Active and Passive Surface Wave Testing: Addressing Uncertainty using Open-Source Tools

Fundamentals of Active-Source and Passive-Wavefield Surface Wave Testing

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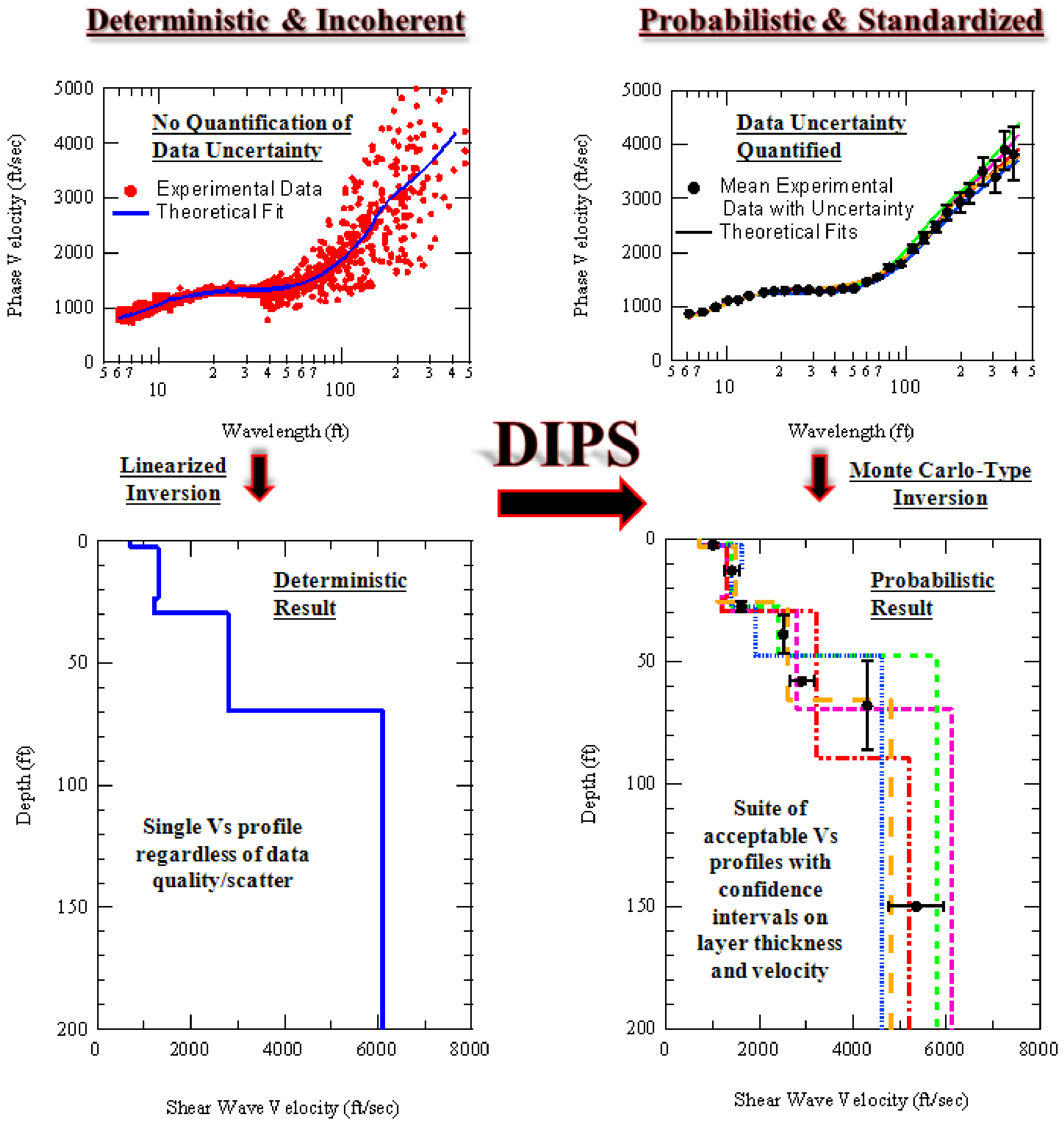
Utah State University, Logan, Utah; 29 July – 1 August 2024

Quantifying Uncertainty in Surface Wave Methods

Presidential Early Career Award for Scientists and Engineers (PECASE)

NSF CAREER: Revolutionizing Surface Wave Methods for Engineering Analyses – from Deterministic and Incoherent to Probabilistic and Standardized (DIPS)



<u>In 2010, I wrote the following</u>: Traditionally, surface wave methods (SWM's) have been used to provide a single, deterministic Vs profile for each site tested, without consideration given to uncertainty…

An ever increasing number of researchers and practitioners are using SWM's without understanding the uncertainty in their results…

It is likely that no other non-standardized test is used in geotechnical engineering more widely than SWM's.

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Guidelines for the Good Practice of Surface Waves Analysis

Bull Earthquake Eng
DOI 10.1007/s10518-017-0206-7

Foti et al. (2018)

CrossMark

ORIGINAL RESEARCH PAPER

Guidelines for the good practice of surface wave analysis: a product of the InterPACIFIC project

Sebastiano Foti[1] · Fabrice Hollender[2] · Flora Garofalo[1] · Dario Albarello[3] · Michael Asten[4] · Pierre-Yves Bard[5] · Cesare Comina[6] · Cécile Cornou[5] · Brady Cox[7] · Giuseppe Di Giulio[8] · Thomas Forbriger[9] · Koichi Hayashi[10] · Enrico Lunedei[3] · Antony Martin[11] · Diego Mercerat[12] · Matthias Ohrnberger[13] · Valerio Poggi[14] · Florence Renalier[15] · Deborah Sicilia[16] · Valentina Socco[1]

- 54-page “overview” without too many nitty-gritty details
- 11 Appendices with more details and references

As of 2024, there are still no widely recognized standards for surface wave testing. Thus, the state of practice is highly variable, ranging from horrible to excellent (unfortunately with more examples of horrible).

If everyone would follow these guidelines, it would help.

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ISO International Standard for Passive Surface Wave Methods

DRAFT INTERNATIONAL STANDARD

ISO/DIS 24057

More recently (2022), an effort led by the Japanese

ISO/TC **182**

Secretariat: **BSI**

Voting begins on:
2021-11-30

Voting terminates on:
2022-02-22

Array measurement of microtremors to estimate shear wave velocity profile

Reference number
ISO/DIS 24057:2021(E)

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Why Surface Waves?

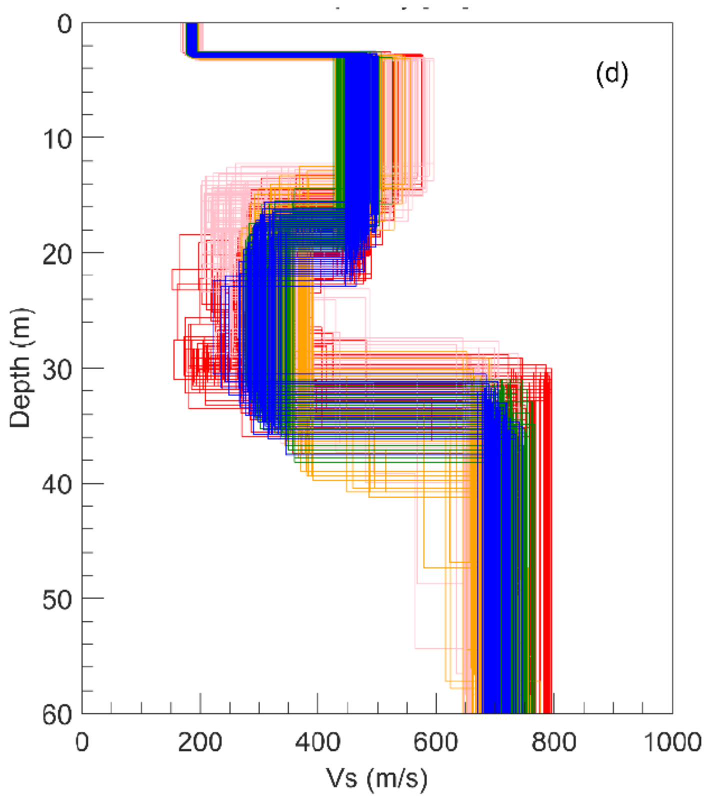
Goal: accurate/reliable V_S profile

Pro's:

- Non-invasive (source and receivers on surface)
- Economical/rapid field testing
- Can detect inverse low velocity layers
- Can tailor testing for shallow (<1 m) to deep (>1 km) profiling

Con's:

- Complicated data processing (especially inversion)
- Non-unique solution



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Surface Wave Methods

- Many different methods with various acquisition, processing, and inversion techniques.

Our preferred approach and the methods we will be focusing on in this course

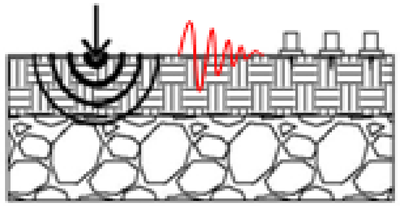
- Active-source:
  - SASW: spectral analysis of surface waves (Stokoe et. al 1994)
  - MASW: multi-channel analysis of surface waves (Park et al. 1999, Foti 2000)

- Passive-source:
  - ReMi^{TM}: refraction microtremor with *linear arrays* (Louie 2001)
  - MAM: microtremor array measurements with *2D arrays* (Okada 2003, Tokimatsu et al. 1992)

Generalized Surface Wave Testing: 3 Steps

Acquisition

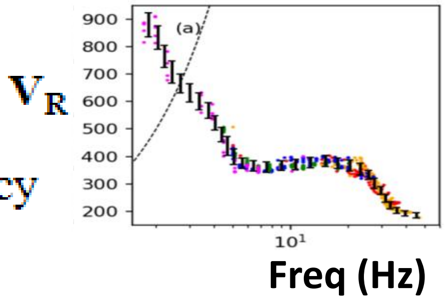
Field Data Collection:
Measurement of stress waves at the ground surface



Active & Passive Methods

Processing

Dispersion Curve:
Rayleigh Wave Phase Velocity vs. Wavelength/Frequency

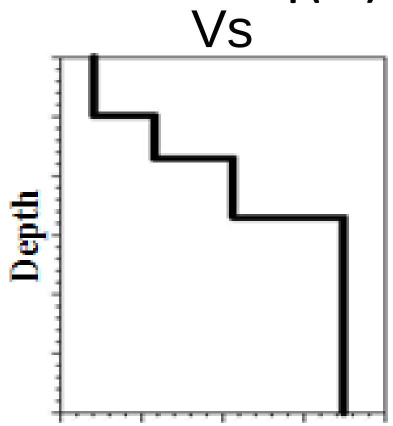


Robustly determined by experts (modes!)

Inversion

Shear Wave Velocity Profile:
Variation of Small Strain Shear Modulus vs. Depth

$$G_{max} = \rho V_S^2$$



Still challenging for experts: highly non-unique

Brief aside…

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Inversion Challenges

$$???? = 9$$

What is the correct mathematical expression?

If I told you it was an addition problem would that help?

$$6 + 3 = 9$$

$$12 - 3 = 9$$

$$27/3 = 9$$

$$3*3 = 9$$

$$(81)^{0.5} = 9$$

A-priori information helps to constrain the inverse problem

Never forget surface wave inversion is non-unique!!!

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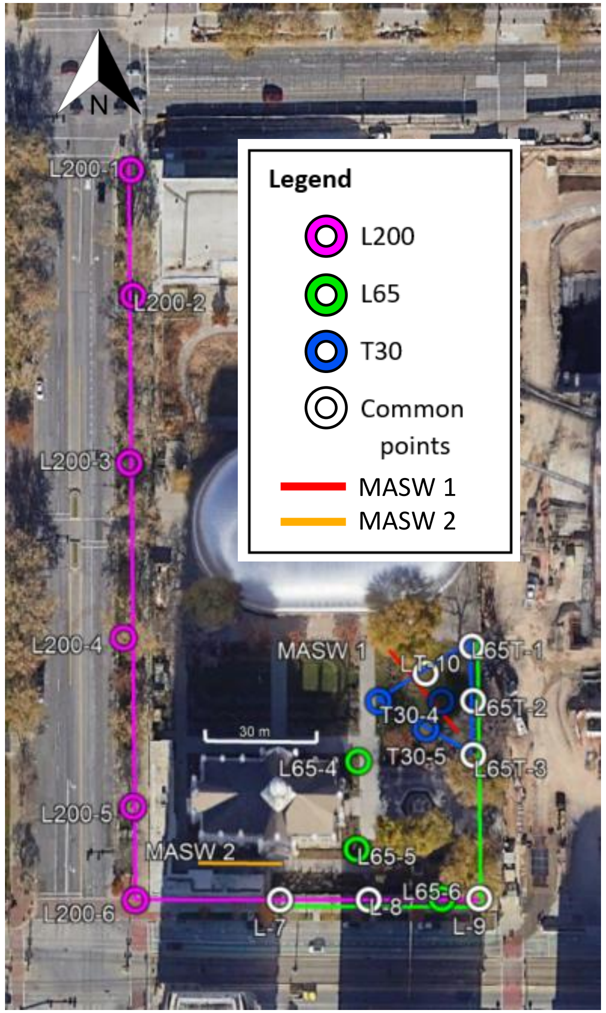
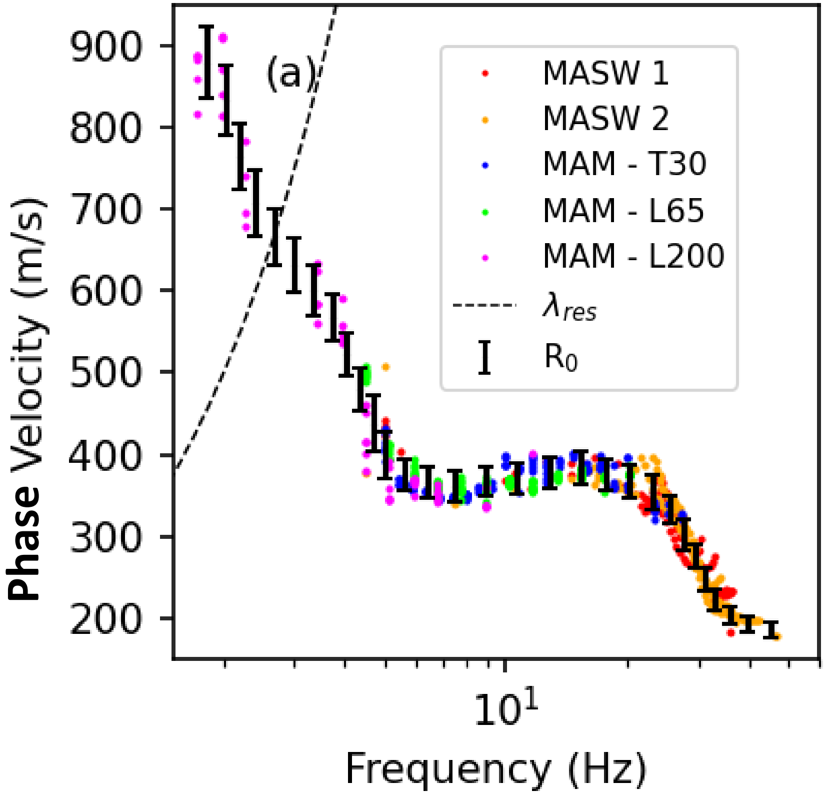
Big Picture Example

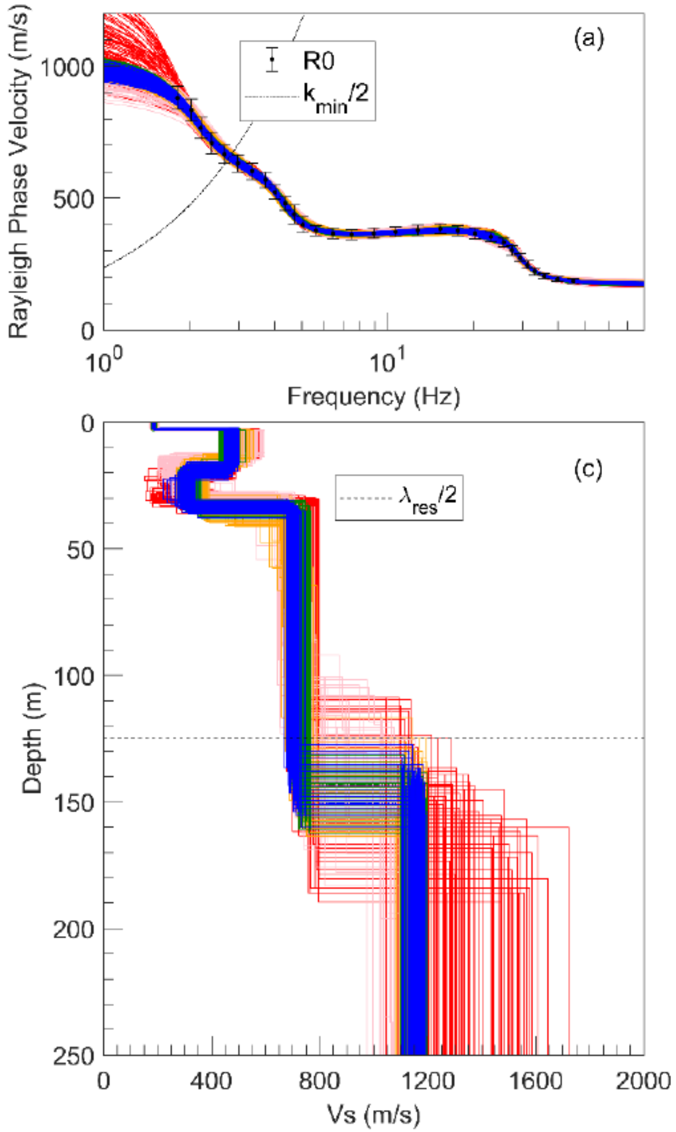
Acquisition of Waveforms using Sensor Arrays



Processing Waveforms to Obtain Dispersion Data (Phase Velocity, Vr vs. Frequency)



Inversion for Shear Wave Velocity (Vs) Profile(s)



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What is Dispersion?

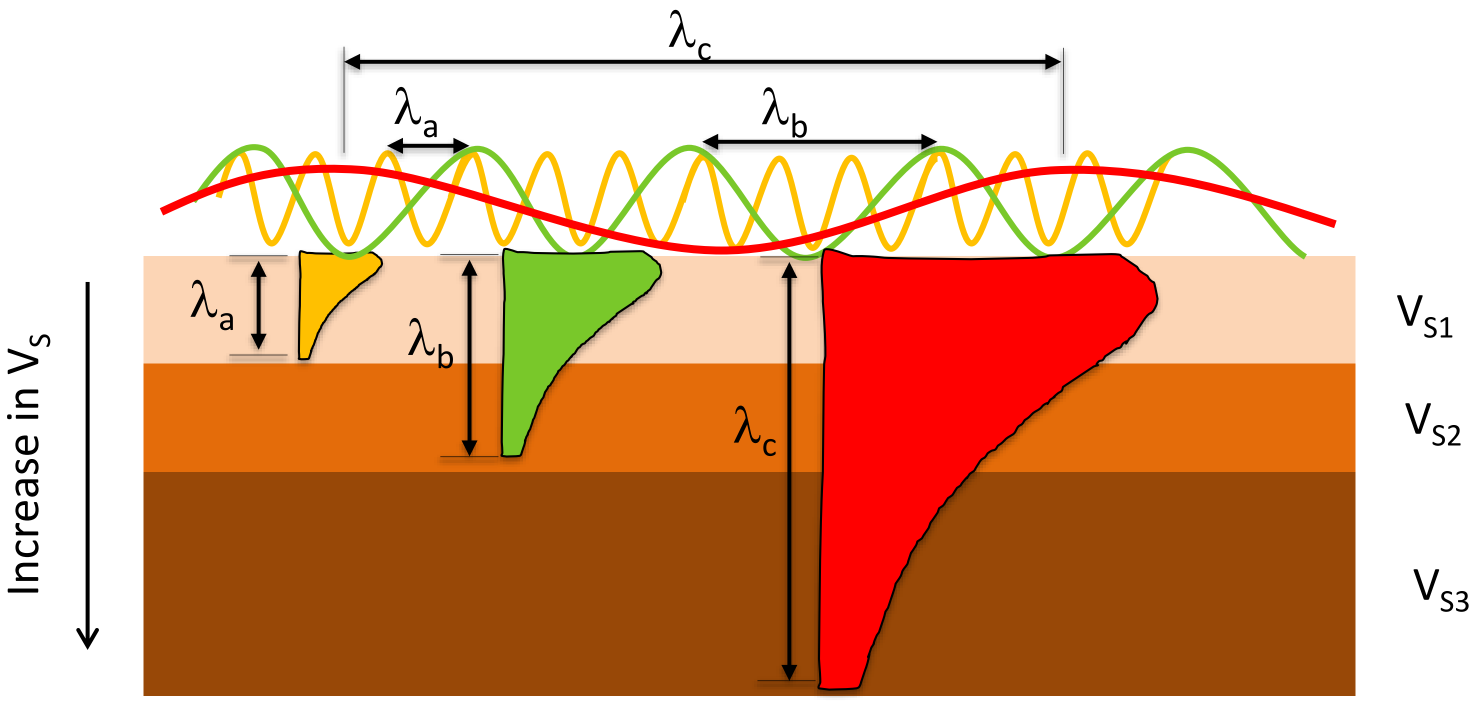
What is Dispersion?

- Surface waves are dispersive in layered deposits
  - Different frequencies/wavelengths travel at different phase velocities (Vr)
  - Why? Different wavelengths (λ) sample different depths and materials
  - **Wavelength is roughly related to depth: D ~ λ/(2 or 3)**

$V = f * \lambda$

Short λ ~ High f

Long λ ~ Low f



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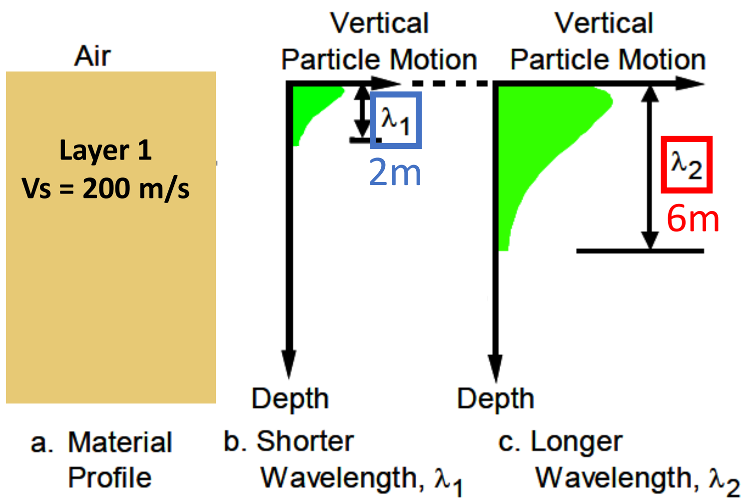
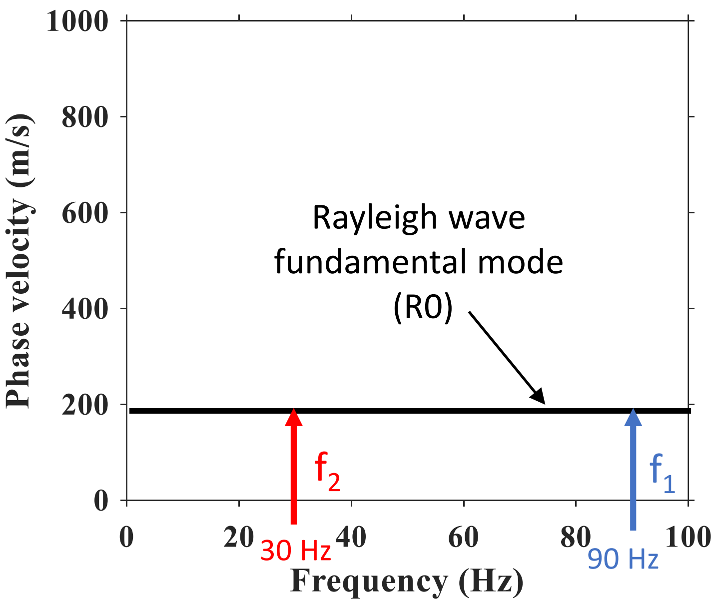
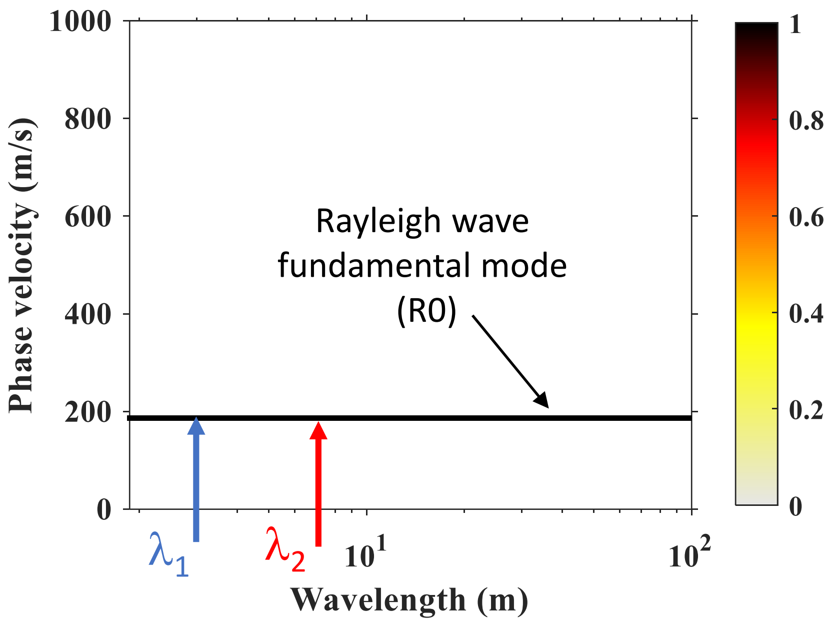
Dispersion in a Half-Space (uniform model)







Vr ~ 0.9*Vs

Vr ~ 0.9*200 m/s ~ 180 m/s

Dispersion curves in terms of <u>*both*</u> frequency and wavelength

$Vr = f * \lambda$

Short λ ~ High f

Long λ ~ Low f

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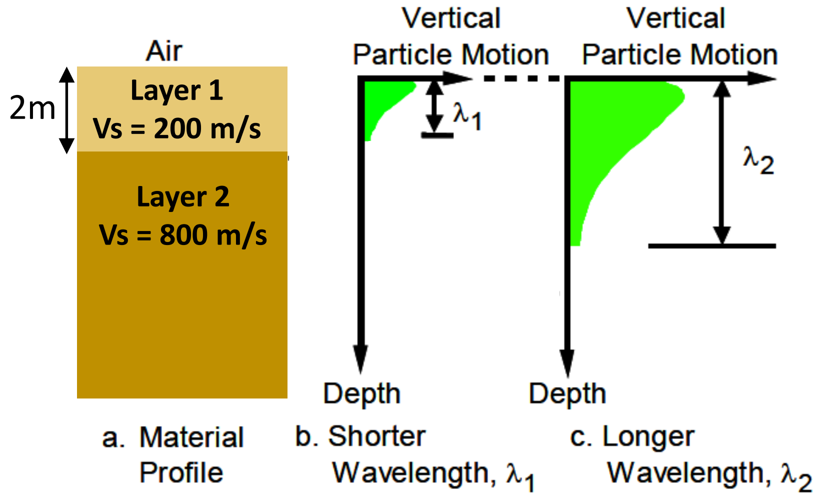
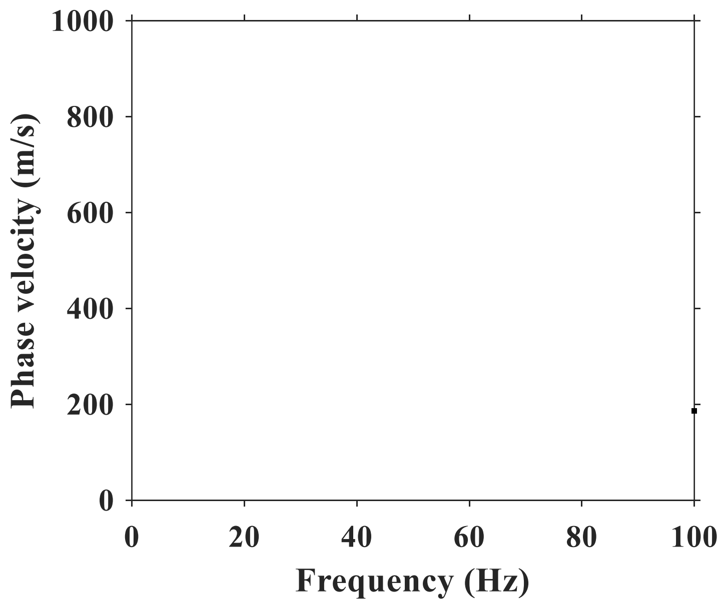
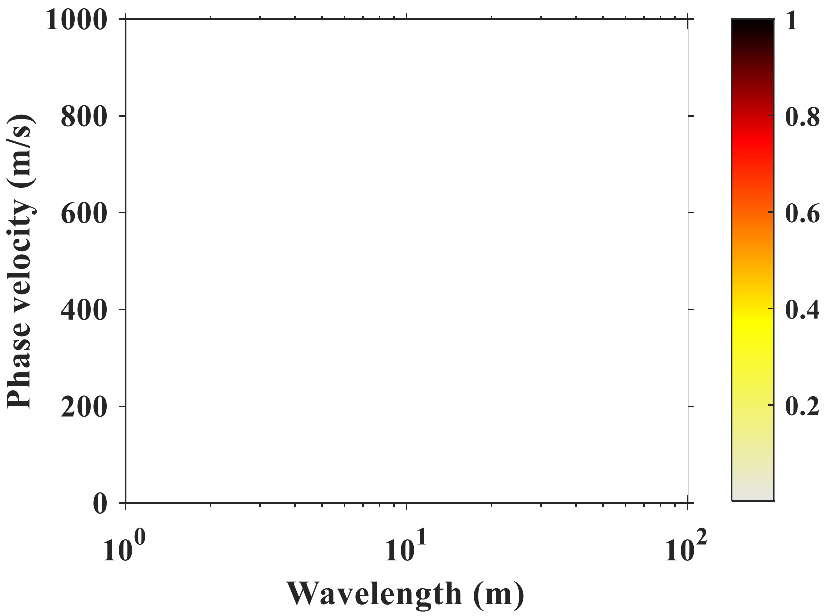
Dispersion: One Layer Over a Half-Space

Sketch here







Vr ~ 0.9*Vs

What will the dispersion curve look like?

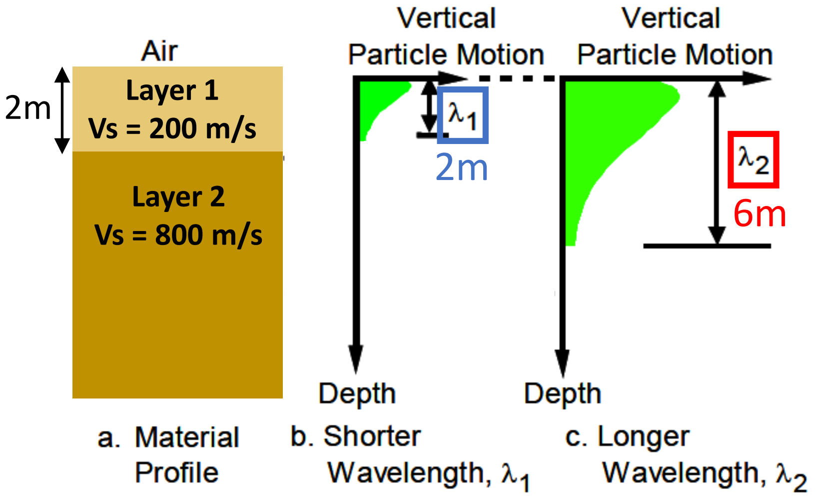
Dispersion curves in terms of <u>*both*</u> frequency and wavelength

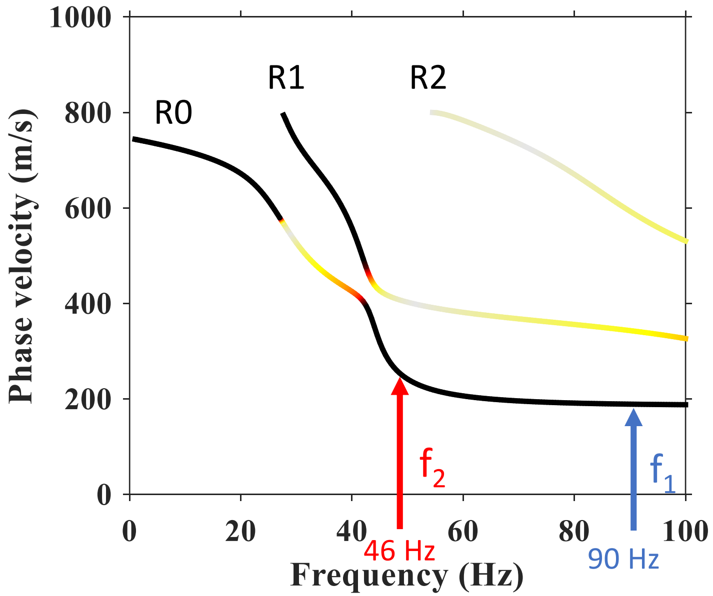
Vr = f * λ

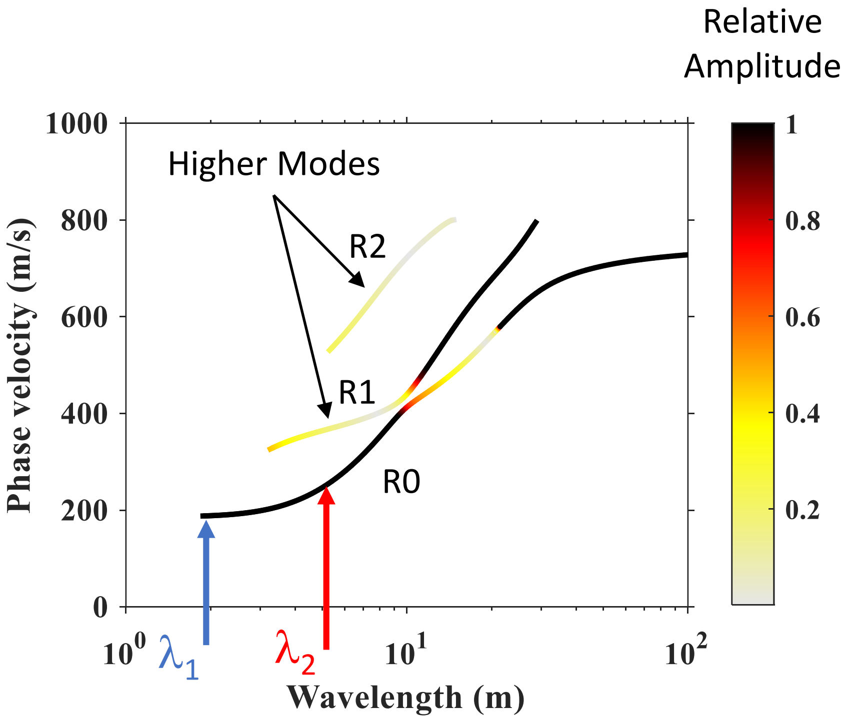
Short λ ~ High f

Long λ ~ Low f

Dispersion: One Layer Over a Half-Space







Vr ~ 0.9*Vs

- *Theoretical dispersion modes*: same frequency travels at different velocities
- We try to isolate the fundamental mode whenever possible during data processing (discussed later)

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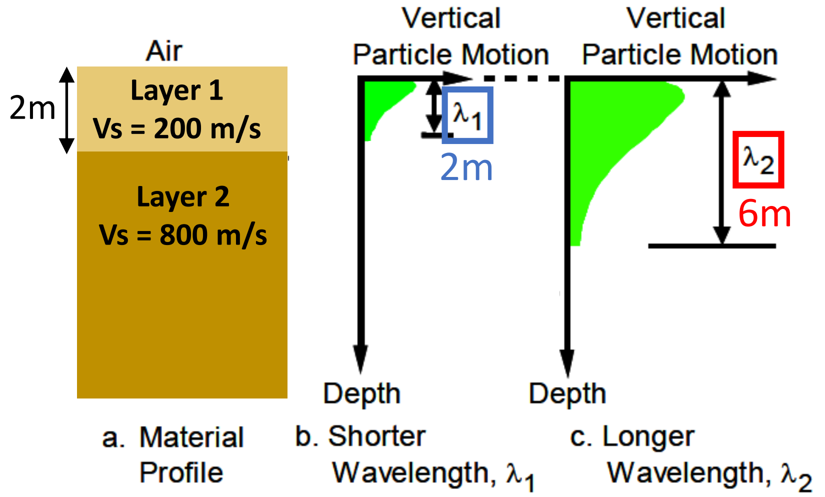
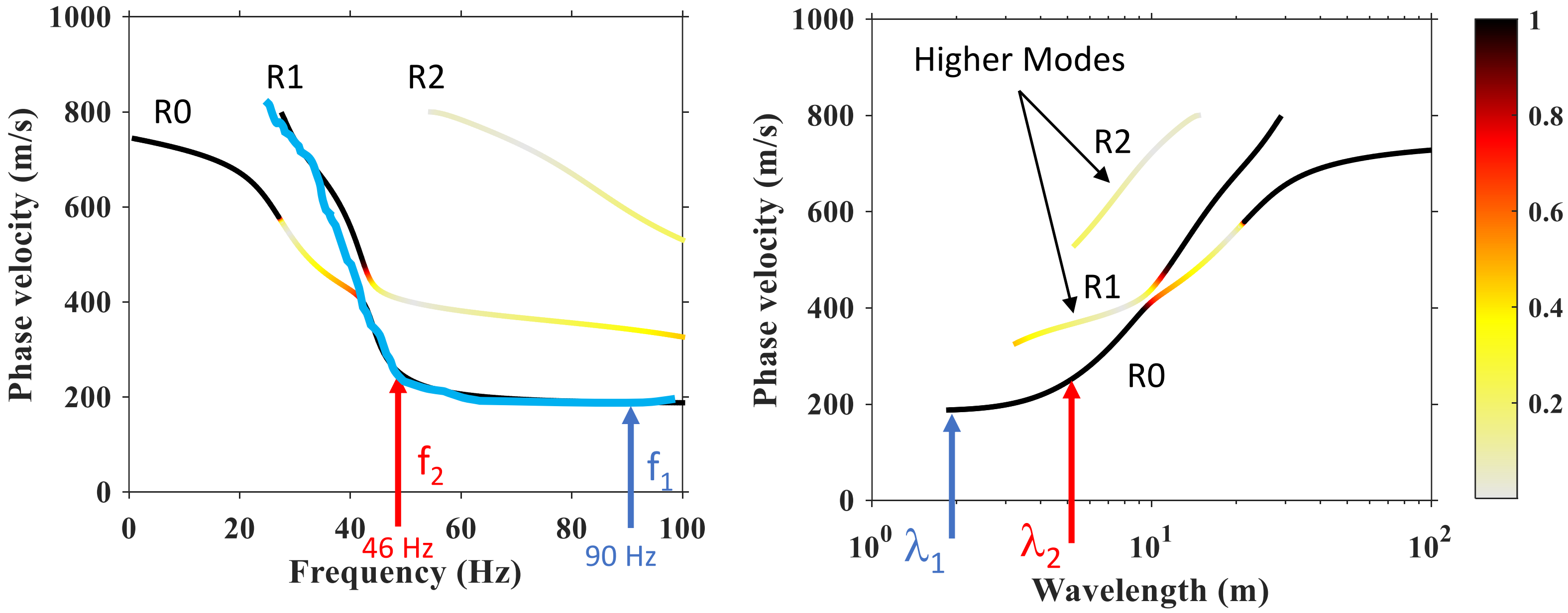
Dispersion: One Layer Over a Half-Space



Vr ~ 0.9*Vs

What your field experimental dispersion data *could* look like! (Effective/Superposed/Mixed-Mode)



- *Theoretical dispersion modes*: same frequency travels at different velocities
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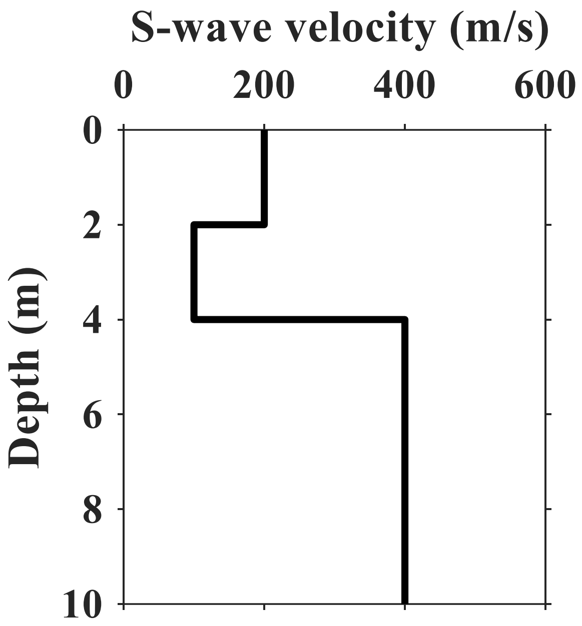
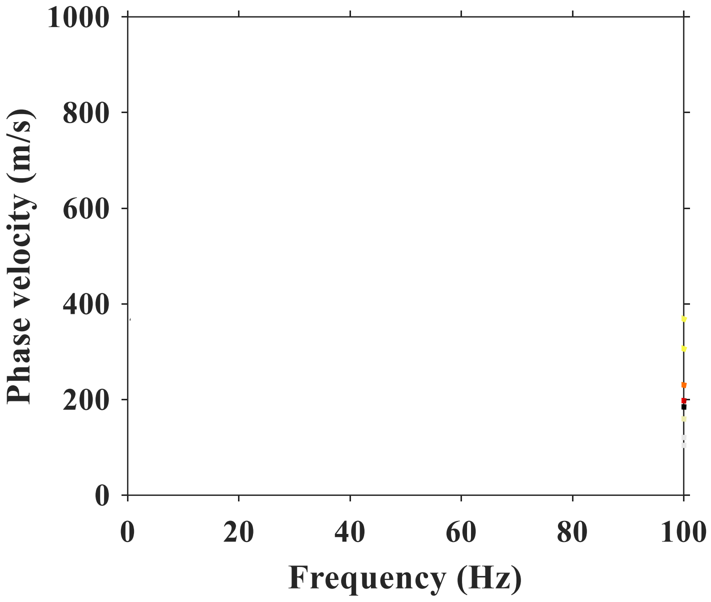
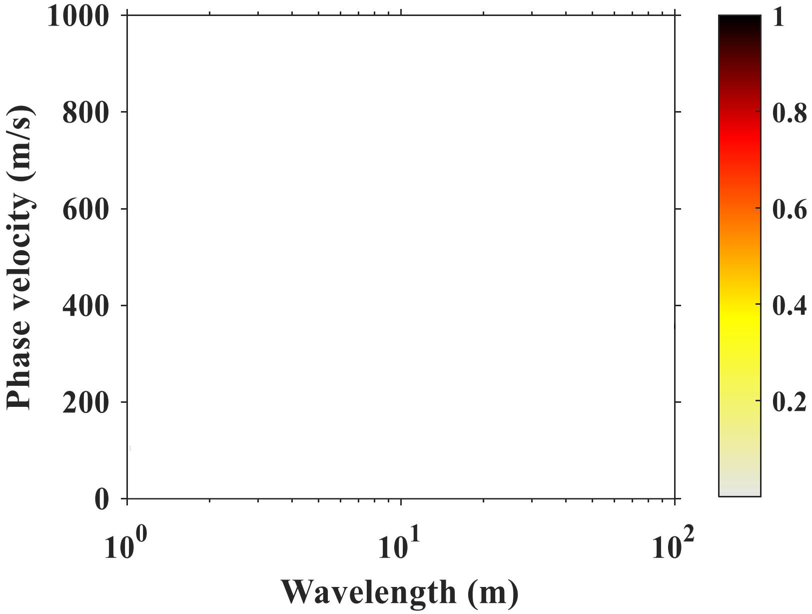
Dispersion: Low Velocity Layer (LVL)

Sketch here







Vr ~ 0.9*Vs

What will the dispersion curve look like?

Dispersion curves in terms of *both* frequency and wavelength

Vr = f * λ

Short λ ~ High f

Long λ ~ Low f

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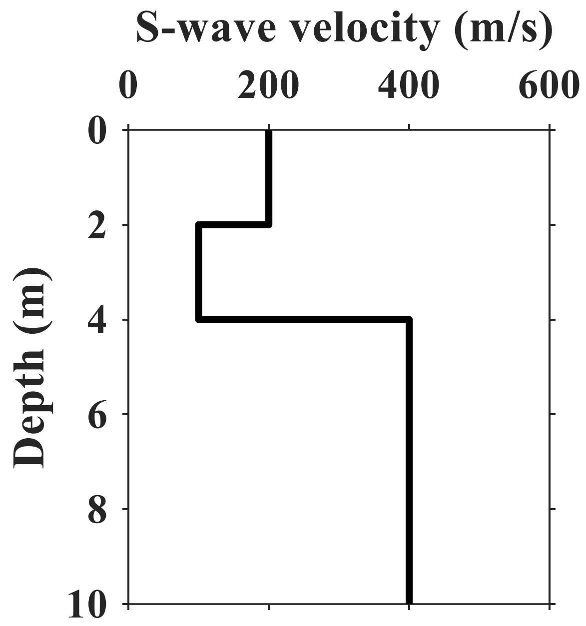
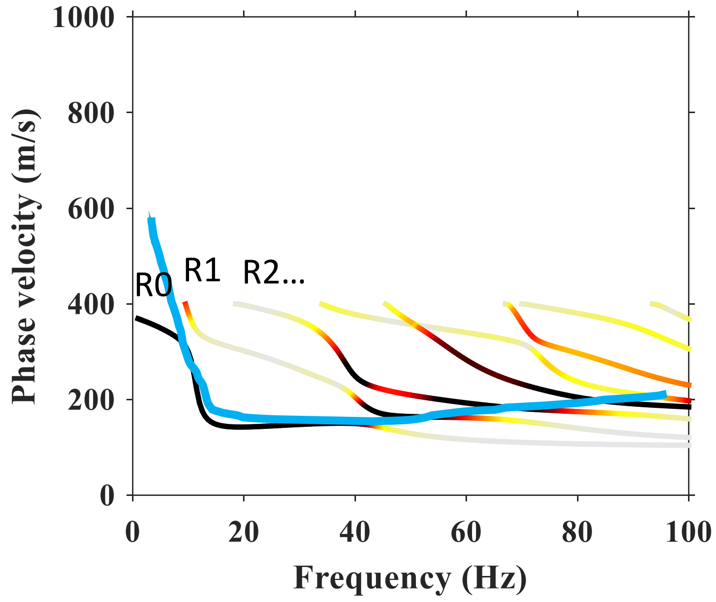
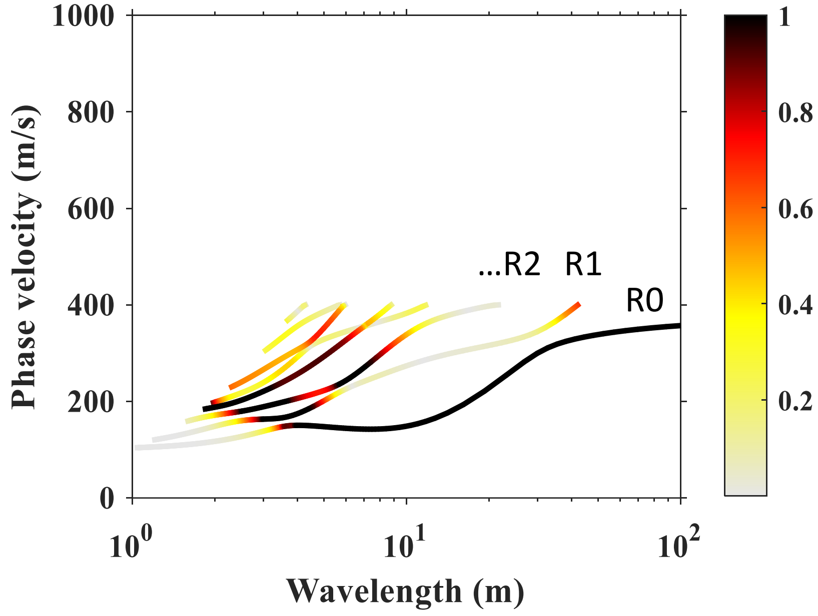
Dispersion: Low Velocity Layer (LVL)



What your field experimental dispersion data *could* look like! (Effective/Superposed/Mixed-Mode)





- *Theoretical dispersion modes*: same frequency travels at different velocities
- We try to isolate the fundamental mode whenever possible during data processing (discussed later)

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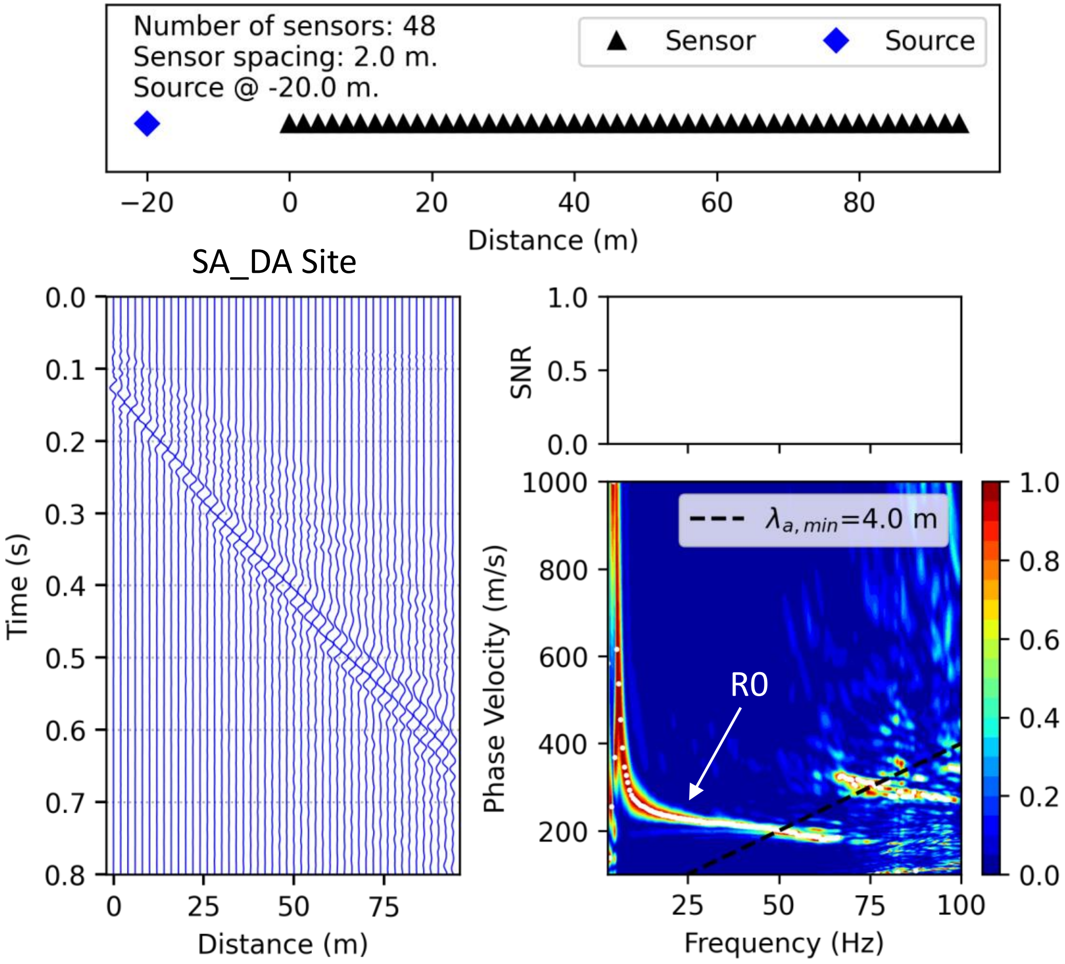
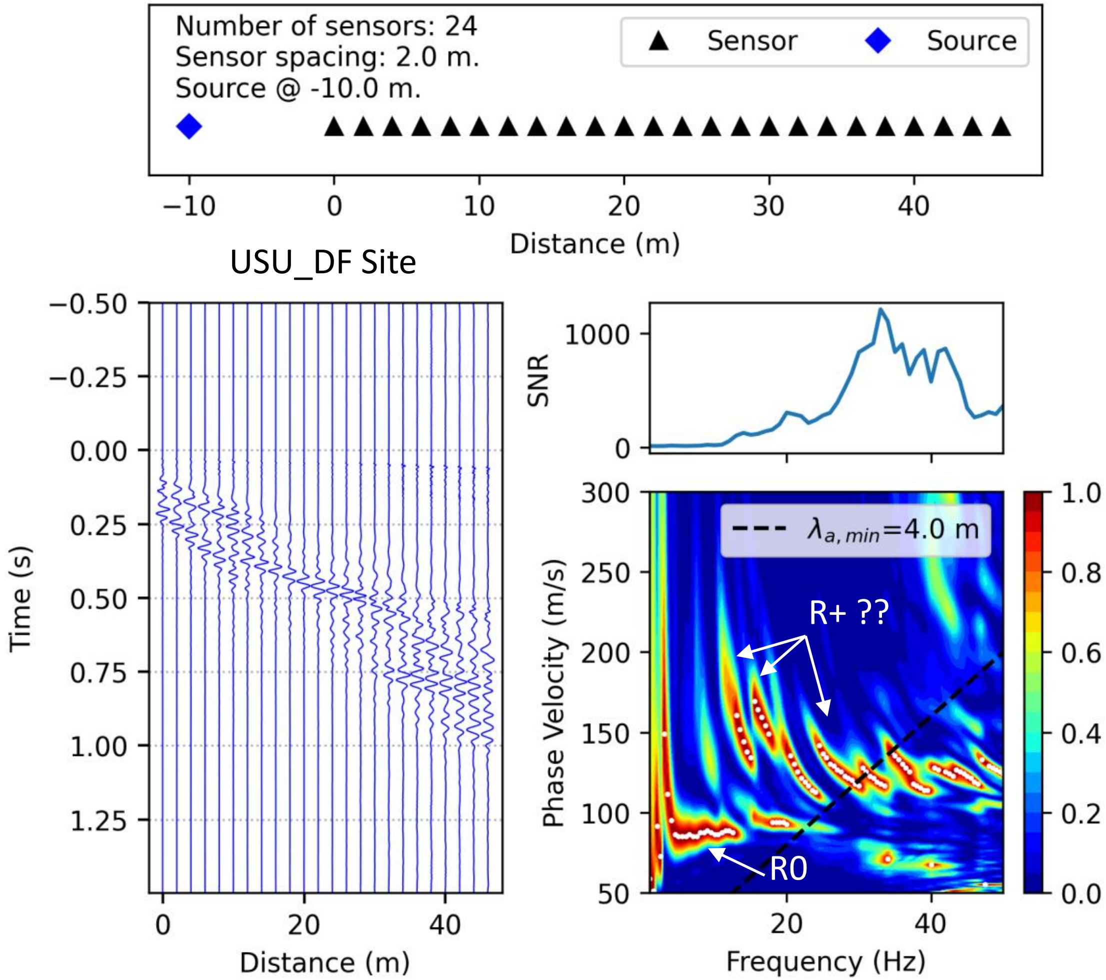
What Your Dispersion Data Might Really Look Like…

"Easy" Site (clear, broadband R0 trend)



"Difficult" Site (some R0, lots of higher modes)



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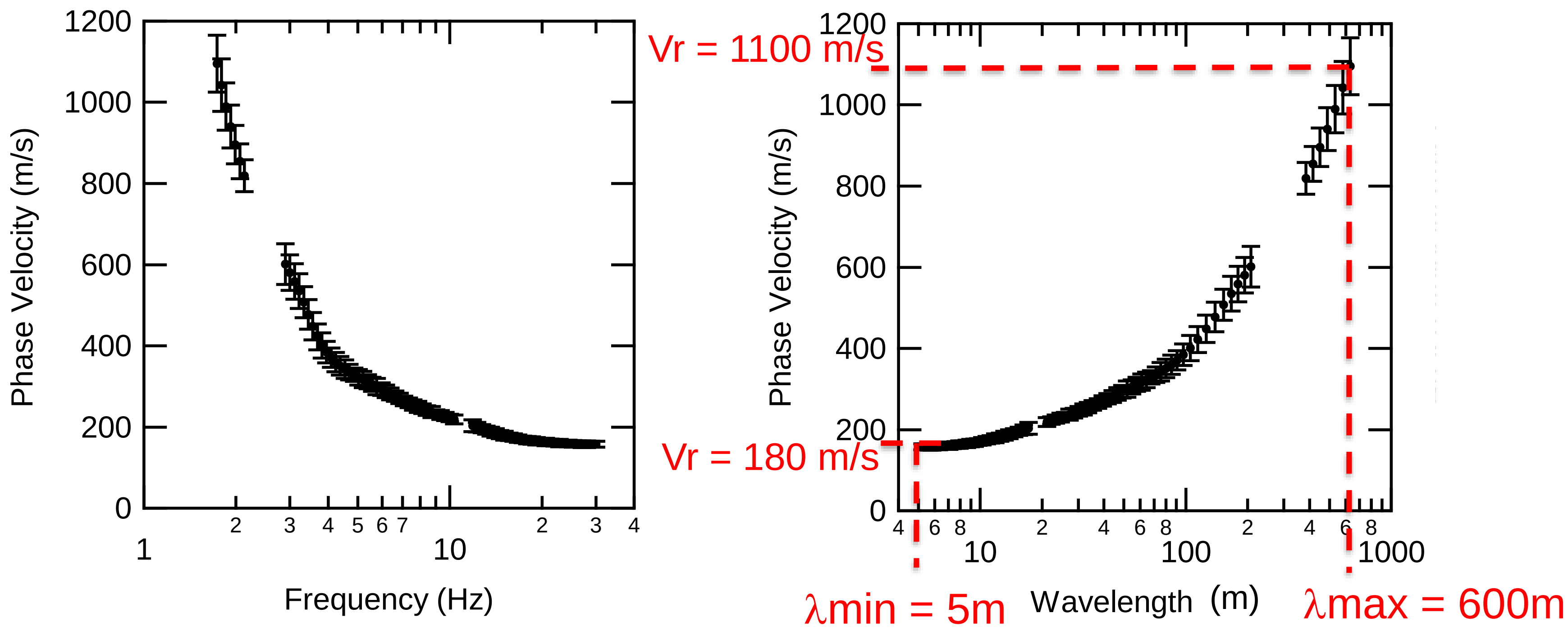
"Reading" Dispersion Data



λ = wavelength

- ****Can't resolve surface layers less than ~ 2.5 m thick (λmin/2)****
- ****Can't resolve layers deeper than ~ 200 – 300 m (λmax/2 or 3)****
- Surface layer Vs ~ 200 m/s (1.1*Vr at λmin); deepest layer Vs > 1200 m/s (1.1*Vr at λmax).

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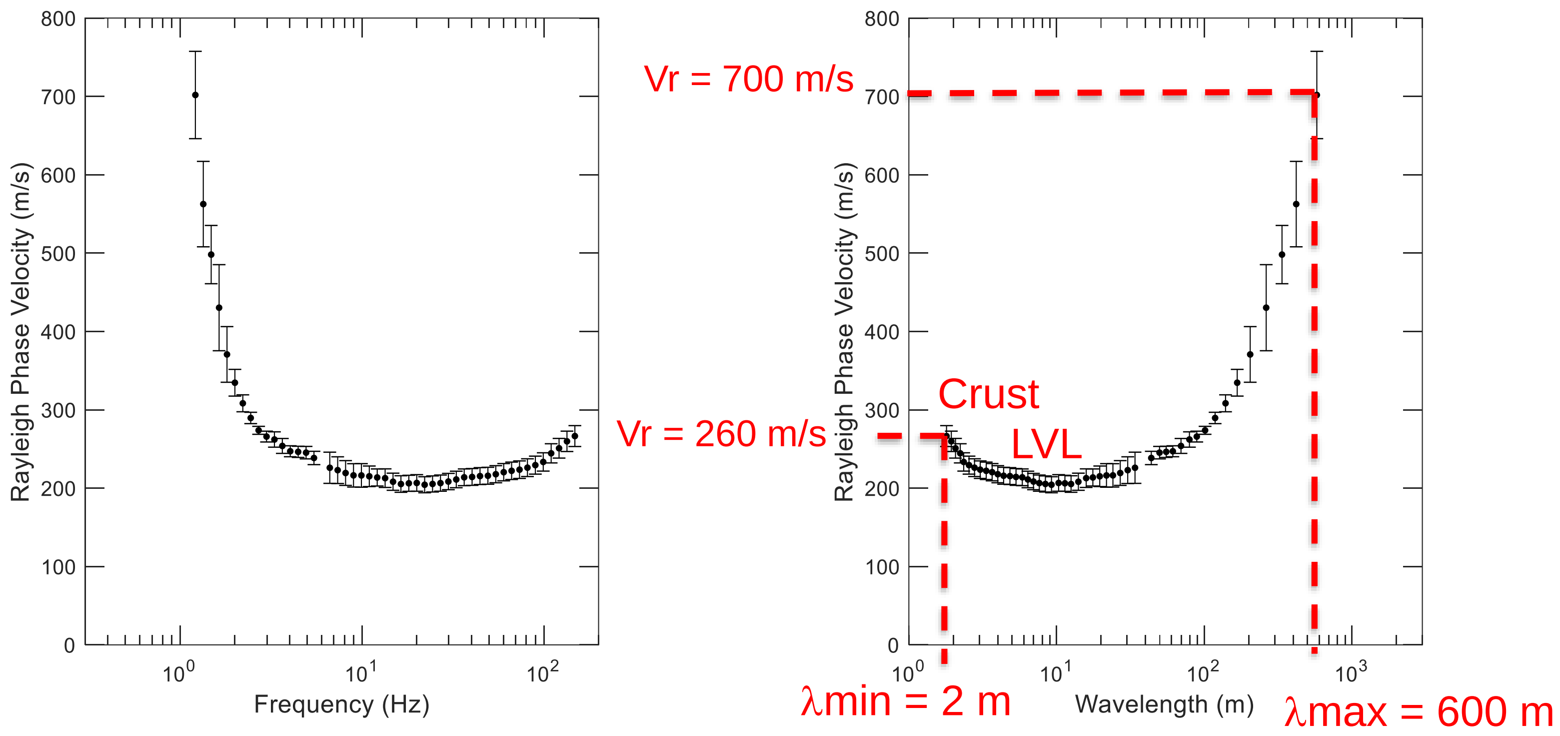
“Reading” Dispersion Data with Low Velocity Layer



- **Can’t resolve surface layers less than ~ 1.0 m thick (λmin/2)**
- **Can’t resolve layers deeper than ~ 200 – 300 m (λmax/2 or 3)**
- Surface layer Vs ~ 290 m/s (1.1*Vr at λmin); deepest layer Vs > 700 m/s (1.1*Vr at λmax).
- Dip in dispersion data is clear evidence of a low velocity layer (LVL) beneath a stiff crust.

MASW acquisition

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Surface Wave Methods

- Many different methods with various acquisition, processing, and inversion techniques.

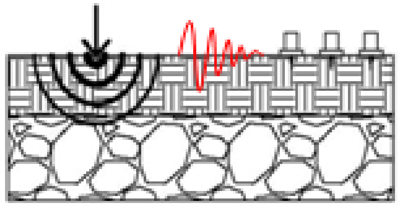
- Active-source:
  - SASW: spectral analysis of surface waves (Stokoe et. al 1994)
  - MASW: multi-channel analysis of surface waves (Park et al. 1999, Foti 2000)

- Passive-source:
  - ReMi™: refraction microtremor with *linear arrays* (Louie 2001)
  - MAM: microtremor array measurements with *2D arrays* (Okada 2003, Tokimatsu et al. 1992)

Generalized Surface Wave Testing

Acquisition

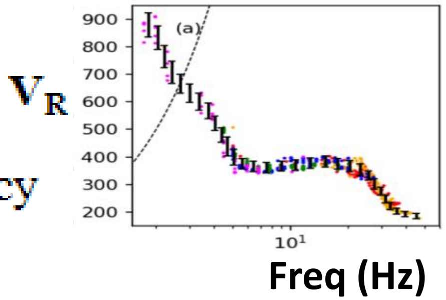
Field Data Collection:
Measurement of stress waves at the ground surface



Active & Passive Methods

Processing

Dispersion Curve:
Rayleigh Wave Phase Velocity vs. Wavelength/Frequency

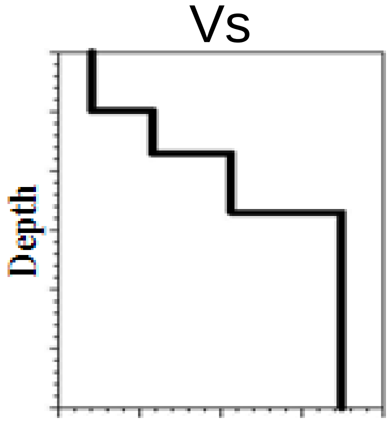


Robustly determined by <u>experts</u> (modes!)

Inversion

Shear Wave Velocity Profile:
Variation of Small Strain Shear Modulus vs. Depth

$$G_{max} = \rho V_S^2$$



Still challenging for experts: highly non-unique

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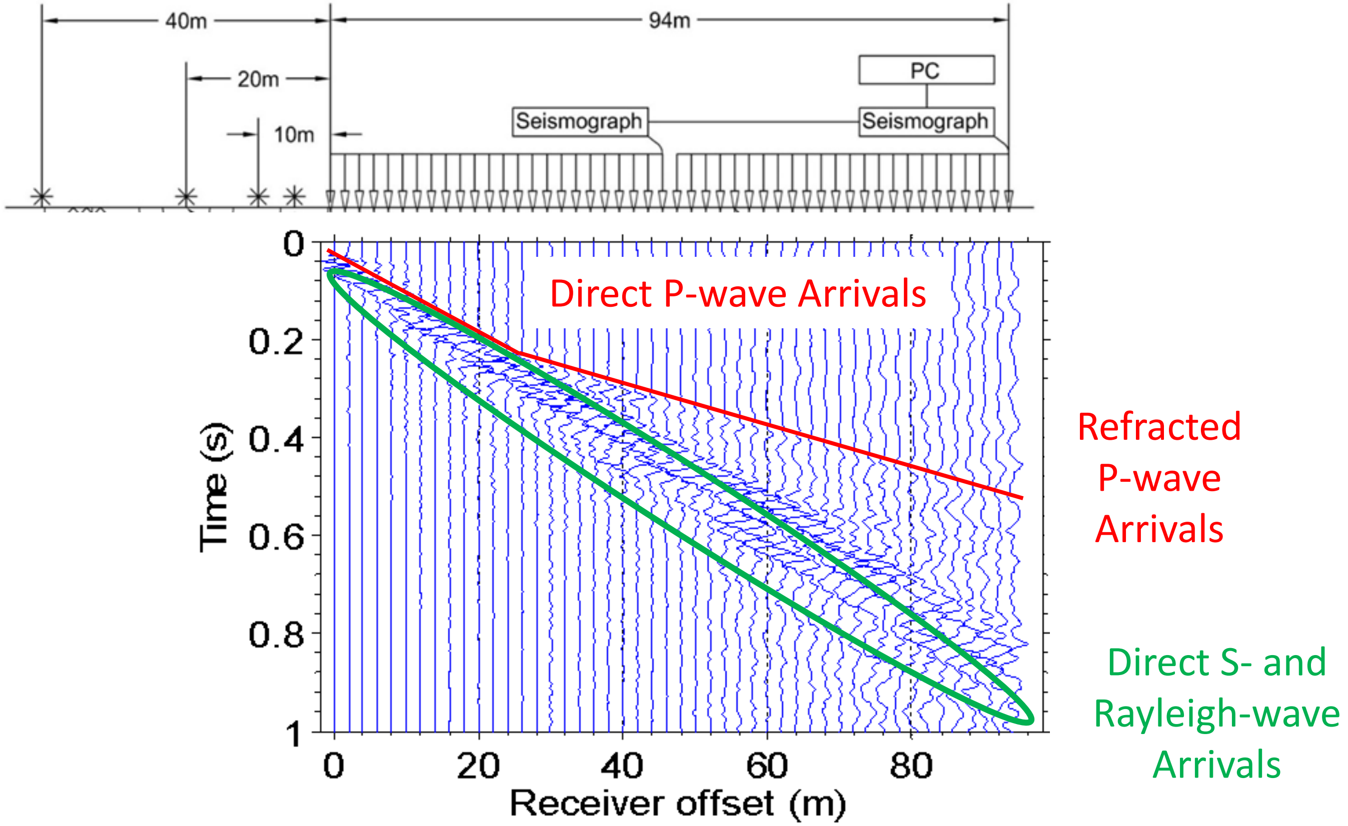
MASW Data Acquisition: Waveforms

- **<u>Goal</u>**: Record waveforms across space (distance) and time with strong surface wave energy from an active source
- The waveforms below were generated by a sledgehammer at a single source location and recorded by 48 vertical geophones



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MASW Test Setup: Ideal Source Configuration

- Source location
  - Multiple offsets from end of line: identify **near-source effects <u>and</u> quantify uncertainty**
    - Otherwise could **underestimate** velocities at depth
    - Will discuss near-source/nearfield effects later
  - Multiple impacts (3-5) at each offset: improve **signal to noise ratio (SNR)**
    - Otherwise could **overestimate** velocities at depth
    - Measuring effects of off-line noise rather than the signal from the active source

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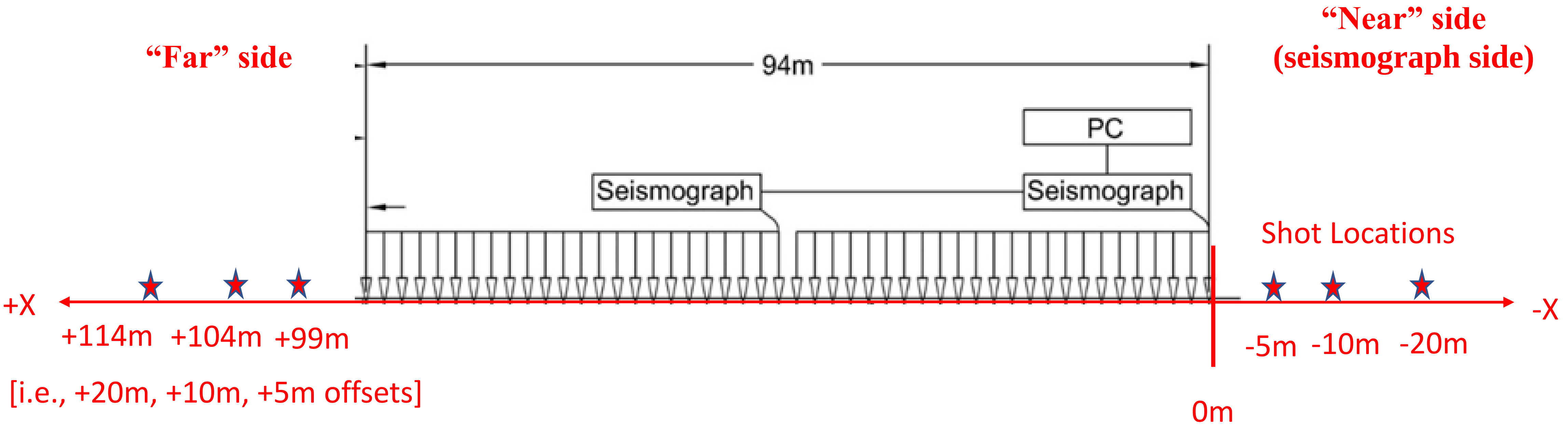
MASW Array Coordinate System



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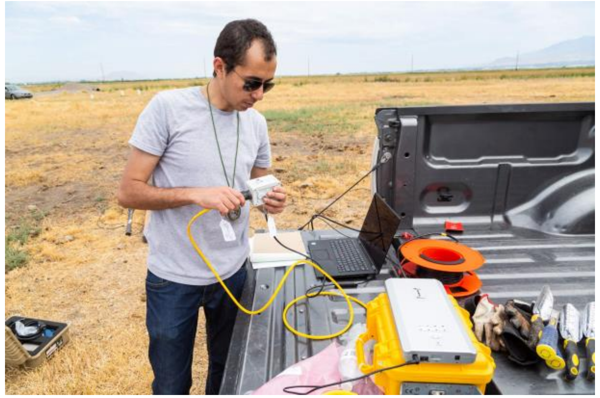
MASW Data Acquisition: Test Setup

- Source (broadband)
  - hammer, drop weight, bulldozer, vibroseis (shaker) truck
- Receiver Type
  - geophones (4.5-Hz most common)
- Number of Receivers
  - Typically 24 or 48
- Receiver Spacing
  - Variable, depending on depth of interest
  - 1m to 5m are common, with 2m being most typical
- Digitizers/Seismograph
  - 24 channel seismograph (Geometrics Geode)



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MASW Data Acquisition: Source

Sledgehammer (vertical for Rayleigh)

Sledgehammer & Plank (for Love)

Vibroseis

Accelerated Weight Drop

(from A.J. Martin, GeoVision)

MASW Data Acquisition: Geophone Array (video)

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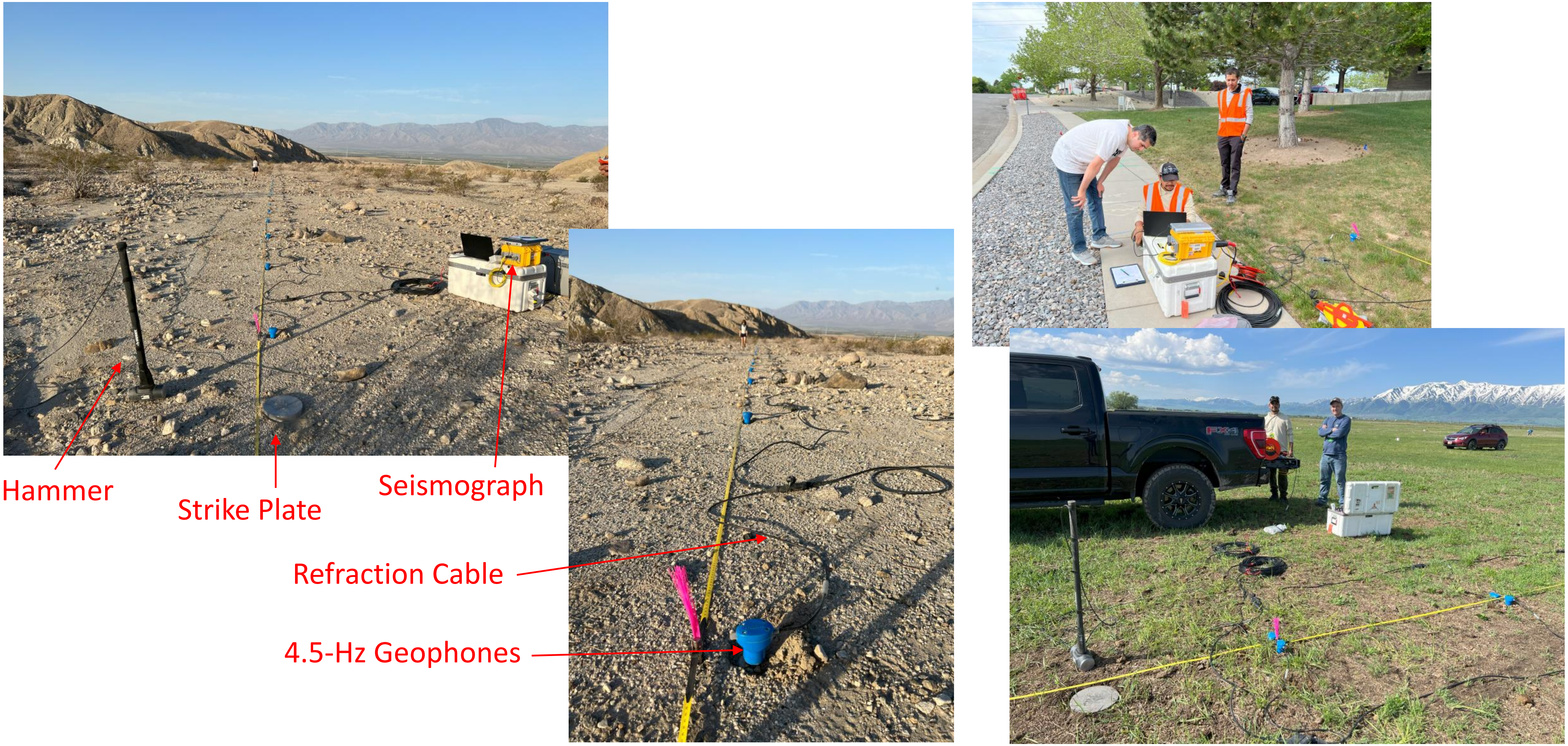
MASW Data Acquisition: Test Setup



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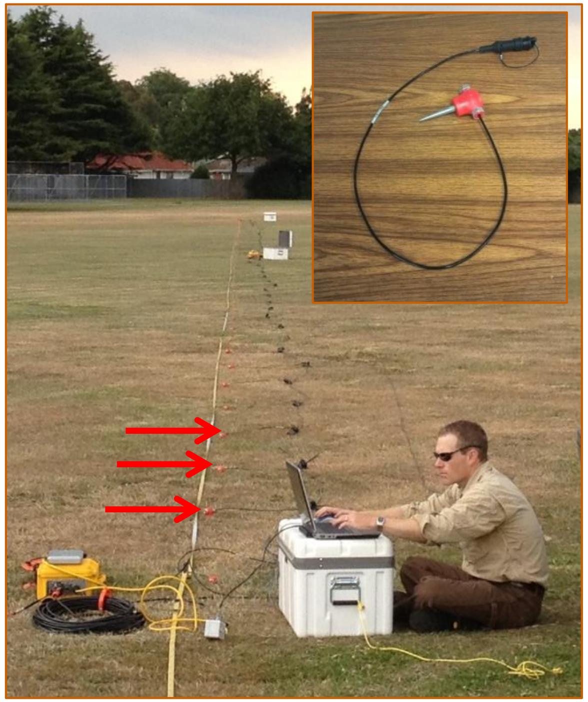
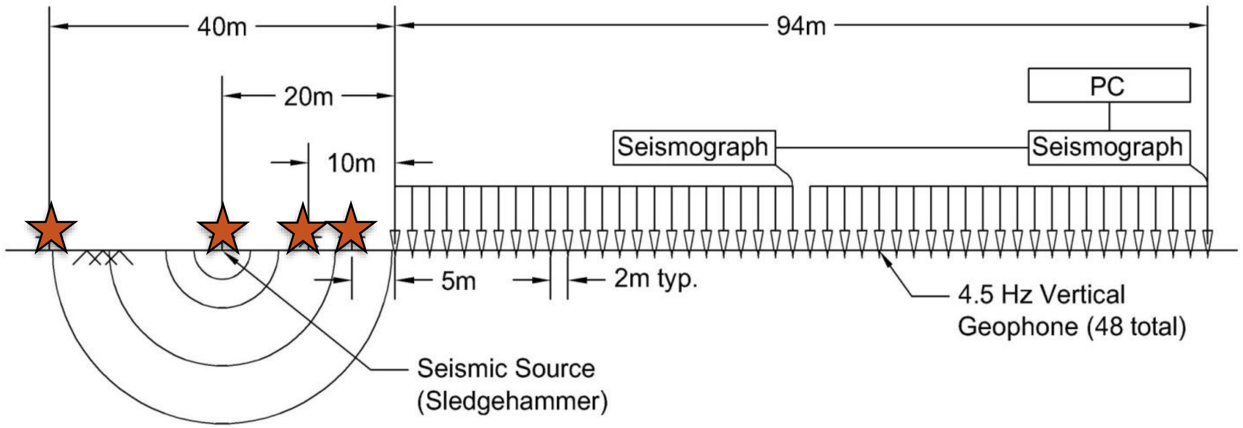
MASW Data Acquisition: Test Setup

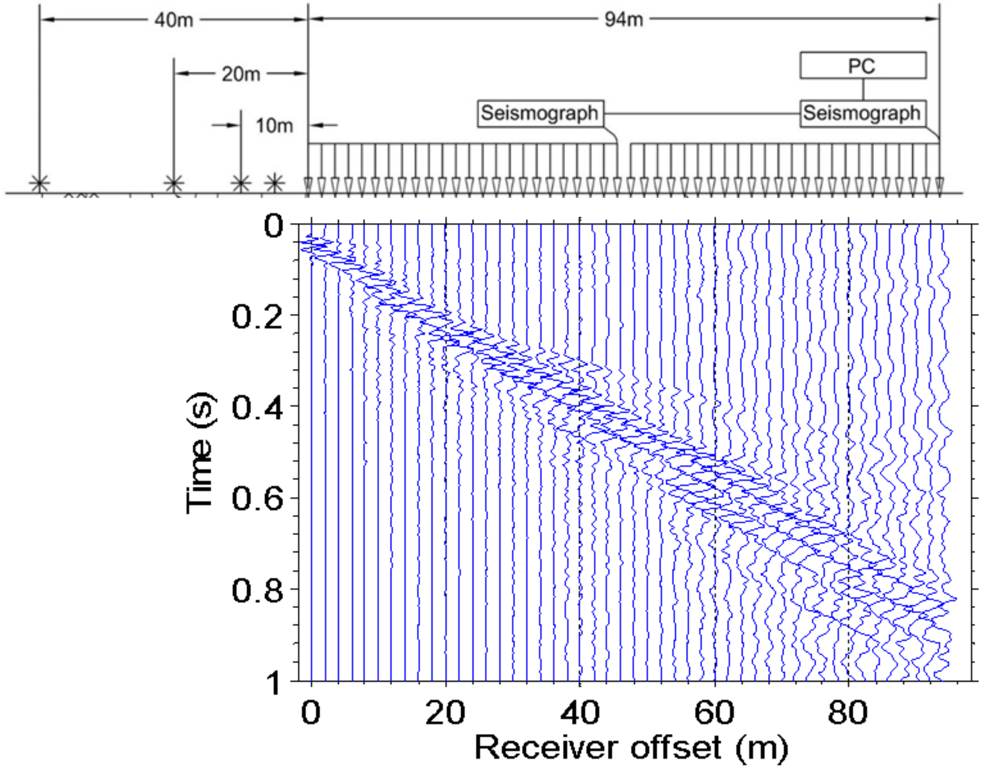




- Linear array of 24-48, 4.5-Hz vertical (Ray.) or horizontal (Love) geophones
- Constant geophone spacing (dx) of 1m – 5m
- Array lengths (L) of 23m, 46m or 94m typical… up to 235m possible (rare)
- Source at multiple locations off both ends of array; 5 m, 10 m, 20 m, 40 m
- Other combinations used depending on space, desired profiling depth…

MASW Data Acquisition: Waveforms

- Stack (average) 5-10 shots at each source location to increase the signal-to-noise ratio (SNR)
- These are 48 stacked waveforms from a single source location



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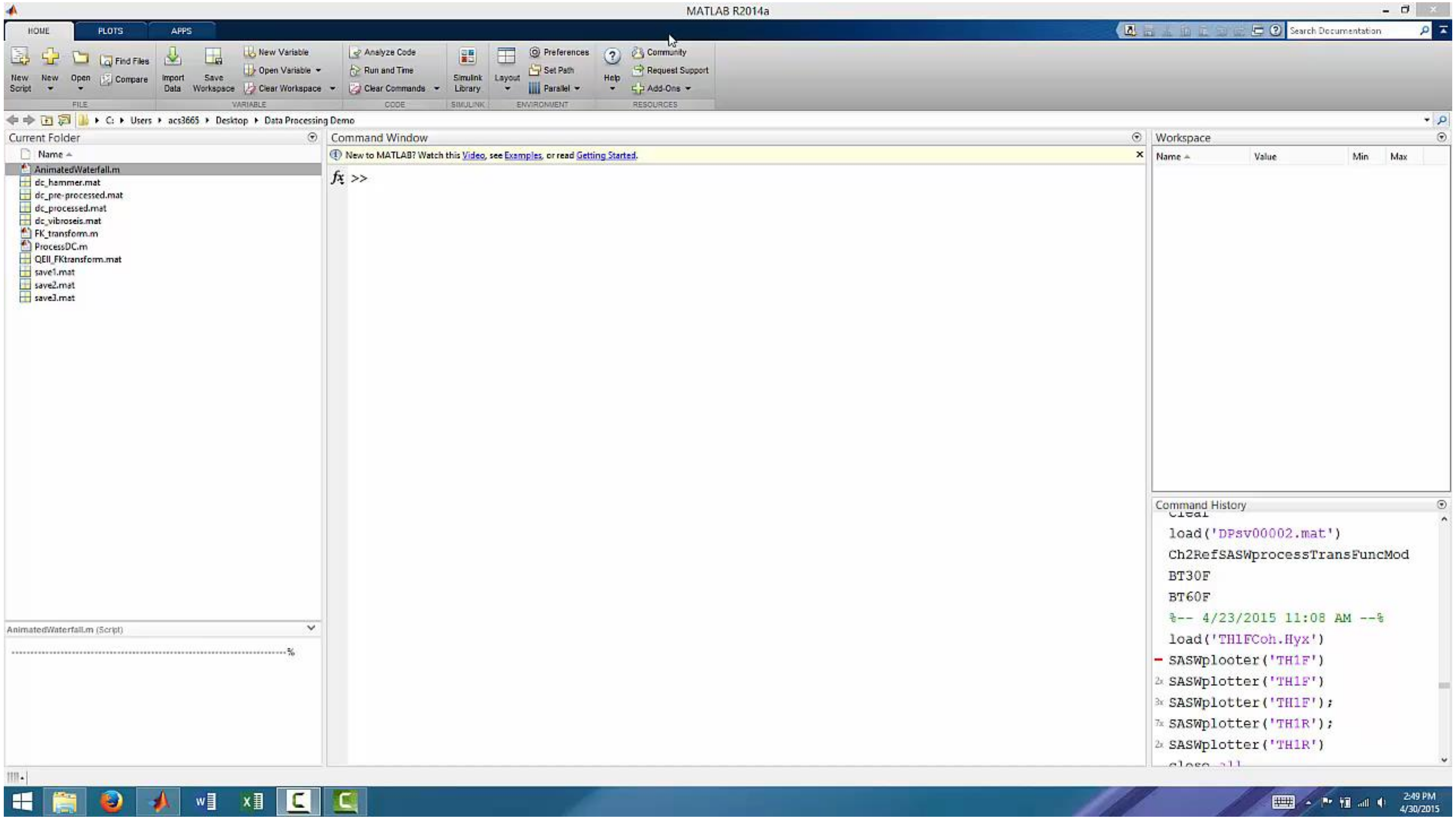
Video: Waveforms from 3 Shot Locations



48, 4.5-Hz geophones
2-m spacing
94-m array
Sledgehammer source

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Stacking to Increase SNR

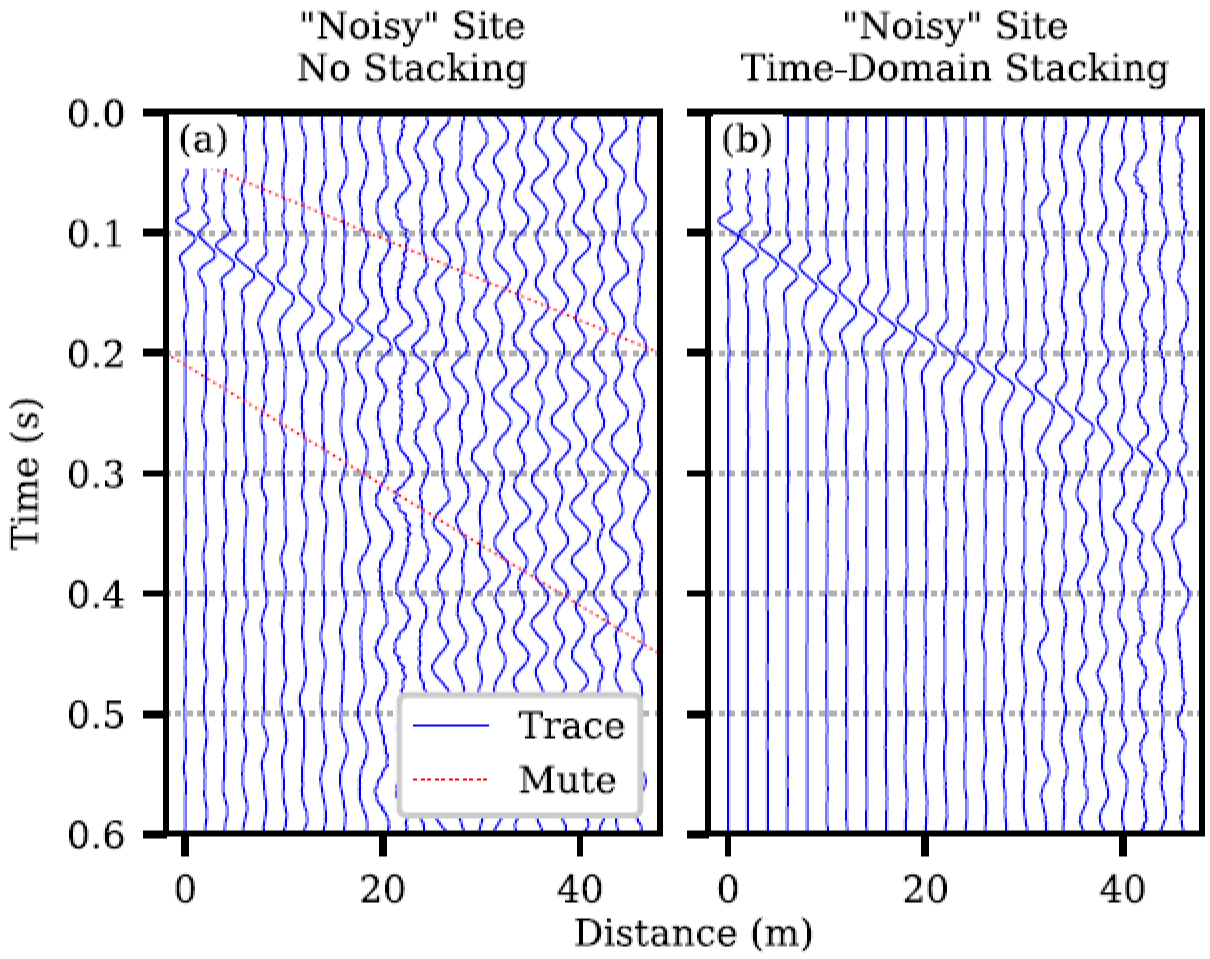

Fig. 3 Seismic records acquired using a 24-channel MASW array with 2-m spacing at a site with significant background noise (i.e., a “noisy” site). **a** shows the seismic records from a single source impact located 20 m off of the end of the array, **b** shows the time-domain stacked seismic records from ten source impacts at the same source location. Diagonal dotted lines in **a** show the selected boundaries for time-domain muting

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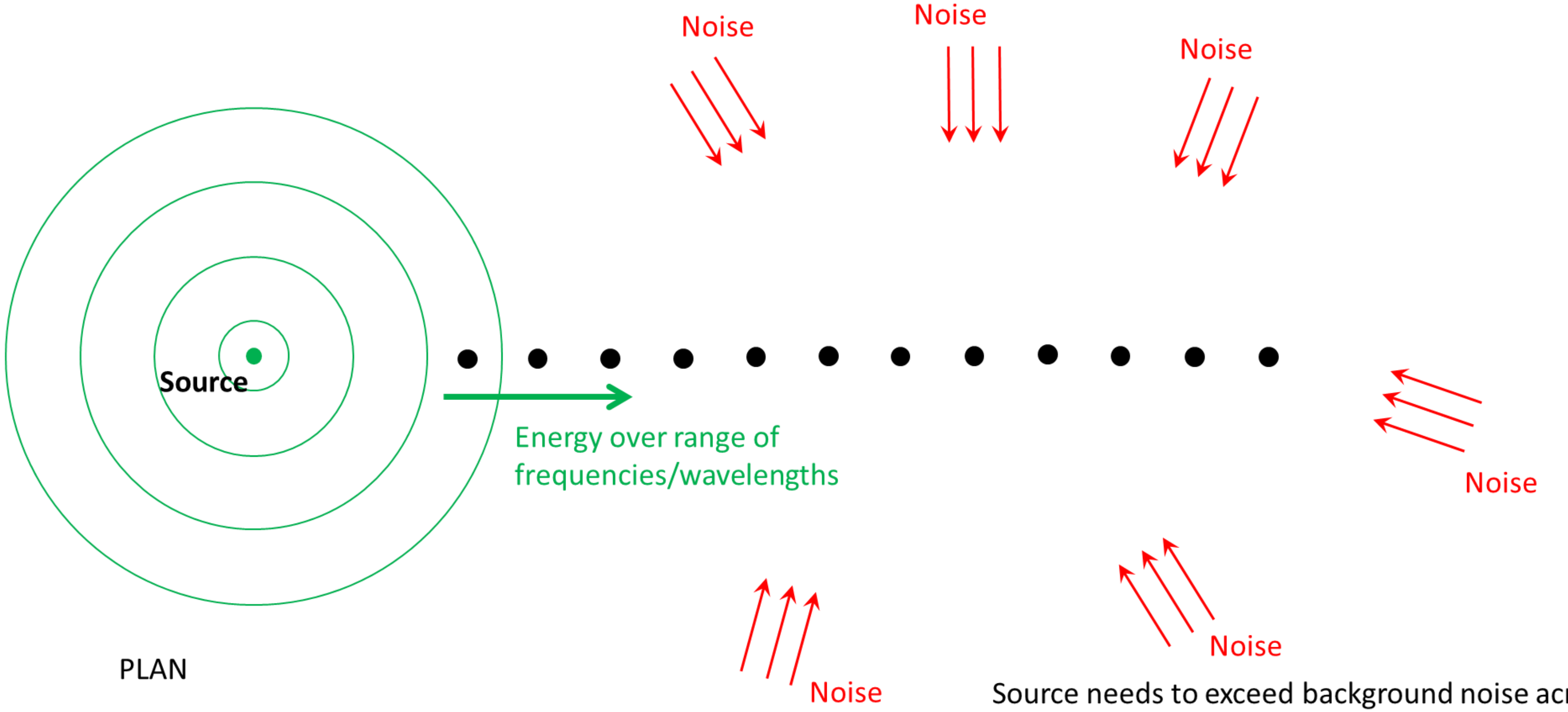
Off-line Noise

- MASW data processing proceeds under the assumption that the waves are propagating in-line/along the array.



Source needs to exceed background noise across all frequencies of interest

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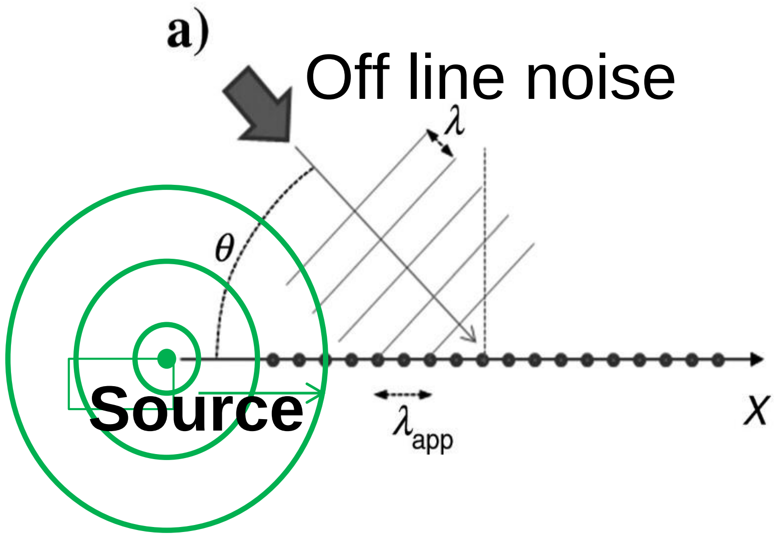
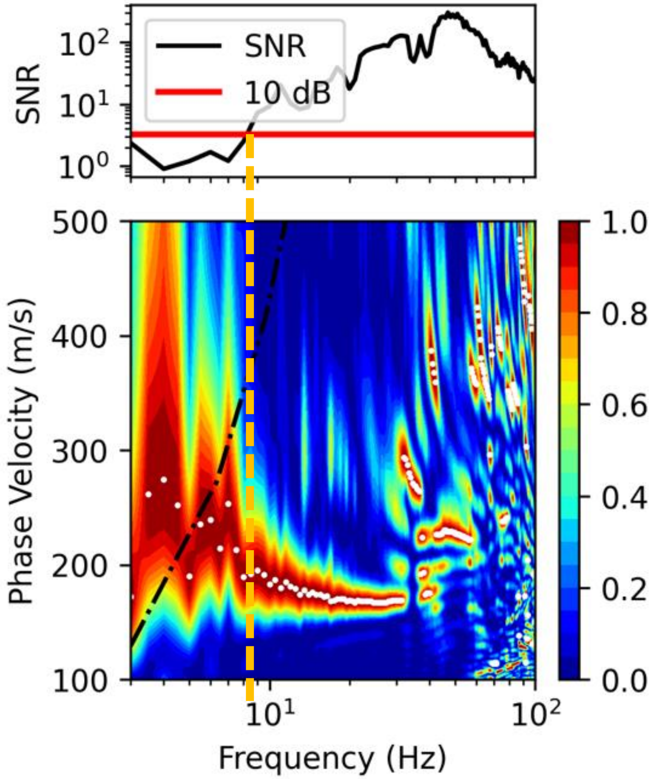
Off-line Noise

- If strong/energetic off-line noise is measured, it will contaminate the processing, resulting in apparent higher velocities.





- Important to assess signal to noise ratio (SNR) as a function of frequency for each active shot to determine if measuring source or noise.
- According to Wood and Cox (2012), should be careful about using data at frequencies where SNR < 10 dB (amplitude ratio < 3)… more on this topic later

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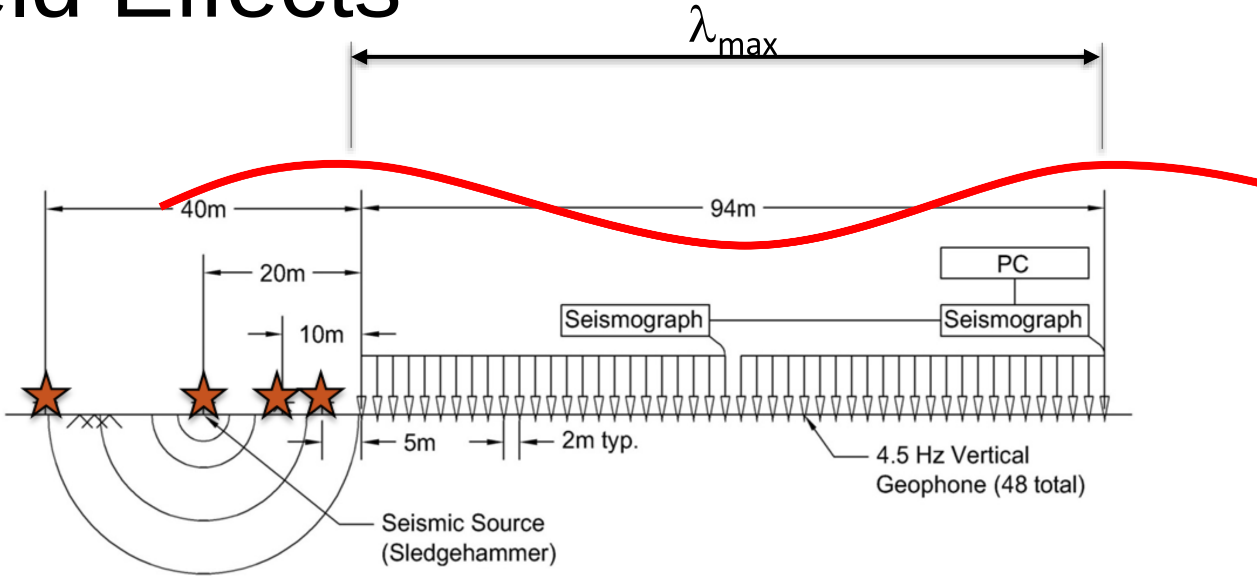
Depth of Profiling and Nearfield Effects



- **A rule-of-thumb is that the array length (L) needs to be at least 2 times the desired depth of profiling:**
  - **L ~ 2*D or D ~ ½ *L**
  - So, to develop Vs profiles down to 30m, L ~ 2*30m = 60m

Another way to say this is that the maximum wavelength (λmax) that can be reliably extracted from an array is equal to L. So, D ~ ½ * λmax.

- <u>However</u>, it also depends greatly on the source location
- For a given array length, you can profile deeper by using larger source offset distances… you just need a powerful, low frequency source!
- If you put the source too close to the array, your wavefield will be contaminated by nearfield effects (more on nearfield effects later)

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Depth of Profiling and Nearfield Effects

- Common mistakes I observe are:
  1) Trying to profile too deep for a given array length and source location. This will result in Vs profiles that are inaccurate at depth.

  2) Using only one source location and putting it too close to the array. This can result in poor dispersion data and will most likely cause under-estimation of Vs.

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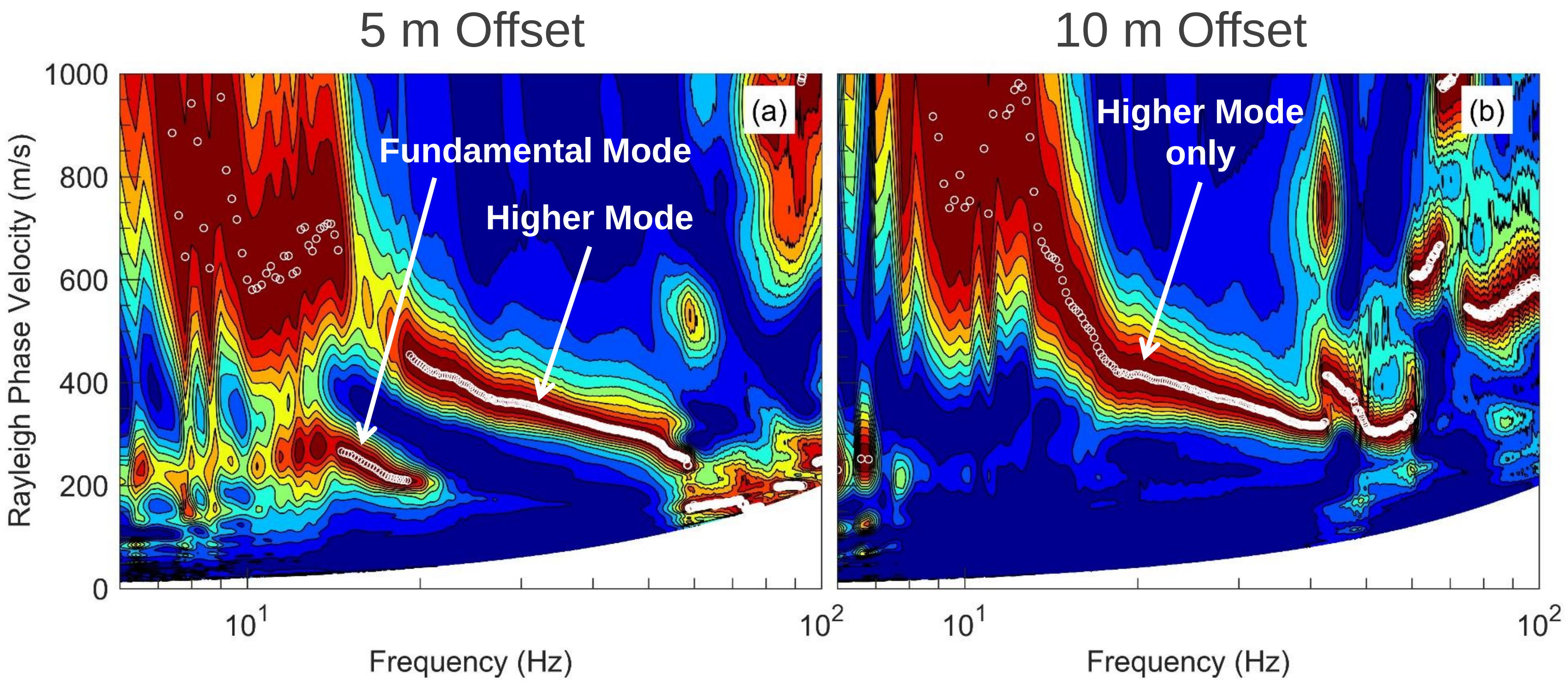
Source Offset Effects

- Using multiple source offsets helps to improve mode segregation and mode misidentification
- Misidentifying higher modes as the fundamental mode causes serious errors in the inverted V_S profile (V_S significantly over-estimated)
- **Always use multiple shot locations**!



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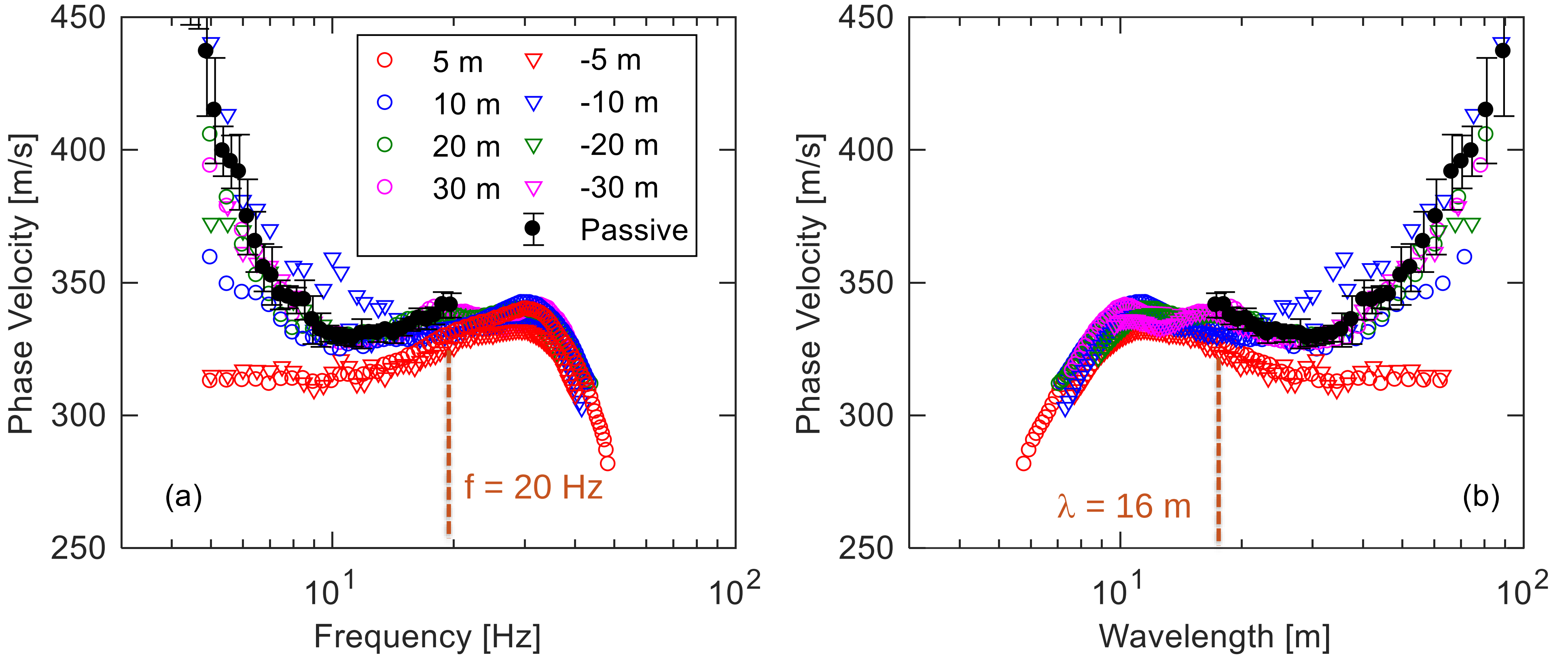
Source Offset: Nearfield Effects

- **Placing the source too close to the array is a bad idea**!
- Waves must propagate a certain distance relative to their wavelength before they fully develop and yield the correct phase velocity
- Recording wavelengths that haven’t fully developed results in “nearfield effects”
- Nearfield effects generally result in underestimating phase velocity
- Using multiple source offsets helps one to identify nearfield effects and remove contaminated data

Source Offset: Nearfield Effects



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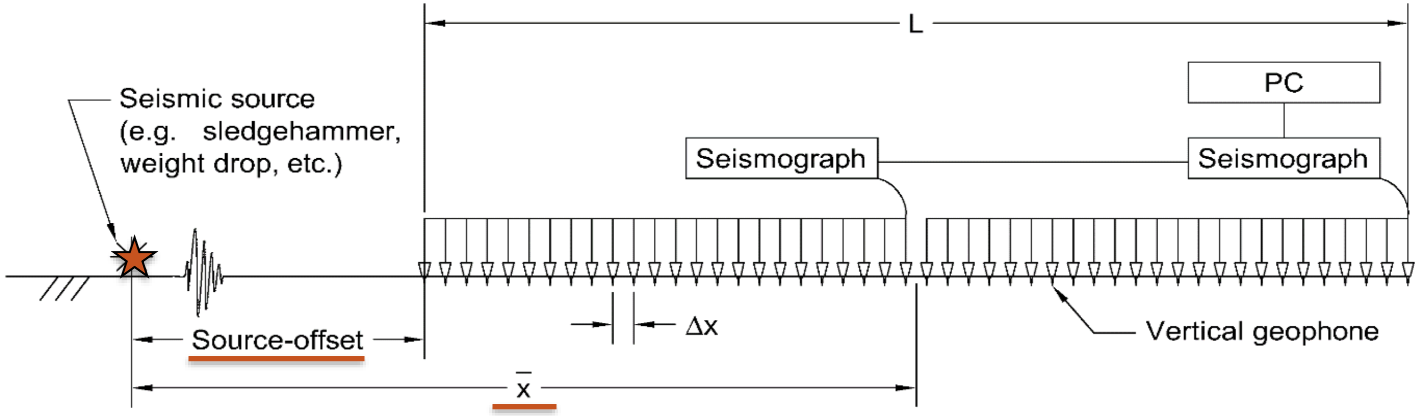
Nearfield Criteria: "array center distance"



$\bar{x}$ = L/2 + source offset

<u>MASW:</u>

- Yoon and Rix (2009): for most soil profiles the error in phase velocity is less than 10% provided $\lambda_{max} < 1 * \bar{x}$ (where $\bar{x}$ is the array center distance)
- Li and Rosenblad (2011): for high Poisson's ratio (i.e., saturated) sediments it may be possible to set λ_{max} as high as $2 * \bar{x}$
- In reality nearfield effects are site dependent and difficult to predict. I use multiple source offset locations to experimentally identify them. **I am also careful not to extract wavelengths that are greater than λ_{max} = 1 to 2 * $\bar{x}$ no matter how good the data looks**

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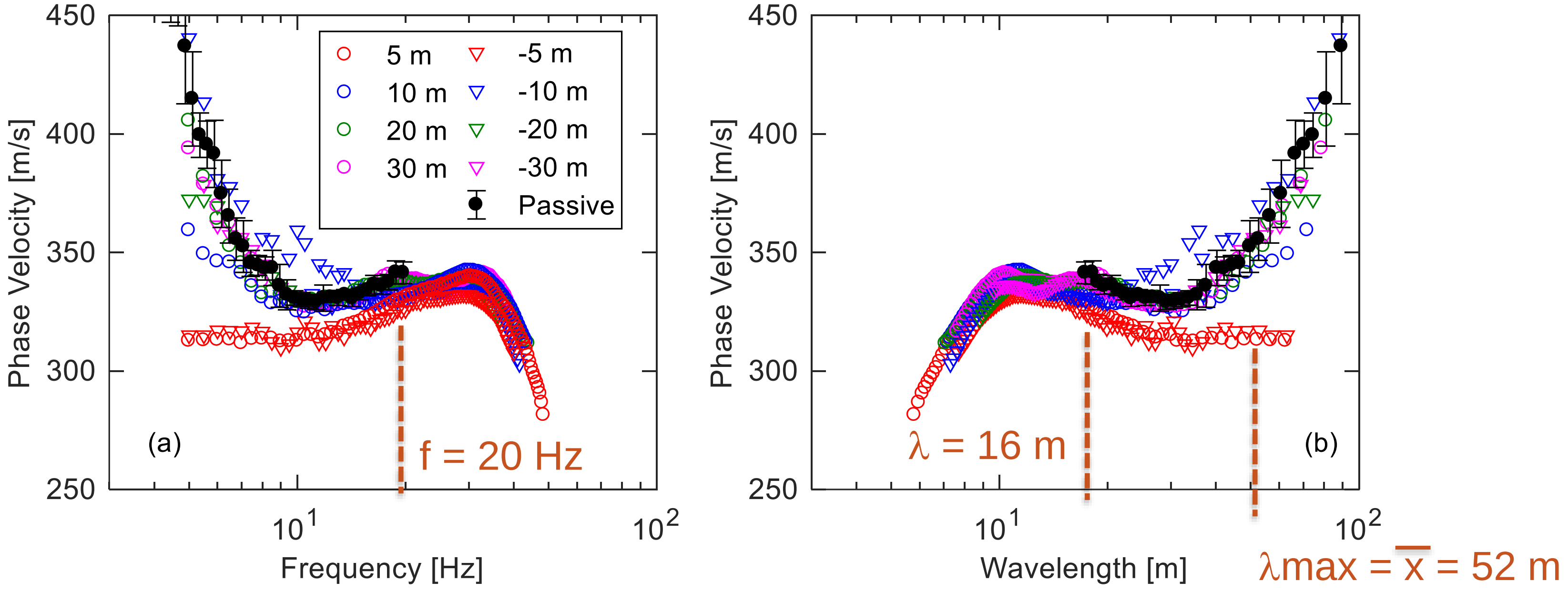
Nearfield Effects: Example 1

- Example Site "X": 94 m array (48 geophones at 2 m spacing)
- For the 5 m source offset, $\bar{x}$ = 5 m + 47 m = 52 m
- Without the other source offsets, wavelengths out to 52 m may have been used according to common nearfield criteria (i.e., $\lambda_{max} = 1 * \bar{x}$)
- In reality, for the 5 m offset, the actual λ_{max} ~ 16 m = $0.3 * \bar{x}$



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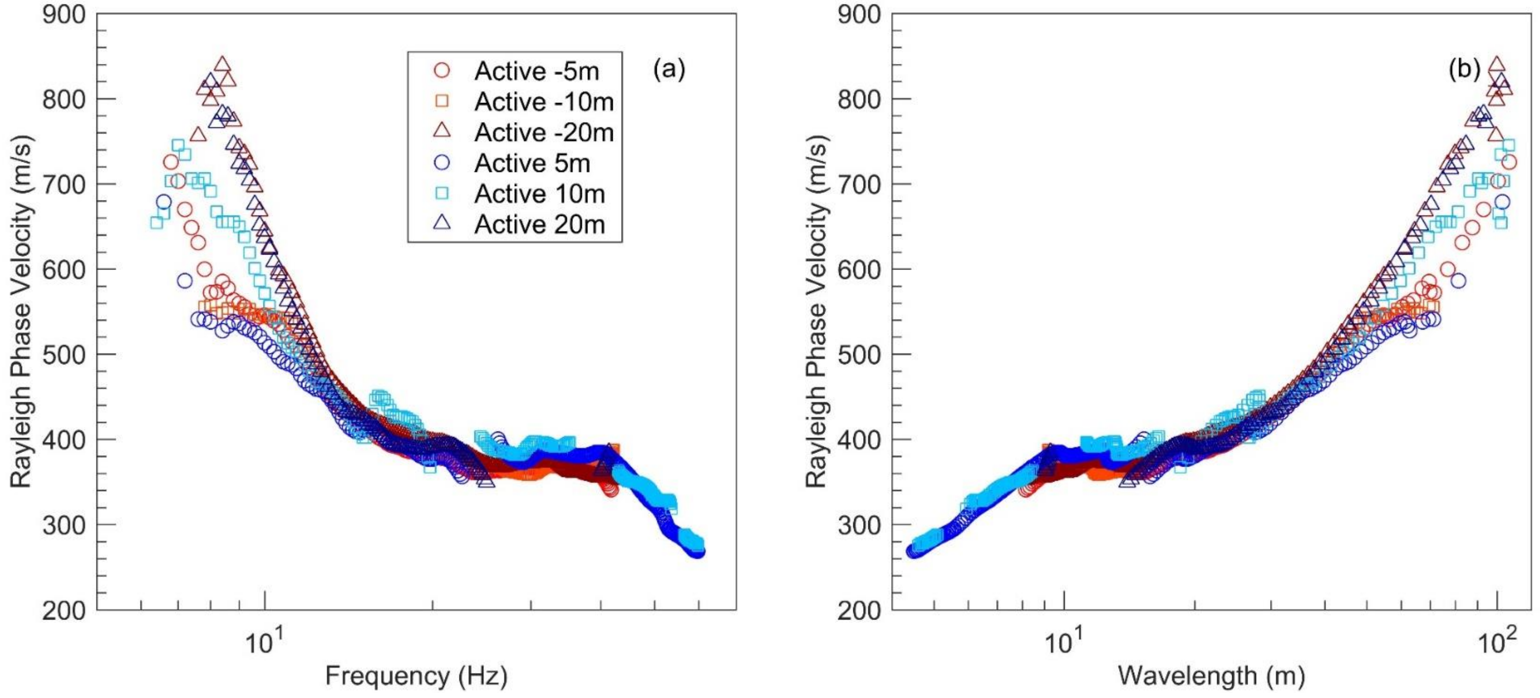
Nearfield Effects: Example 2

- Your turn…: TexNet Site SN02: 46 m array (24 geophones at 2 m spacing)
- Find:
  - Experimental λ_{max} for the 5 m source offsets using the dispersion data
  - Theoretical λ_{max} for the 5 m source offsets based on $\lambda_{max} = 1 * \overline{x}$



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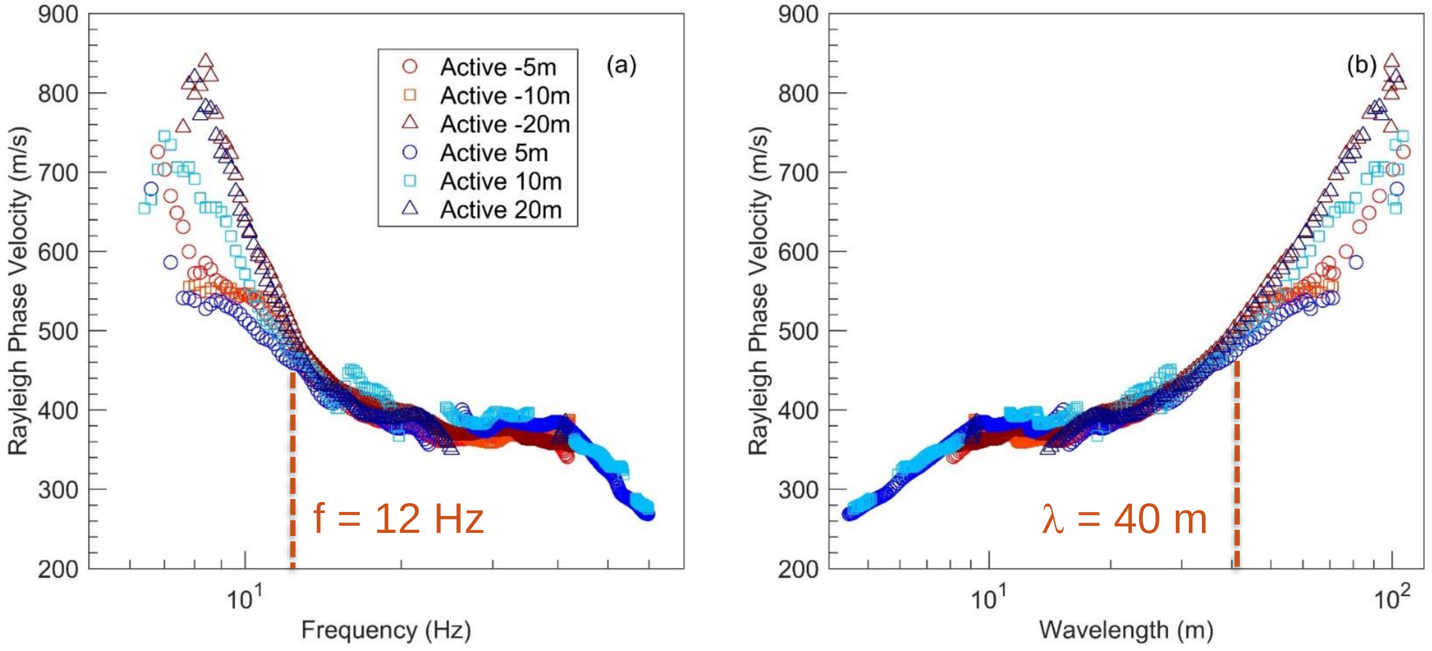
Nearfield Effects: Example 2

- TexNet Site SN02: 46 m array (24 geophones at 2 m spacing)
- For the 5 m source offset, the experimental λ_{max} ~ 40 m
- For the 5 m source offset, $\overline{x}$ = 5 m + 23 m = 28 m
- So, the theoretical $\lambda_{max} = 1 * \overline{x} = 28$ m
- At this site, for the 5 m offset, experimental λ_{max} ~ 40 m = 1.4 * $\overline{x}$



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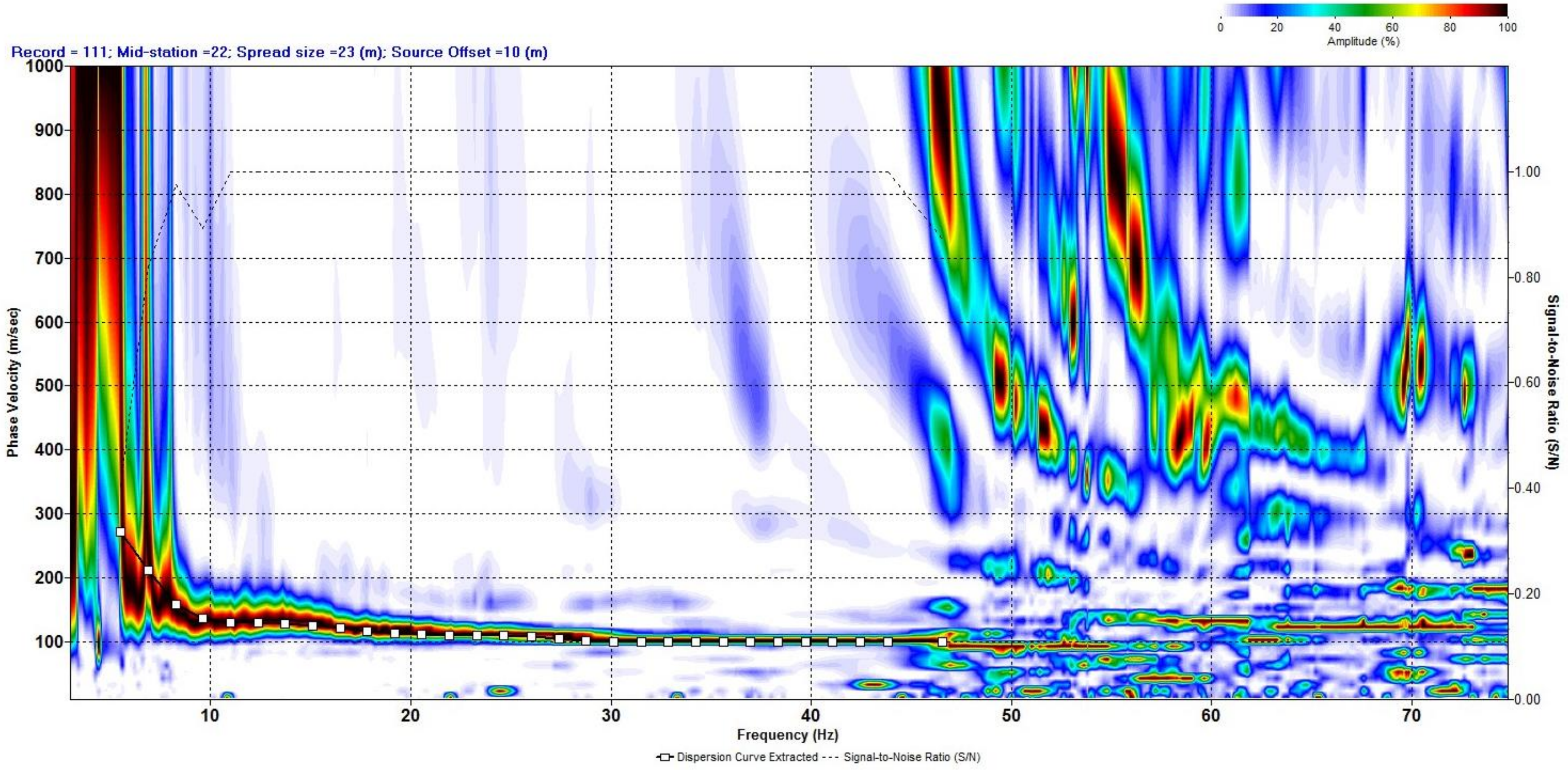
Case History #1: from a common commercial software

- Read this dispersion data and tell me what you observe:
  - L = 23m, source offset = 10m

$$\lambda = Vr/f$$



Experimental λ_{min} =
Experimental λ_{max} =
Inverted Vs_{min} ~
Inverted Vs_{max} >
LVL layers? =
Nearfield criteria
- $1*\bar{x}$ =
- $2*\bar{x}$ =

Quality of picks at low frequencies?

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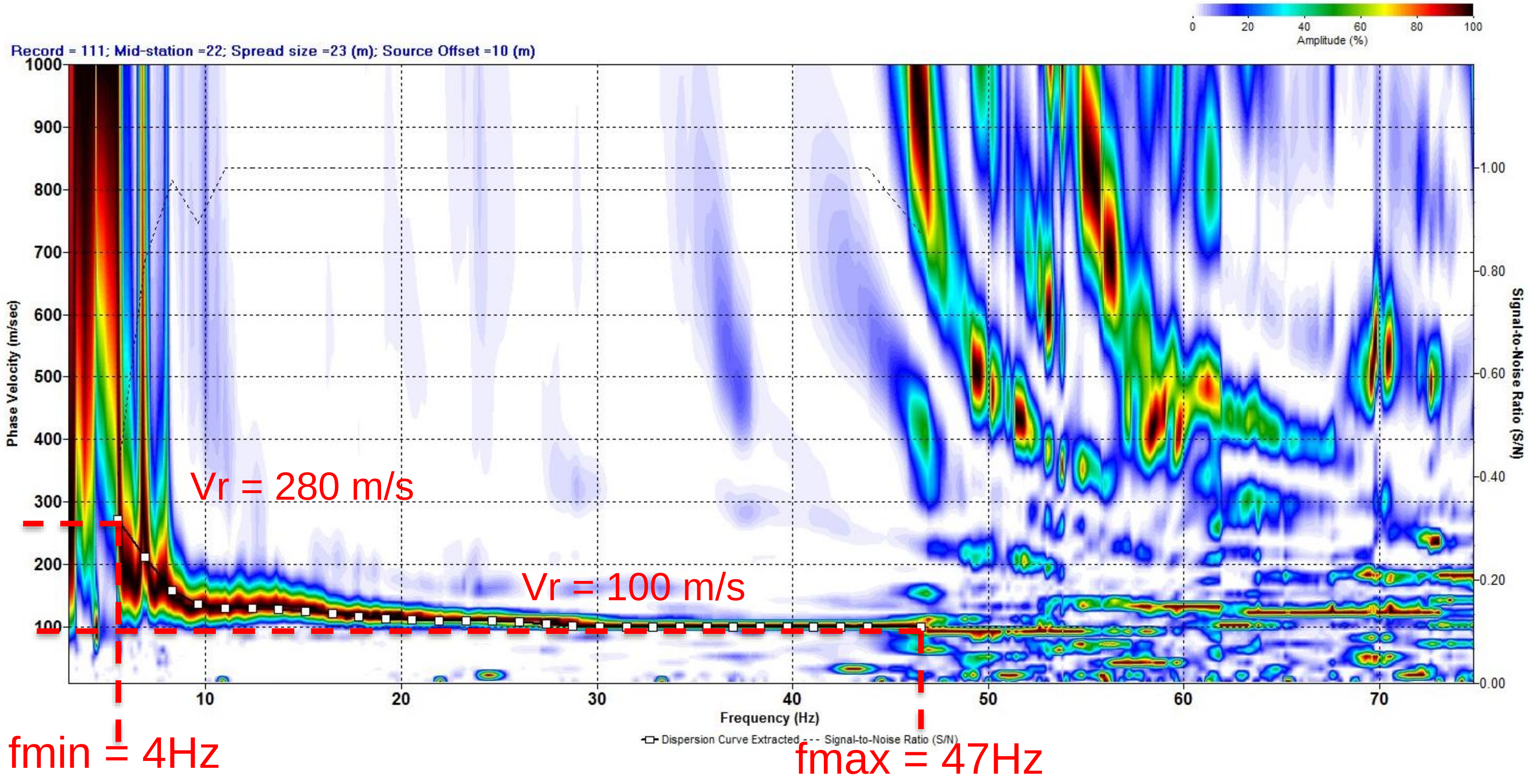
Case History #1: from a common commercial software

- Read this dispersion data and tell me what you observe:
  - L = 23m, source offset = 10m

$$\lambda = Vr/f$$



Experimental λ_{min} = ~2m
Experimental λ_{max} = 70m
Inverted Vs_{min} ~ 110 m/s
Inverted Vs_{max} > 310 m/s
LVL layers? = No
Nearfield criteria
- $1*\bar{x}$ = 23/2 +10 = 22m
- $2*\bar{x}$ = 44m

Quality of picks at low frequencies?

They have significantly violated near-field criteria by picking dispersion data out to λ_{max} = 70m!

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Summary Advice on MASW Acquisition

- Data Acquisition
  - I find that **using a 24-channel MASW array with a 2-m geophone spacing (L = 46m) is good for many sites**.
  - However, **you should assume that you will NOT be able to profile deeper than about 15m – 20m with this setup when using a sledgehammer source**. While it might be possible at some sites, it will not be possible at most.
  - One limiting factor is the frequency content of a sledgehammer source; It is rare to measure good dispersion data a frequencies less than about 8Hz – 10Hz with a sledgehammer.
  - If you want to profile deeper (e.g., 30m) using ONLY an active-source, you will need to use longer arrays and a more powerful low-frequency source (like an accelerated weight drop).
  - **The array length should be ~2*depth of interest, but source type and source offset are also important** (recall the array center distance criteria of Yoon and Rix for determining the maximum experimental wavelength)
  - **The source should not be placed any closer than 5m – 10m from the first geophone** to avoid strong nearfield effects.
  - **Multiple shots locations off each end of the array should be used whenever possible**.
  - It is a good idea to stack at least 3 – 5 shots at each shot location to increase the SNR.
  - Use a pre-trigger delay of at least 0.5s and a record length of at least 2.0s at most sites. This may need to be adjusted.
  - Use a sampling rate of 2ms – 4ms (i.e., sampling frequency of 500Hz – 250Hz) at most sites. This may need to be adjusted.
  - Collecting both Rayleigh-wave (vertical geophone) and Love-wave (horizontal geophone) data helps at complex sites, but I recognize we haven't really talked about Love-wave testing yet (limited time).
  - **Combining active- and passive-source methods is highly recommended in order to profile deeper than about 15m - 20m.**

Sample MASW Data Sheet

Utah State University
Field Data Sheet for:
Multi-channel Analysis of Surface Waves (MASW)
and/or Seismic Refraction

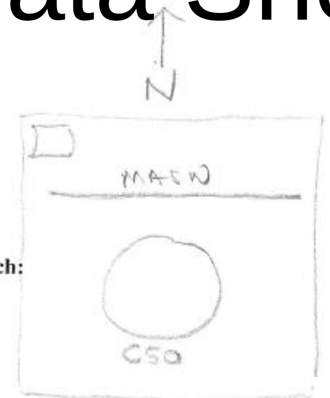
Project: DRAINAGE FARM

Site/Array Name: MASW

Date and Time: 23 MAY 2023 / 09:30

Personnel: DR. COX, ASER, NISHKARSHA, TYLER, KYLE

Sketch:



Raw Data Folder: C://Drainage Farm MASW - 20230523

Source: 16 lb sledge hammer

Geophones: Geospace GS-11D 4.5 Hz
Serial No. 289421-01 to 289421-24 (24 vertical) with 289421-25 to 30 backup
Serial No. 289430-01 to 289430-24 (24 horizontal) with 289430-25 to 30 backup

Digitizer(s): Geometrics Geode, Serial No. 6507

Number of geophones: 24 Geophone spacing: 2 m

First geophone location: 0 m Last geophone location: 46 m

Test Information:

Test Type	Source Location	Sample Rate	Record Length	Trigger Delay	Raw File Names	
P-WAVE REF	-1 m	31.25 µS	2 sec	-0.25 s	1 - 5	
" "	47 m	31.25 µS	2 sec	-0.25 s	6 - 10	
MASW R	51 m	2 ms	2 sec	-0.5 s	11 - 15	
" "	56 m	2 ms	2 sec	-0.5 s	16 - 20	
" "	66 m	2 ms	2 sec	-0.5 s	21 - 25	
" "	- 5 m	2 ms	2 sec	-0.5 s	26 - 30	
" "	-10 m	2 ms	2 sec	-0.5 s	31 - 35	
" "	-20 m	2 ms	2 sec	-0.5 s	36 - 40	
MASW L	-5 m	2 ms	2 sec	-0.5 s	41 - 45	S→N
MASW L	"	"	"	"	46 - 50	N→S
"	-10 m	"	"	"	51 - 55	S→N
"	"	"	"	"	56 - 60	N→S

Notes:

Performed by:

Signature:

Date:

Checked by:

Signature:

Date:

Park et al. (2007)

MAM acquisition

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Surface Wave Methods

- Many different methods with various acquisition, processing, and inversion techniques.

- Active-source:
  - SASW: spectral analysis of surface waves (Stokoe et. al 1994)
  - MASW: multi-channel analysis of surface waves (Park et al. 1999, Foti 2000)

- Passive-source:
  - ReMi^{TM}: refraction microtremor with *linear arrays* (Louie 2001)
  - MAM: microtremor array measurements with *2D arrays* (Okada 2003, Tokimatsu et al. 1992)

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A Brief Word on Linear Array Passive Methods

- The use of passive-source linear array methods is "strongly discouraged" in the Guidelines for the Good Practice of Surface Wave Analysis (Foti et al. 2018). I am a co-author of these guidelines and I also believe we should avoid using passive-source linear array methods in engineering practice whenever it is possible to use more theoretically robust methods.

- We are not the only people who feel this way. Passive-source linear array methods were left out of the new ISO 24057 standard "Array measurement of microtremors to estimate shear wave velocity profile".

- We will discuss challenges associated with using passive-source linear array methods later in the course.

Passive-Source Methods

- Record **background/ambient/microtremor noise** from unknown sources at known receiver locations
- "Passive" refers to use of this background noise

- Cultural/Anthropogenic Sources (frequencies typically > 1Hz – 5Hz)
  - Vehicles
  - Machinery
  - Etc.

- Natural Sources (frequencies typically < 1Hz – 5Hz)
  - Wind
  - Waves
  - Distant/small earthquakes (microtremors)
  - Etc.

Passive Sources

- The location and timing of the sources is unknown and assumed to be random (unless the array is placed next to a constant noise source like a road)

- Direction of propagation in relation to the array is unknown *a priori*

- Waves with different predominant frequency bands may propagate from different directions

- The frequency content is typically lower than that from active sources
  - Longer wavelengths
  - Can characterise deeper deposits

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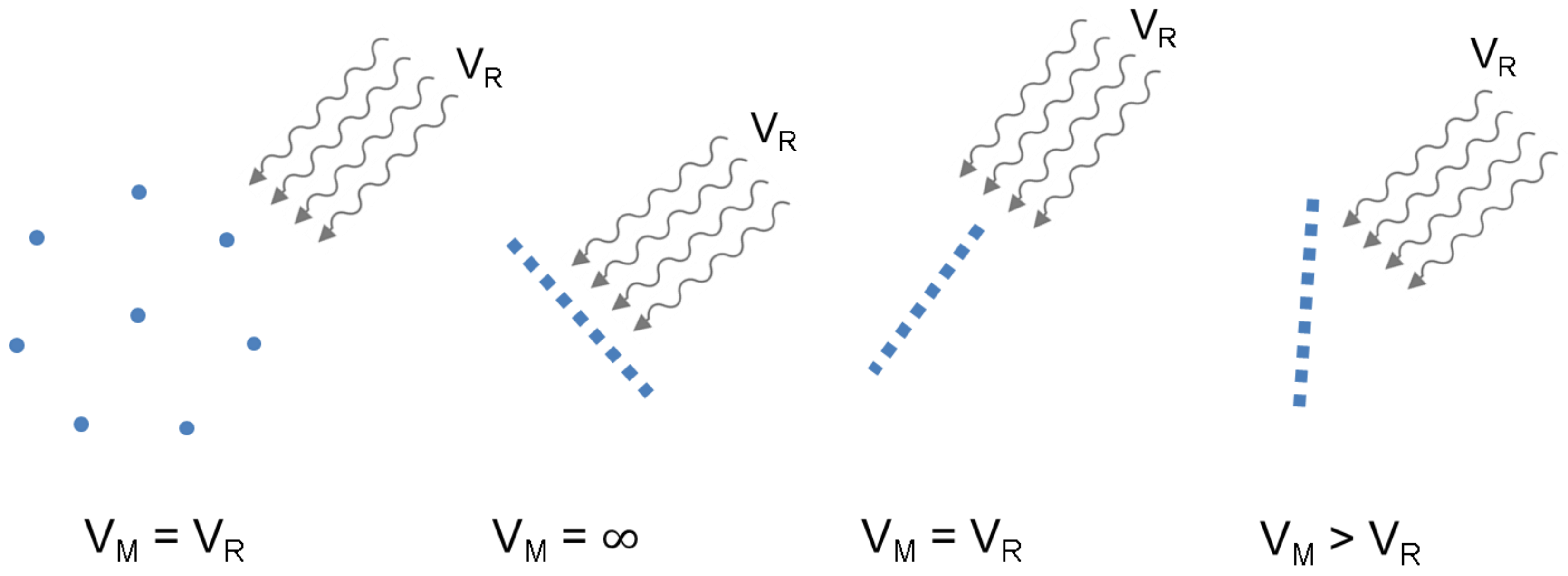
Recording Ambient Noise

- Effect of noise propagation direction and array type (2D vs. linear array)
- Linear arrays can only measure the true/actual velocity if the waves are *serendipitously* propagating in-line with the array.

*Serendipitously means something that happens by chance or luck.



V_M = measured velocity
V_R = actual phase velocity

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2D Array Methods

- 2D array methods are often generalized at MAM (microtremor array methods), although there are a number of different names

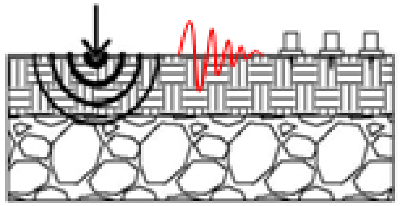
- Strengths:
  - It is possible to determine the direction of ambient wave propagation when using a 2D array of receivers. Not all 2D array processing methods do this, but FK-based methods do, and for that reason I prefer them.

- Weaknesses:
  - It can be difficult to layout 2D receiver arrays at some test sites
  - The data processing procedures are more involved

Generalized Surface Wave Testing

Acquisition

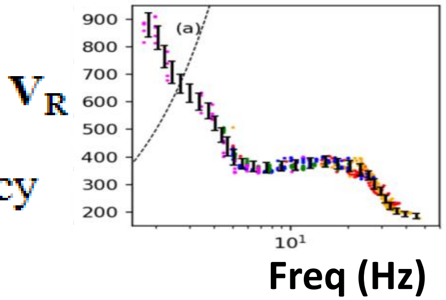
Field Data Collection:
Measurement of stress waves at the ground surface



Active & Passive Methods

Processing

Dispersion Curve:
Rayleigh Wave Phase Velocity vs. Wavelength/Frequency

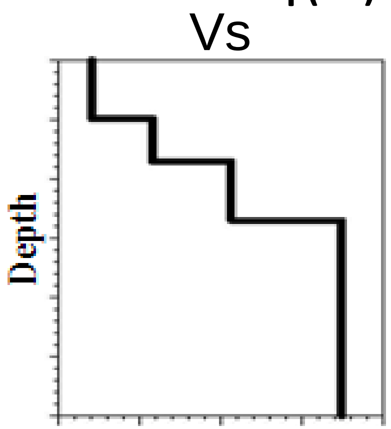


Robustly determined by experts (modes!)

Inversion

Shear Wave Velocity Profile:
Variation of Small Strain Shear Modulus vs. Depth

$$G_{max} = \rho V_S^2$$



Still challenging for experts: highly non-unique

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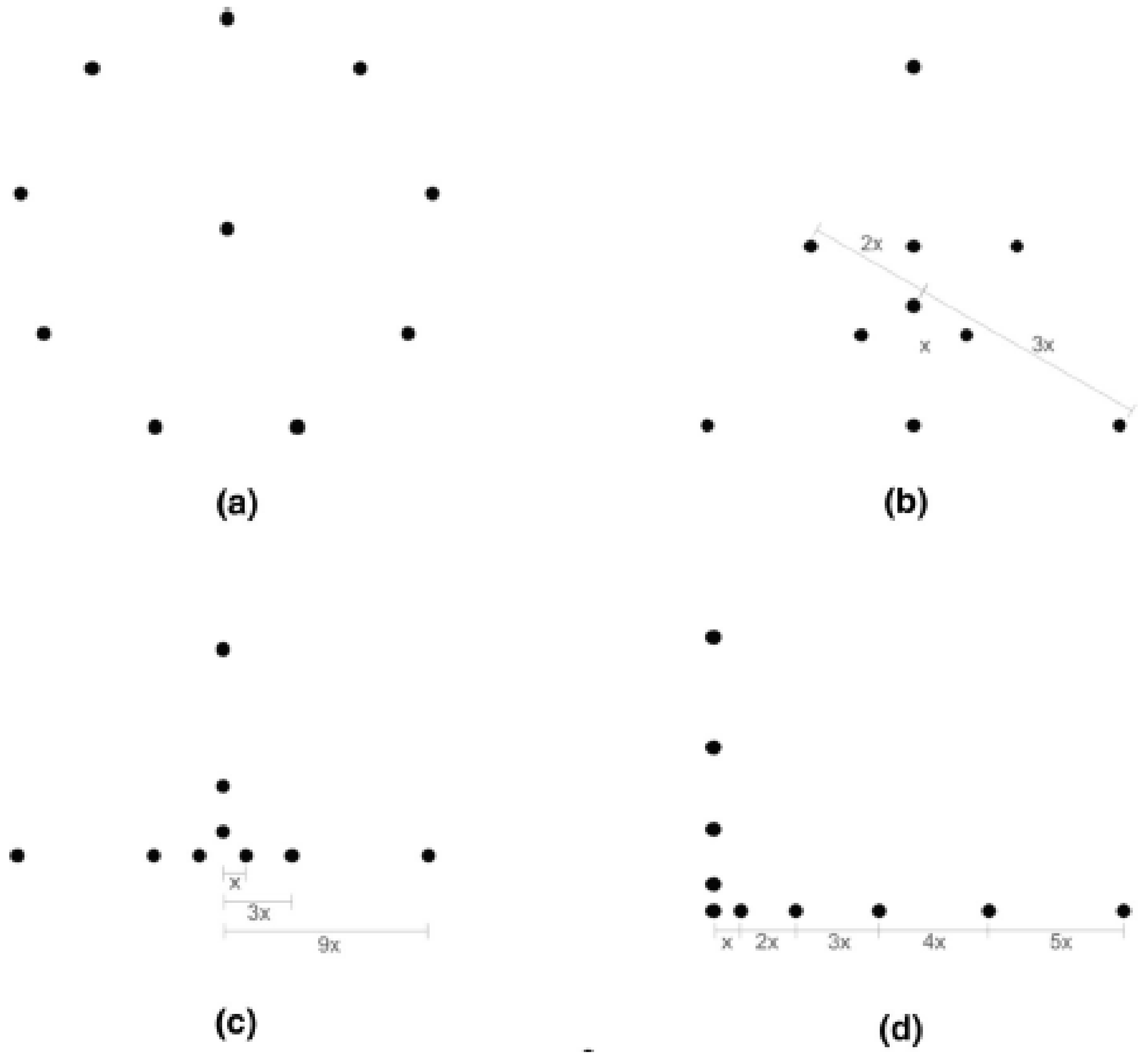
2D Array Types

- Circular
- Triangle
- T-shaped
- L-shaped
- Irregular Arrays



Foti et al. (2018)

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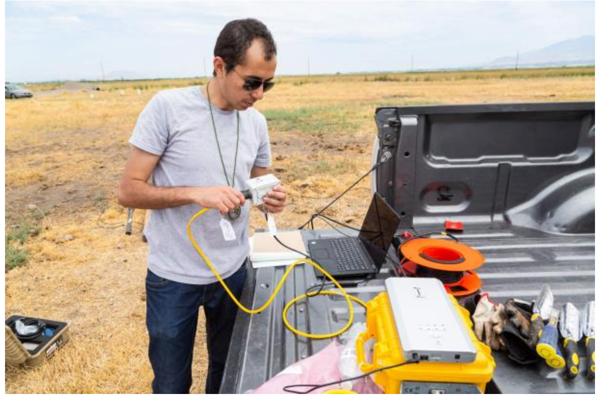
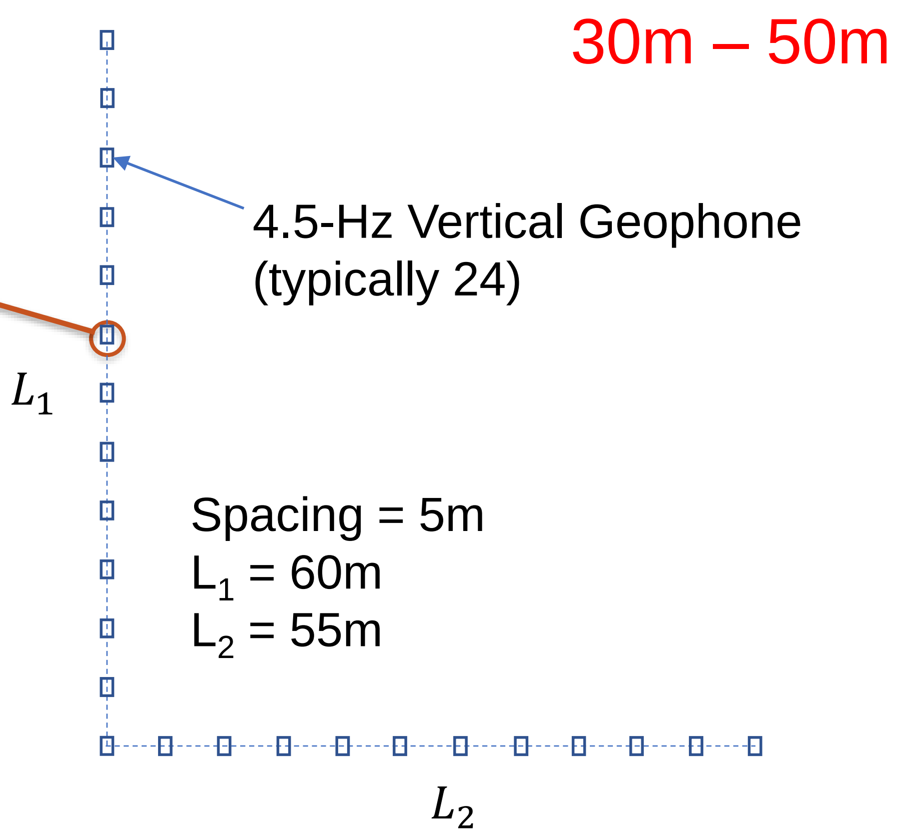
MAM Data Acquisition: Setup for **Shallow Profiling**



- Standard MASW equipment can be used
- L-shaped arrays are preferred/easiest
- 24, 4.5-Hz vertical geophones
- Trying to extend depth of MASW profiling, so 5-m geophone spacing likely needed
- Rule-of-thumb… can profile ~ as deep as maximum array aperture
- 20+ 30 - 60 second noise records collected (recording times of 10 – 30 minutes)

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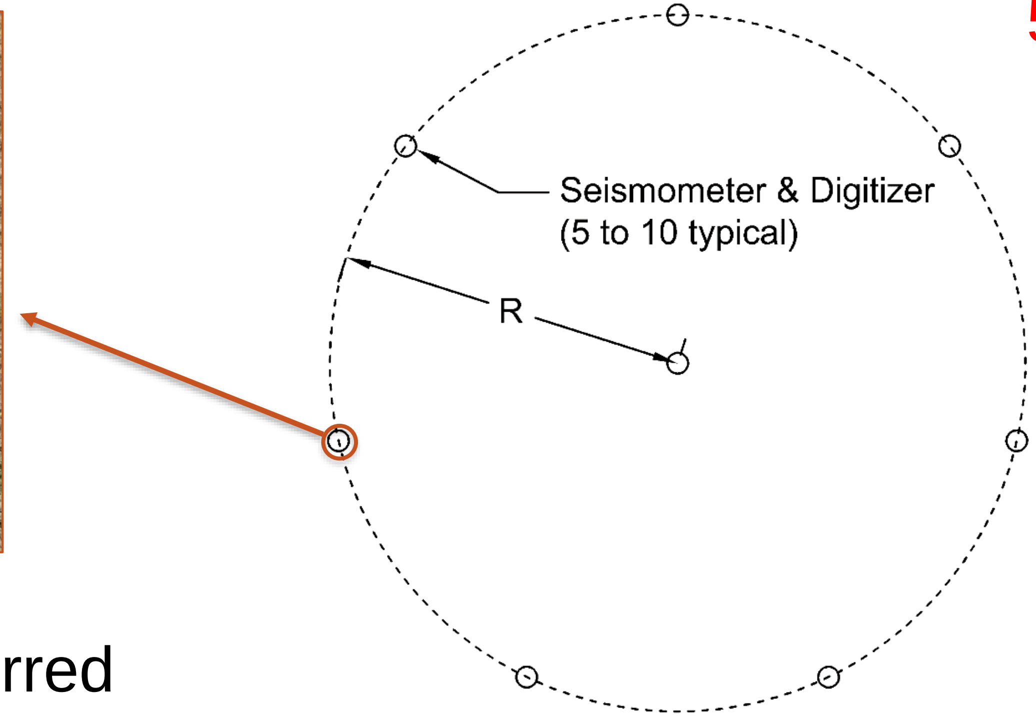
MAM Data Acquisition: Setup for **Deep Profiling**

50m – 1km



- Circular and triangular arrays preferred
- Six to 10, 3-component broadband seismometers
- Array diameters of 50m, 150m, 400m, 1000m… depending on needs
- Rule-of-thumb… can profile ~ as deep as maximum array aperture
- Recording times of 30 min to 2 hours common (longer for larger arrays)

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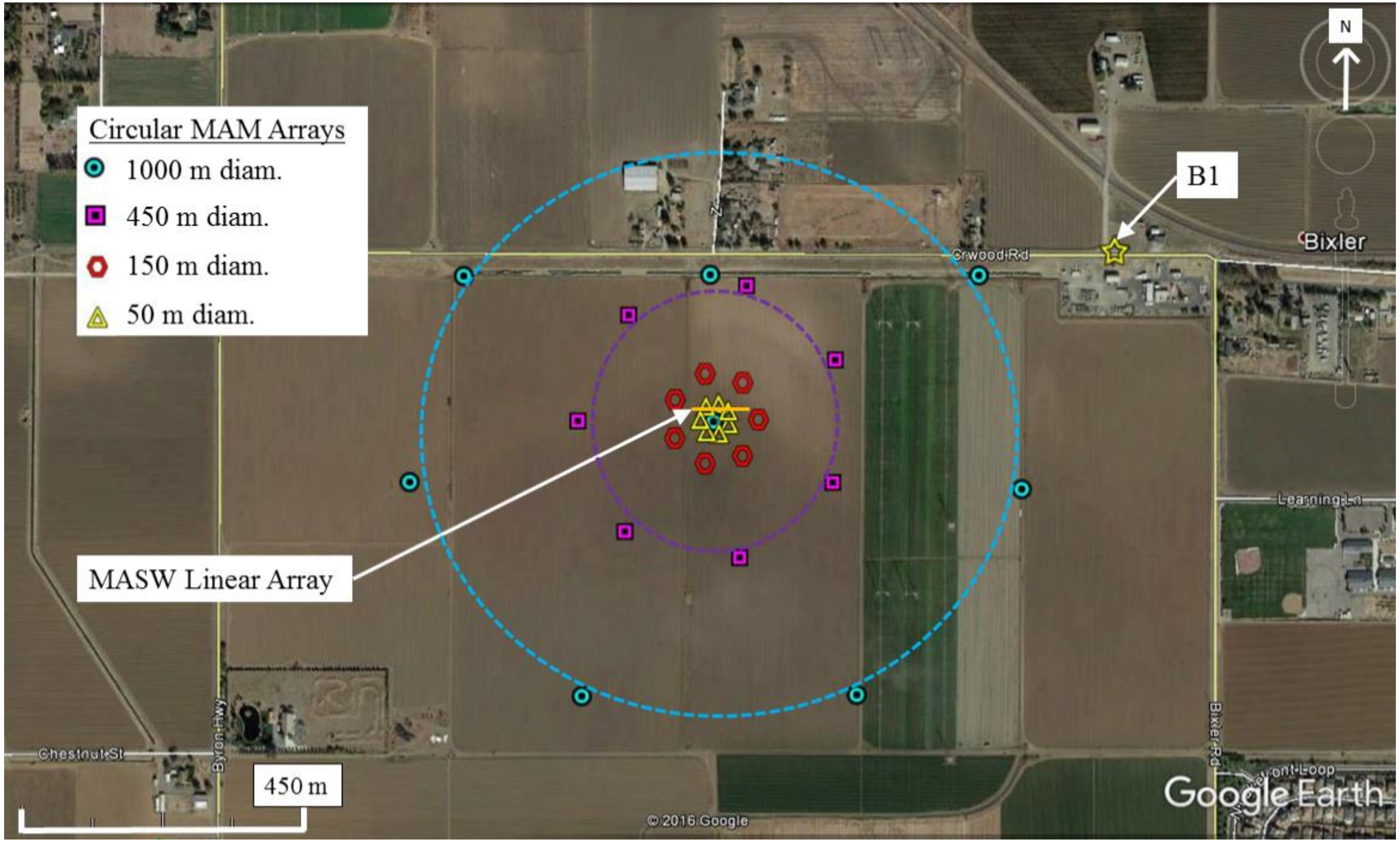
MAM Setup for Deep Vs Profiling: Example 1



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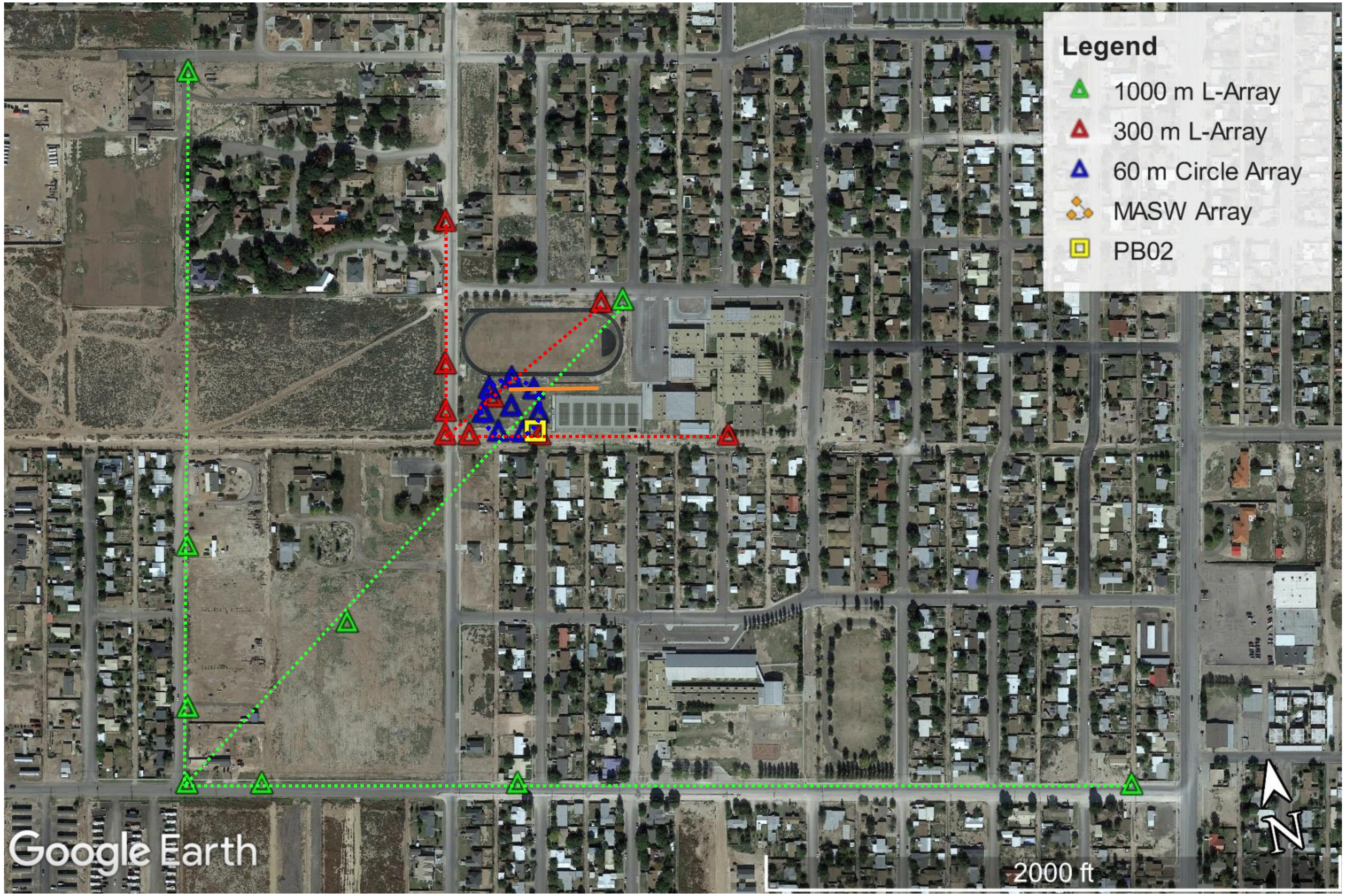
MAM Setup for Deep Vs Profiling: Example 2



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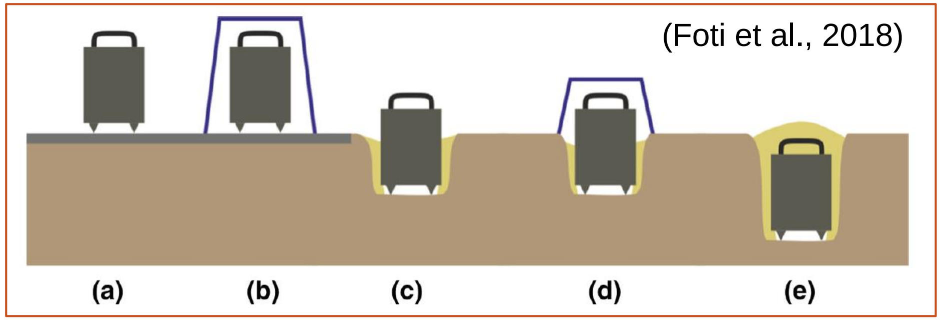
MAM Data Acquisition: Equipment for Deep Profiling

Nanometics Trillium Compact Seismometers

- 3-component
- Can also use for HVSR testing
- Flat response 100 Hz – 20s or 120s

Nanometrics Taurus, Centaur, or Pegasus Digitizers

- 24-bit
- GPS synchronized



- Methods of placing the sensors are shown from least likely to produce high quality data (a) to most likely (e).

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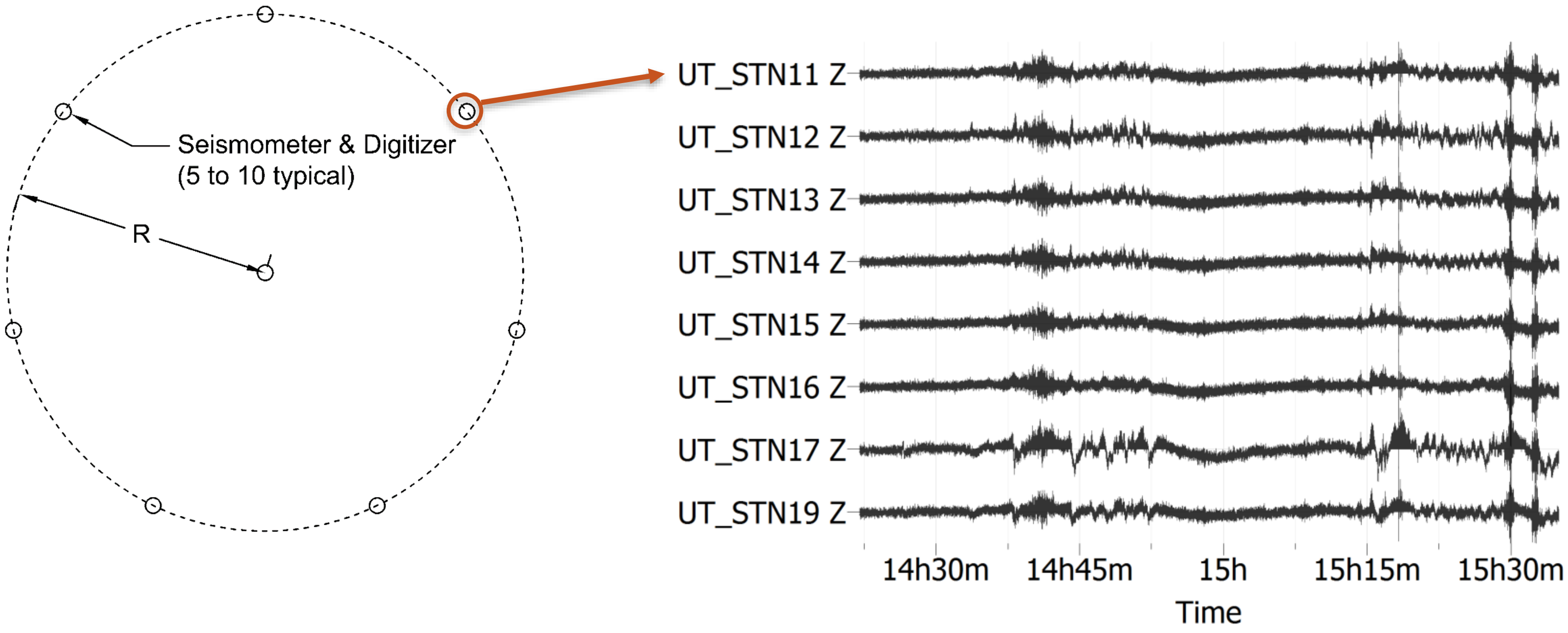
MAM Data Acquisition: Waveforms



- One hour of ambient noise recorded on each sensor
- These are only the vertical components for Rayleigh wave dispersion
- The horizontal components are used for H/V and Love wave dispersion

Summary Advice on MAM Acquisition

- Data Acquisition
  - **Combined active- and passive-source methods highly recommended for Vs profiling greater than 20m deep**
  - **In my opinion, passive-source MAM should never be done without active-source MASW (both are needed)**
  - Circular arrays of 3-component broadband seismometers are the best for deep Vs profiling.
  - 4.5-Hz vertical geophones are typically sufficient for creating ~ 60-m aperture L-arrays, which should be enough for Vs30 profiling in most cases. A refraction cable with 5-m takeouts will be required for this type of testing.
  - **You should assume that you will NOT be able to profile deeper than approximately 1*(array aperture). Or, in other words, you should not extract wavelengths > ~ 2*(array aperture)**.
  - Use a sampling rate of 4ms - 10ms (i.e., sampling frequency of 250Hz – 100Hz) at most sites. This may need to be adjusted.
  - Record at least 30min – 60min of ambient noise for arrays less than 100m aperture. Arrays greater than 100m aperture will require longer recording times to resolve lower frequencies.

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Shallow Example of Combining MASW & MAM

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USU SMASH Lab: Vs30 Profiling

Live walk-through of report

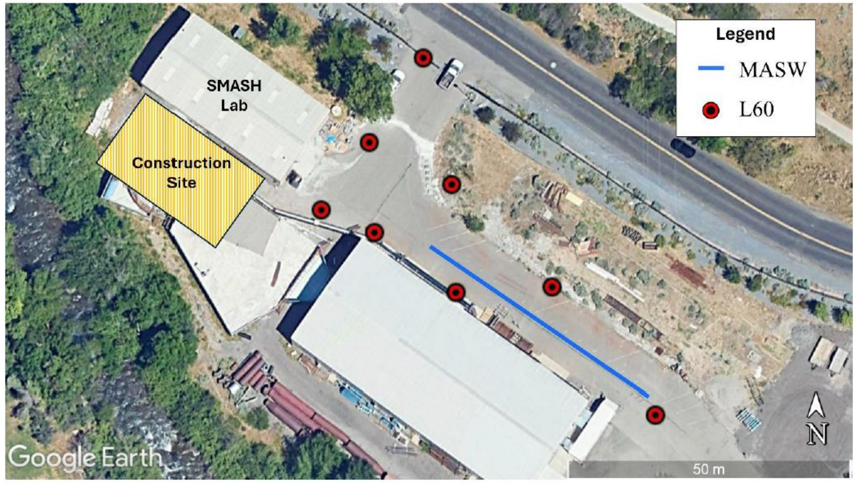

Figure 1: Plan view of the linear MASW array and 60-m L-shaped MAM array (L60) locations used for surface wave testing at the **SMASH Lab site**. Shown in the yellow shaded area is the planned location for a new structure adjacent to the existing SMASH Lab.

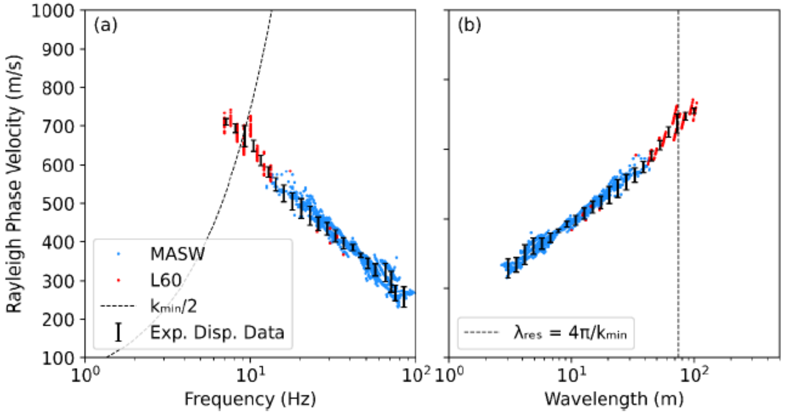

Figure 3: Mean and +/- one standard deviation experimental Rayleigh wave dispersion data calculated from the individual MASW (i.e., active-source) and MAM (i.e., passive-wavefield) data collected at the SMASH Lab site and presented in terms of (a) frequency, and (b) wavelength.

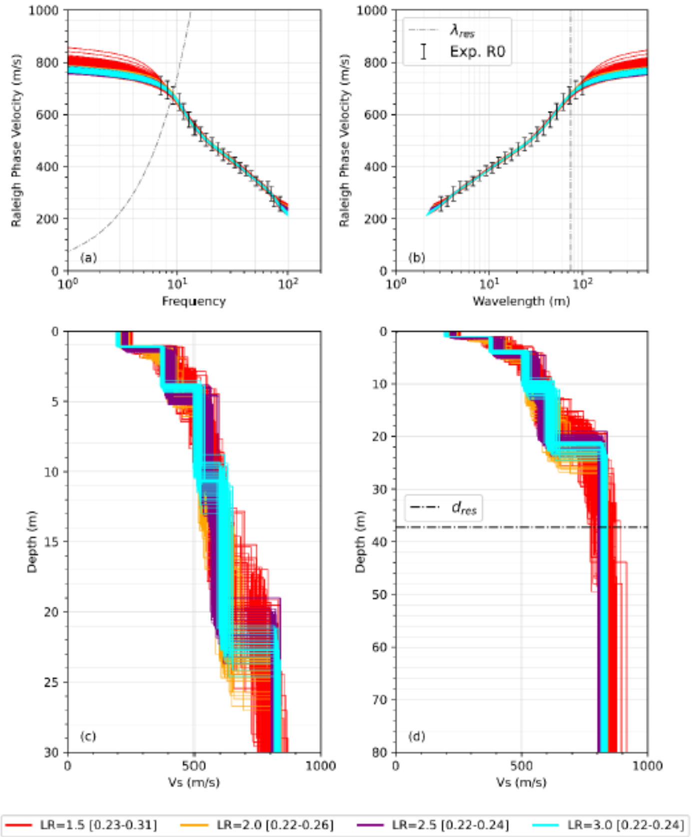

Figure 5: Inversion results for the SMASH Lab site based on a fundamental mode interpretation/inversion of the experimental Rayleigh wave dispersion data (R0). Shown for each inversion parameterization (i.e., LR= 1.5, 2.0, 2.5, and 3.0) are the **100 lowest misfit Vs profiles**: (a and b) theoretical fundamental Rayleigh wave dispersion curve along with the experimental dispersion data in terms of frequency and wavelength, respectively; and (c and d) Vs profiles shown to depths of 30 m and 80 m, respectively. The array resolution depth limit ($d_{res} = \lambda_{res}/2$) is shown at 37 m. The dispersion misfit values for each inversion parameterization are indicated in brackets in the legend.

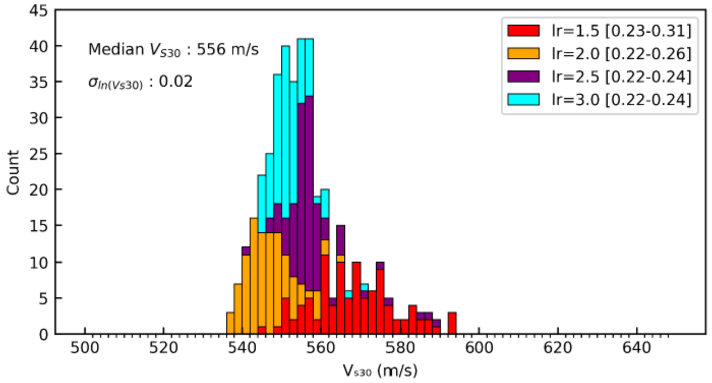

Figure 6: Distribution of V_{s30} values for the SMASH Lab site obtained from the 100 lowest misfit Vs profiles for each inversion parameterization (400 total Vs profiles), binned in 2-m/s intervals and organized by inversion parameterization, with the dispersion misfit values indicated inside brackets in the legend.

Table 1: Summary of V_{s30} values derived from the surface wave inversions at the SMASH Lab site with associated uncertainty in **Metric units**.

Parameter	Lognormal median	Lognormal Standard Deviation (σ_{ln})	Median + σ	Median - σ	Seismic Site Classification	
					ASCE 7-16	ASCE 7-22
V_{s30} (m/s)	556	0.02	569	543	C	C

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<u>Deep</u> Example of Combining MASW & MAM

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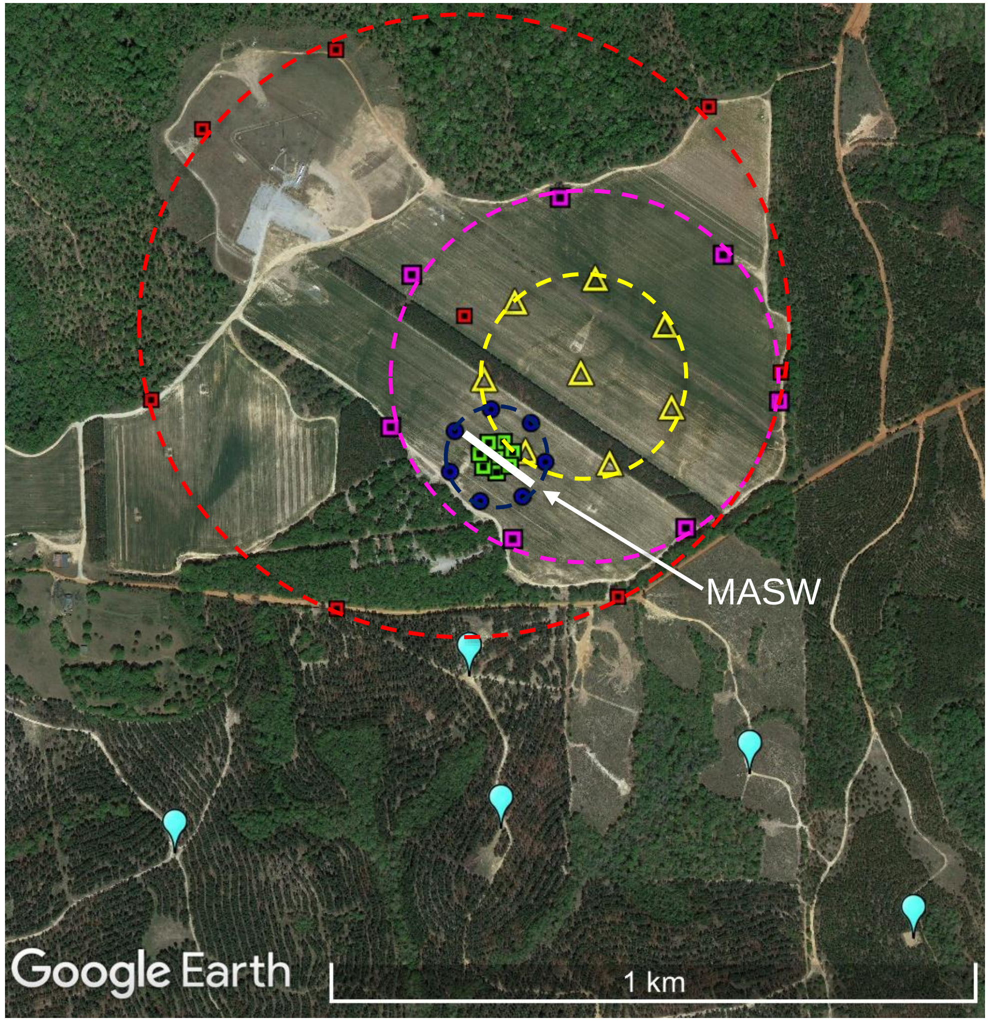
Example MASW Dispersion Data with Statistics

For an important facility in the Southeastern U.S.; We will call it Site "G"



Passive-source (MAM)
- 1,000 m diam.
- 550 m diam.
- 300 m diam.
- 150 m diam.
- 50 m diam.
- Single station (H/V)

Target Vs profiling depth = +500m

Damm et al. (2021)

Two days to acquire field data

MASW
- Linear array of 48 4.5-Hz vertical geophones
- Equal spacing of 2m (94-m long array)
- Four hammer locations (5, 10, 20 & 30m) each side

MAM
- Circular arrays of 8 broadband seismometers
- Array diameters of 50, 150, 300, 550, and 1,000m
- Recording times of 1 to 12 hours per array

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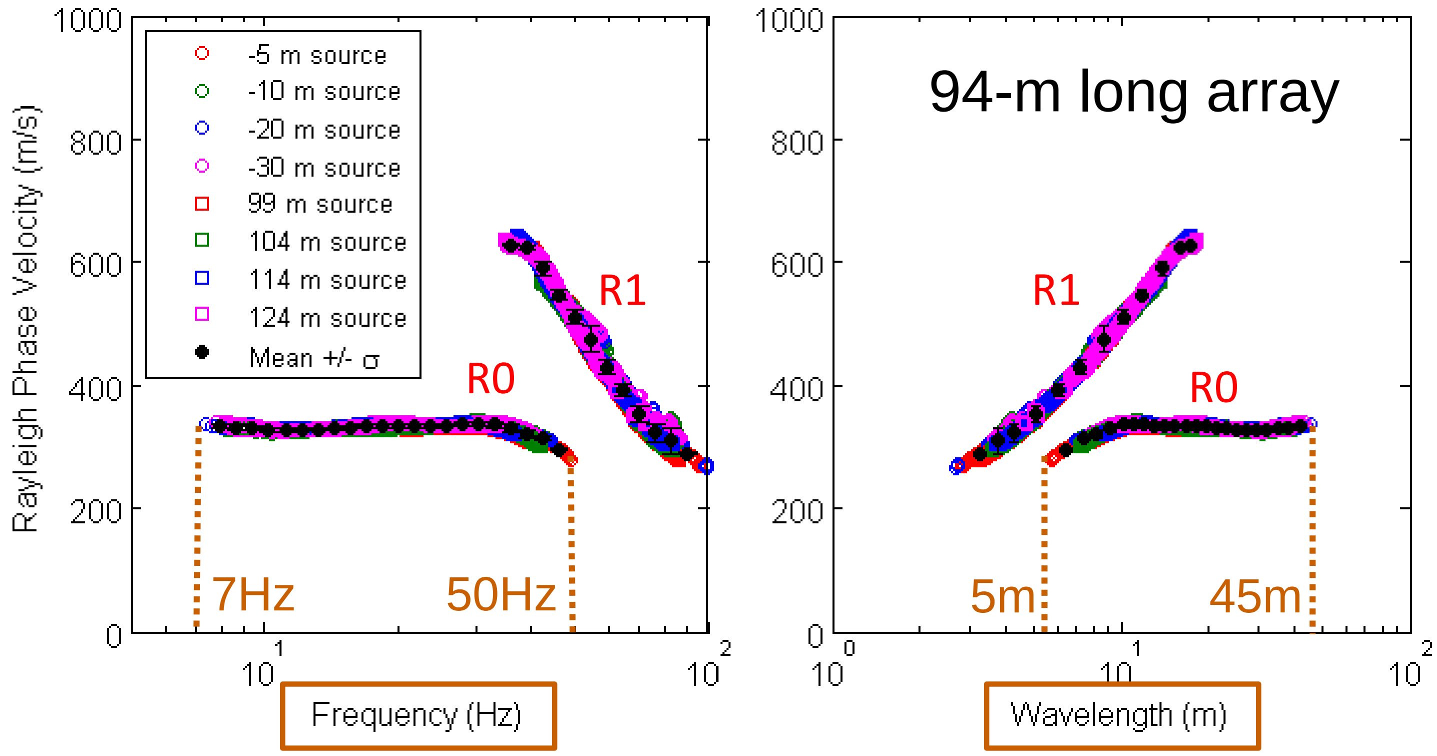
Example MASW Dispersion Data with Statistics

- Multiple Source-Offset Technique to Estimate Uncertainty
- Resolved fundamental Rayleigh mode (R0) and 1st-higher (or effective) mode (R1)
- Excellent agreement between source offsets (minimal variability)



- λ_{max} = 45m
- D ~ 45m/(2 or 3) = 22-15m

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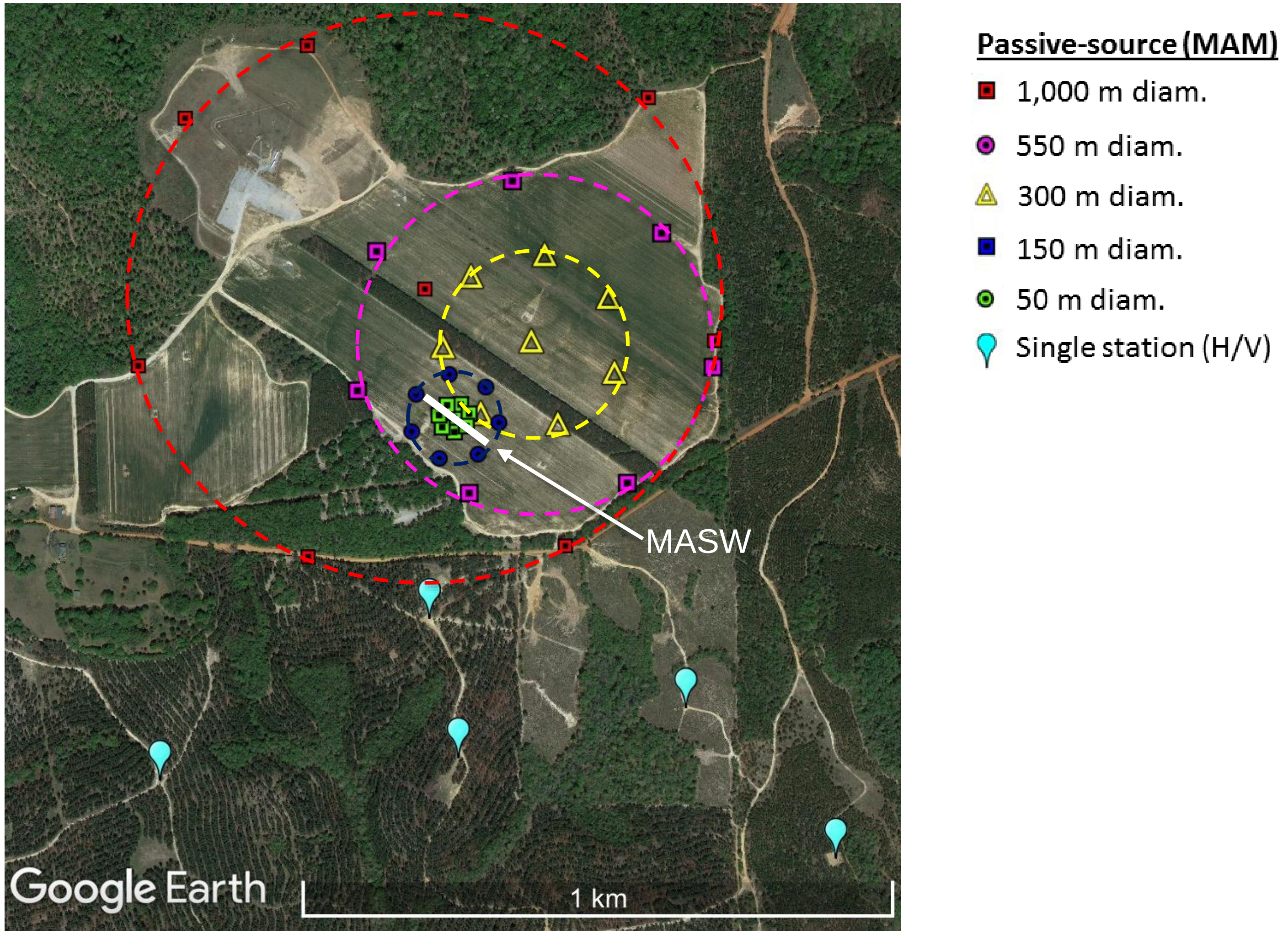
Example MAM Dispersion Data with Statistics

For an important facility in the Southeastern U.S.; We will call it Site "G"



Target Vs profiling depth = +500m

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MASW

- Linear array of 48 4.5-Hz vertical geophones
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- Circular arrays of 8 broadband seismometers
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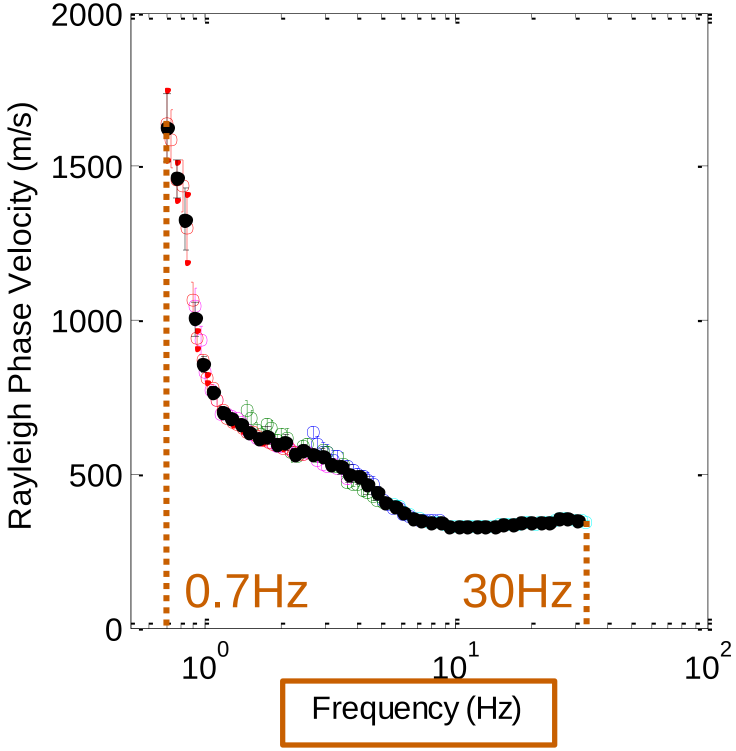
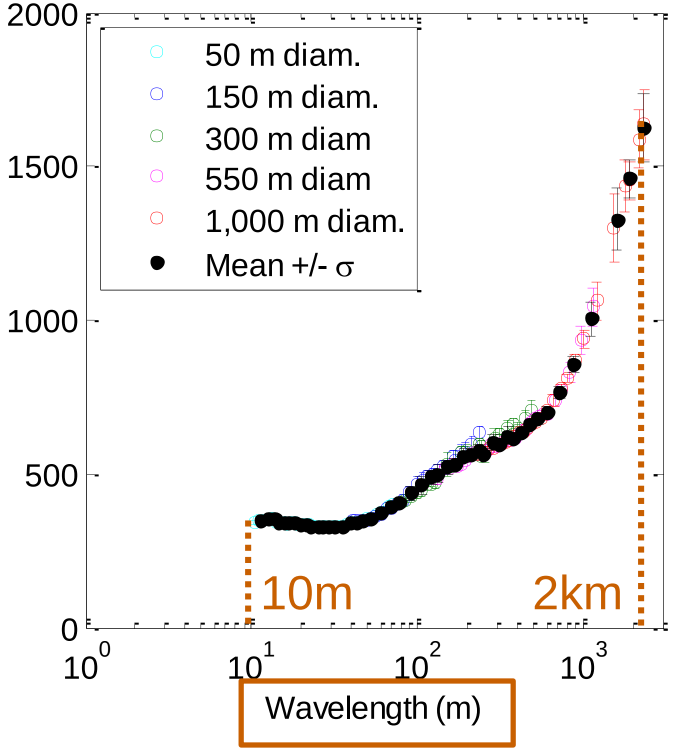
Example MAM Dispersion Data with Statistics

- Dispersion data for each circular array processed individually
- All dispersion data were cutoff based on array response criteria (wavenumbers between k_{max} and $k_{min}/2$) (Wathelet et al. 2008)
- Excellent agreement between HFK dispersion data from all arrays





- λ_{max} = 2km
- D ~ 2km/(2 or 3) = 1km – 650m

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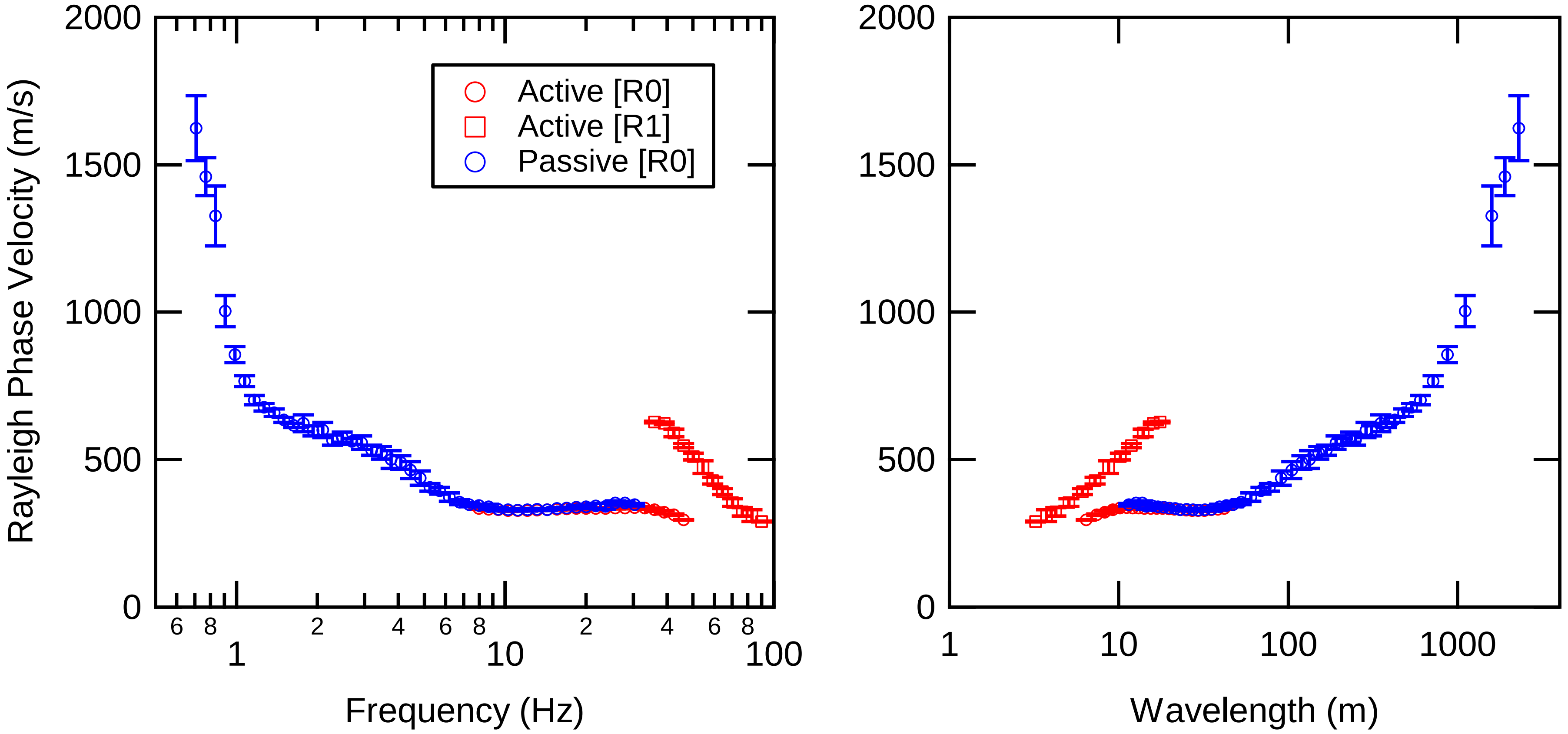
MASW & MAM Dispersion Data Comparison

- Excellent agreement between fundamental mode active-source (MASW) and passive-source (MAM) dispersion data.



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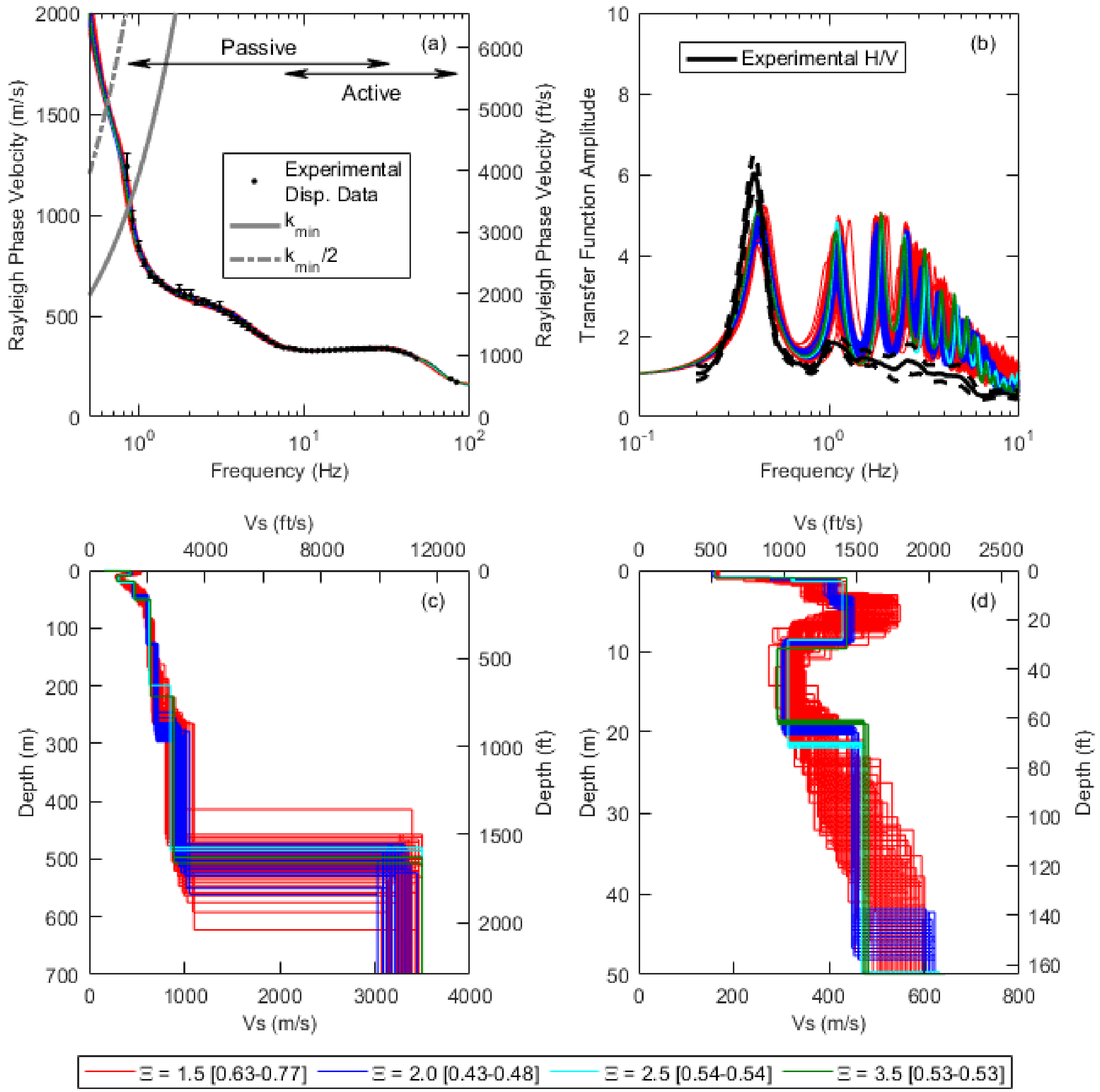
Inversion of MASW & MAM Dispersion Data



Cox & Teague (2016)
Layering ratio inversion parameterization

Inversion results based on a fundamental mode interpretation/inversion of the experimental Rayleigh wave dispersion data. Shown for each inversion parameterization (i.e., layering ratios Ξ = 1.5, 2.0, 2.5, and 3.5) are the **100 lowest misfit:** (a) theoretical Rayleigh wave dispersion curves along with the experimental dispersion data; (b) theoretical shear wave transfer functions with the lognormal median experimental H/V curve; and (c and d) Vs profiles shown to depths of 700 and 50 m, respectively. The dispersion misfit values for each inversion parameterization are indicated in brackets in the legend.

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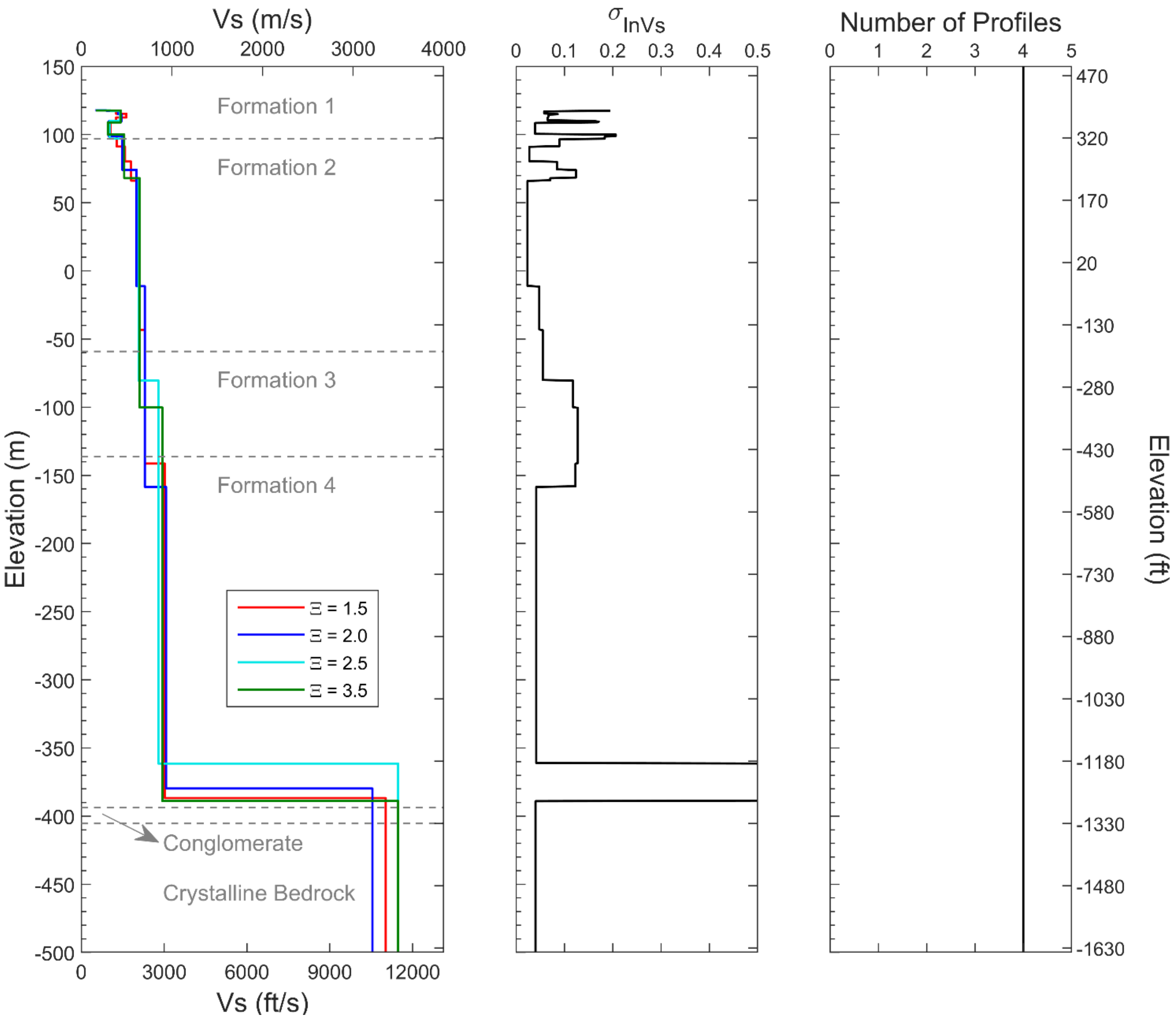
Median Vs Profiles vs. Deep Borehole Log

Blind Study Results:

- 4 median Vs profiles from MASW/MAM
- Measured over ~1km

- Deep borehole log ("point" measurement)

- Ξ = 2.5 is a bit of an outlier… is it "wrong"?



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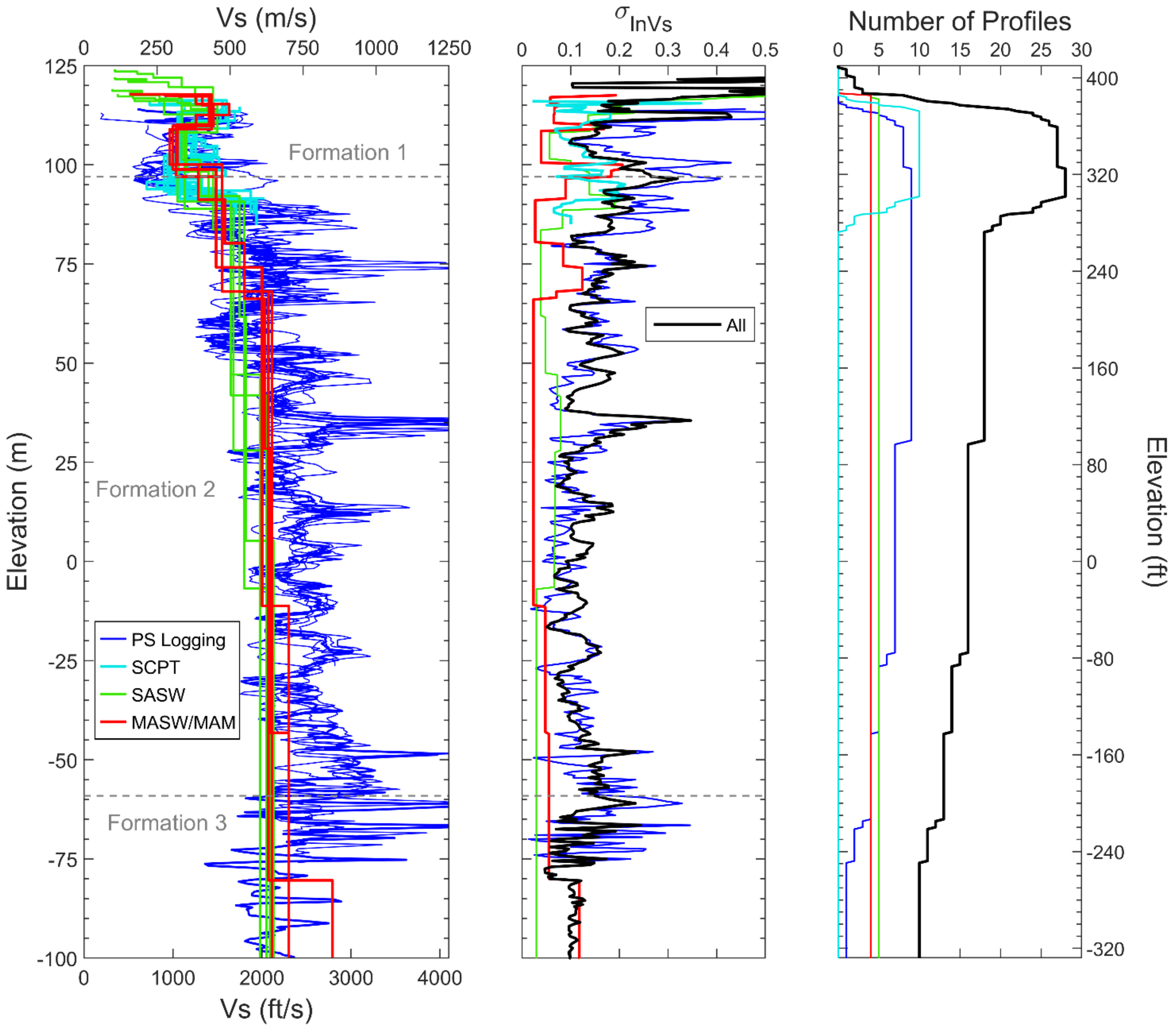
All Invasive and Non-Invasive Vs Profiles

<u>Blind Study Results</u>:

- **Top 225 m**
- PS logging
- SCPT
- SASW
- MASW/MAM



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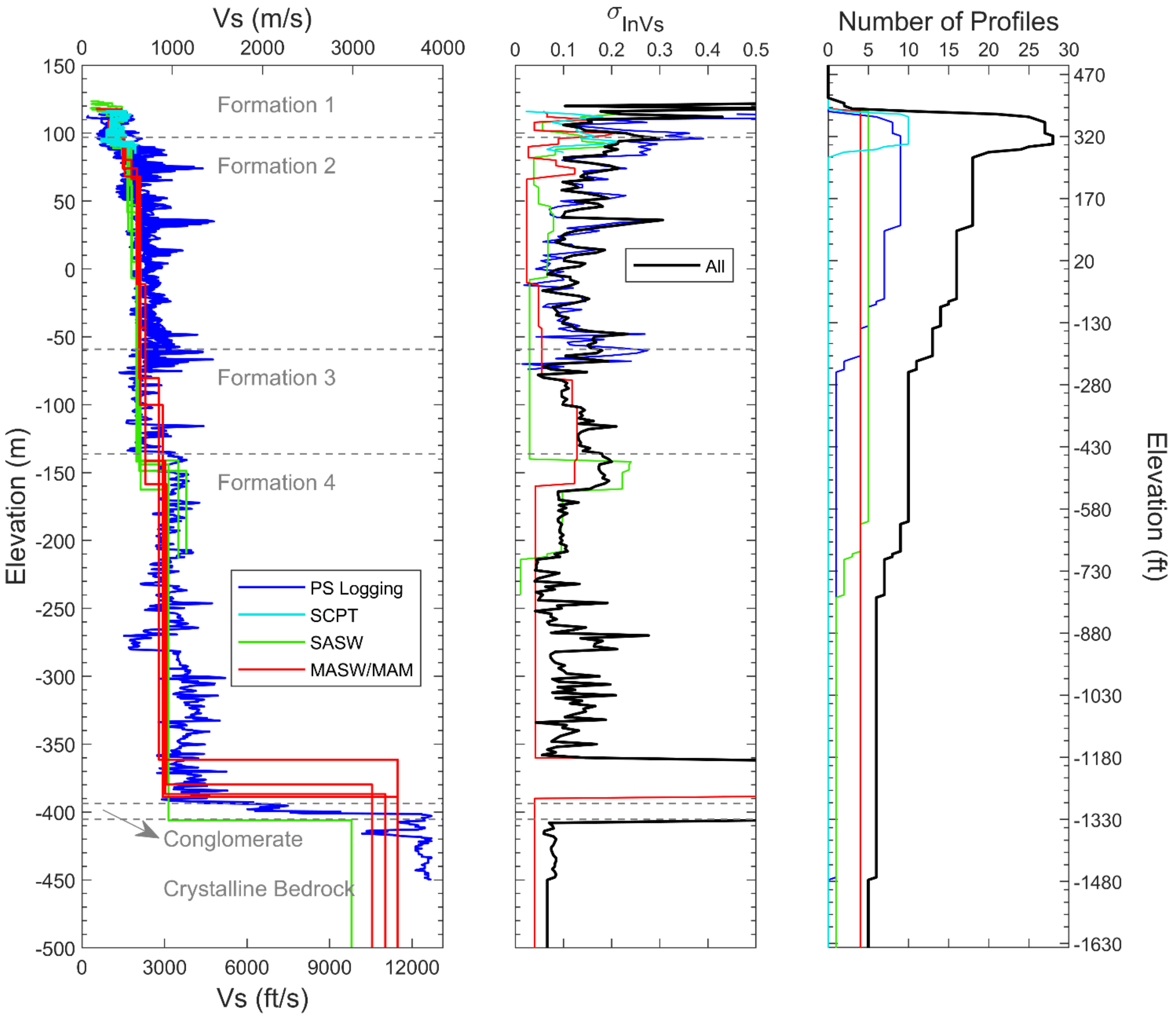
All Invasive and Non-Invasive Vs Profiles

Blind Study Results:
- **Top 650 m**
- PS logging
- SCPT
- SASW
- MASW/MAM



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Questions?

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