"Can Geophysics and Nondestructive Evaluation (NDE) Help the Geotechnical Engineer or Geoscientist?"

Larry Olson, PE
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September 23, 2025

Midwest Geotechnical Conference

OLSON ENGINEERING, Inc.

Corporate History

Olson Engineering founded in 1985

- Imaging Infrastructure for Assessment, Monitoring and Repair with NDE and Geophysics

Olson Instruments began in 1993

- NDE Instruments for testing concrete, asphalt, masonry and wood materials of structures, pavements and foundations

Wheat Ridge, Colorado (Denver)
Branch - Rockville, Maryland (Washington, DC) –

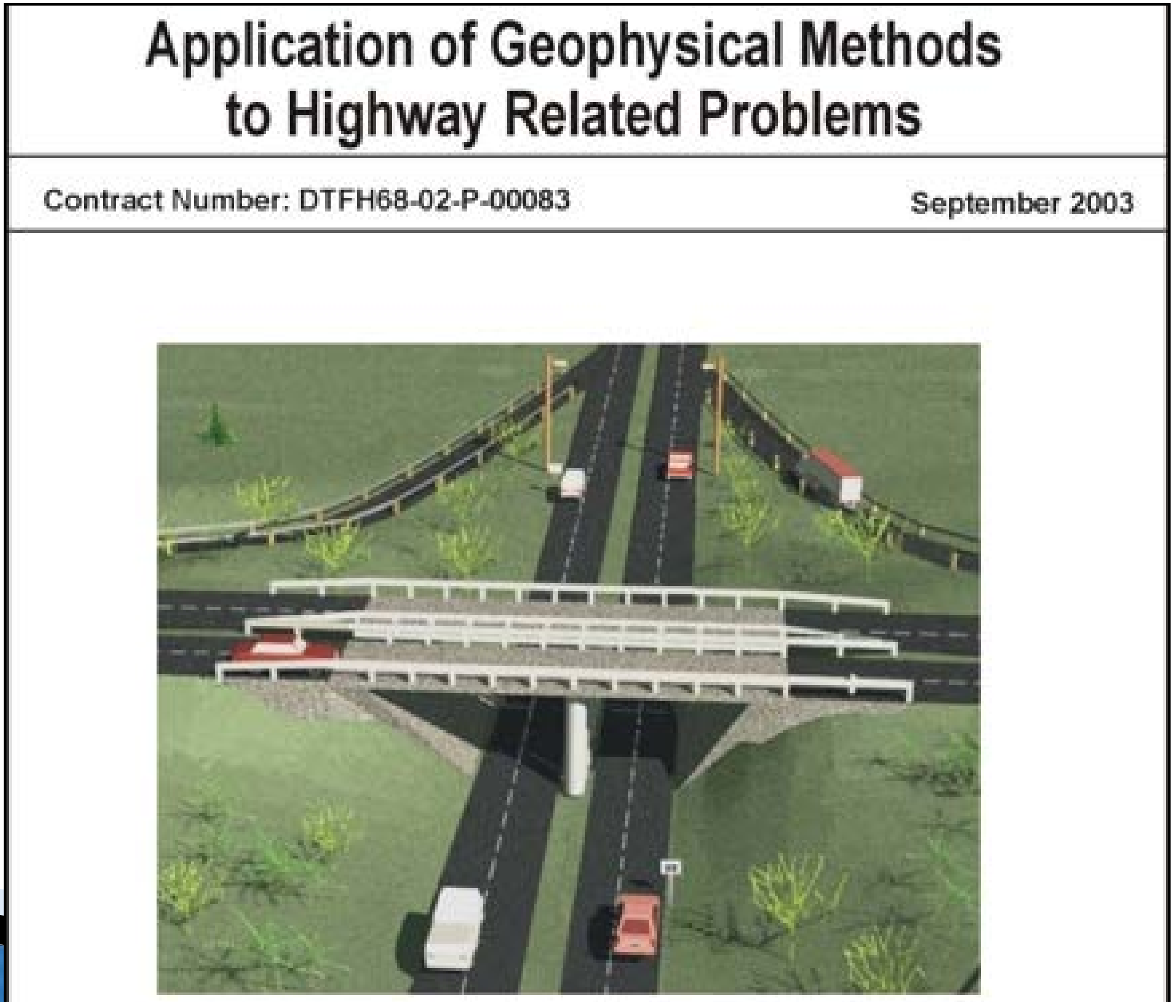
➢ Registered PE's in 30+ states including IN, MI, MN and WI

OLSON ENGINEERING, Inc.

Consulting Services for Bridges, Buildings, Dams, Foundations, Tunnels, Pavements and Imaging Subsurface Conditions

- **NDE Condition Assessment for Structural Integrity and Foundations**
- **Geophysics for Engineering, Environmental, Groundwater & Mining**
- Load Tests/Structural Health Monitoring
- Vibration Monitoring
- Applied Research and Development (instruments and services)
- Training/Seminars – 3-Day Olson Instruments Class each year (NDE & GP)
  - ASCE Structural Condition Assessment of Existing Structures
  - ASCE Bridge Condition Assessment and Performance Monitoring
  - ASCE Course to CADWR on Concrete Dam Inspection and Repair
  - ASCE Course on Concrete Dam Assessment with NDE and Geophysics for Embankment Dams

FHWA Manual:
“Application of Geophysical Methods to Highway Related Problems”


Application of Geophysical Methods to Highway Related Problems

Contract Number: DTFH68-02-P-00083 September 2003

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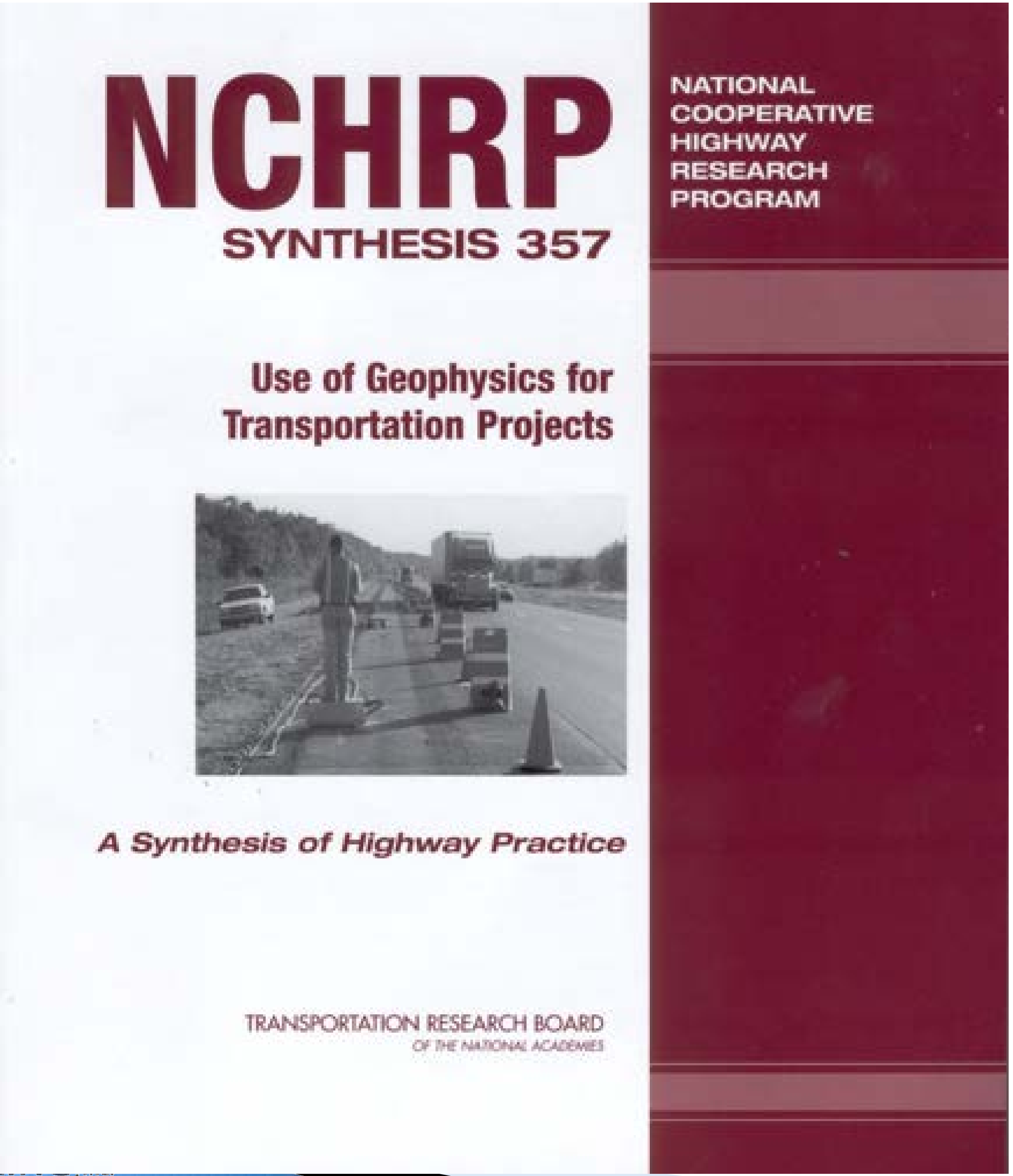

2005 NAS SYNTHESIS STUDY → TRB, NCHRP, FHWA & DOT's

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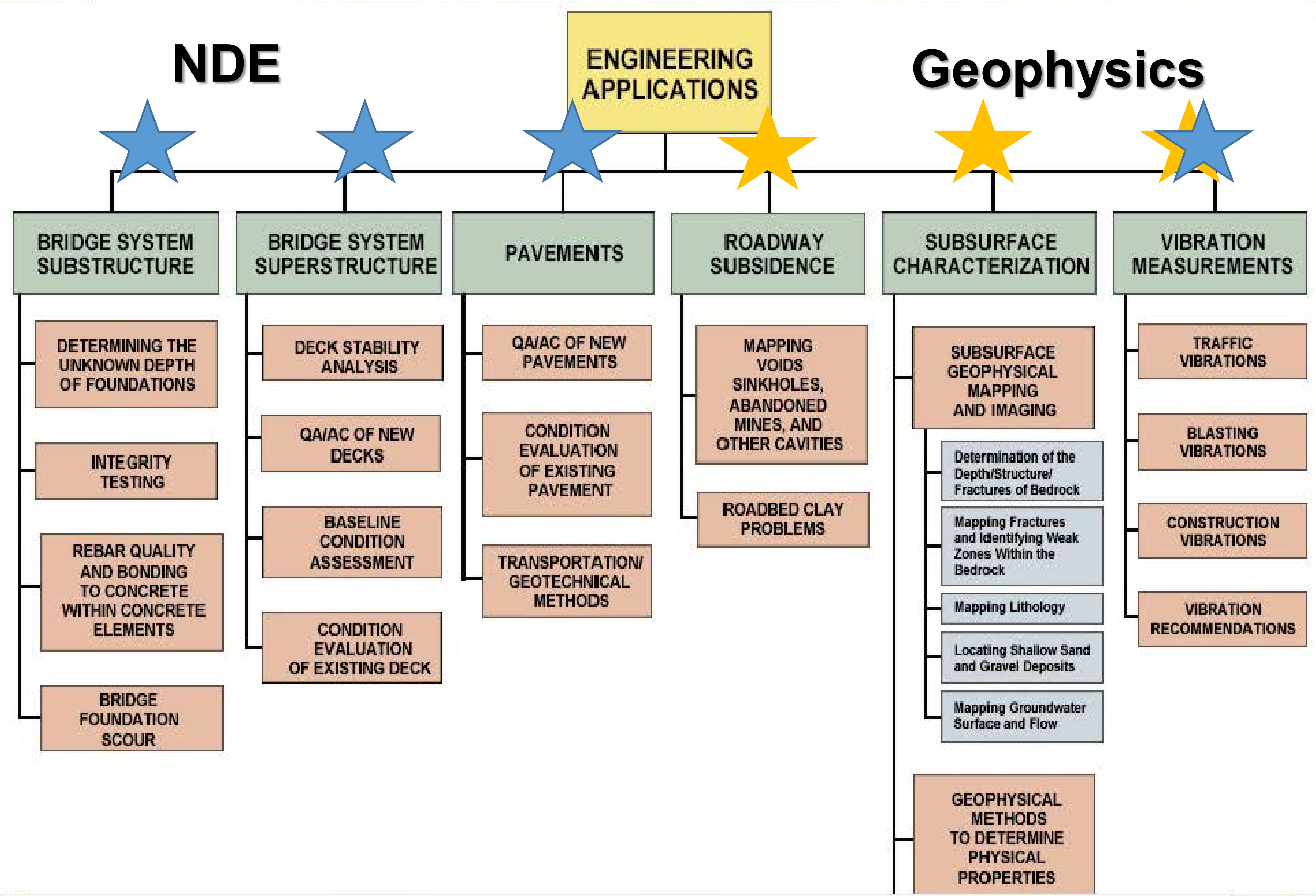

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GEOPHYSICS IS:

THE MEASUREMENT OF *CONTRASTS* IN PHYSICAL PROPERTIES…

Physical, electrical, mechanical or chemical ***contrasts*** in the soil, rock, ground water / or pore 'fluids'!

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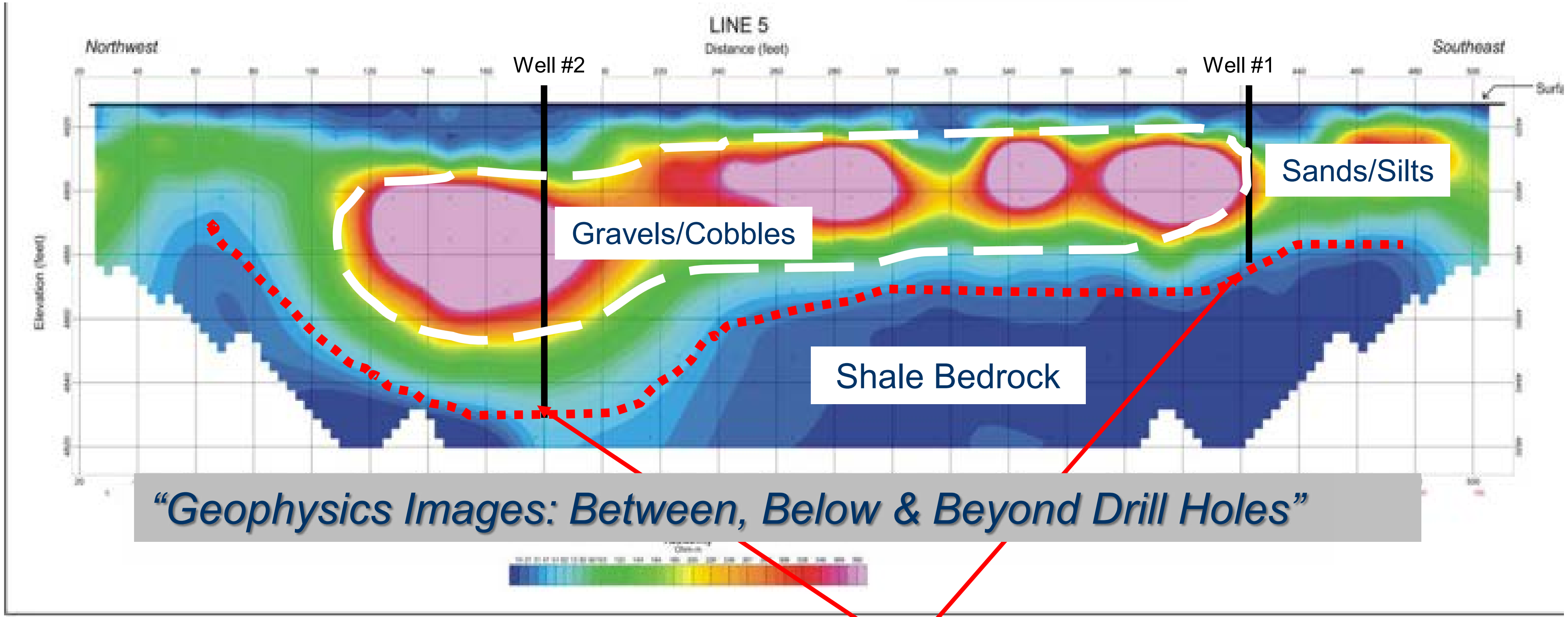
Geophysics vs. NDE

- GEOPHYSICS: Images the subsurface
- NDE: Non-Destructive Evaluation Images man-made structures

"Geophysics Detects: Physical Properties … Not The Geology"

e.g., Electrical Resistivity Images map **contrasts** in the materials



"Geophysics Images: Between, Below & Beyond Drill Holes"

Borings map the geology!!

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ADVANTAGES OF GEOPHYSICS

- Fast and continuous data acquisition
- Better coverage versus a point measurement(s)
- Site accessibility (*i.e., remote, difficult, etc.*)
- ‘**Anomalies**’ detected
- Environmentally and archeologically sensitive
- Non-intrusive (*i.e., safer on an embankment*)
- Cost effective (*e.g., optimize drilling programs*)
- 1D, 2D and 3D data acquisition and visualization
- 4D (time-lapse) acquisition

When to Use Geophysics and which method?

- **Seismic Velocities and Moduli for Earthquake Design of Bridges**
  - Multi-channel Analysis of Surface Waves (MASW)
  - Seismic Refraction Tomography (SRT)
  - Crosshole/Downhole Seismic (CS/DS)

- **Voids below pavements, Sinkholes, Abandoned Mines, Karst**
  - **Ground Penetrating Radar (GPR)**
  - **Electrical Resistivity Imaging Tomography (ERT)**
  - **Crosshole Seismic Tomography**

- **Mechanically Stabilize Earth (MSE) Walls for Corrosion Risk and Remaining Service Live**
  - **Electrical Resistivity Imaging Tomography (ERT)**

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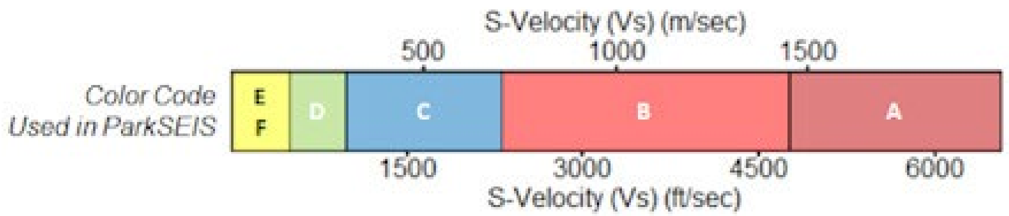
Why Seismic?

- Vs30 or Vs100 site classification (NEHRP) and for building and bridge seismic design in general
- Building code compliance (IBC)
- Low-strain dynamic moduli for construction planning
- Liquefaction risk for embankment dams or foundations
- Rippability of material for surficial excavation and cost estimates

Seismic Site Classification ($Vs^{30\text{-}m}$ or $Vs^{100\text{-}ft}$)



NEHRP* Seismic site classification based on shear-velocity (Vs) ranges.

Site Class	S-Velocity (Vs) (ft/sec)	S-Velocity (Vs) (m/sec)
A (Hard Rock)	> 5,000	> 1500
B (Rock)	2,500 – 5000	760 – 1500
C (Very Dense Soil and Soft Rock)	1,200 – 2,500	360 – 760
D (Stiff Soil)	600 – 1,200	180 – 360
E (Soft Clay Soil)	< 600	< 180
F (Soils Requiring Add'l Response)	< 600, and meeting some additional conditions.	< 180, and meeting some additional conditions.

* National Earthquake Hazard Reduction Program (www.nehrp.gov)

SEISMIC METHODS:

Seismic:

- Body Wave Methods
- Surface Wave Methods

Stress Wave Basics - Elastic Moduli

$$G = \rho V_S^2$$

$$M = \rho V_P^2$$

$$\nu = [0.5(\frac{V_P}{V_S})^2 - 1]/[(\frac{V_P}{V_S})^2 - 1]$$

$$E = 2G(1+\nu)$$

G = Shear Modulus
M = Constrained Modulus
ρ = Mass Density (unit weight/gravity)
V_s = Shear Wave Velocity
V_p = Compressional Wave Velocity
ν = Poisson's Ratio
E = Young's Modulus

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Typically obtained through geotechnical sampling:
ρ = Mass Density (unit weight/gravity)

Typically obtained through geophysical investigations:
V_s = Shear Wave Velocity
V_p = Compressional Wave Velocity

Basic Concepts

Body Waves ***versus*** Surface Waves

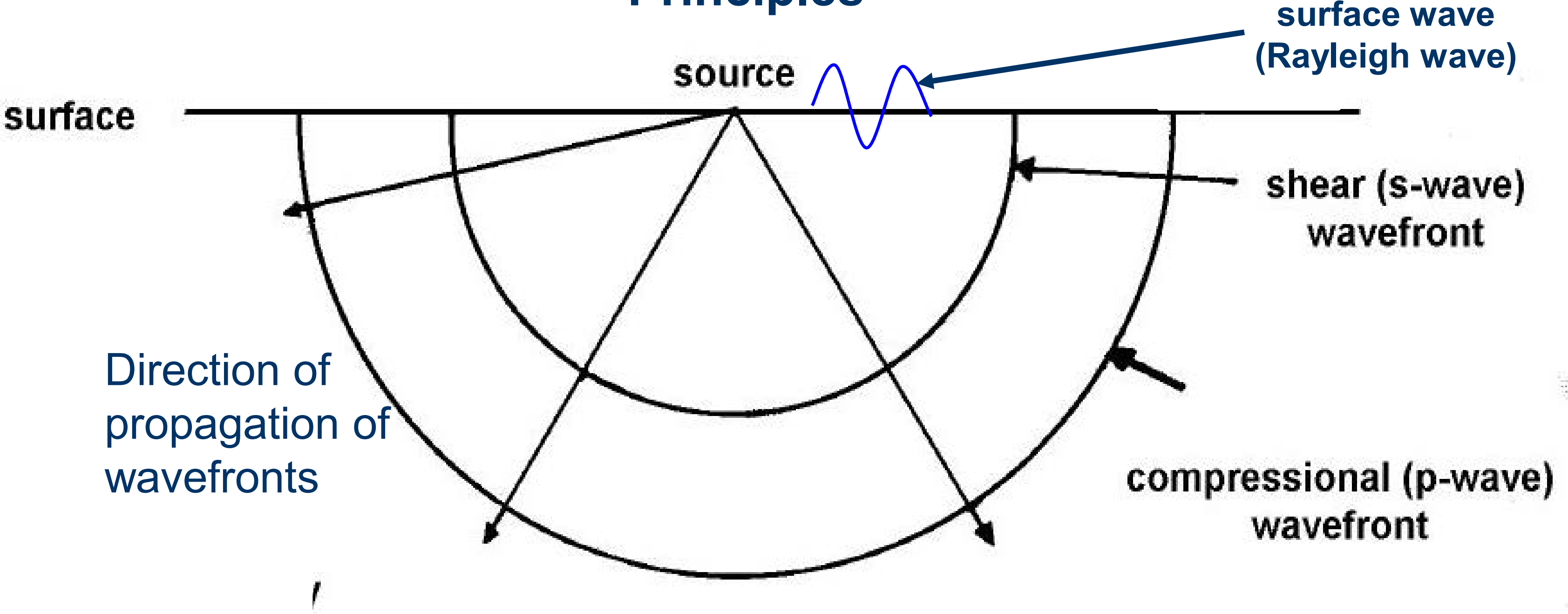
Body Waves:
- Compressional Waves (P)
- Shear Waves (S)

Surface Waves:
- Rayleigh Waves
- Love Waves

http://www.geo.mtu.edu/UPSeis/waves.html

Basic Concepts

Principles

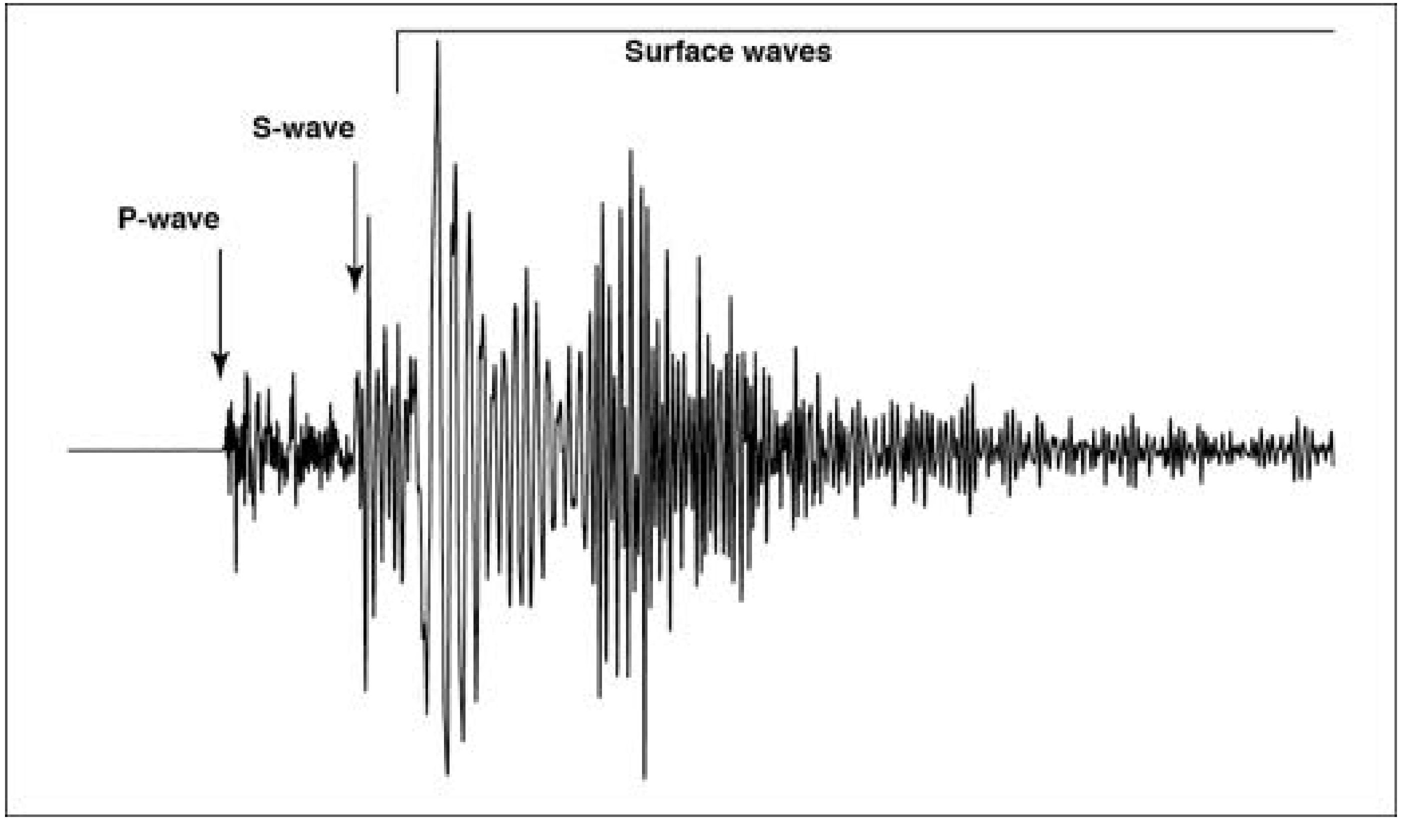


P-Waves are related to density - bulk modulus (fast)

S-Waves are related to stiffness - shear modulus (slow)
--- ***not*** affected by pore-fluids ---

Surface-Waves are *related* to the shear wave velocity (slowest)

Basic Concepts



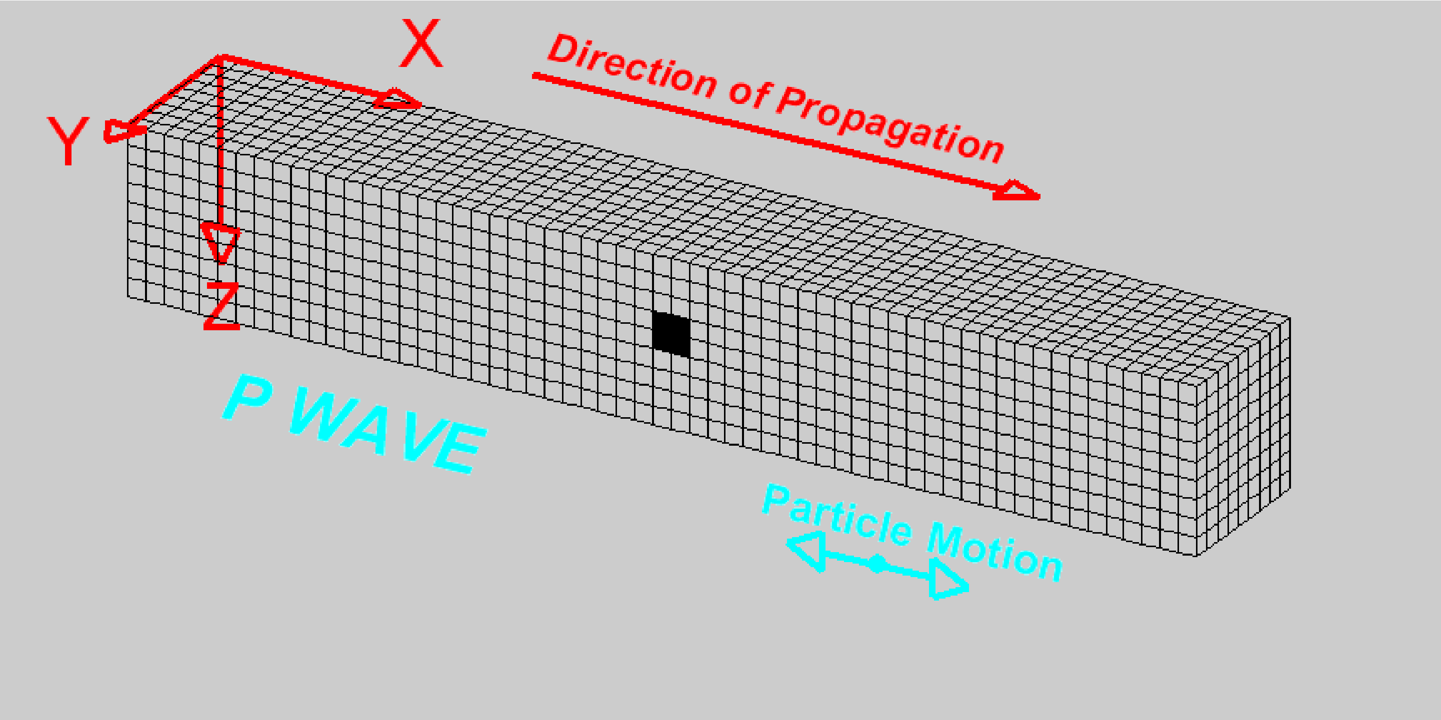
http://www.geo.mtu.edu/UPSeis/waves.html

Basic Concepts

Body Waves

Compressional Wave
Primary Wave
P-wave
Fastest wave velocity, V_P
> Particle motion is longitudinal, compressions and rarefactions in the direction of wave propagation.

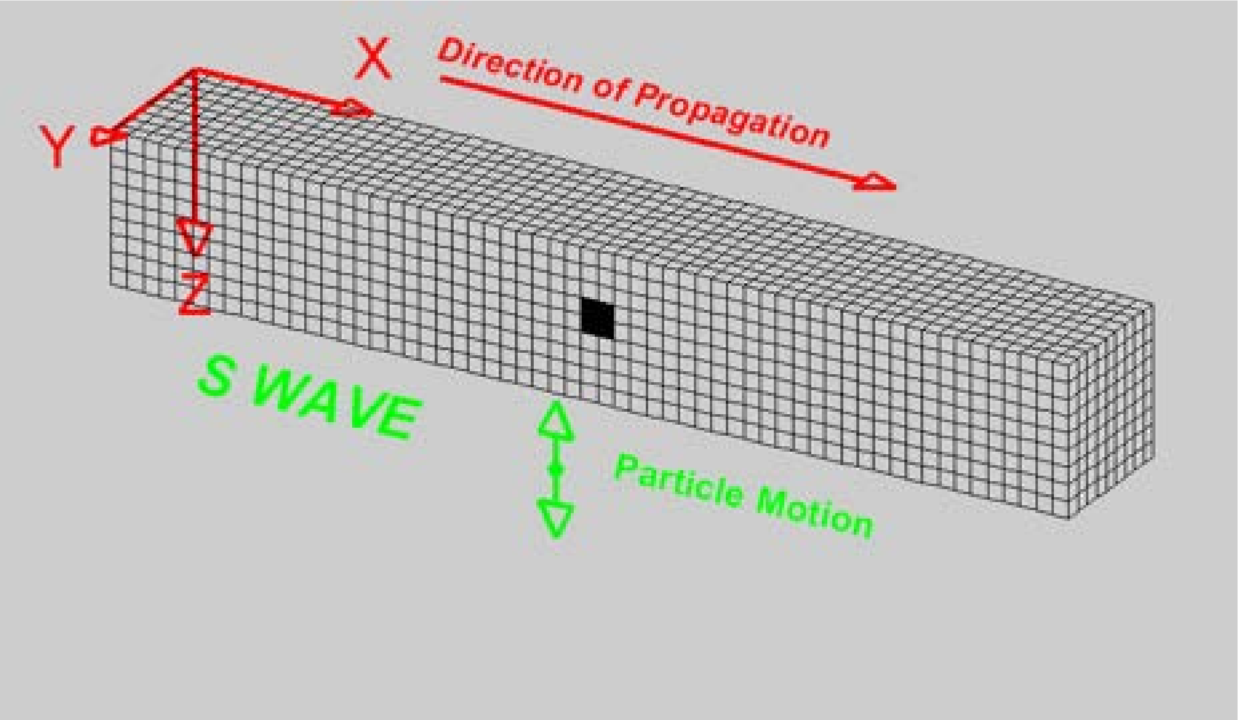
Often referred to as acoustic imaging



Basic Concepts

Body Waves

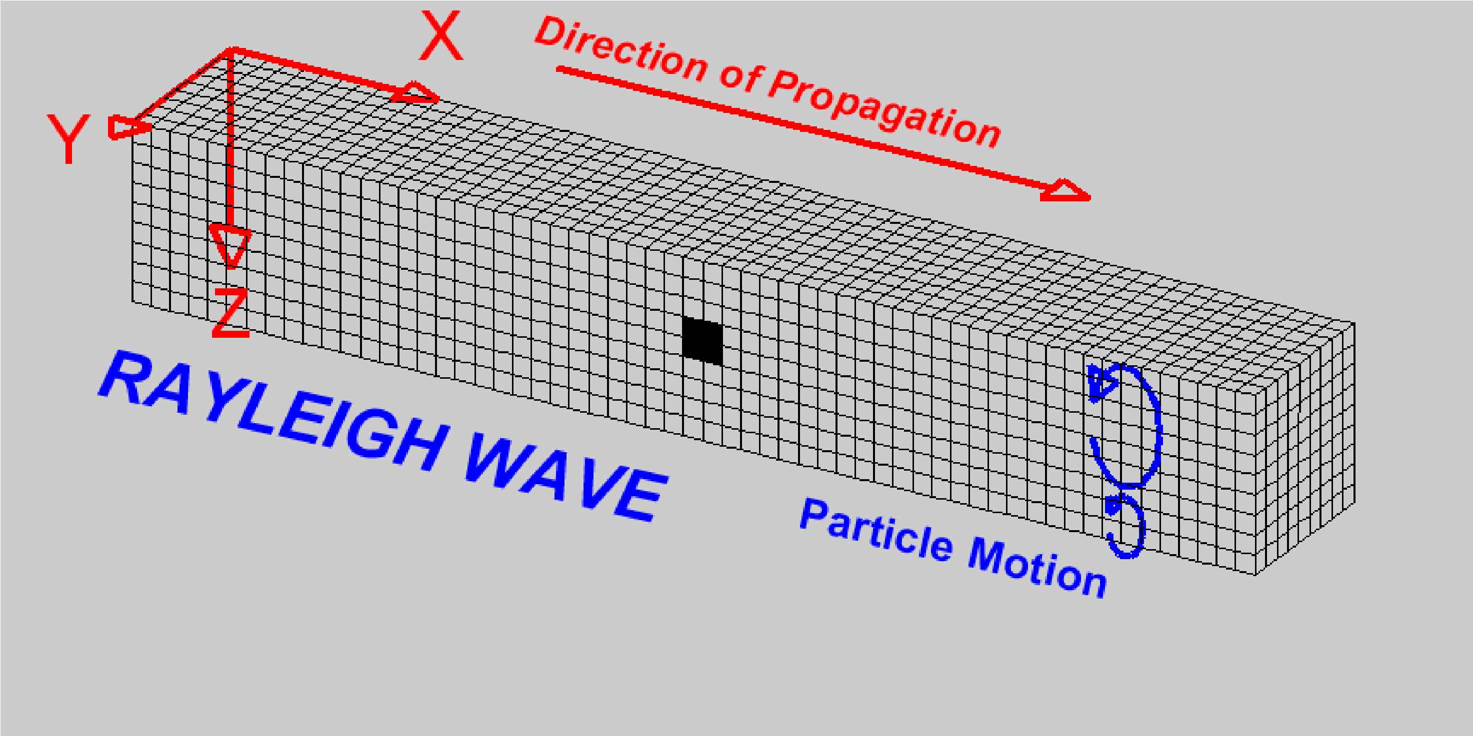
Shear Wave
Secondary Wave
S-wave
V_S
> Particle motion is transverse, polarized in either direction* to the direction of wave propagation (*SV & SH waves).



Basic Concepts

Surface Waves

Rayleigh Wave or Surface Wave "*Ground Roll*"
R-Wave
V_R
> Particle motion is elliptic and retrograde to the direction of wave propagation.



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SEISMIC METHODS:

- **Borehole Methods**
- Body Wave Methods
- Surface Wave Methods

Borehole Seismic Methods

- Crosshole Seismic Technique (1970’s)
- Downhole Seismic Technique/Seismic Cone (1960’s)
- Oyo PS Suspension Logging (1990’s)

*Slide courtesy of **GEOVision***

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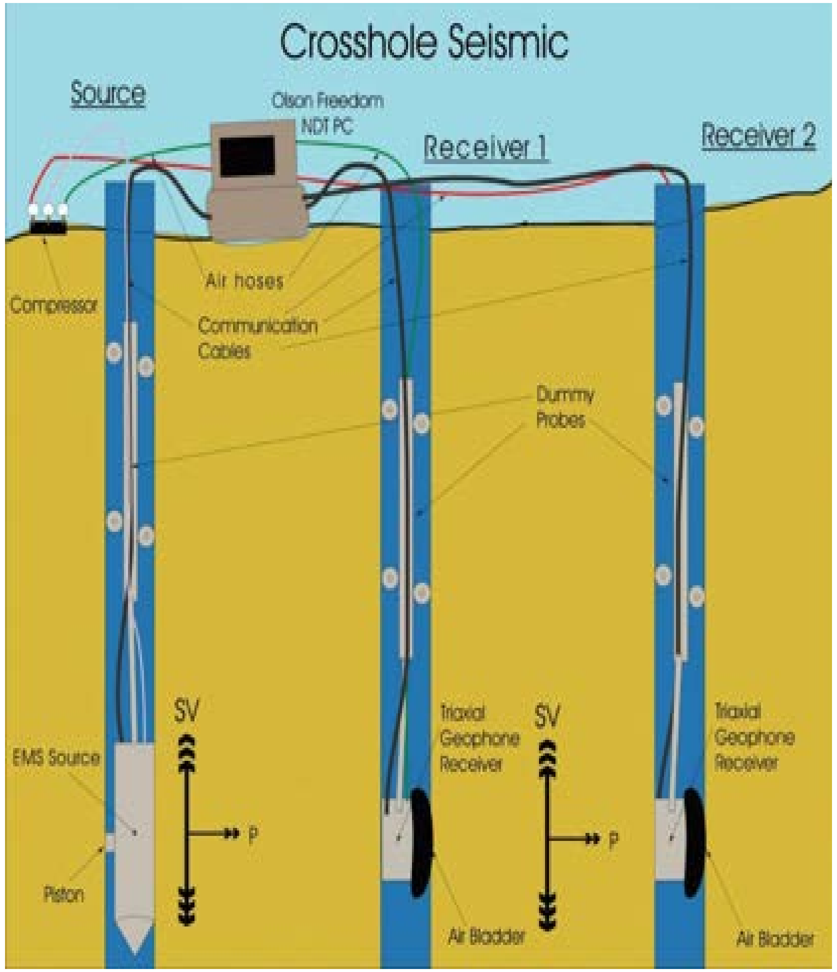
Crosshole Seismic (CS) Test Setup

- 2 – 3 cased and grouted boreholes (~ 10 ft apart)
  - Deviation Logging tool to get X, Y, Z of all 3 borings with depth for accurate distances at measurement depths for velocity calculations.
  - Uses the Solenoid as a source in one borehole
- Uses 1 – 2 triaxial Geophones as receivers in the rest of the boreholes



ASTM INTERNATIONAL Designation: D 4428/D 4428M – 07

Standard Test Methods for Crosshole Seismic Testing[1]

Olson Instruments CS Equipment P-SV Source and Triaxial Geophones with Air Bladders and Field PC

CS Test Setup

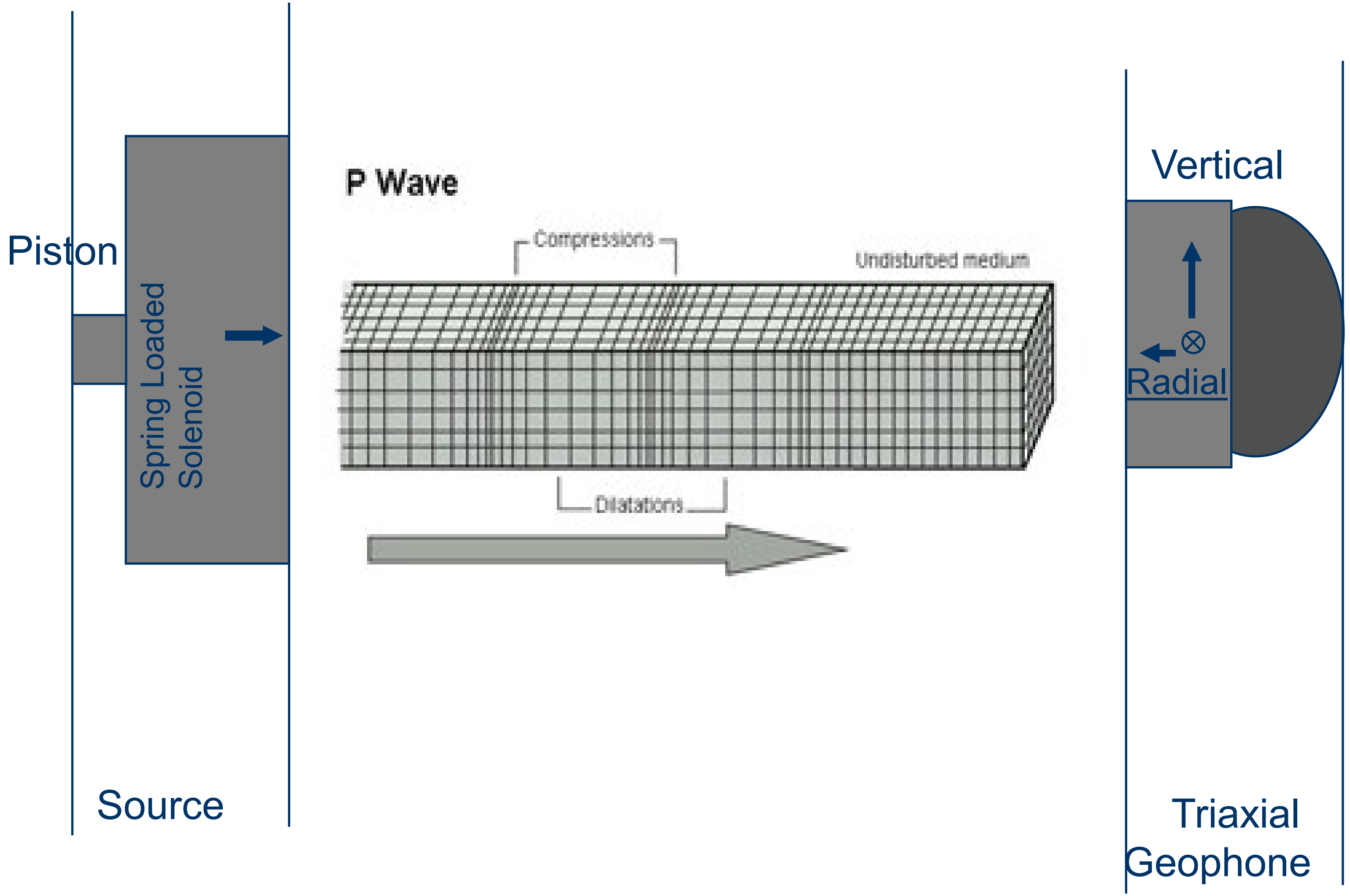
CS Source and Receiver

- P-SV electromechanical source with three directions of impact-radial (horizontal), up and down – coupled to casing wall with air pressure
- 1 Tri-axial geophone receiver per borehole – vertical, radial, transverse – coupled with pressure to air tube

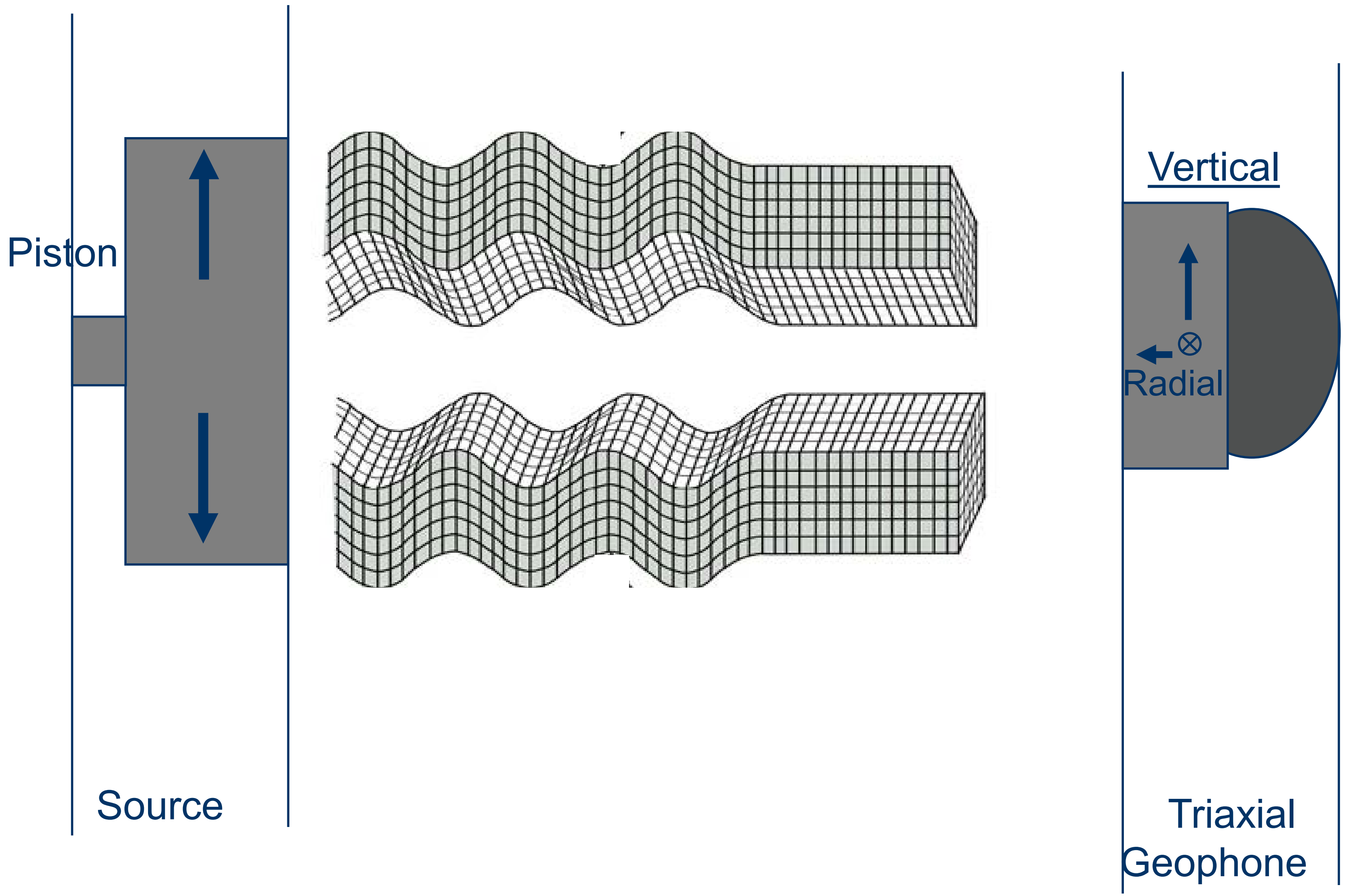
P-SV Source

Tri-axial Geophone Receiver

CS Test Procedure – P Wave



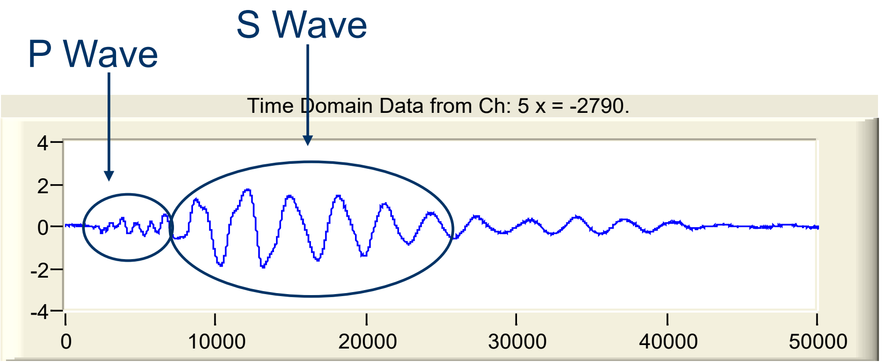
CS Test Procedure – S Wave



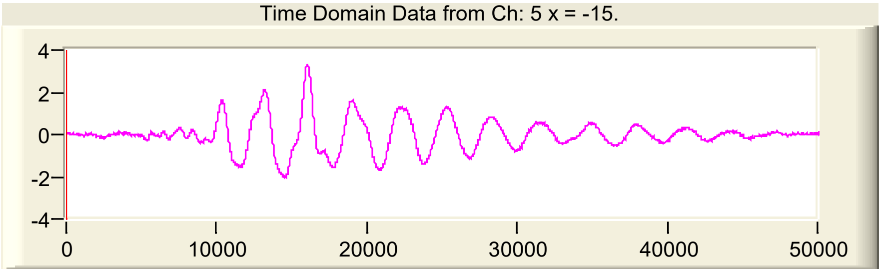
CS Tests – Sensitivity for Each Component

Source Direction	Receiver Component	Sensitivity	
		P Wave	S Wave
Radial	Vertical		
	Radial	✓	
	Transverse	✓	
Up	Vertical		✓
	Radial		
	Transverse		
Down	Vertical		✓
	Radial		
	Transverse		

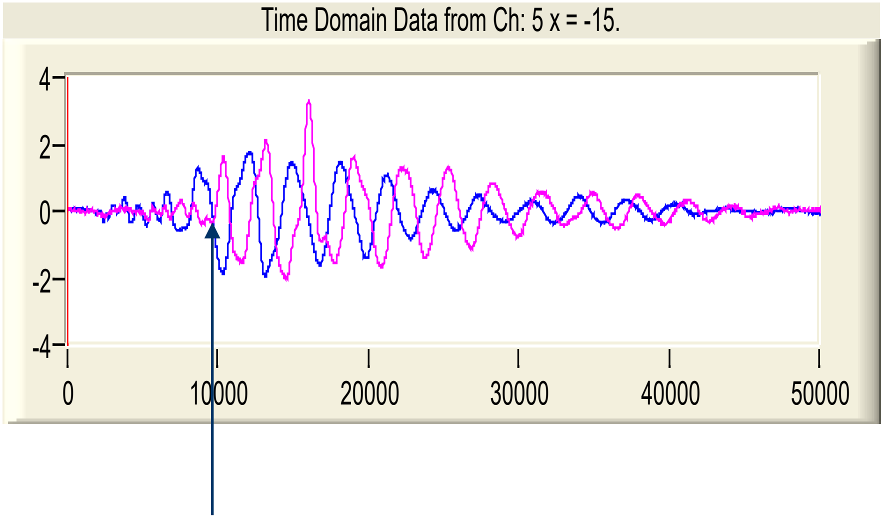
Example of P and S Waves from the CS Test



Vertical Response from “Up” direction of Impact

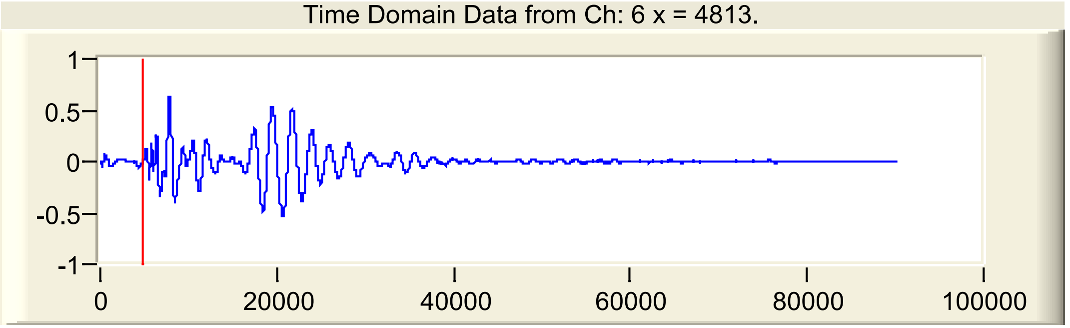


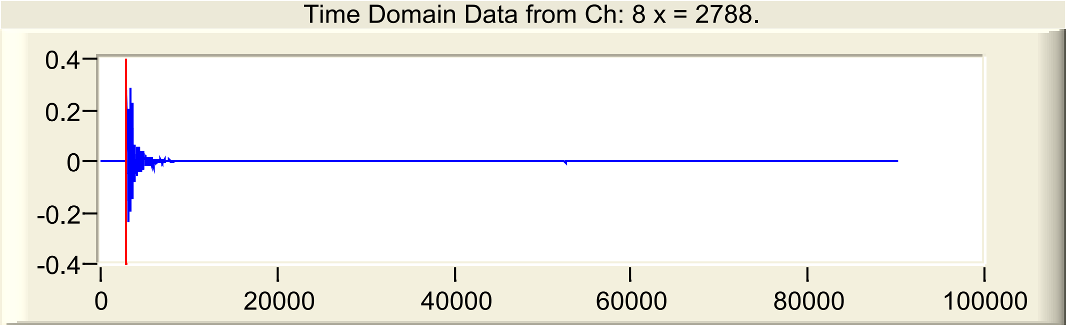
Vertical Response from “Down” direction of Impact



Arrival of S Wave

Calculation of P Wave Velocity from the CS Test





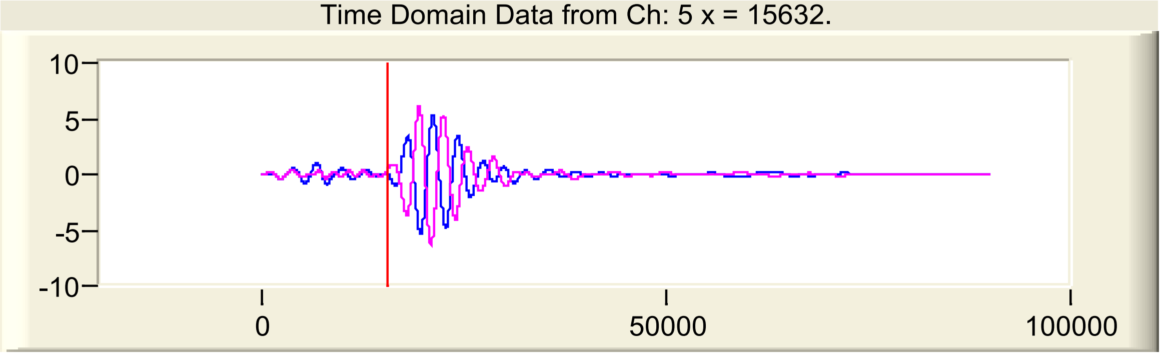
t_p = 4813 – 2788 = 2025 us

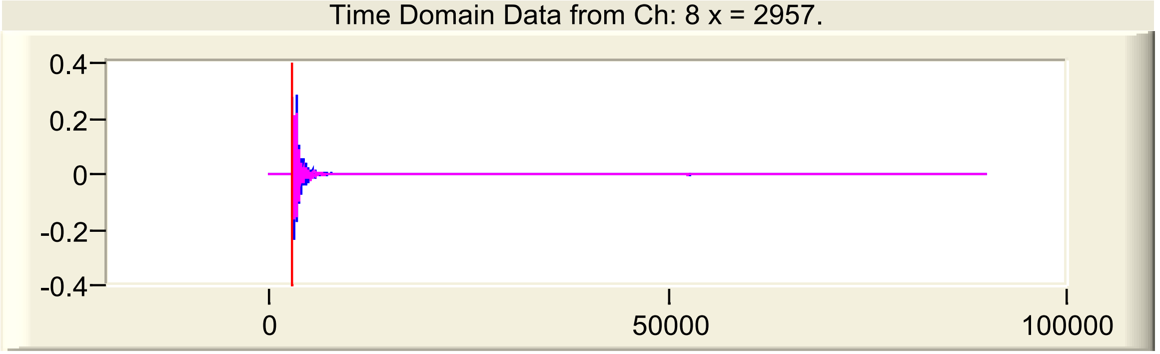
Distance = 3.048 m.

Vp = 3.048 / 1000000/2025
= 1,505 m/s

Note: This is a velocity of water in the saturated soil

Calculation of S Wave Velocity from the CS Test



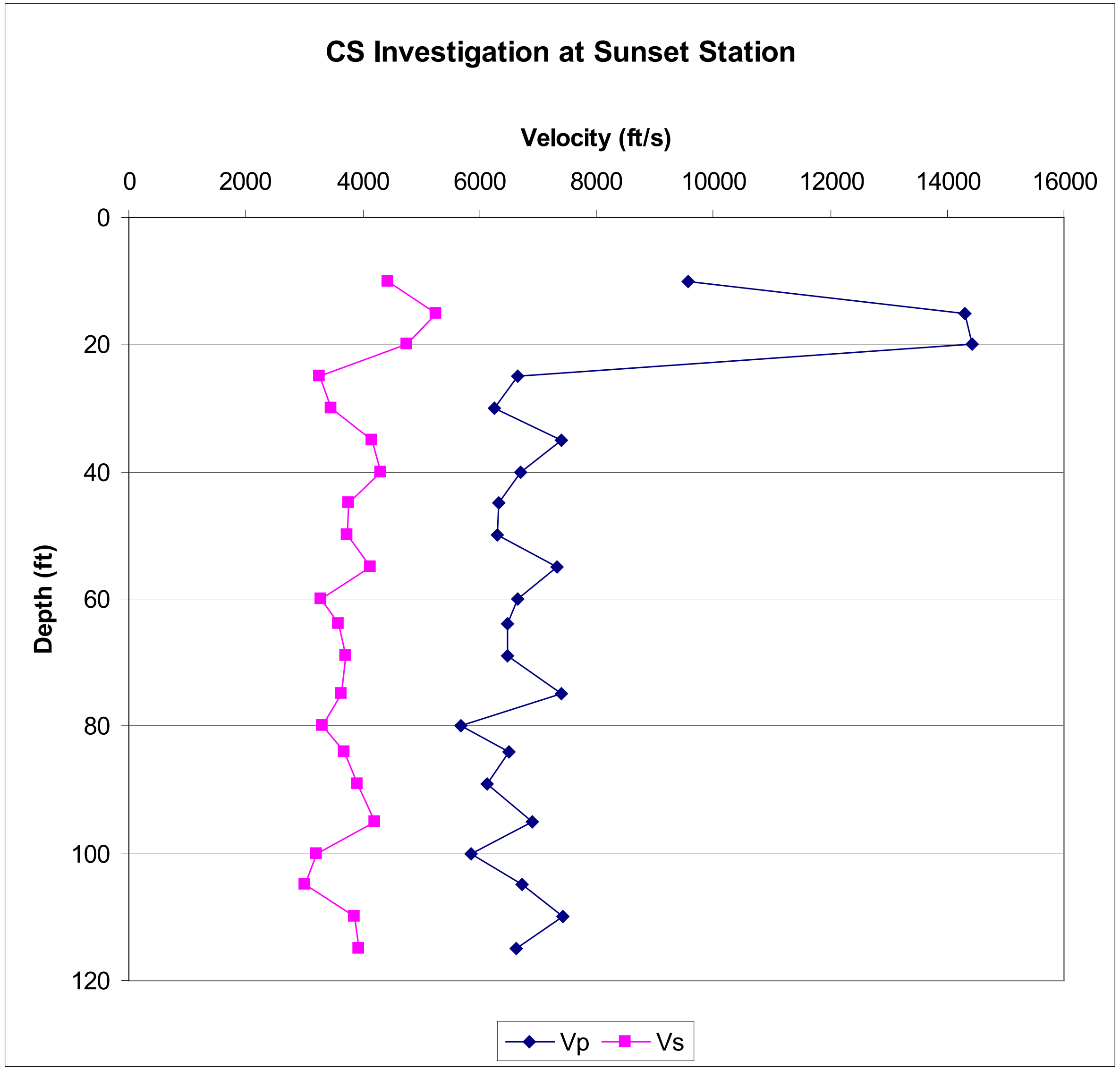


t_s = 15632 – 2957 = 12675 us

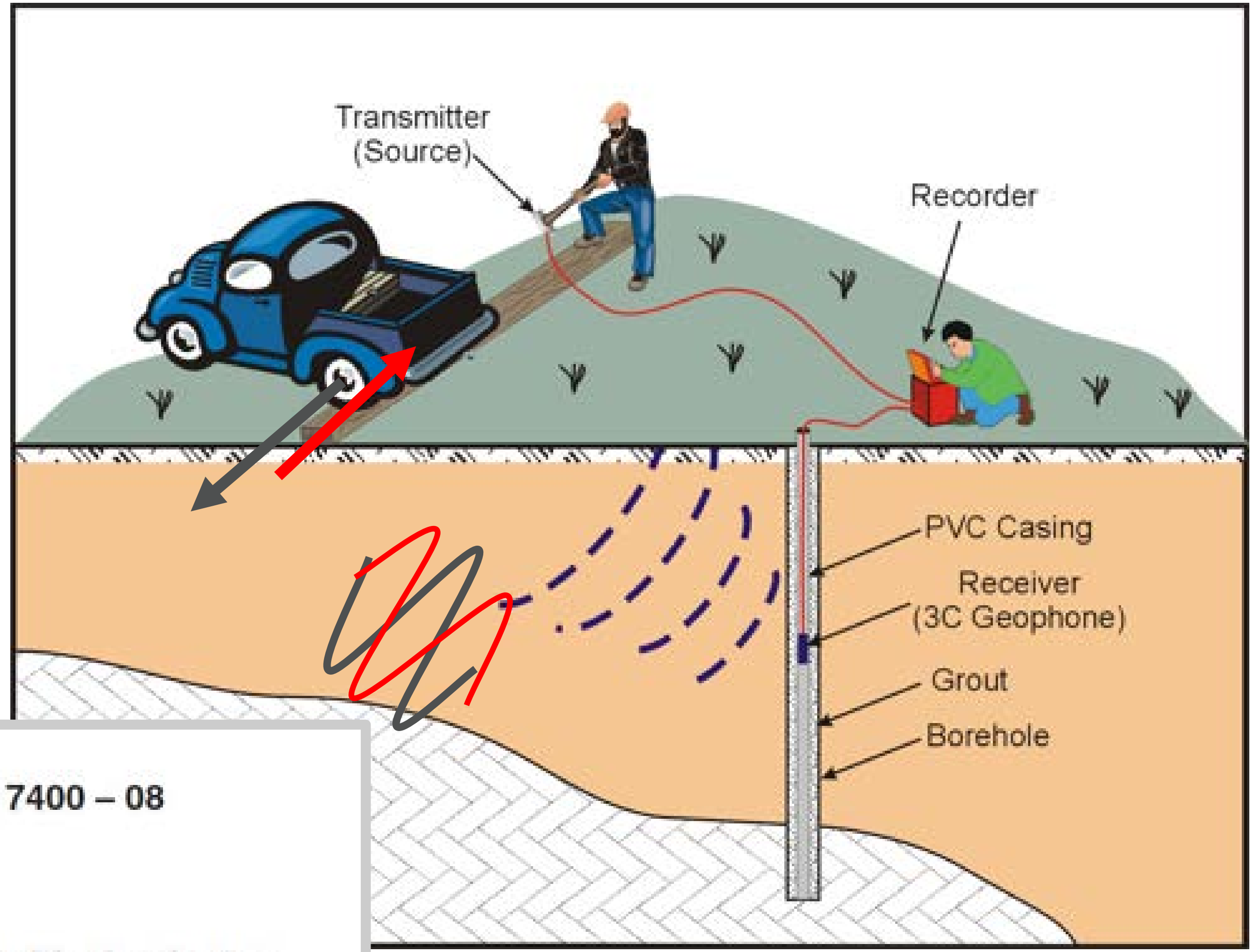
Distance = 3.048 m.

Vp = 3.048 / 1000000/12675
= 240 m/s

P and S Waves Velocity Profiles



Downhole Seismic Method: P- & S-wave Survey Set-up



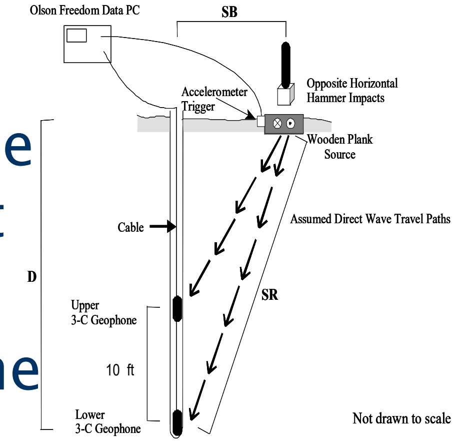
Designation: D 7400 – 08

INTERNATIONAL

Standard Test Methods for Downhole Seismic Testing[1]

Downhole Seismic (DS) Test Setup

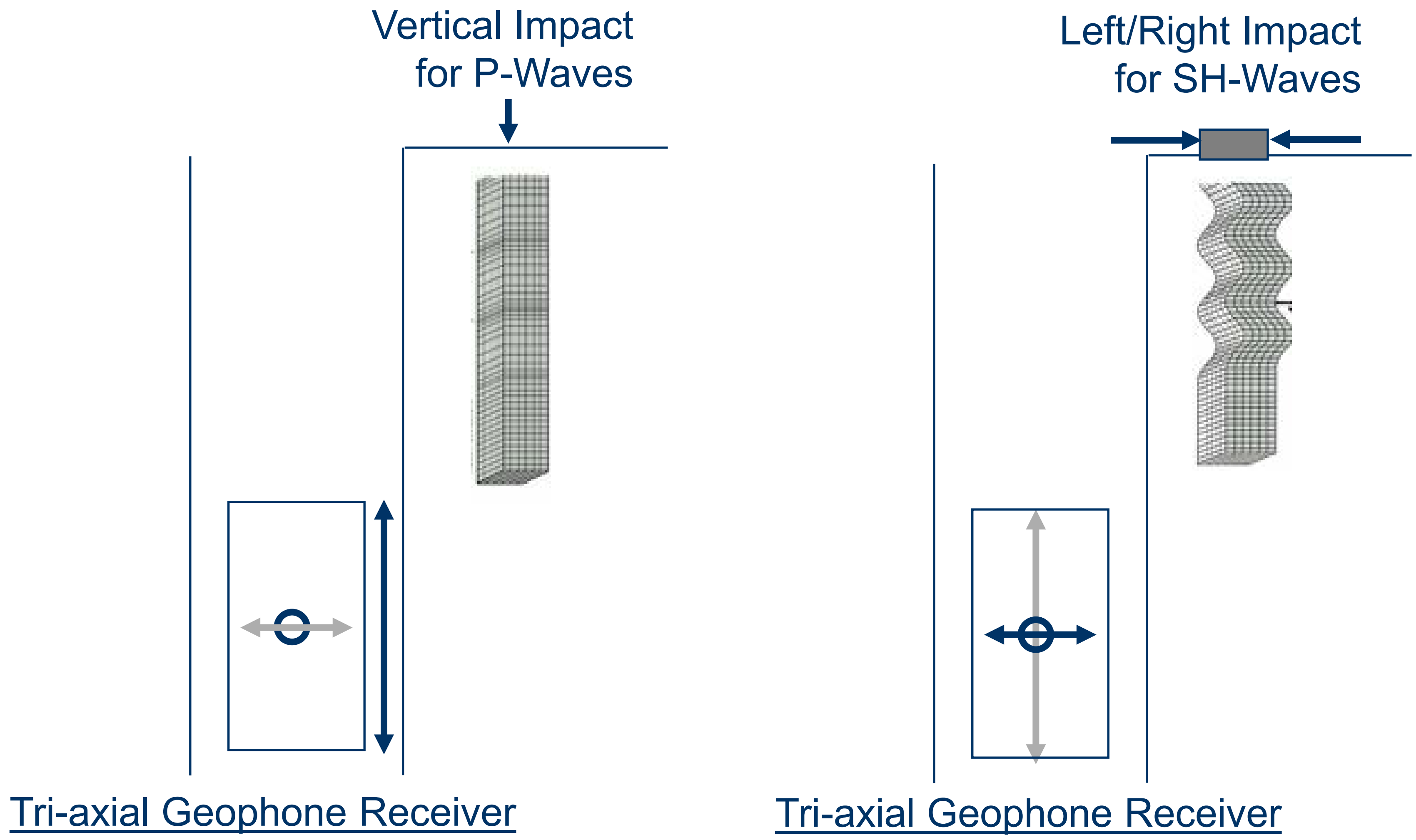
- Borehole technique
- Only require 1 borehole for two receivers (10 ft apart vertically)
- Source is applied on the top of the ground



DS Source and Receiver

- Wooden plank source with sledge hammer impact – vertical, left and right directions
- 2 Tri-axial geophone receivers per borehole – vertical, radial, transverse

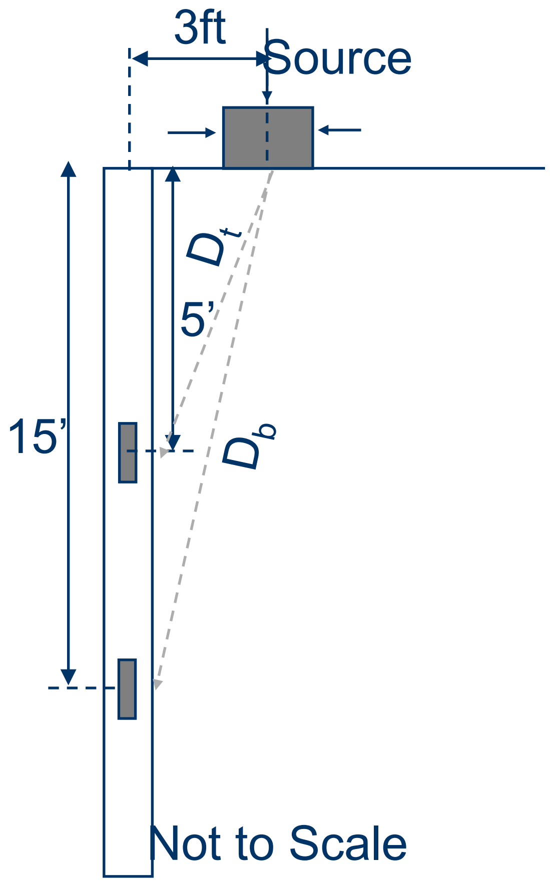
DS Test Procedure

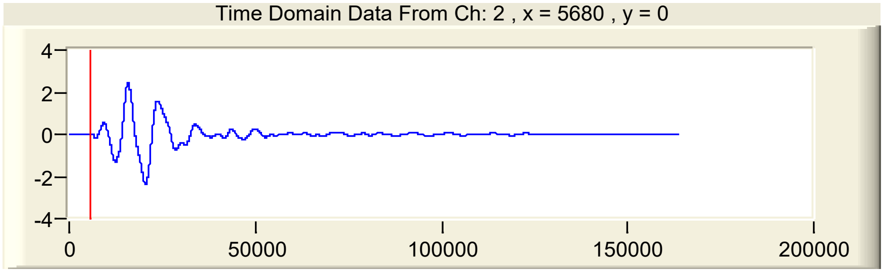


DS Test – Sensitivity of Each Component

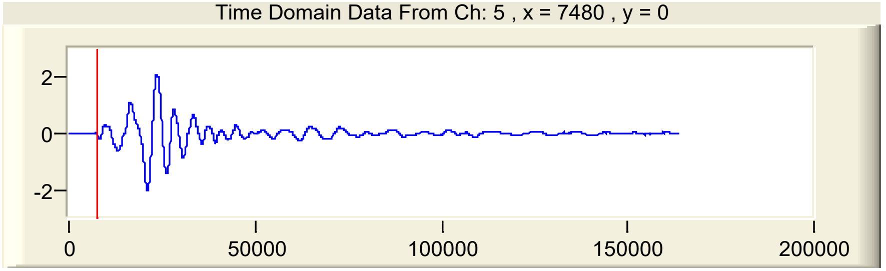
Source Direction	Receiver Component	Sensitivity	
		P Wave	S Wave
Vertical	Vertical	✓	
	Radial		
	Transverse		
Left	Vertical		
	Radial		✓
	Transverse		✓
Right	Vertical		
	Radial		✓
	Transverse		✓

Example P Wave from the DS Test





Waveform from vertical component (top geophone) from vertical impact



Waveform from vertical component (bottom geophone) from vertical impact

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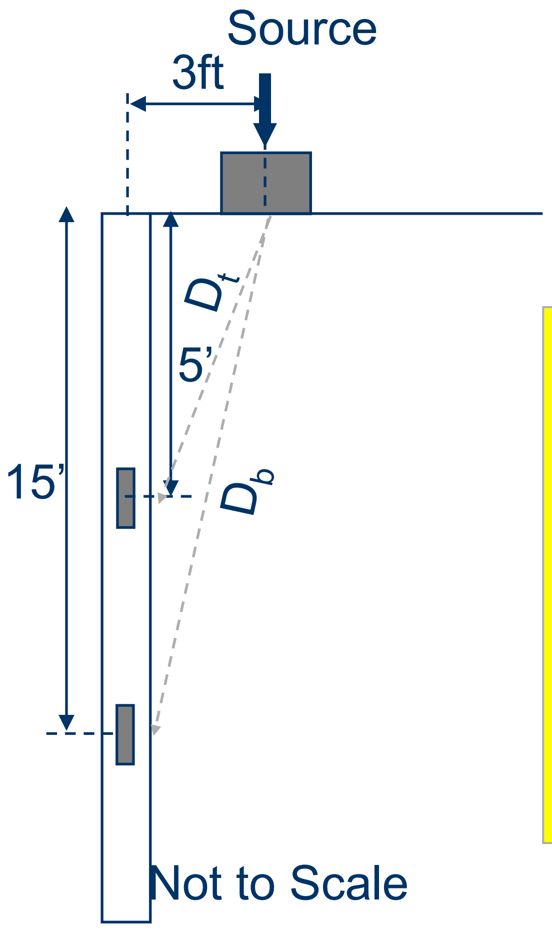
Calculation of P-Wave Velocity from the DS Test



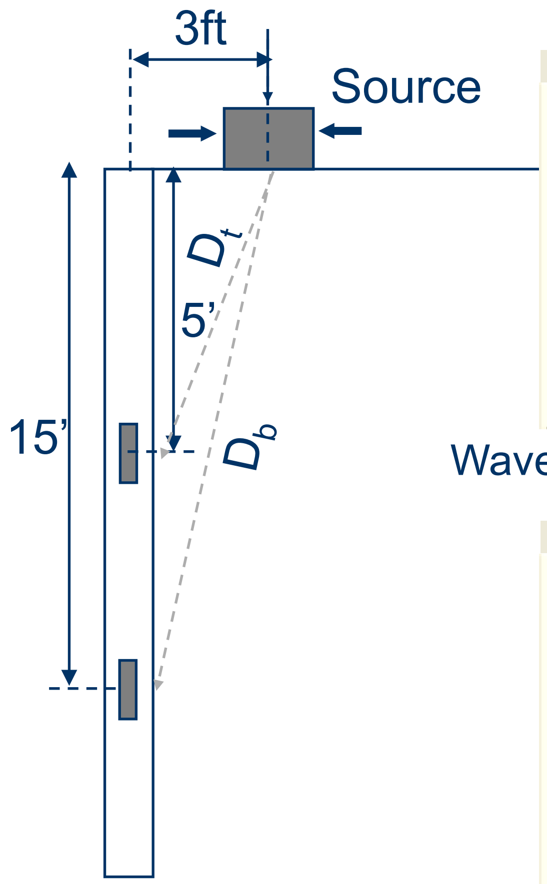
$$D_t = \sqrt{(5^2 + 3^2)} = 5.83$$

$$D_b = \sqrt{(15^2 + 3^2)} = 15.30$$

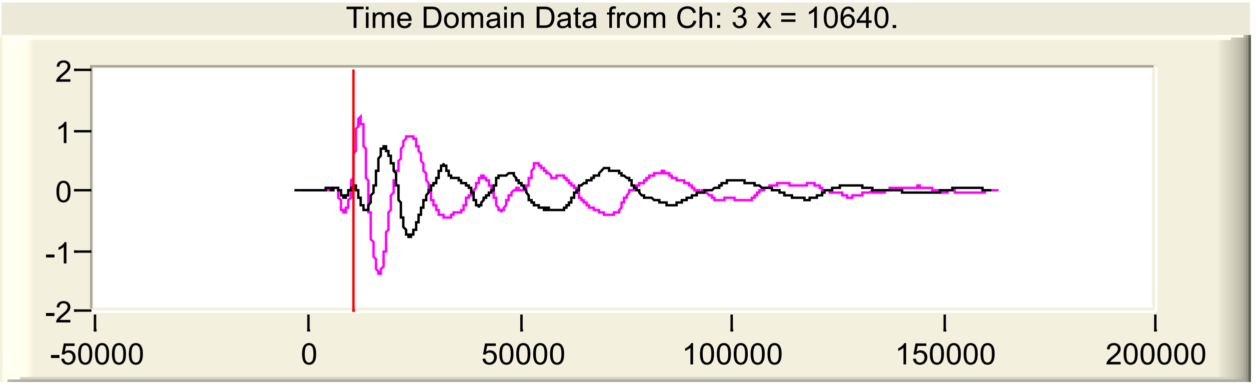
$$V_p = \frac{D_b - D_t}{t_b - t_t}$$

$$V_p = \frac{15.3 - 5.83}{7480 - 5680} = 0.005261\, ft/us = 5261\, ft/s$$

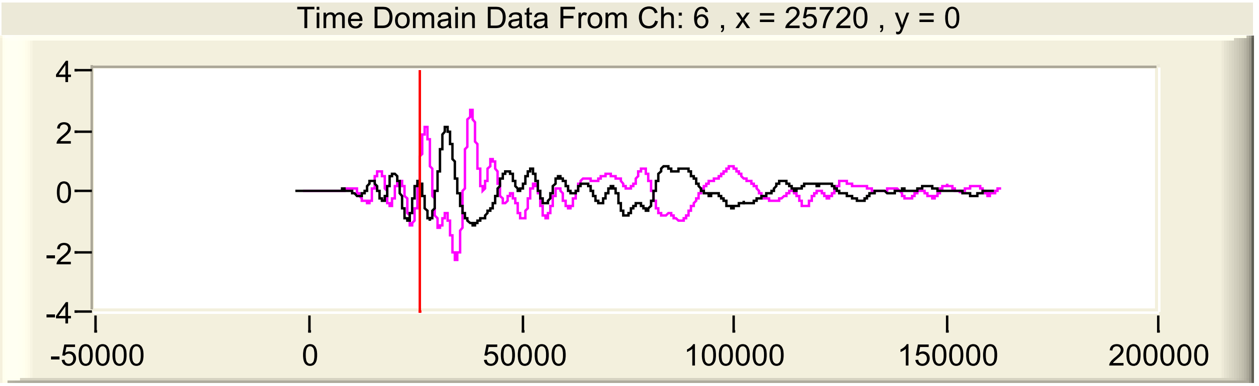
Example S Wave from the DS Test



Not to Scale

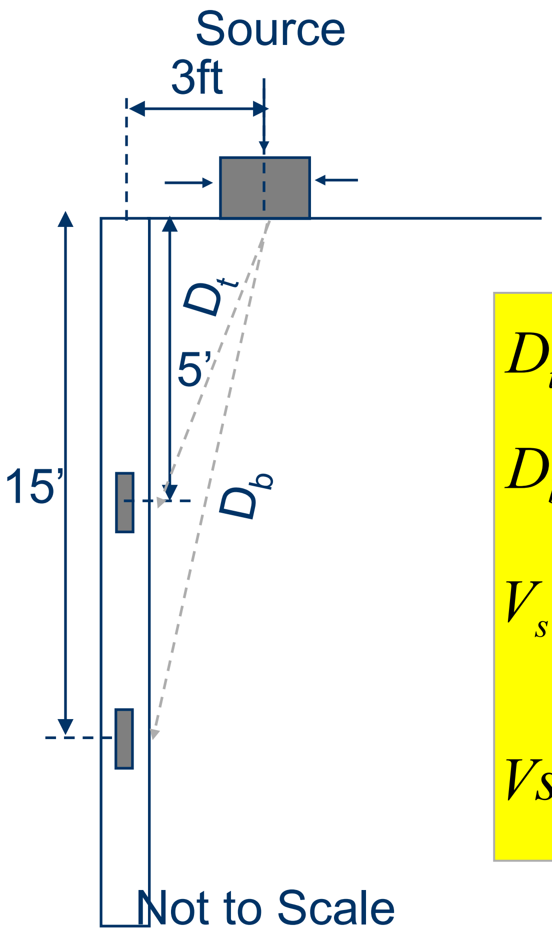


Waveform from radial component (top geophone) from left/right impacts



Waveform from radial component (bottom geophone) from left/right impacts

Calculation of S-Wave Velocity from the DS Test



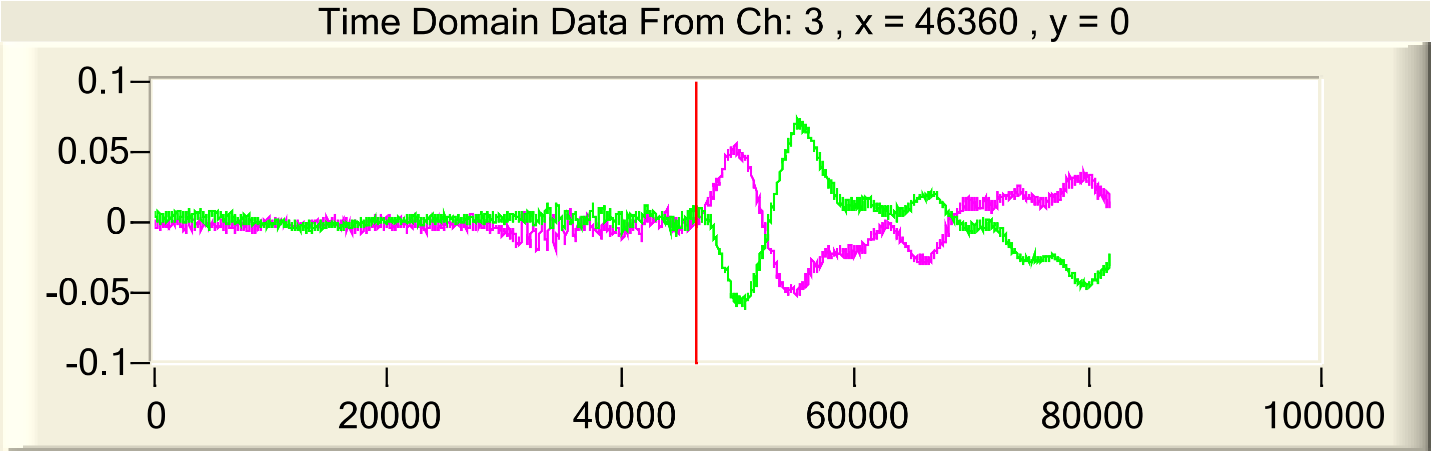
$$D_t = \sqrt{(5^2 + 3^2)} = 5.83$$

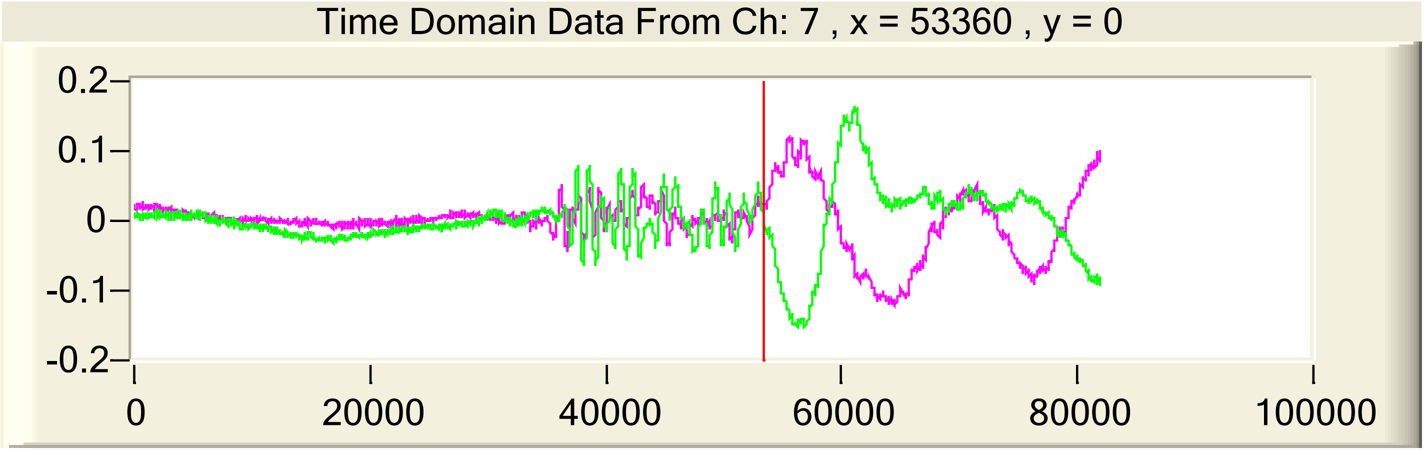
$$D_b = \sqrt{(15^2 + 3^2)} = 15.30$$

$$V_s = \frac{D_b - D_t}{t_b - t_t}$$

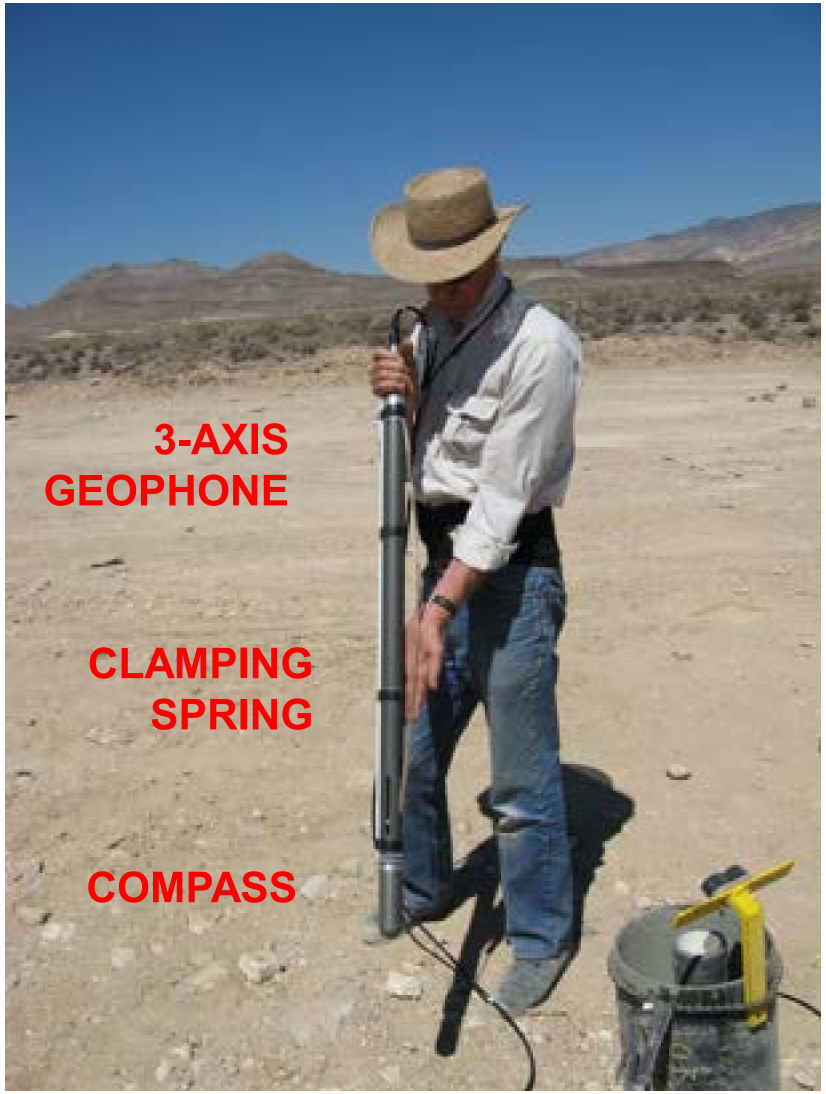
$$Vs = \frac{15.3 - 5.83}{25720 - 10640} = 0.0006279\, ft/us = 627\, ft/s$$

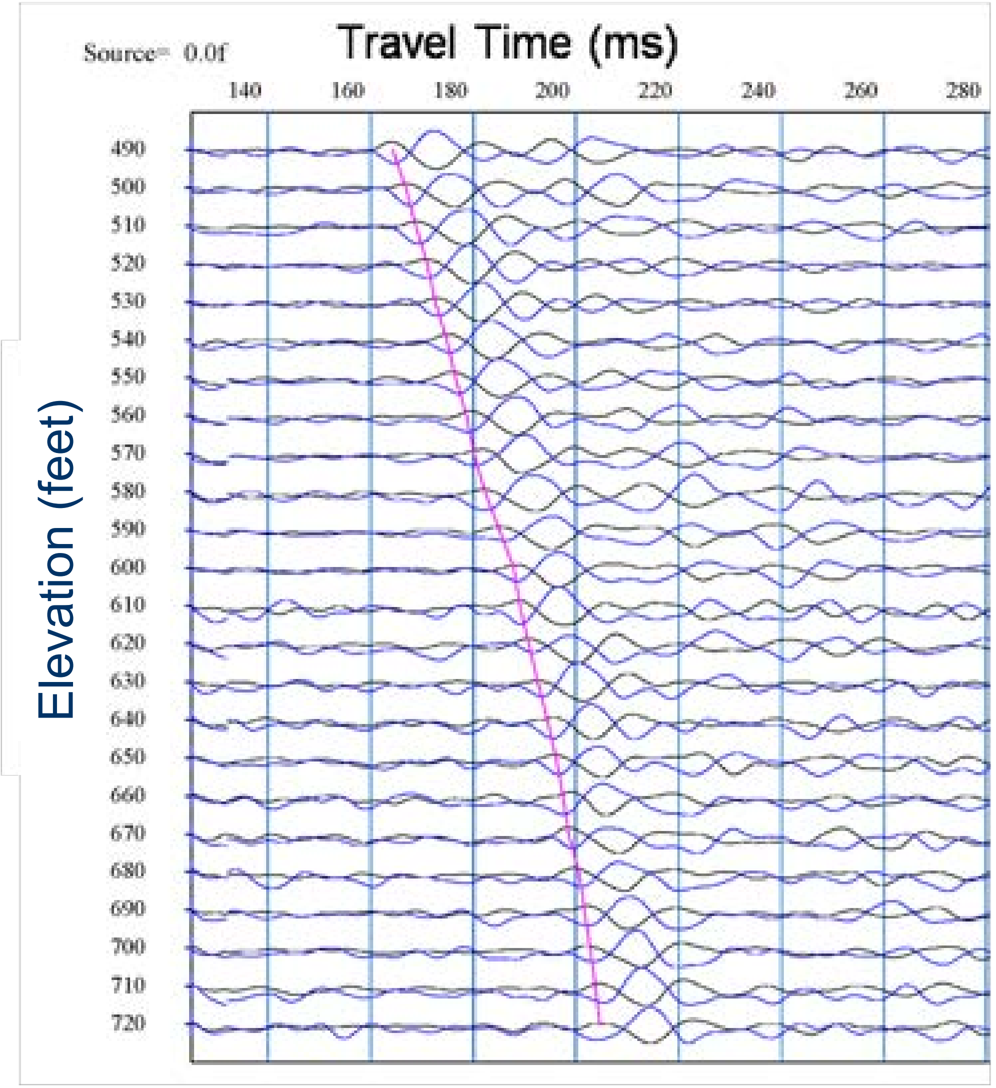
Examples of horizontally polarized shear waves (SH-Waves)



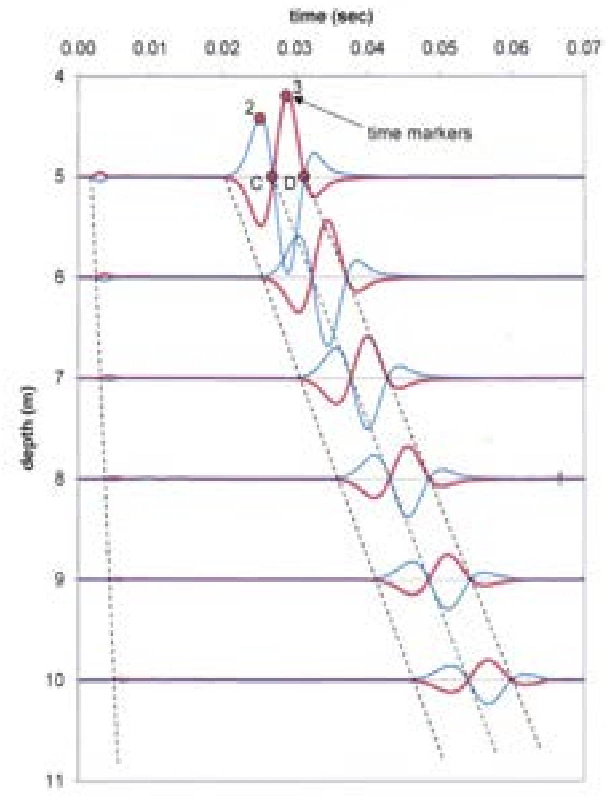


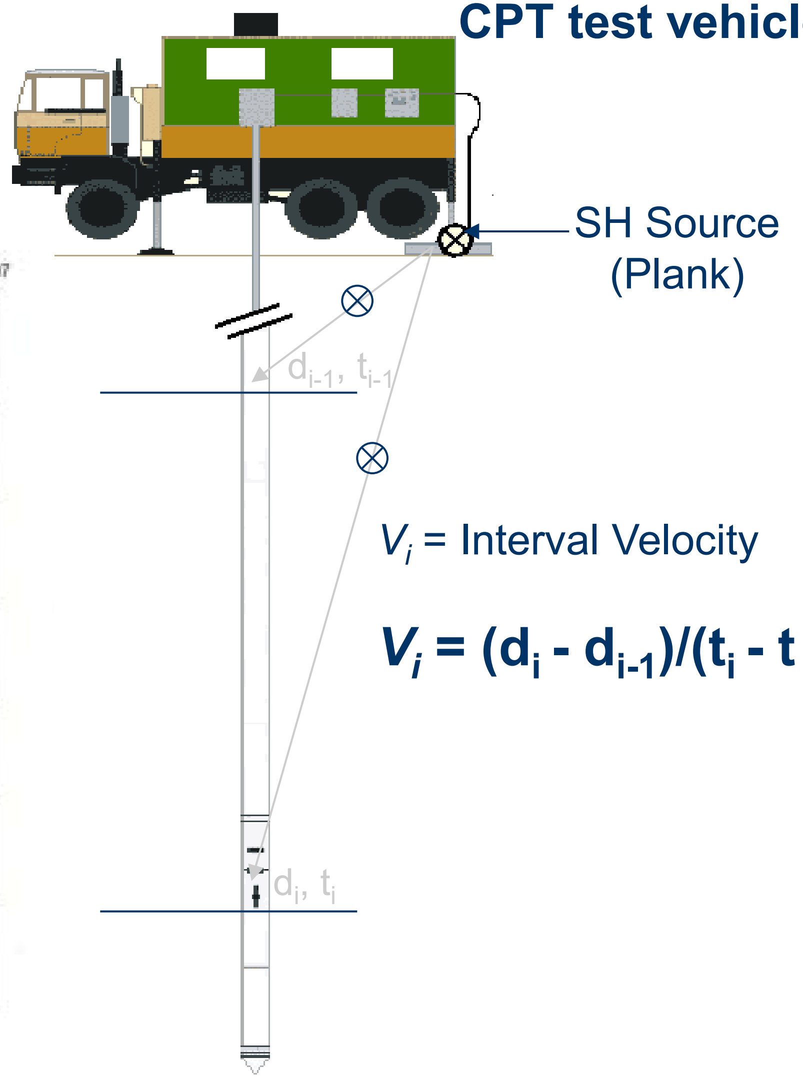
GeoStuff Downhole: P- & S-wave Triaxial Geophones & SH Results





Downhole: Cone Penetrometer CPT P- & S-wave Equipment





V_i = Interval Velocity

$$\mathbf{V_i = (d_i - d_{i-1})/(t_i - t_{i-1})}$$

Borehole Seismic Benefits

- Very good detail of velocity structure & layering
- Well constrained and **unique** solutions
- Direct measurements of P- and S-wave velocity
- Simple computations for velocity (*and moduli*)
- Easy and quick data acquisition (*1-person?*)
- Repeatable measurements

SEISMIC METHODS:

- Borehole Methods
- **Body Wave Methods**
- Surface Wave Methods

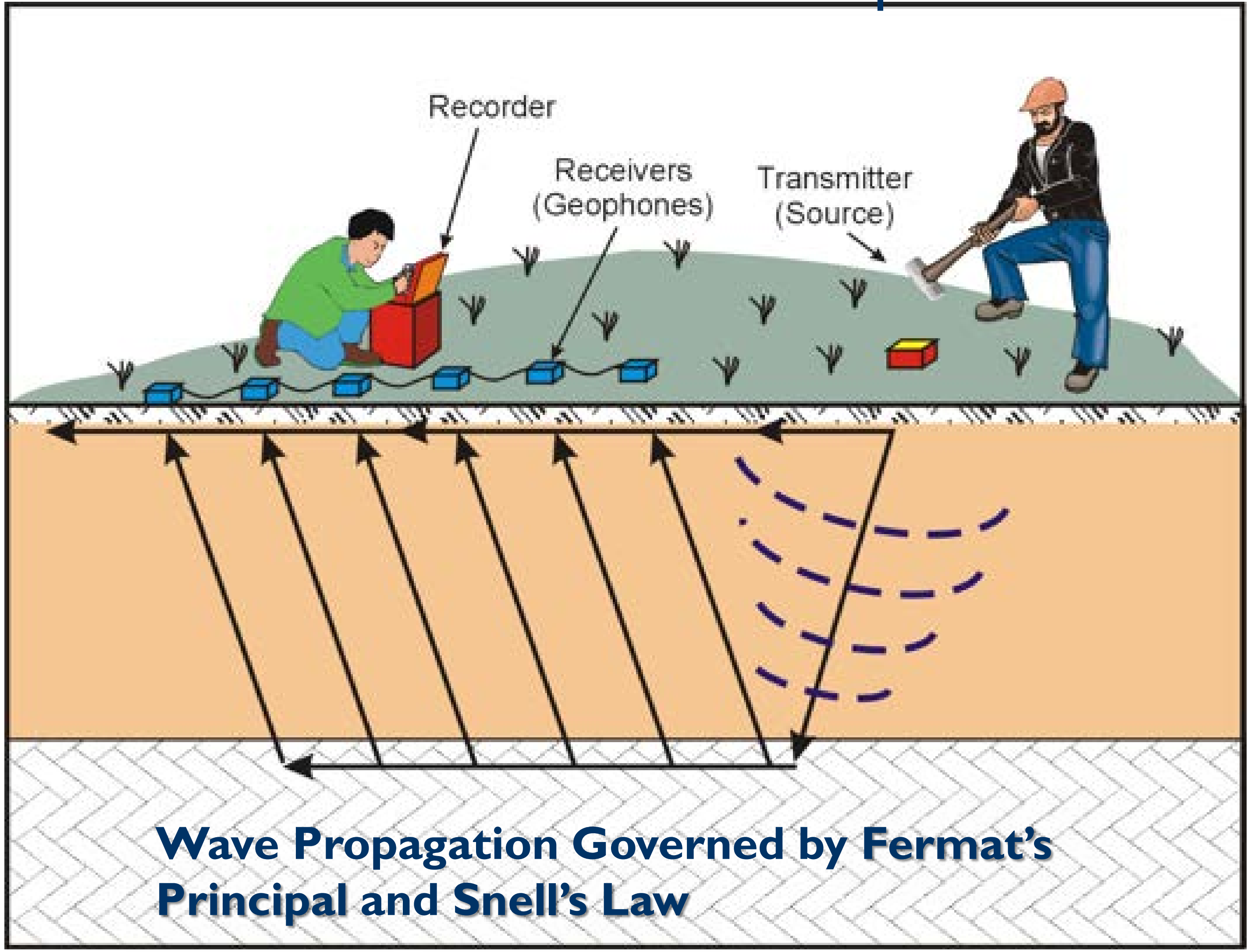
Body Wave Method: Seismic Refraction w/ Tomography (SRT)

Portable Instrumentation

Engineering-scale
24-Channel seismograph
& laptop

Seismic Refraction Method w/ P-Waves

P-wave Field Setup

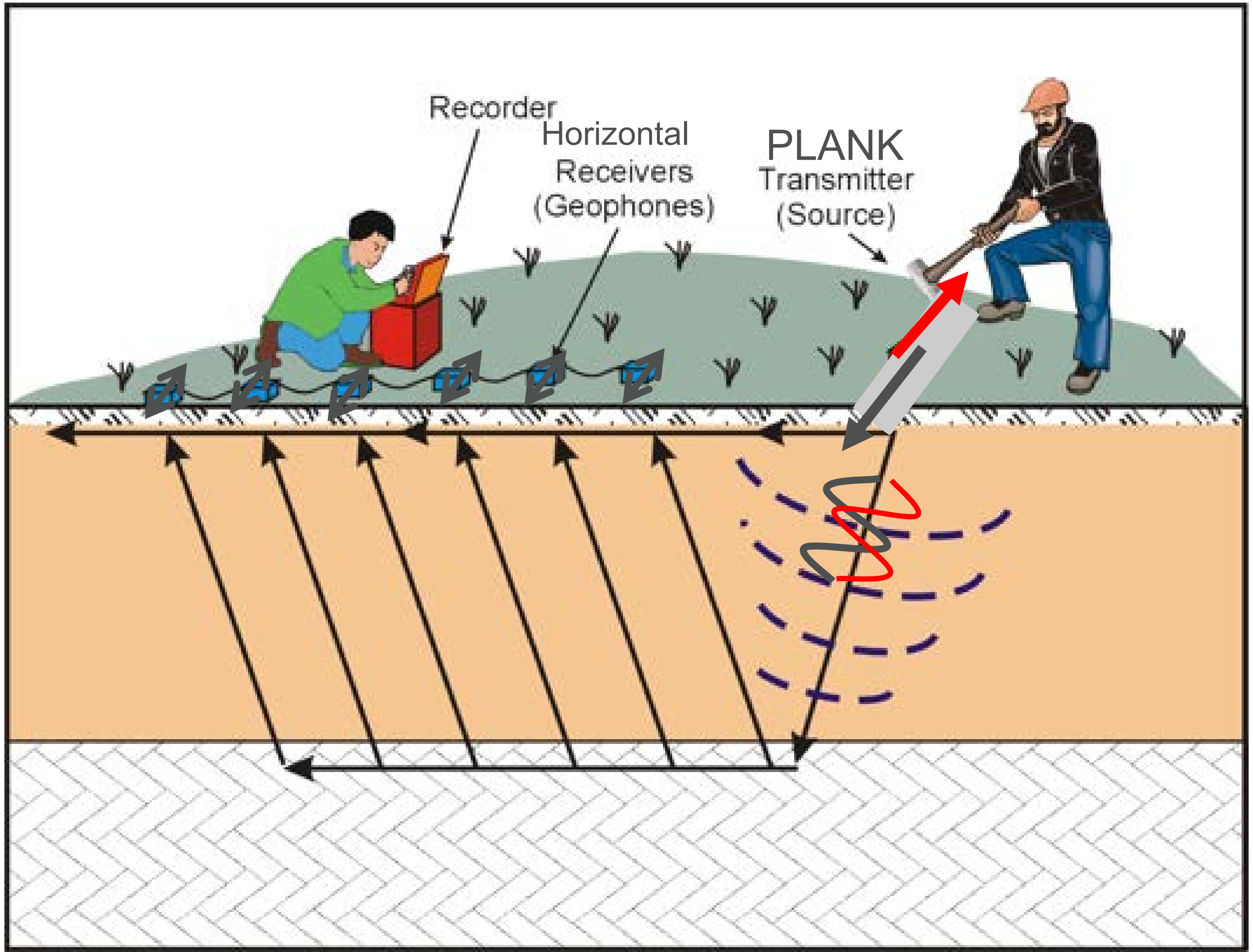


Field Set-up: P-waves and Surface Wave Sources

Seismic waves use an Impulsive (impact) Source

Any impulsive (or vibratory) source can create both body & surface waves – the receivers used to record them is what makes the difference

S-wave Field Setup (SH)

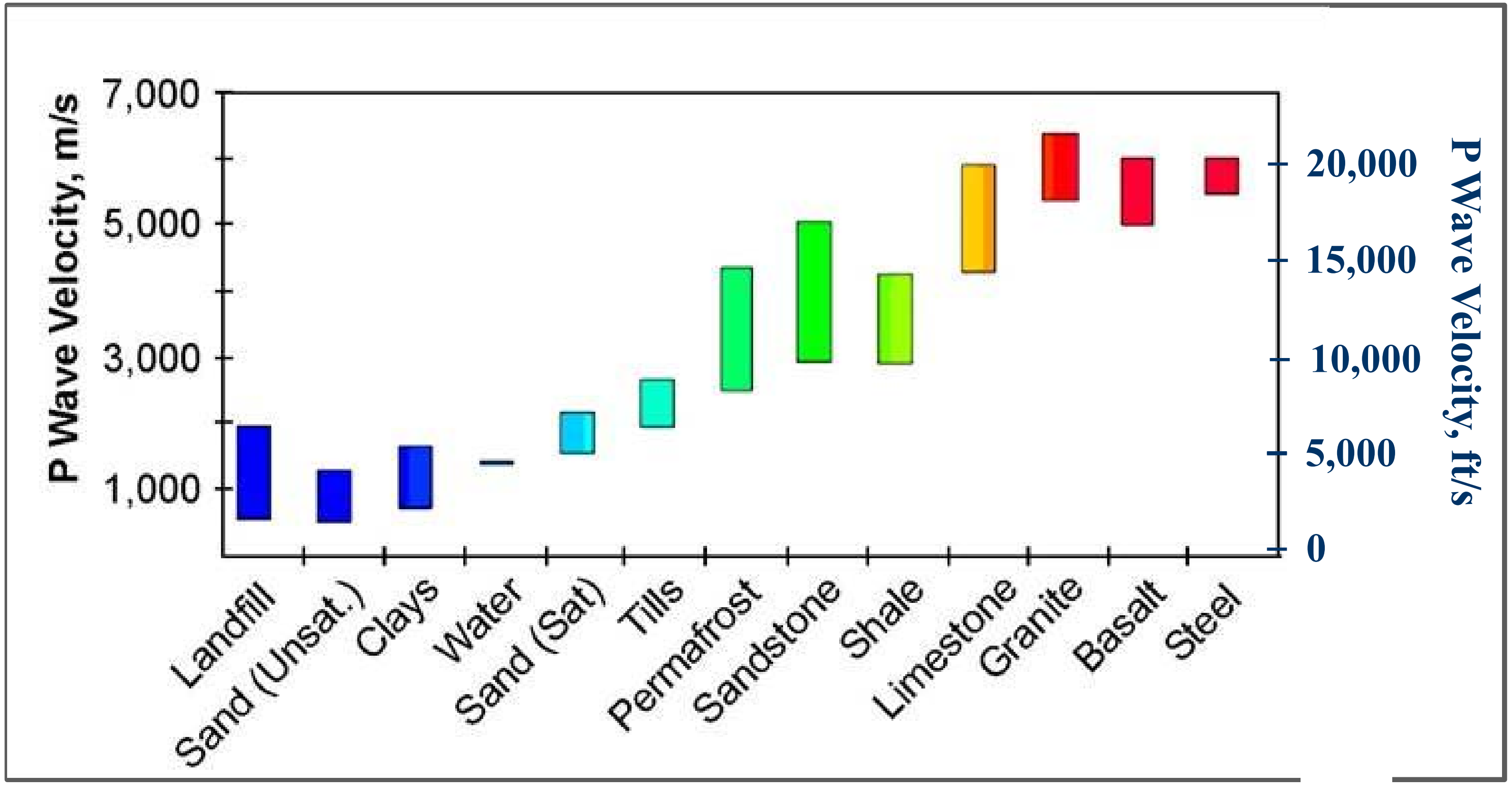


Applications (Vp or Vs)

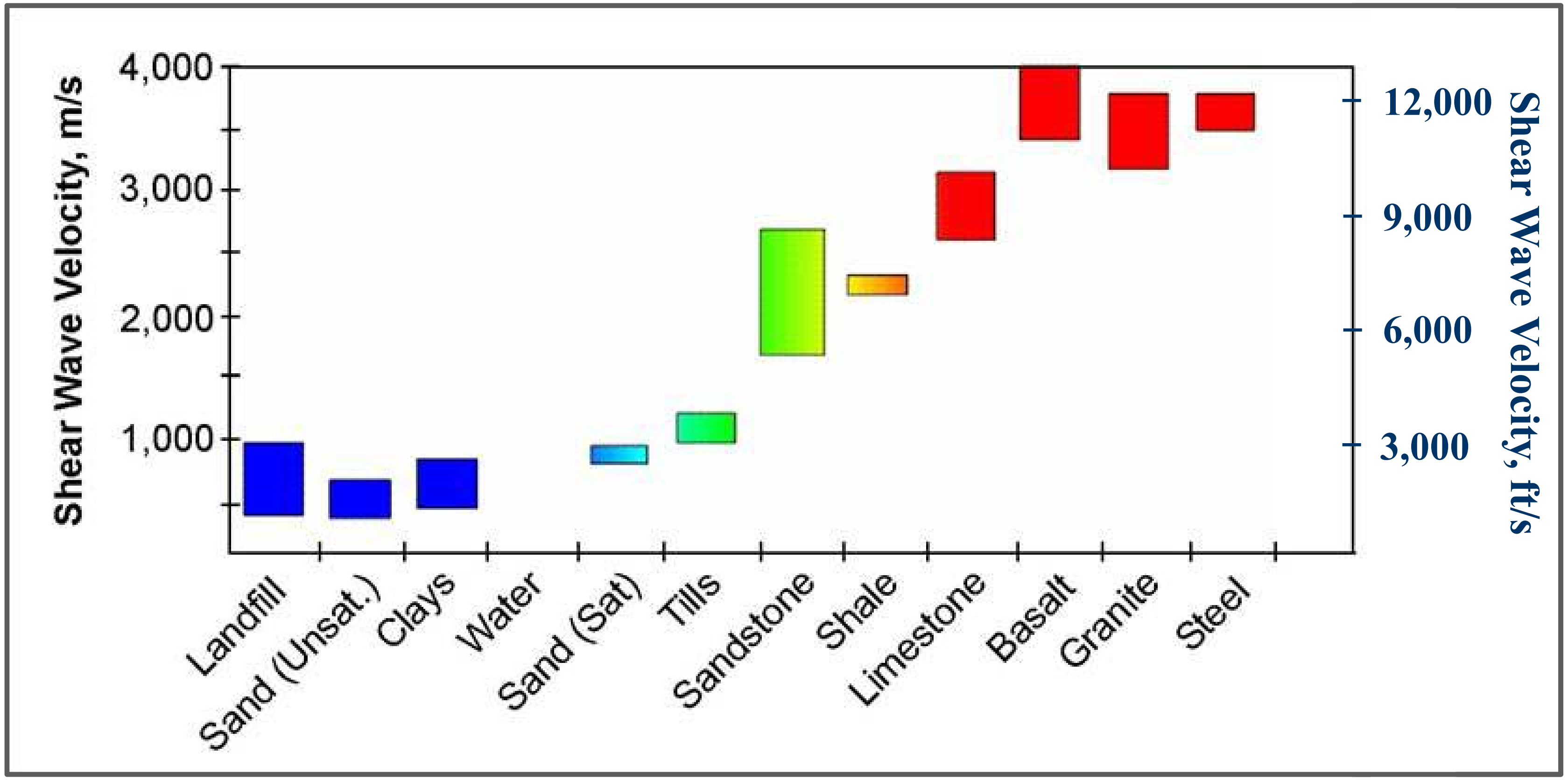
- Depth to bedrock
- Competency of rock – rippability
- Soil variability, stiffness & induration
- Soil saturation (water table)
- Rockmass characterization
- Liquefaction potential
- IBC Site Classification

LATERAL AND VERTICAL (2D) DISTRIBUTION OF P- and/or S-WAVE VELOCITY

P-Wave Velocities of Soils and Rock



S-Wave Velocities of Soil and Rock

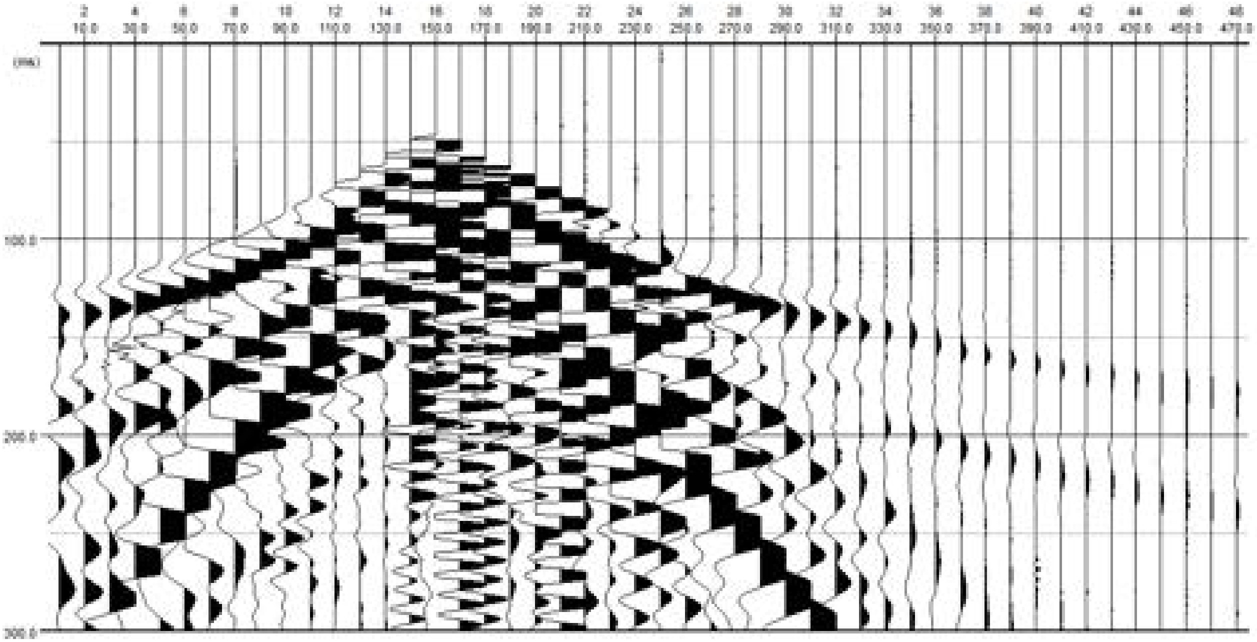


Seismic refraction theory: velocity & depth

Reciprocal times & Intercept Times

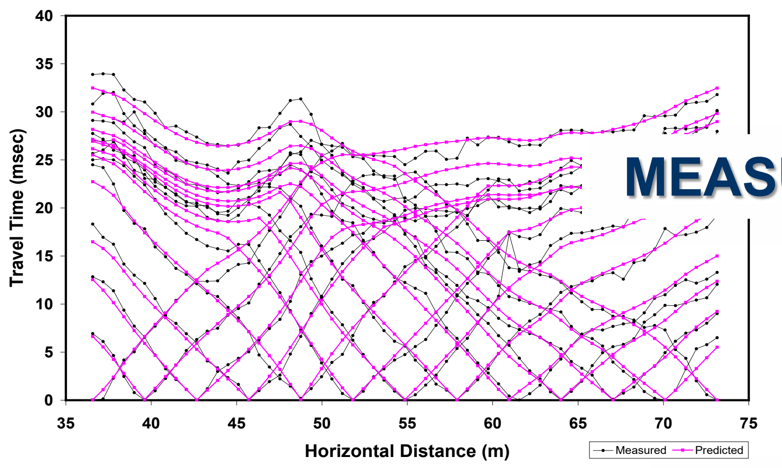
This analysis method allows for calculation of depth, but is based on apparent layer velocities due to raypath geometry; apparent velocities are not the true velocities of each layer.

Note that velocities must increase with depth for refraction to occur with the SRT method. Slow velocity layers below fast velocity layers prevent refraction.

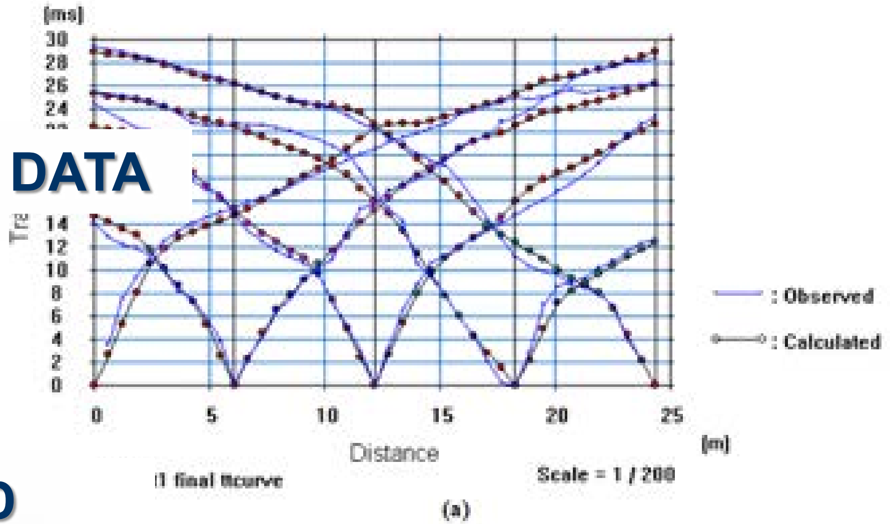


SRT Modeling – 2D Tomography

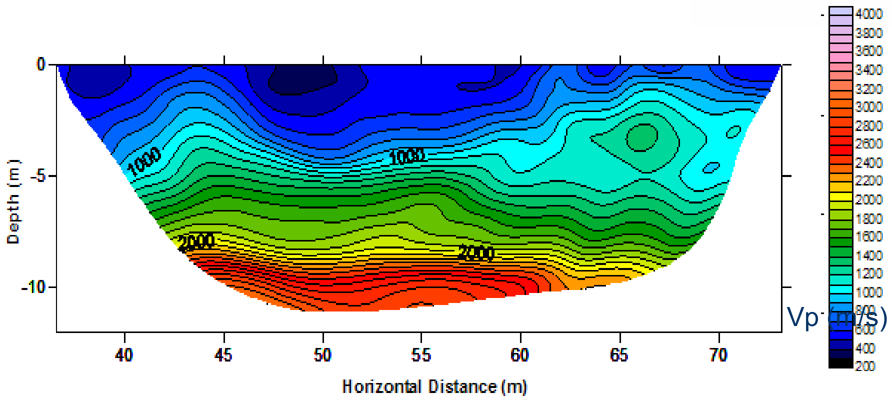
Travel Time Curves and Resulting Solutions



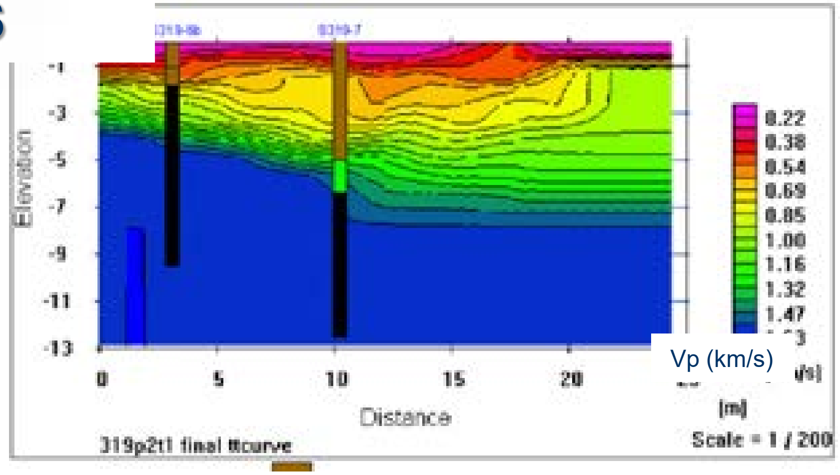
MEASURED DATA



MODELED RESULTS



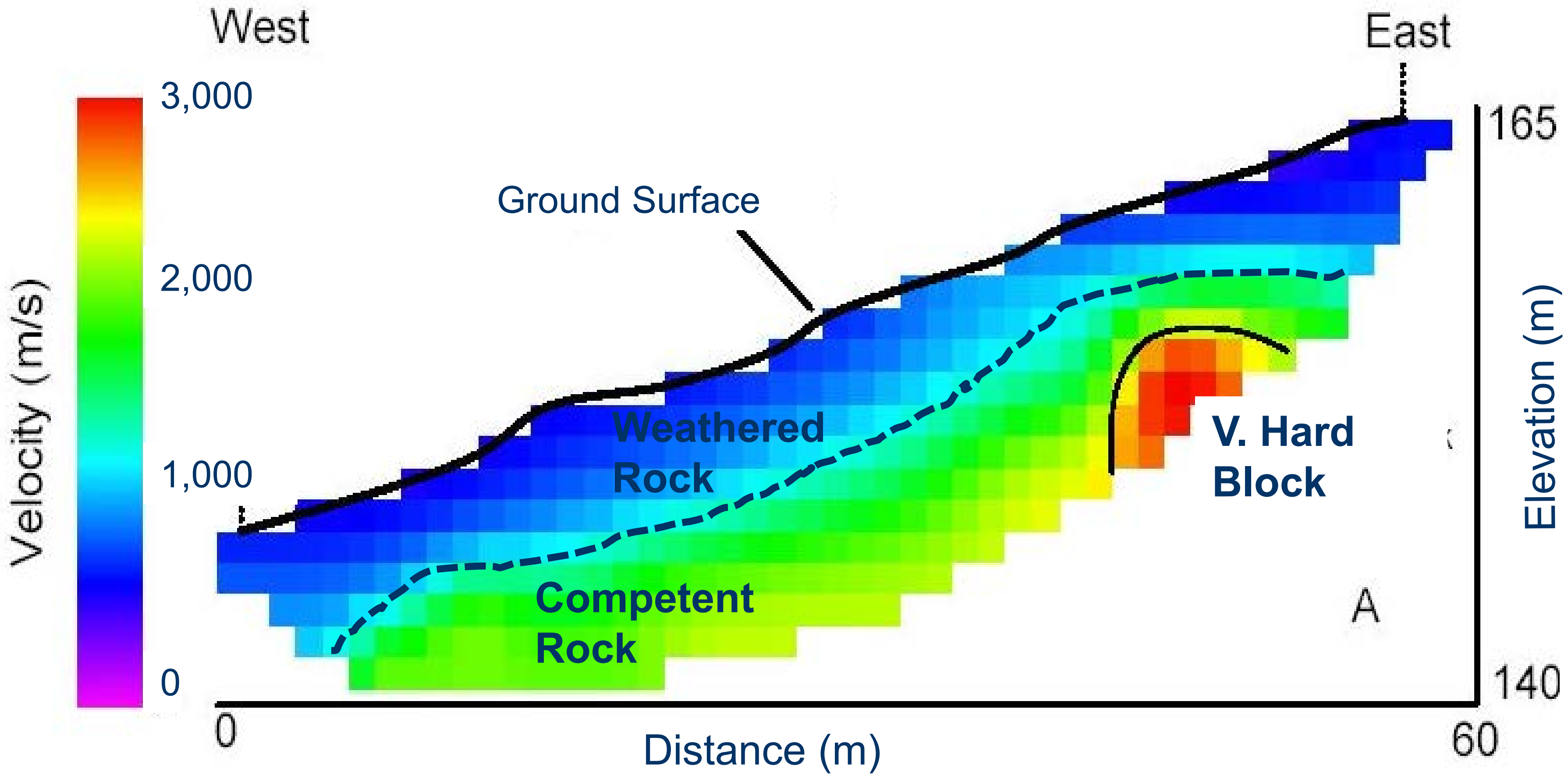
(a) Rayfract



Models courtesy of Univ. of Florida

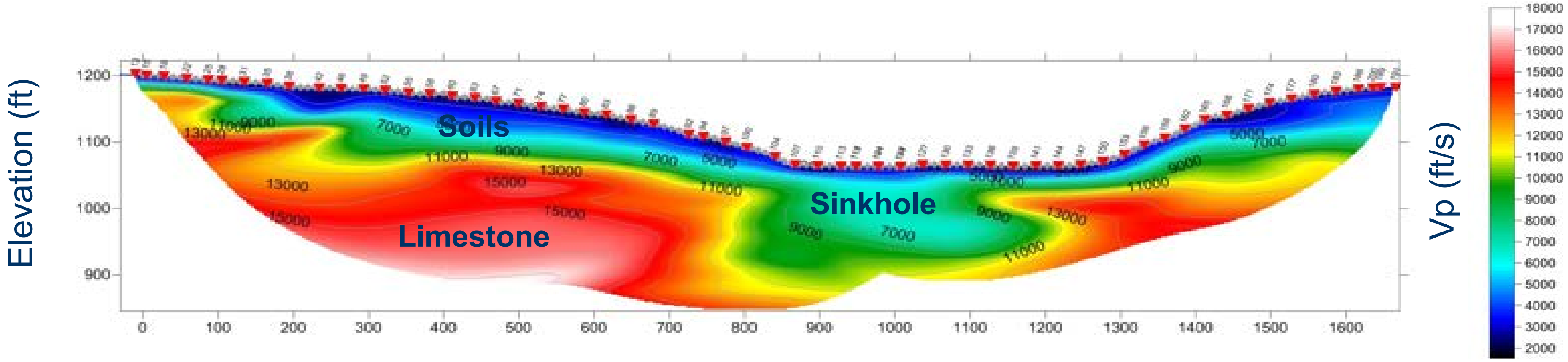
2D Seismic Refraction Tomography Example

Excavation / Construction / Rippability



Source unknown

SRT sinkhole mapping

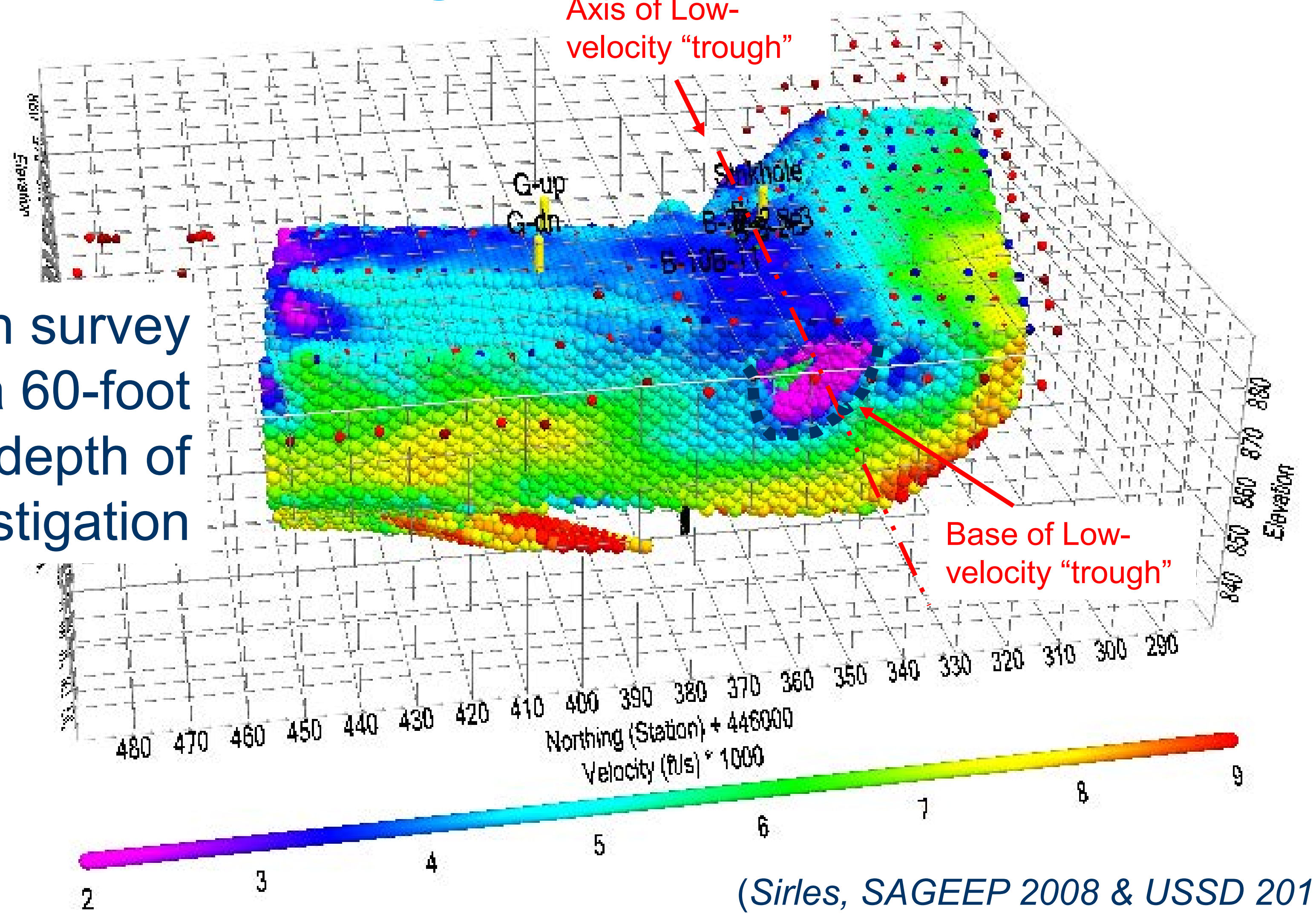


ACROSS A VALLEY

3D Refraction Tomography Example of Sinkhole in Dam

Sinkhole Investigation – Chilhowee Dam, TN

120-ch survey with a 60-foot depth of investigation



(*Sirles, SAGEEP 2008 & USSD 2011*)

Seismic Refraction for rock rippability

The rippability of various rock types for different P-wave velocities using a **D9 Caterpillar** tractor (in this example)

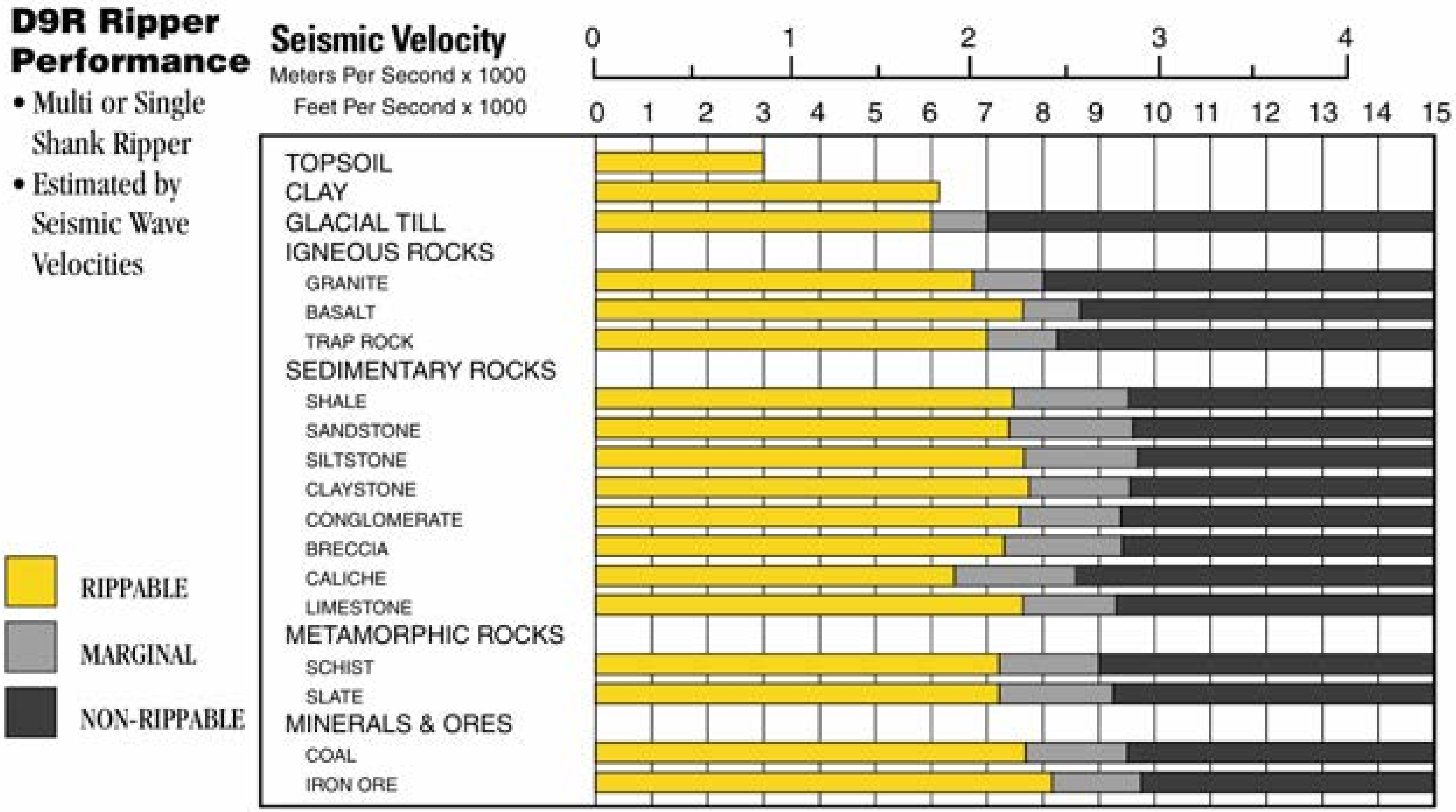


Chart taken from Caterpillar **“Handbook of Ripping”** (2000)

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Seismic refraction limitations

- Velocities must increase with depth
- Depth of investigation limited by line length & by source type
- Pore fluids affect P-wave velocities, not S-waves (in soils)
- S-waves are difficult to generate and analyze with refraction
- GRM-type reciprocal processing “assigns” layers
- Tomographic solutions have smoothing and edge effects (called artifacts)
- More difficult in noisy environments or paved surfaces

Seismic refraction benefits

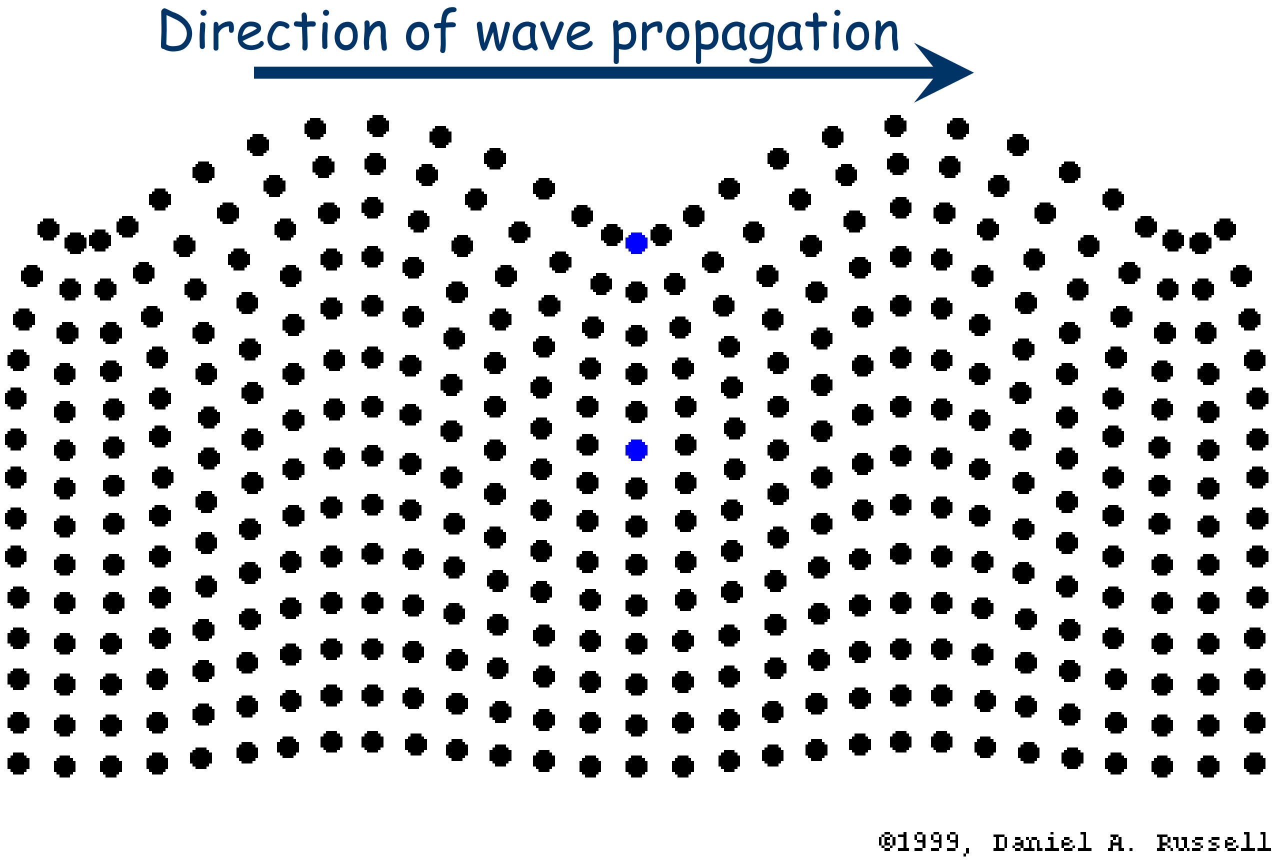
- Provides velocity distribution – vertically AND horizontally
- Defines layer contacts (e.g., dense soils, bedrock, etc.)
- Can account for topography in the processing (need to obtain elevation data)
- Works well in remote & rugged terrain
- Spreads can be acquired contiguously to achieve longer line lengths
- Material properties between and below geotechnical borings
- Can cover long distances – relatively quickly!
- Correlate Vp data with rippability charts, compute Bulk Modulus
- Correlate Vs data with SPT N-values, compute Shear Modulus
- Many equipment manufactures and vendors (cabled and wireless systems)
- Many sources of software available (GRM and Tomography codes)
- Data can be acquired and processed in 2D and 3D with commercially available instrumentation and software

SEISMIC METHODS:

- Borehole Methods
- Body Wave Methods
- **Surface Wave Methods**

Surface Wave Methods

Rayleigh wave particle motion



Rayleigh Waves – particle motion is 'elliptic and retrograde', discovered in 1885 by John William Strutt, 3rd Baron of Rayleigh in England known as Lord Rayleigh

Surface Wave Methods

Basic Concepts

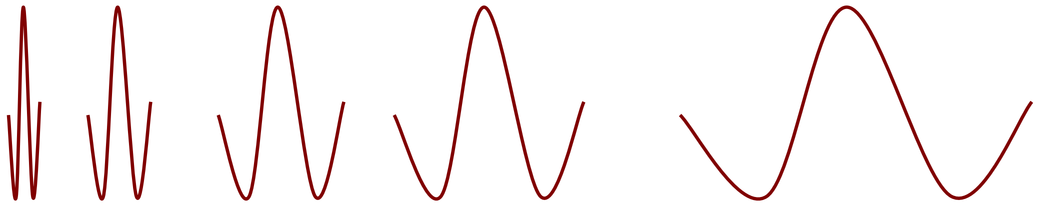
- Body waves travel at a speed independent of their frequency

- Surface waves are '*dispersive*' which means they travel at a speed that is dependent upon their frequency.

→ ***This affects how they are measured and how they are analyzed.***

→ ***Unlike Seismic Refraction, Surface Waves can determine velocities of fast over slow over fast layers***

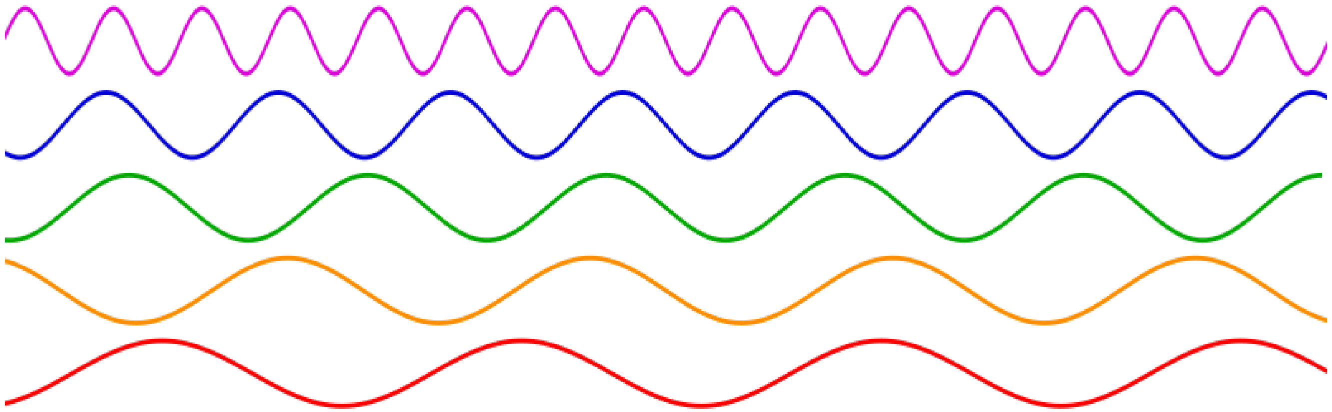
Frequency
(cycles/second or Hz)



Surface Wave Methods

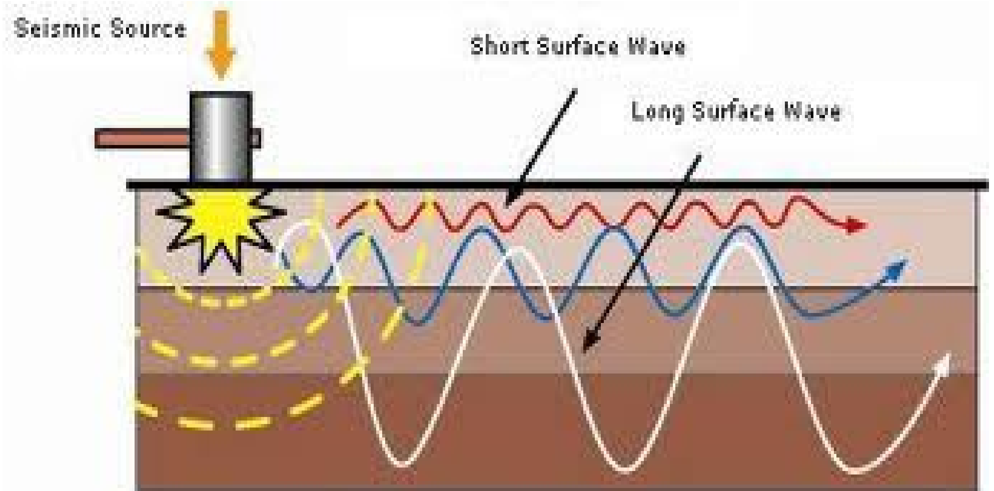
Basic Concepts

Seismic Trace



High frequency or short wavelength

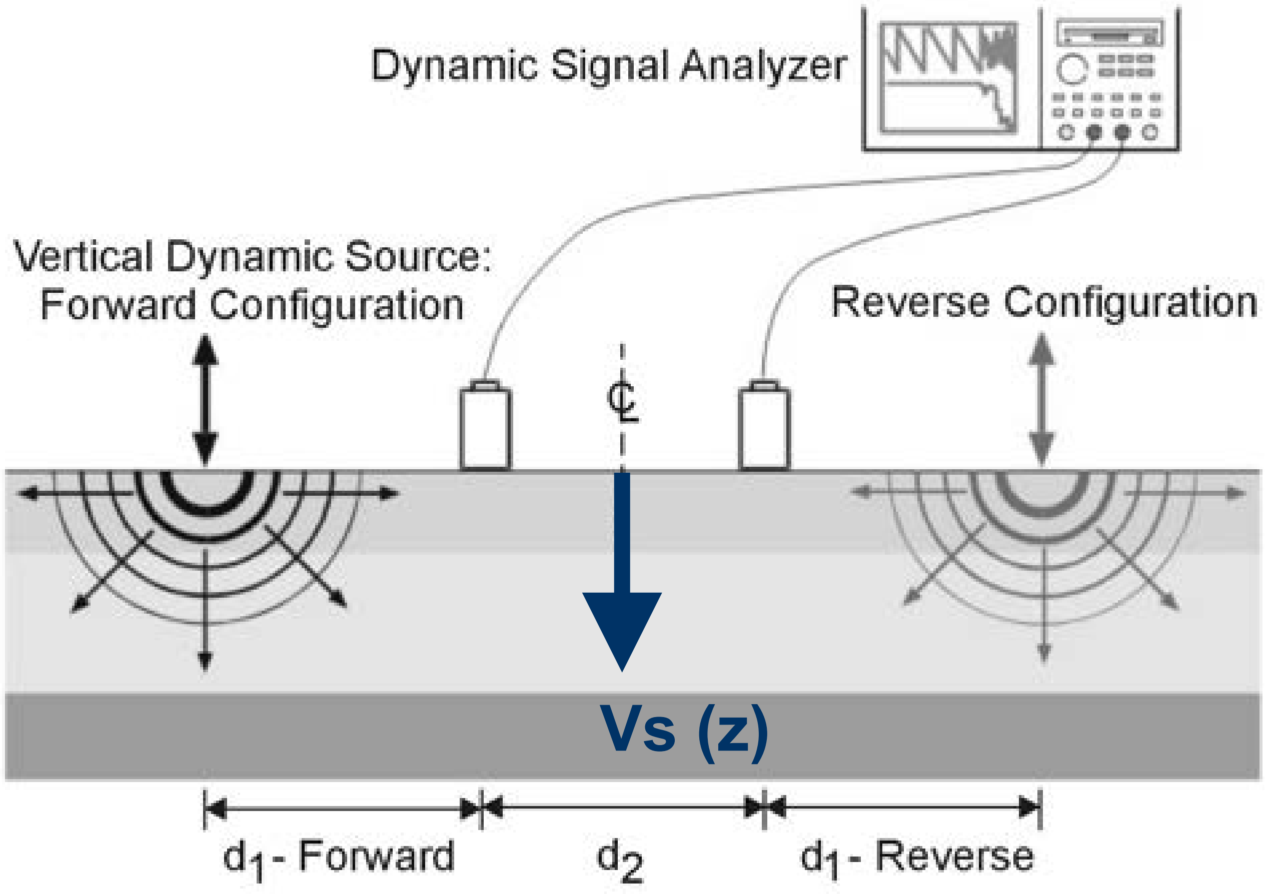
Low frequency or long wavelength



Shallow

Deep

Surface Wave Methods
Spectral Analysis of Surface Waves

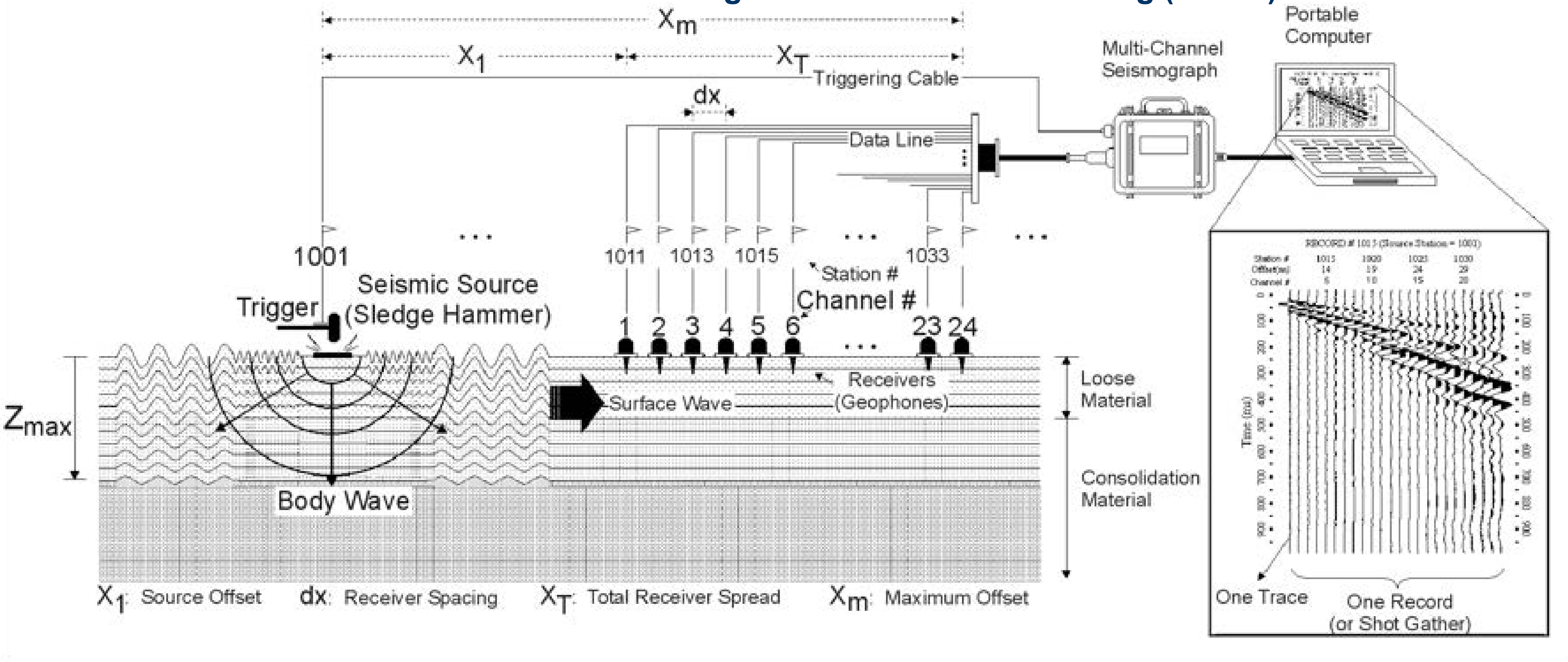


Recording:
- Spectral Analyzer
- 2 channels (*often 4*)
- Low Frequency Geophones (1Hz)
- Record FFT data (cross-power spectra)
- Velocity = frequency x wavelength from phase calculations between 2 receivers

Researched in 1979 by Prof. Kenneth H. Stokoe, II at the University of Texas at Austin with Scott Heisey, MS and then Soheil Nazarian, Ph.D.

Surface Wave Methods Multi-Channel Analysis of Surface Waves (MASW)

Produce ONE Record and get one SASW-like sounding (model)



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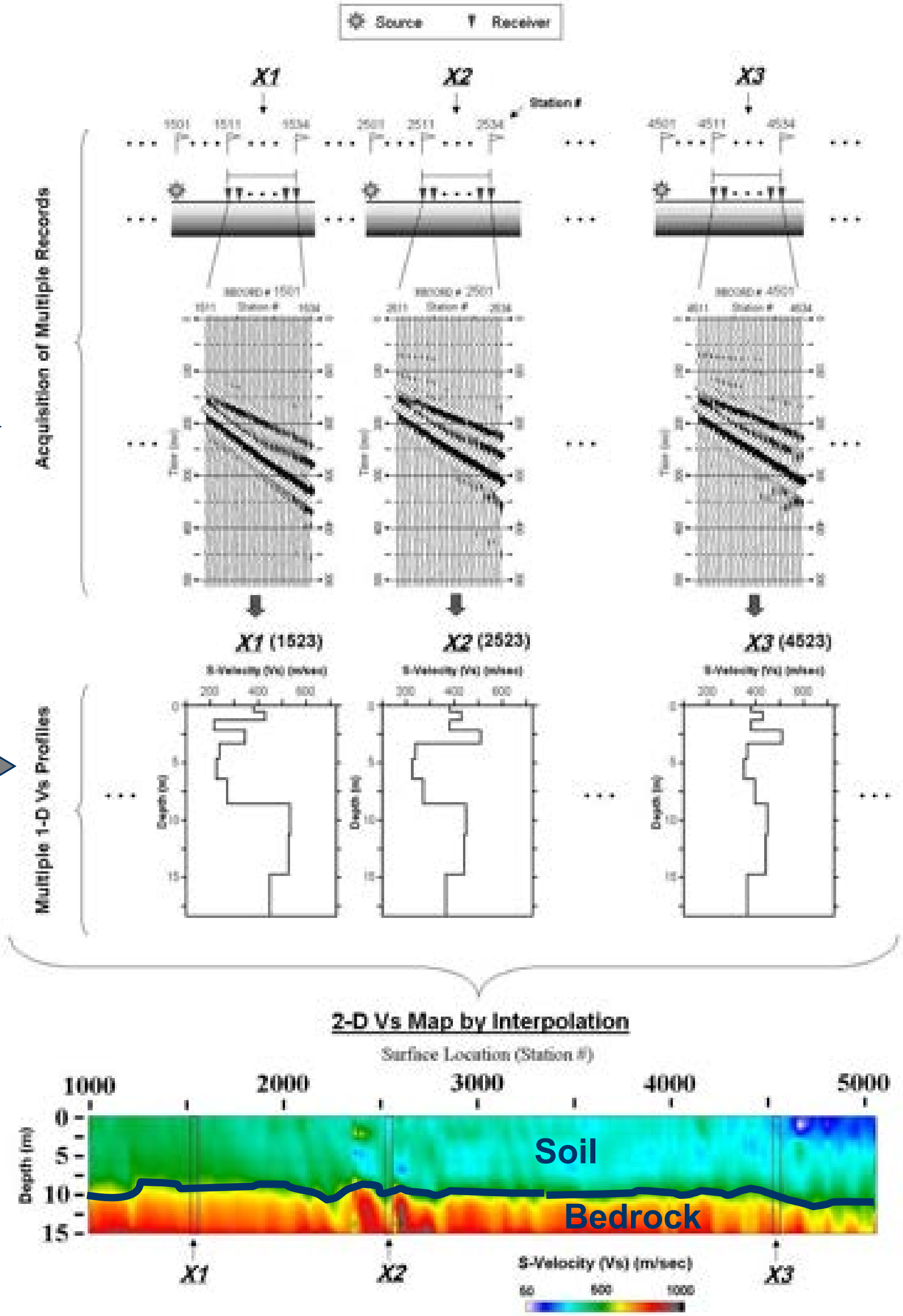
MASW Data Analysis

Acquire ***multiple*** records by moving the same source-receiver configuration after each acquisition

Prepare multiple number of 1-D Vs profiles by following previous 3-step procedure.

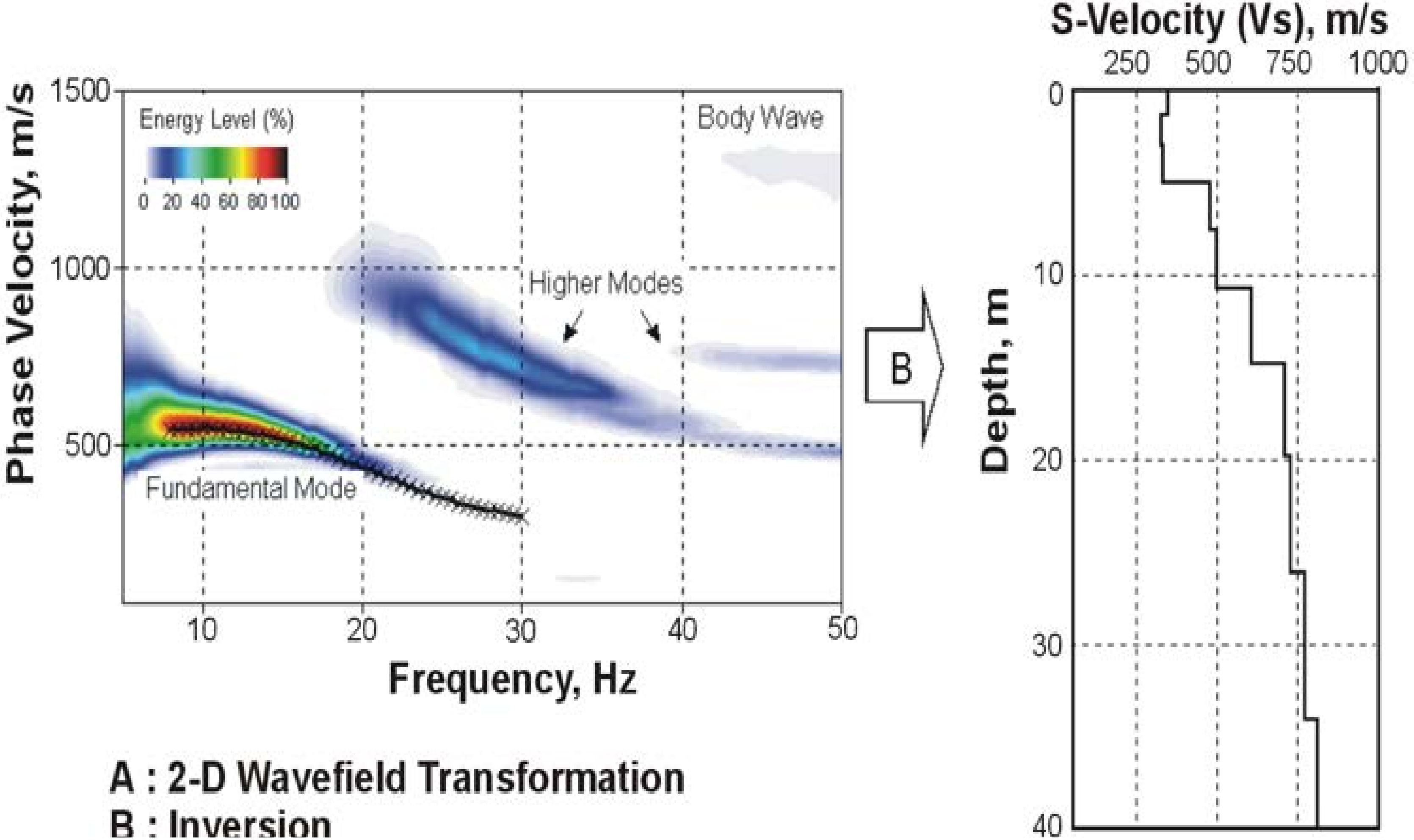
Construct a 2-D Vs cross-section by using an appropriate interpolation scheme; interpret for geologic layering.



MASW data analysis

Extraction of Signal Dispersion Curve

1-D S-Velocity (Vs) Profile



A : 2-D Wavefield Transformation
B : Inversion

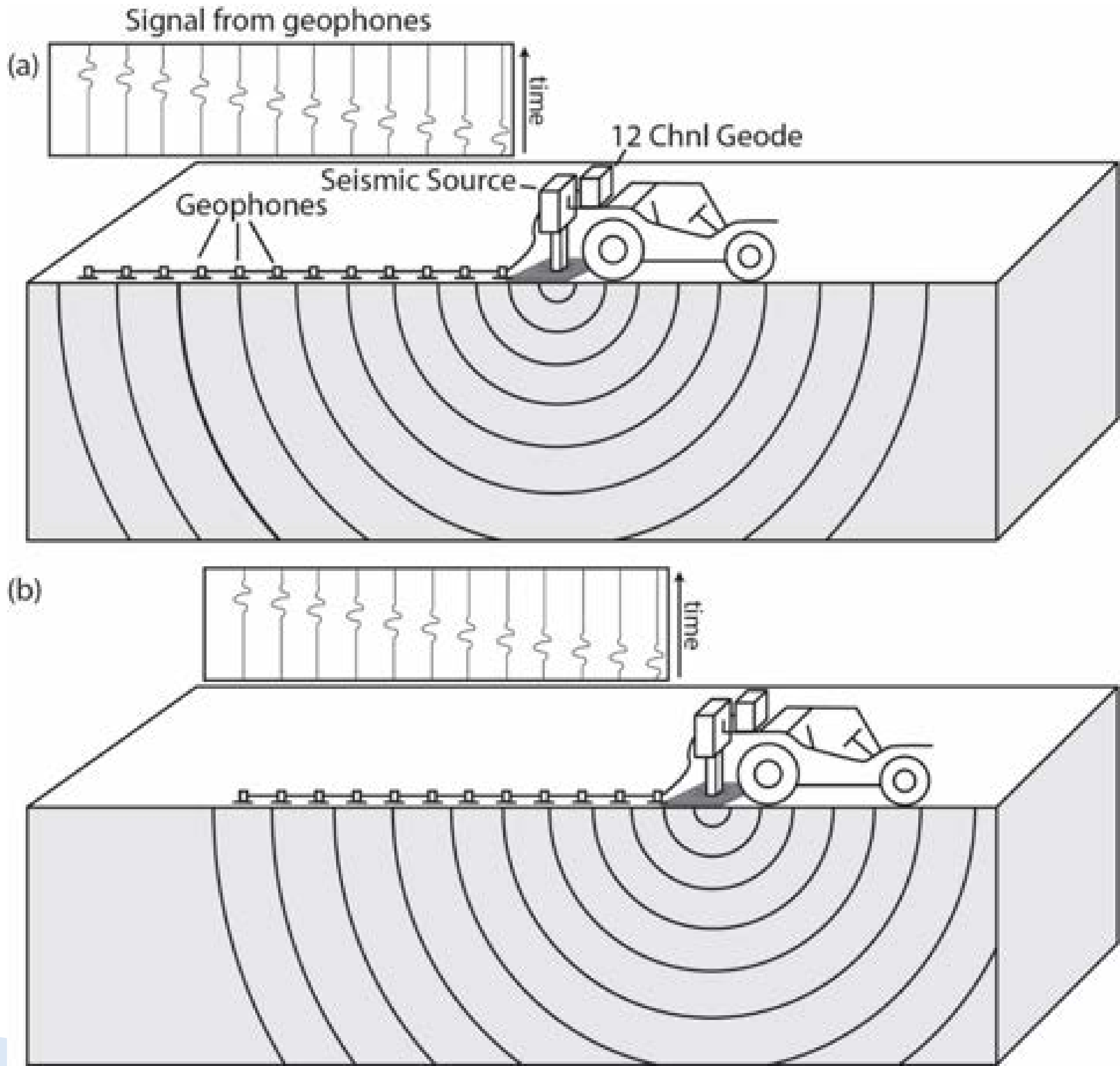
Seismic Surveys with Utility Terrain Vehicle (UTV), Accelerated Drop Weight (AWD) and towed Landstreamer Geophone Array

Multi-Channel Analyses of Surface Waves (MASW) for Shear Wave Velocity (S-wave, Vs) and Bedrock Depth

&

Seismic Refraction Tomography (SRT) data for Primary Compressional Wave (P-wave, Vp) and Bedrock Depth/Rippability

MASW and SRT analyses are both possible from same data



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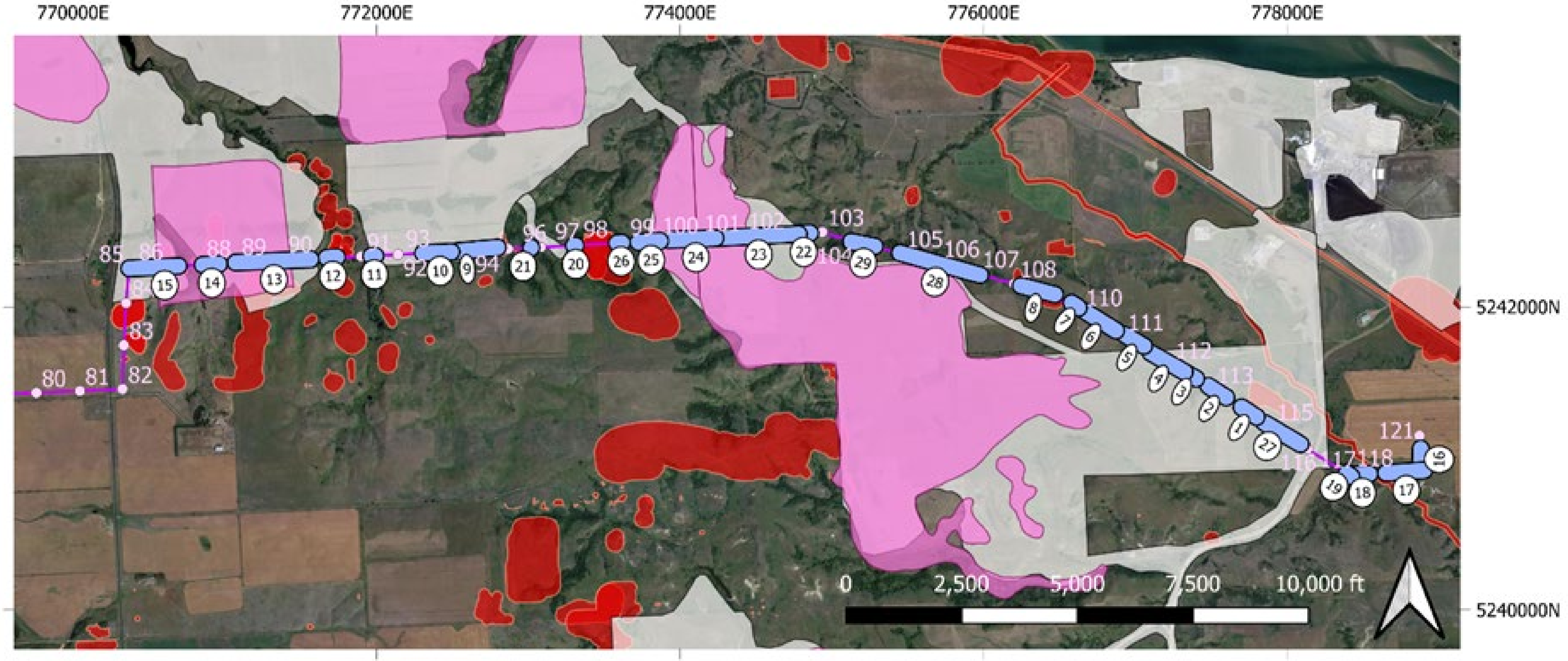
Polaris Ranger XP1000 UTV with GPS & Mini-Accelerated Weight Drop of 80 lbs impacting a nylon/ aluminum strike plate to impart seismic energy (left & center photos) and the towed Landstreamer 24-channel geophone array on skid plates spaced at 6 ft - 42 ft behind the AWD strike plate (right photo).

Map view of the MASW survey area for overburden/bedrock depth with the full transmission line with labeled towers as well as the cultural avoidance areas (red), SSURG mine spoils (white) and NDGS mine spoils (pink). Seismic survey line locations are shown as blue polylines covering from the start to the end of each line of landstreamer geophone array coverage



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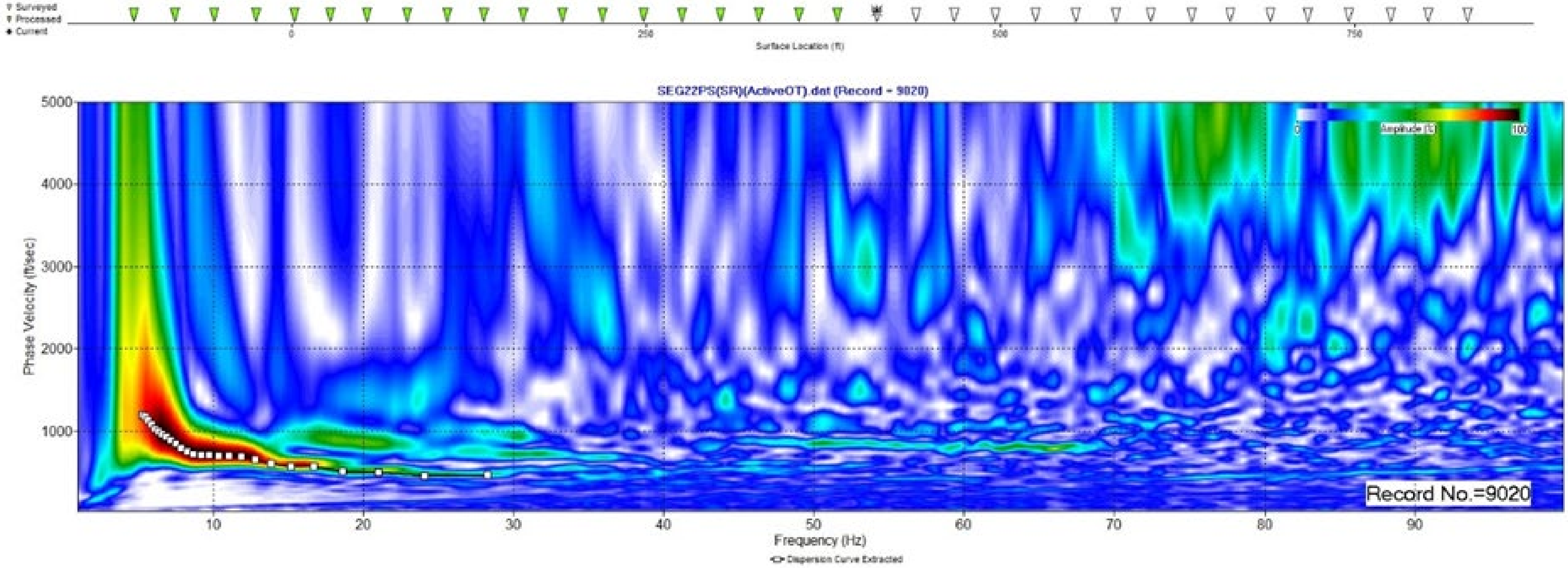
Plot of a composite dispersion curve generated from 24 channels of the MASW surveys collected on Line 9 at the project site (shot record 20). The inversion model fitting of the data is show by the small white squares from frequencies of ~5 to 30 Hz in the plot above (ParkSeis MASW Software)



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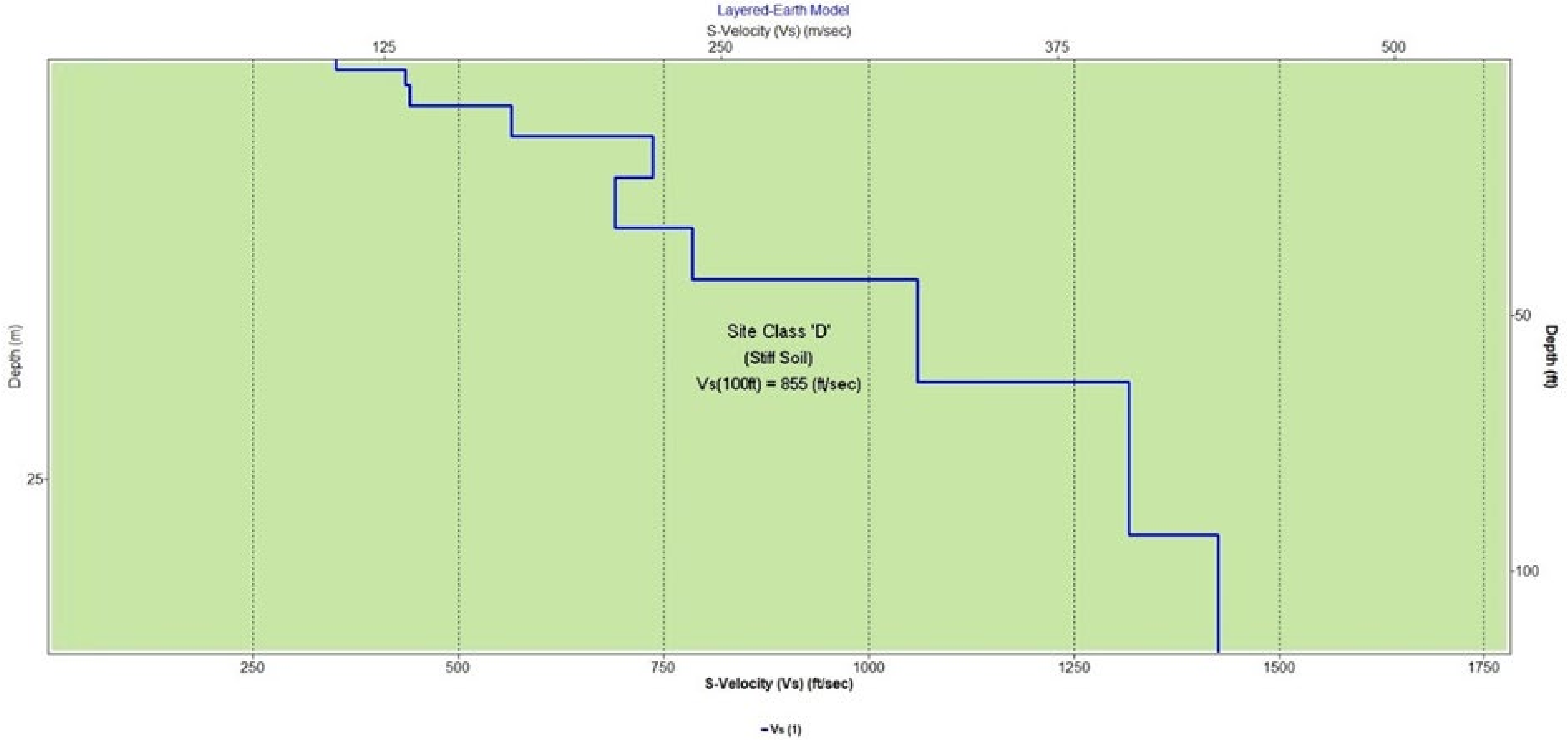
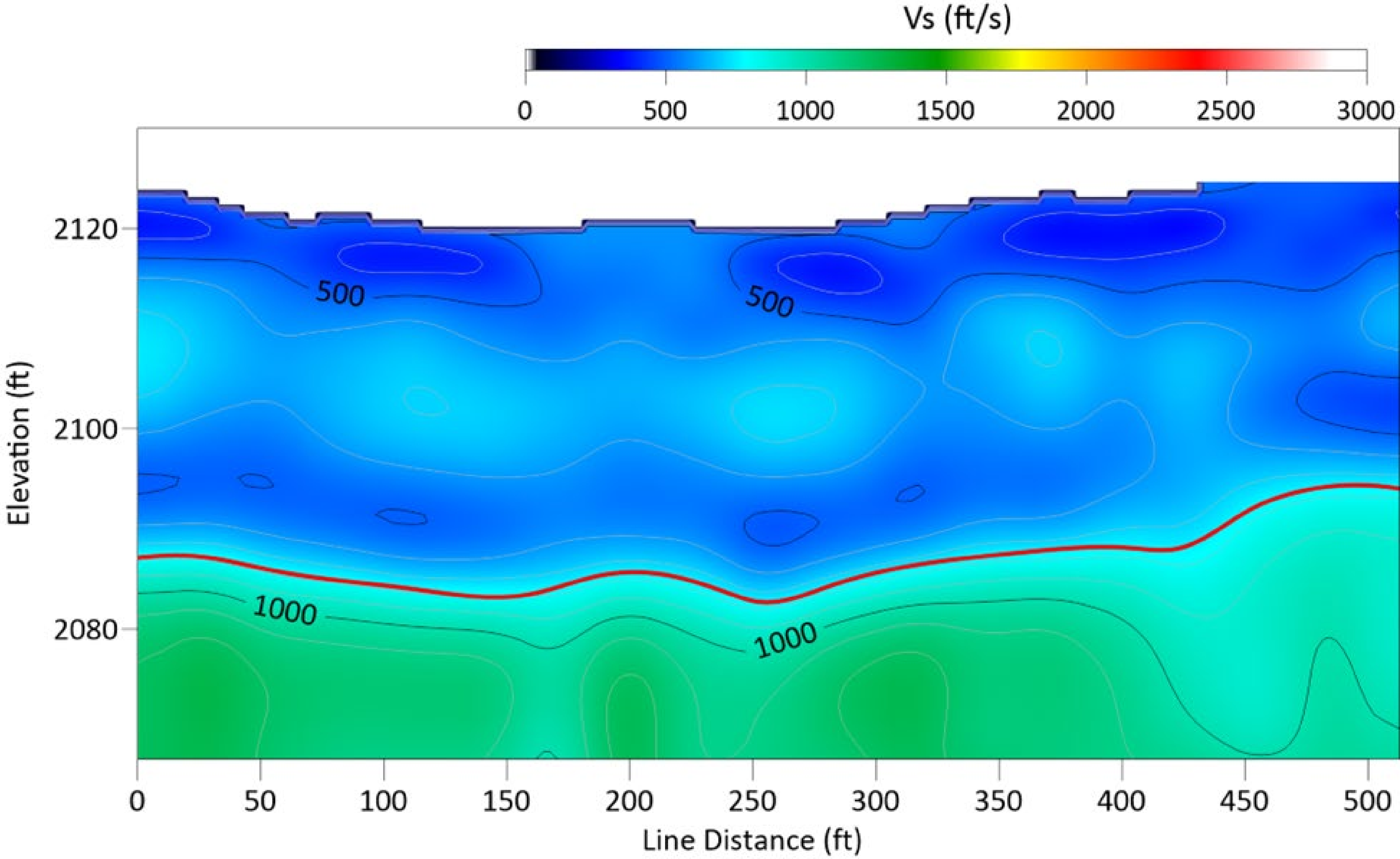
An aerial map view from QGIS presenting the location of seismic survey lines 12, 11, 10, and 9 (blue) with labeled towers as well as the cultural avoidance areas (red) and SSURG mine spoils (white).

Averaged 1-D Vs 100-ft site classification for Line 9 with depth model from ParkSeis MASW inversion analyses plotted to 100 feet in blue lines.



Dell Notebook in UTV Cab for Data Recording and UTV with Landstreamer Geophone Array for MASW and SRT Surveys at 8 Wind Turbine Sites to get Vs and Vp velocity vs. depth profiles using 16-lb Sledgehammer impacts to plate

Golden Software Surfer gridded MASW topography corrected results for turbine site GEO-004 with elevation plotted in ft and distance Easting from the start to the end of the line in ft. Bedrock depth is interpreted at ~35 ft where the red horizon is drawn.



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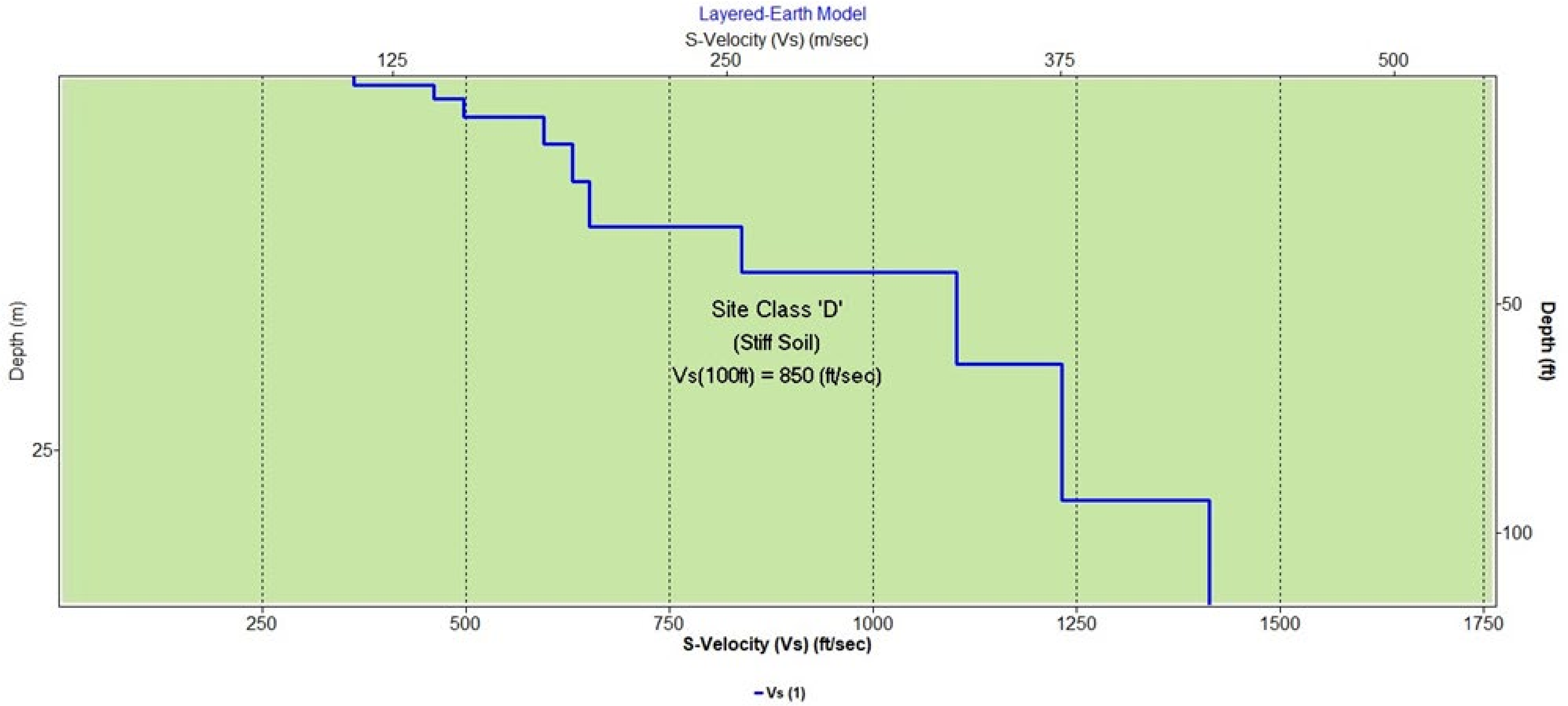
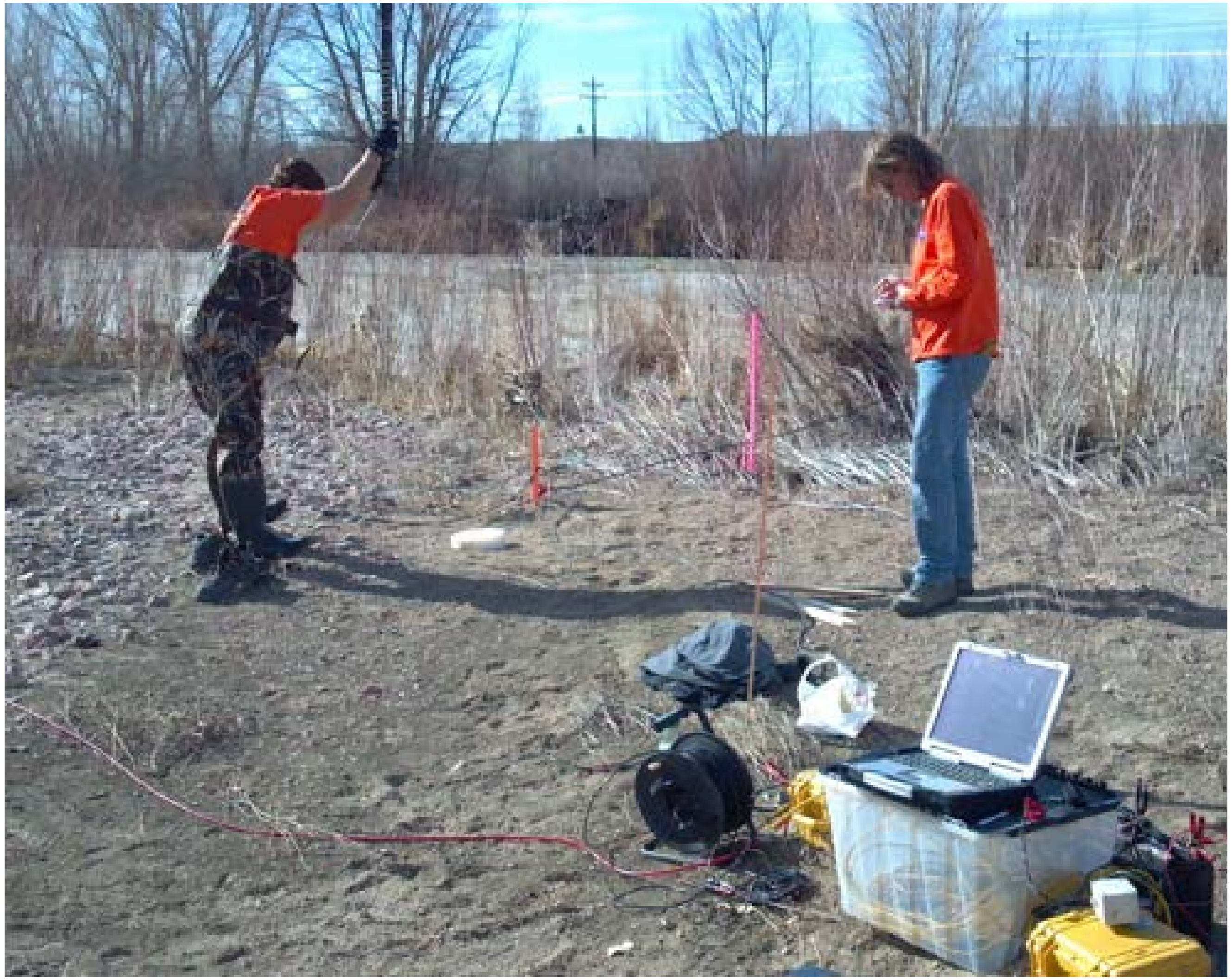
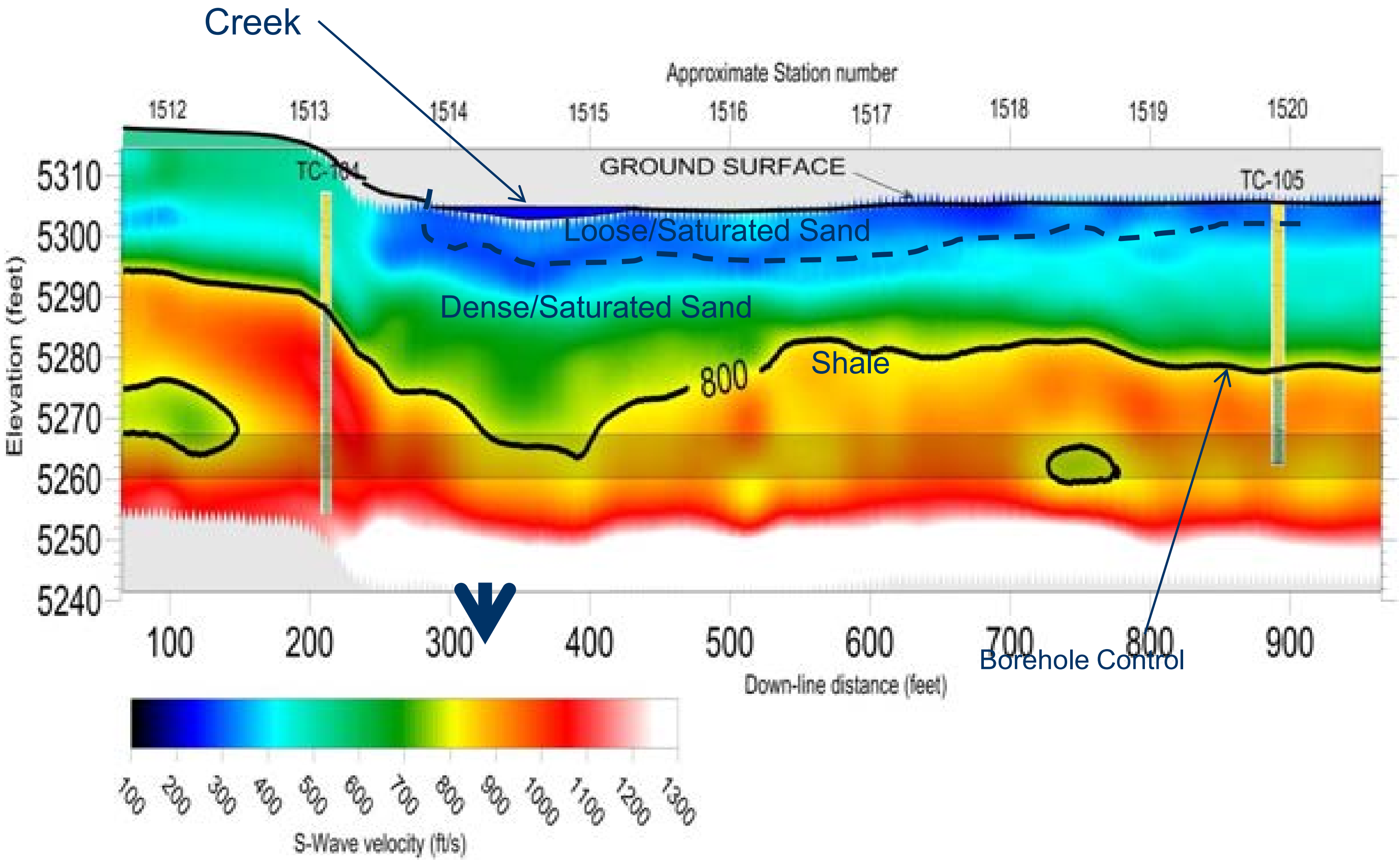
Averaged 1-D Vs100-ft site classification for turbine site GEO-004 with depth model in blue plotted to 100 feet.



MASW data collection across a creek



MASW 2D Shear Wave Velocity Profile from across a creek



Vs30 (or Vs100') Basic Concepts (International Building Code Spec)

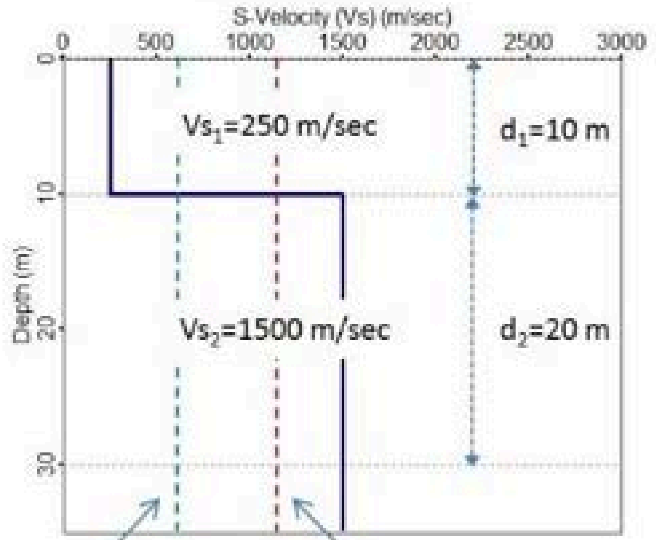
Site Class	Soil Profile Name	Average Properties in Top 100 feet, See Section 1613.5.5		
		Soil shear wave velocity, $\bar{v}_S$, (ft/s)	Standard penetration resistance, $\bar{N}$	Soil undrained shear strength, $\bar{S}_u$, (psf)
A	Hard rock	$\bar{v}_S > 5{,}000$	N/A	N/A
B	Rock	$2{,}500 < \bar{v}_S \le 5{,}000$	N/A	N/A
C	Very dense soil and soft rock	$1{,}200 < \bar{v}_S \le 2{,}500$	$\bar{N} > 50$	$\bar{S}_u > 2{,}000$
D	Stiff soil profile	$600 \le \bar{v}_S \le 1{,}200$	$15 \le \bar{N} \le 50$	$1{,}000 \le \bar{S}_u \le 2{,}000$
E	Soft soil profile	$\bar{v}_S < 600$	$\bar{N} < 15$	$\bar{S}_u < 1{,}000$
E	---	Any profile with more than 10 feet of soil having the following characteristics: 1. Plasticity index PI>20, 2. Moisture content w≥40%, and 3. Undrained shear strength $\bar{S}_u < 500$ psf		
F	---	Any profile containing soils having one or more of the following characteristics: 1. Soils vulnerable to potential failure or collapse under seismic loading such as liquefiable soils, quick and highly sensitive clays, collapsible weakly cemented soils. 2. Peats and/or highly organic clays (H>10 feet of peat and/or highly organic clay where H = thickness of soil) 3. Very high plasticity clays (H>25 feet with plasticity index PI>75) 4. Very thick soft/medium stiff clays (H>120 feet)		

Surface wave methods benefits
Vs30m (Vs100ft) Calculations

Evaluation of Average S-Velocity (Vs^{30})

(for Top 30 m)

Layer Model (Example)



$\overline{Vs_2} \cong 563\ (m/sec) = Vs^{30}$

(Method 2)

$\overline{Vs_1} \cong 1083\ (m/sec)$

(Method 1)

<u>Methods To Calculate Average Shear-Velocity ($\overline{Vs}$)</u>

(for Top 30 m)

Method 1: $\overline{Vs_1} = \sum Vs_i \times \left(\frac{d_i}{30}\right)$

(Vs_i = shear-wave velocity, d_i = thickness of i-th layer)

Method 2: $\overline{Vs_2} = \frac{\sum d_i}{\sum t_i} = \frac{\sum d_i}{\sum\left(\frac{d_i}{Vs_i}\right)}$

(t_i= one-way travel time in i-th layer)

$\overline{Vs_1} = \left(250 \times \frac{10}{30}\right) + \left(1500 \times \frac{20}{30}\right) \cong 1083\ (m/sec)$

$\overline{Vs_2} = \frac{(10+20)}{\left(\frac{10}{250}+\frac{20}{1500}\right)} \cong 563\ (m/sec) = Vs^{30}$

$Vs^{30} = \overline{Vs_2}$ **(Method 2!)**

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Surface wave methods benefits

- Easy acquisition – 1D and 2D
- Image low-velocity layers beneath high-velocity layers
- Investigate very shallow to deep
- Great for highways, runways, tarmacs, etc. (i.e., hard surfaces)
- Non-intrusive evaluation of shear modulus
- Large volumes = bulk measurement
- ANY seismic source works!

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Combining body & surface wave methods

- “P, S, and S” Approach
- Refraction tomography for Vp
- MASW for shallow Vs
- Passive Surface-Waves for deep Vs

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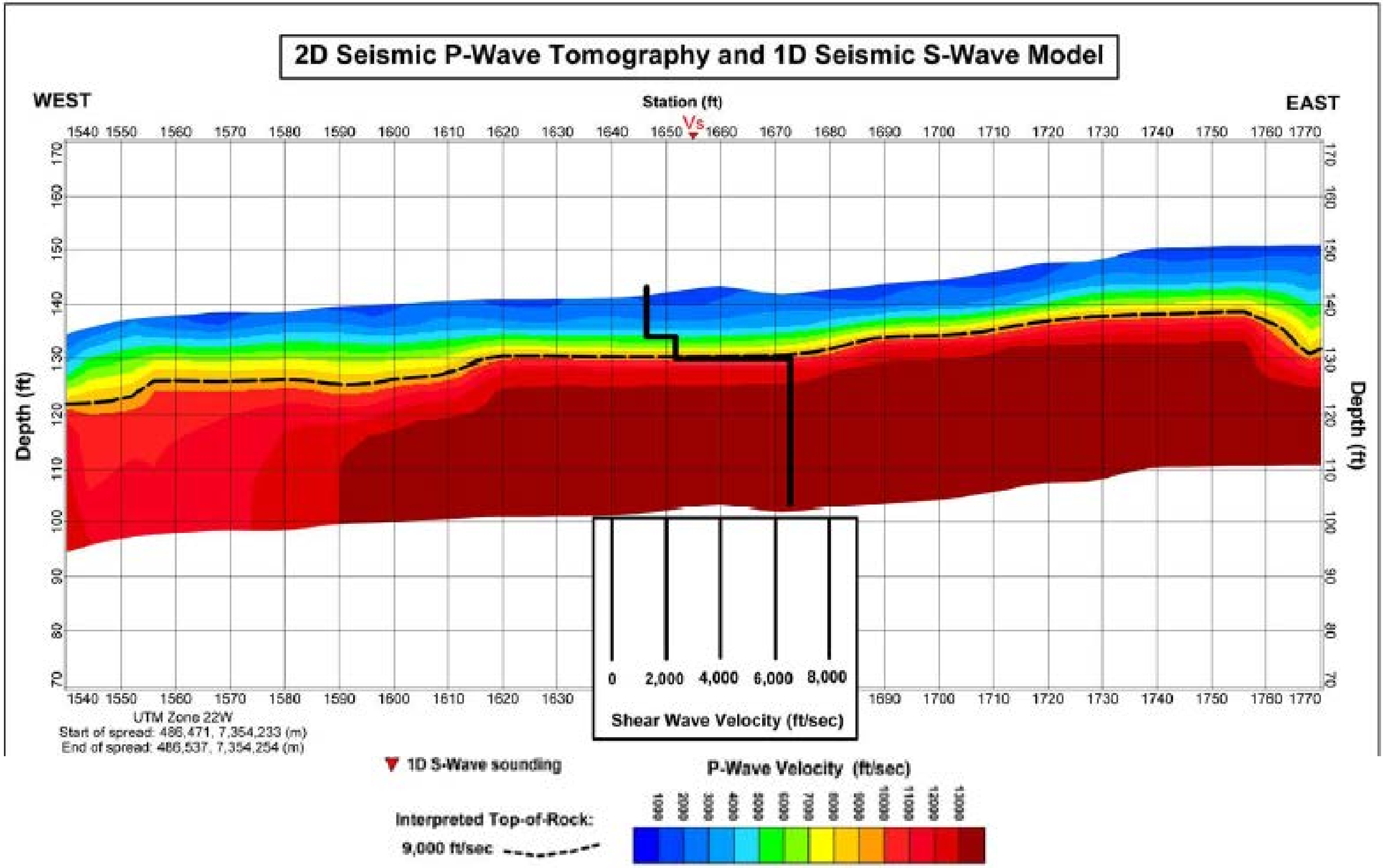
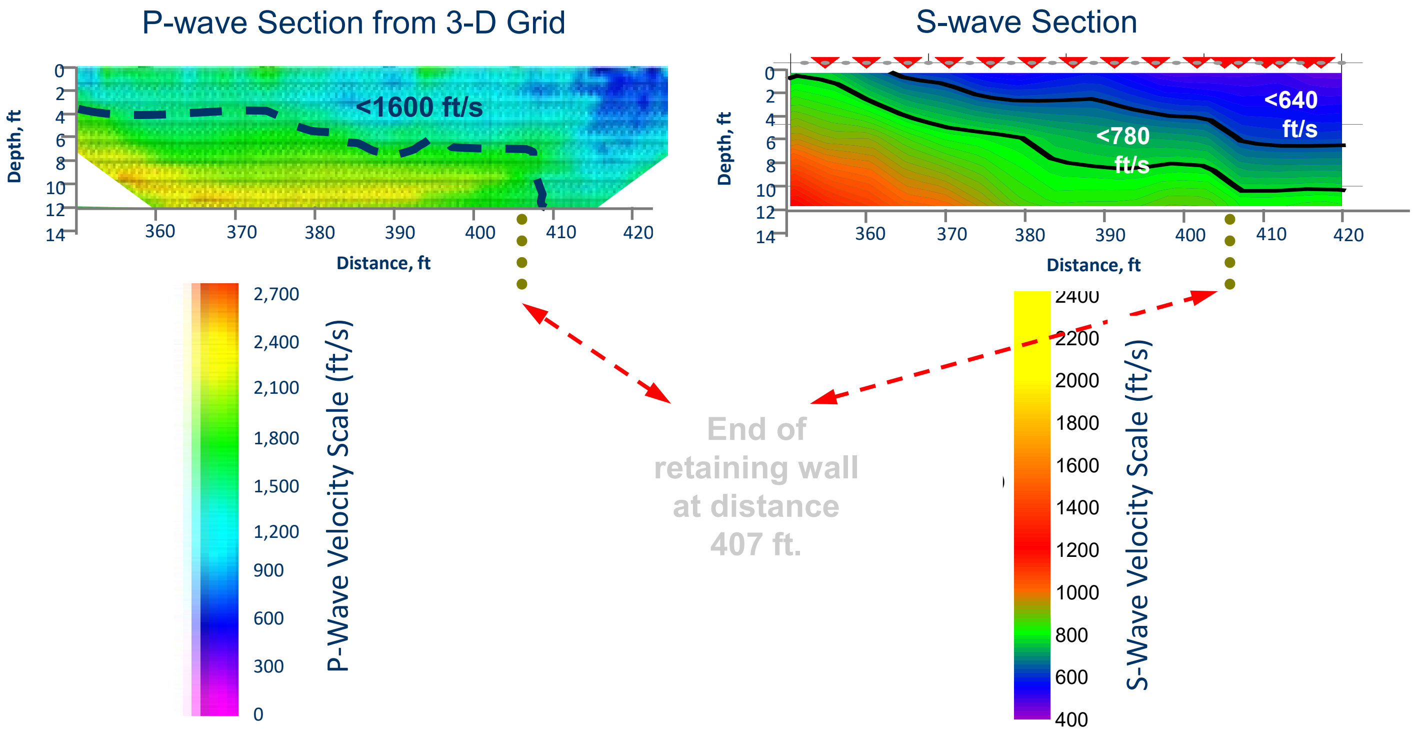
Combining body & surface wave methods



Combining body & surface wave P- and S-wave Velocity Results



2D Refraction Tomography Example

Combined Vp and Vs results to produce Elastic Moduli

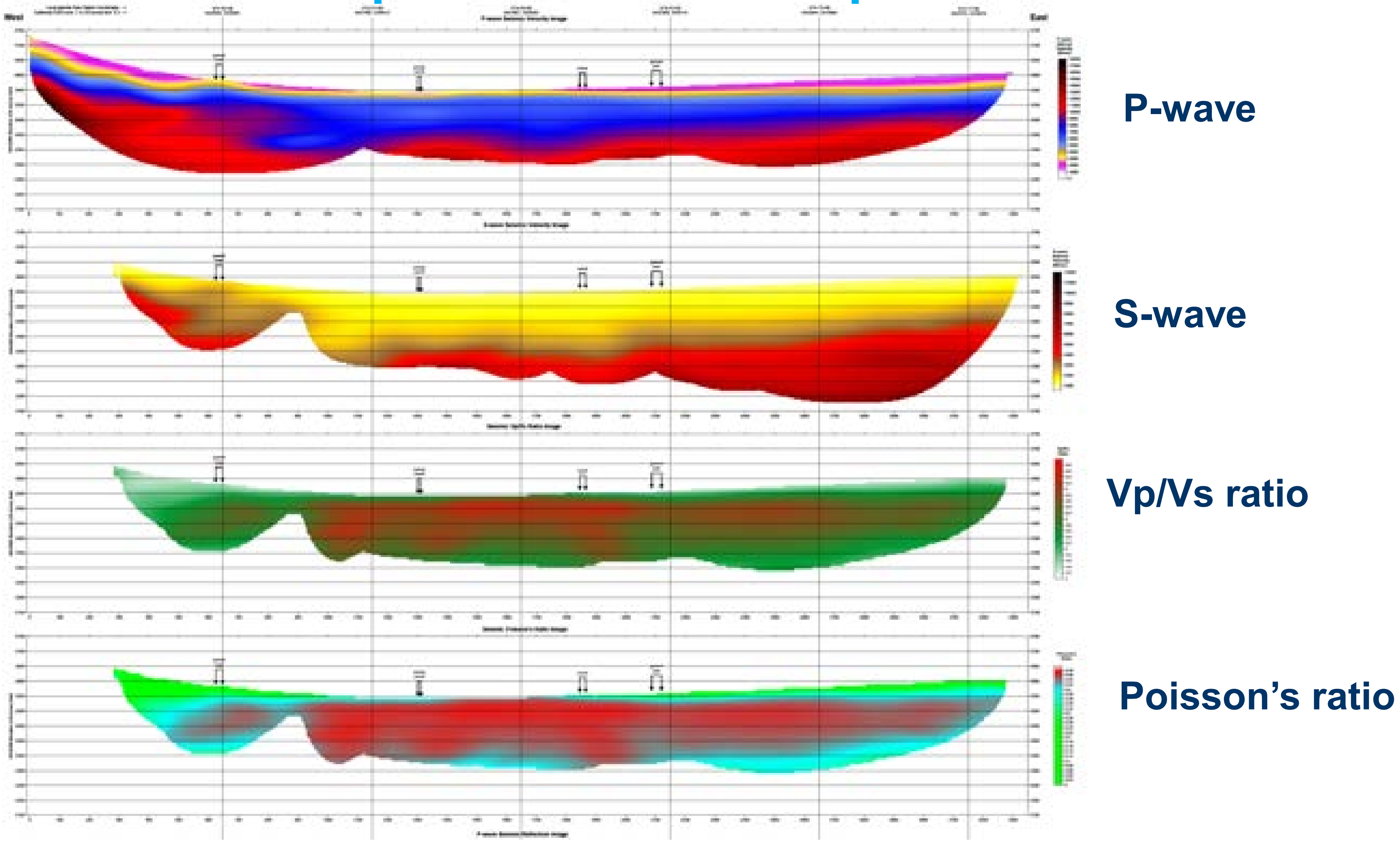


Image courtesy of USGS

Can you help with tunnel alignment for TBM?

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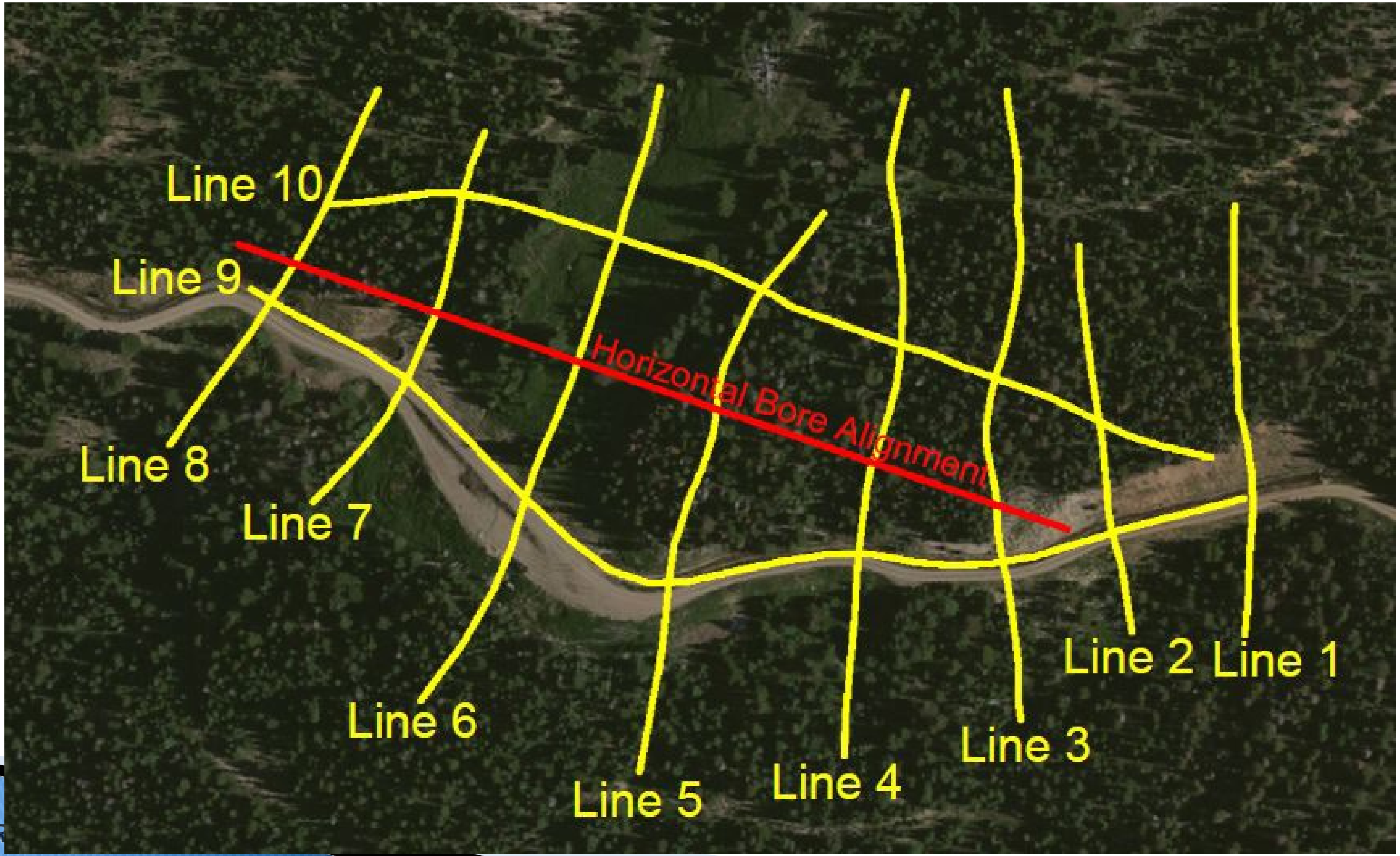
Deep Tunnel Bore (water transfer) – Seismic Refraction Tomography Lines to map Bedrock



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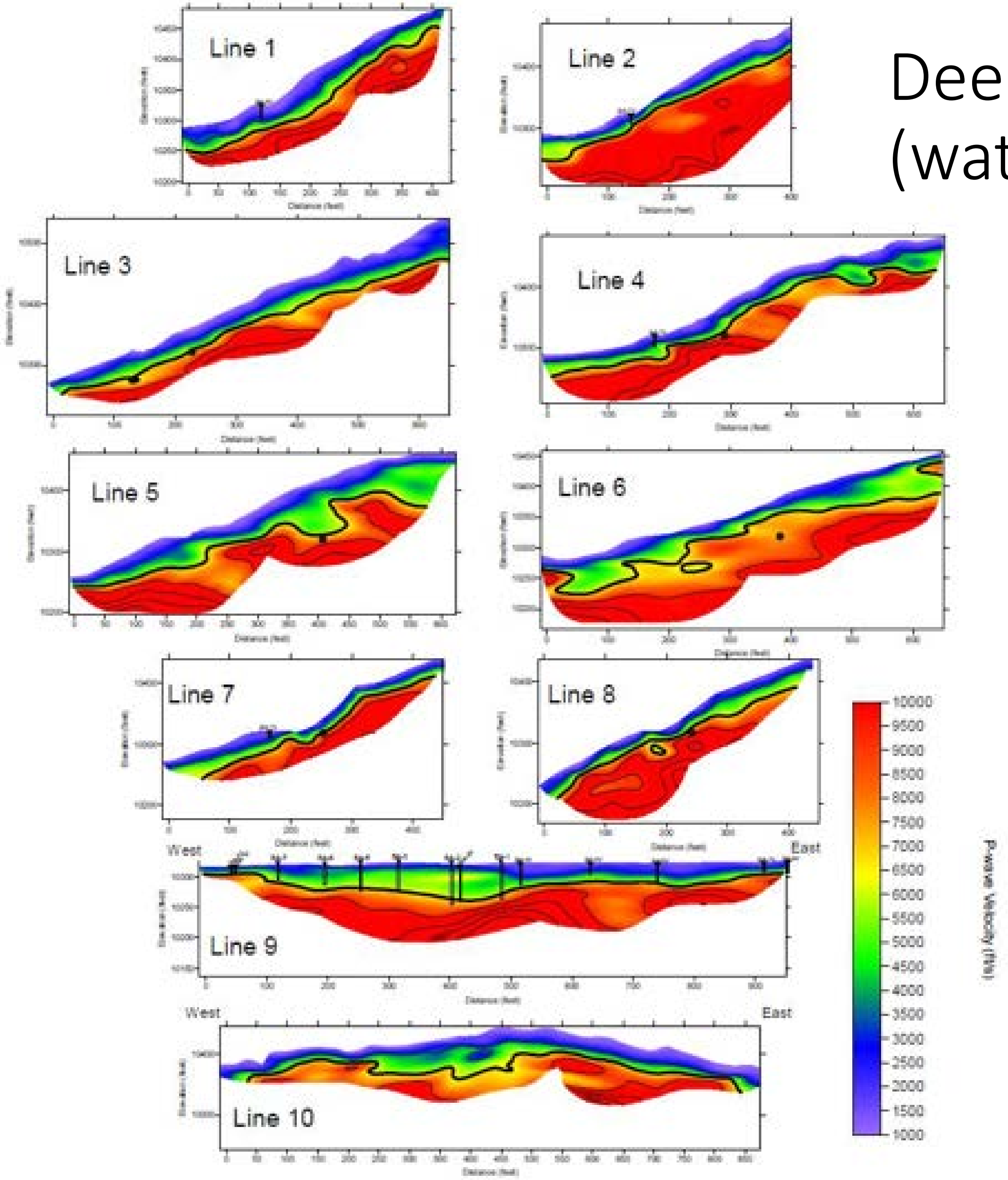
Deep Tunnel Bore (water transfer)



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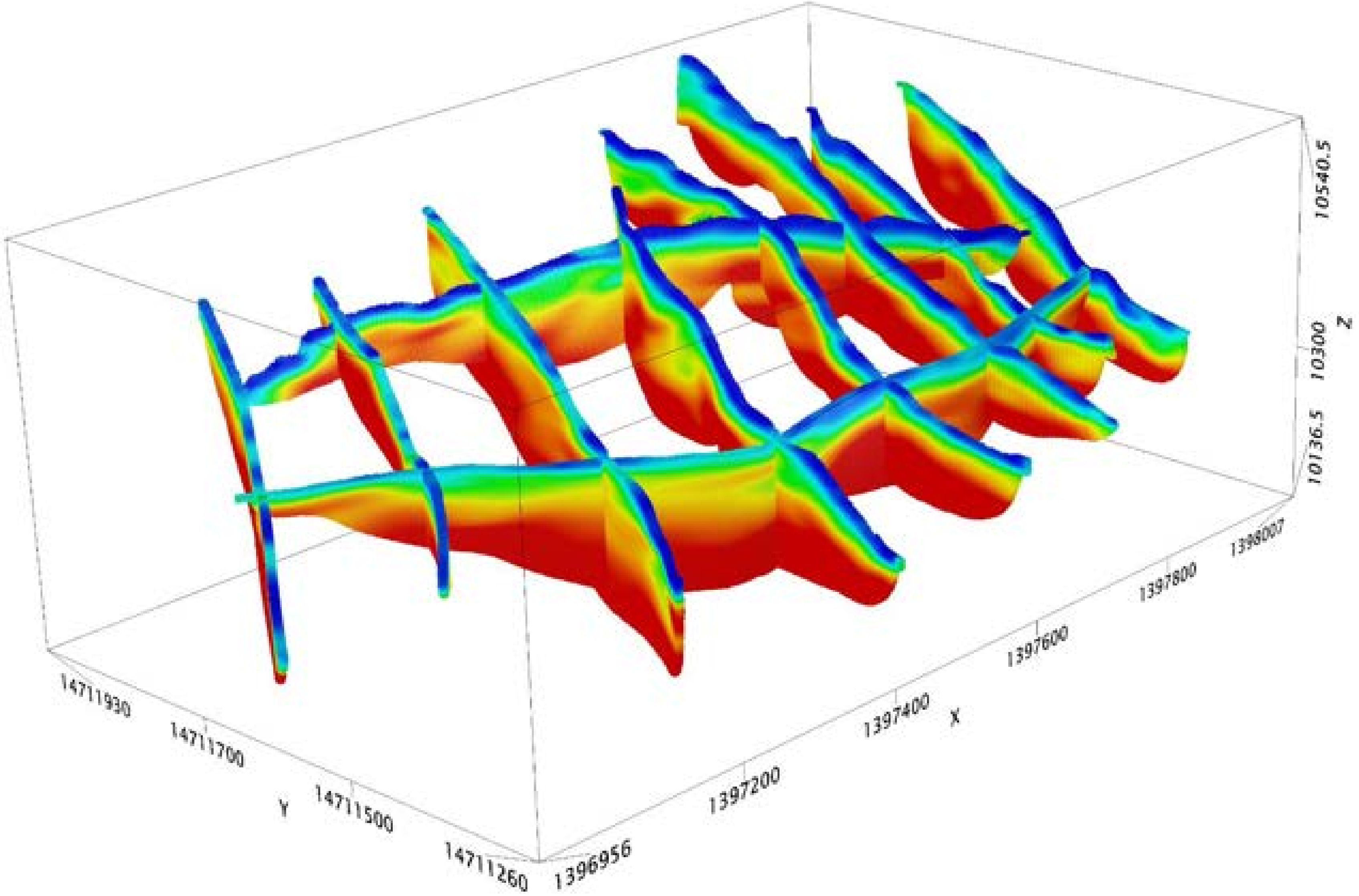
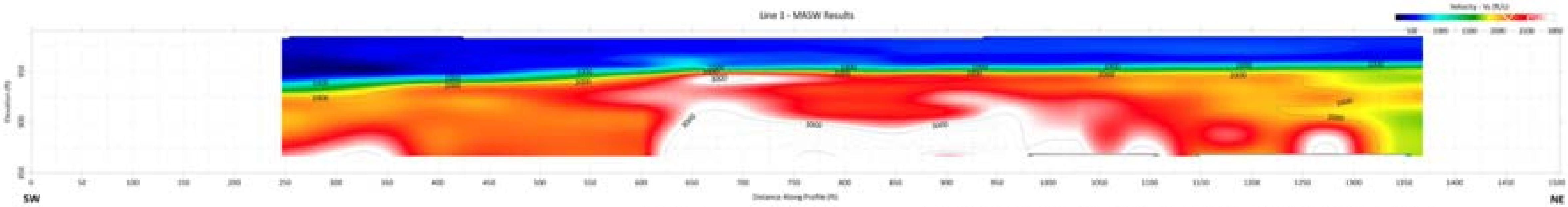
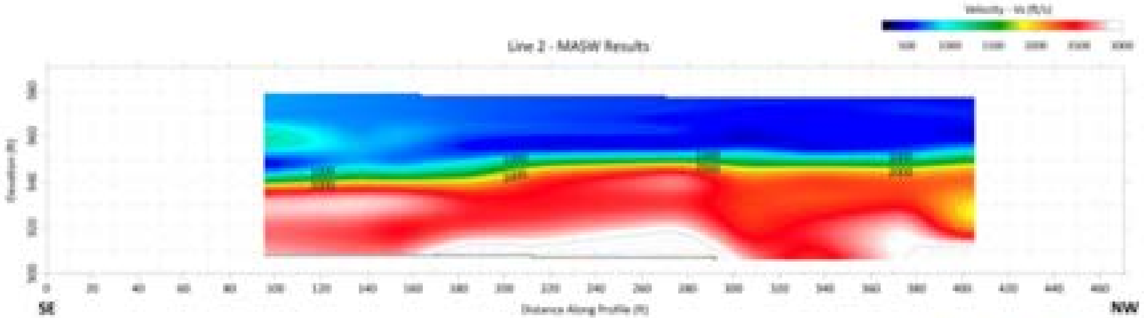
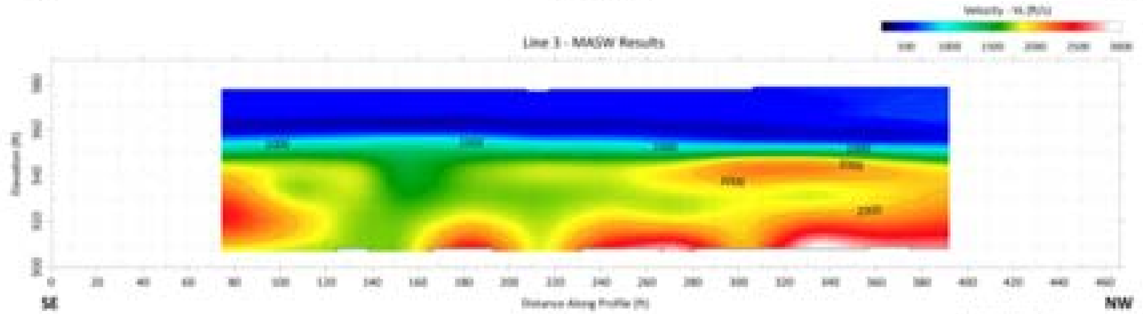
3-D View of Seismic Refraction Tomography Velocities for Deep Tunnel Bore (water transfer)

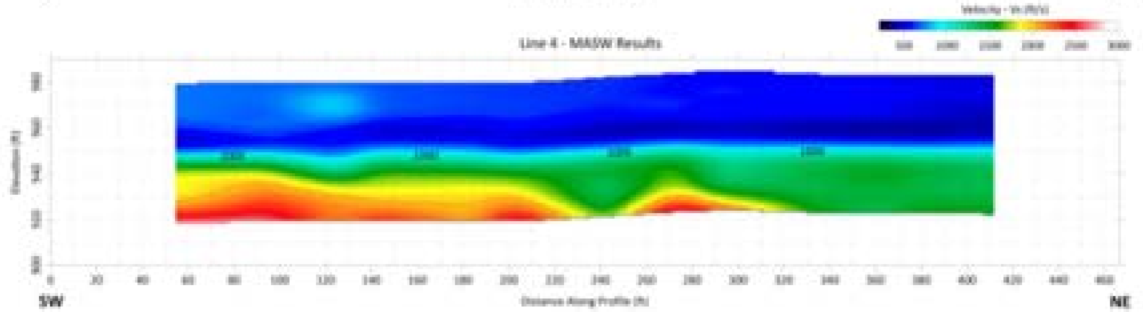


MASW for tunnel alignment looking for any paleochannels or areas of lower velocities in the bedrock for development of a tunnel. Note topography and elevations.

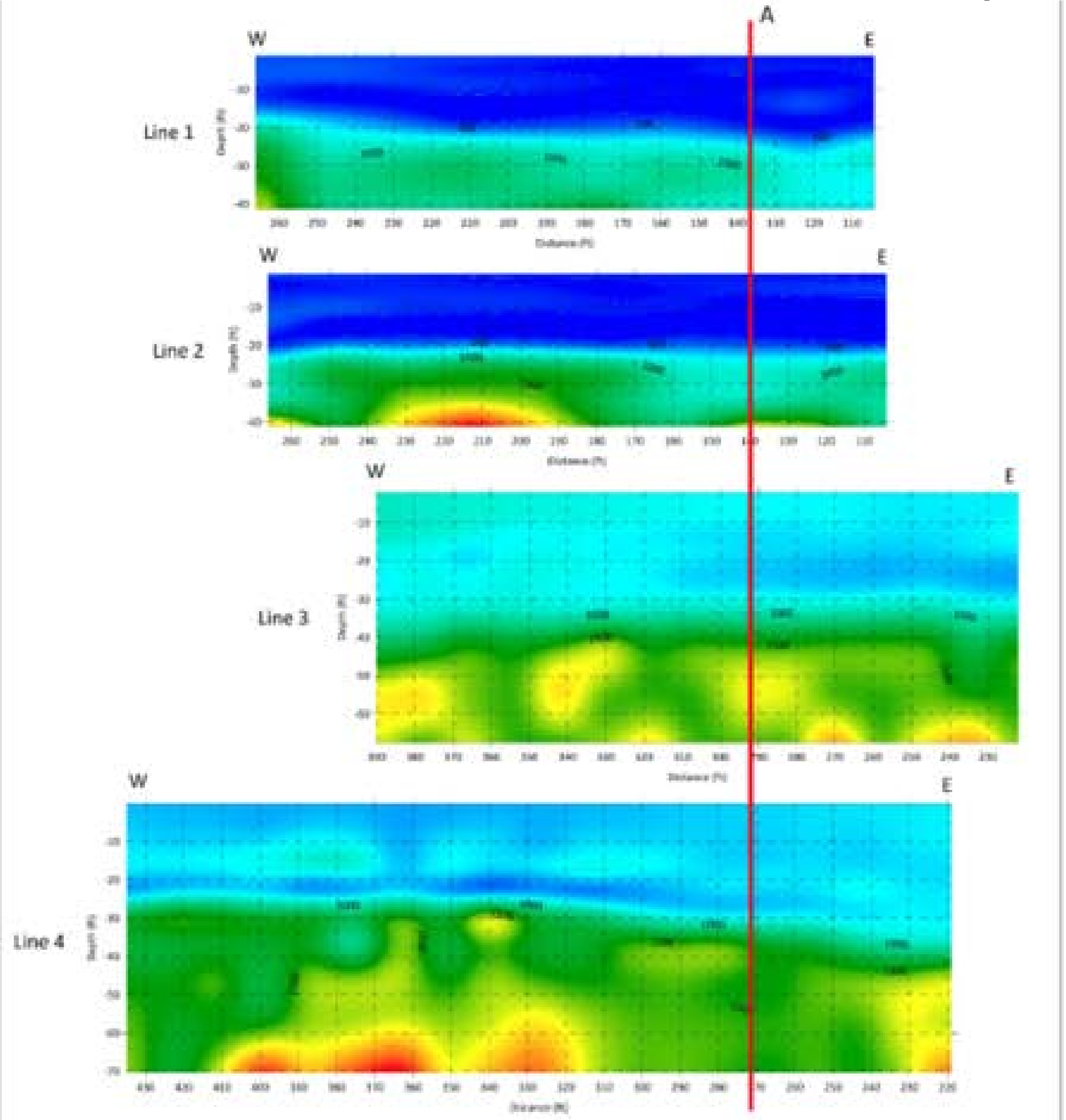


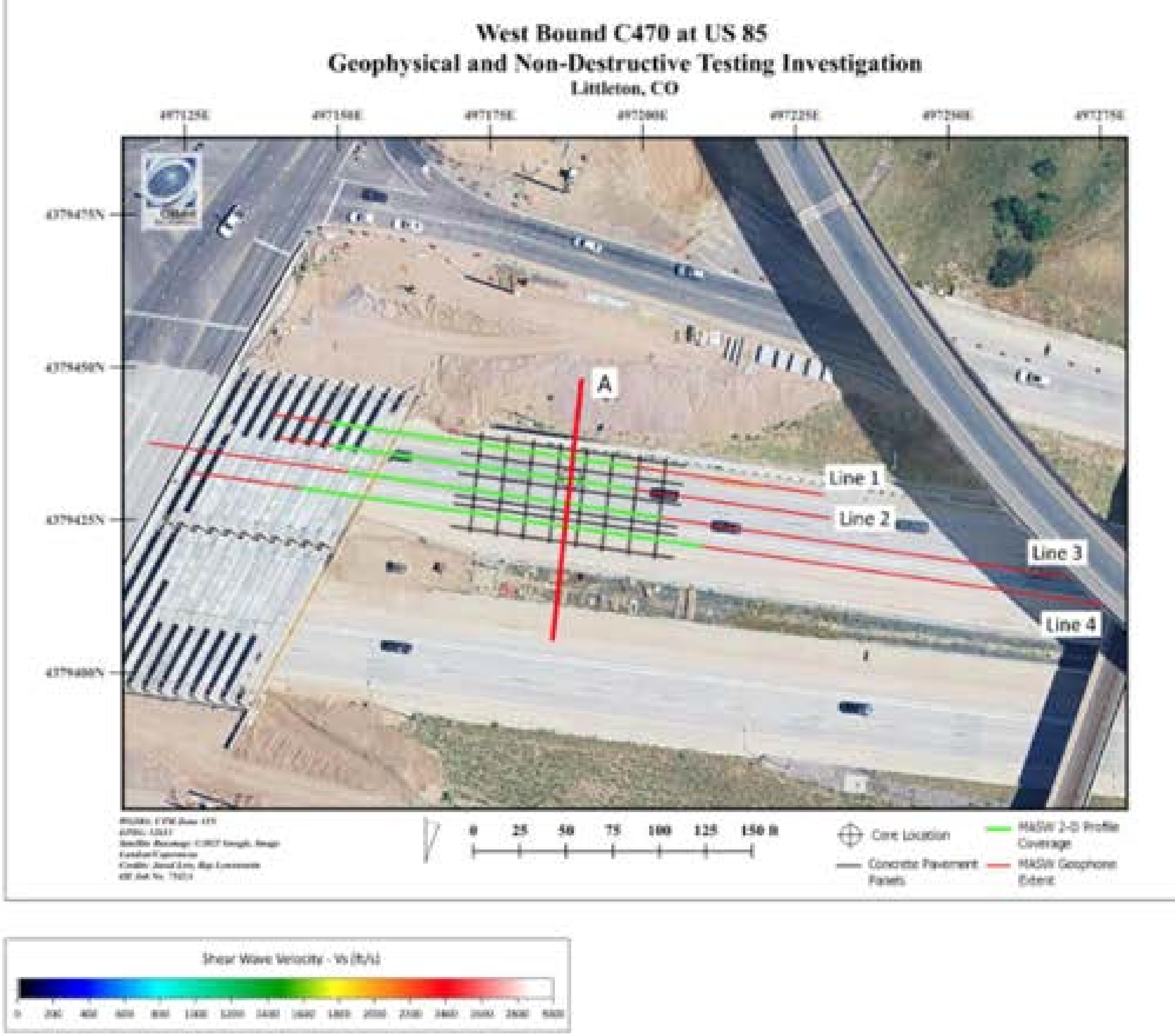






MASW Seismic Surveys on Interstate to check for soil and bedrock support/shear moduli conditions below concrete pavement





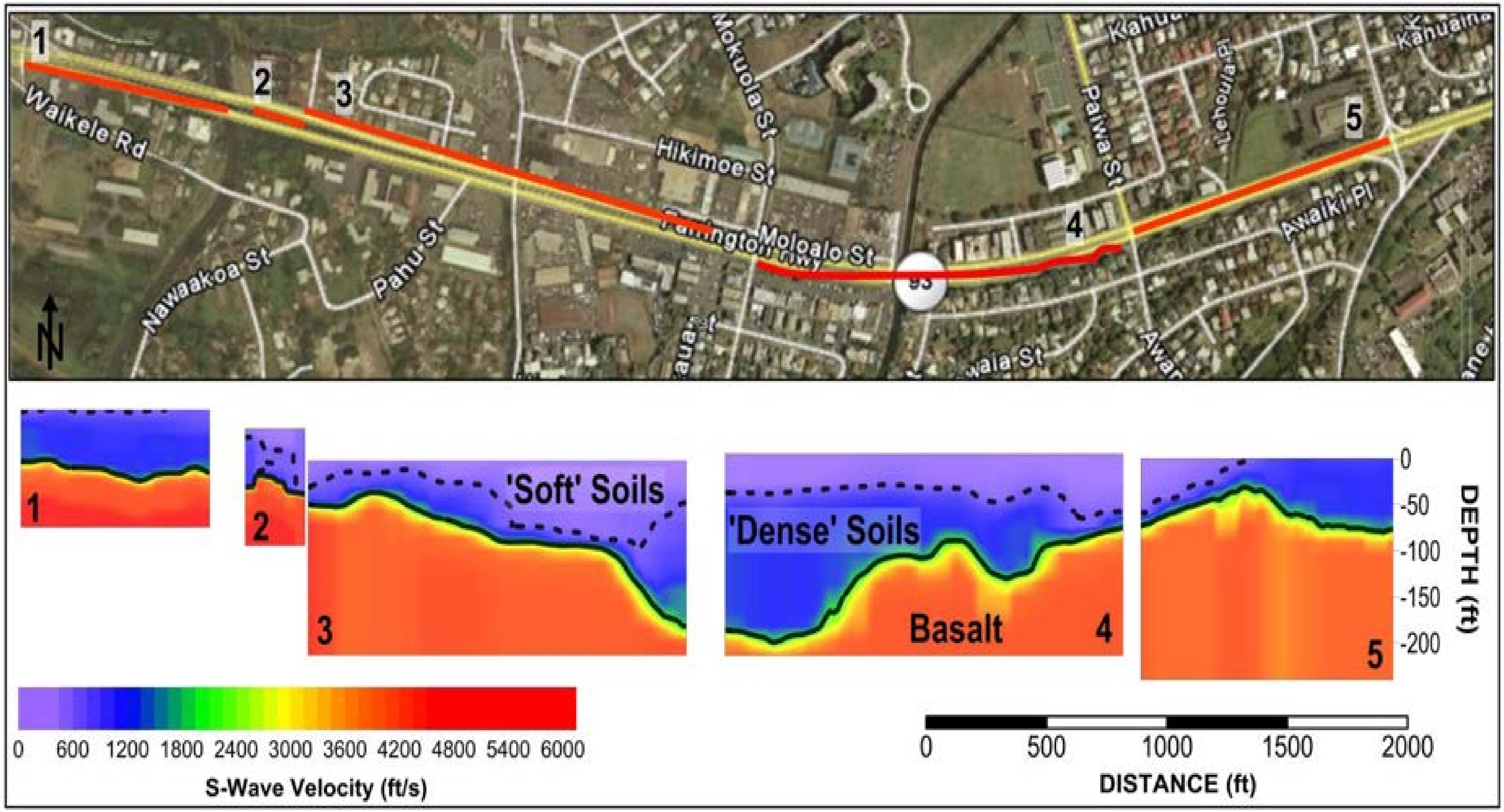
Can seismic work in urban settings?

Passive Surface Waves = 1D Extended to 2D Results

DANGEROUS SITE CONDITIONS

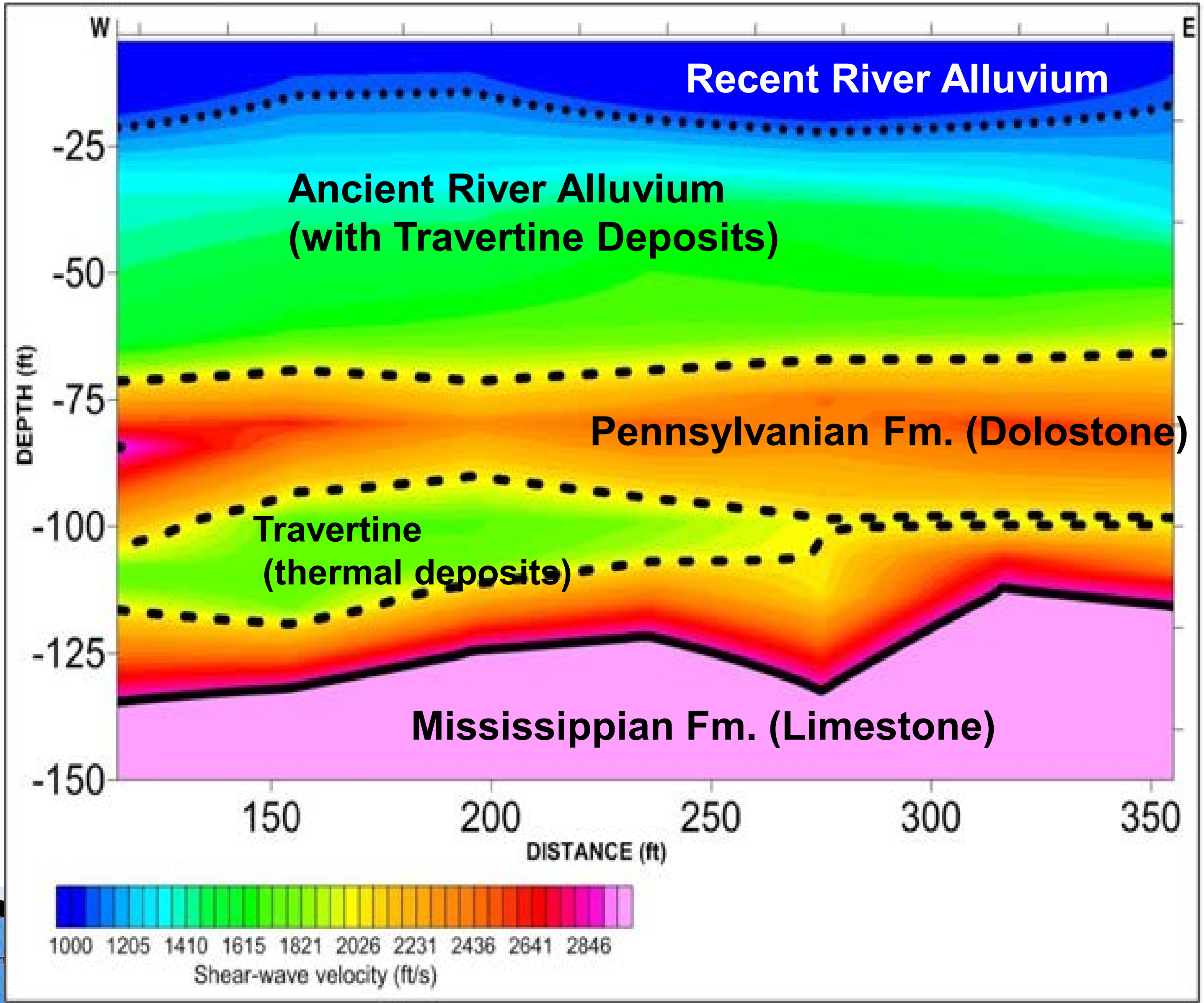
HEAVY TRAFFIC AREAS

Vs Under a State Highway



Can you image layering (Vs) next to an Interstate?

2D MASW For New Bridge Construction (Line 1)



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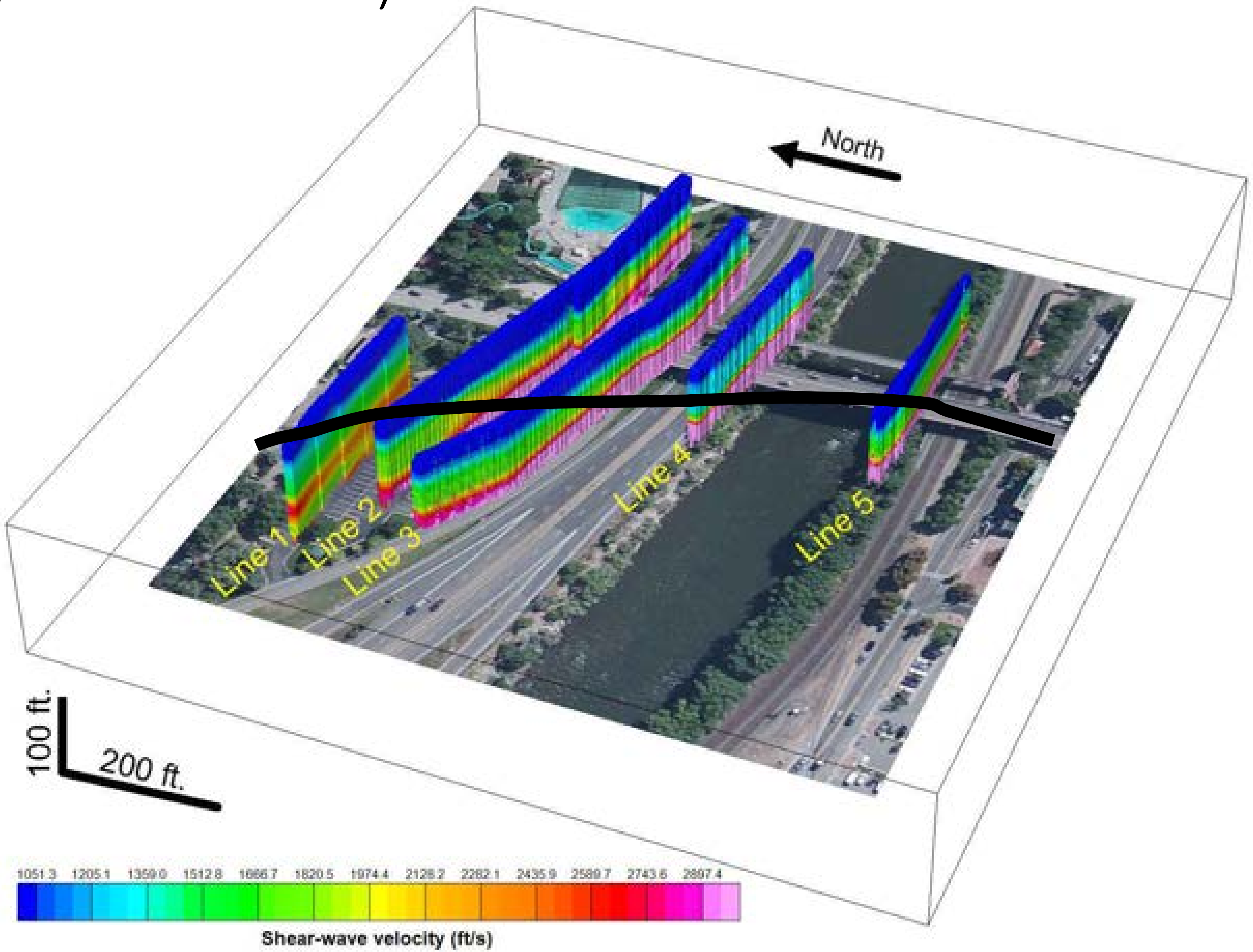
2D MASW For New Bridge Construction (*and legal avoidance*!)



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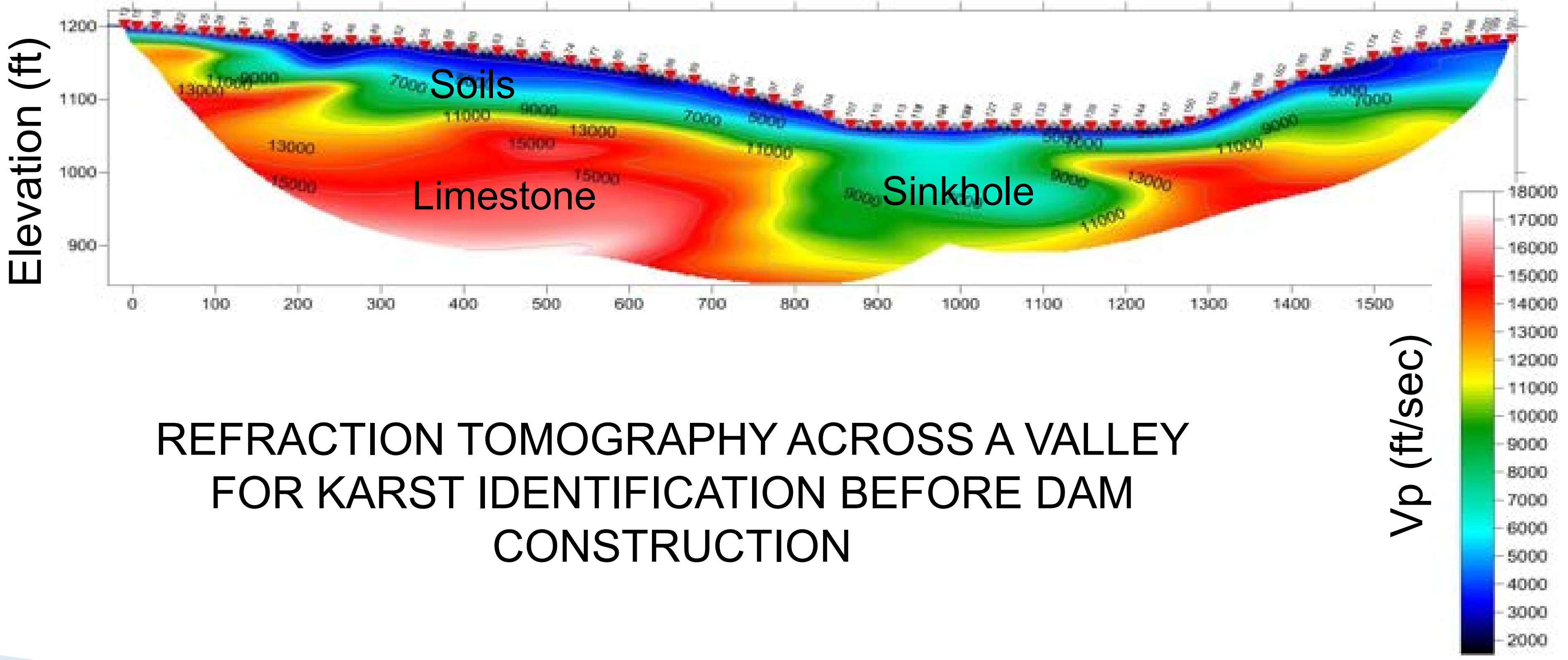
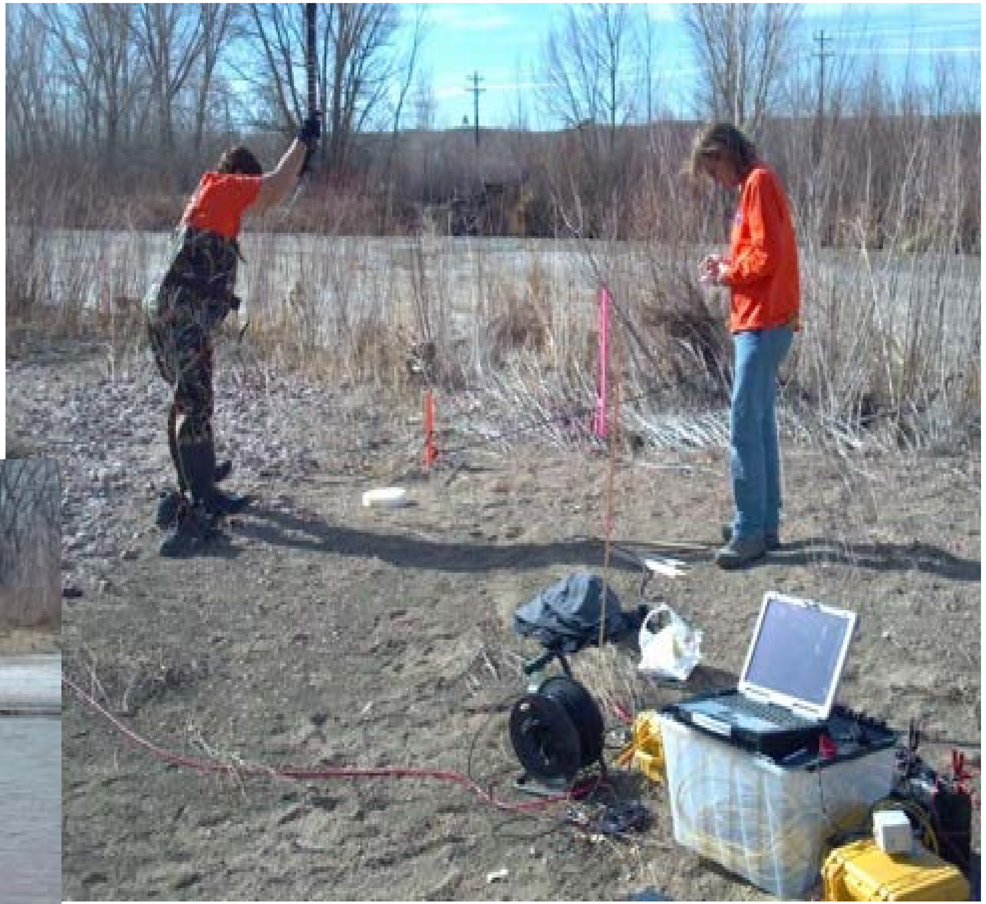
Can you image karst? Perhaps with SRT if larger sinkhole as shown below but SASW is better than MASW

Karst Example



REFRACTION TOMOGRAPHY ACROSS A VALLEY FOR KARST IDENTIFICATION BEFORE DAM CONSTRUCTION

Can you provide paleo-channel mapping under a river?



Seismic profiling for Pipe Jacking

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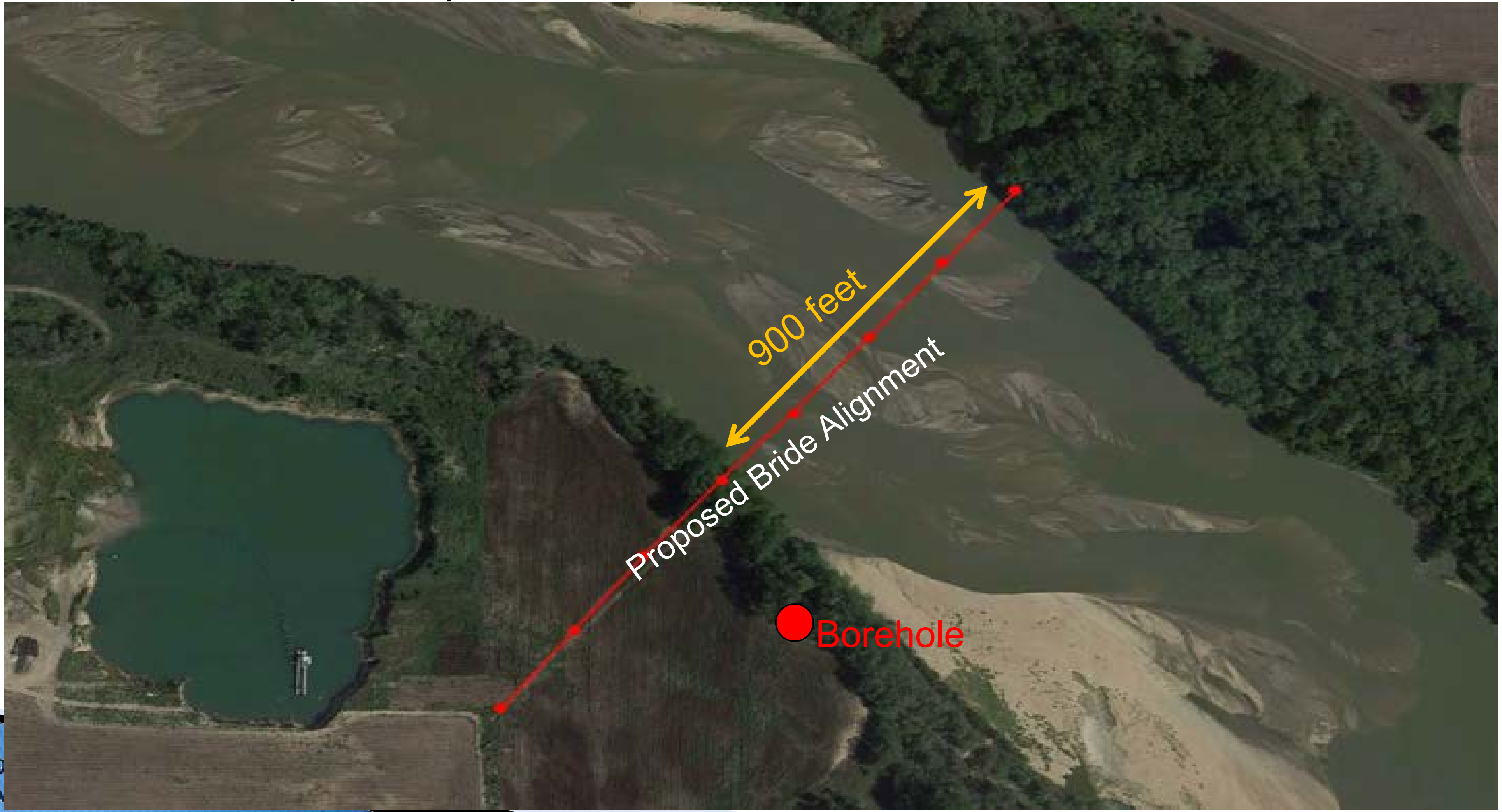
Can you provide soil/rock character under a river, for a *new* bridge foundation design?

***Active source (backhoe) on west end of line**



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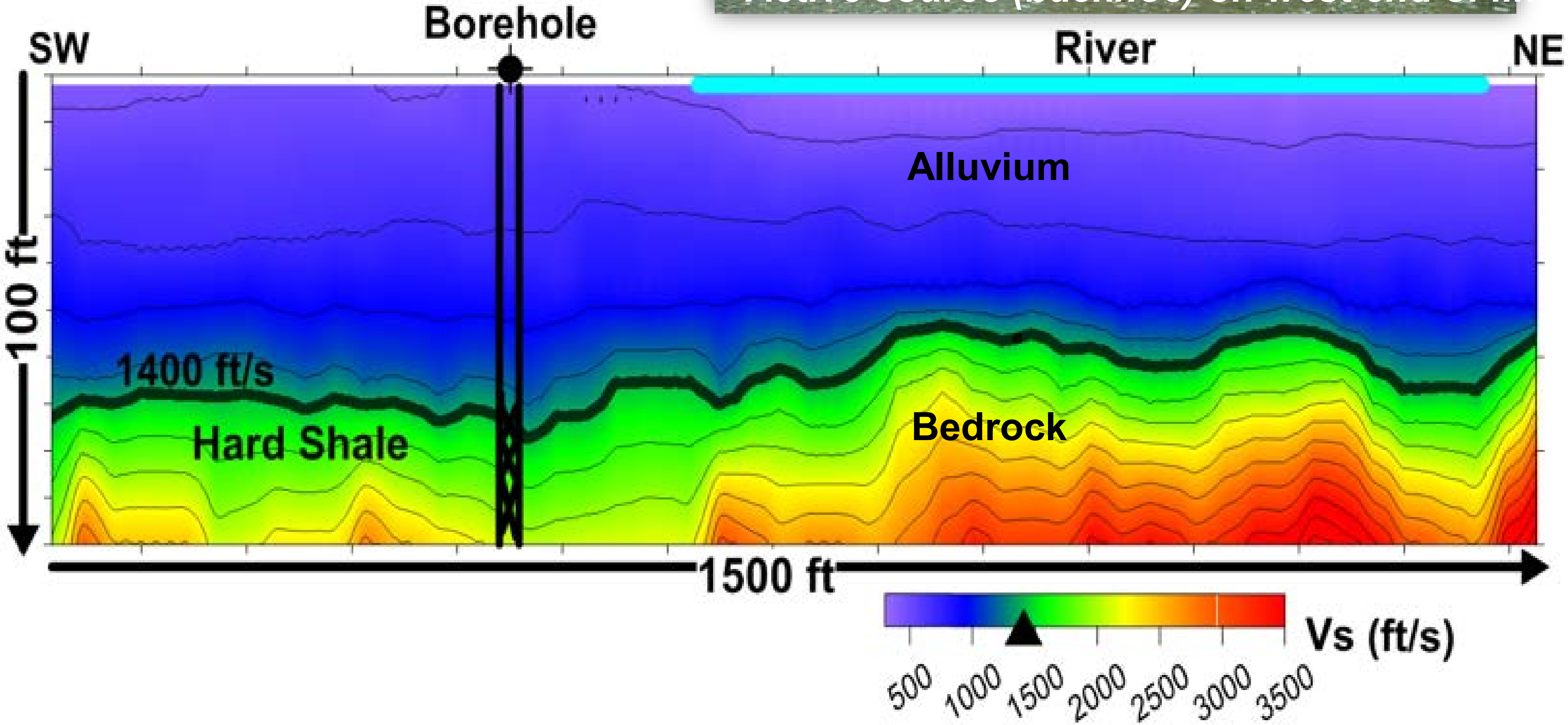
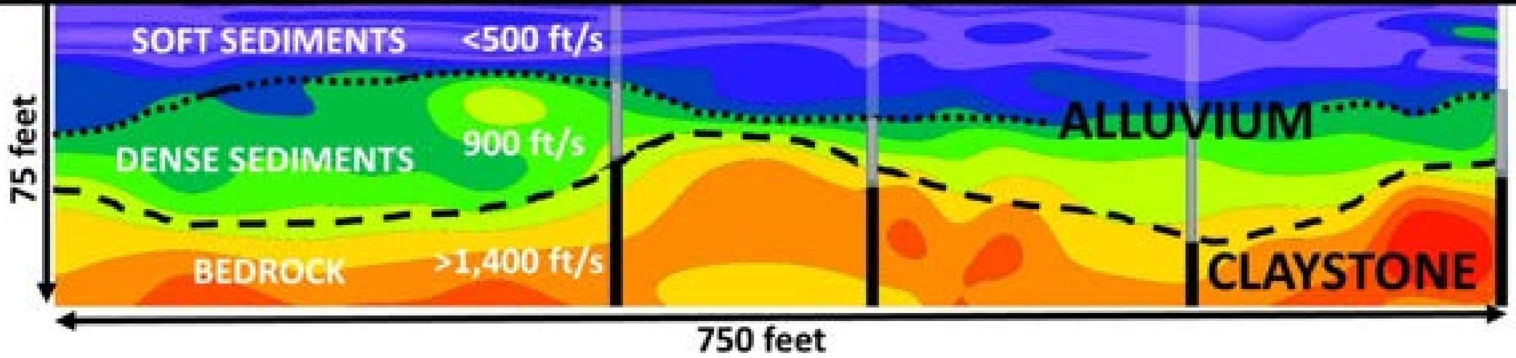
Soil and rock characterization with MASW*



RED RIVER - OKLAHOMA



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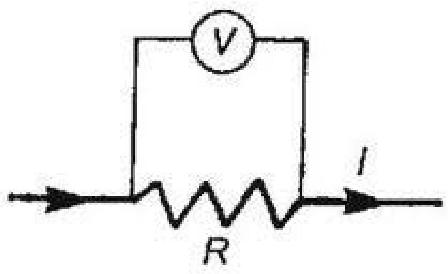
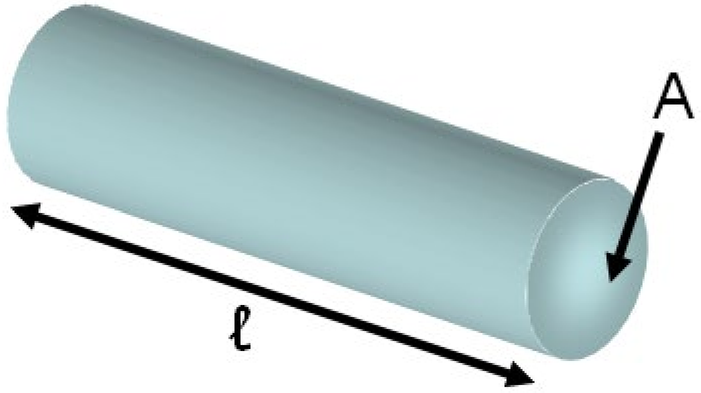
Electrical Resistivity Measurements



Resistance measured in ***ohms***

R = V/I

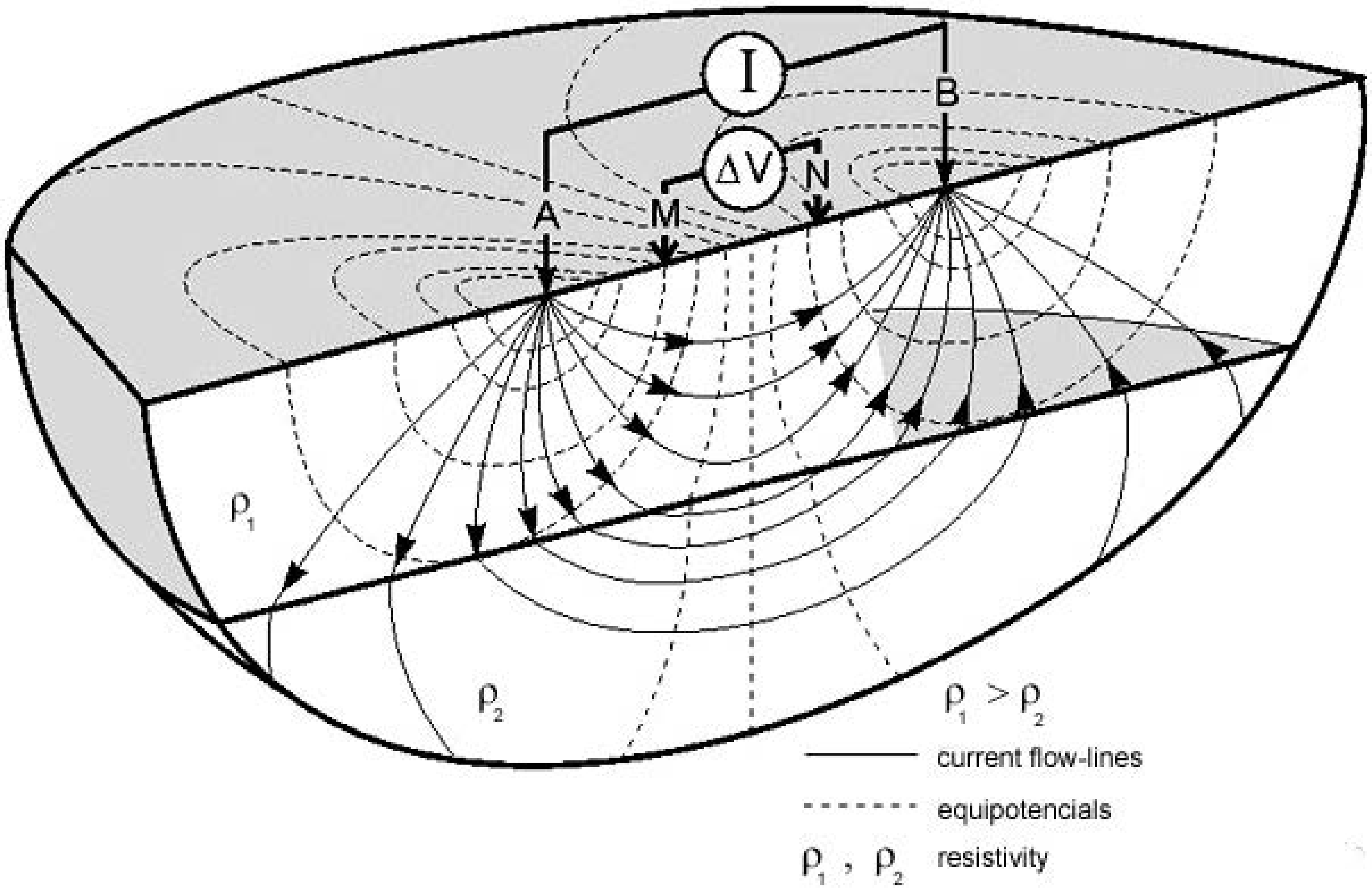
Flow of current governed by Ohm's Law



Resistivity $\rho = RA/\ell$

Resistivity is measured in ***ohm-meters***

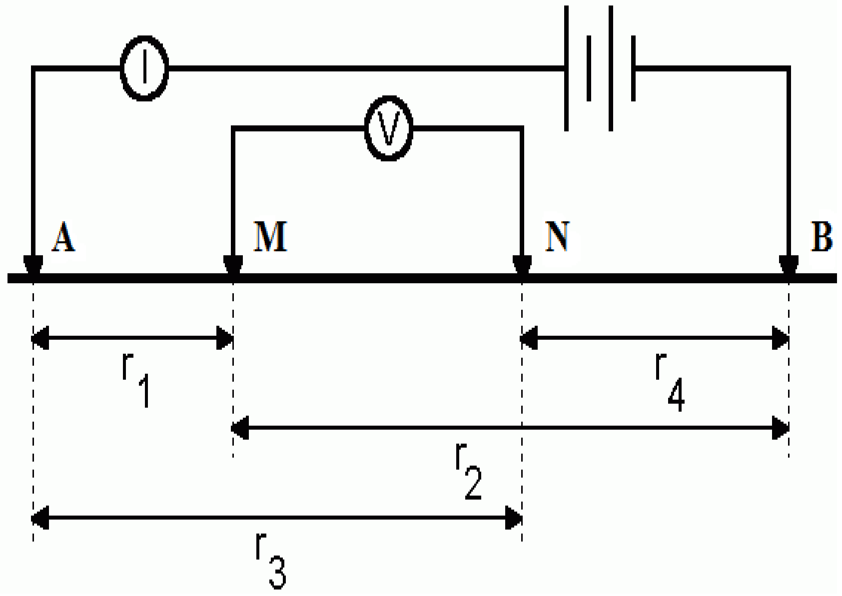
“*Simplified*” Electric Field



Calculation of Apparent Resistivity

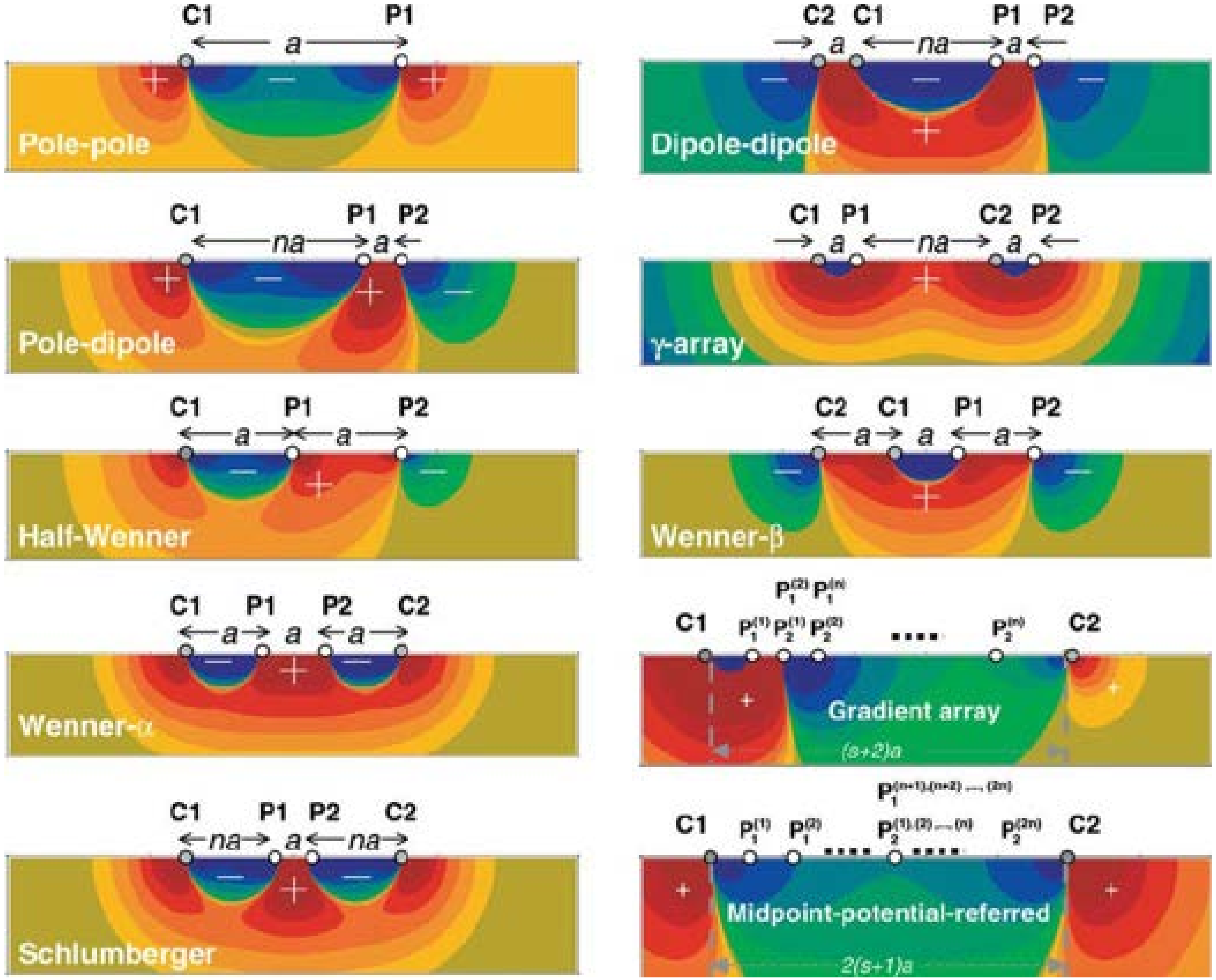
Generic Example:

Resistivity computations are governed by the geometry of I (current amperage) and V (voltage difference) in the *electrode configuration*



$$\rho_a = \frac{2\pi V}{I}\frac{1}{\left(\frac{1}{r_1}-\frac{1}{r_2}\right)-\left(\frac{1}{r_3}-\frac{1}{r_4}\right)}$$

Electrical Resistivity Imaging (ERI) or also called Tomography (ERT) – Testing Arrays

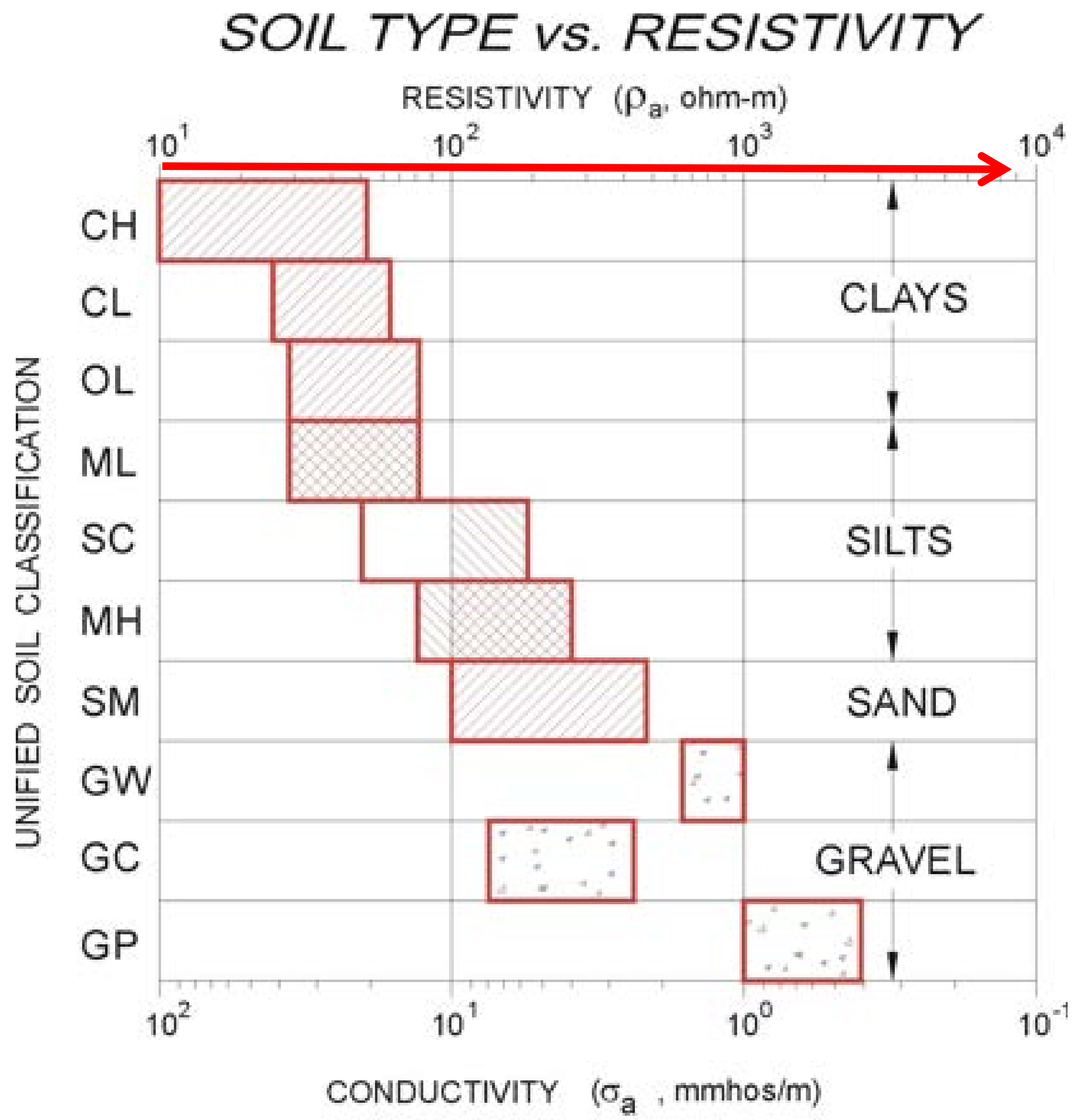


Resistivity Applications

→ Good method to find ***RESISTIVE*** targets

- Embankment subsidence
  - Voids / Sinkholes/ Abandoned Mines/Karst
- General mapping (geology, internal layers, drains)
- Depth-to-Bedrock (foundation / abutments)
- Sand and gravel deposits (seepage paths)
- Groundwater (static or flow conditions)
- Clay mapping (core, impermeable layers)

Material Properties (*USC soils*)



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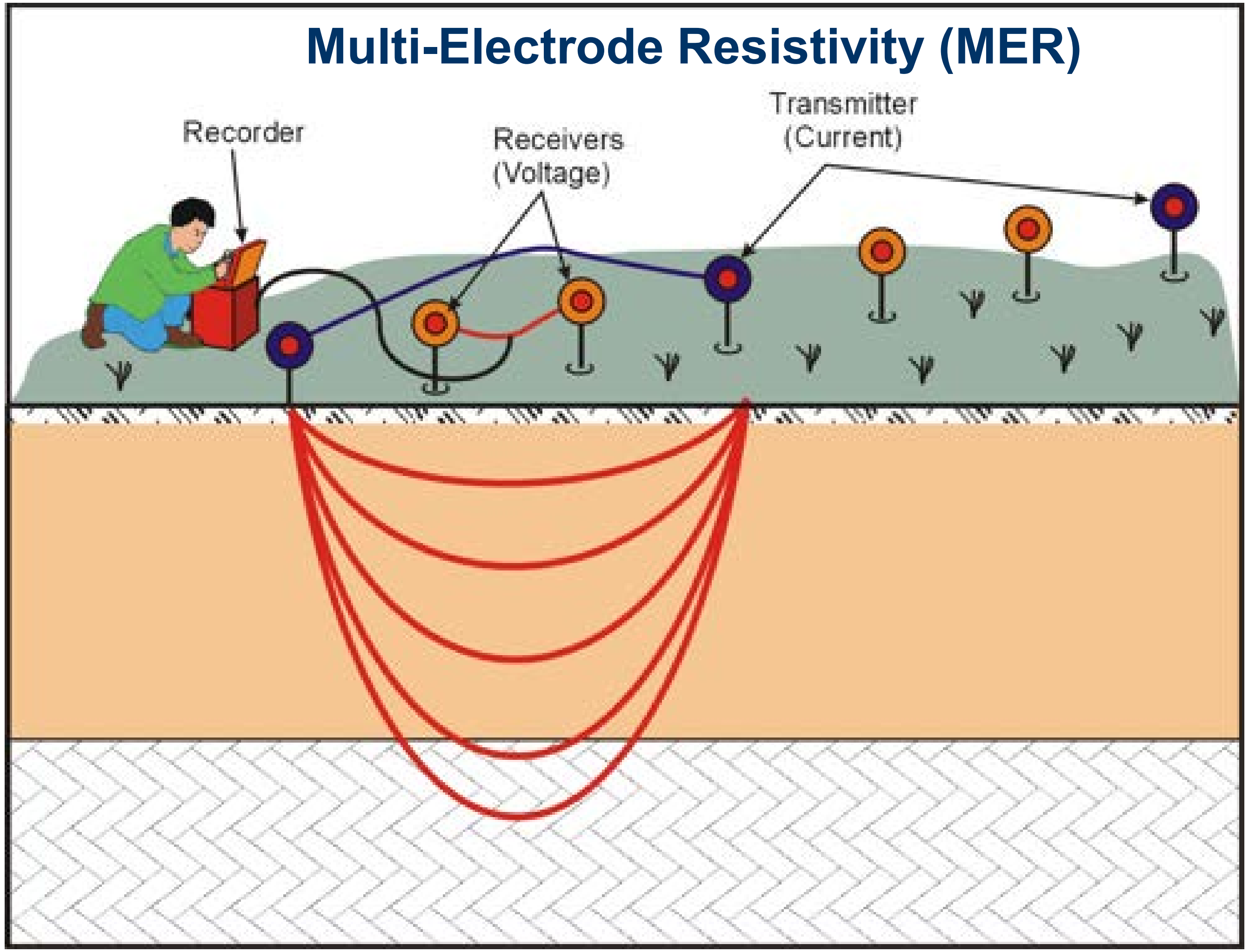
Example Material Ranges

Increasing Resistivity

Material	Typical Minimum (ohm-m)	Typical Maximum (ohm-m)
Topsoil	70	300
Clay	5	100
Sand and Gravel	100	5000
Sandstone Bedrock	30	5,000
Shale Bedrock	50	4,500
Limestone/Dolomite Bedrock	200	4,000
Crystalline Bedrock	1,000	500,000
Void	Infinite	Infinite

2D Electrical Resistivity Imaging



2D ERI - Equipment

AGI Sting R1

IRIS SyscalPro

AGI Sting R8

AGI Super Sting (R8)

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ERI Data Analysis

Measure — **Resistance (V/I)**

↓

Calculate — **Apparent Resistivity**

(Measure → Calculate: Pre-Processing)

↓

Model Inversion — **Earth or True Resistivity**

"Tomography"

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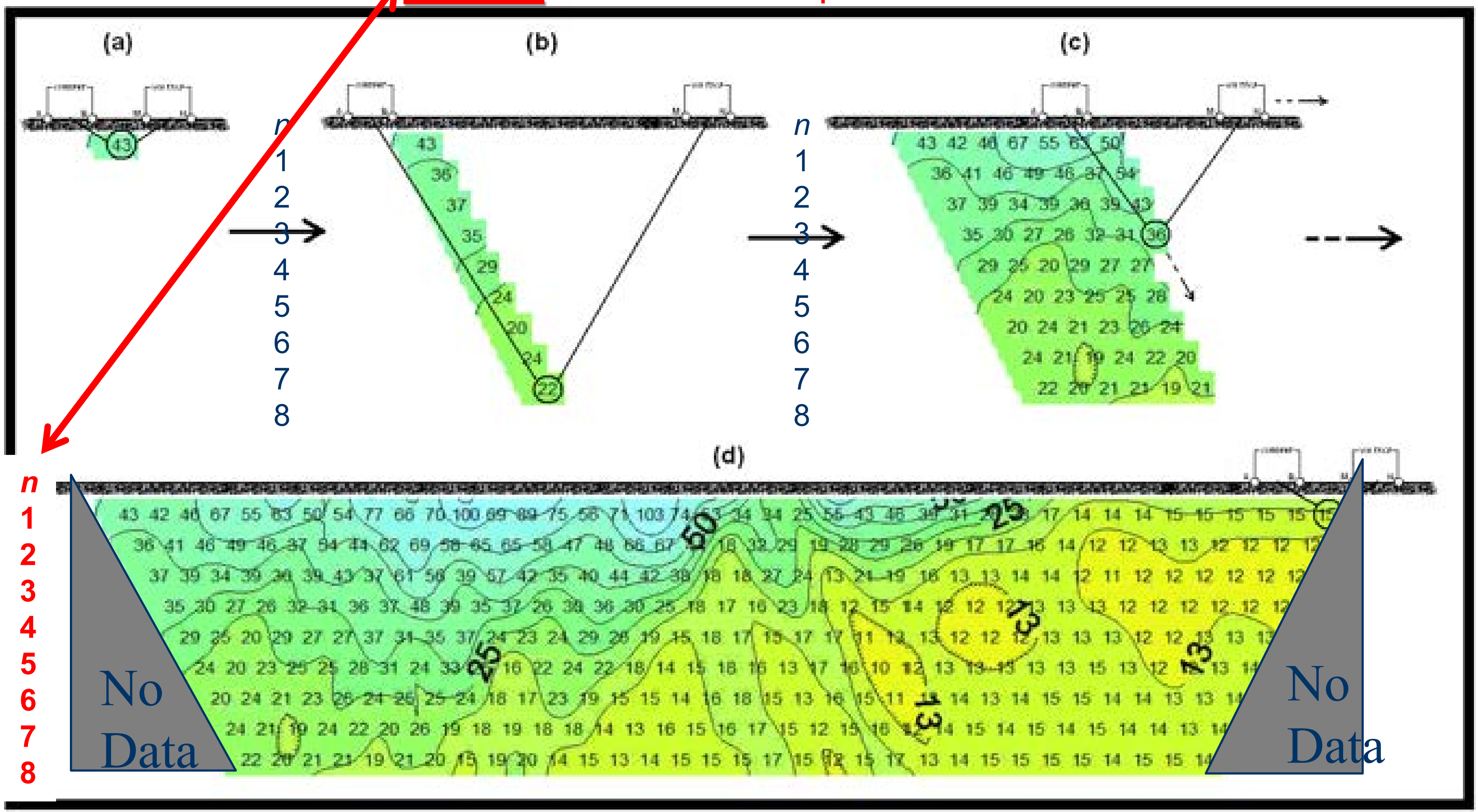
2D ERI – Modeling 'Dipole-Dipole' Data

Pseudo-Section Development



Electrical Resistivity 2D Images

Mapping sand and gravel lenses in clay

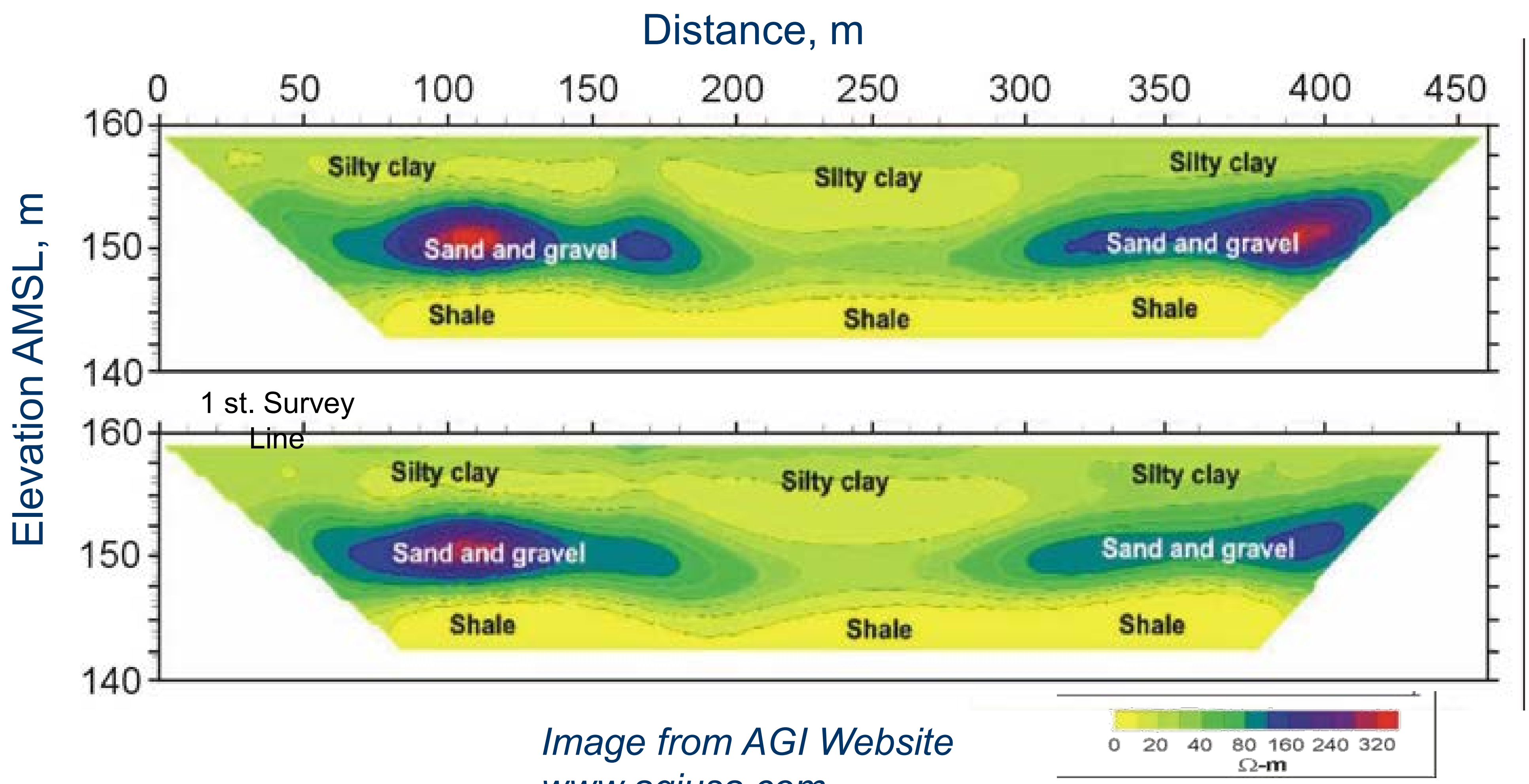
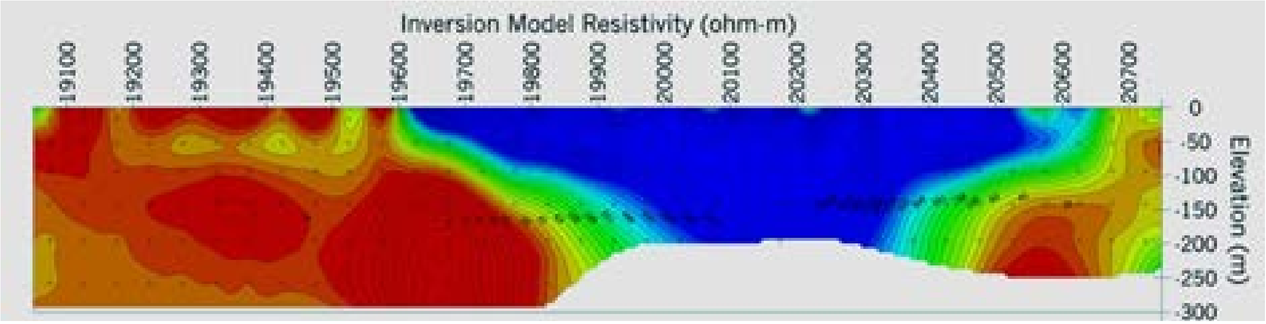


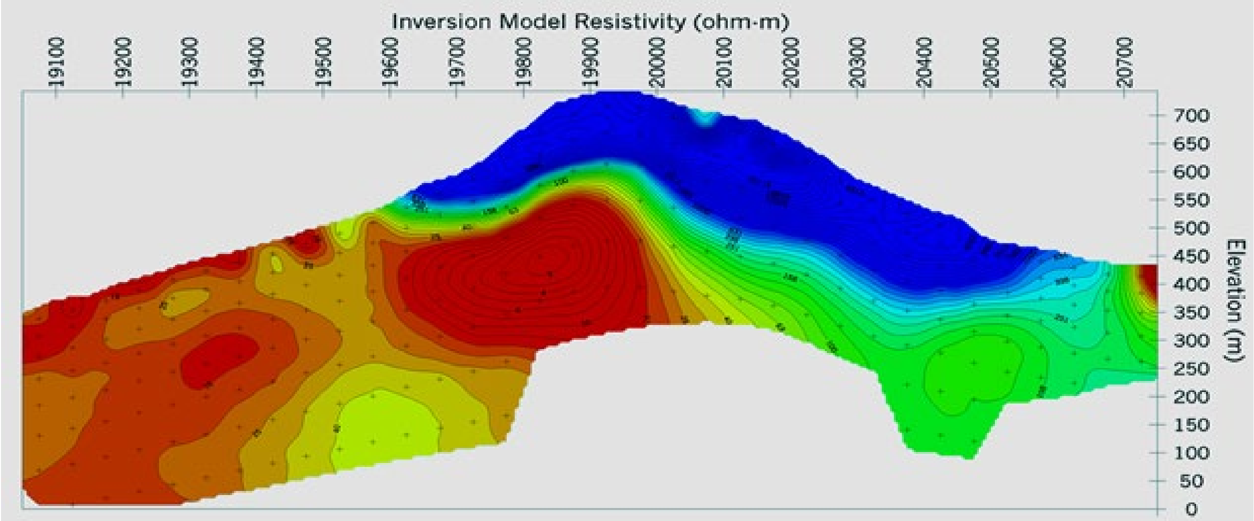
Image from AGI Website
www.agiusa.com

Need for Topographic Correction

Without Topographic Corrections



With Topographic Corrections



ERI Survey to detect old Adit Mine Tunnel in Colorado Rockies

ABEM Terrameter LS-2 84 Channel ERI system

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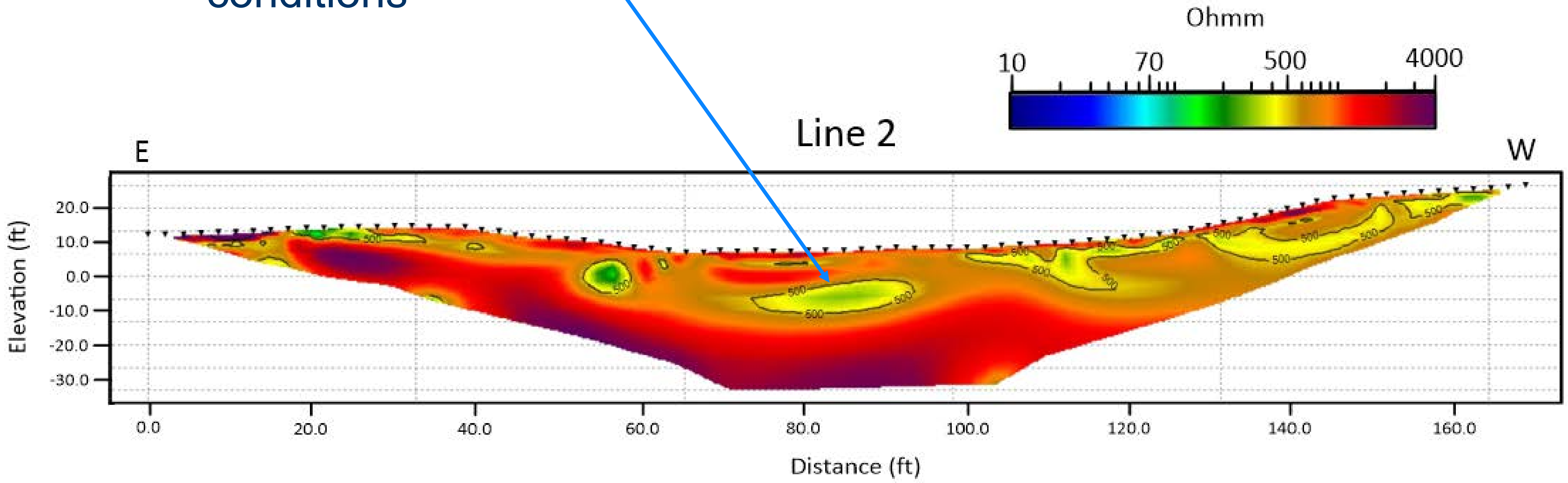
Aerial obtained from Google Earth Pro with approximate ERT line locations and numbers in blue. ERT lines were located by LYBD at 5 (Line 1), 25 (Line 2) and 50 ft (Line 3) up slope

2D ERI inversion at Mine Adit Tunnel Site in Colorado Rockies for Line 2

Adit Tunnel estimated to be ~ 6 ft tall by 4 ft wide at about 80 ft at depths of 14 to 20 ft below-grade with lower resistivity values of 300 to 500 Ohm-m vs resistivity values of 1000-2000 Ohm-m around it - indicates Tunnel is water-filled vs. higher resistivity air-filled conditions



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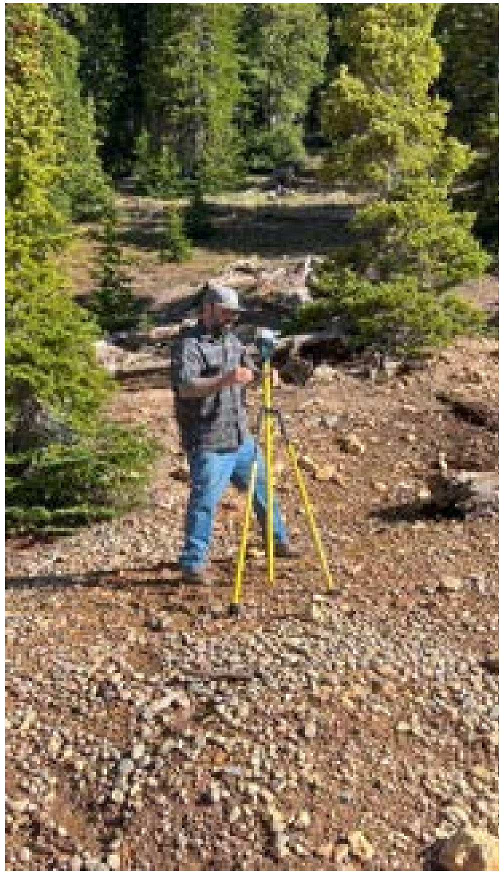
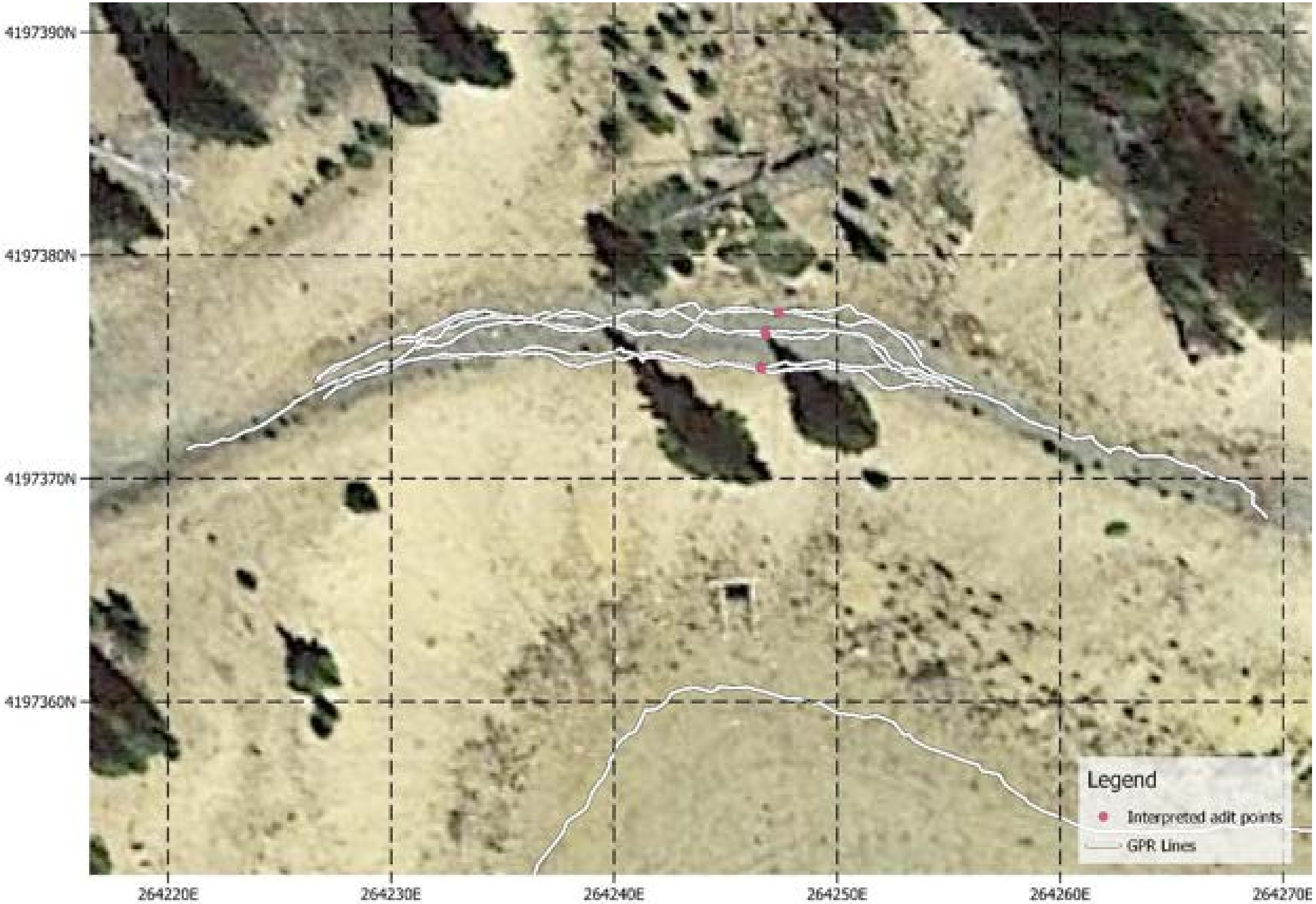
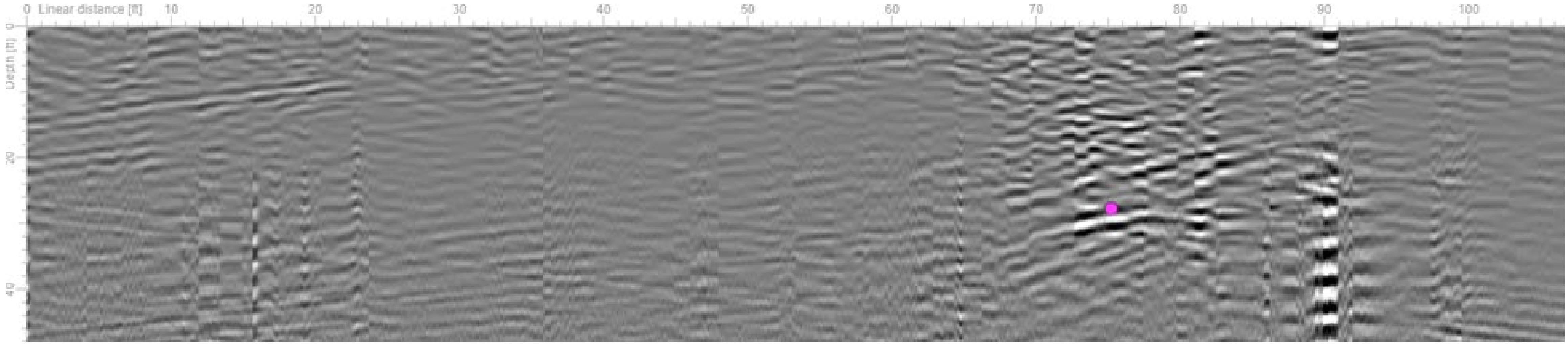
Impulse Radar Crossover 730 (CO730) GPR unit with Emlid Rover GPS on pole and distance wheel being pulled from west to east along GPR Line 3 on the bench/shelf

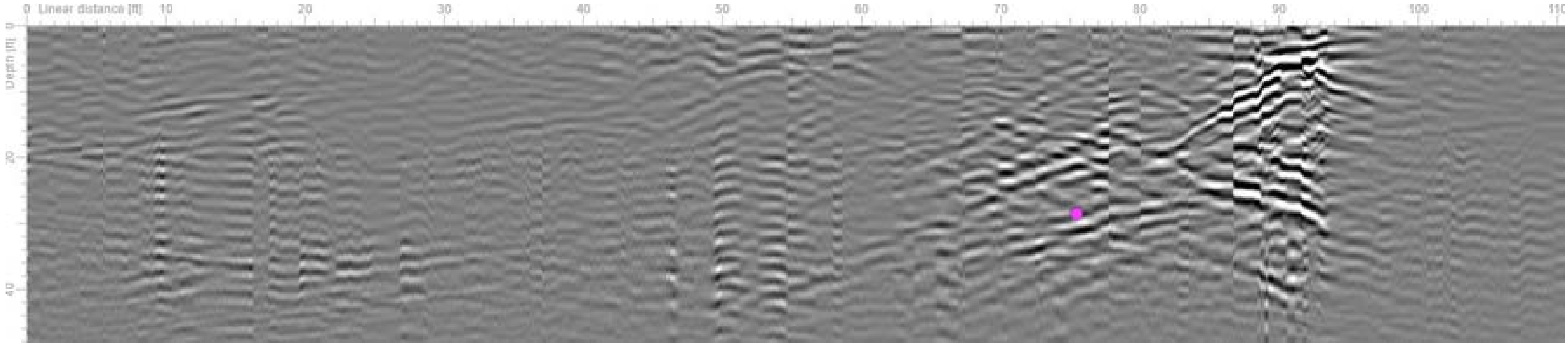




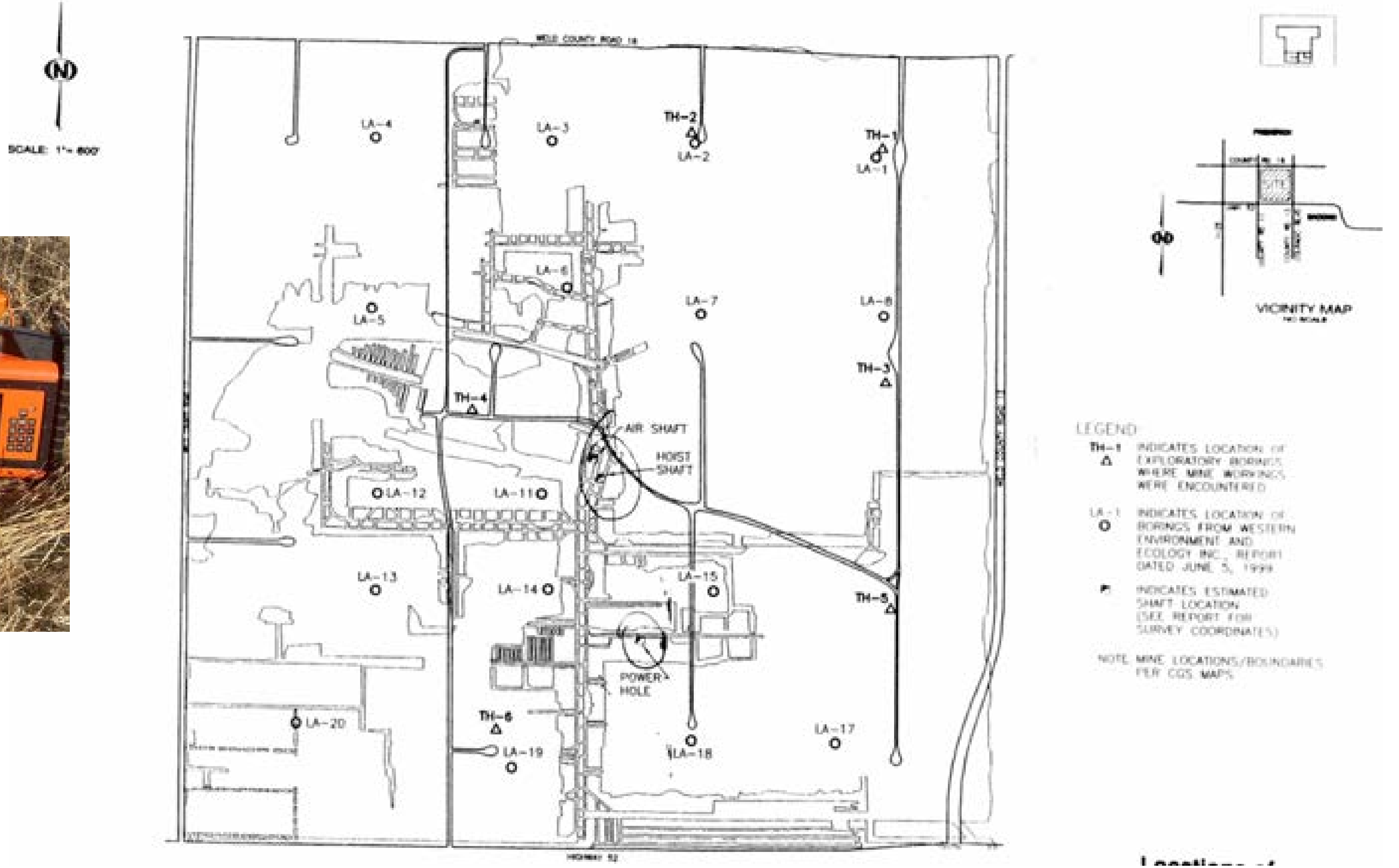
4197390N
4197380N
4197370N
4197360N
264220E
264230E
264240E
264250E
264260E
264270E
Legend
Interpreted adit points
GPR Lines

GPR Lines 3W-E and 4W-E showing Adit Tunnel at ~28 ft deep. Boring confirmed it!





ABEM Terrameter LS2 ERI on Old Abandoned Coal mine with coal seams in depth range of 180-210 ft deep



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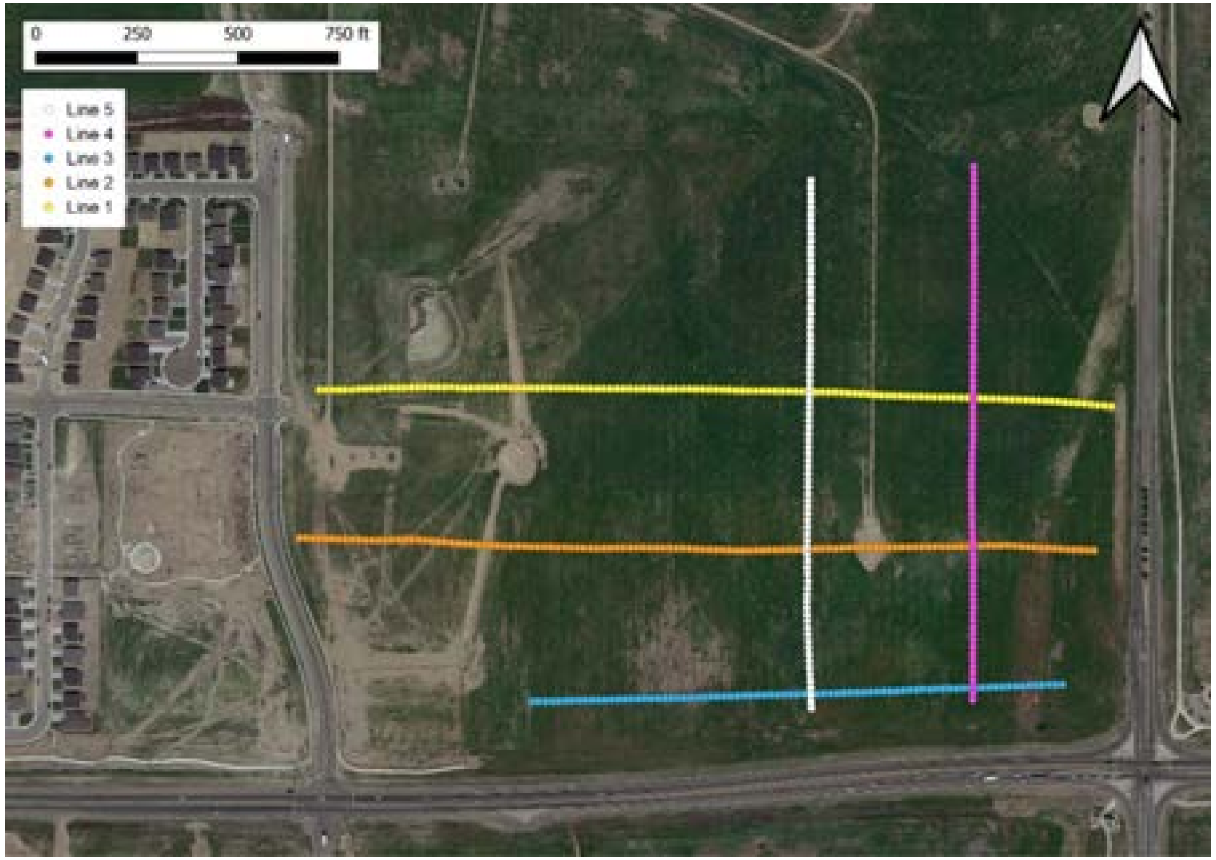
ERT Survey Lines of ~400 to 600 m (1300 to 2000 ft in length and field electrodes at 5 m (16.3 ft)



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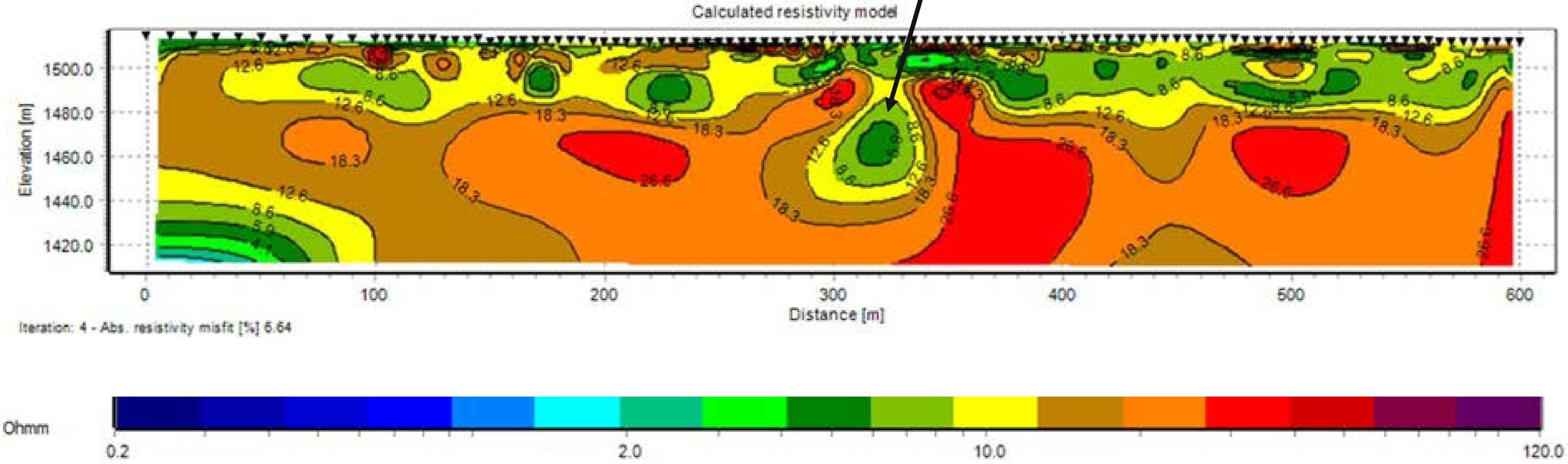
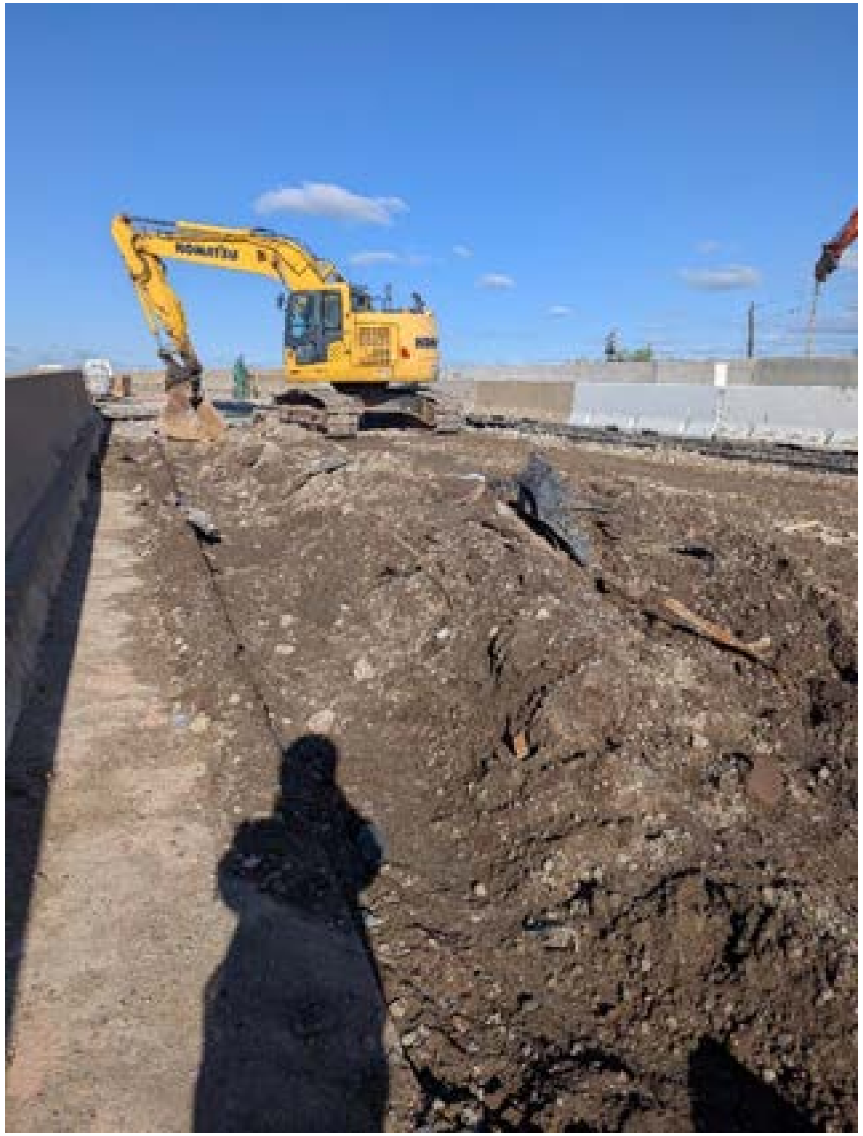
Line 1 2D ERT Resistivity Data Inversion Results. The less resistive anomaly located at 320-meters down the line has the potential to be mining related fluid-filled voids



Excavation exposed corroded zinc strips within the top foot of material for Maryland DOT’s 1995 Reinforced Earth Co. Wall



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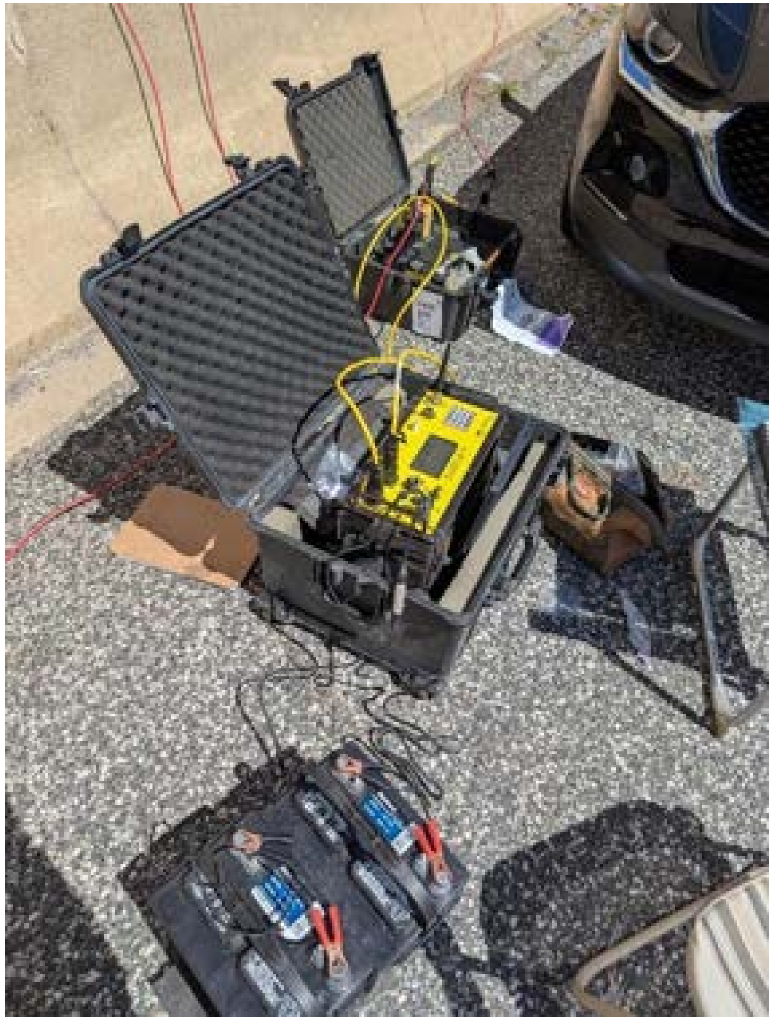
AGI SuperSting R8 ERT system with steel electrodes drilled and driven between panel joints



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Backfill soils were specified by MD DOTto have a 3000 Ohm-cm (30 0hm-m) resistivity or greater in 1995 and other backfill specifications

Aggressiveness	Resistivity Ohm-cm (Ohm-m)	Color Code
Very Corrosive	< 700 (7)	
Corrosive	700 – 2000 (7 - 20)	
Moderately corrosive	2000 – 5000 (20 -50)	
Mildly corrosive	5000 – 10000 (50 – 100)	
Non- corrosive	> 10000 (100)	

Property	Criteria	Test Method
Resistivity	> 3000 ohm-cm	AASHTO T-288
pH	> 5 and < 10	AASHTO T-289
Chlorides	< 100 PPM	ASMT D4327
Sulfates	< 200 PPM	ASTM D4327
Organic Content	1% max.	AASHTO T-267

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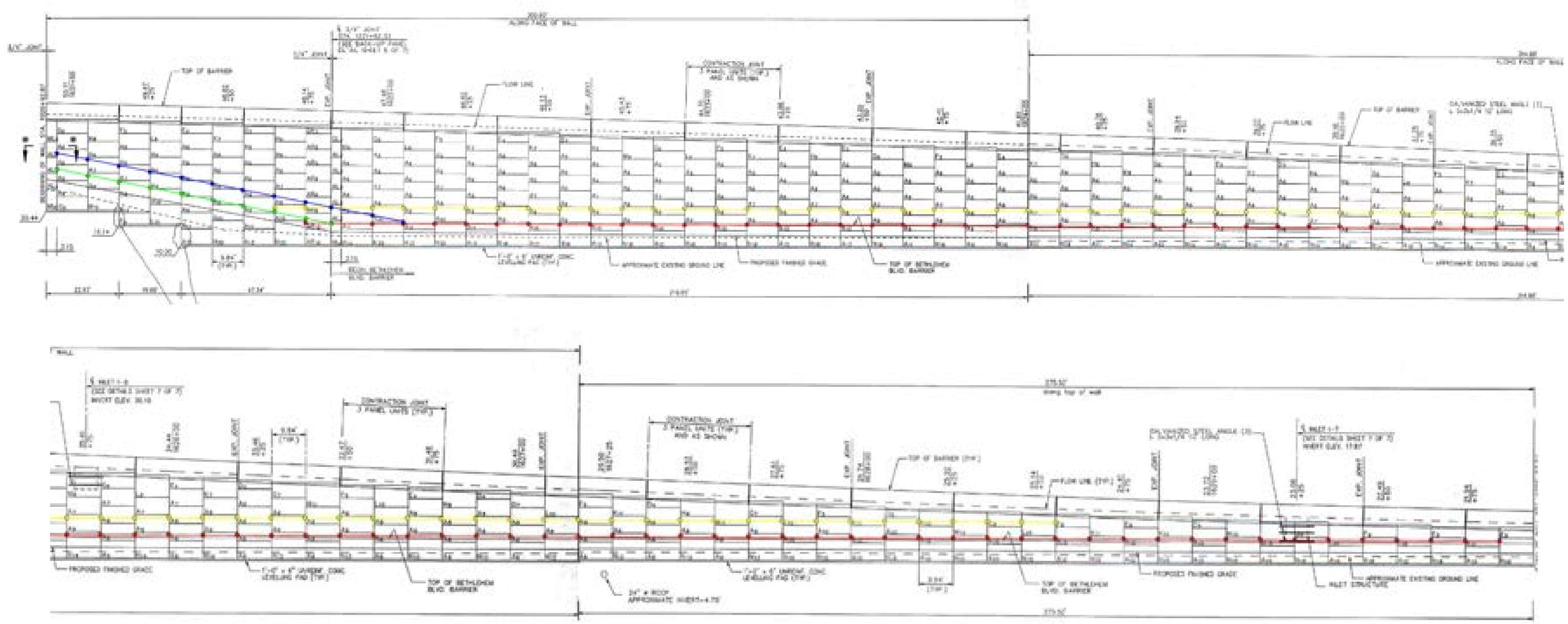
ERT horizontal lines were done at 3.5 and 8.5 ft above grade



Vertical ERT Line 5 Electrodes were placed ~1ft from the edge of the roadway within the soft grassy topsoil about 9 ft behind the concrete MSE wall panels

Inverted horizontal resistivity profiles in Ohm-m of the two MSE wall lines at 3.5 ft above grade (Lines 1 and 3 west sloped end).

Horizontal resistivity profiles in Ohm-m of the two MSE Wall lines at 8.5ft above grade (Lines 2 and 4 west sloped end)

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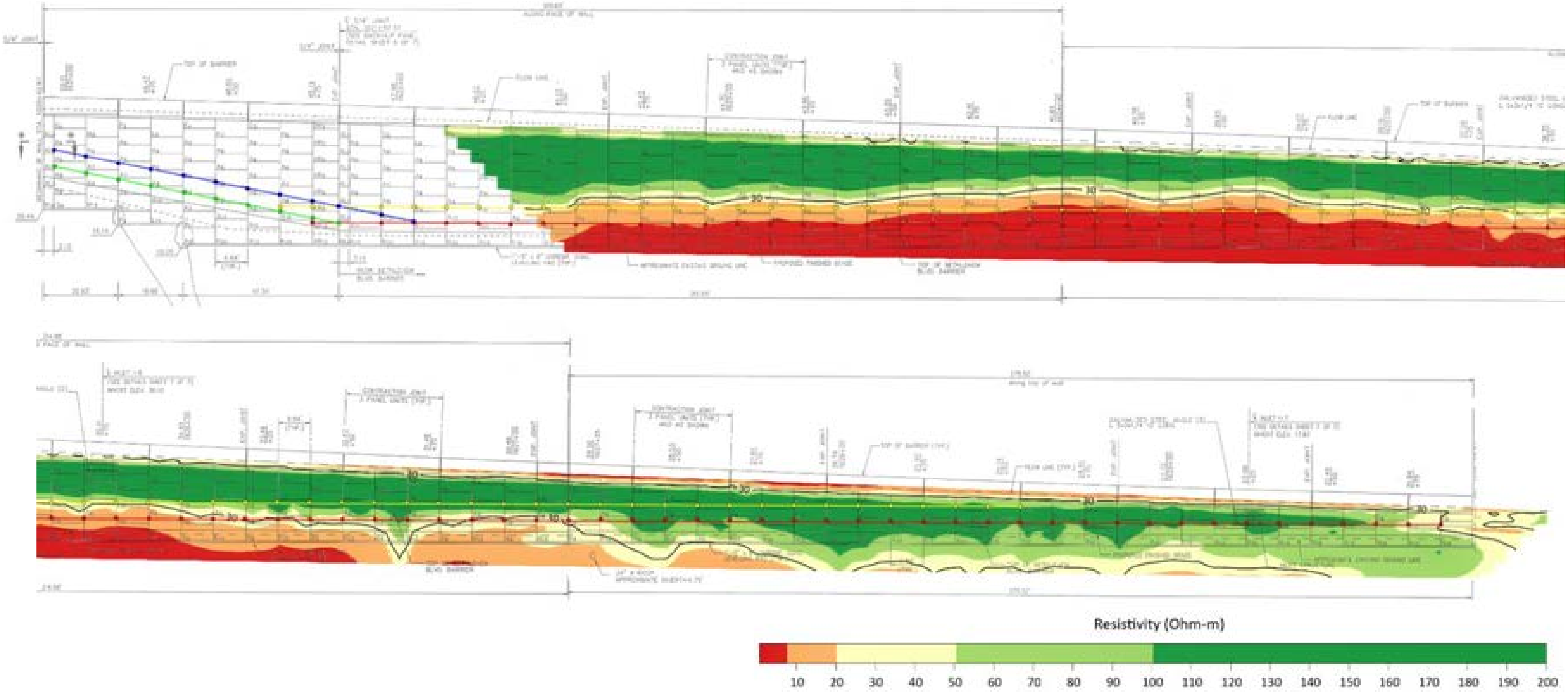
Inverted resistivity profile in Ohm-m of Line 5 along the grassy shoulder strip ~ 9ft behind the wall and 1ft from east-bound I-695 underlaying the transparent plan of the ~ 35 ft high MSE retaining wall



Estimation of RECO Zinc Coated Strips loss of Zinc Coating and Strip Steel Corrosion Rates

- Zinc Coating Loss for 2 years = 15µm/year * 2 years = 30 µm
- Years for Zinc Coating to be lost = (86 – (2*15 µm/year))/(4 µm/year) + 2yrs = 16 yrs
- Strip Steel Loss = number of years x 12 µm/year

Strip Service Life Analyses for Design and Yield Stresses for Backfill Corrosion Rates

- **Design Stress** Maximum Reinforcement Tension - FT = FY x 0.55 x Area of strip, (4)
- so for the wall, FT = 65 ksi x 0.55 x Area of strip, (5)
- Strip Gross Area = 4 millimeter x 50 millimeter = 200 mm^2 = 0.31 square inches (6)
- Strip Net Area at ½ inch diameter bolted Tie Strip panel connection = 0.22 square inches (7)
- then for a Gross Area Strip FT = 6.20 kips = 65 ksi x 0.55 x Minimum Area of Strip (8)
- solving for Minimum Area at end of service life is then = 0.173 square inches (9)
- **Yield Stress (failure & no safety factor)** – FT = 6.20 kips = 65 ksi x 1 x Minimum Area (10)
- then solving for needed 75 year life Minimum Strip Area = 0.095 square inches (11)

End of Service Life Years Estimates for Design Stress and Yield Stress on Strips and at Tie Strips with Bolts

Backfill Corrosion Aggressivness	Years for Design Stress Strip Section to corrode from 0.31 (Gross Area) to 0.173 (Minimum Area at 75 year service life) square inches	Approximate Year for Design Stress Strip Section to corrode from 0.31 (Gross Area) to 0.173 (Minimum Area at 75 year service life) square inches	Years for Design Stress Tie Strip Section to corrode from 0.22 (Net Area) to 0.173 (Minimum Area at 75 year service life) square inches	Approximate Year for Design Stress Tie Strip Section to corrode from 0.22 (Net Area) to 0.173 (Minimum Area at 75 year service life) square inches	Years for Yield Stress Strip Section to corrode from 0.31 (Gross Area) to 0.095 (Minimum Area at 75 year service life) square inches	Approximate Year for Yield Stress Strip Section to corrode from 0.31 (Gross Area) to 0.095 (Minimum Area 75 year service life) square inches	Years for Yield Stress Tie Strip Section to corrode from 0.22 (Net Area) to 0.095 (Minimum Area at 75 year service life) square inches	Approximate Year for Yield Stress Tie Strip Section to corrode from 0.22 (Net Area) to 0.095 (Minimum Area at 75 year service life) square inches
Very Corrosive	47.1	2051	16.2	2020	74.0	2078	43.0	2047
Corrosive	58.9	2067	20.2	2028	92.5	2100	53.8	2061
Moderately Corrosive (3000 Ohm-cm)	73.7	2086	25.3	2037	115.6	2128	67.2	2079
Mildly Corrosive	92.1	2109	31.6	2049	144.5	2162	84.0	2101
Non-Corrosive	115.1	2139	39.5	2064	180.6	2205	105.0	2129

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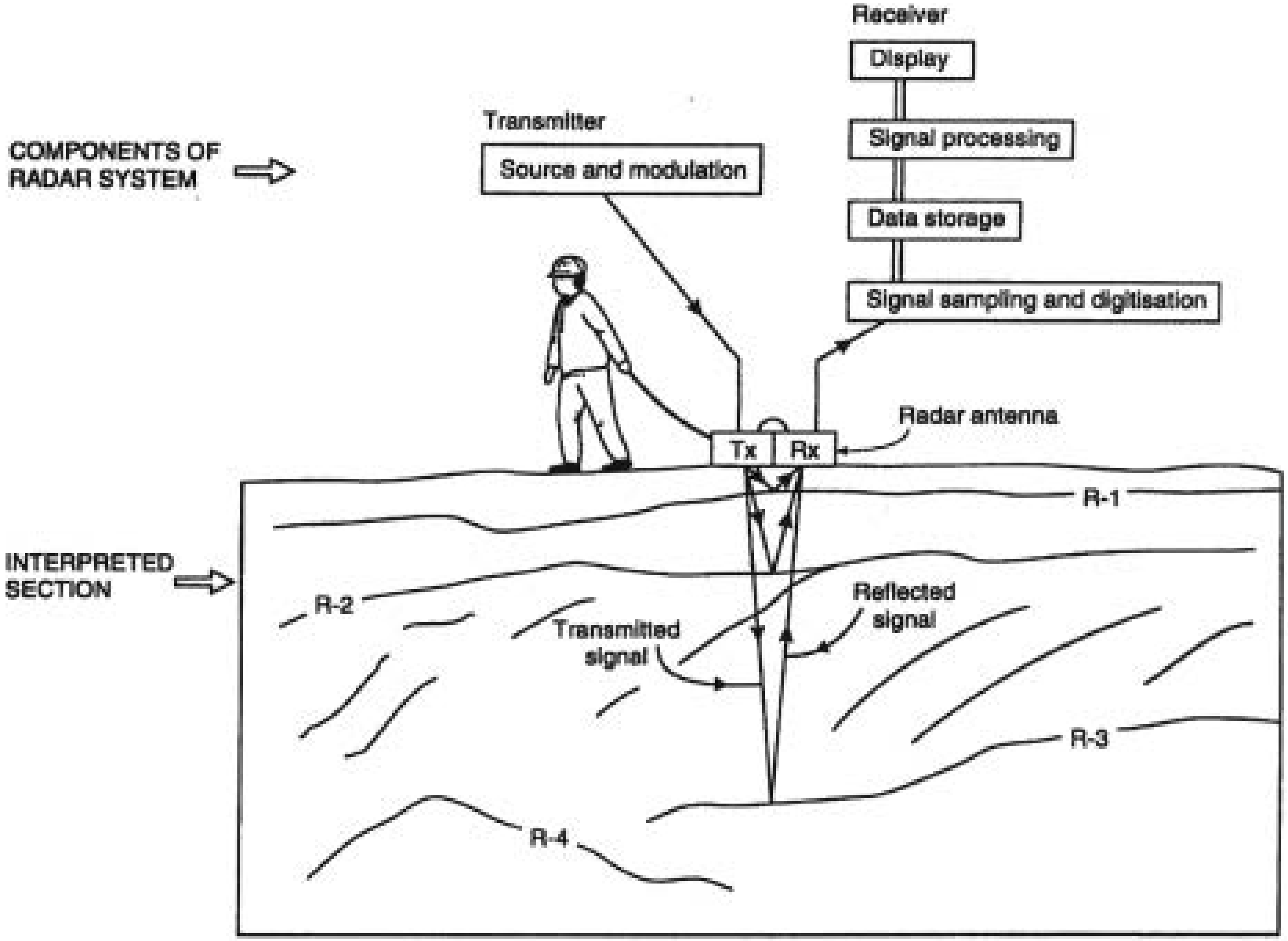
ERI Survey Benefits

- Used for Karst/Sinkhole/Mineworks Mapping
- Works in some environments seismic cannot
- Rapid data acquisition (*MER*)
- Semi-automated processing (*also a limitation*)
- Differentiates soils well (*coarse vs. fine*)
- 1D, 2D, 3D, and 4D options
- Good vertical resolution (*soundings*)
- Good lateral resolution (*profiles*)
- Corrosion risk and remaining service life estimation for aging MSE Walls

ERI Survey Limitations

- High contact resistance at dry sites
- Man-made cultural interference (*utilities*)
- Geometry of anomalies not well-defined
- Limited depth of investigation (*by equipment*)
- Modeling can be very well matched to field data but the interpretation can be non-unique

What is ground penetrating radar (GPR)



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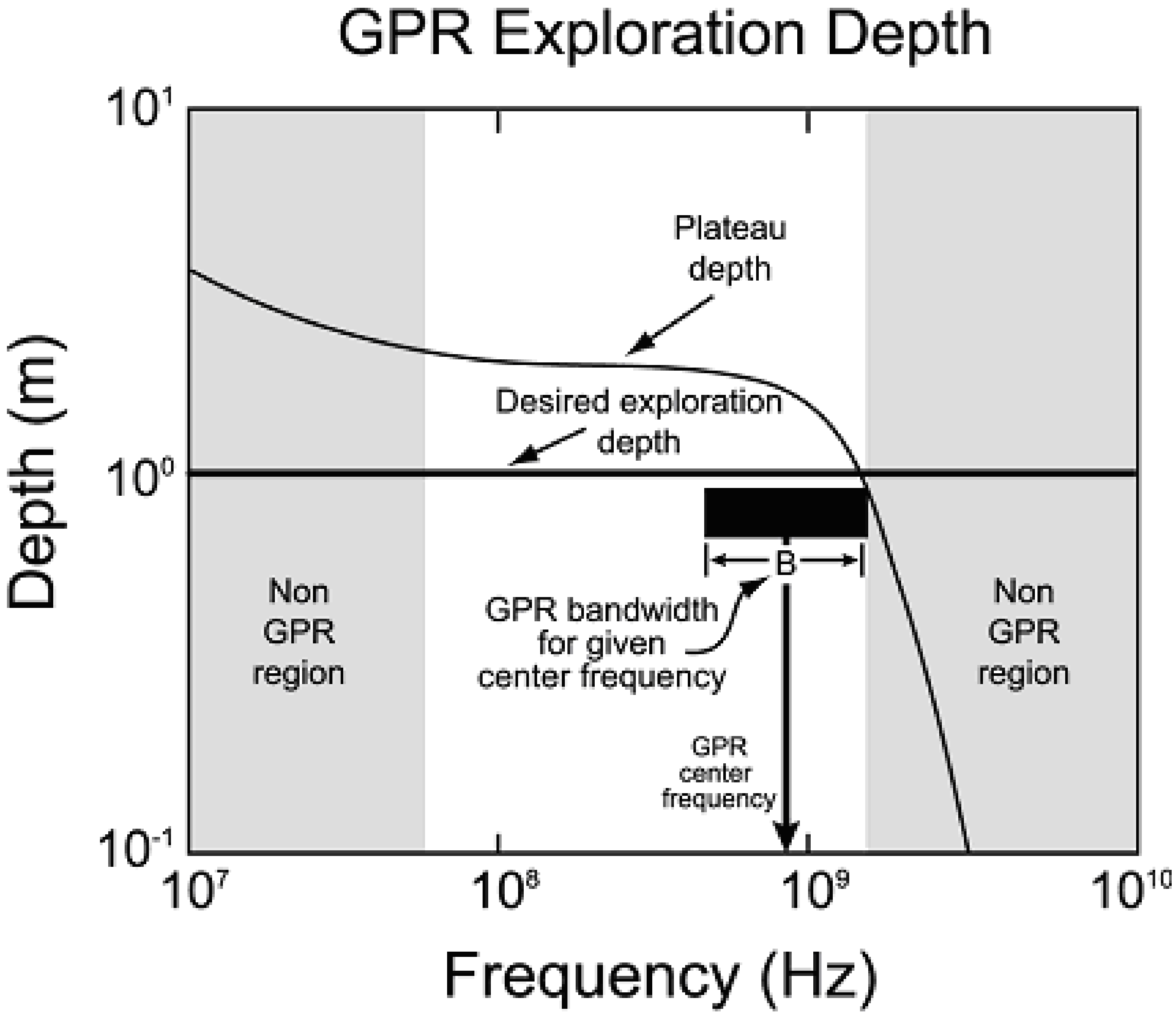
Penetration versus resolution versus frequency



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Penetration versus resolution versus frequency

Antenna	Approximate Penetration in Dense Wet Clay	Approximate Penetration in Clean Dry Sand	Example of Smallest Visible Object
100 MHz	20 ft (6m)	60 ft+ (18m+)	Tunnel @ 60 ft (18m) depth 2 ft (60 cm) Pipe @ 20 ft (6m) depth
250 MHz	13 ft (4m)	40 ft (12m)	3 ft. (90 cm) Pipe @ 12m 6in. (15 cm) Pipe @ 13 ft (4m)
500 MHz	6 ft (1.8m)	14.5 ft. (4.4m)	4in. (10 cm) pipe @ 4m 3/16 in. (0.5 cm) hose 1.8m and less
1000 MHz	3 ft (90 cm)	6 ft (1.8m)	3/16 in. (0.5 cm) hose @ 3 ft. (90 cm) Wire mesh, shallow
2000 MHz	.5 ft (15 cm)	2 ft. (60 cm)	Monofilament fishing line

GPR sampling

- Equivalent time sampling
  - For a 512 samples per trace measurement, 512 pulses must be transmitted
- Hyperstacking
  - Collects multiple points on a trace simultaneously (~16 to 64) with a sliding window
- Real-time sampling
  - Collects all 512 points on a trace at one time

GPR survey design

- Survey goals
- What are the knowns
  - Target dimensions
  - Target properties
  - Ground cover information
  - Terrain
- Antenna selection
- Decide on an approach
- Determine the survey type (1D, 2D, 3D)
- Establish grid and setup parameters
- Is post processing necessary

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ImpulseRadar CrossOver 730 system with 70 and 300 MHz antennas on Interstate Pavements with water coming up through cracks as 2 cast iron pipe waterlines were ruptured ~10-12 ft deep by horizontal driller

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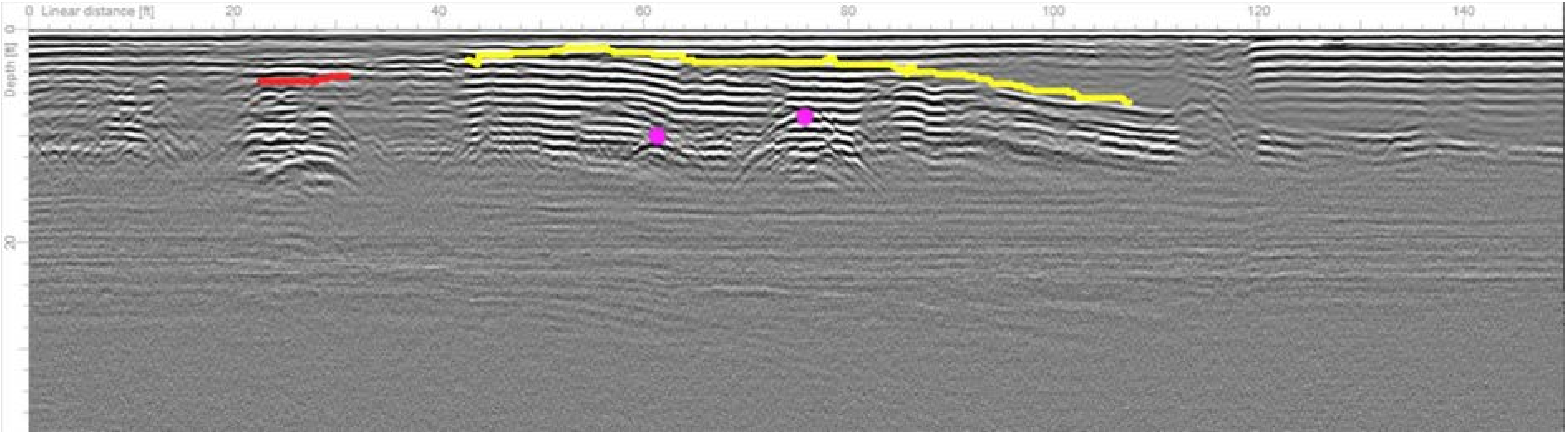
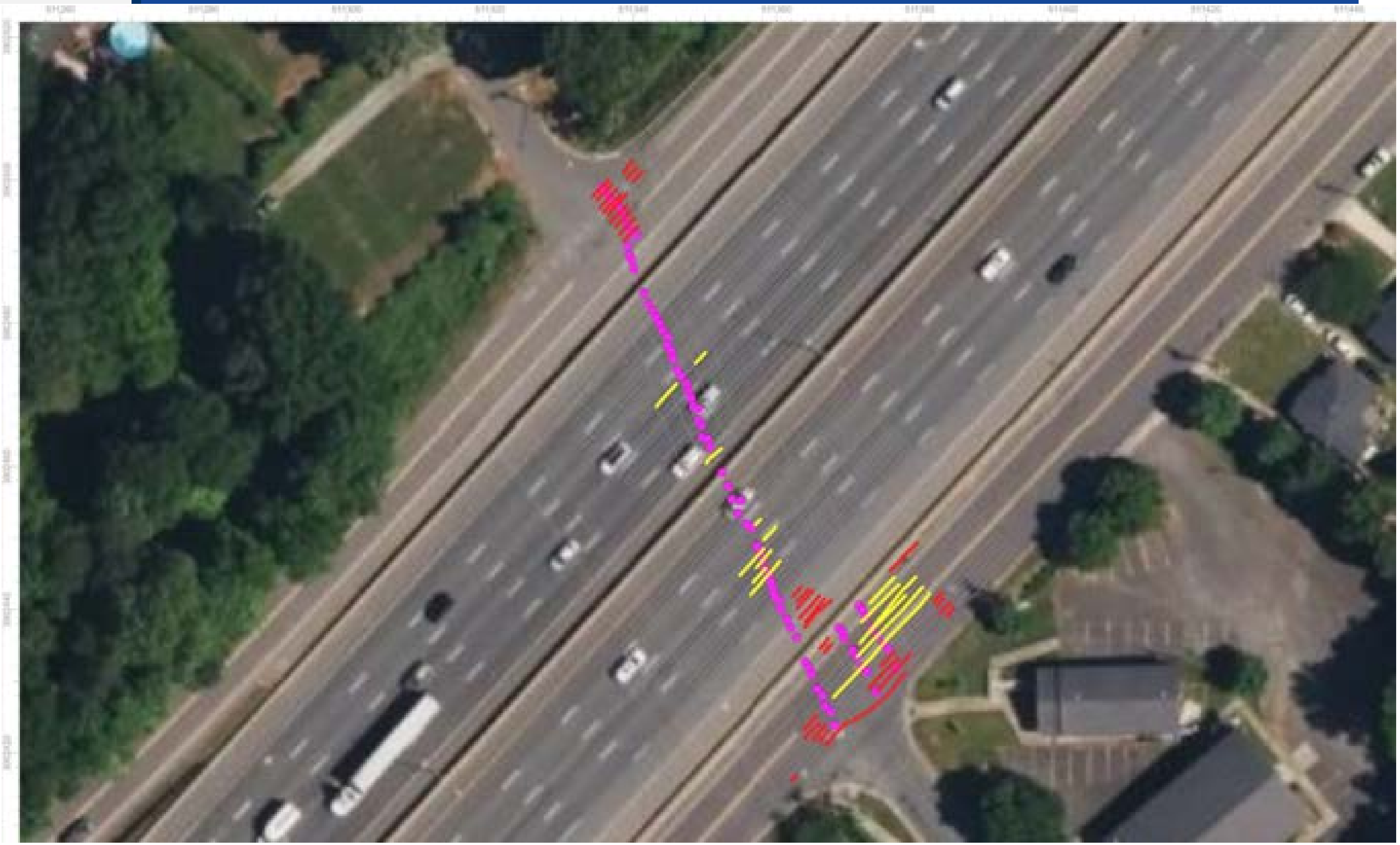
GPR Results over more severe (red) to moderate (yellow) voids and cast iron water pipe reflections (purple dots)



GPR Scan Lines at 3 ft spacings longitudinally with some crossing scans

GPR lines with Severe (red) to Moderate (yellow) Voids and Cast Iron Water Pipes (purple dots)



Large voids indicated by GPR were confirmed by excavation and filled with gravel and grouted

Note large void about 12 ft x 6 x 10 ft deep below 18 inches of asphalt on 4 inches of concrete pavement on interstate outside lane

Thank You!

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Questions?

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