 4.5). Note that the mechanisms indicate thrust and strike-slip motions and a compressional stress regime, but with a wide range of maximum compression axis orientation.

On November 6, 2003 a magnitude 2.6 (mblg) shock occurred near Rockville, VA. It was not reported felt.

The largest earthquake instrumentally recorded to date in central Virginia occurred on December 9, 2003. The USGS NEIC mb magnitude estimate is 4.5. Figure 8 shows the U.S. Geological survey community internet intensity map for this shock. The preliminary NEIC epicenter location was in central Powhatan county, well south of the James River. The author was able to improve this preliminary location by applying a region specific velocity model and by incorporating arrival time data from ANSS strong motion station CVVA and S wave arrivals from short period regional network stations. This event was actually two separate, virtually identical earthquakes separated in time by 12 seconds and in space by less than 1 km (Kim and Chapman, in preparation). The epicenter location derived by the author (see also Table 1) is 37.774N, 78.100W, with HYPOELLIPSE horizontal error estimate 8.8 km. The focal depth is not usefully constrained by the arrival time data, and was fixed at 10 km. The nearest station (CVVA) distance is 47 km. Only one other station (CBN) is within 200 km of the epicenter. The epicenter cited above (Table 1), and shown in Figures 6, 7 and 8 is in western Goochland County, near the small community of Fife. It is approximately 20

km to the northwest of the preliminary location communicated in most early media reports. It lies within the area of maximum shaking intensity, in western Goochland, eastern Fluvanna, and northern Cumberland counties.




| INTENSITY | I | II-III | IV | V | VI | VII | VIII | IX | X+ |
|---|---|---|---|---|---|---|---|---|---|
| SHAKING | Not felt | Weak | Light | Moderate | Strong | Very strong | Severe | Violent | Extreme |
| DAMAGE | none | none | none | Very light | Light | Moderate | Moderate/Heavy | Heavy | Very Heavy |

Figure 8. Adapted from the U.S. Geological Survey community internet intensity map of the December 9, 2003 central Virginia earthquake. The X indicates the instrumental epicenter. Locations of Charlottesville and Richmond are indicated by C and R, respectively.

The December 9, 2003 shock was felt over approximately 200,000 sq. km, in much of Virginia, Maryland, Washington, DC and in north-central North Carolina, and a few areas of Delaware, New Jersey, New York, Pennsylvania, West Virginia and Ohio. The shock attained a maximum modified Mercalli (MM) intensity of VI near the epicenter with reports of slight damage at Bremo Bluff and Kents Store, Va. (*Preliminary Determination of Epicenters*, weekly listing).

Initial reports indicated an unusually long duration for a magnitude 4.5 earthquake. Many persons reported duration of shaking lasting up to 30 seconds. Observers in the epicentral area and many at distant locations (e.g., Waynesboro and Blacksburg, VA) reported feeling two successive "bumps" with approximately ten-second time separation. Seismograms at stations in western Virginia (Figure 9) indicated that the event was actually two earthquakes of equal magnitude. No aftershocks were reported immediately following the earthquake, and interviews with persons in the epicentral area suggest that none were felt. Three days after the 9 December 2003 shock, a temporary network of five broadband seismographs was installed by a field crew from CERI (Center for Earthquake Research & Information, University of Memphis) and Virginia Tech in the epicentral area. No aftershocks were recorded during one month of deployment.

The source mechanism determined from regional waveform inversion indicates predominantly thrust-faulting at a depth of about 10 (±2) km (Kim and Chapman, in preparation). The shock with combined sub-events attained the seismic moment, $M_0$ =2.64 (±1.01) × $10^{15}$ N m (Mw 4.3). It is likely that the two sub-events occurred on the same fault plane striking NNE–SSW (190°) and dipping steeply to the west (dip=69°). The two sub-events may have ruptured a combined area of about 400 m in radius on a 800 m long NNE − SSW trending fault. A static stress drop, $\Delta\sigma$, of 180 (±69) bars is estimated assuming the source radius of about 400 m for the two sub-events. The focal mechanism indicates a subhorizontal *P*-axis trending N301°E and plunging 19° . Similar to several other previously determined focal mechanism solutions in central Virginia (Figure 7), the P-axis orientation of the December 9, 2003 event is not consistent with the N60-65°E regional average trend of the maximum horizontal compressional stress ($S_{Hmax}$) in eastern North America. The local stress field around the 9 December 2003 event is, therefore, rotated at least about 45° clockwise relative to that of average ENA. Figure 7 shows that focal mechanisms in central Virginia are variable, suggesting a complex stress regime.

The seismicity in this area occurs in the depth range from near surface to 16 km, in allochthonous metamorphic and igneous rocks of Proterozoic and Paleozoic age that have a complex history of ductile and brittle deformation.

The December 9, 2003 earthquake has a well-constrained focal depth of 10+/-2 km from the waveform inversion (Kim and Chapman, in preparation). This depth is consistent with the depths of other shocks in the central Virginia seismic zone that were accurately located by the local network prior to 1996. The seismic reflection data in the seismic zone show that this recent event and other well-located shocks in the western Goochland and Chopawamsic terranes of the central Virginia Piedmont occurred in allochthonous rock: hence, they could be related to Paleozoic thrusts. The epicenter of the December 9 shock is approximately 6 km to the northwest of the Spotsylvania high strain zone. Even in view of the large uncertainty in the epicenter (Hypoellipse SEH 9.0 km) it seems unlikely that the

event was related to that feature. However, two other major Paleozoic faults are certainly plausible candidates. The Lakeside Fault is mapped 2 km to the southeast of the epicenter and the Little Fork Church Fault is approximately 2.5 km to the northwest of the epicenter (David Spears, personal communication). It seems possible that the earthquake may have been associated with either the Lakeside or Little Fork Church faults. It is equally possible that it was unrelated to any mapped fault. The focal mechanism indicates a strike somewhat consistent with the mapped faults, but the steep 69 degree dip to the west is not consistent with an eastward dipping thrust that would presumably be subhorizontal at the focal depth.

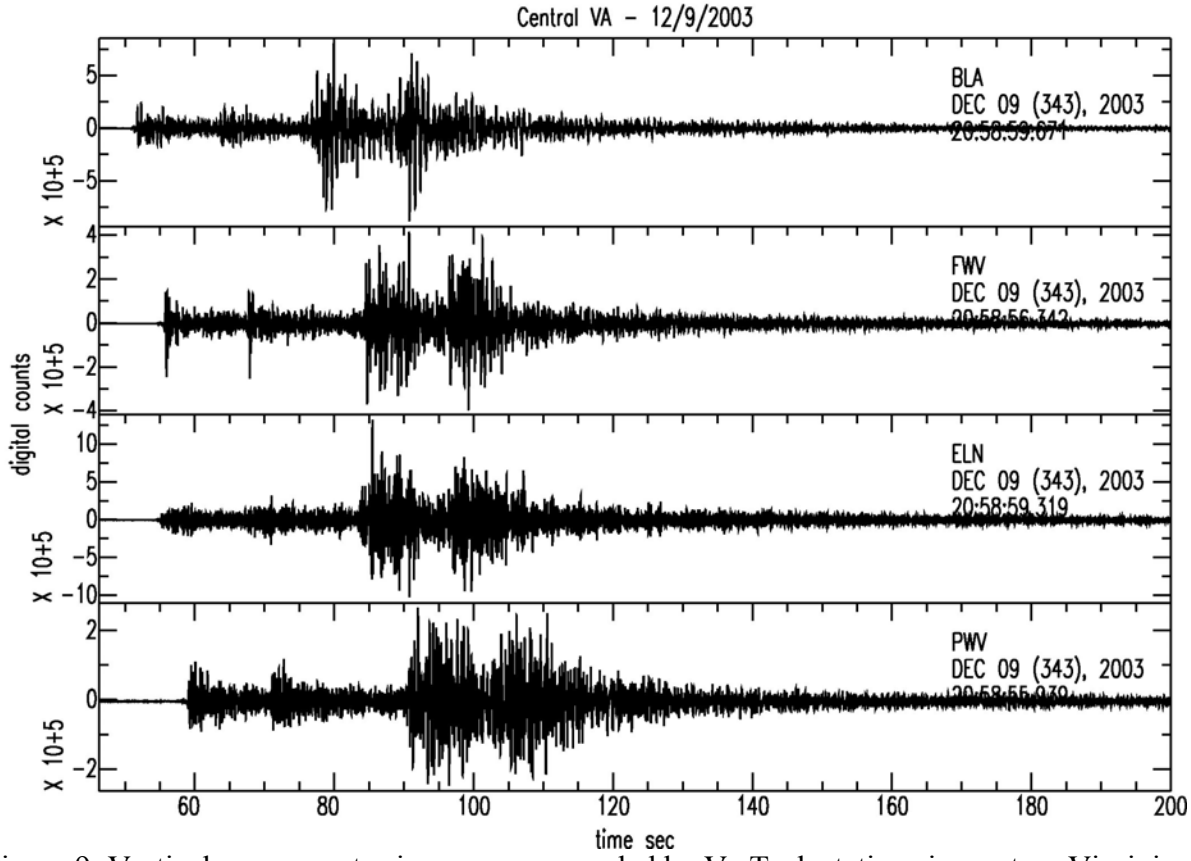



Figure 9: Vertical component seismograms recorded by Va Tech stations in western Virginia from the December 9, 2003 central Virginia shock. Note that the earthquake was a double event, comprised of two nearly identical sub-events separated by 12 seconds.

**TABLE 1**

**Local Earthquakes Detected, 2001-2003**

| Date (UTC) yr/mo/da | origin time Hr:Mn:S | Lat. Deg. | Lon. Deg. | Depth km | Mag mblg | Intensity MM |
|---|---|---|---|---|---|---|
| 2001/03/28 | 11:19:24.6 | 37.310 | 80.812 | 0.1 | 2.6 | not felt |
| 2001/06/25 | 23:04:48.2 | 38.460 | 77.824 | 5.0F | 2.5 | III |
| 2001/09/03 | 02:05:57.9 | 37.369 | 78.231 | 5.0F | 2.5 | not felt |
| 2001/09/22 | 16:01:20.6 | 38.026 | 78.396 | 0.4 | 3.2 | IV |
| 2001/10/01 | 09:55:59.5 | 37.262 | 80.099 | 11.2 | 1.8 | not felt |
| 2001/11/08 | 01:15:12.2 | 37.090 | 80.840 | 3.6 | 1.8 | not felt |
| 2001/11/18 | 17:15:45.3 | 37.226 | 80.344 | 11.6 | 1.6 | not felt |
| 2001/12/04 | 21:15:13.9 | 37.726 | 80.752 | 8.5 | 3.1 | not felt |
| 2002/03/27 | 08:25:03.3 | 37.753 | 82.171 | 7.7 | 2.1 | not felt |
| 2003/05/05 | 16:32:33.9 | 37.655 | 78.055 | 2.8 | 3.9 | IV-V |
| 2003/11/06 | 12:22:49.2 | 37.783 | 77.634 | 9.5 | 2.6 | not felt |
| 2003/12/09 | 20:59:18.7 | 37.774 | 78.100 | 10.0F | 4.5 | VI |

## PROJECT PUBLICATIONS


Dunn, M. M. and M. C. Chapman (2004) Relocation of eastern Tennessee earthquakes using HYPODD, Seismological Research Letters,75, no. 3, p. 440.

Kim, W.-Y. and M. Chapman (2004) The 9 December 2003 central Virginia earthquake, Seismological Research Letters, 74, no. 2, p. 286.

Kim, W. -Y. and M. Chapman(2005). The 9 December 2003, Mw 4.3 Central Virginia, Earthquake: A Complex Event in the Central Virginia Seismic Zone, submitted to Bulletin of the Seismological Society of America.

Southeastern U.S. Seismic Network Operators, (2001). *Southeastern U. S. Seismic Network Bulletin No. 35*, (compiled by M. C. Chapman, E. C. Mathena), Virginia Tech Seismological Observatory, Dept. Geological Sciences, Blacksburg, Va, 67 p.

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Southeastern U.S. Seismic Network Operators, (2002). *Southeastern U. S. Seismic Network Bulletin No. 37*, (compiled by M. C. Chapman, E. C. Mathena), Virginia Tech Seismological Observatory, Dept. Geological Sciences, Blacksburg, Va, 53 p.

Southeastern U.S. Seismic Network Operators, (2004). *Southeastern U. S. Seismic Network Bulletin No. 38*, (compiled by M. C. Chapman, E. C. Mathena and J. A. Snoke), Virginia Tech Seismological Observatory, Dept. Geological Sciences, Blacksburg, Va, 69 p.