Network Locational Testing And

Velocity Variations In

Central Virginia

by

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1. INTRODUCTION

Network monitoring of the Central Virginia Seismic Zone (as defined in Bollinger, 1973) began in early 1974 (Dames and Moore, 1977). Since that time over 40 earthquakes have been located in the area. These locations depict a region of spacially diffuse but persistant, seismic energy release. There is no discernable epicenter pattern to indicate the location or orientation of the source or sources within the zone.

To test and ultimately to improve the accuracy of computed earthquake hypocenters, 24 blasts originating from three quarries within the area were located using network arrival times. In the location of blasts originating from two of the quarries, the average 'locational error' (defined to be the distance between the shot point and the computed epicenter) was considered to be excellent (< 1.5 km). However, for a third quarry, large locational errors (> 6.0 km) between the computed epicenters and the actual quarry site required further examination of the techniques used to locate earthquakes in that locale. Testing of the hypocentral location programs (HYPO71 and HYPOELLIPSE), and the velocity model employed, showed that the observed errors were the probable result of lateral velocty variations and/or the asymmetric distribution of network stations in that area.

Network station delays (corrections) were derived using two methods that approximate origin times for observed blasts. These methods allow for the development of relative station delays without the expenditure of time and funds for extensive field work.

Incorporating station delays, it was possible to observe zones in which lateral velocity differences are apparent. A pattern of alternating high and low velocity zones was observed that trends roughly parallel to the Blue Ridge Province (to the west of the study area). This 'velocity banding', has previously been observed in Piedmont and Coastal Plain provinces of Georgia, North and South Carolina.

Chapter 2 contains an assessment of the locational cabability of the network (using signals from local quarry blasts), and a comparison of the HYPO71 and HYPOELLIPSE locational programs. In Chapter 3 is a description of the development and testing of different suites of station delays for individual network stations. In Chapter 4 velocity variations within the network area implied by the station delays will be evaluated. Appendix 1 contains a general description of the Central Virginia - North Anna network while Appendix 2 contains the magnification curves for network stations used during this study.

2. ASSESSMENT OF LOCATIONAL CAPABILITIES

Introduction

Presently, two hypocentral location programs are in use at the Virginia Tech Seismological Observatory. HYPO71 (Lee and Lahr, 1974), an established and widely used location program, is being replaced by HYPOELLIPSE (Lahr, 1980). In the interest of determining how HYPO71 locations compare with HYPOELLIPSE locations, given identical circumstances, an empirical test was performed. Both programs, HYPO71 and HYPOELLIPSE, were used to locate 24 blasts, originating from three quarries. Locations for all 24 blasts were calculated using the central Virginia velocity model (Chapman, 1979), a single weighting scheme, and identical arrival time data from the Central Virginia - North Anna Network. A comparison of program accuracy and flexibility is presented.

Comparison Of Hypocenter Location Programs

HYPOCENTER CALCULATION. Both HYPO71 and HYPOELLIPSE computer programs are used to determine hypocentral locations for seismic events. HYPOELLIPSE employs Geiger's method (Geiger, 1912) to minimize the travel time residuals. HYPO71 also uses Geiger's method to minimize travel time residuals, but in doing so, it employs step-wise, multiple regression techniques. For sparse data, it has been found (Tarr, 1981, personal communication) that HYPOELLIPSE is, in general, more stable than HYPO71.

All 24 blasts in this study were located using the central Virginia P wave velocity model (Table 1). Note thhat for this study no source-to-station distance was ever greater than the upper layer crossover distance for this model. Thus, only the surficial layer was tested in this study. The associated S wave travel times were calculated assuming a Vp/Vs ratio (1.73) representative of the surficial layer of the central Virginia velocity model. Moreover, all of the calculations to locate blast epicenters were initiated using the same trial focal depth (5.0 km). Thus, all computations of blast locations (using either HYPOELLIPSE or HYPO71) were performed from identical input data.

TABLE 1

The Central Virginia Velocity Model
(Developed By Chapman, 1979)

Velocities				Crossover Dist.	
P Wave (Km/Sec)	S Wave (Km/Sec)	Vp/Vs	Depths (Km)	P Wave (Km)	S Wave (Km)
6.09	3.53	1.73	00.0-15.0	0	0
6.50	3.79	1.72	15.0-36.0	166	159
8.18	4.73	1.73	36.0-99.0	290	285

STATION DELAYS. For the application of station delays, HYPO71 requires that a single P wave delay be entered for each station. The corresponding S wave delay is then taken to be the product of the P wave delay and the assumed Vp/Vs ratio. In HYPOELLIPSE, the application of different station delays for a particular network station is allowed for P and S wave arrival times. Thus, if both P and S wave station delays are available, then HYPOELLIPSE would be preferable to HYPO71.

ERROR MEASURES. In the calculation of a hypocenter, HYPO71 generates two error measures to indicate possible horizontal and vertical variation in the calculated solution. One measure is the standard error of the epicenter (ERH) and the other measure represents the standard error in the depth (ERZ). It should be noted that these standard errors involve statistical assumptions not necessarily met in earthquake locations (Lee and Lahr, 1974, page 22). Exceptions to the statistical assumptions would include any bias that had a non-random influence on the root mean square (RMS) travel time residual (e.g. inadequacy in the velocity model or an asymmetric station distribution).

In the computation of hypocenters using HYPOELLIPSE, an error ellipsoid is generated (about the hypocenter) which represents the one standard deviation (68% confidence) volume of that solution (Lahr, 1980, page 1). Generated from this ellipsoid is a horizontal projection ellipse about the solution epicenter (given as two axis lengths with associated azimuths) and a vertcal projection ellipse (given as a single vertical axis depicting the greatest vertical deviation of the ellipsoid from the hypocenter; Lahr, 1980, page 31). The semi-major axs of the horizontal projection ellipse corresponds to ERH, and the vertical projection to ERZ as described above for HYPO71.

<u>WEIGHTING SCHEME</u>. In the computation of hypocenters, both location programs (HYPO71 and HYPOELLIPSE), allow the Geophysicist to weight P and S phase arrival times by means of a weighting factor between zero and unity. Occasionally, large differences in hypocenter locations for the same data set may be observed given small changes in the weighting of just a few phase arrival times. To avoid this potential

instability, an empirical weighting scheme was employed for this study. A linear scale was established so that in the final hypocentral solution those phase arrival time residuals in the ranges of 0.00-0.25, 0.25-0.50, 0.50-0.75, or 0.75-0.99 seconds, had weightings of 1, 3/4, 1/2, and 1/4, respectively. Any arrival time residual of greater than 0.99 seconds was zeroed and was therefore not considered in the computation of the hypocenter. In general, some small variations in the above residual ranges (±0.04 seconds) were tolerated because of an interdependance between weight and travel time residual. That is, the larger the weight given to an arrival time, the smaller the residual tends to be. Downweighting of an arrival could therefore be the result of either poor arrival time readings or large velocity variations in the area not adequately represented by the central Virginia velocity model.

<u>LOCATION COMPARISON CRITERIA</u>. For the comparison of different sets of blast locations that were derived using similar data and/or computational techniques, several guidelines were developed. These guidelines allowed for the quantification of different locational results and parameters. The selection of a preferred set of locations

was determined using the three following subjective criteria.

i) One set of blast locations would be considered superior if there was a pronounced improvement in the average locational error (defined as the epicentral distance from the source to the computed location) for the eight blasts from a particular quarry. This criterion would then be utilized as a measure of the general locational accuracy to be expected for the subject area.

ii) If the error ellipsoids generated from one set of HYPOELLIPSE solutions (or ERH generated from HYPO71) enclosed the actual shot location more often than other sets of locations, then this would be considered an improvement in the statistical measures generated by the program. Another indication of relative ellipse confidence measures would be a method of comparing sizes of resulting surface error ellipses. Such a method could be quantified by employing an 'equivalent radius' measure, which would be defined as the square root of the product of the semi-major and the semi-minor axes. This method would allow relative ellipse sizes to be compared using a linear measure (e.g. kilometers). A similar technique was devised to compare relative surface error ellipse size to the HYPOELLIPSE locatonal errors (criterion i, above). In this case radial distances; 1) from the quarry to the closest point enclosed by the error ellipse (a minimum distance) and, 2) from the quarry to the furthest point enclosed by the error ellipse (a maximum distance), were determined for all eight HYPOELLIPSE solutions at a particular quarry. This 'minima - maxima' range of distances (in kilometers) helped to relate statistical uncertainties generated from HYPOELLIPSE to the actual locational error. Note that if the ellipse enclosed the the quarry location then the minima distance was defined to be zero. Thus these three measures (ellipse enclosure, equivalent radius, and the minima - maxima radial distances) are the result of an attempt to quantify better the relationship between the statistical assumptions of HYPOELLIPSE and the actual situation.

iii) If there was an appreciable improvement in the azimuthal distribution of computed locations around the quarry then this would be considered a reduction of any influences causing systematic mislocations. That is, if one set of blast locations were more symmetrically distributed about the quarry than another, they would be chosen as preferred. This criterion would be a measure of any systematic bias influencing the computed locations. Such a bias may be caused by the distribution of network stations about the quarry, or due to large velocity inhomogeneities in the local geologic structure, or a combination of these (and other) factors. This criterion may be described by a measure similar to that used to describe station distribution about a computed solution (i.e. gap; as used in HYPO71 or HYPOELLIPSE). Thus, define a 'locational gap' as representing the largest azimuthal angle, in degrees, between computed locations as viewed from the actual quarry location. In general, a locational gap of greater than 180° would be considered an indication of bias.

In this chapter, these criteria will be used to compare HYPOELLIPSE and HYPO71 calculated solutions. In the following chapter these criteria will be more fully utilized when it will be necessary to compare HYPOELLIPSE solutions that differ only in that they employ different suites of station delays.

Blast Study

INTRODUCTION. Twenty-four blasts from three quarries (eight each) were located using the HYPO71 and HYPOELLIPSE locational programs. In all cases, computed locations were performed using the central Virginia velocity model (Table 1; Chapman, 1979), a trial focal depth of 5.0 km and, identical arrival time data from the Central Virginia - North Anna Network. The three quarries were located near the towns of Arvonia, Verdon, and Manakin, Virginia (designated as a, b, and g; Figure 1). All three quarries generated vibrations that, in general, produced high signal-to-noise seismograms at several network recording stations (Figures 2, 3, and 4). Reading accuracy for most P and S phase arrival times is assumed to be ± 0.1 seconds.

LOCATIONAL ACCURACY TESTING RESULTS. For the Arvonia quarry an average locational error of 1.0 km was determined using both HYPO71 and HYPOELLIPSE (Table 2). For HYPO71, four of the eight blast locations had a locational error less than ERH (Figure 5 (A)). Using HYPOELLIPSE, five of the eight solutions had error ellipsoid surface projections that included the actual shot point (Figure 5 (B)). Evaluation of locational gaps showed that both HYPO71 and

FIGURE 1

Map of the Central Virginia - North Anna Seismic Network. Indicated by the open triangles are the locations of network stations of the Central Virgina and North Anna Subnetworks. Also shown (solid stars) are the locations of quarry 'a' near Arvonia, quarry 'b' near Verdon, and quarry 'g' near Manakin, Virginia.

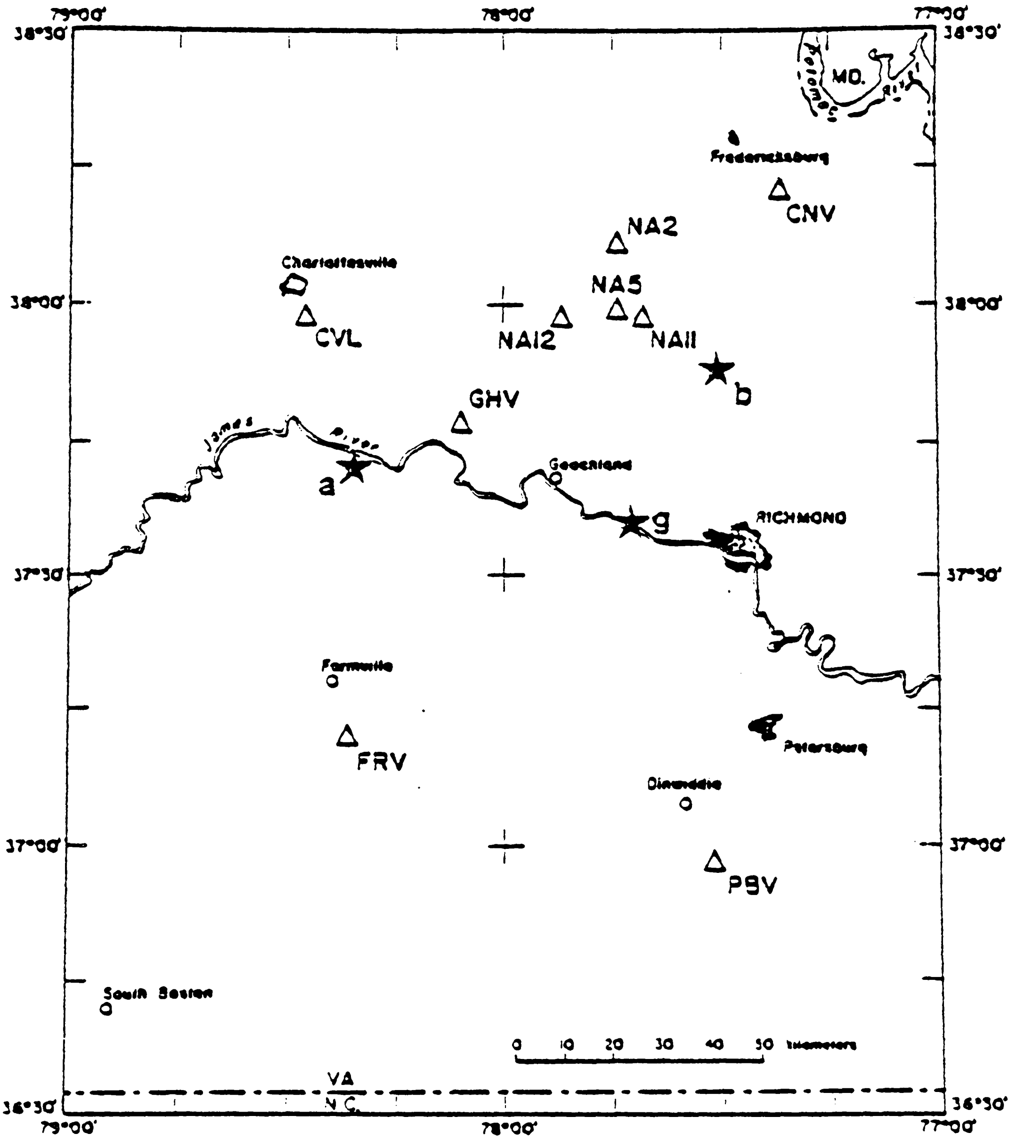

79°00'
78°00'
77°00'
38°30'
38°00'
37°30'
37°00'
36°30'
MD.
Fredericksburg
CNV
NA2
Charlottesville
NA5
CVL
NA12
NA11
b
GHV
James River
Goochland
a
g
RICHMOND
Farmville
FRV
Petersburg
Dinwiddie
PSV
South Boston
0 10 20 30 40 50 kilometers
VA
N.C.

FIGURE 2

Seismograms recorded by three stations of the Central Virginia - North Anna network. This blast originated from quarry a located near Arvonia, Virginia, at 19:13 (UCT) on 11 July 1980 (Blast C). The seismogram trace is deplaced once every 60 seconds and the trace separation is 2.5 mm. Note that the blast signals are on the traces indicated by A, B, and C.

A) Pen and ink visual seismogram from GHV (Central Virginia Subnetwork) at an epicentral distance of 24 km. The magnification is 30K at 1.0 Hz.

B) Heated stylus visual seismogram from FRV (Central Virginia Subnetwork) at an epicentral distance of 54 km. The magnification is 78K at 1.0 Hz.

C) Heated stylus visual seismogram from NA2 (Noth Anna Subnetwork) at an epicentral distance of 71 km. The magnification is 53K at 1.0 Hz.

Magnification curves for these stations are presented in Appendix 2.

A

B

C

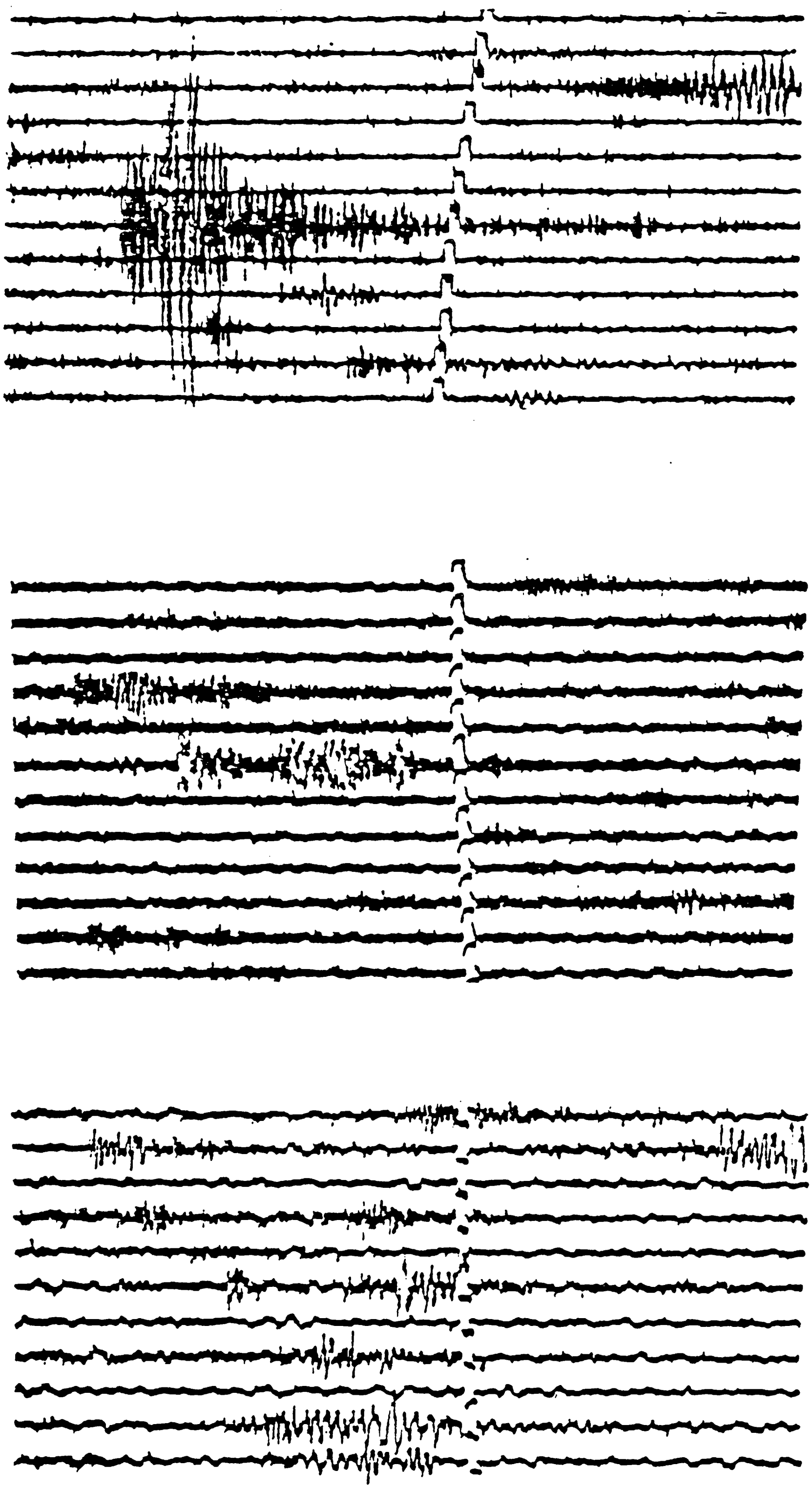


FIGURE 3

Seismograms recorded by three stations of the North Anna and the Central Virginia Subnetworks. This blast originated from quarry b located near Verdon, Virginia, at 19:41 (UCT) on 24 September 1980 (Blast B). The seismic trace is deplaced once every 60 seconds and the trace separation is 2.5 mm. Note that the blast signals are on the traces indicated by A, B, and C.

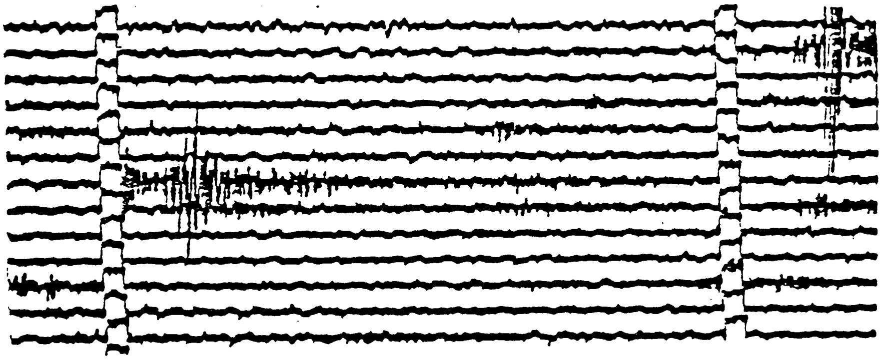
A) Heated stylus visual seismogram from NA2 (North Anna Subnetwork) at an epicentral distance of 35 km. The magnification is 53K at 1.0 Hz.

B) Pen and ink visual seismogram from GHV (Central Virginia Subnetwork) at an epicentral distance of 53 km. The magnification is 30K at 1.0 Hz.

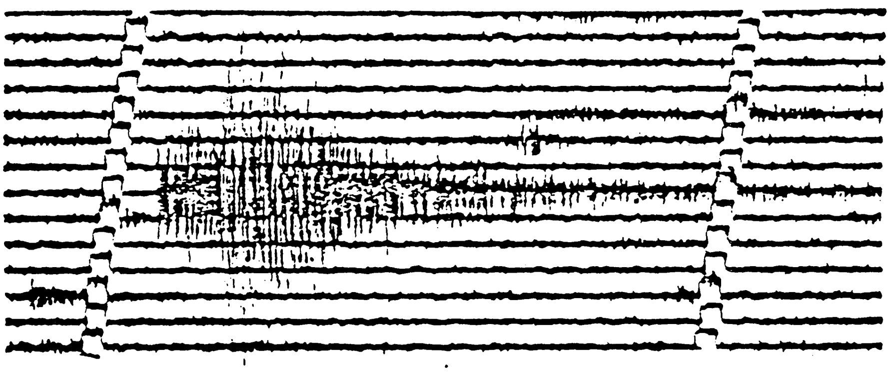
C) Heated stylus visual seismogram from FRV (Central Virginia Subnetwork) at an epicentral distance of 106 km. The magnification is 78K at 1.0 Hz.

Magnification curves for these stations are presented in Appendix 2.

A



B



C

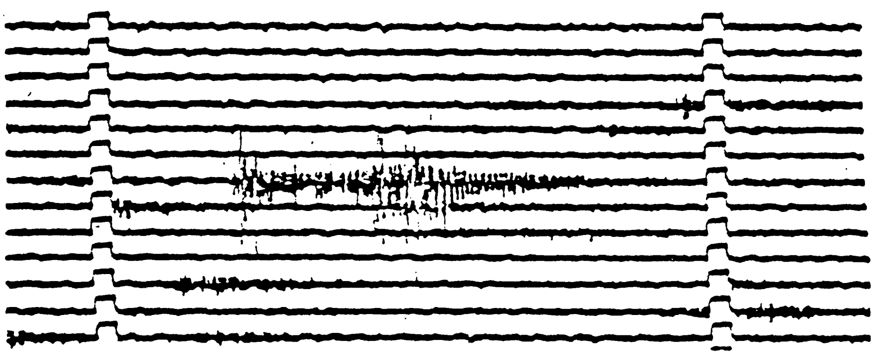


FIGURE 4

Seismograms recorded by three stations of the Central Virginia and the North Anna Subnetworks. This blast originated from quarry g located near Manakin, Virginia, at 16:20 (UCT) on 16 May 1981 (Blast G). The seismic trace is displaced once every 60 seconds and the trace separaton is 2.5 mm. Note that the blast signals are on the traces indicated by A, B, and C.

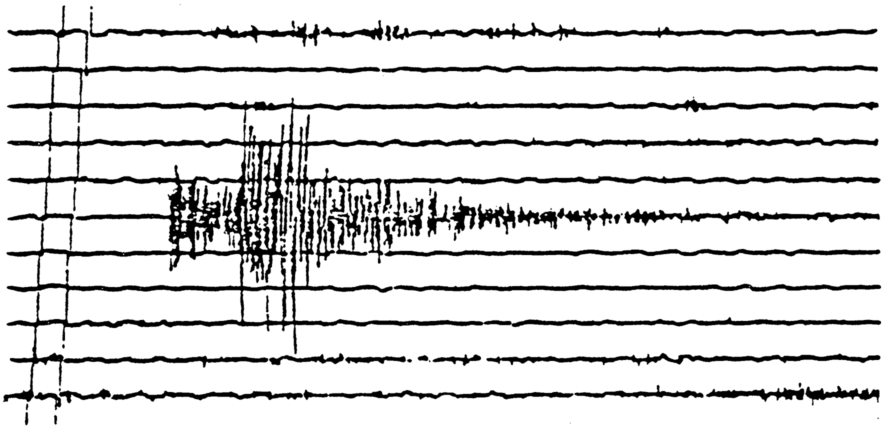
A) Pen and ink visual seismogram from GHV (Central Virginia Subnetwork) at an epicentral distance of 41 km. The magnification is 26K at 1.0 Hz.

B) Heated stylus visual seismogram from NA2 (North Anna Subnetwork) at an epicentral distance of 59 km. The magnification is 79K at 1.0 Hz.

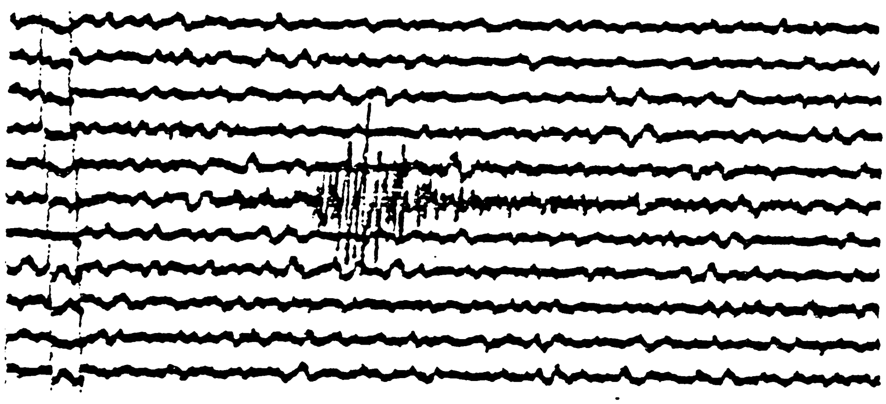
C) Heated stylus visual seismogram from FRV (Central Virginia Subnetwork) at an epicentral distance of 71 km. The magnification is 34K at 1.0 Hz.

Magnification curves for these stations are presented in Appendix 2.

A



B



C

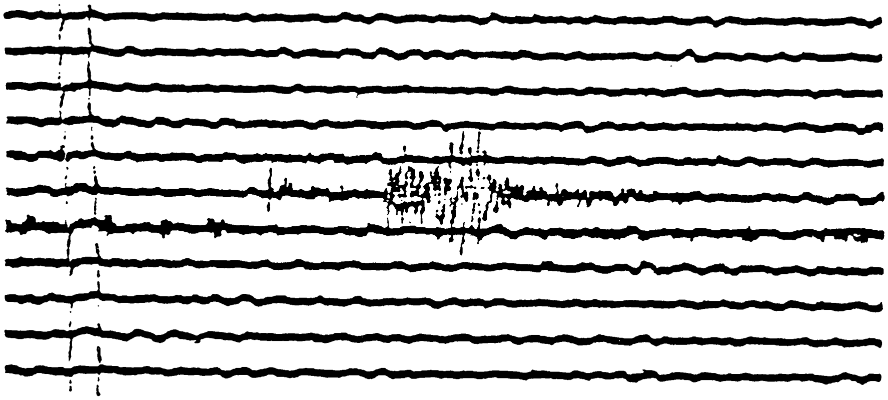


TABLE 2

Comparison Of Locational Accuracy Between HYPO71 And HYPOELLIPSE, Using 24 Quarry Blasts (see Note below)

		HYPO71				HYPOELLIPSE			
Quarry	Blast	Error (Km)	ERH (Km)	Depth (Km)	ERZ (Km)	Error (Km)	ERH (Km)	Depth (Km)	ERZ (Km)
a	A	1.5	0.7	0.9	29.1	1.3	1.2	0.4	99.0
a	B	1.8	1.0	0.6	50.9	1.7	1.4	1.9	30.8
a	C	1.4	0.5	1.2	16.2	1.4	0.9	0.8	50.8
a	D	1.3	1.0	5.0	6.8	1.4	1.7	1.0	65.5
a	E	0.6	0.7	9.6	2.5	0.3	1.2	7.8	6.3
a	F	0.4	1.0	5.0	6.7	0.3	2.0	9.9	4.5
a	G	0.3	0.6	7.6	2.4	0.6	1.1	6.5	6.2
a	H	0.7	0.7	2.1	11.5	0.9	1.3	1.3	40.8
b	A	6.0	1.3	5.0	15.9	7.9	2.5	18.4	8.8
b	B	6.7	1.5	5.0	13.4	6.9	2.2	3.4	34.7
b	C	3.5	1.0	9.3	2.2	3.7	1.9	9.5	4.7
b	D	7.6	0.6	8.3	3.3	7.6	1.1	9.9	3.0
b	E	6.7	0.8	1.1	24.1	6.9	1.2	0.8	63.9
b	F	3.6	1.3	5.0	7.8	4.2	1.9	1.8	39.8
b	G	6.8	1.8	0.2	99.0	10.6	1.7	0.6	55.4
b	H	4.8	1.8	11.2	2.3	4.1	3.0	10.2	4.8
g	A	0.4	0.3	9.5	1.8	2.2	2.3	12.5	11.9
g	B	1.6	0.8	5.0	9.3	1.7	1.4	3.0	31.8
g	C	0.4	0.9	0.1	99.0	0.3	1.5	2.8	40.6
g	D	0.7	1.0	1.5	42.8	1.2	1.6	0.7	99.0
g	E	1.9	0.9	5.0	11.8	1.8	1.5	0.2	99.0
g	F	2.5	0.8	0.3	99.0	2.3	1.4	3.9	24.6
g	G	0.6	0.5	0.3	99.0	0.7	1.5	4.5	21.9
g	H	1.3	0.6	5.0	8.0	1.5	1.1	3.2	26.5

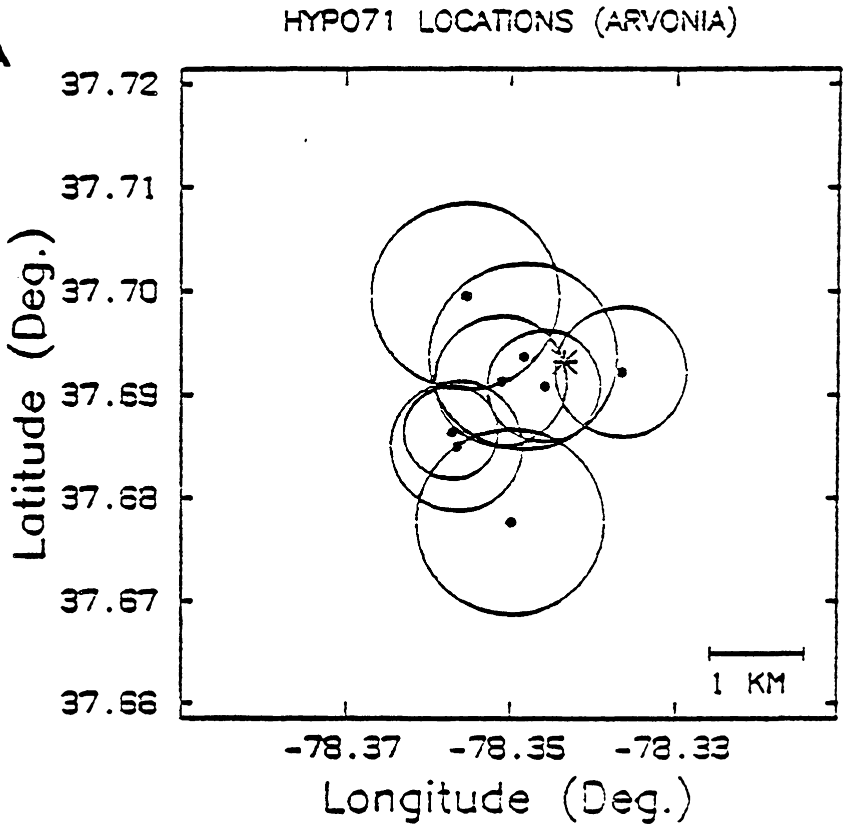
NOTE

Listed for each computed location are: the locational error (Error), the standard horizontal error (ERH), the computed depth (Depth), and the standard vertical error (ERZ).

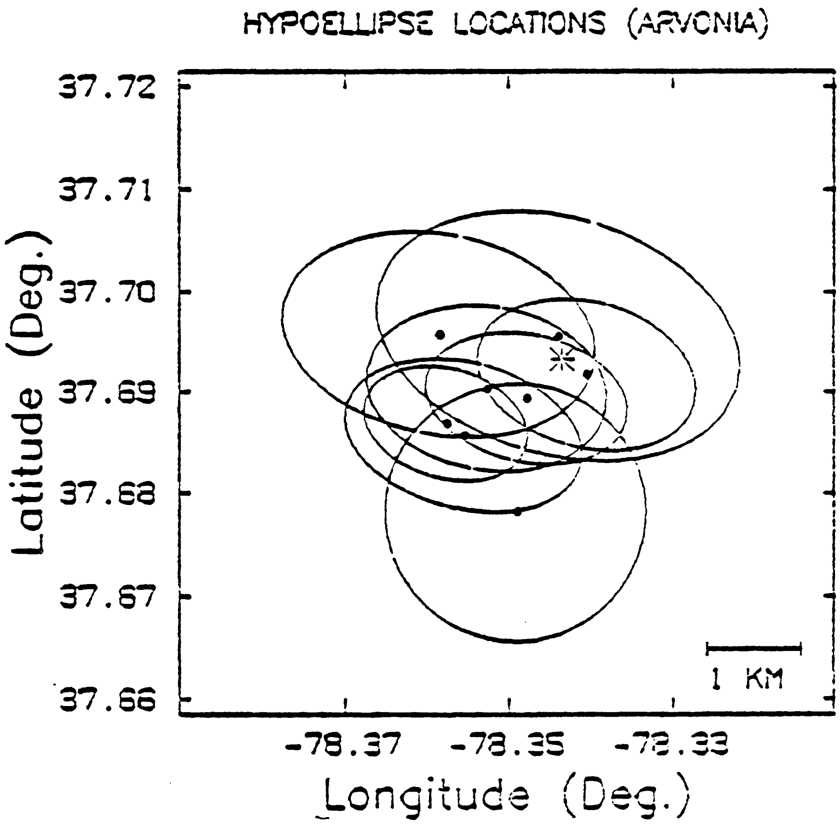
FIGURE 5

Epicenter maps showing computed locations (solid circles) for eight blasts originating from a quarry (star) near Arvonia, Virginia. Shown are eight locations computed using HYPO71 (A), and HYPOELLIPSE (B). All HYPO71 locations (solid circles) are shown with their computed values for standard horizontal error (ERH). All HYPOELLIPSE locations (solid circles) are shown with the surface projection of their error ellipsoid.

A


HYPO71 LOCATIONS (ARVONIA)
37.72
37.71
37.70
37.69
37.68
37.67
37.66
Latitude (Deg.)
1 KM
-78.37
-78.35
-78.33
Longitude (Deg.)

B


HYPOELLIPSE LOCATIONS (ARVONIA)
37.72
37.71
37.70
37.69
37.68
37.67
37.66
Latitude (Deg.)
1 KM
-78.37
-78.35
-78.33
Longitude (Deg.)

HYPOELLIPSE generated similar solution distributions with gaps of 157° and 132°, respectively.

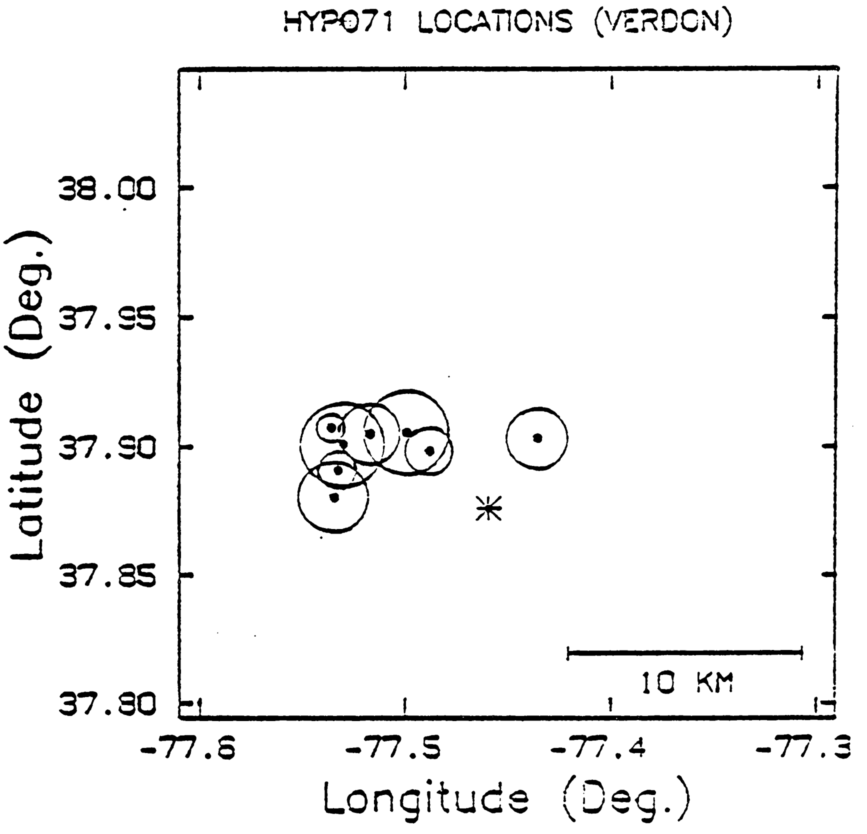
For the Verdon quarry a lower level in locational accuracy was observed. The average locational error was 5.7 ± 1.2 km (95% confidence interval) for HYPO71 and 6.5 ± 1.7 km for HYPOELLIPSE (Table 2). In none of the eight blast locations were the computed horizontal error statistics from HYPO71 or HYPOELLIPSE large enough to accommodate these locational errors (Figure 6). An indication of this bias in the locations is suggested by the large locational gaps observed (239° and 235°, for HYPO71 and HYPOELLIPSE, respectvely). Note that in only one of the eight cases (Blast C; which also had the smallest locational error), did HYPOELLIPSE calculate a solution with smaller locational error than HYPO71. This result, though statistically insignificant, may indicate that HYPOELLIPSE has a slightly greater susceptibility to external biasing influences than HYPO71.

For the Manakin quarry the average locational error was 1.2 ± 0.6 km and 1.5 ± 0.5 km for the HYPO71 and HYPOELLIPSE solutions, respectively (Table 2). Both HYPO71 and

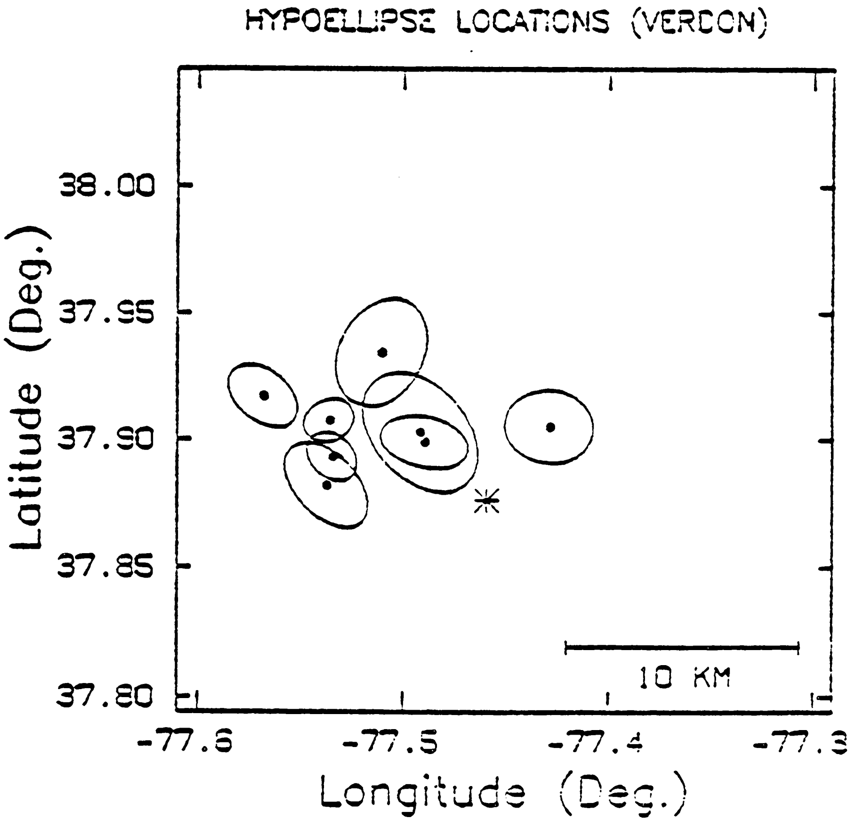
FIGURE 6

Epicenter maps showing computed locations (solid circles) for eight blasts originating from a quarry (star) near Verdon, Virginia. Shown are eight locations computed using HYPO71 (A), and HYPOELLIPSE (B). All HYPO71 locations (solid circles) are shown with their computed values for standard horizontal error (ERH). All HYPOELLIPSE locations (solid circles) are shown with the surface projection of their error ellipsoid.

A


HYPO71 LOCATIONS (VERDON)
38.00
37.95
37.90
37.85
37.80
Latitude (Deg.)
10 KM
-77.6
-77.5
-77.4
-77.3
Longitude (Deg.)

B


HYPOELLIPSE LOCATIONS (VERDON)
38.00
37.95
37.90
37.85
37.80
Latitude (Deg.)
10 KM
-77.6
-77.5
-77.4
-77.3
Longitude (Deg.)

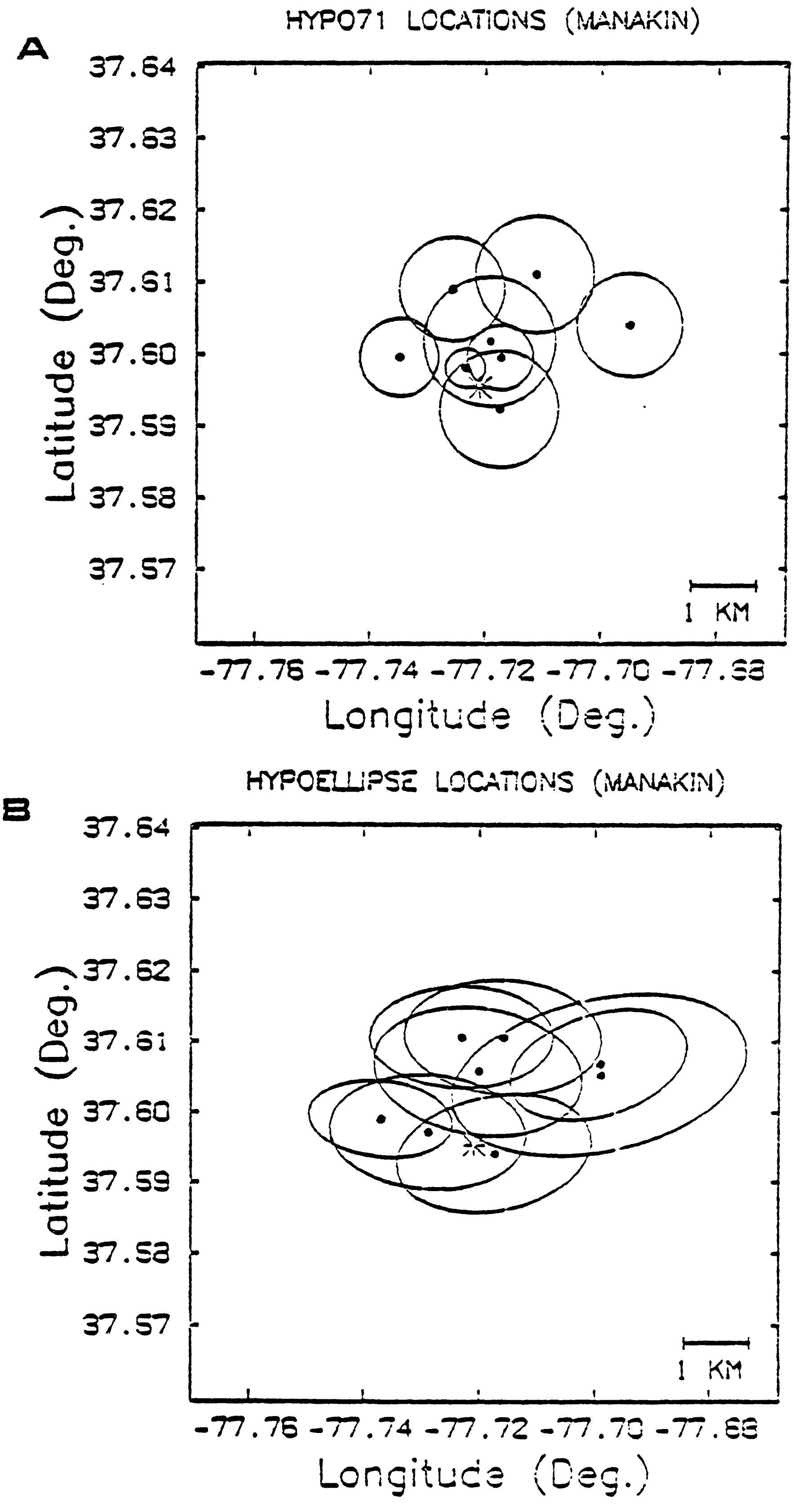
HYPOELLIPSE generated two of eight locations that had standard horizontal errors large enough to include the actual shot point (Figure 7). In this case both HYPO71 and HYPOELLIPSE indicated, through the locational gap criterion, that some biasing was present with locational gaps of 173° and 152°, respectively. Note that in both cases (HYPO71 and HYPOELLIPSE) seven of the eight locations are north of the actual quarry location.

For the entire network, an average locational accuracy of 2.6 ± 1.0 km for HYPO71 and of 3.0 ± 1.2 km for HYPOELLIPSE was observed. This difference (between the HYPO71 and HYPOELLIPSE locational accuracy) is not significant because of the dispersion in the locational errors observed in this study. That is, for most of the blasts located in this study, horizontal error measures generated from the two programs (ERH for HYPO71 and the error ellipse for HYPOELLIPSE) depicted surface areas that were spacially nondistinct.

<u>DEPTH CONTROL TESTING RESULTS</u>. Depth control was observed to be only fair throughout this study (Table 2). Beginning with a trial focal depth of 5.0 km, the average

FIGURE 7

Epicenter maps showing computed locations (solid circles) for eight blasts originating from a quarry (star) near Manakin, Virginia. Shown are eight locations computed using HYPO71 (A), and HYPOELLIPSE (B). All HYPO71 locations (solid circles) are shown with their computed values for standard horizontal error (ERH). All HYPOELLIPSE locations (solid circles) are shown with the surface projection of their error ellipsoid.



A
HYPO71 LOCATIONS (MANAKIN)
Latitude (Deg.)
37.64
37.63
37.62
37.61
37.60
37.59
37.58
37.57
1 KM
-77.76 -77.74 -77.72 -77.70 -77.68
Longitude (Deg.)
B
HYPOELLIPSE LOCATIONS (MANAKIN)
Latitude (Deg.)
37.64
37.63
37.62
37.61
37.60
37.59
37.58
37.57
1 KM
-77.76 -77.74 -77.72 -77.70 -77.68
Longitude (Deg.)

calculated focal depth was 4.3 ± 1.4 km for HYPO71 and 4.8 ± 1.9 km for HYPOELLIPSE. In 75% of the cases, HYPO71 generated a focal depth such that the value of the standard vertical error, ERZ, included a point at the surface (i.e. points with zero depth). Similarly, 66% of the HYPOELLIPSE solutions had computed focal depths close enough to the surface so that the error ellipsoid enclosed points on the surface. These levels of precision in the depth determinations (2/3 to 3/4 including the true surface focus) are really about all that can be expected in this study. Because the source is at the surface it is impossible (except for an origin time geophone) to have at least one station within a horizontal distance of one focal depth - the standard condition for good focal depth estimates (Lee and Stewart, 1981, page 18). Also, the station density would have to be greater before the average calculated focal depths would depart significantly from the trial focal depth.

Conclusions

In the comparison of HYPO71 to HYPOELLIPSE locations and error statistics, no discernable differences could be detected. However, the HYPOELLIPSE locational program is considered more useful than HYPO71 because of its ability to manage both P and S wave station delays and to generate improved error measures (i.e. error ellipsoids) in specifying the computed hypocenter. For these reasons the HYPO71 locational program will no longer be used in calculating hypocentral locations in this study.

The average locational error for events throughout the central Virginia area is estimated to be roughly 3.0 km. This locational error is, however, greatly dependent on the area in which the event occurs. That is, for events in the Arvonia or Manakin areas an average HYPOELLIPSE locational errors of 1.0 and 1.5 km, respectively, were observed, while in the Verdon area this accuracy was 6.5 km. Quite possibly these mislocations in the Verdon locale, are due to either lateral velocity inhomogeneities in the central Virginia area and/or the asymmetric pattern of network recording stations present.

3. STATION DELAY DEVELOPMENT

Introduction

The large locational errors observed in the Verdon test necessitated further investigation into possible causes and remedies. An initial examination of several slight perturbations of the velocity model (including a thin, low-velocity surficial layer) yielded no net improvement in the HYPO71 locations (Sibol, 1981). A next step was to determine if individual network station delays could be derived that would improve overall locational capability.

Three different sets of station delays were developed for the Central Virginia - North Anna Network. Two of the sets were derived using data from this study. These station delay suites were developed using a Closest Station Method (CSM) and a Single Iteration Method (SIM). As will be shown subsequently these two methods generated station delays that were either relative to one network station (the CSM) or were all interrelated (the SIM). Though these methods generate 'relative' station delays, they are easier and less expensive to obtain than absolute network station delays generated through extensive field experimentation. A third, independantly derived, suite of station delays was developed when 25 earthquakes in the Central Virginia Seismic Zone were relocated using the Joint Epicenter Determination (JED) method (Viret, 1982). The station delays produced by that study were included herein for completeness. Obviously, the desire is to determine the set of station delays that will provide optimal locations for seismic events within the Central Virginia Seismic Zone.

The Closest Station Method (CSM)

TECHNIQUE. The closest station method (CSM) requires that an origin time be determined for each blast. The method assumes that the upper layer P wave velocity of the central Virginia velocity model (6.09 km/sec to a depth of 15 km) is a good approximation to the true velocity for the travel path between the shot location and the closest station. Because the distance between the quarry and the closest station should be well determined (herein estimated to be within ±100 m), a P wave travel time (distance / P wave velocity) may then be determined to within the ± 0.1 seconds (controlled by the reading accuracy of the seismograms). This travel time is then subtracted from the P wave arrival time to produce an estimate of the origin time of that blast.

By using the estimated origin time and fixing the hypocenter of each blast at the quarry (assuming a depth of 0.0 km), P and S wave travel time residuals were generated for each station from which arrival time readings were available. Although this could have been done manually it was actually performed using an option available from the

HYPO71 computer program. For the eight blasts observed from a quarry, several such P or S wave residuals may be averaged and then used to generate station delay values for each network station. Station delays from a single quarry were determined by first averaging the P or S wave residuals for a particular network station, deleting all of those residuals greater than one standard deviation from the average, and reaveraging. In this way, obviously erroneous values (the probable result of low signal-to-noise seismograms) would be discarded from the data set.

For applying the CSM to the three quarries discussed, the following empirical criteria were selected.

i) The station chosen for the origin time calculation should have a P wave arrival time for all eight blasts originating from the quarry. This would then link all of the CSM origin time calculations to a single station and therefore, a single ray path. Thus, this criterion would ensure a stable reference for the resulting P and S phase delays between different network stations.

ii) The network station used in the CSM should be at a large enough distance from the shot so that the P wave travel path is mostly in the basement rock and therefore does not spend an appreciable time in any low velocity surficial layer that may be present. Chapman (1979) noted such a surface layer with a P wave velocity of 5.62 km/sec and a thickness varying from zero to less than three kilometers (with a measured crossover distance of 15 km). It is possible that greater thicknesses of this surficial layer exist in areas outside of his refraction profile line. To minimize the time delay effect due to such a layer, the source - station distance should be large enough to ensure that only a small percentage of the travel time (from the source to the station) may be spent in such a low velocity layer. Thus, the P wave velocity of 6.09 km/sec, assumed by the central Virginia velocity model to a depth of 15 km, should be an adequate approximation of the P wave velocity between the shot and the station chosen. Exceptions to this criteria would be either those stations located at the quarry (portables used to determine an origin time precisely) or permanent stations near the quarry for which the travel path velocity is well determined. Thus, this criterion serves to limit errors in the station delay suite introduced due to local velocity variations that are not adequately represented in the velocity model used for the region.

iii) The P wave arrivals for the station chosen should be impulsive for all eight blasts observed. This would help to minimize errors in the origin time calculation due to arrival time reading errors resulting from low signal-to-noise seismograms.

For the Arvonia and Manakin quarries, station GHV was chosen to determine origin times because it met all of the above criteria (epicentral distances: 23.6 and 40.6 km, respectively). For the Verdon quarry, network station NA2 (epicentral distance: 34.8 km) was chosen because the seismograms for that station exhibited very impulsive P wave arrivals for all eight blasts observed from that quarry (criteria iii above). Moreover, the source - station distance was large enough to minimize any travel time delays due to thin, low velocity layers, that may exist at the surface in the area (criteria ii above).

<u>ADVANTAGES AND DISADVANTAGES</u>. In the CSM technique the resulting origin time is a function of velocity inhomogeneities along the P wave travel path from a quarry to the chosen network station. As such, the resulting P and S phase station delays for the remaining network stations are not interdependent. That is, the resulting set of station delays are a function of a single, impulsive, P wave arrival time at the closest station for each blast being considered.

Alternately, if the origin time is a function of one particular travel path for which the P wave velocity is assumed to be known, then any error in that assumption will bias the entire set of station delays for that region by some fixed amount. Therefore, any resulting conclusions of velocity variations with azimuth or distance would be a function of the azimuth and distance from the quarry to the closest station. Note though, that errors in the computed travel time would be proportional to the source - station distance, and to the inverse of the velocity squared. Thus, only in those cases where there existed large velocity variations, different from the assumed velocity structure, would large errors in the computed origin time be expected.

The Single Iteration Method (SIM)

TECHNIQUE. Using HYPO71, station delays were developed for the Central Virginia - North Anna Network using the single iteration method (SIM). The SIM generated origin times by employing several user options available in HYPO71.

Using a trial hypocenter that corresponded to the actual location of the quarry (with a trial focal depth of 0.0 km) the program was allowed to run one iteration of Geiger's step-wise multiple regression of the travel time residuals (Lee and Lahr, 1974, page 33). Thus, the four parameter earthquake location problem (Lee and Stewart, 1981, page 130) is reduced to an overdetermined, one parameter problem of calculating an origin time. That is, of the four variables that may be adjusted, only the change in the origin time is significant. Because the phase arrival time residuals represent the difference between the observed arrival time and the calculated arrival time for that phase, the station delay represents the difference, in time, between the actual and theoretical travel paths and velocities.

For the eight blasts observed from a given quarry, several such P or S wave residuals were used to derive an average station delay value for all network stations. Station delays from a single quarry were determined by first averaging the P or S wave residuals for a particular network station, deleting (as in the CSM) all of those residuals greater than one standard deviation from the average, and reaveraging.

ADVANTAGES AND DISADVANTAGES. An advantage of using the SIM is that all of the available P and S phase arrival time data are used to determine one variable (origin time). Furthermore, the set of station delays developed using the SIM are not a function of one P wave travel path (as with the CSM) but instead are an average over all P and S wave travel paths in the network area. Therefore, this method should provide a more generalized view of the relationship between the geologic structure of the region and the central Virginia velocity model.

A problem with the SIM is that all of the station delays are developed relative to each other (through HYPO71). They are, therefore, dependent on both impulsive and emergent P and S wave arrival time readings. As such, all of the resulting station delays for a single blast could be influenced by one or two poor arrival time readings. Therefore, in these computations, when an anomalously large P or S wave residual was observed for a blast, that arrival time was given zero weight. All other arrivals were given full weighting.

A Comparison Of The CSM And The SIM

GENERAL. The CSM and SIM differ only in the origin times produced. Hence, the station delays for a given blast for one of the methods will differ from those generated using the other method by a single additive constant. In general, the origin times derived from these two methods (the CSM and the SIM) for a given blast were different. In particular, origin times calculated for blasts originating from the Verdon quarry differed by as much as half a second. This is not surprising since both would give the same origin time only if the velocity model employed were a perfect representation of the actual velocity variations in the central Virginia region (i.e. all velocities and depths were correct and there were no lateral inhomogeneities). Therefore, particularly in the case of the Verdon quarry, large velocity variations may be expected in this locale.

ORIGIN TIME COMPARISON. Three of the blasts from the Arvonia quarry (blasts F, G, and H; on 11 July 1980) were monitored by two portable, smoked paper recording seismographs (Sprengnether MEQ-800's) placed within a few hundred meters of the shot point (station codes: ARV1 and ARV2; at epicentral distances of 410 and 210 meters respectively; Sibol, 1980). Both of these systems had recording speeds of 2 mm/sec and therefore yield P wave arrival times to a precision of ± 0.05 seconds.

A comparison of the observed P wave arrival times at ARV2 and the computed origin times using the CSM and the SIM is instructive (Table 3). For the three origin times determined using the CSM, the calculated origin times were an average of 0.06 seconds later than the P wave arrival time at ARV2. For the three origin times determined using the SIM, the calculated origin times were an average of 0.07 seconds earlier. These differences between the calculated origin times and the P wave arrival time at ARV2 are well within the reading error of seismograms (assumed to be ± 0.1 seconds) recorded at the network stations and therefore imply that both methods (the CSM and the SIM) yield reasonable origin time estimates. Although this implied

TABLE 3

Comparison Of Origin Times For Three Blasts
Originating From A Quarry Near Arvonia, Virginia,
And Occurring On July 11, 1980

Blast	Hr:Mn	HYPO71 (1) Initial (Sec)	HYPO71 (1) SIM (Sec)	CSM (2) (Sec)	ARV2 P Wave Arrival Time (3) (Sec)
F	14:10	21.75	19.67	19.87	19.75
G	15:31	54.00	52.05	52.12	52.09
H	18:26	03.85	01.84	01.97	01.94

NOTE

(1). The HYPO71 locational program uses an initial origin time estimate (Initial) of the form: ORG = PMIN - Z/5.0 - 1.0; where ORG is the initial estimate of the origin time, PMIN is the earliest P wave arrival time recorded at a network station (GHV in this case), and Z is the trial focal depth (5.0 km). Using the Single Iteration Method (SIM) an adjusted origin time was calculated.

(2). Origin time determined using the Closest Station Method (CSM). This estimate was determined using network station GHV.

(3). P wave arrival time recorded at the temporary station ARV2 located 210 meters from the shot point.

accuracy was observed only for blasts at the Arvonia quarry, it does give some basis for confidence when considering origin times calculated for the 16 blasts from the other two quarries where portable seismographs were not used.

The Joint Epicenter Determination (JED) Method

TECHNIQUE. During the computation of hypocenters in the Joint Epicenter Determination (JED) method, station delays are developed from the input earthquake P and S arrival time data. The JED method was employed to relocate 25 earthquakes in the Central Virginia Seismic Zone (Viret, 1982) and is, therefore, independent of this study. The station delays produced by that study are included herein for completeness.

ADVANTAGES AND DISADVANTAGES. A major advantage of the JED method is that it uses a large data set to produce station delays. That is, the delays produced by the JED method for a particular station will be a function of the number of P and S wave arrival times for that station which are available from approximately 25 earthquakes. In either of the other two methods (the CSM or the SIM) the maximum number of P or S wave arrival times available for the determination of a station delay in this study was restricted arbitrarily to eight per station.

A disadvantage to the JED method is that it applies to the entire region of the Central Virginia Seismic Zone.

Therefore it may not produce a detailed enough set of station delays to take into account effects due to more localized velocity structure variations. Furthermore, the method relates all of the earthquakes to one 'master' event. If this event is not well located, or if the general seismicity is so diffuse that the 'slave' events are not effectively relocated, then the resulting set of station delays will reflect this inadequacy. Given this vastly different method of station delay developement no detailed intercomparisons can be made between the JED set of station delays and those produced using the CSM or the SIM.

Results

STATION DELAYS. Using both the CSM and the SIM, station delays were developed for each of the three quarries (Table 4). Station delays for a P or an S wave at a particular network station are derived from up to eight phase arrival times.

In the comparison of station delays derived from either the CSM or the SIM, no discernible pattern could be recognized between the three different quarries. Therefore, one set of station delays (derived using a particular method) could not be combine with a set of station delays (derived from the same method) from another quarry (Verdon with Manakin SIM station delays, or Arvonia with Manakin CSM station delays, for example). Furthermore, because the six sets of station delays (two per quarry) must be considered separately, requires that events in different areas of the Central Virginia Seismic Zone be subject to different delay sets. That is, for events in the western half of the network, the station delay suites derived from the Arvonia quarry blasts are applicable. For events in the northeastern section of the zone, the station delay suites

TABLE 4

Listing Of Station Delays For The Central Virginia - North Anna Network;
Generated Using The Closest Station Method (CSM), The Single Iteration Method (SIM),
And The Joint Hypocenter Determination Method (JHD)

Quarry	Method	Phase	NA2	NA5	NA11	NA12	CNV	CVL	GHV	FRV	PBV
a	CSM	P	+0.16	---	---	-0.08	-0.35	-0.03	+0.00	-0.32	+0.09
		S	-0.05	---	---	+0.67	---	-0.12	+0.11	-0.17	-0.72
a	SIM	P	+0.21	---	---	-0.09	-0.30	+0.10	+0.04	-0.27	+0.28
		S	-0.02	---	---	+0.60	---	-0.14	+0.15	-0.11	-0.52
b	CSM	P	+0.00	+0.06	+0.07	+0.13	+1.09	+0.13	+0.08	+0.40	+1.53
		S	-0.02	+0.03	-0.51	+0.43	+1.75	-0.36	-0.42	+0.70	+2.69
b	SIM	P	-0.24	-0.21	-0.27	-0.21	+0.76	-0.10	-0.27	+0.09	+1.28
		S	-0.36	-0.27	-0.86	+0.09	+1.37	-0.63	-0.71	+0.44	+2.30
g	CSM	P	+0.14	---	---	-0.01	---	+0.29	+0.00	+0.44	+0.36
		S	+0.26	---	---	+0.07	---	+0.28	+0.01	+0.70	+0.14
g	SIM	P	+0.02	---	---	-0.24	---	+0.02	-0.22	+0.18	+0.17
		S	+0.15	---	---	-0.11	---	+0.05	-0.23	+0.29	-0.21
	JHD	P	+0.15	+0.22	+0.02	+0.07	+0.21	+0.28	+0.30	+0.43	+0.52
		S	-0.22	+0.32	-0.04	+0.14	-0.22	+0.39	+0.52	+0.75	+0.65

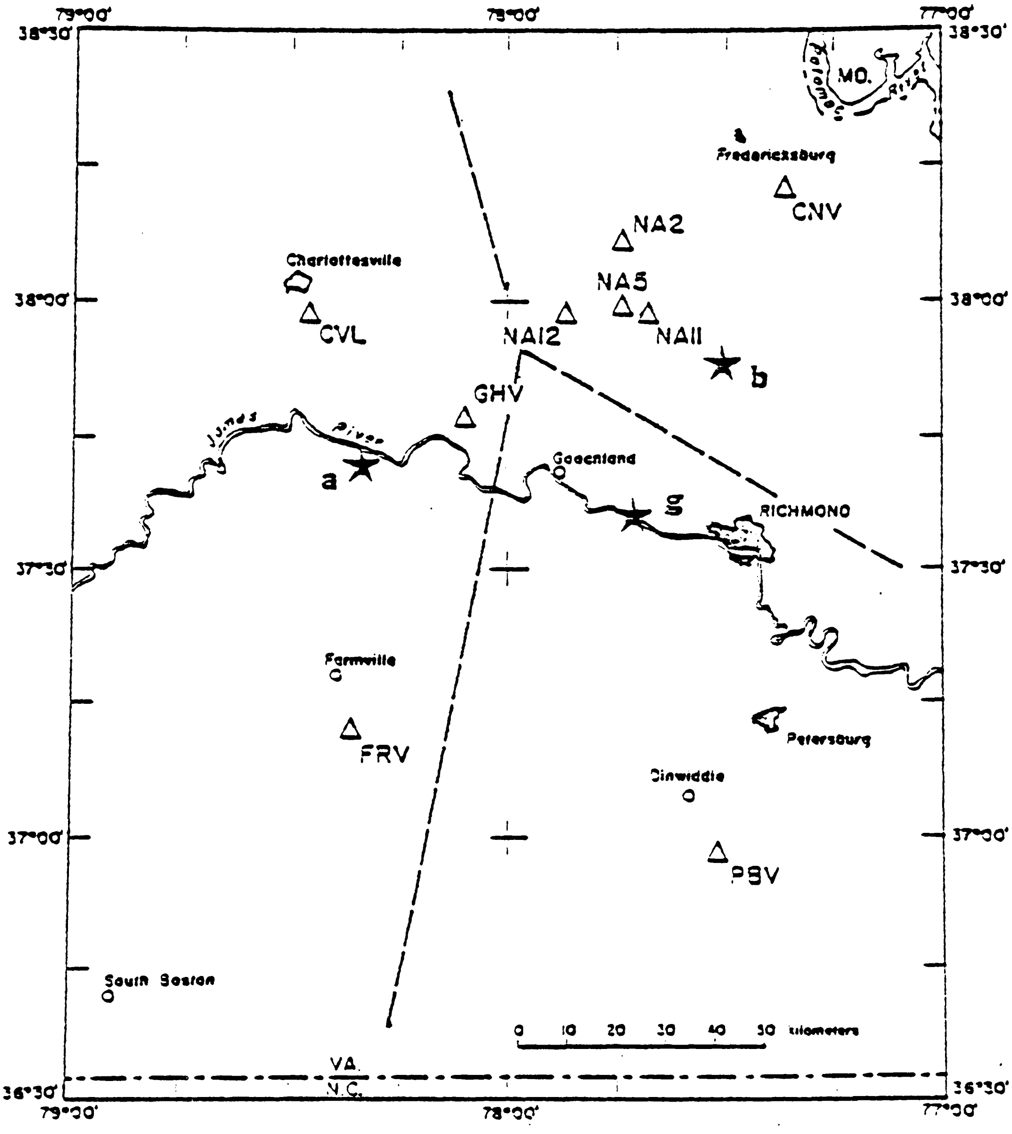
derived from the Verdon quarry blasts should be employed. Finally, for seismic events in the central-southeastern part of the zone the resulting station delay suite from the Manakin quarry experiment should be applied.

One technique for dividing the zone into three sections would be to employ the method of Thiessen polygons (Segretto, 1977, personal communication). That method involves drawing bisectors between all of the poles in an area (quarry locations) so that polygonal shapes are generated (Figure 8). Thus all points enclosed within a given polygon are closest to the pole central to that polygon.

In the comparison of station delays derived from each quarry, using the CSM and the SIM, several interesting results are apparent. For example, in the case of the station delay suites derived for the Arvonia area, only small differences exist between those delays derived using the CSM and those derived using the SIM. In this case, for almost all of the stations, the difference between the P or S delays derived from the two methods is less than the reading accuracy assumed for the seismograms (± 0.1 seconds). This similarity is not as evident for the station

FIGURE 8

Map of the Central Virginia - North Anna Seismic Network. Indicated by the open triangles are the locations of network stations of the Central Virgina and North Anna Subnetworks. Also shown (solid stars) are the locations of quarry 'a' near Arvonia, the location of quarry 'b' near Verdon, and the location of quarry 'g' near Manakin, Virginia. The network is divided into three sections (dashed lines) according to the method of Thiessen polygons.


79°30'
78°00'
77°00'
38°30'
38°00'
37°30'
37°00'
36°30'
MD.
Fredericksburg
CNV
NA2
Charlottesville
NA5
CVL
NA12
NA11
b
GHV
Goochland
a
g
RICHMOND
Farmville
FRV
Petersburg
Dinwiddie
PBV
South Boston
0 10 20 30 40 50 kilometers
VA.
N.C.

delay suites derived for the Manakin area. Moreover, in the case of the Verdon quarry, large differences between station delays derived for individual stations using these two methods were observed. In this case, differences between P and S wave station delays for the same station (derived from the CSM and the SIM) ranged from 0.3 to 0.4 seconds.

In the evaluation of HYPOELLIPSE locations for a particular quarry using different station delay suites, the set of criteria developed and discussed in the previous chapter, will be employed.

ARVONIA. For the Arvonia quarry, no improvement in the locational accuracy was observed for relocations performed using either the CSM, or the SIM sets of station delays. The average locational error using these sets of station delays was 1.2 and 1.1 km, respectively (Figure 9 and Table 5). The blast relocations using the JED set of station delays had an average locational error three times that observed in the other two cases. Since this was also generally the case for the Verdon and Manakin blast relocations, the JED set of station delays will be deleted from consideration throughout the remainder of this study.

FIGURE 9

HYPOELLIPSE location comparison criteria for eight blasts originating from a quarry near Arvonia, Virginia. Indicated are location comparison criteria for HYPOELLIPSE solutions calculated using no station delays (NSC), the closest station method suite of station delays (CSM), and the single iteration method suite of station delays (SIM).

LOCATION COMPARISON CRITERIA; ARVONIA

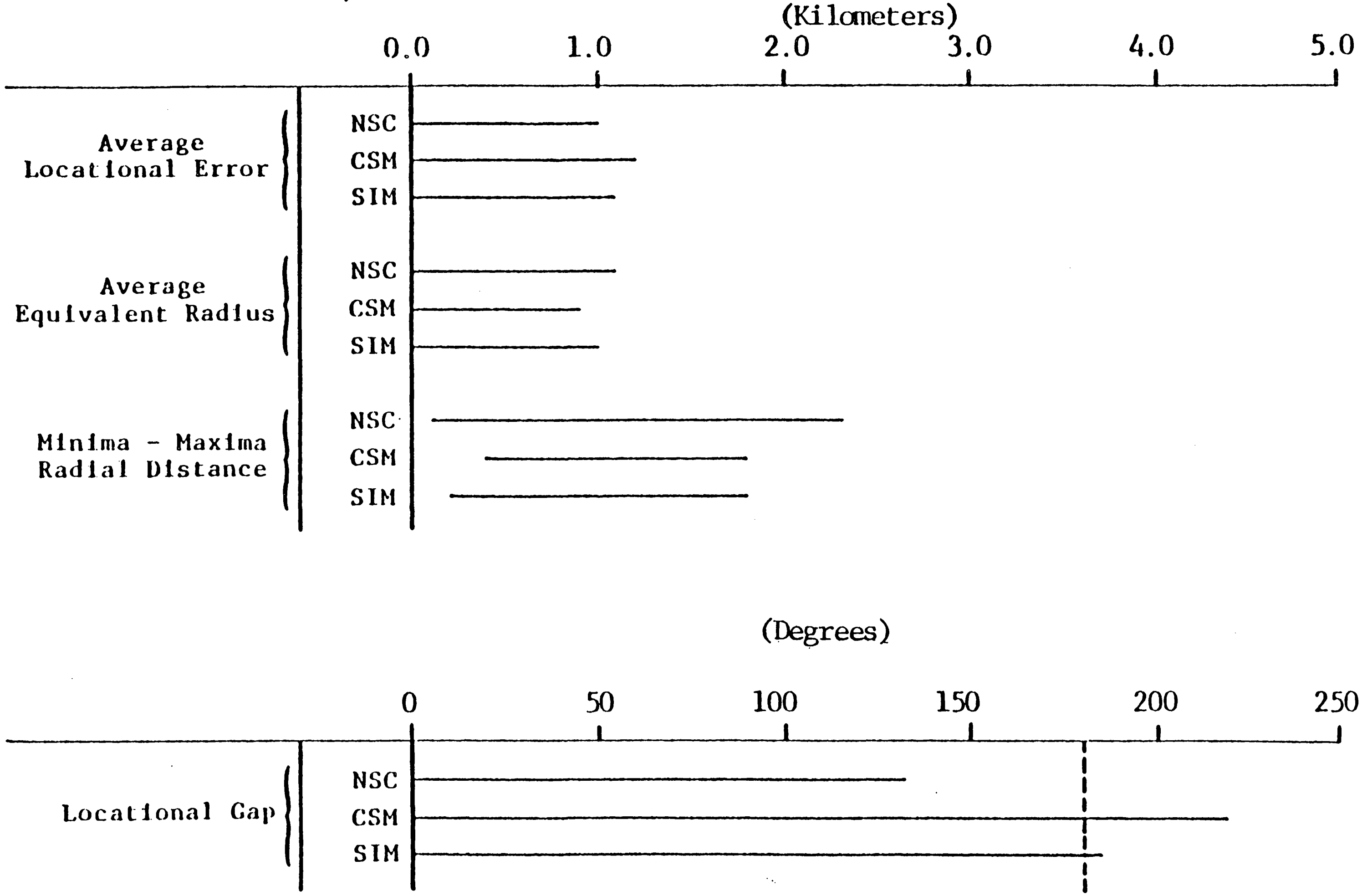


TABLE 5

HYPOELLIPSE Locational Errors For Eight Blasts Originating From A Quarry Near Arvonia, Virginia, (a); Located Using The Central Virginia Velocity Model, And Three Suites Of Station Delays

Station Delay Suites (see NOTE below)

	NSC				CSM				SIM				JED			
Blast	Error (Km,Deg)	RMS	Ph	Gap	Error (Km,Deg)	RMS	Ph	Gap	Error (Km,Deg)	RMS	Ph	Gap	Error (Km,Deg)	RMS	Ph	Gap
A	1.3,232	0.17	10	164	0.4,32	0.15	10	160	0.4,352	0.15	10	161	4.4,242	0.23	9	172
B	1.7,197	0.18	9	163	1.2,143	0.07	9	159	0.7,156	0.11	9	160	3.4,250	0.21	8	170
C	1.4,241	0.13	10	164	0.5,21	0.12	10	160	0.6,338	0.10	10	161	4.0,242	0.27	9	171
D	1.4,282	0.22	10	164	1.4,2	0.19	10	160	1.5,340	0.20	10	161	3.1,168	0.28	9	160
E	0.3,122	0.15	10	160	1.9,54	0.16	10	156	1.8,47	0.19	10	156	3.1,149	0.29	9	158
F	0.3,350	0.24	10	161	2.1,26	0.16	10	157	2.0,22	0.21	10	158	2.7,154	0.30	9	159
G	0.6,222	0.12	9	162	1.0,41	0.10	9	159	0.9,23	0.08	9	159	3.2,174	0.23	8	161
H	0.9,249	0.14	8	163	1.1,27	0.11	8	159	1.1,11	0.12	8	160	2.9,172	0.29	7	161
Avgs:	1.0,SW	0.17	10	163	1.2,NE	0.13	10	159	1,1,NNE	0.15	10	160	3.4,SSE	0.26	9	164

NOTE

HYPOELLIPSE locational errors (distance and azimuth from the quarry to the computed epicenter; Error) are given for eight blast locations determined when no station delays were employed (NSC) and when three different suites of station delays were used during computation. The three suites of station delays were generated using either the Closest Station Method (CSM), the Single Iteration Method (SIM), or the Joint Epicenter Determination (JED) method.

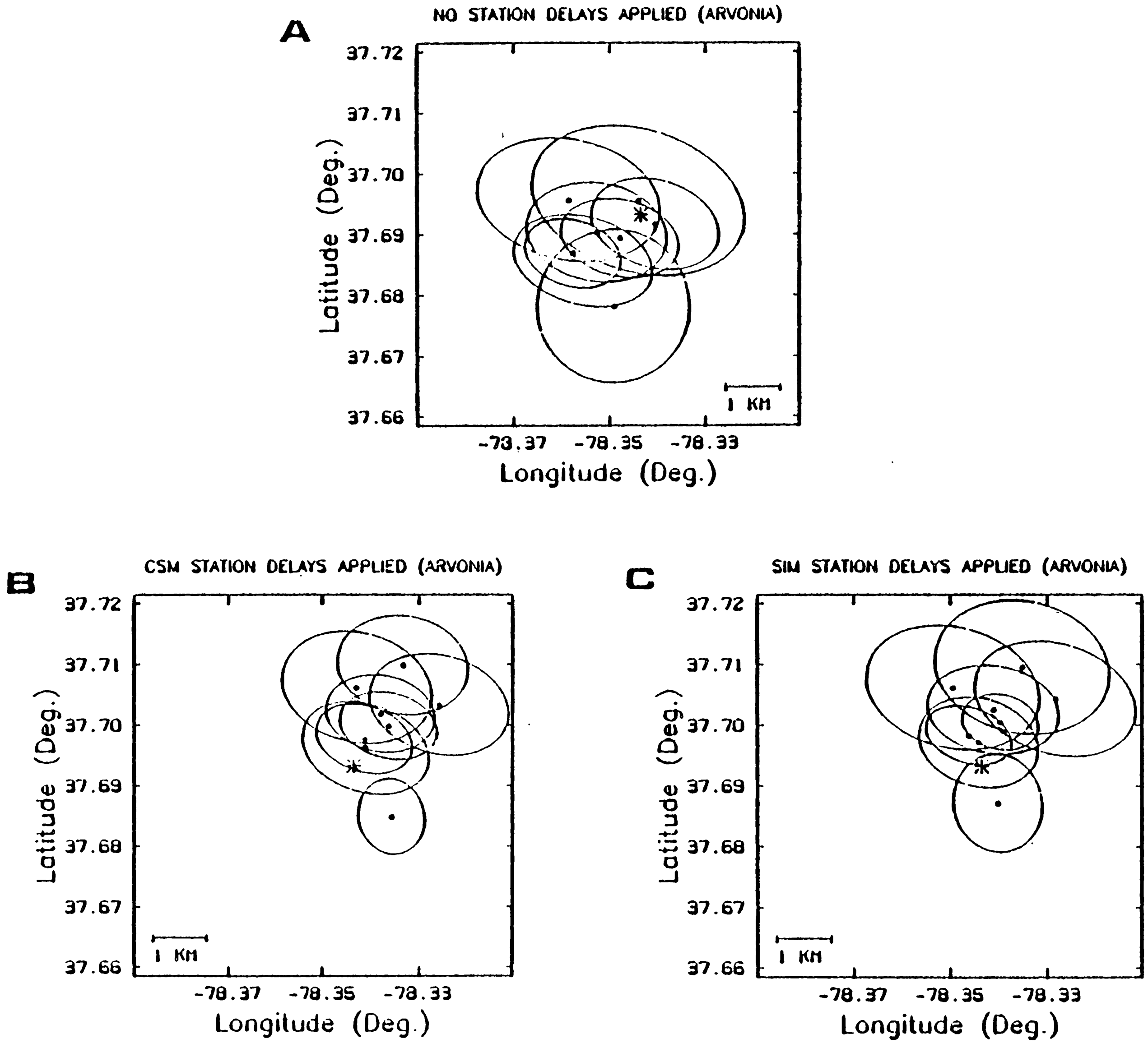
For each solution three HYPOELLIPSE parameters are listed. These parameters include: the root mean square residual (RMS) in seconds, the number of P and S phases used in the calculated solution (PH), and the largest azimuthal separation, in degrees, between stations as seen from the calculated epicenter (GAP).

For the case where no station delays were applied, five of the eight error ellipsoid surface projections contained the shot point (Figure 10). The other two sets of solutions, produced using the CSM and the SIM, each had only two blast relocations with error ellipsoid surface projections that enclosed the quarry site. This degrading of the locational accuracy may indicate that some systematic bias is being introduced by the station delays. Note that the locations, originally distributed soutwest of the quarry, relocate to the northeast of the actual quarry locations. This northeasterly bias was accompanied by a deterioration of the quality of the locational gap. This quantity, originially 132°, was expanded to 219° and 184° for the CSM and the SIM sets of relocations, respectively.

It may be possible that it is due to the concentration of network stations located to the northeast of this quarry is the source of the bias. With regard to the other comparison criteria, little variation was observed for the average equivalent radius (approximately 1.0 km) and the minima - maxima radial distance measures (approximately (0.1 km, 2.0 km)).

FIGURE 10

Epicenter maps showing HYPOELLIPSE locations (solid circles) for eight blasts originating from a quarry (star) near Arvonia, Virginia. All locations include the calculated epicenter and the surface projection of their corresponding error ellipsoid. Shown are HYPOELLIPSE locations calculated with; no station delays applied (A), the CSM suite of station delays applied (B), and the SIM suite of station delays applied (C).


A
NO STATION DELAYS APPLIED (ARVONIA)
B
CSM STATION DELAYS APPLIED (ARVONIA)
C
SIM STATION DELAYS APPLIED (ARVONIA)
Latitude (Deg.)
37.72
37.71
37.70
37.69
37.68
37.67
37.66
Longitude (Deg.)
-78.37
-78.35
-78.33
1 KM

VERDON. For the Verdon quarry, dramatic improvement in the locational error was observed for station delay suites derived from both the CSM and the SIM (Figure 11 and Table 6). In these two cases the original locational error of 6.5 km was reduced to 4.1 and 4.4 km (the CSM and the SIM, respectively). More importantly, for the CSM relocations four of the eight HYPOELLIPSE relocations have error ellipsoid surface projections that enclose the actual quarry position compared to no previous enclosures (Figure 12). A similar, but somewhat lesser improvement was observed for the SIM relocations. Here the average locational error was reduced from 6.5 km to 4.4 km but only one of the blasts relocations, C, included the actual shot point within its error ellipsoid surface projection.

An examination of both sets of blast relocations shows that one blast (A; Table 6) was clearly a poor relocation (Figure 12). Note that when blast A was originally located, the solution had a locational error of 7.9 km and was calculated using ten phases (five P and five S arrival times). When blast A was relocated using the CSM set of station delays this locational error increased to 14.7 km and used only six phases (two P and four S phase arrival

FIGURE 11

HYPOELLIPSE location comparison criteria for eight blasts originating from a quarry near Verdon, Virginia. Indicated are location comparison criteria for HYPOELLIPSE solutions calculated using no station delays (NSC), the closest station method suite of station delays (CSM), and the single iteration method suite of station delays (SIM).

LOCATION COMPARISON CRITERIA; VERDON

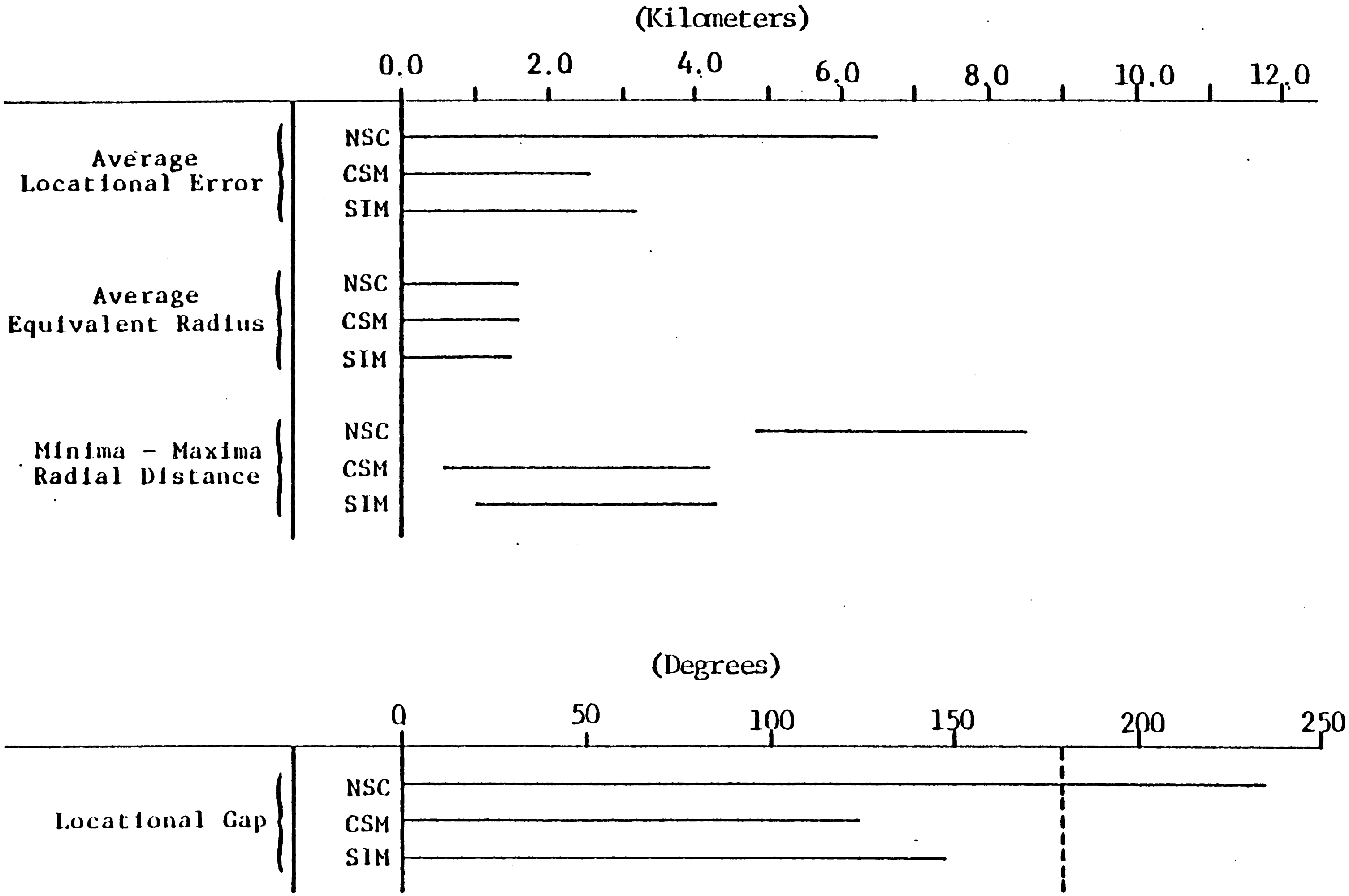


TABLE 6

HYPOELLIPSE Locational Errors For Eight Blasts Originating From A Quarry Near Verdon, Virginia, (b); Located Using The Central Virginia Velocity Model, And Three Suites Of Station Delays

Station Delay Suites (see NOTE below)

	NSC				CSM				SIM				JED			
Blast	Error (Km,Deg)	RMS	Ph	Gap	Error (Km,Deg)	RMS	Ph	Gap	Error (Km,Deg)	RMS	Ph	Gap	Error (Km,Deg)	RMS	Ph	Gap
A	7.9,325	0.25	10	216	14.7,39	0.16	6	246	12.8,54	0.23	8	252	13.9,3	0.24	7	220
B	6.9,275	0.21	10	149	3.4,208	0.22	11	161	2.8,196	0.15	11	163	8.5,259	0.23	10	148
C	3.7,314	0.10	8	259	1.7,239	0.20	8	259	1.9,133	0.17	8	264	6.1,263	0.18	8	250
D	7.6,297	0.16	12	148	2.6,302	0.16	11	158	1.5,348	0.14	11	162	8.4,276	0.22	12	147
E	6.9,286	0.20	14	149	1.5,252	0.23	11	160	1.7,343	0.13	11	161	7.0,266	0.24	14	150
F	4.2,40	0.18	11	226	6.8,83	0.16	10	231	7.5,95	0.19	11	230	1.0,286	0.21	12	216
G	10.6,296	0.27	14	202	0.4,15	0.20	14	163	4.3,105	0.20	15	216	7.1,268	0.23	13	195
H	4.1,316	0.23	13	215	1.8,307	0.20	13	216	2.5,51	0.24	14	223	7.6,280	0.21	13	204
Avgs:	6.5,WNW	0.20	12	196	4.1,W	0.19	11	199	4.4,E	0.18	11	209	7.5,W	0.22	11	191

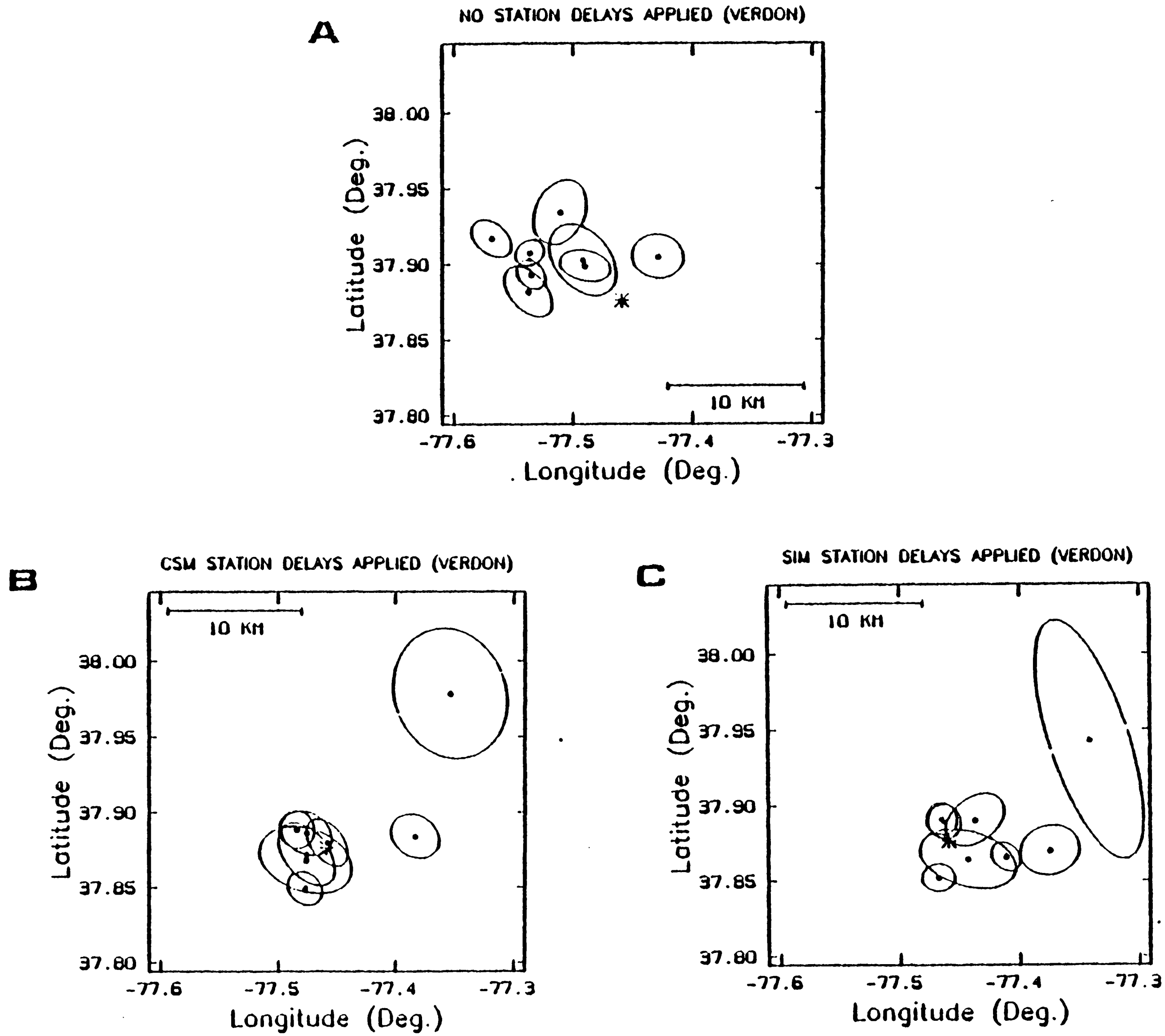
NOTE

HYPOELLIPSE locational errors (distance and azimuth from the quarry to the computed epicenter; Error) are given for eight blast locations determined when no station delays were employed (NSC) and when three different suites of station delays were used during computation. The three suites of station delays were generated using either the Closest Station Method (CSM), the Single Iteration Method (SIM), or the Joint Epicenter Determination (JED) method.

For each solution three HYPOELLIPSE parameters are listed. These parameters include: the root mean square residual (RMS) in seconds, the number of P and S phases used in the calculated solution (PH), and the largest azimuthal separation, in degrees, between stations as seen from the calculated epicenter (GAP).

FIGURE 12

Epicenter maps showing HYPOELLIPSE locations (solid circles) for eight blasts originating from a quarry (star) near Verdon, Virginia. All locations include the calculated epicenter and the surface projection of their corresponding error ellipsoids. Shown are HYPOELLIPSE locations calculated with; no station delays applied (A), the CSM suite of station delays applied (B), and the SIM suite of station delays applied (C).


A
NO STATION DELAYS APPLIED (VERDON)
38.00
37.95
37.90
37.85
37.80
Latitude (Deg.)
10 KM
-77.6
-77.5
-77.4
-77.3
Longitude (Deg.)
B
CSM STATION DELAYS APPLIED (VERDON)
10 KM
38.00
37.95
37.90
37.85
37.80
Latitude (Deg.)
-77.6
-77.5
-77.4
-77.3
Longitude (Deg.)
C
SIM STATION DELAYS APPLIED (VERDON)
10 KM
38.00
37.95
37.90
37.85
37.80
Latitude (Deg.)
-77.6
-77.5
-77.4
-77.3
Longitude (Deg.)

times) during computation. Examination of the seismograms for blast A showed that low signal-to-noise seismograms may have accounted for poor arrival time readings. However, when large residual arrival time data were deleted from the CSM calculations, no improvement resulted. Rather a degradation of solution quality occurred. Blast A was the only relocation (other than F) that showed an increase in its locational error. If one were to consider blast A to have a large enough locational error to be deleted from the blast relocation data suite, then the actual locational error (for the seven remaining locations) in the Verdon locale would be 2.6 km.

Other locational comparison criteria also showed major improvement once station delays were applied. For example, the locational gap, originally 235°, was reduced to 125° and 147° when the CSM and the SIM station delays were applied, respectively. Moreover, while the average equvalent radius remained roughly the same (approximately 1.6 km); in the case where the CSM set of station delays was used, four surface ellipses enclose the shot point whereas none had done so before. Also, the minima - maxima radial distances decreased from (4.8 km, 8.5 km), to (0.6 km, 4.2 km) and

(1.0 km, 4.3 km) for the cases where the CSM and the SIM suites of station delays were employed.

MANAKIN. For the relocation of the eight blasts originating from the Manakin quarry, no clearly superior set of locations was apparent (Figure 13 and Table 7). The average location error originally observed of 1.5 km was equivalent to the average locational error observed when the SIM station delays were employed. A slightly larger error of 1.7 km was observed for those relocations conducted using the CSM set of station delays. In all three cases, two of the eight relocations had error ellipsoid projections that enclosed the actual quarry location (Figure 14). The orginial eight HYPOELLIPSE locations had seven of eight located north of the actual shot position and therefore produced a large locational gap of 173°. Notice, however, that the eight relocations determined using the CSM and the SIM sets of station delays are distributed somewhat more symmetrically about the quarry location (with locational gaps of 82° and 114°, respectively) than are the eight original locations they have shifted southward. With the majorty of the observing stations located primarily to the north of the Manakin quarry, either velocity model

FIGURE 13

HYPOELLIPSE location comparison criteria for eight blasts originating from a quarry near Manakin, Virginia. Indicated are location comparison criteria for HYPOELLIPSE solutions calculated using no station delays (NSC), the closest station method suite of station delays (CSM), and the single iteration method suite of station delays (SIM).

LOCATION COMPARISON CRITERIA; MANAKIN

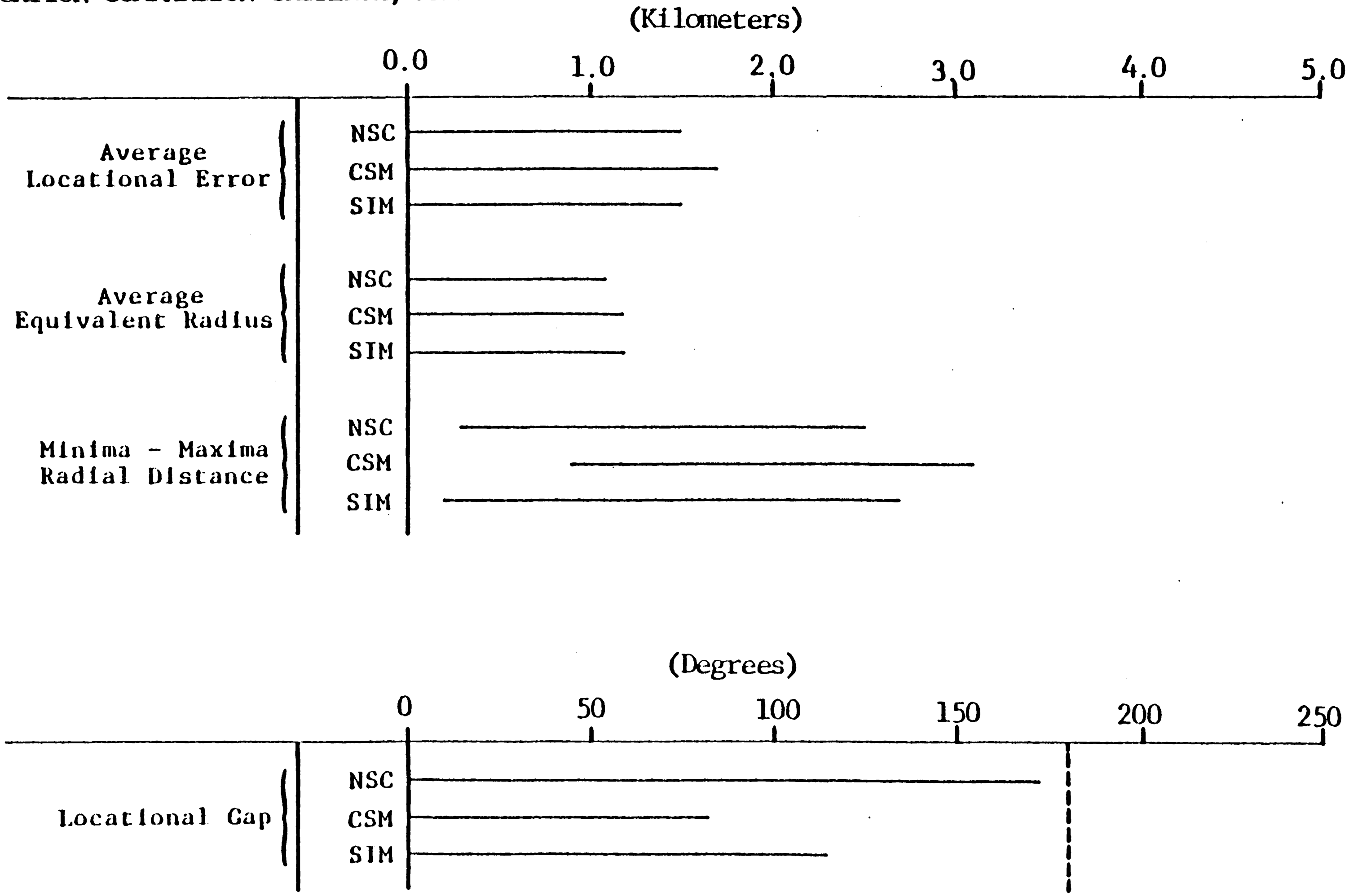


TABLE 7

HYPOELLIPSE Locational Errors For Eight Blasts Originating From A Quarry Near Manakin, Virginia, (g); Located Using The Central Virginia Velocity Model, And Three Suites Of Station Delays

Station Delay Suites (see NOTE below)

Blast	NSC Error (Km,Deg)	NSC RMS	NSC Ph	NSC Gap	CSM Error (Km,Deg)	CSM RMS	CSM Ph	CSM Gap	SIM Error (Km,Deg)	SIM RMS	SIM Ph	SIM Gap	JED Error (Km,Deg)	JED RMS	JED Ph	JED Gap
A	2.2,60	0.22	10	253	1.0,121	0.14	10	252	2.0,88	0.16	10	254	1.6,151	0.22	10	252
B	1.7,354	0.19	12	168	2.0,57	0.19	10	236	2.9,47	0.25	11	173	1.5,119	0.23	10	237
C	0.3,113	0.21	12	169	2.0,204	0.22	12	166	1.0,157	0.17	12	169	3.2,242	0.23	11	163
D	1.2,3	0.20	12	169	2.4,335	0.20	10	167	0.9,35	0.26	12	169	3.7,264	0.23	11	162
E	1.8,15	0.17	11	170	2.4,267	0.15	10	164	0.6,142	0.20	12	169	2.3,279	0.21	11	164
F	2.3,56	0.20	10	189	1.0,219	0.20	10	182	0.8,130	0.12	10	185	1.7,254	0.24	9	181
G	0.7,286	0.19	11	167	2.4,216	0.21	11	165	1.5,219	0.13	11	166	3.7,204	0.29	11	165
H	1.5,286	0.12	10	166	0.2,161	0.10	9	168	2.2,281	0.17	10	165	4.7,248	0.19	10	160
Avgs:	1.5,N	0.19	11	181	1.7,SSW	0.18	10	188	1.5,E	0.18	11	181	2.8,SW	0.23	10	186

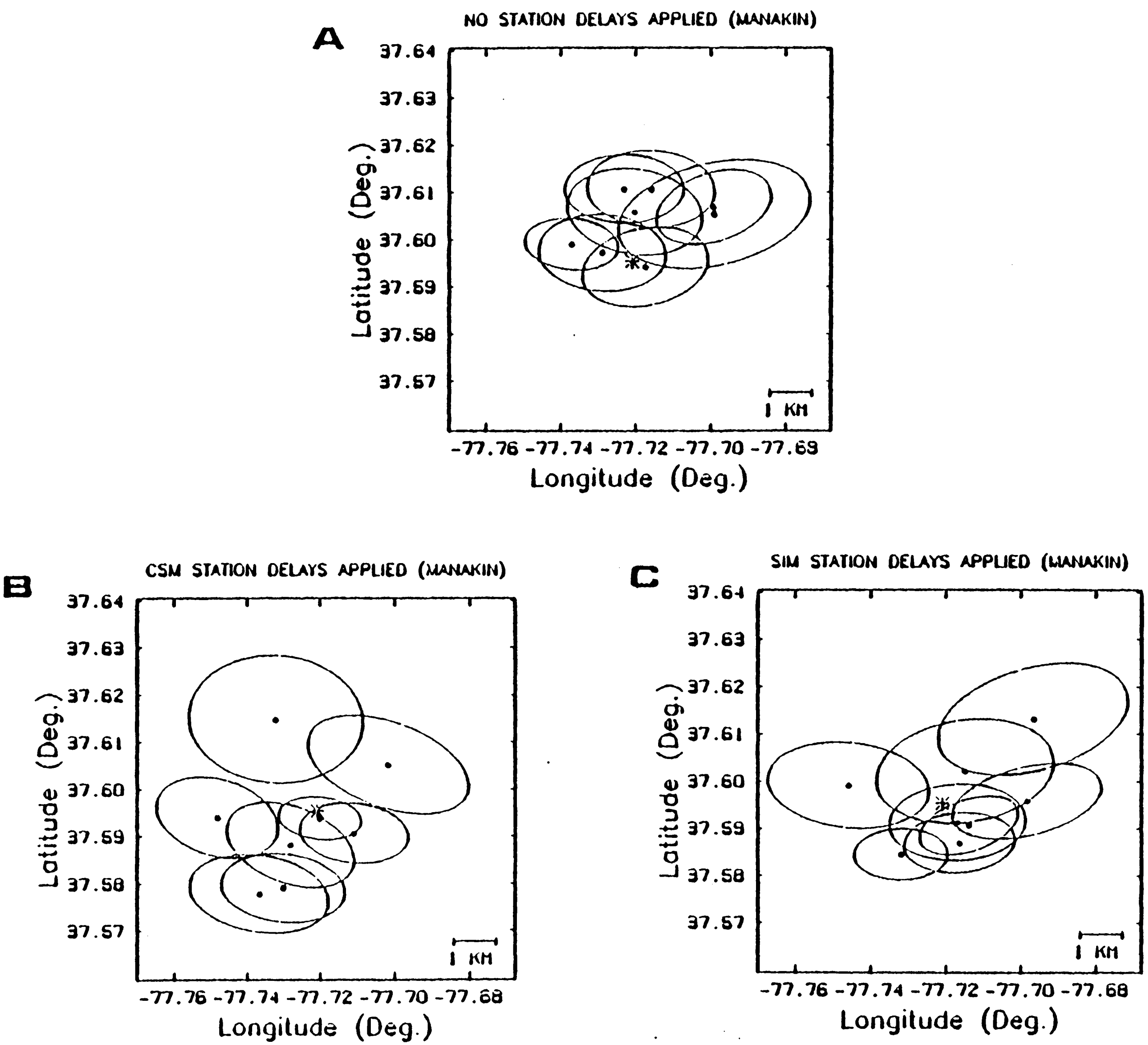
NOTE

HYPOELLIPSE locational errors (distance and azimuth from the quarry to the computed epicenter; Error) are given for eight blast locations determined when no station delays were employed (NSC) and when three different suites of station delays were used during computation. The three suites of station delays were generated using either the Closest Station Method (CSM), the Single Iteration Method (SIM), or the Joint Epicenter Determination (JED) method.

For each solution three HYPOELLIPSE parameters are listed. These parameters include: the root mean square residual (RMS) in seconds, the number of P and S phases used in the calculated solution (PH), and the largest azimuthal separation, in degrees, between stations as seen from the calculated epicenter (GAP).

FIGURE 14

Epicenter maps showing HYPOELLIPSE locations (solid circles) for eight blasts originating from a quarry (star) near Manakin, Virginia. All locations include the calculated epicenter and the surface projection of their corresponding error ellipsoids. Shown are HYPOELLIPSE locations calculated with; no station delays applied (A), the CSM suite of station delays appled (B), and the SIM suite of station delays applied (C).


A
NO STATION DELAYS APPLIED (MANAKIN)
37.64
37.63
37.62
37.61
37.60
37.59
37.58
37.57
Latitude (Deg.)
-77.76 -77.74 -77.72 -77.70 -77.68
Longitude (Deg.)
1 KM
B
CSM STATION DELAYS APPLIED (MANAKIN)
37.64
37.63
37.62
37.61
37.60
37.59
37.58
37.57
Latitude (Deg.)
-77.76 -77.74 -77.72 -77.70 -77.68
Longitude (Deg.)
1 KM
C
SIM STATION DELAYS APPLIED (MANAKIN)
37.64
37.63
37.62
37.61
37.60
37.59
37.58
37.57
Latitude (Deg.)
-77.76 -77.74 -77.72 -77.70 -77.68
Longitude (Deg.)
1 KM

inadequacies or network station asymmetry, must be suspected.

In all three cases, the average equivalent radius for the surface projection ellipse were approximately 1.1 km. In the comparison of the minima - maxima radial distances, slightly larger disparities exist. The range observed for the original eight locations (0.3 km, 2.5 km) was equal to that derived when the CSM station delays were applied (0.9 km, 3.1 km), and only slightly increased when the SIM station delays were applied (0.2 km, 2.5 km). While all of the ranges were approximately equal (around 2.3 km), the lower end of the scale was smallest (0.2 km) when the SIM set of station delays were applied. Thus, on average, the error ellipses generated using the SIM set of station delays were slightly closer to the actual shot location than in either of the other two cases.

Conclusions

ARVONIA. Because none of the blast relocations sets produced solutions superior to the orginal blast locations, no station delays need be applied to events in the Arvonia locale. This will imply that a general locational error of approximately 1.0 km is expected in the calculation of earthquake epicenters in this area.

VERDON. In the case of the locating events in the Verdon area, the CSM set of station delays were chosen to be superior (Table 8). For this set of relocations an average locational error of 2.6 km was observed while 50% of the HYPOELLIPSE relocations generated error ellipsoid suface projections that included the quarry.

MANAKIN. In this case no one set of blast relocations proved to be statistically more accurate than those locations originally observed when no station delays were applied. The main difference between the original locations and those performed using station delays was the redistribution of locations about the quarry (i.e. an observed decrease in the locational gap). Note though that

TABLE 8

Listing Of Preferred Station Delays
(Both P And S Phases)
For The Central Virginia - North Anna Network;
Divided According To General Area Of Application
(See Figure 8)

Network Station	Arvonia Locale P	Arvonia Locale S	Verdon Locale P	Verdon Locale S	Manakin Locale P	Manakin Locale S
NA2	---	---	+0.00	-0.02	+0.02	+0.15
NA5	---	---	+0.06	+0.03	---	---
NA11	---	---	+0.07	-0.51	---	---
NA12	---	---	+0.13	+0.43	-0.24	-0.11
CNV	---	---	+1.09	+1.75	---	---
CVL	---	---	+0.02	+0.05	+0.02	+0.05
GHV	---	---	+0.08	-0.42	-0.22	-0.23
FRV	---	---	+0.40	+0.70	+0.18	+0.29
PBV	---	---	+1.53	+2.69	+0.17	-0.21

the CSM set of relocations had a slightly larger average locational error than either the original eight locations or those derived using the SIM suite of station delays. Moreover, the results of the minima - maxima radial distance test, indicated that the SIM set of locations was judged to be preferable to other sets of locations. Although the SIM set of relocations is not significantly better than the others (Figure 13) it is preferred and therefore chosen as the station delay suite to be used in this area. Thus, an average locational error of some 1.5 km may be expected when calculating earthquake epicenters in the Manakin area.

Thus, it has been shown that in one case clearly superior locations were determined when station delays were employed. In the other two cases, where the original blast locations were considered to be good to excellent, no distinct improvement could be observed.

4. VELOCITY VARIATONS

Introduction

The velocity model used to locate events in the Central Virginia Seismic Zone assumes a P wave velocity of 6.09 km/sec and an S wave velocity of 3.53 km/sec for the surface layer (Table 1). Employing this model and the SIM, velocity variations in the central Virginia area were mapped, and a possible pattern of velocity 'banding' was identified. Several examples of velocity banding and anisotropy have been documented previously in the southeastern United States. Three are of particular interest in this study, and will now be discussed briefly.

Velocity Anisotropy In The Southeastern U. S.

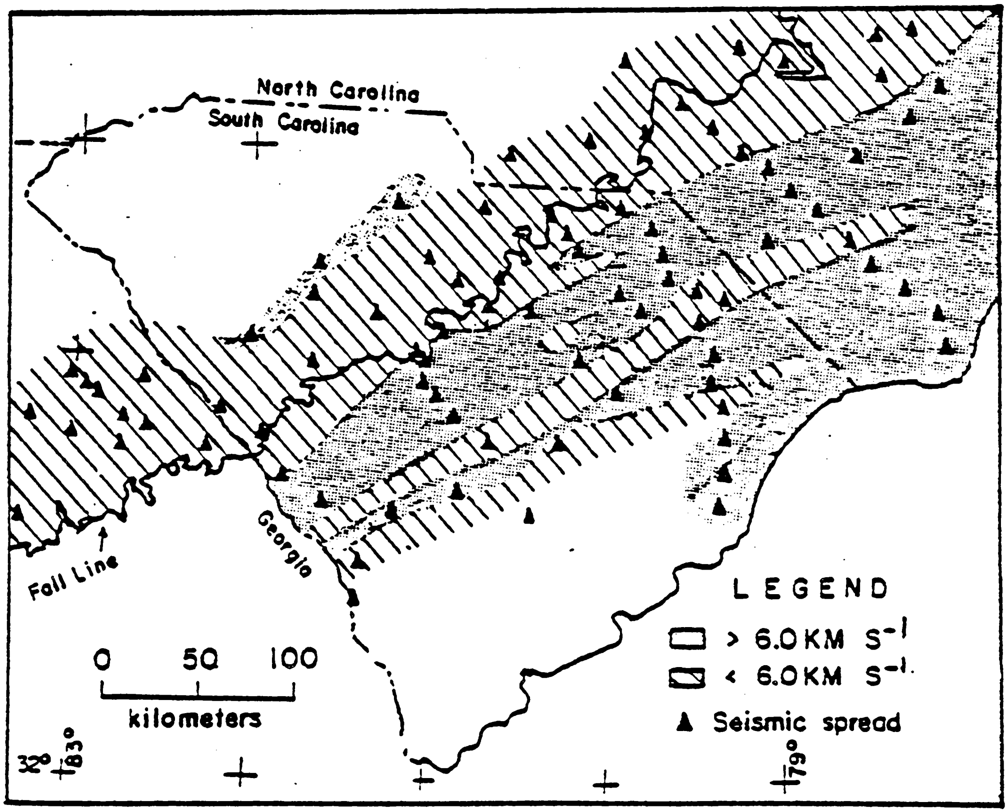
GEORGIA, NORTH AND SOUTH CAROLINA. Velocity anisotropy has been detected and measured in the Piedmont and Coastal Plain provinces of Georga, South Carolina, and North Carolina (Dorman, 1972). For example, the average P and S wave velocities for the upper crust in northern Georgia, were measured to be 6.2 and 3.6 km/sec, respectively. Fluctuations in these velocities, as a function of azimuth, varied by about 0.75 and 0.45 km/sec for P and S,, respectively. This result implies that 12% anisotropy exists in the region.

Interpreting over 60 short seismic refraction profiles (of Bonini and Woollard, 1960), Dorman noted the presence of bands of alternating high (>6.0 km/sec) and low (< 6.0 km/sec) velocities (Figure 15). These bands of alternating basement velocities ranged from 3.9 to 6.9 km/sec and trended northeasterly subparallel to the Appalachian highlands.

SOUTHEASTERN VIRGINIA. Crustal studies performed in southwestern Virginia have shown that P and S Wave velocities vary with asimuth (Moore, 1979). The P wave

FIGURE 15

Map of velocity banding observed in the Piedmont and Coastal Plain provinces of Georgia, North, and South Carolina (from Dorman, 1972). These alternating high and low velocity bands were documented using data from over 60 short refraction profiles (solid triangles), in the region (Bonini and Wollard, 1960).


North Carolina
South Carolina
Georgia
Fall Line
0 50 100
kilometers
32°
83°
79°
LEGEND
> 6.0 KM S^-1
< 6.0 KM S^-1
Seismic spread

crustal velocity ranges from 5.45 to 6.03 km/sec (perpendicular and parallel to the trend of the Valley and Ridge province, respectively). This result implies that a 10% P wave anisotropy exists for the upper crust in southwestern Virginia.

The S wave crustal velocity ranged from 3.24 to 3.51 km/sec (perpendicular and parallel to the trend of the Valley and Ridge province, respectively). This implies 8% S wave anisotropy in the upper crust in this area.

CENTRAL VIRGINIA. The 17 station North Anna Seismic Network was operated from January 1974 through July 1977, and monitored seismic activity in the vicinity of the North Anna nuclear facility. In the calibration of that network, three high explosive blasts were detonated and from the resulting data, station delays were derived (Dames and Moore, 1977). Even though the network was highly concentrated around the power plant site (average station spacing: 6 km, maximum aperture: 35 km), some variations of the resulting station delays with azimuth were observed. This variation ammounted to a 4% anisotropy within the small network area.

Effective Velocities

TECHNIQUE. In the computation of origin times using the SIM, observed P and S wave travel times were determined for all network station readings. Employing the aforementioned method that was applied in the calculation of station delays, all of the observed travel times from a quarry to a network station were averaged. Moreover, it was noted that the distance between the quarry and each network station should be well determined (±100 meters). Using those distances and the average travel time for the P and S wave to a network station, an approximate value for the P and S wave velocity from the shot point to each network station was derived.

A note of caution should be made here. These velocities are not true medium phase veloctíes because the origin time was computed assuming the central Virginia model P and S wave velocities. Therefore, the velocities derived from this technique are termed herein to be 'effective' velocities. These effective velocities should be useful in comparing variations of velocity as a function of distance and azimuth from the source.

For each quarry at least five stations were used to develop travel times using the aforementioned procedure. For each station a minimum of three travel times was employed.

<u>RESULTS</u>. The average for the effective P wave velocities, derived for the three quarry areas, was 6.09 ± 0.11 km/sec (95% confidence level; Table 9). This is as expected since it is the value assumed by the central Virginia velocity model used to derive the effective velocities. Individual values for the effective P wave velocity, however, ranged from 5.44 km/sec (quarry b; CNV) to 6.42 km/sec (quarry b; NA5) thereby indicating a significant range of variation.

The central Virginia velocity model assumes a S wave velocity of 3.53 km/sec. An effective average S wave velocity of 3.50 ± 0.06 km/sec was determined (Table 9). This derived value is well within the experimental error cited by Chapman in the development of the central Virginia velocity model. However, values for the effective S wave velocity ranged from 3.13 km/sec (quarry b; CNV) to 3.66 km/sec (quarry b; NA5).

TABLE 9

Effective P and S Wave Velocities Observed For Blasts Originating From Three Quarries In Central Virginia

Quarry (1)	Station Code	Effective Velocity P Wave (Km/Sec)	S Wave (Km/Sec)	Ph. (2)	Vp:Vs (3)	Delta (Km) (4)	Az. (Deg) (5)
a	GHV	6.09	3.43	8:8	1.78	23.7	62
a	CVL	6.00	3.57	8:8	1.68	33.6	342
a	NA12	6.15	3.36	5:5	1.83	52.0	52
a	FRV	6.28	3.54	8:7	1.77	54.4	181
a	NA2	6.00	3.52	8:8	1.70	71.2	47
b	NA5	6.42	3.66	4:3	1.75	24.6	302
b	NA2	6.36	3.65	8:8	1.74	34.8	323
b	CNV	5.44	3.13	5:3	1.74	38.4	18
b	GHV	6.29	3.69	7:7	1.70	53.4	260
b	CVL	6.14	3.62	8:8	1.70	84.5	278
b	PBV	5.65	3.25	7:7	1.74	99.2	181
b	FRV	6.06	3.47	8:8	1.75	106.0	225
g	GHV	6.30	3.59	8:8	1.75	40.6	303
g	NA12	6.29	3.55	8:8	1.77	45.2	342
g	NA2	6.08	3.49	8:8	1.74	59.1	358
g	PBV	6.00	3.56	7:8	1.69	70.1	166
g	FRV	6.00	3.47	8:8	1.73	71.4	232
g	CVL	6.08	3.51	7:7	1.73	78.0	303

Note

(1). Quarry: three quarries, designated as either a, b, or g, were used to test the locational capabilities of the Central Virginia - North Anna Network.

(2). Ph. : the number of P and S phase arrivial times used to determine the effective velocities.

(3). Vp:Vs : a ratio of the average effective P wave velocity to the average effective S wave velocity.

(4). Delta: an epicentral distance, in kilometers, between the source and the station (Bullen, 1947). For each quarry, stations are listed in order of increasing delta.

(5). Az.: the azimuth from the source to the station with respect to north.

The value of the Vp/Vs ratio for the surface layer of the central Virginia velocity model is 1.73. Comparison of the effective P wave velocity to the effective S wave velocity gives a value of 1.74 ± 0.02 for the Vp/Vs ratio.

Discussion And Conclusions

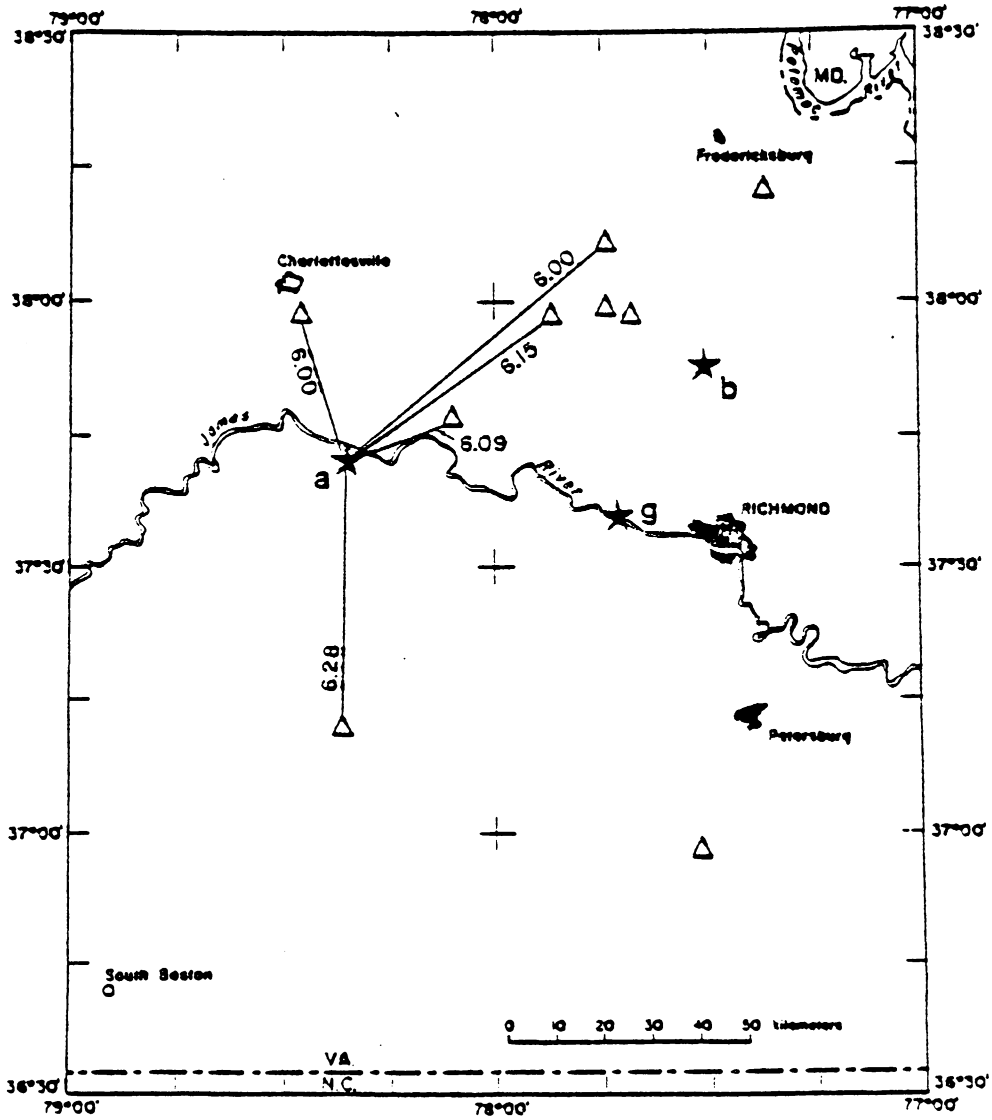
Examination of the effective velocities as a function of azimuth provides several interesting results (Figure 16 and Table 9). In the case of quarry b, network stations CNV and PBV have average effective velocities well below 6.09 km/sec (5.44 and 5.65 km/sec, respectively). Furthermore, in the case of quarry g, the average effective P wave velocity for network station PBV was one of the lowest observed (6.00 km/sec). It would seem that in these cases, the P wave velocity assumed by the present model (6.09 km/sec) is a serious overestimation of the the true P wave velocity for the assumed ray paths. Note, though, that these two stations are the eastern boundary of the network and are located on the relatively softer and younger sediments of the Coastal Plain province. Therefore, a lower value of the P wave velocities would be expected in these areas.

The remainder of the observed effective velocities exhibit a pattern of high and low velocities (Figure 16). In particular, those travel paths that indicated higher P wave velocities than the average (6.09 km/sec), seem to be

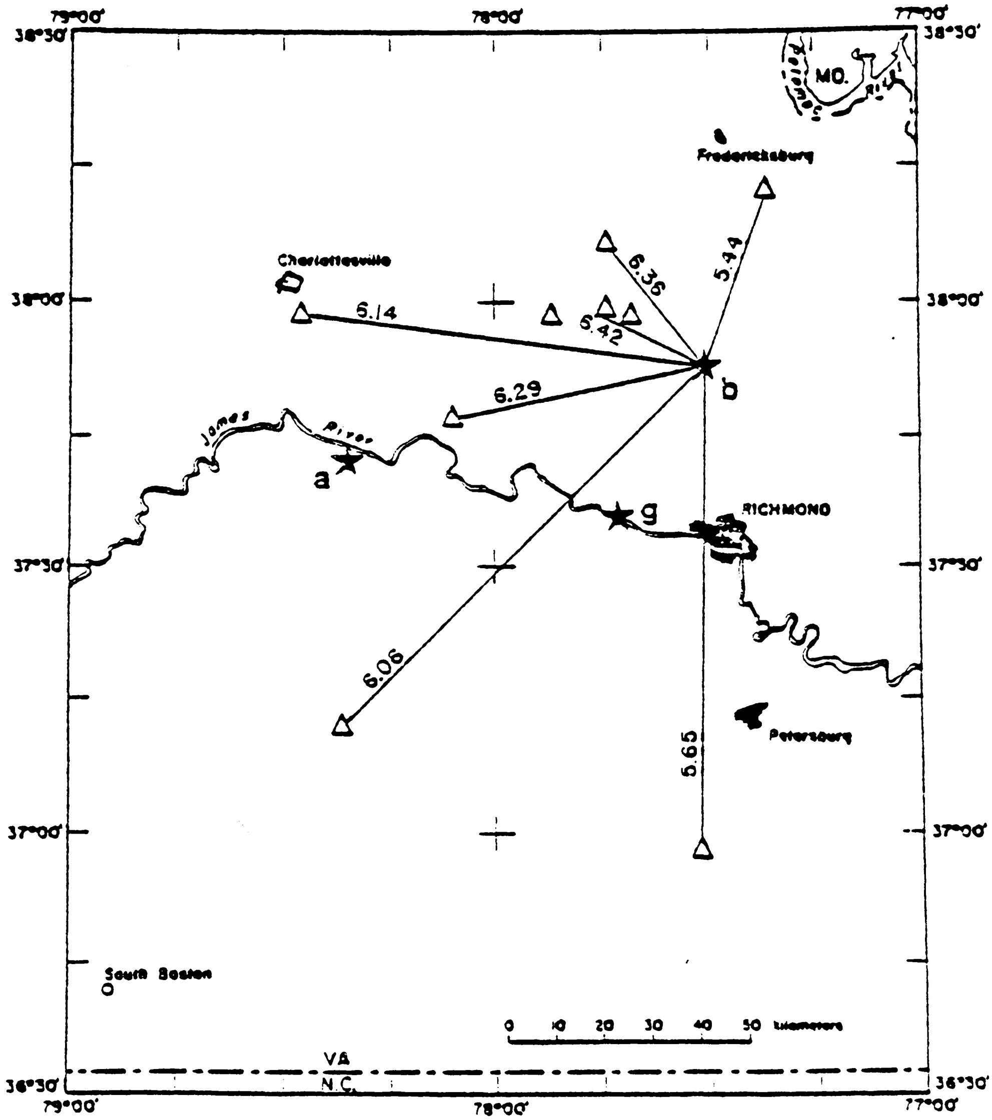
FIGURE 16

Map of the Central Virginia - North Anna Seismic Network. Shown are the locations of network stations (open triangles) of the Central Virginia - North Anna Network. Indicated are the locations of three quarries (solid stars) in the central Virginia area that were used to test the locational capabilities of the Central Virginia - North Anna Network. The average values for the effective P wave velocities for each station are indicated from quarry a near Arvonia, Virginia (A), from quarry b near Verdon, Virginia (B), and from quarry g near Manakin, Virginia (C). Some evidence of velocity banding is present, in the resulting pattern of velocities (from A, B, and C), as a high velocity band (> 6.2 km/sec), trending northeast through the network area (D).

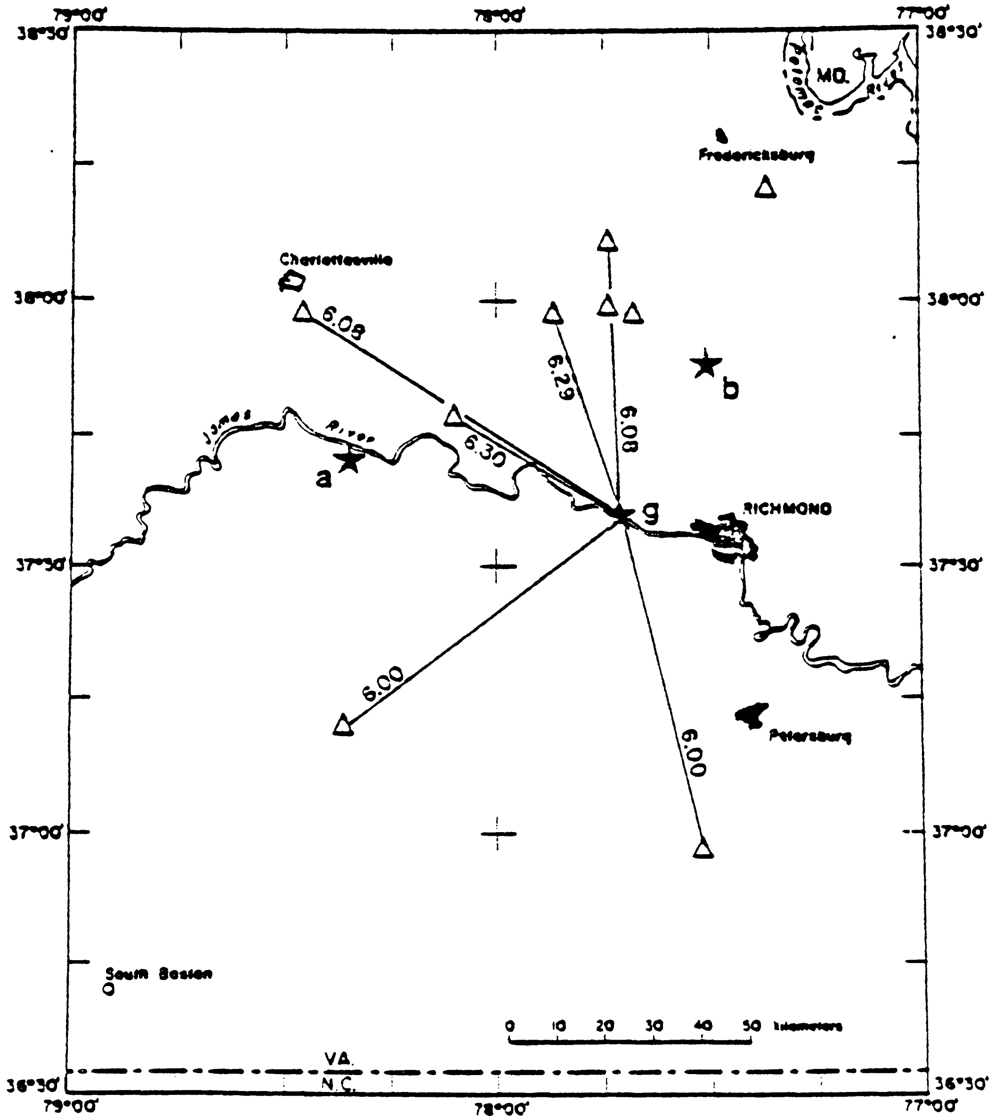
A


79°00'
78°00'
77°00'
38°30'
38°00'
37°30'
37°00'
36°30'
MD.
Fredericksburg
Charlottesville
6.00
6.15
6.00
6.09
6.28
James
River
a
b
g
RICHMOND
Petersburg
South Boston
0 10 20 30 40 50 kilometers
VA.
N.C.

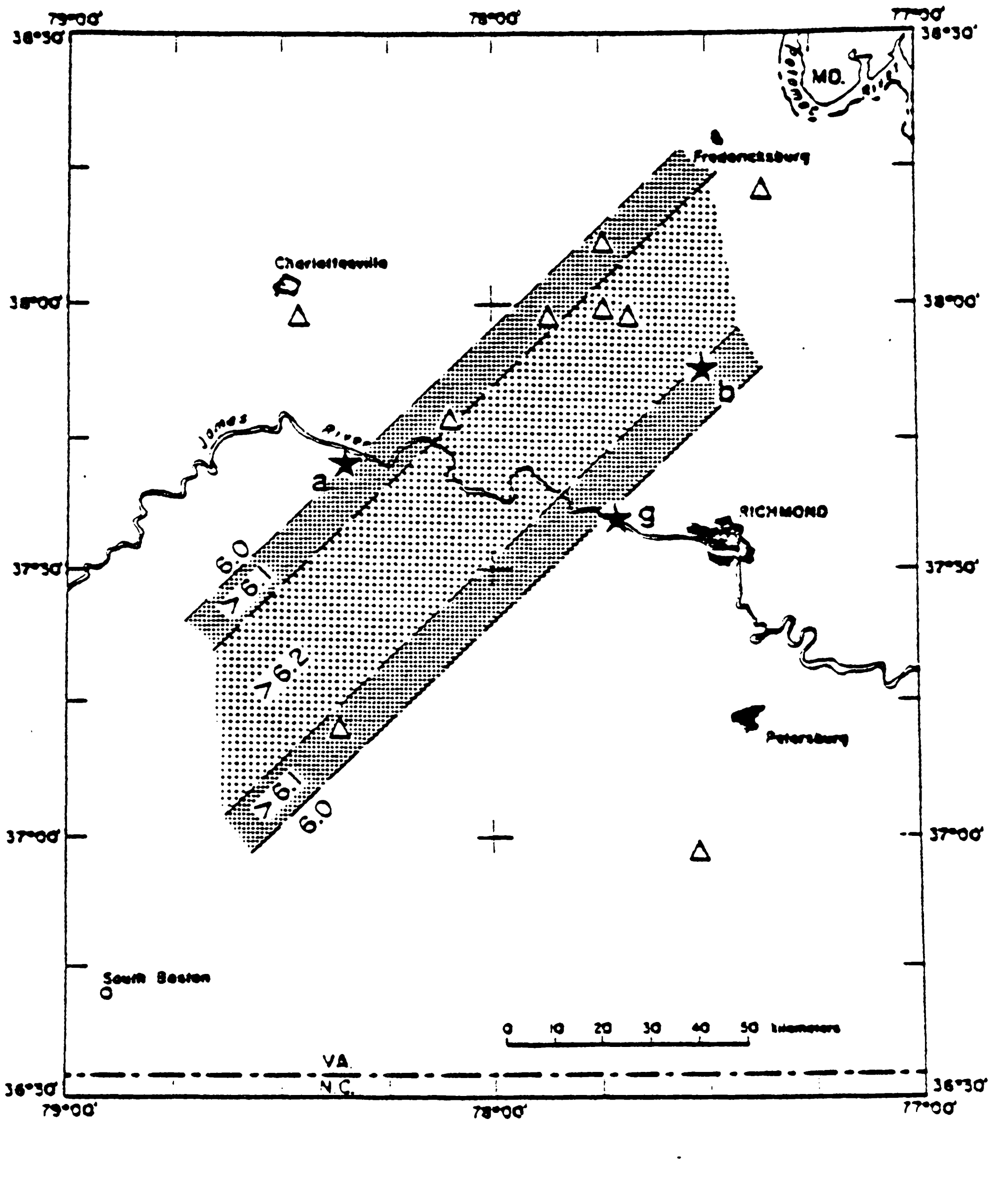
B


79°00'
78°00'
77°00'
38°30'
38°00'
37°30'
37°00'
36°30'
MD.
Fredericksburg
Charlottesville
James River
RICHMOND
Petersburg
South Boston
6.14
6.36
5.44
6.42
6.29
6.06
6.65
a
b
g
0 10 20 30 40 50 kilometers
VA
N.C.

C


79°00'
78°00'
77°00'
38°30'
37°30'
38°00'
37°00'
36°30'
MD.
Fredericksburg
Charlottesville
James River
RICHMOND
Petersburg
South Boston
6.08
6.29
6.08
6.30
6.00
6.00
a
b
g
0 10 20 30 40 50 kilometers
VA.
N.C.

D


79°00'
78°00'
77°00'
38°30'
38°00'
37°30'
37°00'
36°30'
MD.
Fredericksburg
Charlottesville
James River
RICHMOND
Petersburg
South Boston
a
b
g
6.0
6.1
6.2
6.0
6.1
0 10 20 30 40 50 kilometers
VA.
N.C.

restricted primarily to a zone some 25 km wide and striking northeastly (Figure 16 (D)). Moreover, those travel paths that represent lower than average effective velocities are either partially or completely external to this zone. This zone of higher velocties indicates that there exists a form of velocity banding, within the central Virginia Piedmont, similar to that observed elsewhere in the southeastern United States (Dorman, 1972). Although the orientation and general dimensions of this band are not tightly constrained by the data, the high velocity band does seem to parallel the northeast trend of the Blue Ridge Province of western Virginia. Geologic studies indicate that northeast-striking, higher velocity, volcanics are present in the area, and granitic rock units exist in the same general area where lower velocities (< 6.0 km/sec) were observed (Glover, 1982, personal communication).

Examination of the effective velocities with respect to distance (using all three quarries), indicated that no revisions of the present velocity model are necessary. That is, the present model serves as a good average for use in the location of shallow events within the Central Virginia Seismic Zone. The appropriateness of the velocity model is based in part on the fortuitous circumstance that the reversed refraction profile, used to derive the model, was oriented roughly perpendicular to the observed velocity banding (Chapman, 1979). Thus the velocities derived from that study represented a good average for the central Virginia area.

SUMMARY AND RECOMMENDATIONS

__SUMMARY__. The average locational precision of events within the central Virginia area has been improved. The average locational error of 3.0 km first observed in the area, was reduced to 1.7 km. This improvement was the result of station delays that were derived for different locales within the central Virginia area. These station delays were developed using two similar methods of approximating origin times for blasts originating from quarries of known location. For the location of seismic events within the Central Virginia Seismic Zone locale-dependant station delays will be employed. For events located with these suites of delays, an average locational error of about 1.7 km might be anticipated on the basis of this study.

Moreover, application of these methods show that major velocity variations exist within the Piedmont province of central Virginia. A zone of alternating high and low velocities, apparently trending roughly northeast (parallel to the Blue Ridge Province of western Virginia), indicates the presence of velocity banding similar to that previously observed in the Piedmont province of Georgia, North and South Carolina.

RECOMMENDATIONS. Following are several recommendations that are felt would help to increase locational capabilities in the central Virginia area.

(1). A reconfiguration of the Central Virgina Subnetwork seems to be in order. Network stations PBV and CNV are far enough removed from modern seismic activity in the zone to justify a relocation of these stations.

(2). At least one, preferably two, new stations should be added to the Central Virginia Subnetwork. The present average station spacing of 40 km provides poor depth control for the majority of events in the zone.

(3). A short program of monitoring blasts from the three quarries used in this study, could greatly improve the understanding of velocity variations in the area. With exact origin times known, the effective velocities discussed could be verified. This would be a fairly simple task considering the excellent rapport developed during earlier portions of the field work with the quarry operators.

REFERENCES

Bollinger, G. A., (1973). Seismicity and Crustal Uplift in the Southeastern United States, American Journal of Science, Vol. 273A, 1973, pp. 396-408.

Bollinger, G. A., and E. Mathena (1981). Seismicity Of The Southeastern United States, Bulletin No. 8, (January 1, 1981 - June 30, 1981), November 1981, 97 p.

Bullen, K. E., (1963). An Introduction To The Theory Of Seismology, Third Edition, Cambridge University Press, London, 381p.

Bonini, W. E. and G. P. Woollard (1960). Subsurface Geology Of North Carolina-South Carolina Coastal Plain From Seismic Data, Bulletin Of The American Association Of Petroleum Geologists, Vol. 44, March 1960, pp. 298-315.

Chapman, M. C., (1979). Seismic Velocity Structure Of Central Virginia, Master's Thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 146 p. (also in Nuclear Regulatory Commission Publication NUREG/CR-1217, Washington, D.C., January 1980, pp. 1-133).

Dames and Moore (1977). A Seismic Monitoring Program At The North Anna Site In Central Virginia, January 21, 1974, Through August 1, 1977, Submitted To Virginia Electric And Power Company, 1977, 244 p.

Dorman, L. M. (1972). Seismic Crustal Anisotropy In Northern Georgia, Bulletin Of The Seismological Society Of America, Vol. 62, February 1972, pp. 39-45.

Geiger, L, (1912). Probability Method For The Determination Of Earthquake Epicenters From The Arrivial Time Only, in Bulletin Of St. Louis University, 8 (1), 1912, pp. 60-71 (also in Macelwane, J. B. and F. W. Sohon (1932), Introduction to Theoretical Sesmology, St. Louis University Press, pp. 289-296).

Lahr J. C. (1980). HYPOELLIPSE/MULTICS: A Computer Program For Determining Local Earthquake Parameters, Magnitude, And First Motion Pattern, United States Geological Survey Open-File Report 80-59, Revised: April 1980, 59 p.

Lee, W. H. K., and J. C. Lahr, (1974). HYPO71: A Computer Program For Determining Hypocenter, Magnitude, And First Motion Pattern Of Local Earthquakes, United States Geological Survey Open-File Report 75-311, Revised: January 1974, 134 p.

Lee, W. H. K., and S. W. Stewart, (1981). Principles And Applications Of Microearthquake Networks, Advances Geophysics; Supplement 2, Academic Press, New York, NY, 293 p.

Moore, T. P., (1979). Crustal Velocity Structure In Southwestern Virginia, Master's Thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 75 p. (also in Nuclear Regulatory Commission Publication NUREG/CR-1217, Washington D. C., January 1980, pp. 134-187).

Sibol, M. S., (1980). Central Virginia Blast Survey - Arvonia Area, in Bollinger, G. A., (1980), Central Virginia Regional Seismic Network, Project Report No. 77-134-12, September 1981, under Nuclear Regulatory Research Contract No. NRC-04-77-134, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, Appendix.

Sibol, M. S., (1981). Central Virginia Blast Survey - Verdon Area, in Bollinger, G. A., (1981), Virginia Regional Seismic Network, Project Report No. 77-134-16, September 15, 1981, under Nuclear Regulatory Research Contract No. NRC-04-77-134, Mod. 6, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, Appendix 2.

Viret, M., (1982). Relocation Study Of Virginia Earthquakes (1959-1981) Using The Joint Hypocenter Determination And Joint Epicenter Determination Methods, Master's Thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 115 p.

APPENDIX 1

A DESCRIPTION OF THE CENTRAL VIRGINIA - NORTH ANNA SEISMIC NETWORK

Introduction

The Virginia Tech Seismological Observatory presently operates nine network stations in central and eastern Virginia. These nine stations constitute the Central Virginia - North Anna Network and monitor seismic activity over a 10,000 km^2 area (Figure 17).

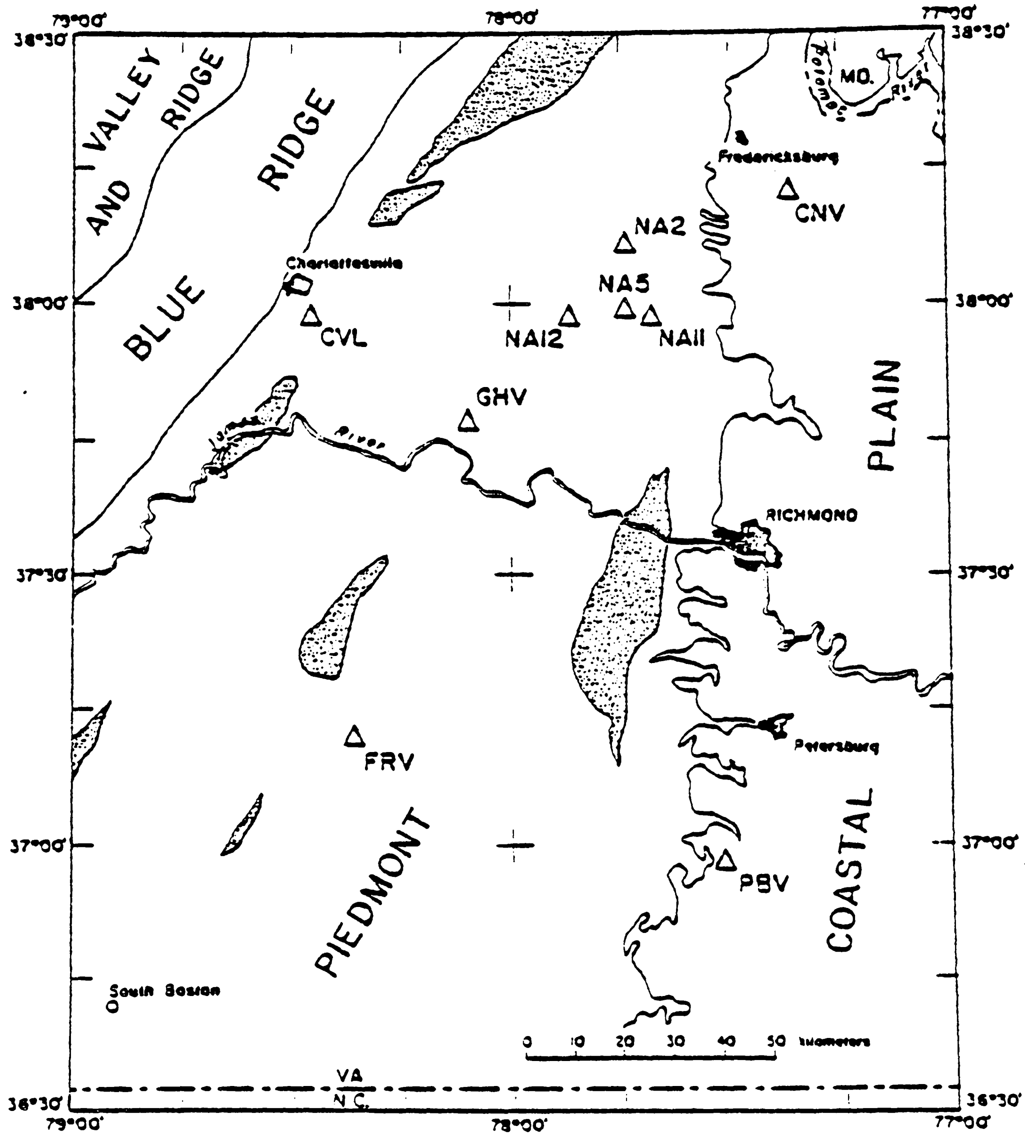
Data from the network are telemetered into a central recording facility on the Virginia Tech campus in southwestern Virginia. Recording of the data is duplicated using visual, photographic, and magnetic tape recorders.

Instrumentation

The instrumentation for the network is Mark Products Model L4-C, 1 Hz, vertical seismometers with Sprengnether telemetry components (amplifiers, filters, voltage-controlled-oscillators). Incoming data are recorded visually (Sprengnether VR-60s or Geotech Helicorders), on 16 mm film (Geotech Develocorder), and on FM magnetic tape

FIGURE 17

Map of the Central Virginia - North Anna Seismic Network. Indicated (open triangles) are the locations of network stations of the Central Virgina and North Anna Subnetworks. The Central Virginia Subnetwork consists of five stations (station codes: CNV, CVL, GHV, FRV, and PBV) with a maximum aperature of 140 km. The North Anna Subnetwork consists of four stations (station codes: NA2, NA5, NA11, and NA12) with a maximum aperature of 20 km. Also shown (solid lines) are the major geologic provinces: the Coastal Plain, Piedmont, Blue Ridge, and the Valley and Ridge. Indicated (shaded regions) are the Triassic basins of the Piedmont province of central Virginia. Geology adapted from the Geologic Map Of Virginia, Virginia Division of Mineral Resources, 1963.


79°00'
78°00'
77°00'
38°30'
38°00'
37°30'
37°00'
36°30'
VALLEY
AND
RIDGE
BLUE
RIDGE
Charlottesville
CVL
NA12
NA5
NA11
NA2
Fredericksburg
CNV
MD.
GHV
River
RICHMOND
Petersburg
FRV
PBV
PIEDMONT
COASTAL
PLAIN
South Boston
0 10 20 30 40 50 kilometers
VA
N.C.

(two 14 channel Geotech analog magnetic tape recorders; Model 19429). Impulsive, high signal-to-noise seismograms, are assumed to yield arrival time readings accurate to within ± 0.1 seconds on visual records and to ± 0.05 seconds on film and magnetic tape records.

All recorders are synchronized using a satellite clock (Kinemetrics Model 468-DC) as a central recording facility time code generator with a Systron - Donner (Model 8120) serving as a back-up chronometer. The satellite clock is checked daily and is considered to be precise to within ± 1 msec.

Detailed information on site and instrumental characteristics for the network (magnification curves, passband settings, etc.) are presented in the even-numbered issues of the Observatory's semiannual seismicity bulletin. Relevent excerpts from Bulletin No. 8 (Bollinger and Mathena, 1981) are presented in Appendix 2.

The North Anna Subnetwork

The North Anna subnetwork consists of four closely spaced stations (station codes: NA2, NA5, NA11, and NA12) located around the North Anna nuclear facility (Figure 17). These stations have an average station spacing of 6 km and a maximum aperture of 20 km. This smaller network is contained within the larger Central Virginia Subnetwork. The four North Anna stations are a remnant of a larger, 17 station network employed to monitor seismic activity in the area of a nuclear power plant. That study, utilizing the 17 station array, was conducted by Dames and Moore (for the Virginia Electric Power Company) from 24 January 1974 through 1 August 1977 (Dames and Moore, 1977). At the end of that period, 13 stations were dismantled and the present four station subnetwork was transferred to the Virginia Tech Seismological Observatory for operation.

The Central Virginia Subnetwork

The Central Virginia Subnetwork consists of five stations (station codes: CNV, CVL, GHV, FRV, and PBV) operating since late 1978 (Figure 17). The subnetwork has an average station spacing of 43 km and a maximum aperature of 140 km. The stations are located in the Piedmont and Coastal Plain provinces of central and eastern Virginia.

The average network station spacing was determined from the areal coverage of the network and the number of stations in the network (Lee and Stewart, 1981, page 165). Notice that of the nine stations in the Central Virginia - North Anna Network, seven are located in the upper third portion of the network area (i.e., north of station GHV; Figure 17). If all nine stations are considered, an average station spacing of 32 km is implied This result is an unrealistic description of the network and is misleading because of the highly asymmetric configuration of the network stations. A closer approximation to the effective station spacing might be to consider the North Anna Subnetwork as one station located at a central point within that subnetwork (NA5, for example). This approximation would then indicate a more appropriate average station spacing of 40 km for the Central Virginia - North Anna Network.

APPENDIX 2

Following are several excerpts from Bulletin No. 8 of Seismicity of the Southeastern United States, November 1981 (Bollinger and Mathena, 1981). Included are several magnification curves for the Central Virginia Subnetwork (Figure 18) that apply for the period January 1979 through December 1980.

Following these are several magnification curves (Figures 19 and 20), dated January 1981, that apply toward seismogram records used in the study of those blasts originating from a quarry operating near Manakin, Virginia.

SEISMIC STATIONS IN VIRGINIA

GENERAL INFORMATION

Station: Central Virginia Network (CNV, CVL, GHV, PBV and FRV)

Operated By: Dr. G. A. Bollinger

Address: Department of Geological Sciences
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061

Telephone: (703) 961-6729

Address to Obtain Records: Same as above

Type of Station Reports: Preliminary seismogram readings sent to USGS, Golden, Colorado

SITE INFORMATION

Code	Station Name	Latitude (Deg. N)	Longitude (Deg. W)	Elevation (Meters)	Date Opened	Date Closed	Foundation Geologic Age
CNV	Corbin	38.2050	77.3733	70	7/78	-	Tertiary clastics
CVL	Charlottesville	37.9813	78.4608	167	7/78	-	Precambrian
GHV	Goochland	37.7942	78.1073	107	10/78	-	Paleozoic meta-morphics
PBV	Petersburg	36.9823	77.5312	49	11/78	-	Petersburg granite
FRV	Farmville	37.2030	78.3593	216	12/78	-	Triassic igneous

INSTRUMENTATION

Code	Seismometer	T_o (Sec)	T_g (Sec)*	Type Recording**	Magnification at T_o	Remarks
CNV	SPZ (L4-C)	1.0	0.1	F,T	16.5K	-
CVL	SPZ (L4-C)	1.0	0.1	F,T	60K	-
GHV	SPZ (L4-C)	1.0	0.1	V,F,T	30K	-
PBV	SPZ (L4-C)	1.0	0.1	F,T	32.5K	-
FRV	SPZ (L4-C)	1.0	0.1	F,T	75K	-

Timing System: Systron-Donner Time Code Generator 8120

Direction of Motion on Records: Up on record for up on ground

System Response Curves: See attached

SHORT HISTORY/COMMENTS

*High-cut filter setting
**V= visual; F= 16 mm film; T= FM magnetic tape

SEISMIC STATIONS IN VIRGINIA

GENERAL INFORMATION

Station: North Anna Network (NA2, NA5, NA11 and NA12)

Operated By: Dr. G. A. Bollinger

Address: Department of Geological Sciences
Virginia Polytechnic Institute and State University
Blacksburg, Virginia 24061

Telephone: (703) 961-6729

Address to Obtain Records: Same as above

Type of Station Reports: Preliminary seismogram readings sent to USGS, Golden, Colorado

SITE INFORMATION

Code	Station Name	Latitude (Deg. N)	Longitude (Deg. W)	Elevation (Meters)	Date Opened	Date Closed	Foundation Geologic Age
NA2	North Site	38.1270	77.7470	82	10/78	-	All on
NA5	Central Site	37.9930	77.7470	76	8/78	-	metamorphics
NA11	Southeast Site	37.9830	77.6850	84	-	-	of uncertain
NA12	West Site	37.9830	77.8795	125	8/78	-	age

INSTRUMENTATION

Code	Seismometer	T_o (Sec)	T_g (Sec)*	Type Recording	Magnification at T_o	Remarks
NA2	SPZ (L4-C)	1.0	0.1	V,F,T	-	-
NA5	SPZ (L4-C)	1.0	0.1	T	-	-
NA11	SPZ (L4-C)	1.0	0.1	T	-	-
NA12	SPZ (L4-C)	1.0	0.1	T	-	-

Timing System: Systron-Donner Time Code Generator 8120

Direction of Motion on Records:

System Response Curves:

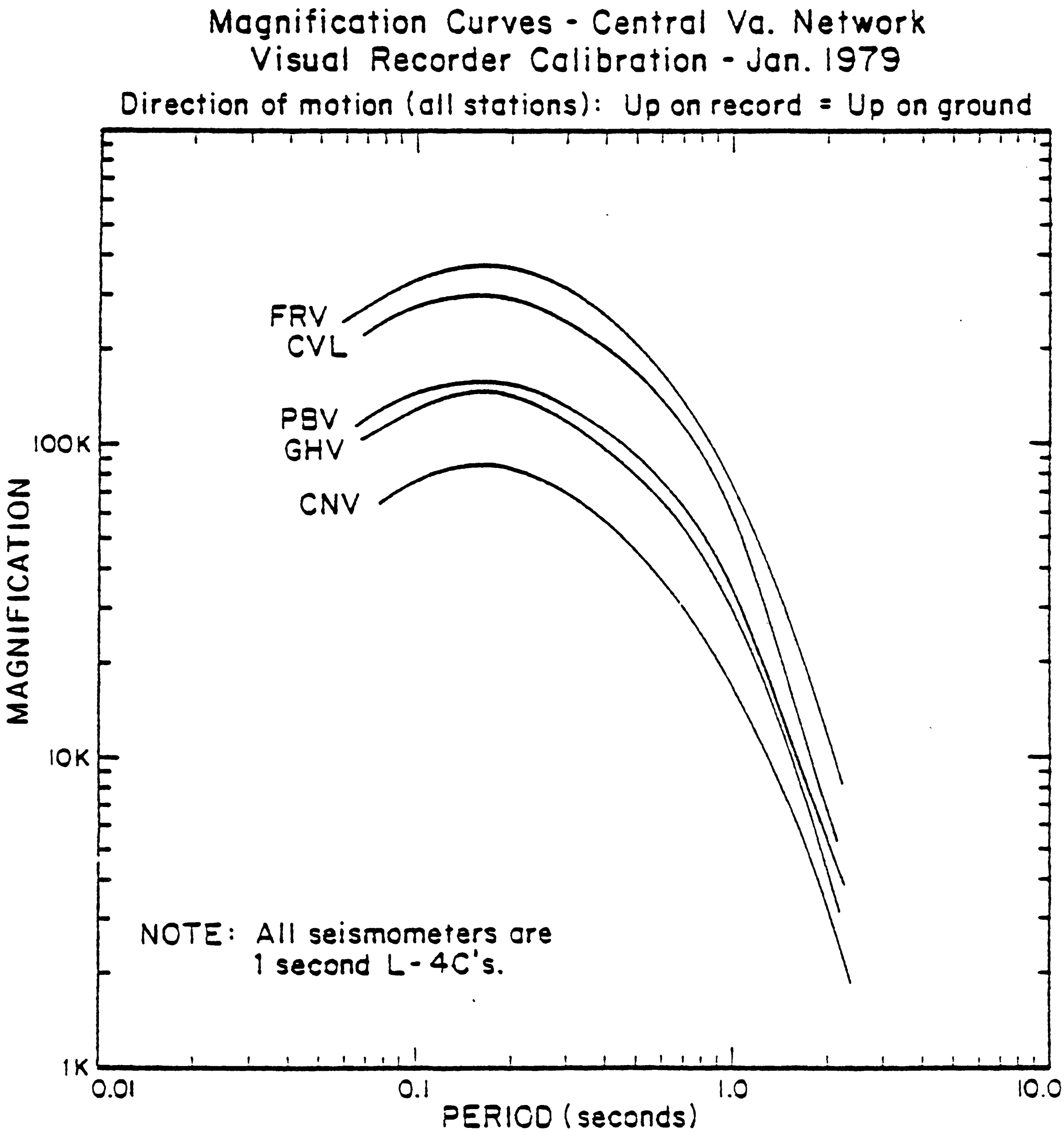
SHORT HISTORY/COMMENTS

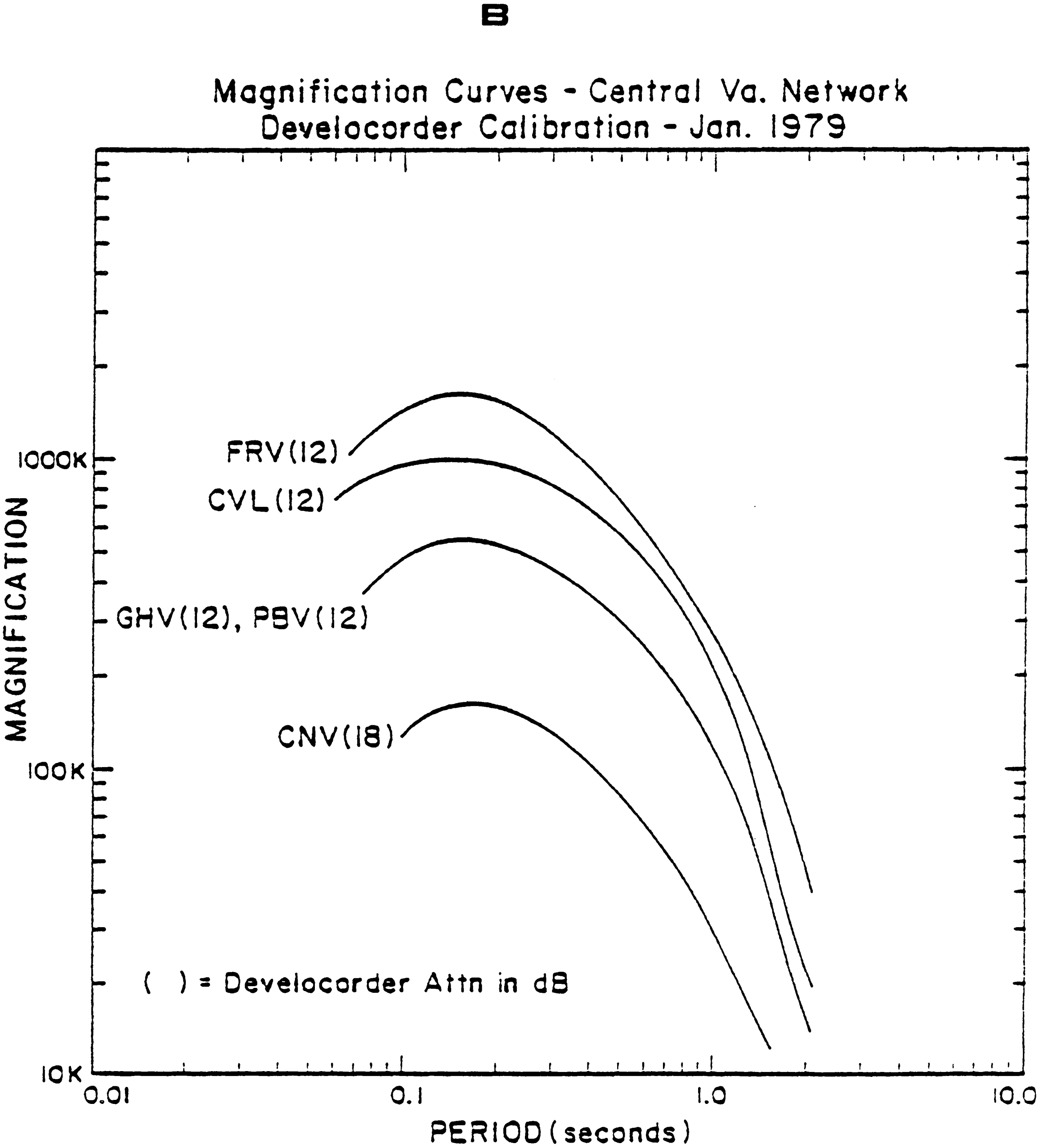
*High-cut filter setting

FIGURE 18

Magnification curves for the Central Virginia Subetwork used during the period January 1979 through December 1980 (Bollinger and Mathena, 1981). Curves are designated for the five stations; CNV, CVL, GHV, FRV, and PBV. Shown are sets of curves for seismograms recorded using either pen and ink visual recorders (A), a 16 mm film record and playback system (Develocorder; B), or an analog magnetic tape record and playback system (C).

A


Magnification Curves - Central Va. Network
Visual Recorder Calibration - Jan. 1979
Direction of motion (all stations): Up on record = Up on ground
FRV
CVL
PBV
GHV
CNV
MAGNIFICATION
100K
10K
1K
NOTE: All seismometers are
1 second L-4C's.
0.01
0.1
1.0
10.0
PERIOD (seconds)


B
Magnification Curves - Central Va. Network
Develocorder Calibration - Jan. 1979
MAGNIFICATION
1000K
100K
10K
FRV(12)
CVL(12)
GHV(12), PBV(12)
CNV(18)
( ) = Develocorder Attn in dB
0.01
0.1
1.0
10.0
PERIOD (seconds)

C

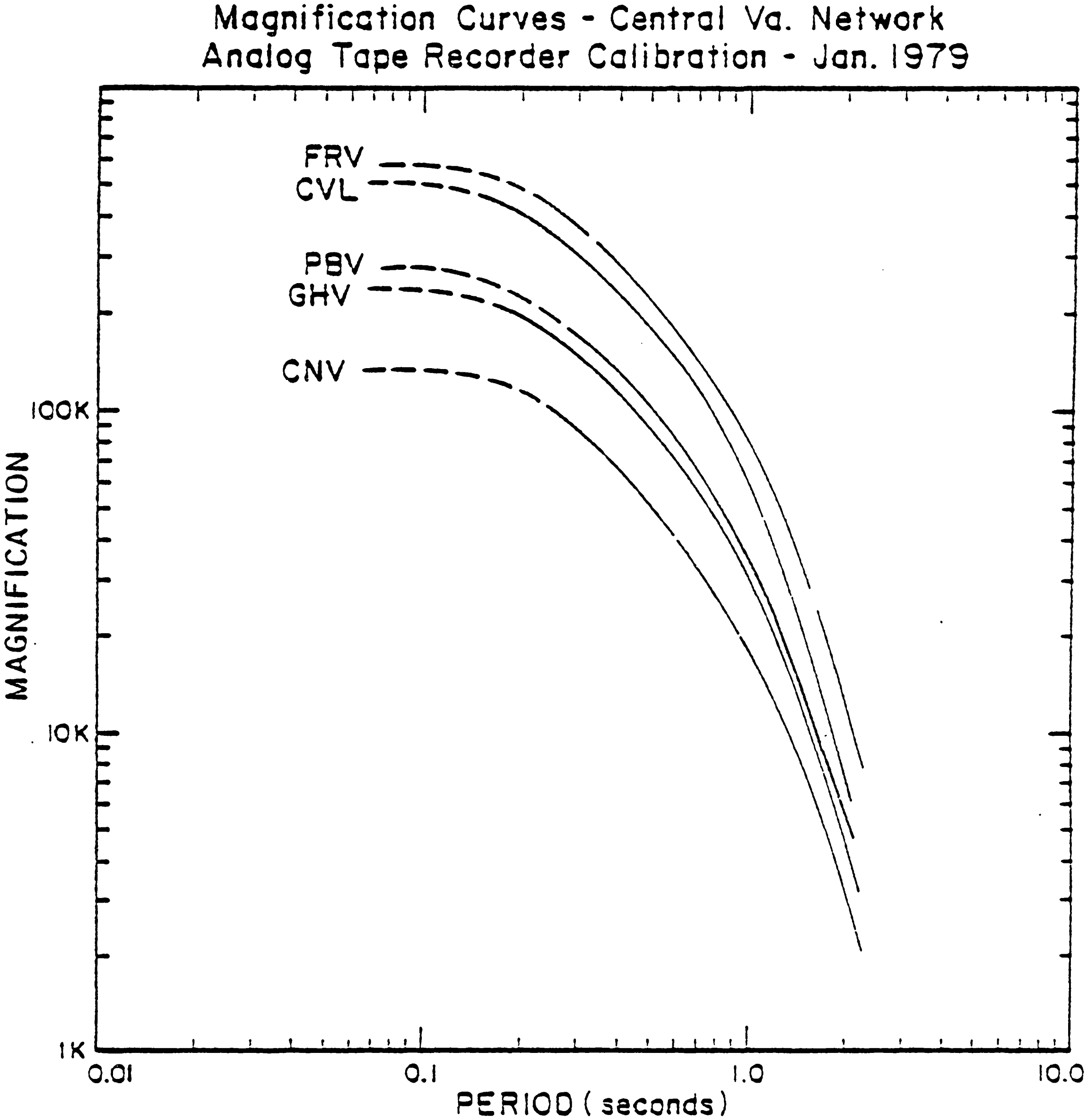

Magnification Curves - Central Va. Network
Analog Tape Recorder Calibration - Jan. 1979
FRV
CVL
PBV
GHV
CNV
MAGNIFICATION
100K
10K
1K
0.01
0.1
1.0
10.0
PERIOD (seconds)

FIGURE 19

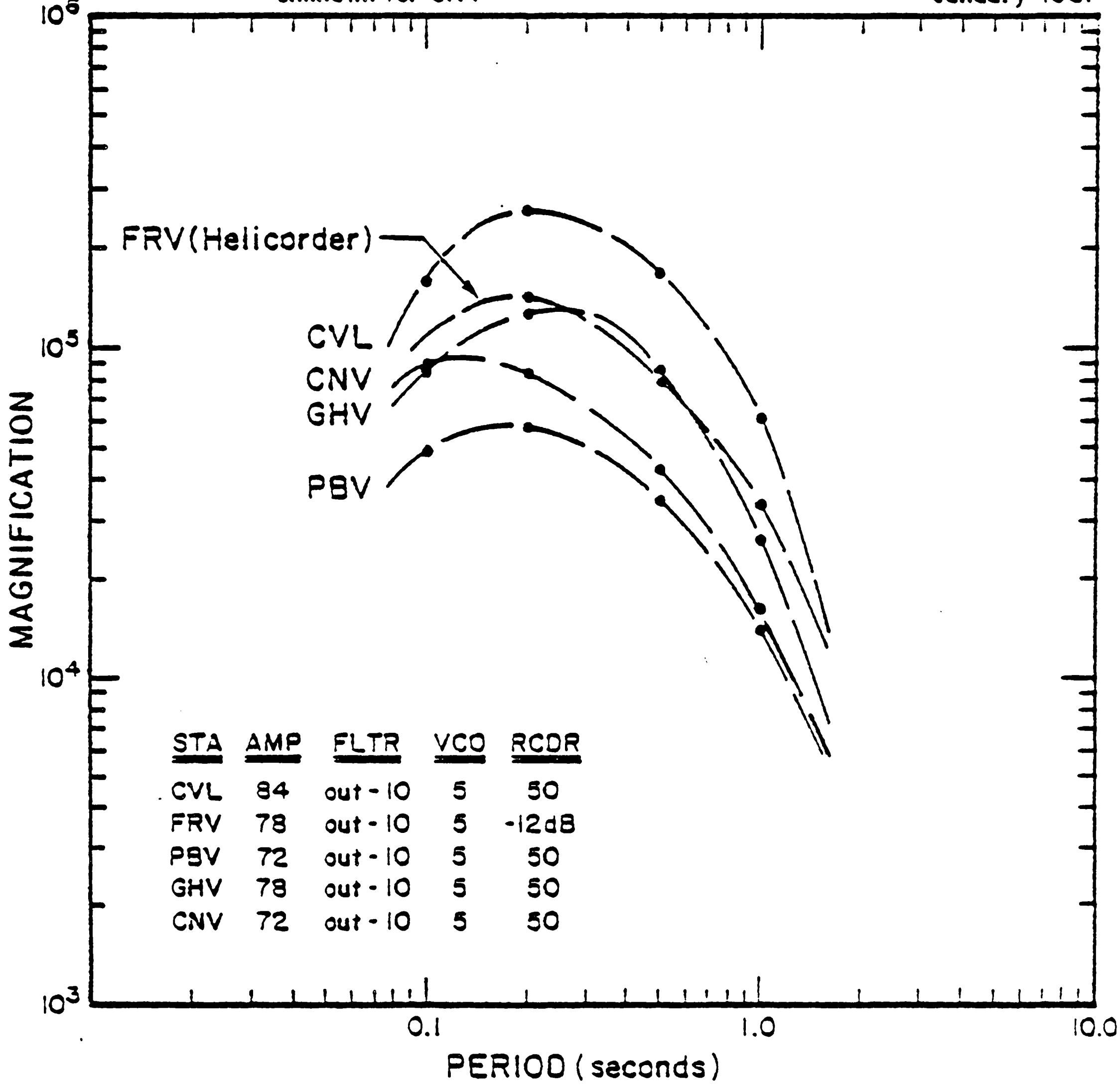
Magnification curves for the Central Virginia Subetwork used from January 1981 through the present. Curves are designated for the five stations; CNV, CVL, GHV, FRV, and PBV. Shown are sets of curves for seismograms recorded using either pen and ink visual recorders (A), a 16 mm film record and playback system (Develocorder; B), or an analog magnetic tape record and playback system (C).

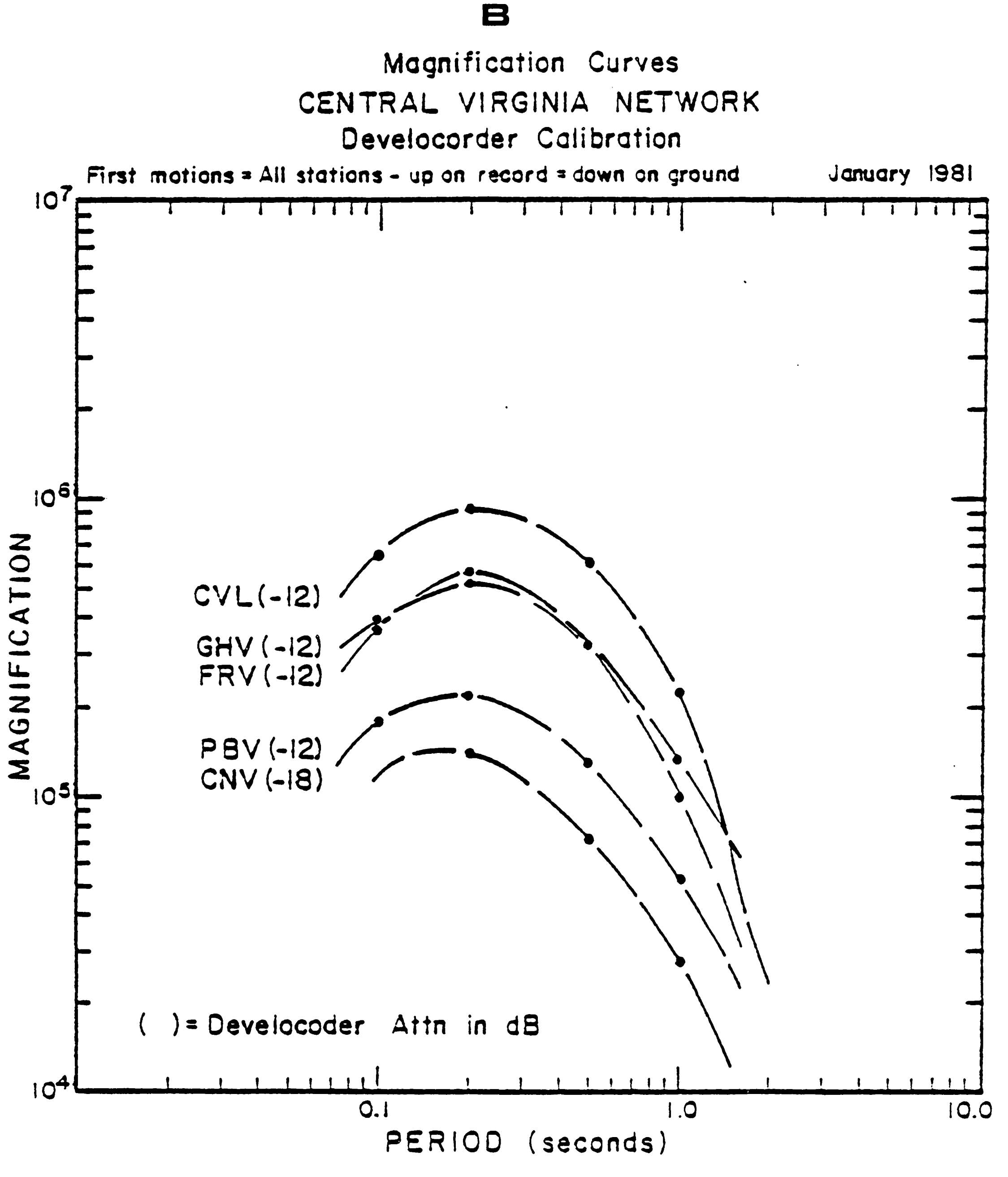
A

Magnification Curves
CENTRAL VIRGINIA NETWORK
Visual Recorder Calibration

First motions: up on record = up on ground for CVL, GHV, FRV, PBV
unknown for CNV

January 1981




B
Magnification Curves
CENTRAL VIRGINIA NETWORK
Develocorder Calibration
First motions = All stations - up on record = down on ground
January 1981
10^7
10^6
10^5
10^4
MAGNIFICATION
CVL(-12)
GHV(-12)
FRV(-12)
PBV(-12)
CNV(-18)
( ) = Develocoder Attn in dB
0.1
1.0
10.0
PERIOD (seconds)

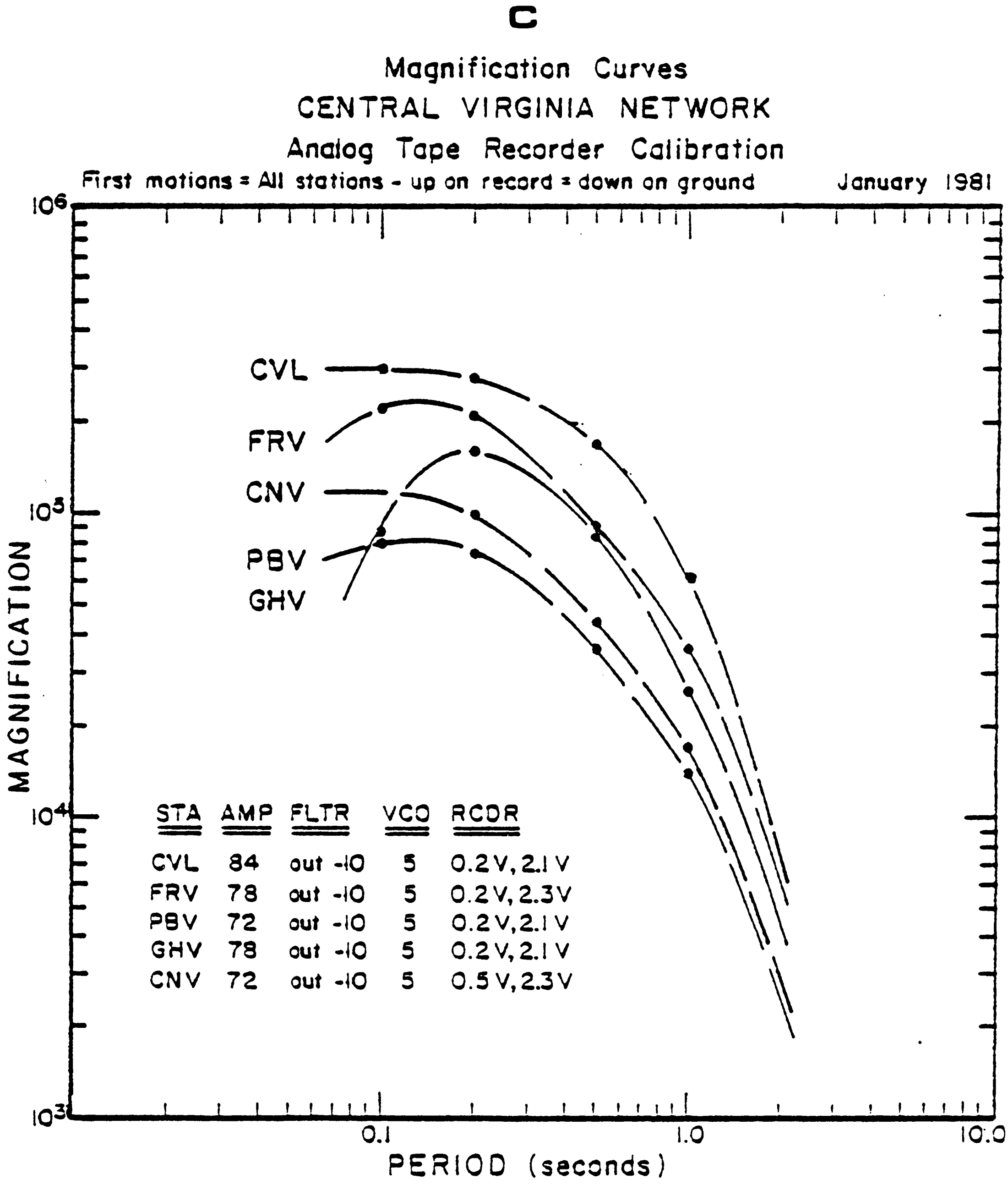

C
Magnification Curves
CENTRAL VIRGINIA NETWORK
Analog Tape Recorder Calibration
First motions = All stations - up on record = down on ground
January 1981
10^6
10^5
10^4
10^3
MAGNIFICATION
CVL
FRV
CNV
PBV
GHV
STA AMP FLTR VCO RCDR
CVL 84 out -10 5 0.2V, 2.1V
FRV 78 out -10 5 0.2V, 2.3V
PBV 72 out -10 5 0.2V, 2.1V
GHV 78 out -10 5 0.2V, 2.1V
CNV 72 out -10 5 0.5V, 2.3V
0.1
1.0
10.0
PERIOD (seconds)

FIGURE 20

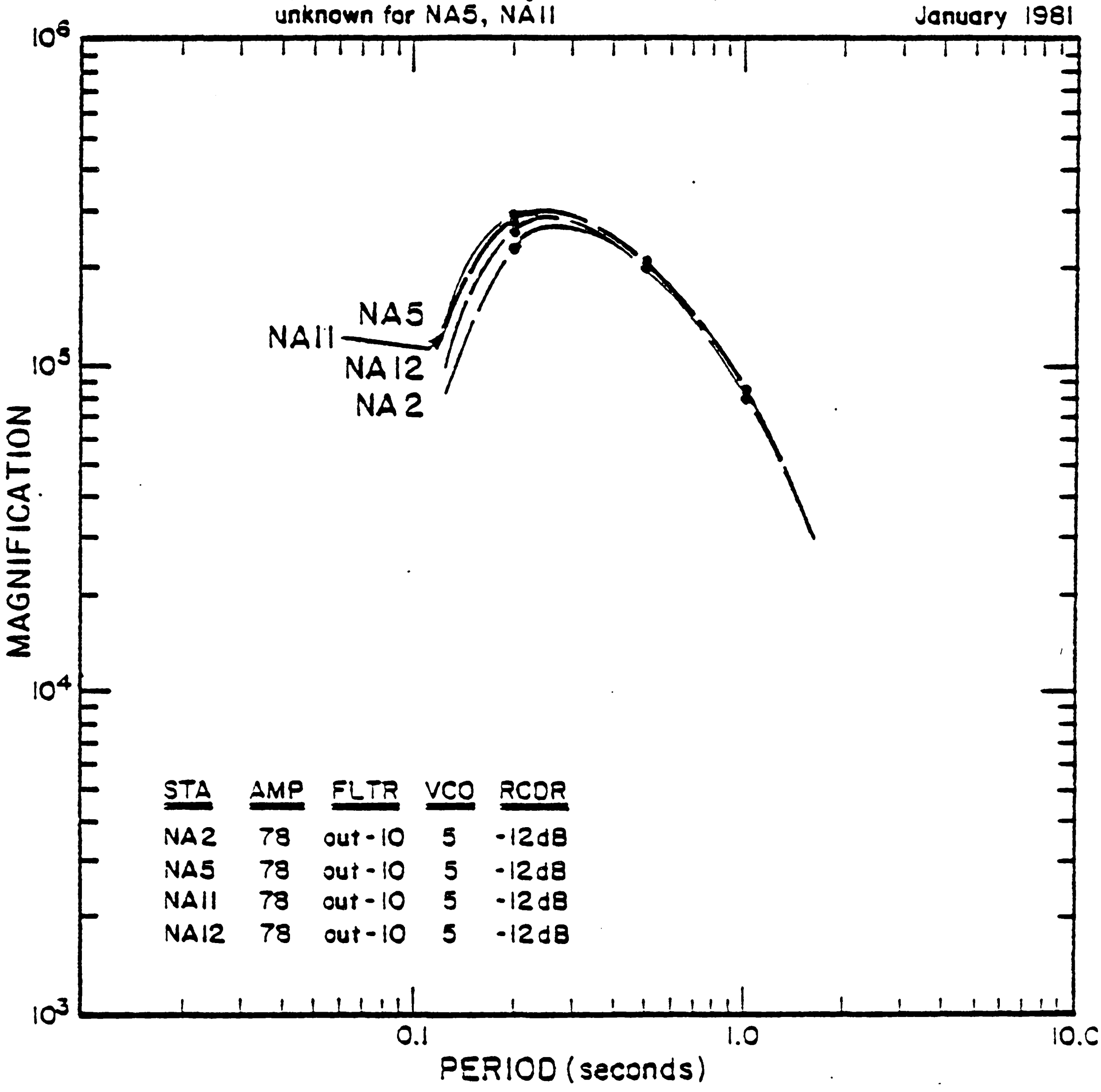
Magnification curves for the North Anna Subnetwork used from January 1981 through the present. Curves are designated for the four stations; NA2, NA5, NA11, and NA12. Shown are sets of curves for seismograms recorded using visual recorders (either heated stylus (A), or pen and ink (B)), a 16 mm film record and playback system (Develocorder; C), or an analog magnetic tape record and playback system (D).

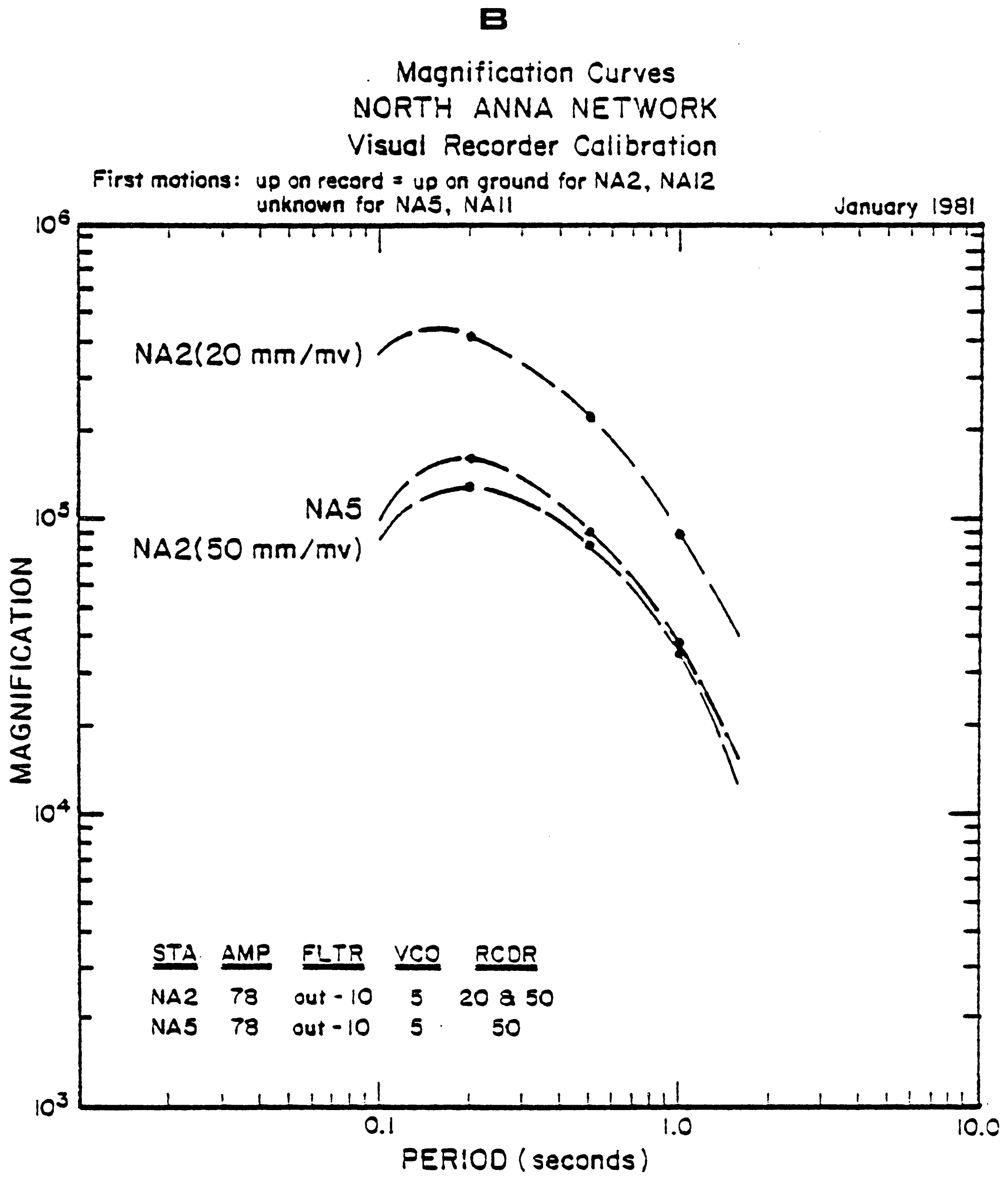
A

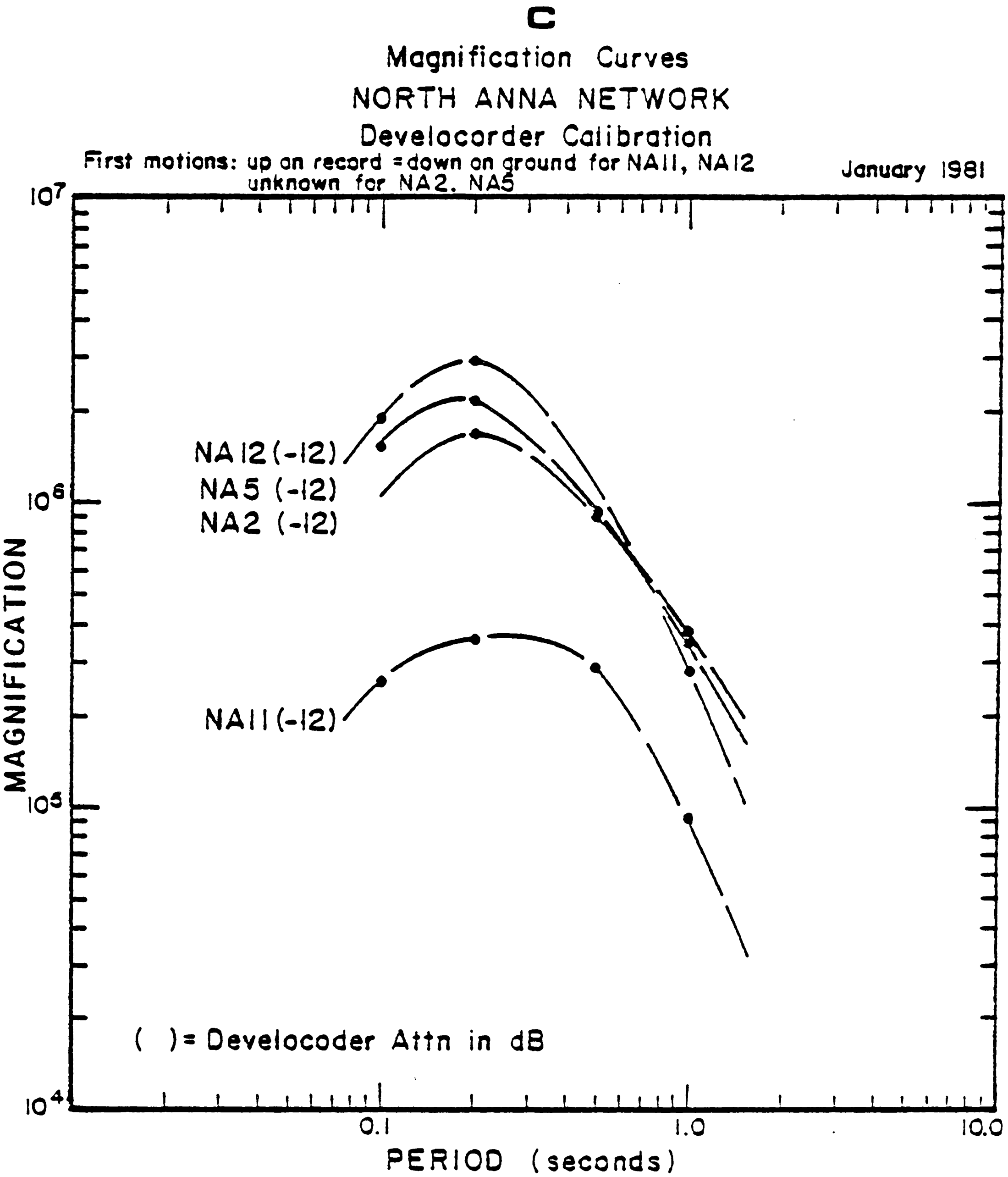
Magnification Curves
NORTH ANNA NETWORK
Helicorder Type Recorder Calibration

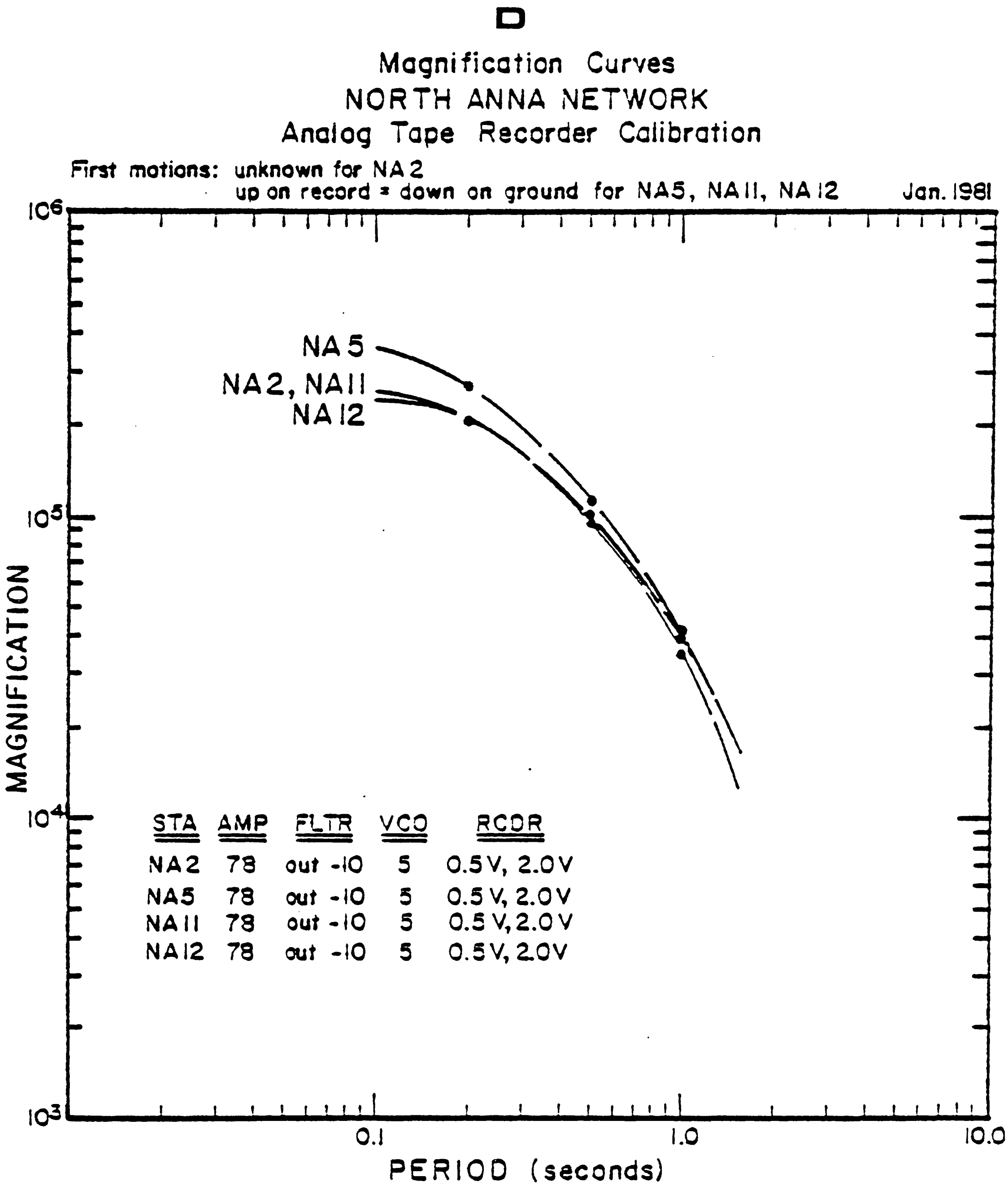
First motions: up on record = up on ground for NA2, NA12
unknown for NA5, NA11

January 1981




B
Magnification Curves
NORTH ANNA NETWORK
Visual Recorder Calibration
First motions: up on record = up on ground for NA2, NA12
unknown for NA5, NA11
January 1981
10^6
10^5
10^4
10^3
MAGNIFICATION
NA2(20 mm/mv)
NA5
NA2(50 mm/mv)
STA AMP FLTR VCO RCDR
NA2 78 out - 10 5 20 & 50
NA5 78 out - 10 5 50
0.1
1.0
10.0
PERIOD (seconds)


C
Magnification Curves
NORTH ANNA NETWORK
Develocorder Calibration
First motions: up on record = down on ground for NA11, NA12
unknown for NA2, NA5
January 1981
10^7
10^6
10^5
10^4
MAGNIFICATION
NA12 (-12)
NA5 (-12)
NA2 (-12)
NA11 (-12)
( ) = Develocoder Attn in dB
0.1
1.0
10.0
PERIOD (seconds)


D
Magnification Curves
NORTH ANNA NETWORK
Analog Tape Recorder Calibration
First motions: unknown for NA 2
up on record = down on ground for NA5, NA11, NA12
Jan. 1981
NA 5
NA2, NA11
NA 12
STA AMP FLTR VCO RCDR
NA2 78 out -10 5 0.5V, 2.0V
NA5 78 out -10 5 0.5V, 2.0V
NA11 78 out -10 5 0.5V, 2.0V
NA12 78 out -10 5 0.5V, 2.0V
MAGNIFICATION
10^6
10^5
10^4
10^3
0.1
1.0
10.0
PERIOD (seconds)

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Network Locational Testing And

Velocity Variations In

Central Virginia

by

Matthew Steven Sibol

ABSTRACT

Twenty-four blasts from three quarries operating in the central Virginia area were used, first to test the locational capabilities of the Central Virginia - North Anna Network and then to generate relative station delay suites for network stations.

Using two different methods of approximating blast origin times, the Closest Station Method (CSM) and the Single Iteration Method (SIM), station delays were derived for different areas within central Virginia. Application of these station delay suites reduced locational errors in the general area from an average of 3.0 ± 1.2 to 1.7 ± 0.6 km (95% confidence level). In both cases, the average equivalent radii, a linear measure of error ellipse size, were 1.3 km. However, this result depends primarily on the improvement at one of the three quarries, where the locational error was reduced from 6.5 km to 2.6 km.

Utilizing one of these methods (the SIM), lateral varational patterns in velocity were inferred and determined to be velocity banding similar to that observed in the Piedmont province in Georgia, North and South Carolina.