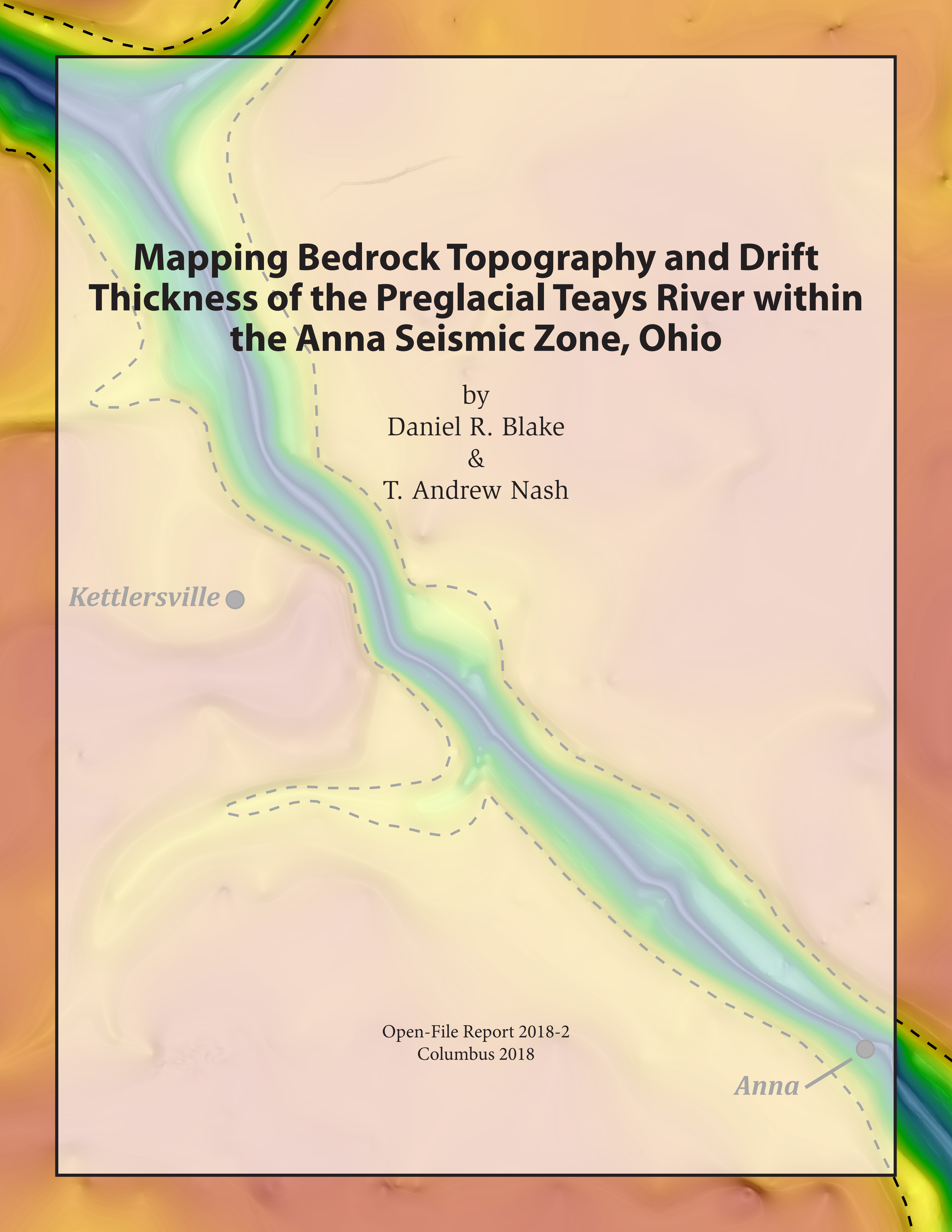

# Mapping Bedrock Topography and Drift Thickness of the Preglacial Teays River within the Anna Seismic Zone, Ohio

by
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&
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## DISCLAIMER

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## ABBREVIATIONS USED IN THIS REPORT

### *Units of Measure*

| | |
|---|---|
| centimeter(s) | cm |
| foot/feet | ft |
| feet per second | ft/s |
| Hertz | Hz |
| kilometer(s) | km |
| magnitude | M |
| mile(s) | mi |
| miles per hour | mph |
| second(s) | s |
| shear wave velocity | $V_s$ |

### *Other*

| | |
|---|---|
| elevation | elev |
| H-to-V Spectral Ratio | HVSR |
| mean sea level | m.s.l. |
| U.S. Geological Survey | USGS |

# Mapping Bedrock Topography and Drift Thickness of the Preglacial Teays River within the Anna Seismic Zone, Ohio

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## ABSTRACT

Previous mapping efforts in the Botkins and New Knoxville quadrangles in Ohio were inadequate to define the geomorphology of the preglacial Teays River valley. To better characterize the near-subsurface geology in the Teays River valley, data points were collected using a pair of Moho Tromino® Tomographs. This data resulted in a detailed bedrock-topography map, which shows a well-defined buried valley that is more gorge-like than previously interpreted. The Village of Anna, Ohio, sits directly on top of the deepest section of the buried valley (651 feet), which may explain why it suffered moderate damage in comparison to nearby towns during the earthquakes of 1937. Documenting the thickness and shear wave velocity of the glacial drift in each of the Botkins and New Knoxville quadrangles will lead to increased understanding of the likelihood and behavior of seismic amplification from earthquakes. Continued H-to-V Spectral Ratio mapping of the preglacial Teays River valley will help define seismic risk in the area and better reconstruct the geomorphology by redefining bedrock depth in the glaciated portion of the state where it was previously unknown.

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## INTRODUCTION

The surficial geology of the Botkins and New Knoxville 7.5-minute quadrangles is characterized by glacial sediments with subtle surface topography. This landscape hides a complex series of deeply buried faults below a surface of glacial materials deposited during at least three Pleistocene glacial advances (fig. 1). Geologists widely accept that in regions where thick glacial materials overlie bedrock, there is a greater risk for destructive shaking during a large earthquake.

The Botkins and New Knoxville quadrangles are located within a region in western Ohio referred to as the "Anna Seismic Zone." Since 1776, more than 40 earthquakes have been cataloged in the Anna Seismic Zone (Ohio Seismic Network, 2017). The two largest earthquakes in Ohio's history occurred in the Anna Seismic Zone on March 2 and 9, 1937, and were magnitude 4.9 and 5.4, respectively (fig. 2). The latter remains the largest earthquake recorded in the state. The 1937 events caused moderate damage to the Village of Anna, but nearby towns within approximately 10 miles (mi; Botkins, New Knoxville, and Kettlersville) reported little to no damage.

What contributed to the greater damage observed in the Village of Anna remains uncertain. Geologists have long speculated that Anna experienced more shaking relative to nearby communities because it was built directly above the preglacial Teays River Valley, while nearby towns were built over shallow bedrock (Ver Steeg, 1936; Westland and Ross, 1940). Thick sequences of Pleistocene glacial materials that fill the Teays River Valley may amplify shaking forces experienced at the ground surface.

Previous investigations lacked sufficient data to accurately describe the geologic framework in the Botkins and New Knoxville quadrangles. Technological advancements in the field of passive seismic research have provided new techniques to map the subsurface. The Ohio Department of Natural Resources, Division of Geological Survey (Ohio Geological Survey) employed the H-to-V Spectral Ratio (HVSR) method using a set of MoHo Trominos® to update a series of maps and visualize the subsurface by calculating the elevation of bedrock underneath glacial materials. This updated series of bedrock-topography and drift-thickness maps provides ample data to determine the true location of the buried valley and may shed light onto why the Village of Anna experienced moderate damage during the 1937 earthquakes.

## PREVIOUS WORK

Ohio's bedrock geology was first characterized by the Mather and Newberry surveys (Hansen and Collins, 1979). The first statewide bedrock-geologic map for Ohio was completed in 1870 by the Newberry Survey. The most recent version was compiled by Slucher and others (2006) at a 1:500,000 scale. The first statewide bedrock-topography map

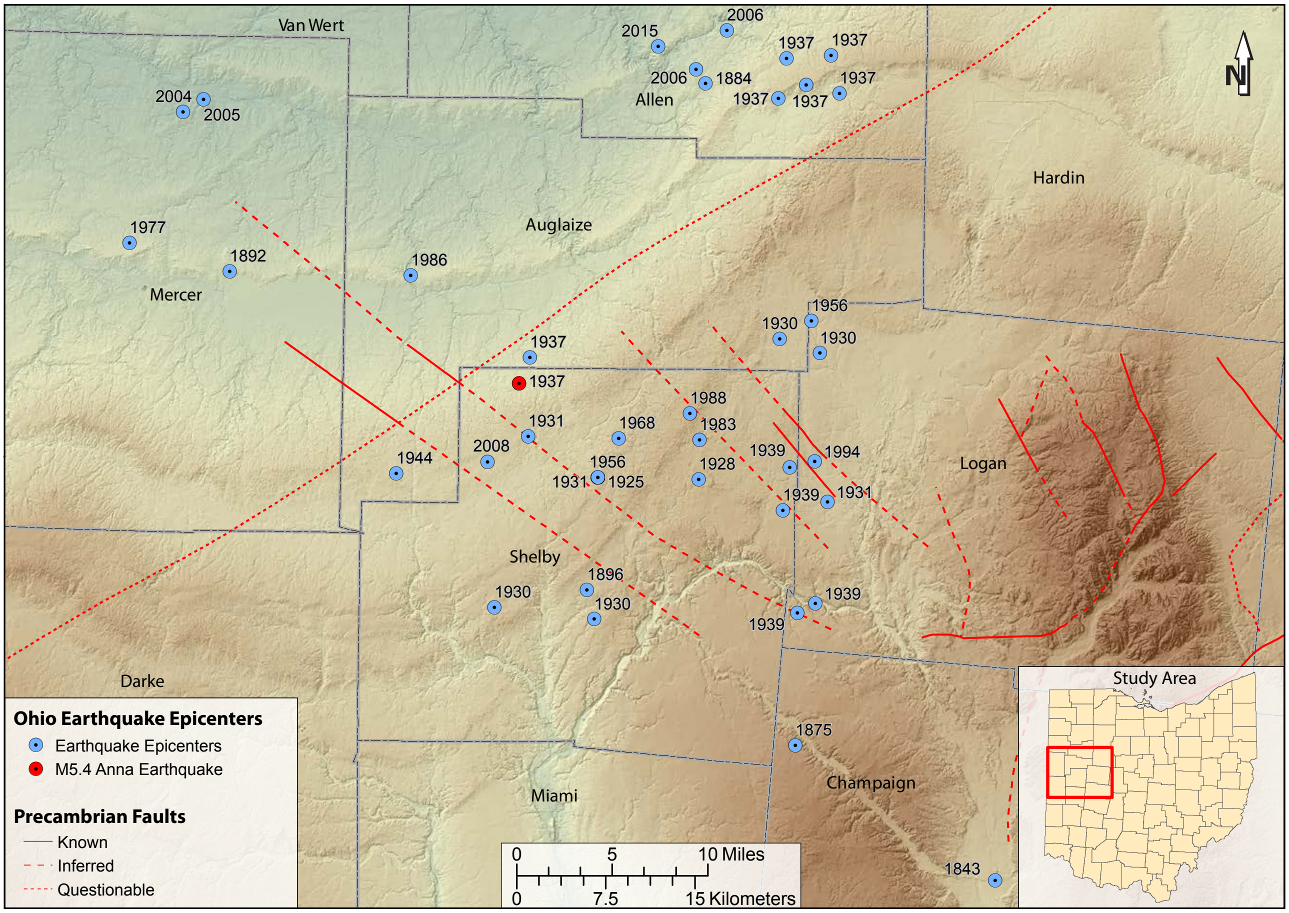


**FIGURE 1. Earthquake epicenters and Precambrian faults within the Anna Seismic Zone, Ohio.**

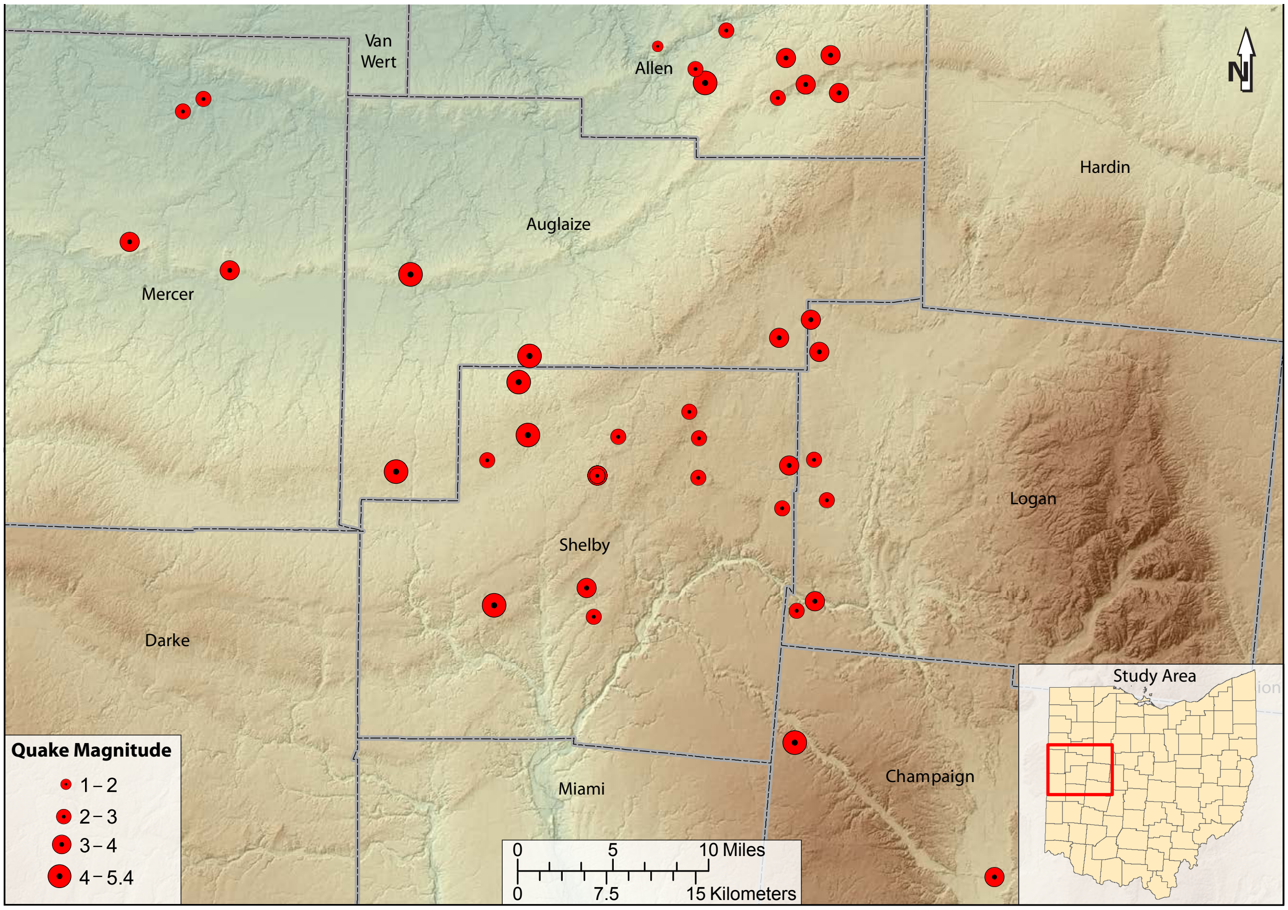


**FIGURE 2. Distribution of earthquakes within the Anna Seismic Zone, Ohio. Each earthquake is categorized by magnitude.**

of Ohio was completed by Brockman and others (2003). This effort was followed by a release of the first shaded drift-thickness map of Ohio (Powers and Swinford, 2004). The HVSR method was tested in Franklin County, Ohio (Haefner and others, 2010). These reports and associated data provided a wealth of information that was used in this study.

## PROJECT AREA AND PURPOSE

Seismic risk refers to the risk of physical damage during earthquakes because of ground shaking experienced by infrastructure and the built environment. Western Ohio contains two important geologic features with potential implications for seismic risk: the Anna Seismic Zone and the valley of the preglacial Teays River. The Anna Seismic Zone is an area of historically greater seismic activity, and the Teays River Valley is a buried-valley system where thicker glacial sediments have the potential to increase shaking intensity during an earthquake. The deepest section of the Teays River Valley in Ohio occurs in western Ohio and partially overlaps the Anna Seismic Zone. However, the Teays River Valley in western Ohio has been detected mainly using water well logs, and its width, depth, and in some areas, its exact location are subject to some uncertainty. The purpose of this study was (1) to test methods to better constrain the location of the Teays River Valley and (2) to investigate whether the location of the Village of Anna, with respect to the Teays River Valley, may contribute to greater seismic risk.

## THE ANNA SEISMIC ZONE

Historically, the Anna Seismic Zone is one of the most seismically active areas in Ohio. The earliest earthquake on record occurred in 1875, and since then, more than 40 earthquakes have shaken the region (Ohio Seismic Network, 2017). The two largest earthquakes in the Anna Seismic Zone occurred within a seven-day period on March 2 and 9, 1937, and were magnitude 4.9 and 5.4, respectively. The latter remains the largest earthquake recorded in the state. The 1937 events caused moderate damage to the Village of Anna and surrounding communities. The M5.4 quake was felt in eight states—Ohio, Indiana, Michigan, Kentucky, Wisconsin, West Virginia, Illinois, and Pennsylvania—as well as parts of Canada. The most commonly reported damage included toppled chimneys, broken windows, and cracked plaster. The town's church was badly damaged, and the high school was damaged beyond repair and required demolition. Rotated and crooked gravestones in Anna's cemeteries were also noted after the earthquakes (Westland and Ross, 1940).

## PREGLACIAL DRAINAGE IN WEST-CENTRAL OHIO

The Botkins and New Knoxville quadrangles are located within the glaciated region of Ohio that covers about two-thirds of the state (fig. 3). Glaciers advanced into these quadrangles at least three times during the Pleistocene Epoch, which included the Pre-Illinoian, Illinoian, and Wisconsinan glaciations. Sediments entrained by ice, water, and wind were deposited during each of these glaciations, filling in and smoothing over the preglacial landscape, which was previously characterized by the deeply incised Teays drainage system (fig. 4).

The Teays River was the master stream for a large preglacial drainage network, which had its headwaters in the Appalachian Mountains of North Carolina (Hansen, 1995). The Teays River entered Ohio from Kentucky through a valley in Wheelersburg, Ohio, and continued north towards Chillicothe, Ohio (Stout and others, 1943). In Chillicothe, the location of the Teays River Valley is obscured beneath thick glacial deposits (Pavey and others, 1999; Erber and Spahr, 2017). Previous studies traced the buried valley northwestward through Madison, Champaign, Clark, Shelby, Auglaize, and Mercer Counties before it flowed into Indiana (Stout and others, 1943; Norris and Spicer, 1958). This stream rapidly incised the carbonate bedrock of west-central Ohio, creating a steep-walled valley and generally flat uplands adjacent to the valley (Norris and Spicer, 1958). Each major glacial advance that entered the region contributed to the burial of the Teays River Valley, but the first significant advance of pre-Illinoian ice likely had the most effect in the reorganization of drainage patterns in Ohio. Subsequent glacial advances during the Illinoian and Wisconsinan periods finished burying the deep valley and flattened the modern landscape in west-central Ohio. The modern landscape now exhibits generally low relief, with minimal change in topography controlled by the ridges of the St. Johns and the Mississinewa Moraines (Forsyth, 1956).

## METHODS

### H-to-V Spectral Ratio (HVSR)

The HVSR passive seismic method is widely accepted as a technique to assess seismic risk (Nogoshi and Igarashi, 1971; Nakamura, 1989). The HVSR method takes advantage of the theory of fundamental resonance, which is the lowest natural frequency of vibration determined by physical parameters of a material. The fundamental resonance frequency of a uniform, low-velocity surface layer is associated with a wavelength that is four times the thickness of the surface layer (Reynolds, 2011). The HVSR method estimates the ratio between the Fourier

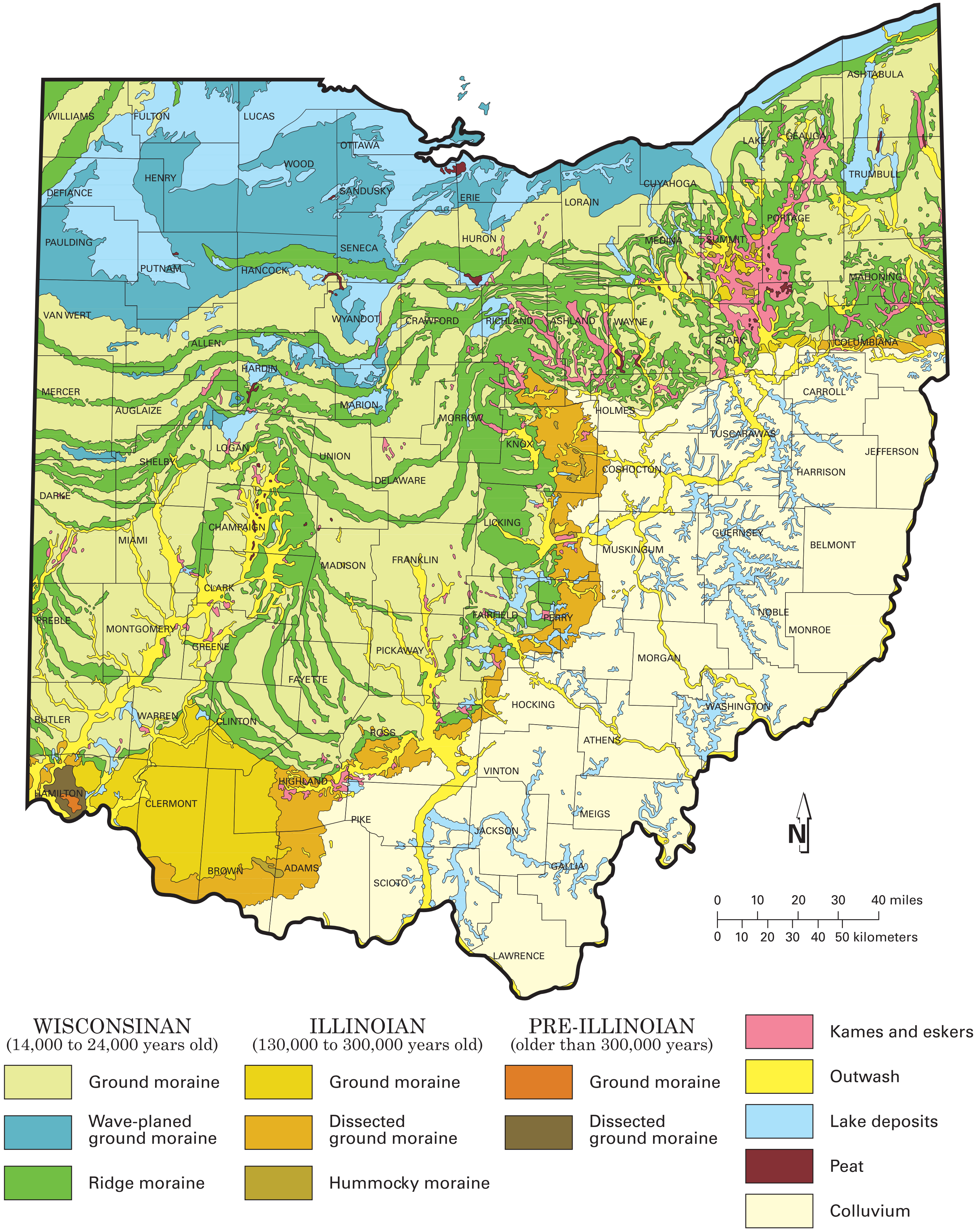


**FIGURE 3. Glacial map of Ohio (Ohio Geological Survey, 2005). Approximately two-thirds of the state is covered by glacial materials.**

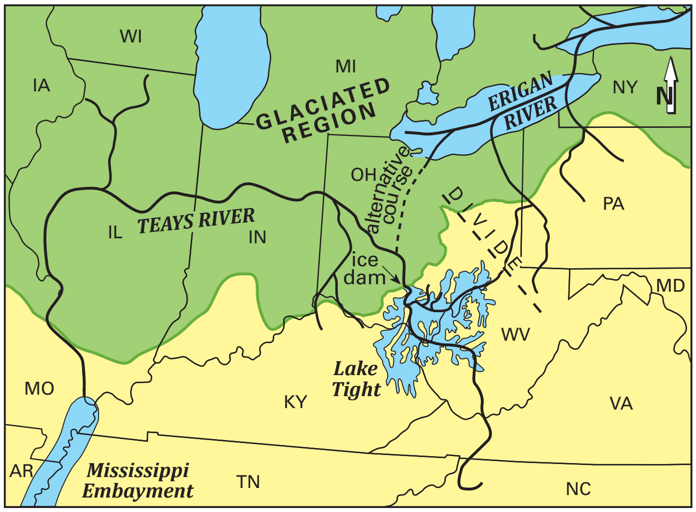


**FIGURE 4. Classic interpretation of the preglacial Teays River System in the north-central United States (from Hansen, 1995).**

amplitude spectra of the horizontal (H) to the vertical (V) components of ambient noise vibrations at one single station (Nakamura, 1989). H-to-V spectral ratios in the peak frequency range are not affected by the fundamental mode Rayleigh wave but instead by the local site characteristics, allowing for a direct comparison with the s-wave transfer function (Nakamura, 1989; Fah and others, 2001). This model is valid under the assumptions that the sediments are soft, the bedrock is hard (or has significantly higher acoustical impedance), and the bedrock-sediment interface is a horizontal plane.

## Field Acquisition

HVSR data were acquired in the Botkins and New Knoxville quadrangles with MoHo Tromino® 3G Digital Tomographs (fig. 5). The field area was partitioned into a grid (fig. 6) and data were collected at 0.5-mi (0.8-km) spacing along each east–west road. Each record was collected by following a set of modified field procedures described in Chandler and Lively (2014). The Tromino® was programmed with specific parameters, which included sampling rate, record length, and frequency range. Sampling rate and record length are dependent on the expected frequency range, which in turn depends on the thickness of the glacial sediments and their shear wave velocities. Because sediment thickness is highly variable in the region, the Ohio Geological Survey selected a wide frequency range (128 Hz) and a long recording time (16 minutes) to capture signals in the expected frequency range of 0.5–64 Hz (Chandler and Lively, 2014).

To improve the seismic signal, additional quality-control steps were taken, which include the use of a tri-field meter, soil penetrometer, and wind-speed meter (anemometer). The tri-field meter was used first to measure the strength of the electromagnetic field, to determine if a site had excessively noisy magnetic and electric fields, and also to determine the intensity of electromagnetic waves (radio and microwave). Second, a spring-operated, aluminum, pocket-sized soil penetrometer was used to measure the compressive strength of the soil, to determine if the site was too stiff for siting the instrument. Finally, an anemometer was used to determine wind speed at the time of the recordings (Mucciarelli and others, 2005).

The ideal site is flat and located away from trees, corn stalks, or other tall structures that might vibrate if wind gusts occur during the sampling period. Spikes (5 cm long) provided with the Tromino were screwed into the bottom of the instrument, and the instrument was pressed into the soil slowly, allowing the spikes to penetrate the soil and the body of the instrument to couple to the ground. The unit was leveled, if necessary, without loosening the spikes in the soil. During placement, the instrument was oriented toward geographic north using the iPhone 7 compass application, allowing for the detection of directional signal bias along both horizontal axes.

Following these procedures, a significant amount of interference and noise was eliminated. Wind-related interference was mitigated by keeping the device covered by a large bowl during data collection and only collecting data on dates when the wind speed was below 10 mph. Anthropogenic sources of noise were removed by moving the instrument away from the sources (typically overhead or buried power lines).

## Post-Processing

Data were imported into GRILLA® for post-processing, analysis, and interpretation. The post-processing (de-trending, tapering, and padding with zeros) is performed automatically by GRILLA®. The amplitude spectra of the three components (vertical, east-west, and north-south) were computed for each 20-second (s) window via Fast Fourier Transform and smoothed with a triangular 10 percent window, as recommended in

**FIGURE 5. The MoHo Tromino® Tomograph in the field at an ideal site. The ground surface was cleared of any vegetation before positioning the Tromino® instrument.**

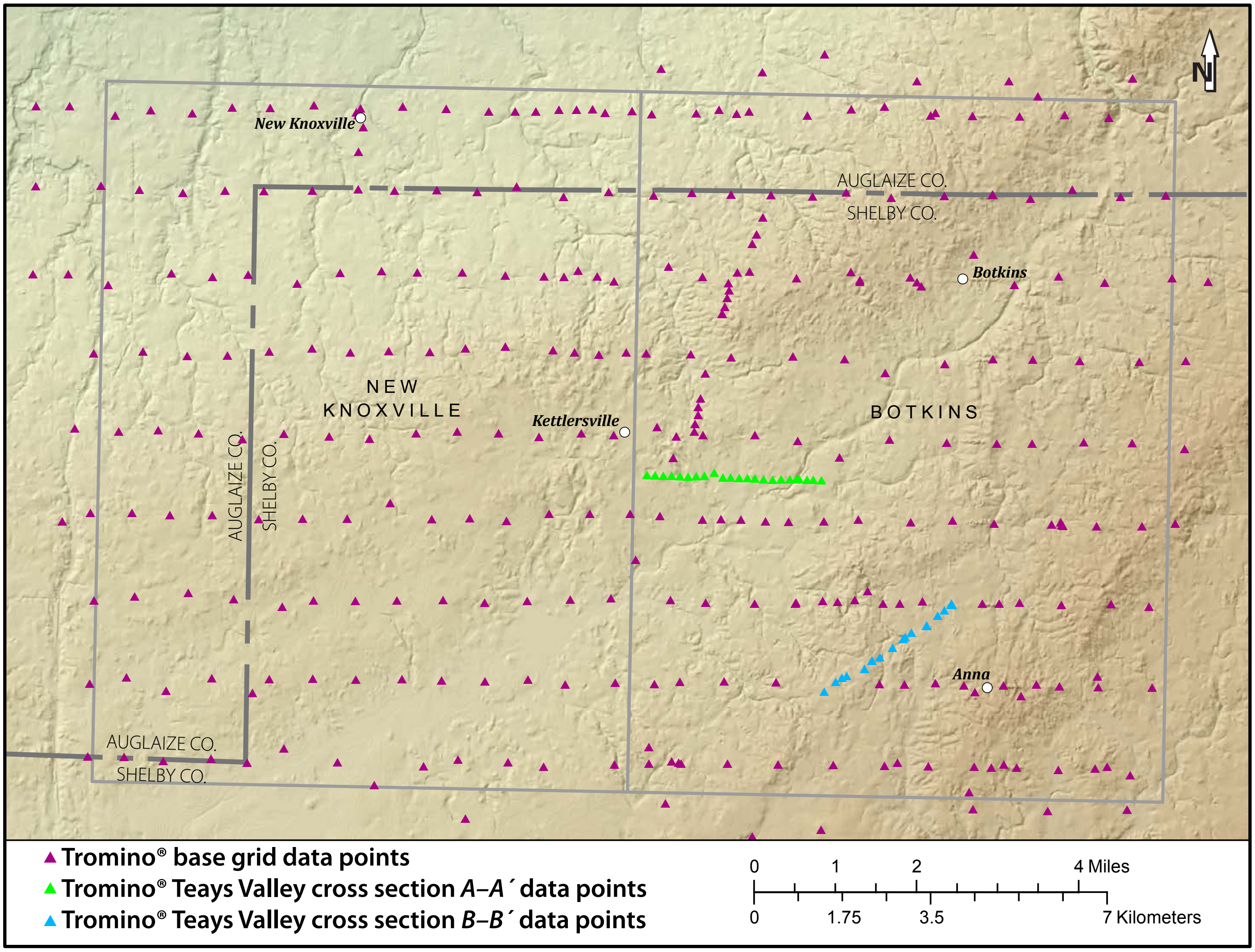


**FIGURE 6. Data points collected in the Botkins and New Knoxville quadrangles, Ohio. Each point was collected with the MoHo Tromino®. A total of 368 points were collected.**

the manual (Chandler and Lively, 2014). The geometric average of the two horizontal spectra (the square root of the product) is divided by the vertical spectrum to obtain the horizontal-to-vertical spectral ratio (HVSR). Both the spectra of the components and the HVSR are then averaged for all sampling windows.

The results were compared with nine statistical criteria developed by the SESAME (Site EffectS Assessment using AMbient Excitations) consortium as guidelines for evaluating the reliability and clarity of HVSR data (Chandler and Lively, 2014). These criteria test for adequate sampling of the selected HVSR peak, for statistical consistency of amplitudes and peak frequencies of averaged HVSR spectra, and for amplitude of the HVSR peak (SESAME, 2004). If several criteria were unfavorable, the analysis was repeated using a larger window with greater smoothing, usually a 40-s window with 20 percent smoothing. In a few cases, a 60-s window with 30 percent smoothing was tried, and the smallest window that satisfied all or most of the criteria was selected as the best interpretation (Chandler and Lively, 2014).

## Interpretation

Data interpretation methods were derived from Chandler and Lively (2014). Assuming that the observed HVSR peak adequately represents the fundamental resonant frequency of sediment, and if the sediment-basement contact is flat with a strong acoustic impedance contrast (>2.5), the HVSR peak frequency can be empirically related to sediment thickness (Ibs-von Seht and Wohlenberg, 1999; Lane and others, 2008).

For the simplest case of a uniform sediment layer:

$$m = \frac{V_s}{4fh_v} \qquad (1)$$

where $m$ = thickness of the sediment layer, $V_s$ = shear wave velocity, and $fh_v$ = HVSR peak frequency.

Shear wave velocities tend to increase non-linearly with depth, because of compaction and other factors, and the distribution of shear wave velocities in a sediment layer can be more effectively approximated by a power law in the form (Budny, 1984):

$$V_s(Z) = Vs0*(1+Z)^\wedge x \qquad (2)$$

where $z$ = depth; $V_s0$ = shear wave velocity at the surface; $Z = z/z0$, with $z0 = 1\text{m}$; and $x$ = describes the depth dependence of shear wave velocity.

And in this case, the thickness of the sediment ($m$) is:

$$m = ((V_s0(1-x)/4fr)^\wedge 1/1-x)-1 \qquad (3)$$

Ibs-Von Seht and Wohlenberg (1999) demonstrated that an empirical relationship could be established between $m$ and the observed HVSR peak frequency as follows:

$$m = a*fhv^\wedge b \qquad (4)$$

where parameters $a$ and $b$ are determined empirically by collecting HVSR data at control points (water wells) that span a wide range of thicknesses and include a sufficient number of points for reasonable statistics.

## Calibration Curve

Because of a lack of published shear-wave velocity data for the unconsolidated materials in the study area, a localized calibration curve was created to estimate bedrock depth (fig. 7). A total of 58 wells were selected within the Botkins and New Knoxville quadrangles for analysis (fig. 8). Mostly water wells, they represented points of known bedrock depth, from 41 to 235 ft, which were used to calibrate HVSR measurements taken with the Tromino® instrument placed close to the wells. The localized calibration curve shows peak frequency plotted against the bedrock depth using a power regression, which is represented in the form $y = ax^\wedge b$. The curve shows a good fit ($R^2 = 0.8477$; fig. 7).

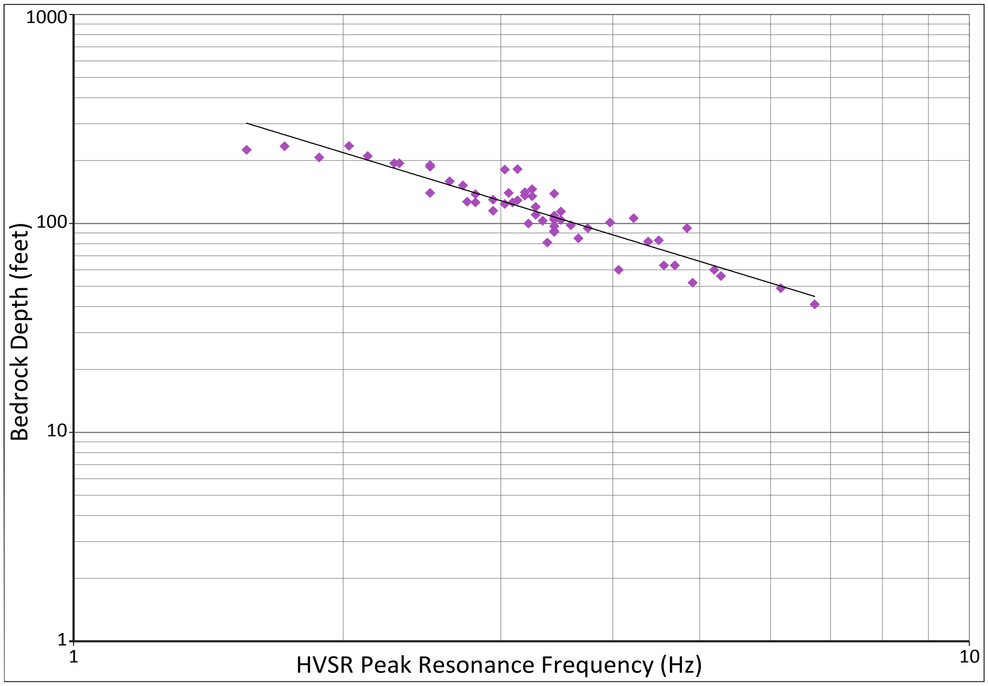


**FIGURE 7. Localized calibration curve created for the Botkins and New Knoxville quadrangles, Ohio. The curve was created using the HVSR data in a power regression function (y = ax^b) . The a value = 539.98, b value = –1.307, and the $R^2$ = 0.8477.**

## Mapping Techniques

New bedrock-topography and drift-thickness raster surfaces were created using a modified version of the ArcGIS® tool created by Erber and Spahr (2017). Bedrock elevation points from water well logs were verified for location and log accuracy. Well logs with inadequate location data or lithologic information were not used in the interpolation of the bedrock surface. Bedrock elevation points from water well logs and Tromino® measurements were contoured by hand with a 50-ft contour interval. The custom GIS tool by Erber and Spahr (2017) uses the Topo to Raster tool to interpolate a hydrologically correct bedrock surface with a 10-ft cell size. This bedrock topography raster is then subtracted from a 2.5-ft resolution digital elevation model (DEM) to create a drift-thickness raster with a 10-ft cell size. The Plus/Minus raster surface was created by using the Minus tool to subtract the new bedrock-topography surface from the original bedrock-topography surface. Other raster surfaces of velocity and frequency were interpolated from Tromino® data points using Inverse Distance Weighted (IDW) interpolation.

## RESULTS

The HVSR method used in this study produced new frequency, velocity, bedrock-topography, and drift-thickness data. The HVSR map shows the peak frequency within the Botkins and New Knoxville quadrangles (fig. 9). The highest frequency recorded by the Tromino® was 6.97 Hz. The lowest frequency recorded by the Tromino® was 0.88 Hz. The velocity map shows the estimated speeds at which shear waves travel through glacial material within the Botkins and New Knoxville quadrangles (fig. 10). The calculated velocities range from 974 to 2,279 ft/s. The updated bedrock-topography (BT) map shows changes in elevation of the bedrock surface buried beneath glacial material (fig. 11). The elevation range reported in this study ranges from 367 to 963 ft above m.s.l. The drift-thickness (DT) map shows the amount of unconsolidated sediment from the land surface to the bedrock surface (fig. 12). Drift thickness varies in the study area from 39 to 651 ft.

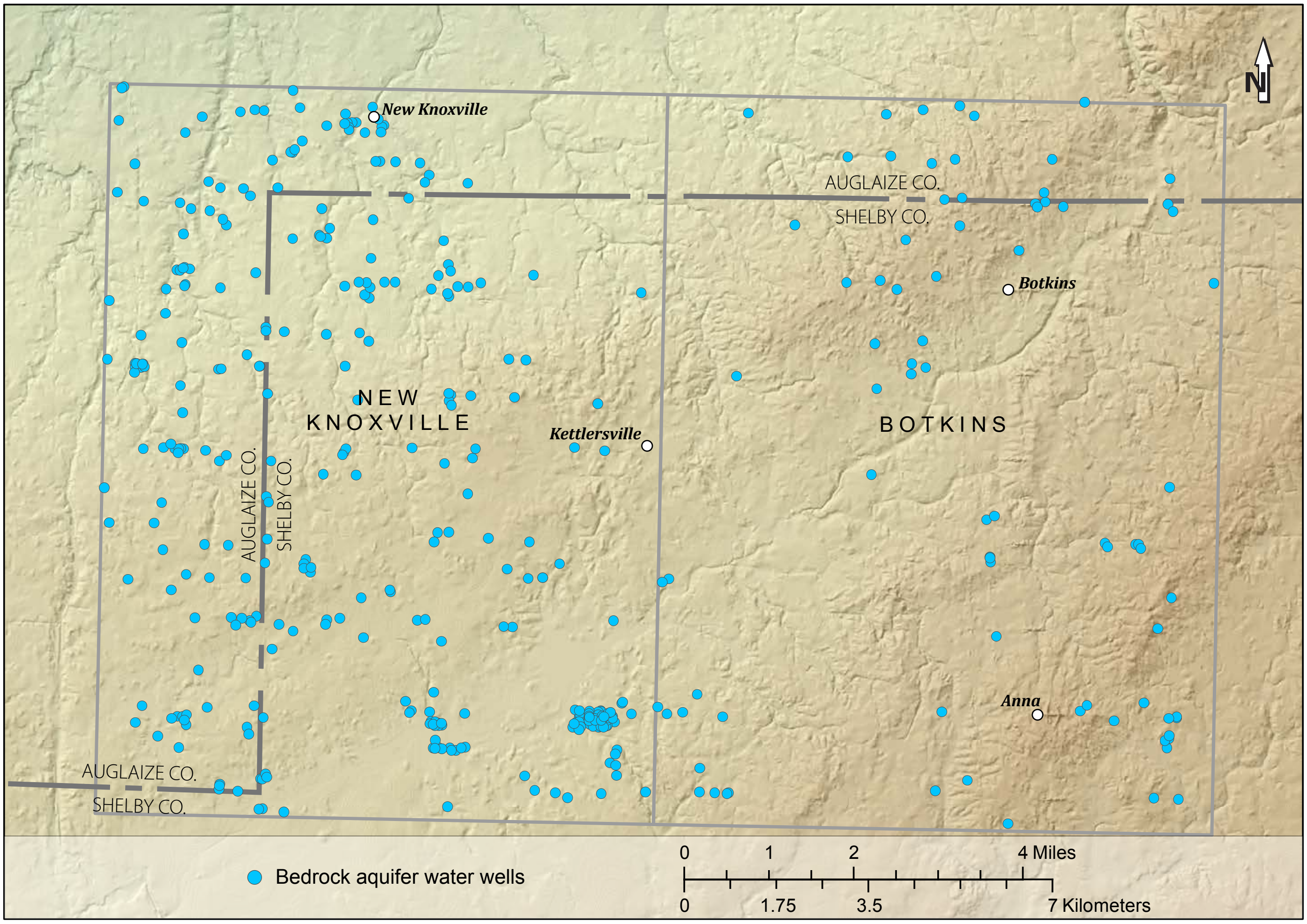


**FIGURE 8. Distribution of water wells that penetrate bedrock in the Botkins and New Knoxville quadrangles, Ohio.**

## DISCUSSION

### Regional Framework of the Teays River Valley

Improved mapping of the Teays River Valley in the Botkins and New Knoxville quadrangles allowed for a new interpretation of how this valley segment fits into the greater regional picture of preglacial drainage (fig. 11). Geophysical studies and drilling records from Indiana have traced the route of the Teays River Valley from west-central Ohio to the Mahomet valley in Illinois (Fidlar, 1948; Wayne, 1956). Gray (1991) and Bleuer (1991) described the Teays Valley in eastern Indiana as a relatively straight, steep-walled gorge, which is vastly different from their findings of complex branching valley morphology in western Indiana. The updated bedrock-topography map (fig. 11) falls more in line with Gray (1991) and Bleuer's (1991) description of the bedrock valley in eastern Indiana, which is likely controlled by carbonate bedrock in both segments of the valley. While there are many similarities between the bedrock valley of eastern Indiana and the segment of the Teays River Valley mapped in western Ohio, there are also some key differences.

The key differences between the present research in western Ohio and the work done by Gray (1991) and Bleuer (1991) in east-central Indiana pertain to the thalweg elevations and stream flow directions. In the updated bedrock topography map, near the Village of Anna (fig. 11), a minimum elevation of 367 ft above m.s.l. was recorded. Our findings also indicate that the Botkins segment of the Teays River Valley flowed in a generally northwestern direction towards Indiana. Gray (1982) and Bleuer (1991) reported that the deepest bedrock is at approximately 500 ft above m.s.l., although the exact elevations of the thalweg (deepest part) were not always well defined in their mapping efforts. Mapping of the bedrock topography in Adams County, Indiana, shows a relative bedrock high in the Marion segment of the Teays River Valley near Berne, Indiana (Gray, 1982). The configuration of bedrock-topography contours in Gray (1982) show an eastern flow direction toward Ohio east of Berne, Indiana, and a westward flow direction west of Berne, Indiana. Ohio Geological Survey findings follow the consensus view that the Teays flowed out of Ohio toward the west. Results from bedrock-topography mapping in Indiana and the present study

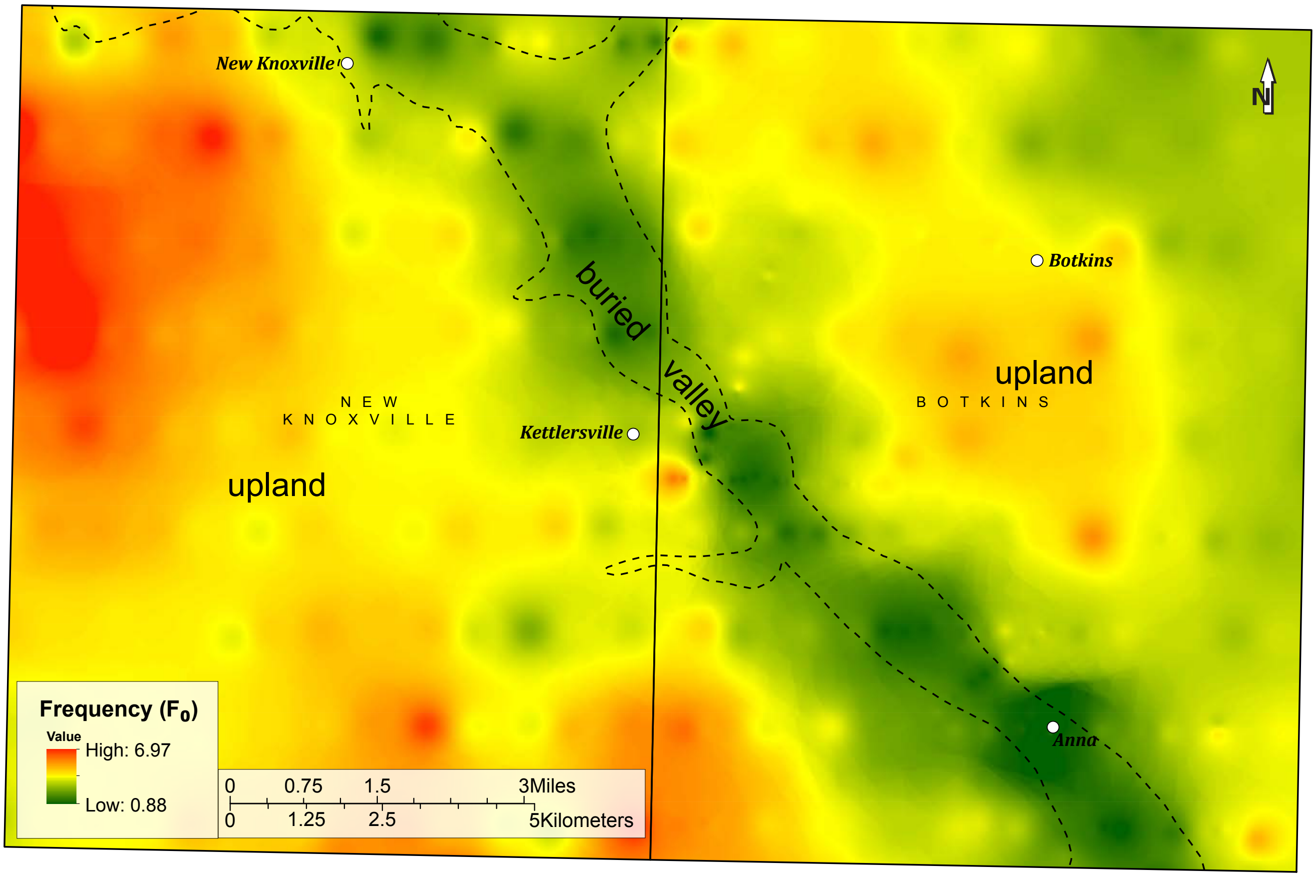


FIGURE 9. The Moho Tromino® recorded the fundamental resonant frequency at 368 data points in the Botkins and New Knoxville quadrangles, Ohio. The data points were then rasterized in ArcGIS® using the IDW interpolation tool.

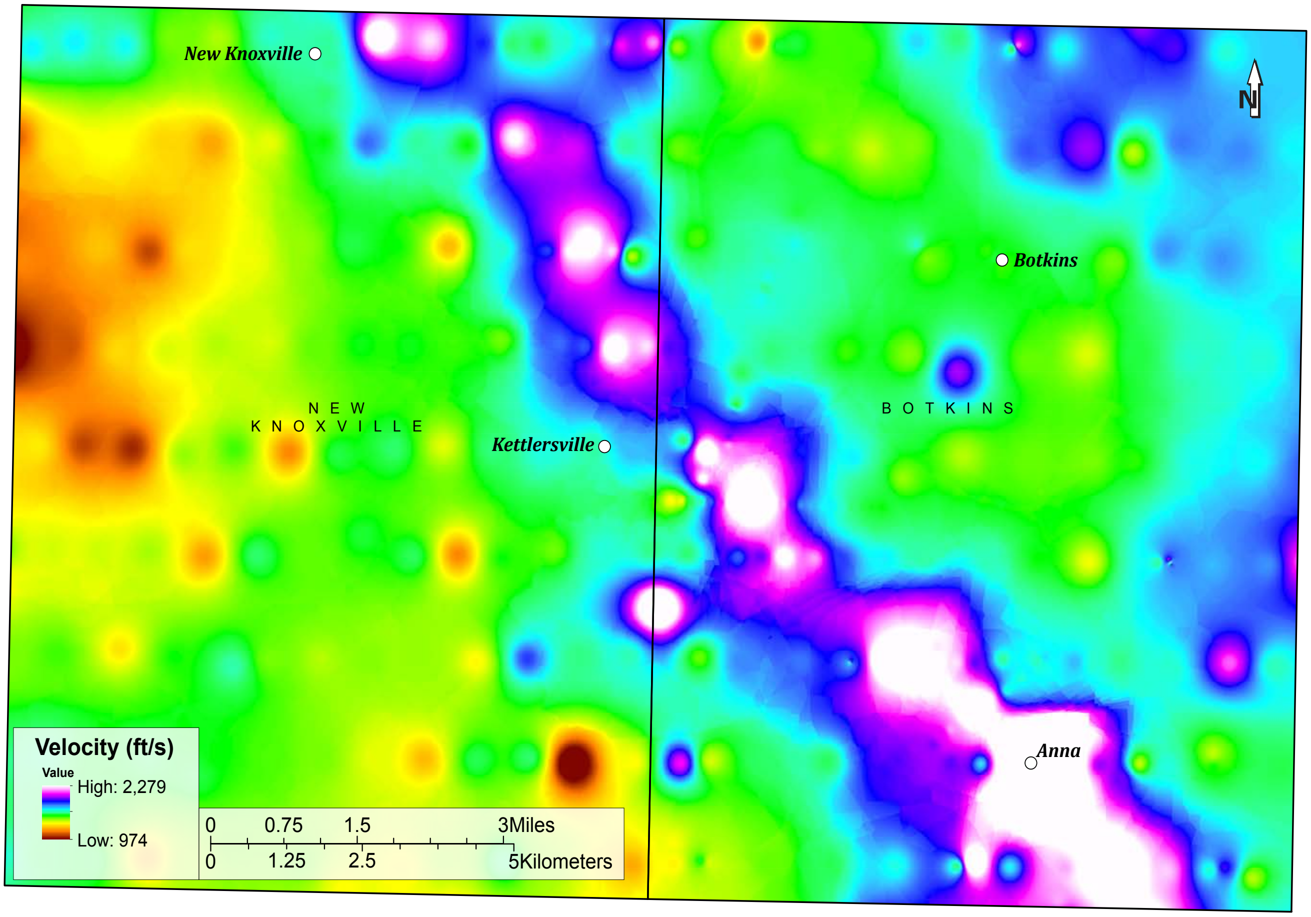


FIGURE 10. Shear wave velocity data were calculated following Equation 1 (Ibs-von Seht and Wohlenberg, 1999; Lane and others, 2008) with data recorded by the MoHo Tromino®. The data points were then rasterized using the IDW interpolation tool.

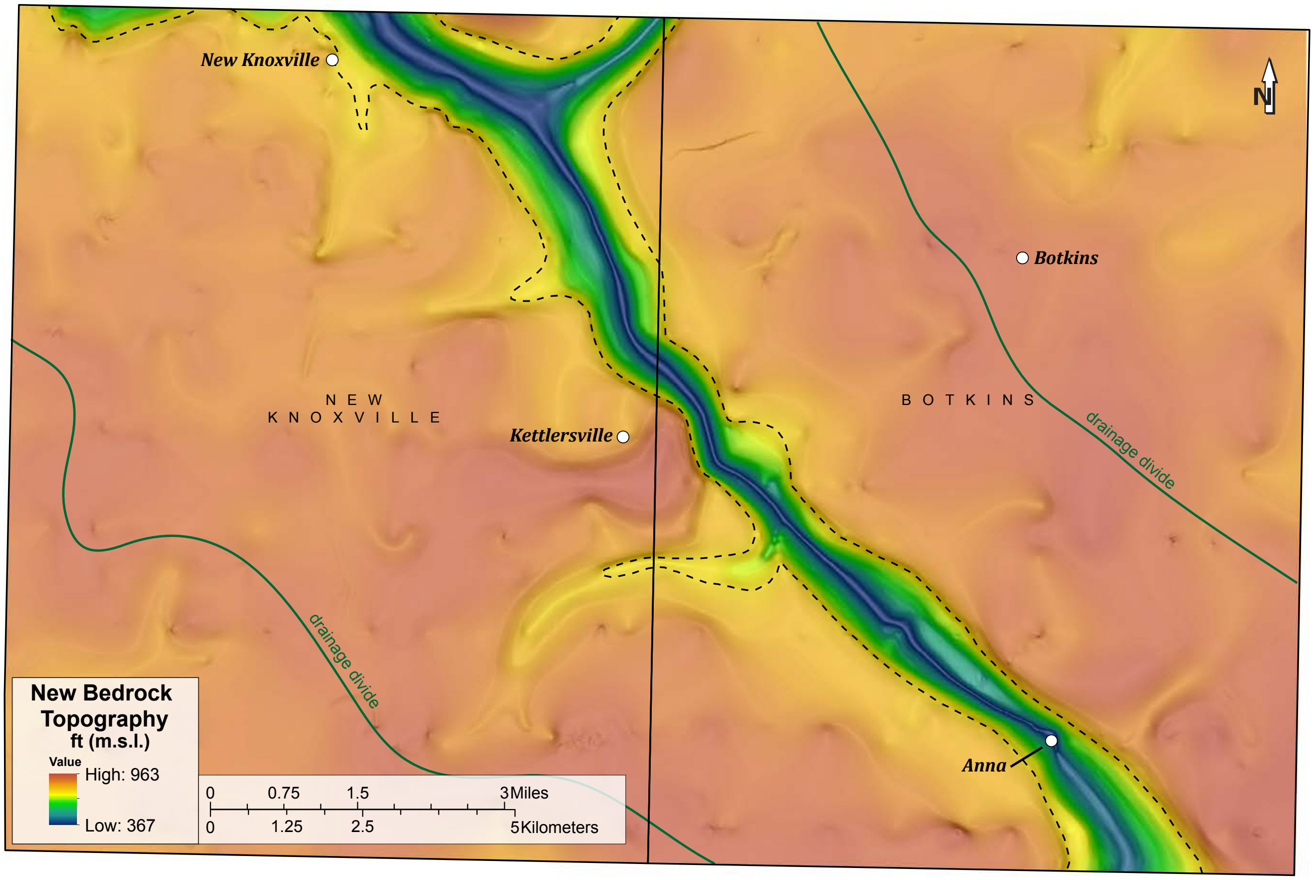


**FIGURE 11.** Bedrock topography, data were calculated following Equation 4 (Ibs-von Seht and Wohlenberg, 1999) with data recorded by the MoHo Tromino®. The surface was created using a modified version of the ArcGIS® tool created by Erber and Spahr (2017).

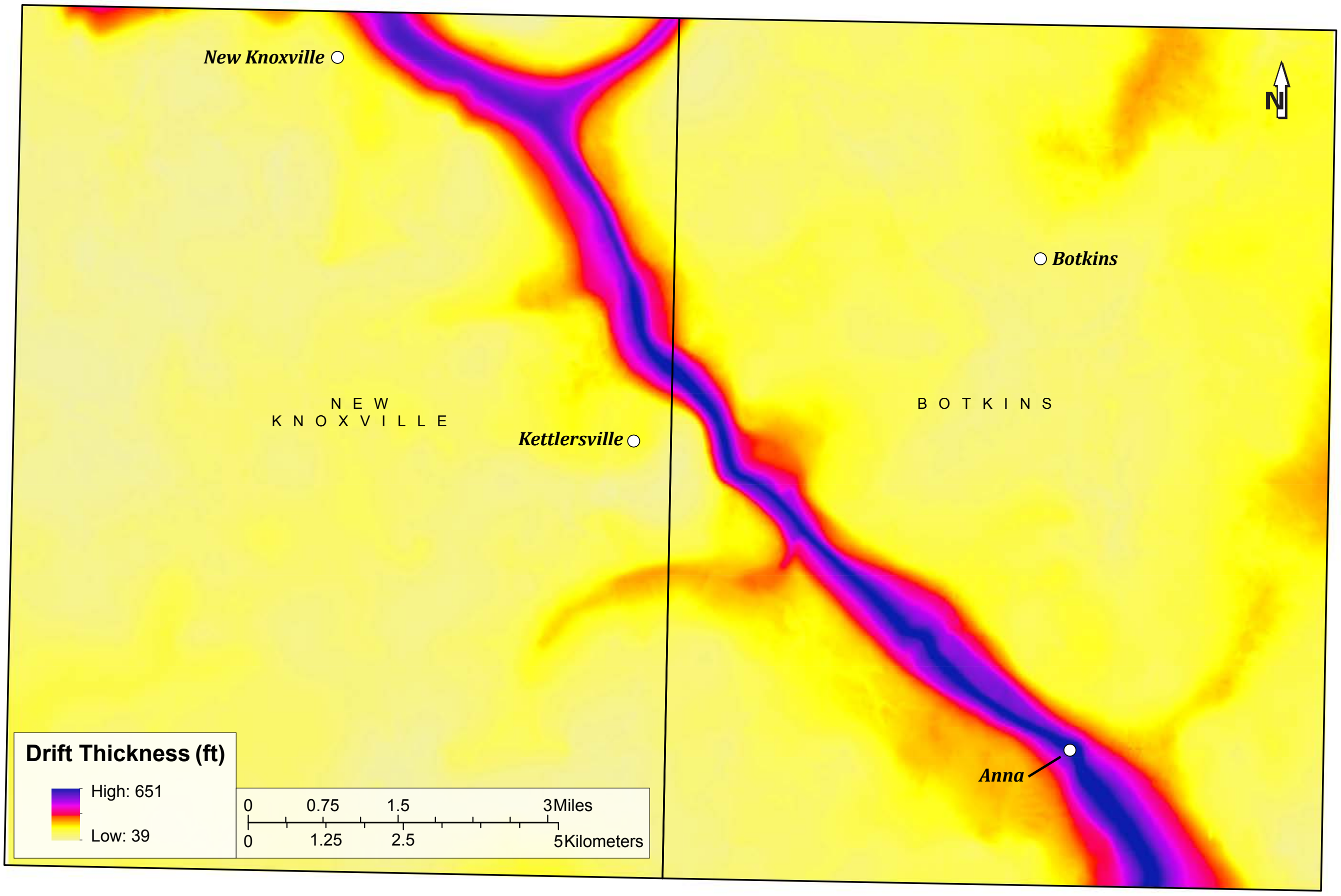


**FIGURE 12.** Drift thickness was calculated by subtracting the Digital Elevation Model (DEM) from the updated bedrock topography surface.

seem to contradict each other. This highlights the need for detailed geophysical investigations of the Teays River Valley across west-central Ohio and east-central Indiana to better reconstruct the regional preglacial drainage network.

## Bedrock Topography

The original bedrock-topography map by Brockman and others (2003), constructed largely from well records, illustrates a buried valley that ran northwest–southeast through the New Knoxville and Botkins quadrangles (fig. 13). The present study added 368 HVSR points to the dataset, which were calculated following Ibs-von Seht and Wohlenberg (1999) and interpolated in the updated bedrock-topography map. Clearly, the original bedrock-topography map was heavily smoothed and lacked sufficient data points, especially in the deeper sections of the valley, which were mostly estimated, thus introducing a large amount of error into the original bedrock topography map (fig. 14). With the latest data, the upland region shows little change, likely because of the high concentration of water wells that penetrate bedrock in the uplands. The buried valley shows the greatest change, as is expected because of the very sparse well control in that area.

The new location of the buried valley has been mapped over two miles northeast of Kettlersville from its original location. Compared to the original bedrock topography surface, the updated bedrock topography surface shows a much narrower, gorge-like valley. The buried valley has an average width in the Village of Anna of 0.75 mi. The buried valley has a much more linear trend than originally interpreted by Slucher and others (2006). Four new tributaries have been identified on the bedrock surface. These tributaries are erosional features on the bedrock surface. These features were not identified in the original bedrock topography because of sparse well control. The tributaries sit at a higher elevation than the thalweg, which is indicative of rapid down cutting in the buried valley or a later stage of drainage when the Teays River Valley was partially filled with Pre-Illinoian materials. A ridge lies on each side of the buried valley, acting as a drainage divide.

## Modeling

The original bedrock-topography surface was separated by elevation into two physiographic regions: the upland and the buried valley (Brockman and others, 2003). These physiographic regions were then applied to the derivative surfaces and interpreted based on their individual characteristics (table 1).

**TABLE 1.** ***Physiographic regions separated into classes by elevation***[1]

| | Upland Region | Buried Valley | Data Range |
|---|---|---|---|
| Fundamental Resonant Frequency (Hz) | 3.00–6.97 | 0.88–3.00 | 0.88–6.97 |
| Shear Wave Velocity ($V_S$ ft/s) | 974–1,600 | 1,600–2,279 | 974–2,279 |
| Updated Bedrock Topography (elev. in ft above m.s.l.) | 750–963 | 367–750 | 367–963 |
| Drift Thickness (ft) | – | – | 39–651 |

[1] In ft above m.s.l.

## Buried Valley Detection

Bedrock elevation data from water well logs and the HVSR grid were insufficient to accurately characterize the shape of the Teays bedrock valley. Water wells are seldom drilled to bedrock within the buried valley because relatively shallow sand-and-gravel aquifers tend to produce enough water for domestic use. The location of the valley can be partially inferred by the location of these wells completed in sand-and-gravel aquifers, but no reconstruction of the bedrock surface or valley morphology can be made from this data. Transects perpendicular to streamflow with 0.1-mi spacing were necessary to fully characterize the valley morphology and location in areas with sparse bedrock elevation data. Each transect was about 2 mi long to ensure a complete capture of the buried valley. Three transects were completed in areas where the valley was mapped previously. Of those three transects, two provided a complete record of the valley and parts of the upland on either side (figs. 15, 16, and 17). Data points collected on the HVSR grid may only provide one or two bedrock elevation data points within the valley because the maximum valley width is only about one mile. The few deep seismic points collected on the grid are too widely spaced to reconstruct the valley morphology or trace the thalweg of the valley. More control on the bedrock elevation within the valley is needed to fully define the valley morphology.

Transect *A–A´* (fig. 16) is located northwest of the Village of Anna, Ohio, and has an east–west trend. Transect *A–A´* is approximately 2 mi long and is composed of 18 points. Two points were discarded because of an excess of local background noise. The range of bedrock elevation values for this transect is 888.3 to 508.6 ft above m.s.l. A prominent bench or terrace was interpreted at an elevation of approximately 500–520 ft above m.s.l. on the eastern edge of the valley. The slope of the valley walls ranges from about 15° to 30°, with slopes in the upland area of around 1° to 5°. This trend in slope is generally consistent throughout the Botkins segment of the Teays River Valley.

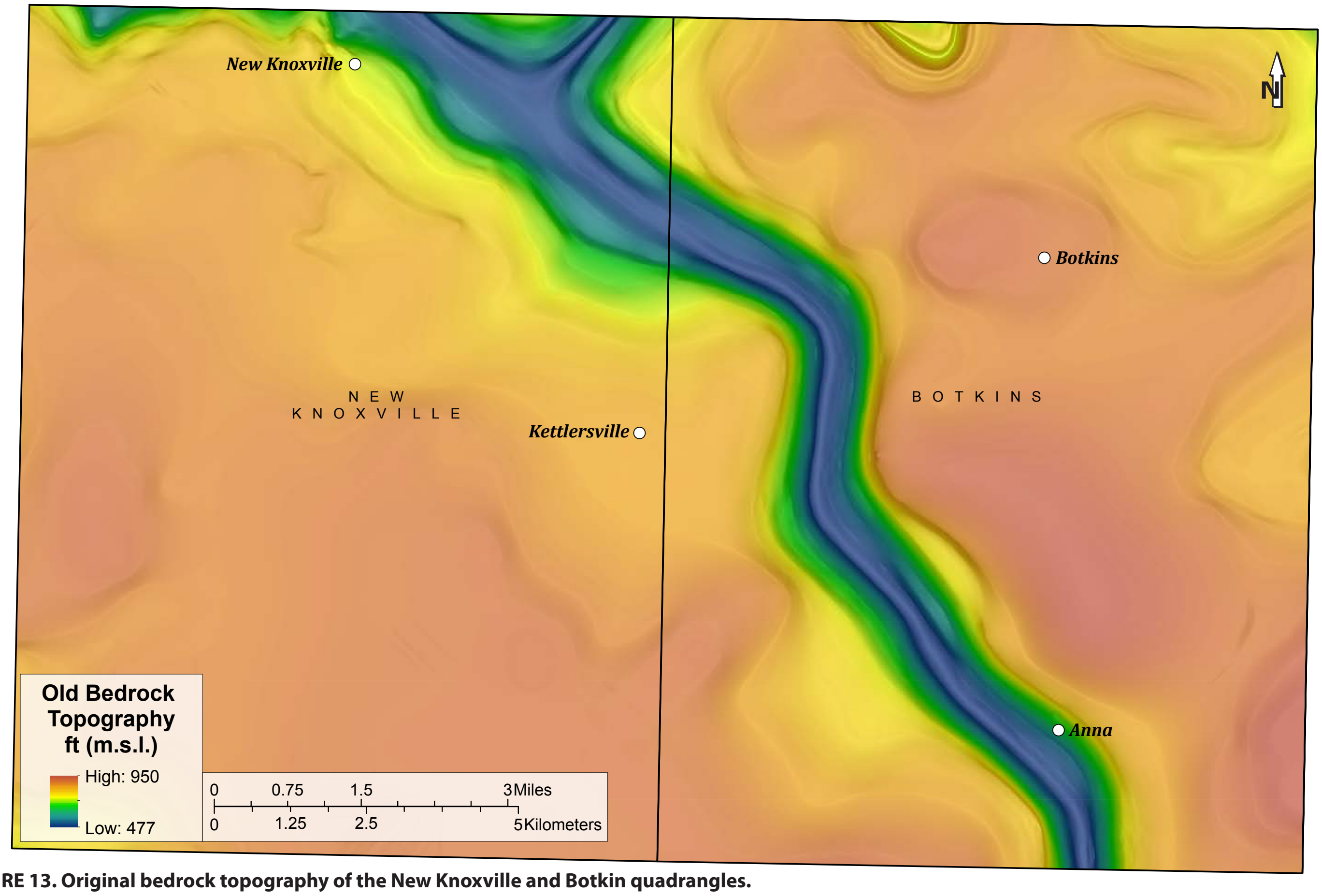


**FIGURE 13. Original bedrock topography of the New Knoxville and Botkin quadrangles.**

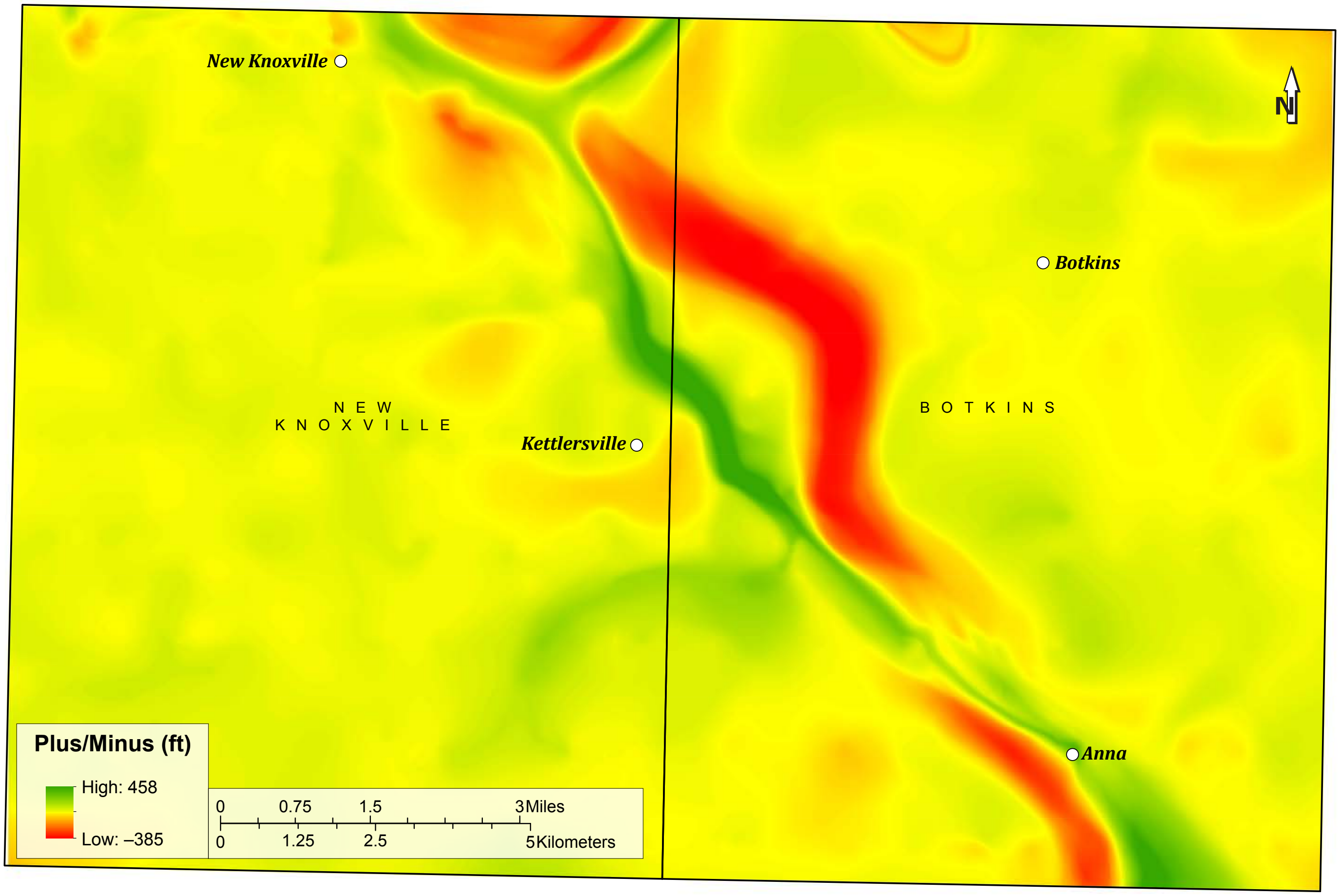


**FIGURE 14. Changes in elevation between the original bedrock topography and the updated bedrock topography in the study area. The data points were calculated using the subtract tool.**

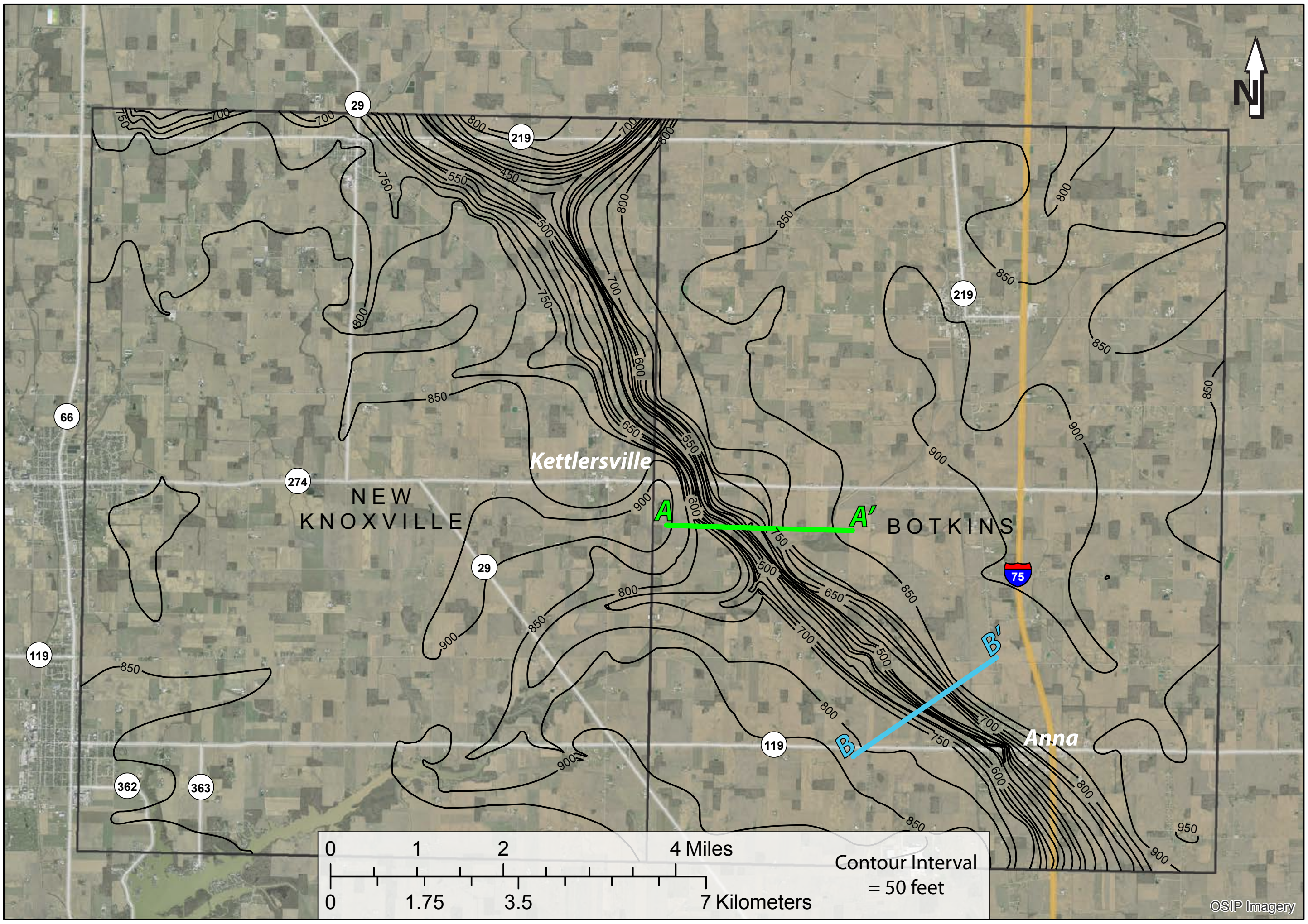
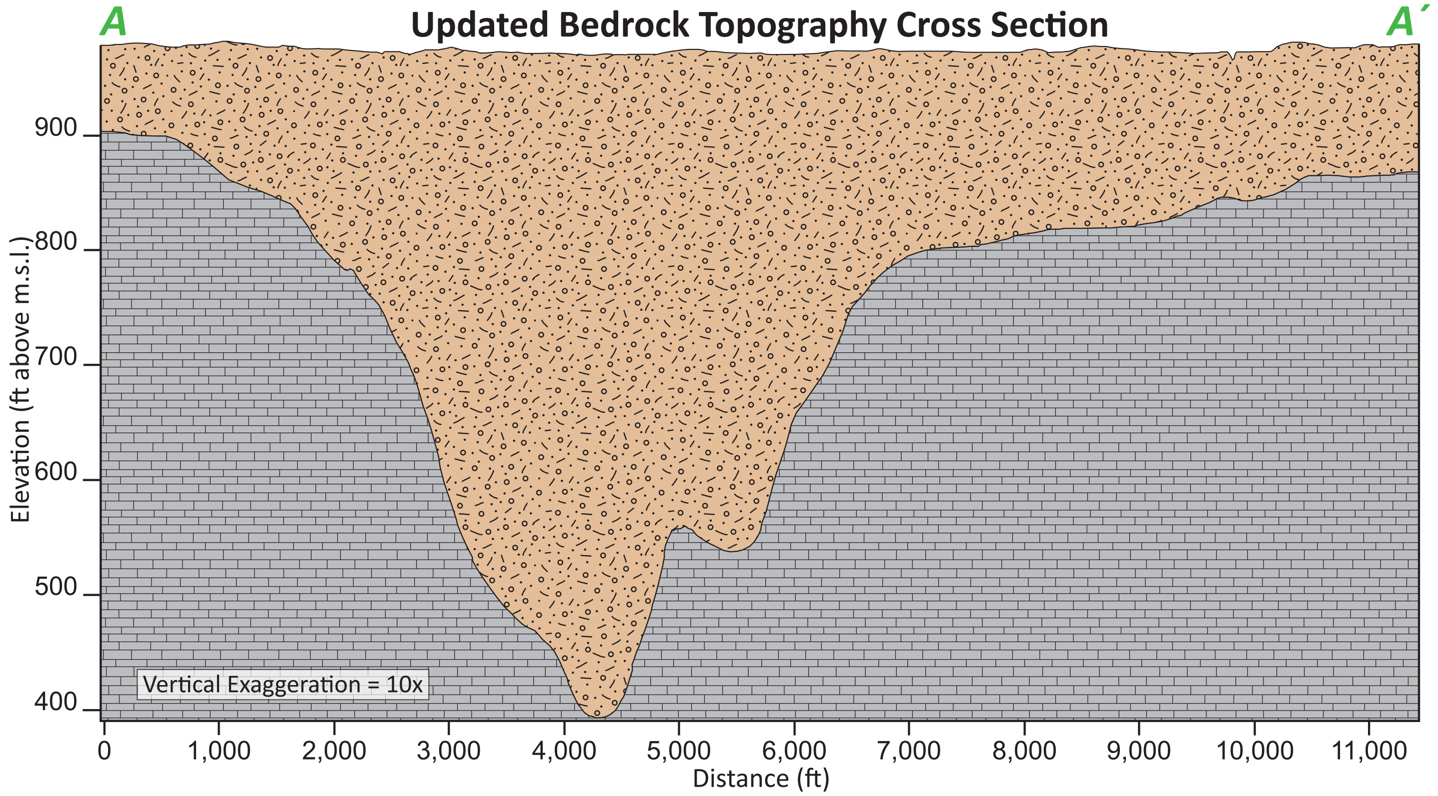


**FIGURE 15. Bedrock topography of the New Knoxville and Botkins quadrangles showing locations of cross sections *A–A´* and *B–B´*.**

Two nearby wells confirm the subsurface structure in Transect *A–A´*. Well #990067 recorded a bedrock depth of 145 ft in gray limestone, which correlates with the nearest data point (461-27-001-0809), which has a calculated depth of 148.1 ft; the two points are approximately 0.1 mi apart. With the addition of the HVSR data, the deepest part of the valley in Transect *A–A´* was mapped 0.3 mi to the southwest. The previous drift-thickness model estimated a maximum depth to bedrock of 531 ft, which differs from the HVSR value (500.4 ft) by only approximately 30 ft. The valley structure at this location is much broader. The location of the valley just northwest of the Village of Anna did not shift significantly from initial bedrock-topography mapping efforts (Brockman and others, 2003). The primary difference between the two iterations of bedrock-topography mapping is the width of the valley (fig. 15). The updated bedrock-topography map (fig. 11) depicts a valley with a width of about 0.65 mi, while the valley was originally mapped as about 1.25 mi wide at this location. Both iterations of mapping depict a flow direction of generally northwest.

Transect *B–B´* (fig. 17) is located east of the Village of Kettlersville, Ohio, and has an southwest-to-northeast trend. Transect *B–B´* is approximately 2.2 mi long and is composed of 23 points. The range of bedrock elevation values for this transect is 903.1–466.9 ft above m.s.l. The slope of the valley walls ranges from about 15° to 30°, with slopes in the upland area of around 1° to 5°. Again, this trend in slope is pervasive in the mapping area.

Transect *B–B´* shows a significant change in the valley location, valley width, and streamflow direction between recent and previous iterations of bedrock-topography mapping. The location of the deepest point in the valley east of Kettlersville shifted by 0.6 mi west (fig. 11). The valley width decreased from 1.3 mi in previous bedrock topography mapping to just 0.75 mi (Brockman and others, 2003). The direction of streamflow rotated about 45° west. Initial mapping of the bedrock topography indicated that the buried valley turned north and ran parallel to the Village of Kettlersville (fig. 13). Improved bedrock-topography mapping shows that the valley continues toward the northwest instead (fig. 11). The previous drift-thickness model estimated a maximum depth to



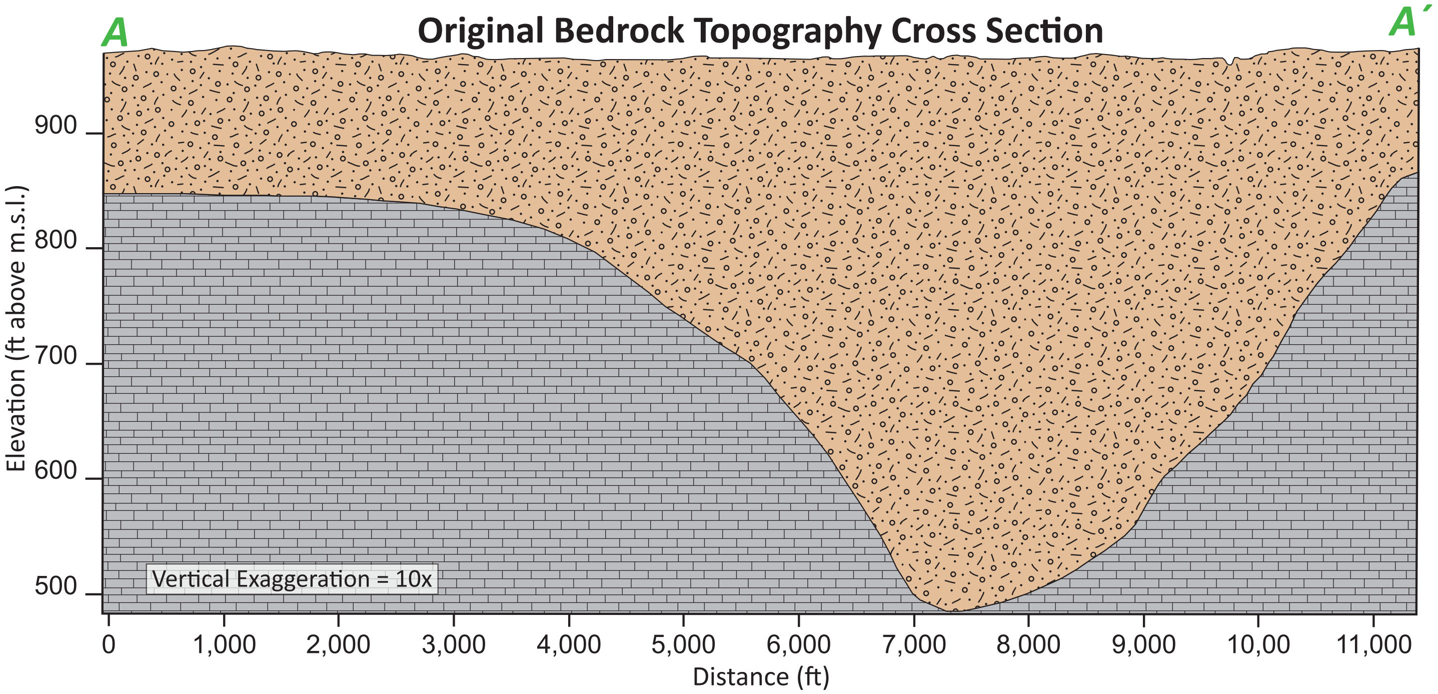


**FIGURE 16. Cross section *A–A´* is a direct comparison between the detailed interpretation from the updated bedrock topography (top) and the original bedrock topography (bottom). Vertical exaggeration is 10x.**

bedrock of 491 ft, which differs from the calculated value of 500.4 ft by only approximately 9 ft. Because there are no water wells in the immediate area, we must rely on calculated values to define the subsurface structure (Ibs-von Seht and Wohlenberg, 1999).

## Shaking Intensity and Seismicity in the Region

The behavior of seismic waves is dependent on the density of the material through which the waves travel. Bedrock has high relative density and facilitates the transfer of seismic energy efficiently with low amplification, meaning the perceived shaking is typically low. In contrast, unconsolidated sediments like those associated with the Teays River Valley, amplify seismic waves and result in more intense shaking during earthquakes. It is likely that the ground

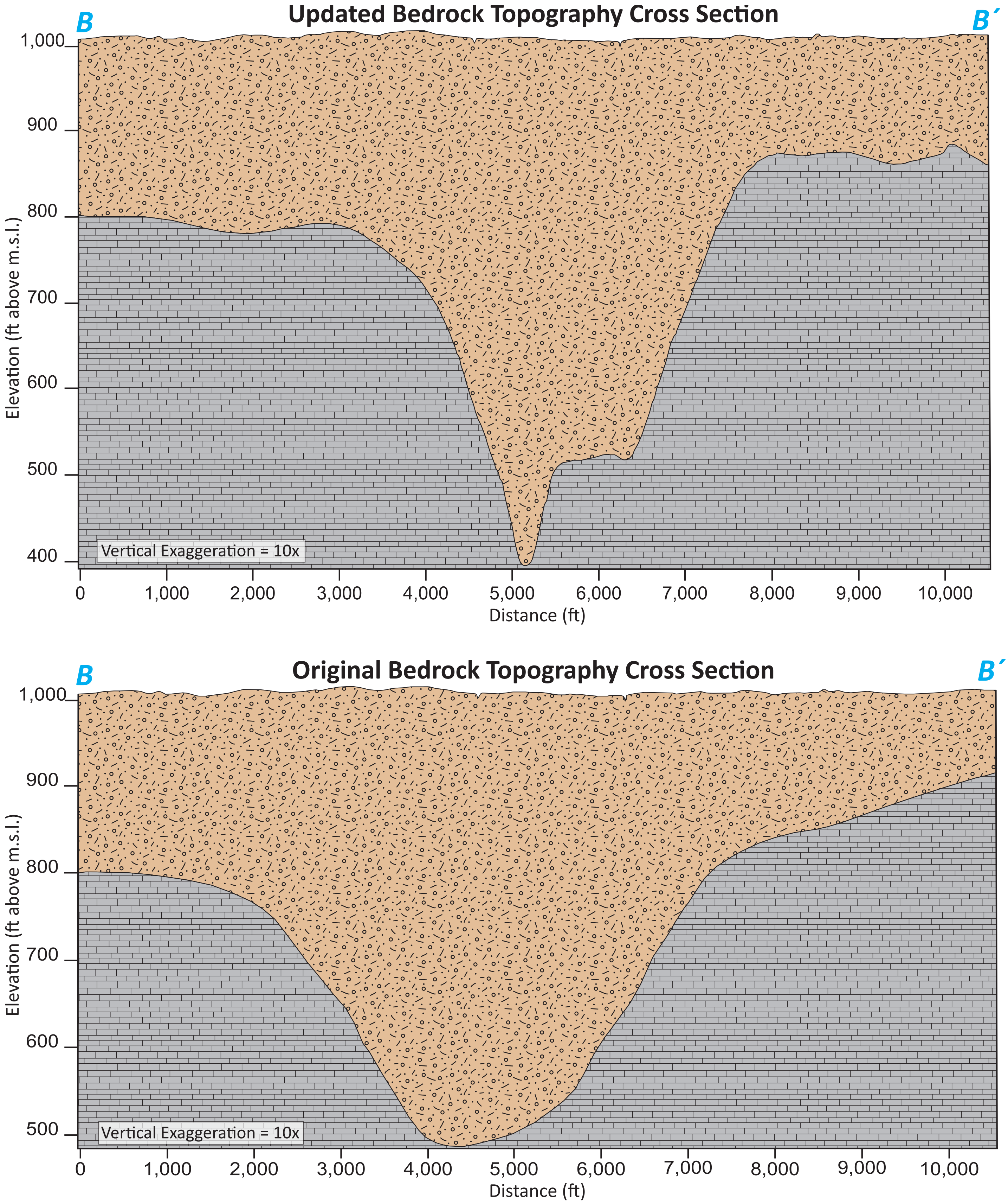


**FIGURE 17. Cross section *B–B´* is a direct comparison between the detailed interpretation from the updated bedrock topography (top) and the original bedrock topography (bottom). Vertical exaggeration is 10x.**

motion experienced during the 1937 earthquakes in Anna was amplified in the buried valley, which is infilled with unconsolidated sediments (Shrake and others, 2010). The damage reported in the Village of Anna was also certainly linked to its proximity to the earthquake epicenter (40.4°N, 84.2°W).

According to Westland (1940), the "walls of brick buildings were cracked, plaster was shaken down, and various pieces of furniture were upset. Walls of public school buildings were so badly cracked that the building was declared unsafe. Chimneys snapped off at the roof; others were destroyed by a twisting motion. Minor damage was described at the St. Jacob's Lutheran church and the Methodist Episcopal church." The March 9, 1937, event was assigned an VIII Intensity on the Wood-Nuemann Scale (Wood and Nuemann, 1931) by the U.S. Coast and Geodetic Survey, which is consistent with the damage described in West (1940).

Nearby towns, including Jackson Center, Sidney, and Botkins, all reported minimal damage (for example, damaged chimneys and cracked plaster). Similar experiences were documented by Workman (2008) from the personal experiences of residents of New Knoxville and Kettlersville, which were also located within the uplands region.

The amount of damage reported could also be linked to the degree of population and/or urbanization of Anna relative to nearby communities. Urbanization results in a higher number of structures that are subject to damage during an earthquake. A detailed comparison and analysis of the degree of urbanization of the affected areas was beyond the scope of this project. However, data from the U.S. Census Bureau shows that the population of Sidney, Ohio, was approximately 20 times greater than that of Anna during the 1930s (U.S. Decennial Census, 2010), suggesting population and urbanization differences do not account for why greater shaking was experienced in Anna than elsewhere.

## CONCLUSIONS

A well-defined buried valley, which is more gorge-like than previously interpreted, can now be traced through the Botkins and New Knoxville quadrangles. It is important to note that the Village of Anna, Ohio, sits directly on top on the deepest section of the buried valley (651 ft), which may explain why it suffered moderate damage in comparison to nearby towns during the earthquakes of 1937. Documenting the thickness and shear wave velocity of the glacial drift in the Anna Seismic Zone will lead to increased understanding of the likelihood and behavior of seismic amplification from earthquakes throughout the region.

Continued HVSR mapping of the preglacial Teays River Valley north of the current study area would provide greater data and opportunity to further define the morphology of the buried valley. This would include detailed mapping in the Celina, St. Mary's, and Moulton quadrangles, with the eventual goal of tracing the preglacial Teays into Indiana and reconciling some of the discrepancies noted between this study and the results of Gray (1982) and Bleuer (1991).

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