Seismic Refraction Survey of Pleistocene Drainage Channels in the Lower Great Miami River Valley, Ohio

GEOLOGICAL SURVEY PROFESSIONAL PAPER 605-B

Prepared in cooperation with the Miami Conservancy District and the Ohio Department of Natural Resources, Division of Water, Columbus, Ohio

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By JOEL S. WATKINS *and* ANDREW M. SPIEKER

GROUND WATER IN THE LOWER GREAT MIAMI RIVER VALLEY, OHIO

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By Joel S. Watkins and A. M. Spieker

ABSTRACT

Largely on the basis of seismic refraction data, the U.S. Geological Survey mapped the bedrock surface of the ancestral Great Miami River valley between Dayton, Ohio, and the Ohio River and determined the thickness of sand and gravel deposits in the buried valley. The data indicate that a major buried valley, 200–300 feet deep and about 2 miles wide, is entrenched in the bedrock. The ancestral valley generally follows the course of the present Great Miami River but is north and west of the river throughout much of its course. A younger buried valley, about 100 feet deep, is cut into bedrock below the present course of the Great Miami River.

Seismic velocities in saturated and unsaturated sands, clays, and gravels within the buried valley vary systematically. In the unsaturated deposits, higher velocities are correlative with high clay content. Higher velocities are thought to be caused by higher water content of the clays. A general northeast-southwest decrease in velocity in the saturated outwash deposits is thought to reflect better sorting in outwash deposits farther from the edge of the receding glacier.

Field and interpretational procedures were varied during the course of the investigation. Use of cables about 10 times as long as the mean depth to bedrock significantly increased productivity over use of shorter cables. Delay-time intrepretation techniques, obtained with long cables, yielded results that were more consistent internally and more consistent with geological inferences of valley gradients than were the output data inferred from graphical techniques.

INTRODUCTION

PURPOSE AND SCOPE

In September 1962 the U.S. Geological Survey made a seismic refraction survey of the ancestral Great Miami River valley in southwestern Ohio, between Hamilton and the Ohio River (fig. 1). A second seismic survey was made of the ancestral Great Miami River valley in the area between Hamilton and Dayton, Ohio, in September 1963.

The primary purpose of these surveys was to obtain data concerning the thickness and extent of water-bearing sand and gravel deposits in southwestern Ohio. These data were used to estimate the coefficients of transmissibility, storage, and other hydrogeologic parameters of the ground-water reservoir to aid in the efficient development of ground-water resources in southwestern Ohio. In these surveys over 50 miles of seismic refraction traverse were shot, mainly along roads, in the Great Miami River valley between West Carrollton and the Ohio River (fig. 1). Two adjoining valleys—the Mill Creek valley between Hamilton and Cincinnati, and the Dicks Creek valley southeast of Middletown—were studied near their intersections with the main valley of the ancestral Miami River.

Two open-file reports (Watkins, 1963; Watkins and Spieker, 1964) summarize the purpose and scope of the investigations and detail the results of interpretations of seismic refraction data. Some additional data collected near Trenton, Ohio, were provided by R. E. Mattick (written commun., 1964).

The seismic refraction survey was not designed to study seismic operations and techniques nor to do seismic research. Instrumentation was limited to relatively unsophisticated portable equipment during much of both seasons, although a 7000B Houston Technical Laboratories model unit was available for part of the 1963 field season. Emphasis was placed on detecting first arrivals; later arrivals were observed only incidentally. Energy levels between different geophone channels generally could be quantitatively compared. The equipment did not include magnetic tape recorders.

By the beginning of the 1963 field season it became evident that significantly more efficient seismic opera-

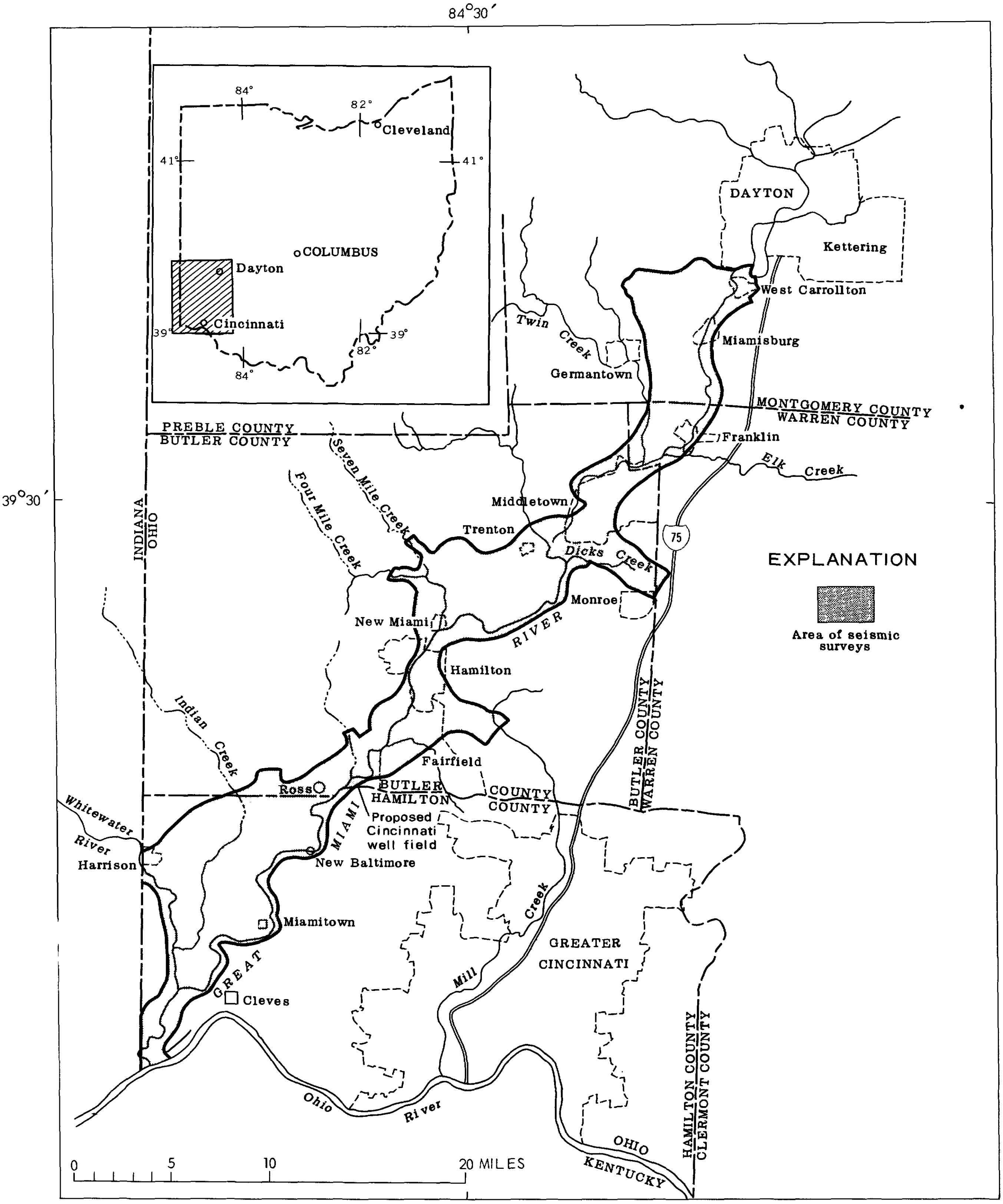


FIGURE 1 —Area of seismic surveys in southwestern Ohio.

tions were feasible and that more information could probably be obtained from the seismic data than was being obtained at that time. It was equally evident that cherished dogma concerning accuracy of seismic refraction data was, in some areas at least, fallacious, and that further investigation was required.

Despite the instrumental limitations and the necessity to satisfy the basic goals of the survey, the study area had a high density of seismic data by the end of the 1963 field season. The large quantity of data was thought to possibly offset the relatively low quality of some of the data. By agreement with the cooperating agencies, the authors were able to reshoot some problem areas in 1963, to auger several test holes to examine subsurface materials, and to conduct inhole velocity surveys in the fall of 1964.

Geologic logs of varying quality were available for several wells in the study area for comparison with the seismic data. Some excellent well logs were also available, notably those from the city of Cincinnati's proposed well field[1] and those from the U.S. Atomic Energy Commission's facility near Fernald. Two AEC wells and one Cincinnati test well were subsequently included in the inhole velocity surveys.

This report is not intended to represent a complete investigation of problems inherent in seismic investigations of glacial aquifers in southwestern Ohio; rather, it is an interim report which summarizes the problems encountered and which proposes some tentative interpretations to account for the observed phenomena.

PREVIOUS INVESTIGATIONS

Warrick and Winslow (1960) conducted seismic surveys in parts of Ohio in search of buried channels which might contain usable ground-water supplies. Their exploration, however, was more of a reconnaissance than the present investigation. Unpublished Geological Survey seismic data from reconnaissance surveys were made available by R. M. Hazlewood (oral commun., 1962). The Ohio Division of Water allowed the authors to examine some unpublished seismic data which the division had commissioned prior to the 1962 field season.

ACKNOWLEDGMENTS

The seismic surveys on which this report is based were made in cooperation with the Ohio Department of Natural Resources, Division of Water, C. V. Youngquist, chief, and the Miami Conservancy District, Max L. Mitchell, chief engineer. Informal cooperation was provided by the Cincinnati Water Works Department, Charles M. Bolton, superintendent. In addition to financial cooperation, the cooperating agencies provided some of the personnel and equipment necessary to complete the surveys. The Ohio Division of Water made available the power auger for drilling shotholes. This drill rig was operated by Norman C. Bailey, formerly with the Division of Water.

The senior author directed the field parties and interpreted the siesmic data. He was assisted by Zvi Yuval in 1962 and by R. E. Mattick in 1963. The junior author was responsible for the selection of sites to be surveyed and for all geological interpretations.

The authors thank the following governmental units for granting permission to run seismic surveys along public roads and on publicly owned land: The Ohio Department of Highways; the Highway Departments of Butler, Hamilton, and Montgomery Counties; the cities of Fairfield, Hamilton, and Middletown; and the U.S. Atomic Energy Commission (Fernald plant). Armco Steel, Baltimore & Ohio Railroad, and Dayton Power & Light Co. granted access to their property to conduct surveys. The authors also thank many farmers and individual homeowners who gave permission to enter their property.

The Cincinnati Water Works Department, the Ohio Division of Water, the Southwestern Ohio Water Co., and the U.S. Atomic Energy Commission permitted the authors to measure seismic velocities in wells at their respective facilities.

FIELD PROCEDURES

SHOTHOLE DEPTHS AND ENERGY SOURCE

Nominal shothole depths of 10–14 feet were found to be satisfactory for energy coupling. Shotholes were drilled with a mobile truck-mounted auger, which functioned adequately in sand and silt but which drilled with difficulty in coarse gravel or boulders. Where holes would not stay open to the desired depth, two shallow holes, each 6 feet deep, were drilled 10 feet apart, and the charge was halved between them. Each half was capped, and they were fired simultaneously. On very rare occasions, where 6-foot holes could not be drilled and there was no danger to property, personnel, or livestock, the crew dug shallow holes for the dynamite.

Water tamping of holes was found to be faster and easier and, generally, to provide better energy coupling than dirt tamping. However, water tamping was not often possible because of the potential danger from overhead powerlines.

[1] The Cincinnati well field southwest of Fairfield was "proposed" at the time the present report was written and is referred to as such in the other three chapters of the series (Prof. Papers 605-A, 605-C, and 605-D). In the meantime, production wells have been drilled, and the pipelines are under construction. As of February 1970, it is estimated that the well field will be placed in operation sometime in 1972. The terminology "proposed Cincinnati well field" is retained in this report to maintain consistency with the other three chapters.

Charge size ranged from 1.25 to 15 pounds. Nominal charge sizes were as follows:

Charge size (lb)	*Spread length (ft)*
1.25– 2.5	1, 100
2.5 – 5.0	2, 200
5.0 –10.0	4, 400
15.0	9, 020

FIELD-DATA ANALYSIS

Some preliminary picking and plotting of data were performed in the field for guidance in selecting optimum spread locations. A limited amount of interpretation was done in the field, primarily of data from the proposed city of Cincinnati well-field area. Most of the data were analyzed after fieldwork was completed.

FIELD PROBLEMS

The two most common problems were seismic noise and difficulties in drilling in coarse gravel and boulders. Most noise originated from nearby powerlines and from traffic along roads adjacent to seismic spreads; but other noise sources, such as that from trains or from cattle grazing near the seismic spreads, occasionally delayed operations.

THE BEDROCK SURFACE

SEISMIC-LINE DESIGNATIONS

Definition of the bedrock surface was the primary objective of seismic surveys in the lower Great Miami River valley. Plate 1 is a contour map showing the altitude of the top of bedrock in the area included in these surveys. Locations and designations of the seismic lines are also shown. Lines which were shot in 1962 are designated by letters, and those which were shot in 1963 are designated by numbers. Basic depth-to-bedrock data are available in two open-file reports (Watkins, 1963; Watkins and Spieker, 1964).

The bedrock contours on plate 1 were drawn on the basis of the authors' interpretation of the seismic data and logs of wells. In general, basic data (such as the locations of seismic lines and wells) are shown in black, and interpretations (such as the determined depth to bedrock and the bedrock contours) are shown in red. Only those depth determinations actually used in defining the contours are shown on plate 1. Several depth determinations are anomalous, for reasons discussed in the sections on geophysical interpretations.

THE BURIED-VALLEY SYSTEM

The Pleistocene aquifer system of the lower Great Miami River valley consists of sand and gravel outwash deposited in bedrock valleys that were carved by melt waters from receding continental ice sheets. The following discussion is confined to the characteristics and the origin of these bedrock valleys. The hydrogeologic characteristics of the aquifer system are discussed in the first chapter of the present series (Spieker, 1968c).

The buried-valley system defined in the present study actually consists of two separate interglacial drainage systems, each formed in a different interglacial age. Both valleys slope from the northeast to the southwest. The more prominent of the two valleys is about 2 miles wide and 200–300 feet deep (below the floor of the present Great Miami River valley). Although this ancient valley follows the general direction of the Great Miami River, it is west or north of the present river over much of its course. A somewhat lesser valley cut into bedrock, about half a mile wide and 100 feet deep, follows for the most part the present course of the Great Miami River.

Both valleys are the result of changes imposed on the preexisting drainage system by the Pleistocene glaciation. The drainage of southwestern Ohio prior to the glaciation has been the subject of considerable controversy. Evidence in the Cincinnati area and in northern Kentucky (Durrell, 1961) suggests that the preglacial drainage in southwestern Ohio flowed north into the Teays River, the principal preglacial stream in the Midwest (Fenneman, 1916, p. 112–119). Conversely, evidence in the Dayton area (Norris and Spieker, 1966, p. 18–23) suggests that this preglacial drainage flowed south. Both sides of the controversy are reviewed in the report of Norris and Spieker (1966, p. 18–23). The present seismic survey provided no evidence as to the nature of the preglacial drainage of southwestern Ohio.

Onset of the glaciation forced a rearrangement of drainage into the present system, dominated by the Ohio River. These changes gradually evolved during the complex sequence of glaciation of the Pleistocene Epoch. The general changes were described by Durrell (1961) for the area south of Middletown and by Norris, Cross, and Goldthwait (1948, p. 29–31) for the area north of Middletown.

The more prominent buried valley is part of the interglacial drainage system that developed in southwestern Ohio prior to the Illinoian Glaciation. This drainage system is referred to by some as the "Deep Stage" system, a term defined by Stout (in Stout and others, 1948, p. 73–85). In the present series of reports this drainage system is referred to as the valley of the ancestral Great Miami River, or the major buried valley.

The major buried valley can be readily identified on plate 1 as the large, 2-mile-wide trough extending across the report area in a southwesterly direction from West Carrollton. It is separated from the present course of the Great Miami River by bedrock highs in three reaches: between West Carrollton and Carlisle, between Trenton and New Miami, and between Fernald and

Cleves. In the vicinity of Middletown and Hamilton-Fairfield, the Great Miami River flows directly over this major buried valley. Significantly, these two cities, largest in the report area, are located where the valley is widest, a result of the river flowing over the major buried valley at these two sites.

North of Middletown the cross section of the major buried valley is V-shaped with a rounded floor. South of Hamilton the valley has steep walls and a flat floor. Its configuration between Middletown and Hamilton is transitional between these two shapes.

The average gradient of the floor of the major buried valley in the 63 miles from West Carrollton to the Ohio River is about 2 feet per mile. This value refers to the gradient of the bedrock floor and not of the stream, which no doubt meandered and, therefore, had a gradient that was flatter than the slope of the floor. The definition of the bedrock surface is not sufficiently precise to permit calculation of the valley floor's gradient for shorter reaches. The gradient north of Hamilton, however, seems to be steeper. Durrell (1961, p. 52) stated that the gradient of the ancestral Ohio River valley floor, which includes the reach of the ancestral Great Miami south of Hamilton, is 1.3 feet per mile.

The site of Fairfield, about 3 miles south of Hamilton, was the confluence of the ancestral Great Miami and Ohio Rivers (Durrell, 1961, p. 52 and fig. 3). The ancestral (pre-Illinoian, or "Deep Stage") Ohio River flowed northwest from Cincinnati, through what is now the Mill Creek valley, to Fairfield, thence west and south, and rejoined its present course near Lawrenceburg, Ind. That the ancestral Ohio was a larger stream than the ancestral Great Miami is the probable explanation for the buried valley's more mature development and flatter gradient south of Hamilton.

A narrow channel incised in the flat valley floor downstream from Middletown is inferred from several depth determinations which indicate a bedrock altitude of 350 feet or lower. The location of this channel is only approximate, as not enough control points are available to define its exact position.

A major tributary buried valley enters the valley of the ancestral Great Miami River in the southeastern part of Middletown. The Armco East Works is at the junction of these two buried valleys. The tributary has been referred to variously as the ancestral valley of Todds Fork, Monroe Creek, and Dicks Creek.

Parts of the ancestral Great Miami River valley were blocked during either the Illinoian or the Wisconsin Glaciation, or perhaps both. This blockage caused a relocation of the drainage to essentially the present course of the Great Miami River. A new channel was cut in three reaches: from West Carrollton to Carlisle, from Trenton to New Miami, and from New Baltimore to Cleves.

The bedrock floor of this relocated valley is about 100 feet higher in altitude than the floor of the ancestral valley, ranging in altitude from about 575 feet near West Carrollton to about 450 feet at Cleves. The valley has steep walls throughout its course, and its floor is narrow in the upper reaches and is wide and flat in the lower reaches. At the O. H. Hutchings Station of the Dayton Power & Light Co., near Chautauqua, the valley is only 500 feet wide.

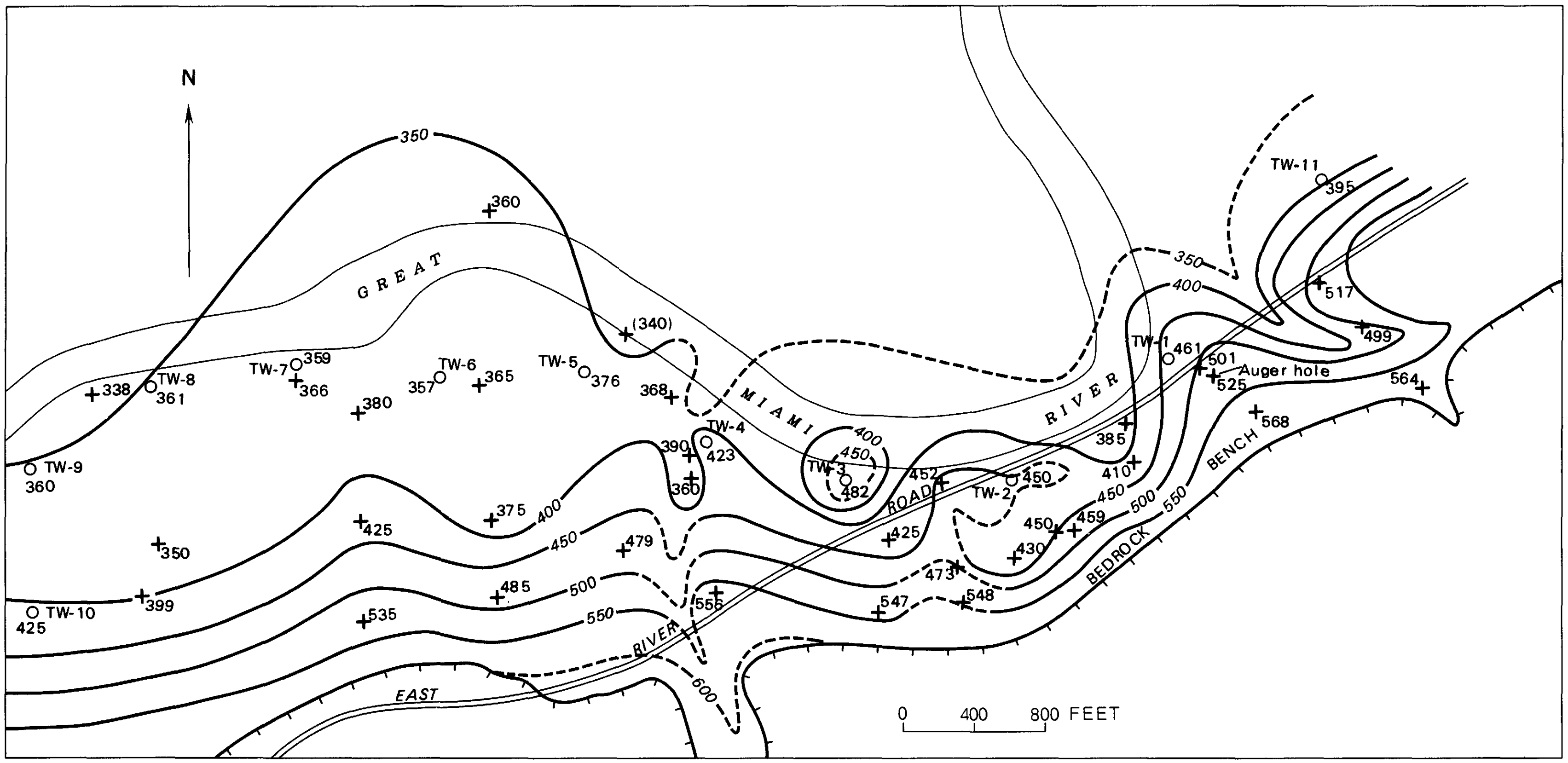
PROPOSED CINCINNATI WELL-FIELD AREA

As part of the 1962 program, a proposed well-field site for the city of Cincinnati (Butler County), approximately 5 miles southwest of Hamilton, was surveyed in detail. The proposed well field is nearer the northern and northwestern Cincinnati suburbs than the present water intakes in the Ohio River, and water could be piped from the well field to consumers without the extensive processing required to make Ohio River water usable. The location of the proposed site is shown in figure 1 and on plate 1. The proposed well field is adjacent to the Great Miami River; hence, good recharge characteristics could be expected. Other well fields in similar geologic settings in the ancestral Great Miami River valley yield abundant quantities of good-quality water.

The objectives of the seismic studies were to determine the depth to bedrock and to provide a guide for subsequent test drilling. The proposed well field was divided into a preferred area east of line E, which was more conveniently accessible for pipeline and waterworks installation, and a less convenient area west of line H (pl. 1, west half).

Intersecting seismic lines were planned where topography and accessibility permitted. It was thought that interlocking seismic lines would eliminate some ambiguity in interpretation and improve the overall quality of results.

Figure 2 is a detailed bedrock contour map of the proposed Cincinnati well-field area. Examination of the results (modified from Watkins, 1963) indicated that the seismic survey had delineated a shallow bedrock bench that extends throughout much of the preferred area. The deeper bottom of the glacial valley was located under the alternate area. Data from intersecting seismic lines were generally consistent, except at the intersection of lines C and D. Data from the west end of line C were interpreted to indicate a bedrock depth of 60 feet, whereas data from the east end of line D were interpreted to indicate a bedrock depth of 106 feet. Reshooting these two 1,100-foot lines in 1963 as a single 2,200-foot line did not entirely remove the ambiguity from the inter-



EXPLANATION

+360
Seismic shot point
Number is altitude of bedrock surface, in feet above mean sea level

+(340)
Seismic shot point
Number is approximate altitude of bedrock surface, in feet above mean sea level

TW-11 O 395
Test well and identification
Number is altitude of bedrock surface, in feet above mean sea level

Outcropping bedrock valley wall

—350— — —
Bedrock contour
Shows altitude of bedrock surface. Dashed where inferred. Contour interval 50 feet. Datum is mean sea level

FIGURE 2.—Contours of the bedrock surface at the site of the proposed Cincinnati well field, west of Fairfield. Contours were drawn on the basis of results from the seismic refraction survey and test-well data.

pretation, but comparison of data from three lines suggests the presence of two layers within the bedrock not recognized from the 1962 field data. For contouring in figure 2, an average value was taken, and the contour was dashed near this point to indicate the uncertainty.

Subsequent to the 1962 field season, the city of Cincinnati drilled 11 test wells, whose locations and depths to bedrock are shown in figure 2. One test hole was augered to bedrock during the 1962 field season. Irregularities of the bedrock surface and multiple refractions from within the bedrock are thought to be mainly responsible for differences between the drilled depths and the depths inferred from seismic data in the valley-wall area.

Agreement between seismic and drill data from the bottom of the glacial valley (test wells 5–9) is good, and the average error is less than 10 percent. The test hole augered on the bedrock bench reached bedrock at a depth within 1 foot of that inferred from the seismic data. At the southeast end of line G and the south end of line F, bedrock was penetrated during shothole drilling at depths comparable to those suggested by the seismic data.

Comparison of drilled depths and seismically determined depths indicates that reliable depth data were obtained in the bottom of the valley, where bedrock surfaces are relatively flat. The seismic data are believed to be sufficiently accurate to determine the general configuration of the valley walls, but the determinations are not as accurate as those on the valley floor.

In summary, depth to bedrock was determined with sufficient accuracy to delineate a bedrock shelf beneath much of the preferred area and to indicate that the bedrock in the less preferable area was deep enough to provide adequate aquifer thickness. Subsequent drilling confirmed the general configuration of the bedrock surface interpreted from seismic data.

ACCURACY OF DEPTH DETERMINATIONS

Three velocities, designated v_0, v_1, and v_2, were generally identified on the seismograms. v_0 ranged from 1,000 to 4,500 fps (feet per second) and represented the velocity in a zone of unsaturated material in most areas; v_1 ranged from 4,500 to 7,000 fps and represented the velocity in a zone of saturated sand, clay, and gravel; and v_2 ranged from 9,000 to 18,000 fps and represented the seismic velocity in poorly permeable bedrock. Means and standard deviations of these data are discussed in later sections.

Slotnick's (1950) graphical method was used to interpret most of the data from 1,100-foot lines shot in 1962. The technique has a number of advantages: the interpreter can see a structure cross section as he derives the graphical solution (fig. 3*B*, *C*); it is possible to interpret data of strata with differing dips at opposite ends of the seismic lines; with practice, analysis is reasonably fast; and anomalies in velocity distributions which might be missed by interpretations from formulas are easily detected (specifically, the horizontal variations in the v_1 and v_2 layers commonly yield improbable bedrock configurations), and the method is applicable to as many as three or four layers.

The most serious disadvantage of using the method in the investigation area is that the accuracy with which depth to bedrock is determined is more affected by errors in determination of v_2 than in most other methods. In the investigation area the bedrock surface undulates, and v_2 varies from place to place; hence, determination of an accurate value of v_2 is not everywhere possible. Comparison of the percentage of error in determination of depth to bedrock due to errors in determination of v_1 and v_2 (table 1) suggests that a point can be made for disregarding advantages of the Slotnick method and utilizing critical distances

TABLE 1.—*Percentage of error in inferred depth to bedrock as a function of error in measurement of* v_1 *and* v_2 [1]

Method	Percentage of error in depth to bedrock			
	$v_1=\bar{v}_1+s_1$ $v_2=\bar{v}_2$	$v_1=\bar{v}_1-s_1$ $v_2=\bar{v}_2$	$v_1=\bar{v}_1$ $v_2=\bar{v}_2+s_2$	$v_1=\bar{v}_1$ $v_2=\bar{v}_2-s_2$
Slotnick	14	−13	10	−50
Critical distance	−6	6	6	−8
Delay time	15	−14	−3	5

[1] In this investigation, $\bar{v}_1$=5,700 fps, $\bar{v}_2$=13,100 fps, s_1=650 fps, and s_2=1,700 fps. s_i=standard deviation of all v_i; $\bar{v}_i$=mean of all v_i; s_1=a relative error of about 11 percent for v_1=5,700 fps; and s_2=a relative error of about 13 percent for v_2=13,100 fps.

for calculation of depths to bedrock in the area of investigation. Critical distances were, in fact, used to compute depths to bedrock for many lines in which the bedrock surface is horizontal or nearly horizontal. The Slotnick technique was, nevertheless, retained for those lines for which data indicated significant dips in bedrock surfaces.

The majority of the 1963 data were from lines 2,200 feet long. These data were interpreted, for the most part, by delay-time techniques (Pakiser and Black, 1957) or the reciprocal-time technique of Hawkins (1961). Advantages of delay-time analysis are (1) rapid solutions, (2) depths are obtained for each of 8 to 10 interior geophones (provided that the line length is approximately 10 times the depth to bedrock), (3) more realistic cross sections are derived (fig. 3*A*), and (4) the technique is relatively insensitive to possible errors in v_2.

Disadvantages are (1) the technique is easily applicable only to the two-layer situation (for present data the v_0 layer was "stripped off"—that is, times adjusted to show only traveltimes in v_1 and v_2 layers), (2) the

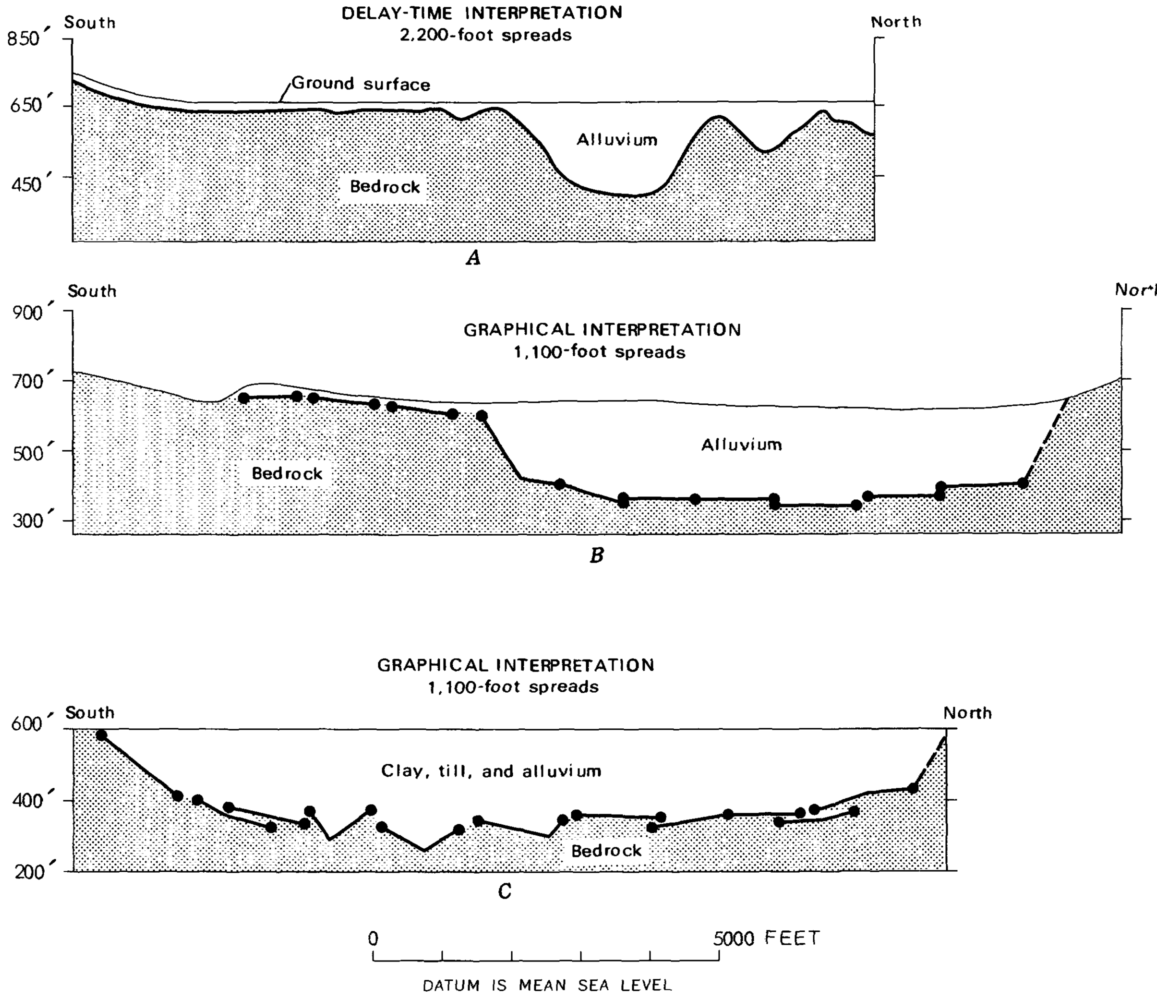


FIGURE 3.—Comparison of results of delay-time and graphical interpretation techniques.

method can be used only with considerable difficulty if first arrivals are from deeper bedrock layers with velocities higher than v_2, and (3) for 12-channel seismic units it is necessary to sacrifice accuracy in the determination of v_1. As indicated in table 1, errors in the determination of v_1 generate slightly larger relative errors in the determination of depth to bedrock. However, the larger errors are compensated to some extent because determination of v_2 is much better than in other techniques, so that relatively little error can be expected from errors in determination of v_2.

In this survey, where extreme accuracy was not a paramount consideration, the primary advantage of 2,200-foot lines was an increase in productivity per unit of time. Approximately 24 miles of traverse were shot in 8 weeks in 1962 as compared with 29 miles in 6 weeks in 1963. The increased productivity was largely attributable to longer line lengths used in 1963.

COMPARISON OF 1962 AND 1963 RESULTS

The lack of sufficient well data in the area of investigation makes it difficult to evaluate the overall accuracy of the determination of depth to bedrock and impossible to unequivocally compare results of interpretation of 1962 and 1963 data. Cincinnati's proposed well field is an exception because the data from 11 test holes indicated that differences in depth to bedrock may average as much as 50 percent along the valley walls but are less than 10 percent in the bottom of the buried valley.

Several remarks seem appropriate, however, concerning indirect methods of examining the accuracy of results. First, good seismic data appear to be consistent with geologic processes. For example, the slope of the valley floor was originally formed by a stream; hence, upstream locations must generally be higher in altitude than downstream locations. Certain limits can be established for maximum and minimum stream gradient with which seismic data can be compared. Second, internal consistency of data suggests better data—that is, adjacent or overlapping spreads should yield consistent depths.

In both respects the 1963 data appear to be better than the 1962 data. The Crosby Road profile (KK–RR) of the 1962 data indicated some depths to be deeper than those at downstream locations, and depths from adjacent or overlapping lines were quite different in some instances.

The apparent improvement of 1963 data could be attributed to more homogeneous subsurface geologic conditions in the 1963 area of investigation as compared with the 1962 area of investigation, or to better interpretive techniques. As there is little apparent geologic difference in the 1962 and 1963 areas of investigation, and as calculations in table 1 show that the 1962 interpretive technique (Slotnick) is more susceptible to certain errors than the 1963 techniques, it is tentatively concluded that the 1963 results are more consistently accurate than 1962 results and that the improvement is largely due to use of the longer lines and delay-time interpretation techniques.

VELOCITY REVERSALS IN TILL IN THE FERNALD AREA

Figure 4 shows times of first arriving seismic energy on line II. These data show an apparent discontinuity in v_I arrivals, a phenomenon also observed on lines J (south end), K (north end), HH, OO (south end), and QQ. For purposes of discussion, the v_I arrivals on these lines have been divided into two groups, the v_I and v_{II}, as shown in figure 4.

Frequencies of v_I arrivals were significantly higher than those of v_{II} arrivals. For example, the v_I modal frequency on line HH was about 125 cps (cycles per second) and about 140 cps on line II, whereas the v_{II} frequencies were roughly 60 cps on both HH and II.

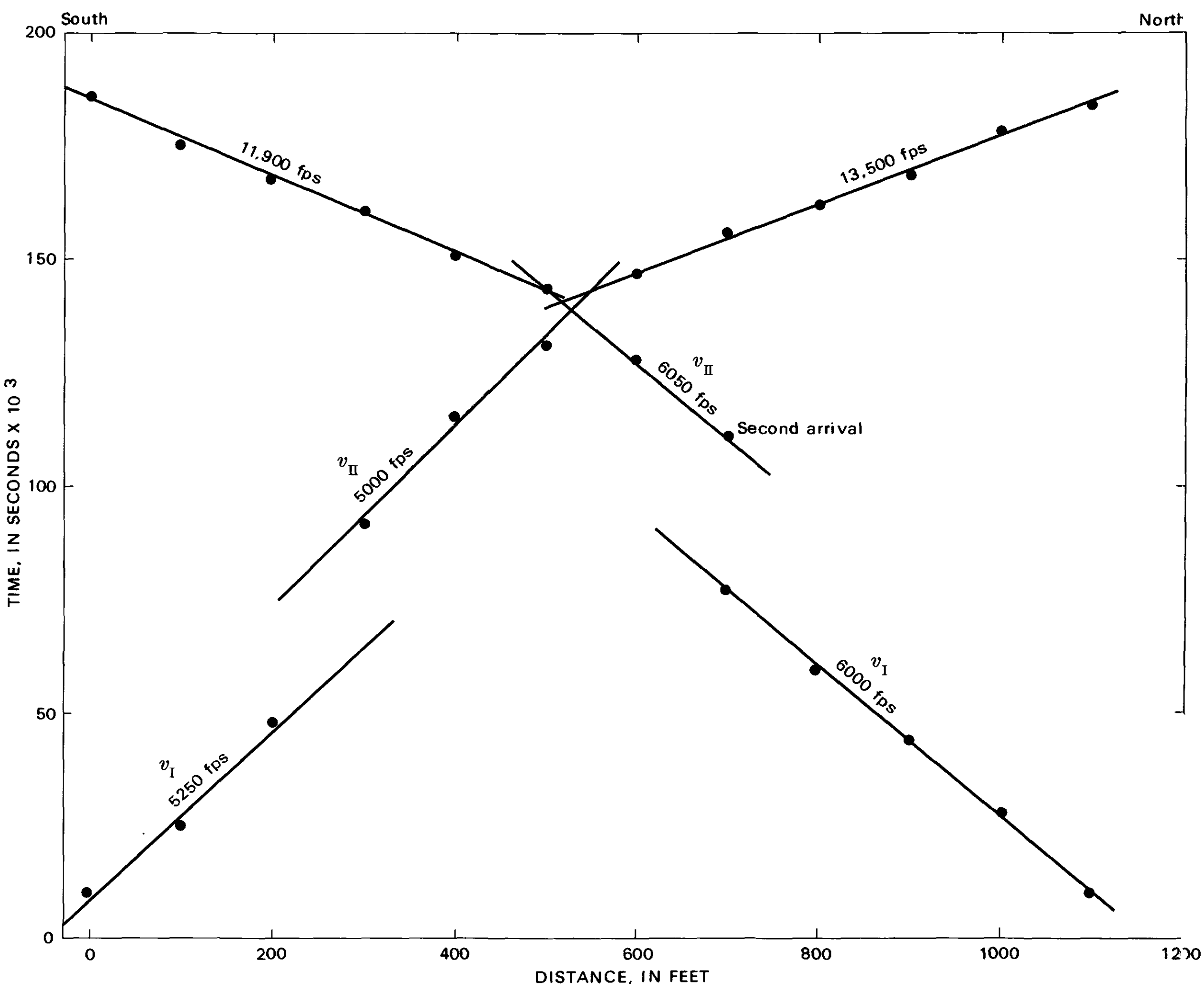


FIGURE 4.—Time-distance plot of first arrivals on line II.

The v_I amplitudes decreased by an order of magnitude from geophone to geophone in some places and were everywhere more highly attenuative with distance from the shot point than were v_{II} amplitudes.

Discontinuities were observed only at specific localities within the Fernald area. They were observed on both ends of II and HH, which are adjacent lines, but not on the south end of JJ, which overlapped II slightly. The south end of line OO, the south end of PP, and both ends of QQ recorded the phenomenon; but the north end of PP, which overlaps the south end of OO, did not.

Both $\bar{v}_I$ and $\bar{v}_{II}$ have characteristic v_1 velocities (for 10 determinations, v_I=5,400 fps, and v_{II}=5,700 fps).

The local geology was examined by means of a test auger hole near the center of line MM. The test-hole log indicated approximately 10 feet of compact clay underlain by 50 feet of apparently saturated silt and fine sand and a few thin intercalated lenses of dry compact clay.

Other investigators have observed similar discontinuities in v_1 arrivals. For example, Domzalski (1956) observed discontinuous arrivals from the following section:

Material	Thickness (ft)	Depth to base (ft)
Peat	1	1
Clay, boulder	6	7
Sand and gravel	61	68
Clay, boulder	58	126

He attributed the phenomenon to velocity reversal (higher velocities in the boulder clay than in the underlying sand and gravel). Press and Dobrin (1956) reported the phenomenon for a section composed as follows:

Material	Thickness (ft)	Depth (ft)	Velocity (fps)
Chalk, Austin	95	95	9, 900
Shale, Eagle Ford	400	495	6, 500
Sandstone, Woodbine	(?)	(?)	9, 900

They concluded that the relatively high attenuation of seismic energy in the Austin Chalk was due to leakage of energy into the underlying lower velocity material. Leakage of low-frequency energy is at a greater rate than leakage of high-frequency energy; hence, the chalk acts as a high-pass filter for horizontally traveling seismic waves. The chalk acts as a low-pass filter for energy traveling vertically and tends to lower the frequencies of waves refracted from underlying horizons.

Characteristics of seismic waves observed in the area of investigation and the presence there of a 10-foot section of compact clay just below the ground surface is consistent with Press and Dobrin's interpretation. In the study area v_I arrivals are probably propagating through compact clay near the surface, and v_{II} arrivals are probably headwaves refracted through saturated alluvium. If v_I arrivals are ignored, v_{II} is taken as 5,500 fps, and a depth of 80 feet is taken as the depth to the v_{II} layer, then $\bar{v}_0$ for material above the v_{II} layer is 3,500 fps, a velocity consistent with other v_0 in the till.

It is not clear why v_I discontinuities are observed in some areas of the till sheet but not in others. It may, however, be significant that on Crosby Road (KK–RR group) lines exhibiting v_I discontinuities are generally at slightly lower altitudes and closer to the edge of a topographic bench than other spreads. A thicker compact clay horizon away from the edge of the bench may transmit sufficient energy to mask v_{II} arrivals, or underlying sand and gravels near the edge of the bench may have lower velocities than sands and gravels at some distance from the edge of the bench, where higher velocities might be caused by a higher degree of saturation. More data are required, however, to determine a mechanism responsible for variations in the distribution of the phenomenon.

SEISMIC VELOCITIES

VELOCITY VARIATIONS IN POROUS MEDIA

Eaton and Watkins (1970) reviewed the factors determining compressional wave velocities in water-bearing rock and sediments. Their conclusions may be summarized as follows:

1. Porosity is the parameter that correlates best with compressional wave velocity. For unsaturated rocks, the Nafe and Drake (1957) equation relating the two, where n=7, 8, or 9, expresses the relation well for porosities less than 0.7 but yields velocities lower than those observed for porosities greater than 0.7 (fig. 5). For saturated sediments and rocks, the Nafe and Drake expression where n=4 or 5 expresses the porosity-velocity relation best (fig. 6).
2. Increases in differential pressure (that is, the difference between the pressure on the rock matrix and the pressure on the pore fluid) are accompanied by increases in velocities. The increase in velocity may be equivalent to an increase of 10 percent for a 500-foot increase in depth in unconsolidated rocks. Pore pressures in impermeable media diminish the rate of increase in compressional velocity with depth.
3. Complete saturation increases compressional wave velocity. Data from the literature regarding the effect of intermediate saturation levels are incomplete and contradictory.

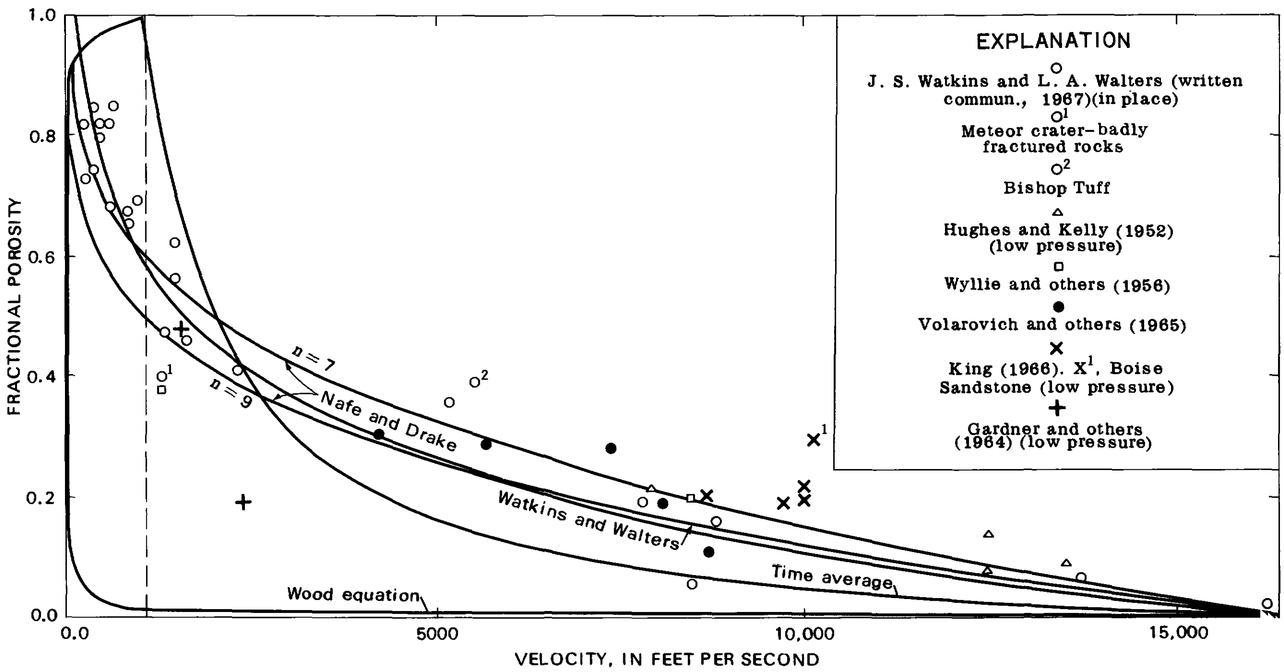


FIGURE 5.—Comparison of experimental data with velocity-porosity equations for unsaturated media, as proposed by Nafe and Drake (1957), by Wyllie, Gregory, and Gardner (1956, time-average equation and Wood equation), and by J. S. Watkins and L. A. Walters (written commun., 1967). Dashed vertical line, velocity of sound in air.

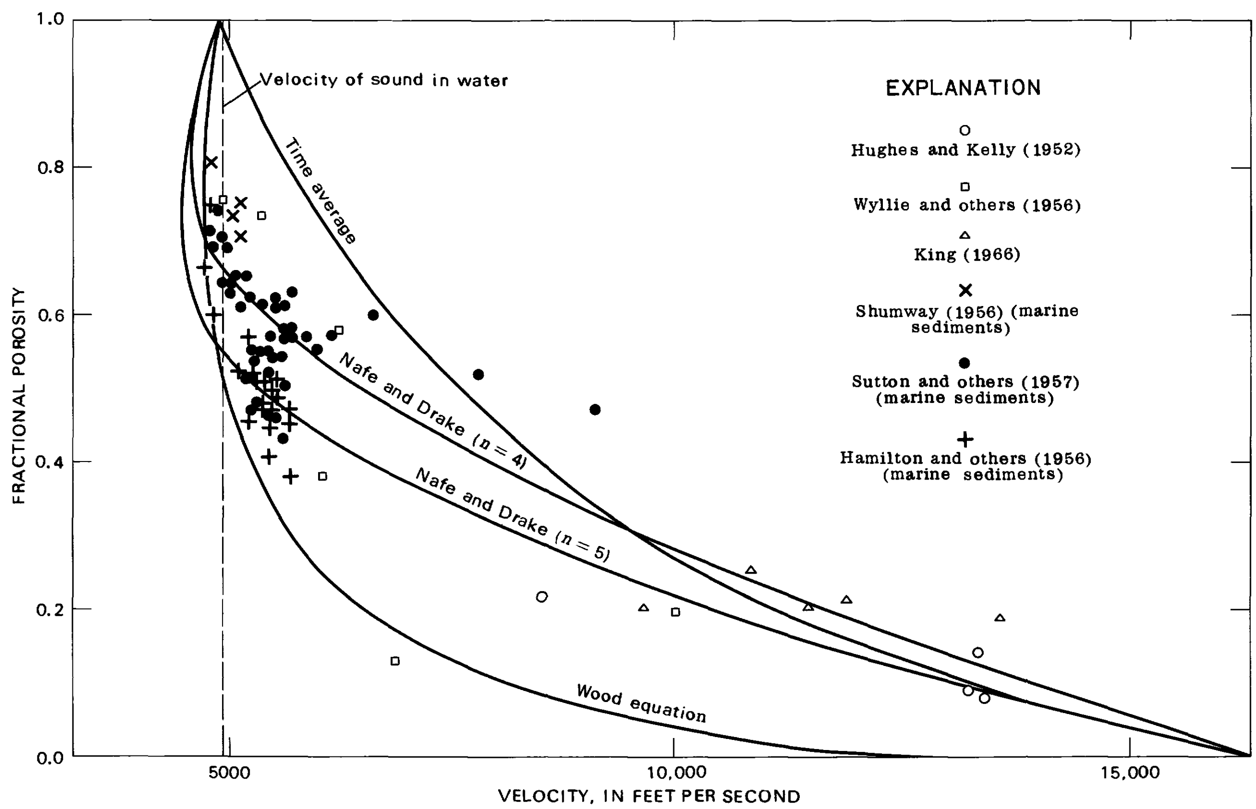


FIGURE 6.—Comparison of experimental data with velocity-porosity equations for saturated media, as proposed by Nafe and Drake (1957) and by Wyllie, Gregory, and Gardner (1956).

4. Compressional-wave velocities observed in saturated unconsolidated sediments increase with increasing grain diameter up to 0.67 mm (millimeter). No data are available for unsaturated media or cemented rocks.
5. Mineral content affects compressional-wave velocity by varying of the elastic moduli of the grains, varying of the elastic moduli of the cement, or by interaction with the saturant. No quantitative data are available to evaluate the relative importance of these mechanisms. Where clays are present, interaction with the saturant may substantially diminish the rigidity of the medium.
6. Cementation significantly increases velocities of saturated and unsaturated rock and alluvium, but no quantitative measure of cementation has been established.

OBSERVED VELOCITIES

REFRACTION MEASUREMENTS

Three, and in some places four, subsurface layers with distinctive seismic velocities were recognized during interpretation of the seismic data. The uppermost layer had a velocity that generally ranged from 1,000 to 4,500 fps. This layer was interpreted as representing the unsaturated zone. The velocity of this layer was designated v_0.

Beneath the v_0 layer, a second layer, whose velocity was designated v_1, was generally present and had velocities that generally ranged from about 4,500 to 7,000 fps. This layer was interpreted as a zone of saturated sand, clay, and gravel above bedrock. Velocities in the third, or v_2, layer generally ranged from 9,000 to 18,000 fps. This layer, in most places, was interpreted as impermeable bedrock underlying sands and gravels filling the old valley. In data from a few spreads, a deeper bedrock layer was recognized in which the velocities generally ranged from 18,000 to 24,000 fps.

THE v_0 LAYER

Shot points in 1962 were normally 25 feet from the nearest geophones. Shotholes were generally 12–14 feet deep and in the unsaturated zone for most lines. The direct arrival through the v_0 layer was generally recorded as a first arrival on the geophone nearest the shot point, although in some areas where the unsaturated zone was thick, direct v_0 arrivals were recorded as first arrivals on two or three geophones nearest the shot point. During the 1963 field season, geophone–shot point distances were commonly 50 feet or more; consequently, v_0 was rarely determinable from first-arrival data.

Velocities tended to vary as a function of location. In the following discussion and in the later discussion of v_1 data, areas are considered in a north-south sequence. As previously mentioned, v_0 data were obtained only in the area south of Hamilton that was investigated in 1962.

In the Mill Creek valley southeast of Hamilton (pl. 1), $\bar{v}_0=3{,}150$ fps with a standard deviation, $s_0=950$ fps. Data are based on 19 determinations from 14 lines. Southwest of Fairfield in six lines bounded by EE and Z, $\bar{v}_0=1{,}500$ fps; in 14 lines north of the proposed city of Cincinnati well field, 21 determinations yielded $\bar{v}_0=1{,}550$ fps; in lines 3–4 miles west, between Q and T, $\bar{v}_0=1{,}850$ fps.

Two 130-foot lines with geophones spaced 10 feet apart and shot points 10 feet off ends of lines were located in the proposed city of Cincinnati well field 200–400 feet south-southwest of TW–2. In these, v_0 ranged from 1,500 to 1,900 fps, averaged 1,675 fps, and had a standard deviation of about 150 fps.

Sixty-two determinations of v_0 from 33 lines on till in the Fernald area yielded $\bar{v}_0=2{,}700$ fps, and $s_0=850$ fps. Two 275-foot lines were near the west end of spread AX east of Harrison and south of this till sheet. The v_0 determinations ranged from 1,920 fps to 2,360 fps, averaged 2,140 fps, and had a standard deviation of 200 fps. Thirty-three determinations from 20 lines in the valley south of Harrison yielded an average of 1,850 fps for $\bar{v}_0$; $s_0=550$ fps.

Mean differences between v_0 recorded at opposite ends of lines were greater than 550 fps in 29 lines in the till area near Fernald and were about 500 fps in 14 lines south of Harrison. In 19 lines near Ross, the mean difference was about 350 fps.

The v_0 data recorded between Hamilton and the Ohio River were smoothed by the following procedure: (1) The area was gridded at 0.25-mile intervals; (2) observed velocities were averaged within a 0.25-mile radius of grid points; (3) the average was multiplied by 0.75; (4) velocities were averaged between 0.25 and 0.50; (5) then the average was multiplied by 0.25; and (6) the weighted averages obtained in steps 3 and 5 were summed. The effect of this procedure was to reduce by 75 percent or more the contribution of local variations in velocity with wavelengths of up to approximately 1 mile, to reduce by 0.25–0.75 the contribution of velocity changes with wavelengths of 1–4 miles, and to pass relatively unaffected velocity changes with wavelengths of greater than 4 miles.

The smoothed data are shown in figure 7.

THE v_1 LAYER

The v_1 data consist of 119 determinations remaining from the 1962 data after some data had been rejected

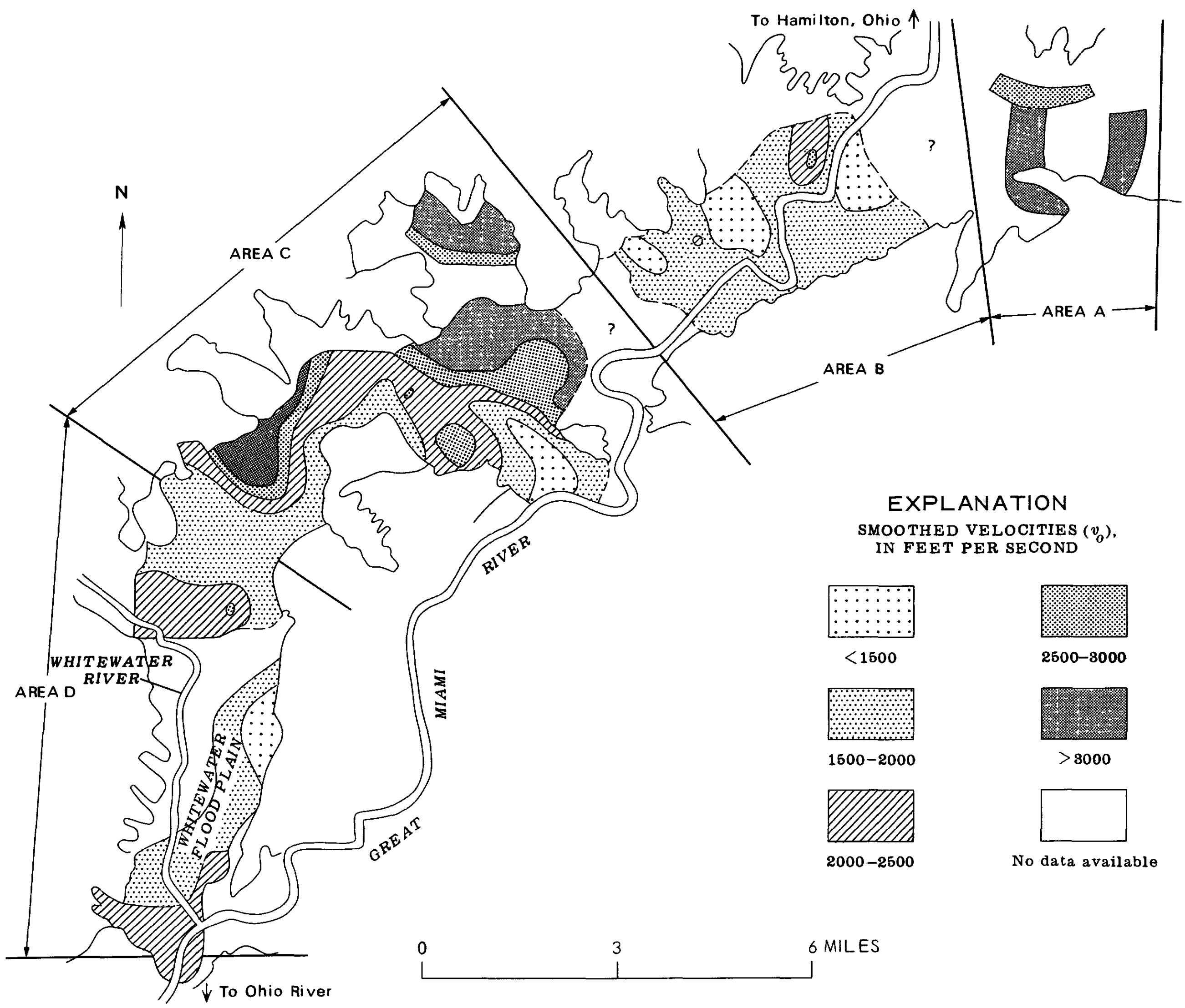


FIGURE 7.—Lateral variation in smoothed velocities of the unsaturated zone between Hamilton and the Ohio River.

because of irregular arrival times or absence of a v_1 layer. Geophone-shot point distances in 1963 data were too large to permit reliable measurement of v_1.

$\bar{v}_1$ varies perceptibly from area to area. For example, in the Mill Creek valley, southeast of Hamilton, 13 determinations yielded $\bar{v}_1$=6,050 fps. In the area extending southwest from Hamilton to the till sheet near Fernald, 25 determinations yielded $\bar{v}_1$=5,950 fps. In the proposed Cincinnati well field, 12 determinations yielded $\bar{v}_1$=6,000 fps. Two short spreads in the well field had $\bar{v}_1$ of 6,000 fps, but values ranged from 5,000 to 6,700 fps.

In the till area near Fernald, $\bar{v}_1$ was 5,500 fps for 29 determinations. Two short lines near AX immediately south of the edge of the till sheet have $\bar{v}_1$ of 5,950 fps, and a range of 5,200–6,700 fps.

In the area south of the till sheet, 22 determinations yielded $\bar{v}_1$ of 5,450 fps. Overall, 119 determinations of $\bar{v}_1$ yielded $\bar{v}_1$=5,700 fps and a standard deviation of about 650 fps. Six determinations on four short lines yielded $\bar{v}_1$=6,000 fps. In the four short lines, two of which were 275 feet long and two of which were 130 feet long, velocities on opposite ends differed by 1,500 and 1,700 fps, respectively. Larger differences were occasionally observed on longer spreads. These are not apparent velocities due to dipping interfaces but are true velocities observed on reversed spreads.

The v_1 data were filtered and plotted in the same manner as the v_0 data (fig. 7) but could not be contoured with confidence at a meaningful contour interval.

THE v_2 LAYER

In the 1962 data, $\bar{v}_2$=13,000 fps for 92 determinations, and s_2=1,400 fps. For the 1963 data, $\bar{v}_2$=13,200 fps for 64 determinations, and s_2=2,000 fps. The smaller standard deviation of the 1962 data probably reflects, in part, some subjectivity in selecting data, for, in deeper parts of the valley, v_2 arrivals were recorded by only one, two, or three geophones on many spreads. In these areas, determination of v_2 was commonly difficult. This led to rejection of a significant number of the determinations. (Values from adjacent lines were used for interpretation of depth.)

Areal distribution in $\bar{v}_2$ was not observed. The possibility that differential erosion created ledges in the bedrock surface of the preglacial valley that could be detected by examining velocities as a function of depth in a given area was considered, but cross sections gave no evidence of such a relationship.

In some areas, additional higher velocity bedrock horizons were detected at depth, particularly in the area between Hamilton and Middletown, but lateral correlation of depths of the higher velocity bedrock layers was questionable. Data were not sufficiently comprehensive to suggest reasons for the questionable results.

The only observed lateral variation in v_2 was the existence of relatively low seismic velocities, 9,000–11,500 fps, where bedrock consisted of an old upland surface covered by a veneer of glacial drift. Table 2 summarizes data from some such lines. The relation is not ubiquitous, for in lines 20 and 34 velocities of 14,000 and 15,000 fps were observed, and in line AM 12,800 fps was observed. In each line, bedrock was confirmed during augering for shotholes.

TABLE 2.—*Bedrock velocities observed where former upland surface is covered by a veneer (less than 25 ft. thick) of sand and gravel*

Spread	v_2 *(fps)*
20	[1] 14,000
52	10,800
51	11,400
33	[1] 10,500
34	[1] 11,000–15,000
35	[1] 11,600
G	[1] 10,100
AM	[1] 9,100–12,800
BN	9,700
BM	9,900
BL	8,800
BI	9,400

[1] Bedrock confirmed during augering for shotholes.

SUMMARY OF REFRACTION MEASUREMENTS

All v_i values varied widely: $s_2/\bar{v}_2=0.13$; $s_1/\bar{v}_1=0.11$; and $s_0/\bar{v}_0=0.23$. Areal distributions in velocities were observed in subsets of $\bar{v}_0$ and $\bar{v}_1$, but variations in $\bar{v}_2$ consisted only of generally lower values in areas where the old upland surface was covered with a veneer of sand and gravel.

INHOLE MEASUREMENTS

After examination of wells and well logs available within the area of investigation, eight wells (pl. 1) were selected for inhole seismic-velocity measurements. All but one of the wells are in the south-central part of the area. A wider distribution was desirable, but attempts to locate other wells for logging in both the northern and the southernmost parts of the area were unsuccessful. All the wells selected are at least 100 feet deep and bottom below the water table. Three wells penetrate bedrock, and the bottom of a fourth is thought to be very close to bedrock.

TW–2 is near the intersection of lines C and D, and AEC–A and AEC–2 are near lines BW and BU, respectively (pl. 1, west half). Mt–49 (pl. 1, east half) and BU–8 (pl. 1, west half) are adjacent to lines 3 and BP, respectively. K–1, B–2, and R–7 (pl. 1, west half) are not near seismic lines, but the velocity data from these holes are thought to be similar to data from the general area.

Sand and gravel were the predominant materials below the water level in all wells (table 3). Examination of water-well logs throughout the area of investigation suggests that materials in these wells are typical of the study area as a whole. Only one log, Mt–49, showed that bedrock was penetrated deeply enough to give useful velocity data from bedrock. The logs of B–2 and K–1 are cursory, and no log of R–7 is available.

Table 4 shows inhole velocities contrasted with velocities observed in nearby refraction lines.

INTERPRETATION OF VELOCITY DATA

In figure 7 heavy dark lines outline the bedrock walls of the valley of the ancestral Great Miami River. The present river flows southward into the valley from the northeast, flows southwest within the valley for about 8 miles, and then debouches southward into a smaller valley (not shown) cut during later Pleistocene time. The river reenters the ancestral valley in the southwest corner of the area shown in figure 7 and flows southward within the ancestral valley for the rest of the distance to its confluence with the Ohio River, about 3 miles south of the area shown in figure 7.

The Whitewater River flows southeastward into the ancestral valley in the west-central part of the area shown in the figure. It turns south and flows within the valley to its confluence with the Great Miami River near the south edge of the area shown in figure 7.

Figure 7 is divided into four generalized areas on the basis of velocities in the unconsolidated alluvium. In area A, surface and near-surface alluvium consist largely of lacustrine clays which have v_0 in excess of 2,500 fps. The relatively high velocities are typical of clays within the area of investigation and are thought to be caused primarily by high water content due to adsorption by clay particles.

Table 3.—*Drillers' logs of wells shot for velocity*

Composition	Thickness (feet)	Depth (feet)
AEC-2		
Soil and fill	5	5
Clay (till)	17	22
Sand	1	23
Clay and gravel	22	45
Gravel	2	47
Clay and gravel	5	52
Gravel	3	55
Clay, sandy	5	60
Sand and gravel	64	124
Clay	16	140
Sand and gravel	70	210
Water level		61
AEC-A		
Fill	5	5
Clay (till)	45	50
Sand and gravel	88	138
Clay	2	140
Water level		70
TW-2		
Soil, clay, gravel	11	11
Sand and gravel	96	107
Water level		24
Mt-49		
Gravel	30	30
Clay	2	32
Gravel	59	91
Clay	4	95
Sand and gravel	117	212
Shale	13	225
Water level		23
BU-8		
Soil and clay	2	2
Clay and boulders (lake clay?)	56	58
Sand	4	62
Hardpan (clay?)	19	81
Sand and gravel	46	127
Clay	17	144
Sand and gravel	66	210
Bedrock(?)		(?)
Water level		59

Area B consists of the flood plain of the Great Miami River and has the lowest average velocity of the four areas. The low v_0 probably indicates high porosities within the relatively well sorted sands and gravels of the flood plain.

Area C consists of a slightly dissected terrace capped in most places with till(?) and clay. Where surface materials consist of till and clay, velocities are generally greater than 2,500 fps. Small streams have transported alluvium over the till sheet and, in places, have cut through into underlying sands and gravels. In the areas underlain by transported alluvium or sands and gravels, velocities range from 1,500 to 2,500 fps. Along a small stream immediately north of the debouchment of the Great Miami River, fluvial sands and gravels have velocities averaging less than 1,500 fps.

The Whitewater River flood plain, area D, has characteristic velocities between 1,500 and 2,500 fps.

The $\bar{v}_1$ decreases from northeast to southwest between Hamilton and the Ohio River, but a relatively abrupt discontinuity occurs between v_1 in the till near Fernald and $\bar{v}_1$ in the area north of the till. The cause of this abrupt change is not known.

The general pattern of decreasing $\bar{v}_1$ from northeast to southwest is thought to be significant and is interpreted as indicative of better sorting and higher porosity in the outwash as the outwash was transported downstream from the receding glacier.

Inhole velocity data and inhole logs are generally consistent with surface-refraction data, although in AEC-2, u_1 is lower than the velocity of sound in water. The low velocities may be due to experimental error resulting from velocity-cable slack in the cased hole. Other inhole u_1 values are within 10 percent of nearby v_1 values. This is considered to be exceptionally good agreement, considering the scatter in v_1 data and the possibility of anisotropy.

Table 4.—*Velocities observed in wells, and in nearby seismic refraction lines*

[u_0 and v_0 are inhole and refraction velocities, respectively, in alluvium immediately below the surface; u_1 and v_1 are velocities in saturated alluvium below the standing water level]

Hole	Inhole velocity (fps)		Refraction velocity (fps)		v_1/u_1 [2]
	u_0 [1]	u_1	v_0	v_1	
TW-2	1,500	5,200	1,700	5,700	1.10
Mt-49 [3]	1,800	6,200	(4)	5,550	.90
BU-8	3,700	6,700	(4)	6,100±200	.90
AEC-A	3,000	4,900	Not present	5,300	1.10
AEC-2 [5]	4,700	4,600	Not present	5,400±400	1.20
K-1	1,500	[6] 7,500?			
B-2	1,800	5,800			
R-7	1,300	6,500			

[1] Average velocity above the water table; transducers did not respond in dry part of hole.
[2] Rounded to nearest 0.05.
[3] u_2=12,800 fps.
[4] Estimated to be 1,700 fps.
[5] Closest line is BU, 1,800 ft away. Other refraction velocities from lines located within 400 ft.
[6] Only three transducers recorded u_1, and one of the values was questionable.

SUMMARY

The U.S. Geological Survey mapped the bedrock surface of the ancestral Great Miami River valley between Dayton, Ohio, and the Ohio River primarily on the basis of seismic refraction data obtained during 1962 and 1963. Limited well data supplemented the seismic data. A knowledge of the altitude of the bedrock surface and of the thickness of overlying sands and gravels was necessary for the efficient utilization of ground-water resources in southwestern Ohio.

The major buried valley in the report area is 200–300 feet deep and about 2 miles wide. This valley was entrenched in the bedrock surface during interglacial ages prior to the onset of the Illinoian Glaciation. It is followed generally by the course of the present Great Miami River, though it is north and west of the Great Miami over much of its course. Illinoian and Wisconsin glaciers blocked this valley and caused the river to carve a new valley along its present course. The younger buried valley is about 100 feet below the present river level.

Detailed seismic surveys were run in an area west of Fairfield along the south wall of the major buried valley, where the city of Cincinnati proposes to develop a new well field. A shallow bedrock shelf extends under much of the eastern half of this area, but in the western half the bedrock valley floor lies 150–200 feet below the land surface. Subsequent test drilling verified the accuracy of the seismic determinations of the depth to the valley floor. Determinations on sloping surfaces were somewhat less accurate.

Three or four subsurface layers with characteristic velocities were inferred from the seismic data. Velocities in the uppermost layer (v_0) ranged from 1,000 to 4,500 fps; this layer generally consisted of unsaturated material. Velocities in the second layer (v_1) ranged from 4,500 to 7,000 fps; the layer, where present, consisted of saturated sand, clay, and gravel. Velocities in the third layer (v_2) ranged from 9,000 to 18,000 fps; this layer consisted of relatively impermeable bedrock. The fourth layer was a higher velocity layer below the bedrock surface. It is not known if the fourth layer consists of a continuous higher velocity stratum or of isolated pockets of higher velocity material. The fourth layer was indicated by seismic data in only a few locations.

Discontinuous second-layer arrivals occurred in parts of the till sheet near Fernald. The discontinuities are probably the result of a velocity reversal in a section comprising a thin stratum of compact clay or till overlying a thicker section of saturated or almost saturated sand and gravel.

Seismic velocities in the first and second layers vary systematically throughout the area. Average first-layer velocities are significantly higher in areas of surface till and lake clay than in areas of dominantly flood-plain deposits. The higher velocities associated with clays and tills are thought to be due to higher water content of clays. Between Hamilton and the Ohio River, average velocities in the second layer decrease from northeast to southwest. The decrease in velocity is thought to be due to better sorting of outwash deposits as the outwash was transported away from the receding glacier.

Modifications in field equipment and procedures in 1963, notably modular seismic-cable units which could be connected as 2,200- or 4,400-foot cables and the utilization of delay-time interpretation techniques, respectively, improved productivity and produced bedrock-depth data which appear superior to 1962 data.

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GEOLOGICAL SURVEY

William T. Pecora, *Director*

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