

January 10, 2019

Mr. Larry J. Gremminger
Sunoco Logistics, L.P.
535 Fritztown Road
Sinking Spring, PA 19608

RE: Geophysical Survey
Sunoco Pipeline, L.P. Pipeline Project
Horizontal Directional Drill S2-0220 – Interstate 81
PA-CU-0136.0003-RD-16
Middlesex Township, Cumberland County, Pennsylvania
RETTEW Project No. 096302009

Engineers
Environmental
Consultants
Surveyors
Landscape
Architects
Safety
Consultants
Geophysicists

Dear Mr. Gremminger:

RETTEW Associates, Inc. completed a multi-technique geophysical survey at the S2-0220, Interstate 81 horizontal directional drill (HDD) site. The purpose of the survey was to detect and delineate subsurface voids or low-density zones that could contribute to potential inadvertent returns (IRs) and/or a loss of returns, and to determine the rock profile and rock rippability for ease-of-excavation along the HDD path. The following report, figures, and attachments describe the methods and results of the investigation.

EXECUTIVE SUMMARY

The multi-technique geophysical survey was completed between October 24 and November 17, 2018. Three different geophysical techniques were utilized to detect and delineate subsurface voids or low-density zones and provide a bedrock profile. These methods, and their general results are as follows:

- Microgravity delineated at least three significant low-density zones in the survey area. These zones could represent minor karst-related air-, water-, or mud-filled voids, or locally deeper rock/thicker soils.
- Seismic refraction confirmed the presence of an irregular bedrock surface and “epikarst” zone.
- Electrical resistivity imaging (ERI) identified a conductive surface layer over a discontinuous resistive layer, with the discontinuities possibly suggesting the presence of fracture zones.

Results from the geophysical techniques are consistent with each other, and with the geology as mapped by the PA Geological Survey; all suggesting that the local bedrock (in limestone zones) is only mildly karstified, with a few potential zones of dissolution cavities (of various sizes) indicated by the low-gravity anomalies. In the limestone zones, the top-of-rock is expected to be pinnacled (highly irregular) with interfingering competent rock and residual clay soil.

SITE DESCRIPTION

The Interstate 81 HDD site is located parallel to Interstate 76 (PA Turnpike), and runs beneath I-81 and South Middlesex Road in Middlesex Township, Cumberland County, Pennsylvania (see **Figure 1**). A geophysical survey was conducted over accessible areas of the HDD alignment and encompassed two



areas roughly 40 feet wide by 530 feet long west of South Middlesex Road, and 40 feet wide by 180 feet long east of South Middlesex Road (**Figure 2**).

The site bedrock geology consists of the Ordovician-aged St. Paul Group (see **Figure 2**, lower center inset). The St. Paul Group is described as very finely crystalline, "birdseye" limestone at its top and base, with granular fossiliferous limestone, black chert, and dolomite in the middle (Berg et al., 1980).

KARST TERRANE

Pinnacled bedrock, closed topographic depressions, and sinkholes are geologic features characteristic of karst terranes — i.e. terranes underlain by soluble carbonate (limestone or dolomite) bedrock in wet climates. In karst terranes, infiltrating precipitation dissolves the carbonate bedrock surface, causing the top-of-rock to retreat downward leaving behind a soil mantle composed of the insoluble clay and/or silica particles formerly bonded in the rock. Within the bedrock, percolating water enlarges fractures, bedding planes, etc. to produce solution openings ranging in size from minor seams to scenic caverns.

The main difference between a sinkhole and a closed depression is that a sinkhole may appear suddenly as a break in the ground surface revealing a hole, whereas a closed depression typically subsides slowly with no break at the surface. The Pennsylvania Geological Survey (PA DCNR Interactive Map, 2017) records no surface depressions within the limits of the survey area (see **Figure 2**), but numerous features occur within a half-mile radius of the site (see **Figure 2**, lower center inset).

Sinkholes and depressions form where particularly enhanced infiltration into a sufficiently-wide solution opening (often called a throat or chimney) washes the soil mantle down into cavities in the underlying rock — a process commonly called soil piping. In areas where the residual soil mantle is clay-rich and cohesive, incipient sinkholes may not display any surficial topographic expression, and are present only as air-, water-, or mud-filled voids which may grow or "stope" upwards. The overlying soil arch may collapse under its own weight, or under the weight of an overlying structure or passing vehicle. The resulting collapse feature, or "sinkhole," is commonly filled with the remains of the soil arch and may display rock at its base. In some cases, surficial subsidence may keep pace with soil piping at depth such that a sinkhole forms by progressive deepening of a surficial depression (sometimes called a subsidence sink), rather than by catastrophic collapse of a stoping void. **Appendix A** depicts this process.

MICROGRAVITY SURVEY

Microgravity meters measure very small local variations in gravity. Several factors can locally affect the acceleration of gravity. One factor is the local density or mass distribution of the bedrock or soils beneath the meter. Gravity highs (mass excesses) commonly represent locally shallow bedrock pinnacles or float blocks in the soil profile or zones of particularly massive bedrock. Gravity lows (mass deficiencies) may represent locally deep bedrock cutters, or clay seams where soil displaces bedrock; air-, water- or mud-filled voids within bedrock; stoping voids in the soil above bedrock; or zones where soils have been made less dense by removal of fines.

The residual microgravity data are shown on **Figure 3**. The values depict the general plan-view shallow mass distribution beneath the survey area. Lower values (red) represent local mass deficiencies (air- or clay-filled voids, or deeper soils). Higher values (blue) represent local mass excesses (bedrock pinnacles or float blocks). Specific microgravity survey parameters are listed in **Appendix B**.

SEISMIC MASW AND REFRACTION SURVEY

Seismic Multi-Spectral Analysis of Surface Waves (MASW) and refraction methods utilize the speed of seismic waves through various geologic layers and features to characterize the subsurface geologic conditions. The methods enable determination of the general material types, and the approximate depth to bedrock or rock profile. MASW can detect low-velocity zones in soils that might represent developing sinkholes, or low velocities below the top of rock that might be associated with karst dissolution features or fractures. The principles of seismic refraction are summarized in **Appendix C**.

The seismic survey consisted of one profile along the HDD center line, with a gap over South Middlesex Road (see blue triangles, upper panel, **Figure 2**). Color-contour velocity models of the seismic profiles for the seismic refraction and MASW are presented on **Figure 4**. The vertical scale represents relative elevation in feet, and the horizontal axis represents an along-profile distance in feet. The color contours represent average seismic velocity variations (compressional- (P-) wave velocities for refraction, and shear- (S-) wave velocities for MASW), with increasing velocities from blue to yellow to orange to brown (refraction – upper cross section), and purple to grey to tan to brown (MASW – lower cross section). Please note that high- and low-velocity data along the first and last fifteen feet of any profile have higher uncertainty. Specific seismic refraction and MASW survey parameters are listed in **Appendix B**.

ERI SURVEY

Electrical resistivity measurements involve driving an electrical current in the ground using current electrodes at the ground surface. The apparent resistivity of the subsurface is determined by measuring the potential difference, or voltage, between two potential electrodes with a known separation and position/orientation relative to the current electrodes. The depth and volume of the subsurface zone represented by the measured apparent resistivity is a function of the geometry of the current and potential electrodes. Apparent resistivities are converted to model or true resistivities by performing a joint inversion of all of the measured apparent resistivities along a profile (or profiles in the case of 3D resistivity).

The resistivity survey consisted of five linear profiles between I-81 and South Middlesex Road, and nine profiles east of South Middlesex Road comprising a 5-foot by 5-foot grid (see orange dots, **Figure 2**). The apparent resistivity data were mathematically inverted using both EarthImager 2D and 3D by AGI to provide a cross-sectional image of each individual profile as well as a 3D model of the subsurface. These are shown in **Figures 5** and **6**. **Figure 5** shows individual 2D cross sections, while **Figure 6** shows a 2-D cross section along the HDD centerline (upper panel) as well as a 3-D block model (lower panels). Specific ERI survey parameters are listed in **Appendix B**.

RESULTS

The microgravity data are depicted on **Figure 3** as color contours representing the relative density of the subsurface, with blue for high-density, green for “site normal,” and red for locally low-density areas. The microgravity display alternating high-density and low-density areas across the survey grid. This is consistent with karstified rocks with a pinnacled rock surface, and/or boulders or float blocks in the soil mantle. Areas of low density could indicate fractures and potential voids.

The seismic refraction data are presented as a cross-sectional profile on **Figure 4**. The data indicate a general three-layer stratigraphy consisting of a residual soil mantle, the epikarst zone, and competent bedrock. The uppermost layer has average P-wave velocities generally less than 6,000 feet per second

(fps) with a thickness of approximately 5-15 feet. This is consistent with a relatively compact residual clay soil mantle (shaded blue to yellow). The deepest layers have velocities over 12,000 fps (shaded orange to brown) consistent with competent bedrock (Carmichael, R. S., 1989). The zone between roughly the 6,000 and 12,000 fps contours is commonly referred to as the “epikarst” in carbonate rock, and is not really a “layer” in the stratigraphic sense. Instead, it contains soil interfingering with rock pinnacles and/or float material. This transition zone contains competent rock pinnacles, float material, and/or dipping lithologic layers that may stick-up or cut-across the smoothed contours and may impede excavation (see **Appendix C**).

The MASW seismic cross section is presented below the seismic refraction cross section (**Figure 4**). The MASW velocity model shows velocity changes within the bedrock layer across the profile. Velocity lows below the bedrock surface could indicate fractures or karst dissolution features which might be potential pathways for IRs.

The seismic velocity models from the ray-tracing method (not shown) were compared to standard ripping charts (see **Appendix D**, Caterpillar, Inc., 1995) using the inferred/assumed layer compositions to determine the general rippability of each stratum. In general, the surficial layer down to about the top of inferred epikarst (wavy dashed contour) should be readily to marginally rippable with a D9 multi- or single-shank ripper doing open field ripping, based on a weighted average velocity of about less than 6,000 fps. Below the 6,000-fps contour, ripping will get more difficult with depth, with the transition zone expected to become non-rippable below the 12,000-fps contour (based on the average ray-trace velocity of over 17,000 fps and Caterpillar charts). The 6,000-fps contour represents the top of the epikarst/weathered rock and not the actual surface which is often non-resolvable in karst terranes. For trenching (as opposed to open field ripping), material below approximately the 3500-fps contour color (greenish blue) may become non-rippable (for a CAT-330 tracked excavator or equivalent). The selection of the contour cut-off for trenching is based on correlations between the ray-tracing models (not shown), material properties, and various excavation strategies investigated by Kirsten (1982). The Limitations section contains additional important information regarding rippability estimation by seismic and other means.

The electrical resistivity results are shown in **Figure 5** and **6**. The electrical profiles show a general two-layer model with a conductive upper layer over a more resistive lower layer, indicative of moist, conductive unconsolidated material over more resistive low-porosity bedrock. The upper layer is relatively uniform, with some irregularities that could represent near-surface disturbances given the site development history. The deep conductive anomalies below the inferred top-of-rock may represent fractures or mud-filled voids within bedrock.

CONCLUSIONS

In general, the geophysical survey results display anomalies indicative of a karstified terrane with potential for IRs and/or loss of returns along much of the surveyed HDD path. **Figure 7** summarizes the anomalous areas with various hatching patterns. Overlapping hatching indicates the highest risk of IR, but any anomalous areas have an enhanced risk which is already elevated due to the bedrock geology.

If pipeline installation involves open trenching, and rock removal is required, blasting is not recommended since this can produce overshot cracks that provide pathways for soil piping into deeper underlying solution cavities.

Once pipeline installation is complete (by any method), since subsidence in karst terranes is driven by

infiltrating water, site grading and stormwater control will be key to preventing future subsidence.

LIMITATIONS

The survey described above was completed using standard and/or routinely accepted practices of the geophysical industry, and the equipment employed represents, in RETTEW's professional opinion, the best available technology. RETTEW does not accept responsibility for survey limitations due to inherent technological limitations or unforeseen site-specific conditions. We will notify you of such limitations or conditions, when they are identifiable.

The survey is based on observation of current subsurface conditions. Therefore, while the results of this survey can be used to guide further investigations, RETTEW cannot make any warranties concerning future sinkhole occurrence — particularly under the influence of altered surface and subsurface drainage patterns due to grading and construction activities.

Rippability, while historically closely-correlated with seismic P-wave velocity, also depends on geotechnical properties of the material, on the specific method of excavation, and on the variety and size of equipment employed. For mechanical excavation, the teeth or other cutting elements must be forced into discontinuities of competent rock masses, or penetrate the fabric of weak rocks. Thus, joint or fracture spacing, aperture, and infilling will all play a role in determining whether existing discontinuities in apparently-competent rock masses can allow mechanical excavation. The strength of the intact rock will also control whether fresh discontinuities can be induced during excavation activities. Therefore, while seismic data can provide reliable guidelines, RETTEW recommends that the rocks to be excavated be checked for these other geotechnical characteristics through examination of local outcrops, test pits, or boring logs.

We have enjoyed and appreciated the opportunity to have worked with you. If you have any questions, please do not hesitate to contact the undersigned.



Charles H. Rhine, MSc, PG
Senior Project Manager



Timothy D. Bechtel, PhD, PG
Senior Project Manager



Felicia Kegel Bechtel, MSc, PG
Director of Geophysics

Enclosures

Figure 1: Topographic Basemap

Figure 2: Data Coverage Map and Geologic Setting

Figure 3: Residual Microgravity Results

Figure 4: Seismic Survey Results

Figure 5: Electrical Resistivity Survey Results 10144+50 to 10149+50

Figure 6: Electrical Resistivity Survey Results 10151+00 to 10153+00

Figure 7: Geophysical Results Summary
Appendix A: Schematic Karst Processes
Appendix B: Geophysical Survey Parameters
Appendix C: Introduction to Seismic Refraction
Appendix D: Caterpillar Ripping Charts

References

Berg, T.M., Edmunds, W.E., Geyer, A.R., and others, 1980, Geologic Map of Pennsylvania, PA Geological Survey, 4th series.

Carmichael, R. S. (1989), Physical Properties of Rocks and Minerals, CRC Press.

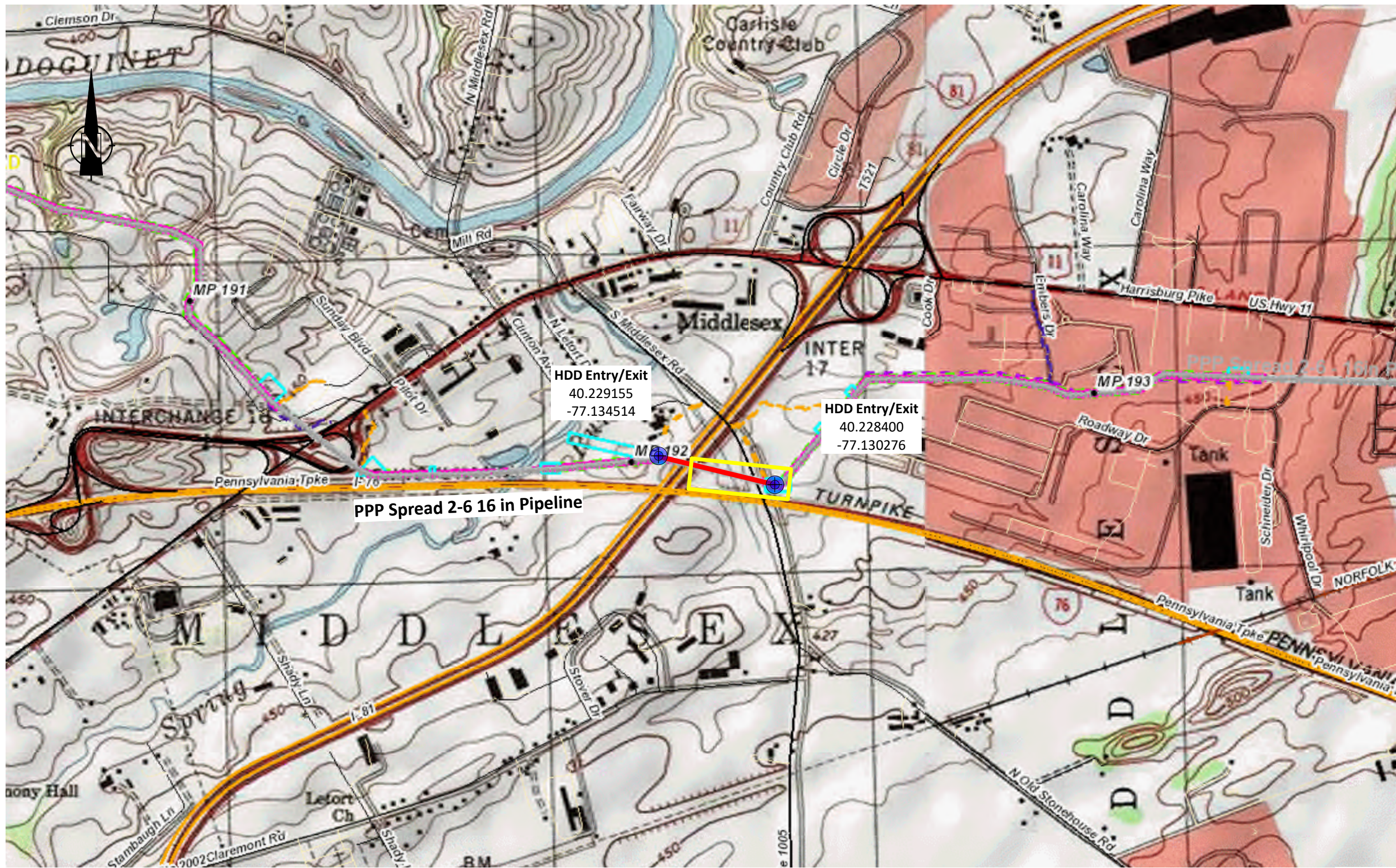
Caterpillar Tractor Company (1995), The Applicator, Caterpillar Tractor Company Marketing Division.

Kirsten, HAD (1982). A classification system for excavating in natural materials. Civil Engineering (Siviele Ingenieurswese), 24(7), 293-308.

PA Department of Conservation and Natural Resources Geology Interactive Map, (<http://www.gis.dcnr.state.pa.us.html>), 2017.

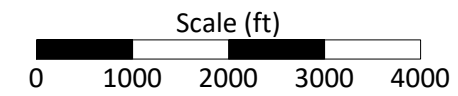
Z:\Shared\Projects\09630\096302009 - Spread 4\GP\S2-0220 I-81\Report\Final\I-81 Final Geophysics Report 2010-01-10.docx

ENCLOSURES



Geophysical Survey Legend

- Proposed 16" HDD Alignment
- Geophysical Survey Area
- ⊕ HDD Entry/Exit Point



Notes:
 Basemap from TetraTech Sunoco Site, extracted 11/2018.

SURVEY DATE:	11/17/2018
REVIEW NO.:	096302009
REVIEWED BY:	FKB
DRAWN BY:	CHR
DATE:	01/05/2019
SCALE:	1" = 2000'
FIGURE NO.:	1 of 7



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Figure 1: Topographic Basemap

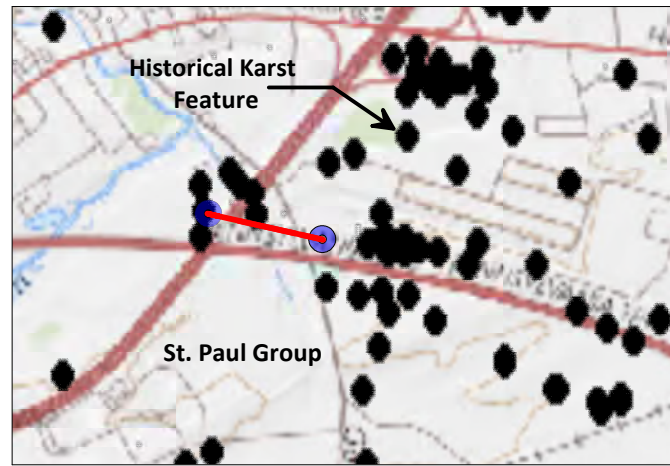
Interstate 81
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 PA-CU-0136.0003-RD-16

CUMBERLAND COUNTY, PA

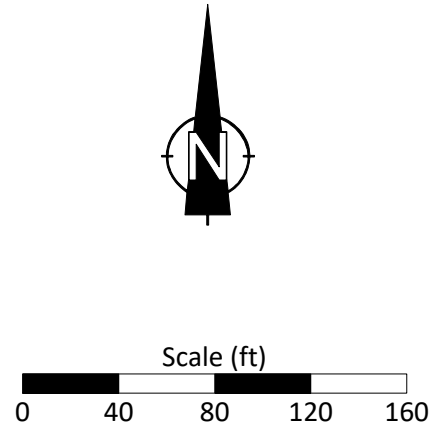
MIDDLESEX TOWNSHIP



Notes:
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 Survey profiles/stations from DGPS survey by RETTEW.
 Geologic information from DCNR WMS Server, extracted 11/2018,
 and Wood (1980).

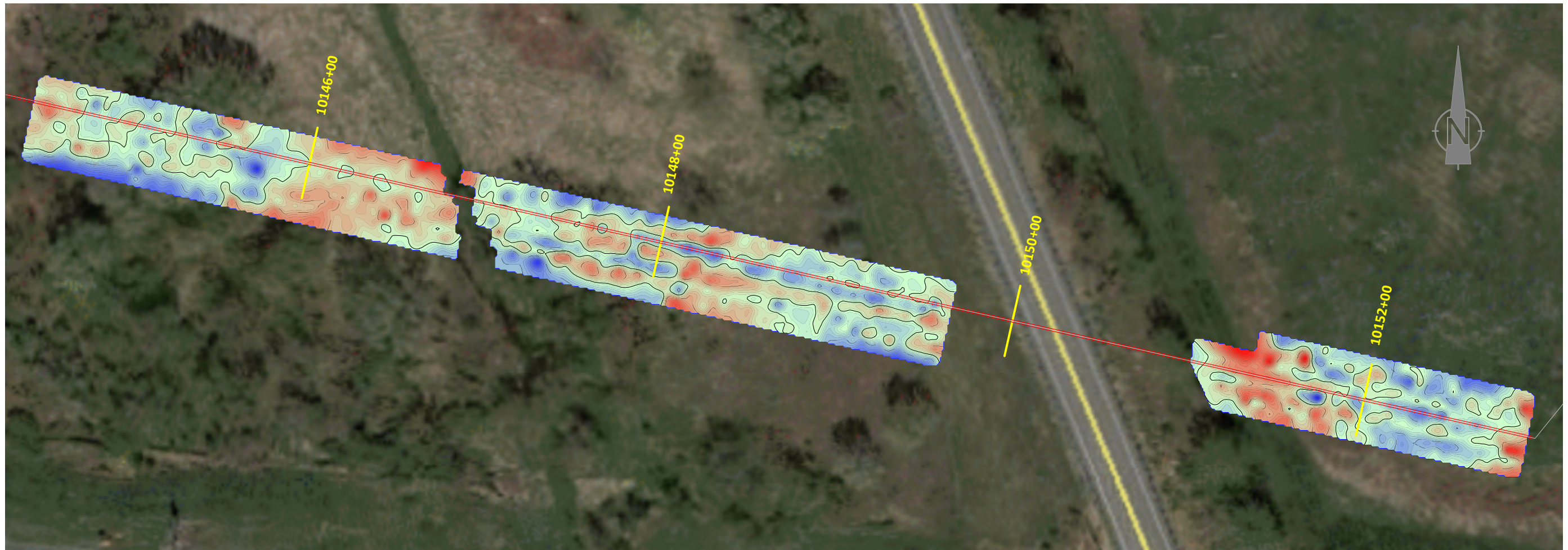


- Geophysical Survey Legend**
- Electrical Resistivity Station
 - ◆ Microgravity Survey Station
 - ▼ Seismic Geophone Location
 - 11638+00 Proposed 16" HDD Product Line with Station Number
 - - - - - Geologic Fracture (mapped by others)



SURVEY DATE:	11/17/2018
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REVIEWED BY:	FKB
DRAWN BY:	CHR
DATE:	01/05/2019
SCALE:	1" = 80'
FIGURE NO.:	2 of 7

Figure 2: Geophysical Data Coverage Map
 Interstate 81
 S2-0220
 PA-CU-0136.0003-RD-16
 CUMBERLAND COUNTY, PA
 MIDDLESEX TOWNSHIP



SURVEY DATE: 11/17/2018
 RETIEW No.: 096302009
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 DATE: 01/05/2019
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 FIGURE NO.: 3 of 7



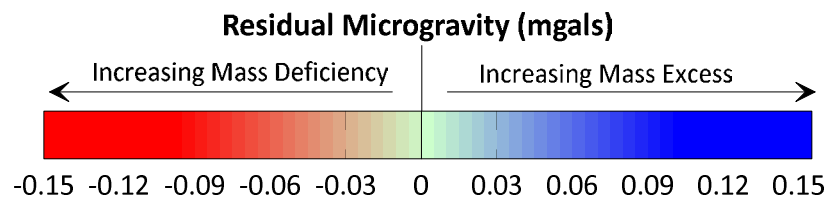
RETIEW
 RETIEW Associates, Inc.
 3020 Columbia Avenue, Lancaster, PA 17603
 Phone (717) 394-3721 Fax (717) 394-1063

CUMBERLAND COUNTY, PA

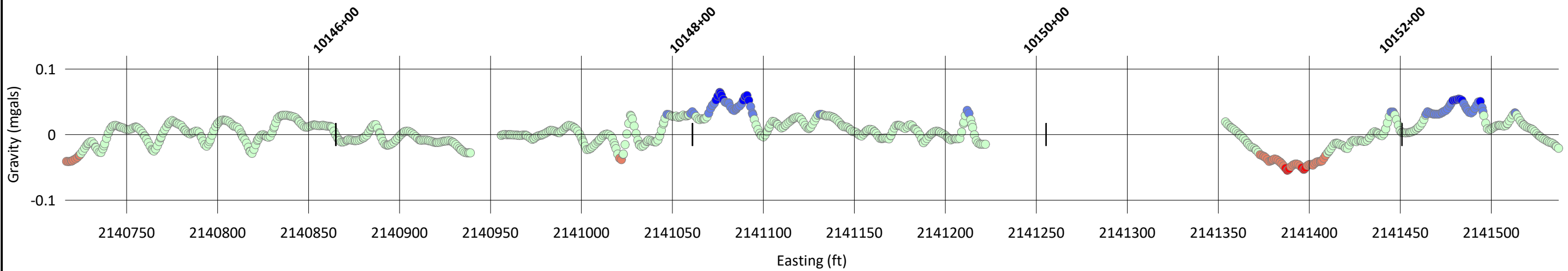
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Figure 3: Residual Microgravity Results

Interstate 81
 S2-0220
 PA-CU-0136.0003-RD-16



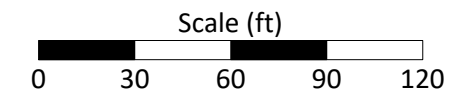
Geophysical Survey Legend
 16" Product Line with Station Number

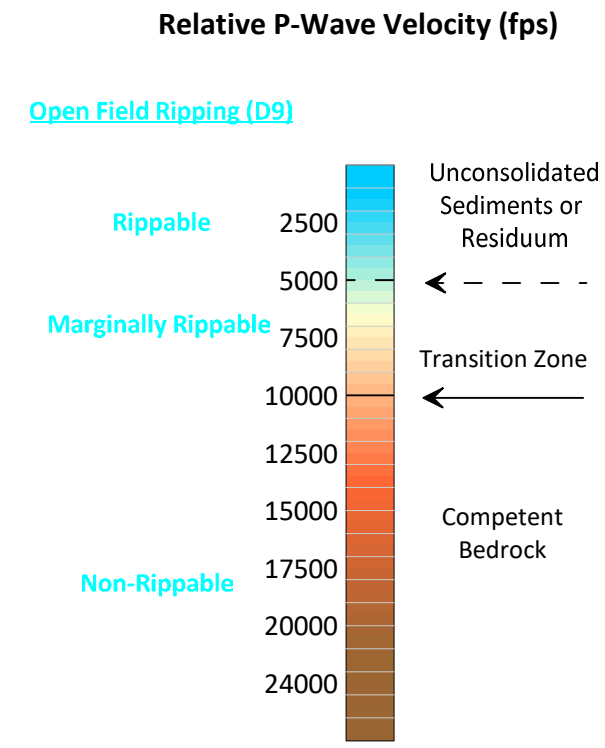
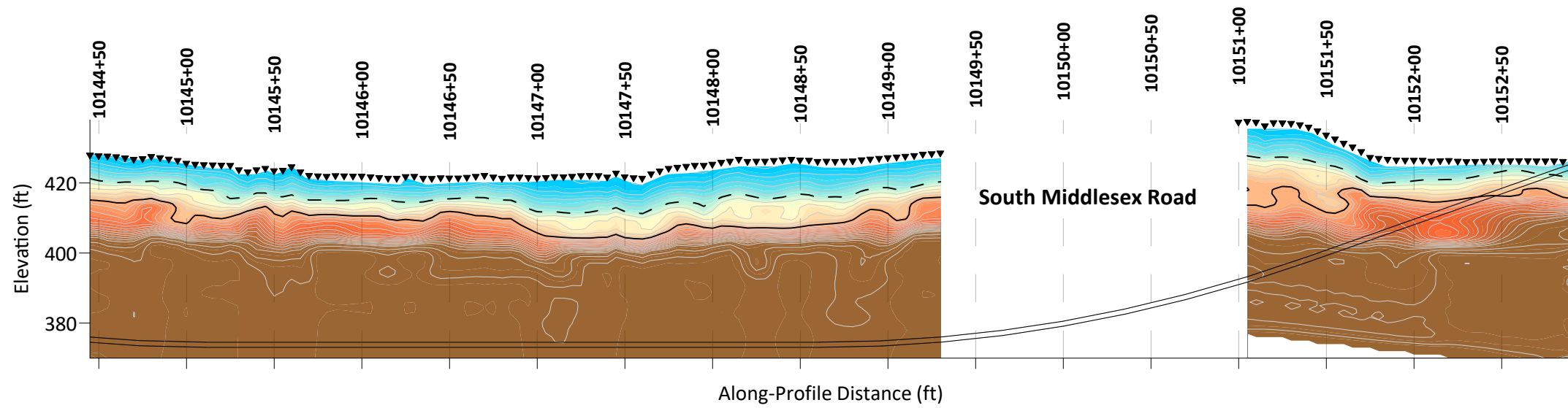


Notes:

Basemap from Google Earth Pro, extracted 11/2018.

Microgravity data from Scintrex CG-5 gravimeter, with Bouguer correction.





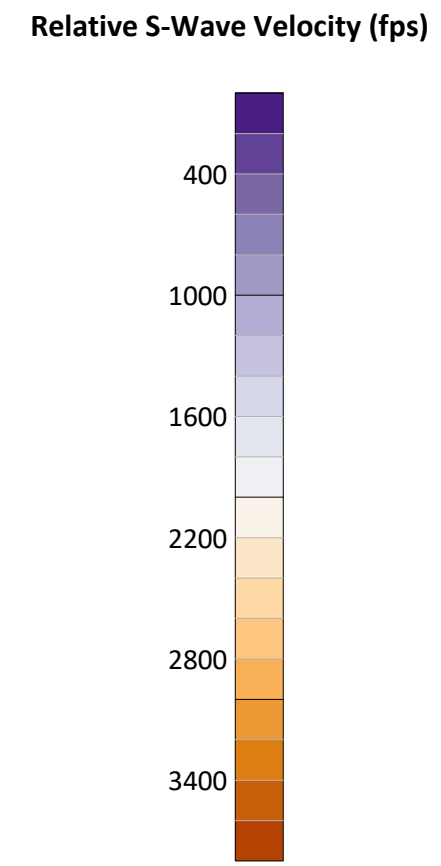
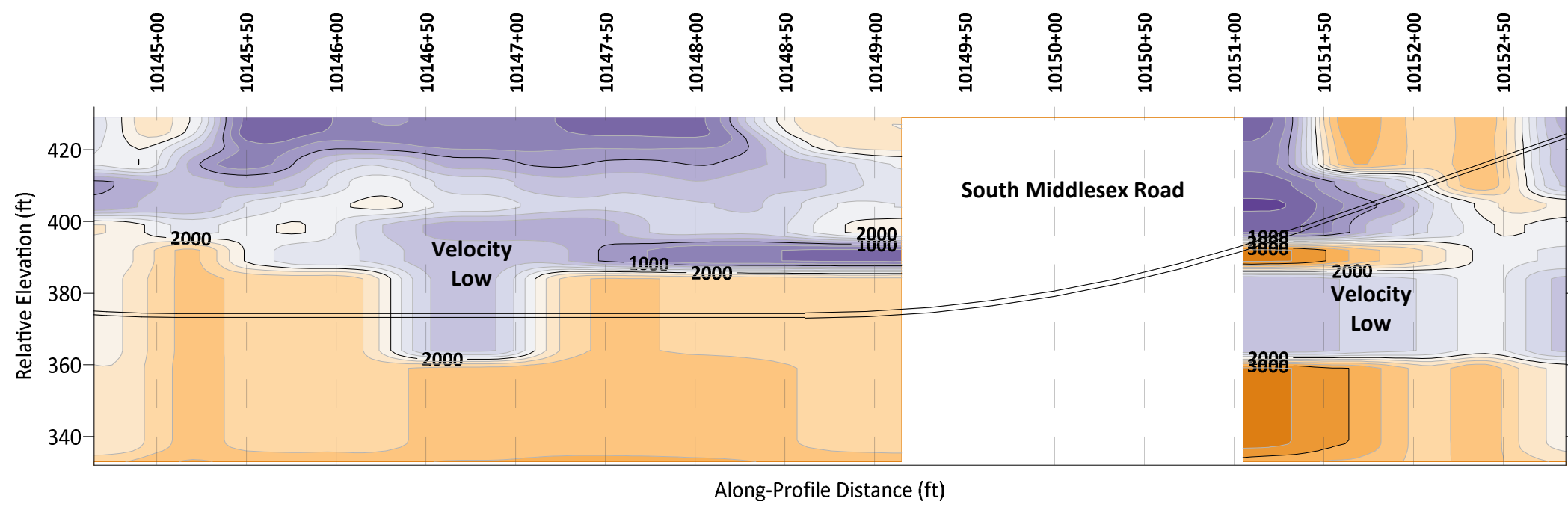
Weighted Average P-Wave Velocity

$V_1 = 848.5$ fps

$V_2 = 17,365$ fps

Geophysical Survey Legend

- ▼ Seismic Geophone Location
- Proposed 16" HDD
- Station Number



Notes:

Seismic data from Geometrics 24-channel Geode with 4.0 Hz geophones.

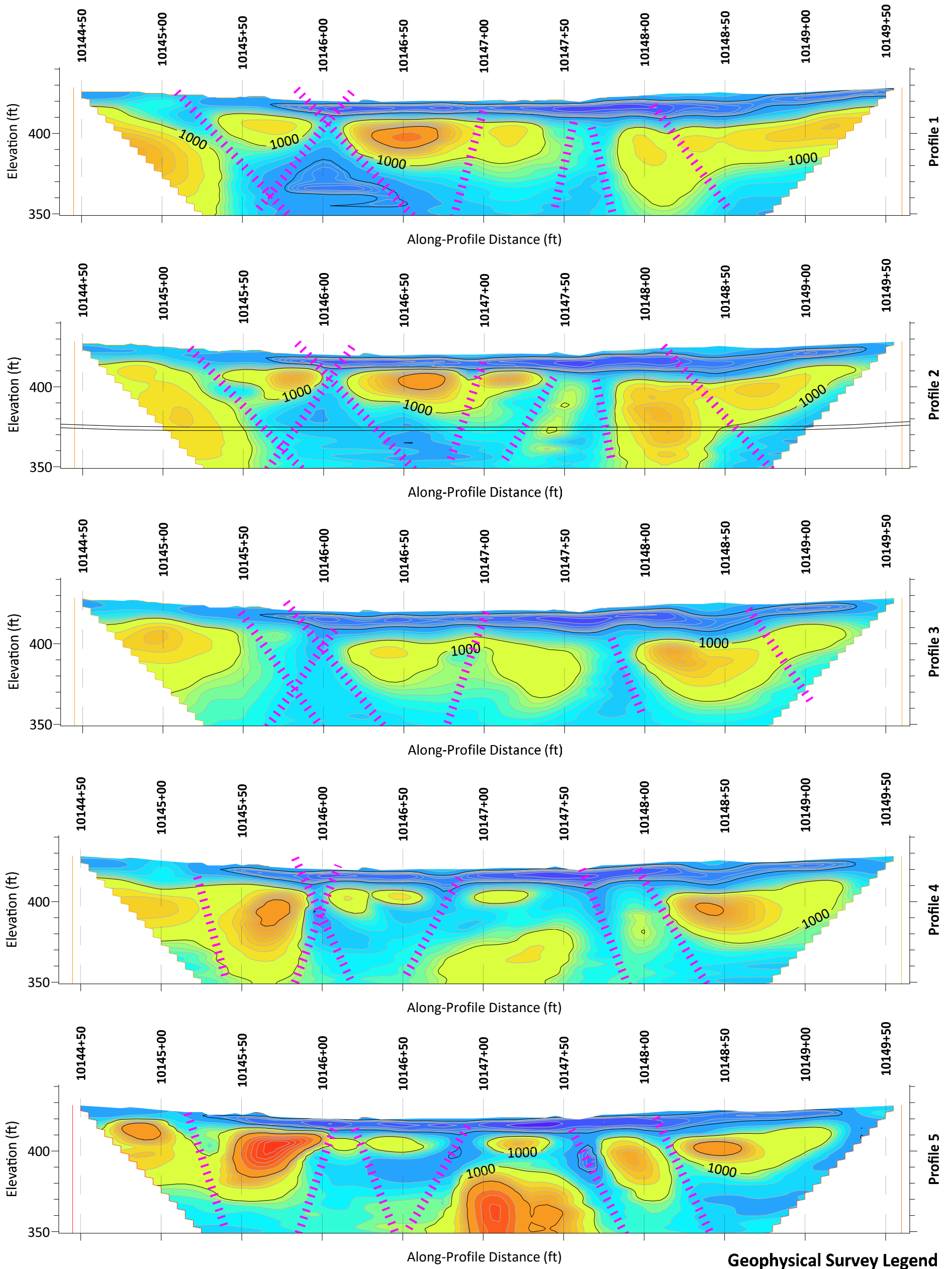
Relative seismic velocity models from SeisImager (by Oyo Corporation) tomographic and ReMi inversions.

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Figure 4: Seismic Survey Results

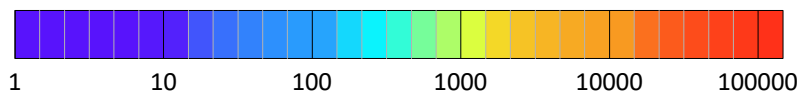
Interstate 81
 S2-0220
 PA-CU-0136.0003-RD-16



Geophysical Survey Legend

- Possible Fracture Zone
- Proposed 16" HDD
- Station Number

Electrical Resistivity (ohm*m)



Notes:
 Resistivity data from AGI Super Sting 112-channels, 5-ft electrode spacing.
 Resistivity models from EarthImager 2D (by AGI Corporation) inversions.

Figure 5: Electrical Resistivity Survey Results
10144+50 to 10149+50

Interstate 81
 S2-0220
 PA-CU-0136.0003-RD-16

MIDDLESEX TOWNSHIP

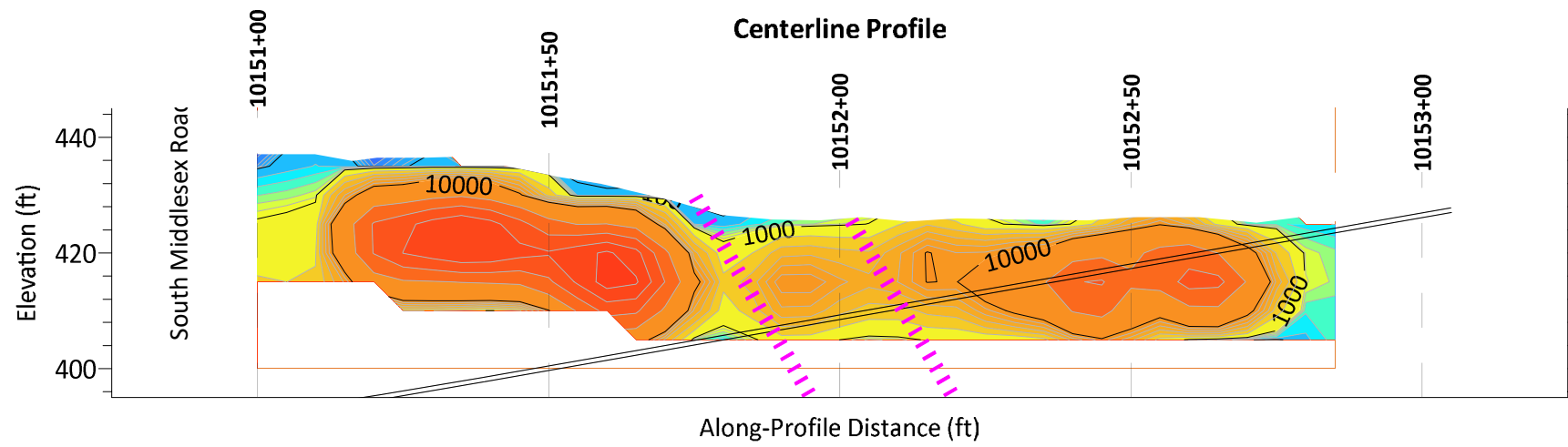
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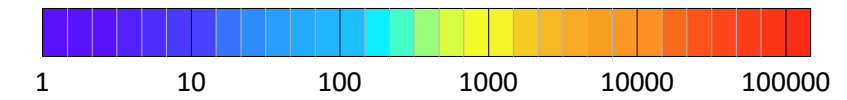
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 DATE: 01/05/2019
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 FIGURE NO. 5 of 7



Geophysical Survey Legend

- Possible Fracture Zone
- Proposed 16" HDD
- Station Number

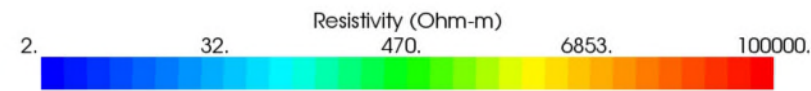
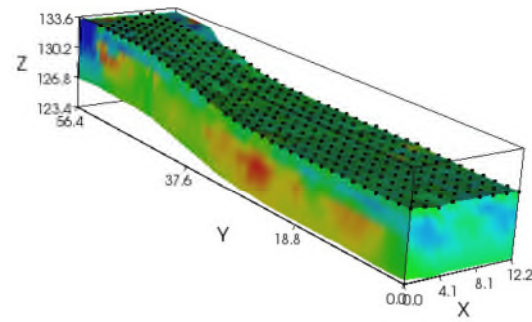
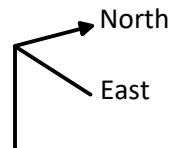
Electrical Resistivity (ohm*m)



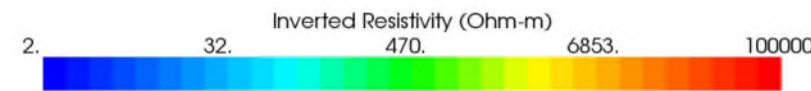
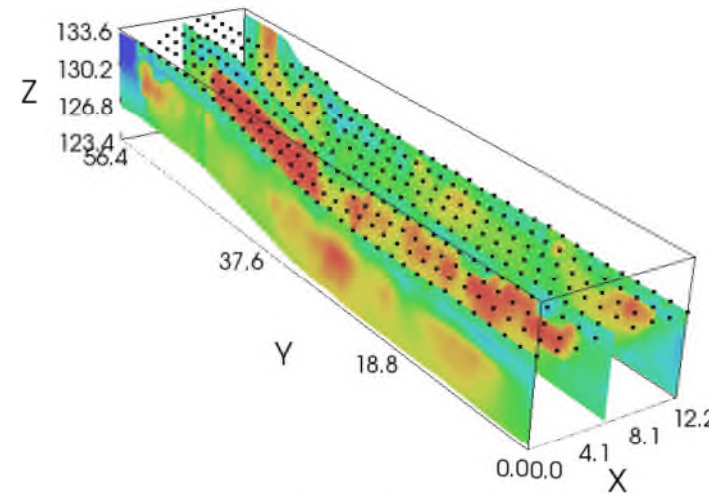
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RETTEW No.:	096302009
REVIEWED BY:	FKB
DRAWN BY:	CHR
DATE:	01/05/2019
SCALE:	NA
FIGURE NO.:	6 of 7

Figure 6: Electrical Resistivity Survey Results
10151+00 to 10153+00
 Interstate 81
 S2-0220
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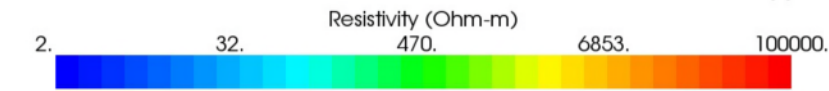
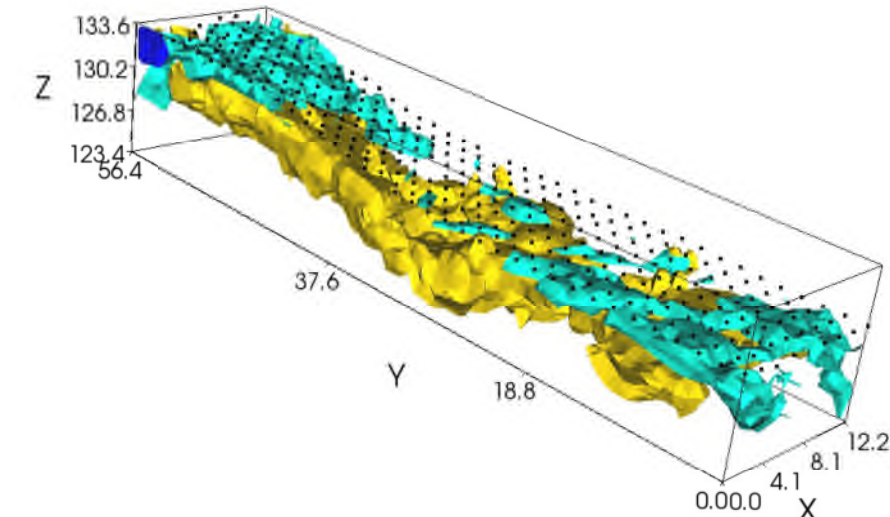
Inverted Resistivity Image



X Slices of Inverted Resistivity



3D Resistivity Contour Plot






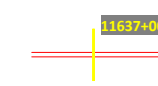

Notes:

Resistivity data from AGI Super Sting 112-channels, 5-ft electrode spacing.

Resistivity models from EarthImager 3D (by AGI Corporation) inversions.



Geophysical Survey Legend

-  Electrical Resistivity Suspected Fracture Zone
-  Microgravity Low-Density Area
-  Seismic Low-Velocity Zone
-  Proposed 16" HDD Product Line with Station Number
-  Geologic Fracture (mapped by others)

Notes:

- Basemap from Google Earth Pro, extracted 11/2018.
- Survey profiles/stations from DGPS survey by RETTEW.
- Geologic information from DCNR WMS Server, extracted 11/2018.

SURVEY DATE: 11/17/2018
 RETTEW No.: 096302009
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 DATE: 01/05/2019
 SCALE: 1" = 80'
 FIGURE NO.: 7 of 7



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Figure 7: Geophysical Results Summary

Interstate 81
 S2-0220
 PA-CU-0136.0003-RD-16

CUMBERLAND COUNTY, PA

MIDDLESEX TOWNSHIP

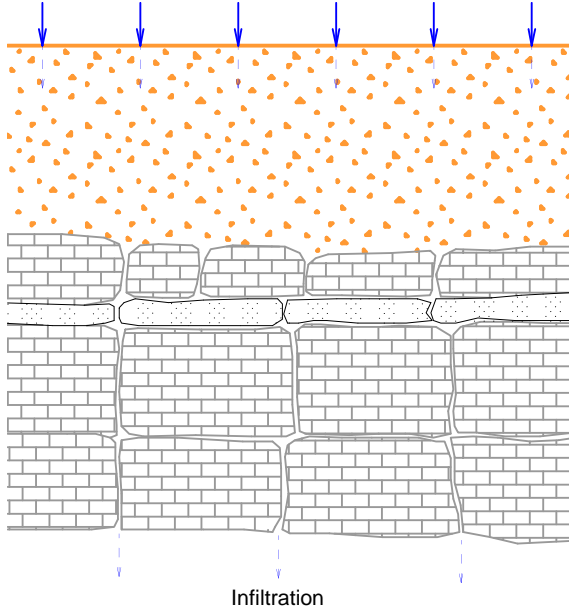
APPENDIX A
Schematic Karst Processes

I

Precipitation

Soil

Carbonate Bedrock



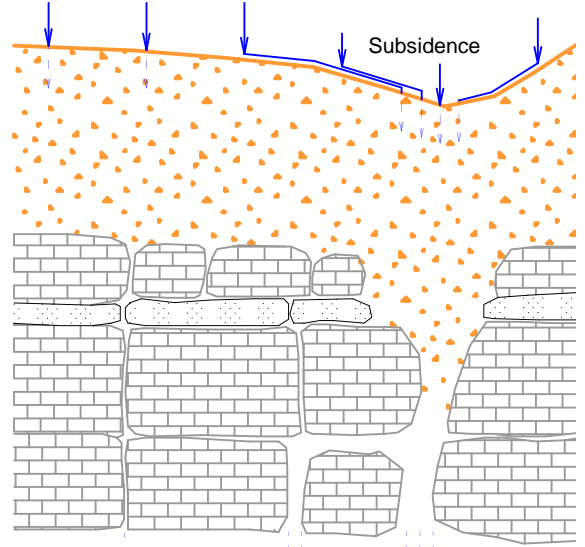
Infiltration

II

Precipitation And Run-Off

Soil

Carbonate Bedrock



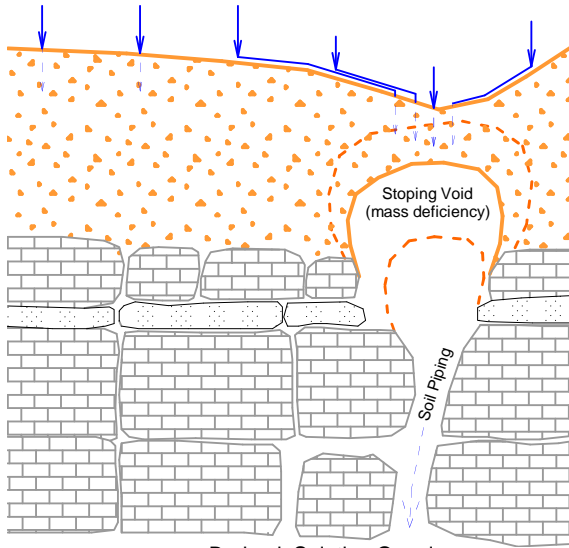
Concentrated Infiltration into and Dissolution of Bedrock Cavities (mass deficiencies)

III

Enhanced Precipitation and Run-Off

Soil

Carbonate Bedrock



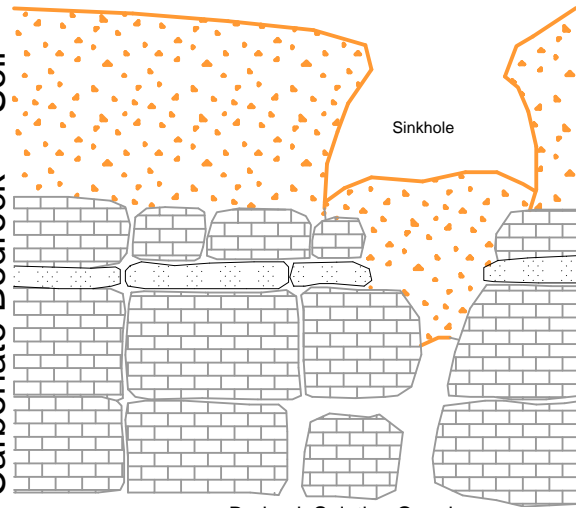
Bedrock Solution Opening (Mass deficiencies)

IV

Soil Arch Collapse

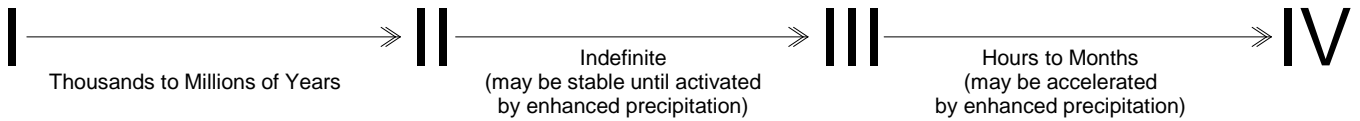
Soil

Carbonate Bedrock



Bedrock Solution Opening (Mass deficiencies)

Typical Time Scale



Schematic Karst Processes

Rev. 02/2018



APPENDIX B
Geophysical Survey Parameters

Geophysical Survey Parameters -- I-81

	Spacing ¹ (feet)	Shot Interval ² (feet)	Offset ³ (feet)	Spread Length ⁴ (feet)	Array Type ⁵	Effective Depth ⁶ (feet)	Lateral Resolution ⁶ (feet)	Vertical Resolution ⁶ (percent)	System
Seismic Refraction	5	40	20	120		24	5	15	Geometrics Geode
Seismic MASW	5	5	20	120		40	5	25	Geometrics Geode
ERI	5		20	280	dipole-dipole	75.6	15	variable	AGI Sting R-8
MicroGravity	5		20			size-depth trade-off	depends on depth	depends on depth	Scintrex CG-5

¹ *geophone, electrode, or station*

² *Seis (27-lb slidehammer source)*

³ *distance between parallel profiles*

⁴ *ERI or Seis*

⁵ *ERI*

⁶ *rule-of-thumb only (most depend on site-specific soil properties, sampling interval, depth, and target dimensions)*

APPENDIX C
Introduction to Seismic Refraction

INTRODUCTION TO SEISMIC REFRACTION

BY TIMOTHY D. BECHTEL, PHD, PG

ENERGY

Mechanical elastic (seismic) waves generated by a hammer blow, weight drop, or explosion.

SENSITIVITY

Sensitive to elastic properties or moduli – generally strongly correlated with density.

BASIC EQUIPMENT

Recording Seismograph (generally 24 or more channels); Geophones (one for each channel); Geophone cable; Hammer or weight plus strike plate or explosives; Trigger switch.

COMMON APPLICATIONS

Determination of the depth and dip of soil horizons and bedrock surfaces. Recent processing advances allow some detection and delineation of discrete targets.

PRINCIPLES

In a uniform isotropic earth, the shock wave from a blow or explosion at the surface travels outward and downward in a hemispherical wave front like a three-dimensional ripple from a pebble in a still pond. At any point on the wave front, a straight line from the shock source to the wave front depicts the path of the seismic wave and is called a ray path (see **Figure SR-1**). In reality, there are several independent shock waves; the fast-moving primary, compressional or P wave front; the slower moving secondary, shear or S wave (both of which form hemispherical wavefronts); and several disk-like wave fronts that travel only along the surface of the earth (called surface waves or ground roll). For the purposes of most seismic refraction surveys, only the fastest moving wave front — the P wave — is considered. S-wave refraction is used in selected circumstances where complete determination of elastic moduli is desired — particularly when it may be desirable to eliminate the effects of water saturation.

In a layered earth, the hemispherical P shock wave defined by the radially distributed P ray paths are deflected according to the laws of optics (Snell's Law) at interfaces between materials with differing seismic velocities (i.e. densities or elastic properties). Figure SR-2 depicts the deflection of ray paths due to an increase in P velocity at a bedding plane. The type of deflection that a ray path will undergo is dependent upon the angle at which it strikes the interface, and falls into one of four categories:

Some direct rays (green in **Figures SR-2** and **SR-3**) travel parallel to the ground surface at the seismic velocity of the upper layer, do not strike the underlying interface, and consequently are not deflected.

Reflected rays (purple in **Figures SR-2** and **SR-3**) arise where direct rays strike the interface, and a portion of the energy is reflected symmetrically back towards the surface.



The portion of the energy of the incident direct wave that is not reflected upward is refracted or bent as it crosses the interface – making refracted waves in the lower layer (red in **Figures SR-2** and **SR-3**).

At a precise angle called the critical angle, the incident ray is refracted directly along the interface, and travels at the higher seismic velocity of the lower layer (see Critically Refracted Wave in **Figure SR-3**). As this critically refracted or head wave races along beneath the interface, it generates a secondary elastic disturbance that travels back to the surface along ray paths that define a wave front analogous to the bow wake of a ship. These returning rays again travel at the slower velocity of the upper layer.

To perform a refraction survey, a linear array of ground motion sensors or geophones is spaced out from the seismic source or shot point, forming a geophone spread. Each geophone is connected to a separate channel in a seismograph which records a wiggle trace representing the ground motion resulting from the passage of the various seismic rays.

As depicted in the time-distance (T-X) curve in **Figure SR-4**, the layered earth structure can be determined by analyzing the seismographic wiggle traces. At distances close to the seismic source, the first wiggle or ground motion (the first arrival after the shot) is due to passage of the direct wave travelling at the velocity of the upper layer. Reflected waves arrive later since they have by definition traveled a greater distance at the same velocity (additional later wiggles are caused by passage of the more slowly travelling S and surface waves). Beyond a distance dictated by the critical angle, the first arrival of seismic energy represents the head wave of the critically refracted ray. These refracted rays also by definition travel a greater distance than the direct wave. However, along part of their path, they have traveled at the higher velocity of the underlying more consolidated layer. At greater distances from the shot point, where the path length in the higher velocity layer becomes significant, the head wave arrivals actually race past the direct wave and become the first arrival (see labeled crossover in **Figure SR-4**). By extension, it can be shown that if a third layer with even greater velocity lies at greater depth, the head wave from this layer will become the first arrival at a sufficient distance from the shot point.

In conventional seismic refraction, only the first P wave arrivals can be reliably selected on a wiggle trace record. The later reflected P wave arrivals are generally obscured by the slower-travelling S and surface waves, and the very slow air blast or sound wave from the shot. To interpret a seismic refraction record, the first arrival travel times are measured for each wiggle trace and plotted at the appropriate point on a time-distance (T-X) curve (see **Figure SR-4**). In a plane-layered earth, these first arrivals define a series of line segments, each representing a discrete layer. The seismic velocity of each layer is simply the reciprocal of the slope of the associated line segment. The thickness of each layer can be calculated from the distances where the line segments intersect. The mathematics for these calculations are easily derived, and can be found in any introductory geophysics text.

True geologic strata are rarely perfectly horizontal. The effect of a dipping interface on a travel time curve cannot be recognized using a single shot point. Calculations based on a T-X curve from a single shot point should always be considered as producing apparent depths to interfaces and apparent seismic velocities for all but the uppermost layer. To determine the true depths and dips of interfaces and the true seismic velocities, it is necessary to reverse the seismic line; that is, move the shot point to a location at or beyond the farthest geophone in the spread, and repeat the shot. The calculation of true depths, dips and velocities from reversed seismic lines is also readily performed.

CAPABILITIES

Conventional seismic refraction can yield accurate measurements of depths and attitudes of soil horizons, groundwater tables, and other relatively distinct and planar strata. Modern computer analysis of multi-fold seismic refraction data (i.e. with many and overlapping shot points) can provide delineation of undulating or even irregular (as opposed to simply planar) interfaces. The latest generation of computer processing techniques require very high-fold data, but in favorable conditions, are capable of resolving even discrete targets such as foundation elements, tunnels or cavities, and can resolve gradational boundaries as well as distinct interfaces. The seismic P-wave velocities of materials are generally an indication of relative density or compaction. S-wave refraction data (collected using specialized geophones, shock sources and field procedures) can provide S-wave velocities that bear a well-constrained empirical relationship to standard penetration test (SPT) N values and therefore bearing capacity. For surveys where matching P- and S-wave velocities are determined, the dynamic elastic moduli of subsurface materials can be calculated (including Poisson's Ratio, Young's or Bulk Modulus, and Shear Modulus or Rigidity).

LIMITATIONS

Seismic data is collected at spaced geophones, and therefore does not provide continuous profile data. If geophones are spaced too widely, thin layers can be missed entirely.

Conventional refraction interpretations are only accurate where the velocity of strata increase with depth. Velocity inversions not only alter the data, but are particularly insidious since the presence of a low velocity zone at depth is not apparent in first arrival data. The latest generation of computer processing techniques do allow detection and delineation of laterally restricted low velocity zones (e.g. tunnels, cavities, gravel lenses, etc.).

Sharp or dramatic interface relief such as limestone pinnacles cannot always be resolved even with very tight geophone spacing. Therefore, refraction profiles of expectedly irregular interfaces should be assumed to represent somewhat smoothed versions of actual relief (see e.g. Figure SR-5).

Seismic records can contain noise due to heavy machinery vibrations, vehicular traffic, and sometimes even wind or distant earthquakes. Care must be taken to identify potential sources of seismic noise prior to beginning a survey.

The effective survey depth is limited to approximately 1/5 of the greatest shotpoint to geophone distance. Therefore, very deep surveys may require impractically long lines (requiring consideration of other geophysical techniques such as seismic reflection).

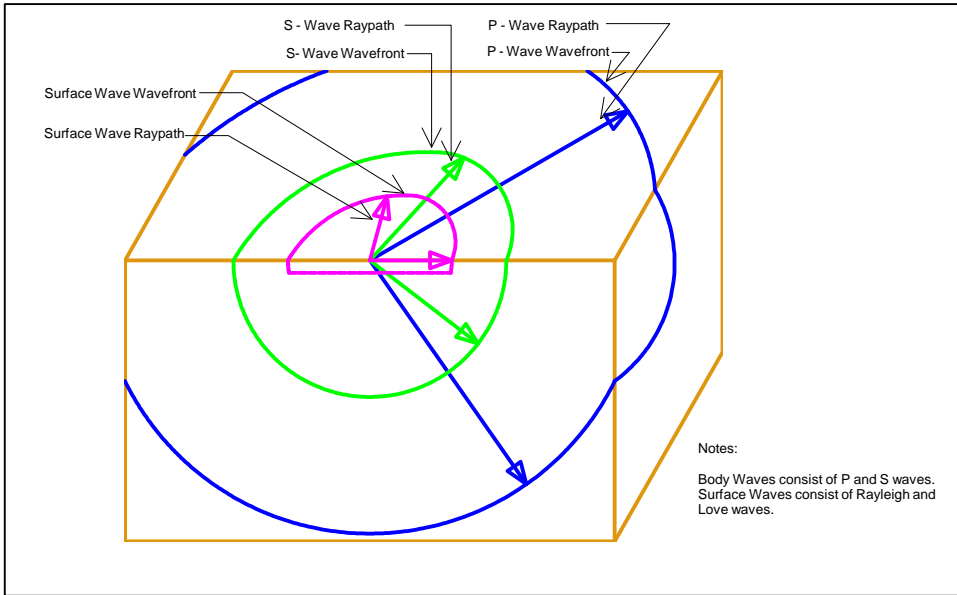


Figure SR-1

Seismic Wave Types

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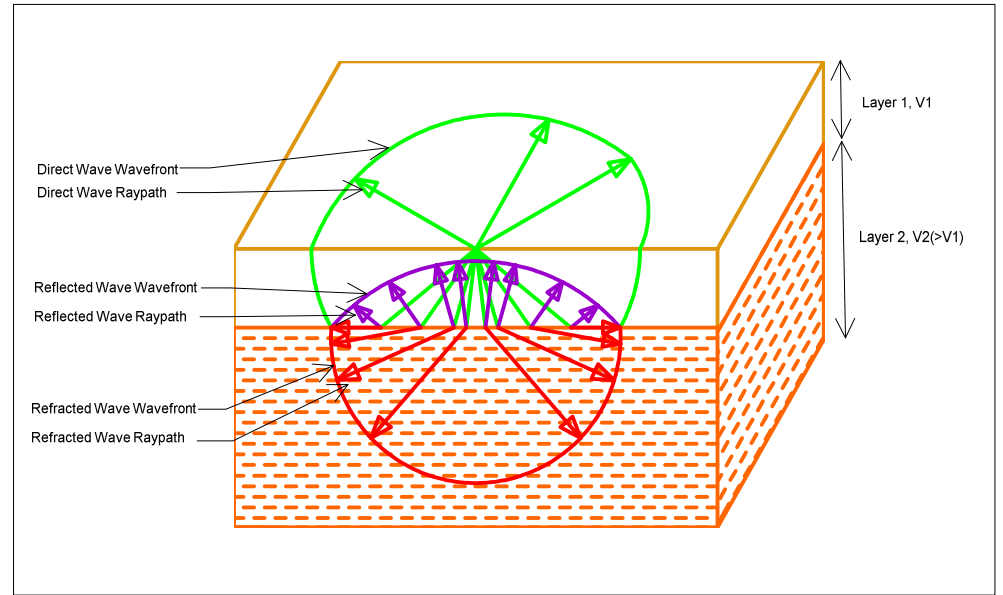


Figure SR-2

Effect of Layering
on Body Wave Raypath

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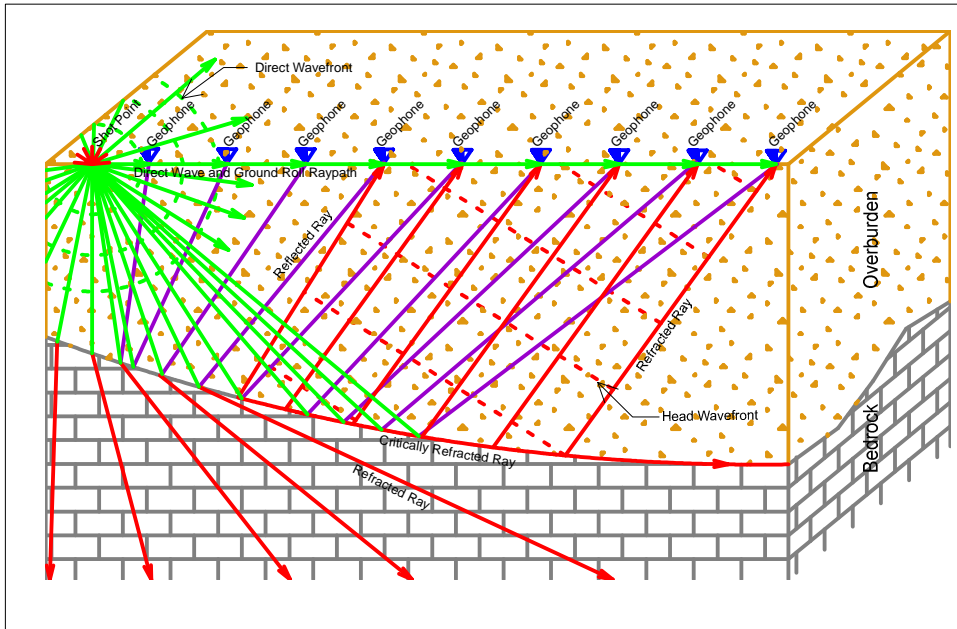


Figure SR-3

Seismic Ray Path Geometry

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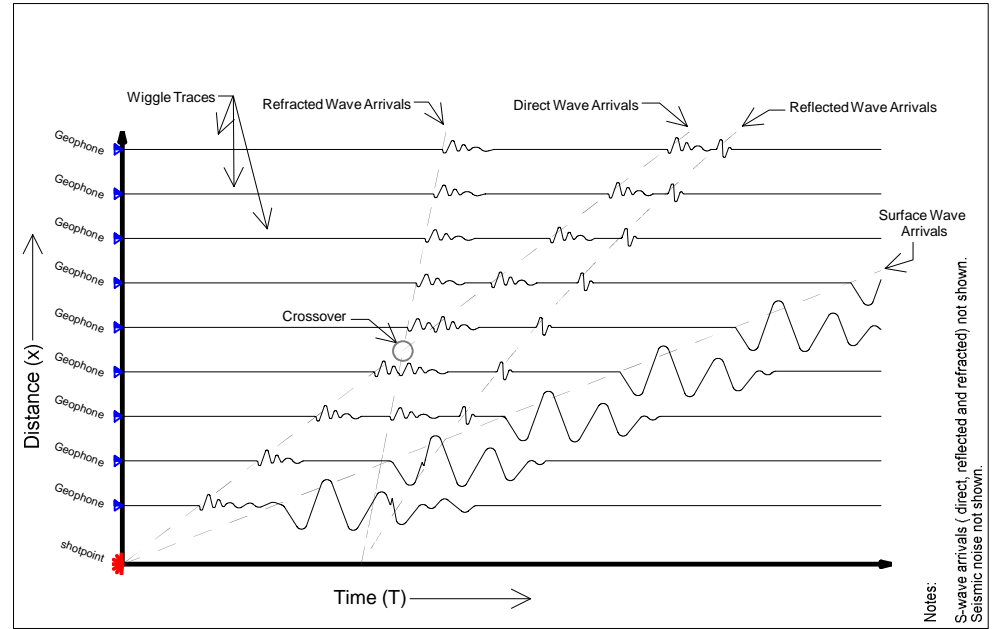


Figure SR-4

Idealized
Seismic Record
and T- X Graph

Rev. 04/2018



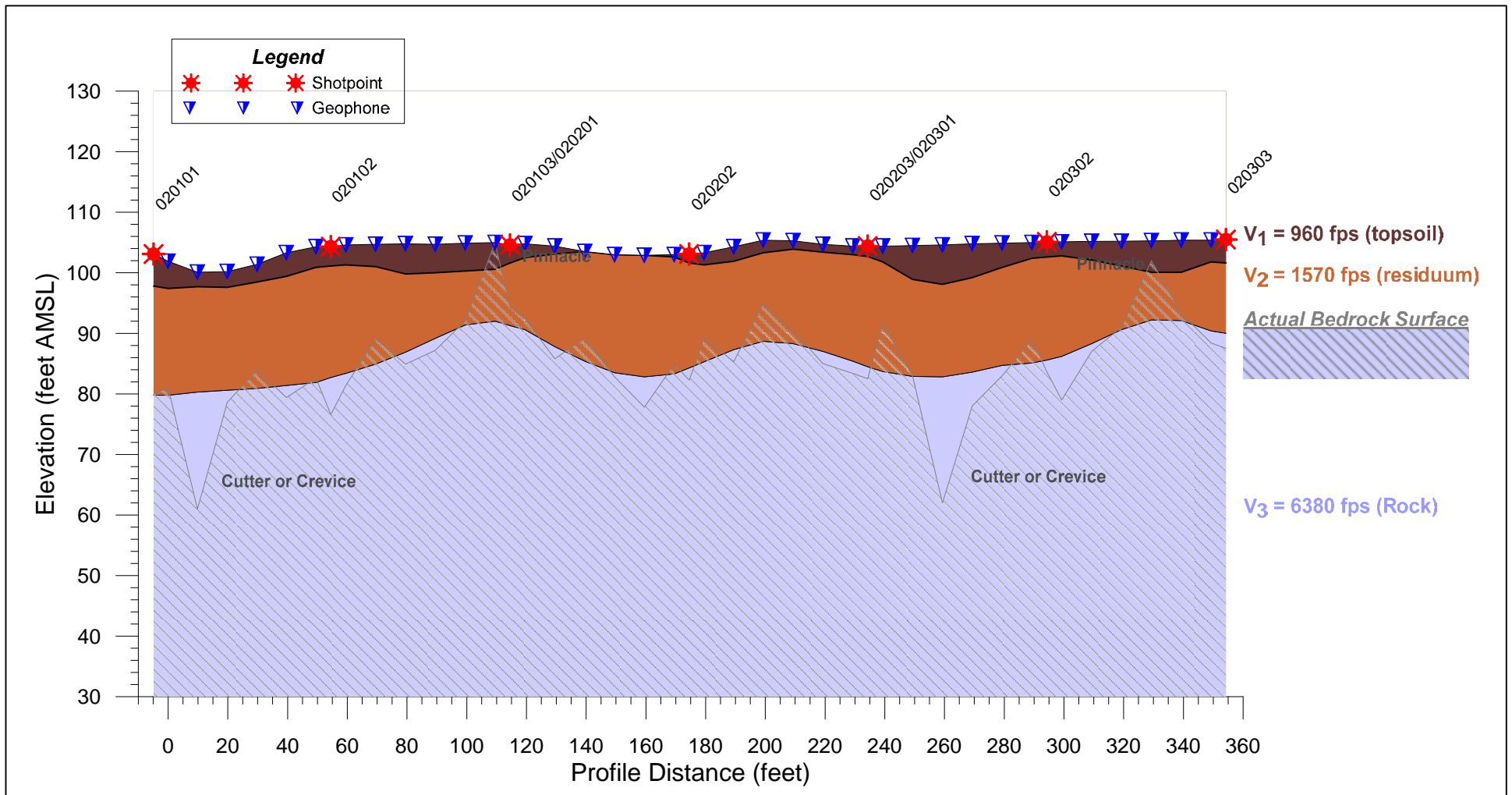


Figure SR-5

Example Karst Terrane Seismic Profile

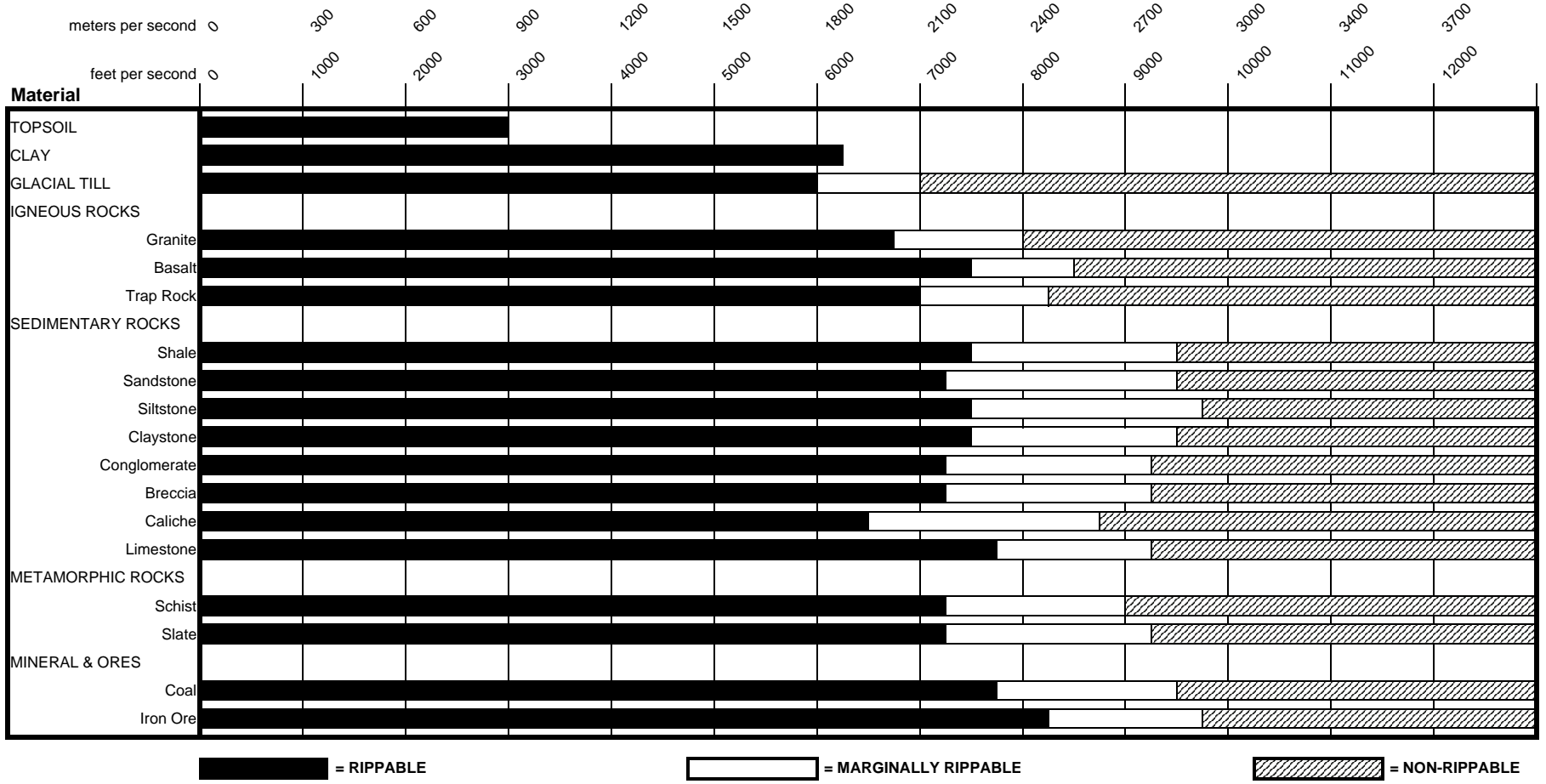
Revised 04/2018



APPENDIX D
Caterpillar Ripping Charts

Ripping Chart *
D9R
 Multi or Single Shank No. 9 Ripper
 Estimated by Seismic P-Wave Velocities

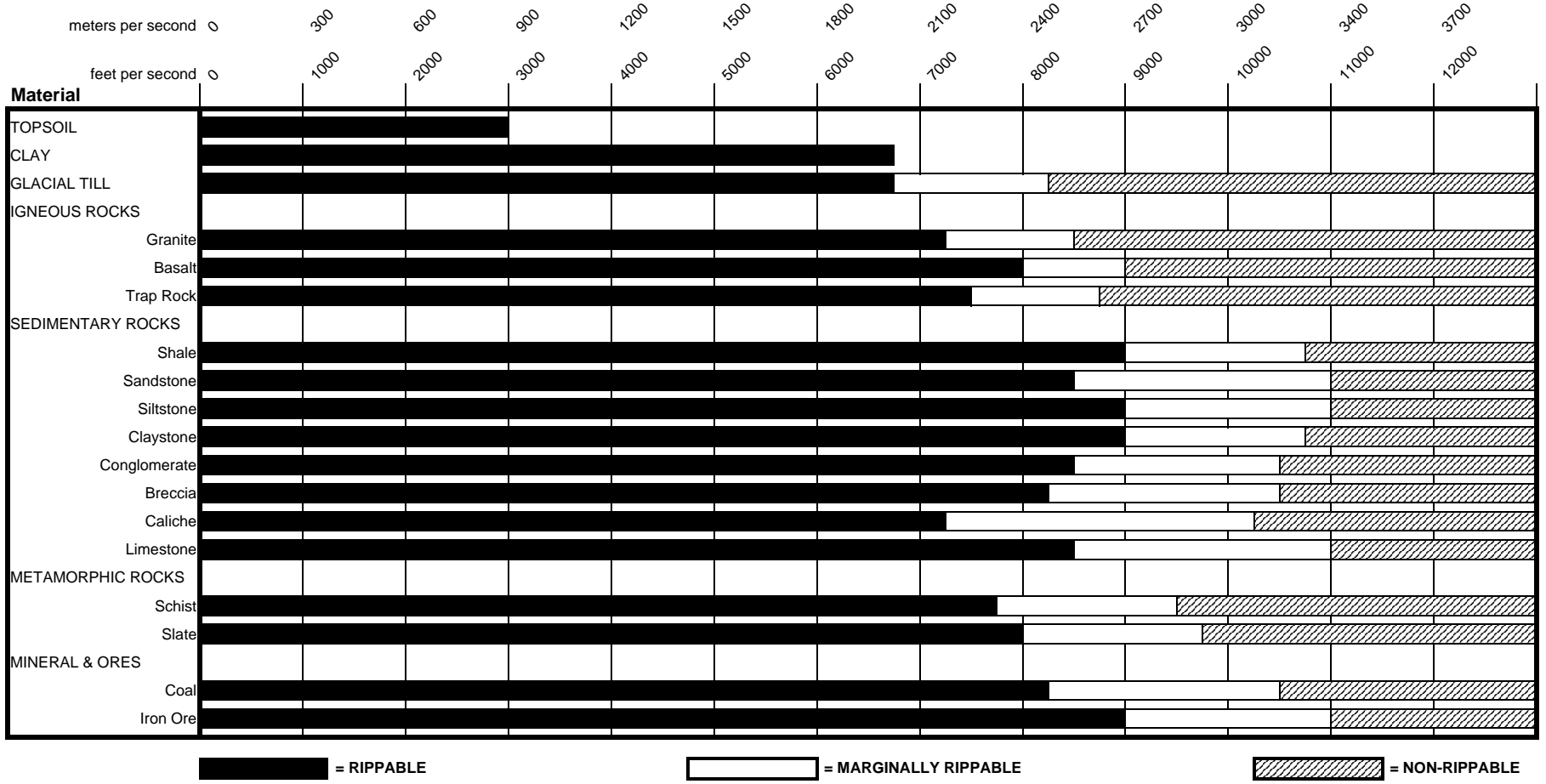
Seismic Velocity



* Caterpillar Performance Handbook, Edition 26, Caterpillar, Inc., Peoria, Illinois

Ripping Chart *
D10N
 Multi or Single Shank No. 10 Ripper
 Estimated by Seismic P-Wave Velocities

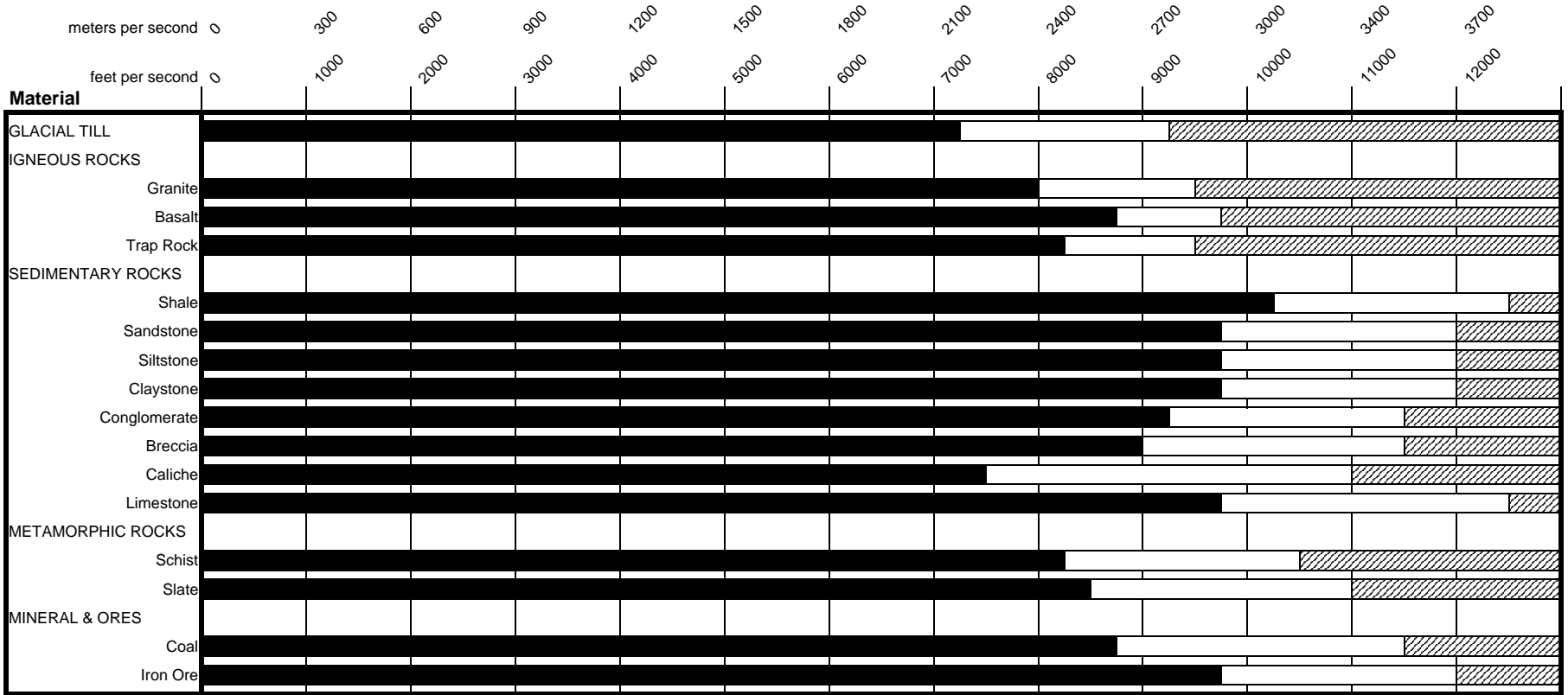
Seismic Velocity



* Caterpillar Performance Handbook, Edition 26, Caterpillar, Inc., Peoria, Illinois

Ripping Chart *
D11N
Multi or Single Shank No. 11 Ripper
Estimated by Seismic P-Wave Velocities

Seismic Velocity



= RIPPABLE

= MARGINALLY RIPPABLE

= NON-RIPPABLE

* Caterpillar Performance Handbook, Edition 26, Caterpillar, Inc., Peoria, Illinois