NUREG/CR-4502

Virginia Regional Seismic Network

Final Report (1977-1985)

Prepared by G. A. Bollinger, J. A. Snoke, M. S. Sibol, M. C. Chapman

Virginia Polytechnic Institute and State University

Prepared for
U.S. Nuclear Regulatory
Commission

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ABSTRACT

Eight years of monitoring with a 20-station regional network has produced epicenters ($M \leq 4$), focal depths and mechanisms of adequate number and quality to reveal considerable differences between the two seismically active portions of Virginia. Those two areas (southwestern (Giles County) and central parts of the state) are separated by only some 200 km. Despite their proximity, the two zones exhibit remarkable differences in geometrical/mechanical characteristics. In Giles County, seismic energy is released by predominately strike-slip faulting in a near vertical, tabular zone (~40 km long) that is below the Appalachian decollement. In central Virginia, the seismicity is derived from mixed dip-slip and strike-slip faulting in a large, coin shaped volume (~100 km diameter; ~10 km vertical thickness), above the major detachment faulting. Stress estimates, as derived from single- and composite-focal mechanism solutions P-axes, are NE to ENE in Giles County and NW to NE in central Virginia.

The causes for the observed variability are unknown. The two zones are in different tectonostratigraphic (suspect) terranes and that difference could be relevant. The recently proposed Hydroseismicity model (Costain and Bollinger, 1985) ascribes the observed seismicity variations in Virginia and throughout the Southeast to different drainage basin hydrologic characteristics plus differences in upper crustal fracturing.

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EXECUTIVE SUMMARY

This is the final report for U.S. Nuclear Regulatory Commission Contract No. NRC-04-77-134 with the Seismological Observatory of the Virginia Polytechnic Institute and State University entitled "Virginia Regional Seismic Network." The contract period was from May 1, 1977, to July 31, 1985. During the contract period, a seismic network of 20 stations was established and operated in Virginia and environs. The data gathered by that network were analyzed to investigate the causes of the seismicity in the state and to assess the earthquake hazard of the region. This report describes the operation and data acquisition of the network, the analysis of that data and the major research accomplishments during the contract period. A summary of those accomplishments is as follows:

The eight years of monitoring with a 20-station regional network developed epicenters ($M \leq 4$), focal depths and mechanisms of adequate number and quality to reveal considerable differences between the two seismically active portions of Virginia. Those two areas are in the southwestern (Giles County) and central parts of the state and are separated by only some 200 km. Despite their spatial proximity, the two zones exhibit remarkable differences in geological and mechanical characteristics. In Giles County, seismic energy is released by predominately strike-slip faulting in a near vertical, northeastly-trending tabular zone (~40 km long) that is <u>below</u> the Appalachian decollement. In central Virginia, the seismicity is derived from mixed dip-slip and strike-slip faulting in a large coin shaped volume (~100 km dia; ~10 km vertical thickness), <u>above</u> the major detachment faulting. Stress estimates, as derived from single- and composite-focal mechanism solutions P-axes, are NE to ENE in Giles County while they vary from NW to NE in central Virginia.

The causes for the observed variability are unknown. The two zones are in different geologic/topographic provinces (Giles County: Valley and Ridge, central Virginia: Piedmont) but, because the Giles County activity is sub-detachment, that aspect does not appear to be a controlling one. They may also be in different tectonostratigraphic (suspect) terranes and that difference could be relevant. The recently proposed Hydroseismicity model (Costain and Bollinger, 1985) ascribes the observed seismicity variations in Virginia and throughout the Southeast to different drainage basin (Giles County: New River; central Virginia: James River) hydrologic characteristics plus differences in upper crustal fracturing due primarily to an ancestral period of extensional tectonics.

The research results described above were reported by 67 publications (11 refereed journals, 4 NUREG documents, 15 seismicity bulletins, 7 others and 30 abstracts) and 32 quarterly reports (#04-77-134-1 through 32).

VIRGINIA REGIONAL SEISMIC NETWORK

INTRODUCTION

When this project was initiated in 1977, it was known that there was a persistent, low-level release of seismic energy in the southwestern and central portions of Virginia. Historical seismicity studies had also shown that release to be highly variable, with the largest events (mb = 5.8 and 5.0 with MMI = VIII and VII, respectively) occurring just before the turn of the century (1897 and 1875). However, the accuracy of epicentral determinations for the early shocks was very low: ranging from unknown for historical shocks to ± 50 km or more for pre-1978 events, because of sparse seismograph density (one seismograph station in Virginia, less than 10 in the entire southeastern U.S.). There was <u>no</u> knowledge of focal depths or focal mechanisms (except for those few results generated by the Virginia Electric and Power Company's North Anna microseismic network at their project site in Louisa County, central Virginia). Thus, the state of knowledge at project initiation was characterized by the absence of any geological or tectonic understanding of the persistent seismic activity in the state as well as the lack of an ability to note spatial or temporal changes at an early stage.

To address these deficiencies, a seismic study employing a multi-station, telemetered network of seismographs was initiated under Nuclear Regulatory Commission funding (Contract No. NRC-04-77-134). The proposed eight station network was coarse but considered adequate for an initial evaluation of the problem. With time, the network grew to the present total of 20 stations.

The datum for the proposed research was observational and consisted of five tasks and three objectives. The following chapters report, in turn, on the results obtained and the progress made on each of those project tasks and objectives.

PROJECT TASK 1. OPERATION OF A 20-STATION TELEMETERED SEISMIC NETWORK

Seismic monitoring under this contract consisted of the installation and operation of a conventional 20-station network (Figures 1-3) of short-period (1 Hertz) vertical (SPZ) and in two cases, pairs of horizontal (SPH) seismometers. Signals from those sensors were filtered to a 1-10 Hertz pass band, then telemetered to a central recording facility on the Virginia Tech campus. Recording was analog on single-component pen-and-ink visual drums and multi-channel 16 mm film and FM magnetic tape units. Chronology of that process was as follows:

1. 5/7 Station Giles County, Virginia, Subnetwork - Aperture about 60 km; five SPZ stations (BLA, Blacksburg, VA; NAV, Narrows, VA; PUV, Pulaski, VA; PWV, Princeton, WV; HWV, Hinton, WV) operational by April 1978; SPH sensors (N-S and E-W) added at station PUV in February, 1980; SPZ radio-telemetry stations WMV (Walker Mountain, VA) and VWV (Virginia-West Virginia line) added in November, 1982, and July, 1982, respectively. Additionally, the WWSSN station, BLA, operational since October, 1962, is also located in Blacksburg, VA.

2. 5/9 Station Central Virginia Subnetwork - Aperture approximately 150 km; five SPZ stations (CVL, Charlottesville, VA; GHV, Goochland, VA; FRV, Farmville, VA; CNV, Corbin, VA; PBV, Petersburg, VA) operational by December, 1978. Horizontals were added at FRV in May, 1980, and then removed in September, 1983, due to construction activity near the site. Four SPZ stations from the previously operational 17 station North Anna network (NA2, NA5, NA11 and NA12) were added in July, 1979.

3. 4 Station Bath County, Virginia, Subnetwork - This SPZ network was installed by the Virginia Electric and Power Company (Vepco) to monitor pre-filling seismicity at their pumped-storage reservoir project in Bath County. At Vepco's request and with their support, the results from this subnetwork were routinely included in the analysis and reporting of this project beginning in July, 1979.

4. Calibration - The calibration results for the network have been reported in Quarterly Reports Nos. 14 (#77-134-14, March 15, 1981) and 15 (#77-134-15, June 15, 1981) and in Bollinger and Wheeler (1982). Figures 4-6 show representative sets of these calibrations, begun in 1979 and repeated periodically throughout the contract period.

5. Noise Study - The levels of microseismic background noise were reported by Sibol (1980; SEUSSN Bull. No. 5) who made 600 amplitude and period measurements at eight network stations. At network sites, the average levels were 5-10 nanometers at 2.3 Hertz. At the BLA WWSSN Observatory, the noise levels were 3-5 nanometers at 0.9-3.5 Hertz. With the initiation of digital recording, this study needs to be updated by application of Fourier analysis.

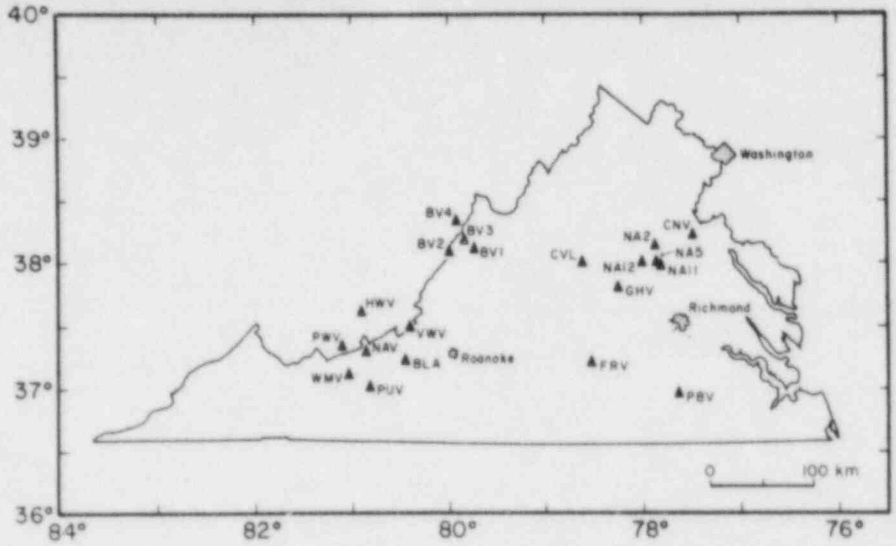


Figure 1. **The Virginia Tech Seismic Network. This network is comprised of the following subnetworks: the 7-station Giles County subnetwork in the western part of the state, the 4-station Bath County subnetwork (stations with "BV-" prefix) in north-central Virginia, the 4-station (North Anna ("NA-" prefixes), and the 5-station central Virginia subnetworks in the central portion of the state. All stations have short-period vertical seismometers, with the exception of BLA (a Worldwide Standard Seismograph Network station) and stations PUV and FRV (which also have short-period horizontal sensors). All stations are telemetered to a central recording facility in Blacksburg, Virginia.**

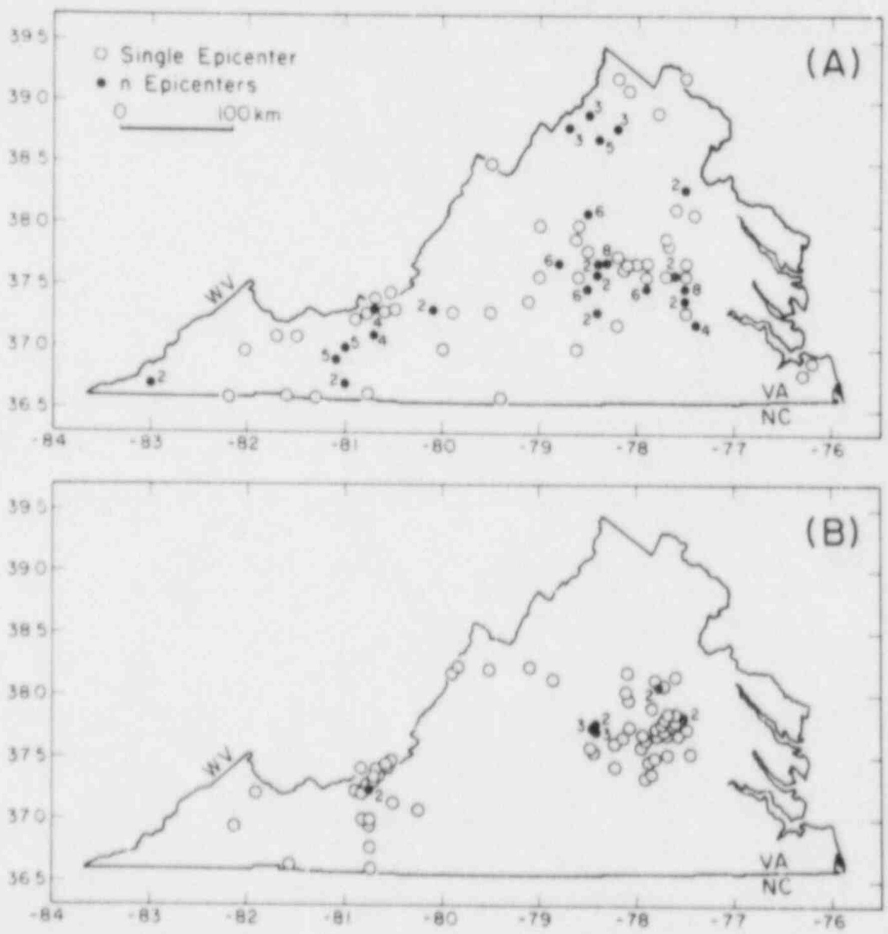


Figure 2. Historical seismicity (A) in Virginia (after Reagor and others, 1980) for the time period 1774-1977. Modern seismicity (B)(after Bollinger and Mathena, 1983; Bollinger and Wheeler, 1982) for the time period 1978-1982. The 48 events shown in central Virginia include 14 selected pre-network instrumental hypocenters.

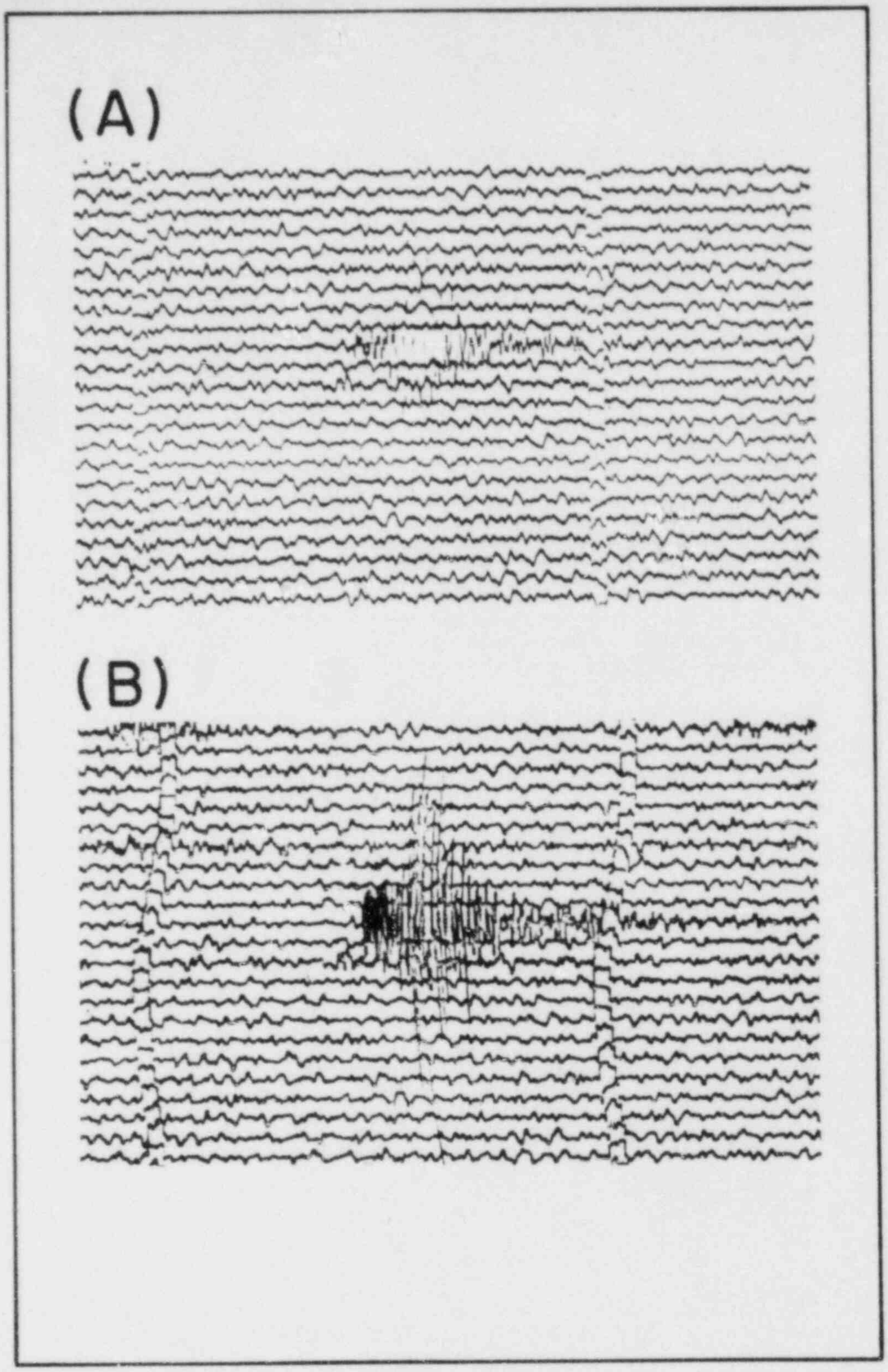


Figure 3. Two different, short-period, vertical seismograms for the same microearthquake that occurred near Narrows, VA (January 28, 1978; Event #32. Magnitude (Md) = 1.6; minute marks every 60 mm on original seismograms. Both transducers located on the same pier at Blacksburg, VA. A) BLA WWSSN: magnification is 50,000 at 1 Hz and 4,500 at 10 Hz. B) BLA network visual: magnification is 28,000 at 1 Hz and 65,000 at 10 Hz. Note the increase in signal-to-noise ratio achieved by the increased magnification of the higher ground frequencies by the network station.

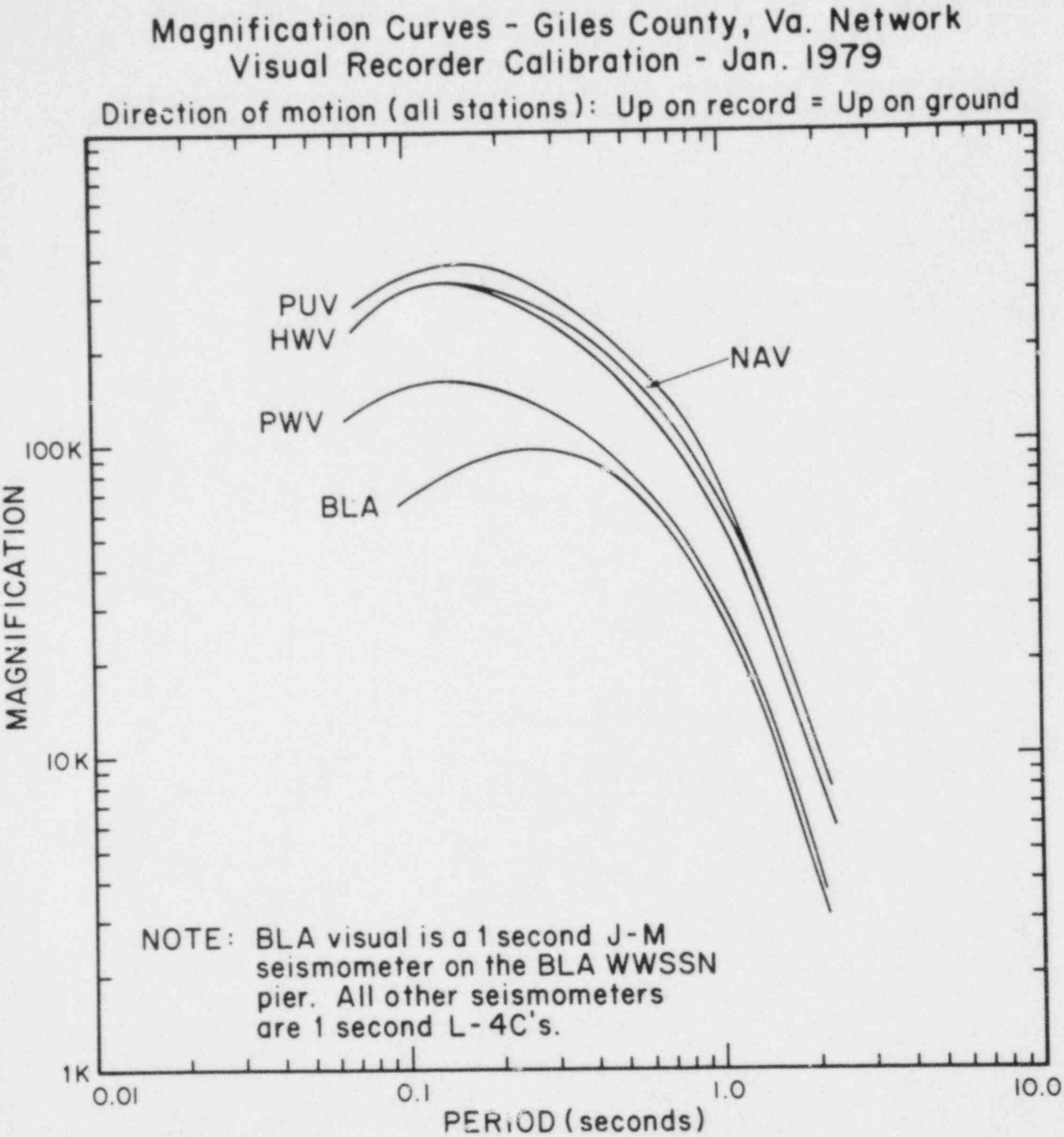
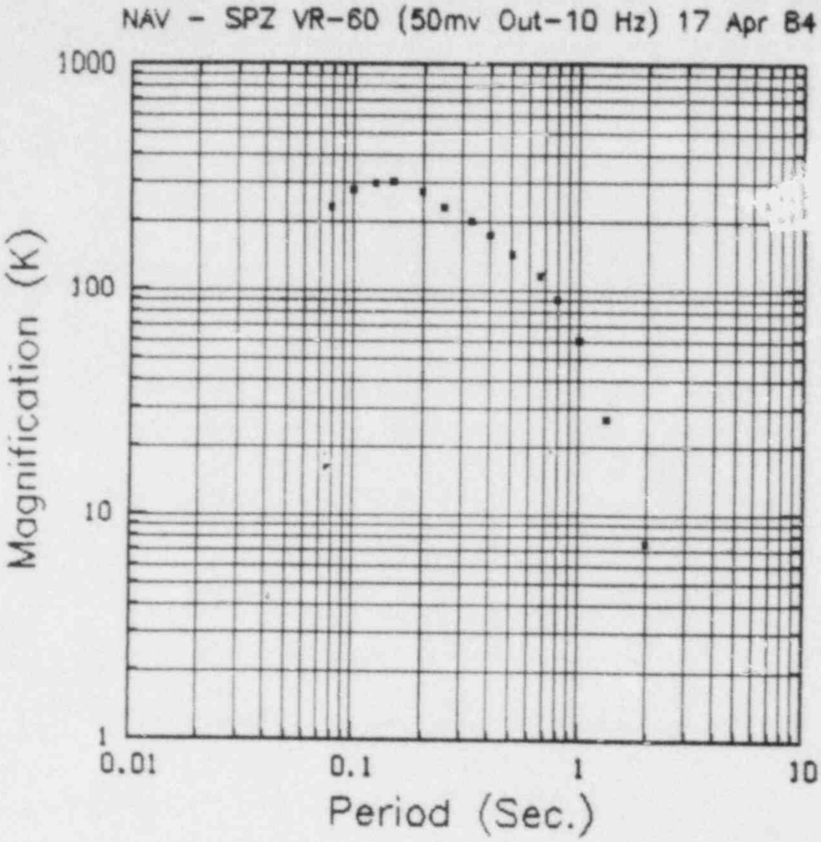


Figure 4. Magnification curves for the Giles County subnetwork of the Virginia Tech Seismic Network: Visual (pen-and-ink) recorders.

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     Input Data:
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          Calib. coil resistance (ROHMS)......=  688.00000 (Ohms)
          Calib. coil motor constant (K)......=    0.49550 (Nt/Amp)
          Mass in seismometer (MASS)..........=    0.98590 (Kg)
     Output:
          Number of frequencies in sweep (N)=   14
          Calib. voltage (O-P; VOLOP).........=    0.01450 (Volts)
          Calib. current (CALCUR).............= 0.00002108 (Amps)
             (NOTE: CALCUR = VOLOP / ROHMS..... (Ohms Law)).
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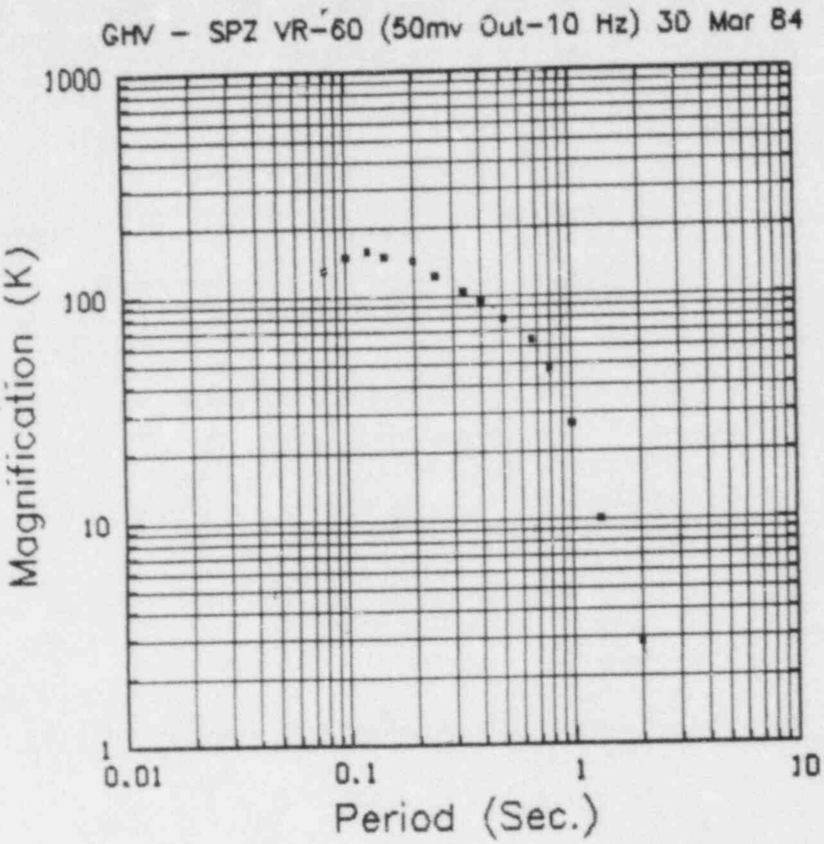
Freq. (Hz)	Ampl. (P-P, mm)	Period (Sec)	Magn. (K)	Magnification
0.50	16.0000	2.000	7.45	0.745417E+04
0.75	25.7000	1.333	26.94	0.269398E+05
1.00	32.2000	1.000	60.01	0.600061E+05
1.25	31.3000	0.800	91.14	0.911389E+05
1.50	27.7000	0.667	116.15	0.116145E+06
2.00	19.6000	0.500	146.10	0.146102E+06
2.50	15.3000	0.400	178.20	0.178201E+06
3.00	12.2000	0.333	204.62	0.204617E+06
4.00	7.9000	0.250	235.55	0.235552E+06
5.00	5.9000	0.200	274.87	0.274873E+06
6.67	3.7000	0.150	306.76	0.306756E+06
8.00	2.5000	0.125	298.17	0.298167E+06
10.00	1.5000	0.100	279.53	0.279531E+06
12.50	0.8000	0.080	232.94	0.232943E+06

Period	Magn.
2.00	7.5
1.33	26.9
1.00	60.0
0.80	91.1
0.67	116.1
0.50	146.1
0.40	178.2
0.33	204.6
0.25	235.6
0.20	274.9
0.15	306.8
0.12	298.2
0.10	279.5
0.08	232.9

Figure 5. Plot and data listing for recent (1984) calibration of station NAV at Narrows, VA.

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     The title is................: GHV - SPZ VR-60 (50mv Out-10 Hz) 30 Mar 84

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          Calib. coil resistance (ROHMS)....=  687.00000 (Ohms)
          Calib. coil motor constant (K)....=    0.48000 (Nt/Amp)
          Mass in seismometer (MASS)........=    0.98350 (Kg)
     Output:
          Number of frequencies in sweep (N)=   14
          Calib. voltage (O-P; VOLOP).......=    0.03300 (Volts)
          Calib. current (CALCUR)...........= 0.00004803 (Amps)
             (NOTE: CALCUR = VOLOP / ROHMS..... (Ohms Law)).
```

Freq. (Hz)	Ampl. (P-P, mm)	Period (Sec)	Magn. (K)	Magnification
0.50	13.6000	2.000	2.86	0.286276E+04
0.75	21.4000	1.333	10.14	0.101354E+05
1.00	32.2000	1.000	27.11	0.271120E+05
1.25	36.0000	0.800	47.36	0.473618E+05
1.50	33.7000	0.667	63.84	0.638437E+05
2.00	23.8000	0.500	80.16	0.801572E+05
2.50	18.1000	0.400	95.25	0.952498E+05
3.00	13.8000	0.333	104.57	0.104575E+06
4.00	9.1000	0.250	122.59	0.122593E+06
5.00	6.9000	0.200	145.24	0.145243E+06
6.67	4.0000	0.150	149.84	0.149836E+06
8.00	3.0000	0.125	161.66	0.161662E+06
10.00	1.8000	0.100	151.56	0.151558E+06
12.50	1.0000	0.080	131.56	0.131561E+06

Period	Magn.
2.00	2.9
1.33	10.1
1.00	27.1
0.80	47.4
0.67	63.8
0.50	80.2
0.40	95.2
0.33	104.6
0.25	122.6
0.20	145.2
0.15	149.8
0.12	161.7
0.10	151.6
0.08	131.6

Figure 6. Plot and data listing for recent (1984) calibration of station GHV at Goochland, VA.

6. **Network Detection and Location Capability Study** - The theoretical detection and location capabilities of the Virginia Regional Seismic Network were estimated by Tarr (1980; SEUSSN Bulletin No. 5; Bollinger and Sibol, 1985) using the algorithm NETWORK. Figure 7 shows maps of contoured 90% detection threshold magnitudes for detection by five or more stations and of 90% confidence location ellipses for minimum magnitude earthquakes detected by five or more stations. Figure 8 depicts 90% confidence location ellipses, on a $\frac{1}{2}^{\circ}$ latitude and longitude grid, for magnitude 2.0 and 3.0 shocks detected at five or more seismic stations. In these figures, it is assumed that a signal-to-noise ratio of 2.0 was necessary for a detection with a probability of 0.5 and that the noise, assumed to have a mean value of 20 nm for all stations, is the only factor limiting a station's operating magnification. Finally, both signal amplitudes and noise amplitudes are assumed to be lognormally distributed.

Detection appears to be complete down to a magnitude of 2.0 for all of Virginia except at the extreme western tip. Location is good (small error ellipses) for all but the periphery of the state at the 3.0 level magnitude. However, that magnitude level is well-located throughout the entire state when the other stations of the Southeastern U.S. Seismic Network are also considered (Tarr, 1980; SEUSSN Bulletin No. 5).

7. **Determination of Earthquake Magnitude** - A relationship between earthquake magnitude (mb) and the duration of earthquake vibrations as recorded by the VTSO network was first reported in December, 1980 (#77-134-13). That study analyzed 102 data points (mb-duration pairs) from earthquakes that occurred prior to 1981. Subsequently, in March, 1984 (#77-134-26), 83 new data points were added and the least-squares regression analysis repeated. The initial (1980) equation was:

$$MD = (-3.38 \pm 0.09) + (2.74 \pm 0.06) \log D \text{ for } n = 102,$$

and the current (1984) equation is,

$$MD = (-3.42 \pm 0.19) + (2.83 \pm 0.11) \log D \text{ for } n = 185,$$

where,

MD = Duration magnitude for VTSO (Virginia Tech Seismological Observatory network

$\pm$ = Confidence intervals are 90%

D = Duration (sec) from onset of P-wave until return to background noise level

log = Logarithm to the base 10

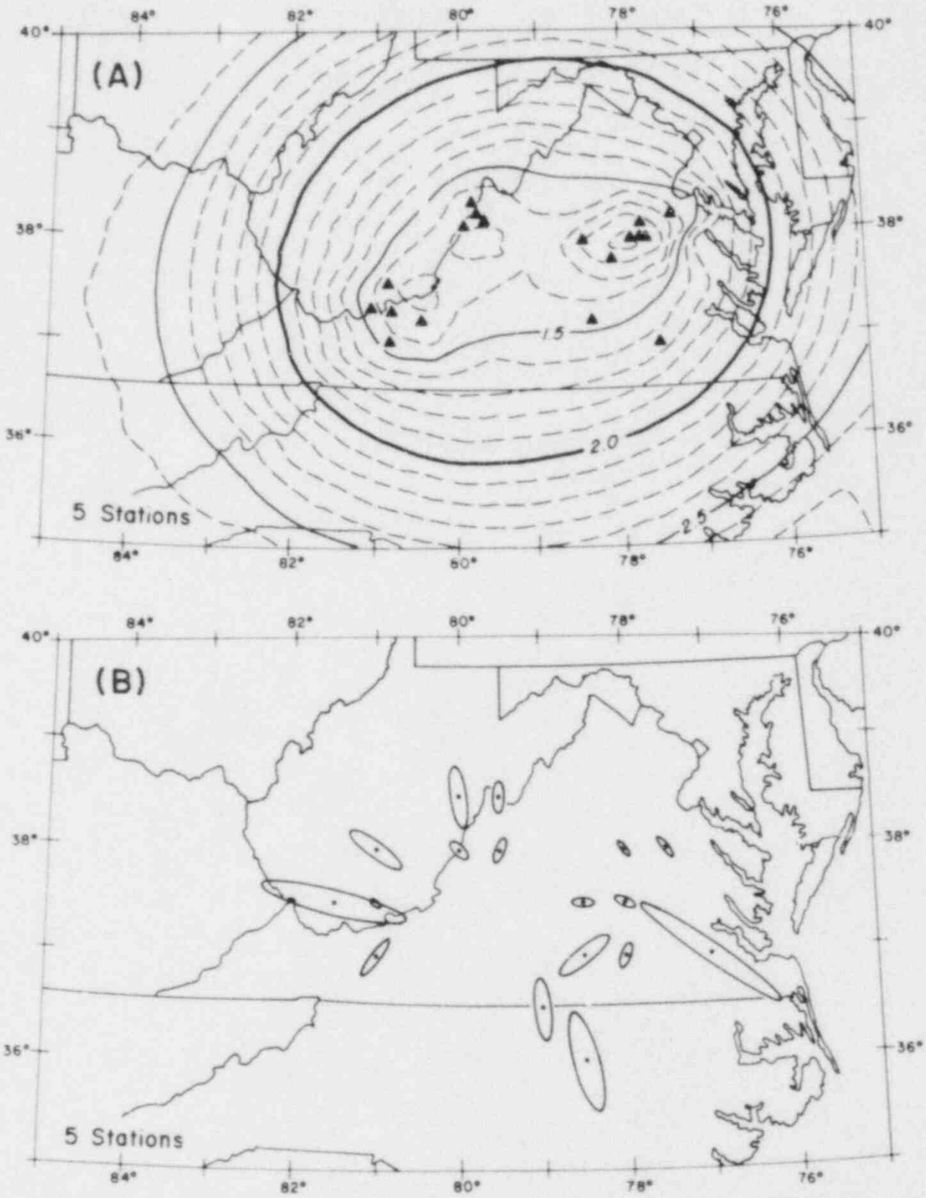


Figure 7. **Detection and location capability by any five stations (solid triangles) of the Virginia Tech Seismic Network. (A) Ninety percent probability threshold (mb) magnitudes for detection by five or more stations. Contour interval = 0.1 mb unit. (B) Ninety percent confidence location ellipses, on a ½° latitude and longitude grid, for events detected by five or more stations. Ellipses are not plotted if their semi-major axes are >100 km or if their 95% confidence interval on the focal depth is >100 km (after Tarr, 1980). Interpolate only between adjacent grid points with plotted ellipses; do not extrapolate to undefined grid points.**

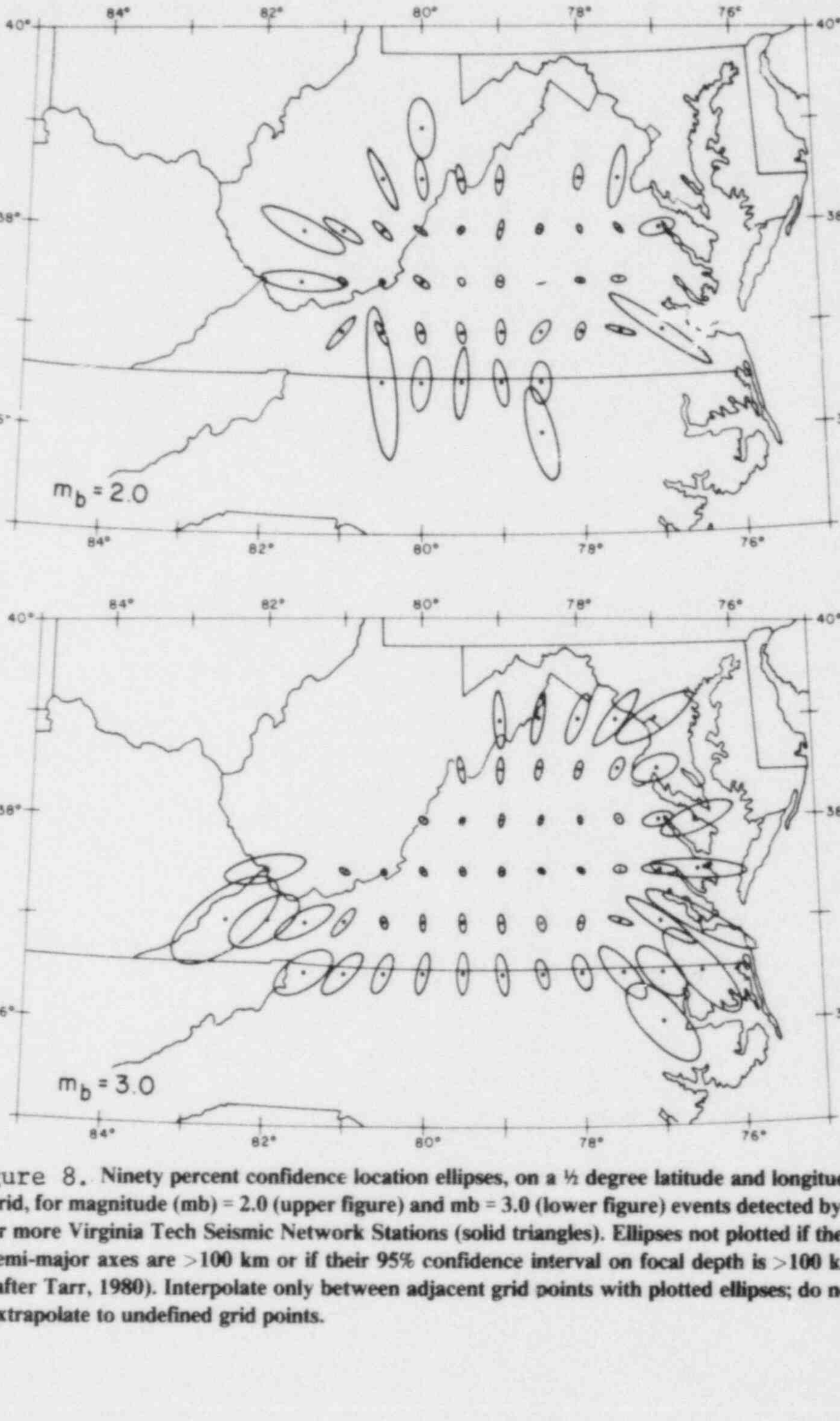


Figure 8. **Ninety percent confidence location ellipses, on a ½ degree latitude and longitude grid, for magnitude (mb) = 2.0 (upper figure) and mb = 3.0 (lower figure) events detected by 5 or more Virginia Tech Seismic Network Stations (solid triangles). Ellipses not plotted if their semi-major axes are >100 km or if their 95% confidence interval on focal depth is >100 km (after Tarr, 1980). Interpolate only between adjacent grid points with plotted ellipses; do not extrapolate to undefined grid points.**

8. **Digital Recording** - On April 1, 1985, the Virginia Tech Seismological Observatory network digitizing was declared officially on line. Downtime during the first months of operation was less than 5% and caused mainly by power line outages. The digital system was triggering on an average of 13 events/day, most of which are explosions associated with mining in West Virginia and Kentucky. Comparison of the trigger times with continuous analog recordings from stations NAV and GHV in western and central Virginia, respectively, indicate that approximately 70% of the identifiable signals at those stations triggered the system and were digitally recorded. Digitized signals, mostly teleseisms and clearly recorded explosions, were stored on tape for possible further analysis.

The digital system consists of 20 short period vertical component stations located in Virginia and West Virginia. One of these stations (PUV) also has two horizontal components. With a time channel, this brings the total number of channels currently being digitized to 23. The 20 stations are the same ones used formerly with the analog system. The analog output from each of these stations is either radio telemetered or transmitted by phone line to the central recording facility located in Blacksburg, Virginia. At the recording facility, analog signals are routed to a 48 channel multiplexer/analog-to-digital converter. The multiplexing, digitizing, storage of event files and analysis are all done on one of two PDP-11/34 processors which is dedicated to the digitizing and initial storage process. Event files are subsequently transferred to the other PDP 11/34 system via a direct parallel port for analysis and subsequent archival storage on magnetic tape.

PROJECT TASK 2. MONITORING SEISMIC ACTIVITY AND CONDUCTING VELOCITY STUDIES

Network Monitoring As of 1 August 1985 in Terms of Operational Statistics

Station Listing by Subnetwork (Including Components and Locations)	Cumulative Totals Years of Operation	Cumulative Totals Down-Time
<u>Giles County Subnetwork</u>:		
VWV - SPZ - Potts Mountain, WV	3.13	13.5%
PWV - SPZ - Princeton, WV	7.46	2.1%
HWV - SPZ - H .on, WV	7.38	1.1%
NAV - SPZ - Na 'ows, VA	7.85	2.0%
BLA - SPZ - Bla sburg, VA	7.85	0.7%
PUV - SPZ - Pulaski, VA	7.49	1.3%
PUV - SPNS - Pulaski, VA	5.55	0.8%
PUV - SPEW - Pulaski, VA	5.55	0.8%
WMV - SPZ - Walker Mountain, VA	2.87	5.4%
NETWORK AVERAGE:	6.13	2.2%*
<u>Central Virginia Subnetwork</u>:		
CNV - SPZ - Corbin, VA	7.14	1.1%
CVL - SPZ - Charlottesville, VA	7.14	2.0%
GHV - SPZ - Goochland, VA	6.64	2.0%
FRV - SPZ - Farmville, VA	6.72	4.7%
PBV - SPZ - Petersburg, VA	6.81	2.7%
SUBNETWORK AVERAGE:	6.89	2.5%*
<u>North Anna Subnetwork</u>:		
NA2 - SPZ - Brokenburg, VA	6.83	5.2%
NA5 - SPZ - Buckner, VA	7.02	3.2%
NA11 - SPZ - Beaver Dam, VA	6.30	11.4%
NA12 - SPZ - Mineral, VA	6.95	12.3%
SUBNETWORK AVERAGE:	6.78	7.9%*
<u>Bath County Subnetwork</u>:		
BV1 - SPZ - Burnsville, VA	6.95	12.4%
BV2 - SPZ - Mountain Grove, VA	7.05	25.9%
BV3 - SPZ - Lightner, VA	6.95	25.0%
BV4 - SPZ - Dunsmore, WV	6.47	21.9%
SUBNETWORK AVERAGE:	6.86	21.3%*

*Subnetwork averages for the cumulative downtime percentages are weighted according to the years of operation per station.

NOTES: Giles County, Central Virginia, and North Anna Subnetwork maintenance by the VTSO staff.

Bath County Subnetwork maintenance by VEPCO.

Downtime for the network stations has been very low except at the North Anna subnetwork, especially NA11 and NA12, and the VWV station of the Giles County subnetwork. The North Anna stations are just wearing out. They were initially installed in 1976 and are now scheduled for replacement. Erratic local telephone lines are also a problem in this case. The VWV station is one of the two radio-telemetered stations (the other is WMV). VWV experienced a series of vandalism downtimes following its initial installation, but those apparently have been eliminated; downtime during the most recent quarter was 1.6%.

9. **Velocity Studies** - Velocity studies were conducted for the Giles County locale (T. P. Moore), the central Virginia area (M. C. Chapman) and the region (D. A. Carts). These results (Table 1) were reported in NUREG/CR-1217 (Bollinger, Chapman and Moore) and in NUREG/CR-2253 (Bollinger and Carts). The efficacy of these models was tested by:

   a. Locating quarry blasts (Figure 9; Bollinger and Wheeler, 1982; Figure 10; Bollinger and Sibol, 1985 and Sibol and Bollinger, 1982; NUREG/CR-3080)

   b. Joint relocation techniques (Viret and others, 1984, 1985)

   c. Wadati, X^2-T^2 and Pn time-term analyses (Chapman and Bollinger, 1984, 1985).

Our general conclusion from these velocity model tests is that the models are entirely adequate for the station-spacing present and that our error estimates from well-constrained hypocentral solutions are realistic.

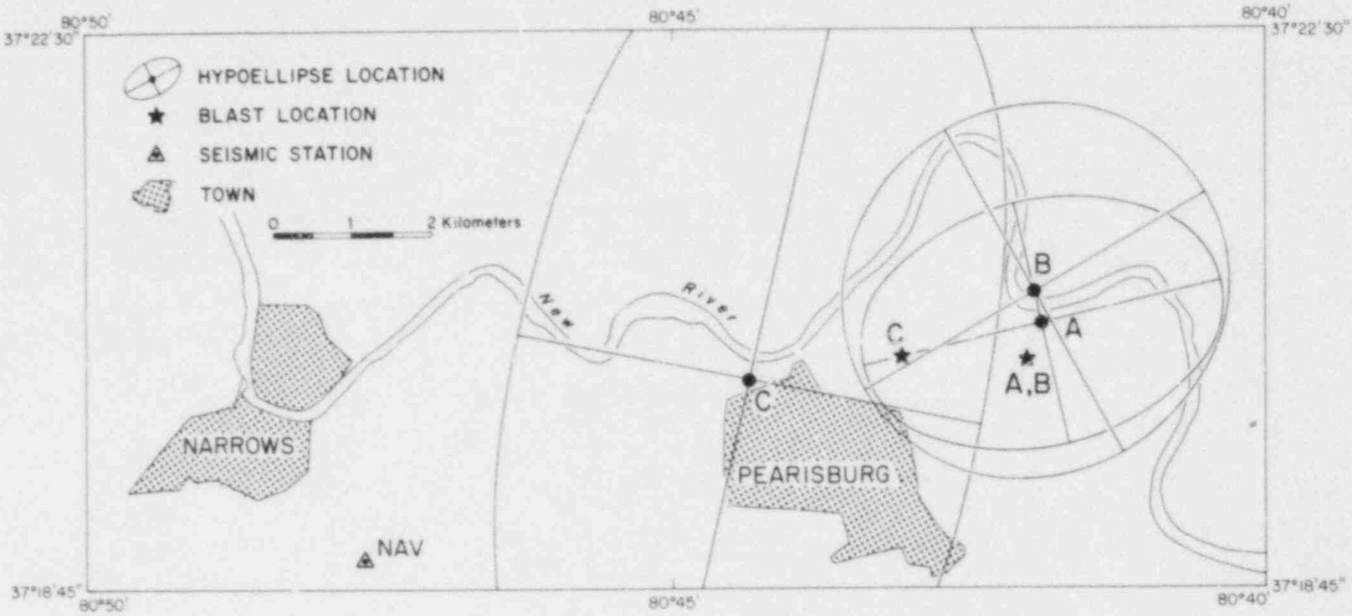
TABLE 1

LOCAL AND REGIONAL CRUSTAL VELOCITY MODELS FOR VIRGINIA

	P-Velocity	S-Velocity	Vp/Vs	Depth	Crossover Distance P-Wave	Crossover Distance S-Wave
	Giles County-Bath County Areas					
	5.63	3.44	1.64	0.0	0	0
VPI1	6.05	3.52	1.72	5.7	60	106
	6.53	3.84	1.70	14.7	115	192
	8.18	4.79	1.71	50.7	260	409
	Central Virginia Area					
	6.09	3.53	1.73	0.0	0	0
VPI2	6.50	3.79	1.72	15.0	166	159
	8.18	4.73	1.73	36.0	290	285
	Southeastern United States					
	6.25	3.65	1.71	0.0	0	0
	8.11	4.59	1.77	40.0	222	237

VPI3	Station Corrections:	Pn	Sn
	Coastal Plain	+1.68 sec	+2.74 sec
	Piedmont	+1.40 sec	+2.28 sec
	Elsewhere	0.00 sec	0.00 sec

Units: Velocities in km/sec; depths and crossover distances in km



HYPOELLIPSE EPICENTER LOCATION ERRORS FOR
GILES COUNTY, VIRGINIA, BLASTS

Blast ID	Date of Blast	Difference: Actual and Calculated Epicenter (km)	ERH* (km)
A	December 3, 1979	0.5	2.2
B	December 6, 1979	0.9	2.4
C	May 20, 1980	2.0	5.7

HYPOELLIPSE DETERMINATION OF FOCAL DEPTHS FOR
GILES COUNTY, VIRGINIA, BLASTS

Blast ID	Date of Blast	Trial Focal Depth (km)	Solution Focal Depth (km)	ERZ* (km)
A	December 3, 1979	4.0	0.5	57.7
		10.0	0.2	99.0
B	December 6, 1979	0.0	0.0	99.0
		5.0	2.5	16.7
C	May 20, 1980	4.0	2.2	14.3

*ERZ = standard error of the solution focal depth (Lahr, 1979)

Figure 9. Actual locations of Blasts A, B and C shown by stars. Computer locations shown by solid circles with 68 percent confidence ellipses. Location of Narrows, VA, seismic station (NAV) shown by open triangle with center dot symbol.

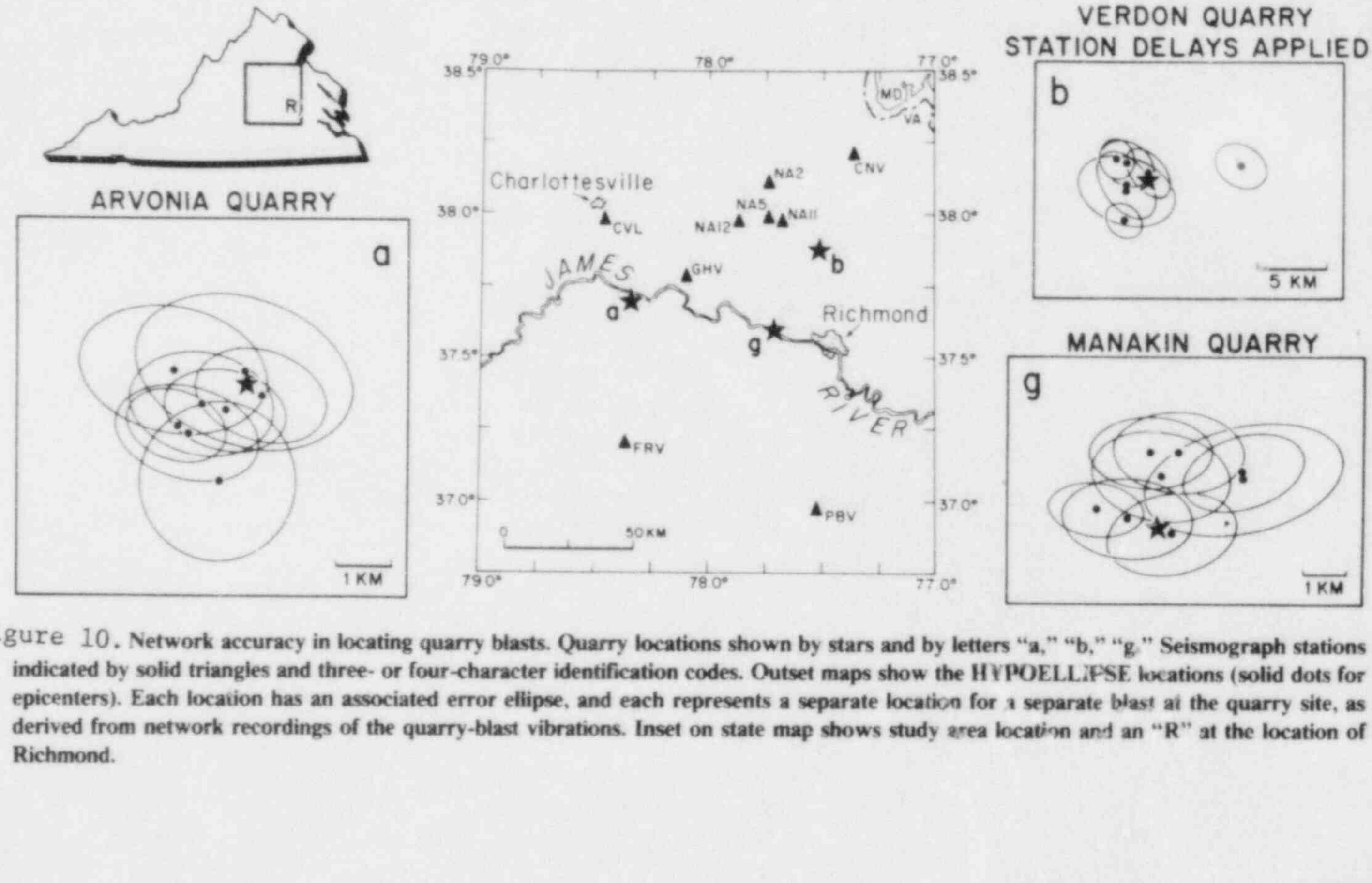


Figure 10. Network accuracy in locating quarry blasts. Quarry locations shown by stars and by letters "a," "b," "g." Seismograph stations indicated by solid triangles and three- or four-character identification codes. Outset maps show the HYPOELLIPSE locations (solid dots for epicenters). Each location has an associated error ellipse, and each represents a separate location for a separate blast at the quarry site, as derived from network recordings of the quarry-blast vibrations. Inset on state map shows study area location and an "R" at the location of Richmond.

PROJECT TASK 3 AND OBJECTIVE 1. DETERMINATION OF EARTHQUAKE HYPOCENTERS AND FOCAL MECHANISMS AND DEVELOPMENT OF GEOLOGIC MODELS FOR EACH OF THE ACTIVE AREAS

For the contract period, August 1977 through July 1985, 90 earthquakes, ranging in magnitude from -0.8 to 4.2, were detected and located in Virginia and West Virginia (Figure 11). The hypocentral parameters for these shocks have been reported routinely in Quarterly Reports (#77-134-1 through 32) and in the semiannual Southeastern United States Seismic network (SEUSSN) Bulletins (see Appendices A and B herein). Additionally, the availability of the entire SEUSSN catalog was announced to the professional community in the Bulletin of the Seismological Society of America, (SEUSSN Contributors, 1985) and at a Geological Society of America meeting (Bollinger and SEUSSN Contributors, 1985).

NUREG/CR-4288 presented focal mechanism analyses for 23 Virginia earthquakes (11 in the Giles County seismic zone and 12 in the central Virginia seismic zone; Figures 12-14; Tables 2-5) and for 37 earthquakes in the southeastern Tennessee seismic zone. These analyses were in the form of 17 single-event focal mechanisms (SEFM) and 12 composite focal mechanisms (CFM) and were based on 280 P-wave polarities and 254 (SV/P)z amplitude ratios.

The computer program, FOCMEC (Snoke and others, 1984), was used to determine families of focal mechanism solutions that are consistent, within pre-defined error allowances, with the input P-wave polarities and the (SV/P)z amplitude ratios. FOCMEC systematically searches the focal sphere for focal mechanisms consistent, within prescribed error limits, with the input data. In FOCMEC, a searching algorithm examines the focal sphere for acceptable focal mechanism solutions by relating the observed data to theoretical data associated with a rotating set of orthogonal B, A, and N axes, where B is the null axis, and A and N are the poles (normals) to the nodal planes. The density of focal sphere coverage is controlled by a preset increment of axes rotation. The 5° increment of focal sphere coverage used for all events herein results in more than 25,000 possible orthogonal nodal plane orientations being tested within the focal sphere.

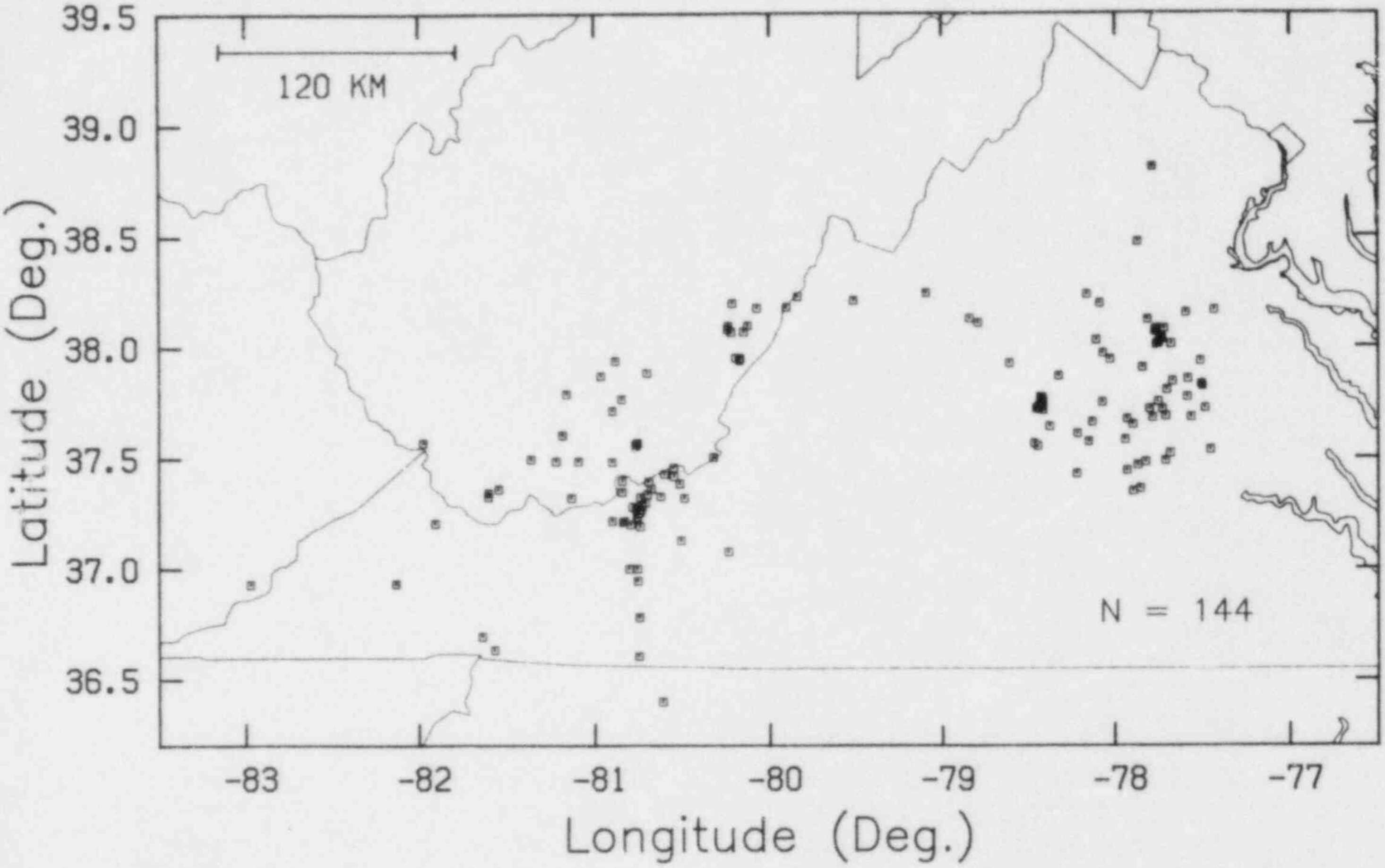


Figure 11. Instrumental epicenter map for Virginia. Included on this figure are 54 pre-network instrumentally located events. See Appendix B for hypocenter listing.

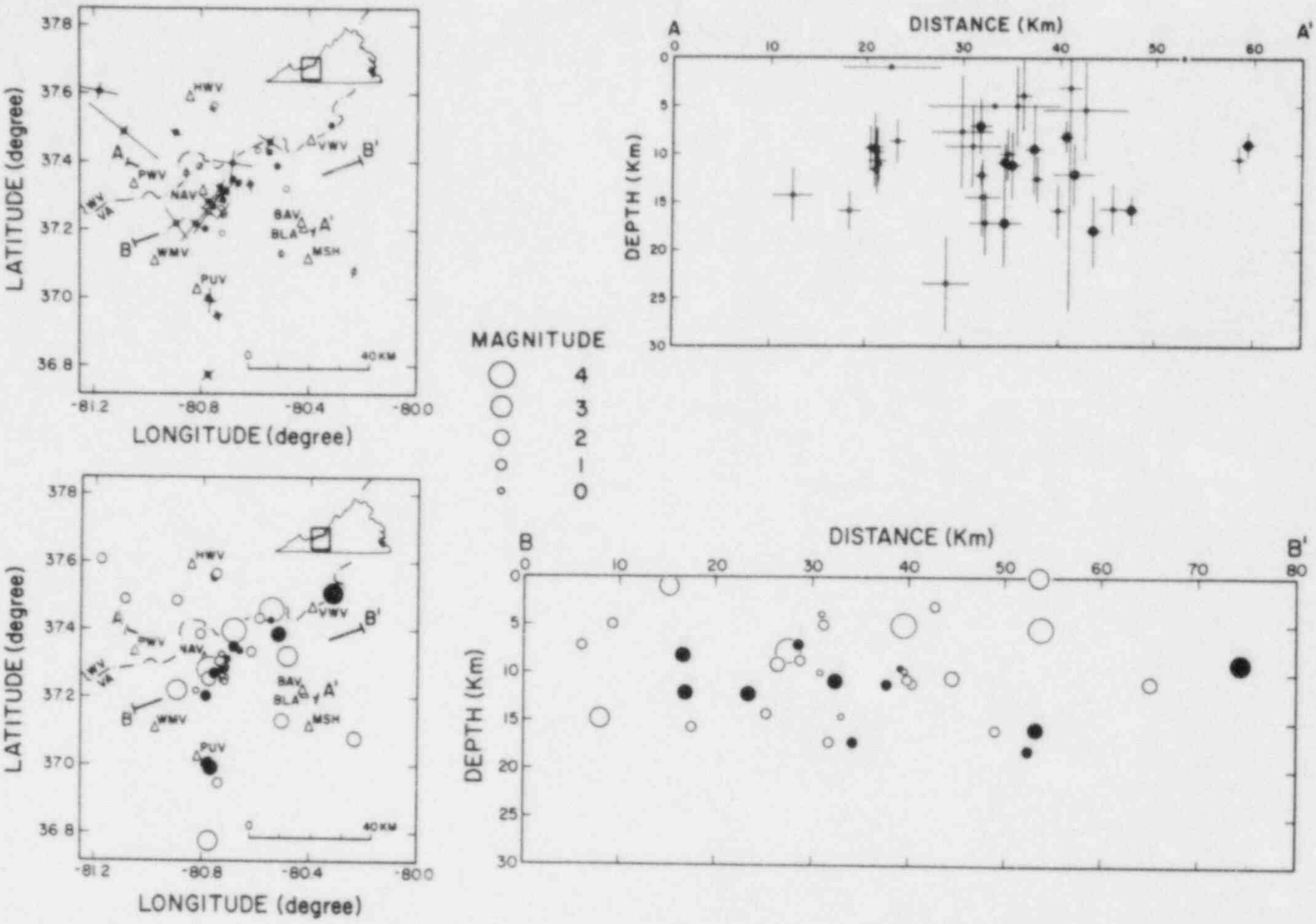


Figure 12: Upper left: Network located and pre-network instrumentally located events in Giles County and vicinity are shown with horizontal error axes. Dark circles are study events and stations are represented by open triangles. Upper right: The events in cross section A-A' of upper left figure are shown with their vertical and horizontal error axes. The larger circles are study events. This cross-section is oriented perpendicular to a strike of N20°E. Lower left: Same map as upper left figure except that events are scaled to magnitude. Again, darkened circles are study events. Lower right: The events in cross section B-B' from lower left figure are shown. This cross section is perpendicular to a trend of N25°W.

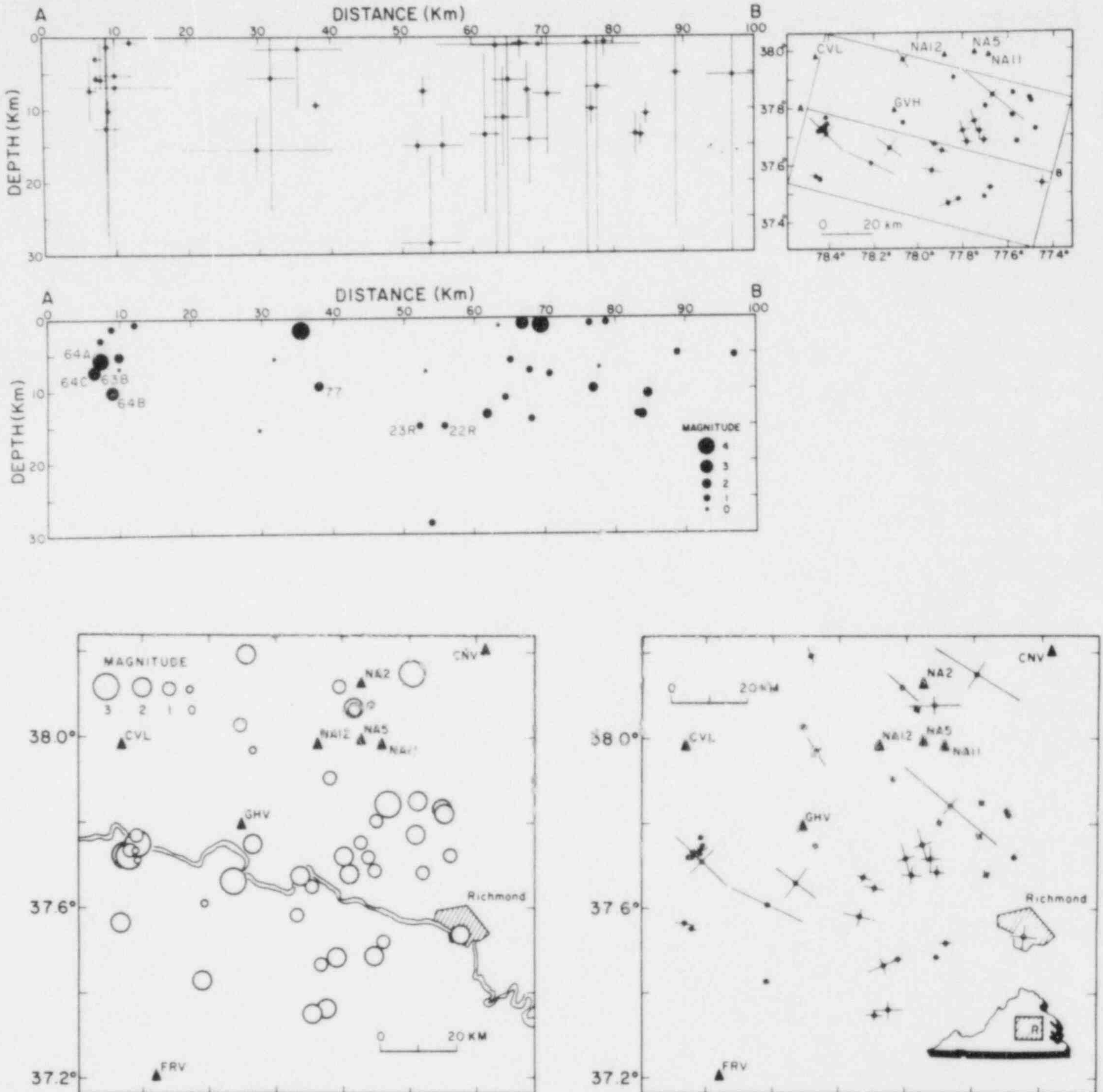
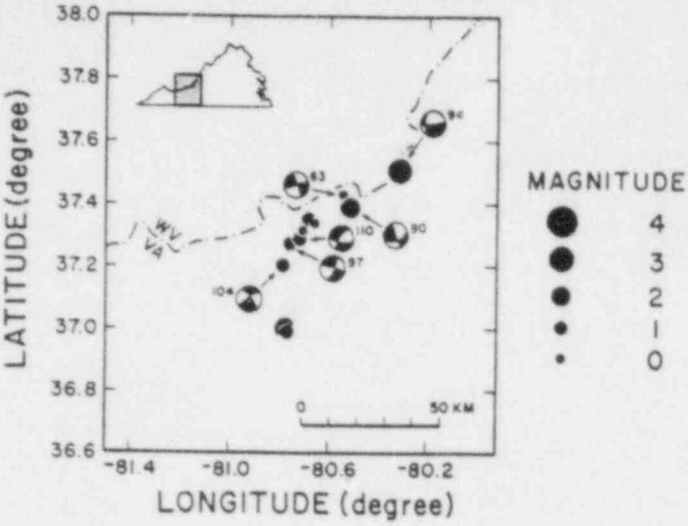
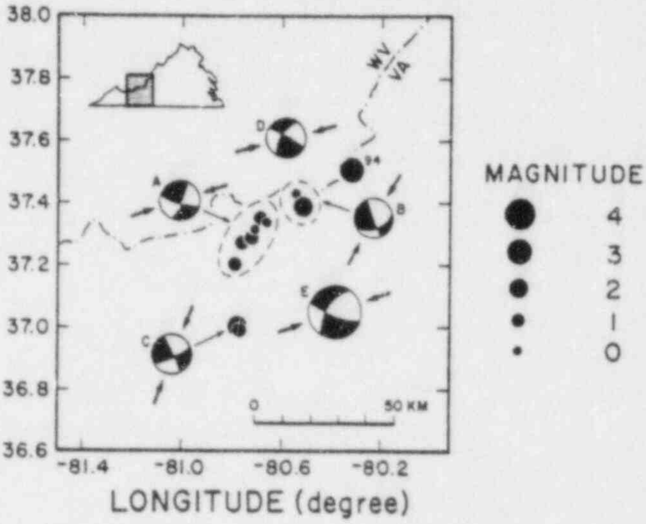


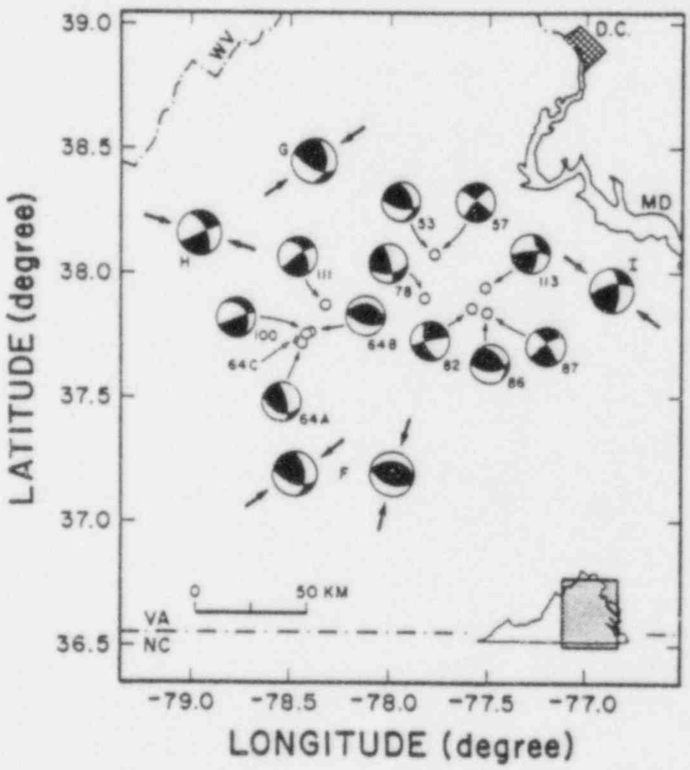
Figure 13. **Instrumentally located earthquakes in the central Virginia seismic zone (Bollinger and Mathena, 1983). Left-hand figure shows epicenters (circles) scaled according to magnitude. Irregular double line marks course of James River. Right-hand figure shows epicenters (solid dots) with associated error-ellipse axes. Seismograph-station locations indicated by solid triangles with three- or four-character identification codes. Inset state map depicts study area. R = Richmond. Upper pair of figures shows hypocenters with error-ellipse axes.**



The six SEFM preferred nodal planes for Giles County obtained by the layered velocity model are presented. The shaded areas are compressional quadrants and the white areas are dilatational quadrants.



The preferred nodal planes from the five Giles County CFM using the layered velocity model are shown. Quadrant shading is the same as in Figure 9. The HEAVY arrows correspond to the trend of the P axes for each CFM. See Table 3 for the earthquakes that are included in each CFM.



The preferred nodal planes for all central Virginia SEFM and CFM solutions are shown. Smaller mechanisms are SEFM events and CFM have HEAVY arrows showing their P axis trend. Shaded areas are compressional, and white areas are dilatational quadrants. Open circles are event locations. Note that two preferred solutions are shown for CFM F.

Figure 14. Focal mechanism solutions for Giles County and central Virginia. Plots lower hemisphere, equal area, compressional quadrants dark.

TABLE 2
GILES COUNTY, VIRGINIA, FOCAL MECHANISM SOLUTION PARAMETERS

EVT	STRIKE	DIP	SLIP	P(TREND,PLUNGE)	T(TREND,PLUNGE)	B(TREND,PLUNGE)
63	N20°W S70°W	85°E 88°N	-178° -5°	S25°W,5°	N65°W,2°	N45°E,85°
90	N20°W N70°E	90°E 55°S	145° 0°	N31°E,24°	N71°W,24°	S20°E,55°
94	S N82°E	30°W 86°S	-171° -60°	N21°E,42°	S33°E,34°	S80°W,30°
97	N20°E N70°W	82°E 84°N	-174° -8°	S65°W,10°	N25°W,1°	N70°E,80°
104	S26°W N57°W	64°NW 76°NE	164° 27°	N73°E,7°	S13°E,29°	N30°W,60°
110	S27°W S78°E	66°NW 60°S	-147° -28°	N67°E,40°	N26°W,3°	S60°W,50°
A	N20°E S69°E	86°E 75°S	165° 4°	N66°E,7°	N26°W,13°	S5°W,75°
B	N20°W N70°E	90°E 45°S	135° 0°	N35°E,30°	N75°W,30°	S20°E,45°
C	N25°W N65°E	86°NE 81°SE	171° 4°	N20°E,3°	N70°W,9°	S50°E,80°
D	S29°W N59°W	60°NW 88°NE	177° 30°	N71°E,19°	S11°E,23°	N55°W,60°
E	S30°W S70°E	60°NW 73°S	-161° -31°	N67°E,34°	S17°E,9°	S85°W,55°

TABLE 3
CENTRAL VIRGINIA FOCAL MECHANISM SOLUTION PARAMETERS

EVT	DIP	STRIKE	SLIP	P(TREND,PLUNG)	T(TREND,PLUNGE)	B(TREND,PLUNGE)
53	41°W	N19°W	139°	S34°W,13°	N32°W,57°	S60°E,30°
	64°S	S76°E	56°			
57	82°NW	S40°W	174°	N85°E,1°	S5°E,10°	N10°W,80°
	84°NE	N50°W	8°			
64A	67°E	N14°W	117°	N56°E,18°	N66°W,58°	S25°E,25°
	35°SW	S67°E	42°			
64B	35°N	N82°W	81°	S14°W,10°	N41°E,79°	N75°W,5°
	55°S	S72°E	96°			
78	79°E	N14°W	136°	N43°E,21°	N64°W,38°	S25°E,45°
	47°S	N86°E	15°			
82	61°W	S22°E	-8°	S61°E,26°	N22°E,14°	S85°W,60°
	83°N	S72°W	-151°			
86	42°NE	N44°W	129°	S19°W,9°	N52°W,63°	S75°E,25°
	59°S	N89°E	60°			
87	79°NE	N33°W	17°	S81°E,3°	S11°W,20°	N0°,70°
	74°SE	S53°W	168°			
100	45°NE	N27°W	-5°	N60°W,33°	S11°W,27°	N70°E,45°
	86°SE	N66°E	-135°			
111	59°NE	N25°W	16°	N72°W,11°	S11°W,33°	N35°E,55°
	76°NW	S56°W	148°			
113	63°E	N3°E	14°	N42°W,10°	S42°W,28°	N65°E,60°
	78°N	S87°W	152°			
F(1)	35°N	N82°W	81°	S14°W,10°	N41°E,79°	N75°W,5°
	55°S	S72°E	96°			
F(2)	58°E	N9°W	132°	N52°E,4°	N44°W,55°	S35°E,35°
	51°S	S69°E	43°			
G	48°E	N1°W	141°	S56°W,8°	N23°W,54°	S40°E,35°
	52°S	S72°E	49°			
H	65°NE	N24°W	2°	N67°W,16°	S17°W,19°	N60°E,65°
	88°N	S85°W	155°			
I	66°E	N4°W	26°	N55°W,0°	S35°W,35°	N35°E,55°
	66°N	S74°W	154°			

TABLE 4
EASTERN TENNESSEE FOCAL MECHANISM SOLUTION PARAMETERS

EVT	STRIKE	DIP	SLIP	P (TREND, PLUNGE)	T (TREND, PLUNGE)	B (TREND, PLUNGE)
2	N 76E	78S	9	N30E, 3	N60W, 15	N130E, 75
	N 16W	81E	168			
13	N 76W	64N	16	N123W, 7	N143E, 29	N20W, 60
	N173W	76W	153			
14	N 80W	86N	9	N55E, 3	N145E, 9	N55W, 80
	N170W	81W	176			
22	N 78E	74S	- 12	N36E, 20	N56W, 3	N155W, 70
	N172E	79W	-163			
23	N 63E	84SE	- 35	N14E, 28	N115E, 19	N125W, 55
	N157E	56SW	-173			
28	N 42W	78NE	27	N88E, 10	N177W, 28	N20W, 60
	N138W	63NW	166			
29	N 69E	87SE	- 20	N23E, 16	N117E, 11	N120W, 70
	N161E	70SW	-176			
30	N 71W	85N	- 70	N143W, 46	N1W, 37	N105E, 20
	N 29E	21E	-166			
31	N 83W	74N	- 53	N134W, 48	N20W, 20	N85E, 35
	N 27E	40E	-154			
34	N 67W	63N	31	N60E, 0	N150E, 40	N30W, 50
	N 7E	63W	149			
36	N 56W	71NE	- 7	N99W, 18	N169E, 8	N55E, 70
	N 36E	83SE	-161			
1	N180E	84W	8	N45W, 1	N45E, 10	N140W, 80
	N 90E	82S	176			
2	N 95E	86S	3	N50E, 1	N40W, 5	N150E, 85
	N 5E	87E	176			
3	N 74W	85N	30	N56E, 17	N154E, 24	N65W, 60
	N167W	60W	174			
4	N176W	57N	13	N121W, 14	N140E, 31	N10W, 55
	N173W	79W	147			
5	N107E	62S	- 11	N68E, 27	N28W, 12	N40W, 60
	N158W	80W	-151			
6	N 93E	61S	- 8	N54E, 26	N43W, 14	N160W, 60
	N173W	83W	-150			
7	N 79E	76S	- 5	N36E, 14	N56W, 6	N170W, 75
	N171E	85W	-165			

In FOCMEC, polarity data are analyzed first to determine if they are consistent with each pair of orthogonal nodal planes. If the number of polarity errors is within a pre-specified number of allowable errors, then the difference between theoretical amplitude ratios and the corresponding observed (SV/P)z amplitude ratios is compared to the preset error allowance. All ratios and ratio error allowances are represented as logarithms to insure linearity of the differences. If the number of acceptable ratio differences (within the preset error allowance) is less than a specified number of allowed ratio errors, a valid solution is declared and its parameters are output. The B, A, and N axes are then incremented for the next iteration. A companion program, FOCPLT, plots the output of FOCMEC in a variety of possible formats on the focal sphere: station distributions, superposed nodal planes from multiple solutions, single solution nodal planes with polarities and ratios, SH and SV nodal surfaces, etc.

PROJECT TASK 4 AND OBJECTIVE 2. CORRELATION OF SEISMIC RESULTS WITH LOCAL AND REGIONAL GEOLOGIC FEATURES AND DELINEATION OF THE SEISMICALLY ACTIVE AREAS IN VIRGINIA AND ENVIRONS - PRINCIPAL RESULTS

The principal results obtained for this project task are summarized in the following lists of conclusions:

I. Giles County, Virginia, Seismic Zone

A well-defined seismic zone has been detected in southwestern Virginia that has an orientation not related to the surrounding geologic structures. Rather, the orientation of the zone appears to be related to features below the Appalachian overthrust belt. A damaging earthquake that is important in evaluating seismic hazard in the southeastern United States occurred in the zone in 1897.

Thus, project results have provided the first, direct instrumental evidence of an active seismic zone in the Southeast that did not parallel the surficial tectonic fabric. Similar results obtained subsequently for southeastern Tennessee suggest that zone is representative of the host southern Appalachians.

We draw the following conclusions from our instrumental studies:

A. The Giles County seismic zone is centered at Pearisburg, strikes northeast and dips nearly vertically. It is about 40 km long, 10 km wide, and from 5 to 25 km deep.

B. The seismic zone is in the basement beneath the rocks detached by thrusting. The zone lies some 20° counterclockwise to the trend of the detached structures of the southern Appalachian region and more closely parallels the trend of the Appalachians in the northern part of the state.

C. Although conclusive evidence is lacking, it is likely that (1) this seismic zone is the same one that produced the 1897, $m_b = 5.8$, shock and that the seismic events felt in the locale during the last two decades suggest an apparent resumption of strain energy release after a seismic quiescence of four to five decades and (2) the northeast-trending seismic zone is most probably the result of reactivation of one or more normal faults formed initially in the Eocambrian.

D. The focal mechanism study results for 11 earthquakes in the Giles County seismic zone show mainly strike-slip mechanisms on steeply dipping ($73° \pm 16°$), NNE (right-lateral motion) and ESE (left-lateral motion) trending nodal planes. However, some (4/11) of the solutions show similar movement on nodal planes rotated 45° counterclockwise.

E. In Giles County, a rather consistent stress regime is present throughout the area. The P axis trend as estimated from eight different sets of focal mechanism solutions has a mean and standard deviation of N46°E±24° and the plunge is 14°±20°. The mean and standard deviation for the T axis trend and plunge are S41°E±24° and 1°±20°, respectively. The Giles County seismic zone as defined originally by Bollinger and Wheeler (1983) is corroborated by these focal mechanism results. However, it is probable that some portions of the zone may be more complex structurally than originally defined.

F. In Giles County, where the seismic activity is occurring beneath the Appalachian decollement, faulting and inferred stress orientations are much more uniform than in central Virginia, some 200 km away, where the seismicity is occurring near and above the decollement.

II. Central Virginia Seismic Zone

The central Virginia seismic zone is an area of persistent, low-level seismicity in the Piedmont province of that state. Its north-south dimension is about 120 km, and it extends some 150 km in an east-west direction from Richmond to Lynchburg. The results of instrumental monitoring there by the Virginia Regional Seismic Network during the past five years (34 network-determined hypocenters, 1978-1982; $M \leq 4.0$ but mostly smaller, not-felt shocks) were interpreted along with 96 pre-network (pre-1978) earthquakes, (for the most part, larger, felt events with noninstrumental locations). The spatial distribution exhibited by the combined set of 130 hypocenters is diffuse, both vertically and horizontally. Such a pattern favors multiple, rather than singular, seismogenic structures. Seventy-five percent of the focal depths are in the upper one-third of the crust, at depths of 11 km or less. These multiple, shallow sources are interpreted, on the basis of independent reflection seismic results, to be along and above a master detachment fault.

From our studies of the central Virginia seismic zone, we have developed the following initial conclusions:

A. Approximately 5 years of seismic-network monitoring in central Virginia has corroborated the existence there of a seismic zone that is more active than adjacent areas. That is, both felt- and non-felt earthquakes have been detected instrumentally and have been located in the same area that had been previously identified as seismically active on the basis of historical, primarily noninstrumental data.

B. There are elements of spatial stationarity and temporal persistence to the seismicity there, at least in terms of decades to centuries.

C. The spatial pattern exhibited by the hypocenters is diffuse, both horizontally and vertically. That diffuseness has been demonstrated to be real; it is not due to data set incompleteness or to errors in the detection or calculation schemes.

D. A tendency toward earthquake sequences and a possible temporal periodicity of some type in the occurrence of events in the zone has been observed. An explanation for these intriguing characteristics has not yet been formulated.

E. The depth distribution of foci in the zone shows the majority to be in the upper third (11 km) of the crust.

F. An interesting, but probably fortuitous, epicenter pattern is present in the network-located data set. An envelope to those epicenters would define an almost circular curve. It will be interesting to see if the location of future earthquake activity in the zone continues to support this geometry.

G. There was uncertainty in the epicentral coordinates for the MMI VII, mb 5.0 shock of December 23, 1875. A special archival study has been conducted to establish as accurately as possible the location of this important earthquake (Oaks, Sherry and G. A. Bollinger, Eqke. Notes, accepted for publication).

H. Focal mechanisms from central Virginia exhibit much more scatter in mechanism types and nodal plane orientations than those determined for Giles County. The P axes in central Virginia are generally northeast trending for shallow earthquakes (<8 km) and northwest trending for deeper ones (>8 km). The focal mechanisms exhibit a mixture of reverse and strike slip faulting on planes that dip $62° \pm 16°$. There is a tendency for strike-slip to dominate over dip slip as a mode of faulting for the deeper events in central Virginia, a result consistent with the increase in lithostatic pressure with depth interchanging the relative sizes of the three principal stresses.

I. Despite the spatial proximity of the two seismic zones in Virginia the focal mechanism results are quite different. As previously mentioned, the uniformity of stress axes found in Giles County does not hold for the seismicity in central Virginia. In central Virginia, the trend of the generally sub-horizontal P axis appears to rotate, or perhaps be offset, from northeast to southeast as the events become deeper. The scarcity of data from larger earthquakes ($M \geq 4$) may result in neither of these generalizations being valid for the dominant tectonics of the zone. Clearly, the answer will require additional focal mechanisms from larger shocks.

III. Eastern Tennessee Seismic Zone

To aid our investigation of the neotectonic processes in Virginia, we have also determined 11 SEFM and 7 CFM from 37 events that occurred in the Southern Appalachians of eastern Tennessee between September 1981 and July 1983. Following are the basic conclusions from those investigations (Bollinger and others, 1985, NUREG/CR-4288).

A. A major proportion of the seismic energy release in the study area has occurred in the basement, below the detached upper sedimentary layers.

B. Fault motion for SEFM and CFM solutions is predominantly strike-slip along nearly vertical north-south (right-lateral) or east-west (left-lateral) nodal planes. The average P-axis trend is about N50°E, with a nearly horizontal plunge. This orientation is consistent with both the P-axis orientation determined for the nearby Giles County, Virginia region (N46°E from Munsey, 1984) 300 km to the northeast and the inferred trend of the principal compressive stress (ENE sigma-one) for the midcontinent region (Zoback and Zoback, 1980, State of Stress in the Conterminous U.S., J. Geophys. Res., 85, pp. 6113-6156).

C. Limits placed by the focal mechanism results on the region in which the maximum compressive stress can exist, based on the assumption that it may lie anywhere in the quadrant containing the P-axis, were about N38°E to N63°E, with plunges ranging from about 12° to -30°. The average P-axis orientation for SEFM and CFM solutions lies near the center of these regions of maximum compressive stress. Thus the location of the average P-axis (which may be biased by concentrations in fault plane orientations) suggests that fractures in the region are rather uniformly distributed.

D. One sub-region of the study area is an exception to the preceding general orientation of nodal planes and/or P-axes. The nodal planes for some events in the southernmost portion of the study area are oriented more clockwise than the regional average. These focal mechanisms are, nevertheless, still generally consistent with the inferred regional stress regime.

IV. The Host Region - The Southeastern U.S.

A. Vertical Distribution of Earthquake Foci

Seven years (1977-84) of seismic network monitoring in the southeastern U. S. has resulted in a catalog of 255 earthquakes ($0 \leq M \leq 4.2$) with depth error estimates (ERZ) $\leq$ 5 km. Focal depths from the Valley & Ridge and Blue Ridge provinces (mean depth 12 km) were combined for analysis as were those for the Piedmont and Coastal

Plain provinces (mean depth 8 km). The mean focal depths between these two regions were shown to be statistically different. The 90% depths of earthquakes within the Valley & Ridge-Blue Ridge (20 km) are also significantly deeper than those of earthquakes occurring in the Piedmont and Coastal Plain provinces (13 km; Figure 15).

First order models of crustal rheology using a range of possible strain-rates and rock types for the middle and lower crust can be reconciled with the depth data if, e.g., ductile strain-rates within the Valley & Ridge-Blue Ridge are on the order of 100 times larger than those within the Piedmont and Coastal Plain, whereas a similar strain-rate for the two regions could imply that the crust of the Valley & Ridge-Blue Ridge contains a higher percentage of quartz-poor rocks at middle to lower crustal depths.

The actual situation is virtually certain to be more complex than that just considered. For example, large differences in crustal thickness occur within the southeastern U. S., with those thicknesses decreasing from more than 50 km beneath portions of the Valley & Ridge-Blue Ridge to less than 35 km beneath the Piedmont. Conceivably, this could affect the rheological behavior of the two regions. Also, the thin-skinned structure of the southern Appalachians may play a fundamental role by providing zones of variable strength within the upper crust. The maximum depth of earthquakes in the Piedmont province correlates approximately with the depth of the southern Appalachian decollement. That correlation suggests possible differences in strain-rate due to differences in the mechanical integrity and coupling between the overlying allochthonous rocks and the underlying autochthonous basement.

B. Horizontal Distribution of Earthquake Foci

The distribution of seismicity in the Southeastern United States is not uniform. Neither is it random: seismicity falls mostly into a few patches and belts that have larger and more frequent earthquakes than do surrounding areas. A tenfold increase in the number of seismographs in the Southeast accompanied the advent of network monitoring, with consequent improvements in capability to detect or locate small earthquakes. The results from such monitoring show that, at least on a time scale of decades, the broad seismicity pattern in the Southeast is spatially stationary to a first approximation. In that region, there are three areas for which epicentral locations and hypocentral depths for a sufficient number of earthquakes are known accurately enough to estimate whether the seismicity occurs in detached rocks, in underlying structural basement, or in both.

As discussed previously, in southern Virginia and eastern Tennessee, both of which are located within the Valley and Ridge province, the seismicity occurs primarily below the basal detachment, within cratonic basement at depths of 5 to 25 km, under east-northeasterly compression, and in subvertical zones that strike generally northwest to northeast. The most probable source structures are compressionally reactivated, Iapetan normal faults that formed in

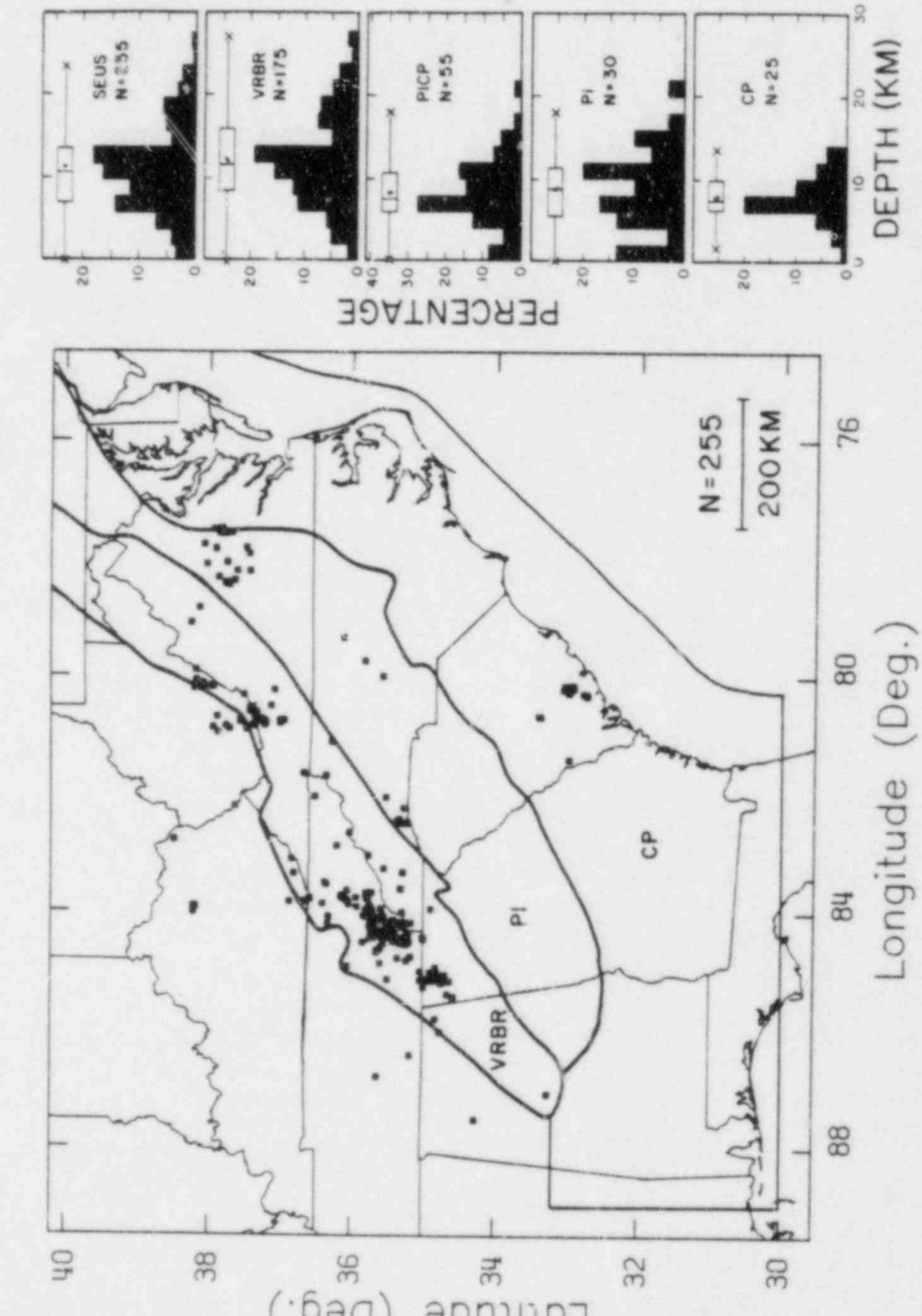


Figure 15. Left: Earthquake epicenters in the southeastern U.S. (SEUS: $0.0 \leq$ magnitude ≤ 4.2 and ERZ ≤ 5.0 km). Major geologic provinces are also indicated: Valley & Ridge-Blue Ridge (VRBR), Piedmont (PI) and Coastal Plain (CP). Right: Histograms showing focal depth distributions for the various geologic provinces, as well as that for the entire region. Shown over each histogram are the number of earthquakes (N) and a box plot of the distribution (Ott, L., 1984, AN INTRODUCTION TO STATISTICAL METHODS AND DATA ANALYSIS, 2nd Ed., Duxbury Press, Boston, MA, 775 p.

the North American craton when the Iapetus Ocean opened in late Precambrian or early Paleozoic time. By analogy with modern, passive continental margins, other such faults should occur elsewhere throughout the craton under and next to the western Appalachians.

As also noted previously, in the Piedmont province of central Virginia, the seismicity defines a diffuse cluster extending from near surface to a depth of 10-15 km. The deeper earthquake hypocenters coincide spatially with a sole detachment that has been interpreted from seismic-reflection profiling to be the southeastward extension of the detachment that underlies the Valley and Ridge province. Only a small percentage (less than 5%) of focal depths have been reliably located below the detachment or a hypothesized root zone.

In the Coastal Plain province of South Carolina near Charleston, seismicity defines several clusters with hypocentral depths from near-surface to 18 km. The nature of the source structure remains unknown, and hypotheses abound: (1) A deep detachment source for the Charleston area, but that remains controversial; (2) A northwest-trending seismogenic fault zone across South Carolina; (3) Alternative interpretations of seismicity involve steeply dipping inferred single or intersecting sets of faults, mostly at or above the depth of the suggested detachment.

If suspect or tectonostratigraphic terranes exist in the Appalachians, then geologic and mechanical differences between such terranes may provide a foundation for interpreting the spatial distribution of seismicity. For example, a published map of suggested terranes is broadly consistent with spatial characteristics of southeastern seismicity and with structural models of seismicity in central and southwestern Virginia and in southeastern South Carolina. Refinement and revision of the preliminary terrane map of Williams and Hatcher (Suspect Terranes and Accretionary History of the Appalachian Orogen, Geology, 10, pp. 530-536, 1982) will improve the definition of boundaries, compositions, structures, and histories of the various terranes.

The suggested association between seismicity and suspect terranes already finds practical application in zoning for seismic hazard. For example, the seismicity of Giles County and areas to the southwest, of central Virginia, and of the vicinity of Charleston, are separated from each other by inferred terrane boundaries. That observation supports Algermissen et al. (U.S.G.S. Open-File Report 82-1033, 1982) in placing these three locales in different source zones with different hazards.

PROJECT TASK 5. PUBLICATION OF A SEISMICITY BULLETIN FOR THE SOUTHEASTERN UNITED STATES

This publication series began with Seismicity of the Southeastern United States, July 1, 1977-December 31, 1977, Bulletin No. 1, dated April, 1978. Listed were the 12 contributors:

Carolina Power and Light Company
E. I. DuPont de Nemours and Company, Inc. (Savannah River Laboratory)
University of Florida
Georgia Institute of Technology
University of North Carolina
University of South Carolina
Union Carbide Corporation
United States Geological Survey
Virginia Division of Mineral Resources
Virginia Polytechnic Institute and State University (Virginia Tech Seismological Observatory)
Washington and Lee University
West Virginia University

and four sponsors:

Department of Energy
National Science Foundation
Nuclear Regulatory Commission
United States Geological Survey

Results from 53 seismograph stations on 55 earthquakes were reported to a mailing list of approximately 100 individuals and institutions.

At the end of the contract period, Bulletin No. 15 for the July 1, 1984-December 31, 1984, time frame had been compiled and distributed (June, 1985). Listed were 14 contributors:

Baptist College at Charleston
Carolina Power and Light Company
University of Florida
Geological Survey of Alabama
Georgia Institute of Technology
Georgia Southwestern College
Memphis State University (Tennessee Earthquake Information Center)
University of South Carolina
Tennessee Valley Authority
United States Geological Survey
Virginia Division of Mineral Resources
Virginia Polytechnic Institute and State University (Virginia Tech Seismological Observatory)
Washington and Lee University
West Virginia University

and six sponsors:

Georgia Power Company
National Science Foundation
Nuclear Regulatory Commission
Tennessee Valley Authority
United States Geological Survey
Virginia Electric and Power Company

Results from 136 seismograph stations and 49 earthquakes were reported to a mailing list of 204.

Availability of the catalog results was announced formally in the Bulletin of the Seismological Society of America, (SEUSSN Contributors, 1985).

PROJECT OBJECTIVE 3. EVALUATION OF THE SEISMIC HAZARD IN THE STUDY AREA

Contributions toward this objective were made in both written and oral format and are described in the following discussions:

Size Estimates and Hypothetical Intensity Maps for the Giles County, Virginia, Seismic Zone for Emergency Planning Applications

In Bollinger (1981), a scheme was developed to estimate fault plane (zone) area that utilized the 68% confidence ellipses on the estimates of the hypocenters in that zone. The approach was to keep the hypocenters inside their error ellipses but to move them toward the centroid of the zone to obtain a minimum estimate of fault area and to move them away from the centroid for a maximum area estimate. In both cases, the areas were determined by connecting the outermost hypocenter plots by straight lines and measuring the area enclosed. The areas obtained for the Giles County zone by this procedure were 80 sq km and 800 sq km. Published magnitude-fault plane area relationships yield estimates of Ms = 6 or 7 for these areas. It was noted that the 1897 shock on the zone was at an Ms = 5.8 level and this was taken as general support for the overall approach.

A hypothetical intensity map for the Giles County seismic zone was also presented in Bollinger, 1981. A study of the relationships between the trend of meizoseismal zones and the strike of surface faulting associated with western U.S. earthquakes showed the data base to favor an increasing tendency, with increasing earthquake magnitude, for there to be a parallelism between causal faults and the dominant trend of the innermost isoseismals. With a strongly developed tectonic fabric, e.g., as in the San Andreas fault system in California or the Appalachian mountains in the eastern U.S., the trend of the outermost (lowest level) isoseismals can be expected to be elongated in a direction subparallel with that fabric. Those geometric constraints were applied to magnitude-intensity and intensity attenuation with distance considerations to develop the subject map.

It was noted that this was not a seismic risk study for engineering purposes.

End of Seismic Quiescence in the Bath County and North Anna Locales in Virginia

A Special Report (#77-134-12A) was issued on October 15, 1980, that dealt with the above topic. On August 21, 1980, a microearthquake sequence (magnitudes less than 2) of at least eight events occurred 30 km WSW of the Bath County, Virginia, dam site. That sequence was followed by an additional microearthquake on October 16, 1980. At North Anna, between August 4, 1980, and October 11, 1980, three microearthquakes occurred some 3-6 km NE of the power plant site.

The Special Report reviewed the past and current monitoring results for both sites, presented seismograms and epicenter maps for the recent microshocks and discussed the impact of this apparent resumption of microseismicity. It was concluded that, while the microearthquakes being considered did constitute an initiation of seismicity for the current monitoring program, they were not particularly anomalous when viewed from the perspective of a longer time frame. That is, sporadic periods of increased microearthquake activity are expectable on the basis of previous reconnaissance surveys in the respective areas (Bollinger and Gilbert, Bull. Seism. Soc. Am., 1974, pp. 1715-1720 and Bollinger, Eqke. Notes, 1975, pp. 3-13).

The ability of network monitoring to detect such seismicity changes serves to focus attention on the subject area at an early stage. In this instance, subsequent monitoring confirmed the ambient-level nature of the observed microseismicity by the absence of its continuation or increase.

Preliminary Results of Combined Seismic Monitoring and Reflection Seismic Surveys in the Central Virginia Seismic Zone

At the 54th Annual Meeting of the Eastern Section, Seismological Society of America, September 27-29, 1982, in Warrenton, Virginia, Dr. Lynn Glover, III presented the above subject results. His presentation was as the featured banquet speaker and he discussed the initial data that showed the seismicity in the zone to be at and above the Appalachian decollement. That very important result has been supported by subsequent monitoring in the area. Glover also speculated on the seismogenic nature of the decollement itself as well as its associated ramp faulting. Focal mechanisms determined later did not support that speculation. As mentioned elsewhere herein, the dip of focal mechanism nodal planes are much steeper than those seen in the Vibroseis results (supported mostly by NRC-04-75-237 and NSF-EAR8009549).

Increased Seismic Activity in Southeastern Tennessee

The above increase i activity was presented in writing (November 29, 1984) as well as orally (early December) by Drs. G. A. Bollinger and A. C. Johnston (Tennessee Earthquake Information Center) to the NRC staff. For the preceding 2½ years, the southeastern Tennessee area had been the most seismically active in the region, both in terms of numbers and sizes of earthquakes. The activity was reported because it represented a change. That is, for the three year period prior to the first half of 1982, the southeastern Tennessee area was much less active than currently and it was not the most active area in the region. This was true for both larger and smaller magnitude events, so the increase was not due to a changing detection threshold as more seismic stations have been added. The change was not interpreted as a cause for concern at that time. The interpretation was that we were probably observing only expectable temporal and spatial variations in the general regional pattern of strain energy release. However, it was felt appropriate to bring the increase to the NRC's attention independent of normal progress reports and to recommend that (1) The Virginia Tech and Memphis State researchers continue to monitor the area closely and (2) Accelerographs at all federal engineered projects and veteran hospitals be checked for proper operation and calibration as promptly as reasonable.

Subsequent monitoring has shown the area to continue to be the most active in the region, but the overall level there, both in numbers and magnitudes, has decreased.

DISCUSSION OF PRINCIPAL RESULTS

The results to date from this project constitute the first detailed instrumental investigations of the two seismic zones in Virginia. Much light has been shed on the seismotectonics of the state. The knowledge on that topic has been advanced to the level where serious constraints now exist for the geologic models of the seismicity.

The two seismic zones--Giles County and central Virginia--are separated horizontally by only about 200 km. They are, however, very different seismologically. The Giles County zone appears to be composed of a small number, probably three or four at the most, of discreet, tabular fault structures, while the central Virginia zone exhibits no such obvious lineations. Rather, the hypocenters in that latter area are spread over a volume whose map view is near circular.

The vertical disparity between the seismic energy release in the zones is equally pronounced: It is sub-decollement (5-25 km) in Giles County and supra-decollement (<13 km) in central Virginia. The mean depths and 90% depths are 12 and 18 km, respectively, in the Giles County and 8 and 14 km, respectively, in central Virginia. The mean depths (12 km in Giles County and 8 km in central Virginia) are statistically different (P-value = 0.01).

The focal mechanism solutions discussed in the preceding chapter also exhibit the pervasive differences that exist between the two Virginia seismic zones. In Giles County there is a predominately strike-slip faulting response to a northeasterly, sub-horizontal maximum compressive stress (P-axes). A very similar stress-faulting combination was found some 400 km southwesterly along strike in southeastern Tennessee. Central Virginia focal mechanisms, on the other hand, display both dip-slip and strike-slip modes of faulting and both northeasterly and northwesterly oriented P-axes. Thus, there is uniformity in the stress and faulting estimates for Giles County (and eastern Tennessee) seismicity and variability in those same estimates for central Virginia.

Reflection seismology studies have been conducted in the two Virginia seismic zones. Gresko and others (1985) have interpreted a series of down-to-the-east normal faults that appear to offset basement reflectors (Precambrian) at 5-10 km depth while overlying Upper Cambrian and Ordovician sequences appear to be undisturbed by the faults. The lack of faulting in the younger strata is taken as evidence that growth along the faults ended during the Cambrian. Thus, these faults could be those Iapetan features postulated by Bollinger and Wheeler (1982, 1983). It is important to note here that the northeasterly-striking nodal planes of the Giles County focal mechanism solutions dip steeply to both the east and west. In particular, however, CFM A (Figure 14), from the principal portion of the zone, dips easterly in accord with the Vibroseis results. Of primary importance here is the fact that both focal mechanism and reflection seismology data sets indicate steeply dipping fault planes and thus are in general agreement.

Reflection seismology in the central Virginia seismic zone (Glover and others, GSA Abstr. w/Prog., 1982, page 467) has been interpreted as a master detachment fault with a complex series of associated listric ramp faults. All of those faults have dips less than 45°, while the dips of the focal mechanism nodal planes are generally greater than 45°. Thus, there is a lack of agreement between the two forms of geophysical data in the sense that the Vibroseis results are apparently not imaging the seismogenic features. Munsey and Bollinger (1985, also Bollinger and others, 1985, NUREG/CR-4288, page 46) suggest that the Mesozoic dikes present in the epicentral area may be acting as seismogenic structures.

The preceding discussions document that much progress has indeed been made in understanding Virginia seismicity. Specifically, we have defined its present geographical location as well as some of its chief geometrical and mechanical characteristics. However, much remains to be done. The following lists some of the more important remaining questions:

1. Why are the neotectonics of Giles County and central Virginia so very different? In particular, why is the central Virginia zone located where it is; why does it exist at all? We at least have a beginning geologic model (reactivated Iapetan normal faults) for Giles County.

2. The Giles County seismic zone (40 km long, NE trend) is not an isolated seismogenic feature. Network monitoring has defined activity some 80 km to its north, west and south. The relation(s), if any, of this outlying seismicity to the main zone is unknown at this stage. Also, because such shocks are outside of the network, they are less-well located and much less apt to develop reliable focal mechanisms.

3. Our results to date are based primarily on small, not-felt earthquakes, although in central Virginia we have instrumental data up to Mb = 4.0. An important question is whether or not the spatial locations and faulting mechanisms inferred from the small earthquakes' data sets are representative of the larger historical shocks and/or the full seismic potential of the zones.

   In Giles County, the consistency exhibited by the small earthquakes' data sets implies that the strain energy release is occurring on a few, well-defined structures in response to a uniform stress field. The observations point to the absence of small scale stress concentrators in the area, which might be expected to produce more scattered orientations of the focal mechanism P-axes. Therefore, for Giles County, we may infer that the larger shocks are likely to occur on the same or similarly oriented structures as do the microearthquakes.

In central Virginia, the existence of small scale stress inhomogeneity is evident in the variability of the focal mechanisms obtained for that zone. Whether that variability is due to multiple smaller and/or larger structures is unclear at this stage. Thus, it is possible that a group of larger earthquakes (because of their greater source volumes) would exhibit more uniform focal mechanism solutions, representative of the large-scale (regional) stress regime.

4. The temporal aspects of Virginia's seismicity have not yet been addressed. In addition to frequency-recurrence relationships, there is also the question of spatial stationarity. For example, northern Virginia was seismically active prior to 1925: 17 shocks, 1856-1924; one shock in 1974, nothing subsequently.

REFERENCES

(see Appendix A)

FIGURE CREDITS

Numbers	Source
1, 2, 7, 8, 10, 13	Geol. Soc. Am. Bull., 96, p. 49-57, Jan., 1985
3, 4, 9	U.S. Geol. Survey Open-File Rept. 82-585, 136 p., 1982
12, 14	NUREG/CR-4288, 83 p., 1985
15	Geophys. Res. Letters, 12 p. 785-788, Nov., 1985
5, 6, 11	This Study

APPENDIX

STUDIES COMPLETED AND PUBLISHED

UNDER THIS CONTRACT

APPENDIX A1 - PRINCIPAL PUBLICATIONS IN REFEREED JOURNALS

1985 Bollinger, G. A. and M. S. Sibol, (1985), Seismicity, seismic reflection studies, gravity and geology of the central Virginia seismic zone: Part I. Seismicity, Geol. Soc. Am. Bull., 96, p. 49-57.

Bollinger, G. A., M. C. Chapman, M. S. Sibol and J. K. Costain, (1985), An analysis of earthquake focal depths in the southeastern United States, Geophys. Res. Letters, 12, p. 785-788.

Bollinger, G. A., A. G. Teague, J. W. Munsey and A. C. Johnston, (1985), Focal mechanism analyses for Virginia and eastern Tennessee earthquakes (1978-1984), NUREG/CR-4288, U.S. Nuclear Reg. Comm., Washington, DC, 83 p.

Munsey, Jeffrey W. and G. A. Bollinger, (1985), Focal mechanism analyses for Virginia earthquakes, Bull. Seism. Soc. Am., 75, in press.

1984 Wheeler, R. L. and G. A. Bollinger, (1984), Seismicity and suspect terranes in the southeastern United States, Geology, 12, p. 323-326.

Viret, M., G. A. Bollinger, J. A. Snoke and J. W. Dewey, (1984), Joint hypocenter relocation studies with sparse data sets--A case history: Virginia earthquakes, Bull. Seism. Soc. Am., 74, p. 2297-2312.

1983 Bollinger, G. A. and Russell L. Wheeler, (1983), The Giles County, Virginia, seismic zone, Science, 219, p. 1063-1065.

1982 Bollinger, G. A. and Russell L. Wheeler, (1982), The Giles County, Virginia, seismogenic zone - Seismological results and geological interpretations, U.S. Geol. Survey Open-File Rept. 82-585, 136 p.

Seeber, L. J. G. Armbruster and G. A. Bollinger, (1982), Large-scale patterns of seismicity before and after the 1886 South Carolina earthquake, Geology, 10, p. 382-386.

1981 Bollinger, G. A., (1981), The Giles County, Virginia, seismic zone - Configuration and hazard assessment, Proc., Eqkes. and Eqke. Eng. - The Eastern U.S., 1, Knoxville, TN, p. 277-308.

Carts, D. A. and G. A. Bollinger, (1981), A regional crustal velocity model for the southeastern United States, Bull. Seism. Soc. Am., 71, p. 1829-1847.

Sibol, M. S. and G. A. Bollinger, (1981), A note on recent seismicity in the Scottsville, Virginia, area, Eqke. Notes, 52, p. 11-22.

1980 Bollinger, G. A., M. C. Chapman and T. P. Moore, (1980), Central Virginia regional seismic network: Crustal velocity structure in central and southwestern Virginia, NUREG/CR-1217, (R6, RA), U.S. NRC, Div. of Reactor Safety Res., Contract No. NRC-04-77-134, 187 p.

APPENDIX A2 - OTHER PUBLICATIONS

1985 SEUSSN Contributors, (1985), Availability of a six-year (1977-1983) earthquake catalog for the southeastern United States derived from network monitoring, Bull. Seism. Soc. Am., 75, p. 629-633.

Bollinger, G. A., M. C. Chapman, J. W. Munsey, A. G. Teague and A. C. Johnston, (1985), Location and character of neotectonic basement faulting in the southern Appalachians, Appalachian Basin Industrial Association Meeting, April 11-12, 1985, vol. 8, p. 215-230.

Sibol, M. S., G. A. Bollinger and E. C. Mathena (ed.), (1985), Seismicity of the Southeastern United States, July 1, 1984-December 31, 1984, Bull. 15, V.P.I. & S.U., Dept. of Geol. Sciences, Blacksburg, VA, June, 78 p.

Sibol, M. S. and G. A. Bollinger (ed.), (1985), Hypocenter listing from southeastern U.S. seismic network bulletins No. 1-14 (July, 1977-July, 1984), Southeastern U.S. Seismic Network Bulletin 14A, V.P.I. & S.U., Dept. of Geol. Sciences, Blacksburg, VA, April, 46 p.

1984 Bollinger, G. A. and M. S. Sibol, (1984), Southeastern U.S. earthquakes, 1981 in Stover, C. W. (ed), United States Earthquakes 1981, U.S.G.S. Sp. Pub., p 112-113.

Sibol, M. S. and G. A. Bollinger (ed.), (1984), Hypocenter listing from southeastern U.S. seismic network bulletins No. 1-12 (July, 1977-July, 1983), Southeastern U.S. Seismic Network Bulletin 12A, V.P.I. & S.U., Dept. of Geol. Sciences, Blacksburg, VA, April, 44 p.

Bollinger, G. A., M. S. Sibol and Ellen Mathena (ed.), (1984), Seismicity of the Southeastern United States, July 1, 1983-December 31, 1983, Bull. 13, V.P.I. & S.U., Dept. of Geol. Sciences, Blacksburg, VA, June, 98 p.

Bollinger, G. A., M. S. Sibol and Ellen Mathena (ed.), (1984), Seismicity of the Southeastern United States, January 1, 1984-June 30, 1984, Bull. 14, V.P.I. & S.U., Dept. of Geol. Sciences, Blacksburg, VA, December, 53 p.

1983 Bollinger, G. A. and M. S. Sibol, (1983), Southeastern U.S. earthquakes - 1981 and 1982, Eqke. Notes, 54, p. 24-29.

Bollinger, G. A. and M. S. Sibol (ed.), (1983), Listing of hypocenters from southeastern U.S. seismic network bulletins No. 1-10 (July 1, 1977-June 30, 1982), Southeastern U.S. Seismic Network Bulletin 10A, V.P.I. & S.U., Dept. of Geol. Sciences and Extn. Div., Blacksburg, VA, April, 36 p.

Bollinger, G. A. and Ellen Mathena (ed.), (1983), Seismicity of the Southeastern United States, January 1, 1983-June 30, 1983, Bull. 12, V.P.I. & S.U., Dept. of Geol. Sciences, Blacksburg, VA, December, 77 p.

Bollinger, G. A. and Ellen Mathena (ed.), (1983), Seismicity of the Southeastern United States, July 1, 1982-December 31, 1982, Bull. 11, V.P.I. & S.U., Dept. of Geol. Sciences and Extn. Div., Blacksburg, VA, May, 95 p.

Sibol, M. S. and G. A. Bollinger, (1983), Network locational testing and velocity variations in central Virginia, NUREG/CR-3080, (RA), U.S. NRC, Div. of Reactor Safety Res., Contract No. NRC-04-77-134, 70 p. (Note: This publication is a transcription of the M.S. Thesis of the senior author.)

1982 Bollinger, G. A. and Ellen Mathena (ed.), (1982), Seismicity of the Southeastern United States, July 1, 1981-December 31, 1981, Bull. 9, V.P.I. & S.U., Dept. of Geol. Sciences and Extn. Div., Blacksburg, VA, May, 47 p.

Bollinger, G. A. and M. S. Sibol, (1982), Southeastern United States earthquakes, 1980, Eqke. Notes, 53, p. 50-52.

Bollinger, G. A. and M. S. Sibol, (1982), Southeastern United States earthquakes, 1980, in Stover, C. W. and C. A. von Hake (ed.), United States Earthquakes, 1980, U.S. Dept. of Interior and U.S. Dept. of Commerce, p. 148-149.

Bollinger, G. A. and Ellen Mathena (ed.), (1982), Seismicity of the Southeastern United States, January 1, 1982-June 30, 1982, Bull. 10, V.P.I. & S.U., Dept. of Geol. Sciences and Extn. Div., Blacksburg, VA, December, 62 p.

1981 Bollinger, G. A. and Ellen Mathena (ed.), (1981), Seismicity of the Southeastern United States, July 1, 1980-December 31, 1980, Bull. 7, V.P.I. & S.U., Dept. of Geol. Sciences and Extn. Div., Blacksburg, VA, May, 40 p.

Bollinger, G. A. and Ellen Mathena (ed.), (1981), Seismicity of the Southeastern United States, January 1, 1981-June 30, 1981, Bull. 8, V.P.I. & S.U., Dept. of Geol. Sciences and Extn. Div., Blacksburg, VA, December, 90 p.

1980 Bollinger, G. A. and Ellen Mathena (ed.), (1980), Seismicity of the Southeastern United States, July 1, 1979-December 31, 1979, Bull. 5, V.P.I. & S.U., Dept. of Geol. Sciences and Extn. Div., Blacksburg, VA, May, 51 p.

Bollinger, G. A. and Ellen Mathena (ed.), (1980), Seismicity of the Southeastern United States, January 1, 1980-June 30, 1980, Bull. 6, V.P.I. & S.U., Dept. of Geol. Sciences and Extn. Div., Blacksburg, VA, November, 89 p.

1979 Bollinger, G. A. and Ellen Mathena (ed.), (1979), Seismicity of the Southeastern United States, January 1, 1979-June 30, 1979, Bull. 4, V.P.I. & S.U., Dept. of Geol. Sciences and Extn. Div., Blacksburg, VA, November, 80 p.

Bollinger, G. A. and Ellen Mathena (ed.), (1979), _Seismicity of the Southeastern United States, July 1, 1978-December 31, 1978_, _Bull. 3_, V.P.I. & S.U., Dept. of Geol. Sciences and Extn. Div., Blacksburg, VA, May, 69 p.

1978 Bollinger, G. A. and C. A. Murphy (ed.), (1978), _Seismicity of the Southeastern United States, July 1, 1977-December 31, 1977_, _Bull. 1_, V.P.I. & S.U., Dept. of Geol. Sciences and Extn. Div., Blacksburg, VA, April, 56 p.

Bollinger, G. A. and Ellen Mathena (ed.), (1978), _Seismicity of the Southeastern United States, January 1, 1978-June 30, 1978_, _Bull. 2_, V.P.I. & S.U., Dept. of Geol. Sciences and Extn. Div., Blacksburg, VA, November, 78 p.

APPENDIX A3 - PUBLISHED ABSTRACTS

1985 Bollinger, G. A. and SEUSSN Contributors, (1985), Availability of a 6-year (1977-1983) earthquake catalog for the southeastern United States derived from network monitoring, GSA Abstr. with Prog., 17, p. 81-82.

Bollinger, G. A., M. S. Sibol and J. K. Costain, (1985), An analysis of earthquake focal depths in the southeastern United States, Eqke. Notes, 55, p. 25.

Bollinger, G. A., J. W. Munsey, A. G. Teague and A. C. Johnston, (1985), Earthquake focal mechanisms for the southern Appalachians, GSA Abstr. with Prog., 17, p. 82.

Viret, Marc, G. A. Bollinger and M. C. Chapman, (1985), Three parameter joint inversion tests of focal depth determinations, Eqke. Notes, 56, in press.

Costain, J. K. and G. A. Bollinger, (1985), A hydrologic model for intraplate seismicity in the southeastern United States, Eqke. Notes, 56, in press; also in GSA Abstr. with Prog., 17, no. 7, p. 554.

Chapman, M. C. and G. A. Bollinger, (1985), Crustal thickness variation in Virginia derived from earthquake traveltimes, Eqke. Notes, 56, in press.

Gresko, M. J., J. W. Munsey and G. A. Bollinger, (1985), Structure of the Giles County, Virginia, seismogenic zone interpreted from seismic reflection data, EOS, Trans. Am. Geophys. Union, 66, in press.

1984 Munsey, J. W. and G. A. Bollinger, (1984), Focal mechanisms for Giles County, Virginia and vicinity Eqke. Notes, 55, p. 8.

Teague, A. G. and G. A. Bollinger, (1984), Provisional focal mechanisms for eastern Tennessee earthquakes, Eqke. Notes, 55, p. 8.

Oaks, S. D. and G. A. Bollinger, (1984), The epicenter of the December 22, 1875 central Virginia earthquake: New findings from documentary sources, Eqke. Notes, 55, p. 11.

Chapman, M. C. and G. A. Bollinger, (1984), Reliability of focal depth estimates from a small network, Eqke. Notes, 55, p. 13.

Snoke, J. A., J. W. Munsey, A. G. Teague and G. A. Bollinger, (1984), A program for focal mechanism determination by combined use of polarity and SV-P amplitude ratio data, Eqke. Notes, 55, p. 15.

1983 Bollinger, G. A., (1983), Seismicity patterns and terrane-mosaics in the southeastern United States, Eqke. Notes, 54, (Abstr.), p. 83.

Bollinger, G. A., L. Glover, III, J. K. Costain, M. S. Sibol and C. Coruh, (1983), The central Virginia seismic zone-Seismicity and subsurface geology, Eqke. Notes, 54, (Abstr.), p. 83-84.

1982 Sibol, M. S., G. A. Bollinger and J. A. Snoke, (1982), Network locational testing and velocity variations in central Virginia, Eqke. Notes, 53, p. 35.

Bollinger, G. A., M. Viret and M. S. Sibol, (1982), Spatial and temporal characteristics of the central Virginia seismic zone, Eqke. Notes, 53 (Abstr.), p. 88-89.

Bollinger, G. A., M. Viret and J. A. Snoke, (1982), Joint hypocenter studies of a selected set of Giles County, Virginia, earthquakes, Geol. Soc. Am. Abstr. with Prog., 14 (Abstr.), p. 6.

1981 Bollinger, G. A. and M. S. Sibol, (1981), Fault source models for Virginia earthquakes, Eqke. Notes, 52, p. 61.

Viret, Marc, G. A. Bollinger and J. A. Snoke, (1981), Relocation of Giles County, Virginia, earthquakes using JHD, Eqke. Notes, 53, p. 32.

Wheeler, R. L. and G. A. Bollinger, (1981), Stress orientations on the Giles County, Virginia, seismogenic zone, Eqke. Notes, 53, p. 32-33.

Bollinger, G. A., (1981), Southeastern United States earthquakes, 1979, Eqke. Notes, 52, p. 40-41 and United States Eqkes., 1979, p. 124-125.

Bollinger, G. A., (1981), Earthquake faults in Virginia, Geol. Soc. Am. Abstr. with Prog., 13, p. 413.

1980 Bollinger, G. A., (1980), Virginia earthquakes--1978, Eqke. Notes, 51, p. 25-26.

Bollinger, G. A., (1980), Southeastern United States earthquakes--1978, Eqke. Notes, 51, p. 27-28.

Bollinger, G. A. and R. L. Wheeler, (1980), The Giles County, Virginia, seismogenic zone, Geol. Soc. Am. Abstr. with Prog., 12, p. 389.

Bollinger, G. A. and M. S. Sibol, (1980), The central Virginia Seismic network-Monitoring results, 1978-1980, Eqke. Notes, 51, p. 13.

Bollinger, G. A. and Russell L. Wheeler, (1980), The Giles County, Virginia, seismic network-Monitoring results, 1978-1980, Eqke. Notes, 51, p. 14.

Carts, D. A. and G. A. Bollinger, (1980), A regional crustal velocity model for the southeastern United States, Eqke. Notes, 51, p. 15.

Wheeler, Russell L. and G. A. Bollinger, (1980), Types of basement faults probably responsible for seismicity in and near Giles County, Virginia, Eqke. Notes, 51, p. 39.

1979 Glover, L., G. A. Bollinger and J. K. Costain, (1979), Geology and seismicity of the central Virginia seismic zone, Geol. Soc. Am. Abstr. with Prog., 11, SE Sec. 28th Ann. Mtg., p. 180.

APPENDIX B - LIST OF INSTRUMENTALLY LOCATED EARTHQUAKES IN VIRGINIA

12-NOV-85 12:48:53 for the program RWVPIEQ

Input date from file ....: VPIEQ.DAT

INSTRUMENTALLY LOCATED REGIONAL/LOCAL EARTHQUAKES (FOR VIRGINIA)

Lab.	-Reg.	Origin Time (UCT) Year Mo Dy	Hr:Mn:Sec	Hypocenter Location Lat-N	Long-W	Depth	Location Parameters NSTA	P/S	GAP	DMIN	RMS	SQD	Error Ellipse Proj (ERH1,AZ1,ERH2,ERZ,Q)	Magnitude Mb/Ml/I	Srce
B	-WV	1933 06 15	01:14:36.8	37-34.08	81-58.38	5.0		/				I	(23.9, -2, 6.5, 0.0,)	/ /	11
C	-WV	1958 10 23	02:29:44.3	37-12.30	81-54.30	5.0		/				I	(9.8,-83, 5.0, 0.0,)	/ /	11
D	-QC	1959 04 23	20:58:40.2	37-23.70	80-40.92	5.0		/				I	(7.0,-82, 4.2, 0.0,)	3.8/ /	11
E	-WV	1965 04 26	15:26:19.7	37-19.50	81-36.12	5.0		/				I	(4.3,-48, 2.7, 5.6,)	3.5/ /	11
F	-CV	1966 05 31	06:18:59.5	37-39.66	78- 7.74	1.6		/				I	(8.2,-44, 3.2, 8.3,)	3.6/ /	11
G	-WV	1967 12 16	12:23:33.4	37-21.60	81-32.40	2.4		/				I	(5.6,-45, 3.1, 7.6,)	/ /	11
H	-QC	1968 03 08	05:38:15.7	37-16.86	80-46.44	7.7		/				I	(3.5,-47, 3.3, 5.8,)	4.1/ /	11
JR	-QC	1969 11 20	01:00:10.6	37-23.89	80-50.02	13.2	8	7/ 5	102	10	0.4	C B	(3.0,+56, 2.8, 3.0,B)	4.6/ /	1
K	-CV	1969 12 11	23:44:37.4	37-50.58	77-40.02	1.0		/				I	(16.0,-50, 2.9, 0.0,)	3.4/ /	11
N	-CV	1971 09 12	00:06:27.6	38- 9.00	77-35.52	4.5		/				I	(13.4,-56, 4.4, 9.1,)	3.6/ /	11
1	-CV	1974 02 28	18:38:	38-00.53	77-40.55	5.0		/			0.0	I	(, , , ,)	/ 1.5/	2
2R	-NV	1974 03 23	09:46:35.3	38-48.42	77-47.16	10.0	12	2/12	186	76	0.2	C D	(5.8,-30, 3.0, 7.2,C)	2.5/ /	1
R	-QC	1974 05 30	21:28:35.3	37-27.42	8)-32.40	5.4		/				I	(4.6,-57, 2.8, 5.1,)	3.7/ /5	11
4	-CV	1974 06 18	15:03:	38-04.76	7'-45.73	1.3		/			0.1	I	(0.5,360, 0.5, 1.6,)	/ 1.0/	2
5R	-CV	1974 08 13	13:26:30.0	37-43.15	7'-47.92	13.4	7	7/ 5	343	34	0.1	C D	(4.4,-16, 2.7,11.1,D)	/ 1.5/	1
6R	-CV	1974 11 07	21:30:57.3	38-14.06	78-09.82	27.5	8	6/10	235	33	0.4	C D	(4.1,+10, 1.8, 2.9,B)	2.4/ 2.7/5	1
7	-QC	1975 03 07	12:45:13.5	37-19.20	80-28.80			/				I	(, , , ,)	/ 3.0/2	5
8R	-CV	1975 04 12	13:30:34.1	37-48.26	77-41.98	7.3	12	12/11	304	14	0.1	B D	(1.2,-14, 0.8, 4.1,B)	/ 1.2/	1
9R	-CV	1975 05 10	12:45:12.8	37-43.08	77-43.52	14.1	13	13/11	315	22	0.3	C D	(3.5, -1, 2.8, 6.4,C)	/ 0.8/	1
10R	-CV	1975 05 28	10:30:37.9	37-45.12	77-44.93	5.9	6	6/ 6	341	31	0.1	C D	(4.7,-17, 2.7,25.2,D)	/ 0.9/	1
11	-CV	1975 08 15	13:42:	38-02.06	77-43.73	0.5		/			0.0	I	(0.1,360, 0.1, 1.0,)	/ 1.5/	2
12	-CV	1975 09 07	19:53:	38-02.03	77-43.70	0.6		/			0.0	I	(0.1,360, 0.1, 0.9,)	/ 2.1/	2
13	-CV	1975 09 18	18:56:	38-01.97	77-43.77	0.7		/			0.1	I	(0.2,360, 0.2, 1.5,)	/ 1.7/	2
S	-QC	1975 11 11	08:10:37.6	37-13.02	80-53.52	1.0		/				I	(6.3,-35, 3.6, 0.0,)	3.2/ /4	11
15	-CV	1975 12 29	02:30:	38-28.22	77-52.24	16.1		/			0.1	I	(0.7,360, 0.7, 1.4,)	/ 1.4/	2

There have been 25 earthquakes listed so far.

INSTRUMENTALLY LOCATED REGIONAL/LOCAL EARTHQUAKES (FOR VIRGINIA)

Lab.-Reg.	Origin Time (UCT) Year Mo Dy	Hr:Mn:Sec	Hypocenter Location Lat-N	Long-W	Depth	NSTA	Location Parameters P/S	GAP	DMIN	RMS	SQD	Error Ellipse Proj (ERH1,AZ1;ERH2; ERZ;Q)	Magnitude Mb/Ml/I	Srce
17R -CV	1976 05 11	01:45:41.8	37-40.75	77-46.89	11.1	14	8/14	325	26	0.2	C:D	(2.9,-86; 2.6; 7.0;C)	/ 1.2/	1
18R -CV	1976 05 20	08:12:50.8	37-32.11	77-26.90	5.3	11	6/10	351	51	0.2	C:D	(3.8,-84; 3.3;35.6;D)	/ 1.2/	1
W -WV	1976 06 19	05:54:13.4	37-20.64	81-36.12	0.9		/				:	(6.4,-35; 3.5; 8.8;)	3.3/ /5	11
X -QC	1976 07 03	20:53:45.8	37-19.26	81- 7.62	1.0		/				:	(7.4,-39; 3.5; 0.0;)	2.1/ /	11
20 -CV	1976 07 19	13:58:	38-01.97	77-44.18	1.9		/			0.0	:	(0.1,360; 0.1; 0.6;)	/ 1.8/	2
21 -VN	1976 09 13	18:54:38.5	36-36.24	80-44.56	18.5	6	6/ 1	155	73	0.1	C:D	(5.1,-35; 2.2; 5.0;C)	3.3/ 2.9/	1
22R -CV	1976 10 30	09:32:49.8	37-38.96	77-53.62	15.0	13	9/12	336	31	0.2	C:D	(3.0,-79; 1.5; 4.4;B)	/ 1.0/	1
23R -CV	1976 10 30	10:57:19.7	37-40.44	77-55.62	15.0	14	13/14	324	30	0.2	C:D	(2.2,-72; 1.4; 1.0;A)	/ 1.3/	1
24R -CV	1976 11 03	18:04:11.1	37-21.64	77-51.02	19.7	13	13/13	341	62	0.2	C:D	(4.4, 88; 2.5;15.7;D)	/ 2.0/	1
25R -CV	1976 11 04	05:57:45.7	37-20.91	77-53.54	16.6	16	16/10	337	64	0.1	C:D	(2.6,-86; 1.7;27.6;D)	/ 2.5/	1
26 -CV	1976 12 02	18:25:	38-09.71	77-25.72	9.2		/			0.1	:	(1.8,360; 1.8; 1.5;)	/ 0.8/	2
27R -CV	1977 01 23	07:11:23.5	37-41.18	77-42.37	7.8	12	12/12	329	26	0.2	C:D	(2.2, 2; 2.2; 8.6;C)	/ 1.1/	1
28R -CV	1977 02 27	20:05:35.5	37-55.51	78-36.51	5.5	8	3/ 8	153	14	0.3	D:C	(6.8,-19; 1.8; 3.9;C)	2.5/ /4	1
29 -CV	1977 03 06	01:28:	38-00.94	77-44.79	0.4		/			0.0	:	(0.2,360; 0.2; 1.0;)	/ 0.7/	2
30 -CV	1977 04 10	03:19:	38-02.03	77-44.41	1.2		/			0.1	:	(0.1,360; 0.1; 0.7;)	/ 0.8/	2
31 -CV	1977 04 24	02:31:	38-00.42	77-45.57	0.7		/			0.1	:	(0.2,360; 0.2; 0.4;)	/ 2.0/	2
31AR-VA	1977 10 23	07:51:41.0	36-55.91	82- 8.04	10.0	7	7/ 1	191	127	0.1	C:D	(5.5,-31; 1.1; 9.0;C)	/ 2.8/	1
32 -QC	1978 01 28	23:13:23.4	37-13.68	80-44.80	4.5	3	3/ 3	243	11	0.1	D:D	(5.9, 34; 1.3; 3.0;C)	/ 1.6/	1
32A -VA	1978 03 17	18:26:34.8	36-46.77	80-44.22	15.9	9	9/ 5	154	28	0.4	C:C	(3.7,-22; 2.8; 5.8;C)	2.8/ 2.6/	1
33 -QC	1978 05 10	04:19:09.6	37-12.80	80-49.82	26.2	3	3/ 3	268	12	0.1	C:D	(4.4, 44; 1.5; 3.0;B)	/ 0.3/	1
34 -QC	1978 05 25	08:30:25.1	37- 0.01	80-47.65	12.1	5	5/ 3	269	3	0.2	C:D	(4.3, 4; 2.7; 3.8;B)	/ 1.5/	1
35 -QC	1978 06 01	01:33:01.0	37-17.99	80-41.98	17.3	3	3/ 3	170	9	0.2	C:C	(8.8, 41; 2.1; 9.1;C)	/-0.2/	1
36 -WV	1978 06 09	04:42:49.4	37-47.36	81- 9.25	14.7	4	3/ 2	340	35	0.1	D:D	(5.7,-66; 3.9;99.0;D)	/ 0.9/	1
37 -QC	1978 07 28	08:39:40.7	37-20.22	80-41.41	11.8	4	4/ 3	146	10	0.3	C:C	(4.9, 39; 2.2; 8.1;C)	/ 0.6/	1
37A -WV	1978 08 14	04:50:05.4	37-56.34	80-52.44	23.0	8	7/ 6	243	39	0.3	C:D	(3.7,-50; 1.2; 3.3;B)	/ 1.6/	1

There have been 50 earthquakes listed so far.

INSTRUMENTALLY LOCATED REGIONAL/LOCAL EARTHQUAKES (FOR VIRGINIA)

Lab.	-Reg.	Origin Time (UCT) Year Mo Dy	Hr:Mn:Sec	Hypocenter Location Lat-N	Long-W	Depth	NSTA	Location Parameters P/S	GAP	DMIN	RMS	SQD	Error Ellipse Proj. (ERH1, AZ1; ERH2; ERZ; Q)	Magnitude Mb/M1/I	Srce
38	-QC	1978 08 30	02:19:38.2	37-21.71	80-40.06	8.4	4	4/ 2	158	12	0.1	C:C	(3.1, 28; 1.0; 6.4;C)	/ 0.5/	1
39	-I	1978 09 14	19:37:06.6	37-29.22	81-12.80	9.9	3	3/ 3	292	22	0.2	D:D	(6.6,-70; 3.6;17.5;D)	/-0.4/	1
41	-CV	1978 10 29	12:22:42.9	38- 1.74	78- 6.34	5.5	3	3/ 3	251	26	0.0	B:D	(1.1,-45; 0.2; 4.7;B)	/ 1.1/	1
42	-CV	1978 11 15	08:33:47.6	37-40.89	77-33.65	13.4	5	4/ 4	196	50	0.2	B:D	(1.5,-33; 1.4; 3.0;B)	3.2/ 1.8/	1
42A	-CV	1978 12 12	09:15:54.0	37-42.83	78-24.77	6.8	3	3/ 1	256	28	0.3	D:D	(9.5,-46; 4.6;29.2;D)	/ 0.0/	1
42B	-BC	1979 09 16	09:39:22.6	38- 4.78	80-14.08	11.3	7	7/ 6	199	28	0.2	C:D	(4.0,-27; 1.4; 4.7;B)	/ 1.6/	1
42C	-BC	1979 09 19	00:45:57.3	38- 5.65	80-13.93	16.5	10	10/10	187	28	0.2	C:D	(1.9,-34; 0.6; 5.2;C)	/ 1.8/	1
42D	-QC	1979 10 31	08:32:47.8	37-36.23	81-10.68	7.2	4	3/ 2	265	30	0.0	D:D	(6.7,-80; 2.9; 8.9;C)	/ 0.7/	1
43	-CV	1979 11 06	03:04:51.3	37-25.68	78-13.15	6.8	10	9/ 7	103	28	0.2	B:C	(1.0,-82; 0.6; 1.8;A)	1.3/ 1.4/	1
44	-CV	1979 11 12	07:21:53.8	37-43.33	77-28.76	5.0	5	5/ 5	173	54	0.2	C:D	(0.9,-81; 0.7;21.4;D)	1.2/ 1.1/	1
45	-VA	1980 01 06	13:50:55.7	36-37.89	81-34.03	3.6	10	10/ 8	323	80	0.4	D:D	(6.6,-47; 4.1; 3.2;C)	1.0/ 1.6/	1
46	-QC	1980 02 18	03:58:55.3	37-25.78	80-35.54	13.0	9	5/ 9	199	22	0.3	B:D	(1.7, 49; 1.2; 3.6;B)	/ 1.1/	1
47	-WV	1980 04 10	22:33:15.7	37-29.21	81- 5.16	5.0	3	3/ 2	253	17	0.2	D:D	(14.8,-52; 2.1;13.9;D)	/ 0.7/	1
48	-NC	1980 04 22	03:14:04.6	36-23.88	80-36.50	0.5	10	10/ 6	128	92	0.3	C:D	(2.9,-77; 1.7; 6.4;C)	2.8/ 2.2/1	1
49	-CV	1980 04 26	03:59:54.8	37-46.35	77-34.92	0.7	7	7/ 7	206	35	0.2	B:D	(1.5,-55; 0.8; 2.2;A)	3.0/ 1.4/	1
50	-CV	1980 05 18	03:31:19.9	37-34.85	77-56.27	28.5	4	3/ 4	215	28	0.3	C:D	(4.4,-77; 2.5;12.2;D)	/ 0.9/	1
51	-CV	1980 05 18	22:33:55.4	37-58.20	78- 4.08	5.6	4	4/ 1	146	17	0.1	C:D	(4.7,-34; 2.1;18.3;D)	/ 0.0/	1
53	-NA	1980 08 04	10:13:32.7	38- 3.97	77-45.86	4.9	8	8/ 7	111	7	0.1	A:B	(0.7,-41; 0.5; 1.6;A)	/ 0.7/	1
55A	-BC	1980 09 21	10:02:46.3	38-10.49	80- 4.20	3.1	8	6/ 5	193	14	0.3	C:D	(3.1,-24; 1.7; 3.3;B)	/ 1.4/	1
57	-NA	1980 09 26	01:31:57.8	38- 4.16	77-46.11	0.4	7	7/ 5	116	7	0.2	C:B	(1.3,-32; 0.9;52.3;D)	3.5/ 2.0/	1
57A	-NA	1980 09 26	05:04:15.7	38- 4.67	77-43.00	4.5	3	3/ 3	222	6	0.2	D:D	(7.5, 88; 2.7; 9.4;C)	/ 0.1/	1
58	-QC	1980 10 09	01:47:01.1	37-13.01	80-49.32	23.5	3	2/ 3	345	11	0.3	D:D	(7.2, 40; 2.3; 4.9;C)	/-0.2/	1
59	-NA	1980 10 11	22:40:28.5	38- 7.20	77-48.67	2.4	4	3/ 3	168	6	0.1	C:C	(5.5,-49; 0.8; 6.8;C)	/ 0.7/	1
60	-QC	1980 10 14	01:20:04.6	37- 4.69	80-13.82	11.0	14	11/13	171	22	0.4	C:C	(2.0, 13; 1.1; 3.1;B)	/ 1.7/	1
61	-BC	1980 10 16	03:48:07.6	38- 3.98	80-12.88	10.0	7	6/ 7	180	27	0.2	B:D	(2.9,-34; 0.9; 3.9;B)	/ 1.1/	1

There have been 75 earthquakes listed so far.

INSTRUMENTALLY LOCATED REGIONAL/LOCAL EARTHQUAKES (FOR VIRGINIA)

Lab.-Reg.	Origin Time (UCT) Year Mo Dy	Hr:Mn:Sec	Hypocenter Location Lat-N	Long-W	Depth	NSTA	Location Parameters P/S	GAP	DMIN	RMS	SQD	Error Ellipse Proj. (ERH1,AZ1,ERH2,ERZ,Q)	Magnitude Mb/Ml/I	Srce
61A -BC	1980 11 05	21:48:14.7	38-10.70	79-54.11	3.8	21	19/10	77	5	0.2	B:A	(0.7,-25, 0.4, 1.0,A)	/ 3.0/1	1
62 -BC	1980 11 25	07:44:04.0	38- 5.70	80- 7.35	15.3	4	4/ 4	324	18	0.1	C:D	(2.9,-42, 2.8, 3.4,B)	/ 0.6/	1
63 -GC	1980 12 02	07:47:38.2	37-25.08	80-32.25	12.2	6	5/ 5	113	25	0.3	C:C	(3.2, 51, 2.0, 7.4,C)	/ 0.4/	1
63A -CV	1981 01 19	21:54:19.3	37-43.94	78-26.18	2.9	7	5/ 7	182	28	0.2	C:D	(1.2,-76, 0.8,18.2,D)	/ 0.6/	1
63B -CV	1981 01 21	16:29:58.1	37-46.08	78-24.98	5.8	7	6/ 3	175	24	0.1	C:C	(1.0, 54, 0.6, 5.1,C)	/ 0.3/	1
64A -CV	1981 02 11	13:44:16.4	37-43.22	78-26.40	5.7	14	14/ 9	79	29	0.2	B:C	(0.7, 68, 0.6, 2.2,A)	3.4/ 2.6/4	1
64B -CV	1981 02 11	13:50:31.4	37-44.87	78-24.69	10.1	12	12/ 7	114	26	0.2	B:C	(1.0, 36, 0.7, 1.6,A)	3.2/ /4	1
64C -CV	1981 02 11	13:51:38.6	37-43.26	78-27.02	7.3	9	8/ 6	128	29	0.2	B:C	(1.1, 60, 0.8, 4.1,B)	2.9/ 2.2/3	1
64D -CV	1981 02 12	10:41:59.0	37-44.03	78-25.17	12.5	3	2/ 3	276	28	0.2	C:D	(2.8, 61, 1.8,14.9,D)	/-0.6/	1
65 -CV	1981 03 20	04:02:03.0	37-31.18	77-40.75	6.9	5	2/ 5	291	49	0.1	C:D	(1.9, 85, 1.0,27.2,D)	/ 0.6/	1
66 -CV	1981 04 09	07:12:54.4	37-28.87	77-49.26	0.8	11	8/10	129	43	0.3	B:C	(1.2, 89, 0.8, 2.1,A)	/ 2.1/	1
67 -CV	1981 04 09	07:34:36.0	37-27.95	77-51.96	1.1	4	2/ 4	267	42	0.3	C:D	(4.4, 68, 2.3,99.0,D)	/ 0.4/	1
68 -BC	1981 04 11	15:29:25.7	38-13.56	79-50.21	10.2	3	3/ 3	254	6	0.1	D:D	(6.6, 55, 1.1, 3.8,C)	/-0.6/	1
69 -CV	1981 04 16	13:49:20.5	37-36.52	78-12.89	15.5	3	3/ 3	189	23	0.1	D:D	(10.7,-65, 0.6, 4.7,D)	/ 0.1/	1
70 -BC	1981 06 06	08:05:58.7	38-12.45	79-30.87	14.3	6	5/ 6	159	13	0.5	D:C	(23.5, 45, 4.7,25.0,D)	/ 0.7/	1
71 -CV	1981 07 30	11:59:48.5	38-11.66	78- 5.26	6.0	10	8/10	180	30	0.3	C:C	(2.7,-22, 1.2, 6.7,C)	3.1/ 1.4/3	1
72 -GC	1981 08 24	11:50:11.2	36-56.71	80-44.76	16.8	7	6/ 7	183	11	0.2	B:D	(1.6,-43, 1.1, 2.8,B)	/ 1.0/	1
73 -GC	1981 11 12	06:24:14.0	37-14.10	80-44.99	9.2	5	2/ 4	223	10	0.2	C:D	(3.9,-67, 1.8,10.7,D)	/ 0.7/	1
74 -CV	1981 11 23	13:14:51.0	38-14.48	79- 5.58	9.8	16	12/11	175	50	0.3	B:C	(1.6, 2, 0.6, 1.4,A)	2.1/ 2.1/3	1
75 -GC	1981 12 04	02:35:56.4	36-59.99	80-44.77	3.5	16	14/ 7	157	7	0.4	C:C	(1.9,-20, 1.2, 2.4,A)	/ 2.0/	1
77 -CV	1982 01 13	13:16:25.0	37-44.95	78- 4.20	9.4	10	6/ 9	170	6	0.2	A:C	(0.8,-67, 0.6, 0.8,A)	/ 1.5/	1
78 -CV	1982 01 18	06:11:41.2	37-54.31	77-50.35	7.4	6	6/ 5	171	9	0.1	B:C	(1.1,-36, 0.6, 2.2,A)	/ 0.3/	1
79 -CV	1982 02 20	04:34:25.8	37-29.17	77-42.40	0.8	9	8/ 7	145	49	0.1	C:C	(0.8,-88, 0.4,79.[illegible],D)	/ 1.5/1	1
80 -CV	1982 04 11	20:01:14.6	37-43.78	78-25.12	1.3	4	4/ 4	277	28	0.1	C:D	(1.9, 24, 0.8,28.1,D)	/ 0.9/	1
81A -CV	1982 05 04	14:54:02.2	37-33.84	78-27.76	5.2	6	5/ 6	139	40	0.3	C:C	(2.8,-80, 1.1, 8.3,C)	/ 1.4/	1

There have been 100 earthquakes listed so far.

INSTRUMENTALLY LOCATED REGIONAL/LOCAL EARTHQUAKES (FOR VIRGINIA)

Lab.-Reg	Origin Time (UCT) Year Mo Dy	Hr:Mn:Sec	Hypocenter Location Lat-N	Long-W	Depth	NSTA	Location Parameters P/S	GAP	DMIN	RMS	SQD	Error Ellipse Proj. (ERH1,AZ1;ERH2;ERZ;Q)	Magnitude Mb/M1/I	Srce
81B -CV	1982 05 04	14:57:31.2	37-33.13	78-26.51	0.7	4	2/ 4	238	39	0.1	C:D	(1.3,-81; 0.5;82.4;D)	/ 0.7/	1
82 -CV	1982 05 06	07:18:10.9	37-51.24	77-34.71	9.7	10	10/ 8	153	17	0.2	B:C	(1.0,-82; 0.7; 2.3;A)	/ 2.0/1	1
83 -GC	1982 05 18	03:16:33.9	37- 7.72	80-29.97	10.5	12	11/ 7	148	9	0.2	B:C	(1.3, 2; 0.8; 1.4;A)	/ 1.6/	1
84 -CV	1982 06 16	18:40:58.6	38- 7.63	78-50.44	10.9	6	6/ 5	125	37	0.1	A:C	(0.7, 9; 0.6; 1.7;A)	/ 2.1/1	1
85 -WV	1982 06 23	16:17:34.1	37-52.21	80-57.42	11.1	17	16/ 9	113	33	0.2	B:C	(1.3,-63; 0.9; 2.0;A)	/ 2.5/	1
86 -CV	1982 06 25	23:03:47.0	37-49.86	77-30.12	13.5	9	9/ 9	166	23	0.1	A:C	(0.9, -6; 0.8; 1.5;A)	/ 1.8/	1
87 -CV	1982 09 20	12:15:32.0	37-49.30	77-29.76	10.6	10	10/10	168	24	0.2	B:C	(0.9,-88; 0.6; 1.5;A)	/ 1.5/	1
88 -GC	1983 01 08	15:53:55.8	37-19.65	80-36.93	4.1	5	4/ 4	139	16	0.2	B:C	(1.9,-13; 1.2; 4.2;B)	/ 1.2/	1
89 -BC	1983 01 21	05:33:20.4	38- 4.03	80- 8.64	17.8	4	4/ 4	327	21	0.1	C:D	(3.3,-44; 2.7; 4.2;B)	/ 0.4/	1
90 -GC	1983 01 25	20:38:58.3	37-23.15	80-30.32	16.7	19	19/17	81	13	0.3	B:A	(0.9,-48; 0.6; 1.2;A)	/ 1.8/	1
91 -VA	1983 02 10	06:18:59.5	36-55.70	82-58.26	1.3	8	8/ 7	189	72	0.3	C:D	(4.0,-29; 0.8; 5.9;C)	/ 2.2/	1
92 -GC	1983 04 20	18:09:56.6	37-20.93	80-49.99	10.4	7	7/ 6	129	5	0.2	B:B	(1.8, 25; 0.9; 2.1;A)	/ 1.2/	1
93A -GC	1983 05 12	00:23:07.0	37-11.49	80-43.88	14.3	5	3/ 5	202	15	0.2	B:D	(2.1,-29; 1.3; 4.0;B)	/-0.5/	1
93B -GC	1983 05 17	02:02:47.7	37-15.27	80-44.09	6.9	7	5/ 7	132	9	0.3	C:B	(2.0,-18; 1.4; 5.2;C)	/-0.1/	1
94 -GC	1983 05 26	01:04:44.8	37-30.35	80-18.95	9.0	19	18/14	109	8	0.2	B:B	(0.9,-37; 0.8; 1.8;A)	2.6/ 2.2/	1
95A -WV	1983 06 10	00:18:40.5	37-56.88	80-09.78	23.6	12	10/12	156	30	0.2	B:C	(2.2,-51; 0.7; 3.8;B)	/ 1.2/	1
95B -WV	1983 06 10	00:24:57.0	37-57.04	80-11.31	18.4	13	13/13	160	31	0.2	B:C	(1.4,-49; 0.4; 3.6;B)	/ 1.2/	1
95C -WV	1983 06 10	00:31:08.3	37-56.30	80-10.08	13.0	12	10/11	156	31	0.3	B:C	(2.7,-56; 0.9; 3.3;B)	/ 0.4/	1
96 -CV	1983 07 03	16:29:24.9	37-38.43	78-22.40	3.5	13	8/13	170	29	0.3	C:C	(1.5,-75; 0.9; 4.2;B)	/ 1.2/	1
97 -GC	1983 07 10	14:05:39.4	37-16.22	80-45.22	7.6	7	7/ 7	89	6	0.3	B:A	(1.2,-18; 1.2; 2.9;B)	/ 1.0/	1
98 -WV	1983 07 20	04:41:40.9	37-53.07	80-41.47	11.0	11	10/11	208	35	0.3	B:D	(2.6,-53; 0.8; 2.7;B)	/ 1.6/	1
98A -WV	1983 07 25	03:27:00.2	37-29.75	81-21.11	29.0	4	3/ 4	299	32	0.1	C:D	(4.9,-81; 2.6; 6.5;C)	/ 0.6/	1
99 -VA	1983 07 30	06:31:52.8	36-41.54	81-38.28	3.0	8	5/ 8	187	43	0.3	C:D	(2.4,-45; 1.2; 6.1;C)	1.5/	1
100 -CV	1983 08 10	12:29:34.1	37-46.35	78-25.46	11.2	8	8/ 6	118	23	0.3	C:C	(3.4,+28; 1.3; 4.9;B)	/ 1.8/	1
101 -GC	1983 08 25	05:04:34.8	37-19.47	80-43.68	14.7	4	3/ 4	279	6	0.2	C:D	(3.0,+29; 1.8; 3.8;B)	/ 0.0/	1

There have been 125 earthquakes listed so far

INSTRUMENTALLY LOCATED REGIONAL/LOCAL EARTHQUAKES (FOR VIRGINIA)

Lab.-Reg.	Origin Time (UCT) Year Mo Dy	Hr:Mn:Sec	Hypocenter Location Lat-N	Long-W	Depth	NSTA	Location Parameters P/S	GAP	DMIN	RMS	SQD	Error Ellipse Proj (ERH1,AZ1;ERH2;ERZ;Q)	Magnitude Mb/Ml/I	Srce
102A-GC	1983 11 13	16:51:06.7	37-33.36	80-45.29	10.0	4	3/ 4	171	9	0.1	B:C	(1.0,-26; 0.5; 2.2;A)	/ 0.4/	1
102B-GC	1983 11 13	17:06:14.1	37-33.53	80-45.23	9.1	4	2/ 4	253	9	0.1	B:D	(1.5,-16; 0.8; 3.7;B)	/-0.8/	1
102C-GC	1983 11 13	17:50:50.1	37-33.55	80-45.17	11.0	5	3/ 5	174	9	0.1	B:C	(1.5,-22; 0.9; 3.5;B)	/ 0.7/	1
103A-GC	1983 11 25	16:22:05.0	37-33.57	80-45.54	8.9	3	1/ 3	360	8	0.0	D:D	(5.5,+63; 3.9;10.4;D)	/-1.2/	1
103B-GC	1983 11 25	16:27:47.8	37-34.10	80-44.71	11.9	5	5/ 5	184	9	0.1	A:D	(0.8,-09; 0.6; 1.7;A)	/ 0.7/	1
103C-GC	1983 11 25	16:50:00.8	37-34.09	80-45.03	11.5	4	2/ 4	260	8	0.1	C:D	(2.7,-13; 1.4; 5.6;C)	/-0.8/	1
104 -GC	1983 12 09	00:11:57.9	37-12.05	80-47.15	12.4	17	17/10	98	13	0.2	B:B	(0.7,-52; 0.6; 1.2;A)	/ 1.3/	1
105 -WV	1983 12 23	10:51:21.9	37-45.94	80-50.21	13.7	6	5/ 6	289	20	0.2	C:D	(2.3,-39; 1.5; 2.3;A)	1.6/ 0.3/	1
106 -CV	1984 02 06	12:27:03.4	37-34.38	78-08.95	0.4	4	4/ 5	174	25	0.1	C:C	(0.5,-83; 0.3;50.5;D)	/ 1.1/	1
107 -GC	1984 03 11	04:01:37.8	37-29.01	80-53.56	14.3	9	3/ 9	161	13	0.2	B:C	(2.1,-62; 1.2; 2.8;B)	/ 1.0/	1
108 -CV	1984 04 12	23:46:30.6	37-56.56	78-01.47	06.1	8	4/ 4	227	14	0.1	C:D	(3.9,-38; 0.6; 4.5;B)	/-0.8/	1
109 -CV	1984 05 29	11:29:35.0	38-06.42	78-47.58	07.4	5	5/ 5	329	33	0.1	C:D	(2.2,-10; 1.4; 7.2;C)	/ 1.3/	1
110 -GC	1984 07 02	19:51:38.7	37-17.07	80-43.24	11.2	9	7/ 9	89	7	0.2	B:A	(1.1,+02; 0.9; 2.3;A)	/ 1.4/	1
111 -CV	1984 08 17	18:05:46.9	37-52.05	78-19.42	08.2	13	13/ 3	104	18	0.2	B:C	(0.9,+18; 0.6; 1.7;B)	4.2/ 4.0/5	1
112 -WV	1984 10 09	05:33:31.5	37-42.77	80-53.44	13.4	9	9/ 9	222	14	0.2	B:D	(0.8,-50; 0.5; 0.6;A)	/ 2.1/	1
113 -CV	1984 10 17	08:57:40.7	37-56.05	77-30.41	14.7	9	8/ 9	202	17	0.2	B:D	(0.9,-27; 0.5; 0.9;A)	/ 1.1/	1
114 -GC	1984 11 17	03:17:28.3	37-15.94	80-43.61	10.3	6	4/ 6	118	8	0.1	A:D	(0.4,+68; 0.3; 1.0;A)	/ 0.0/	1
115 -CV	1984 12 02	12:29:34.1	37-26.52	77-55.57	4.5	6	3/ 6	258	42	0.2	C:D	(0.9,+90; 0.6; 4.2;C)	/ 1.1/	1
116 -BC	1984 12 21	13:12:21.9	38-11.85	80-12.49	5.8	12	10/12	223	26	0.4	C:D	(2.0,-28; 0.5; 2.0;B)	/ 1.6/	1
117 -CV	1985 04 22	18:21:16.0	37-36.15	78-35.91	4.5	8	7/ 8	111	43	0.8	C:C	(1.1,-90; 0.5; 4.1;C)	/ 2.0/	1
118 -GC	1985 06 10	12:22:38.3	37-14.89	80-29.12	11.1	9	9/ 5	99	6	0.3	B:B	(0.9,-17; 0.9; 2.0;B)	3.2/ 2.8/4	1
119 -WV	1985 06 14	07:57:10.2	37-32.05	81-01.19	2.4	5	4/ 3	242	17	0.3	D:D	(3.6,-52; 1.1; 4.4;C)	/ 0.8/	1
120 -VA	1985 06 19	22:28:08.9	37-13.30	82-02.30	0.5	13	13/ 7	183	89	0.4	C:D	(1.6,-27; 1.0; 3.8;C)	/ 3.6/	1
121 -GC	1985 07 02	05:38:24.9	37-14.71	80-34.03	7.7	3	3/ 3	185	14	0.1	B:D	(0.8,+02; 0.4; 2.2;B)	/-0.6/	1

There are 149 earthquakes in this list.

Abbreviations For Regions:

- BC: Bath County, Virginia, area.
- CV: Central Virginia Seismic Zone.
- GC: Giles County, Virginia, Seismic Zone.
- NA: North Anna, Virginia, area.
- KY: Kentucky area.
- NV: Northern Virginia area.
- SC: South Carolinia area.
- TN: Tennessee area.
- VN: Virginia / North Carolina area.
- VW: Virginia / West Virginia area.
- WV: West Virginia.

R : Events that have been relocated for special studies. Calculated using either, a new technique (JHD, JED, HYPOELLIPSE, etc.) or a different velocity model.

Sources and/or References

1: VTSO records, NRC reports, SEUSSN Bulletins, or G. A. Bollinger personal files.
2: Dames and Moore, 1977. 'A Seismic Monitoring Program At The North Anna Site In Central Virginia', - January 24, 1974 Through August 1, 1977. Submitted to VEPCO, 1977.
5: Coffman, Jerry L., and C. W. Stover, 19XX. U. S. Earthquakes, 19XX; annual publication by NOAA and the USGS.
7: USGS Preliminary determination of epcenters, 19XX, monthly listings.
11: Dewey and Gordon, 198?. Relocation of major eastern North American earthquakes using JED/JHD.

NRC FORM 335 (2-84) NRCM 1102, 3201, 3202

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12. SUPPLEMENTARY NOTES

13. ABSTRACT (200 words or less)

Eight years of monitoring with a 20-station regional network has produced epicenters ($M \leq 4$), focal depths and mechanisms of adequate number and quality to reveal considerable differences between the two seismically active portions of Virginia. Those two areas (southwestern (Giles County) and central parts of the state) are separated by only some 200 km. Despite their proximity, the two zones exhibit remarkable differences in geometrical/mechanical characteristics. In Giles County, seismic energy is released by predominately strike-slip faulting in a near vertical, tabular zone (~ 40 km long) that is below the Appalachian decollement. In central Virginia, the seismicity is derived from mixed dip-slip and strike-slip faulting in a large, coin shaped volume (~ 100 km diameter; ~ 10 km vertical thickness), above the major detachment faulting. Stress estimates, as derived from single- and composite-focal mechanism solutions P-axes, are NE to ENE in Giles County and NW to NE in central Virginia.

The causes for the observed variability are unknown. The two zones are in different tectonostratigraphic (suspect) terranes and that difference could be relevant. The recently proposed Hydroseismicity model (Costain and Bollinger, 1985) ascribes the observed seismicity variations in Virginia and throughout the Southeast to different drainage basin hydrologic characteristics plus differences in upper crustal fracturing.

14. DOCUMENT ANALYSIS – a. KEYWORDS/DESCRIPTORS

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Earthquakes
Seismic Network
Hypocenter Bullentin

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