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DEPARTMENT OF TRANSPORTATION

# Depth to Bedrock Seismic Measuring Device

FINAL REPORT

11/30/21

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COMMONWEALTH OF PENNSYLVANIA
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**16. Abstract**

The purpose of this project is to evaluate the use of passive seismic methods to estimate the depth to bedrock. The goal of the project is to establish the accuracy and efficacy of these methods as compared to current and historic core boring taken by PennDOT, with the goal being to eliminate a portion of the core borings currently being performed by the Department. These seismic investigations are used to delineate different geologic conditions such as layer geometry, water table, and the bedrock topography. Civil engineers rely on accurate measurements and assessments of bedrock to build safe, stable buildings, bridges, and wells (Badaoui et al. 2010). The review will also include an investigation of different available methods which are currently being used to perform identical and similar functions. Also, the review will evaluate and recommend the top depth to bedrock seismic measuring methods as well as evaluate and recommend the techniques and procedures that will be best fit the needs of the Pennsylvania Department of Transportation (PennDOT).

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# Depth to Bedrock Seismic Measuring Device

Preliminary Final Report

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November 2021

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# 1. Literature Review

The purpose of this project is to evaluate the use of passive seismic methods to estimate the depth to bedrock. The goal of the project is to establish the accuracy and efficacy of these methods as compared to current and historic core boring taken by PennDOT, with the goal being to eliminate a portion of the core borings currently being performed by the Department. The first step in this process is to perform a literature review. This literature review will examine the underlying technology of depth to bedrock seismic measuring devices and methods which are traditionally passive seismic methods. These seismic investigations are used to delineate different geologic conditions such as layer geometry, water table, and the bedrock topography. Civil engineers rely on accurate measurements and assessments of bedrock to build safe, stable buildings, bridges, and wells. Engineers also rely on bedrock to make sure bridges are safe and secure (Badaoui et al. 2010). The review will also include an investigation of different available methods which are currently being used to perform identical and similar functions. Also, the review will evaluate and recommend the top depth to bedrock seismic measuring methods as well as evaluate and recommend the techniques and procedures that will be best fit the needs of the Pennsylvania Department of Transportation (PennDOT).

The first part of the review will be a background into different geophysical methods which have been employed as well as the applications. Additionally, the relevant American Society for Testing and Materials (ASTM) standards for the technologies will be presented. The next section will detail the primary depth to bedrock evaluation techniques in more detail. Previous agency experience will be established then the recommended techniques will be presented.

## 1.1 Geophysical Methods

Applied geophysics is a vast area of different methodologies which can be used for many different applications ranging from energy exploration to engineering and environmental. Each method is separated by the physics principles which are employed. For example, material properties can be indirectly measured through the use of engineering geophysical methods such as seismic, electrical resistivity, EM and ground penetrating radar (GPR) (Greenhouse and Pehme 2001). The targets of geophysical problems are rarely directly observable and therefore require mathematical interpretation of physical measurements. The ability to conduct geophysical investigations in a variety of different geologic conditions indicated the potential to significantly benefit design and construction activities. One of the most important things which can be gained by employing these methodologies is to reduce risks related to unknown subsurface conditions. However, it is vital that the appropriate techniques be used for the specific engineering objectives.

Telford et al. (1976) outlines that applied geophysics can be divided into the following seven (7) general methods: magnetic, electrical, electromagnetic, seismic, gravitational, radioactive, and well logging. Each of these different methods can be used for varying types of investigations. A summary of a number of different geophysical methods and their applications were performed in NCHRP Synthesis 357 (Sirles 2005). This provides a starting point for selection of the techniques which are most applicable to evaluate the depth of bedrock. All of the primary techniques identified in NCHRP Synthesis 357 to determine the depth of bedrock are seismic methods. These include seismic refraction and seismic reflection tomography, and surface wave (spectral analysis of surface waves (SASW) and multi-channel analysis of surface waves (MASW)). There are also a few secondary techniques which were identified which include time domain electromagnetic soundings, electrical resistivity, induced polarization, and gravity methods (Sirles 2005). This review will focus on the primary methods to identify the depth to bedrock which are typically employed and the third section of the report will outline these in detail.

## 1.2 ASTM Standards

A number of different ASTM standards and guides are available for geophysical investigations and are summarized in Table 2. One of the primary guides which has been available was ASTM D6429 which was the Standard Guide for Selecting Surface Geophysical Methods (ASTM D6429). This guide provided a number of different techniques including seismic refraction and reflection, two (2) of the primary methods to evaluate the bedrock depth. The standard was just withdrawn in March 2020 and was not renewed because the guide does not describe the specific procedures for conducting geophysical surveys and individual guides are being developed for each geophysical method.

The standards for each of the methods which can be used for bedrock depth estimation of provided in Table 1. It is important to note that these are standard guides and not standard test methods. Standard test methods are rigid procedures which do not allow much, if any, flexibility. Standard guides on the other hand allow for more flexibility to acquire the information and data that will meet the goals of the investigation. AASHTO has some guidance for geophysical methods, especially GPR, however there are no published standards for acquiring or processing data for methods to estimate the depth of bedrock.

Table 1. Guides for Depth of Bedrock Geophysical Investigations

| Geophysical Technique | ASTM Guide |
|---|---|
| Seismic Refraction | D5777 |
| Seismic Reflection | D7128 |
| Time Domain Electromagnetics | D6820 |

## 1.3 Depth to Bedrock Methods

This section aims to discuss the primary methods identified to establish the depth to bedrock. All of these techniques are seismic methods, which are the most commonly conduced geophysical surveys for engineering investigations. Seismic waves are generated from an impulse imparted to the surface. Typically, this is via a hammer or explosives or may be obtained from vibration. Then energy from the impulse then travels through the ground as waves. When the waves reach a material layer with different properties (such as density or stiffness), some of these waves are reflected back to the ground surface and others are refracted along the interface, and some continue deeper into the ground. Geophones are used to record the waves which are reflected and refracted back to the ground surface (Parasnis 1979). The next section will detail the types of elastic waves which are transmitted through the ground surface followed by more detail regarding the primary techniques used to identify the depth to bedrock, specifically seismic reflection, refraction, and surface waves (SASW and MASW).

### 1.3.1 Elastic Waves

If a stress is applied to an elastic medium, the energy imparted into the Earth will be in the form of elastic waves. Elastic waves propagate through the ground without causing any permanent deformation. Elastic waves that propagate through the Earth are referred to as seismic waves, which can be classified as either body waves or surface waves (Waters 1978).

Body waves are elastic waves that propagate through the interior of the Earth. Seismic body waves can be further divided into two (2) classes: Longitudinal or P-waves and Transverse or S-waves. P-waves have the highest velocity of all seismic waves, and are sometimes referred to as primary waves. The particle motion of P-waves is in the same direction as the wave propagation and push the particles of material ahead of it, causing compression and expansion of the material. Additionally, P-waves can travel through solids, liquids, and gases. The velocity of P-waves is given by Equation 1 (Cordier 1985).

$$V_p = \sqrt{(\kappa + \frac{4}{3}\,\mu)/\rho} \qquad \text{Equation 1}$$

Where $V_p$ = velocity of P-wave, $\kappa$ = bulk modulus, $\mu$ = shear modulus, and $\rho$ = density of the medium.

Transverse, or S-waves, are sometimes called secondary waves because they travel at a slower speed than P-waves. In S-waves, the particles are displaced at right angles to the direction of wave propagation. The speed of S-waves is given by Equation 2 (Cordier 1985). S-waves travel at approximately 60% of the speed of P-waves. These waves can only travel through a material which has shear strength. Since, fluids and gases do not have shear strength, S-waves do not propagate through them (Waters 1978).

$$V_s = \sqrt{\mu/\rho} \qquad \text{Equation 2}$$

Where $V_s$ = velocity of S-wave, $\mu$ = shear modulus, and $\rho$ = density of the medium.

Surface waves are elastic waves which propagate along the Earth’s surface or at the interfaces between media. Surface waves propagate at speeds that are slower than S-waves. Surface waves can be divided into two (2) different classification just as body waves. The two (2) different types of surface waves are Love and Rayleigh waves. Love waves have particle motion that is similar to S-waves. Rayleigh waves travel in an ellipse similar to ocean waves (Parasnis 1979). Love and Rayleigh waves are a portion of the surface waves in earthquakes. These waves carry greater energy than body waves and arrive later since they are slower than body waves. Since they carry greater energy, they cause significantly more damage than body waves during an earthquake.

### 1.3.2 Seismic Reflection

The seismic reflection method is one of the best geophysical methods because it produces the best images of the subsurface. A source, geophone, and seismograph are needed to collect data for a seismic survey. The source can be a hammer striking the ground, aluminum plate or weighted plank, weights of varying sizes that are allowed to drop onto the ground, rifle shot, harmonic oscillator, waterborne mechanisms, or explosives (Sirles 2005). The source is typically referred to as a shot. The source will vary as a function of the objective of the survey, which also include the depth of investigation and the properties of the rock at the site (Waters 1978).

The sensors which receive the source data back are either accelerometers or velocity transducers and are called geophones. Geophones convert the movement of the ground into a voltage which is recorded by a seismograph and stored with time. The placement and orientation of the geophones on the ground can be in various geometric arrangements which will vary depending on the target and goal of the study (Sheriff and Geldart 1986).

The time required for the waves to travel from a near surface source to the reflectors and back to receivers on the surface are used, along with all available information to determine the structure of the reflecting surface. If we examine the simple case of a reflection from a horizontal surface, we can see how the depth at a reflecting interface (such as at bedrock), z, can be established. Figure 1 shows a seismic wave being reflected off of an interface with seismic velocity $V_o$ above the interface and $V_1$ below the interface. The geophone receiver is a distance x away from the shot which generated the wave.

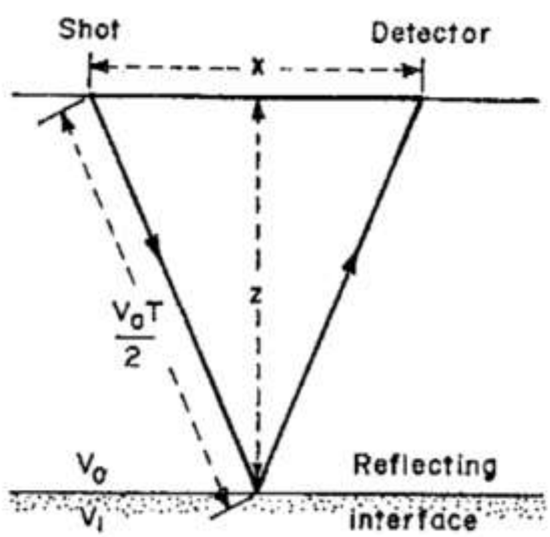



Figure 1. Reflected wave from single interface. ($V_o$ is the constant velocity of a P-wave in layer between surface and reflecting interface) (Chaubey 2007)

The length and time of travel of the wave depicted in Figure 1 can be related using Equation 3, which can be isolated to determine the depth of the layer, z in Equation 4. The ratio of the reflected energy to the incident energy is called the reflection coefficient and is shown in Equation 5.

$$L = 2\sqrt{z^2 + \left({}^{x}/_{2}\right)^2} = V_o T \qquad \text{Equation 3}$$

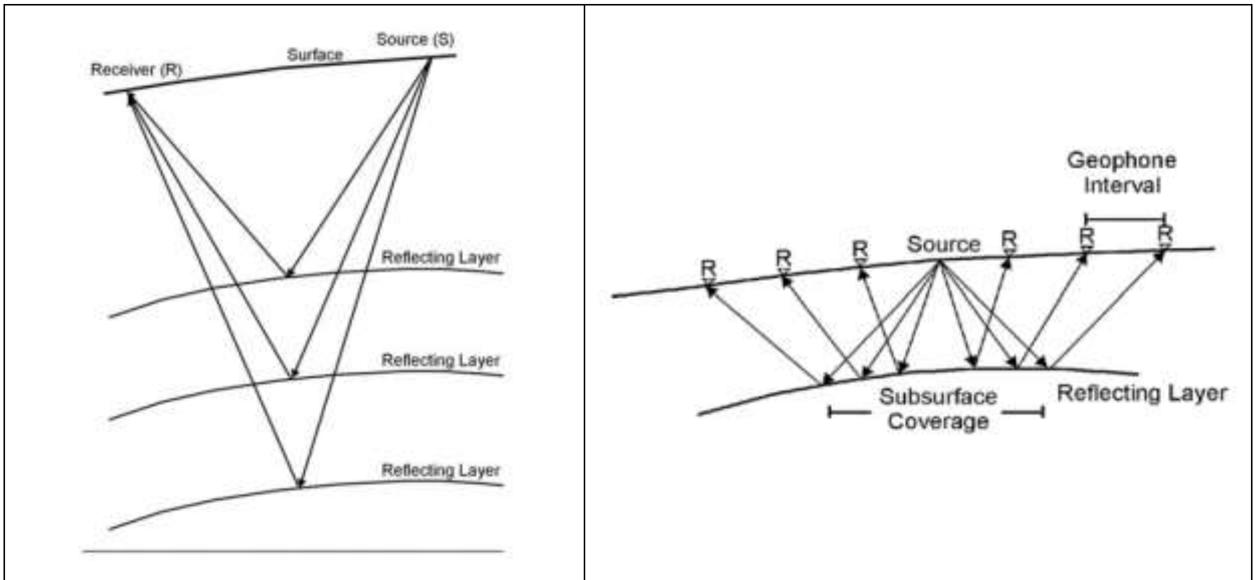
$$z = \frac{\sqrt{(V_o T)^2 - x^2}}{2} \qquad \text{Equation 4}$$

Where L = total path length, T = total travel time, $V_o$ = velocity in material above interface, x = distance between source and receiver, z = depth of layer.

$$R = \frac{\rho_1 V_1 - \rho_o V_o}{\rho_1 V_1 + \rho_o V_o} \qquad \text{Equation 5}$$

Where R = reflection coefficient, $\rho_o$ and $\rho_1$ are the densities of the first and second layers, and $V_o$ and $V_1$ are the seismic velocities of the first and second layers respectively.

Data processing is typically done by geophysicists who specialize in seismic processing. Figure 2a shows the use of seismic reflection through multiple layers. Figure 2b shows the wave paths of a multichannel geophone array. It can be noted that the location of the reflection at the depth of the reflecting layer is exactly half the distance between geophones on the surface. An advantage of the seismic reflection method of this is that is allows for the mapping of multiple layers with each source shot. A disadvantage is that it requires a variation in the field technique depending on the target depth (Telford et al. 1976). Therefore, a trained specialist should be used to ensure that the source magnitude and geophone locations are appropriate to capture the region of interest and that the results from the tests are interpreted correctly.




a b

Figure 2a.  Seismic reflection for multiple reflecting layers, 2b.  Mutli geophone recording array. (Sirles 2005)

## 1.3.3 Seismic Refraction

The refraction seismic method is used to measure the depths and velocities of subsurface layers governed by Snell's law.  It is particularly useful for mapping the depth and topography of the bedrock surface (Nichols et al. 2010).  It can also be used to find the elastic properties of these layers, which are useful for engineering purposes.  In the case of seismic refraction, the subsurface layers must have successively increasing layer velocities with depth (Telford et al. 1976).  At the layer boundaries, part of the incident wave is reflected back to the ground surface, part is transmitted deeper into the ground, and part is refracted along the surface of the layer boundary as illustrated in Figure 3.  This drawing also shows the wave that travels along the ground surface, called the direct wave, and the air wave.  As the refracted wave travels along the refractor surface, seismic energy is continuously refracted back to the ground surface (Parasnis 1979).

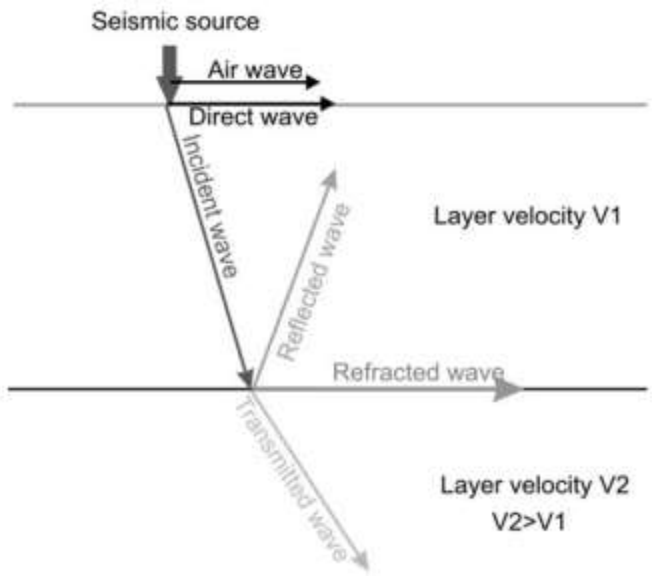



Figure 3. Seismic waves at a layer boundary. (Sirles 2005)

The time required for the waves to travel from a near surface source to the reflectors and back to receivers on the surface are used, along with all available information to determine the structure of the interface surface. We can examine the simple case of a refraction from a horizontal surface, we can see how the depth at a reflecting interface (such as at bedrock), z, can be established (Reynolds 1998). Travel time for the two (2) layers case is the total travel time obtained from the seismic signal path that radiates below the earth's surface as shown in Figure 4. The equation for finding travel time in two (2) layers case is shown in Equation 6. $V_1$ is the seismic velocity above the interface and $V_2$ below the interface. The geophone receiver is a distance x away from the shot which generated the wave.

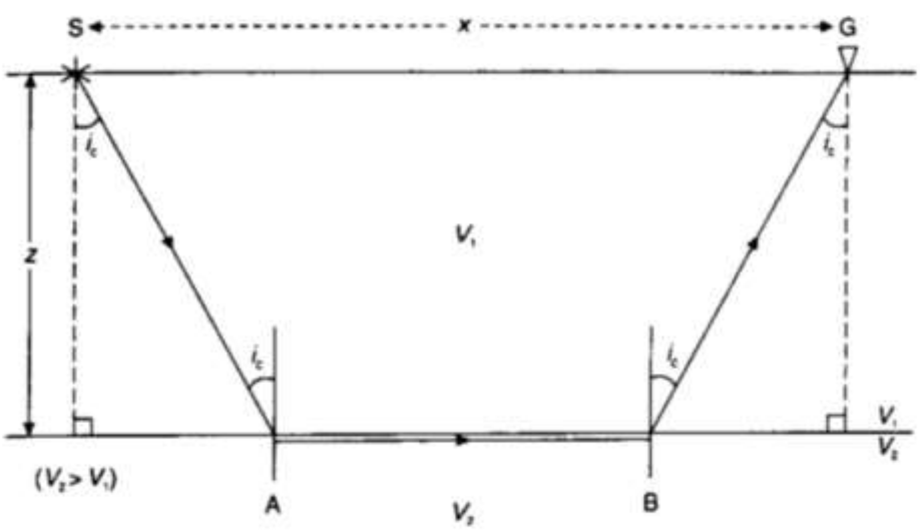



Figure 4. Refracted wave from single interface. (Reynolds 1997)

$$T = \frac{x}{V_2} + 2z\frac{\cos(\theta_{ic})}{V_1}$$ Equation 6

Where T = total travel time, $V_1$ = seismic velocity in material above interface, $V_2$ = seismic velocity in material below the interface, $\theta_{ic}$ = critical angle, x = distance between source and receiver, z = depth of the layer.

The data are interpreted using one of several methods. The most commonly used method is called the Generalized Reciprocal Method (GRM) (Palmer and Burke 1980). This method provides depths and velocities under each geophone and usually produces reliable results. The first step is to pick the first arrival times of the seismic waves for each geophone and each shot. These arrival times are then plotted as a function of distance from the shot location. The time–distance data are then input into the interpretation program and the data are then interpreted to give overburden and refractor depths and velocities (Palmer and Burke 1980).

The main sources of error in computing depth to bedrock from seismic refraction surveys are: low signal-to-noise ratios owing to insufficient source energy, cultural noise, wind noise, rain, or other local sources of vibrations, lateral variations in the overburden velocity, potential "hidden layers" resulting from a low-velocity layer overlain by a higher-velocity layer (velocity reversals) or layers too thin to support refracted wave energy (Mooney 1984).

### 1.3.4 Surface Waves (SASW & MASW)

Active surface wave techniques, such as the spectral analysis of surface waves (SASW) and multi-channel analysis of surface waves (MASW) are proven non-destructive seismic methods that can be used to determine the variation of shear velocity with depth (Stokoe et al., 1994; Brown, 1998; Park et al., 1999; Okada, 2003, Martin, et al., 2006 and Louie, 2001). The basis of surface wave methods is the dispersive characteristic of Rayleigh waves when propagating in a layered medium. The Rayleigh-wave phase velocity depends on the material properties (primarily S-wave velocity with smaller contributions from P-wave velocity, Poisson's ratio and mass density) to a depth of about one (1) wavelength. Surface wave testing consists of collecting surface wave data in the field, generating the dispersion curve and then using iterative forward or inverse modeling techniques to calculate the corresponding shear velocity profile (Martin 2011). Active and passive surface wave techniques are used by numerous practitioners, both in industry and academia, to characterize subsurface S-wave velocity structure. Surface wave techniques are often applied to geotechnical site characterization as part of the design of critical structures.

Testing consists of measuring the surface wave dispersion curve and interpreting it to obtain the corresponding shear wave one dimensional vertical velocity profile. The dispersion curve is the variation of phase velocity of the fundamental mode Rayleigh wave with frequency. There are two (2) main methods used in surface wave exploration. The most common is called SASW testing, which uses two (2) geophones. The other method, which uses a linear array of geophones, is generally called array methods, or Multichannel Analysis of Surface Waves (MASW) (Sirles 2005). An expanding receiver array is used to avoid near-field effects associated with Rayleigh waves and source–receiver geometry is optimized to minimize body wave signal. Microtremor surface wave techniques are also becoming more widely used. Passive sources typically can see deeper than active sources. MASW used in addition to Microtremor can be used to obtain both shallow and deeper interpretations (Kesarwani et al. 2012).

The depth of penetration is determined by the longest wavelengths in the data. Generally, heavier sources generate longer wavelengths. Also, the depth of penetration and resolution are heavily site dependent. Background noise at a site may limit the signal/noise ratio at low frequencies. The field setup requires a distance between the source and most distant receiver of two (2) to three (3) times the maximum penetration depth (Kesarwani et al. 2012).

## 1.4 DOT Experience

NCHRP Synthesis 357 performed a survey of transportation organizations and their experiences with geophysical investigations (Sirles 2005). While slightly dated this study serves as good source of information for overall DOT experiences. From this study, it was found was found that approximately 12% of state DOTs, 25% of Canadian transportation agencies do not use geophysics in their programs (Sirles 2005). It was also found that the majority of agencies who perform geophysical investigations conduct between one (1) and five (5) each year as shown in Figure 5. In looking at the most common applications, bedrock mapping accounted for approximately 1/3 of the most common applications as shown in Figure 6.

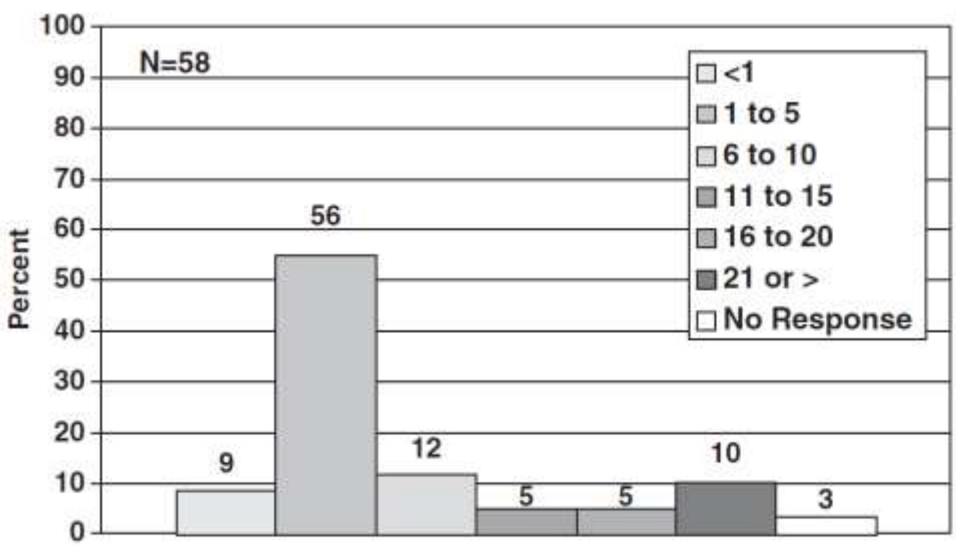



Figure 5. Typical number of geophysical investigations conducted by agencies each year. (Sirles 2005)

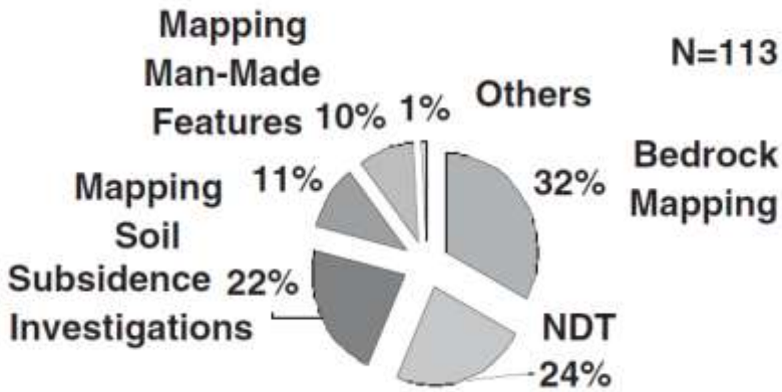



Figure 6. Most common applications of geophysics (Sirles 2005)

Seismic methods, which are the most common way to determine the depth of bedrock, are summarized by type of seismic method used in Figure 7. One of the things which could be observed from the data, is that there is very little agreement on how the type of geophysical method should be chosen. Additionally, across agencies, there is little consensus on who is responsible to select the methods with those duties ranging from the contractor, highway engineer, program manager, an in-house geophysicist. From this it is clear that many agencies perform geophysical investigations on an ad hoc basis that depends on the needs of individual projects.

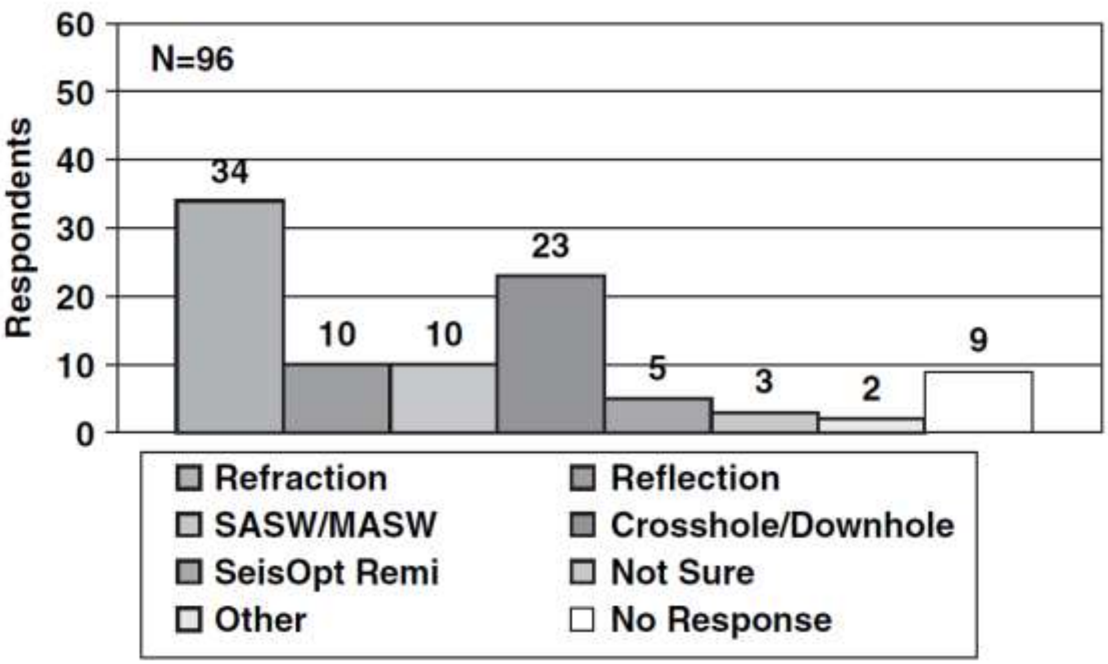



Figure 7. Seismic methods used (Sirles 2005)

## 1.5 Recommended Testing

In discussions with the subcontractor (RETTEW/Enviroscan), the following passive seismic methods should be utilized to estimate the depth of bedrock:

1. ***Refraction Microtremor (ReMi)***, which uses a multi-channel geophone array to record surface wave trains from ambient sources.
2. ***Multispectral Analysis of Surface Waves (MASW)***, which is similar to ReMi in data collection, but uses a completely different style of spectral analysis.
3. ***Horizontal-to-Vertical Spectral Ratio (HVSR)***, which uses a single three-component geophone to measure horizontal versus vertical ground motion due to ambient events. The frequency of the horizontal motion is strongly dependent on the thickness of unconsolidated material, so the peak in the Horizontal/Vertical ratio (H/V amplitude versus signal frequency) is a measure of rock depth.

The following subtasks will be included within the utilization of the recommended methodologies:

1. Seismic data for all the three (3) methods will be collected along one (1) or two (2) sets of orthogonal profiles at each selected location (for ReMi and MASW) and at the intersection of the orthogonal profiles for HVSR. Geophones along each profile (for ReMi and MASW) will be spaced at 10- or 20-foot intervals, depending on site dimensions and depths of interest. Note that closer spacing is preferred for sites with shallow overburden, while greater spacing is better for anticipated deeper overburden, but requires a larger accessible site dimension.

2. Seismic travel times will be recorded for the ReMi and MASW methods using a Geometrics Geode seismograph and Oyo 4.5 Hertz geophones. At each selected location, seismic noise along a geophone array will be measured five (5) to eight (8) times, each with a record length of 15 seconds or greater.

3. For the ReMi method, the multi-channel data will be analyzed using SeisOpt ReMi by Optim Software. From the measured ambient seismic noise, the shear-wave dispersion curve will be derived, and will be modeled to determine the subsurface shear-wave velocity profile. Each profile will be presented and displayed as modeled shear-wave velocity versus depth.

4. For the MASW method, the multi-channel field records will be analyzed using the MASW algorithm developed by the Kansas Geological Survey to present shear-wave vs. depth profile.

5. For the HVSR method, the spectral ratio of horizontal-to-vertical ground motion will be calculated, with the peak in this parameter (i.e. at the frequency producing the greatest horizontal motion) calibrated to the depth to greatest seismic contrast (i.e. sediments vs. bedrock).

These results will then be compared to the core results.  Then the three (3) different methods will be evaluated based on the following criteria: field effort (time and expenses for equipment), processing effort (time and expenses for processing software and personnel), accuracy (how well each method matches the ground truth data to be provided by PennDOT).

## 2. Testing Locations

With the literature reviewed and the recommended testing established, the next step is to identify target sites where we can perform the comparison. These sites need to be locations where PennDOT has historical boring data. The testing sites identified by PennDOT are located in Figure 8 with the locations of the sites displayed on the google map in Figure 9. There are 15 sites in total having bedrock depths ranging from 5.7 ft to 34.6 ft including two sites which had no discernable bedrock. The testing sites are spread across Crawford, Erie, Forest, Mercer, Venango, and Warren counties which are all included in PennDOT District 1. The bedrock types included siltstone, sandstone, and shale while the overburden material consists of silt, sand, gravel, and clay. The varying type of bedrock lithology and overburden material will be an excellent test of the passive seismic methods.

| | Project location | | | | | Boring Information | | | Bedrock Information | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Location | County | County code | SR | SEG | Offset | Boring ID | Station / Section | Offset | Depth to bedrock (ft) | Elevation | Lithology of bedrock | Predominate Overburden Material |
| 1 | Crawford | 20 | 6 | 850 | 820 | RB-1 | 725+79.0 | 9.0 FT. LT. | 11.2 | 1180.2 | Siltstone | SILT and fine to coarse SAND |
| 2 | Crawford | 20 | 322 | 30 | 1919 | RB-1 | 190+62.0 | 9.0 FT. RT. | 16.2 | 1004.8 | Sandstone | SILT and fine to coarse SAND |
| 3 | Crawford | 20 | 1006 | 110 | 1250 | B-1 | | From C.L 20' RT | | | No Bedrock | CLAY, gray with trace of SILT |
| 4 | Erie | 25 | 226 | 10 | 576 | B-1 | 5+78.0 | 7.0 ft. RT. | 14.8 | 943.1 | shale | SILT and fine to coarse GRAVEL |
| 5 | Erie | 25 | 1006 | 110 | 2972 | B-1 | 343+61.0 | 5.0 ft. LT. | 34.6 | | shale | SILT and fine to coarse SAND |
| 6 | Erie | 25 | 19 | 80 | 692 | B-1 | 320+88.4 | 8.0 FT. LT. | | | No Bedrock | CLAY and SILT, little fine Sand |
| 7 | Forest | 27 | 62 | 20 | 0 | RB-1 | B01 | | 10.5/ 18.0 | 1022.7/ 1015.2 | Sandstone/ SILTSTONE interbedded with SANDSTONE | UNSAMPLED |
| 8 | Forest | 27 | 1003 | 60 | 1600 | RB-2 | 141+15.0 | 6.0 FT. LT. | 13.1 | 1390.8 | Sandstone | SILT and fine and medium GRAVEL |
| 9 | Mercer | 43 | 19 | 140 | 1131 | RB-2 | B-17 | 10.0 ft. RT. | 19.5 | | Sandstone | Fine to coarse SAND |
| 10 | Mercer | 43 | 2001 | 50 | 1819 | RB-1 | 124+29.0 | 6.0 FT. LT. | 26.7 | 1120.9 | SANDSTONE interbedded with SHALE | Fine to coarse SAND |
| 11 | Venango | 60 | 38 | 110 | 0 | B-1 | 337+11.0 | 7.0 FT. LT. | 21.5/ 24.5 | 13013/ 1298.3 | Sandstone/ shale | Fine to coarse SAND and SILT, ORGANICS (wood) at 7.5' |
| 12 | Venango | 60 | 3006 | 30 | 1554 | RB-1 | B00 | 8.0 ft. RT. | 15.8 | | SHALE interbedded with SANDSTONE | Fine to coarse SAND and SILT |
| 13 | Warren | 61 | 27 | 490 | 2098 | RB-1 | | 8.0 FT. RT. | 24.4 | 1266.9 | Siltstone | Fine to coarse SAND, some fine to coarse Gravel, little Silt |
| 14 | Warren | 61 | 1021 | 40 | 0 | B-2 | 71+89.0 | 8.0 FT. RT. | 5.7 | 1414.9 | Sandstone | SAND and SILT |
| 15 | Warren | 61 | 2010 | 20 | 1511 | RB-2 | 9+10.0 | 6.0 ft. RT. | 34 | | SILTSTONE interbedded with SANDSTONE | Sandstone boulder at 13.7, Fine to coarse SAND, little Silt, trace fine to coarse Gravel |

Figure 8. Identified sites with boring data available

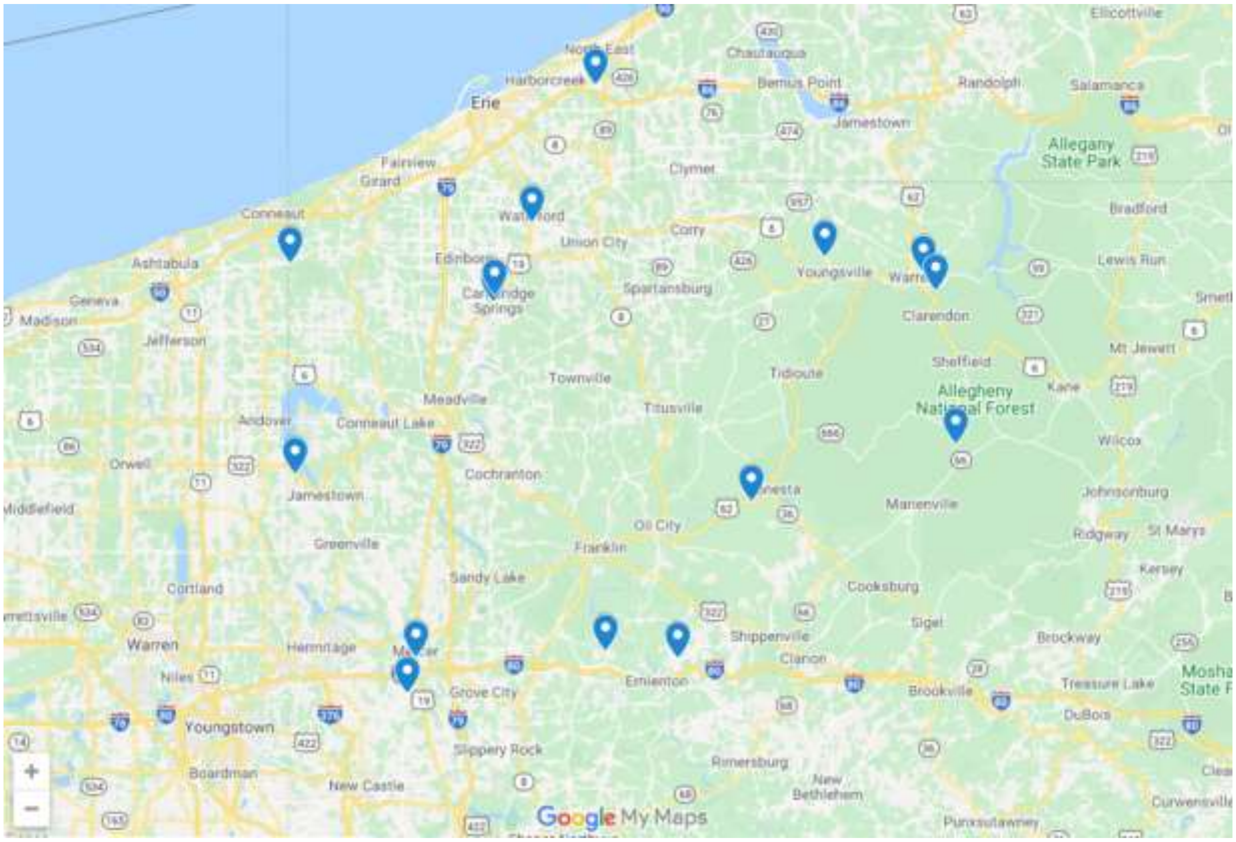



Figure 9. Google map of locations of testing sites

# 3. Field Testing and Results

This chapter summarizes the effort and findings within Task 3 of the project. This includes the data collection and site testing as well as the processed results comparing the different methods to conventional coring. First a summary of the field effort will be presented followed by the results.

## 3.1 Field Testing Review

The field testing of the passive seismic methods was conducted by RETTEW. Testing began on October 11th and carried out over three weeks and was concluded October 29th 2021. Three different testing methodologies were carried out at each site. These included Refraction Microtremor (ReMi), Multispectral Analysis of Surface Waves (MASW), and Horizontal-to-Vertical Spectral Ratio (HVSR). The testing procedure was carried out using the procedure and equipment specified in Section 1.5.

It was initially desired to collect data centered directly on top of the location of the ground truth cores. However, upon visiting the sites, it was determined that this would not be possible. Every effort was made to perform the testing as close as possible to the location of the core, but care needed to be taken to ensure that safety was maintained. This often resulted in the testing being shifted out into the shoulder and moving along the road slightly to ensure that adequate shoulder existed as well as avoiding blind curves. The locations of the testing compared to the ground truth core locations were recorded for comparison purposes.

Additionally, it was desired to collect data in orthogonal directions for both the ReMi and MASW methods. Since testing had to be performed in the shoulder it was also not possible to obtain testing in orthogonal directions. For both the ReMi and MASW testing, geophones are laid out in a line to receive seismic wave data. If data were to be collected in 2 deployments with the geophones laid out perpendicularly to one another, this would allow for a greater domain of interest to be examined and also allow for a three-dimensional representation (both directions horizontally and depth vertically) of the subsurface features. But since we are primarily only interested in comparing the ground truth depth to a depth obtained from the passive testing, it is sufficient to only test with the geophones located along one line.

Of the 15 total sites, only one was unable to be tested. At site 9 in Mercer, there was insufficient room to collect the data in the shoulder in the right of way. While this is not ideal, there were multiple other sites which had similar depths and bedrock lithology so this was deemed acceptable. The following pictures in Figure 10 are from the field testing. With the data collected, it must now be analyzed and interpreted.

(a) Geophone arrangement

(b) Oyo 4.5 Hertz geophone

(c) Sledge hammer and board used to generate signal


(d) Tromino device used to perform HVSR testing

Figure 10. Figures from field testing

## 3.2 Data Analysis and Results

A summary of each of the methods provided by RETTEW (2021) is presented, followed by the results from the testing from RETTEW summarized in Figure 11. Detailed maps of the survey locations and plots of the results from each method developed by RETTEW are presented in Appendix A (RETTEW, 2021).

**Refraction Microtremor (ReMi)**

RETTEW (2021) states that in order to characterize the seismic shear-wave velocity profile, ReMi data were collected by setting arrays of Mark Products 4.5-Hertz vertical geophones spaced at constant 10-foot intervals. For each line, data consisting of ambient seismic surface wave trains were measured for fifteen 30-second records at a sampling interval of 2 milliseconds. The seismic surface-wave data were analyzed using Seis Opt ReMi by Optim. Surface Wave Analysis makes use of the fact that much of the seismic noise at the ground surface consists of Rayleigh waves. Rayleigh waves are vertically-polarized surface waves that typically contain a broad spectrum of frequency content, with lower frequencies sampling progressively greater depths. By decomposing the frequency content of a Rayleigh wave train and measuring the velocity at which each component passes through the geophone array, it is possible to calculate the seismic shear-wave velocity as a function of depth beneath the geophone array. For each seismic profile, the individual seismic records were decomposed, and their spectra averaged to develop a line-average shear-wave velocity dispersion curve that was inverted to provide a best-fit sounding or vertical profile of shear-wave velocity versus depth (RETTEW, 2021). The interpretive shear-wave velocities versus depth are presented as 1-D profiles as shown in Figures developed by RETTEW in Appendix A.

**Multispectral Analysis of Surface Waves (MASW)**

RETTEW (2021) states that the principle of MASW is based on the dispersion of seismic surface waves where the different frequency components of surface wave trains sample differing effective depths, causing the surface wave train to change shape or disperses as it propagates. Therefore, the surface wave train recorded at each geophone in a linear array can be Fourier-transformed, and the velocity of individual wavelengths determined to provide shear-wave velocity as a function of frequency, which is in turn inverted to determine S-wave velocity as a function of depth at each geophone location. For numerous off-set (forward and reverse) shots and receivers, it is possible to construct a cross-sectional image of shear-wave velocity as a function of distance and depth, or, as in this investigation, a 1-D profile presenting shear-wave velocity versus depth and the center of the array. Four off-set shots were taken at each of the MASW arrays (with a 16-lb sledgehammer and composite strike plate) to generate seismic surface waves for Vs and depth estimates. MASW is not strictly a passive seismic method; however, it can still be an effective method along roadways or in other areas with heavy noise.

**Horizontal/Vertical Seismic Ratio (HVSR)**

The HVSR seismic method is a non-invasive, passive seismic technique that uses a single, broad-band three-component seismometer (Tromino) to record ambient seismic noise. RETTEW (2021) summarizes HVSR with the following method description. This method measures two horizontal (north-south and east-west) components and a third, vertical component of ambient seismic signals which occur everywhere in nature. These seismic signals (or microtremors) are created from a multitude of activities such as ocean waves, wind, and anthropogenic activity. The ratio of the average horizontal-to-vertical frequency spectrum is used to determine the fundamental site resonance frequency, where sediment thicknesses (bedrock depths) can be estimated. The primary resonance frequency is deduced from the prominent peaks on the H/V curve (with associated local minimums on the vertical component curve) and is directly related to the strongest acoustic impedance contrast, which is interpreted as a significant stratigraphic boundary (typically the sediment-bedrock interface). The processing consists of estimating the ratio between the Fourier amplitude spectra of the horizontal-to-vertical components to determine resonance frequency and an estimate of shear-wave velocity, which are used to make sediment thickness and bedrock depth estimates. At sites where bedrock depths are unknown, sediment thickness can be calculated if a Vs value is known (such as an average Vs measured from MASW or ReMi). At sites where bedrock depths are known, regression equations can also be used to solve for depth by using a power law function to fit frequency (derived from the HVSR curve) versus the depth to rock. The processed data are typically displayed as a 1-D vertical profile showing shear-wave velocity versus depth as shown in Appendix A.

It is important to note the size and scale of the three different technologies. The ReMi and MASW methods use a series of geophones that are connected in an array that plugs into a laptop using software to record the waveforms from the geophones. The geophones are only a few inches across with two wire leads. Twenty-four geophones were placed in a straight-line array approximately 10 ft apart with the receiver and seismograph recording directly in the middle. The HVSR device is a self-contained box several inches in length, width, and depth and is placed in the middle of the at the same place as the seismograph. The data is downloaded directly from the device to the computer to be processed.

Figure 11 presents the results of the testing in comparison to the borings. In order to determine the most accurate, efficient, and cost-effective method for obtaining bedrock depths throughout the study area, a statistical analysis was completed and a ranking system applied to compare the median percent error (accuracy) of calculated depths to known depths, total time for data collection and processing, and cost ([rate x total time] + equipment) where the lowest sum represents the overall most accurate, efficient, and cost-effective approach (RETTEW, 2021). Below is a data table showing the results of the statistical analysis. Based on the field survey results and analysis in Figure 11, the HVSR method ranked 1 (or best), followed by ReMi and MASW in each of the three categories (accuracy, efficiency, and cost), respectively.

Note, however, that the HVSR data from Site 2 was likely affected by wind. The HVSR percent error calculated for Site 2 was a significant outlier and would likely be reduced if the survey was repeated under calmer conditions. Also note that the HVSR method is a single-channel, self-contained system that can be deployed in the field by one person in roughly 5 minutes, whereas the ReMi and MASW methods require a two-person crew and a roughly 1-hour setup time (which also affects cost). Lastly, confirmatory borings at the center of each seismic array (or Tromino location) as shown on the data coverage maps would allow for a more direct comparison of the results of this study and would further refine the accuracy and effectiveness of each seismic method (RETTEW, 2021).

| | Rock Depth (ft) | | | | Error (%) | | |
|---|---|---|---|---|---|---|---|
| Site | ReMi | MASW | HVSR | Boring | ReMi | MASW | HVSR |
| 1 | 15.4 | 16.7 | 12.2 | 11.2 | 27.3 | 32.9 | 8.2 |
| 2[1] | 16.2 | 16.4 | 6.7 | 16.2 | 0.0 | 1.2 | 141.8 |
| 3 | 45.2 | 43.7 | 46.8 | Not Encountered | | | |
| 4 | 17.8 | 17.4 | 11.1 | 14.8 | 16.9 | 14.9 | 33.3 |
| 5 | 35.6 | 36.5 | 37.5 | 34.6 | 2.8 | 5.2 | 7.7 |
| 6 | 56.5 | NA | 56 | Not Encountered | | | |
| 7 | 21.3 | 17.6 | 21.2 | 21.3 | 0.0 | 21.0 | 0.5 |
| 8 | 18.4 | 17.6 | 14.3 | 13.1 | 28.8 | 25.6 | 8.4 |
| 10 | 25.3 | 23.3 | 27.7 | 26.7 | 5.5 | 14.6 | 3.6 |
| 11 | 25.2 | 23.3 | 26.6 | 24.5 | 2.8 | 5.2 | 7.9 |
| 12 | 22.1 | 23.5 | 17.7 | 15.8 | 28.5 | 32.8 | 10.7 |
| 13 | 26.5 | 23.5 | 24.5 | 24.4 | 7.9 | 3.8 | 0.4 |
| 14 | 7.4 | 7.6 | 14.3 | 5.7 | 23.0 | 25.0 | 60.1 |
| 15 | 18.1 | 23.4 | 26.7 | 24 | 32.6 | 2.6 | 10.1 |

| | | ReMi | MASW | HVSR |
|---|---|---|---|---|
| | Median % Error | 12.4 | 14.8 | 8.3 |
| | Data Collection (hr) | 16.6 | 21.3 | 5.8 |
| | Data Processing (hr) | 10.3 | 10.9 | 4.9 |
| | Total Time (hr) | 26.9 | 32.2 | 10.7 |
| *accuracy based on median %Error* | Accuracy Rank | 3 | 2 | 1 |
| *efficiency based on Total Time* | Efficiency Rank | 2 | 3 | 1 |
| *cost = rate x total time + equipment* | Cost Rank | 2 | 3 | 1 |
| | Accuracy/Efficiency/Cost Rank Sum | 7 | 8 | 3 |
| | OVERALL RANKING | 2 | 3 | 1 |

Figure 11. Results of ReMi, MASW, and HVSR seismic methods (RETTEW, 2021)

[1]The large error with the HVSR technique for site 2 is attributed to the windy conditions at the time of testing. The technique is highly sensitive to vibrations and it is expected that the error would be reduced if the test was repeated under calmer conditions.

# 4. Conclusions and Recommendations

While the HVSR method was very good in a number of instances, the results at Site 2 and 14 produced the largest errors encountered across all three methodologies. The HVSR method is extremely sensitive and the ambient conditions can greatly influence the results so it should only be deployed in calm conditions with as little noise and background interference as possible. This is a very important issue as large discrepancies can be obtained in the results and multiple measurements should always be taken and ideally cross referenced with ground truth borings or another methodology.

The HVSR methodology would additionally be the easiest methodology for PennDOT to adopt as it requires the least amount of equipment to employ, time to test, and interpret the results. The self-contained device can be very quicky deployed by one person with minimal setup and testing time. The primary issue would be the interpretation of the data which ideally would be performed by a trained seismologist. However, it should be possible to interpret the results with training, or to contract out the analysis and interpretation to a company with geophysical expertise.

The cost of the Tromino device to perform the HVSR testing can have a wide range depending on the features and software choices and the price was approximately $10-20 thousand (Moho, 2017). When the cost of a boring can run from hundreds to a few thousand dollars, the overall upfront cost of the technology is minimal in comparison with multiple borings. This device could be very easily employed by PennDOT, however, training would be needed to analyze the data.

While the ReMi and MASW methods also produced reasonable results, it would be much more difficult for PennDOT to employ as the equipment and setup is much more involved. Additionally, the testing time and data analysis takes more time resulting in a larger overall cost. However, these techniques are also valid and produce reasonable results. If either ReMi or MASW were to be employed it would be recommended to have a geophysical company perform the testing and analysis.

As the focus of this study was to detect the depth of bedrock, delineating the water table was not of primary importance. As a result, the water table depth was not found. These technologies should allow for water table to de discerned, but more research should be conducted to verify that this is the case.

There appears to be no discernable trend with the different rock types encountered in this study such that one lithology of overburden or bedrock did not decrease the error between the ground truth boring and the passive seismic methods. In my opinion, the actual type of material is not as important to producing accurate results. It is more important that there be a measurable (detectable) difference in stiffness between the overburden and bedrock such that the technology can detect a difference in shear wave velocity at the layer boundary. In fact, the geology of District 1 may be more difficult to determine the depth of bedrock that other areas of

Pennsylvania with different geology where there is a larger difference in stiffness between the bedrock and overburden material. Therefore, it is my recommendation that passive seismic methods could be used across the state regardless of the geology with the caveat that similar material stiffness near the bedrock location will make the interpretation of the 'true' depth more difficult.

In conclusion, seismic methods provide reasonable predictions of the depth to bedrock for a variety of geological conditions. All three methods tested (ReMi, MASW, and HVSR) can be used to predict the depth to bedrock. Additionally, a benefit of these technologies is that greater depths can be probed than were possible to obtain with the boring. For example, at Sites 3 and 6 where the boring did not encounter bedrock, depths were obtained from the procedures around 45 and 56 feet respectively. If a depth was not able to be obtained from a boring, passive seismic methods would result in the ability to approximate the value in instances where the depth to bedrock is critical.

While testing was not able to be carried out directly at the boring locations, good correlation was still found as reasonably close as possible to the actual locations. While tests of this nature can be exceedingly useful, it is still not a replacement for ground truth boring results. However, by employing boring in conjunction with a passive seismic scan, one would be able to potentially map a much larger area with reasonable accuracy. It is therefore recommended that this technology can be employed in areas where depth to bedrock is needed as a minimally important variable. Finally, borings should still be taken at critical locations for large projects, however, it is the authors opinion that passive seismic methods can be employed in conjunction with borings at strategic locations to reduce the total number of borings needed.

## Acknowledgements

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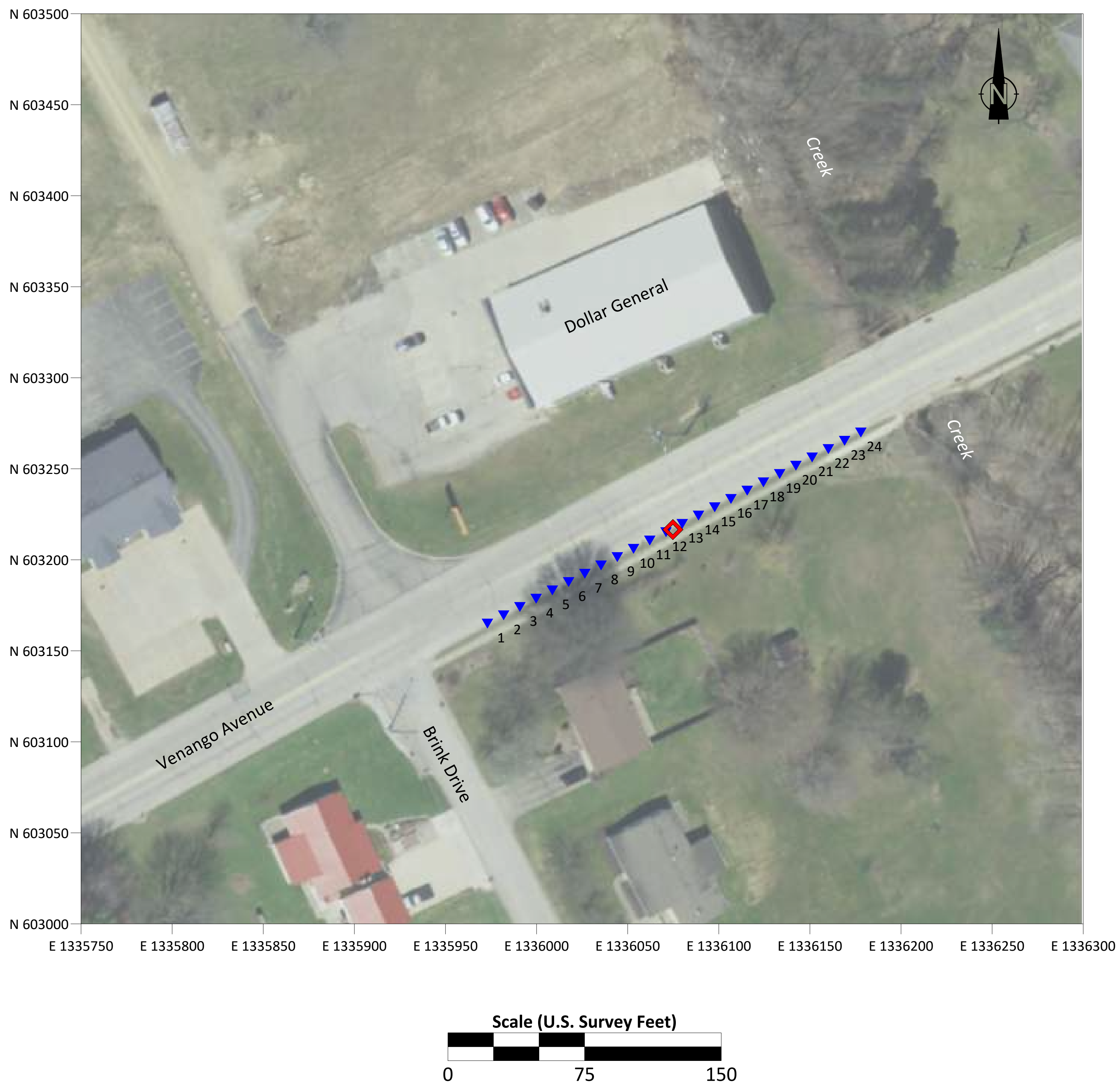
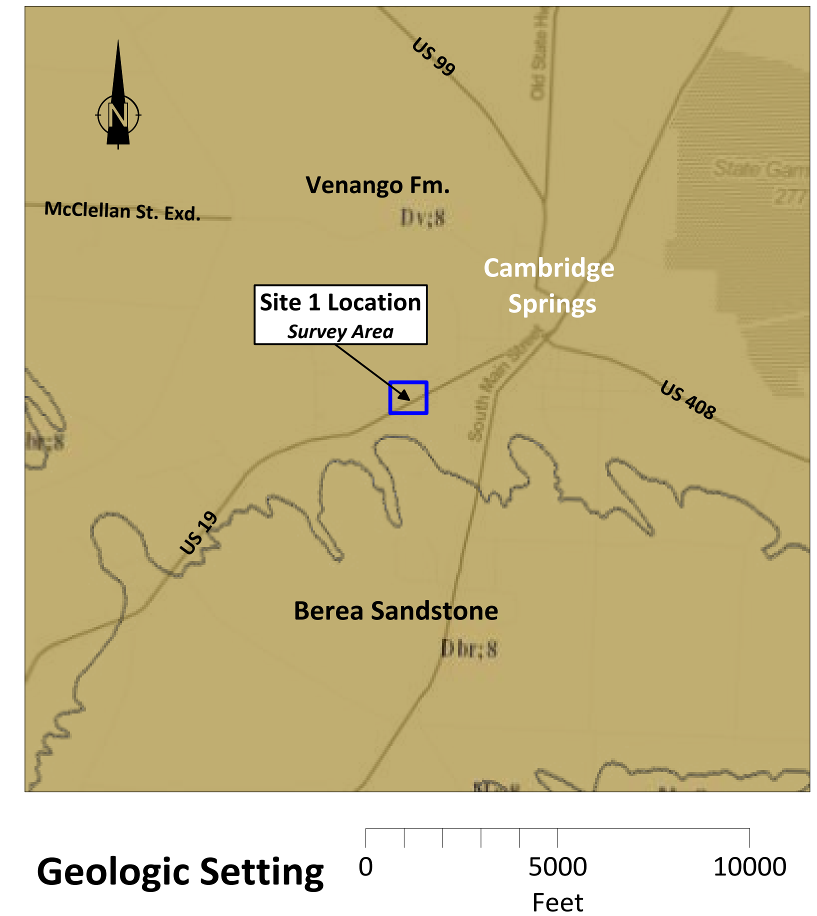
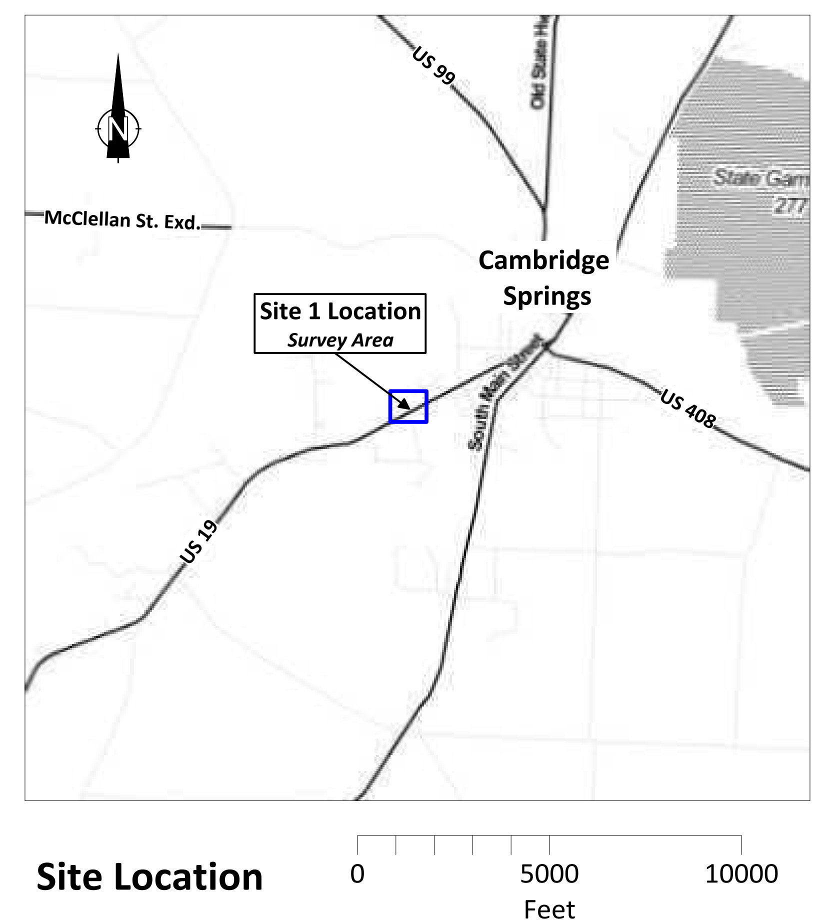
# Appendix A

The following figures were developed by RETTEW including map data and the individual site results showing the shear wave velocity versus depth, the predicted bedrock depths, and the data collection and processing time for each method (RETTEW, 2021).




**Geologic Setting**




**Site Location**

**Notes:**

Basemap image from PASDA Imagery Navigator (2018).

Geologic and geographic information from PASDA WMS Server.

Coordinates in PA State Plane (north), NAD83, U.S. Survey feet.

Survey profiles/stations from field survey and RTK by RETTEW.

**Geophysical Survey Legend**

▼ Geophone Location

◇ Seismograph (Geode/Tromino)

SURVEY DATE: 10/28/2021
RETTEW No.: 105082002
REVIEWED BY: CHR/FKB
DRAWN BY: CTM
REVISION DATE: 11/12/2021
SCALE: Graphical
FIGURE NO. 1A

RETTEW

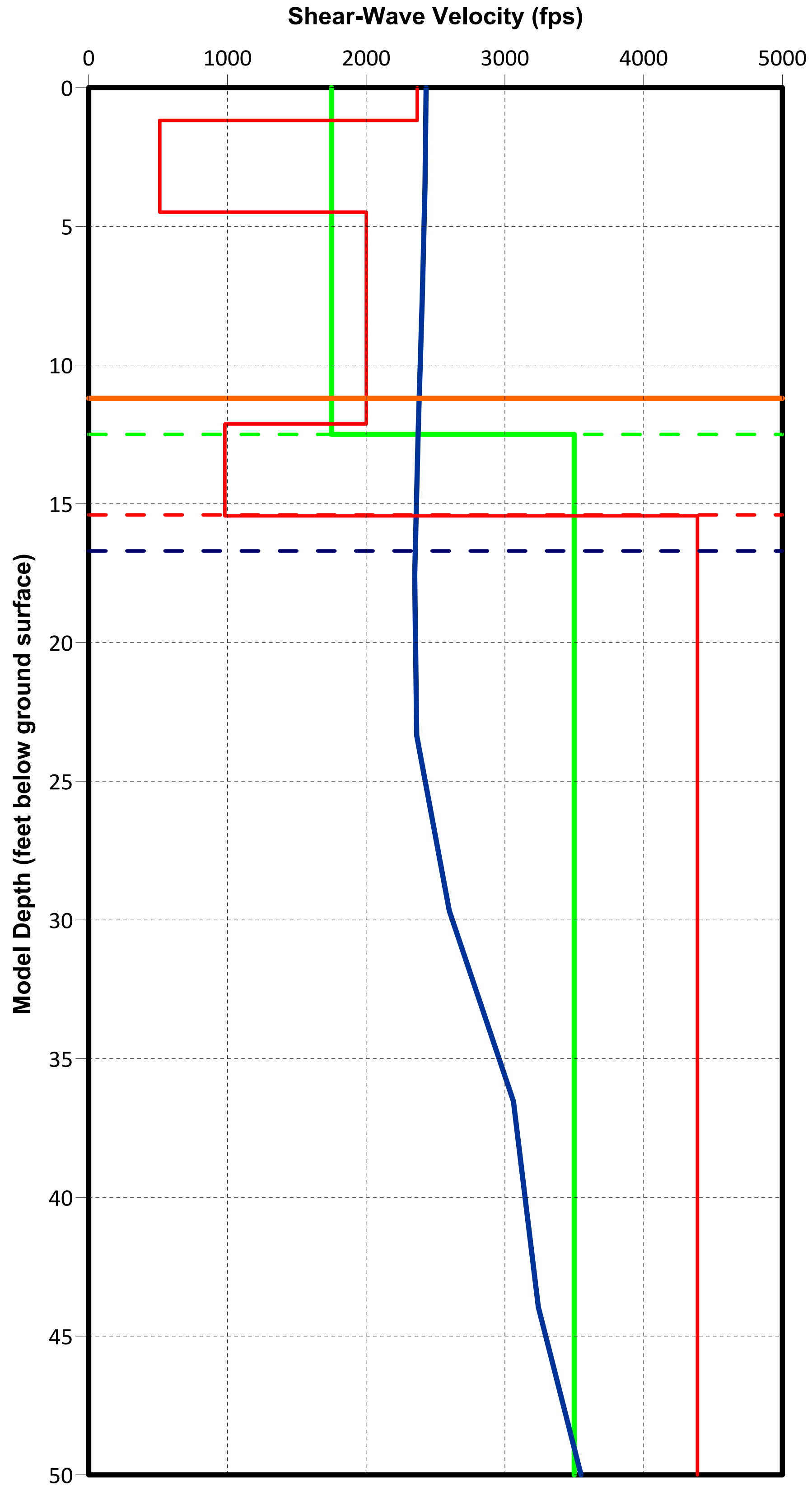
RETTEW Field Services, Inc.
3020 Columbia Avenue, Lancaster, PA 17603
Phone 1-800-738-8395

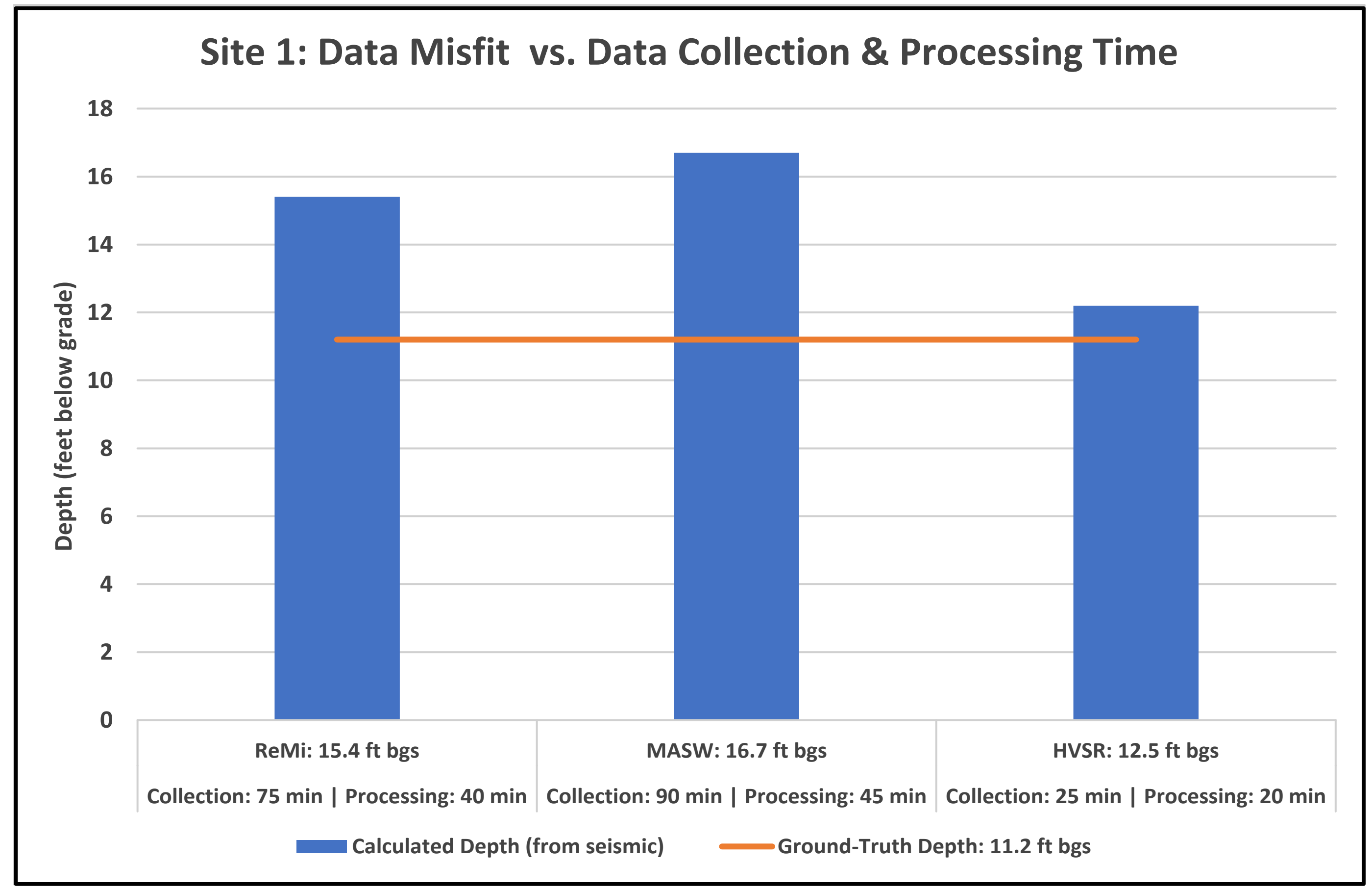
**Figure 1A: Data Coverage and Geologic Setting Site 1**

An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 1

CRAWFORD COUNTY

CAMBRIDGE SPRINGS, PA




**Weighted Average Shear-Wave Velocities**

- Profile 1 ReMi (Seis Opt)
- Profile 2 1-D MASW (Seisimager)
- Profile 3 HVSR (Grilla)
- Depth to Bedrock (from boring)

**Notes:**

MASW and ReMi seismic data from Geometrics 24-channel Geode with 4.5 Hz geophones at a 10-foot spacing.

MASW weighted average shear-wave velocities (Vs) from Geometrics SeisImager. ReMi average Vs values from Seis Opt ReMi by Optim. HVSR average Vs from Grilla by MOHO.

Colored dashed lines correspond to inferred rock depths from each type of survey.

SURVEY DATE: 10/14/2021
RETTEW No.: 105082002
REVIEWED BY: CHR/FKB
DRAWN BY: CTM
REVISION DATE: 11/12/2021
SCALE: Graphical
FIGURE NO. 1B


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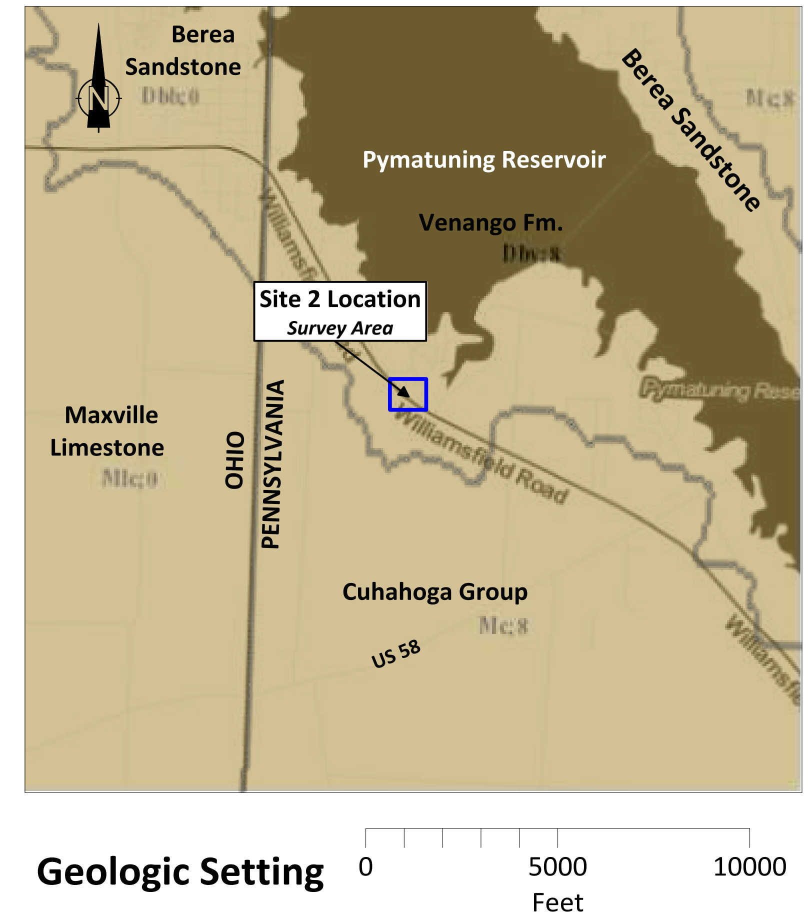
**Figure 1B: Seismic Results Site 1**

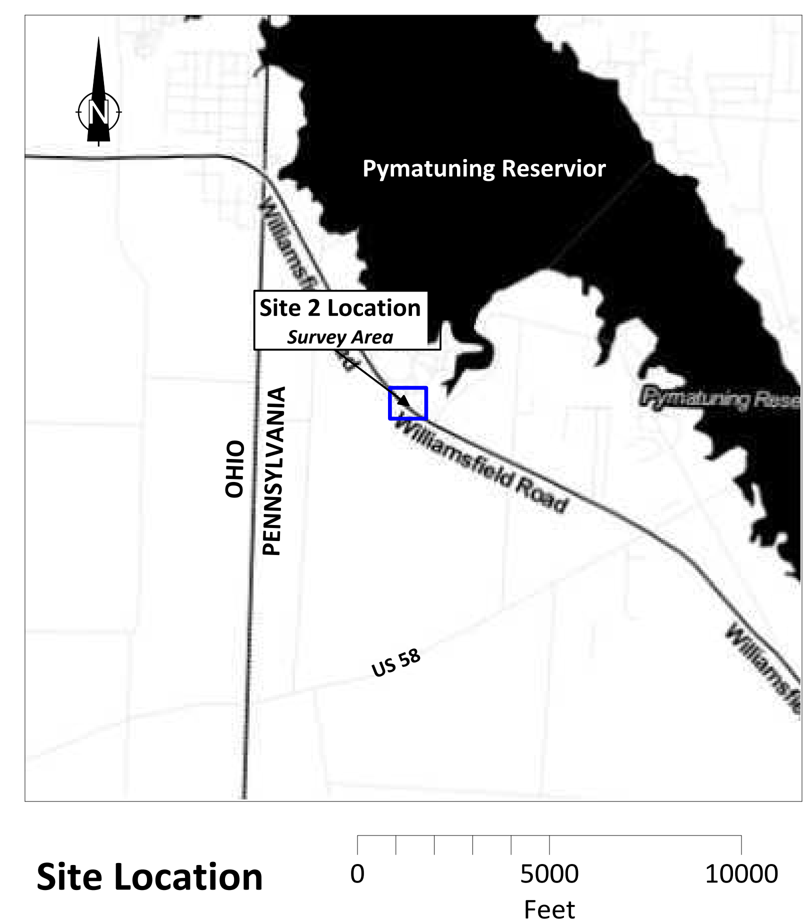
An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 1

CRAWFORD COUNTY

CAMBRIDGE SPRINGS, PA


## Geologic Setting




## Site Location

**Notes:**

Basemap image from PASDA Imagery Navigator (2018).

Geologic and geographic information from PASDA WMS Server.

Coordinates in PA State Plane (north), NAD83, U.S. Survey feet.

Survey profiles/stations from field survey and RTK by RETTEW.

**Geophysical Survey Legend**

- Geophone Location
- Seismograph (Geode/Tromino)

SURVEY DATE: 10/14/2021
RETTEW No.: 105082002
REVIEWED BY: CHR/FKB
DRAWN BY: CTM
REVISION DATE: 11/12/2021
SCALE: Graphical
FIGURE NO. 2A

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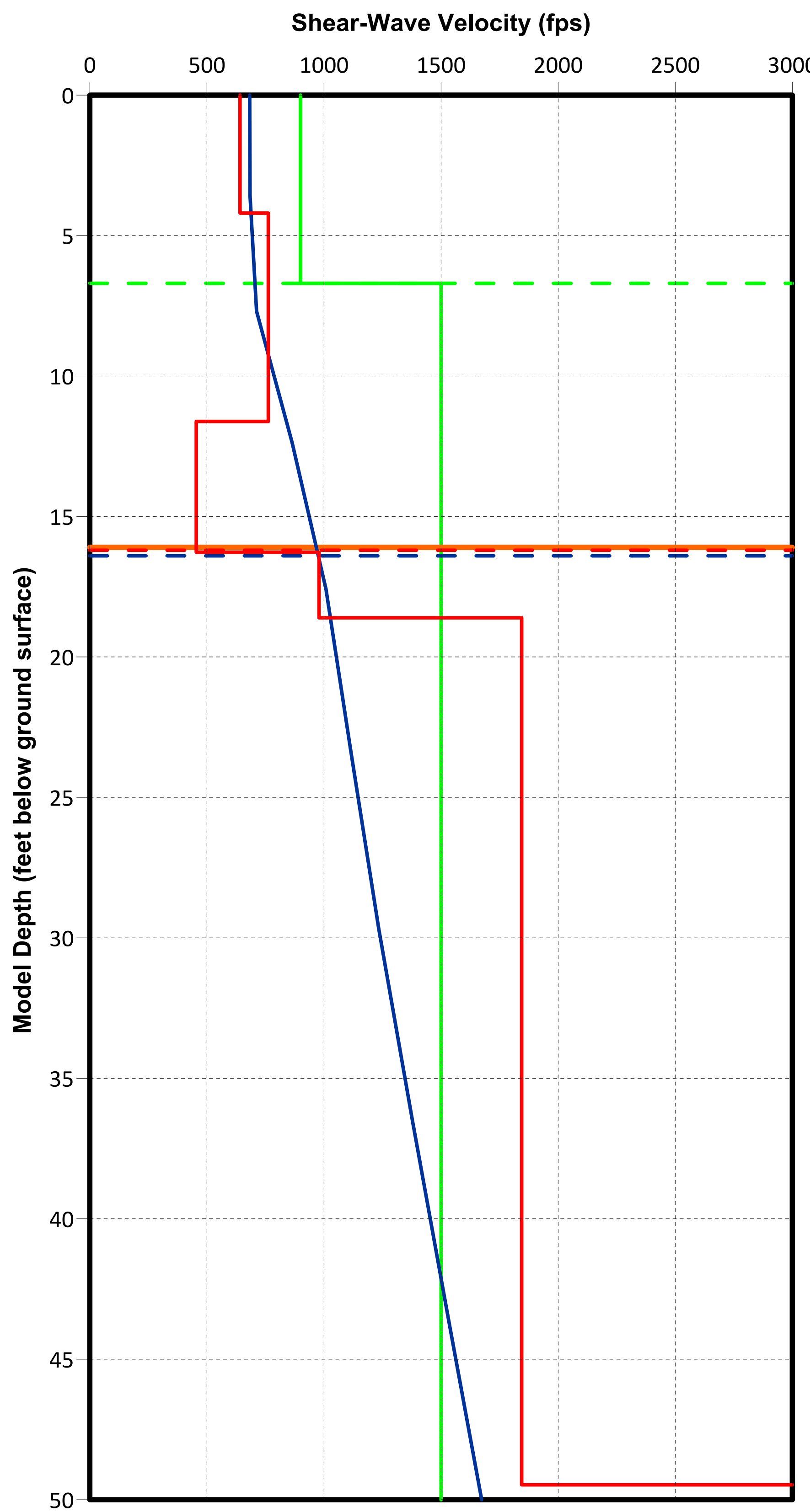
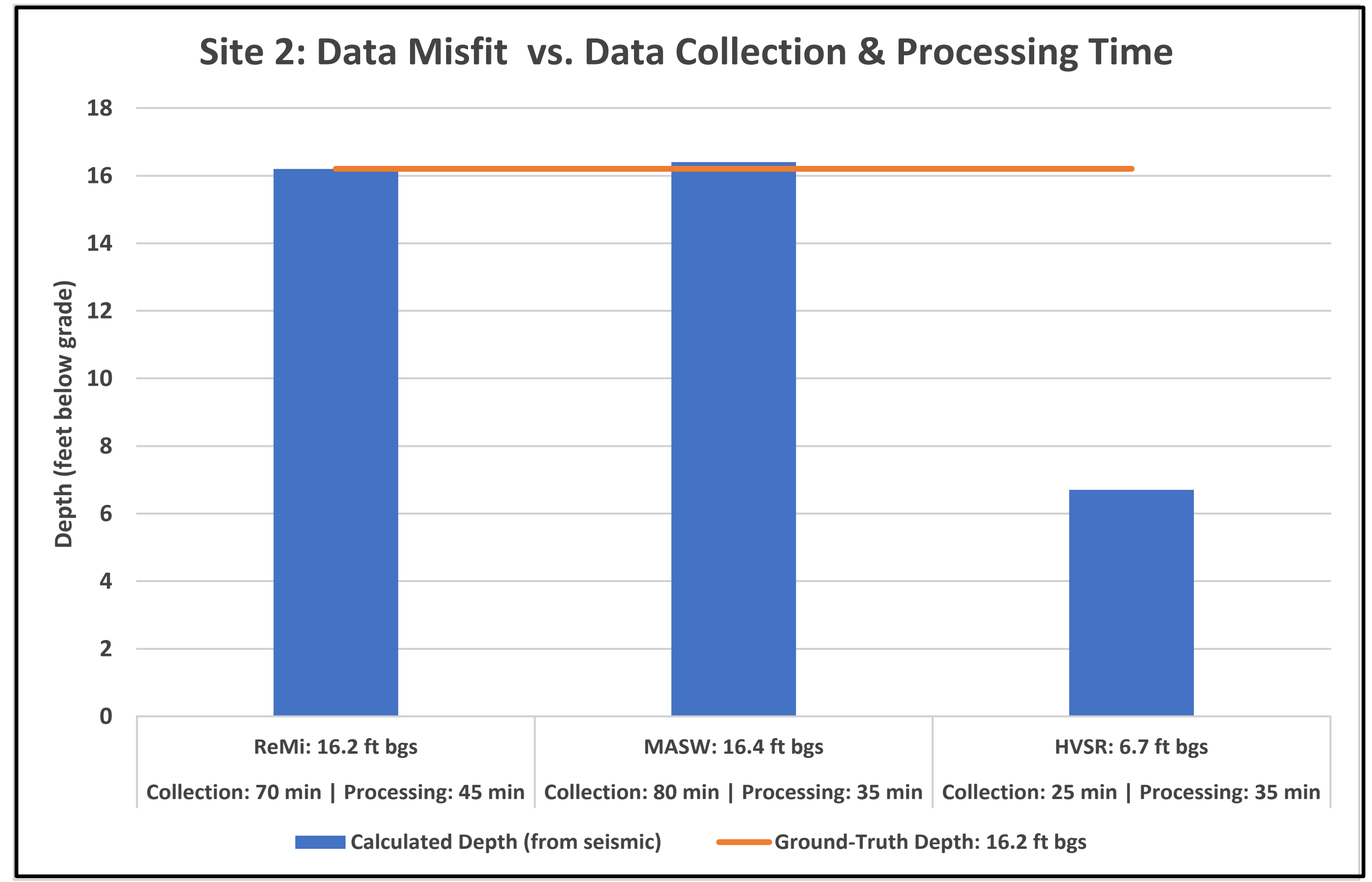
**Figure 2A: Data Coverage and Geologic Setting Site 2**

An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site2

CRAWFORD COUNTY

MEADEVILLE, PA




**Weighted Average Shear-Wave Velocities**

- Profile 1 ReMi (Seis Opt)
- Profile 2 1-D MASW (Seisimager)
- Profile 3 HVSR (Grilla)
- Depth to Bedrock (from boring)

**Notes:**

MASW and ReMi seismic data from Geometrics 24-channel Geode with 4.5 Hz geophones at a 10-foot spacing.

MASW weighted average shear-wave velocities (Vs) from Geometrics SeisImager. ReMi average Vs values from Seis Opt ReMi by Optim. HVSR average Vs from Grilla by MOHO.

Colored dashed lines correspond to inferred rock depths from each type of survey.

SURVEY DATE: 10/14/2021
RETTEW No.: 105082002
REVIEWED BY: CHR/FKB
DRAWN BY: CTM
REVISION DATE: 11/12/2021
SCALE: Graphical
FIGURE NO. 2B

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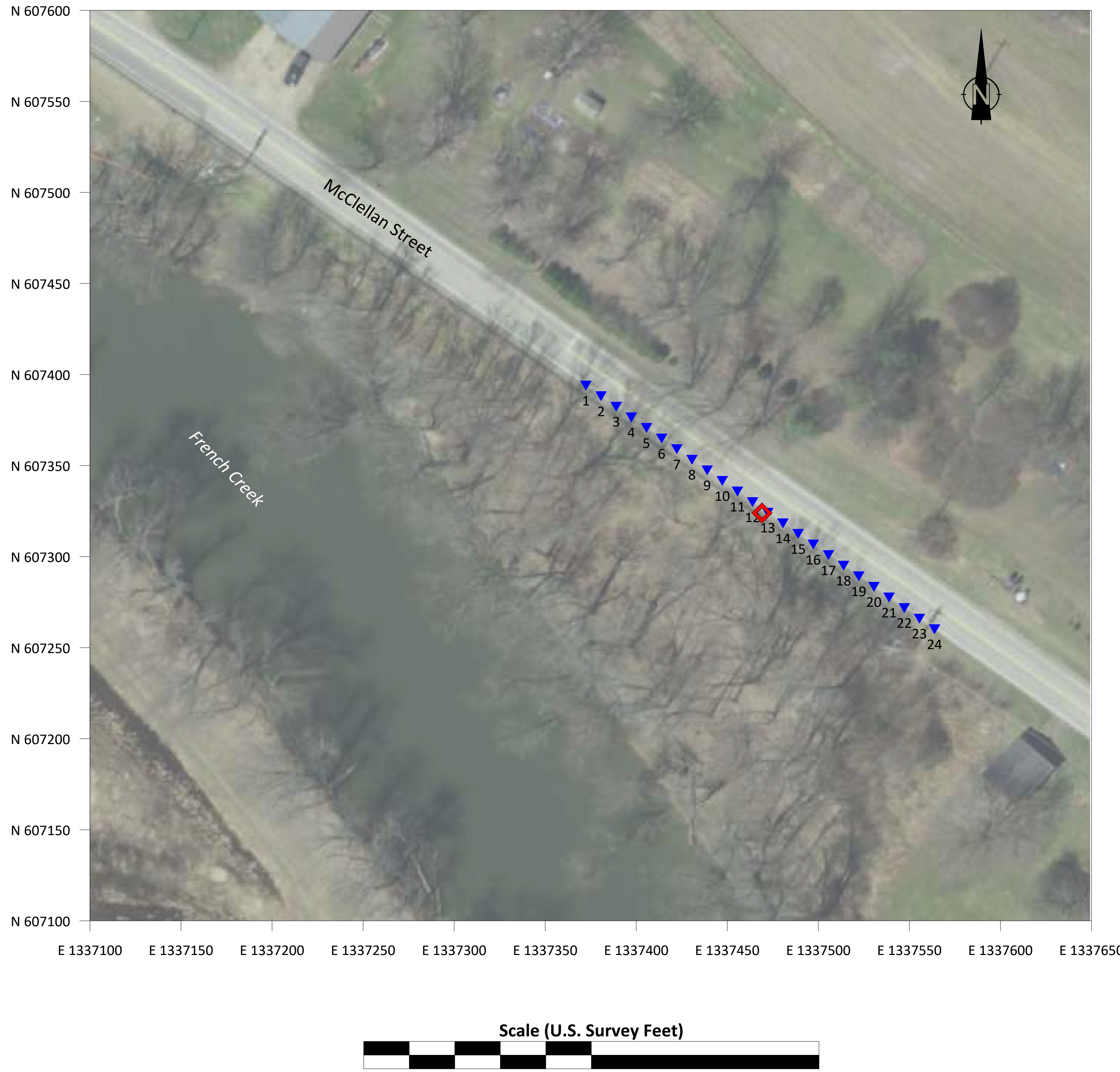
**Figure 2B: Seismic Results Site 2**

An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 2

CRAWFORD COUNTY
MEADEVILLE, PA




**Notes:**

Basemap image from PASDA Imagery Navigator (2018).

Geologic and geographic information from PASDA WMS Server.

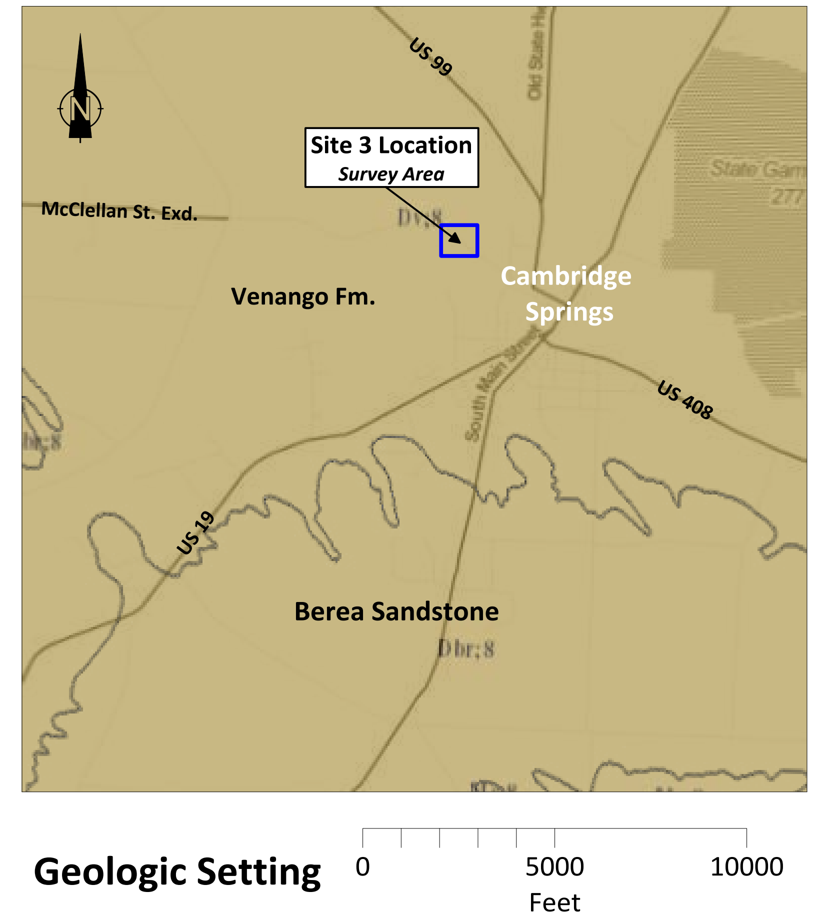
Coordinates in PA State Plane (north), NAD83, U.S. Survey feet.

Survey profiles/stations from field survey and RTK by RETTEW.

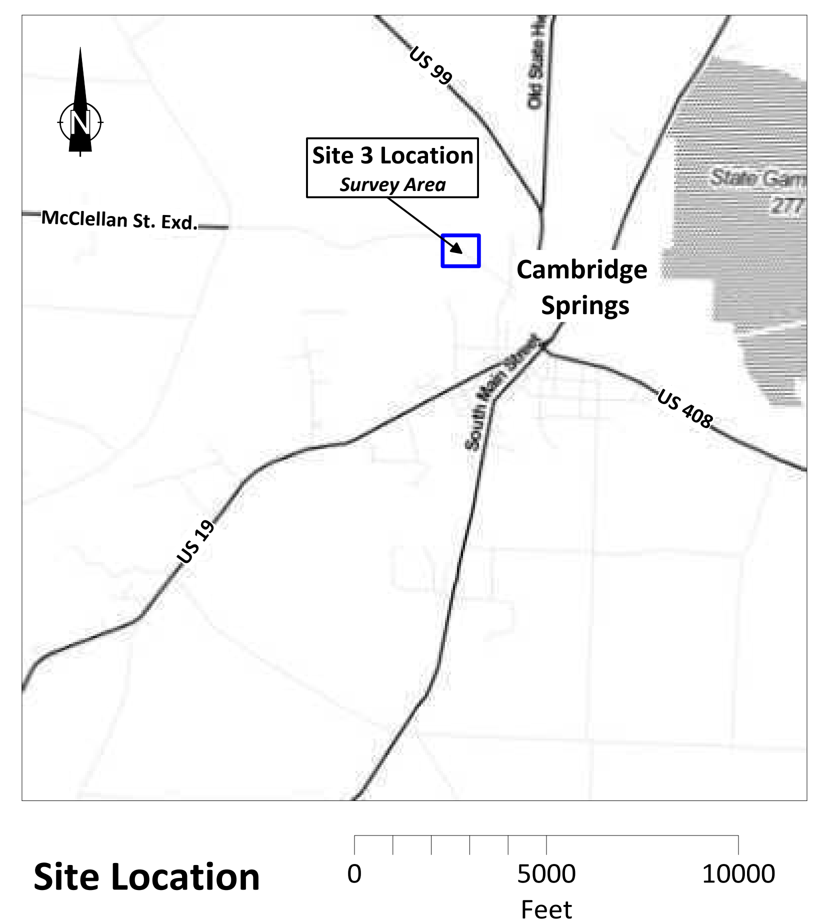
**Geophysical Survey Legend**

▼ Geophone Location

◇ Seismograph (Geode/Tromino)




**Geologic Setting**




**Site Location**

SURVEY DATE: 10/28/2021
RETTEW No.: 105082002
REVIEWED BY: CHR/FKB
DRAWN BY: CTM
REVISION DATE: 11/12/2021
SCALE: Graphical
FIGURE NO. 3A

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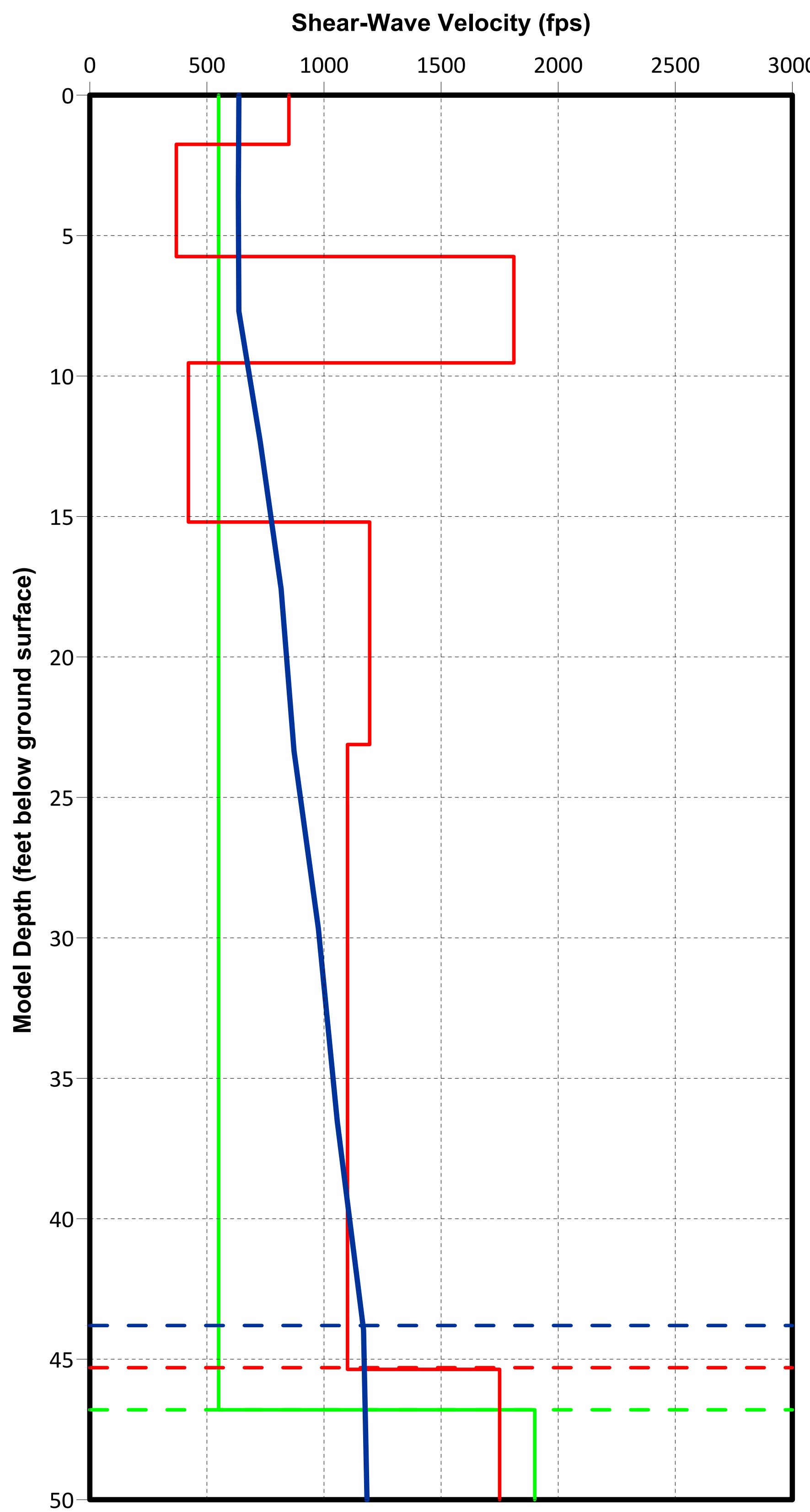
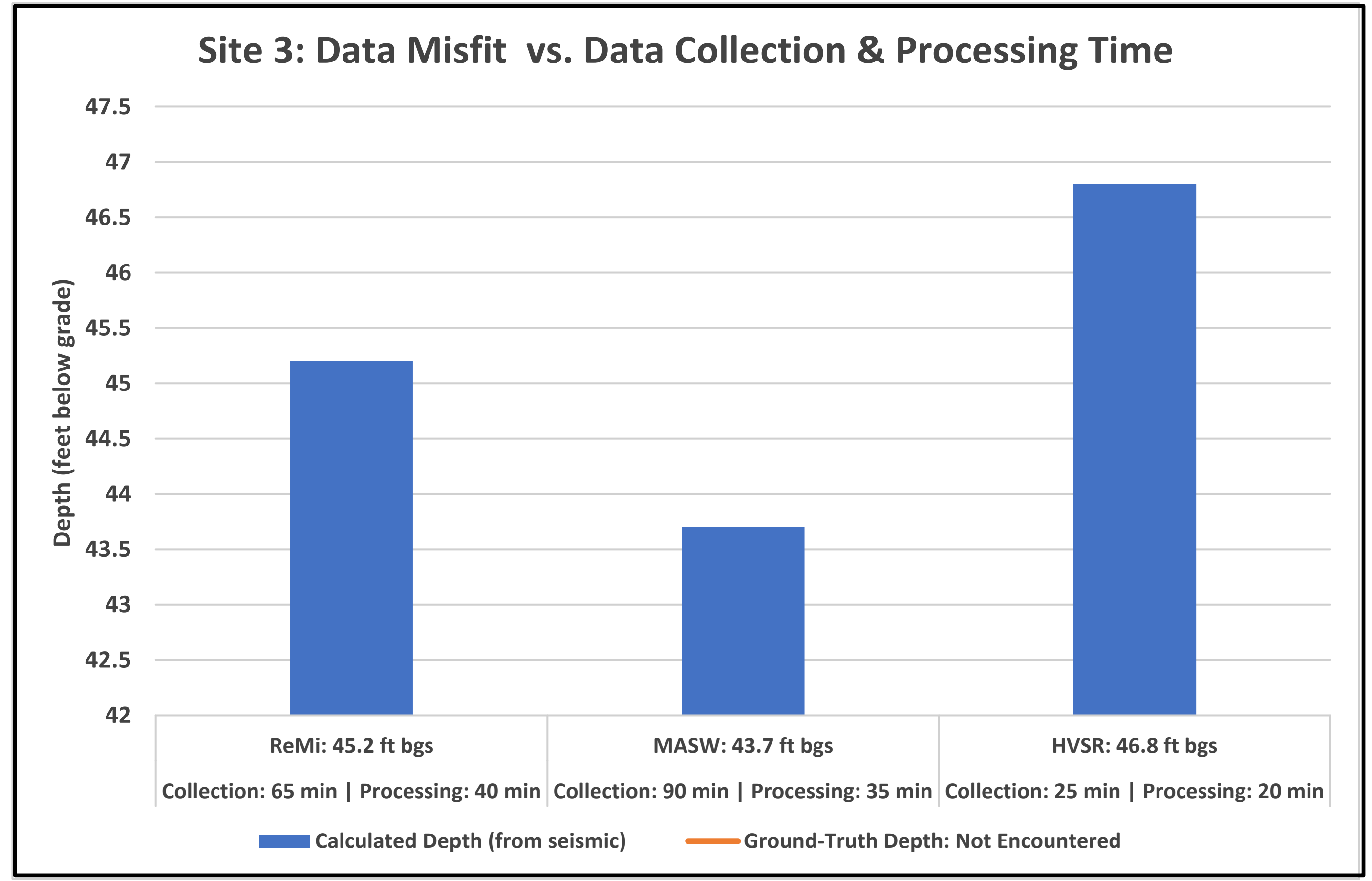
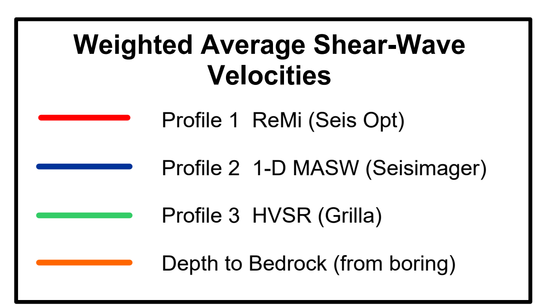
**Figure 3A: Data Coverage and Geologic Setting Site 3**

An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 3

CRAWFORD COUNTY
CAMBRIDGE SPRINGS, PA




**Notes:**

MASW and ReMi seismic data from Geometrics 24-channel Geode with 4.5 Hz geophones at a 10-foot spacing.

MASW weighted average shear-wave velocities (Vs) from Geometrics SeisImager. ReMi average Vs values from Seis Opt ReMi by Optim. HVSR average Vs from Grilla by MOHO.

Colored dashed lines correspond to inferred rock depths from each type of survey.

SURVEY DATE: 10/14/2021
RETTEW No.: 105082002
REVIEWED BY: CHR/FKB
DRAWN BY: CTM
REVISION DATE: 11/12/2021
SCALE: Graphical
FIGURE NO. 3B

RETTEW

RETTEW Field Services, Inc.
3020 Columbia Avenue, Lancaster, PA 17603
Phone 1-800-738-8395

**Figure 3B: Seismic Results Site 3**

An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 3

CRAWFORD COUNTY

CAMBRIDGE SPRINGS, PA


**Notes:**

Basemap image from PASDA Imagery Navigator (2018).

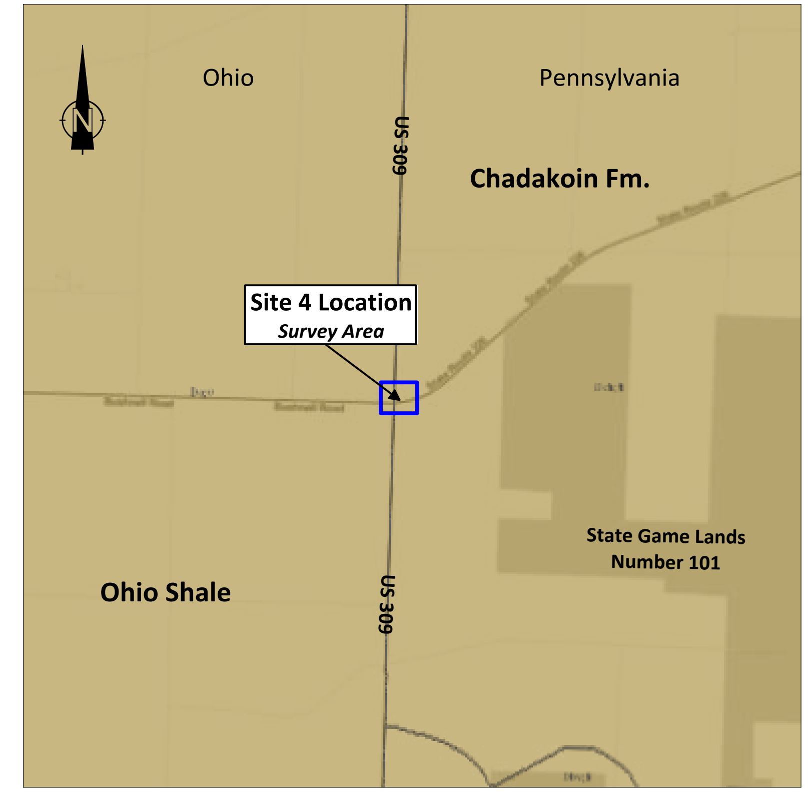
Geologic and Karst information from PASDA WMS Server.

Coordinates in PA State Plane (north), NAD83, U.S. Survey feet.

Survey profiles/stations from field survey and RTK by RETTEW.

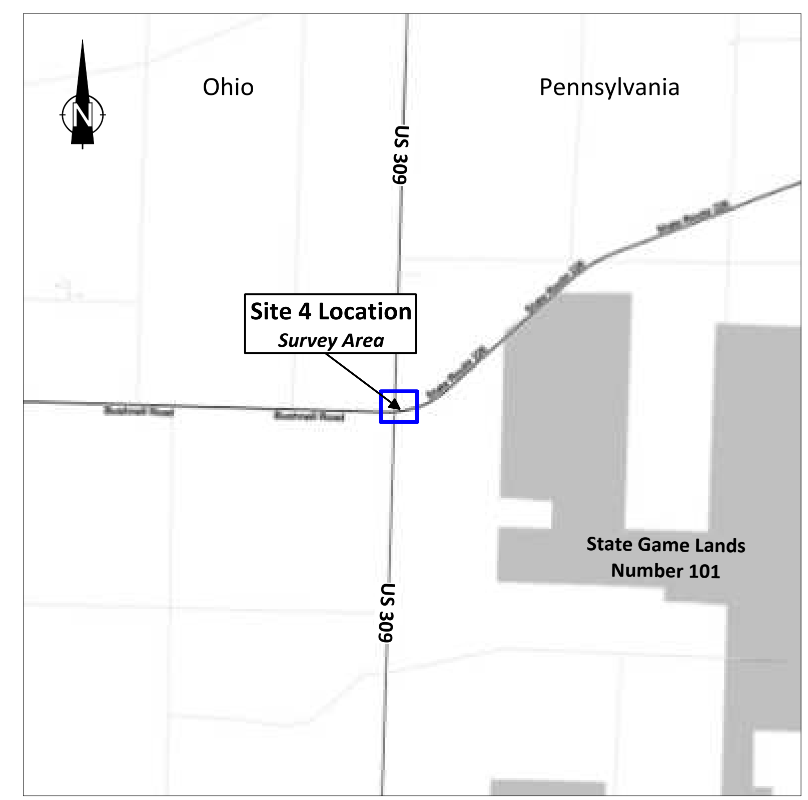
**Geophysical Survey Legend**

- ▼ Geophone Location
- ◇ Seismograph (Geode/Tromino)




**Geologic Setting**

0 5000 10000
Feet




**Site Location**

0 5000 10000
Feet

SURVEY DATE: 10/27/2021
RETTEW No.: 105082002
REVIEWED BY: CHR/FKB
DRAWN BY: CTM
REVISION DATE: 11/12/2021
SCALE: Graphical
FIGURE NO. 4A

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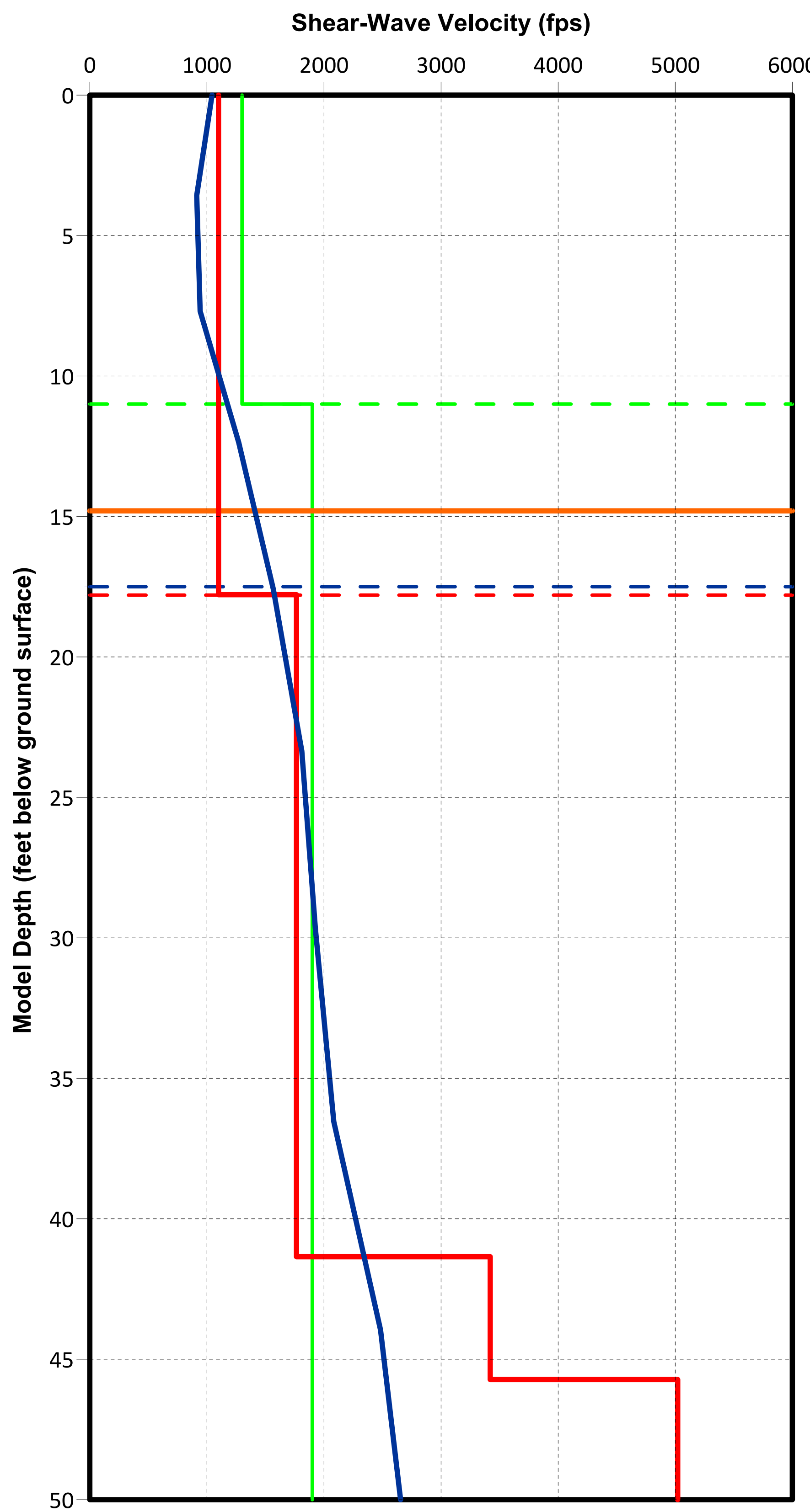
3020 Columbia Avenue, Lancaster, PA 17603
Phone 1-800-738-8395

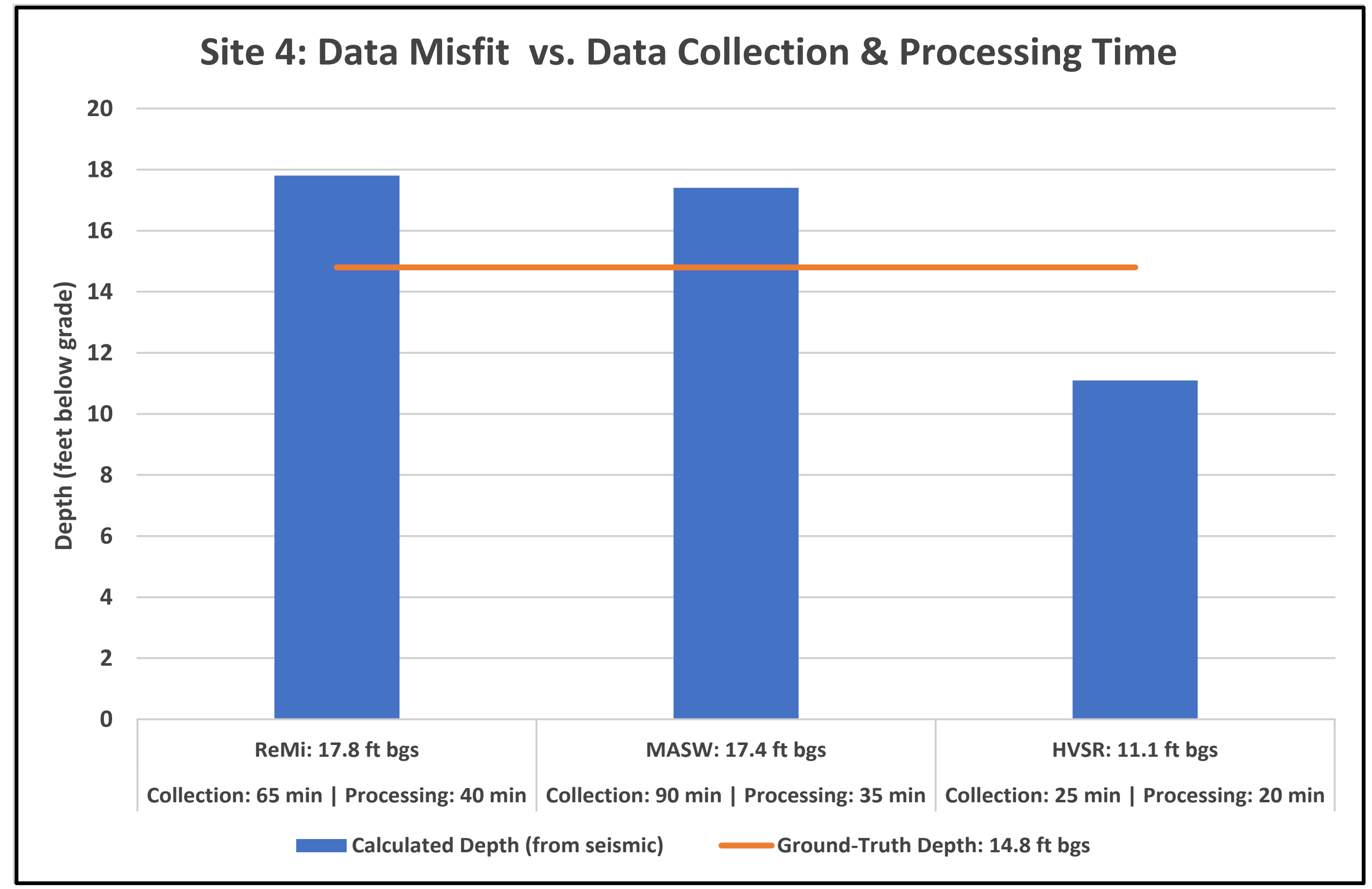

**Figure 4A: Data Coverage and Geologic Setting Site 4**

An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 4

ERIE COUNTY

ERIE, PA




**Weighted Average Shear-Wave Velocities**

- Profile 1 ReMi (Seis Opt)
- Profile 2 1-D MASW (Seisimager)
- Profile 3 HVSR (Grilla)
- Depth to Bedrock (from boring)

**Notes:**

MASW and ReMi seismic data from Geometrics 24-channel Geode with 4.5 Hz geophones at a 10-foot spacing.

MASW weighted average shear-wave velocities (Vs) from Geometrics SeisImager. ReMi average Vs values from Seis Opt ReMi by Optim. HVSR average Vs from Grilla by MOHO.

Colored dashed lines correspond to inferred rock depths from each type of survey.

SURVEY DATE: 10/14/2021
RETTEW No.: 105082002
REVIEWED BY: CHR/FKB
DRAWN BY: CTM
REVISION DATE: 11/12/2021
SCALE: Graphical
FIGURE NO. 4B

RETTEW

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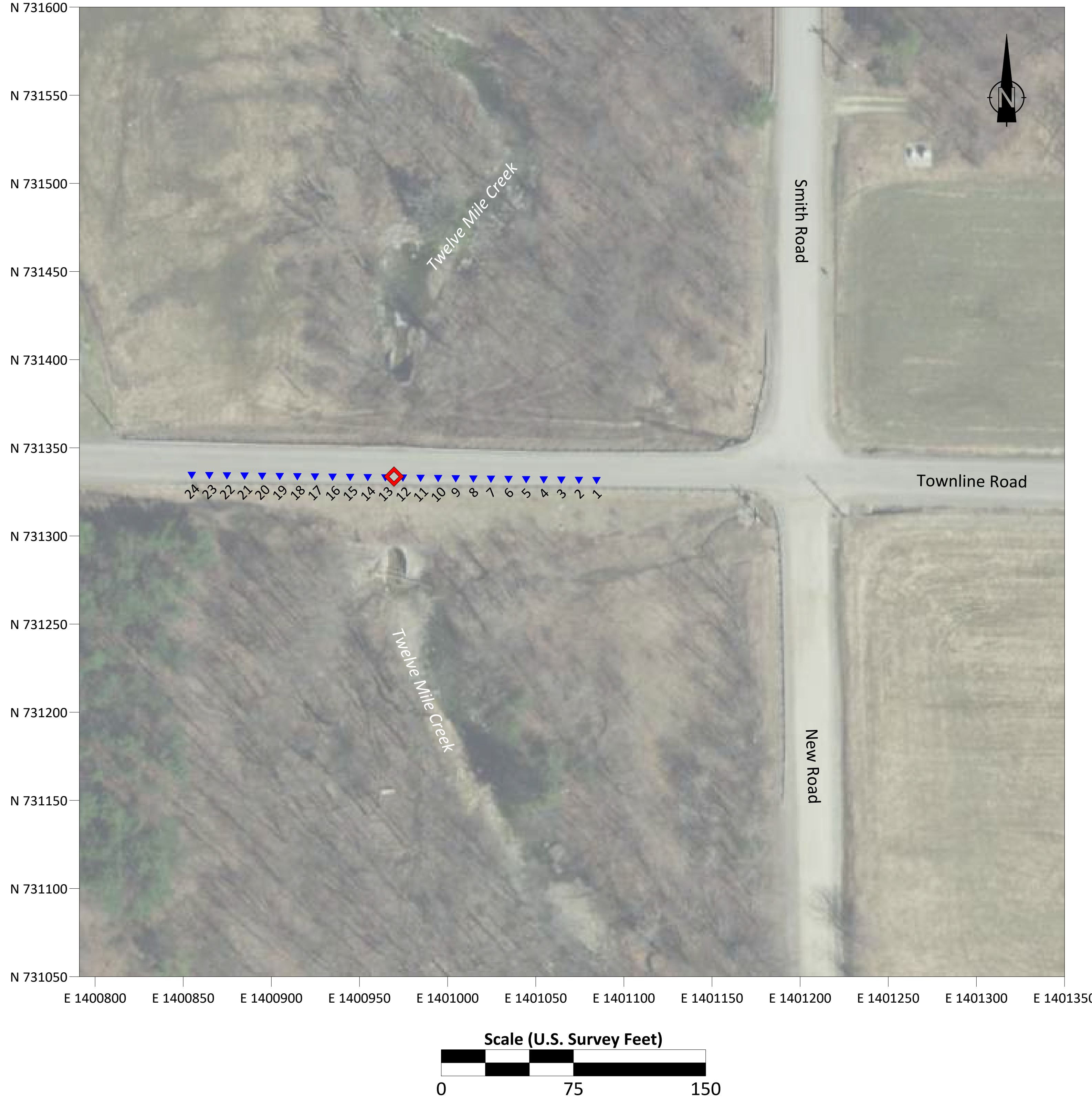
Phone 1-800-738-8395

**Figure 4B: Seismic Results Site 4**

An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 4

ERIE COUNTY

ERIE, PA




**Notes:**

Basemap image from PASDA Imagery Navigator (2018).

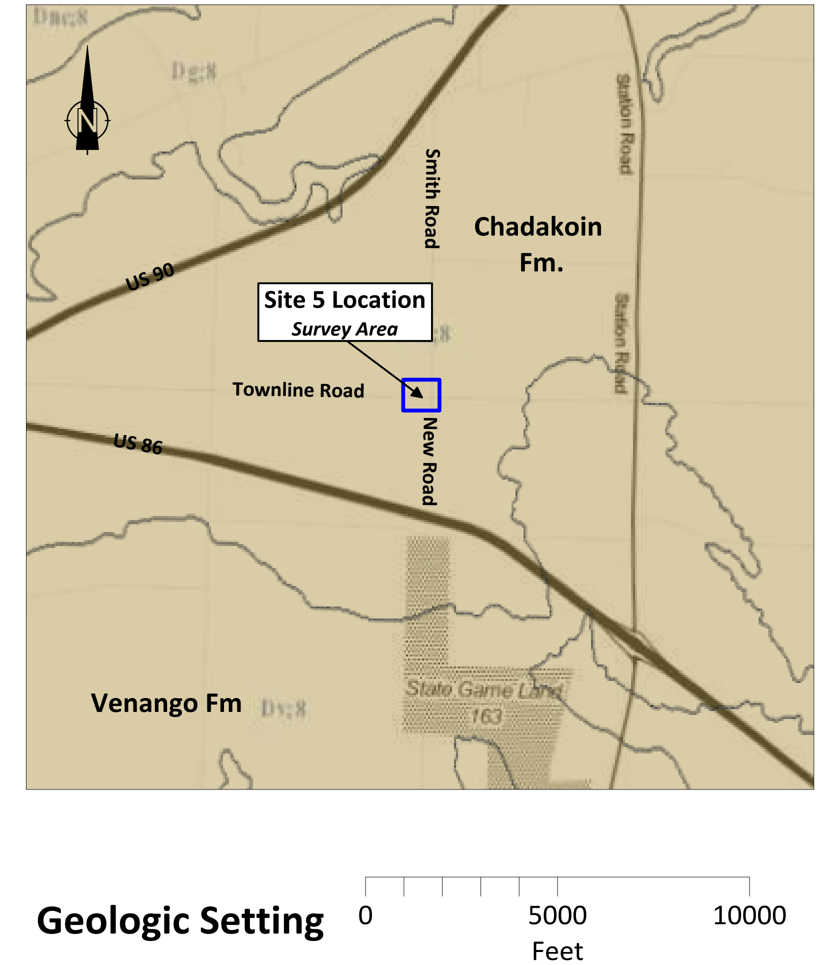
Geologic and Karst information from PASDA WMS Server.

Coordinates in PA State Plane (north), NAD83, U.S. Survey feet.

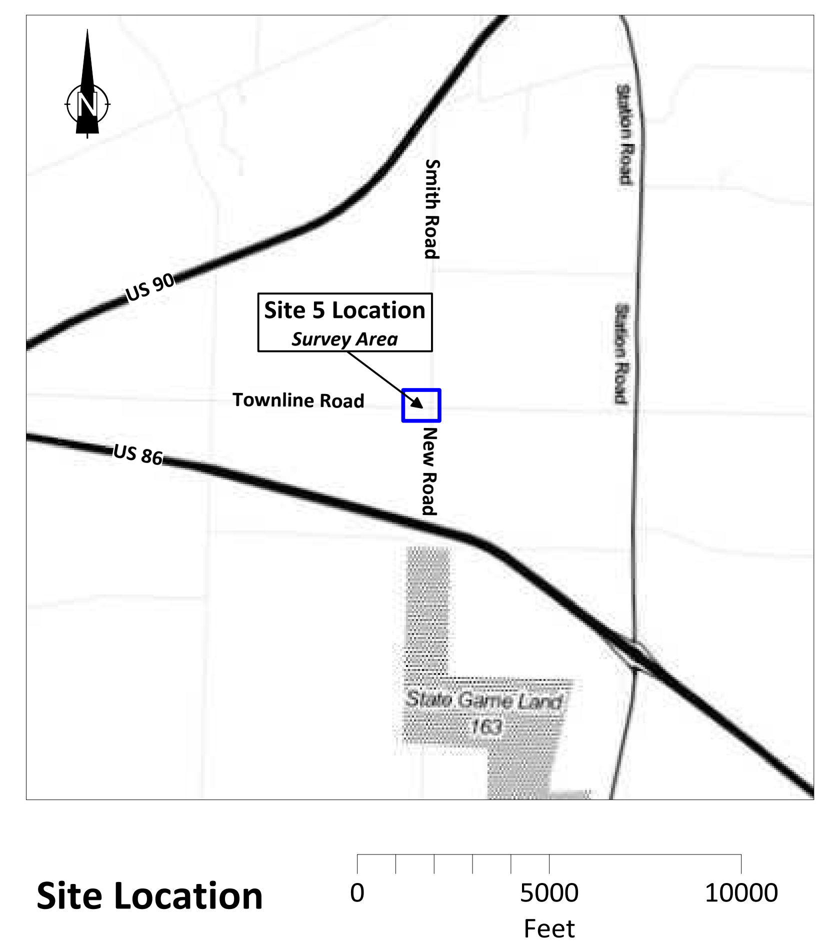
Survey profiles/stations from field survey and RTK by RETTEW.

**Geophysical Survey Legend**

- Geophone Location
- Seismograph (Geode/Tromino)




**Geologic Setting**




**Site Location**

SURVEY DATE: 10/25/2021
RETTEW No.: 105082002
REVIEWED BY: CHR/FKB
DRAWN BY: CTM
REVISION DATE: 11/12/2021
SCALE: Graphical
FIGURE NO. 5A

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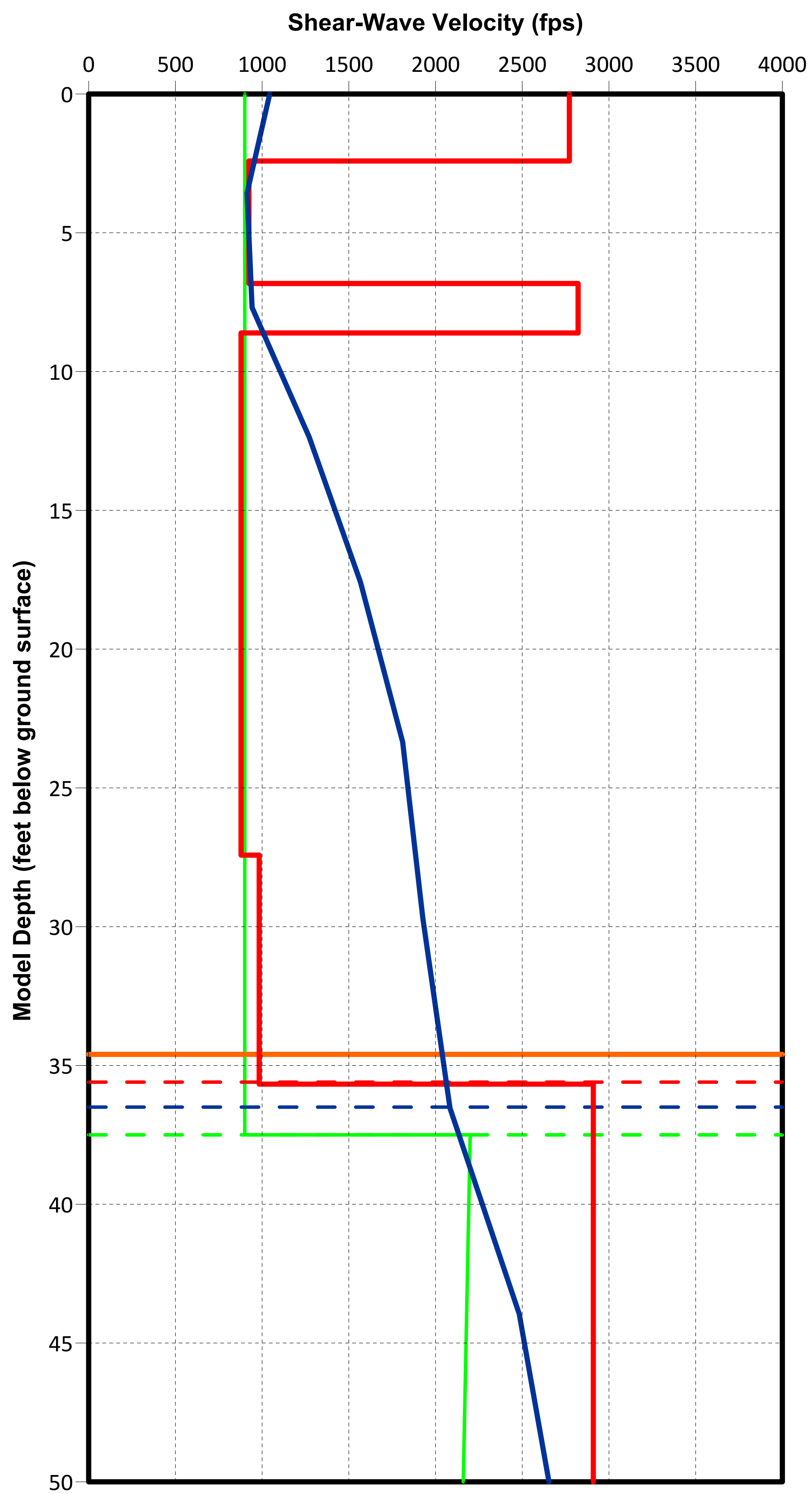
Phone 1-800-738-8395

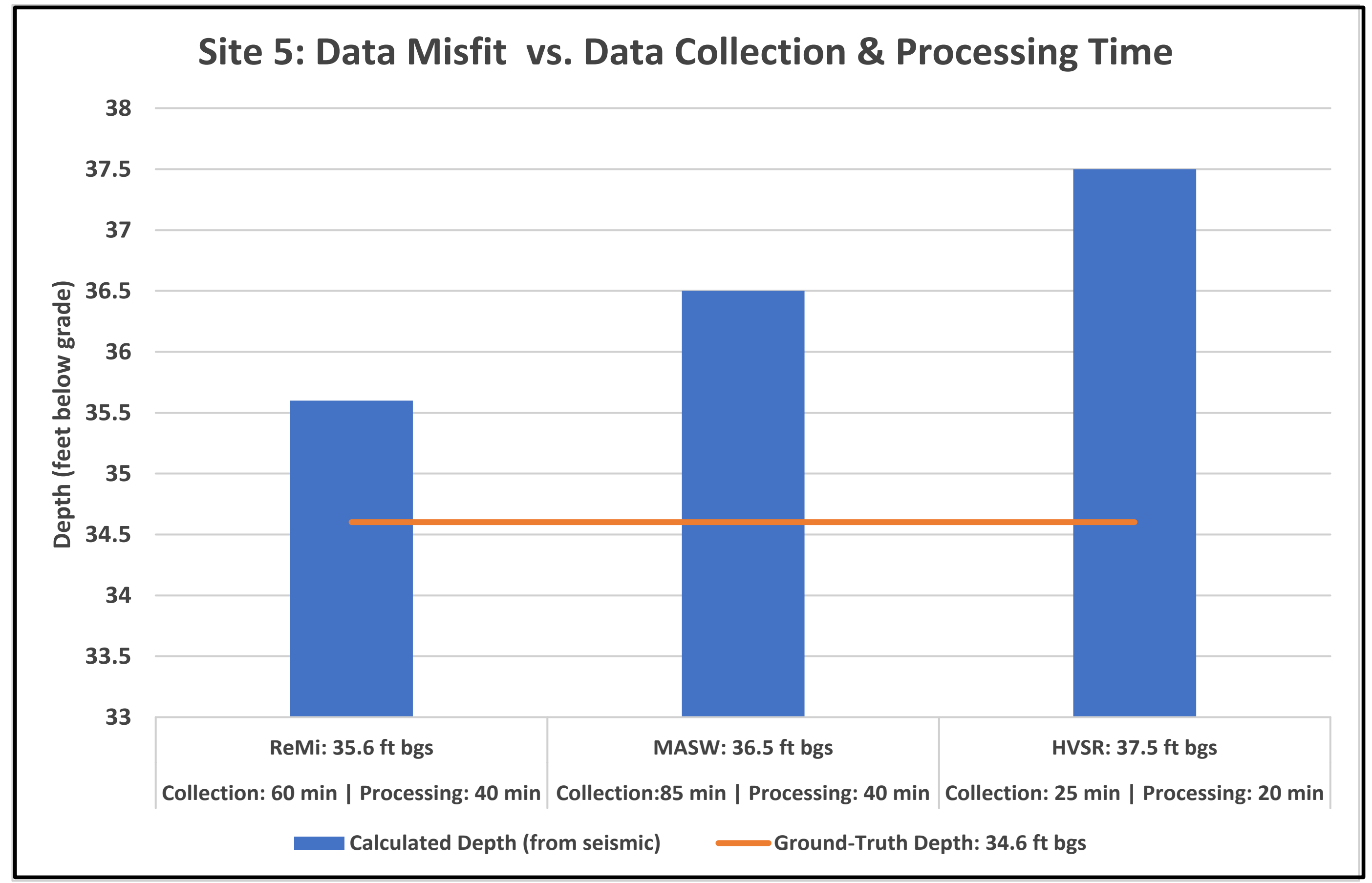
**Figure 5A: Data Coverage and Geologic Setting Site 5**

An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 5

ERIE COUNTY

ERIE, PA




**Weighted Average Shear-Wave Velocities**

- Profile 1 ReMi (Seis Opt)
- Profile 2 1-D MASW (Seisimager)
- Profile 3 HVSR (Grilla)
- Depth to Bedrock (from boring)

**Notes:**

MASW and ReMi seismic data from Geometrics 24-channel Geode with 4.5 Hz geophones at a 10-foot spacing.

MASW weighted average shear-wave velocities (Vs) from Geometrics SeisImager. ReMi average Vs values from Seis Opt ReMi by Optim. HVSR average Vs from Grilla by MOHO.

Colored dashed lines correspond to inferred rock depths from each type of survey.

SURVEY DATE: 10/14/2021
RETTEW No.: 105082002
REVIEWED BY: CHR/FKB
DRAWN BY: CTM
REVISION DATE: 11/12/2021
SCALE: Graphical
FIGURE NO. 5B

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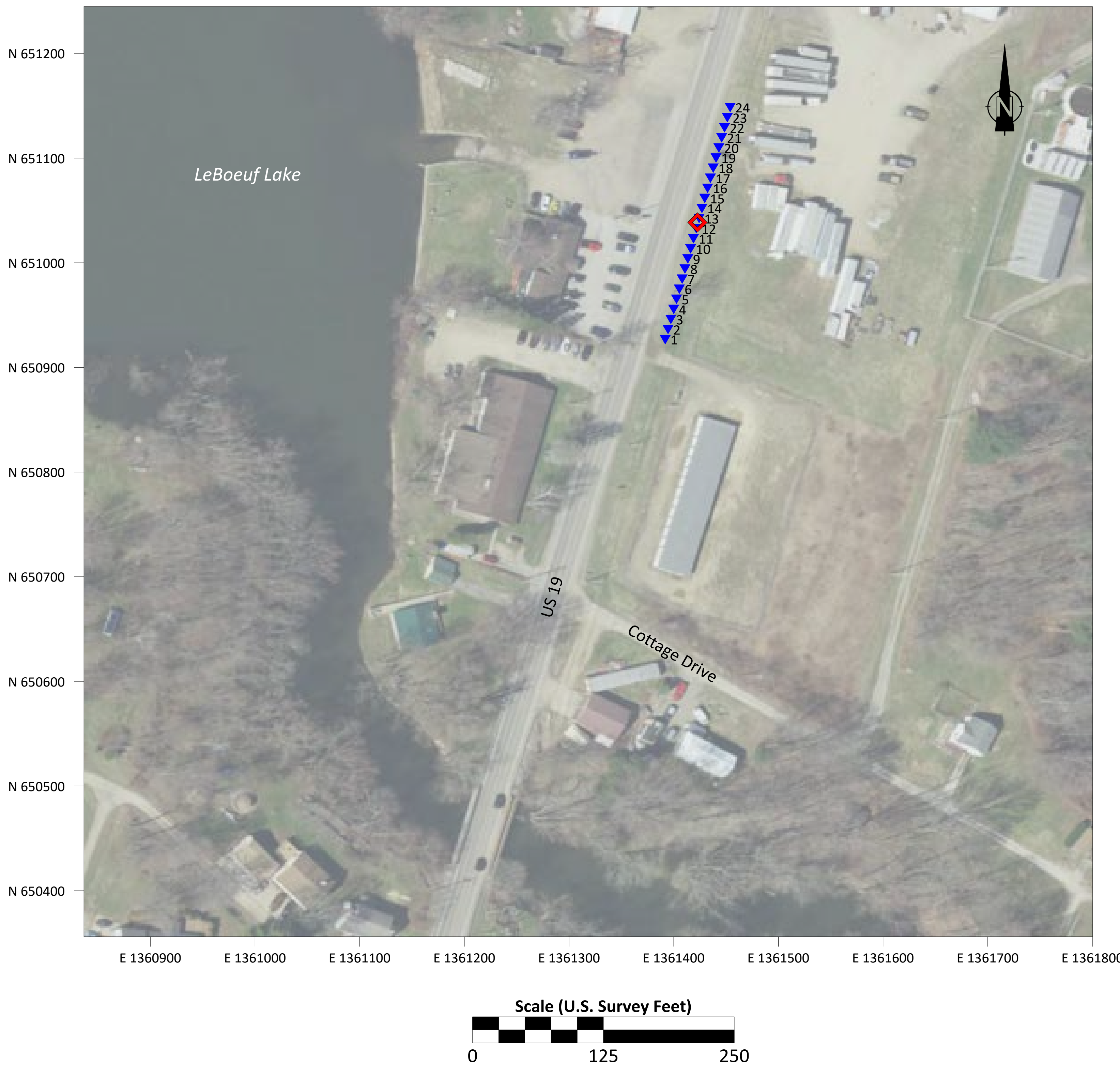
Phone 1-800-738-8395

**Figure 5B: Seismic Results Site 5**

An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 5

ERIE COUNTY
ERIE, PA




**Notes:**

Basemap image from PASDA Imagery Navigator (2018).

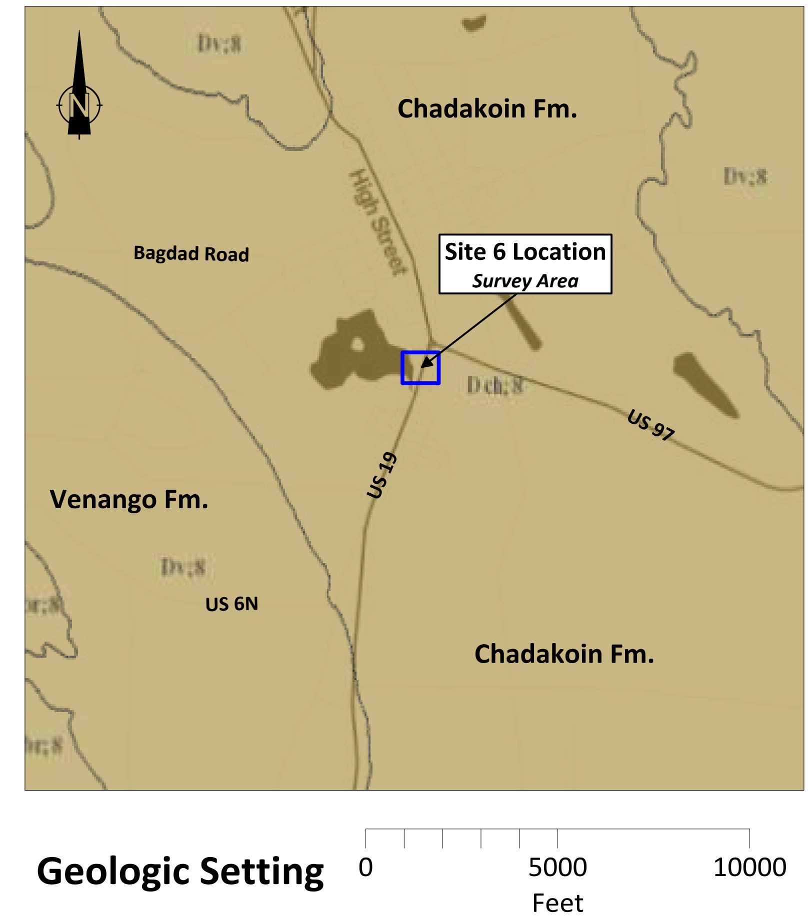
Geologic and geographic information from PASDA WMS Server.

Coordinates in PA State Plane (north), NAD83, U.S. Survey feet.

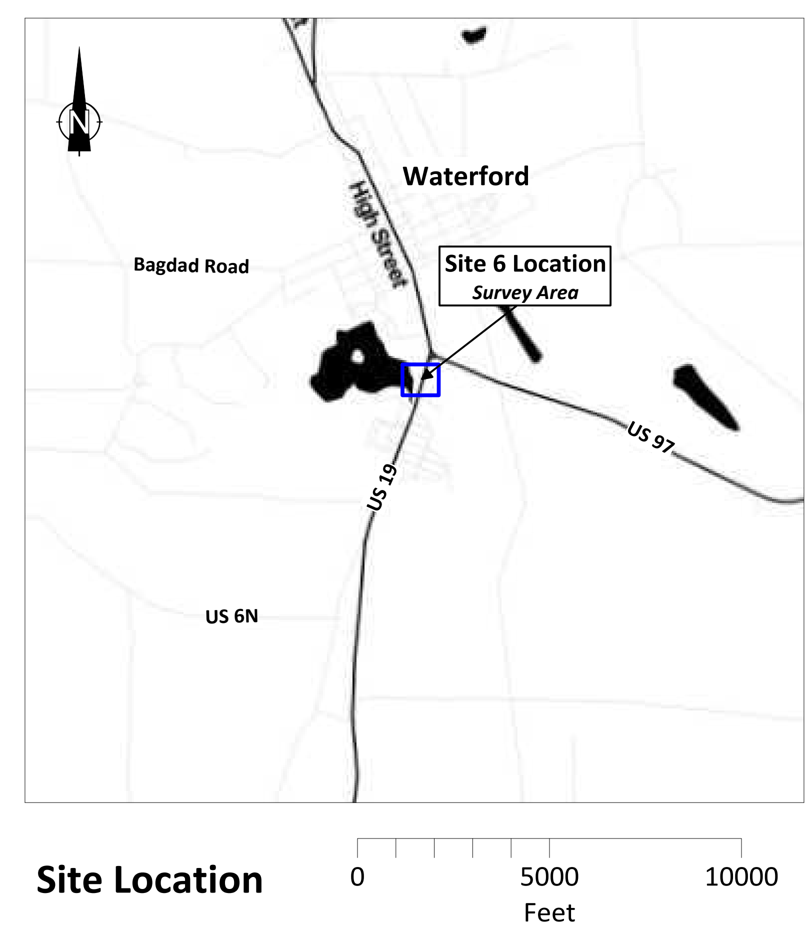
Survey profiles/stations from field survey and RTK by RETTEW.

**Geophysical Survey Legend**

- Geophone Location
- Seismograph (Geode/Tromino)




**Geologic Setting**




**Site Location**

SURVEY DATE: 10/28/2021
RETTEW No.: 105082002
REVIEWED BY: CHR/FKB
DRAWN BY: CTM
REVISION DATE: 11/12/2021
SCALE: Graphical
FIGURE NO. 6A

RETTEW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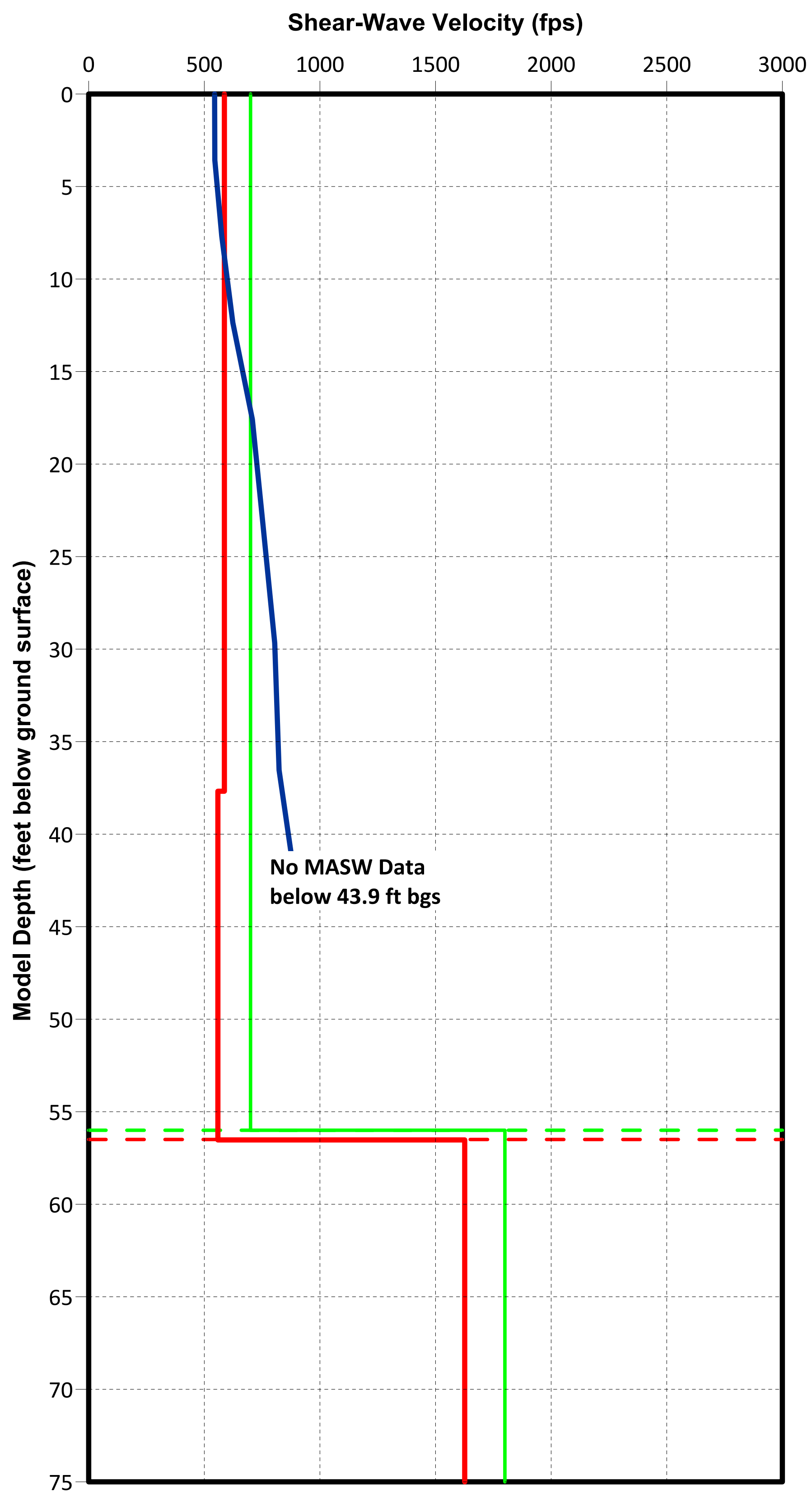
3020 Columbia Avenue, Lancaster, PA 17603
Phone 1-800-738-8395

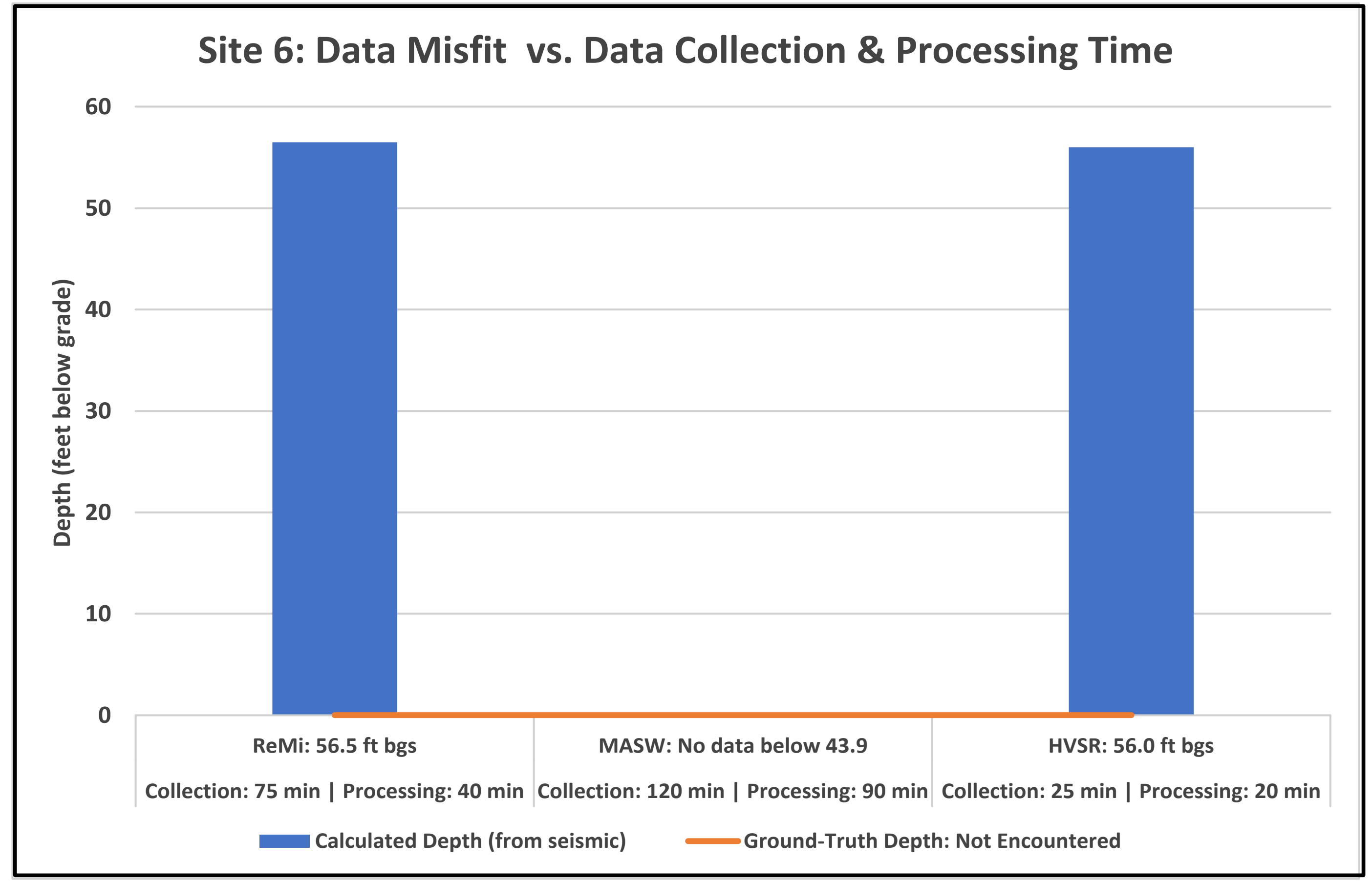

**Figure 6A: Data Coverage and Geologic Setting Site 6**

An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 6

ERIE COUNTY

ERIE, PA




**Weighted Average Shear-Wave Velocities**

- Profile 1 ReMi (Seis Opt)
- Profile 2 1-D MASW (Seisimager)
- Profile 3 HVSR (Grilla)
- Depth to Bedrock (from boring)

**Notes:**

MASW and ReMi seismic data from Geometrics 24-channel Geode with 4.5 Hz geophones at a 10-foot spacing.

MASW weighted average shear-wave velocities (Vs) from Geometrics SeisImager. ReMi average Vs values from Seis Opt ReMi by Optim. HVSR average Vs from Grilla by MOHO.

Colored dashed lines correspond to inferred rock depths from each type of survey.

| | |
|---|---|
| SURVEY DATE: | 10/14/2021 |
| RETTEW No.: | 105082002 |
| REVIEWED BY: | CHR/FKB |
| DRAWN BY: | CTM |
| REVISION DATE: | 11/12/2021 |
| SCALE: | Graphical |
| FIGURE NO. | 6B |

RETTEW

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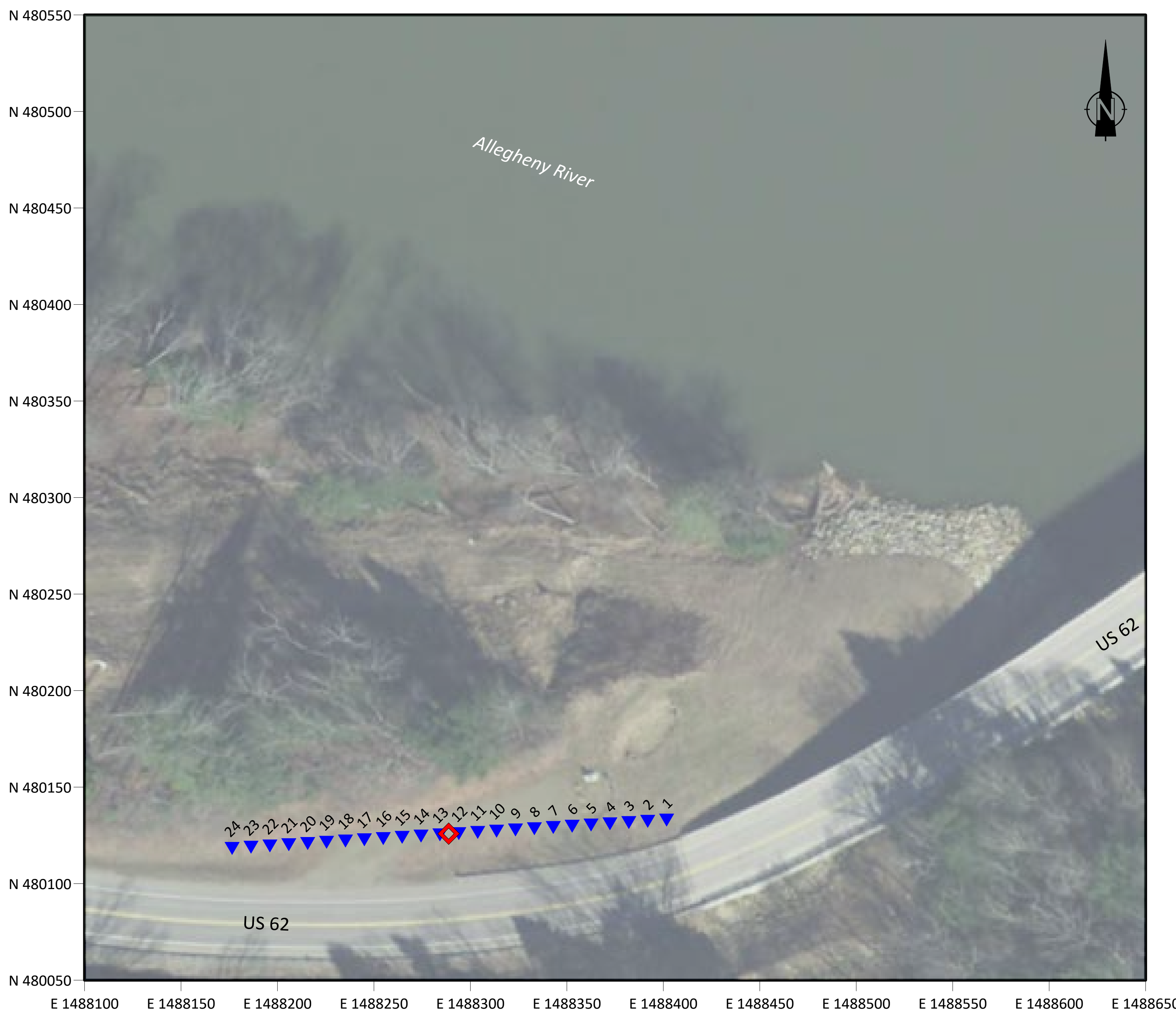
Phone 1-800-738-8395

## Figure 6B: Seismic Results Site 6

An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 6

ERIE COUNTY

ERIE, PA




**Scale (U.S. Survey Feet)**

0 75 150

**Notes:**

Basemap image from PASDA Imagery Navigator (2018).

Geologic and Karst information from PASDA WMS Server.

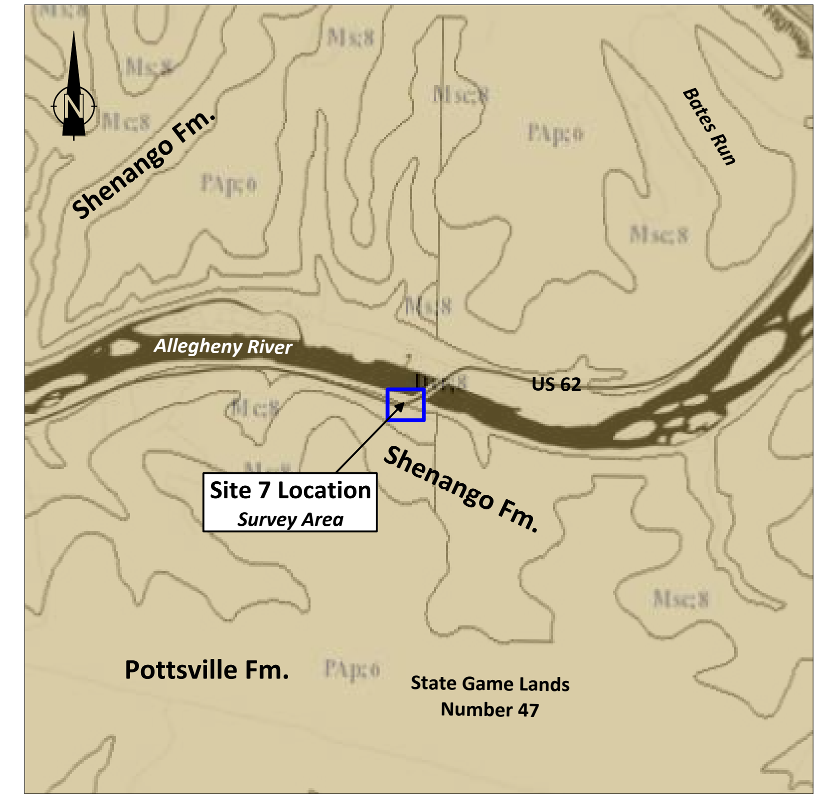
Coordinates in PA State Plane (north), NAD83, U.S. Survey feet.

Survey profile/stations from RTK by RETTEW.

**Geophysical Survey Legend**

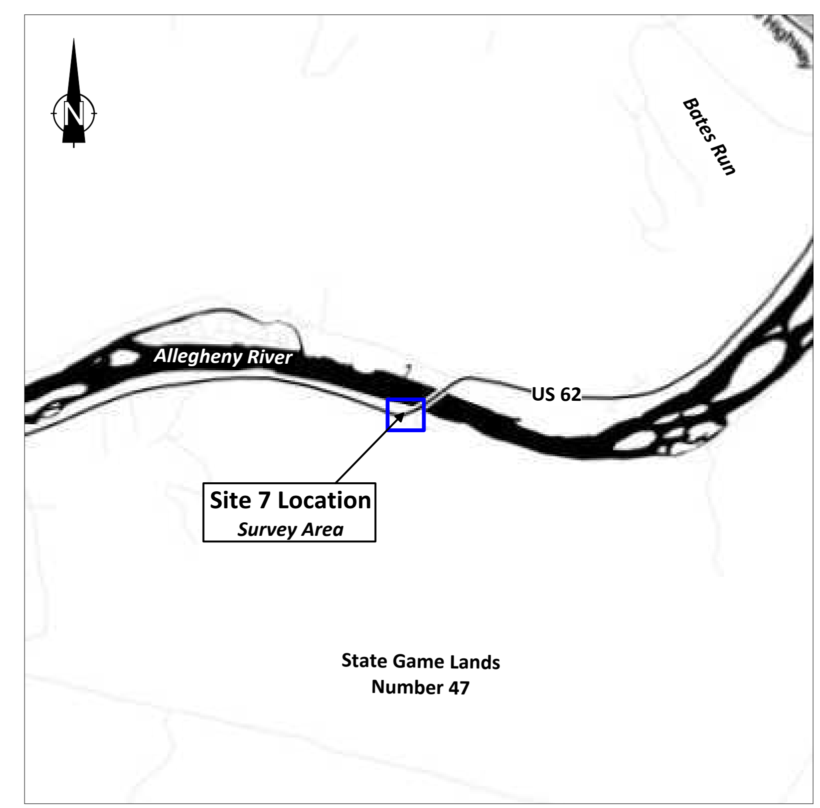
Geophone Location

Seismograph (Geode/Tromino)




## Geologic Setting

0 5000 10000
Feet




## Site Location

0 5000 10000
Feet

SURVEY DATE: 10/18/2021
RETTEW No.: 105082002
REVIEWED BY: CHR/FKB
DRAWN BY: CTM
REVISION DATE: 11/12/2021
SCALE: Graphical
FIGURE NO. 7A

RETTEW
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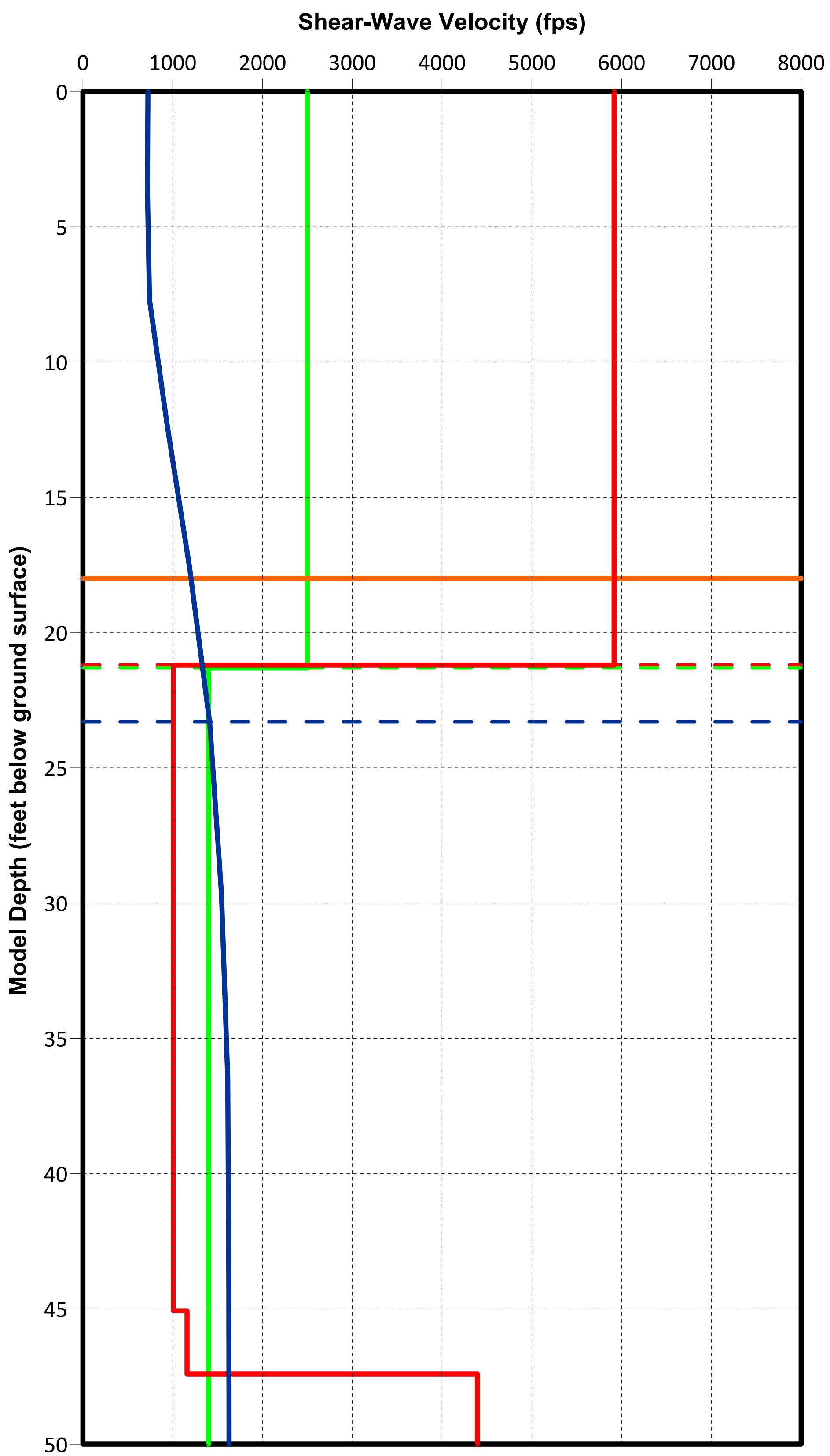
Phone 1-800-738-8395

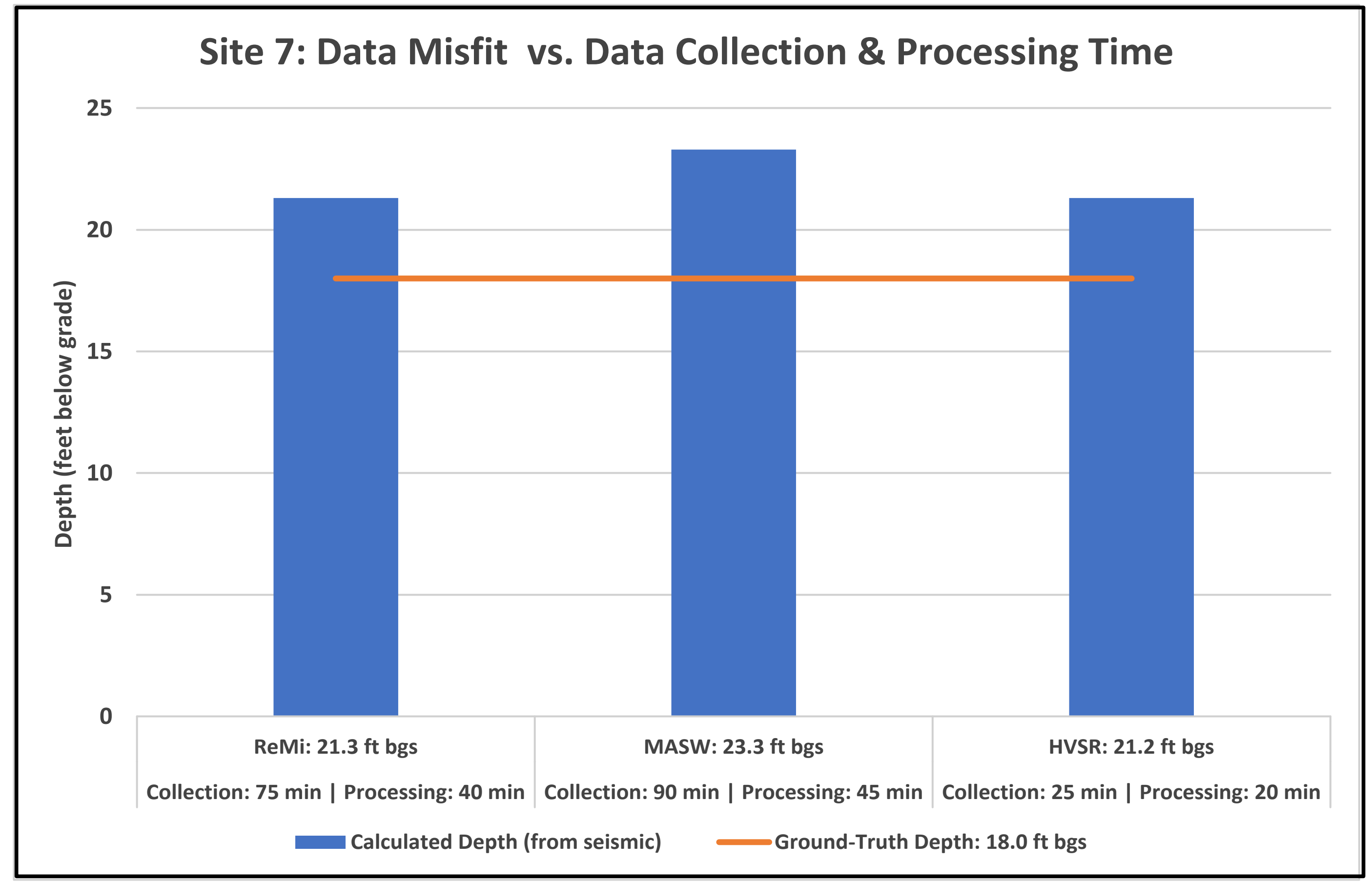
**Figure 7A: Data Coverage and Geologic Setting Site 7**

An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 7

FOREST COUNTY

TIONESTA, PA




**Weighted Average Shear-Wave Velocities**

- Profile 1 ReMi (Seis Opt)
- Profile 2 1-D MASW (Seisimager)
- Profile 3 HVSR (Grilla)
- Depth to Bedrock (from boring)

**Notes:**

MASW and ReMi seismic data from Geometrics 24-channel Geode with 4.5 Hz geophones at a 10-foot spacing.

MASW weighted average shear-wave velocities (Vs) from Geometrics SeisImager. ReMi average Vs values from Seis Opt ReMi by Optim. HVSR average Vs from Grilla by MOHO.

Colored dashed lines correspond to inferred rock depths from each type of survey.

| | |
|---|---|
| SURVEY DATE: | 10/14/2021 |
| RETTEW No.: | 105082002 |
| REVIEWED BY: | CHR/FKB |
| DRAWN BY: | CTM |
| REVISION DATE: | 11/12/2021 |
| SCALE: | Graphical |
| FIGURE NO. | 7B |

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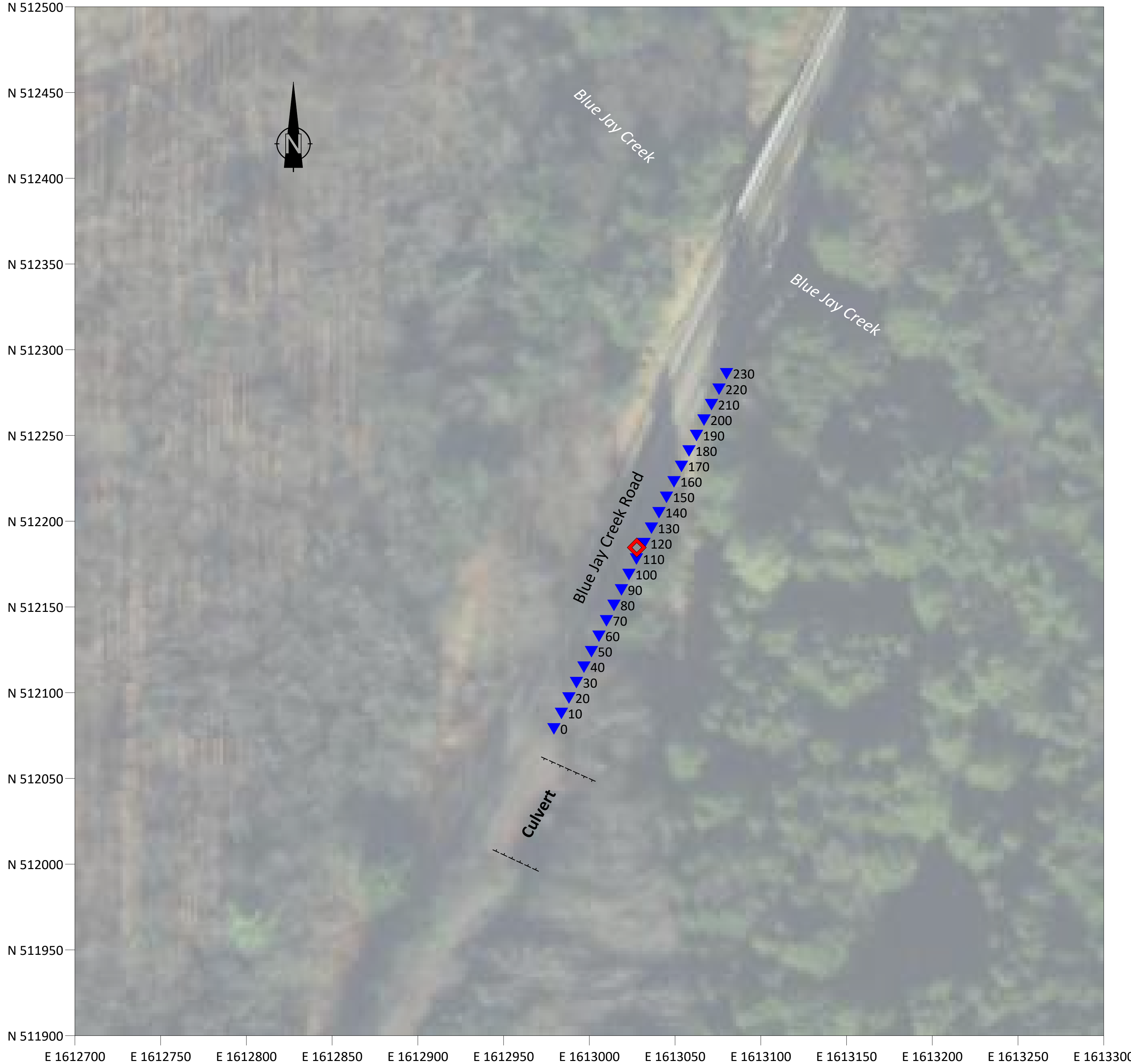
Phone 1-800-738-8395

## Figure 7B: Seismic Results Site 7

An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 7

FOREST COUNTY

TIONESTA, PA




**Notes:**

Basemap image from PASDA Imagery Navigator (2018).

Geologic and Karst information from PASDA WMS Server.

Coordinates in PA State Plane (north), NAD83, U.S. Survey feet.

Survey profile/stations from RTK by RETTEW.

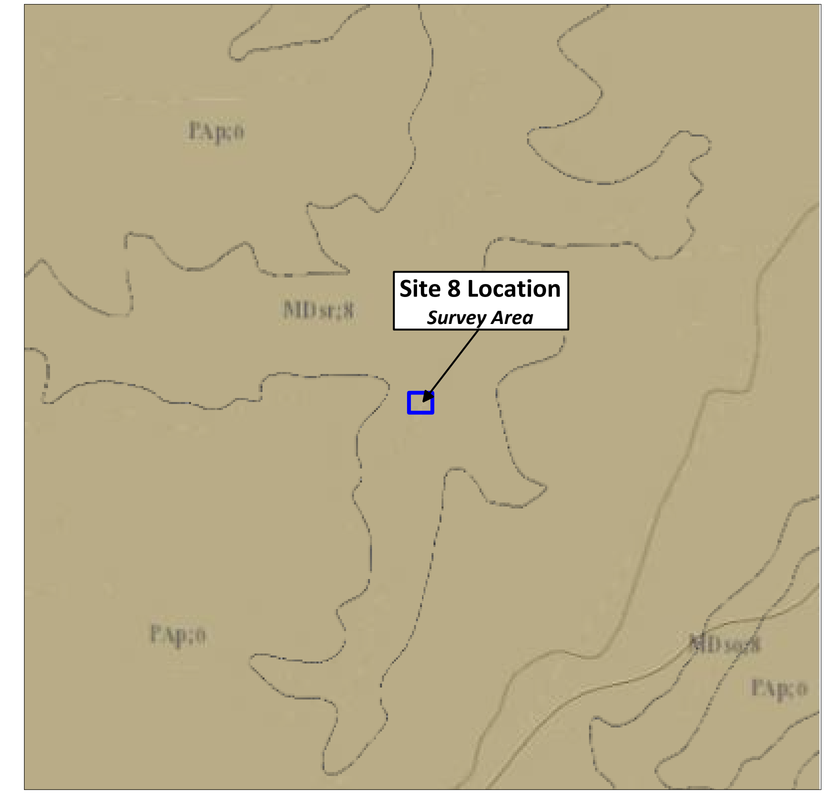
Scale (U.S. Survey Feet)

0 75 150

**Geophysical Survey Legend**

Geophone Location

Seismograph (Geode/Tromino)




**Geologic Setting**

0 5000 10000
Feet


**Site Location**

0 50000 100000
Feet

SURVEY DATE: 10/22/2021
RETTEW No.: 105082002
REVIEWED BY: CHR/FKB
DRAWN BY: CTM
REVISION DATE: 11/12/2021
SCALE: Graphical
FIGURE NO. 8A

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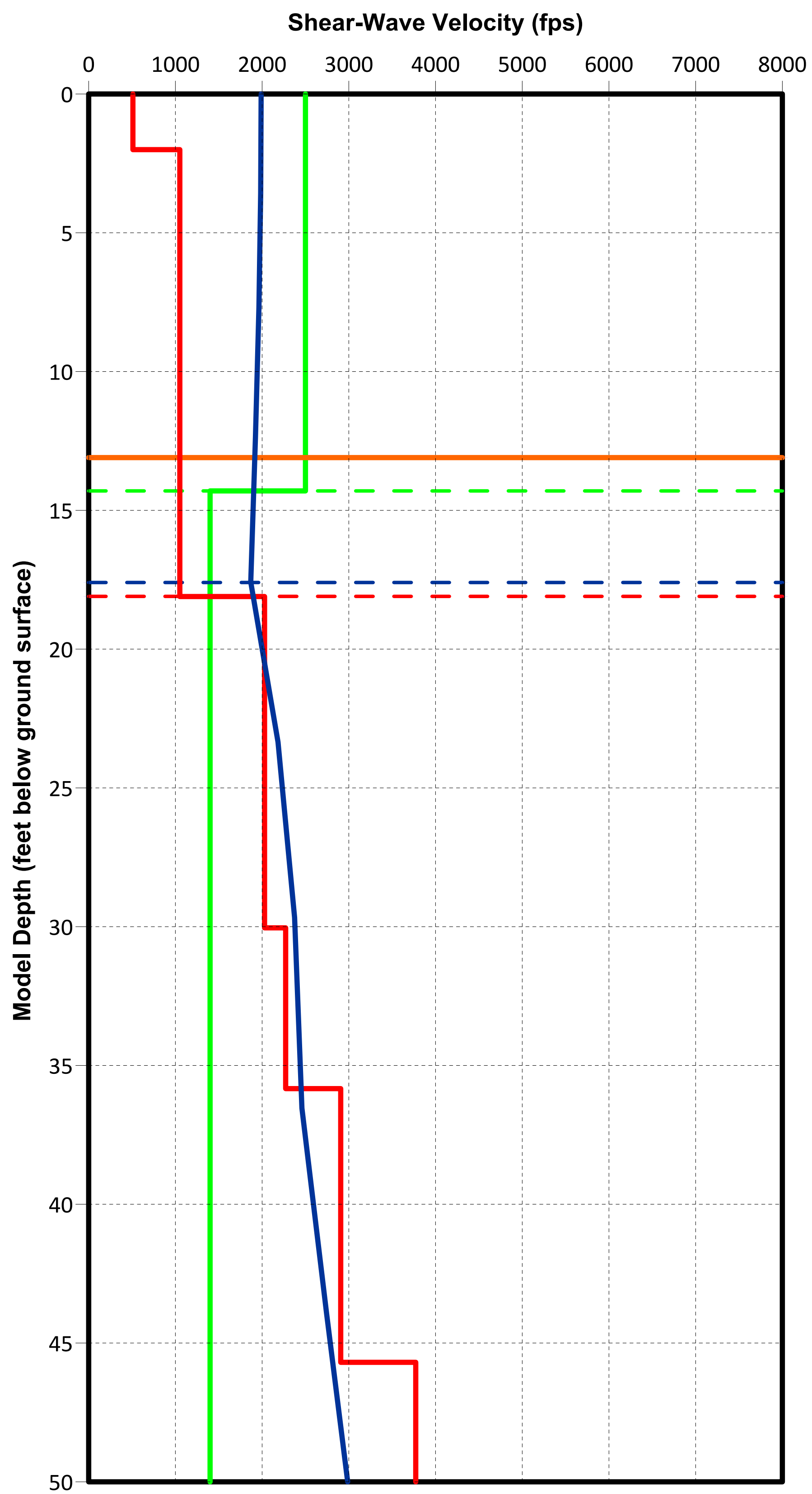
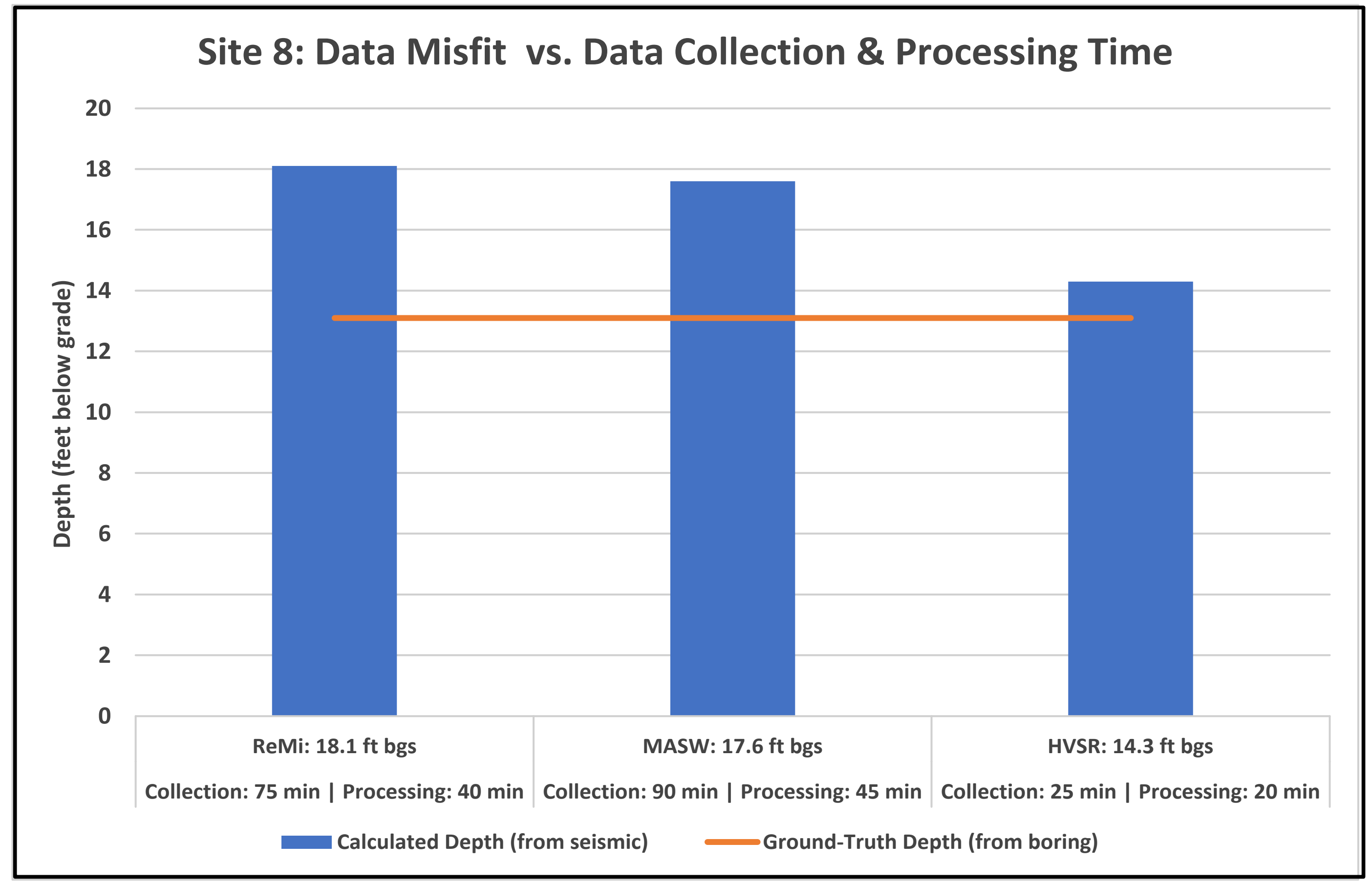
**Figure 8A: Data Coverage and Geologic Setting Site 8**

An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 8

FOREST COUNTY

TIONESTA, PA




**Weighted Average Shear-Wave Velocities**

- Profile 1 ReMi (Seis Opt)
- Profile 2 1-D MASW (Seisimager)
- Profile 3 HVSR (Grilla)
- Depth to Bedrock (from boring)

**Notes:**

MASW and ReMi seismic data from Geometrics 24-channel Geode with 4.5 Hz geophones at a 10-foot spacing.

MASW weighted average shear-wave velocities (Vs) from Geometrics SeisImager. ReMi average Vs values from Seis Opt ReMi by Optim. HVSR average Vs from Grilla by MOHO.

Colored dashed lines correspond to inferred rock depths from each type of survey.

SURVEY DATE: 10/14/2021
RETTEW No.: 105082002
REVIEWED BY: CHR/FKB
DRAWN BY: CTM
REVISION DATE: 11/12/2021
SCALE: Graphical
FIGURE NO. 8B

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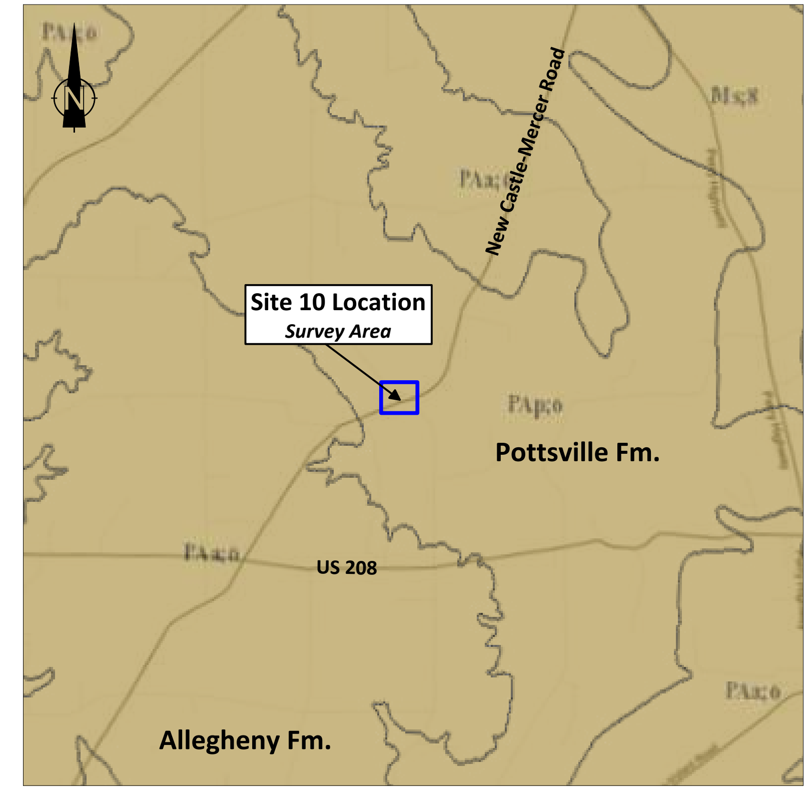
**Site 8B: Seismic Results Site 8**

An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 8

FOREST COUNTY
TIONESTA, PA

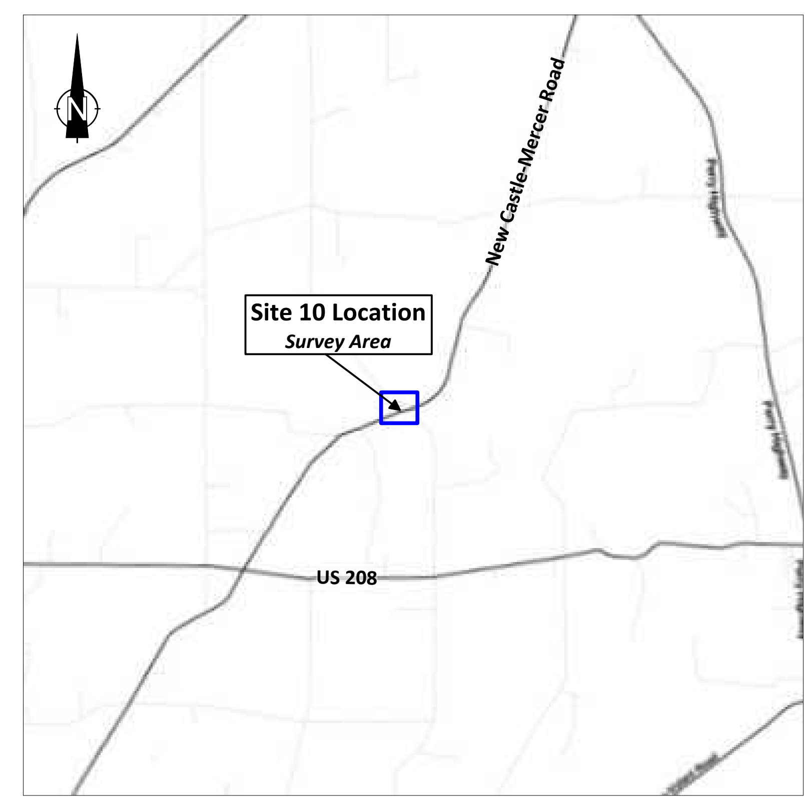

Scale (U.S. Survey Feet)

0 75 150




**Geologic Setting**

0 5000 10000
Feet




**Site Location**

0 5000 10000
Feet

**Notes:**

Basemap image from PASDA Imagery Navigator (2018).

Geologic and Karst information from PASDA WMS Server.

Coordinates in PA State Plane (north), NAD83, U.S. Survey feet.

Survey profiles/stations from field survey and RTK by RETTEW.

**Geophysical Survey Legend**

▼ Geophone Location

◇ Seismograph (Geode/Tromino)

SURVEY DATE: 10/12/2021
RETTEW No.: 105082002
REVIEWED BY: CHR/FKB
DRAWN BY: CTM
REVISION DATE: 11/12/2021
SCALE: Graphical
FIGURE NO. 10A

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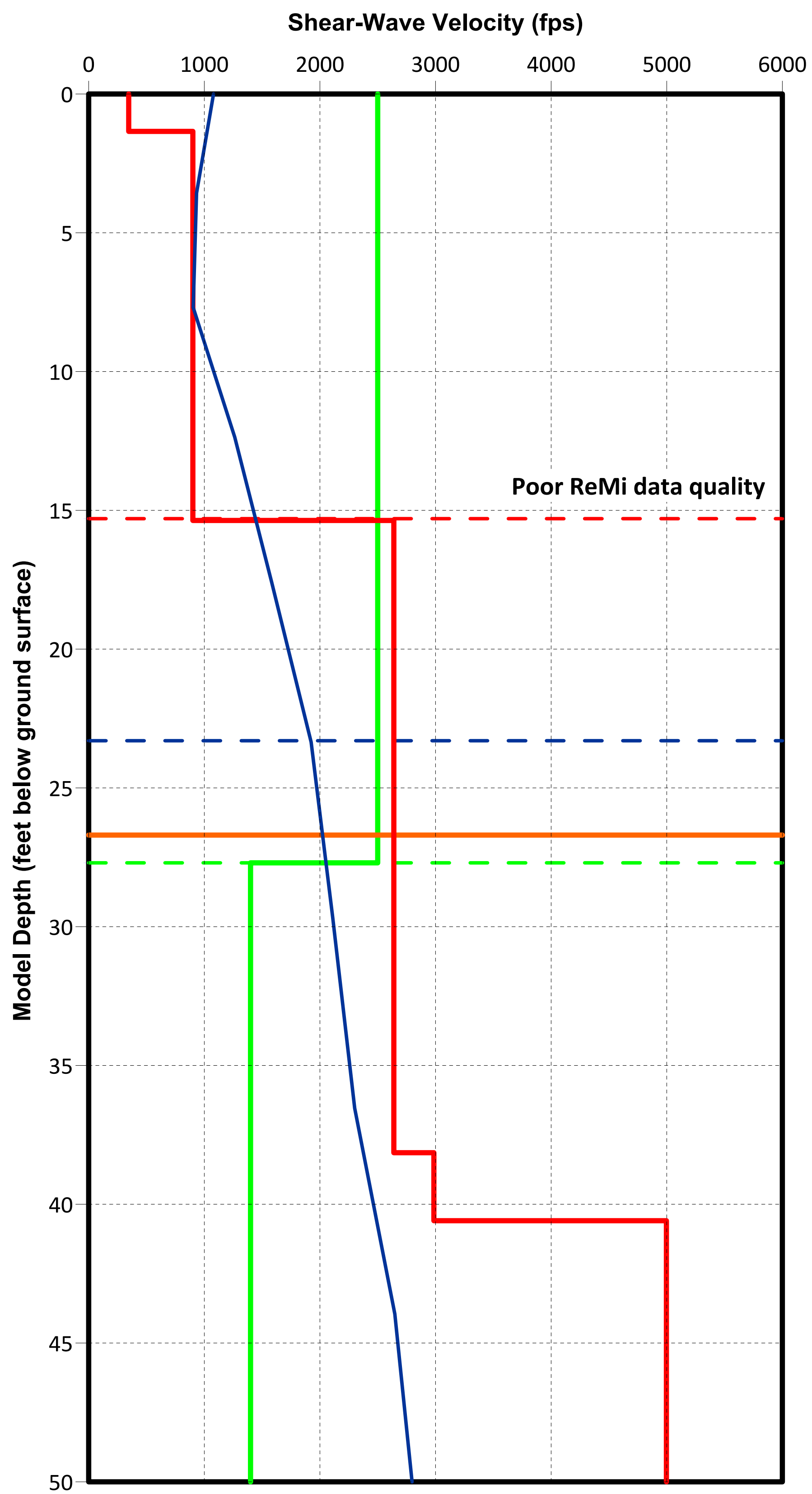
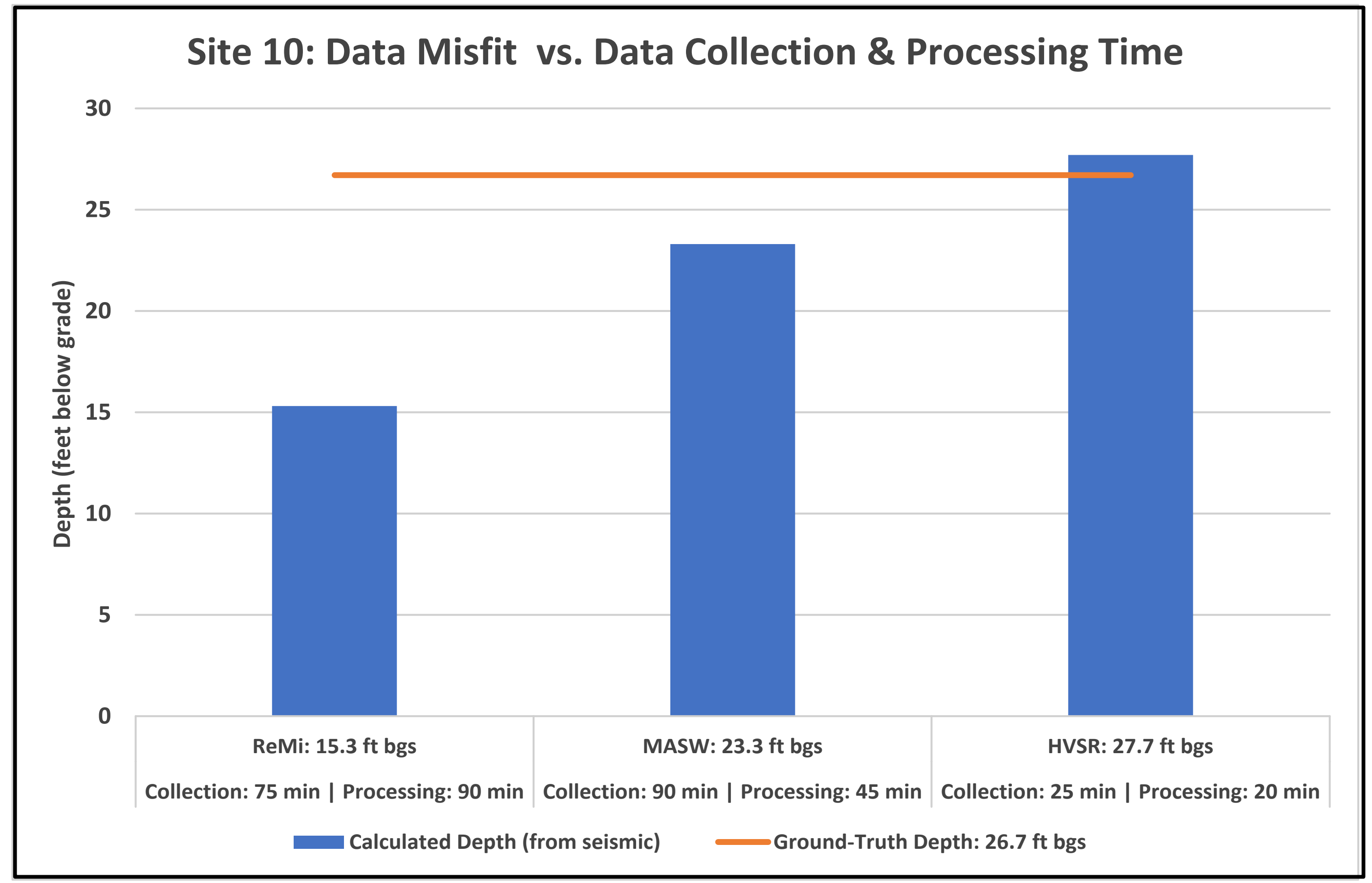
**Figure 10A: Data Coverage and Geologic Setting Site 10**

An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 10

MERCER COUNTY

HERMITAGE, PA




**Weighted Average Shear-Wave Velocities**

- Profile 1 ReMi (Seis Opt)
- Profile 2 1-D MASW (Seisimager)
- Profile 3 HVSR (Grilla)
- Depth to Bedrock (from boring)

**Notes:**

MASW and ReMi seismic data from Geometrics 24-channel Geode with 4.5 Hz geophones at a 10-foot spacing.

MASW weighted average shear-wave velocities (Vs) from Geometrics SeisImager. ReMi average Vs values from Seis Opt ReMi by Optim. HVSR average Vs from Grilla by MOHO.

Colored dashed lines correspond to inferred rock depths from each type of survey.

SURVEY DATE: 10/14/2021
RETTEW No.: 105082002
REVIEWED BY: CHR/FKB
DRAWN BY: CTM
REVISION DATE: 11/12/2021
SCALE: Graphical
FIGURE NO. 10B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Phone 1-800-738-8395


**Figure 10B: Seismic Results Site 10**

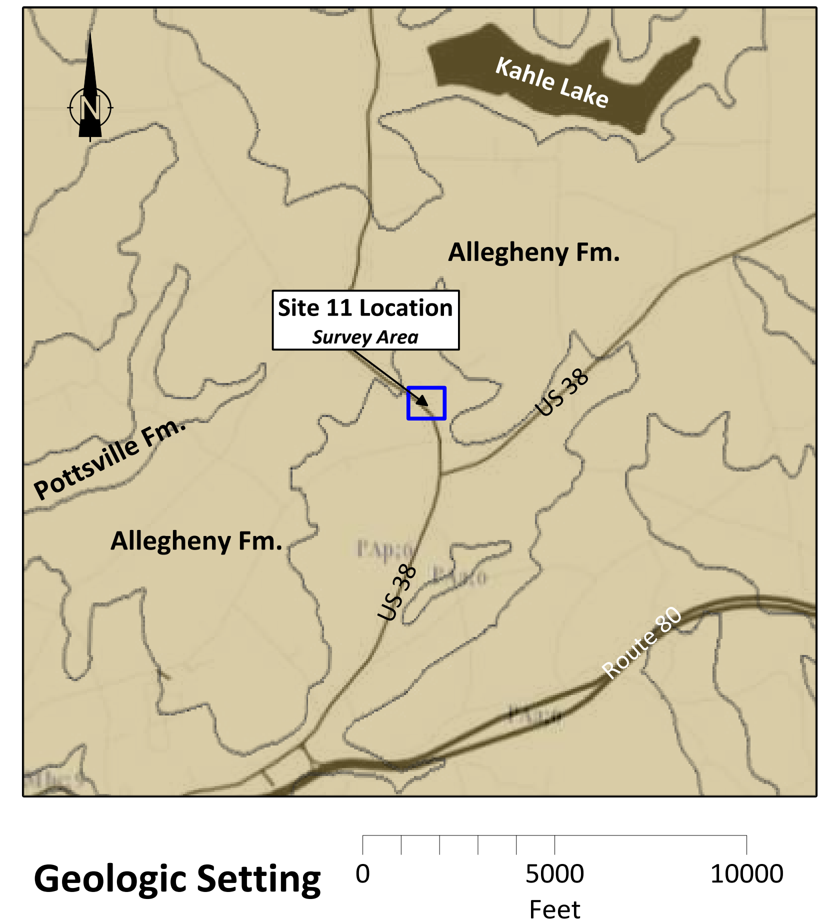
An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 10

MERCER COUNTY

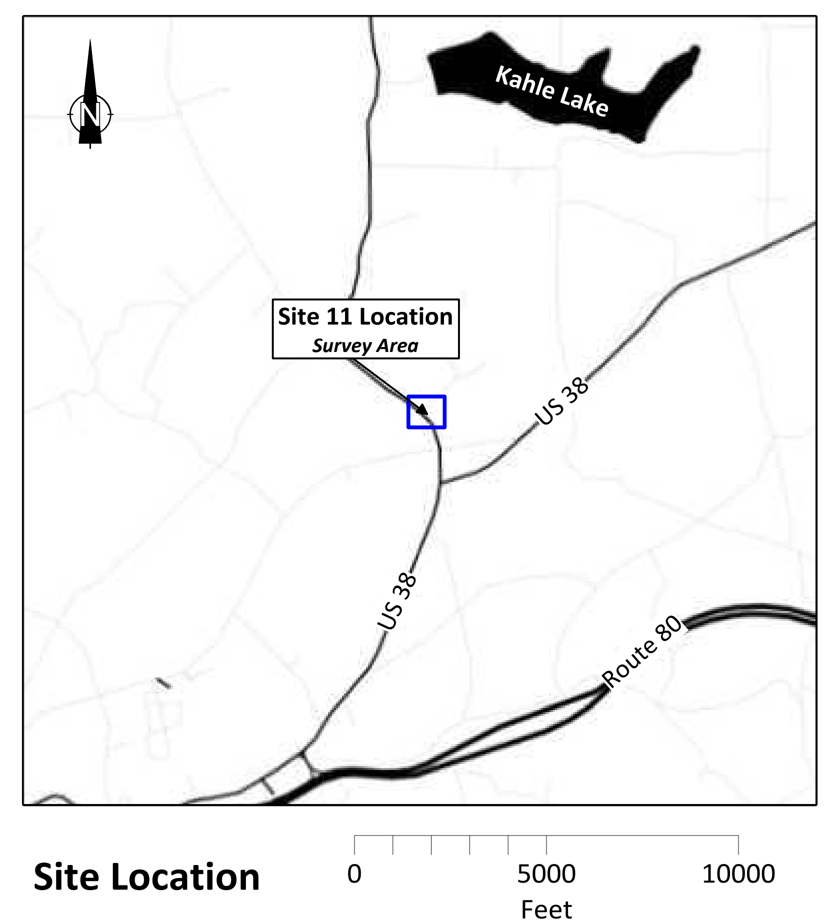
HERMITAGE, PA


**Scale (U.S. Survey Feet)**

0 75 150




**Geologic Setting**




**Site Location**

**Notes:**

Basemap image from PASDA Imagery Navigator (2018).

Geologic and Karst information from PASDA WMS Server.

Coordinates in PA State Plane (north), NAD83, U.S. Survey feet.

Survey profiles/stations from field survey and RTK by RETTEW.

**Geophysical Survey Legend**

▼ Geophone Location

◇ Seismograph (Geode/Tromino)

SURVEY DATE: 10/12/2021
RETTEW No.: 105082002
REVIEWED BY: CHR/FKB
DRAWN BY: CTM
REVISION DATE: 11/12/2021
SCALE: Graphical
FIGURE NO. 11A

RETTEW

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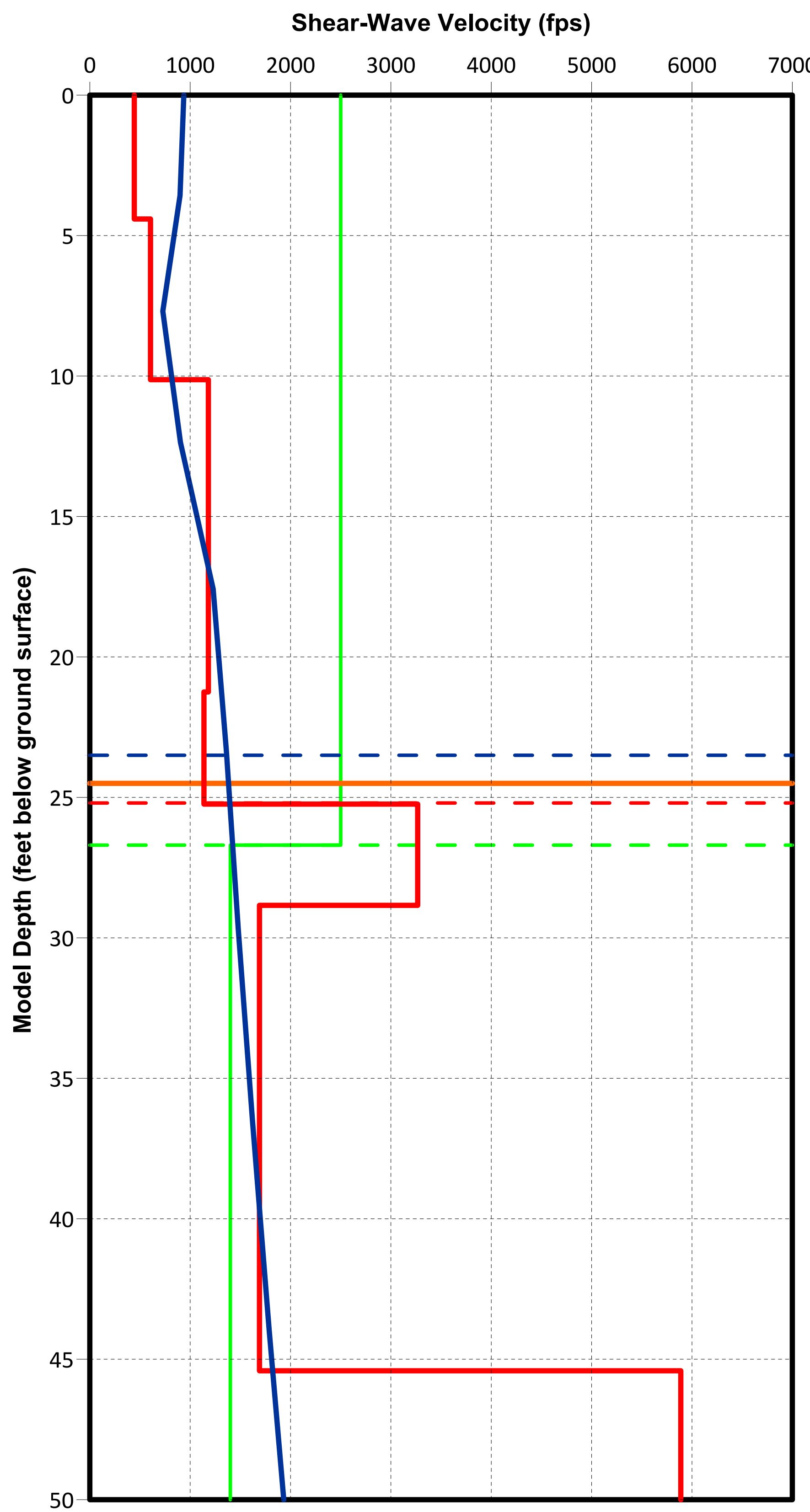
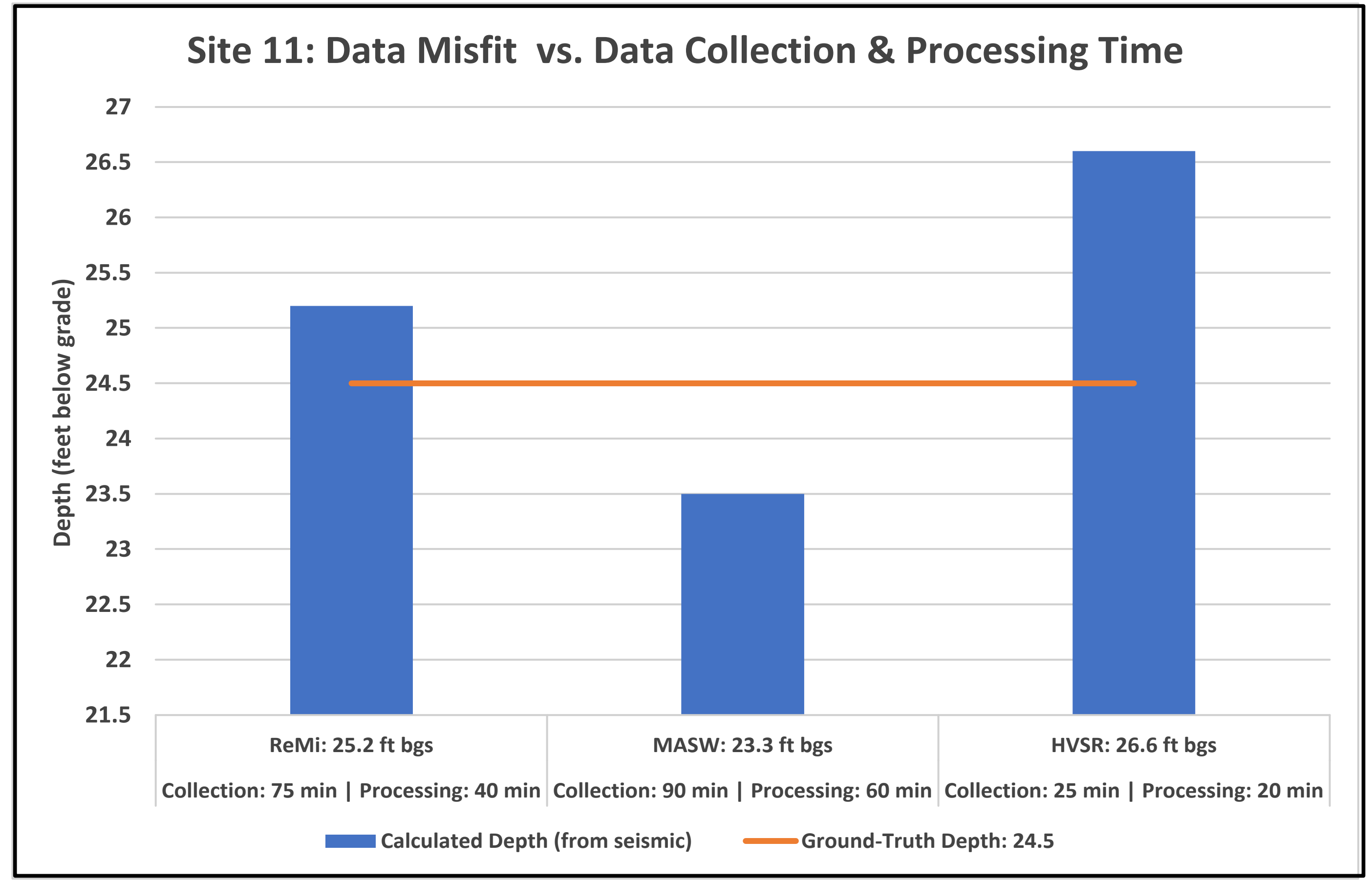
**Figure 11A: Data Coverage and Geologic Setting Site 11**

An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 11

VENANGO COUNTY

OIL CITY, PA




**Weighted Average Shear-Wave Velocities**

- Profile 1 ReMi (Seis Opt)
- Profile 2 1-D MASW (Seisimager)
- Profile 3 HVSR (Grilla)
- Depth to Bedrock (from boring)

**Notes:**

MASW and ReMi seismic data from Geometrics 24-channel Geode with 4.5 Hz geophones at a 10-foot spacing.

MASW weighted average shear-wave velocities (Vs) from Geometrics SeisImager. ReMi average Vs values from Seis Opt ReMi by Optim. HVSR average Vs from Grilla by MOHO.

Colored dashed lines correspond to inferred rock depths from each type of survey.

| | |
|---|---|
| SURVEY DATE: | 10/14/2021 |
| RETTEW No.: | 105082002 |
| REVIEWED BY: | CHR/FKB |
| DRAWN BY: | CTM |
| REVISION DATE: | 11/12/2021 |
| SCALE: | Graphical |
| FIGURE NO. | 11B |

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Phone 1-800-738-8395

# Figure 11B: Seismic Results Site 11

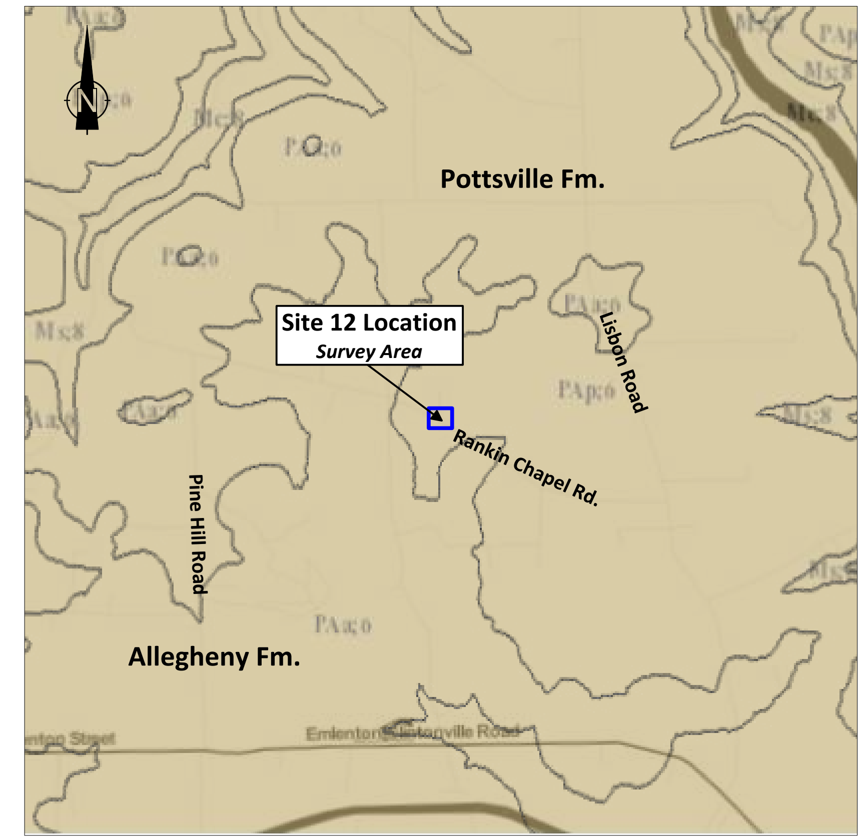
An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 11

VENANGO COUNTY

OIL CITY, PA

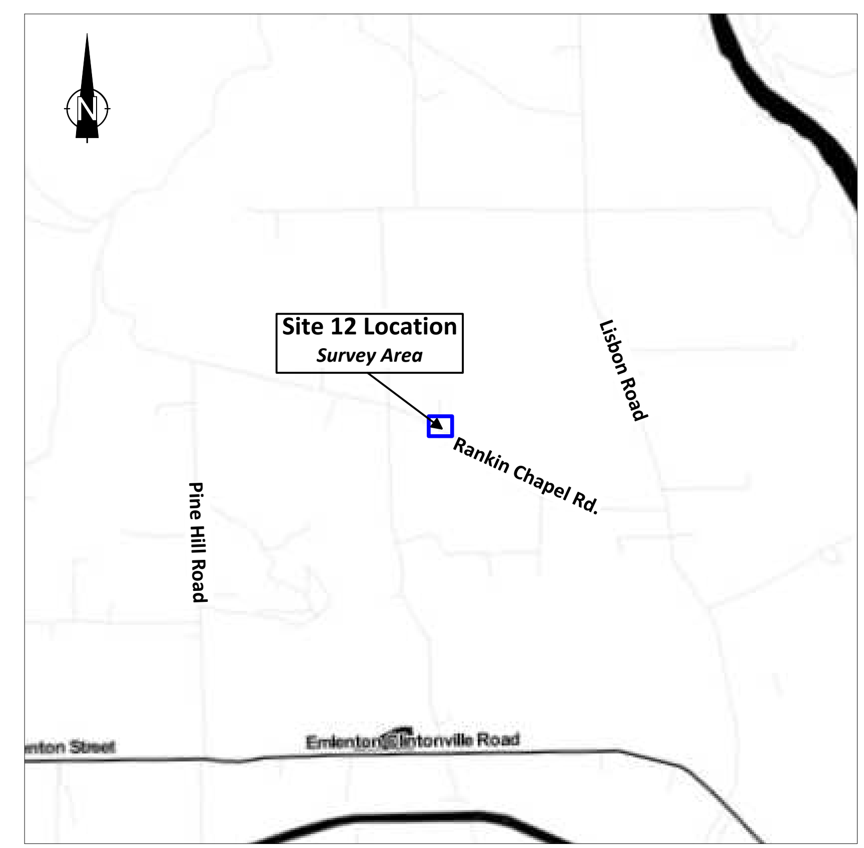

Scale (U.S. Survey Feet)

0 75 150




## Geologic Setting

0 5000 10000
Feet




## Site Location

0 5000 10000
Feet

**Notes:**

Basemap image from PASDA Imagery Navigator (2018).

Geologic and Karst information from PASDA WMS Server.

Coordinates in PA State Plane (north), NAD83, U.S. Survey feet.

Survey profile/stations from RTK by RETTEW.

**Geophysical Survey Legend**

▼ Geophone Location

◇ Seismograph (Geode/Tromino)

SURVEY DATE: 10/11/2021
RETTEW No.: 105082002
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SCALE: Graphical
FIGURE NO. 12A

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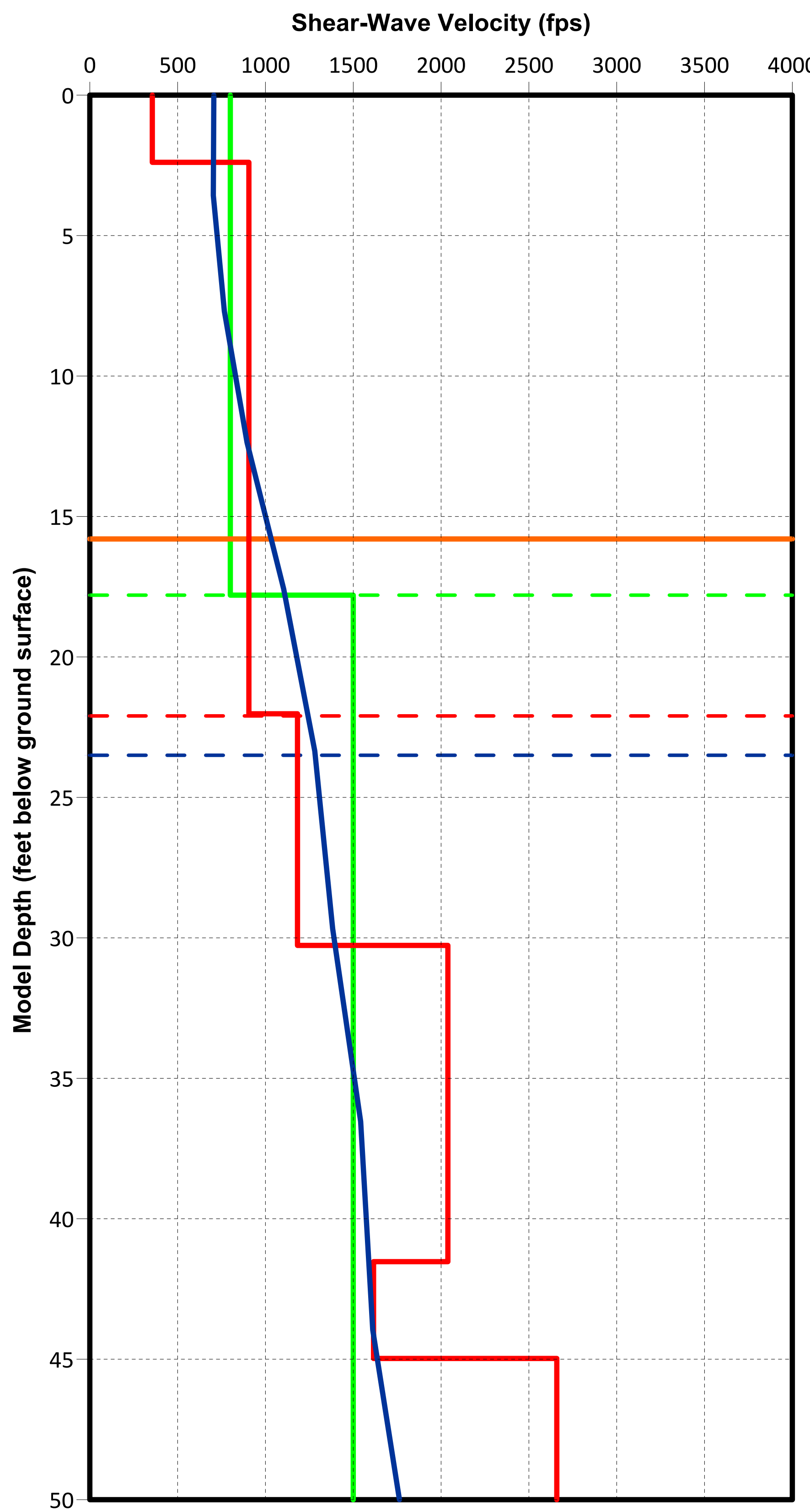
# Figure 12A: Data Coverage and Geologic Setting Site 12

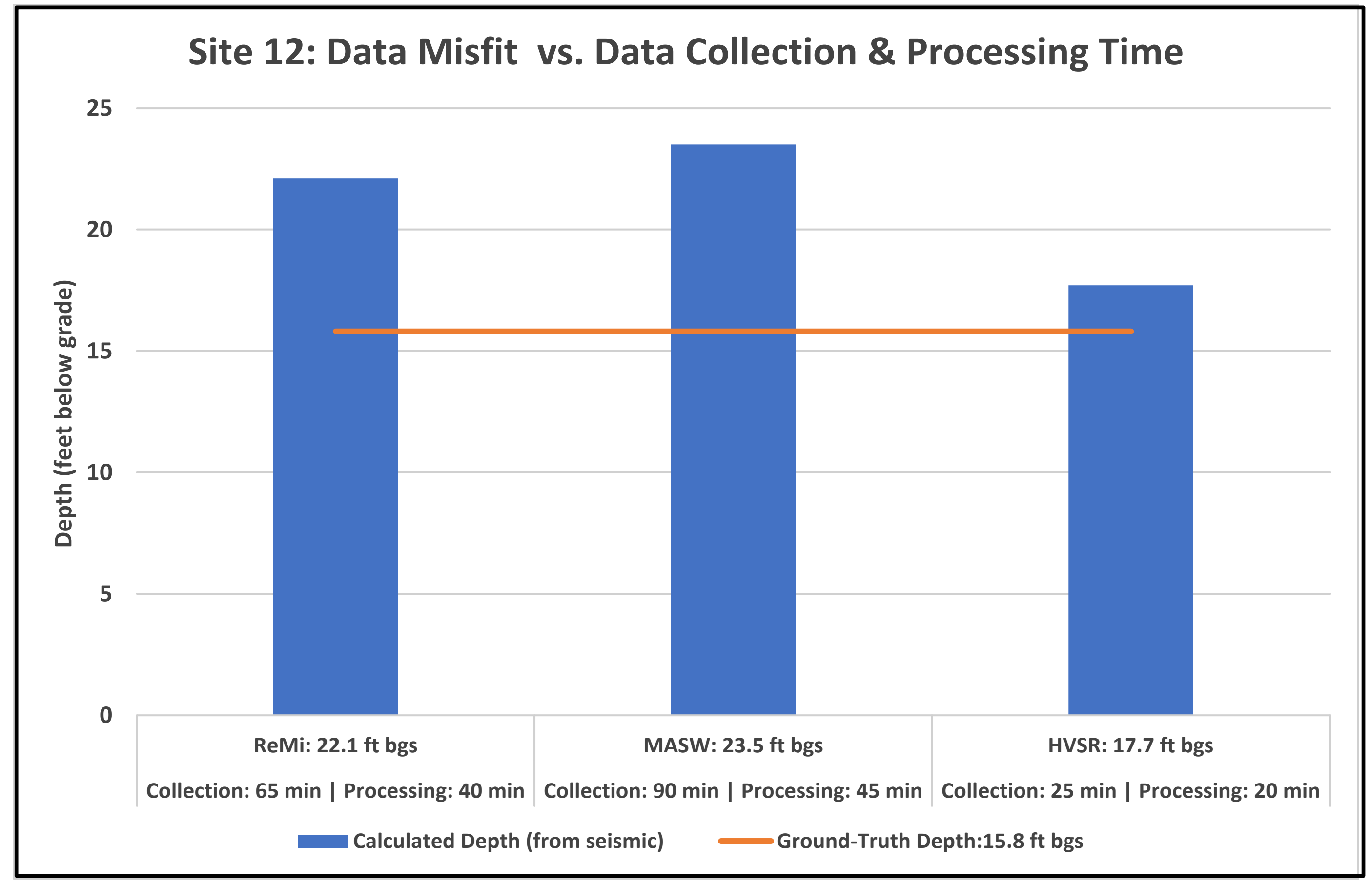
An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site12

VENANGO COUNTY
OIL CITY, PA




**Weighted Average Shear-Wave Velocities**

- Profile 1 ReMi (Seis Opt)
- Profile 2 1-D MASW (Seisimager)
- Profile 3 HVSR (Grilla)
- Depth to Bedrock (from boring)




**Notes:**

MASW and ReMi seismic data from Geometrics 24-channel Geode with 4.5 Hz geophones at a 10-foot spacing.

MASW weighted average shear-wave velocities (Vs) from Geometrics SeisImager. ReMi average Vs values from Seis Opt ReMi by Optim. HVSR average Vs from Grilla by MOHO.

Colored dashed lines correspond to inferred rock depths from each type of survey.

SURVEY DATE: 10/14/2021
RETTEW No.: 105082002
REVIEWED BY: CHR/FKB
DRAWN BY: CTM
REVISION DATE: 11/12/2021
SCALE: Graphical
FIGURE NO. 12B

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**Figure 12B: Seismic Results Site 12**

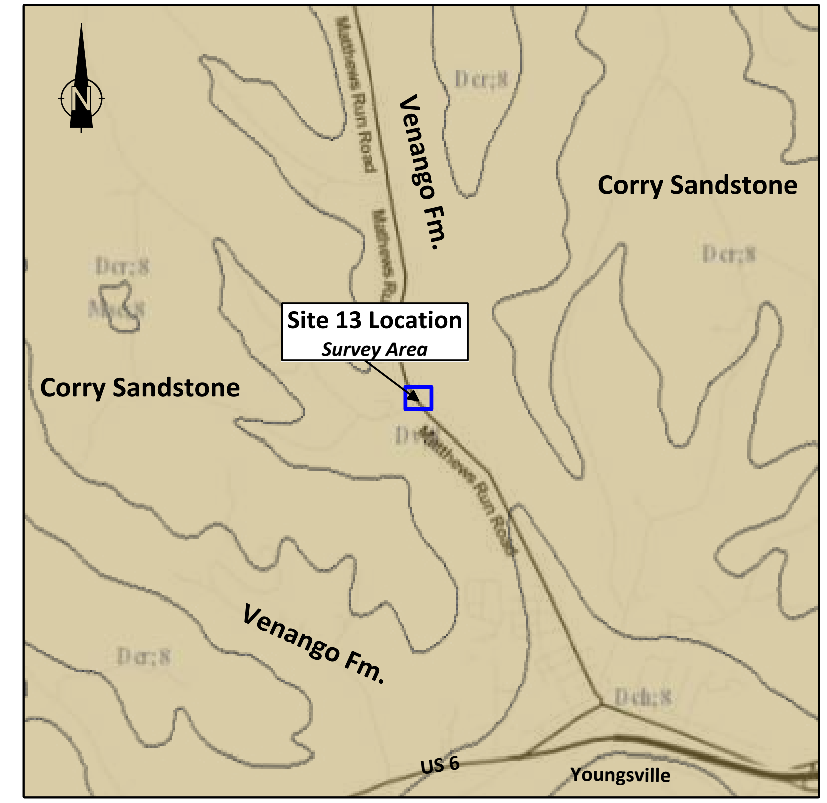
An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 12

VENANGO COUNTY

OIL CITY, PA

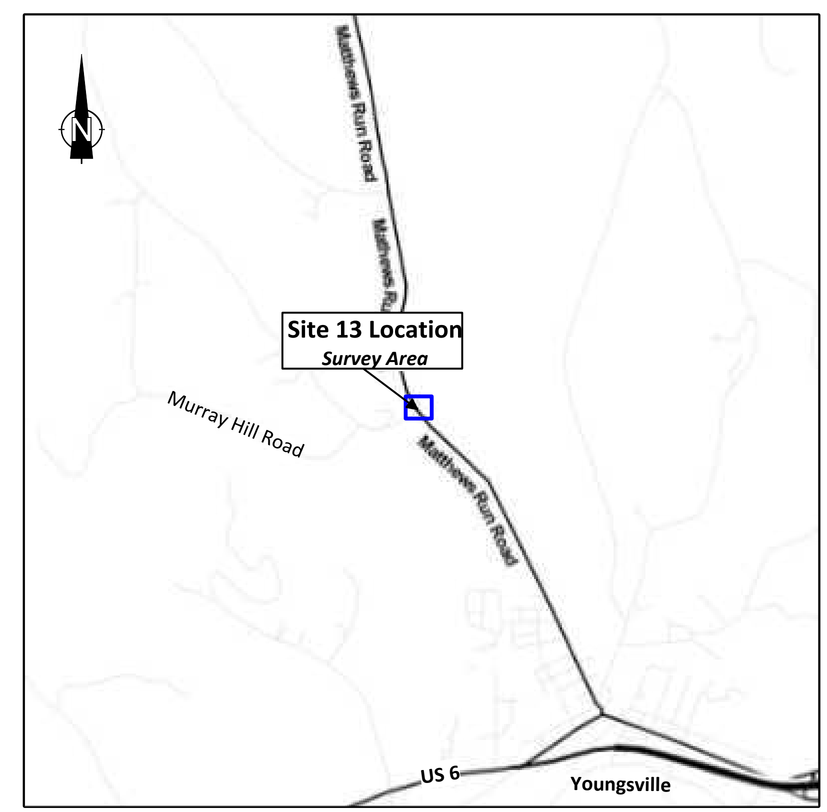

Scale (U.S. Survey Feet)

0 75 150




**Geologic Setting**

0 5000 10000
Feet




**Site Location**

0 5000 10000
Feet

**Notes:**

Basemap image from PASDA Imagery Navigator (2018).

Geologic and Karst information from PASDA WMS Server.

Coordinates in PA State Plane (north), NAD83, U.S. Survey feet.

Survey profiles/stations from field survey and RTK by RETTEW.

**Geophysical Survey Legend**

▼ Geophone Location

◇ Seismograph (Geode/Tromino)

SURVEY DATE: 10/19/2021
RETTEW No.: 105082002
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DRAWN BY: CTM
REVISION DATE: 11/12/2021
SCALE: Graphical
FIGURE NO. 13A

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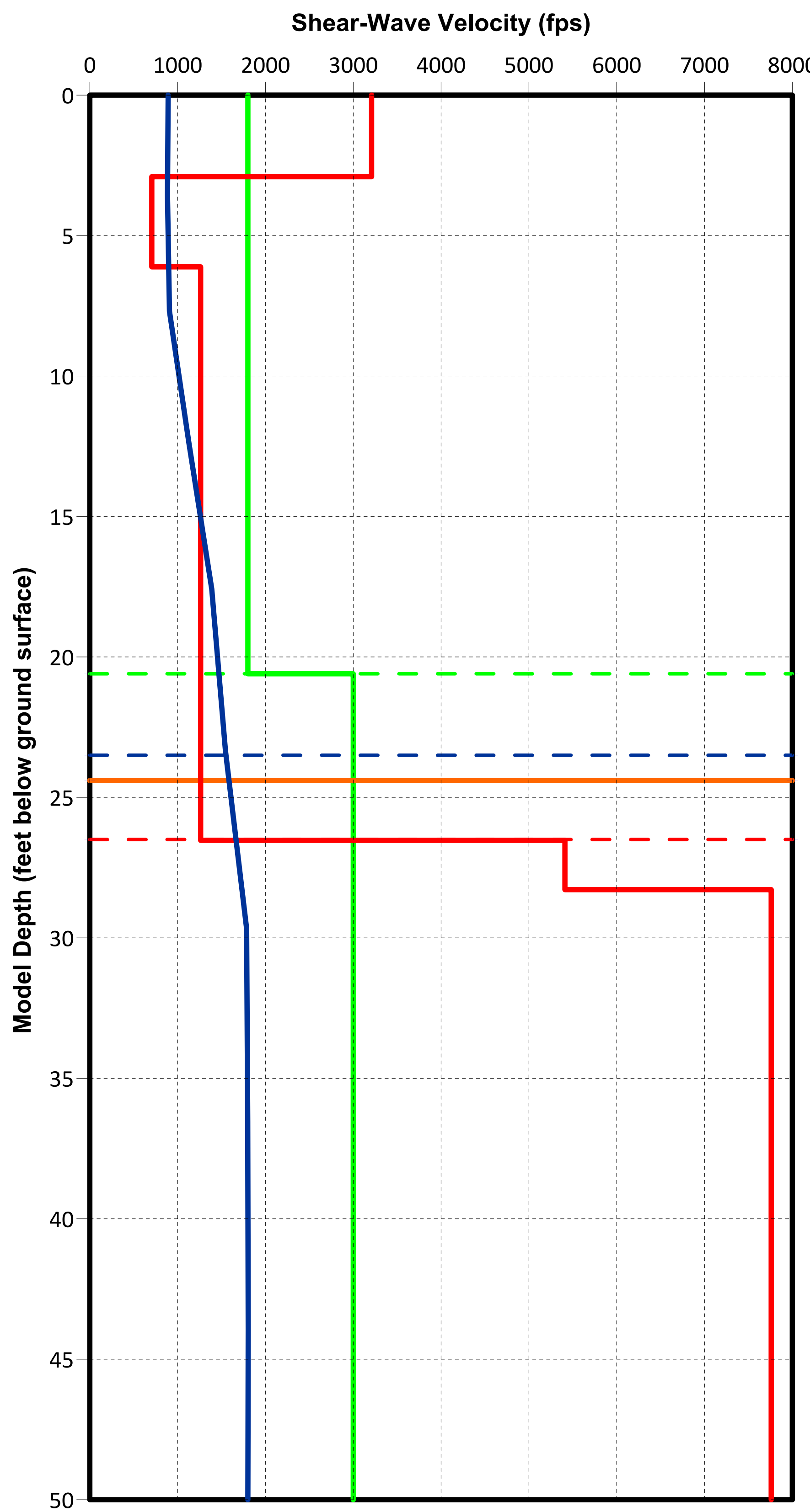
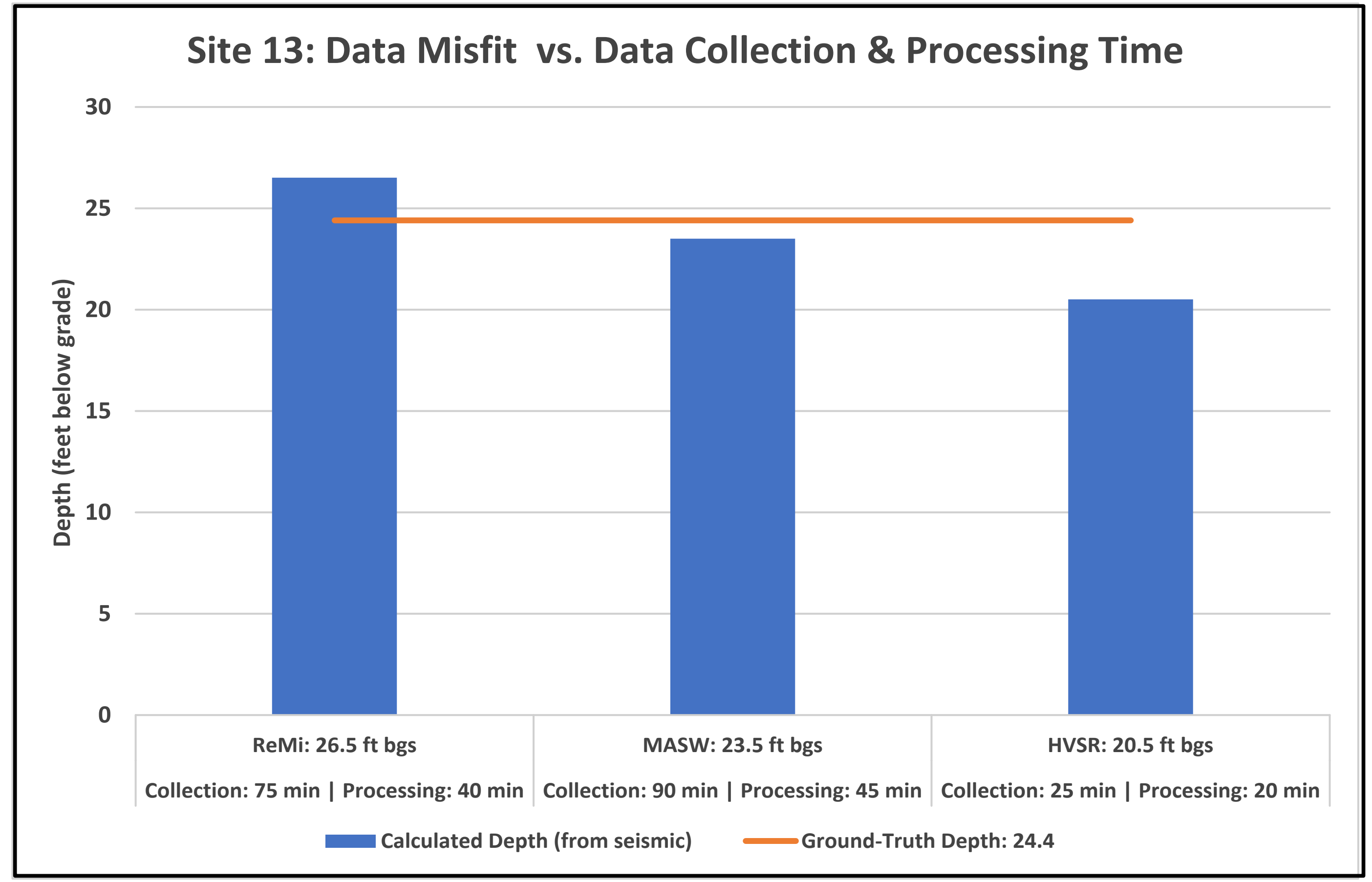
**Figure 13A: Data Coverage and Geologic Setting Site 13**

An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 13

WARREN COUNTY

WARREN, PA




**Weighted Average Shear-Wave Velocities**

- Profile 1 ReMi (Seis Opt)
- Profile 2 1-D MASW (Seisimager)
- Profile 3 HVSR (Grilla)
- Depth to Bedrock (from boring)

**Notes:**

MASW and ReMi seismic data from Geometrics 24-channel Geode with 4.5 Hz geophones at a 10-foot spacing.

MASW weighted average shear-wave velocities (Vs) from Geometrics SeisImager. ReMi average Vs values from Seis Opt ReMi by Optim. HVSR average Vs from Grilla by MOHO.

Colored dashed lines correspond to inferred rock depths from each type of survey.

SURVEY DATE: 10/14/2021
RETTEW No.: 105082002
REVIEWED BY: CHR/FKB
DRAWN BY: CTM
REVISION DATE: 11/12/2021
SCALE: Graphical
FIGURE NO. 13B

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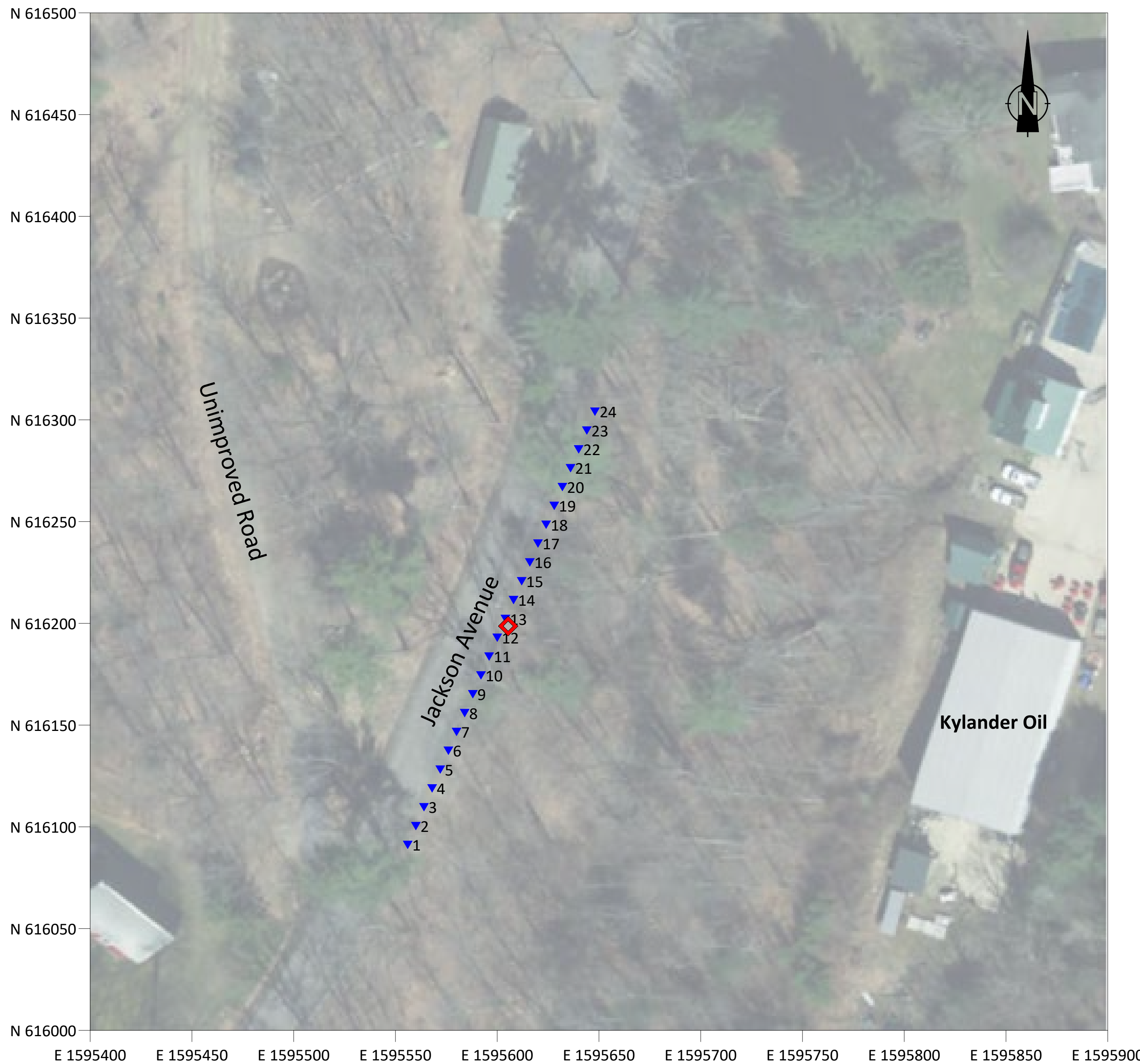
# Figure 13B: Seismic Results Site 13

An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 13

WARREN COUNTY

WARREN, PA




Scale (U.S. Survey Feet)

0 75 150

**Geophysical Survey Legend**

▼ Geophone Location

◇ Seismograph (Geode/Tromino)

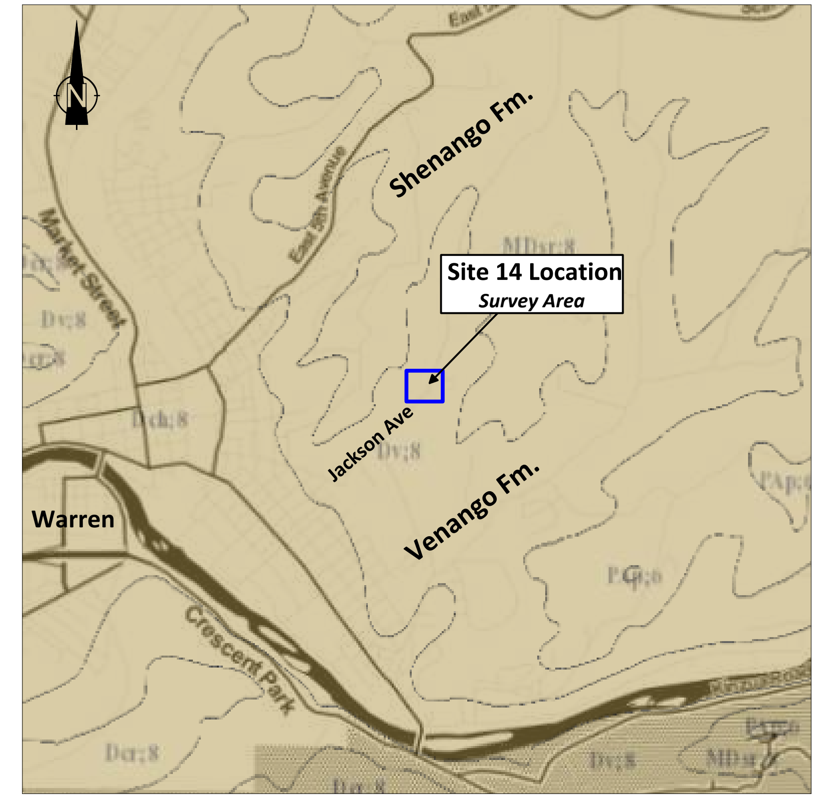
**Notes:**

Basemap image from PASDA Imagery Navigator (2018).

Geologic and Karst information from PASDA WMS Server.

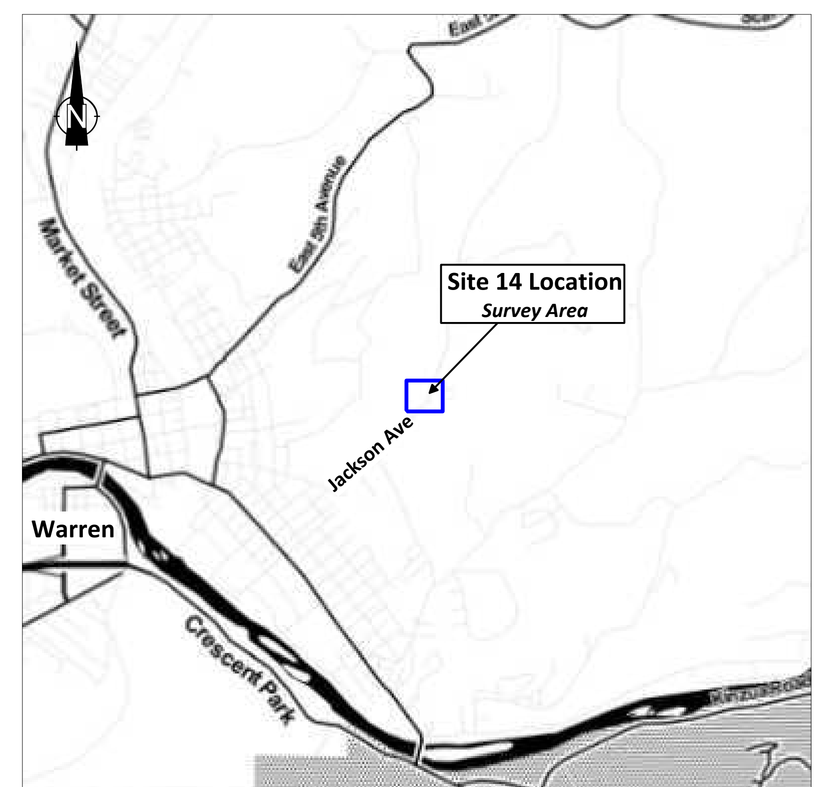
Coordinates in PA State Plane (north), NAD83, U.S. Survey feet.

Survey profiles/stations from field survey and RTK by RETTEW.




## Geologic Setting

0 5000 10000
Feet




## Site Location

0 5000 10000
Feet

SURVEY DATE: 10/20/2021
RETTEW No.: 105082002
REVIEWED BY: CHR/FKB
DRAWN BY: CTM
REVISION DATE: 11/12/2021
SCALE: Graphical
FIGURE NO. 14A

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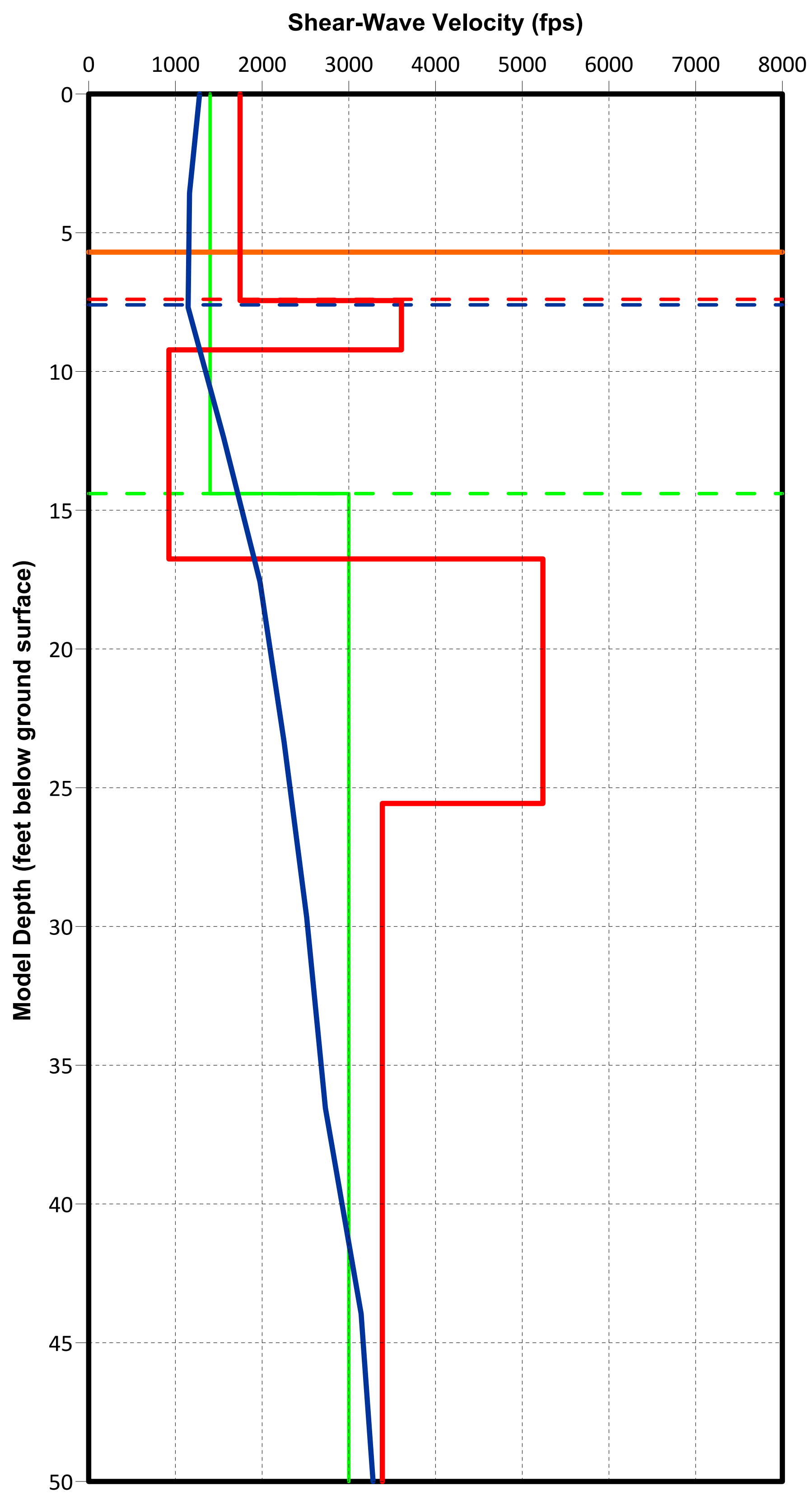
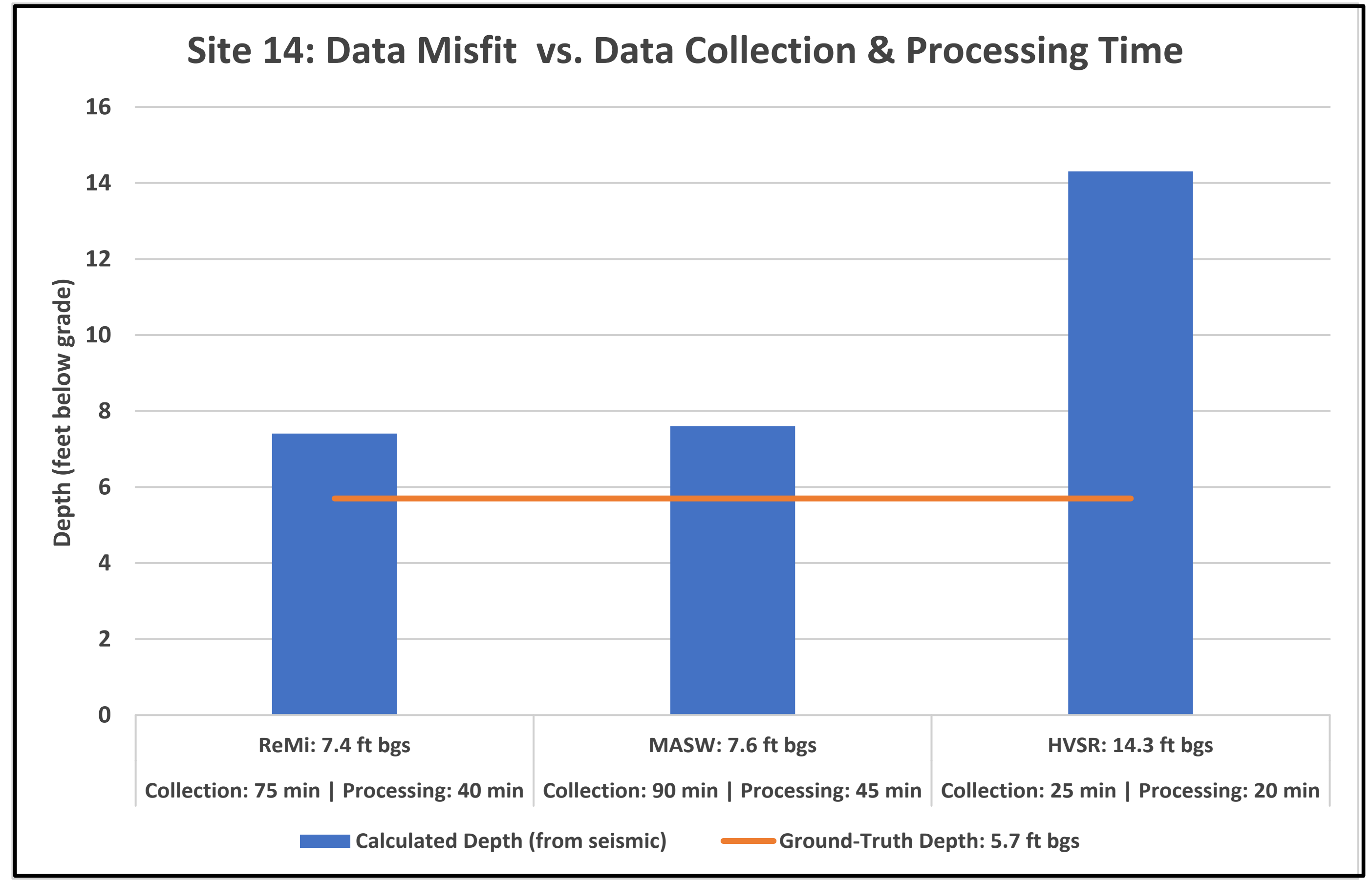
# Figure 14A: Data Coverage and Geologic Setting Site 14

An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 14

WARREN COUNTY

WARREN, PA




**Weighted Average Shear-Wave Velocities**

- Profile 1 ReMi (Seis Opt)
- Profile 2 1-D MASW (Seisimager)
- Profile 3 HVSR (Grilla)
- Depth to Bedrock (from boring)

**Notes:**

MASW and ReMi seismic data from Geometrics 24-channel Geode with 4.5 Hz geophones at a 10-foot spacing.

MASW weighted average shear-wave velocities (Vs) from Geometrics SeisImager. ReMi average Vs values from Seis Opt ReMi by Optim. HVSR average Vs from Grilla by MOHO.

Colored dashed lines correspond to inferred rock depths from each type of survey.

SURVEY DATE: 10/14/2021
RETTEW No.: 105082002
REVIEWED BY: CHR/FKB
DRAWN BY: CTM
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SCALE: Graphical
FIGURE NO. 14B

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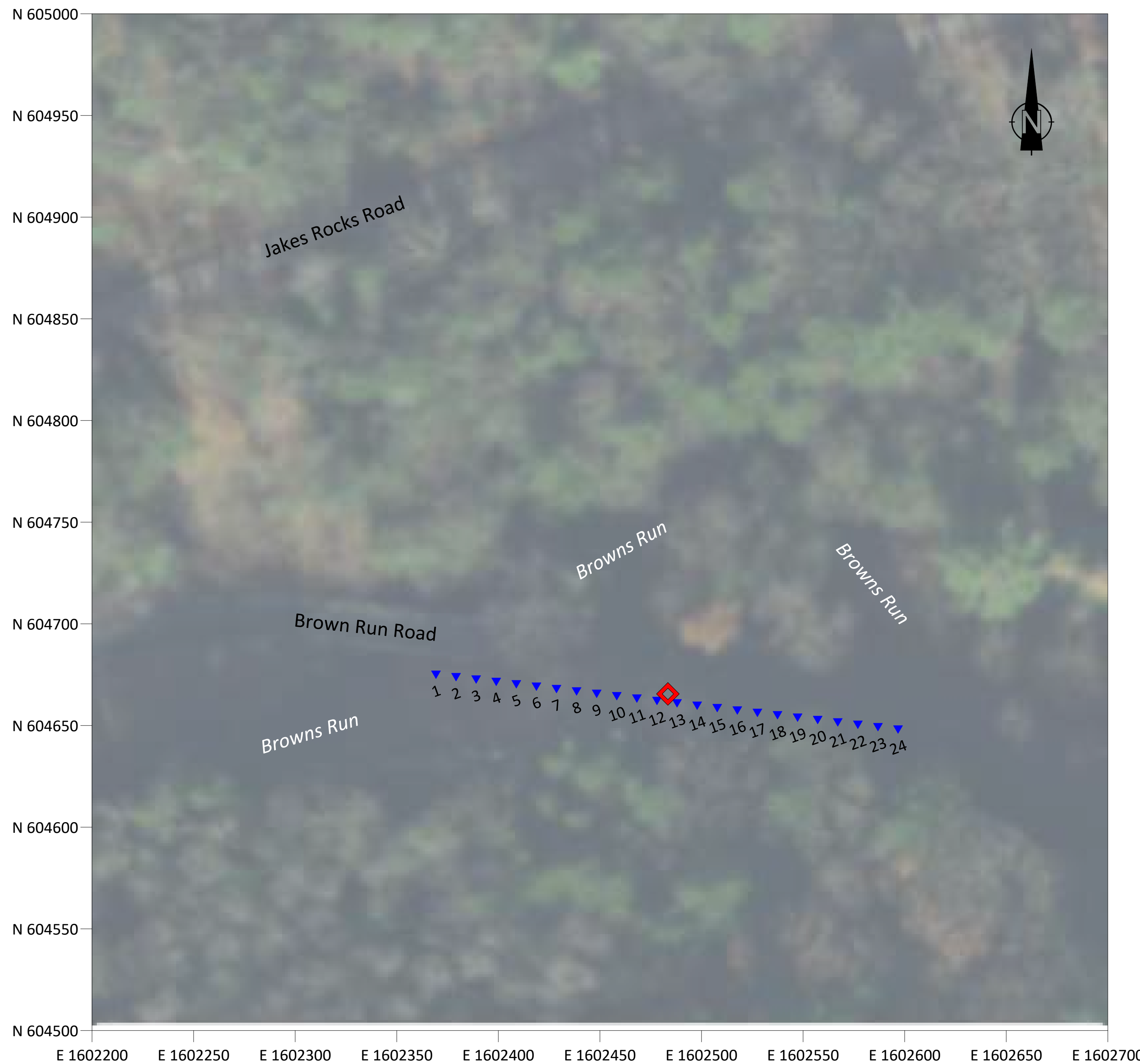
**Figure 14B: Seismic Results Site 14**

An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 14

WARREN COUNTY

WARREN, PA




Scale (U.S. Survey Feet)
0 75 150

**Notes:**

Basemap image from PASDA Imagery Navigator (2018).

Geologic and Karst information from PASDA WMS Server.

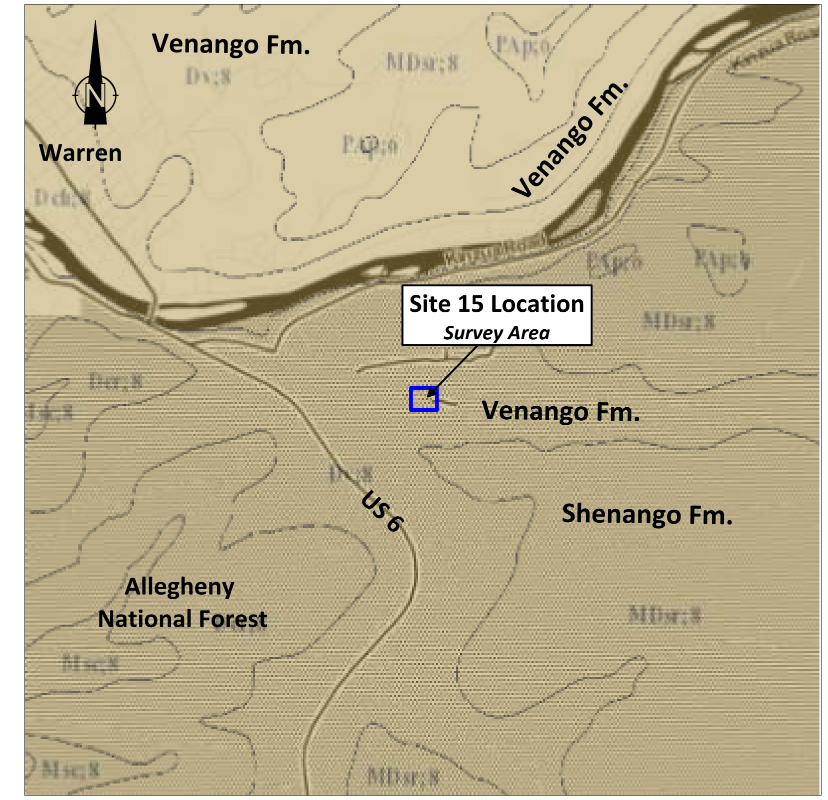
Coordinates in PA State Plane (north), NAD83, U.S. Survey feet.

Survey profile/stations from RTK by RETTEW.

**Geophysical Survey Legend**

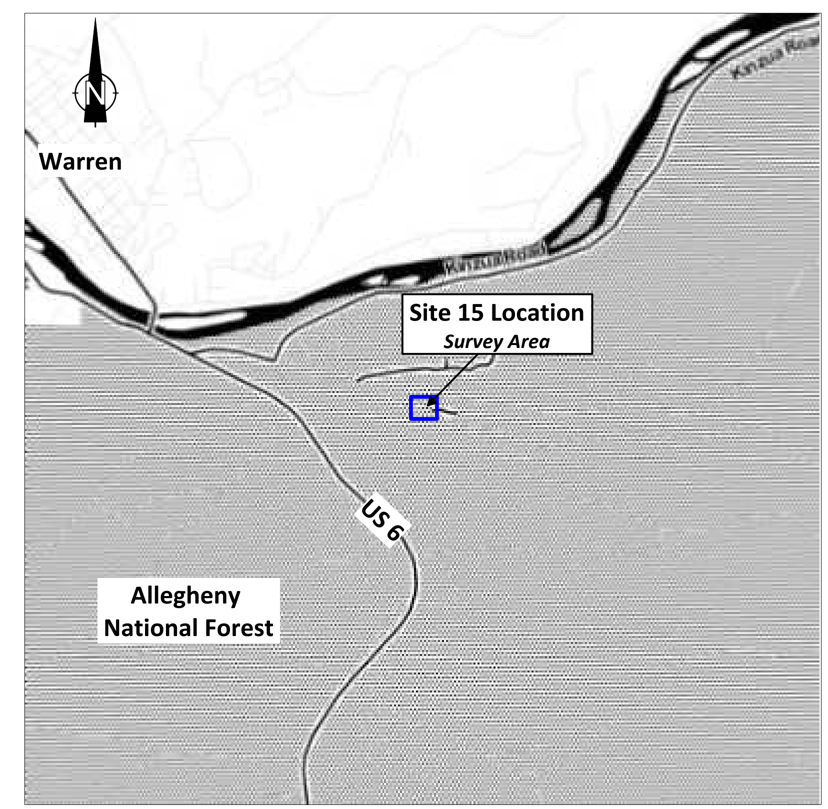
▼ Geophone Location

◇ Seismograph (Geode/Tromino)




**Geologic Setting**

0 5000 10000
Feet




**Site Location**

0 5000 10000
Feet

SURVEY DATE: 10/21/2021
RETTEW No.: 105082002
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REVISION DATE: 11/12/2021
SCALE: Graphical
FIGURE NO. 15A

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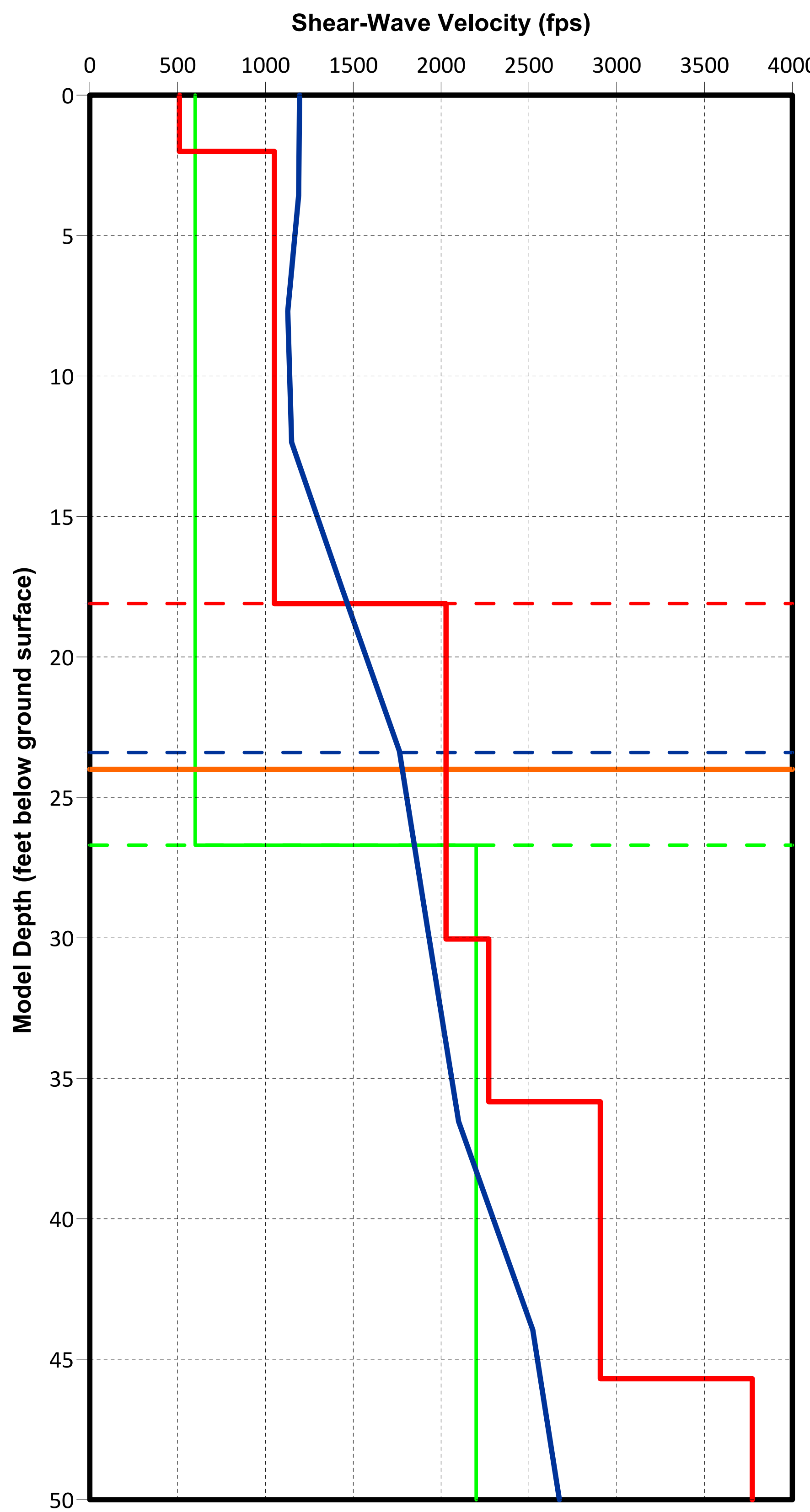
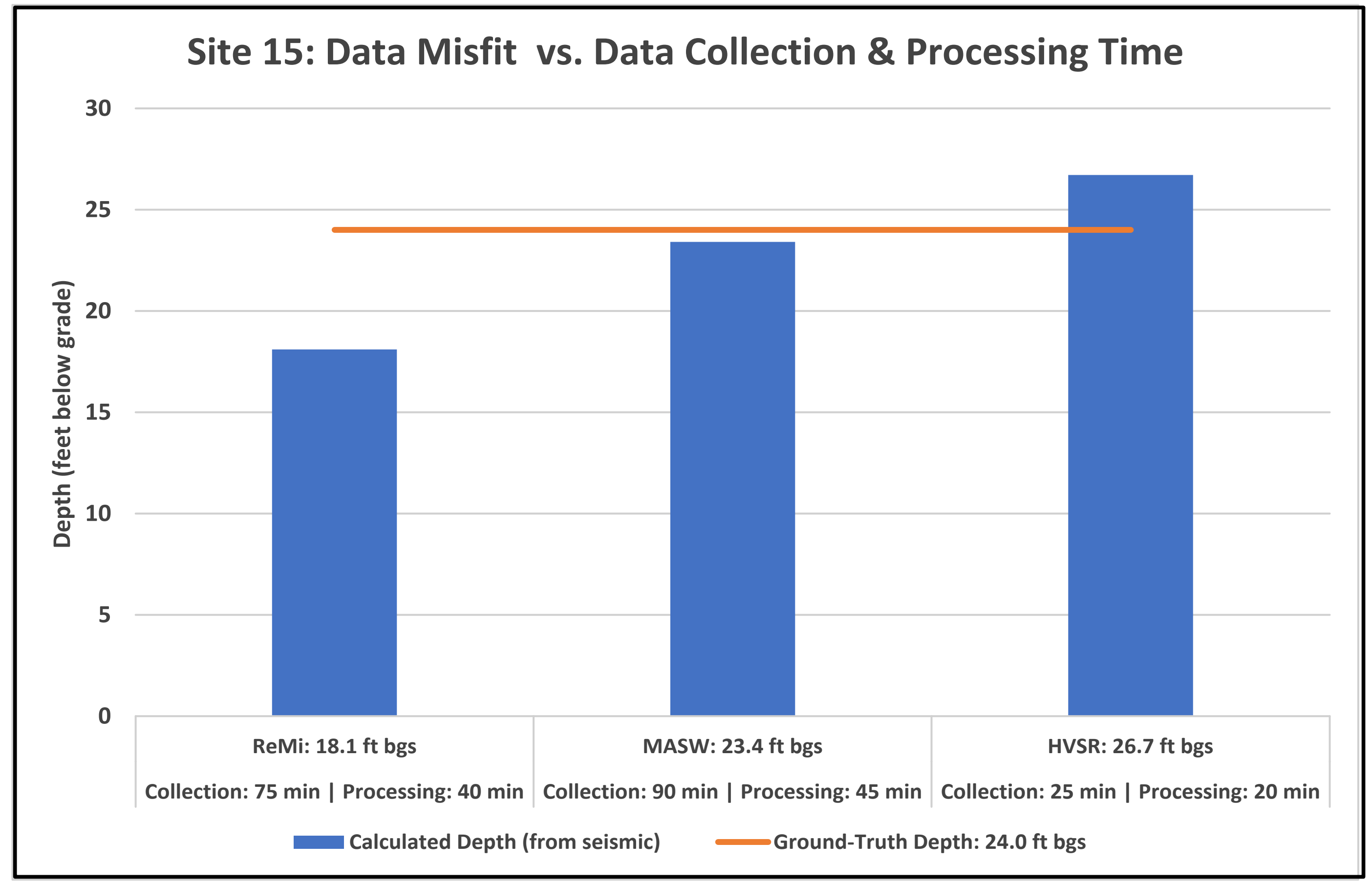
**Figure 15A: Data Coverage and Geologic Setting Site 15**

An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site15

WARREN COUNTY

WARREN, PA




**Weighted Average Shear-Wave Velocities**

- Profile 1 ReMi (Seis Opt)
- Profile 2 1-D MASW (Seisimager)
- Profile 3 HVSR (Grilla)
- Depth to Bedrock (from boring)

**Notes:**

MASW and ReMi seismic data from Geometrics 24-channel Geode with 4.5 Hz geophones at a 10-foot spacing.

MASW weighted average shear-wave velocities (Vs) from Geometrics SeisImager. ReMi average Vs values from Seis Opt ReMi by Optim. HVSR average Vs from Grilla by MOHO.

Colored dashed lines correspond to inferred rock depths from each type of survey.

SURVEY DATE: 10/14/2021
RETTEW No.: 105082002
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DRAWN BY: CTM
REVISION DATE: 11/12/2021
SCALE: Graphical
FIGURE NO. 15B

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**Figure 15B: Seismic Results Site 15**

An Evaluation of Unconsolidated Overburden Thickness
PENNDOT Site 15

WARREN COUNTY

WARREN, PA