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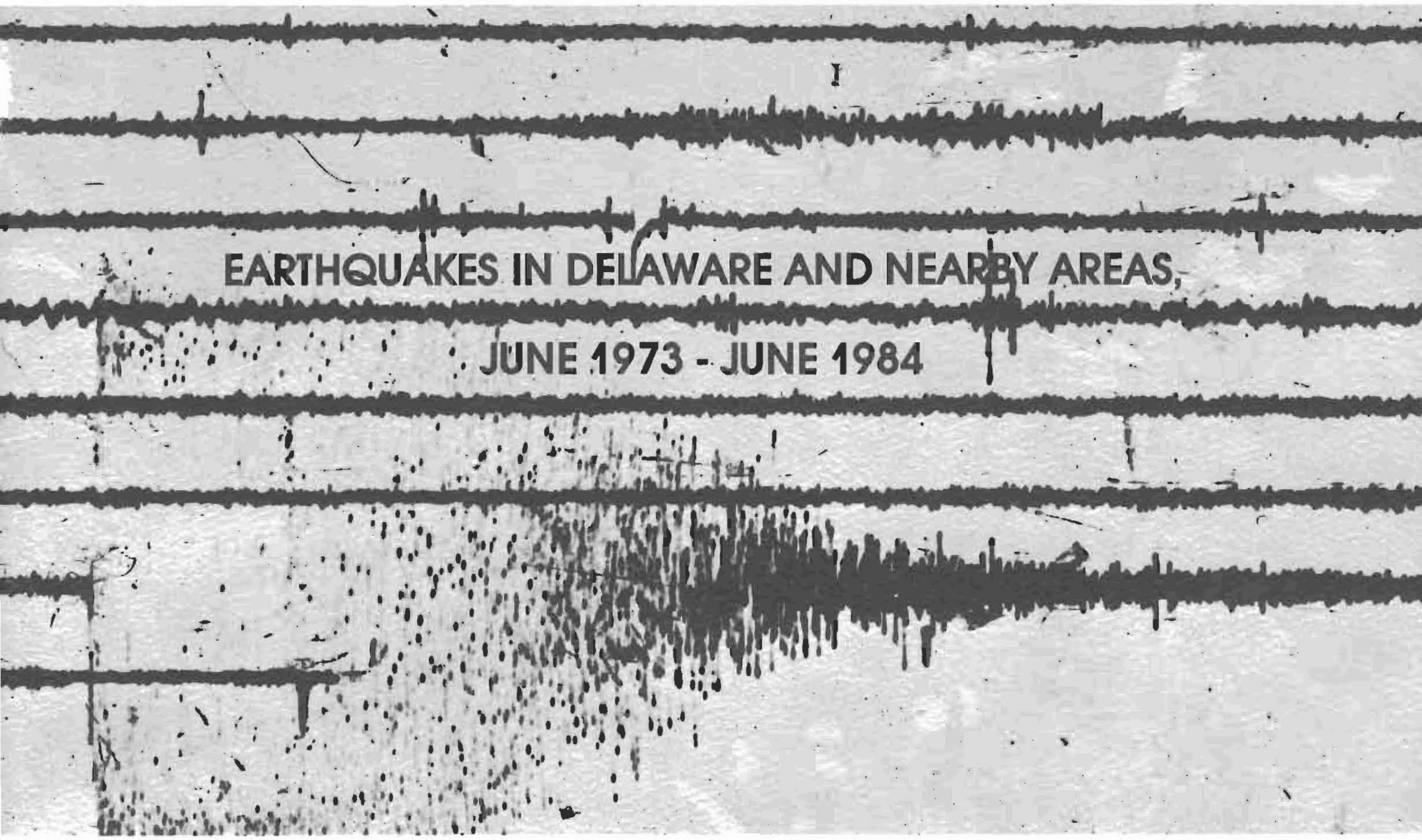

EARTHQUAKES IN DELAWARE AND NEARBY AREAS, JUNE 1973 - JUNE 1984

BY

KENNETH D. WOODRUFF

STATE OF DELAWARE

NEWARK, DELAWARE

JULY 1984

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ABSTRACT

Earthquakes in Delaware and surrounding areas have been well documented historically since about the early 1700's and since 1972 by instrumental records. Most of the Delaware events have occurred in the Wilmington area immediately adjacent to or within rocks of the Wilmington Complex. Since the compilation of earthquakes by Jordan and others (1974) which lists events through May 1974, six felt earthquakes have occurred in northern Delaware and about 20 additional events in Delaware have been recorded on seismographs of the Delaware Geological Survey. Four of the felt events took place from November 1983 through February 1984 and ranged from a magnitude 1.5 to 2.9. The highest intensity for this series of earthquakes was a possible V (Modified Mercalli). Epicenters were generally in the north Wilmington area as determined both instrumentally and by felt reports.

Further monitoring with more stations in the vicinity of Wilmington is needed to accurately locate epicenters and determine fault plane alignment. The possible role of the Wilmington complex rocks in localizing stresses is uncertain.

INTRODUCTION

Purpose and Scope

The occurrence of earthquakes in northern Delaware and adjacent areas of Pennsylvania, Maryland, and New Jersey is well documented by both historical and, more recently, by instrumental records. One of the earliest known events is that described by Acrelius (1874) and occurred on December 30, 1737 at 11:00 p.m. The event was felt in the Philadelphia and surrounding areas for one to two minutes, rattling dishes and windows. The largest known event in Delaware occurred in the Wilmington area on October 9, 1871 and has been described by NOAA (1971) and by Jordan and others (1972). The maximum intensity (Modified Mercalli Scale) was probably somewhat greater than VII although records are poor. The earthquake of February 28, 1973 (magnitude 3.8) appears to be the second largest event and had a maximum intensity of V to VI. Most solutions located the epicenter in or near the Delaware River in northeast Delaware. The 1973 event and the results of aftershock monitoring have been analyzed by Sbar and others (1975). Other known events occurring through March 1974 are listed in Jordan and others (1974).

This report provides information for events occurring in Delaware since the report of Jordan and others (1974) with emphasis on the series of small earthquakes that occurred in the Wilmington area from November 1983 through April 1984. Arrival times for other eastern U. S. earthquakes as recorded by the seismic network of the Delaware Geological Survey (DGS) are presented in Appendix D.

Acknowledgments

Many individuals and groups have aided in researching seismicity of the Delaware area. Operators of other subnetworks within the U. S. Northeast Seismic Network (USNESN) have made data available from their stations upon request. Technical assistance and aftershock monitoring for the Wilmington earthquake of November 17, 1983 have been provided by Leonardo Seeber and John Armbruster of the Lamont-Doherty Geological Observatory.

Charles Scharnberger of Millersville State College maintained contact with the DGS during the investigation of the Lancaster, Pennsylvania event of April 22, 1984. The continuing cooperation of the Maryland Geological Survey and the Pennsylvania Geological Survey during investigations of earthquakes that occur outside Delaware is also greatly appreciated.

John Talley assisted by Roland Bounds, both of the DGS staff, did much of the basic intensity mapping during the last

four Wilmington events. Their work is the basis for some of the intensity maps presented in this report.

Paul Pomeroy of Roundout Associates reviewed the manuscript at the author's request. His continuing assistance as coordinator of the USNESN is gratefully acknowledged.

REGIONAL GEOLOGY

Metamorphic rocks of the Glenarm Series (probable early Paleozoic age) underlie the western part of the Piedmont Province in northern New Castle County. These include gneisses and schists of the Wissahickon Formation and the marble of the Cockeysville Formation which underlies the Pleasant Hill and Hockessin valleys (Woodruff and Thompson, 1979). The Wilmington area is underlain by rocks of the Wilmington Complex which include anorthosites, charnockites, gneisses, gabbros, and amphibolites. The Wilmington Complex has been interpreted as Grenville age (pre-Cambrian) basement remobilized during the Appalachian Orogeny in the Paleozoic (Woodruff and Thompson, 1975). The structural relationship between the Wissahickon Formation and the Wilmington Complex is unclear and has been the subject of much debate. Epicenters of earthquakes in northern Delaware have nearly all been over, or immediately adjacent to, the Wilmington Complex.

South of the Fall Line the Piedmont rocks are covered by unconsolidated and partly consolidated sediments of the Coastal Plain which reach a maximum thickness of possibly ten thousand feet in the southeast corner of the State. Sediments range in age from Jurassic to Holocene and form the inner margin of the Balitmore Canyon trough, a major basin lying offshore of the Mid-Atlantic states. Recent work by Benson and Doyle (1984) and Doyle and Benson (1984) indicate the existence of buried rift basins of probable early Mesozoic age along the landward edge of the Baltimore Canyon trough. Further work by Benson (personal communication) suggests the possibility of buried Triassic basins beneath the Delaware Coastal Plain. However, no earthquakes are known to be associated with these postulated structures.

The crystalline basement surface drops off markedly along the southeast Delaware coast and forms a hinge zone where sediments thicken seaward into the center of the Baltimore Canyon trough.

Epicenters of local earthquakes cannot be related to specific geologic structures at this time. Field observations have also failed to find evidence of recent movement at the surface. Spoljaric (1974) has attributed present stream morphology in both the Wilmington area and parts of southeastern Pennsylvania to recent normal faulting. He also used satellite imagery (1979) to infer the presence of major lineaments in the Delaware Piedmont. One of these lineaments trends northeast-southwest and crosses Brandywine Creek north of Wilmington. Epicenters of the most recent earthquakes in Delaware appear to lie along the Brandywine as discussed in later sections of this report.

DGS SEISMIC NETWORK

The Delaware network consists of stations NED - Newark, BBD - Blackbird State Forest, and GTD - Georgetown (Fig. 1). These are vertical component, short-period systems and signals are transmitted by telephone line to the Survey's offices at the University of Delaware. Station details are given in Appendix A Station NED was established with contributions from the Delaware Department of Emergency Operations and Planning and an anonymous donor and became operational in November 1972. The remaining two stations became operational early in 1977 through grants of both surplus equipment and equipment donations from the U. S. Geological Survey (USGS). The U. S. Northeast Seismic Network, which was also organized about this time and of which DGS is a member, played a major role in arranging the transfer of equipment to the DGS. Currently, replacement equipment and maintenance costs are absorbed by the DGS. The USGS contributes the cost of telephone line charges for transmitting signals from stations BBD and GTD.

Station NED is located over crystalline rocks of the Wissahickon Formation while the remaining two stations rest on unconsolidated sediments of the Atlantic Coastal Plain. Although the Coastal Plain stations can be run at somewhat higher gain than station NED due to less background noise, they show greater attenuation of teleseismic (long distance) and regional events.

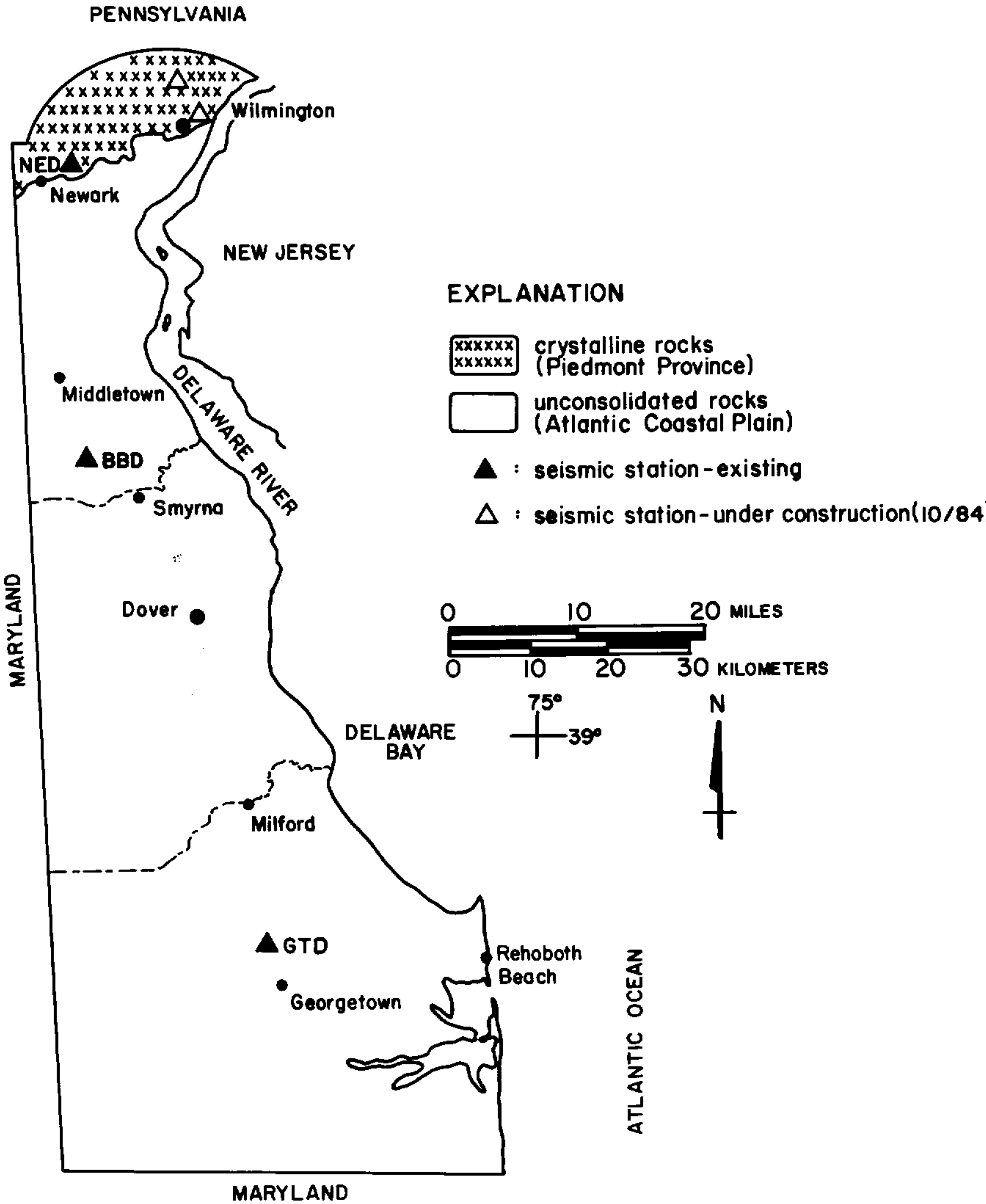

Figure 1. Map of Delaware Showing General Geology and Location of Seismic Stations.

DETERMINATION OF EARTHQUAKE PARAMETERS

An earthquake is characterized by a number of parameters, some of which are difficult to obtain with instruments of limited dynamic range and bandwidth such as now used in the Delaware network. Of immediate interest is the measure of an earthquake's size, usually defined by the Richter magnitude and generally calculated by most networks. The Richter magnitude scale and later modifications are empirical. More quantitative estimates of the size of an earthquake include calculations of the stress drop, seismic moment (strength due to fault slippage), and total radiated energy. Determination of the spectral or frequency content of the earthquake energy is also necessary for some of these estimates. These latter parameters cannot be routinely calculated for smaller earthquakes recorded only on short-period instruments.

The epicenter location or point on the earth's surface below which the earthquake occurs is usually calculated by operators of networks that have a number of stations. Of equal importance in detailed studies is the depth of the event, which, with the epicenter location, fixes the hypocenter or location within the earth. The type of faulting and attitude of the fault plane can also be determined when data are available from several stations and when local geology is known.

Intensity is a subjective indication of the effects of an earthquake and generally varies inversely with the distance from the event. The Modified Mercalli Scale (p. 6) was adopted in the U. S. in 1931 (Evernden and others, 1981) and ranges from I (barely perceptible) to XII (total damage). Intensities are determined after an event by distributing questionnaires throughout the felt and adjacent areas and assigning a Modified Mercalli value to the individual responses.

In the Delaware network, the short instrumental record, relatively few earthquakes, and less than ideal station distribution have hindered the quantification of many of the parameters discussed above. However, with continued monitoring, and the establishment of additional stations in the Wilmington area, data gaps should gradually close. Present methods used in the Delaware network for determining some of these basic parameters are discussed below.

MODIFIED MERCALLI INTENSITY SCALE OF 1931
--abridged from Wood and Neumann, 1931

I. Not felt except by a very few under especially favorable circumstances.

II. Felt only by a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.

III. Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing automobiles may rock slightly. Vibration like passing of truck. Duration estimated.

IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing automobiles rocked noticeably.

V. Felt by nearly everyone, many awakened. Some dishes, windows, etc. broken; a few instances of craked plaster; unstable objects overturned. Disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.

VI. Felt by all, many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage slight.

VII. Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by persons driving automobiles.

VIII. Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. Panel walls thrown out of frame structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts. Changes in well water. Persons driving automobiles disturbed.

IX. Damage considerable in specially designed structures; well-designed fram structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.

XI. Few, if any structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII. Damage total. Practically all works of construction are damaged greatly or destroyed. Waves seen on ground surface. Lines of sight and level are distorted. Objects are thrown upward into the air.

Magnitude Determinations

The usual method of calculating earthquake magnitudes depends on measuring the amplitude of the wave forms recorded by the seismograph and relating this to the amount of actual ground motion. The amount of ground motion is then used in one of the standard magnitude formulas, the first of which was derived by Richter (1935) for California events. Gutenberg (1945) and other workers have since extended Richter's formula for other geographic areas and source distances. Magnitude scales are exponential in character so that an increase of one unit in magnitude is equivalent to about a 30-fold increase in the amount of energy released. An increase of 10-fold, often quoted by news reports when comparing earthquakes differing by one magnitude unit, refers to the increase in amplitude of the wave form recorded by the seismograph.

An alternative approach suggested by Lee and others (1972) uses the length (duration) of the earthquake signal as a measure of magnitude. The signal duration (in seconds) is measured from onset until the amplitude decays to some arbitrary level such as background noise or twice background noise. This has been the approach used for station NED for which the best quality data exist. The signal duration (from onset to background noise) for regional and local earthquake have been plotted against published magnitudes as determined by a body wave magnitude (Mb) formula. Bulletins of individual seismic networks and the "Preliminary Determination of Epicenters" published by the USGS have been consulted in arriving at magnitude values. The results are shown in Figure 2, and have been tested against magnitudes derived by others for more recent events. Values generally agree within 0.1 magnitude units.

Epicenter Determinations

As a minimum, three stations are needed for locating epicenters and these ideally should be spaced equally around the epicenter. Delaware's network does not at the moment have the proper arrangement of stations to accurately determine epicenters for events occurring in northern Delaware. This is due to the shape of the State that forces a linear distribution of stations and the greater need in the past to first determine State-wide seismicity with a minimum of stations. Other stations in the U. S. Northeast Seismic Network have generally been relied upon to supplement the data from Delaware.

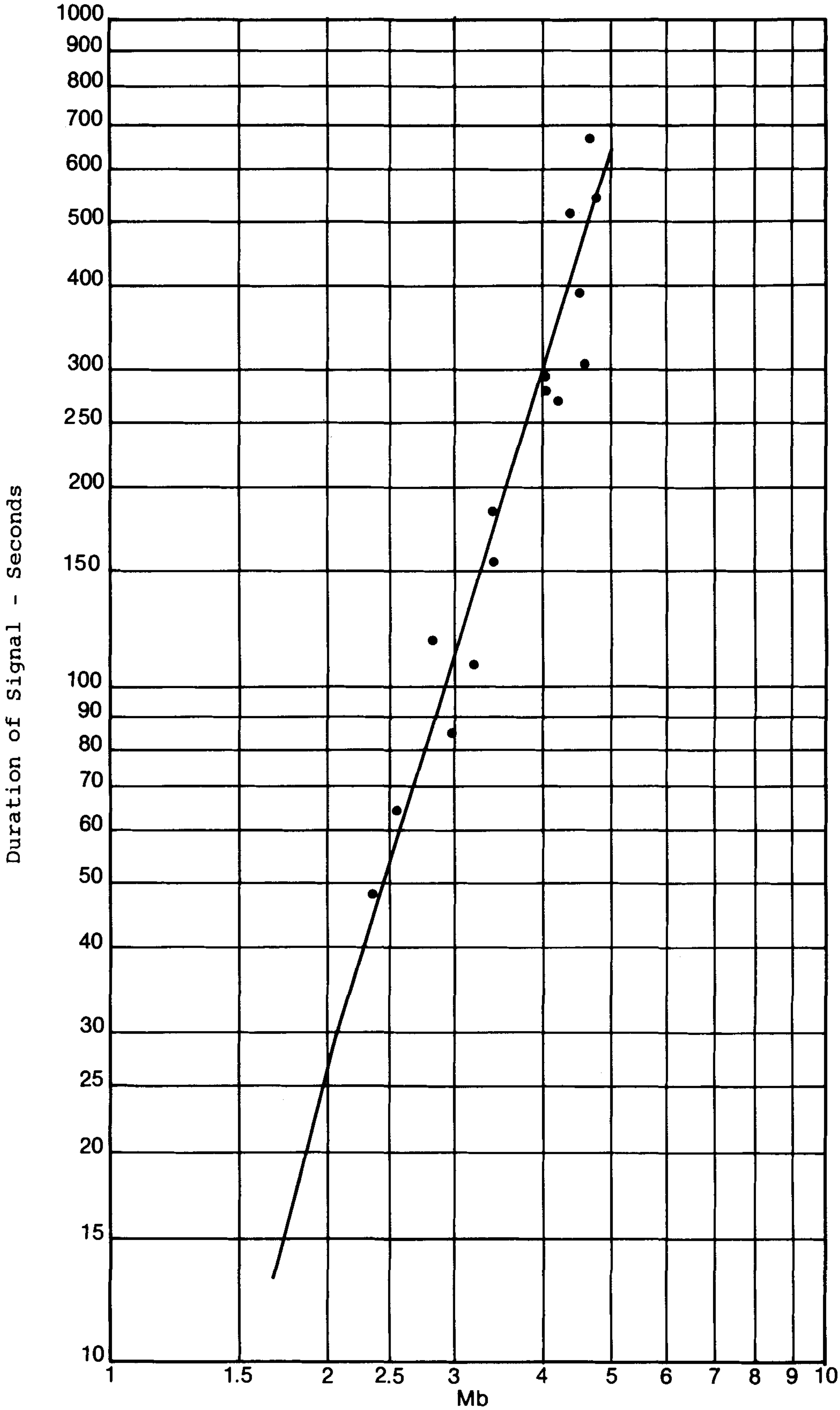

Figure 2. Duration Magnitude for Station NED.

Epicenters can be located by measuring the time between the arrival of the P and S waves. This interval is directly proportional to the distance from the epicenter. Figure 3 is a portion of a seismogram from station BBD for the Philadelphia earthquake of March 11, 1980 and shows particularly well developed S waves. Figure 4 shows the S minus P times at NED (in seconds) plotted against distances to epicenters of previous earthquakes. Figure 5 is a plot of arrival time of only the P wave at NED against distance to epicenters and is a first step in arriving at a picture of a local earth model. The velocities of the P wave arrivals derived from the plot in Figure 5 are indicated. The low velocity segment of 5.5 km/sec may represent an average velocity of a two layer crustal zone. Shallow seismic refraction studies in the Delaware Piedmont (Woodruff, 1971) indicate a local crustal velocity of about 5.4 km/sec.. Sbar and others (1975) noted that this latter velocity yielded the best solution for the location of the aftershocks of the February 28, 1973 Wilmington earthquake. The higher velocity travel time represents P arrivals refracted from the deeper discontinuity between the crust and mantle. Data are not sufficient to construct similar plots for the other two stations. Thus the data from NED must be merged with data from other stations outside of Delaware in order to locate local events.

For a large network, a computer program is usually used to solve a system of equations by an interative technique that gives the most probable location of both the epicenter and depth of an event.

Intensity Mapping

When a felt earthquake occurs, intensity report forms or questionnaires are distributed at key locations by DGS staff as soon as possible. These locations include fire houses, government offices, libraries, and large office or industrial complexes. The local press is encouraged to print a copy of the questionnaire or to publish information on how to report the event. Citizen response is necessary for these surveys and in Delaware is usually enthusiastic. Returned forms are assigned intensity values by two investigators working independently. The two resulting values for each form are then compared, any differences are discussed, and a final value is chosen. Locations for each value are then plotted on 7.5 minute topographic maps (1:24,000 scale) and the intensities are

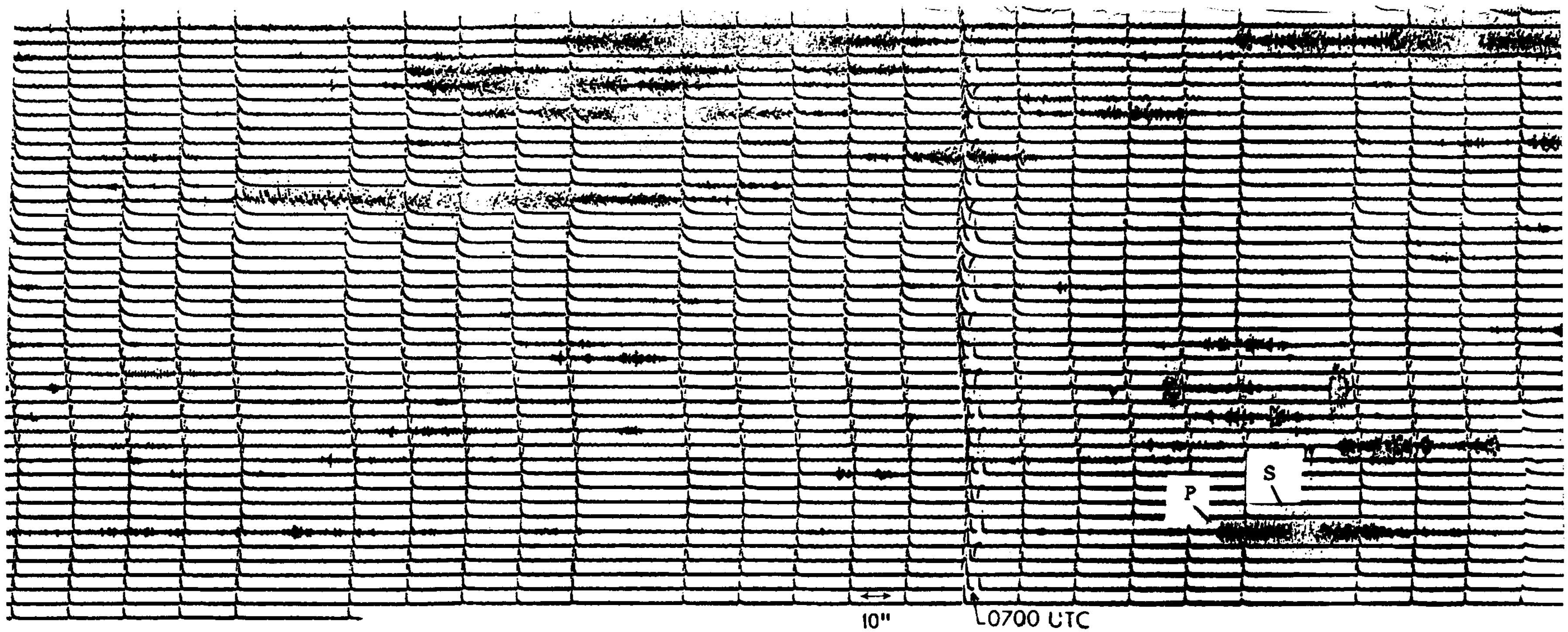

Figure 3. Partial Seismogram from Station BBD Showing Philadelphia Earthquake of March 11, 1980.

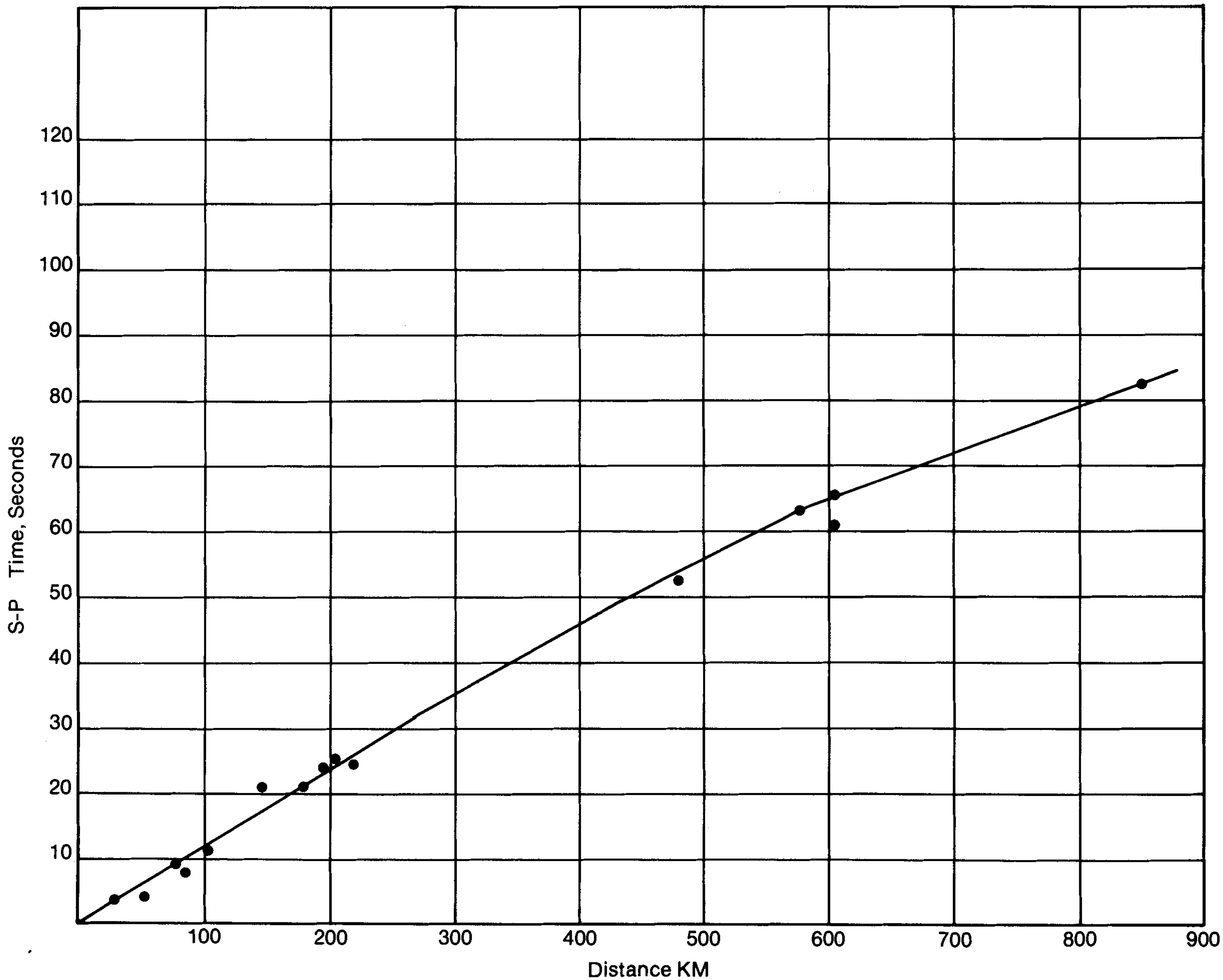

Figure 4. S-P Arrival Times for Station NED

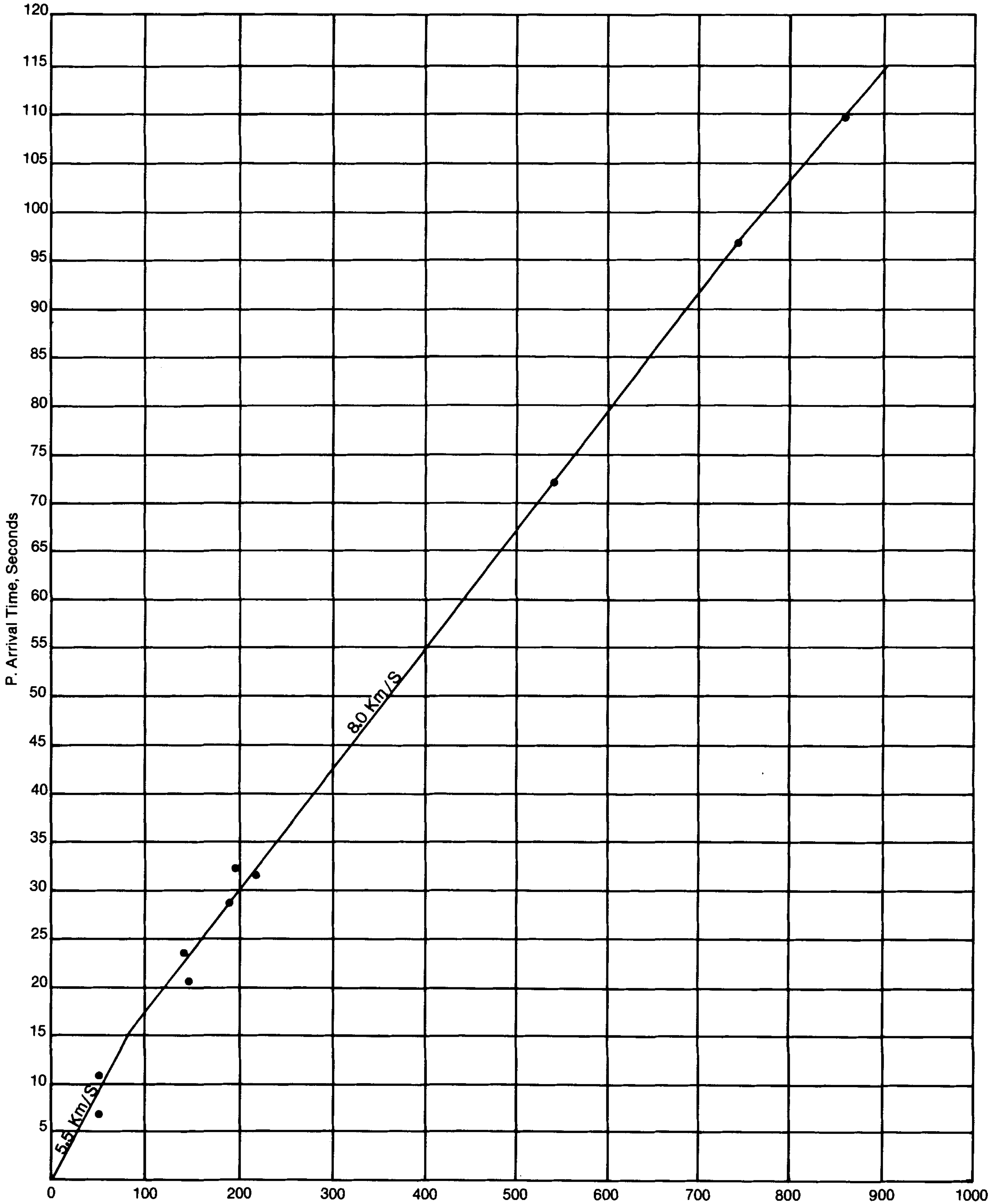

Figure 5. P. Arrival Times for Station NED

contoured. Final intensity maps, edited for anomalous values, are then drawn at a reduced scale. A copy of the questionnaire used in Delaware is included at the end of this report as Appendix B.

Noises usually described as "booms" or "explosions" are nearly always associated with northern Delaware events and for many regional earthquakes. The perception of noise and its characteristics have been analyzed for the February 28, 1973 earthquake by Jordan in Sbar and others (1975). This phenomenon is not taken into account by the Modified Mercalli Scale and is difficult to assess by both observers and analysts. However it appears possible that, at least locally, the duration, frequency, and intensity of noise can be related to epicentral distance and/or depth and could supplement other intensity indications.

POST-1973 EVENTS IN DELAWARE

Since the event of February 28, 1973 six earthquakes large enough to have been felt have occurred in the Wilmington area. These are discussed below and are also listed in Appendix C. Four of these occurred during the period November 1983 through February 1984. Smaller earthquakes which occurred during this period but were not felt are listed only in the Appendix along with suspected earthquakes and other unidentified events. The high level of background noise in the northern Delaware area often produces ambiguous data and prevents operating the detection system at optimum gain.

Times of events in Appendix C are given in Universal Coordinated Time (UTC) according to standard observatory practice. In the text discussions UTC time is followed by local time in parenthesis. Five hours is added to local 24-hour time (four hours to Daylight Savings Time) to convert to UTC.

April 28, 1974

A felt earthquake of probable magnitude 2.4-2.5 occurred at 1419 hours (1919 hours local time) in southwest Wilmington. The maximum consistent Modified Mercalli intensity was IV with three reports indicating a possible maximum of V. Figure 6 indicates

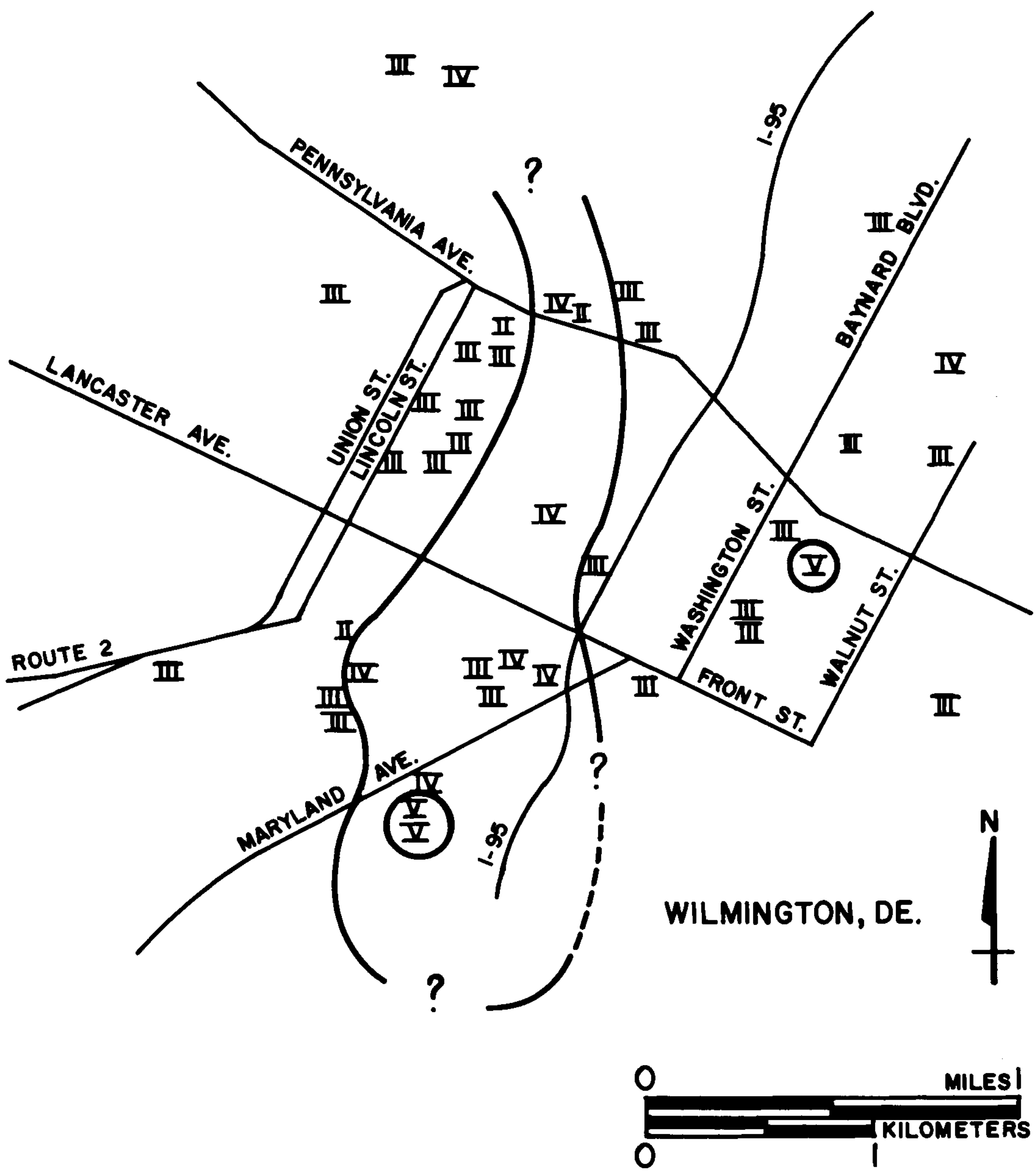

Figure 6. Intensity Map - Earthquake of April 28, 1974.

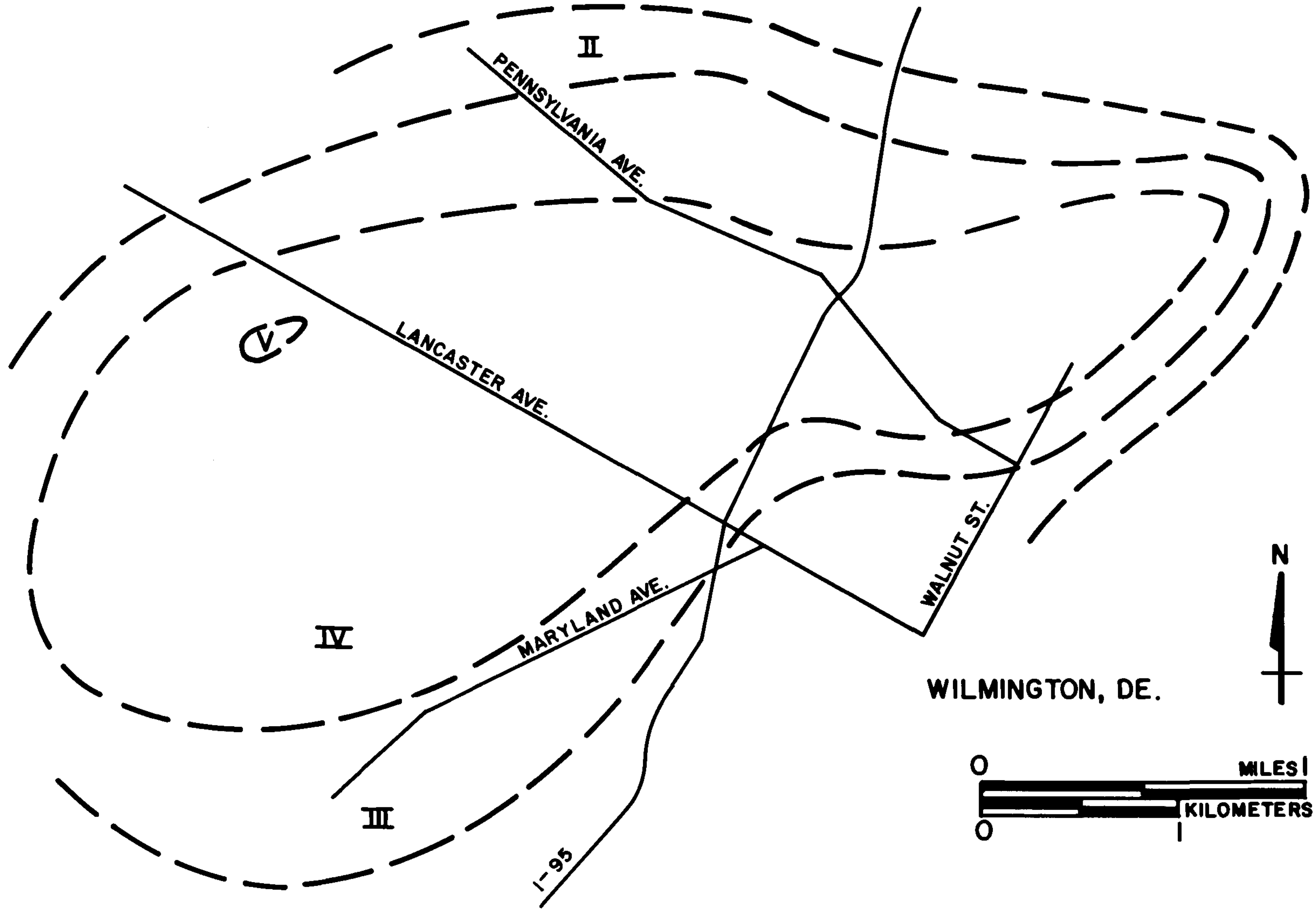

Figure 7. Intensity Map - Earthquake of February 10, 1977

the observed intensities and was drawn from intensity surveys made by the DGS. The earthquake was accompanied by a loud "explosive" sound. Doors, windows, and small objects rattled and some pictures shifted on walls. The event was somewhat unusual in that the felt area was fairly small yet relatively high intensities were recorded. The record from NED indicates that a smaller aftershock occurred about 80 minutes after the initial shock.

February 10, 1977

This event appeared very similar to the earthquake of April 28, 1974. The highest intensity was again V as determined by two reports of cracked plaster. Magnitude was estimated as about 2.5, first from intensity reports and later from signal duration. About 200 felt report forms were evaluated by DGS and the resulting intensity map is shown as Figure 7. An "explosive" noise and high frequency vibrations lasting a few seconds were associated with the earthquake.

November 17, 1983

This was the first and largest earthquake in a series of four events about a month apart. A magnitude 2.9 earthquake occurred at 1955 hours UTC (1455 hours local time) with the highest intensities located to the north and northeast of downtown Wilmington. One report of minor damage was received which indicated a possible maximum intensity of V (see Fig. 8). However investigation revealed the damage may have been previously initiated by groundwater effects and later amplified by the earthquake. An aftershock was recorded on NED about 90 minutes after the main shock. One report of an unknown odor and two reports of anomalous animal behavior, all before the event, were received. The main event was recorded by eight stations on the Lamont-Doherty Geological Observatory (L-DGO) network and these data can eventually be consulted in the Bulletin of the Northeastern U. S. Seismic Network or The Regional Seismicity Bulletin of the Lamont-Doherty Network.

Aftershock monitoring was carried out by researchers from L-DGO with the help of DGS staff and included installation of one portable station in New Jersey and three in the Wilmington, Delaware area. With the exception of the one aftershock

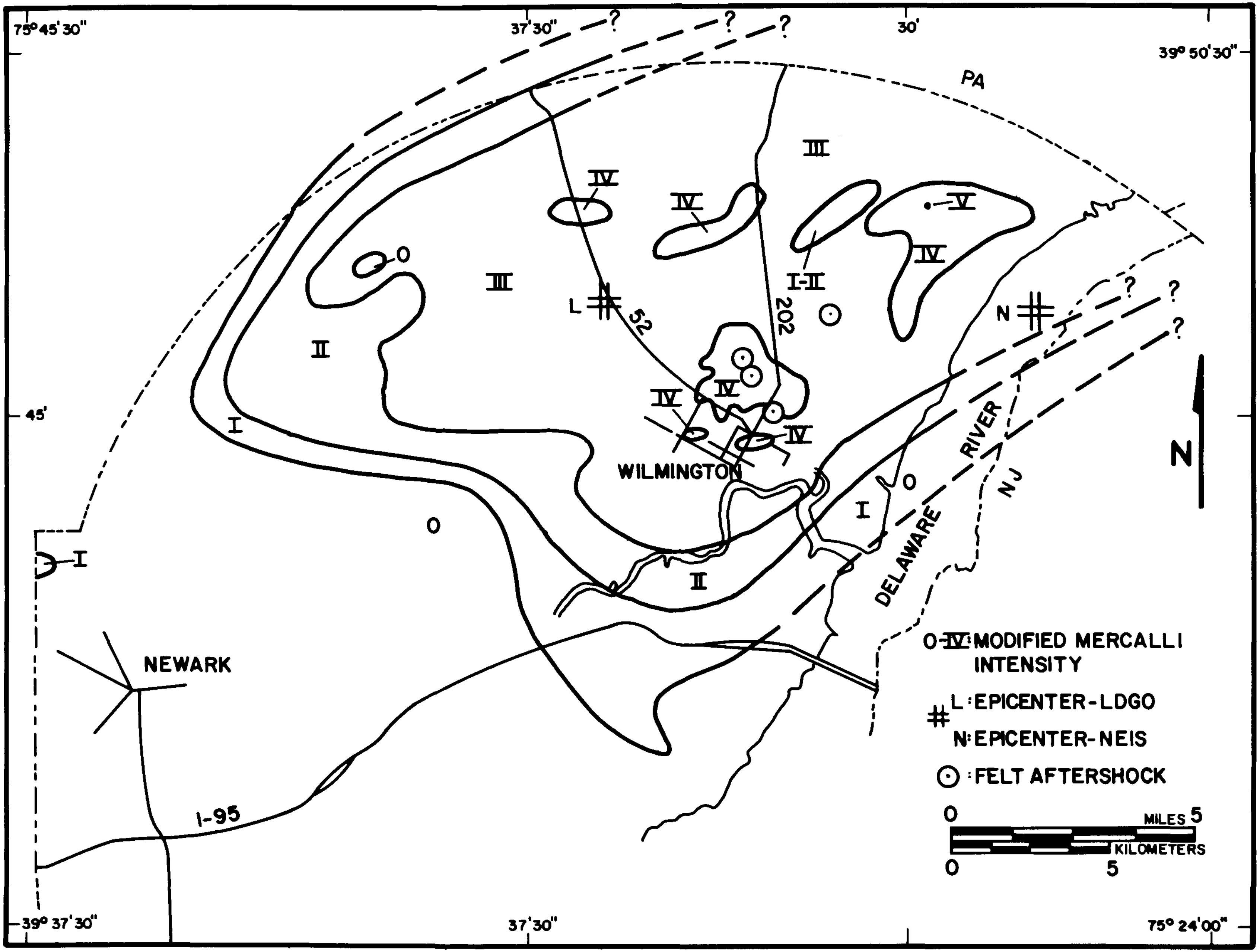

Figure 8. Intensity Map – Earthquake of November 17, 1983

previously mentioned no other aftershocks were recorded, but the high background noise could have obscured very small events.

Both the National Earthquake Information Service (NEIS) and L-DGO placed the epicenter just north of Wilmington (Fig. 8) although NEIS located the event about 8-1/2 minutes of longitude (approximately 6.2 miles) to the east of the L-DGO solution. The main event may have been preceeded by several microseisms recorded at NED although the interpretation is in doubt because of test firing at nearby Aberdeen Proving Grounds in Maryland.

December 12, 1983

A magnitude 2.4 event was recorded by NED on 0515 hours UTC (0015 hours local time). The area of maximum intensity (IV) appeared to be confined to north of Wilmington and tightly centered along Brandywine Creek. The felt area extended to just west of Newark (Fig. 9). No damage was apparent and no aftershocks were recorded. Two residents reported an odor of gas sometime before the event and four reports were received of anomalous animal behavior.

January 19, 1984

The third event in as many months occurred at 2303 UTC (1803 local time) and registered a magnitude of 2.5. A smaller aftershock (magnitude 1.8) was also recorded about 17 minutes after the main shock. Residents reported feeling both the main shock and the aftershock. Intensity reports, particularly of the aftershock, indicated that the epicenter was just north of downtown Wilmington along Brandywine Creek. Intensities are indicated in Figure 10.

February 15, 1984

The smallest of the series of four events had a magnitude of 1.5 and occurred at 1217 UTC (1717 local time). Only a few felt reports were received but these indicated that the felt area was again just north of Wilmington near Brandywine Creek (Fig. 11). The lack of felt reports was due partially to the small size of the event and also to the time of occurrence

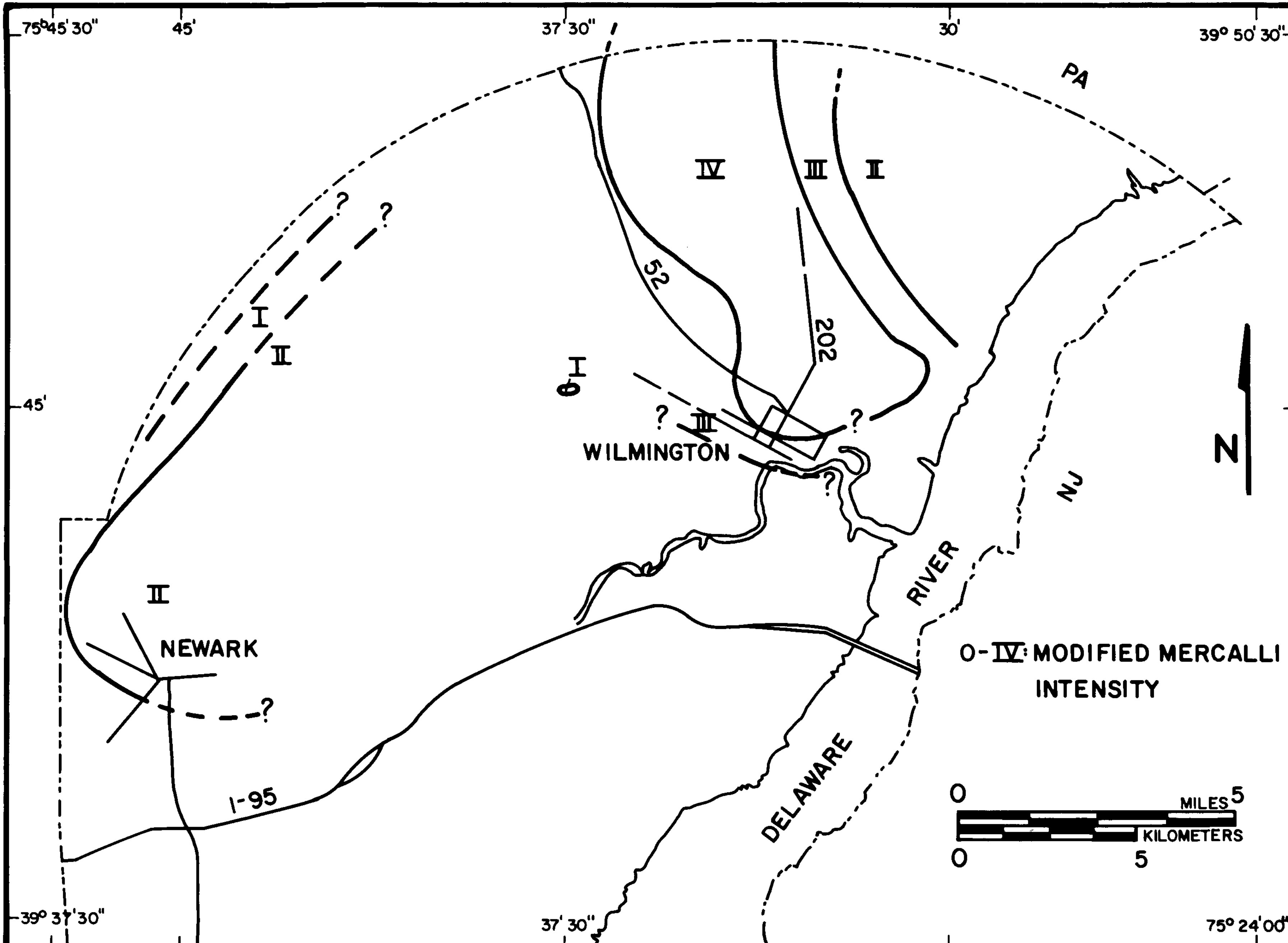

Figure 9. Intensity Map-- Earthquake of December 12, 1983

during the peak of commuter traffic when it probably went unnoticed. Those reports that were received described the event as a "loud boom" and "explosion."

OTHER DELAWARE EVENTS

Several probable earthquakes have been recorded in southern Delaware on station GTD. Particularly distinct signals were noted (UTC time) on September 24, 1978 at 1354 hours, July 1, 1979 at 2358 hours, and August 5, 1979 at 2133 hours. These signals could not be related to man-made activity. Sporadic reports of "booming" noises, occasionally accompanied by rattling of windows and small objects have been received from southern Delaware coastal areas for several years. In many cases the events can be attributed to aircraft, blasting, or possibly military testing. However, reports of at least two earthquakes in the southern part of the State have been documented by NOAA (1971) and Jordan and others (1974). The first was in 1879 and apparently occurred near Dover.

EARTHQUAKES IN NEARBY STATES

Several earthquakes occurred in the eastern part of the U. S. that were recorded by the Delaware network during the period covered by this report. Some of these events were felt in Delaware, and included the Blue Mountain Lake, New York earthquake of October 7, 1983 (magnitude 5.1) and the event near Lancaster, Pennsylvania on April 22, 1984 (magnitude 4.0). The Lancaster event appeared to be the strongest recorded earthquake in the southeastern Pennsylvania-northern Delaware area since at least the Wilmington event of 1871. The data recorded by the Delaware network for the Lancaster event are given in Appendix D. Aftershock monitoring with portable instruments was carried out by researchers from subnetworks of the Northeast U. S. Seismic Network and several aftershocks were recorded. Two of these aftershocks were felt and were also recorded at station NED. Investigations are still continuing on the Lancaster area events. Preliminary results by investigators from the L-DGO and Millersville State College indicate that epicenter locations of the aftershocks migrated northward from the epicenter of the main shock located near the town of Marticville, Pennsylvania.

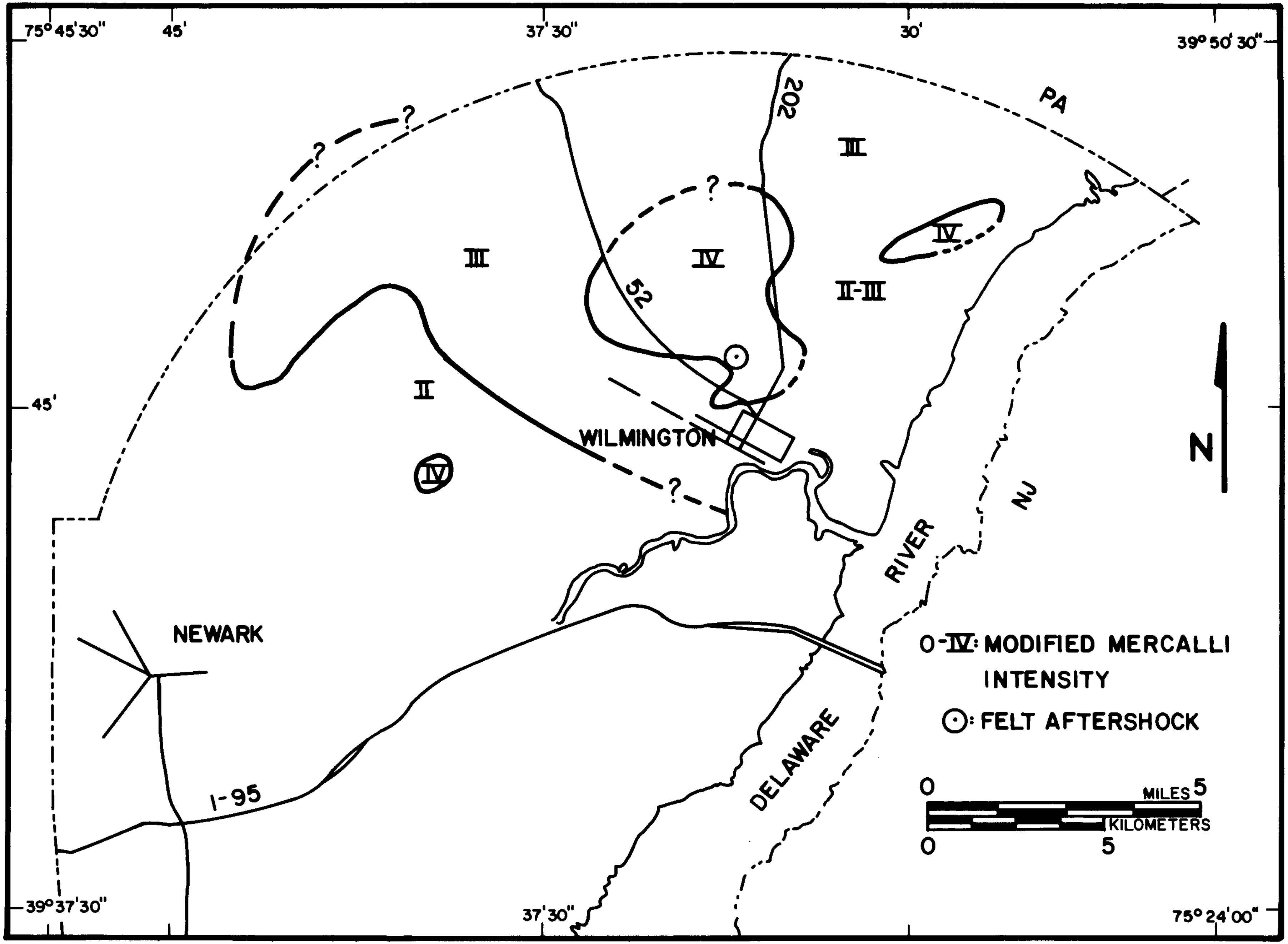

Figure 10. Intensity Map – Earthquake of January 19, 1984

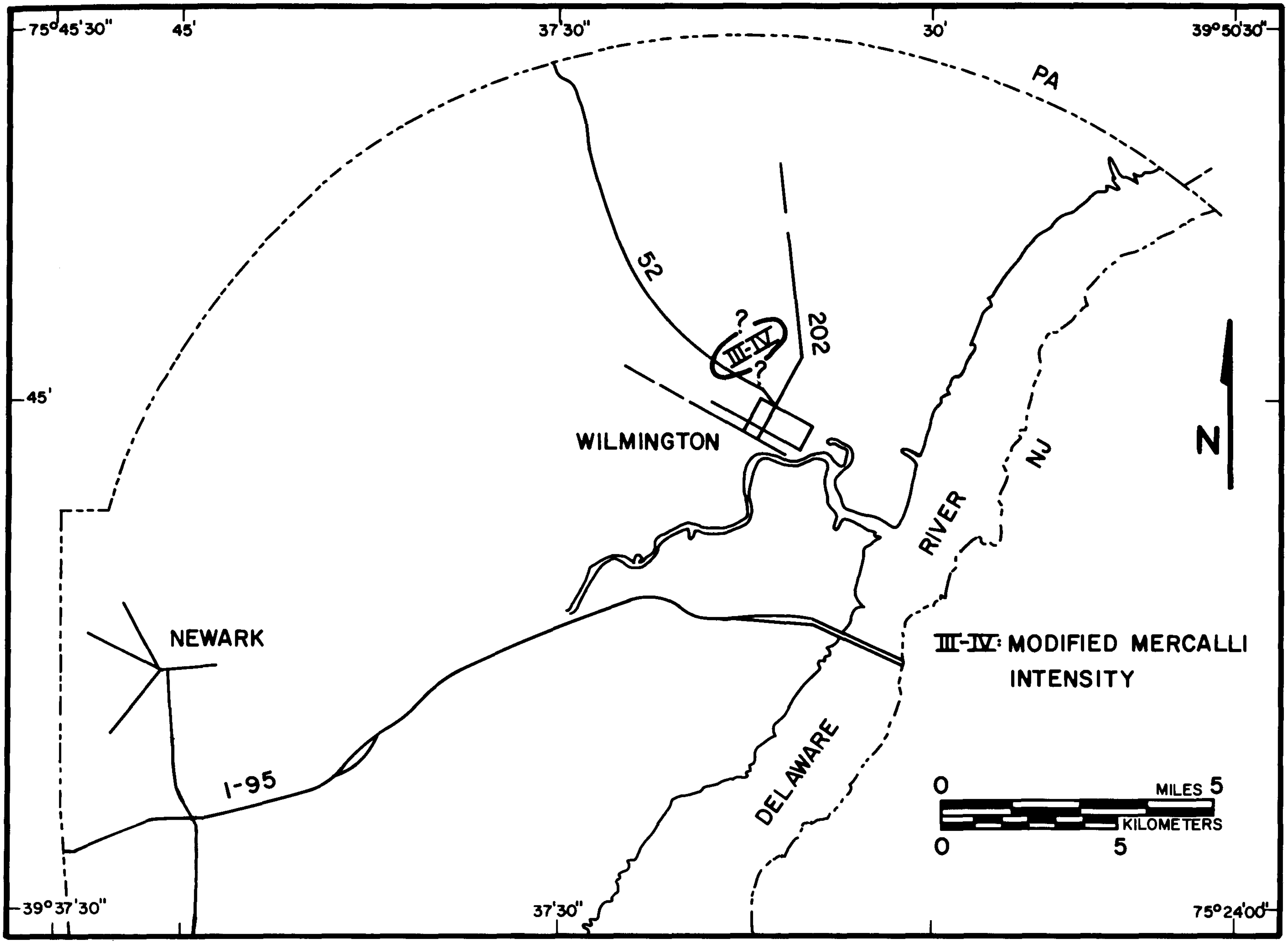

Figure 11. Felt Area for Earthquake of February 15, 1984

The structure defined by the hypocenter locations of all of the shocks appears to cut across regional structural trends. DGS carried out an intensity survey of northern Delaware for the Lancaster event and also received some felt reports from the New Jersey area bordering along the Delaware river. These data will be integrated into the regional data collected by other researchers.

SUMMARY AND RECOMMENDATIONS

Intensity maps of the last four felt earthquakes, one instrumental location, and the location of felt aftershocks, consistently indicate that the probable epicenters of these latest events in northern Delaware are just northwest of downtown Wilmington near Brandywine Park. Epicenters appear to cluster around Brandywine Creek just south of a portion which deviates approximately 90° from its generally southeasterly direction of flow (see Fig. 12). The trend of the stream channel in this anomalous section is parallel to the trend of the Delaware River just to the south (about N30°E) and is the same as the trend of the fault plane solution for the February 28, 1973 Wilmington earthquake (Sbar and others, 1975). This same trend can be noted for both stream alignments and lineaments appearing on aerial photographs in other areas of the Delaware Piedmont.

Detailed monitoring with at least two additional stations will be necessary to more precisely locate both epicenters and depths of events. Future monitoring must be capable of timing events to accuracies on the order of a few hundredths of a second. For both mechanical and electronic reasons, present equipment of the Delaware network produces reliable timing to only about one-tenth of a second. Characteristics of the energy spectra, which determines in large part the degree of shaking, can be obtained by upgrading at least one station in the Wilmington area to a digital, broadband system. This would allow sampling of a much wider frequency range, particularly the higher frequencies, than is now possible and provide data necessary for evaluation of earthquake effects on man-made structures.

Hypocenters defined from instrumental locations should be related to the regional and local geology by detailed geologic mapping and by other geophysical investigations. A seismic

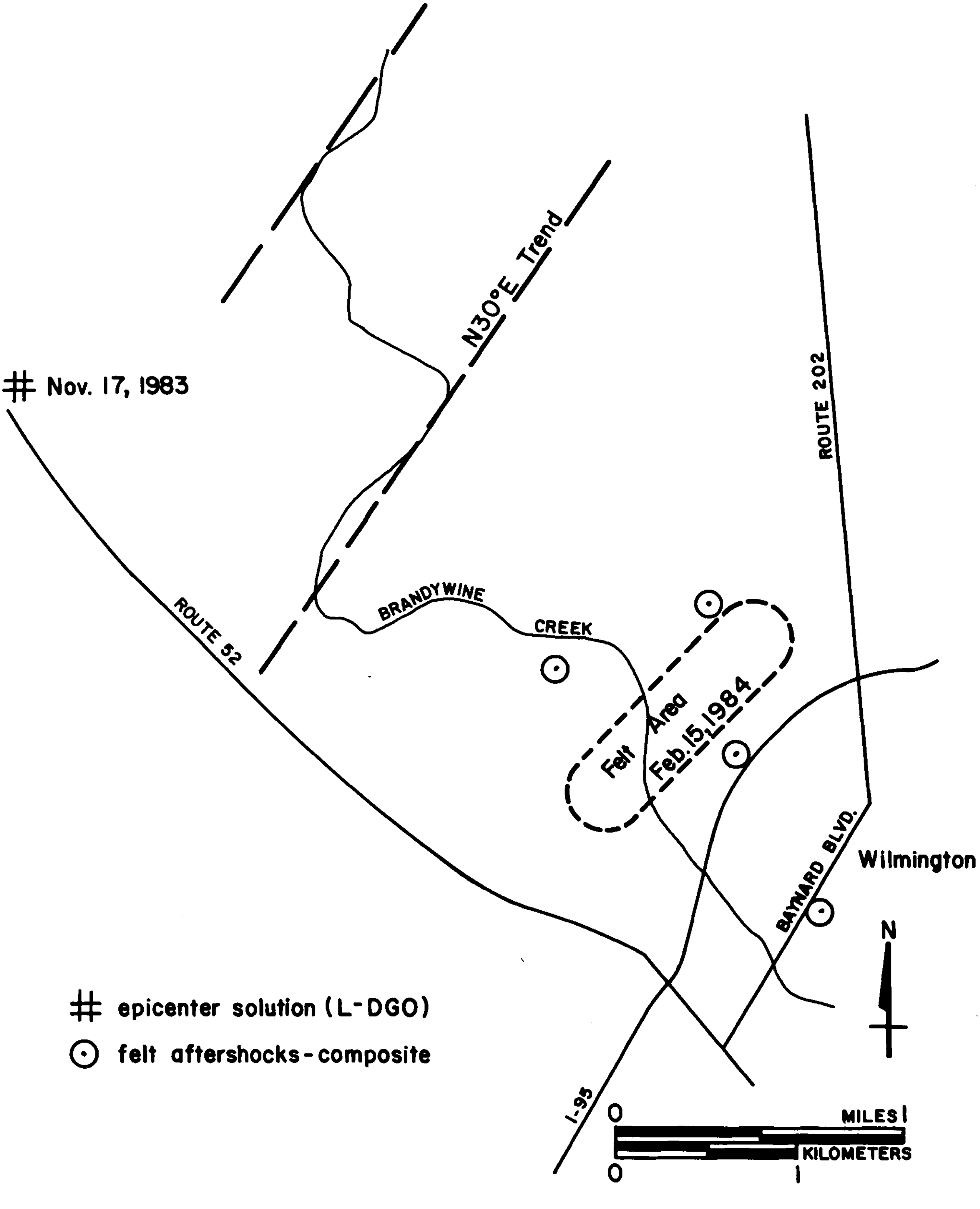

Figure 12. Diagram Showing Trend of Brandywine Creek and Composite Data for Recent Earthquakes in the Wilmington Area.

reflection profile across northern Delaware and adjacent areas would be a necessary part of such investigations as would gravity mapping on both a regional and local scale. The Delaware Geological Survey, the Maryland Geological Survey, and the Pennsylvania Geological Survey have submitted to the U. S. Geological Survey a joint proposal for a long seismic line beginning in the folded section of the Appalachians and terminating near Ocean City, Maryland including a traverse across the Delaware Piedmont near Wilmington. The completion of this line should provide data that would bear on the occurrence of earthquakes in northern Delaware. A program of gravity mapping is planned for northern Delaware which would tie into mapping now underway in adjacent parts of Pennsylvania by William Crawford (personal communication) at Bryn Mawr College.

Results of these findings would have immediate application in nuclear power plant design and siting criteria. Northern Delaware is within the 50 mile ingestion zone of four nuclear power plants. However, information on earthquake recurrence intervals, energy spectra, ground accelerations, and general seismic risk is sparse and requires extrapolation of data from outside the general area. Eventually, questions that must be addressed include the following:

(1) Is the Piedmont of Delaware allocthonous (not in place) as has been suggested for other Piedmont areas of the eastern United States? If so, does this relate at all to the occurrence of earthquakes in Delaware?

(2) Do the Wilmington Complex rocks (and their contact with the Wissahickon Formation) in some way localize stresses or do apparent epicenters within the Complex have no relation to the rock type.

(3) Are the Wilmington events related to a larger pattern of regional stresses tht are also manifested elsewhere in the eastern U. S. or are they due only to local stresses?

(4) What is the significance of the Fall Line as an active structural boundary in northern Delaware? Epicenters of local events are either on or within about two miles of the Fall Line.

The apparent recurring seismicity in the Wilmington area could represent a unique opportunity to gather data that would have both local and regional implications. Advances in instrumentation now make possible a broader scope of monitoring efforts with accompanying improvements in characterization of earthquake parameters and possible hazards.

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APPENDIX A
STATION DATA - DGS Seismic Network

Station	Location	Elev.	Date Open	Site Characteristics	Geophone	Recording
NED	$39^{o}42.25'N$ $75^{o}42.29'W$	47 m	Nov. 1972	Weathered crystalline rock	S-13,vert, 1 hz	visible
BBD	$39^{o}20.77'N$ $75^{o}42.60'W$	18 m	Jan. 1972	Coastal plain sediments	Geospace, vert. 1 hz.	visible
GTD	$38^{o}44.48'N$ $75^{o}24.87'W$	15 m	April 1977	Coastal plain sediments	Geospace, vert, 1 hz.	visible
*(Wilm) area				Weathered crystalline rock		visible
*(Wilm) area				Weathered crystalline rock		visible

* under construction, 1984-1985.

APPENDIX B

THIS SPACE FOR OFFICE USE ONLY

RETURN TO: Delaware Geological Survey
University of Delaware
Newark, Delaware 19716

EARTHQUAKE QUESTIONNAIRE

Please check every question - either underline the words which best describe the event or add additional information

1. Name (optional):________________________
2. Address:________________________
(at time of earthquake)
3. City, Subdivision, Development:__________
4. Telephone No. (optional): ________________________
5. Nearest cross street (for map location):__________
6. Time and date of event:________________
7. The event was felt by: yourself, several people, many people.
8. At the time of the event you were: indoors, outdoors, sitting, standing, driving, sleeping, just awakening.
9. If indoors, the building was a: home, apartment, store, office, other large building.
10. You were in the basement, first floor, second floor,______floor, can't remember.
11. The building is of construction: frame, brick, stone, combination (explain) reinforced concrete, mobile home, an't remember, other________
12. If indoors, you felt the house or building shake: not at all, faintly, moderately, strongly, violently.
13. The motion was rapid, slow.
In a direction: N, NE, E, SE, S, NW, SW, W.
And shook for a time of_____min.,_______sec.
14. Please describe any noises (include direction, length of time of noise, what it sounded like, and anything else unusual):

15. a.___rattling of windows, doors, dishes,______________________
b.___hanging objects, doors, lamps, etc. did or did not swing - if swinging, the direction was N, NE, ________
c.___pendulum clocks did or did not, stop - they faced N, NE,__________
d.___shifted small objects, furnishings,______________________
e.___overturned vases, etc., small objects, furnishings,______________
f.___cracked plaster, windows, mirrors, walls, chinmeys, ground,________
16. Have you ever noted an earthquake in the area before:
Yes (please give approx. date and time), No.

Thank you. Your careful reply will aid us in locating and understanding this event.

APPENDIX C
LISTING OF DELAWARE EVENTS FROM JUNE 1974

Date	Arrival Time (UTC)	Station	Phase	Magnitude[1)]	Remarks
04/28/74	1419:20.0	NED	iP	2.2 M_D	Wilmington area, felt
03/05/75	0920:57.5	NED	iP	1.9 M_D	Local event
03/06/75	0807:58.2	NED	iP	less than 2.0	Local event
03/07/75	0842:41.8	NED	iP	2.0 M_D	Local event
03/11/75	0303:47.0	NED	iP	2.0 M_D	Local event (?)
03/23/76	0727:21.7	NED	iP		
03/26/76	1409:03.2	NED	iP		
02/10/77	1914:25.5	NED	iP	2.6 M_D	Wilmington area, felt
06/05/77	0947:23.3	GTD	iP	?	Small, local event
08/02/77	1729:41.3	GTD	iP		Small, local event
	1729:43.3		S		Small, local event
07/19/78	0749	NED			
07/20/78	0938	NED			
09/4/78	1354:20.0	NED	iP		Suspected local event
07/01/79	2358:44.5	GTD	iP		Suspected local event
08/01/79	2133:30.9	GTD	iP		Suspected local event
02/25/80	0544	NED	iP		Felt, small local event or blast
02/18/81	0850:54.0	NED	iP	?	Small, local event
	0850:55.0		iS		Small, local event
06/07/83	1646:20.5	GTD	eP	?	Felt reports, Lewes-Rehoboth area
	1646:22.0		iS		
11/17/83	1955:09.2	NED	iP	2.9 M_D	Wilmington area, felt
	2128:00.1	NED	iP		Felt aftershock
	2128:01.9		iS		
	2148:06.6	NED	iP		Possible aftershock
12/12/83	0515:12.2	NED	iP	2.4 M_D	Wilmington area, felt
	1642:52.0	NED	iP		Possible aftershock

Date	Arrival Time (UTC)	Station	Phase	Magnitude[1)]	Remarks
01/19/84	2303:37.2	NED	iP	2.5 M_D	Wilmington area, felt
	2303:38.7		S(?)		Wilmington area, felt
01/20/84	0046:13.0	NED	iP	1.8 M_D	Felt aftershock
02/15/84	1217:54.0	NED	iP	1.5 M_D	Wilmington area, felt
	1217:56.)		S		
05/14/84	2251:56.5	NED	iP	1.8 M_D	Wilmington area

1) M_D = Duration magnitude

APPENDIX D
EVENTS OF NEARBY AREAS

Date	Arrival Time (UCT)	Station	Phase	Magnitude[1)]	Remarks
11/22/74	0527:45.3	NED	iP		South Carolina
	0529:07.7		iS		South Carolina
02/16/75	2322:06	NED	eP	4.4 M_b	Ohio
02/24/75	0045:37.5	NED	iP		Maiden Creek, Penna.
	0045:45.7		iS		Possible blast
05/14/75	0533:26.9	NED	iP	2,8 M_D	Northeastern Maryland
03/11/76	2107:49.0	NED	iP	2.5 M_b*	Riverdale, New Jersey.
07/16/78	0639:48.0	NED	iP	3.0 MN	Lancaster, Penna.
	0639:52.4	GTD	iP		Lancaster, Penna.
10/06/78	1925:55.8	NED	iP	3.3 MN	Lancaster, Penna.
01/30/79	1631:12.5	NED	iP	3.5 MN*	Perth Amboy, New Jersey
	1631:18.5	BBD	eP		Perth Amboy, New Jersey
	1631:23.5	GTD	eP		Perth Amboy, New Jersey
03/10/79	0450:02.8	NED	iP	3.1 MN	Bernardsville, New Jersey
	0450:07.89	BBD	iP		Bernardsville, New Jersey
	0450:29.8		S		Bernardsville, New Jersey
04/18/79	0235:48.5	NED	eP	4.0 MN*	Gulf of Maine
	?	BBD	emergent		Gulf of Maine
	?	GTD	emergent		Gulf of Maine
03/05/80	1707:07.4	NED	iP	3.5 MN*	Abington, Penna. area
03/11/80	0600:38.5	NED	iP	3.7 MN*	Abington, Penna. area
	0600:43.5	BBD	iP		Abington, Penna. area
	0600:56.5		S		Abington, Penna. area
12/11/81	0137:38.8	NED	iP	?	Northeastern Maryland?
	0137:40.0	BBD	iP		Northeastern Maryland?
01/11/82	2143:29.0	NED	iP	5.5 MN*	Canada
01/19/82	0015:55.5	NED	iP	4.7 M_D*	New Hampshire
10/07/83	1019:52.0	NED	iP		Blue Mountain Lake, NY
	1020:05.0	GTD	iP		Blue Mountain Lake, NY
	1025:47.5	NED	iP		Blue Mountain Lake, NY
10/11/83	0412	NED	eP		Canada

Date	Arrival Time (UCT)	Station	Phase	Magnitude[1]	Remarks
03/13/84	1716:39.6	NED	iP		Unidentified
	1716:43.6		iS		Unidentified
04/23/84	0136:11.3	NED	iP	4.0 M_D	Lancaster, Penna.
	0136:15.3		S		Lancaster, Penna.
	0136:16.2	BBD	iP		Lancaster, Penna.
	0136:26.4	GTD	iP		Lancaster, Penna.
	0136:42.9		S?		Lancaster, Penna.
	0246:10.2	NED	iP	2.5 M_D	Lancaster, Penna.
	1632:14.1	NED	iP	?	Lancaster, Penna.
	1632:18.1		iS		Lancaster, Penna.
5/10/84	1015:03.9	NED	iP	?	Near Bethlehem, Penna.
	1015:12.9		iS		Near Bethlehem, Penna.
05/17/84	1014:49.9	NED	iP	2.1 M_D	Lancaster, Penna.

* Lamont-Doherty Data

1) M_b = Body-wave magnitude

M_D = Duration magnitude

MN = Nuttli magnitude