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Simplified Seismic Surveys for Non-Intrusive ASCE 7-22 Compliant Site Class, Critical-Zone Characterization, Fault Location, and Basin Structure

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ASCE/SEI 7-22 now requires “Direct” site velocity measurements for determining seismic site classification

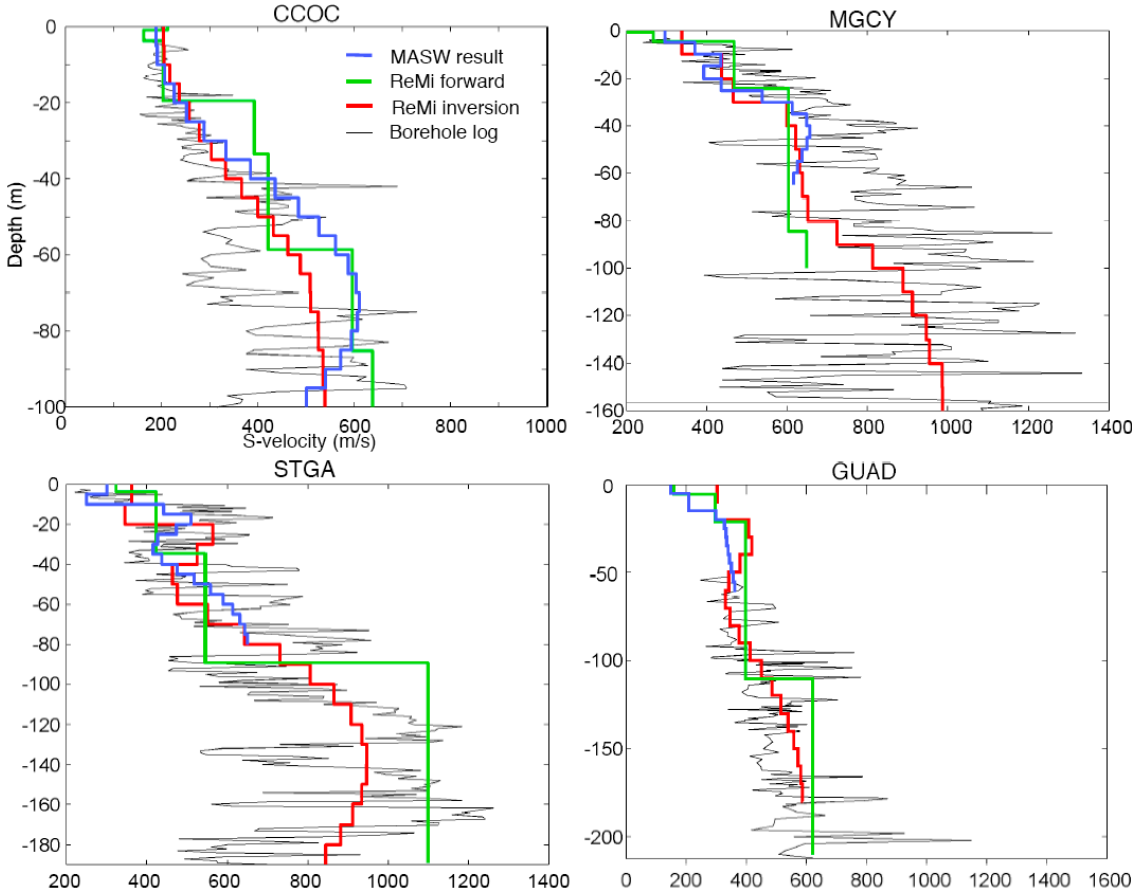
Use the measured time-averaged shear-wave velocity profile from the ground surface to 30 meters depth

- V_{S30} or v_S or Vs30
- Measure the velocity profile with downhole or surface-wave geophysical methods at each site

USGS study in Santa Clara Valley, CA (USA):

W. J. Stephenson, J. N. Louie, S. Pullammanappallil, R. A. Williams, and J. K. Odum, 2005, Blind shear-wave velocity comparison of ReMi and MASW results with boreholes to 200 m in Santa Clara Valley: Implications for earthquake ground motion assessment. Bulletin of the Seismological Society of America, 95, no. 6 (Dec.), 2506-2516.

One of Many Published Comparisons of ReMi Results



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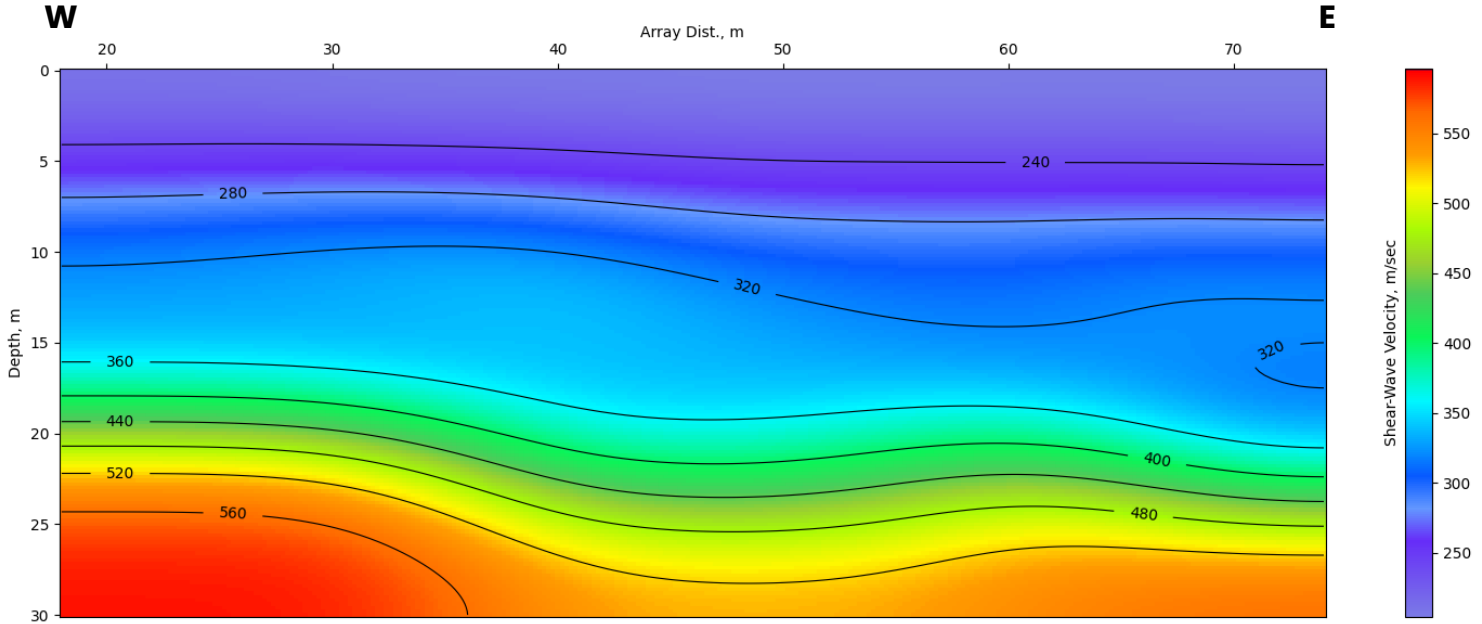
Noninvasive Surface-Wave Guidelines

The US Geological Survey and the Consortium of Organizations for Strong Motion Observation Systems published the peer-reviewed **COSMOS International Guidelines for Applying Noninvasive Geophysical Techniques to Characterize Seismic Site Conditions** volume in 2022.

ReMi guidelines: J. N. Louie, A. Pancha, and B. Kissane, 2021, Guidelines and pitfalls of refraction microtremor surveys: *Journal of Seismology*, June 7, doi.org/10.1007/s10950-021-10020-5, open access

Depth to bedrock – Critical Zone Thickness



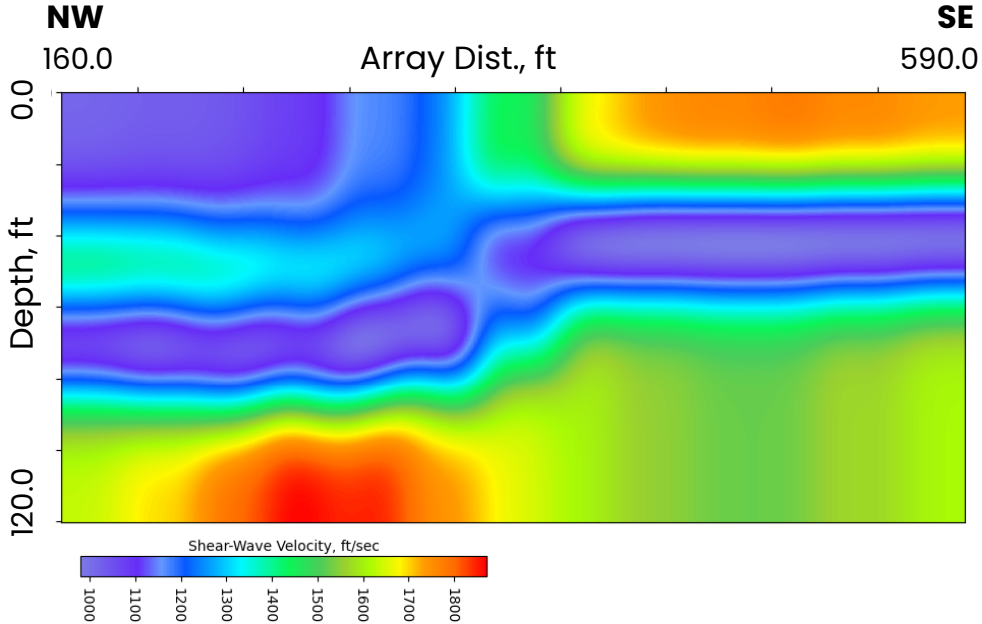
Suelo-Estructura in Guadalajara, Jalisco, Mexico used ReMi 2dS™ software to determine the depth and thickness of layers and bedrock topography. Variations in subsurface bedrock topography are required for rippability, determining overburden removal costs, and placement of engineered structures.

Las Vegas Valley, Nevada Fault Strands

- ReMi™ software 2D S-wave velocity image (right) from fault study in Las Vegas Valley. Caliche layer, shown in orange, overlies displaced velocity reversal, shown in blue.
- The fault is manifested as a lateral velocity discontinuity at the center of the line confirming dePolo's fault location inference.

Inferred fault locations (dePolo) & SW Geotechnical constrained fault location

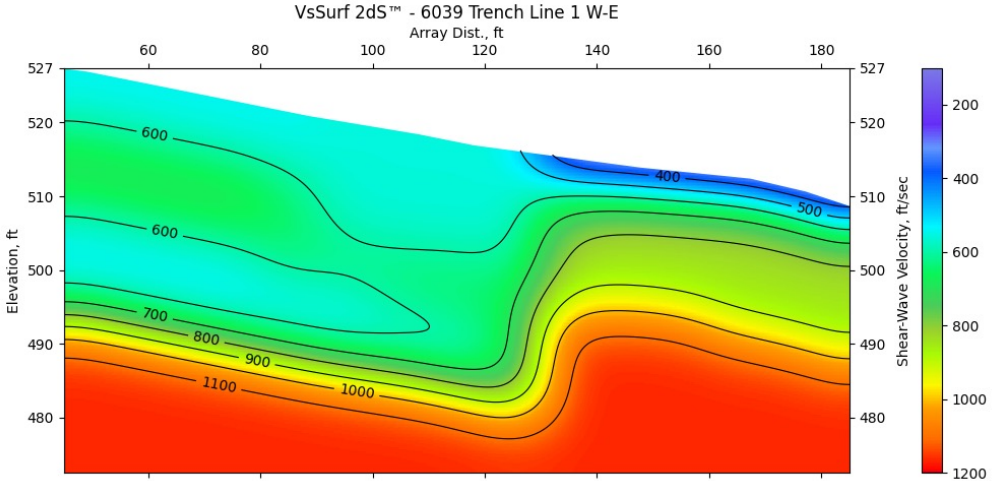
24-channel ReMi™ array 230 m long



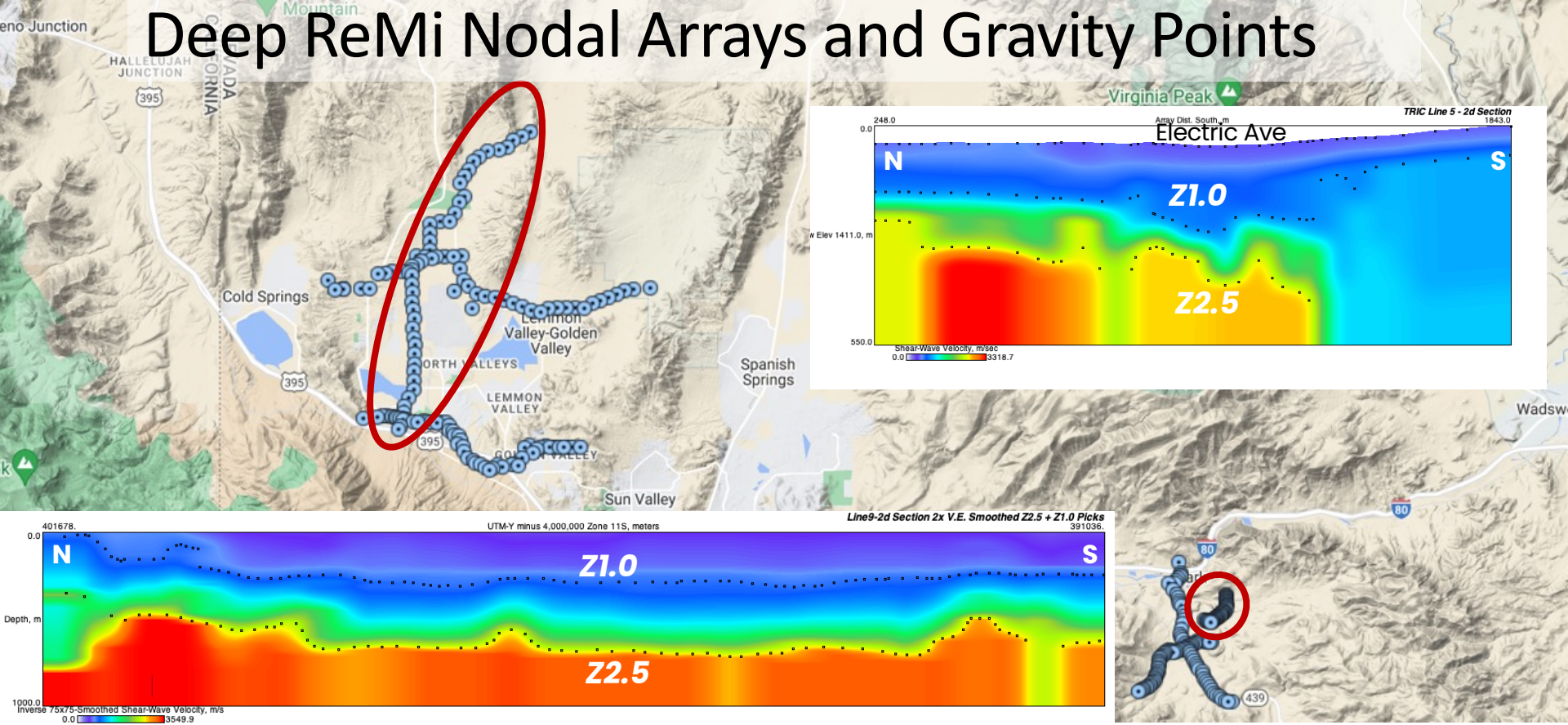
Calaveras Fault (SAF System) Pleasanton, California

- Active strike-slip fault projected to 30-m-wide zone
- ReMi 2dS survey on 70-m-long 24-chan geophone array took 30 minutes

- Lateral Vs discontinuity locates fault to 3 m accuracy
- Targets paleoseismic trenching

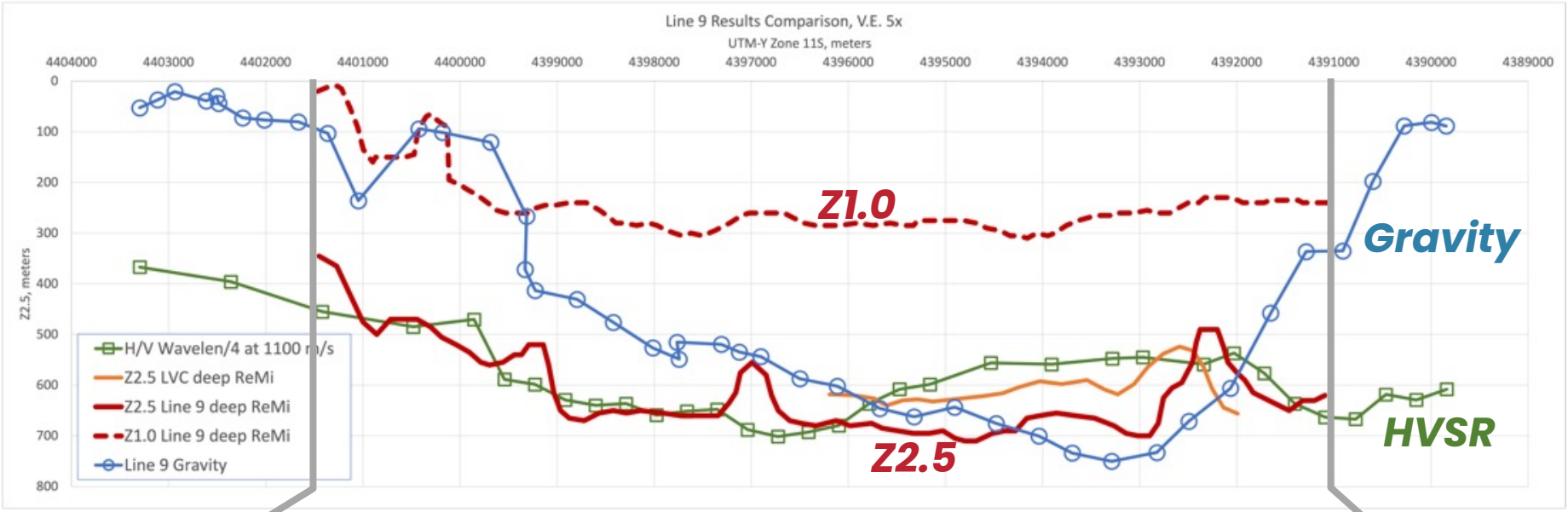


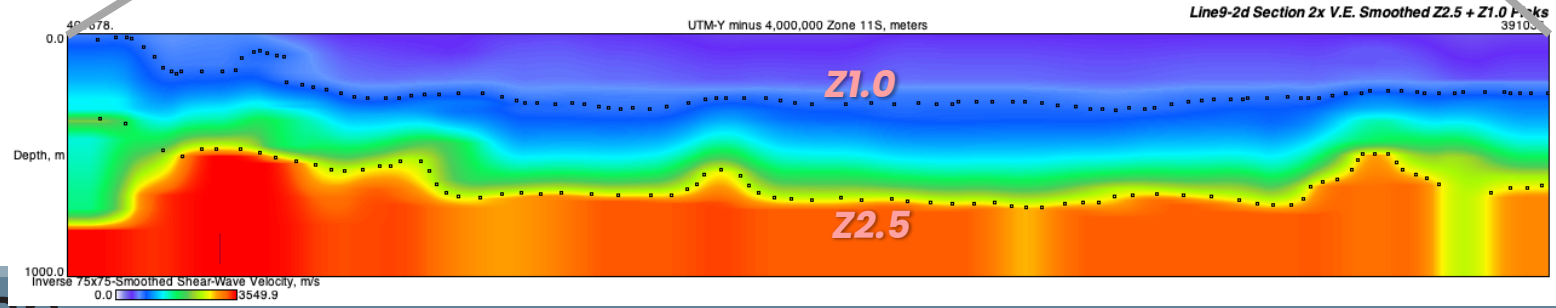
Deep ReMi Nodal Arrays and Gravity Points



The Univ. of Nevada in collaboration with the Univ. of Cincinnati performed 12 hours of recording on a 20 km-long array of 54, 5 Hz 3C PASSCAL-NMT nodals across Lemmon Valley, Nevada, and 4 hrs on a 2 km array across Electric Ave. in TRIC. Deep ReMi shear-wave velocity sections from Terēan analyses.

Deep ReMi Results Correlate with Gravity, HVSR





Conclusions – *Thank You!*

- ReMi meets the requirements of ASCE/SEI 7-22 for velocity measurements and is recommended by geotechnical, engineering, government & academic entities globally
- Practitioners and researchers world-wide rely on ReMi for accurate, non-invasive site classification and characterization
  - An accurate, fast, and cost-effective Vs measurement to enhance borehole and CPT data or other surface-wave methods
  - Site classification plus depth and thickness of layers in ~30 minutes
  - Fault location and anomaly detection takes no additional field time
  - Efficient large-scale characterization of the critical zone
  - Basin shear-wave velocity measurement and aquifer geometry to 1 km depth

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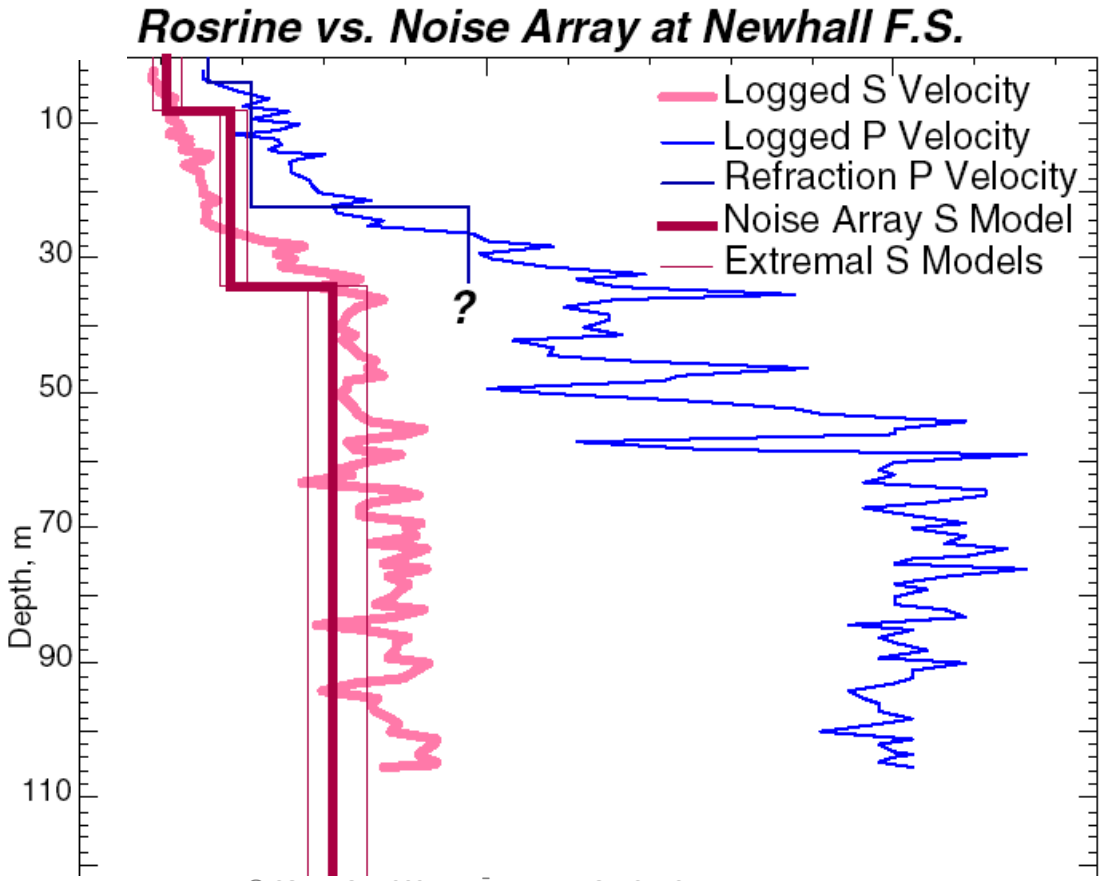
For over 20 years, refraction microtremor has provided practitioners with reliable results:

John N. Louie, 2001, Faster, better: shear-wave velocity to 100 meters depth from refraction microtremor arrays. *Bulletin of the Seismological Society of America*, **91**, no. 2 (April), 347-364.

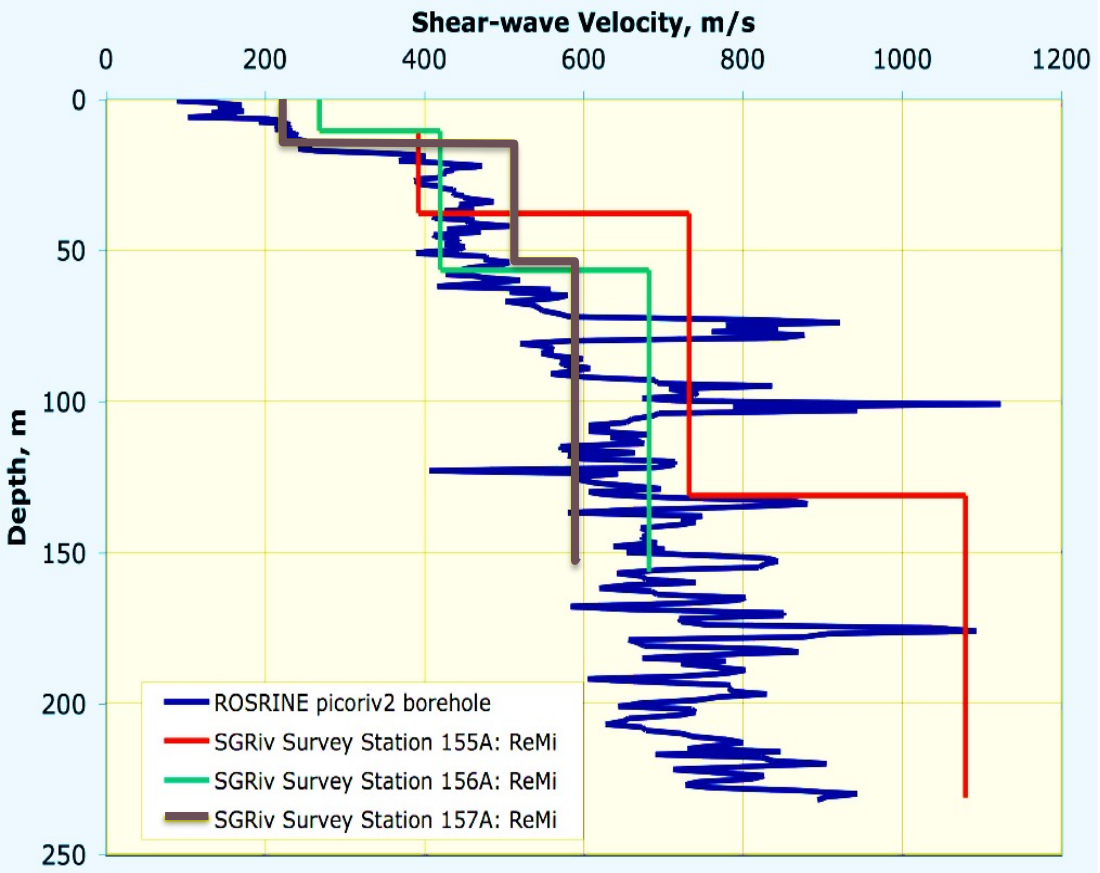
Published Comparisons of ReMi Results



Published Comparisons of ReMi Results

USGS-sponsored study across the Los Angeles Basin:

W. A. Thelen, M. Clark, C. T. Lopez, C. Loughner, H. Park, J. B. Scott, S. B. Smith, B. Greschke, and J. N. Louie, 2006, A transect of 200 shallow shear velocity profiles across the Los Angeles Basin: Bulletin of the Seismological Society of America, 96, no. 3 (June), 1055-1067, 10.1785/0120040093



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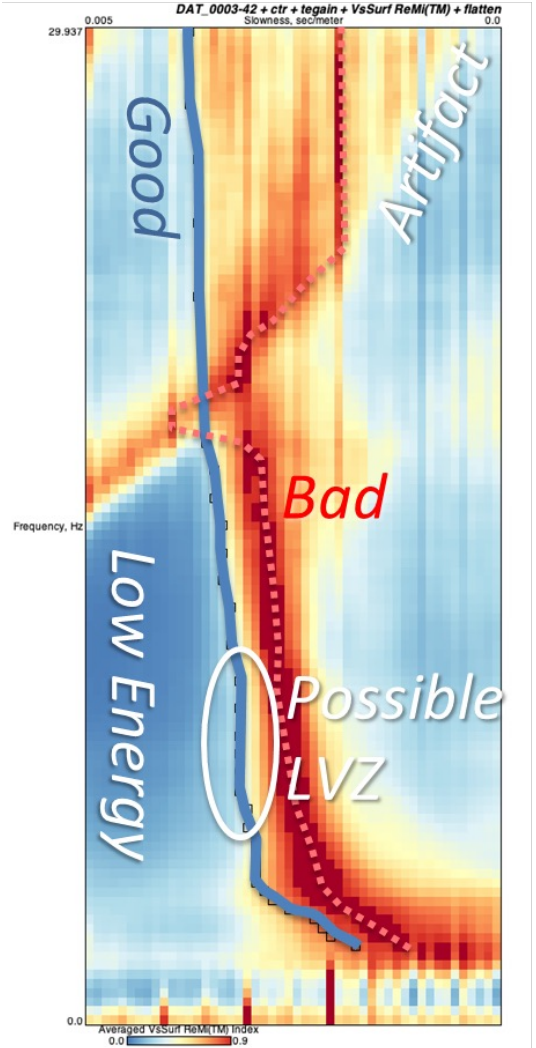
Terēan's Recommendations for Compliant Surface-Wave Data Collection

- *Array at least 200 ft long: Use array length >2 times depth objective*
- *Record for at least 10 min: >20 records at least 30 seconds long*
- *Use an active source: Add in-line signal by hammering off each end of the array*
- *12 or more geophones, <5 Hz: Level and check phones for coupling, connection*
- *QC at the site: Try test processing before leaving site*



Terēan's Recommendations

- *Pick the fundamental mode / low-velocity envelope:* *Always make dispersion picks along* ***lowest-velocity envelope***
- *Picking into gaps:* *Skip frequency bands with no energy along low-velocity envelope*
- *Be consistent:* *Select the lowest velocity curve across all records and tests*
- *Practiced picking:* *Pick by hand*

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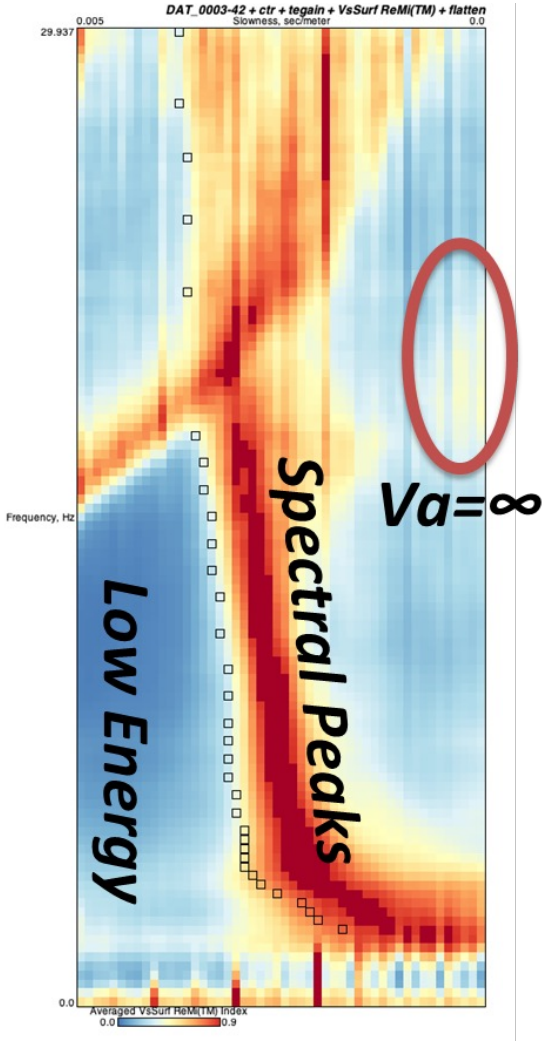

Terēan's Recommendations

- *Explore Vmin & fmax: home in on dispersion, takes just a few minutes*
- *Sum only good records: Exclude dispersion from troublesome records*
- *Directional tests: Examine forward, reverse, and both on all records*
- *Linear velocity: Use linear slowness scale to identify energy broadside to array at infinite apparent velocity*

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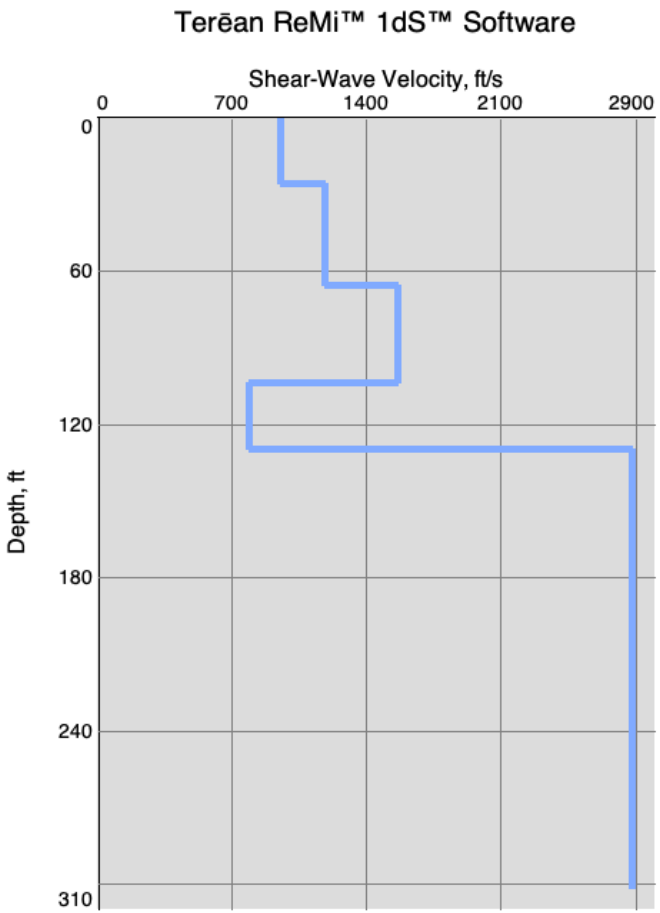

Terēan's Recommendations

- *Use corroborating data: Leave blind tests to the researchers; always use all the information you have - borings, excavation, etc.*
- *Simple models: No need to fit all the dispersion picks exactly; ReMi yields robust Vs100*
- *Only definite LVZs: Learn how to identify potential velocity reversals with depth*

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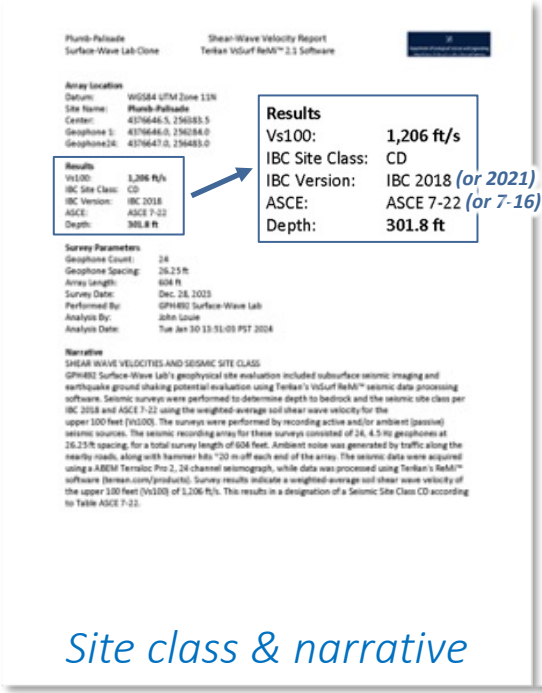
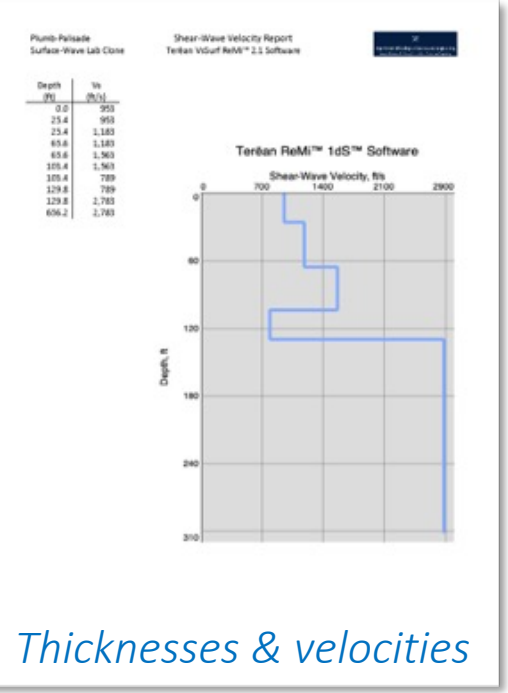
Compliant Surface-Wave Results

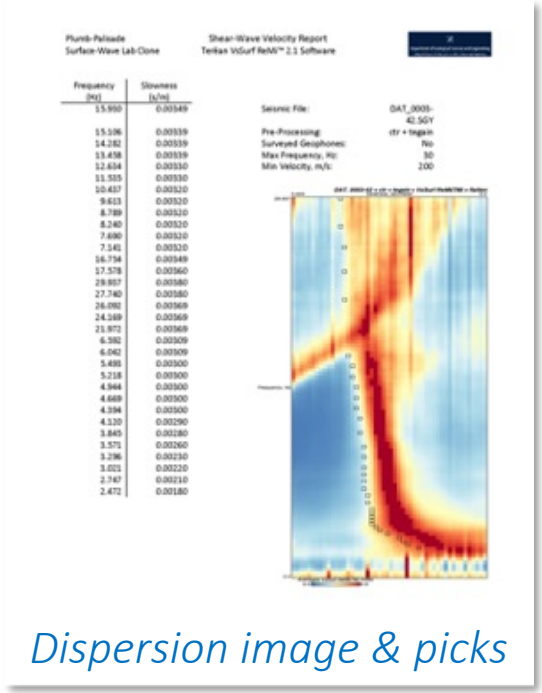
ReMi® software auto-report generation: When analysis is complete (30 min), one button creates a thorough report document.



Site class & narrative



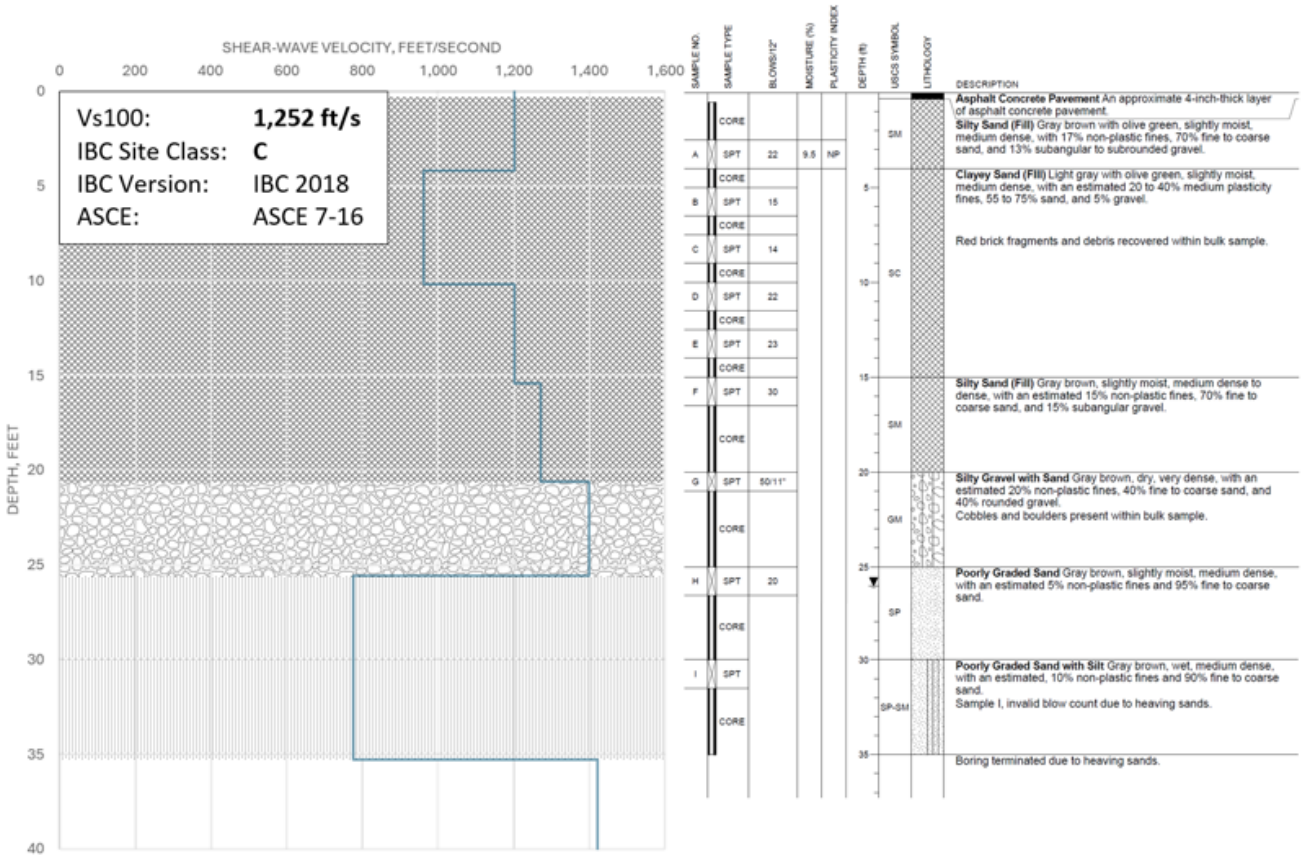
Thicknesses & velocities



Dispersion image & picks

Shows compliance: Reports show all the data any code-enforcement agency needs to demonstrate compliance

Tying borehole data to ReMi data



ReMi™ software analysis (left) correlated with borehole result (right) from Black Eagle Consulting, Reno, NV, USA.

*Identified liquefaction prone layer, **reduced** the number of boreholes required for a project and increased the value by getting a "project-wide" view of the subsurface.*

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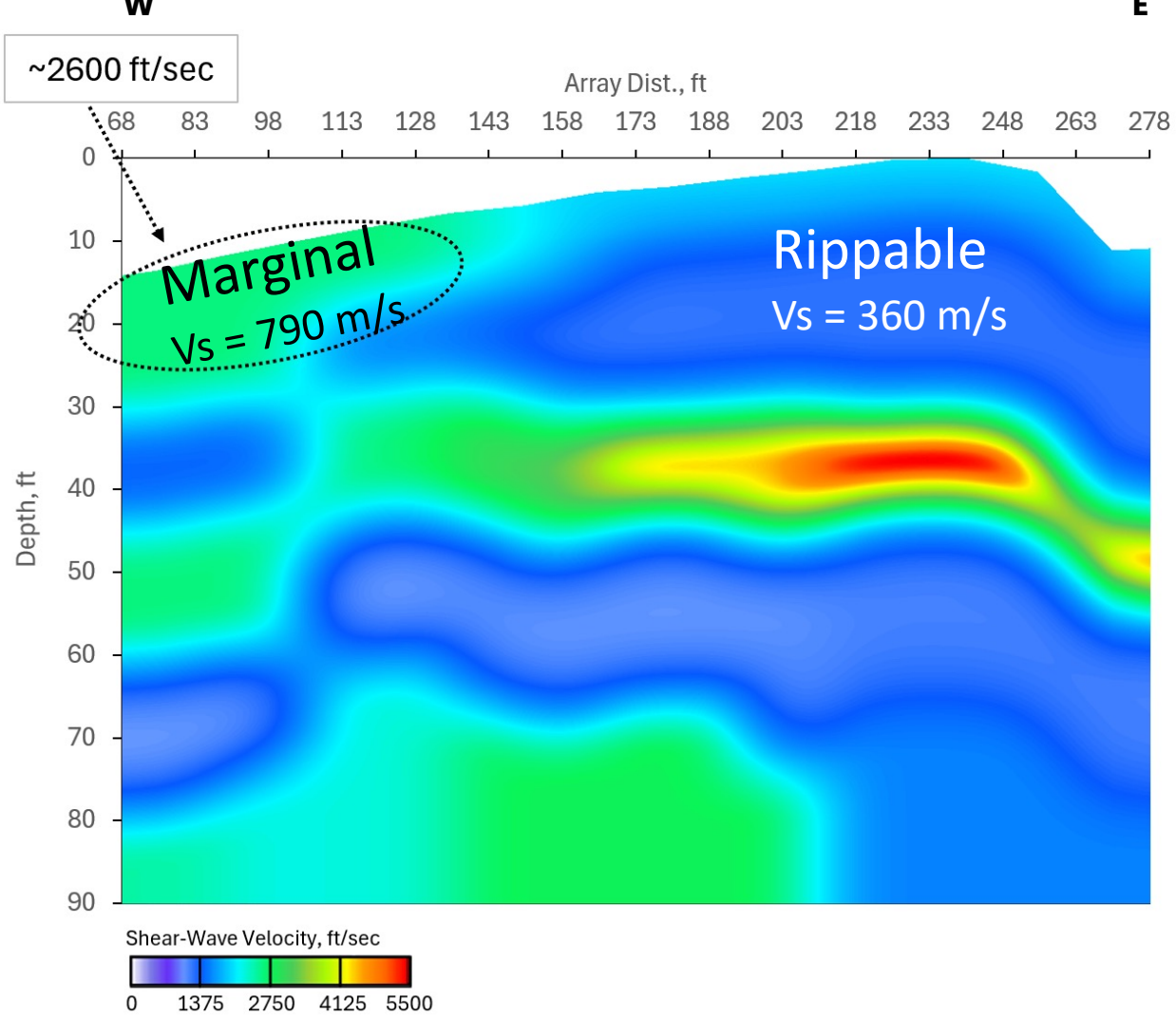
Rippability

ReMi® software includes proprietary technology that allows partitioners to determine rippability of subsurface materials using S-waves.

In this case, the result reveals subsurface material to be rippable to marginally rippable in the upper 10 m



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Example of Large-Scale ReMi

Linear surface-wave array surveys are the most cost-effective

- Commissioned by Clark Co. and City of Henderson, NV at 10,722 sites
- Used active-source linear surface-wave array at each site
- 600 ft long arrays, 24 channel, 4.5 Hz geophones
- Engineers can design to County-measured Vs30 value, or submit their own measurements
- Published in the *Bulletin of the Seismological Society of America, 2017*

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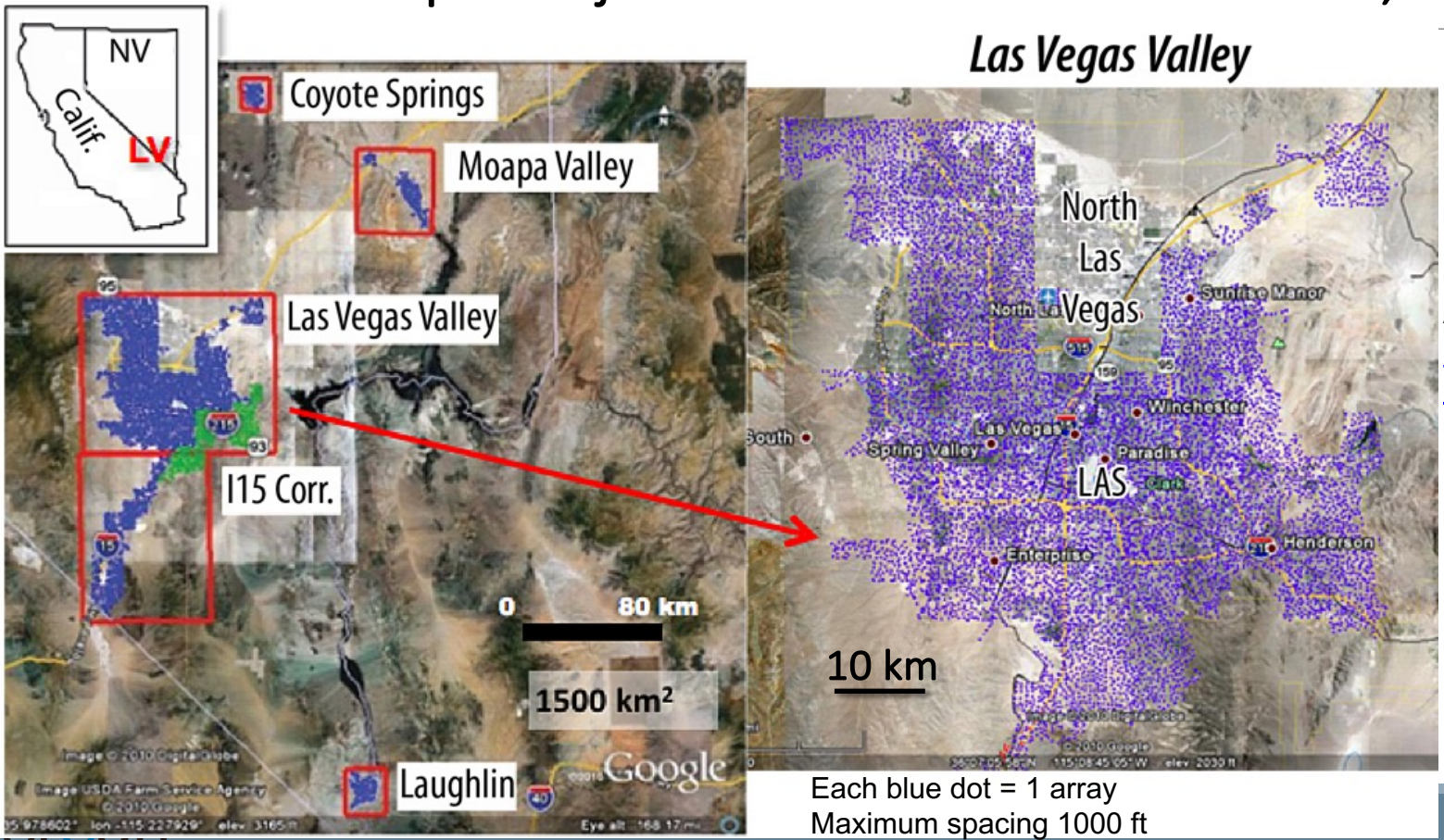
Clark County & Henderson Parcel Map:
Municipal Project for IBC Enforcement – *BSSA*, 2017



10,000 profiles measured over 3 years

All posted at clarkcountynv.gov

OpenWeb GIS

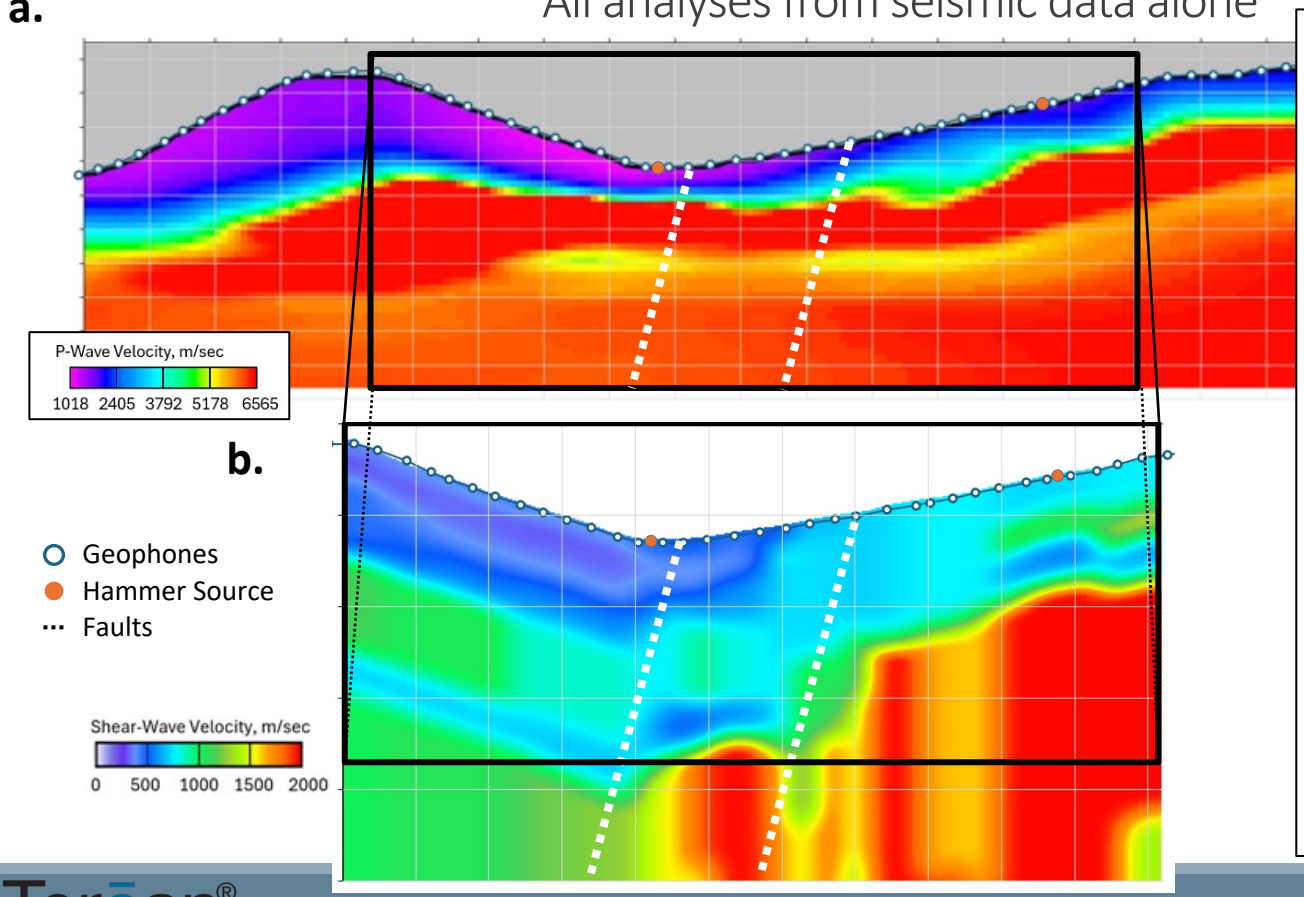
Each blue dot = 1 array
Maximum spacing 1000 ft

Record P-wave seismic refraction data at the same time and on the same array as your recording for S-wave processing in the ReMi™ software.

- Get additional hit points along the geophone array. **You do not need a trigger cable**, and you will continue recording your 30 sec records as normal for the ReMi™ software.
- Check the ReMi™ software's output on the records recorded as normal, to be sure you have compliant, high-quality Vs data.
- Processing: Upload your records and field logs to Terean.com/processing for P-wave tomography processing.

Line 2 ReMi 2d™ P + S Sections

All analyses from seismic data alone



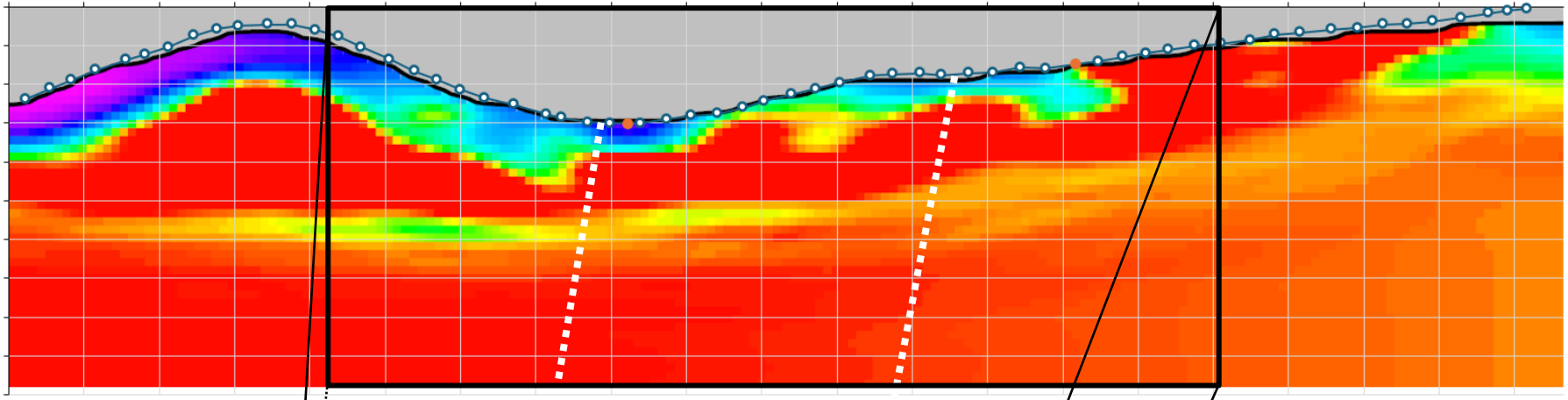
Vp triggerless tomographic results (a) are correlated with Vs results (b). Inferred fault locations projected. Seismic sections are plotted relative to surveyed geophone locations.

The Vp results reveal near-surface velocity structure detail, with thickness consistent with Vs results.

Vs results show greater depth detail. Breaks in velocity structure correlate with inferred fault locations.

a.

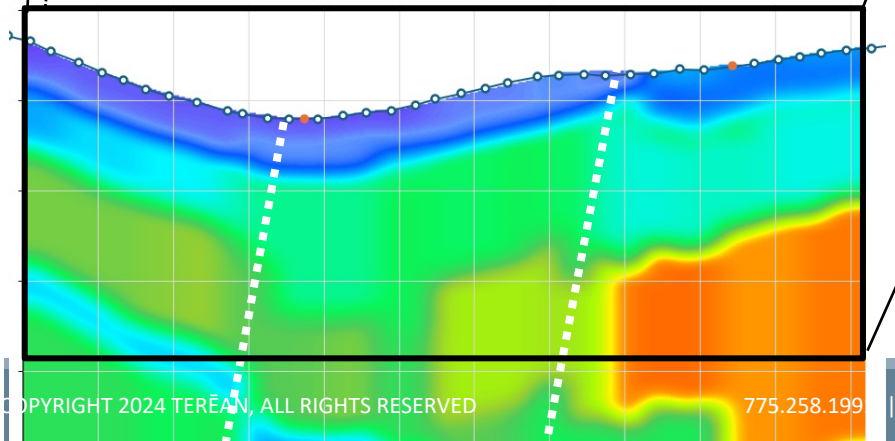
Line 1 ReMi 2d™ P + S Sections All analyses from seismic data alone



P-Wave Velocity, m/sec

1177 2524 3871 5218 6565

b.



Geophones

Hammer Source

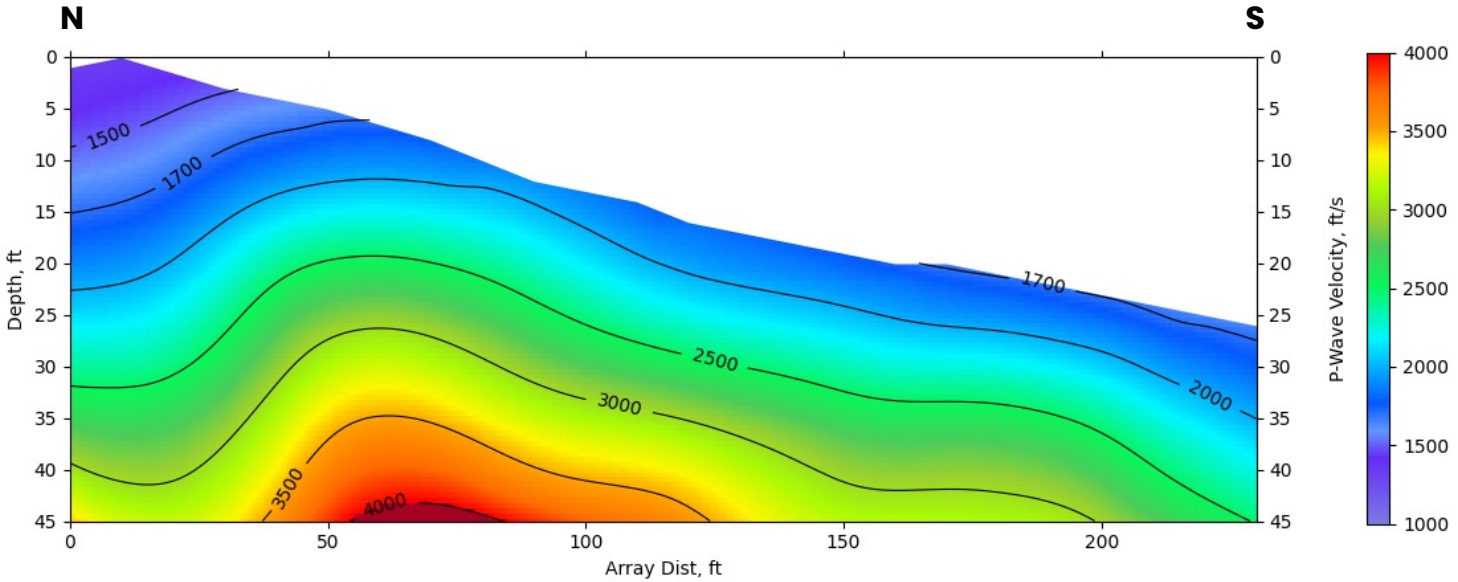
Faults

Shear-Wave Velocity, m/sec

0 500 1000 1500 2000

L1 triggerless Vp tomographic results (a) are correlated with Vs results (b). Inferred fault locations are projected. The Vp results reveal near-surface velocity structure detail, with thickness consistent with Vs results. Vs results show greater depth detail. Offset velocity structure correlates with

VsSurf ReMi 2dP™ Tomography



Vp triggerless tomographic results Geocon collected during field training with Terean showing bedrock at 40 ft depth.