4D Vertical-Seismic-Profiling Monitoring at the Farnsworth CO_2-EOR Field

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Outline

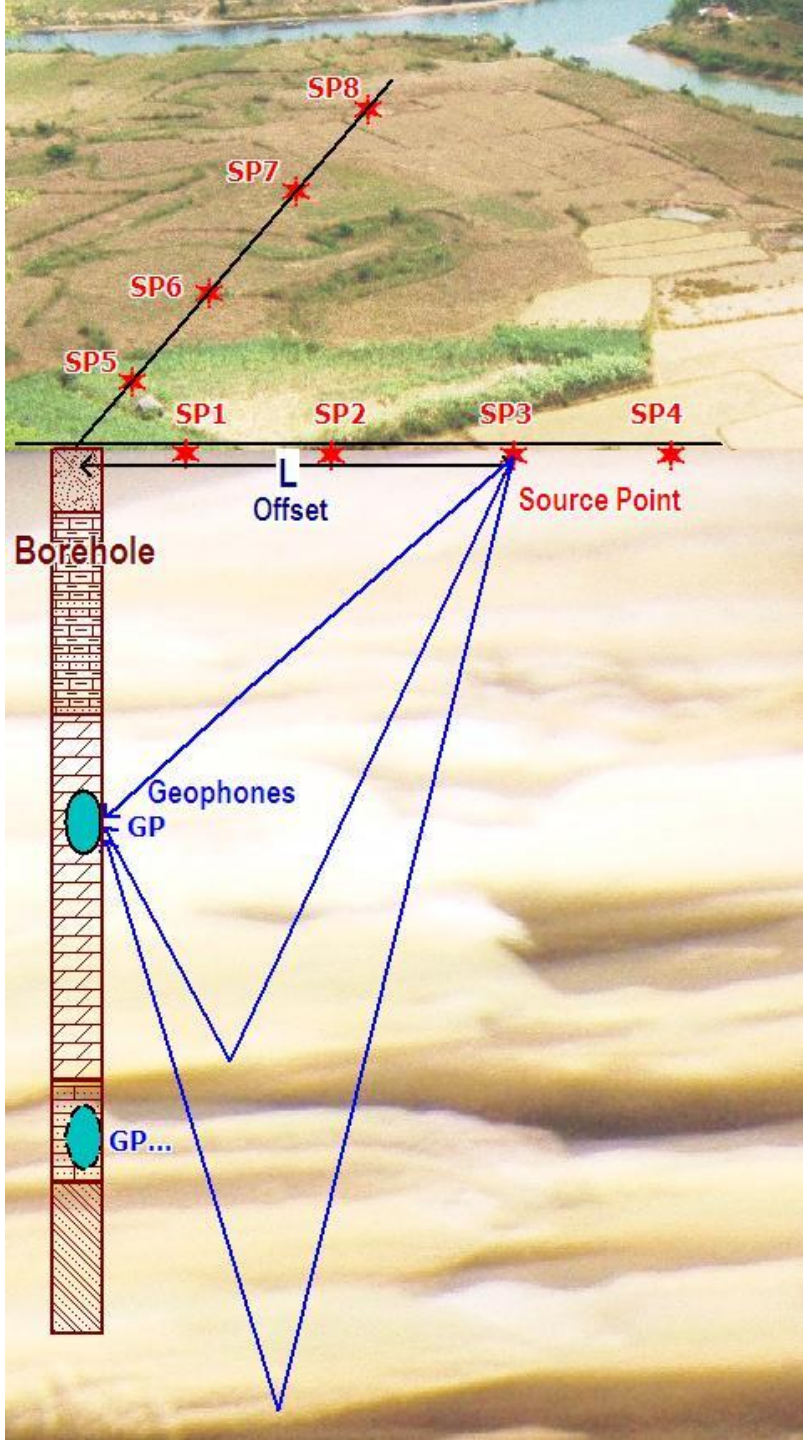
- Background
- Vertical Seismic Profiling Survey
- VSP Wavefield Separation
- VSP Data Interpolation to Fill Acquisition Gaps
- Build Initial Velocity Models
- First-Arrival Traveltime Tomography of VSP Downgoing Waves
- Elastic-Waveform Inversion of VSP Upgoing Waves
- Elastic-Waveform Inversion of Time-Lapse VSP Data to Obtain Spatiotemporal Velocity Changes During CO_2 Injection/Migration

Background

- During the Development Phase of the U.S. Southwest Regional Partnership on Carbon Sequestration (SWP), supercritical CO_2 was continuously injected into the deep oil-bearing Morrow-B formation at the Farnsworth Unit in Texas for Enhanced Oil Recovery (EOR).
- The project goal was to inject a million tons of CO_2.
- The project acquired a baseline and three time-lapse three-dimensional (3D), three component (3C) vertical seismic profiling (VSP) using surface vibroseis sources surrounding an injection well and a production well from 2014 to 2017 for monitoring CO_2 injection/migration.
- We develop a workflow to invert for subsurface velocity changes caused by CO_2 injection/migration. Our elastic-waveform inversion results revealed the spatiotemporal changes of seismic velocities, demonstrating the spatiotemporal evolution of CO_2 plume, moving from the injection well to the production well.

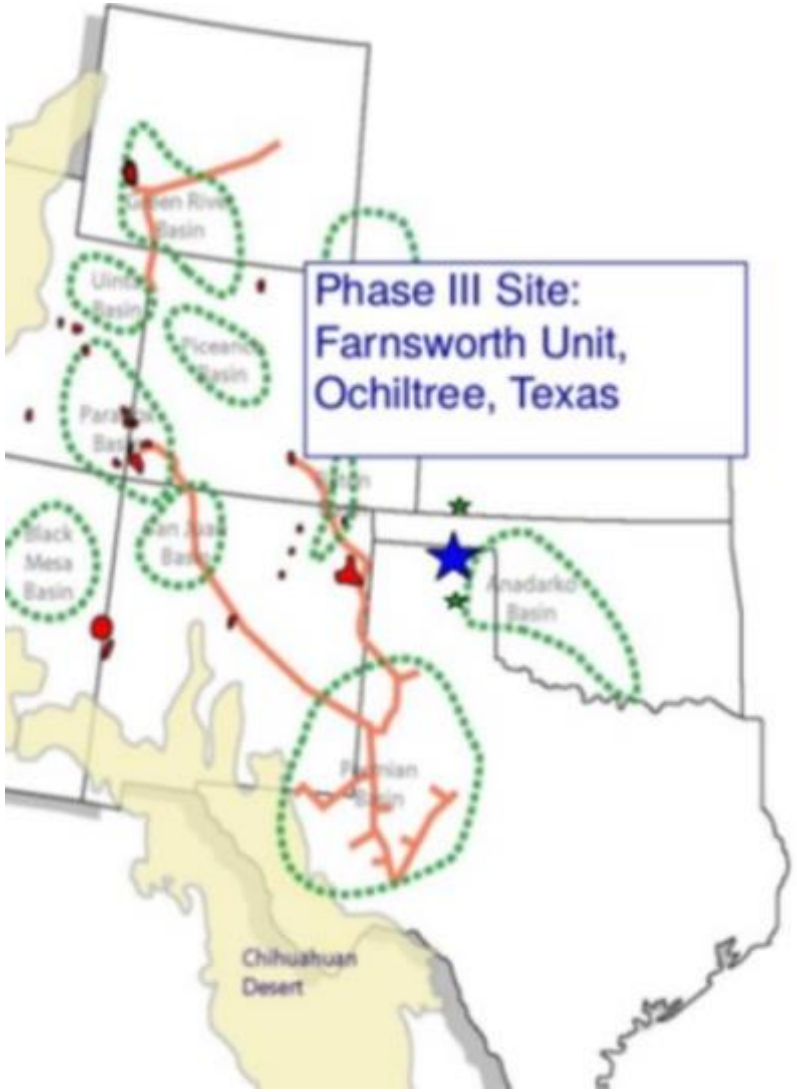
Vertical Seismic Profiling Survey

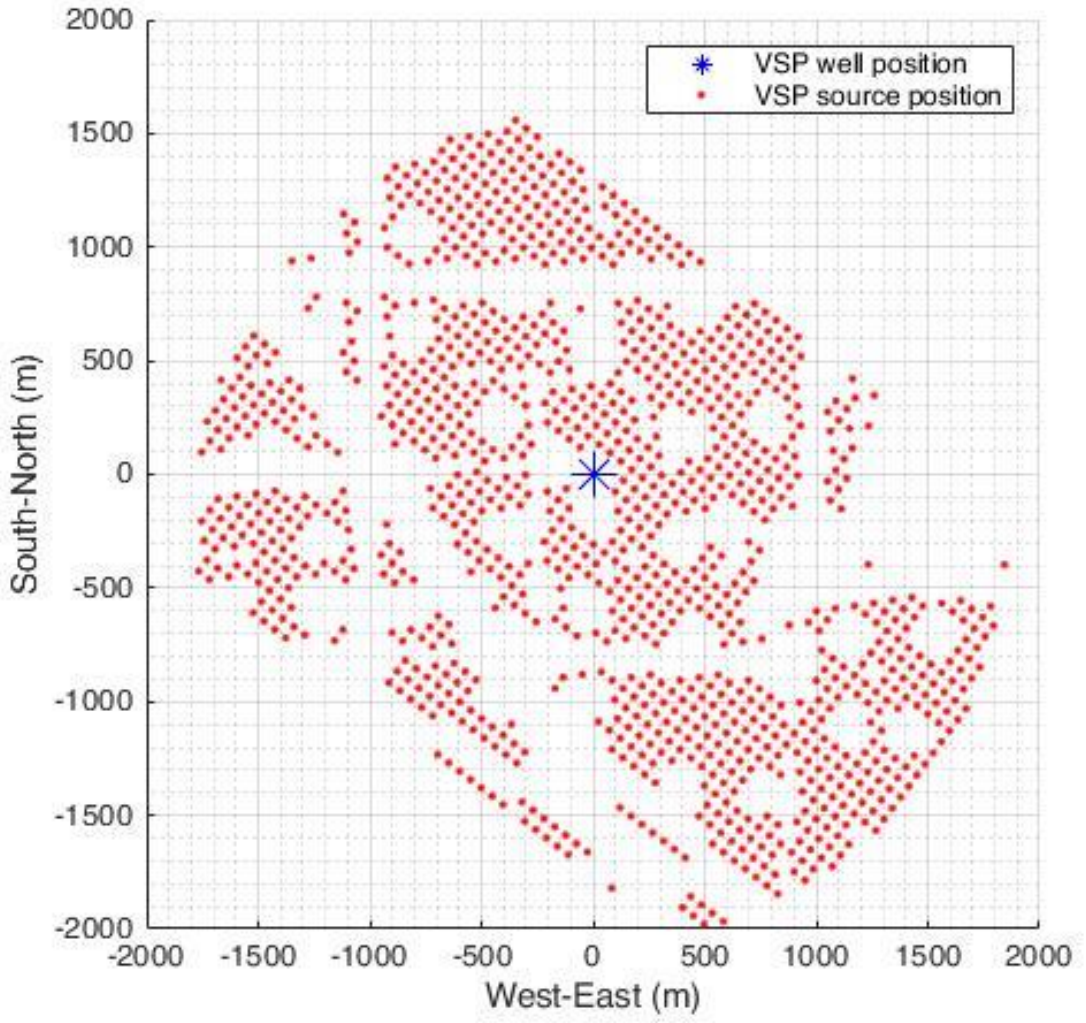
Vertical Seismic Profiling Survey



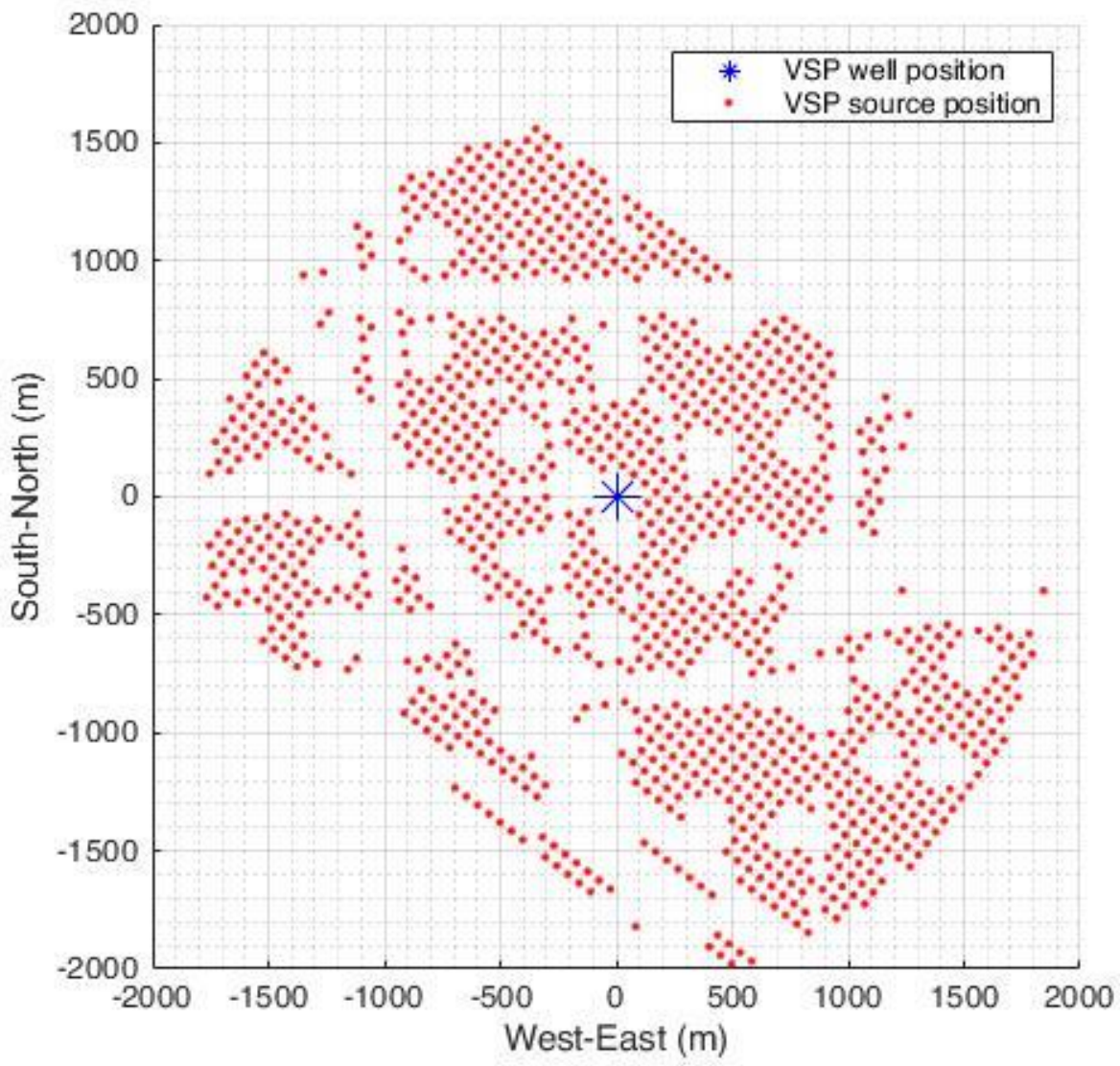
From:
https://en.wikipedia.org/wiki/Vertical_seismic_profile#/media/File:Vertical_Seismic_Profiling_Survey.jpg

Farnsworth CO_2-EOR Field and VSP Acquisition Geometry





- Receivers: processed data at 35 levels (37 levels with two dead levels)
- Depth: 1140 – 1688 m
- Receiver interval: ~50 ft
- Morrow B: centered at ~7750 ft, thickness: ~35 ft



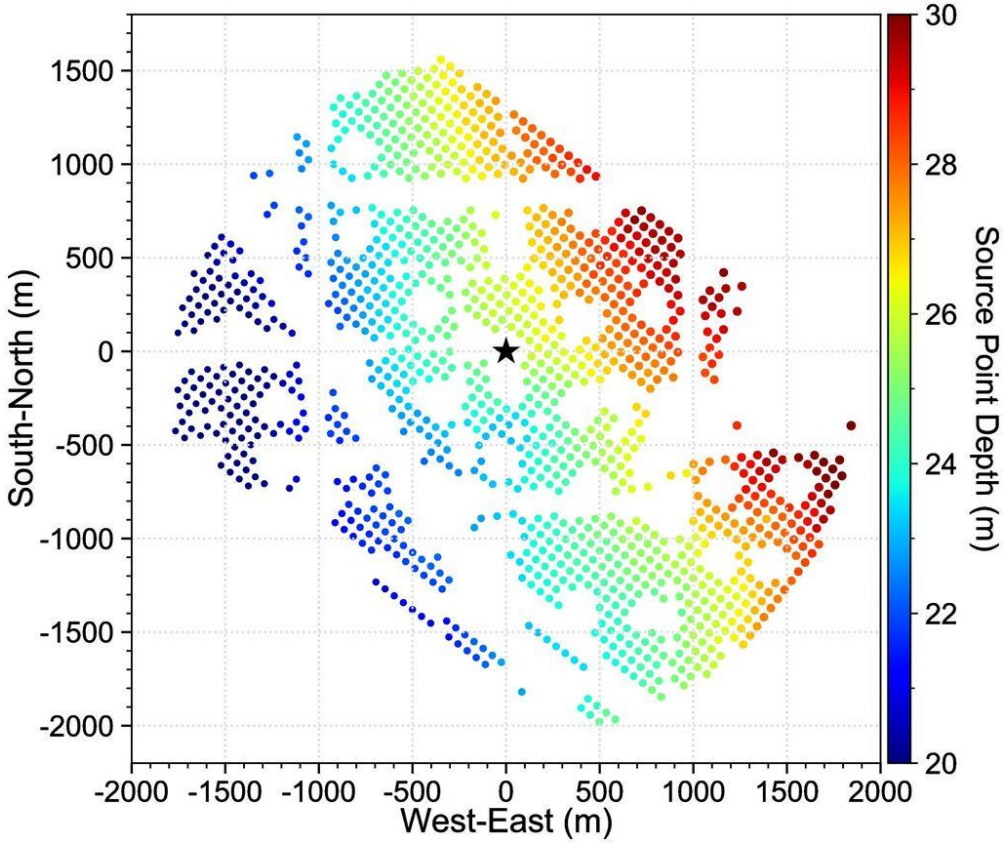
Well Head:

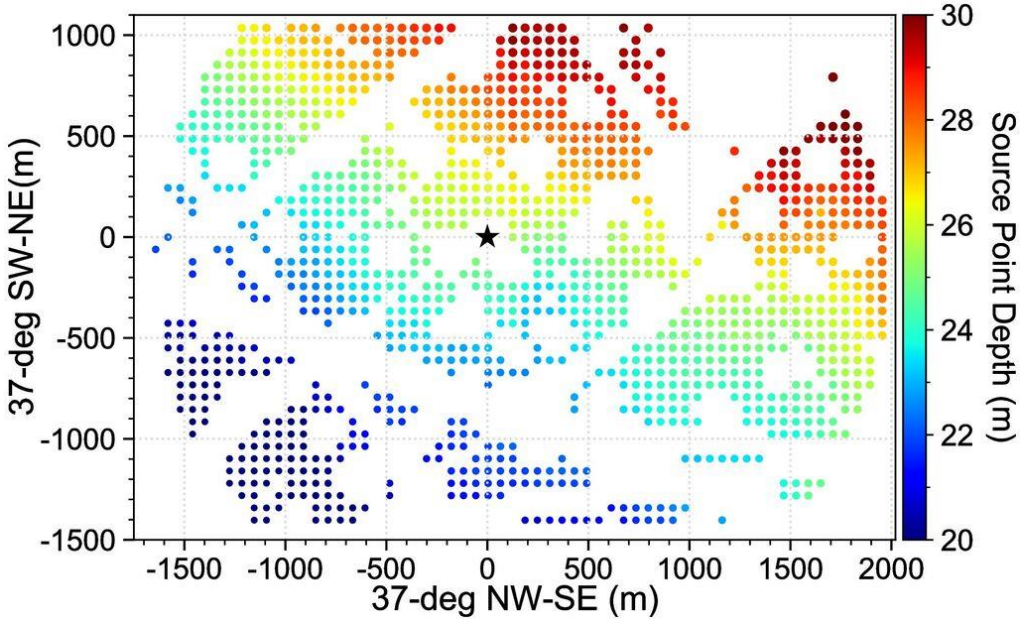
Latitude: 36.26 degree

Longitude: -101 degree

Datum: 3030.5 feet

3D VSP Data Acquisition Geometry: Rotation to Reduce the Model Size and Computational Cost for 3D Inversion





Time-Lapse Seismic Data and CO_2 Injection

- 3D-1C surface seismic data: Nov 2013
- 3D-3C baseline VSP data : February 2014
- 3D-3C monitor1 VSP data : January 2015
- 3D-3C monitor2 VSP data : November 2016
- 3D-3C monitor3 VSP data : December 2017
- 4D VSP: 3D VSP and 1D in time

- Base Line --> Monitor 1: Injected CO_2= 33,070.25 tons
- Base Line --> Monitor 2: Injected CO_2= 76,597.14 tons
- Base Line --> Monitor 3: Injected CO_2= 94,286.38 tons

- Monitor 1 --> Monitor 2: Injected CO_2 = 43,526.89 tons
- Monitor 2-->Monitor 3: Injected CO_2 = 17,689.24 tons

VSP Wavefield Separation

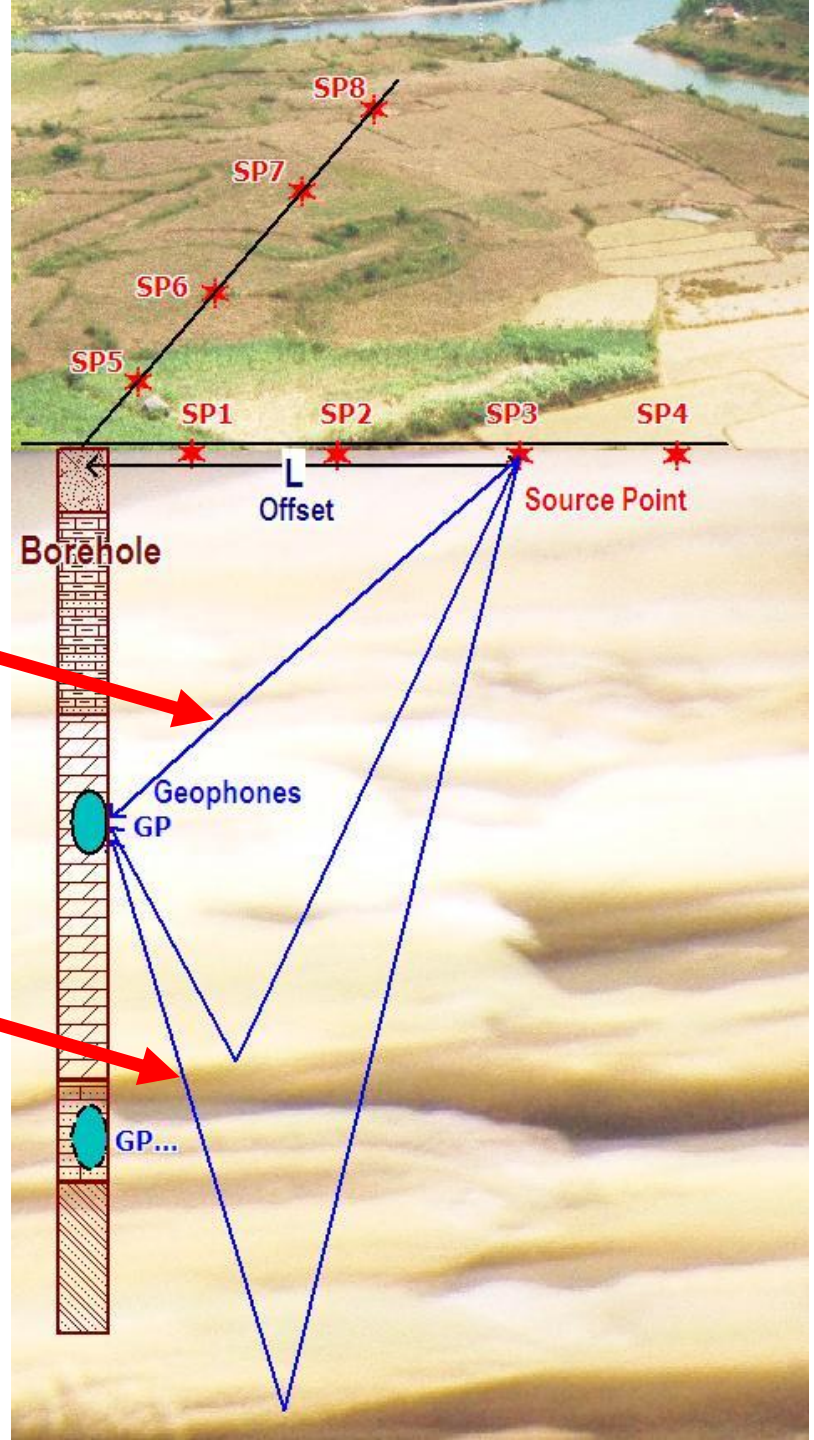
Vertical Seismic Profiling Survey:

Total (Full) Wavefield Contains

Downgoing Waves

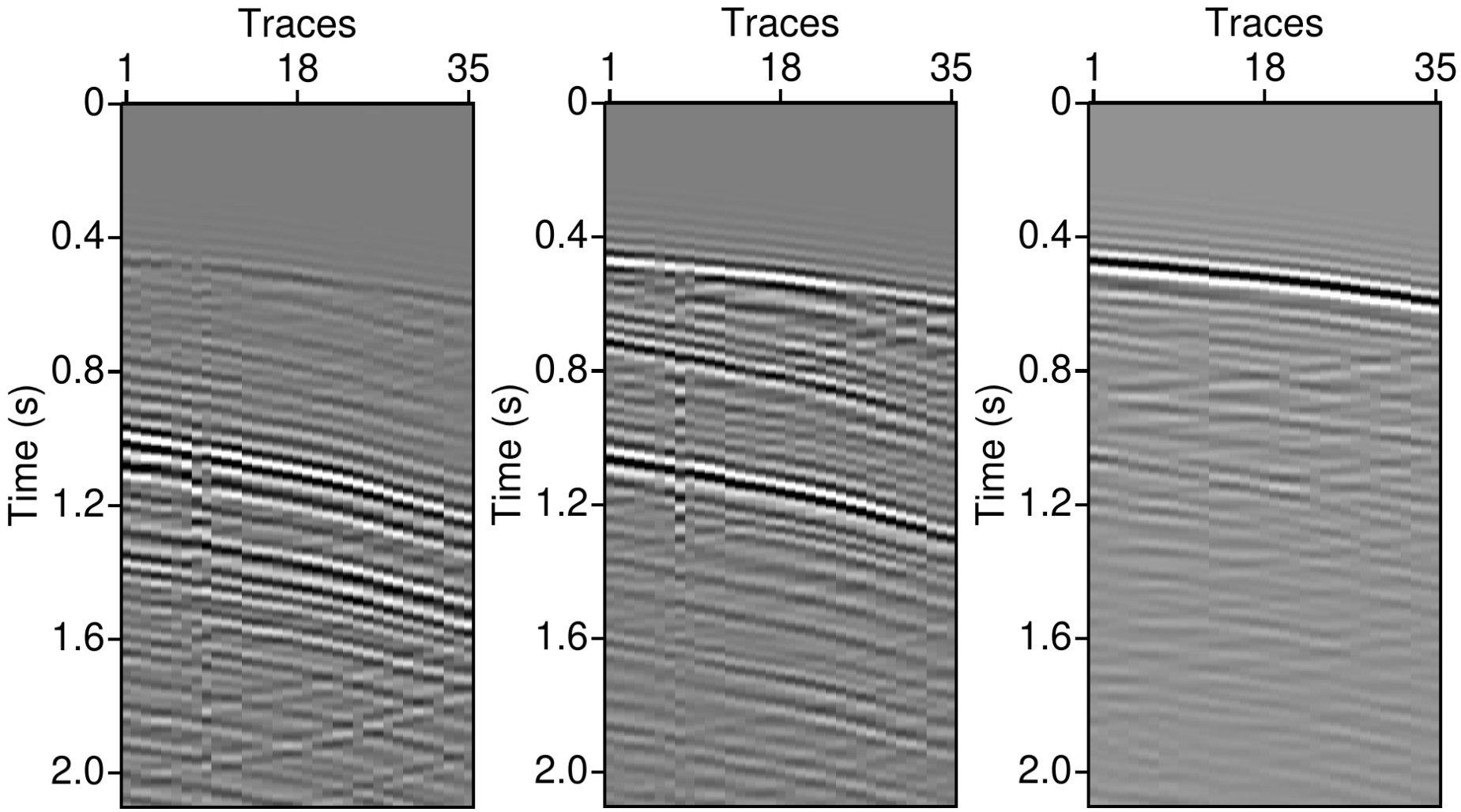
and

Upgoing Waves

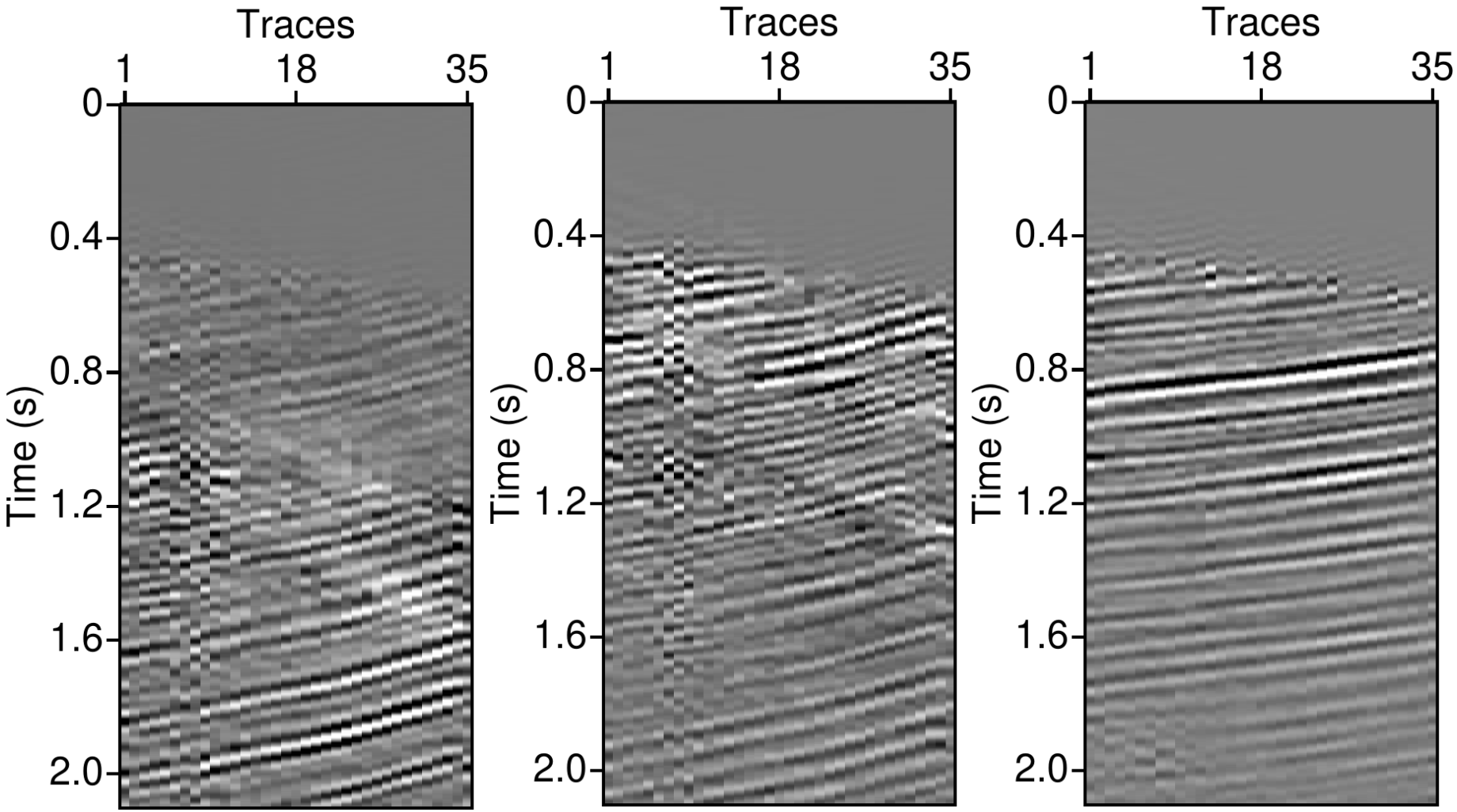


From:
https://en.wikipedia.org/wiki/Vertical_seismic_profile#/media/File:Vertical_Seismic_Profiling_Survey.jpg

X (East), Y (North) and Z (Vertical) Components of Baseline VSP Full Wavefield Data

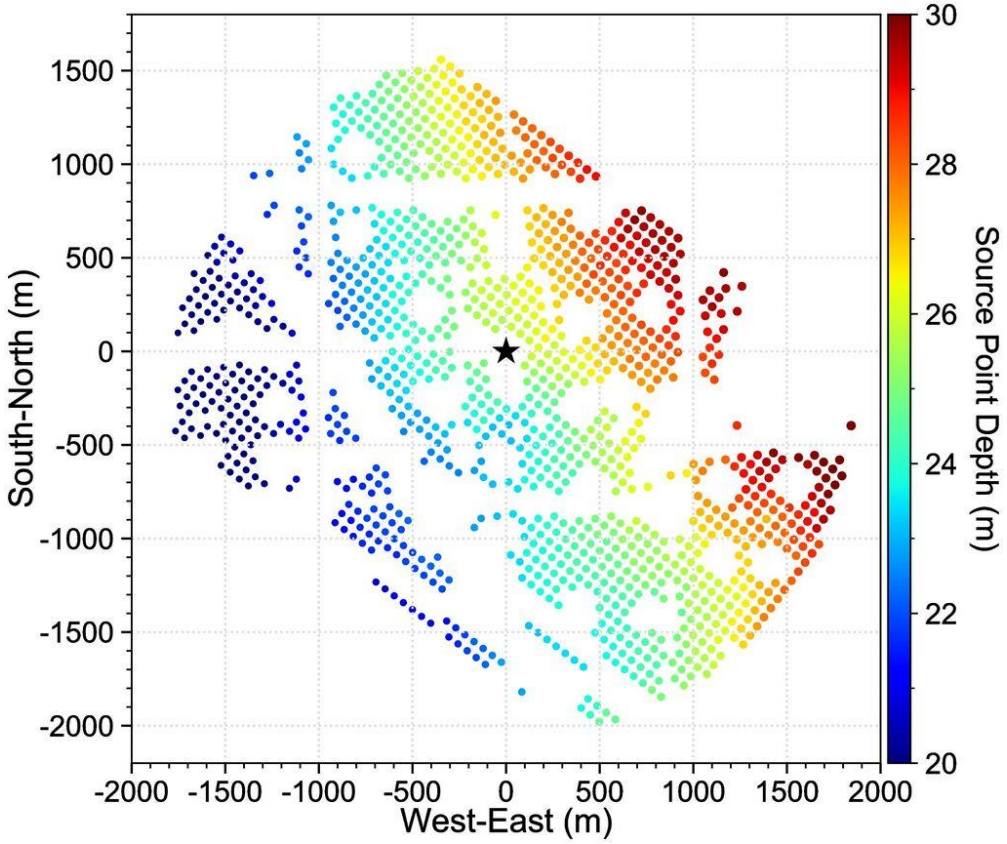


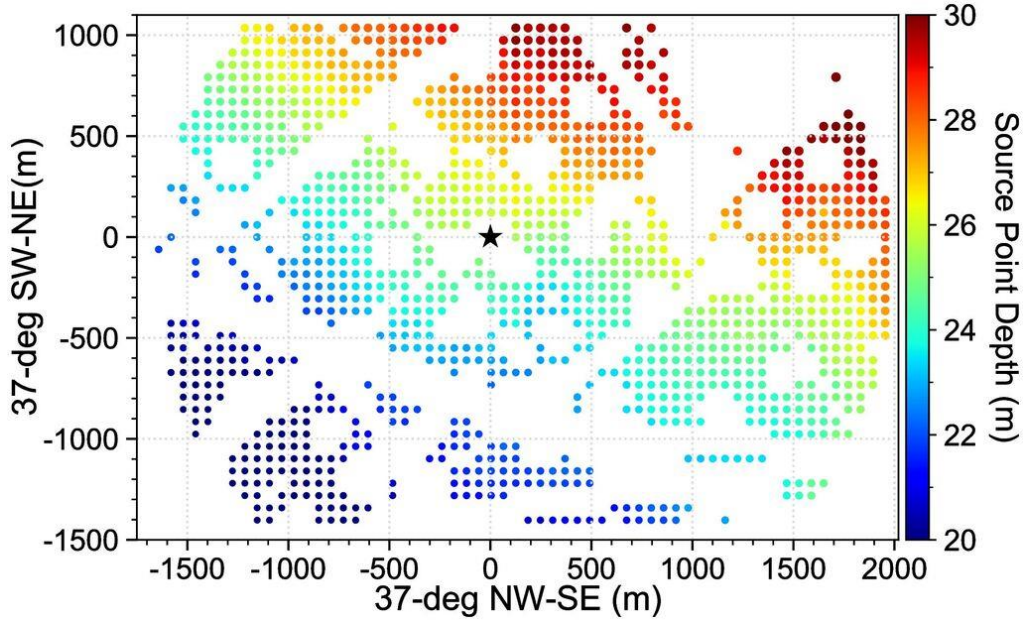
X (East), Y (North) and Z (Vertical) Components of Separated Upgoing VSP Wavefield Data



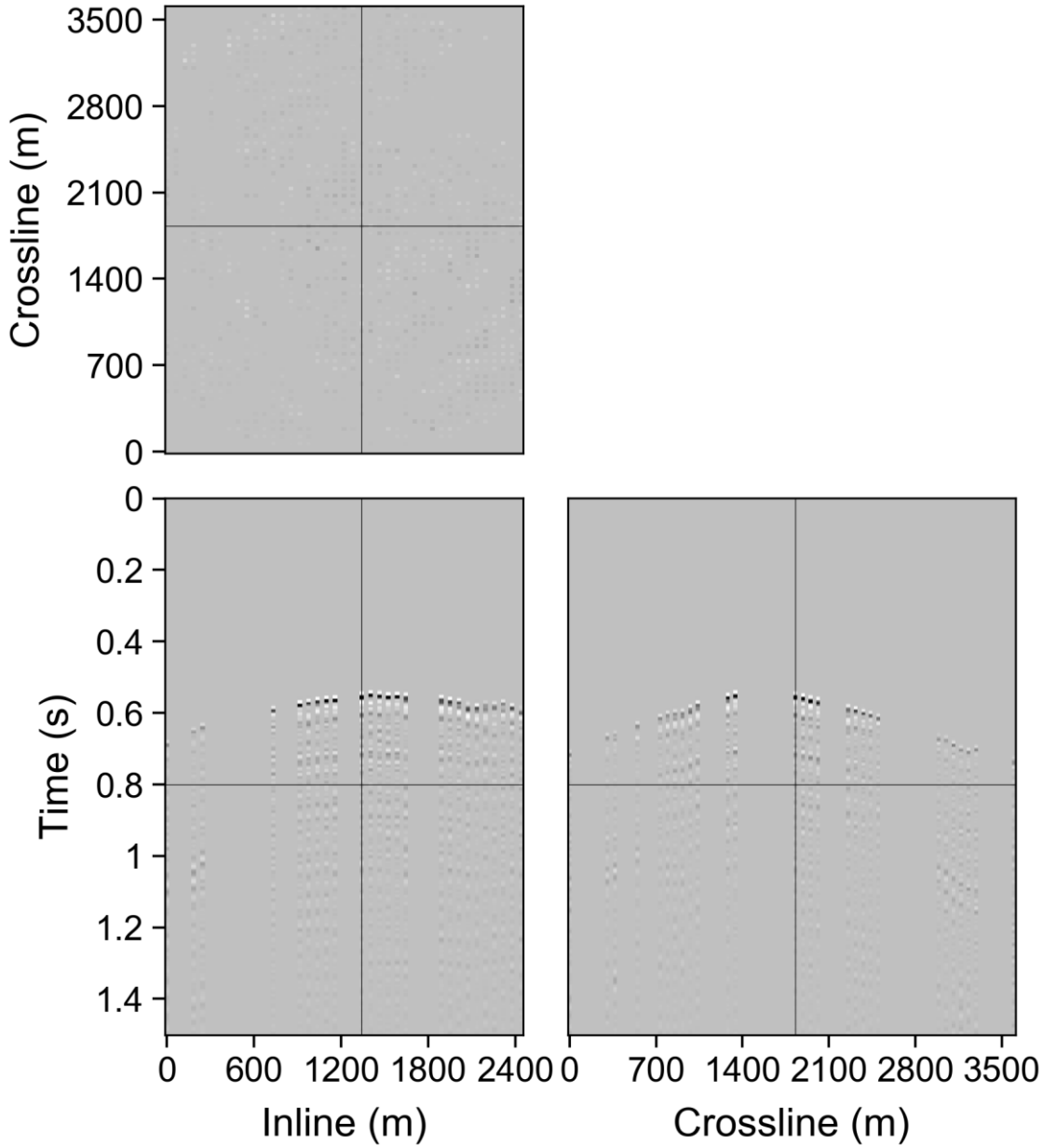
VSP Data Interpolation to Fill Acquisition Gaps

3D VSP Data Acquisition Gaps

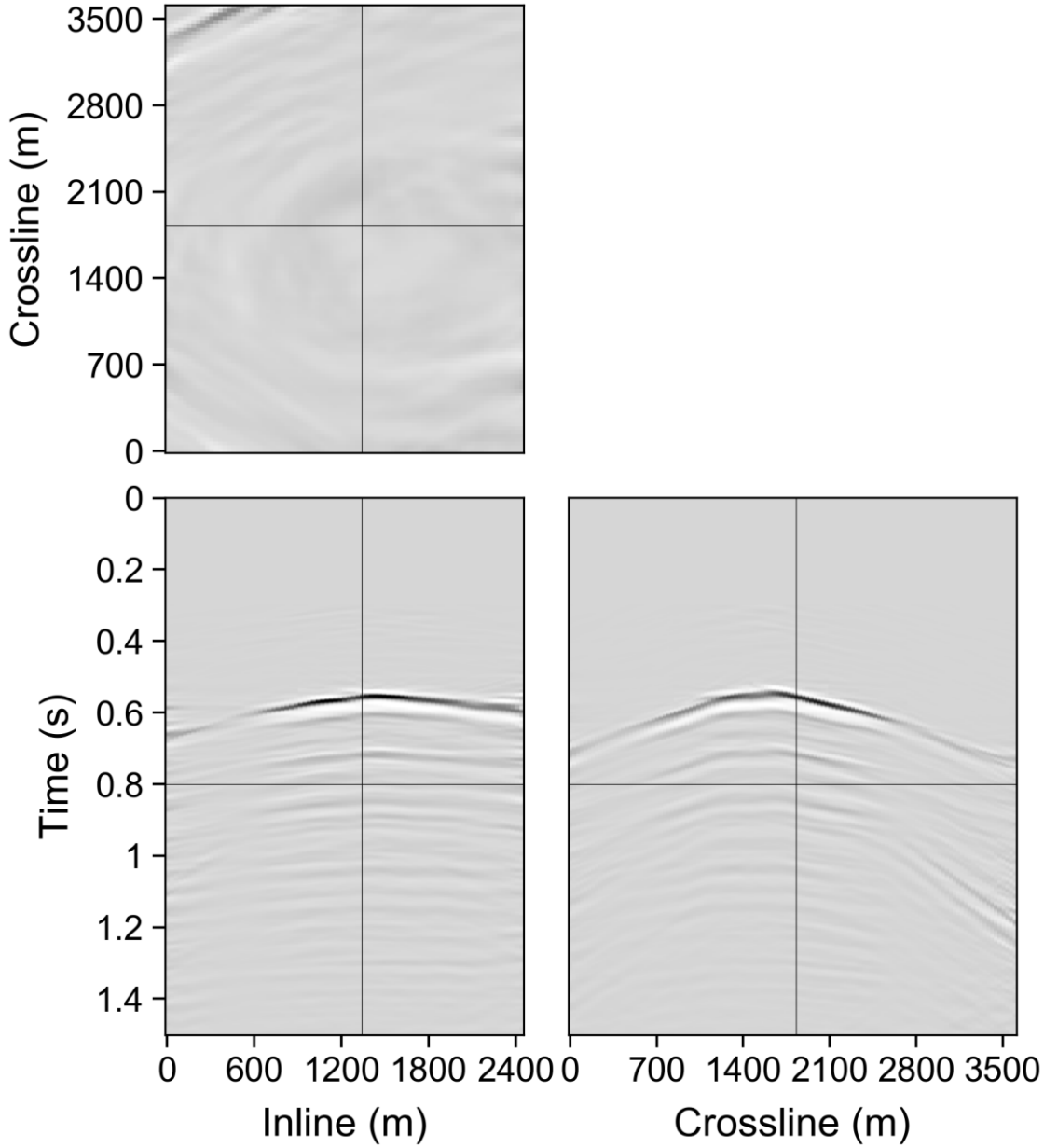




VSP Wavefield with Data Acquisition Gaps

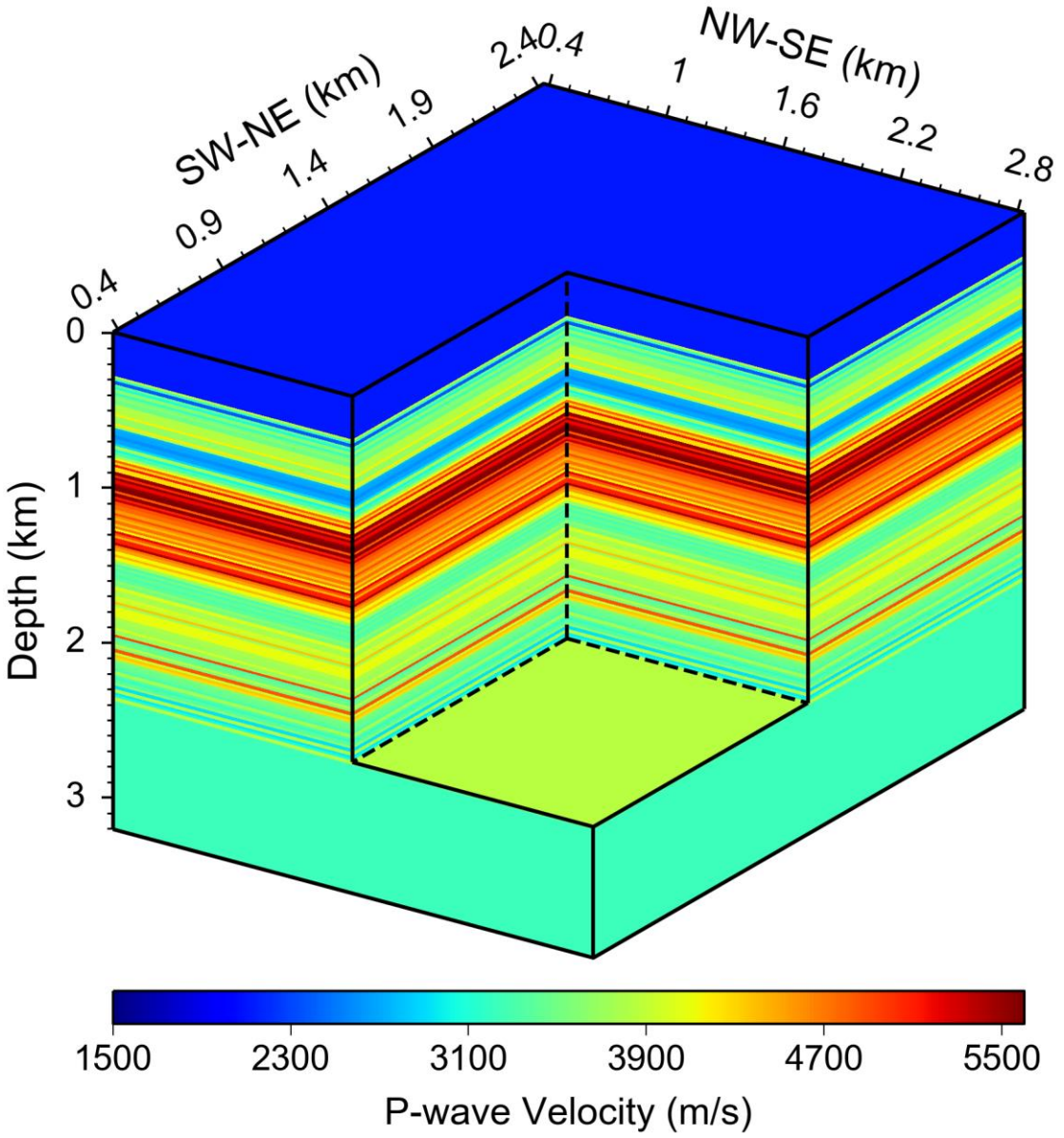


VSP Wavefield after Data Interpolation

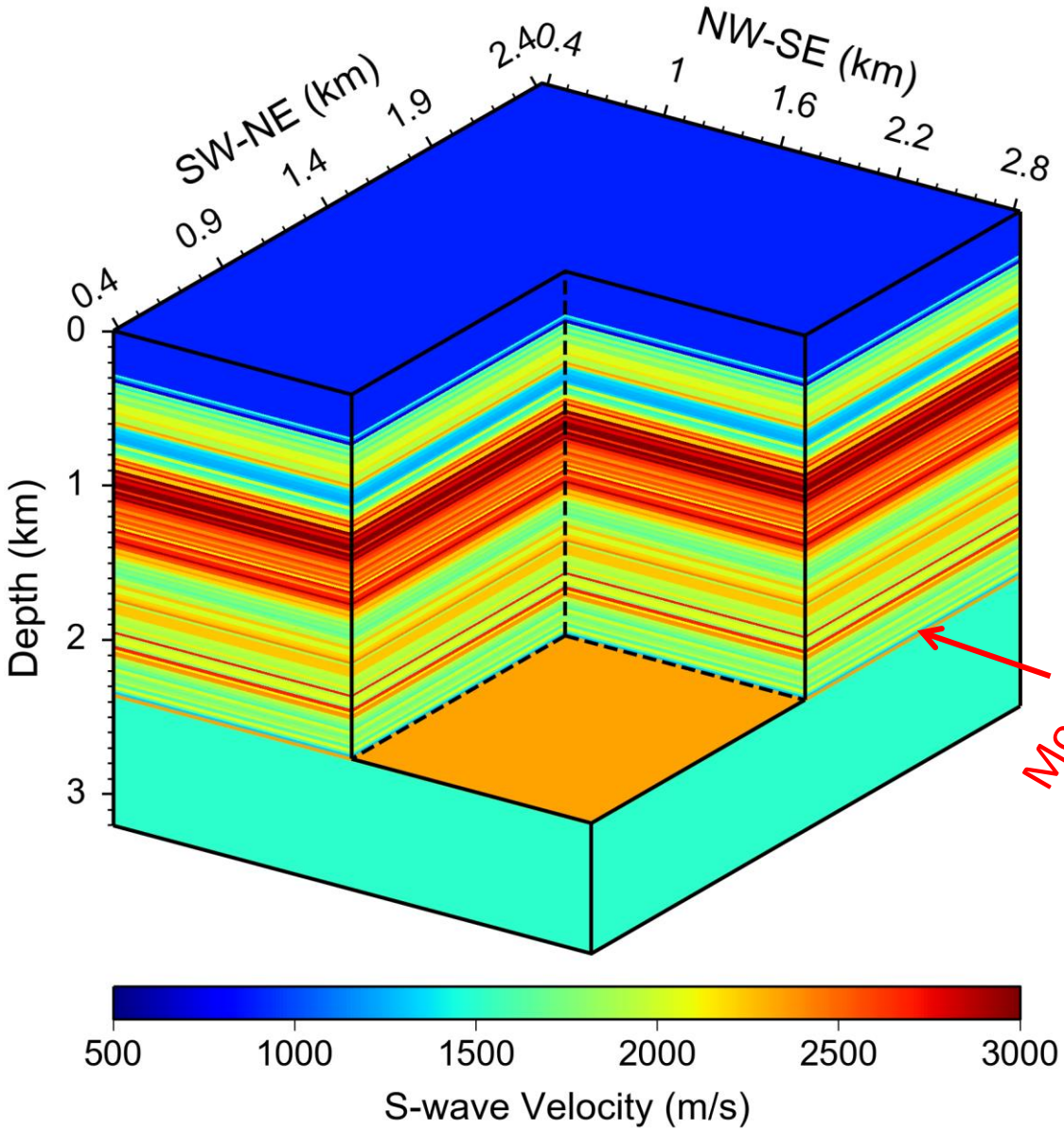


Build Initial Elastic Velocity Models

Initial velocity models from the Schoenberg-Muir Upscaling of Sonic Log Data

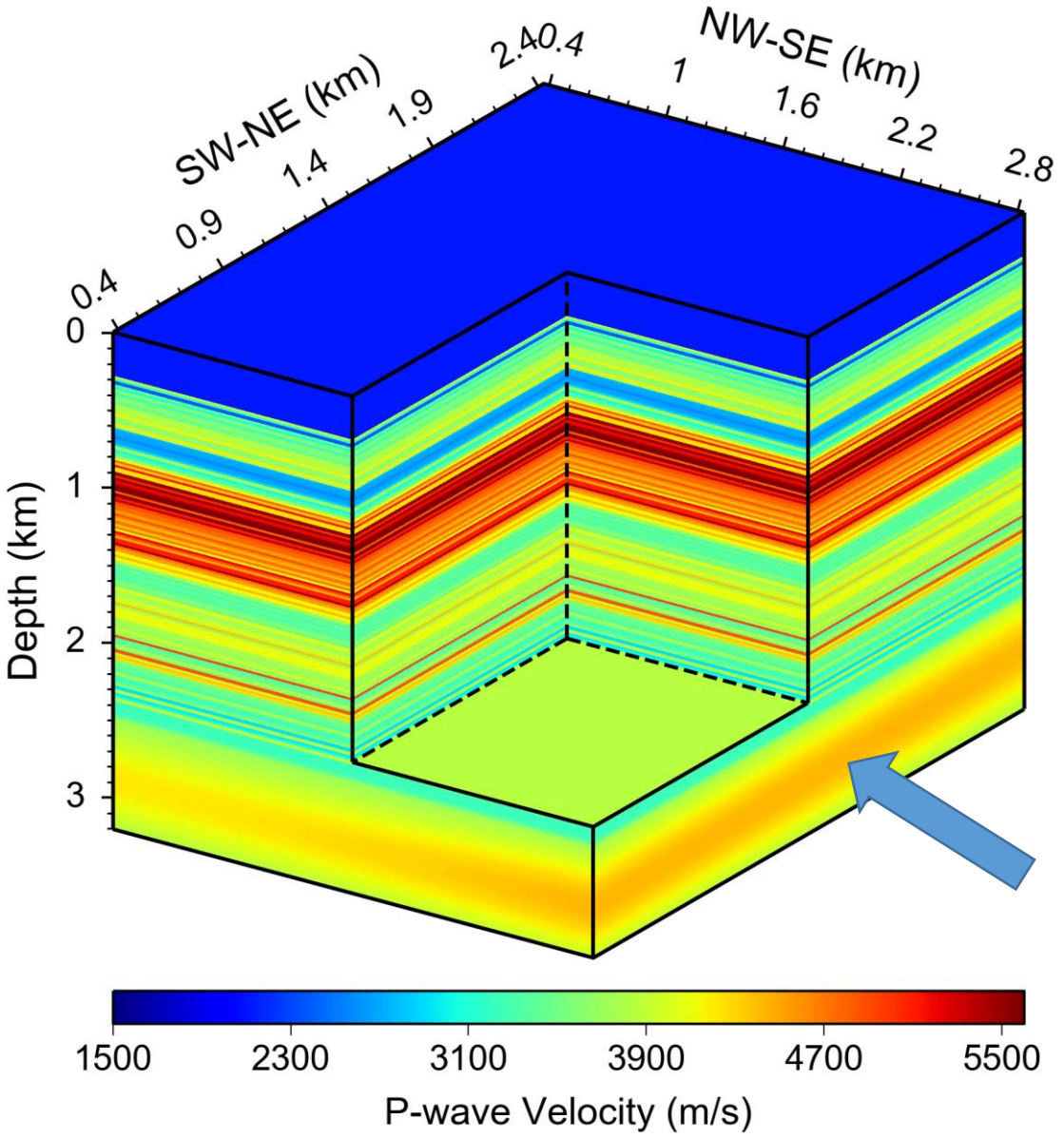


Vp

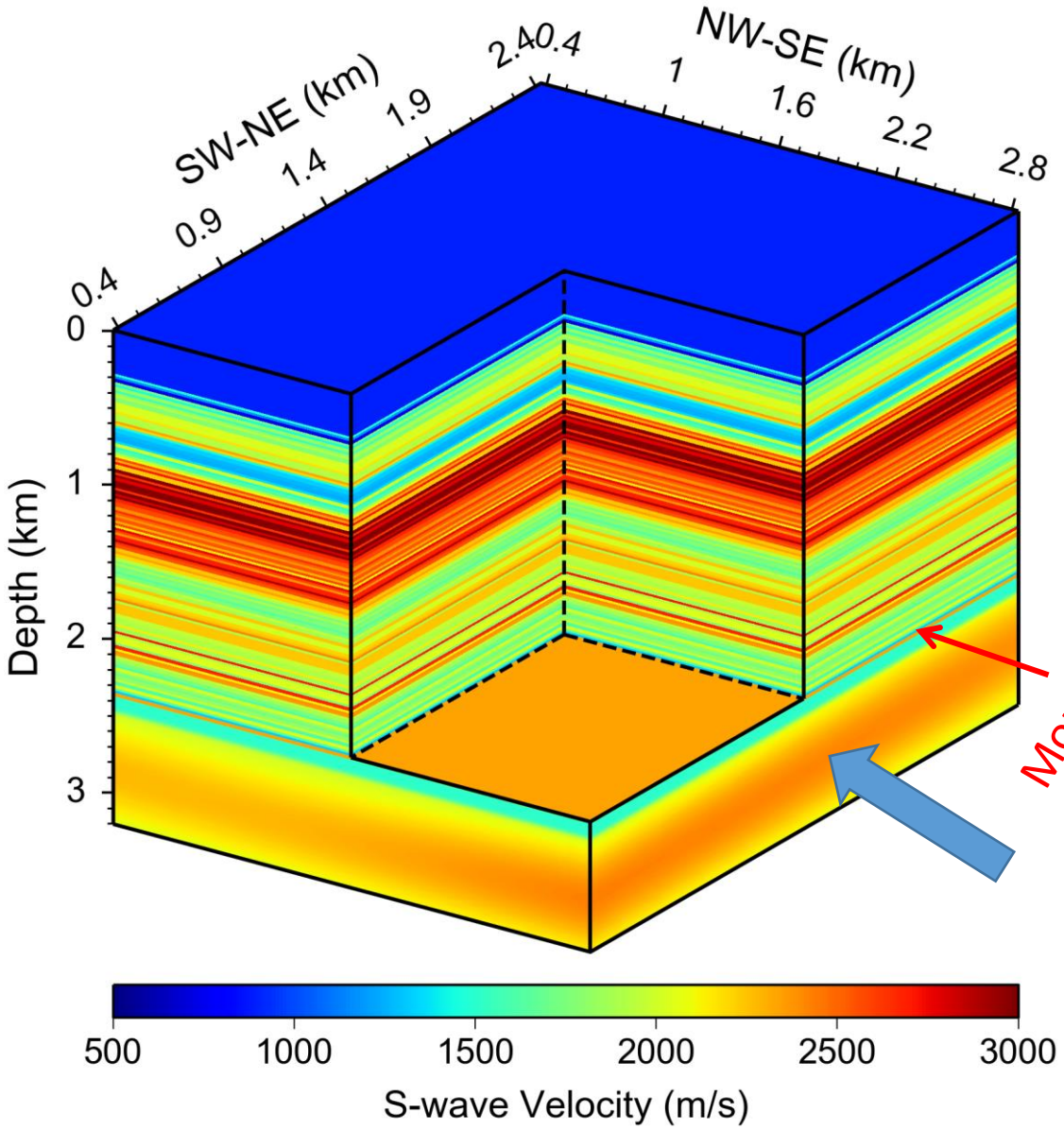


Vs

Combine the Deep-Region Velocity Model from the 3D Surface Seismic Velocity Model



Vp



Vs

First-Arrival Traveltime Tomography of VSP Downgoing Waves

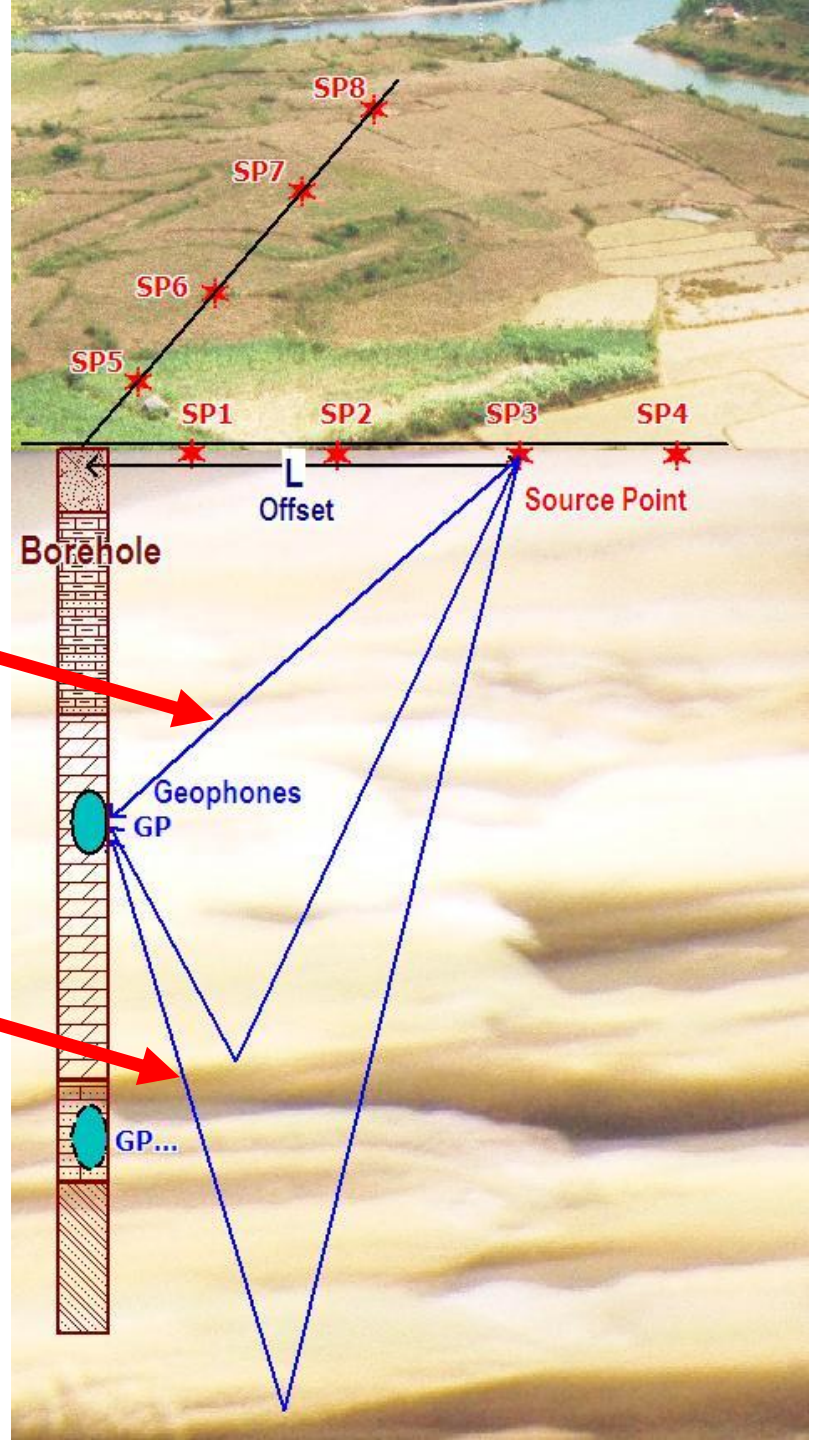
Vertical Seismic Profiling Survey:

Total (Full) Wavefield Contain

Downgoing Waves

and

Upgoing Waves



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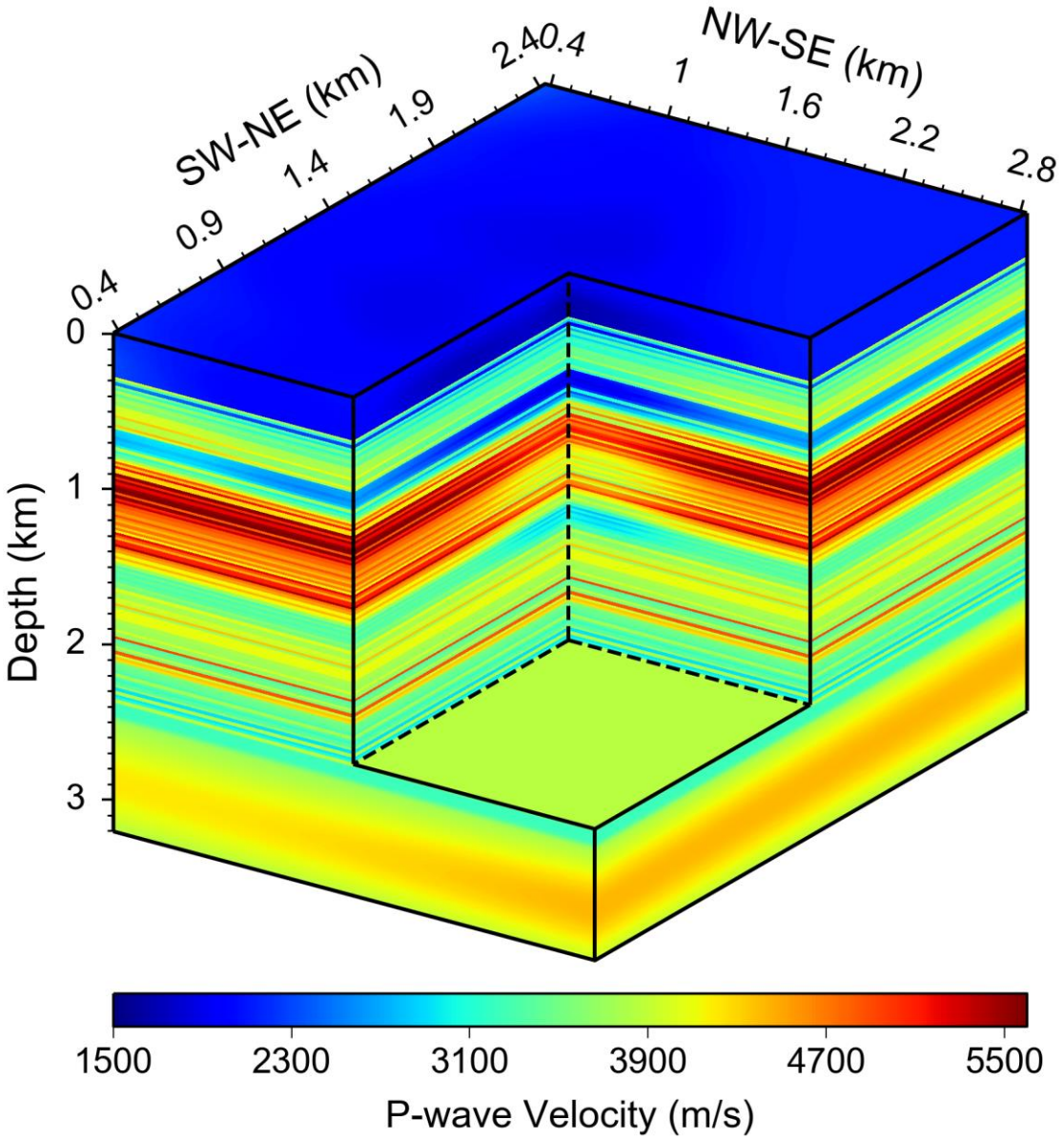
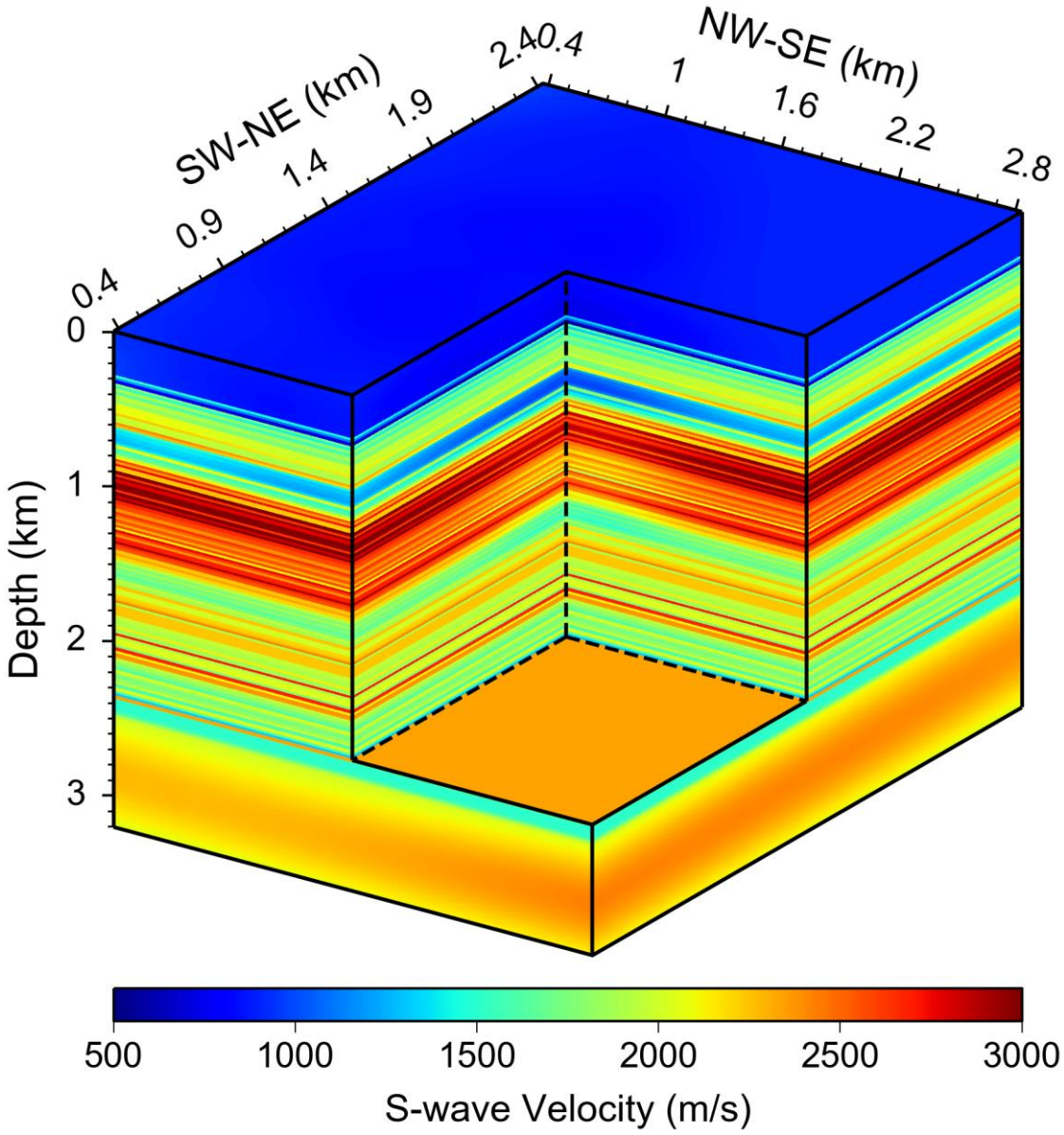
First-Arrival Traveltime Tomography of Downgoing Waves: Baseline VSP Data

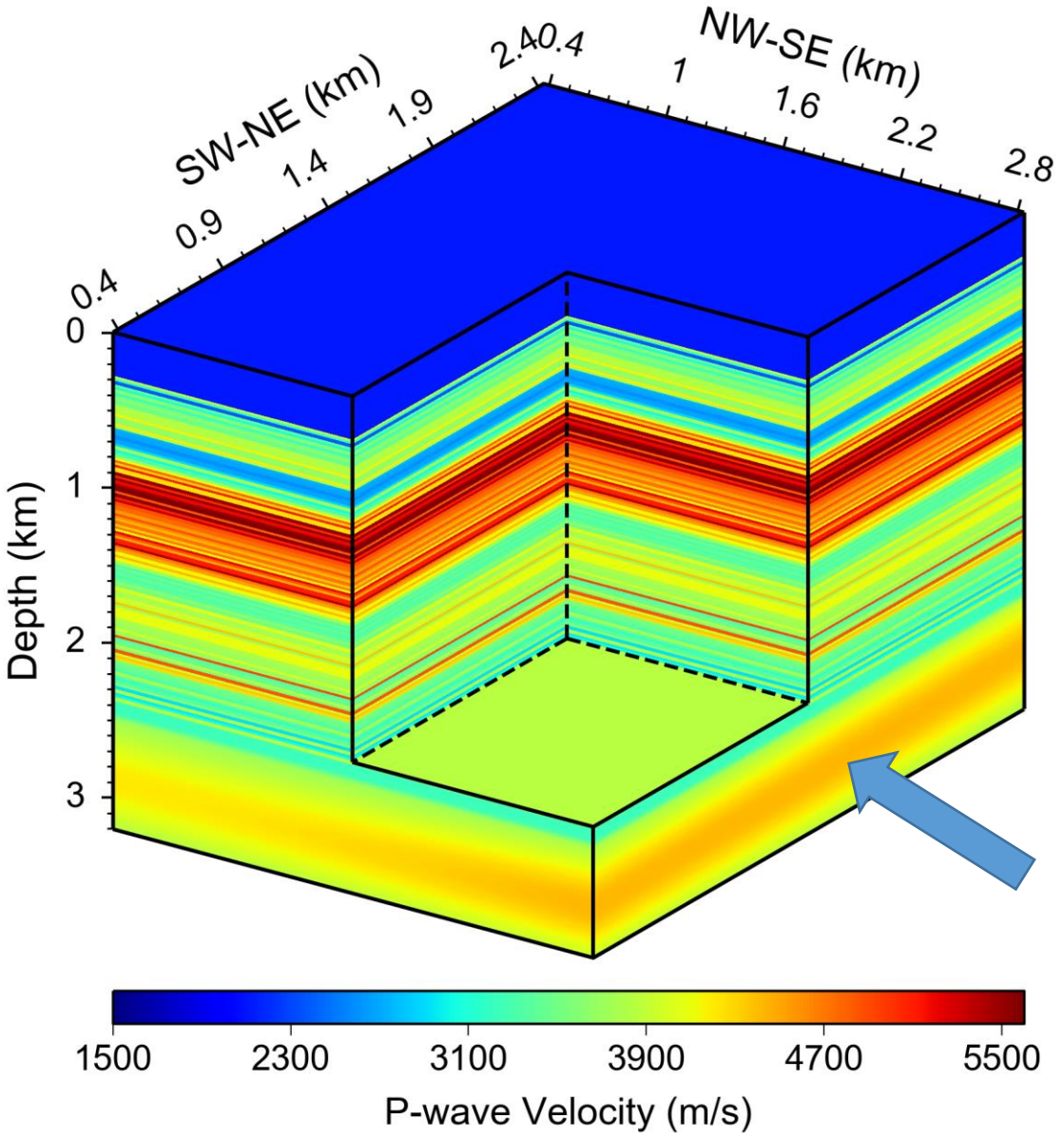


Vp



Vs

Combine the Deep-Region Velocity Model from the 3D Surface Seismic Velocity Model



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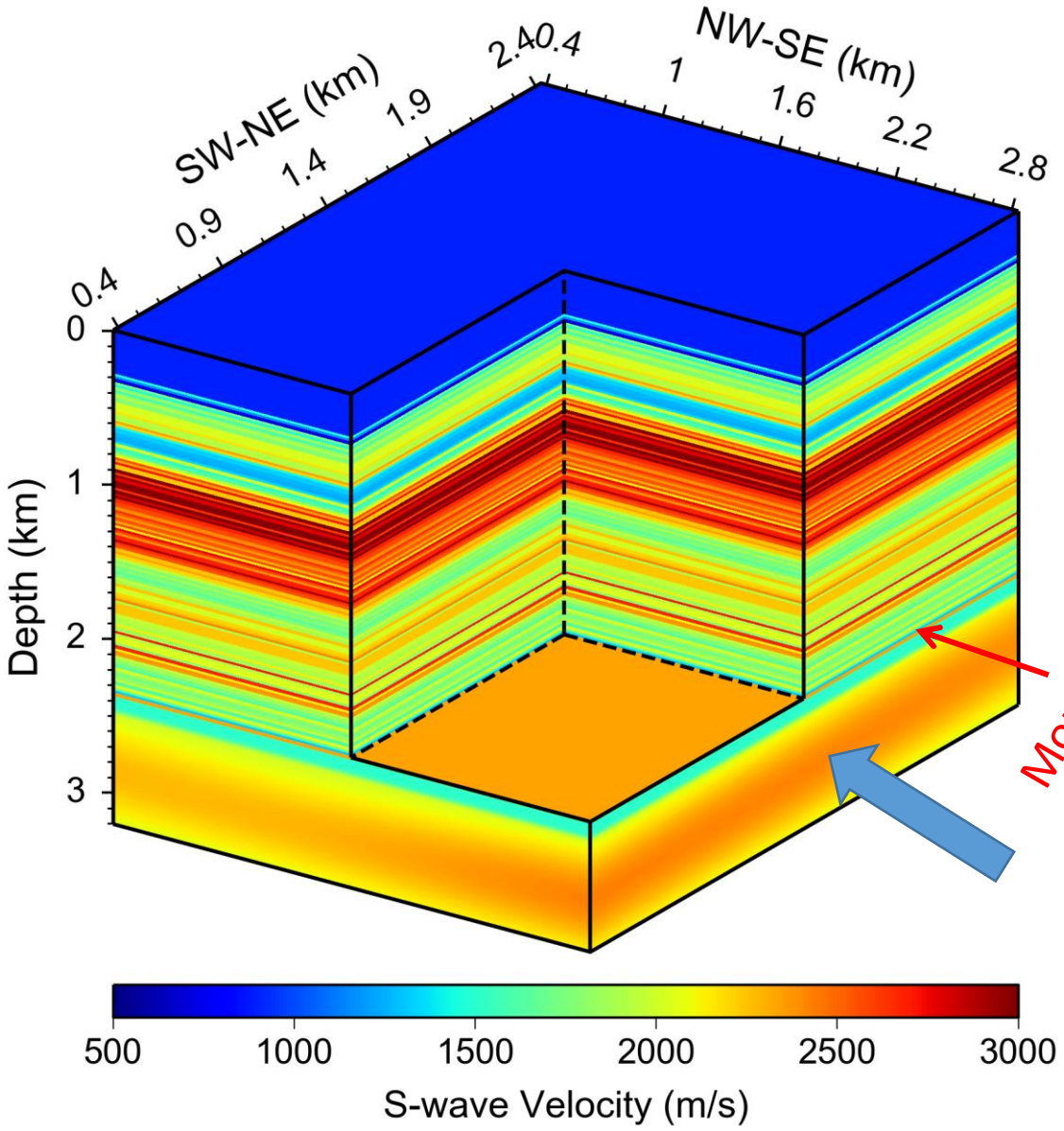
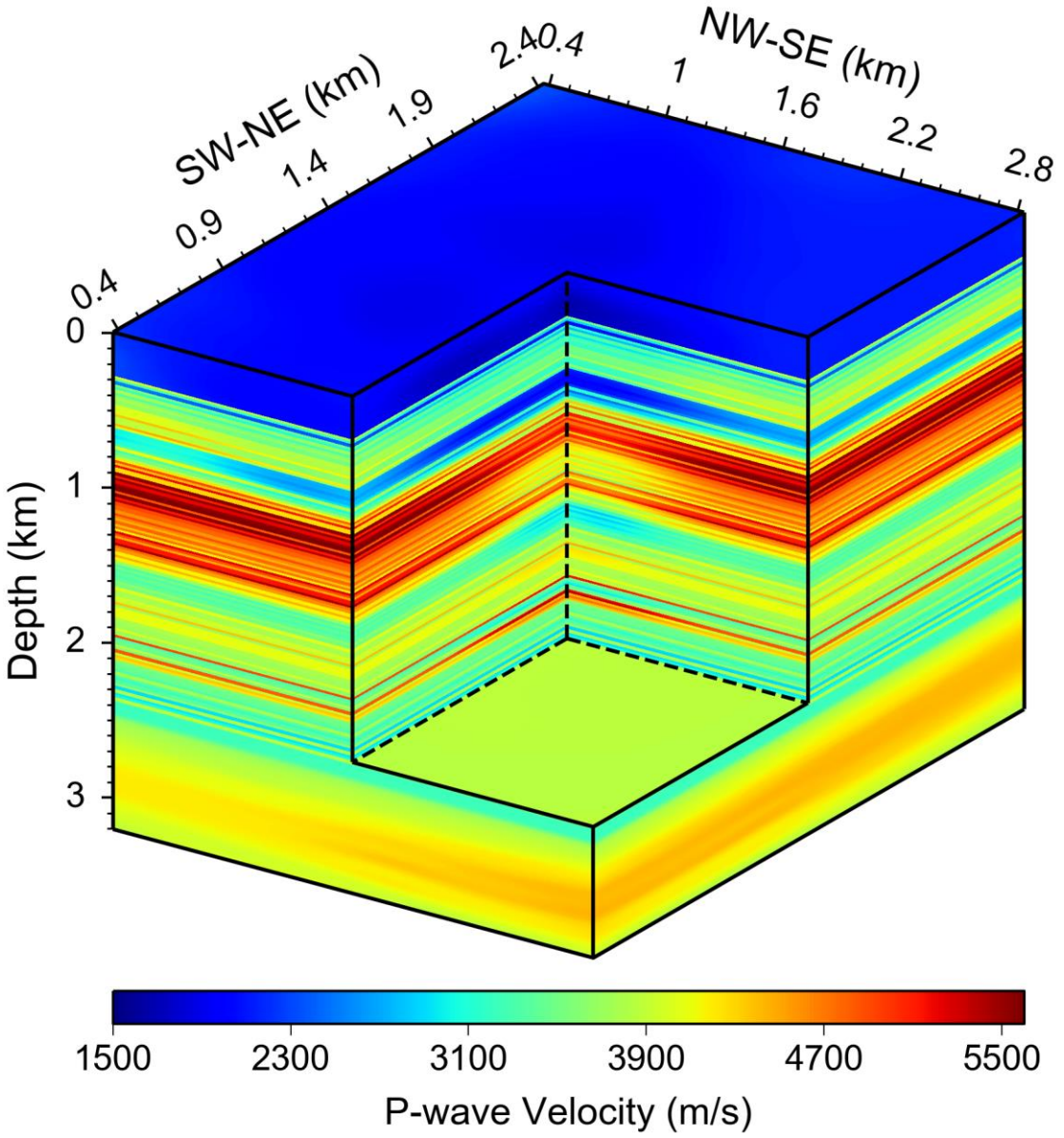


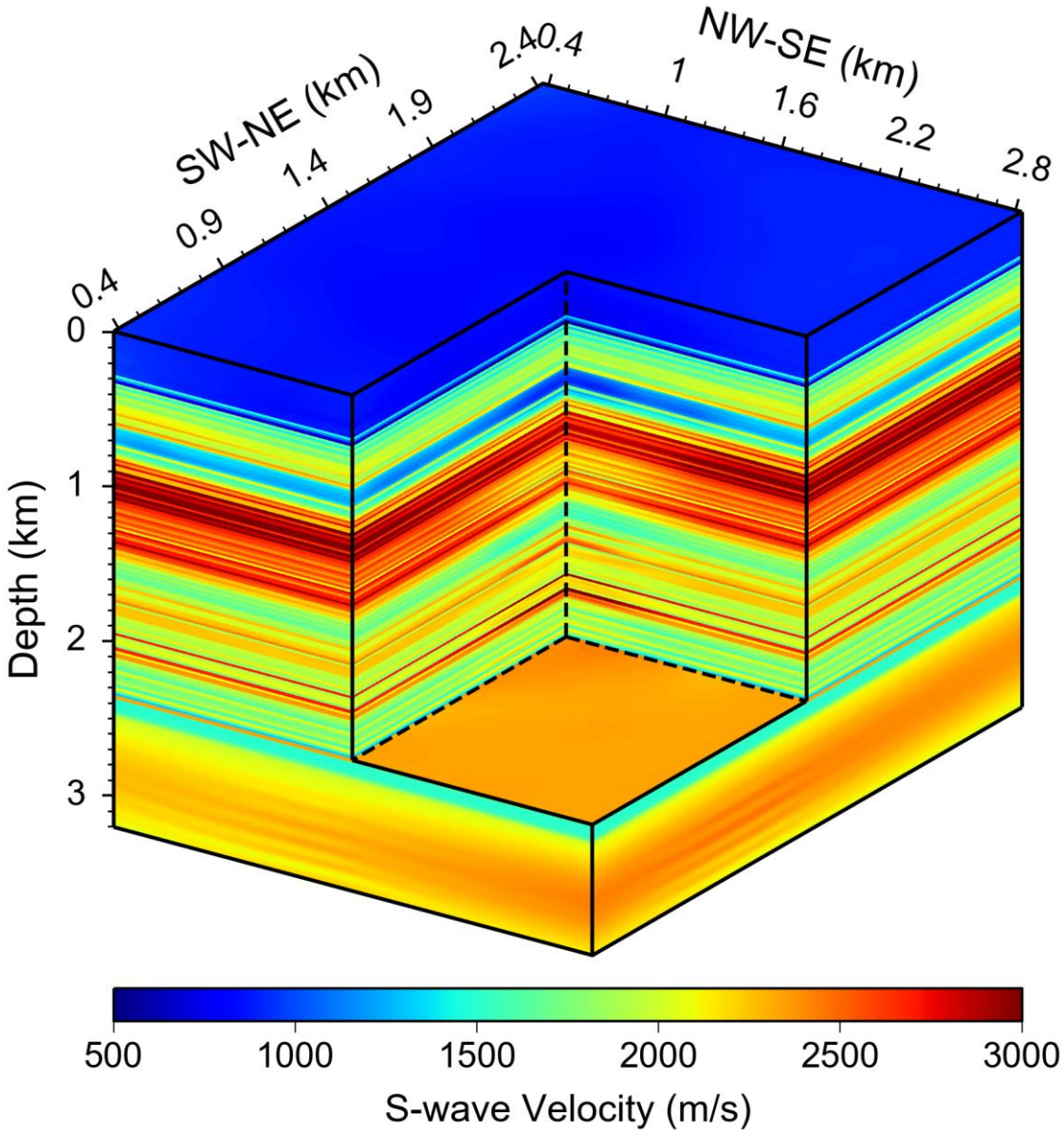
Vs

Elastic-Waveform Inversion of VSP Upgoing Waves

Elastic-Waveform Inversion of Upgoing Waves: Baseline VSP Data

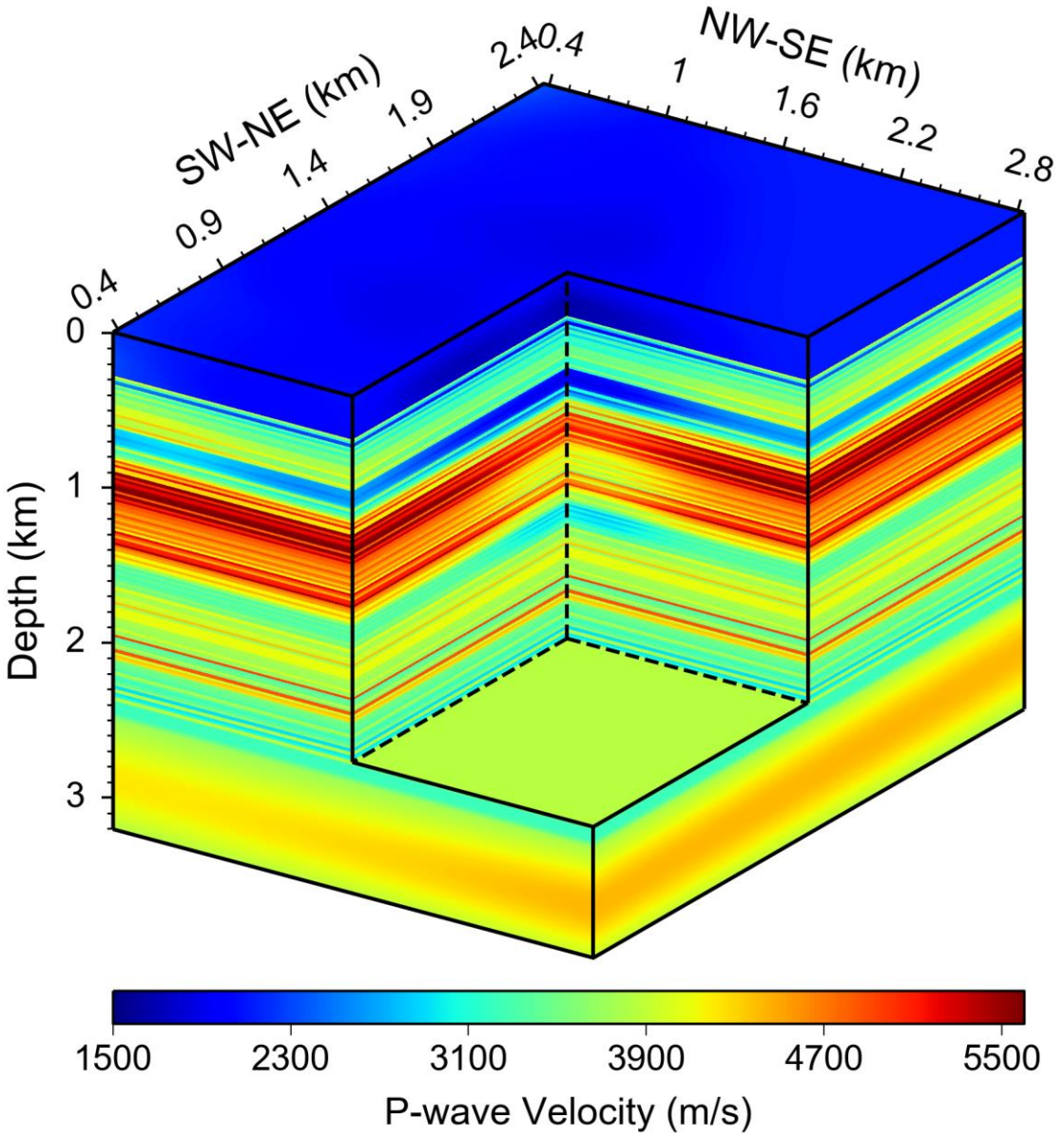


Vp

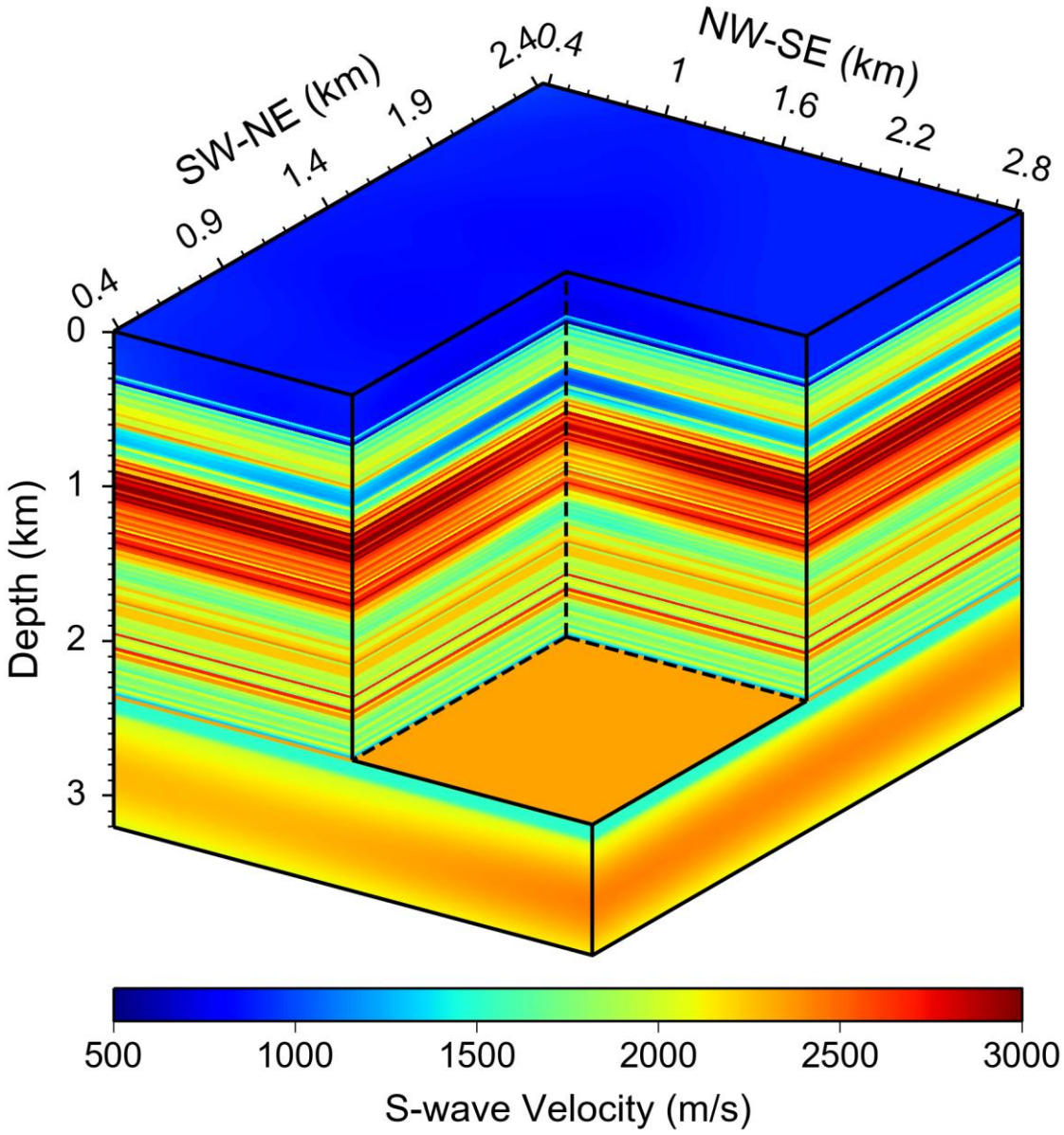


Vs

First-Arrival Traveltime Tomography of Downgoing Waves: Baseline VSP Data

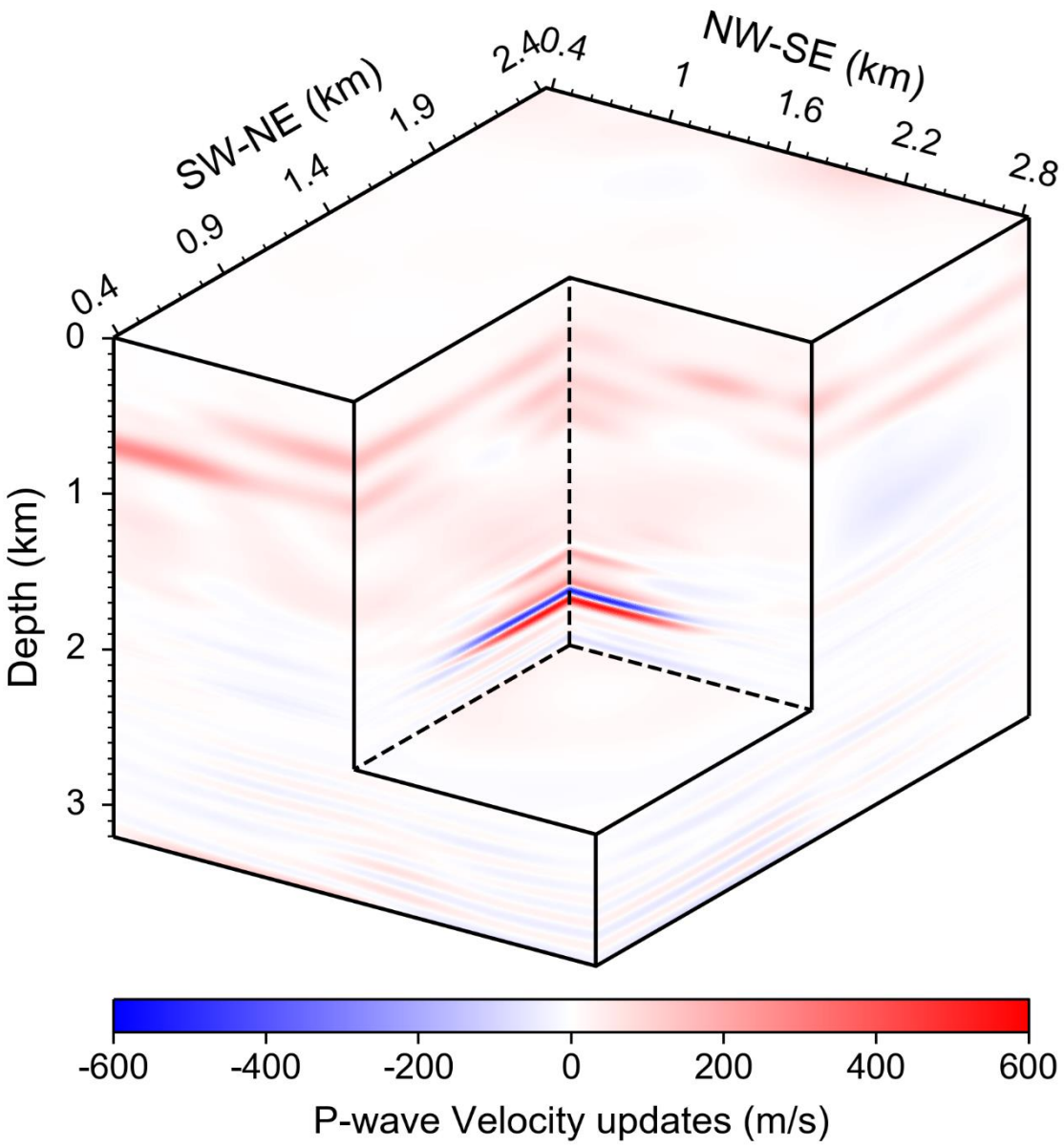


Vp

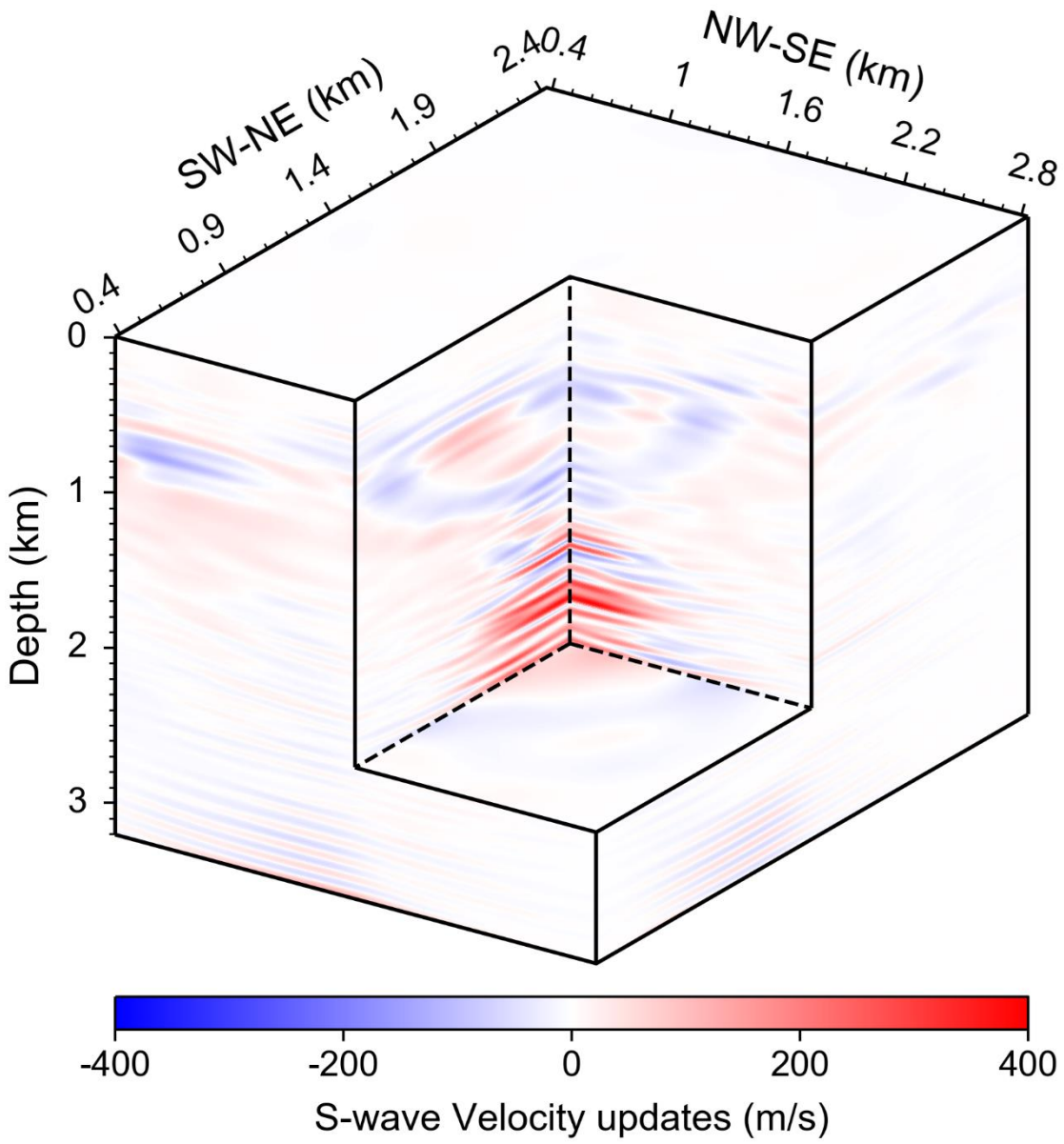


Vs

Velocity Updates of Elastic-Waveform Inversion

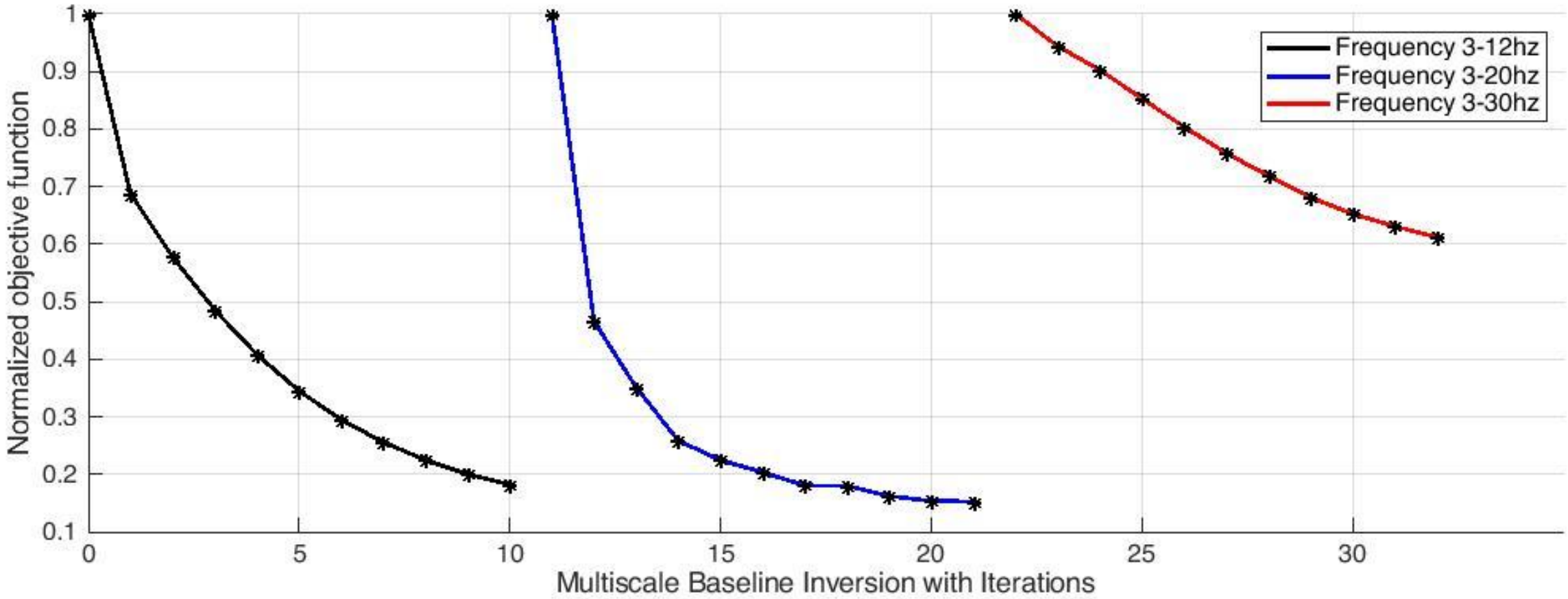


Vp



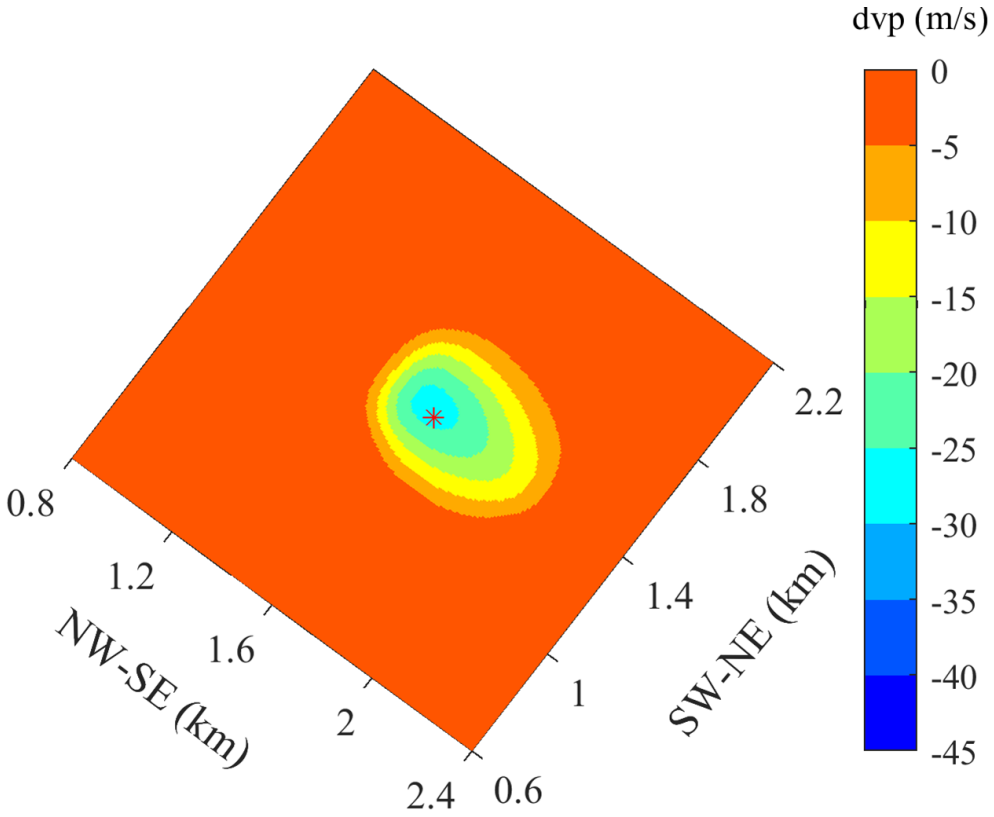
Vs

Convergence Curves of Multiscale Elastic-Waveform Inversion

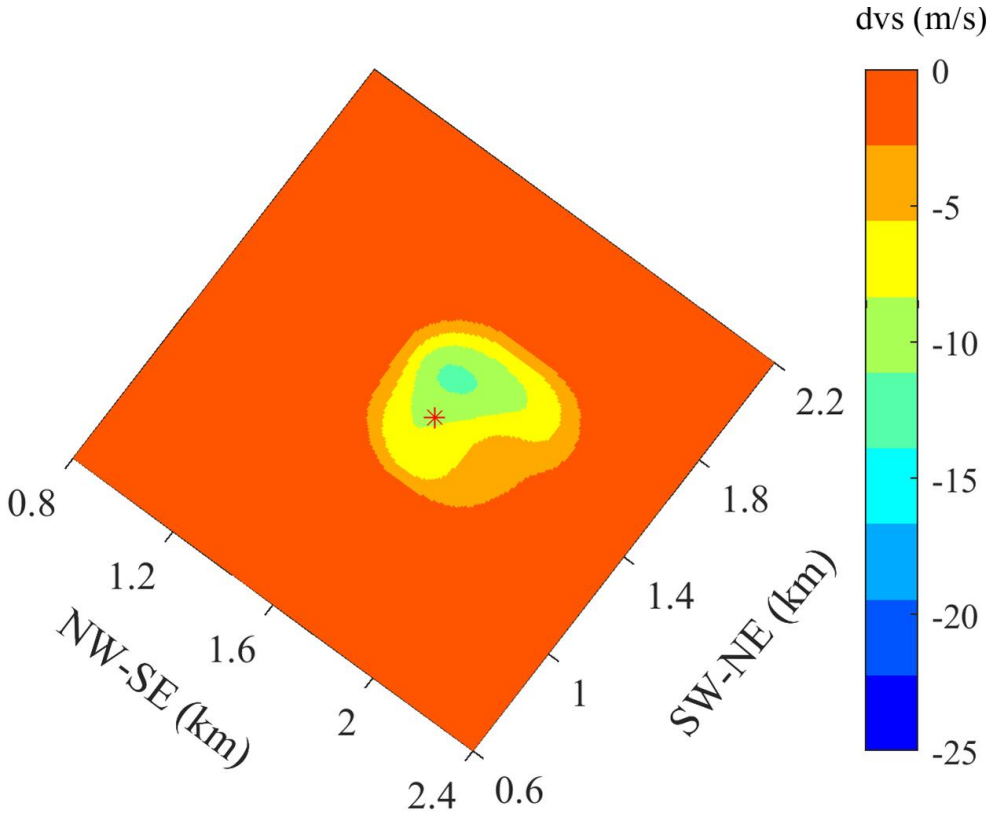


Elastic-Waveform Inversion of Time-Lapse VSP Data to Obtain Spatiotemporal Velocity Changes During CO_2 Injection/Migration

Inverted Time-Lapse Velocity Changes between Baseline and Monitor1 VSP Survey

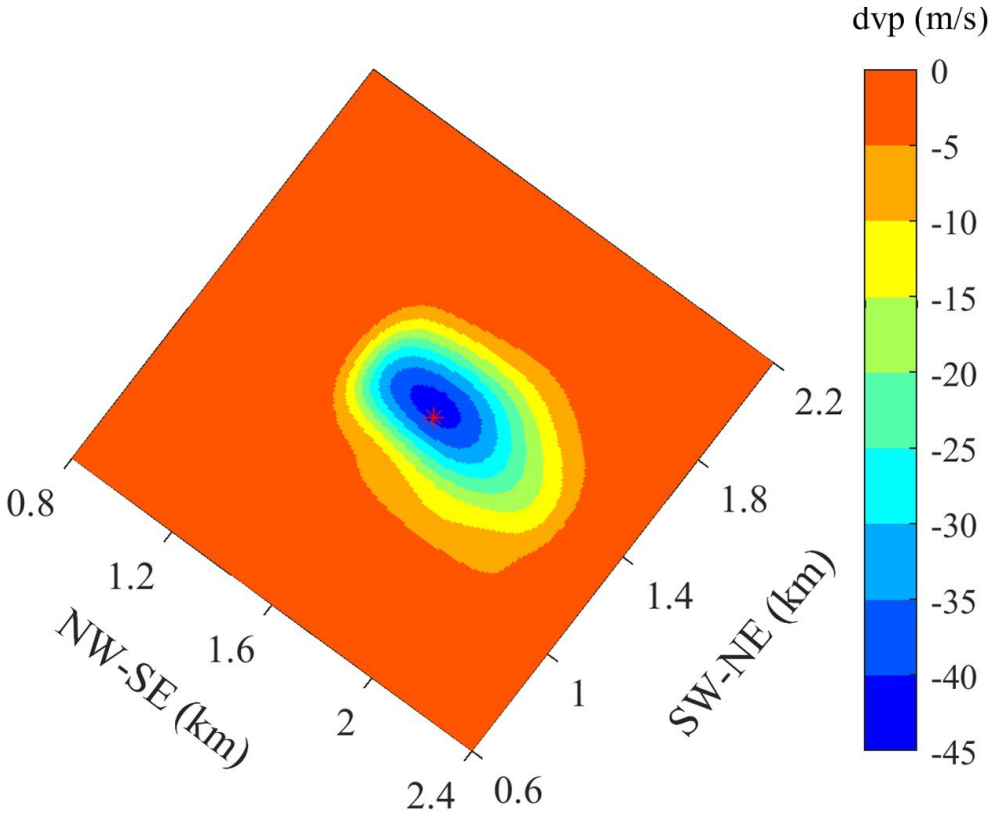


ΔVp

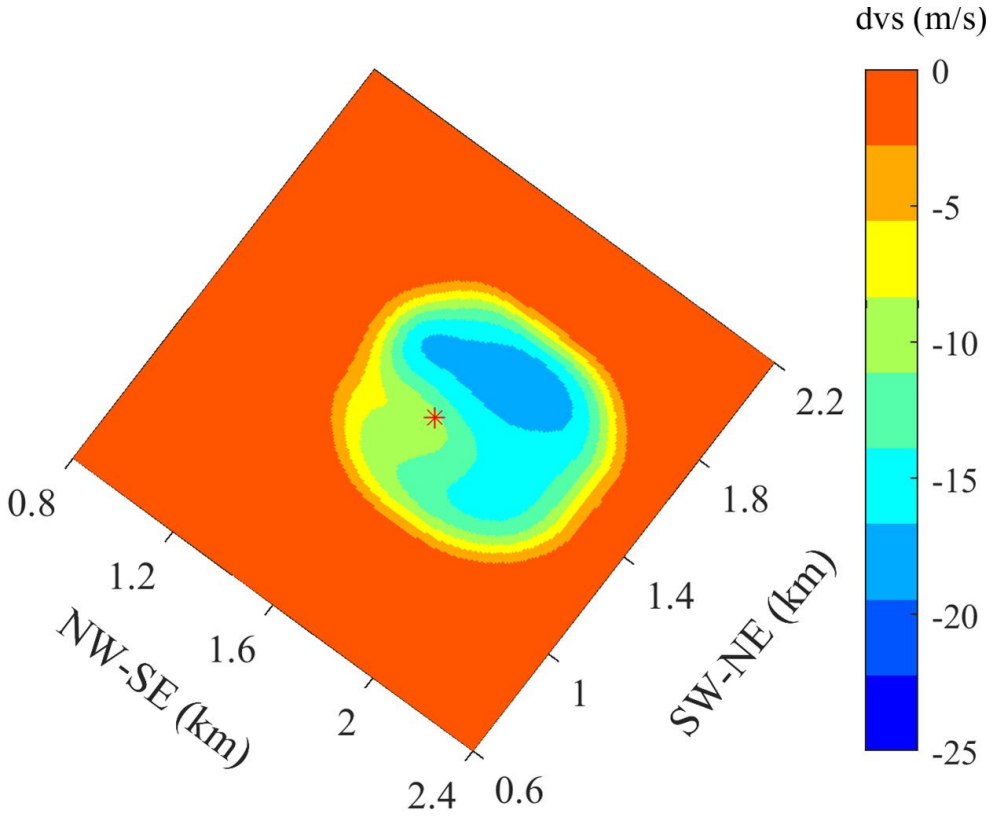


ΔVs

Inverted Time-Lapse Velocity Changes between Baseline and Monitor2 VSP Survey

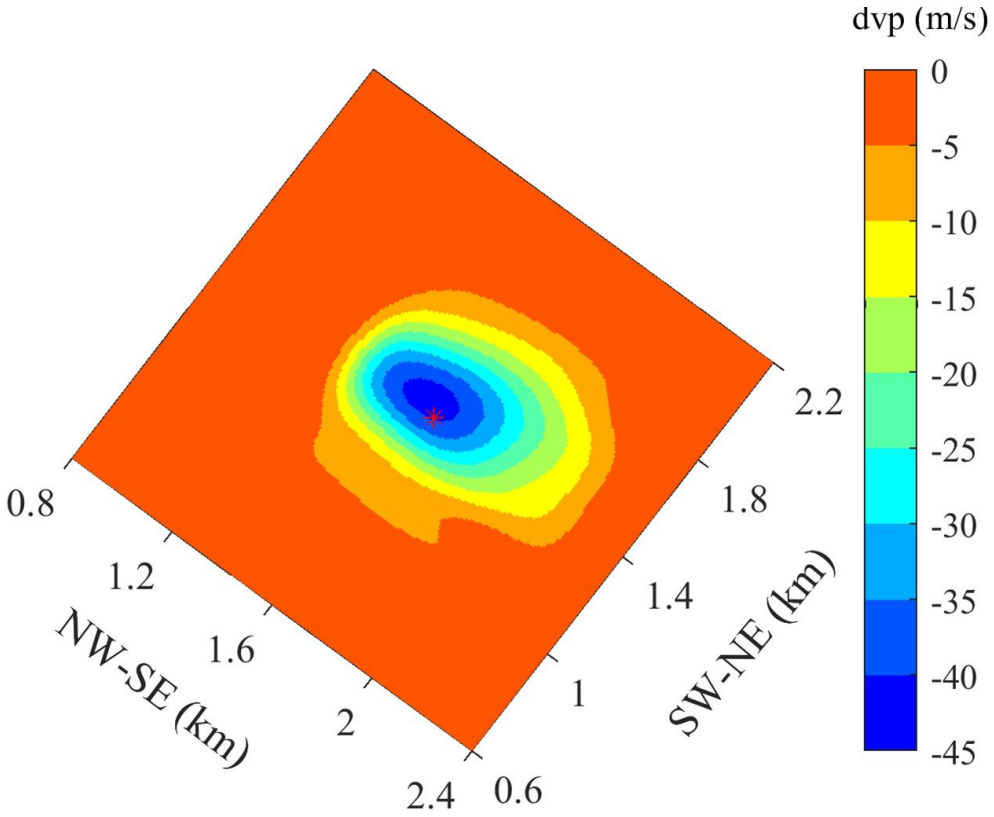


ΔVp

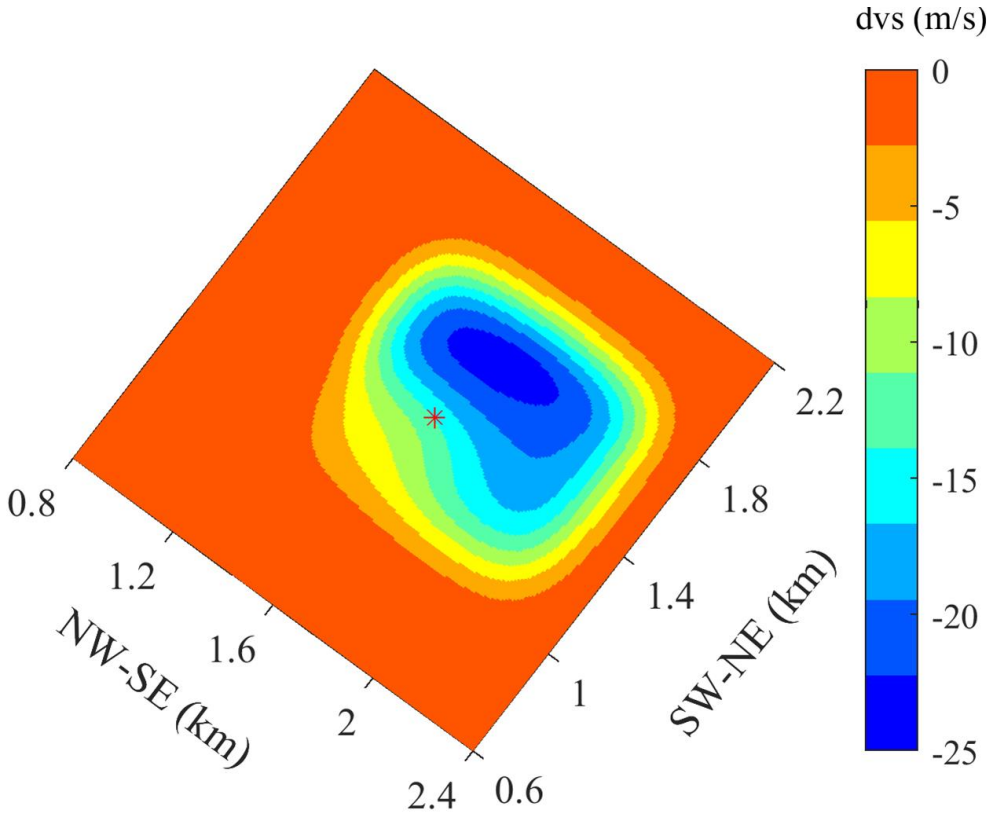


ΔVs

Inverted Time-Lapse Velocity Changes between Baseline and Monitor3 VSP Survey

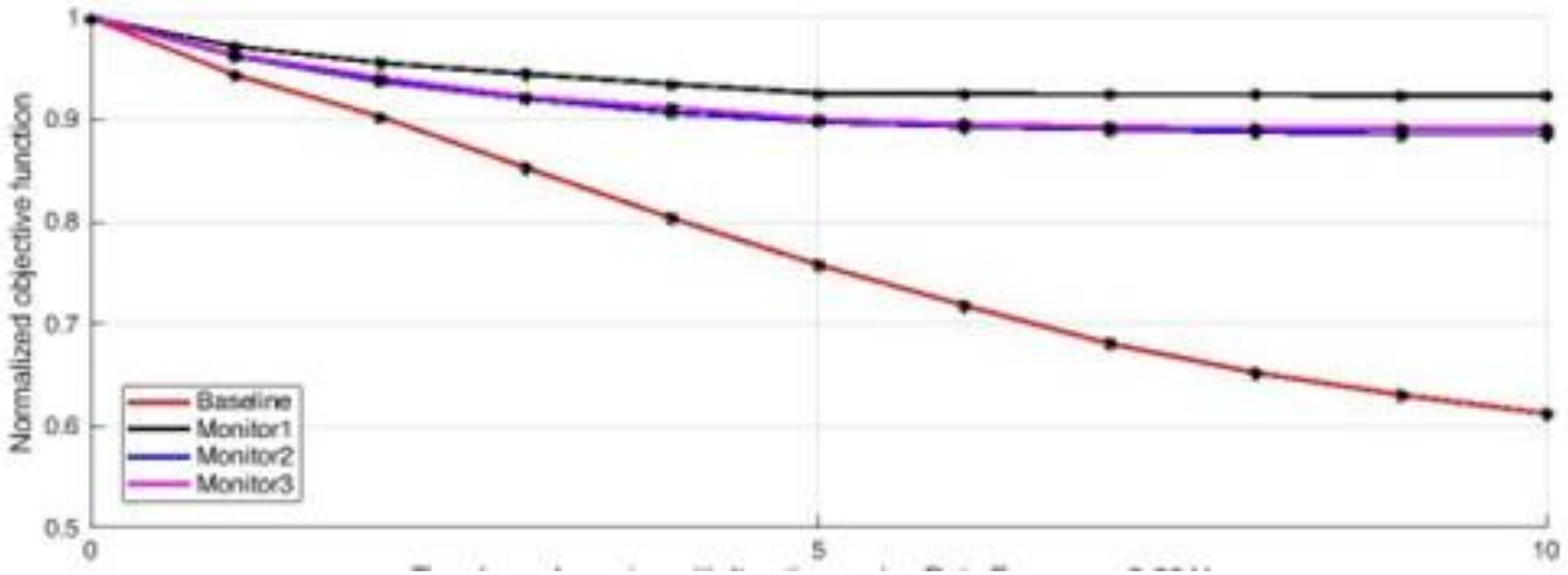


ΔVp

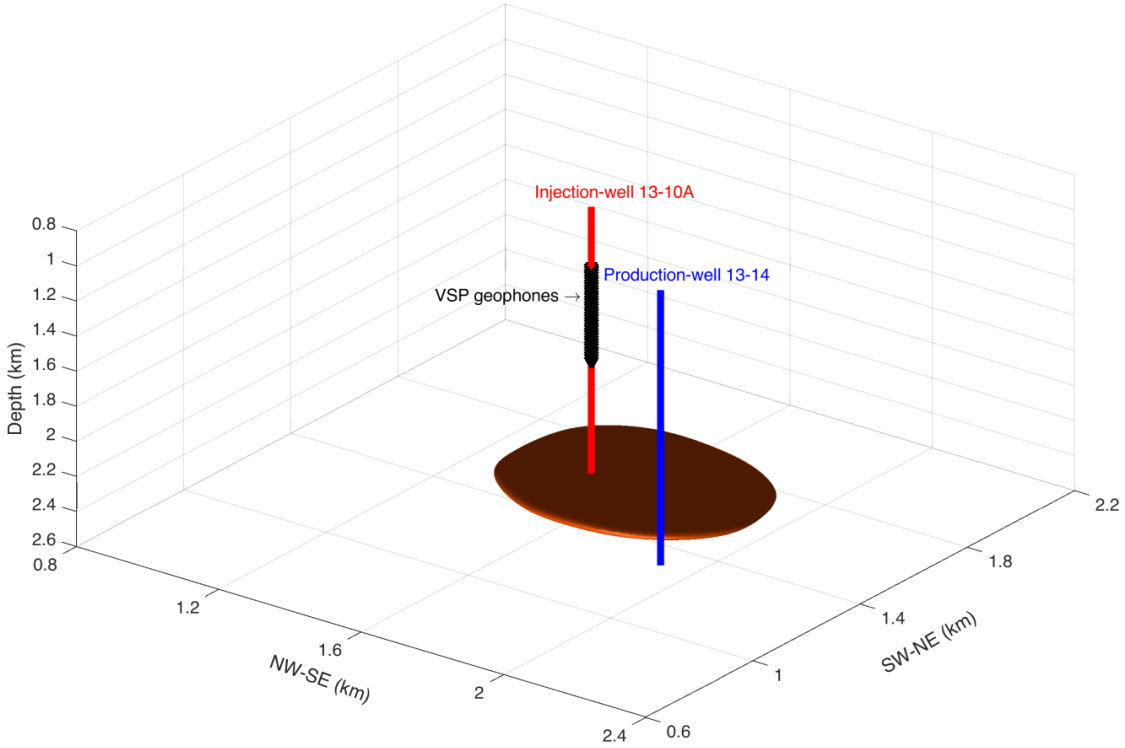


ΔVs

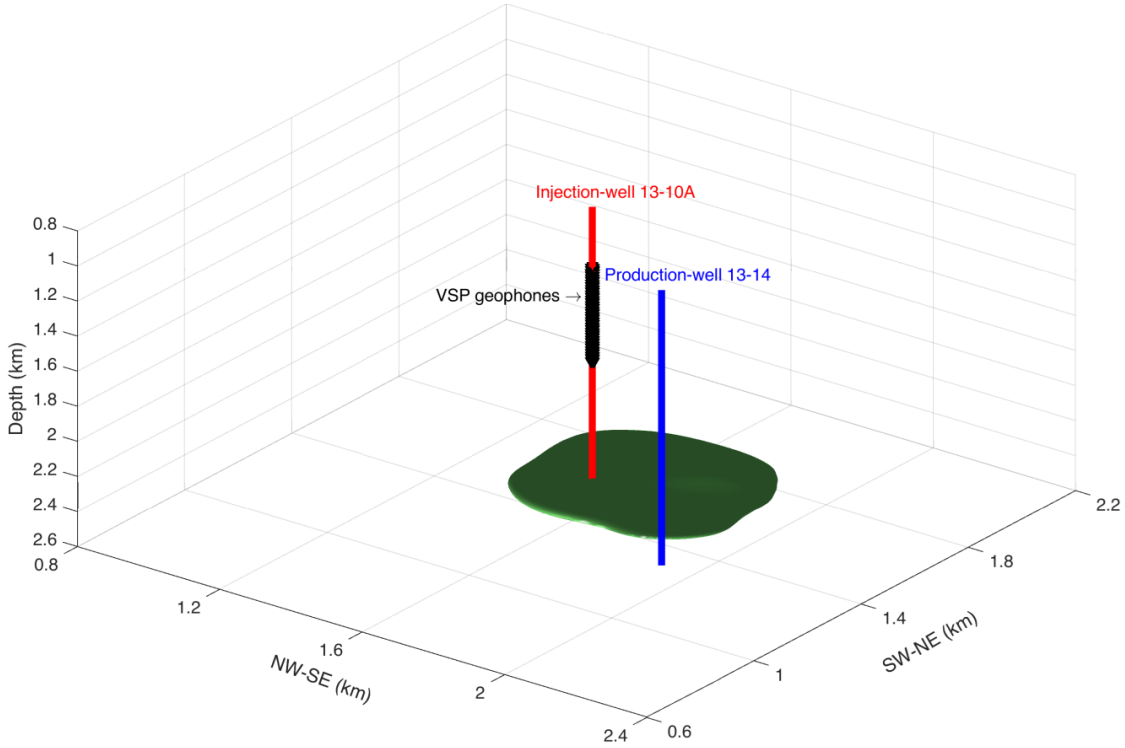
Convergence Curves at the Final Frequency Scale of Multiscale Elastic-Waveform Inversion



Volumetric Time-Lapse Velocity Changes between Baseline and Monitor1 VSP Survey

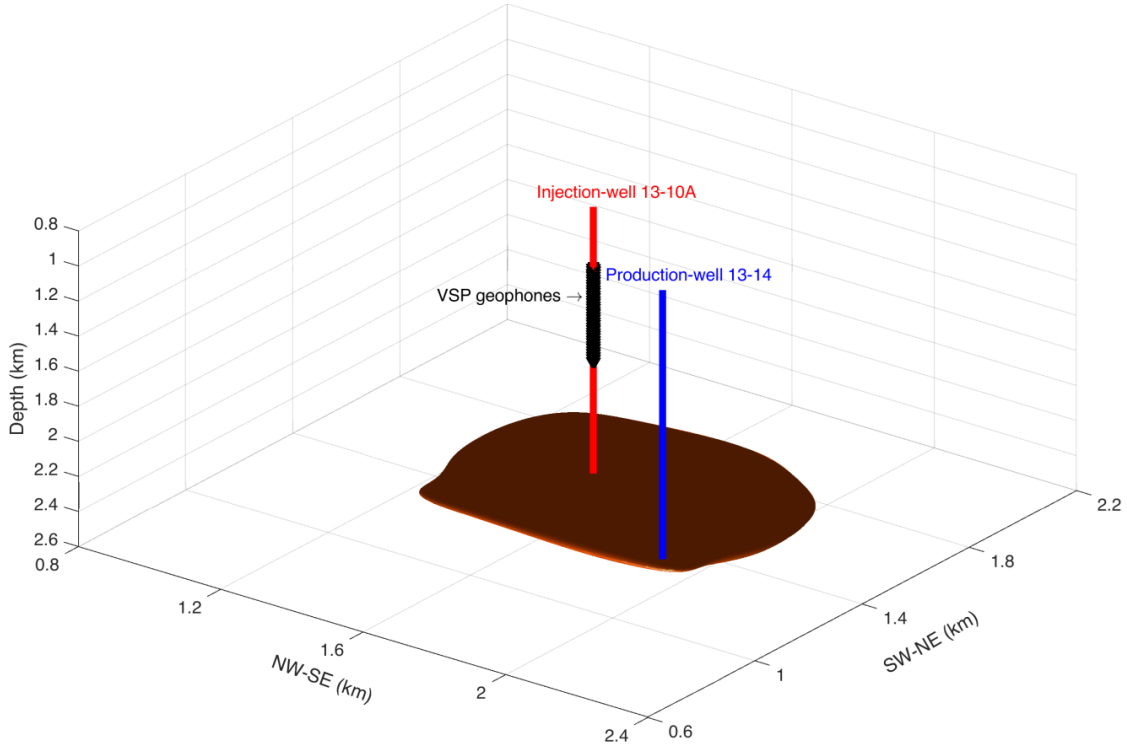


ΔVp

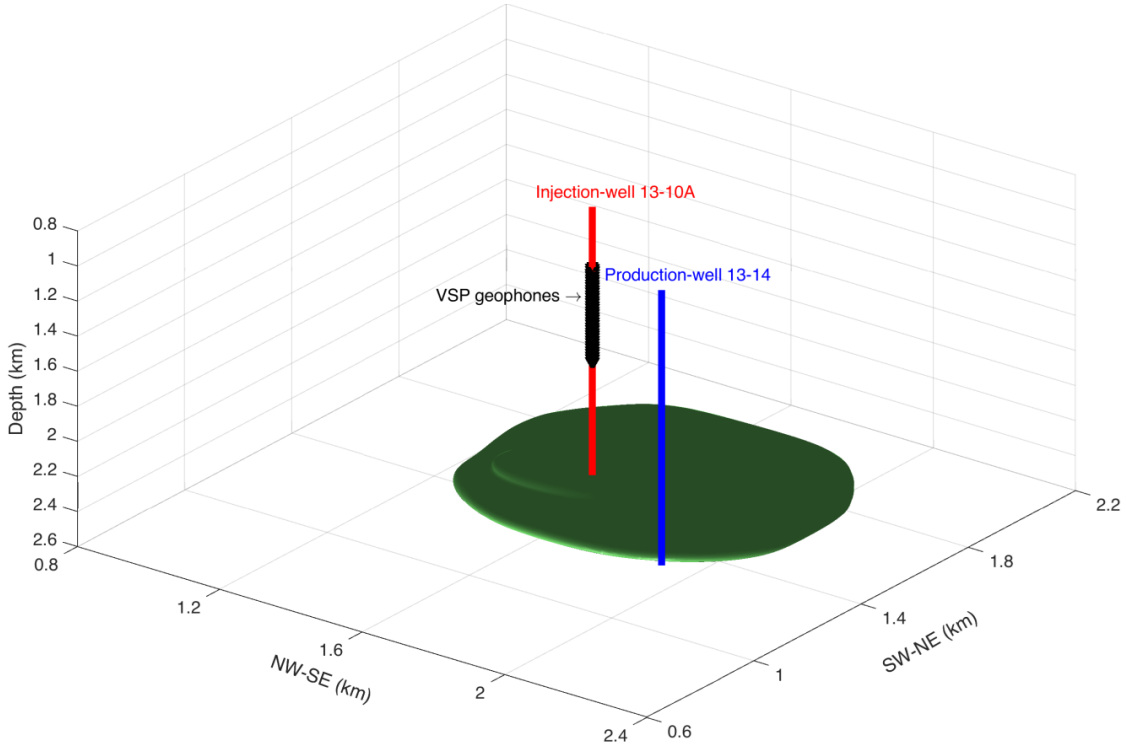


ΔVs

Volumetric Time-Lapse Velocity Changes between Baseline and Monitor2 VSP Survey

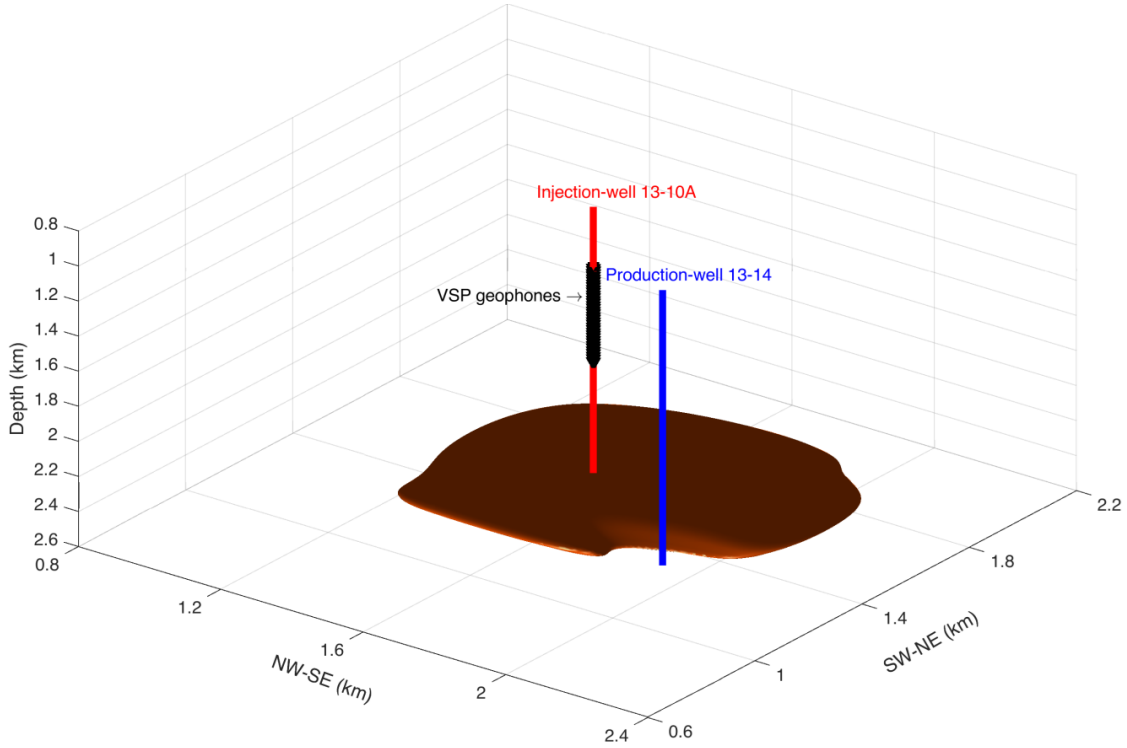


ΔVp

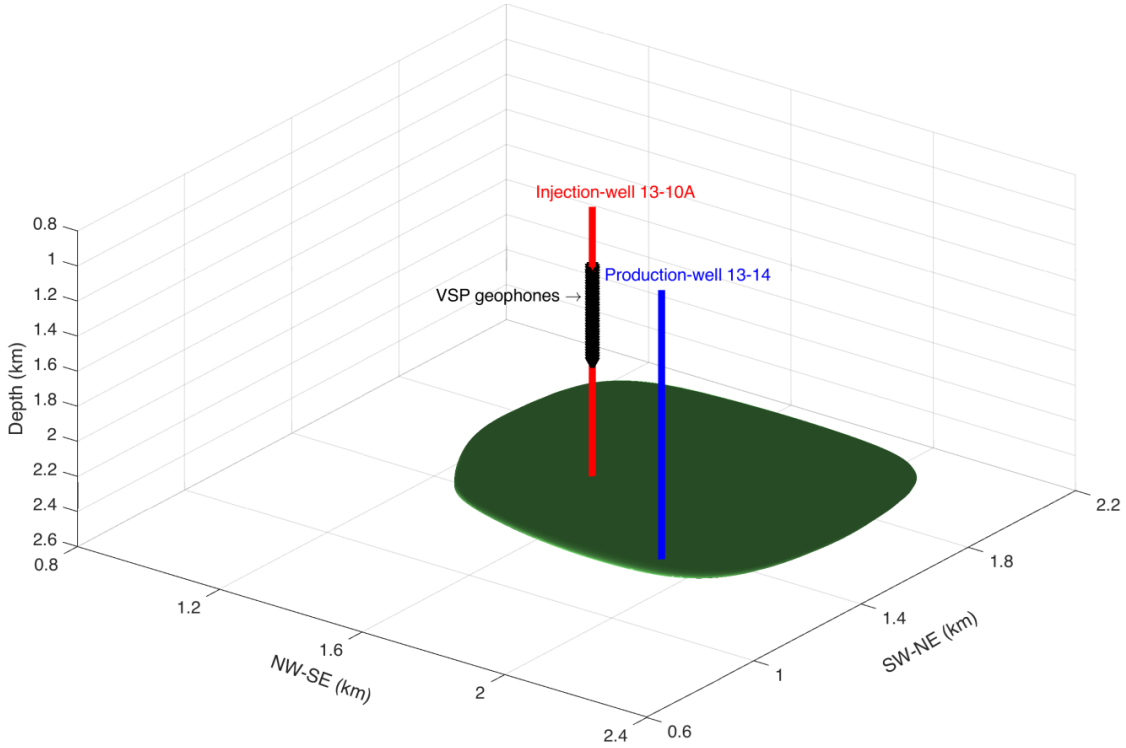


ΔVs

Volumetric Time-Lapse Velocity Changes between Baseline and Monitor3 VSP Survey



ΔVp



ΔVs

Conclusions

- We have developed a workflow combining sonic logging, surface seismic survey, and VSP surveys to build initial subsurface velocity models for time-lapse VSP wavefield inversion.
- We have used 3D traveltime tomography of 3C downgoing VSP data and 3D elastic-waveform inversion of 3C upgoing VSP data to obtain high-resolution baseline velocity models.
- We have employed the spatial prior information to limit the spatial ranges of time-lapse velocity changes and improve the inversion robustness.
- Our elastic-waveform inversion of time-lapse 3D VSP data successfully inverts for the decreasing seismic velocities with the increasing amount of CO_2 injection.
- Our results revealed the spatiotemporal changes of seismic velocities, demonstrating the spatiotemporal evolution of CO_2 plume, moving from the injection well to the production well, or driving oil and gas from the injection well to the production well.