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MARCH, 1974

COMPILED BY
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EARTHQUAKE HISTORY AND GEOLOGY OF NORTHERN DELAWARE

R. R. Jordan (speaker), K. D. Woodruff, and T. E. Pickett

DELAWARE-NEW JERSEY-PENNSYLVANIA EARTHQUAKE OF FEBRUARY 28, 1973

R. R. Jordan, T. E. Pickett (speaker), K. D. Woodruff, *et al*.

SELECTION OF SITES FOR HIGH YIELDING WELLS IN THE DELAWARE PIEDMONT

K. D. Woodruff (speaker), J. H. Talley, and J. C. Miller

TRACE FOSSILS OF THE ENGLISHTOWN FORMATION (UPPER CRETACEOUS), DELAWARE

(Abstract)

H. A. Curran (speaker; Smith College), and T. E. Pickett

Compiled by Thomas E. Pickett

May, 1974

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EARTHQUAKE HISTORY AND GEOLOGY OF NORTHERN DELAWARE

This paper describes seismic activity in a classically "stable" and "inactive" area: the inner Coastal Plain and the Piedmont of northern Delaware. It documents the occurrence of earthquakes in that area, studies of the events, and the results, to date, of our attempts to correlate the earthquakes to the geology.

Principally because of the relative rarity of earthquakes in the East, knowledge of the seismicity of the region has lagged far behind that of other parts of the world. Once the events are experienced, however, it becomes abundantly clear that they are worthy of serious study and that even the initial descriptions of East Coast earthquakes and speculations as to their causes may aid and stimulate additional investigations.

We gratefully acknowledge the advice and assistance provided in the seismic investigations in northern Delaware by seismologists of NOAA, Lamont-Doherty Geological Observatory, Cornell University, and the State University of New York at Binghamton as well as the stimulating discussions with our DGS colleague, Dr. Nenad Spoljaric.

The historic record of earthquakes in northern Delaware begins with the largest event known: that of October 9, 1871. That earthquake was centered at or near Wilmington, Delaware and was of sufficient force to topple chimneys and cause other minor structural damage over a three-county area. It has been estimated to have had a modified Mercalli intensity of at least VII and was one of the largest East Coast seismic events between Charleston and Boston.

In addition to demonstrating the most significant fact that damaging earthquakes can occur in this "quiet" area, the following points are noteworthy:

1. Our records of the 1871 Wilmington earthquake are poor. Of course there was no instrumental record. Evidently no trained observers took note. Our knowledge is derived mainly from newspaper accounts at a time when communications were limited and the primary focus of news attention was the great Chicago fire.

2. As seems to be the case with most East Coast earthquakes, the felt area and the damage area appear to have been large in proportion to the magnitude of the event.

3. The earthquake was accompanied by loud rumbling and an intense explosive sound, leading many observers to conclude that there had been a major explosion at the nearby powder mills.

The occurrence of very few documented earthquakes in a 100-year period between the 1871 event and the recent small to moderate-size earthquakes starting in 1971 appears at first examination to be peculiar; however, a possibly acceptable explanation may be that small, shallow, noisy earthquakes have occurred throughout this period but have gone unnoticed. It is to be remembered that prior to 1972 there was no local instrumentation and that residents in this area customarily ascribe vibrations and booming noises to man-caused explosions in the munitions factories, chemical plants, refineries, and military testing facilities that pervade the area.

With this background we may examine the general geology of northern Delaware and the distribution of its earthquakes in space and time.

Figure 1 defines the study area. The locations of the Fall Zone cities, Newark and Wilmington, and Claymont, Delaware, and Chester and Philadelphia, Pennsylvania are shown together with some of the major drainage features, the Delaware River, Brandywine Creek, and the Elk River. The Fall Zone bisects the area into the Piedmont Province to the northwest and the Coastal Plain to the southeast.

Complex Early Paleozoic crystalline rocks occur northwest of the Fall Zone and the offlapping sequence of Cretaceous and Tertiary units in the Coastal Plain extends to the southeast. The Piedmont is underlain by rocks of the Glenarm Series, principally the Wissahickon Schist, except that the eastern part of the Piedmont comprises the Wilmington Complex, described by Ward (1959) as consisting mainly of mafic banded gneisses. The Wilmington Complex is something of an anomaly among the rocks of the Piedmont and it is mostly within its area that the earthquakes have occurred. This leads to the tentative suggestion that the Wilmington Complex may be at least in part fault-bounded. Certainly its relationship to the Glenarm rocks is poorly understood.

FIGURE 1. STRUCTURAL ELEMENTS.

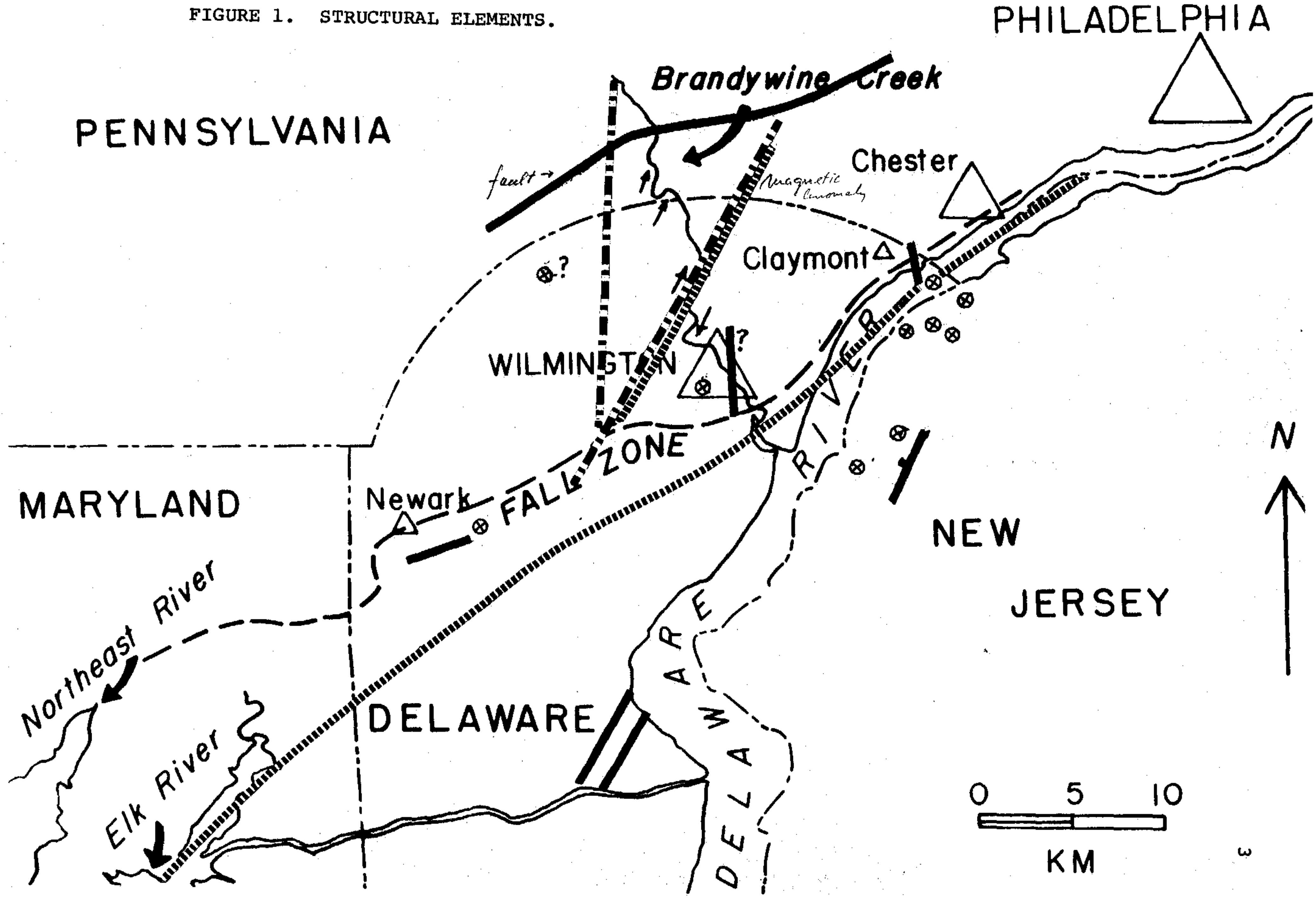

Table 1 lists known Delaware earthquakes. The damaging earthquake of October 9, 1871 has been described. The one the following day is considered to be a relatively strong aftershock. Very little is known of the earthquakes of 1879, 1906, 1937, and 1944. Only that of January, 1944 is placed in the northern Delaware study area. The recollections of long-term residents and comments made on felt-report forms for recent events suggest that several other small earthquakes have occurred in northern Delaware, especially in the late 1930's and early 1940's, but no firm data are available.

July 14, 1971 marks the beginning of a series of documented earthquakes that appears to be continuing to the present day. To what degree this indicates an increase in activity or increases instrumental capability and awareness of earthquakes is difficult to determine; probably both factors are operating.

The list is dominated by 12 events in southwestern Wilmington having the following similar characteristics:

1. They are perceived within a limited area of about 4 square kilometers at an intensity between III and IV.
2. They generate loud, explosive noises that are generally more disturbing to the residents than are the ground vibrations.
3. Their characteristics indicate that they are associated with very shallow, very localized faulting.

The largest recent earthquake is that of February 28, 1973. This is also the most intensively studied event and will be described in the following paper.

The earthquakes of February 10, 1972 and July 10, 1973 were perceived over several hundred square kilometers and appear to have epicentral locations different from those of the two larger events and the localized southwestern Wilmington earthquakes.

The general locations of epicenters are shown on figure 1 as circles enclosing crosses. The apparently coincident locations of at least 10 small events in southwestern Wilmington is indicated by one symbol.

The epicentral location of the 1871 earthquake is not well defined but is recorded in the literature as the eastern bank of the Delaware River just south of Wilmington.

TABLE 1

EARTHQUAKES IN DELAWARE

Date	Location	MM Intensity
10/9/1871	Wilmington	VII+
10/10/1871	Wilmington	IV
3/25/1879	E. Dover	"Strong"
5/8/1906	Seaford	-
12/1937	"Lower Delaware [Bay?]"	-
1/1944	Wilmington	<V
7/14/71	SW Wilmington	III-IV Local
1/2/72	SW Wilmington (2)	
1/6/72	SW Wilmington	
1/22/72	SW Wilmington (2)	
1/23/72	SW Wilmington	
2/10/72	ENE Newark	IV
2/11/72	Hockessin Area	III
2/22/72	SW Wilmington	-
8/13/72	SW Wilmington (2)	III-IV Local
11/27/72	SW Wilmington	
11/29/72	SW Wilmington	
2/28/73	Wilmington-Claymont-Penns Grove	VI
3/1-4/73	Claymont	7 Aftershocks
7/10/73	Wilmington-Claymont	IV
1/15/74	N Delaware	Instrumental Only
3/5/74	N Delaware	Instrumental Only

A few kilometers to the south and east of Wilmington is NOAA's epicentral location for the earthquake of February 28, 1973. The locations of the aftershocks of that event are shown to the southeast of Claymont, in New Jersey. The greatest intensities were recorded in Claymont, Delaware.

It would be very unusual for the faults yielding the earthquakes that have been described to have surface expression and, in addition, outcrops are rare in the urbanized study area. Therefore, reliance must be placed upon indirect methods of study associating geomorphic and geophysical features with the geology and the possible locations of fracture zones. However, neither outcrops nor faults are totally absent as field work has located several faults in the Wilmington area. One in a road cut for I-95 in southwestern Wilmington is a nearly vertical fault and strikes north through that portion of the City that experiences the most frequent small earthquakes. Evidence from stream morphology and a few engineering test borings permit the tentative extension of the trace of this fault for a few kilometers, thereby generating a linear feature that may be plotted with others in attempts to determine a pattern. We have at this time no evidence to indicate whether or not this or similar features are "active." The earthquakes provide unmistakable evidence of some activity, but their association with such geologic features is purely speculative.

Faults and lineations from several sources have been compiled on the generalized map, figure 1.

The faults shown as solid lines include several along the Fall Zone that may be observed in outcrop. That on the northern part of the map is the southwestern portion of the Rosemont fault appearing on the geologic map of Pennsylvania.

On the southern part of the diagram two parallel lines indicate the basement graben identified by Spoljaric (1973).

In New Jersey, East of Wilmington, a line indicates the trend of the faulting that generated the February 28, 1973 Wilmington earthquake as determined from analyses of seismograms of that event.

One significant linear aeromagnetic anomaly, shown by the short, regularly spaced dashes, trends northeast-southwest on the western side of Wilmington. Another, recently published by Higgins, Zietz, and Fisher (1974), and associated with a possible fault zone proposed by those authors, runs from the vicinity of the Elk River in Maryland and is extended along the Fall Zone as suggested by them.

Two of the longer lineations determined from ERTS imagery are shown as dot-dashes.

Offsets of certain reaches of the Brandywine Creek and those reaches of the Delaware River parallel to and deflecting from the Fall Zone are indicated (arrows).

On this simplified diagram we are struck by the near-parallelism of some linear features:

The trend of the fault from the fault plane solution of the February 28, 1973 earthquake is N 28° E. This same trend is found in the basement graben to the southwest and also parallels the course of the Delaware River in the first reach departing from the Fall Zone trend. The same trend of N 25° E to N 30° E is found in some Brandywine Creek offsets and in an aeromagnetic and an ERTS lineation.

Some suggestions of a secondary northerly trend may be found in one pronounced ERTS lineation and the orientation of two exposed faults.

Foliation and other structural features of the Piedmont rocks more nearly parallel the Higgins, Zietz, Fisher (1974) magnetic lineation or the Fall Zone than either of the other trends. An exception is found in southwestern Wilmington where the foliation of the Wilmington Complex rocks trends north-south.

It might be noted that the fault-plane solution for the February 28, 1973 earthquake, in addition to reinforcing the N 30° E trend, indicates a dip-slip mechanism, down to the east. This would be consistent with a positive Piedmont and a relatively negative Coastal Plain.

Any conclusions on the basis of the data now available are obviously highly speculative. However, it appears to the authors that the N 30° E trend, derived from several independent lines of evidence, is significant. The strongest manifestations of this trend lie along the course of the Delaware River from Claymont to Wilmington and its extension to the southwest. Moreover, given the errors inherent in locating earthquake epicenters and the possible offsets of foci at depth from surface traces, the larger earthquakes of the area may lie on this trend. A parallel trend borders Wilmington, and the Wilmington Complex, on the northwest. Some interaction between these zones or some combination of these and the others indicated might account for the repetitive smaller events in southwestern Wilmington.

Perhaps most eastern geologists, influenced by the folds of the Appalachians and the broad warping of the Atlantic

Coastal Plain, tend to emphasize folding rather than faulting in their studies of geologic structure. The evidence suggests, however, that fault structures may be worthy of additional consideration. In northern Delaware several significant fault zones appear to be present and earthquakes have indicated that either these zones or others yet to be found are, to some degree, active.

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DELAWARE-NEW JERSEY-PENNSYLVANIA EARTHQUAKE OF FEBRUARY 28, 1973

The preceding paper deals with earthquake history and the related geology of Delaware. This paper discusses the detailed study of a specific earthquake. The earthquake of February 28, 1973, felt in the mid Atlantic states, provided the basis for a joint investigation by geologists and seismologists at the Delaware Geological Survey, Lamont-Doherty Geological Observatory, Cornell University, and Pennsylvania State University. The study included analysis of the main event from seismic records, questionnaires, interviews, field inspection, and an instrumental study of aftershocks.

On February 28, 1973 at 3:21 a.m. local time, 8.21 GMT, an earthquake occurred near the common juncture of Pennsylvania, Delaware, and New Jersey. The Richter magnitude was 3.81, highest modified Mercalli intensity VI. It awakened many whose initial reaction was that their furnaces had blown up, some nearby explosion had occurred, or distant thunder had occurred, depending on their location.

The regional isoseismal map (Figure 1) shows NOAA's calculated epicenter of the event at 39°43.1'N, 75°26.4'W with a depth of focus of 14.1 km. in New Jersey.

The epicenters of recorded aftershocks are shown in an area near the Delaware-Pennsylvania-New Jersey common boundary, with depths of 5 to 8.5 km.

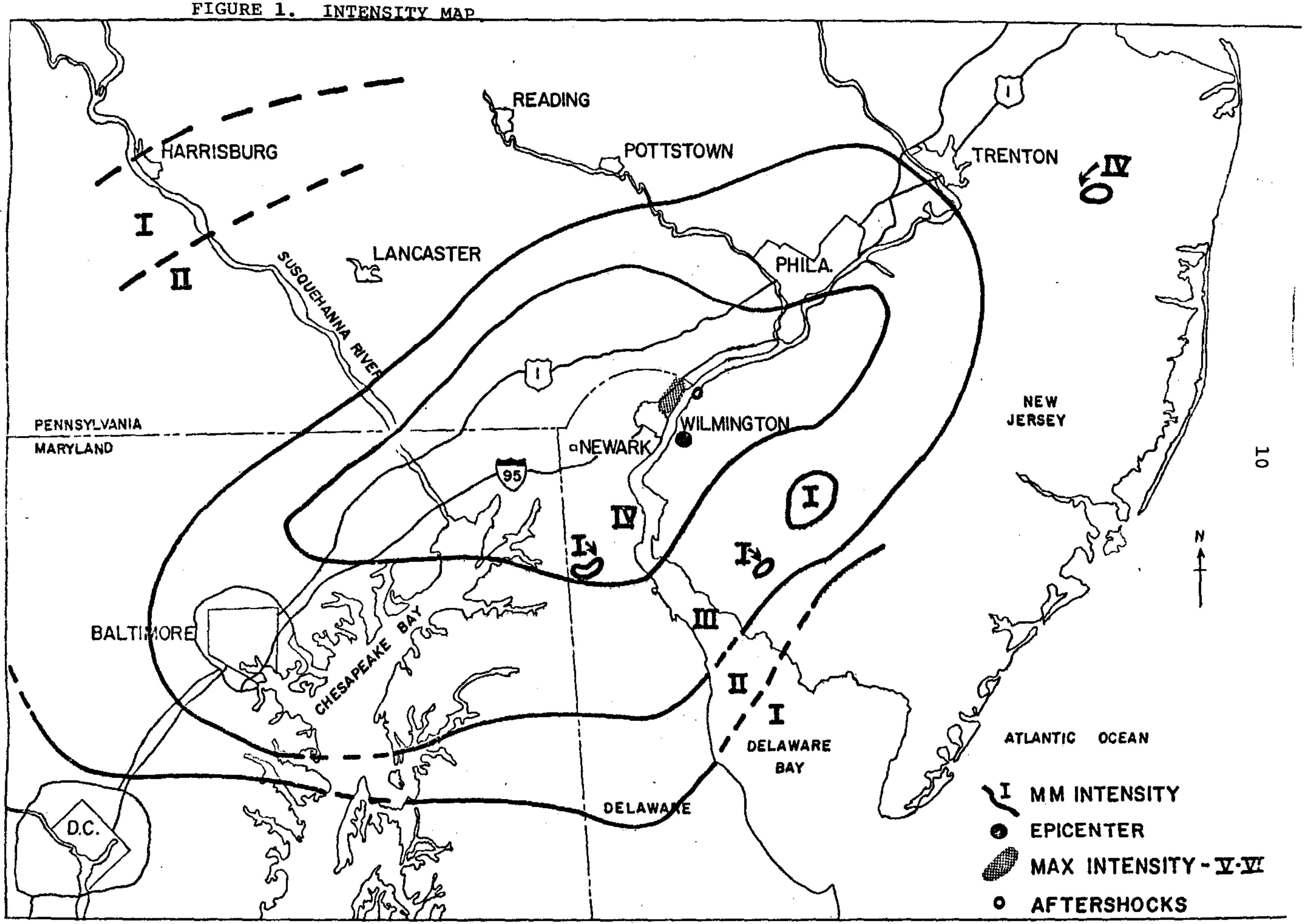
The region of greatest intensity is the area between Wilmington and Claymont, Delaware.

The distance between Philadelphia and Baltimore is approximately 150 km. A line connecting the two cities is roughly the Fall Zone between the Piedmont and Coastal Plain.

The intensity contours roughly follow the regional NE-SW strike. The shock was felt over 15,000 square kilometers, which is the area enclosed by the III intensity contour.

An isoseismal map constructed by NOAA is similar except that values are one unit higher. We suspect that we were more conservative in assigning intensity values.

FIGURE 1. INTENSITY MAP



Peak intensities, including a few VI's were reached mostly north of Wilmington in an area underlain by high-grade mafic gneisses of the Wilmington Complex. Particularly near Claymont intensities attenuate rapidly to the south and east in the sediments of the Atlantic Coastal Plain.

A questionnaire was distributed shortly after the event. This was available in banks, schools, and other public places as well as being published in newspapers and broadcast over radio and television - a total distribution of about 150,000. We received 3800 completed questionnaires. These provided the data to construct charts.

A graph of intensities illustrates that intensities were greater in the Piedmont Province and persisted over longer distances than in the Coastal Plain.

As would be expected, the distribution of various effects correlates well with the intensities. About 70% of persons within 50 km. noted rattling of windows, doors, and small objects. More severe effects reached out over longer distances in the Piedmont than the Coastal Plain. Cracking, mostly of plaster, was found in about 8% of the reports from the Piedmont within 25 km. of the epicenter.

When asked to describe the strength of the shaking produced by the earthquake, as distinct from noises and other effects, residents' answers indicate a good correlation of their perceptions with assigned intensities.

Again, stronger shaking was perceived over greater distances in the Piedmont than in the Coastal Plain.

About 30% of those within 50 km. were able to associate a direction of travel with the motion produced by the earthquake. Directions of motion and noise were probably confused in many cases, however. By whatever combination, a surprising number of residents correctly identified the general direction of travel from epicenter to point of observation.

More than two-thirds perceived a rapid vibration; the remainder felt a slower, swaying action. The reports weakly suggest that the motion slowed with distance and was less rapid on soft rocks.

Two-thirds of the reporters within 25 km. and more than half of those within 50 km. noted the earthquake's noise. This was most often reported as a sharp, explosive sound in close, as opposed to the rumble that predominated at greater distances.

More than one-third of those in the inner Piedmont zone reported the noise to be extremely loud. Many found this to be the most frightening aspect of the earthquake. Some stated that this earthquake was more startling than much larger events that they had experienced elsewhere because of the noise.

The locations of the epicenter of the main shock, the aftershocks, and the highest intensities obviously do not coincide (Figure 1). The aftershock epicenters are roughly 8 km. from the main event epicenter. It is felt that this spread is caused by the general errors inherent in the various location techniques and that the actual location of the main shock was no more than a few kms. from the aftershock cluster.

Local structure and the configuration of recording stations may be significant. The plotting of locations of epicenters is influenced by high seismic velocities in the Wilmington Complex. Also, bedrock is quite shallow in the Claymont area. Most of the portable instrument sites used for aftershock detection were located either to the north or west and did not completely surround the central area. Finally, the distribution of intensities was undoubtedly controlled by details of structure and ground conditions.

In all, 7 aftershocks were recorded on 4 portable instruments at 6 sites during the 2nd to 5th days after the earthquake.

The error in the aftershock epicentral locations is ± 2.5 km. It is, however, impossible to determine if a systematic bias is present for the locations as a set.

Different crustal models were tried in order to check the stability of the locations both with and without the depth fixed.

The data were plotted on a lower hemisphere, equal area projection with solid circles representing compression and open circles dilatations. The data are a composite of both portable and permanent station records of the main event and aftershocks. Phases were identified using an arrival time versus distance plot.

We selected the nearly vertical nodal plane as the fault plane. This strikes N 28° E and is in the vicinity of the Delaware River. The plane is nearly vertical but if the dip is indeed 82° to the northwest this would indicate a reverse fault with the Piedmont up and the Coastal Plain down. This is a solution that is consistent with the regional trend of a tectonically positive Piedmont and a negative Coastal Plain.

The data derived from the study of the February 28th event is supporting evidence for the regional tectonic framework discussed by Jordan in the previous paper.

We believe that, although earthquakes are relatively uncommon in this part of the country, the East is becoming more "quake conscious." The need for taking seismic activity into account in regional planning is apparent. Studies such as ours should be made for future earthquakes so that the seismicity of the East can be better understood and applied.

SELECTION OF SITES FOR HIGH YIELDING WELLS IN THE DELAWARE PIEDMONT

Early in 1971 the City of Newark, Delaware requested assistance from the University of Delaware in locating additional sources of water to supplement a continually growing water need. The University of Delaware in turn asked the Delaware Geological Survey to provide this service. At the time, Newark was served by two well fields, both located in the Coastal Plain sediments to the south of the City. Previous exploration had shown, however, that the possibilities for other wells in the Coastal Plain were very limited. Also, surface water sources were undeveloped and likely to remain so for several years. Thus, the remaining alternatives were to buy water from a private water company or to develop wells in the nearby Piedmont.

The project area is in northwestern Delaware and straddles the Fall Line. The Potomac Formation, a Coastal Plain unit, underlies the southern half of the area while crystalline rocks of the Wilmington Complex and the Wissahickon Formation make up the northern half of the study area.

The Wissahickon Formation has been subdivided by Thompson (work in progress) into three general rock types: (1) a metagraywacke facies, (2) a pelitic facies, and (3) amphibolite pods which generally seem to border the Fall Line to the north and northeast of Newark.

The average yield of wells in the Wissahickon Formation for all rock types was reported by Rasmussen and others (1956) to be about 23 gallons per minute. Later experience by the staff of the Delaware Geological Survey indicates that this figure is probably slightly high. Most wells seem to yield from 10 to 20 gallons per minute. These later yield figures, taken from existing data in the files of the Delaware Geological Survey, are for wells that were usually located without regard to topography or geologic structure.

Many references in relatively current literature mention the possibility of obtaining better than average yielding wells by drilling on so-called fracture traces or lineations; such traces supposedly represent the intersection of some structural plane with the ground surface. Routine plotting of well locations revealed that locally the sites of many of the higher yielding wells in a given area seemed to fall in a straight line. Since the choice of lithologies was somewhat limited, well sites in this study were chosen mainly on the basis of linear traces. Of particular interest were those areas where Piedmont streams flowed on or parallel to fracture traces.

Lineations were plotted on an overlay of a standard 7-1/2 minute quadrangle of the study area. Both air photo pairs and topographic maps were used for identifying the traces. In Figure 1, a sketch map of the western part of the study area, three major sets of lineations can be identified: (1) a set striking about N 20 W, (2) a set striking about N 70 W, and (3) a set striking about N 10 E. A prominent feature is the long N 10 E lineation that aligns with the course of White Clay Creek for about 3500 feet. Magnetometer surveys run in the area showed that relative magnetic lows usually occurred when an inferred lineation was crossed. Some seismic refraction surveys were run but the results were generally inconclusive due to the many possible interpretations. Preference for drilling sites was given to areas where topographic lows corresponded to lineations and where two or more lineations intersected. Thus the working hypothesis at the beginning of the programs was that the lineations were expressions of steeply dipping joints or zones of faulting. A summary of the results of the drilling follows. Well numbers were assigned according to the Delaware Geological Survey grid system and exact locations are available on maps in the Survey's files.

Well number Ca45-22 was drilled in a small pod of amphibolite, the only hole that penetrated amphibolite. Nearby outcrops showed fractured rock at the surface and also some small scale reverse faulting. The rock was also fractured in the top of the test hole but became increasingly harder at depth. The hole went to 245 feet and produced about 40 gpm.

The second hole, Ca45-19, was drilled nearly on top of two intersecting fracture zones and went to 320 feet. Migmatite and some shattered quartz veins were encountered at various depths but again the final yield was only about 30 to 40 gallons per minute.

The next hole, Ca45-20, went to 447 feet and produced about 45 gpm and 342 feet from fractured rock. Notice that the hole was drilled on a short N 70 W striking lineation. A later pumping test showed that the water at depth was probably related to the long northeast lineation parallel to White Clay Creek and not to the lineation on which the hole was drilled.

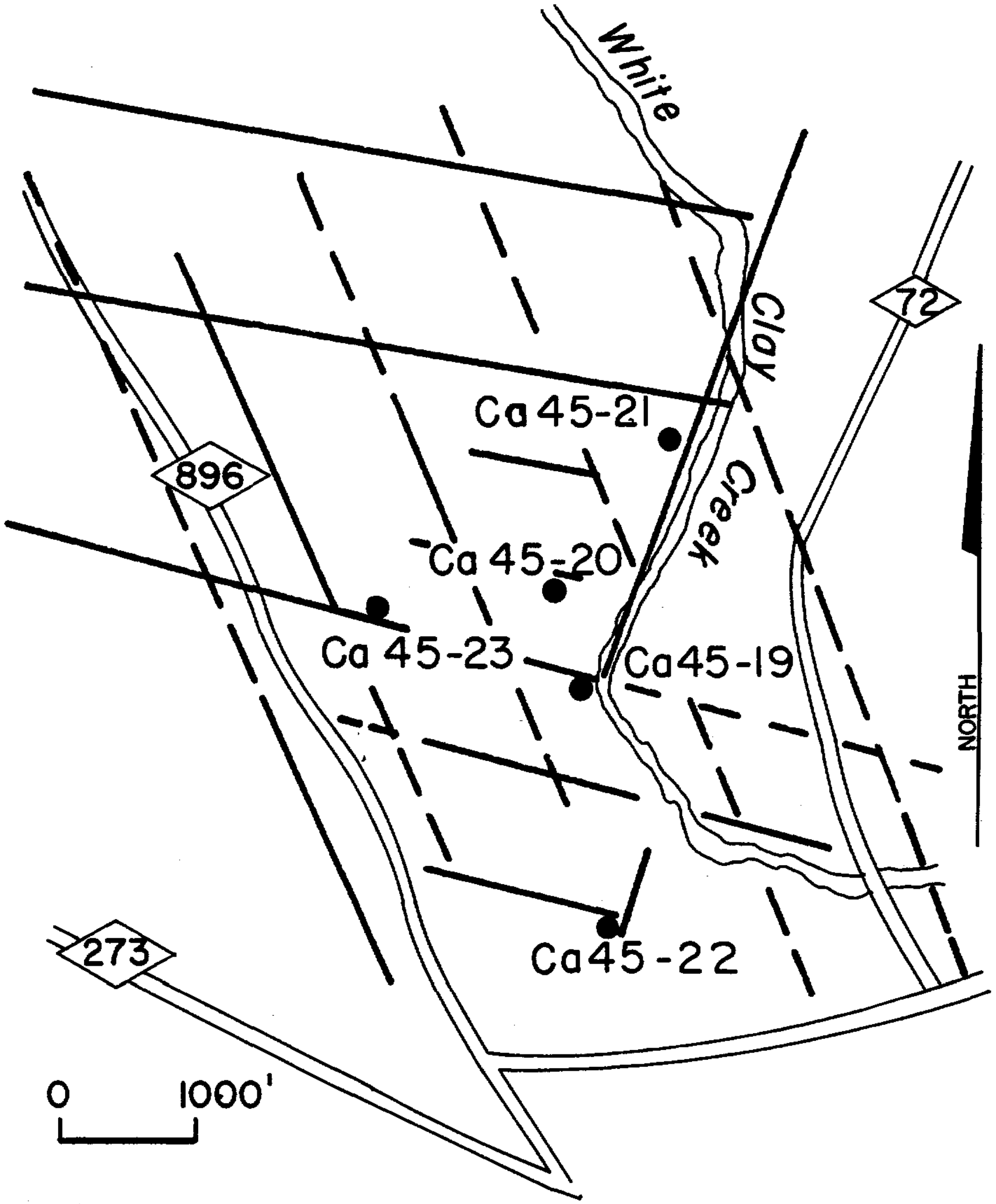


FIGURE 1.

AIR PHOTO LINEATIONS

In the fourth test hole, Ca45-21, a major fracture zone was found between 126 and 237 feet (land surface datum). The well flowed several gallons a minute at land surface and had a head about three feet above land surface. The yield based on the specific capacity was about 750 gallons a minute. When this well was pumped at 300 gallons a minute, it affected the next well to the south, Ca45-20, about 1300 feet away by about two feet. The other well at the southern end of the fracture zone, Ca45-19, was not affected.

The fifth test hole was drilled on a long N 70 W lineation at an elevation about 50 feet above the valley floor. Fractured rock was hit at 316 feet and the specific capacity of the well indicated it could produce over 300 gpm. This well also overflowed at land surface at about 37 gpm and the final head was 33 feet above land surface. A second control point on the fractured zone in the fifth well was obtained when an existing private well about 1300 feet away was deepened. The driller reported a sudden increase in yield at about 313 feet below land surface and later pumping of the deepened well affected the test well of this study quite markedly. Up until this time no such effect had been noticed.

The second half of the study concentrated on areas to the northeast of the City of Newark. One of the most successful test holes was Ca45-39 which was drilled near the intersection of two lineations on the edge of a stream valley. Based on the specific capacity and the distance to the top of the first fracture zone yielding water, the hole is theoretically capable of yielding about 790 gpm. The stream alluvium present here probably acts as a reservoir and feeds water to one or more fracture systems. The major water bearing zone was 170 feet below land surface. Drill cuttings from this depth showed evidence of slickenslides and shattered quartz pegmatites.

The next hole to the east, Cb41-10, was near the intersection of three fracture traces. Intermittently fractured rock occurred between 130 and 178 feet and the final yield was estimated at 430 gallons per minute.

The deepest water producing zone located in this project was from a fractured zone at 375 feet below land surface in hole Cb41-3. A yield of 80 gallons a minute was obtained with some indications that more water might be available. However, deeper drilling and testing were limited by available financing.

The last two holes were drilled on a prominent north-south lineation. Fractured rock was encountered in both holes and both produced about 200 gallons per minute taking into account mutual well interference. This was one of the few locations where field exposures indicated that the lineation in this case was probably a zone of vertical jointing.

A variety of geophysical logs were run in order to learn as much as possible about the actual nature of the fractured zone. In the higher yielding wells gamma logs usually showed a relative low just above the main fracture zone. These lows corresponded to what was reported as a "clay" by the driller. Similar low gamma values have also been noticed locally in highly weathered crystalline rocks and in basement rocks beneath the Coastal Plain. In this study the low gamma peaks are probably indicative of a gouge zone and thus some movement. Gamma lows also were noted opposite zones of water entry either because of an increased hole diameter or because of the presence of quartz veins.

Caliper logs usually confirmed the location of fractured rock sections as deduced from drilling logs. Flow meter surveys usually indicated zones of water entry either opposite or just above fractured rock in several of the holes.

Pump tests were run in nearly all of the producing wells to try to determine long term yield possibilities. The difficulties involved in interpretation of pump tests in hard rock wells are well know but the aquifer coefficients found in this study seem to be fairly reliable guides to predicting well performance. One of the wells tested has been in service now about seven months and is performing almost exactly as predicted. Transmissibilities, as a matter of interest, ranged from 1700 gpd/ft. to 5000 gpd/ft. (old units). Most storage coefficients indicated confined to semi-confined conditions and all of the wells yielding over about two hundred gallons a minute seemed to show a definite recharge boundary. Not enough information was available to theoretically calculate directly the source of recharge. However, for those wells near streams the water quality of the well water was remarkably similar to the stream water. Conversely, continuous temperature logs run in the well indicated a difference of several degrees between well water and the stream water. Probably the recharge was rather devious, mixing was taking place, or the actual stream water had not yet entered the well when the log was run.

Usually a safety factor was added to the final design yield of any particular well. This was to allow for inherent uncertainties of hard-rock well pumping tests and for the universal tendency on the part of officials to ignore pumping regulations several years hence.

The conclusions of the work to date can be summarized as follows:

1. In some cases the lineations represent steeply dipping zones of jointed rock as can be demonstrated locally by field exposures.

2. Some of the lineations appear to be the expression of probably small scale but definite faulting as deduced from a study of geophysical logs. Water may be coming from extension fractures associated with the fault.

3. Various structural elements probably intersect in many cases and thus provide additional recharge possibilities. The locations that produced water most consistently seemed to be near the intersection of two or more surface traces. Locally, foliation may play a role in controlling direction of ground-water movement.

4. The rather simple technique described here seems to work much of the time. The average yield from 15 test wells based on the specific capacities was 170 gpm.

5. It is not always clear exactly what relationship a fractured zone at depth bears to an observed surface trace. In some cases it appears that the zone at depth is parallel to or intersects the structure which actually produces the surface expression.

Still to be answered with any confidence is the question of long-term yield for wells in these Piedmont structures. Some answers should be forthcoming in the next few months.

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TRACE FOSSILS OF THE ENGLISHTOWN FORMATION (UPPER CRETACEOUS), DELAWARE

Silty fine sands of the Englishtown Formation that crop out along the Chesapeake and Delaware Canal in Delaware are characterized by prominent Ophiomorpha shaft and tunnel systems. Closer examination reveals heavy bioturbation throughout the Englishtown and the presence of a diverse ichnofauna which includes Planolites, Skolithos, a radiate feeding burrow, and a small, delicate, branching vertical burrow resembling Chondrites (Figure 1).

Ophiomorpha systems occur in high density in beds toward the top of the unit and are characterized by the extensive development of tunnels. These systems resemble closely the well documented structures formed today by callianassid crustaceans in shoaling intertidal and shallow subtidal environments. Other beds are heavily and distinctively mottled by Planolites, unlined horizontal burrows probably formed by a sediment-ingesting organism or an organism plowing through the substrate. Skolithos consists of delicate shafts representing the dwelling tubes of marine worms. Distinctive radiate structures are found on surfaces parallel with bedding and probably record feeding activity by worms. The delicate, branching, vertical burrows were formed by another worm species which made a weak lining for its burrow.

The assemblage of trace fossils and physical sedimentary characteristics of the Englishtown Formation suggest an intertidal/shallow subtidal Cretaceous environment of deposition comparable to modern intertidal sand flats or the shallow subtidal zone of an embayed, low energy coastline, similar to that of the Sea Islands coast of Georgia. This interpretation is supported by regional geologic mapping which portrays the Englishtown as a shallow water facies of the Matawan Group.

FIGURE 1. TRACE FOSSILS -- ENGLISHTOWN FORMATION