

Seismic elastic double-beam characterization of faults and fractures for CO₂ storage site selection

Project Number: DE-FE0032063

PI: Yingcai Zheng, University of Houston

Subcontract: LANL (Lianjie Huang) & Vecta Oil and Gas Ltd.
(Bryan DeVault)

Project start date: July 1, 2021;
DOE share: \$799,932.
Cost share: \$225,000

U.S. Department of Energy
National Energy Technology Laboratory
2024 Project Review Meeting, Pittsburgh
August 5, 2024

Teams

- **University of Houston**

- Yingcai Zheng (PI)
- Jake Parsons (graduate student)
- Joe McNease (graduate student)
- Hao Hu (past postdoc)



- **Los Alamos National Laboratory**

- Lianjie Huang (Co-PI)
- David Li (graduate research assistant)
- Neala Creasy (postdoc)



- **Vecta Oil and Gas, Ltd.**

- Bryan DeVault (President/CEO; Co-PI)
- Gulia Popov



**FINANCIAL ASSISTANCE
FUNDING OPPORTUNITY ANNOUNCEMENT**



**Department of Energy (DOE)
Office of Fossil Energy (FE)**

**EMERGING CO₂ STORAGE TECHNOLOGIES: OPTIMIZING PERFORMANCE
THROUGH MINIMIZATION OF SEISMICITY RISKS AND MONITORING
CAPROCK INTEGRITY**

Funding Opportunity Announcement (FOA) Number: DE-FOA-0002401

Announcement Type: Amendment 1¹

CFDA Number: 81.089

**EMERGING CO₂ STORAGE TECHNOLOGIES: OPTIMIZING PERFORMANCE
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**AOI 1a - Fault Detection, Characterization, and
Hazard Assessment.**

**No field work. Novel method development. Final
deliverable: a software package for subsurface analysis
for Gigatonne storage scenarios.**

Motivation: induced seismicity is quite common in operating CCS sites

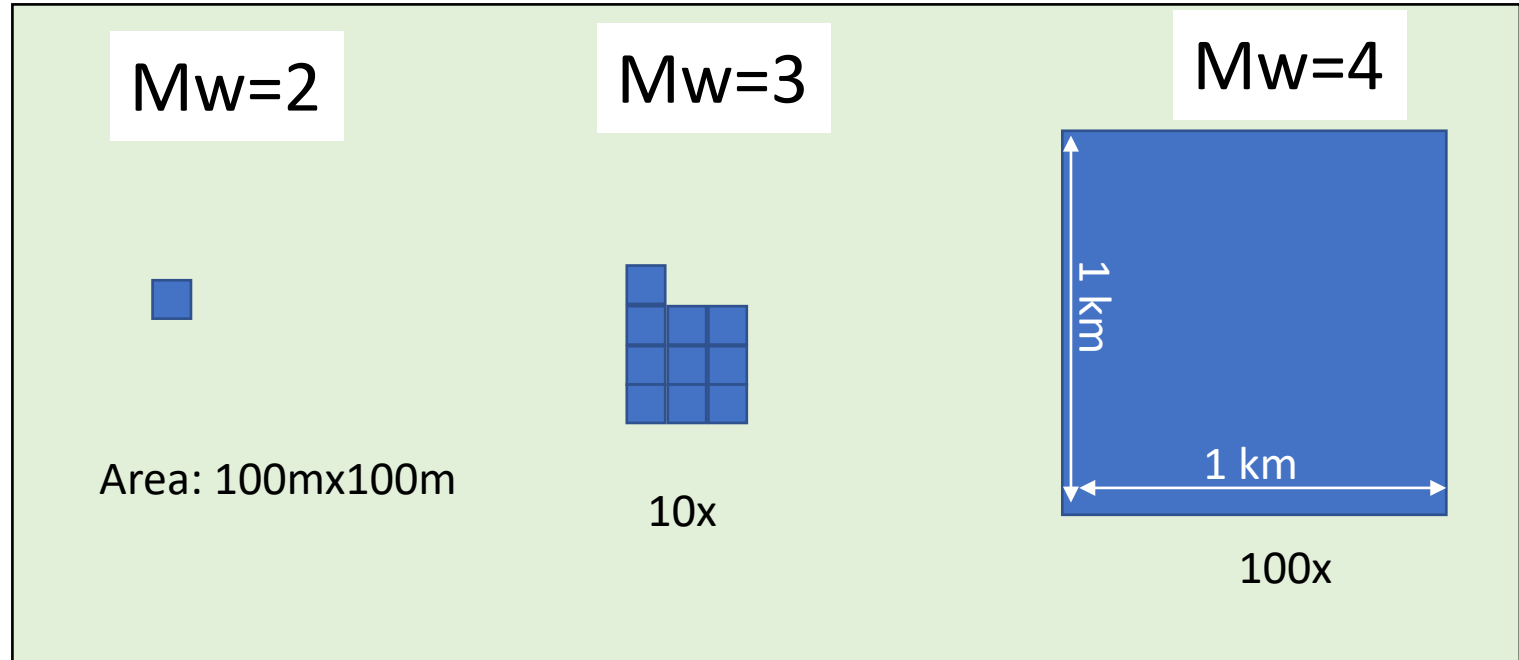
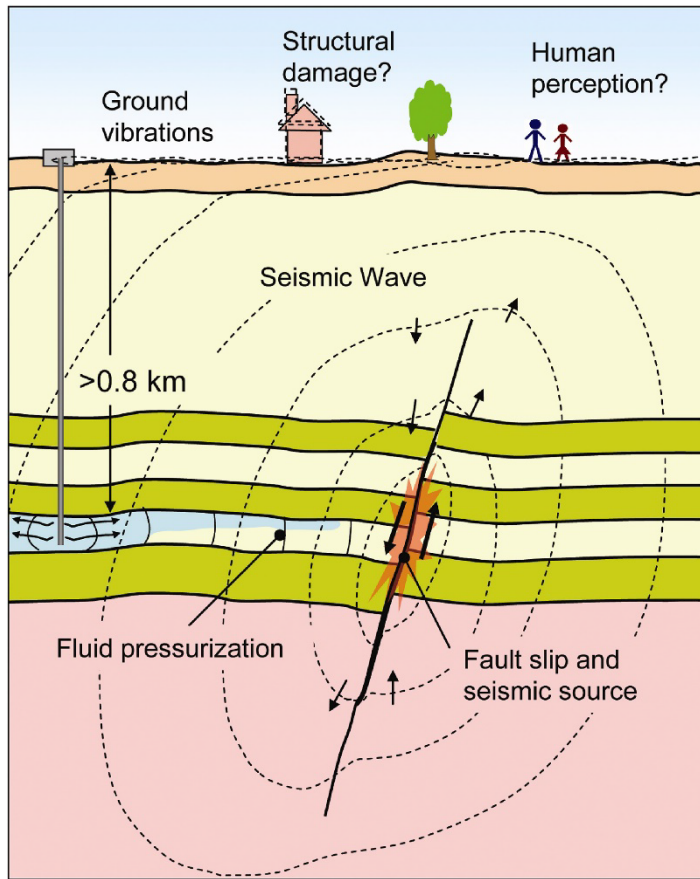
CCS Sites	Start Time	End Time	Injection Amount	Seismic Monitoring (Y/N)	Max Magnitude	Distance from injection	Rock Type	Injection Depth
Decatur, USA	2012	-	2.8Mt	Y	1.55	400m	Sandstone	2140m
In Salah, Algeria	2004	2011	3.8Mt	Y	1.6	1100m	Sandstone	1950m
Otway Australia	2007	--	30000t	Y	0.5	450m	Sandstone/Calcite/Kaolinite	2000m
Weyburn, Canada	2000	2011	15Mt	Y	-0.5	300m	Sandstone	1420m
Sleipner, Norway	1996	-	15Mt (2016)	N	-	-	Sandstone	1000m
Tomakomai, Japan	2016	-	0.2Mt	Y	0.5	1.5km	Sandstone	2400m
Fort Saskatchewan, Canada (Quest)	2015	-	5.7Mt		0.8	70m	Sandstone	2172m

(McNease et al. 2023)

Scientific rationale:

ruptured fault size/area → seismic event magnitude

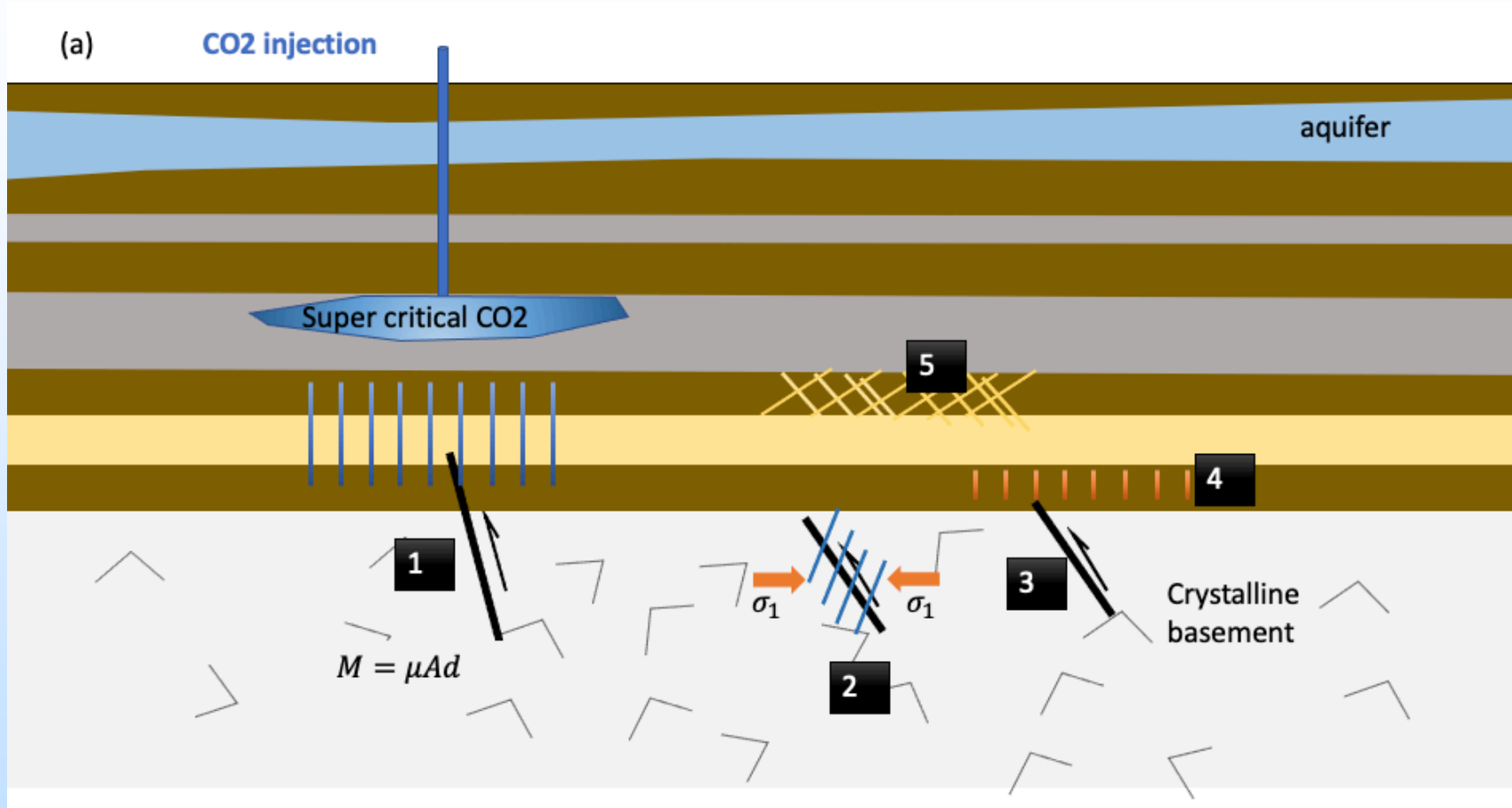
$$M_w = (2/3) \text{Log}_{10}(\mu * \text{Area} * \text{slip}) - 6.0$$



The induced seismic event magnitude should be viewed with respect to the reservoir/seal thickness.

Estimating fault/fracture size → upper bound in event magnitude

Project Goals and Objectives for Gigatonne injection

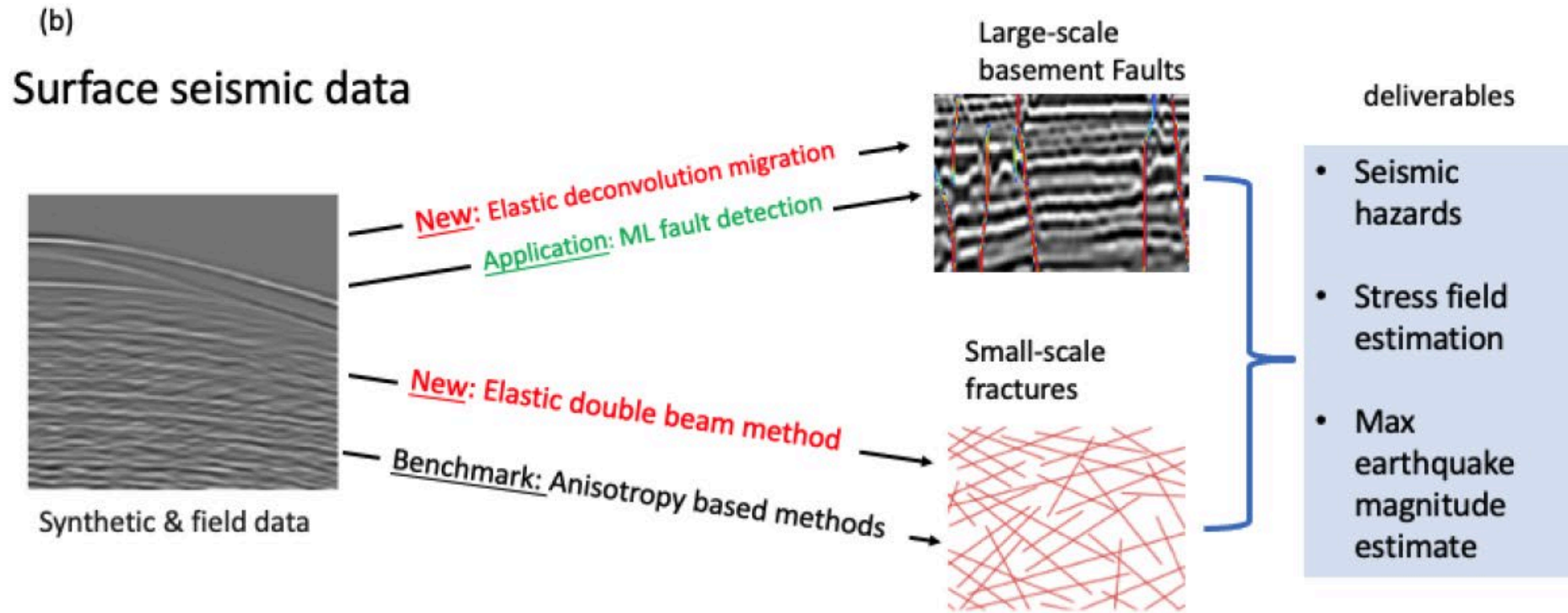


- Small-scale fractures & large-scale faults
- Sedimentary layers & basement
- Stress field
- Potential seismic hazard; max Magnitude;
- Possible fluid pathways for CO₂ plume migration and leakage

Objectives budget periods (BP)

- **BP 1.** Fault detection and fracture characterization in the basement using synthetic 9C surface seismic data (BP-1)
- **BP 2.** Fault detection and fracture characterization in the basement using field 9C surface seismic data (BP-2)
- **BP 3.** Determination of fault stress state and fault activation potential (BP-3)

Technology Roadmap

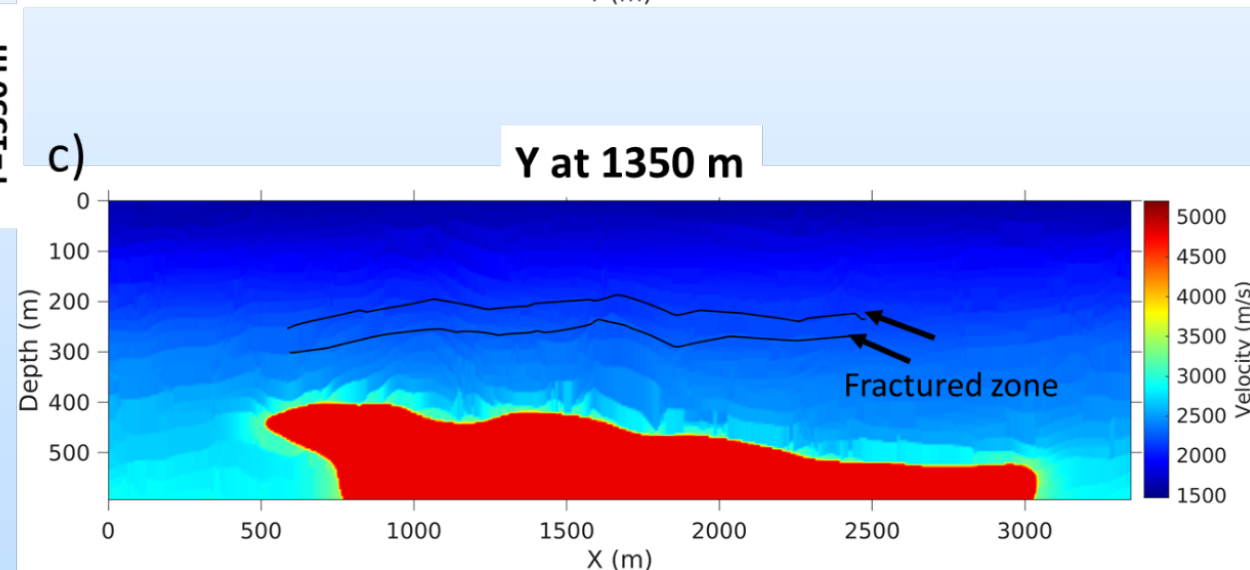
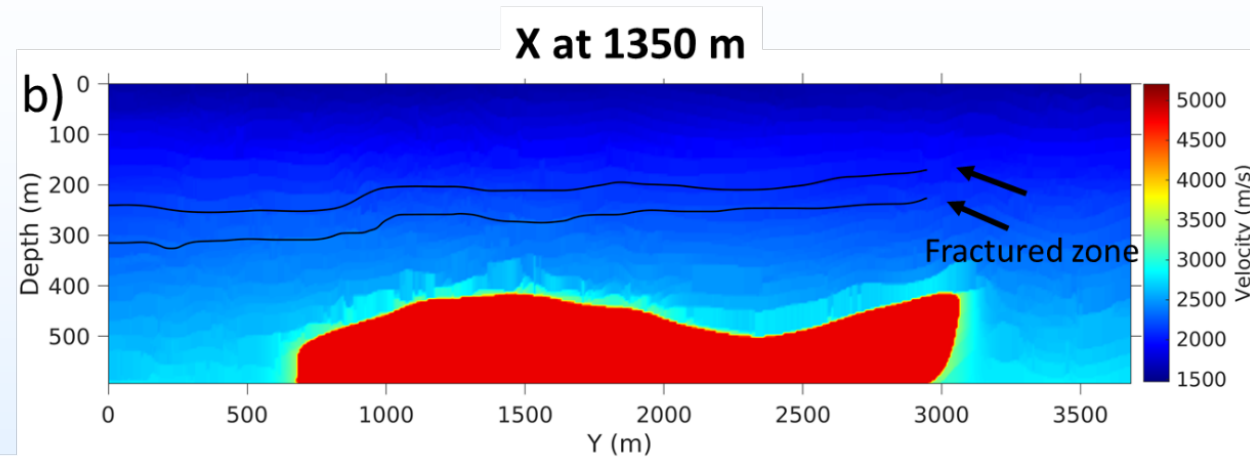
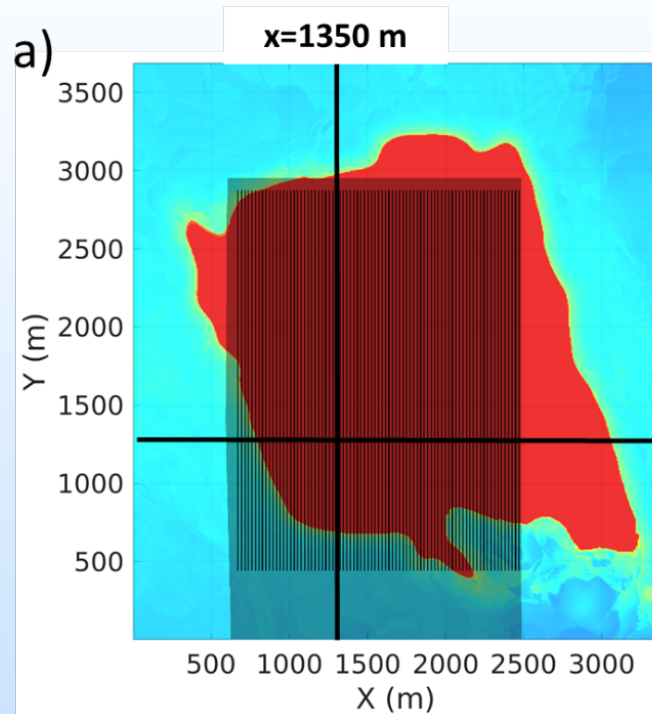




Why another method for fracture characterization?

- Can seismic migration see the small-scale fractures?

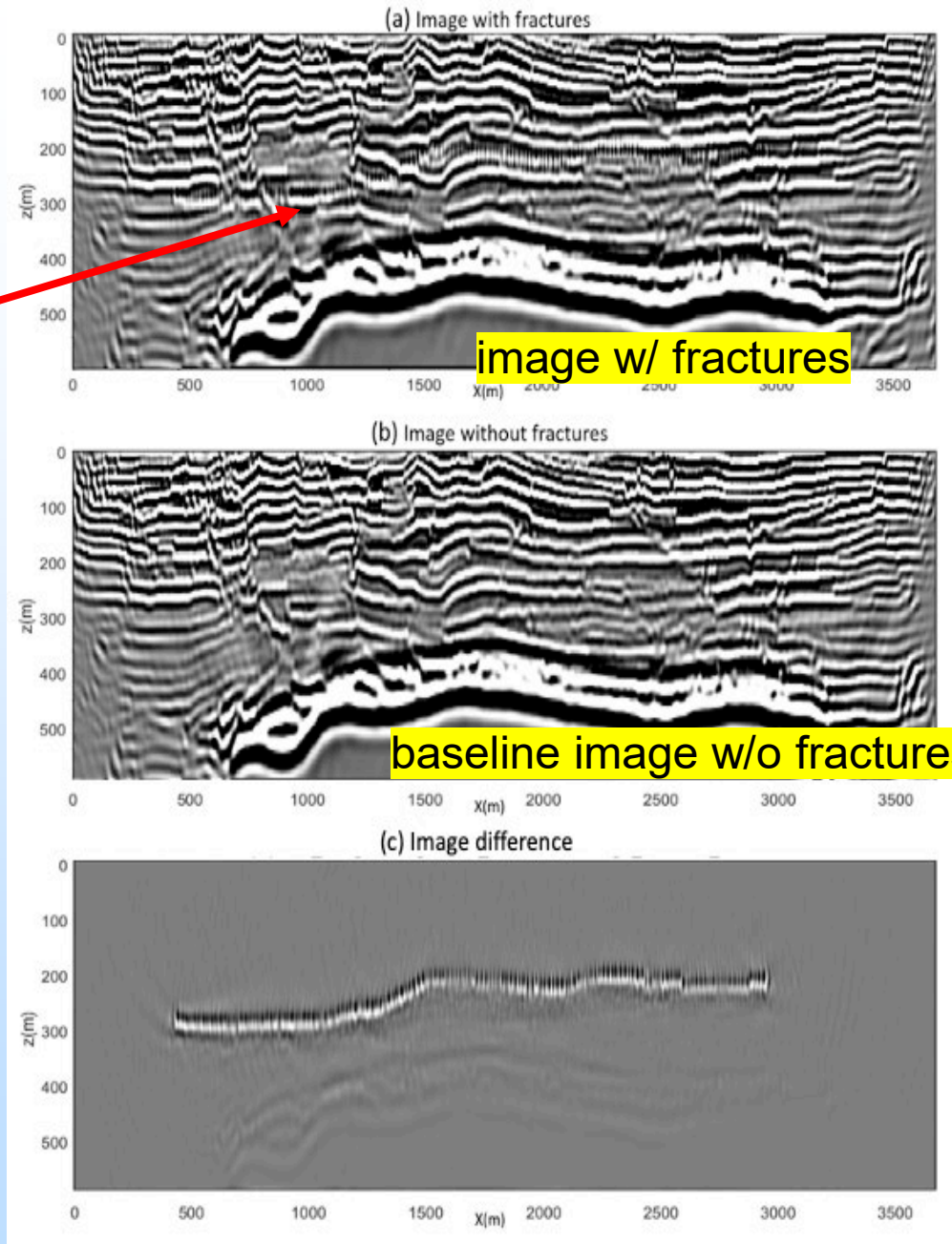
Motivational example: fractures are hard to see



Fractures: vertical; 9m height;
fracture compliance $1e-10$ m/Pa

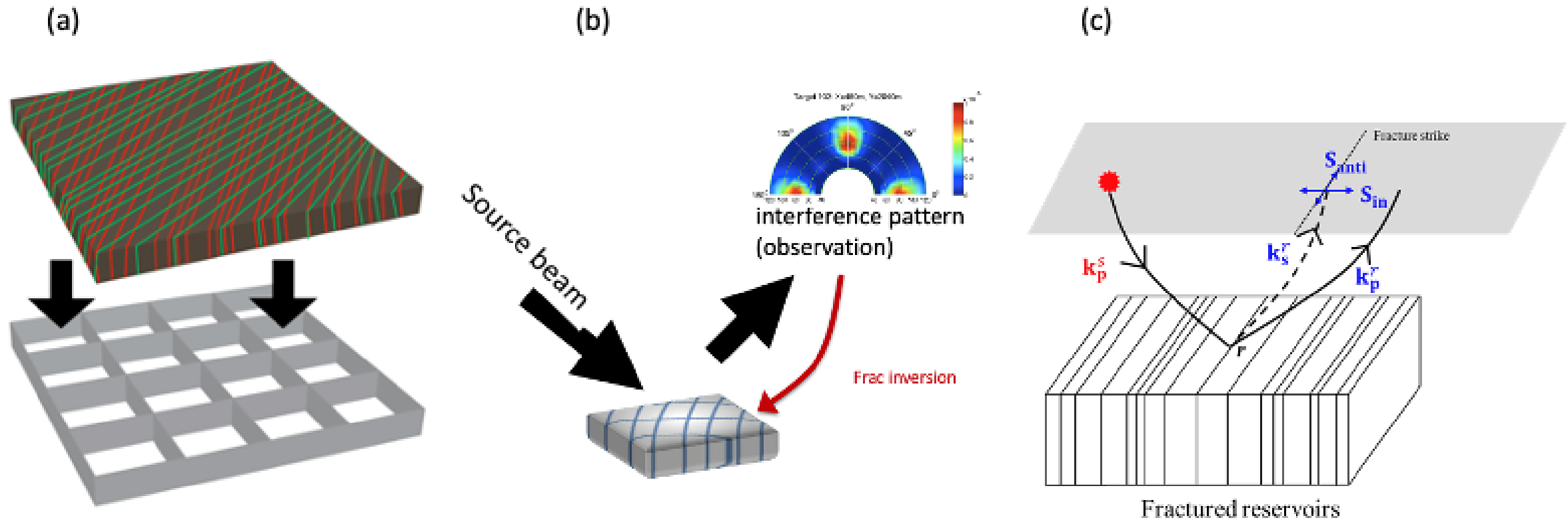
Finite difference modeling: Coates and Schoenberg (1995)

Hard to see fractures
in traditional seismic
migrated images

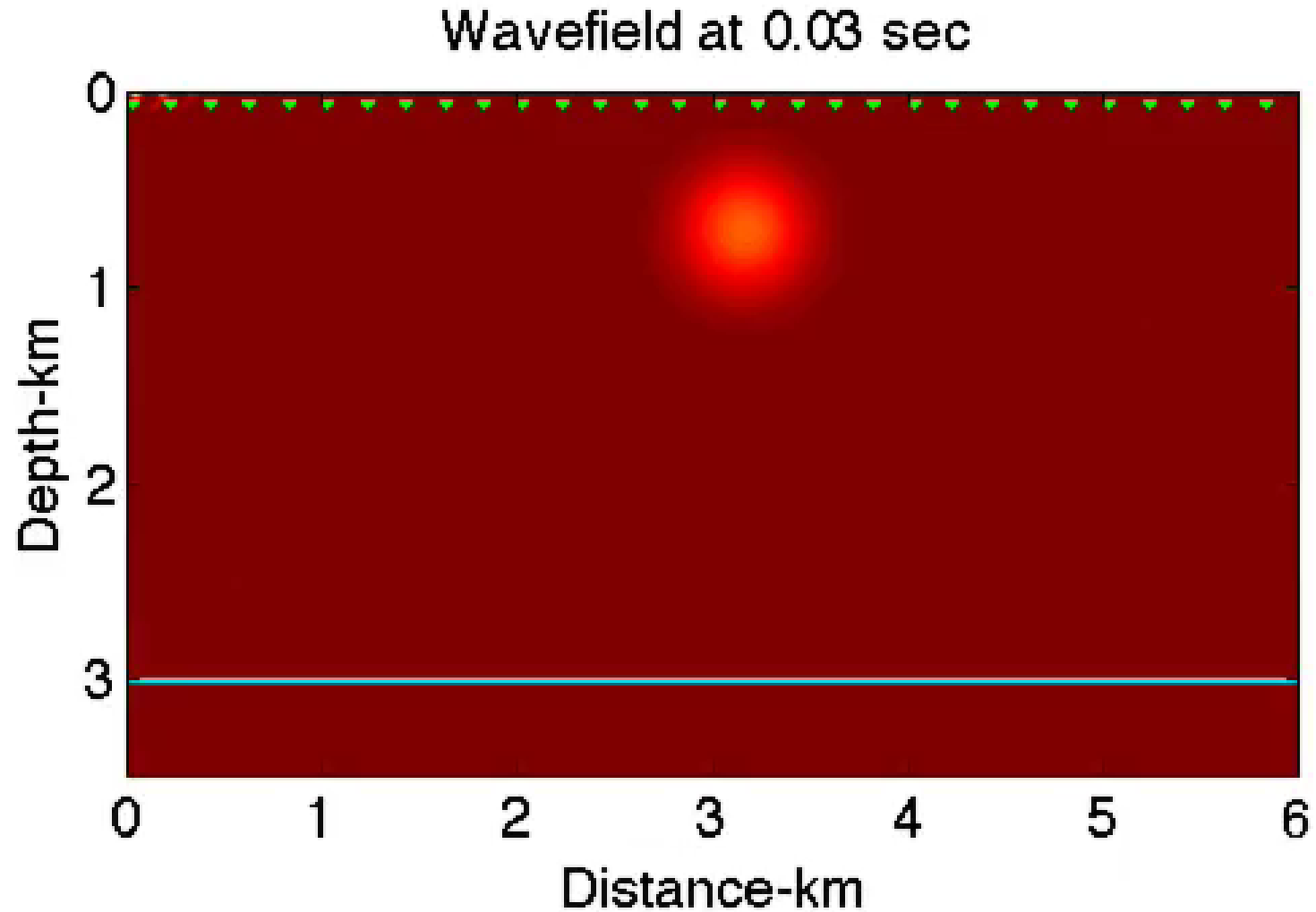


Seismic double-beam method to characterize small-scale fractures

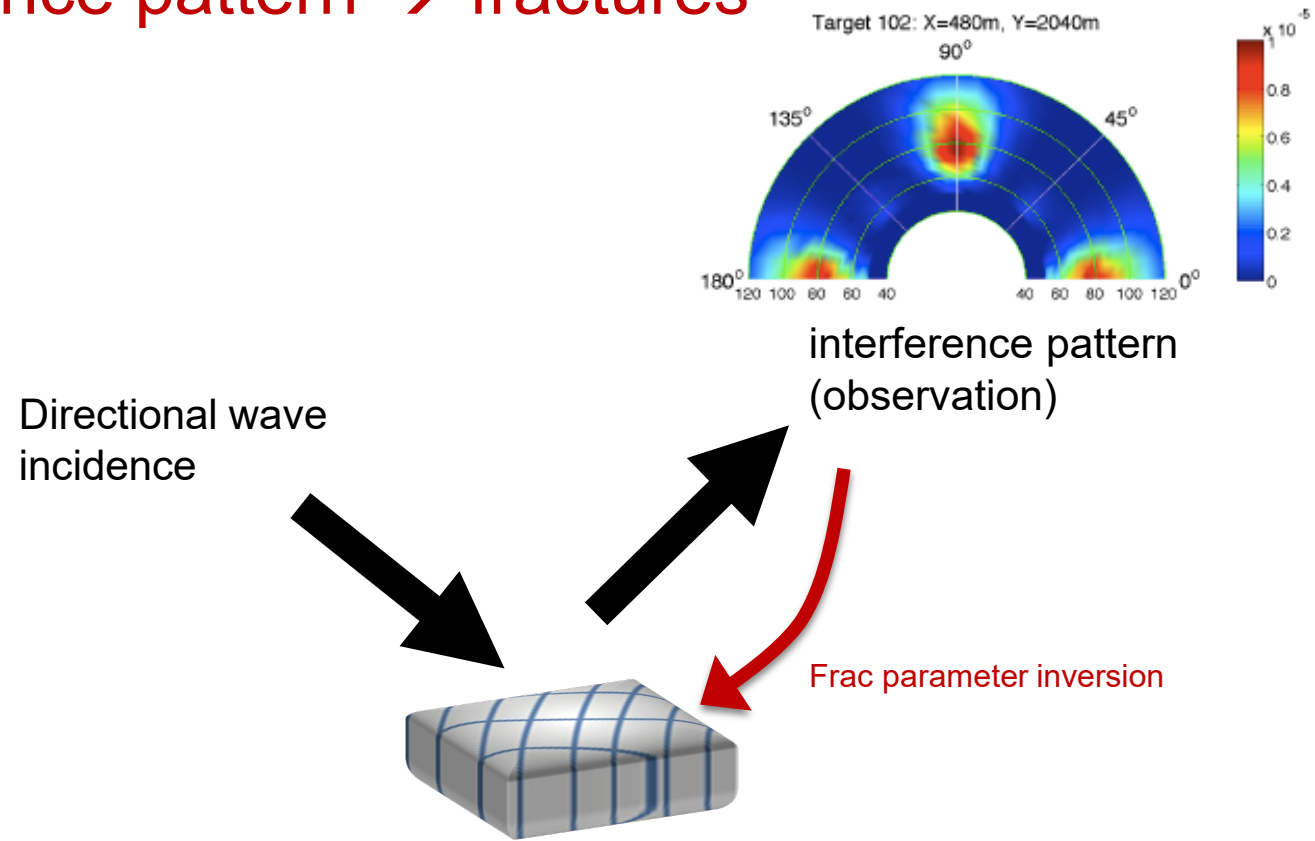
Basic idea of double-beam method



A directional seismic packet can selectively image



Interference pattern → fractures

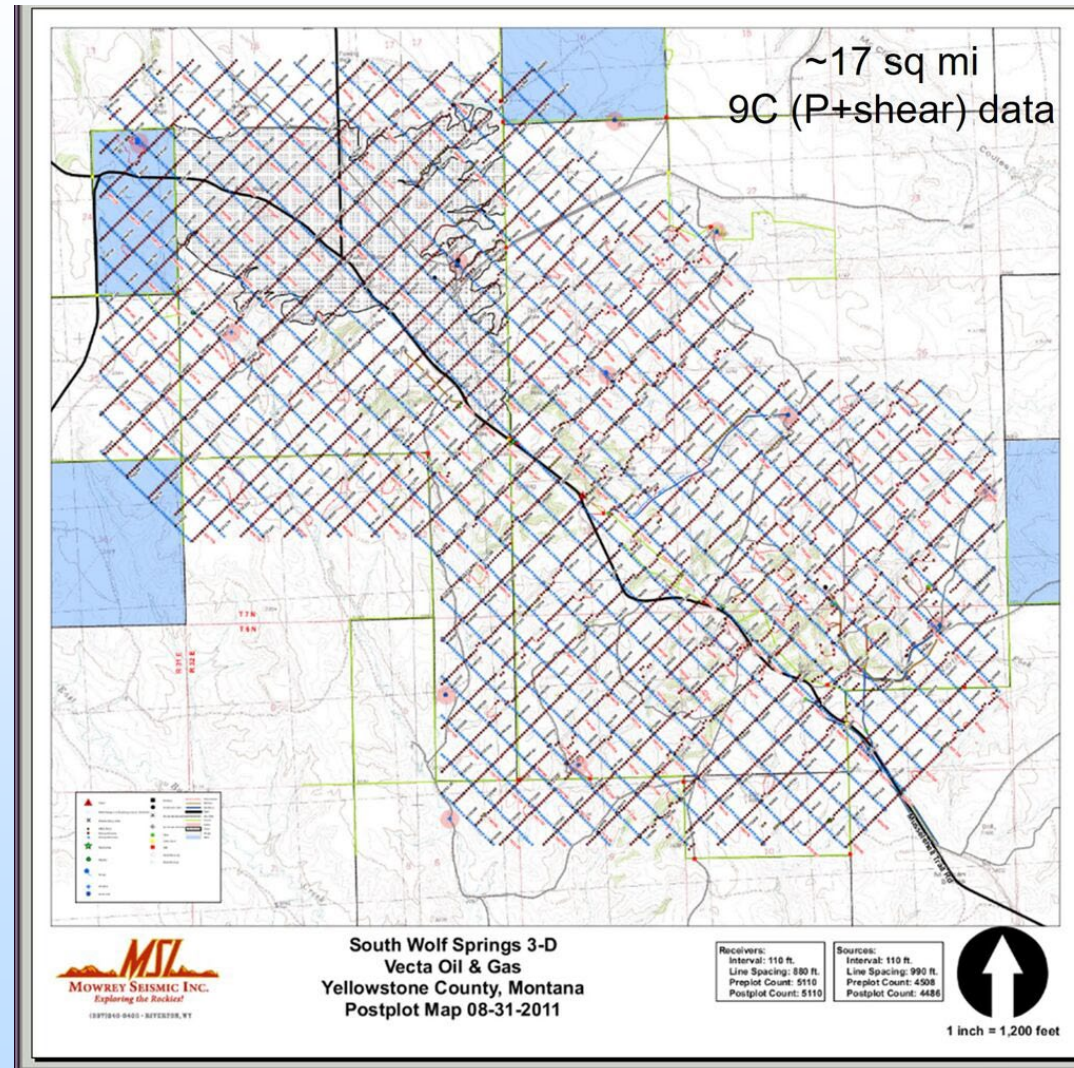


Fractured reservoir

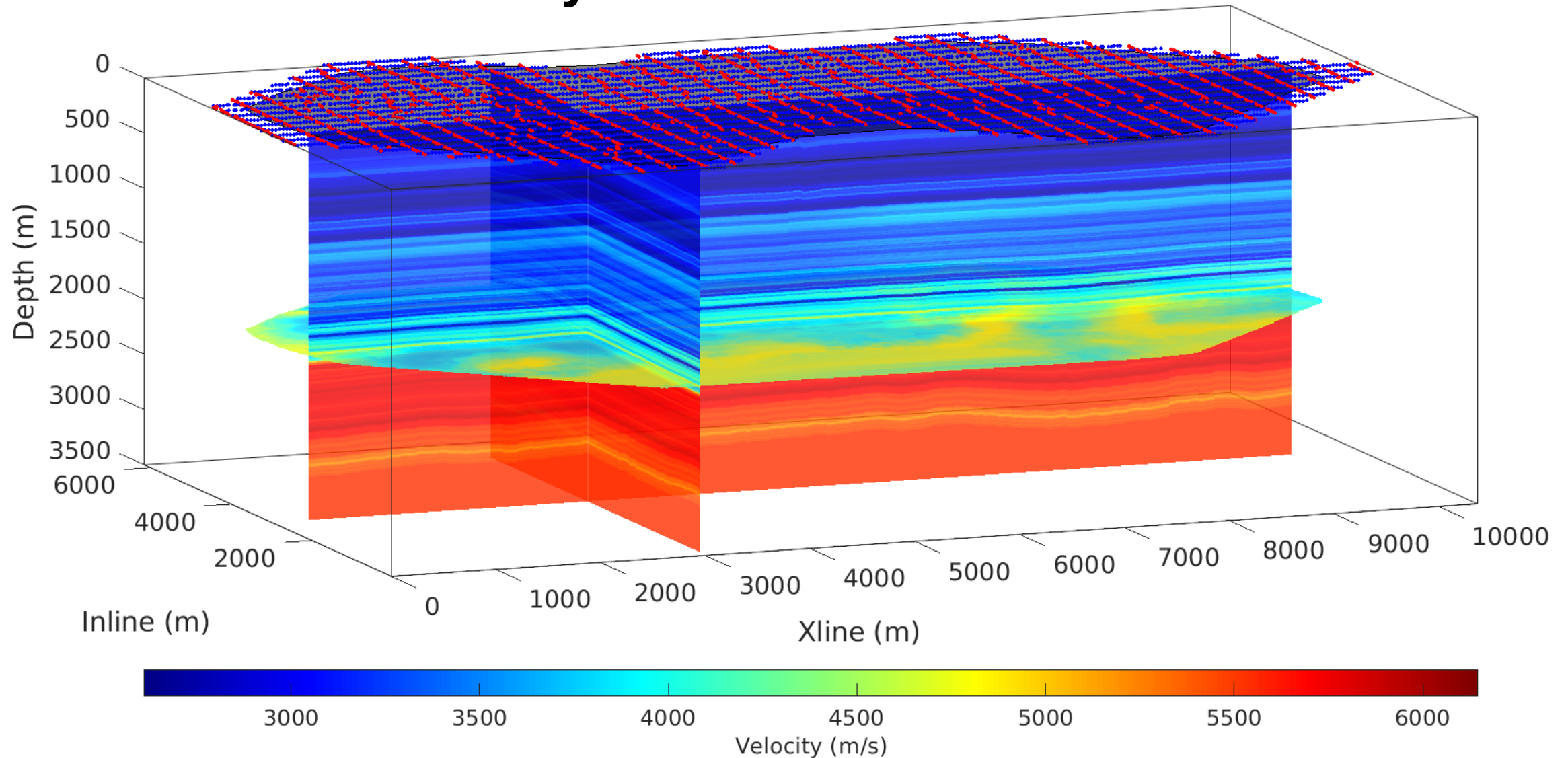
- Fracture orientation
- Density
- Compliance

Build the synthetic elastic model from the
field data

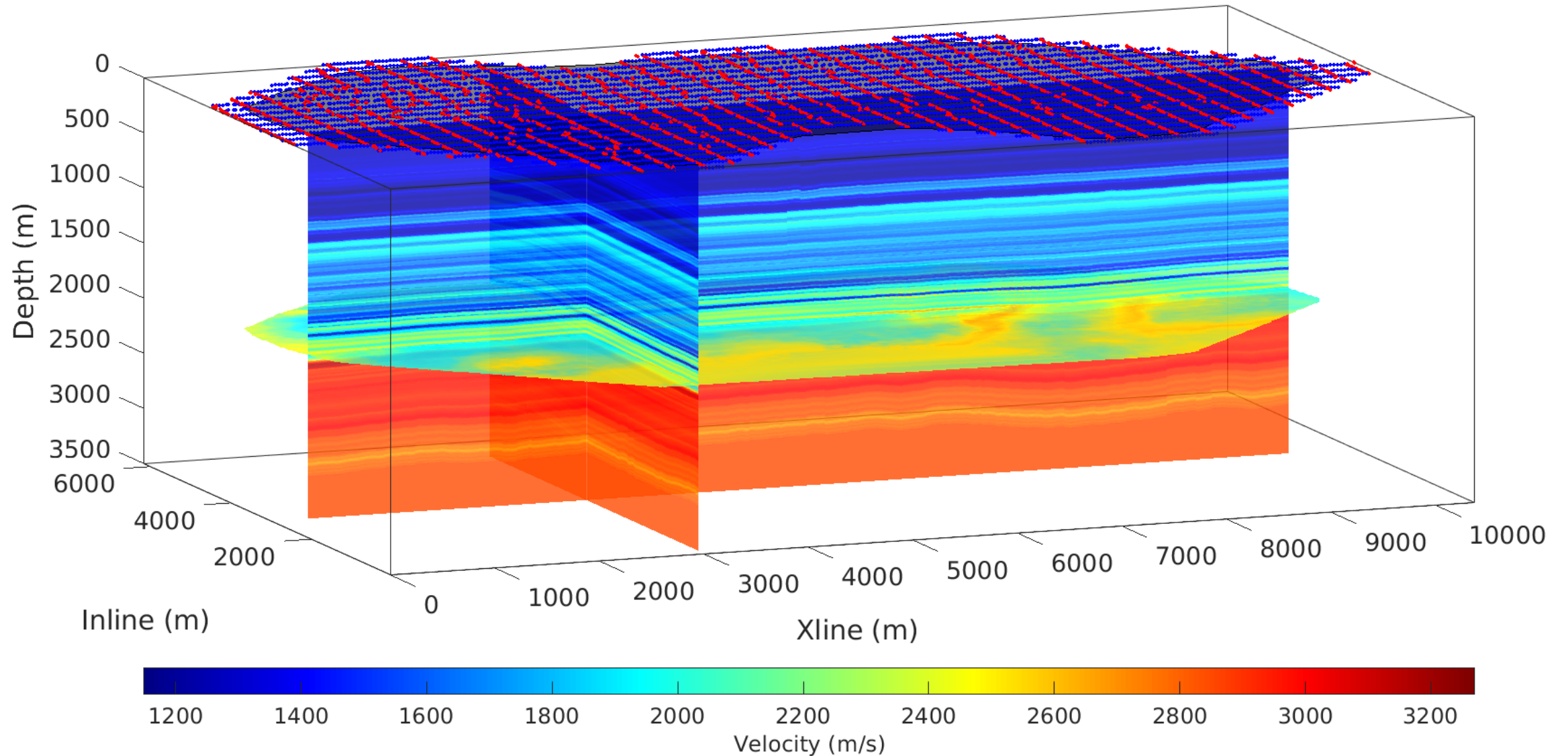
Field seismic data (9C) in Montana



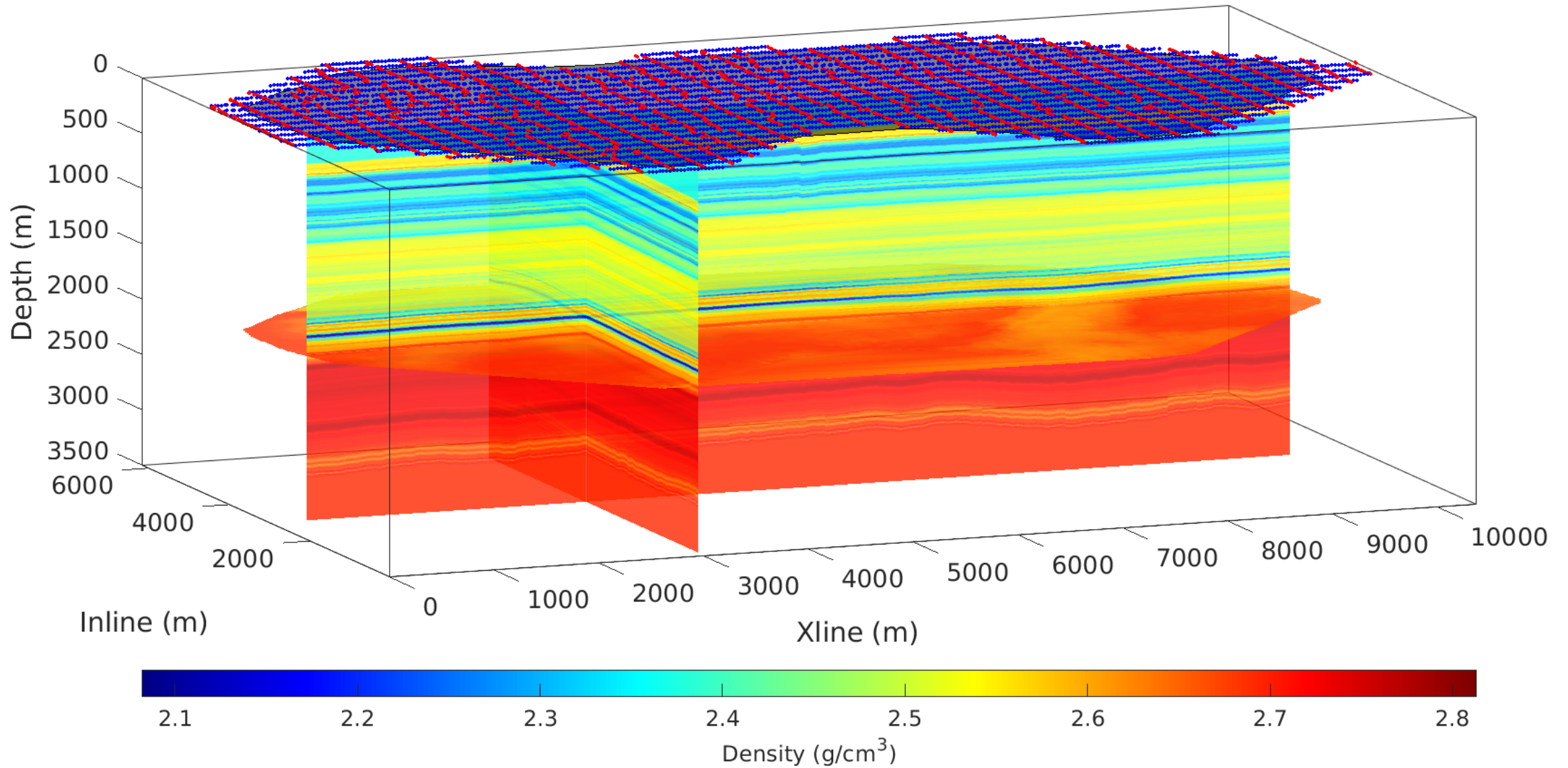
P-wave velocity model from the field Vecta data



Shear-wave velocity model from the field Vecta data



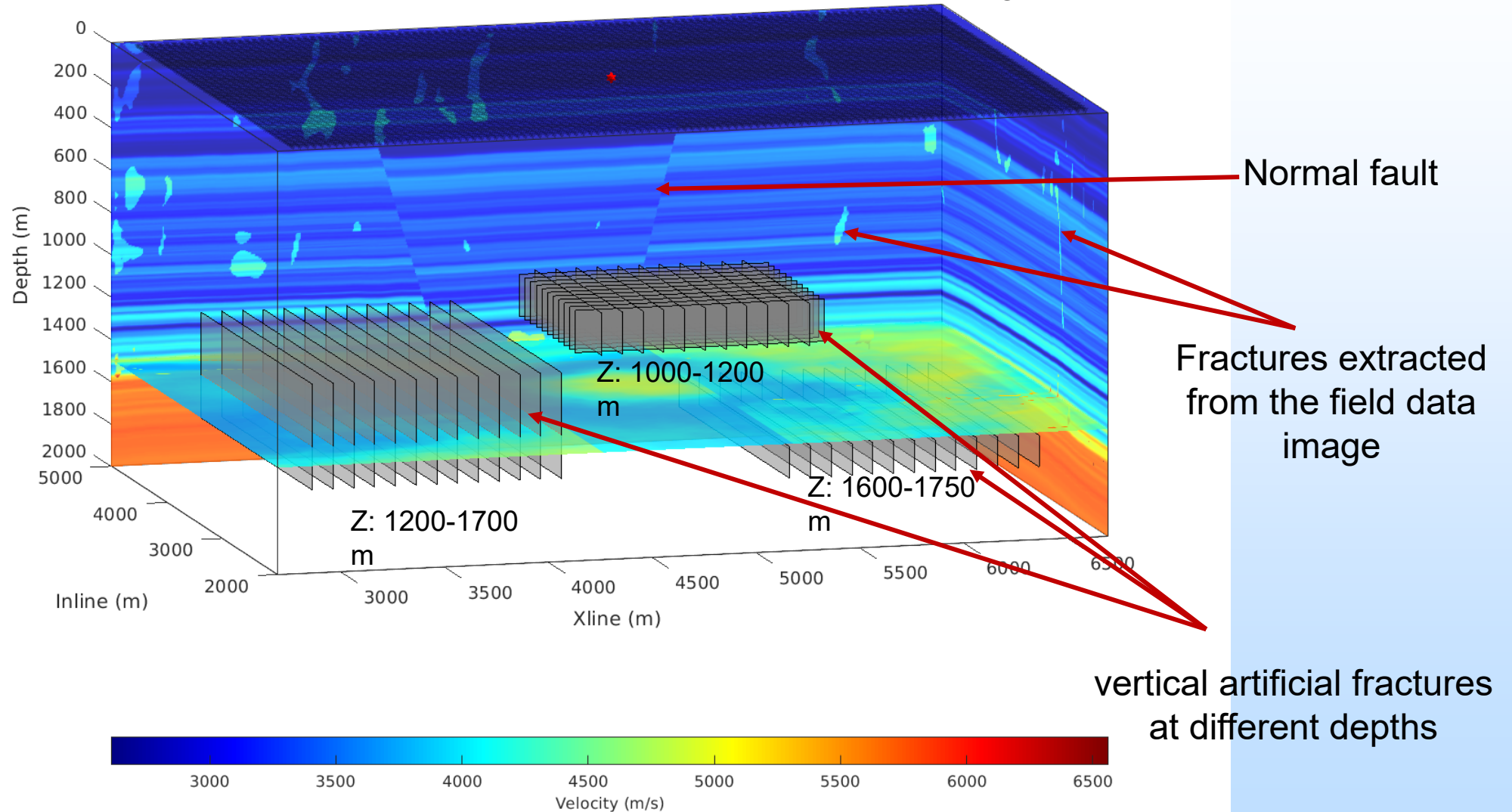
Density model from the field Vecta data

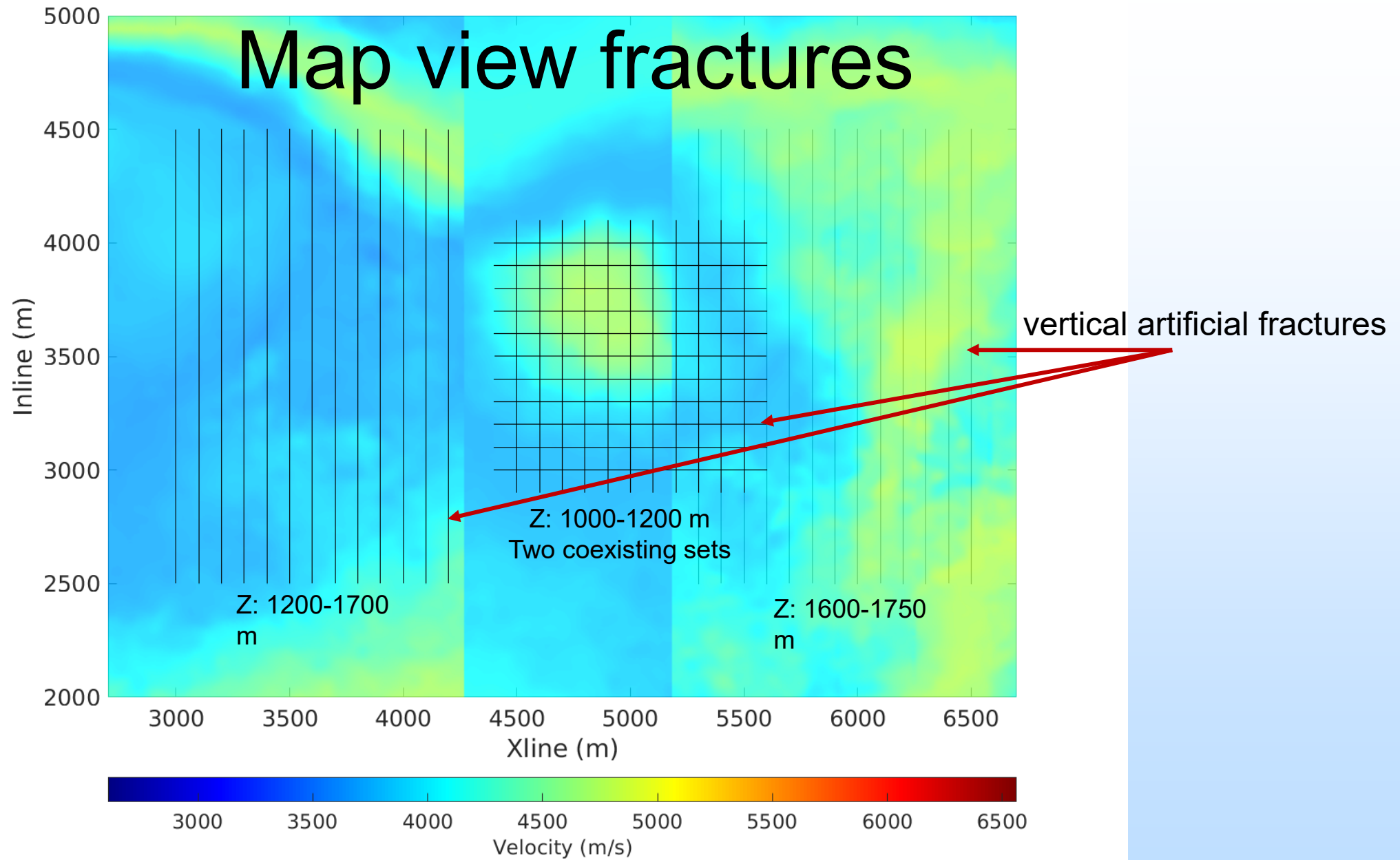


Detection Results: small-scale fractures

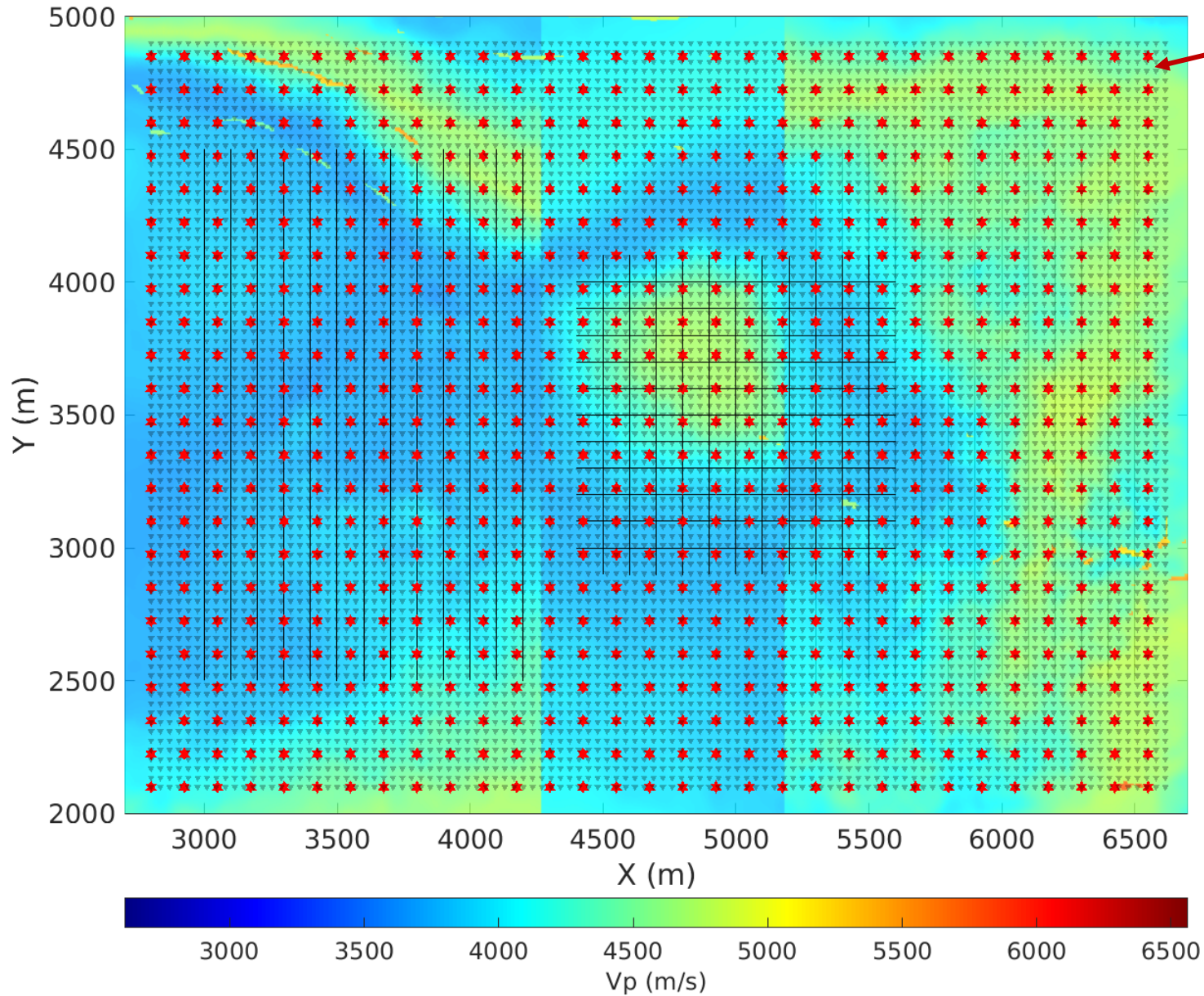
Synthetic Vp model with

- : a normal fault
- : vertical artificial fracture sets
- : small fractures extracted from field data image





Acquisition geometry



★ Source
▼ Receiver

Sources:

X: 2800:125:6550 m

Y: 2100:125:4850 m

Total: $31 \times 23 = 713$

Receivers:

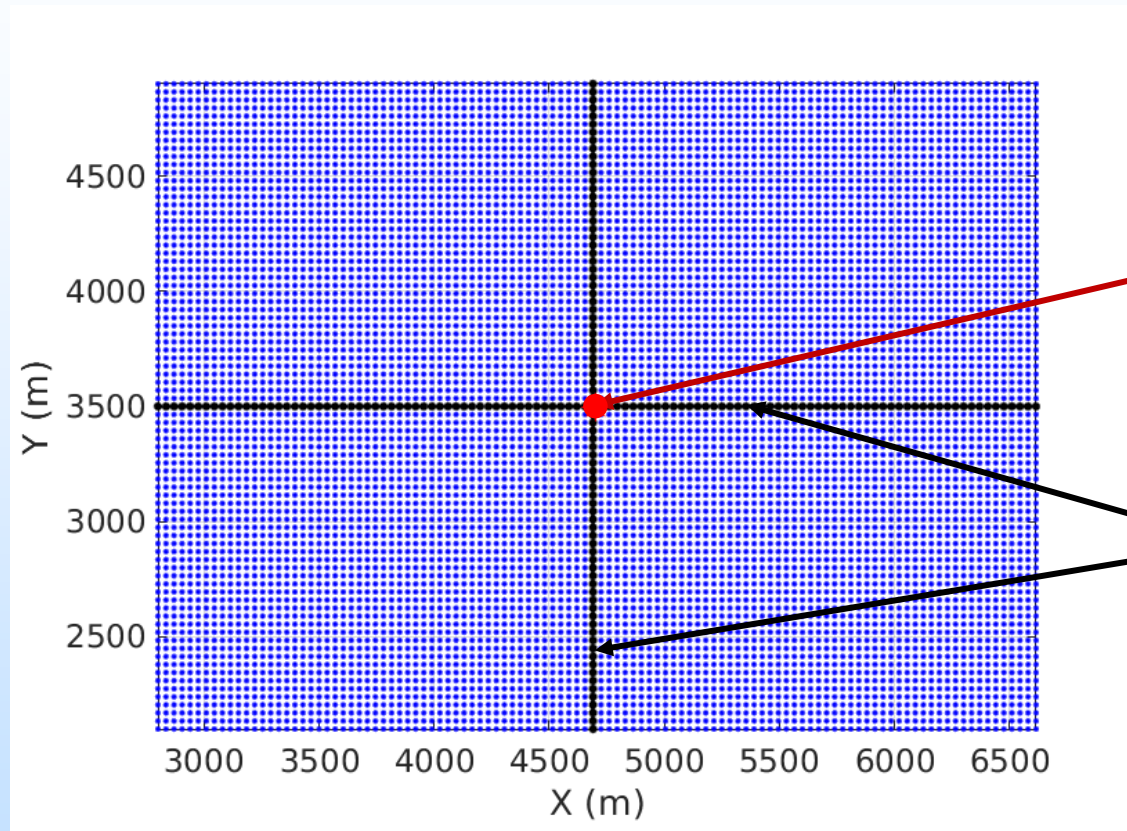
X: 2800:35:6615 m

Y: 2100:35:4900 m

Total: $110 \times 81 = 8910$

Both Source and receivers are at surface

Modeled common-shot gathers at one location with different types of source.

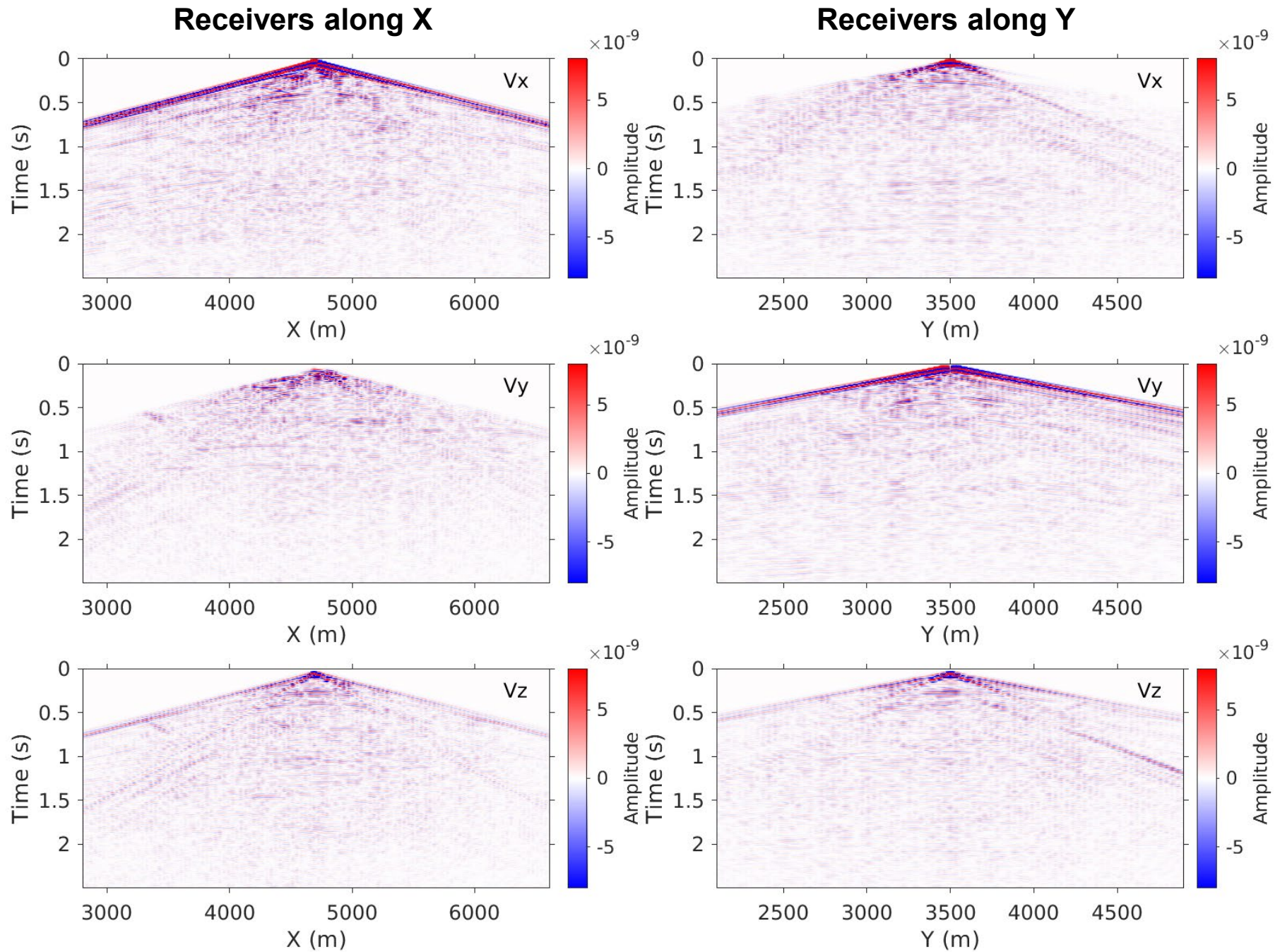


Source

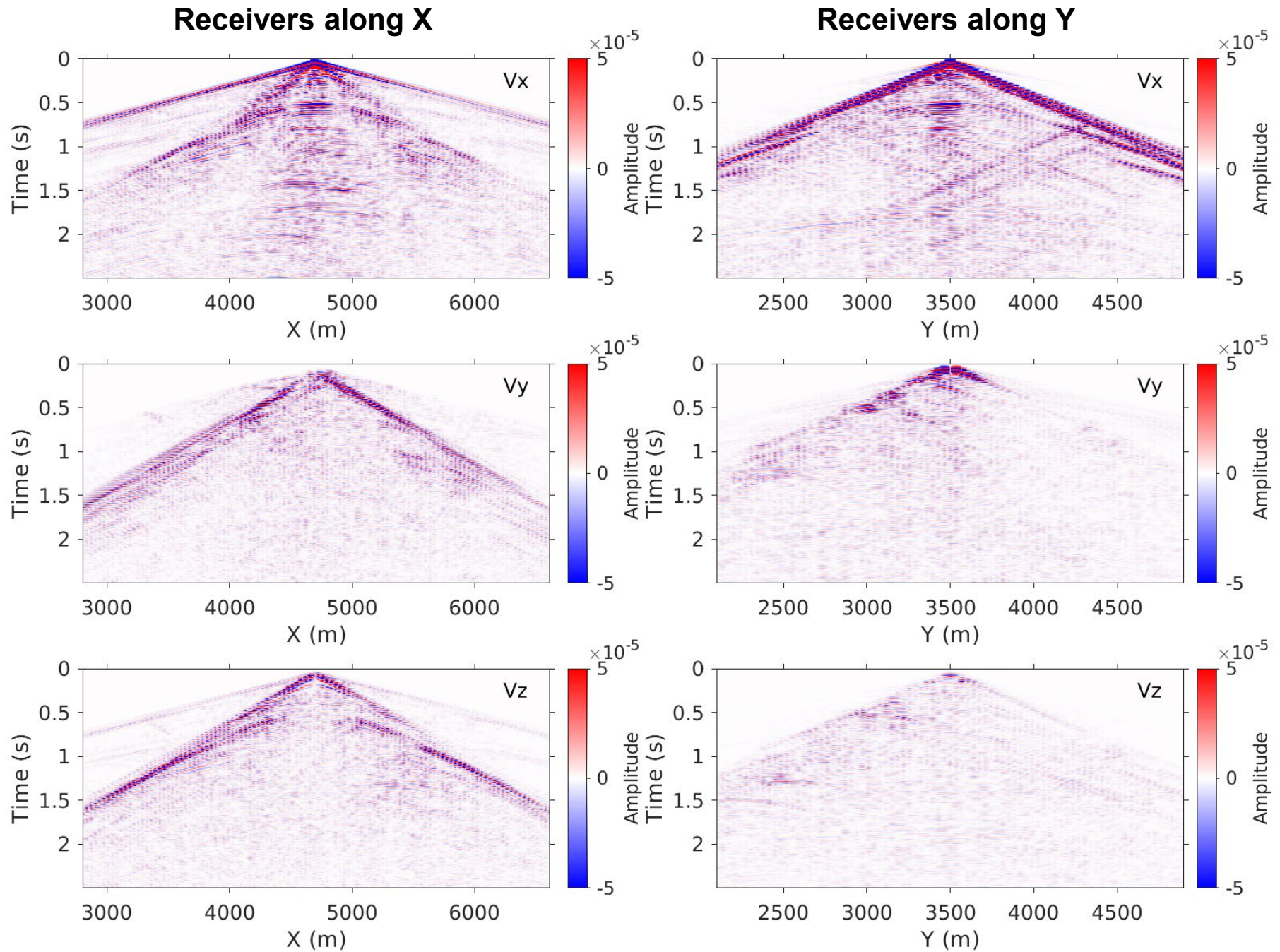
Two receiver lines

Source wavelet: 20 Hz Ricker₂₈

**Explosive
source**



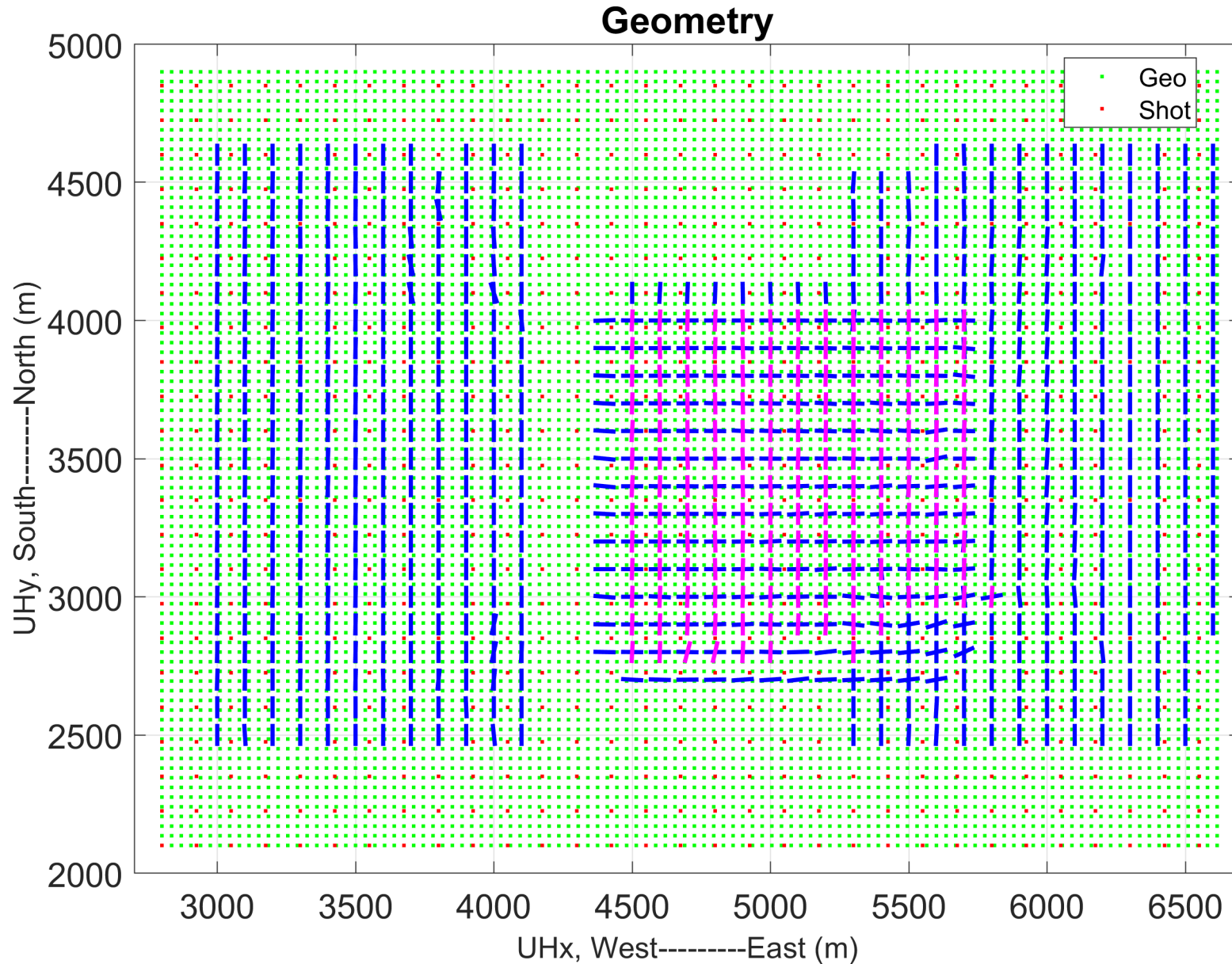
Single force-X



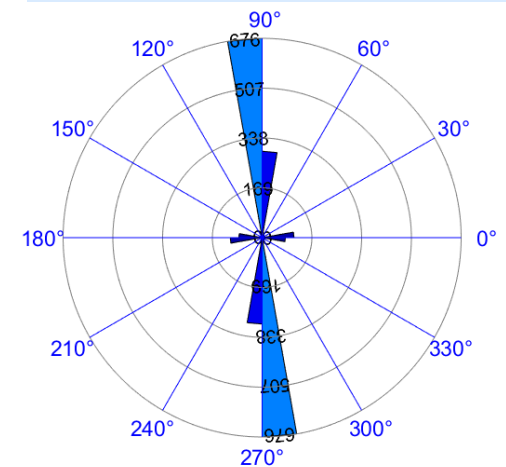
Fracture detection results using Seismic Double-Beam method

(Zheng et al., 2023 SGW for methodology review)

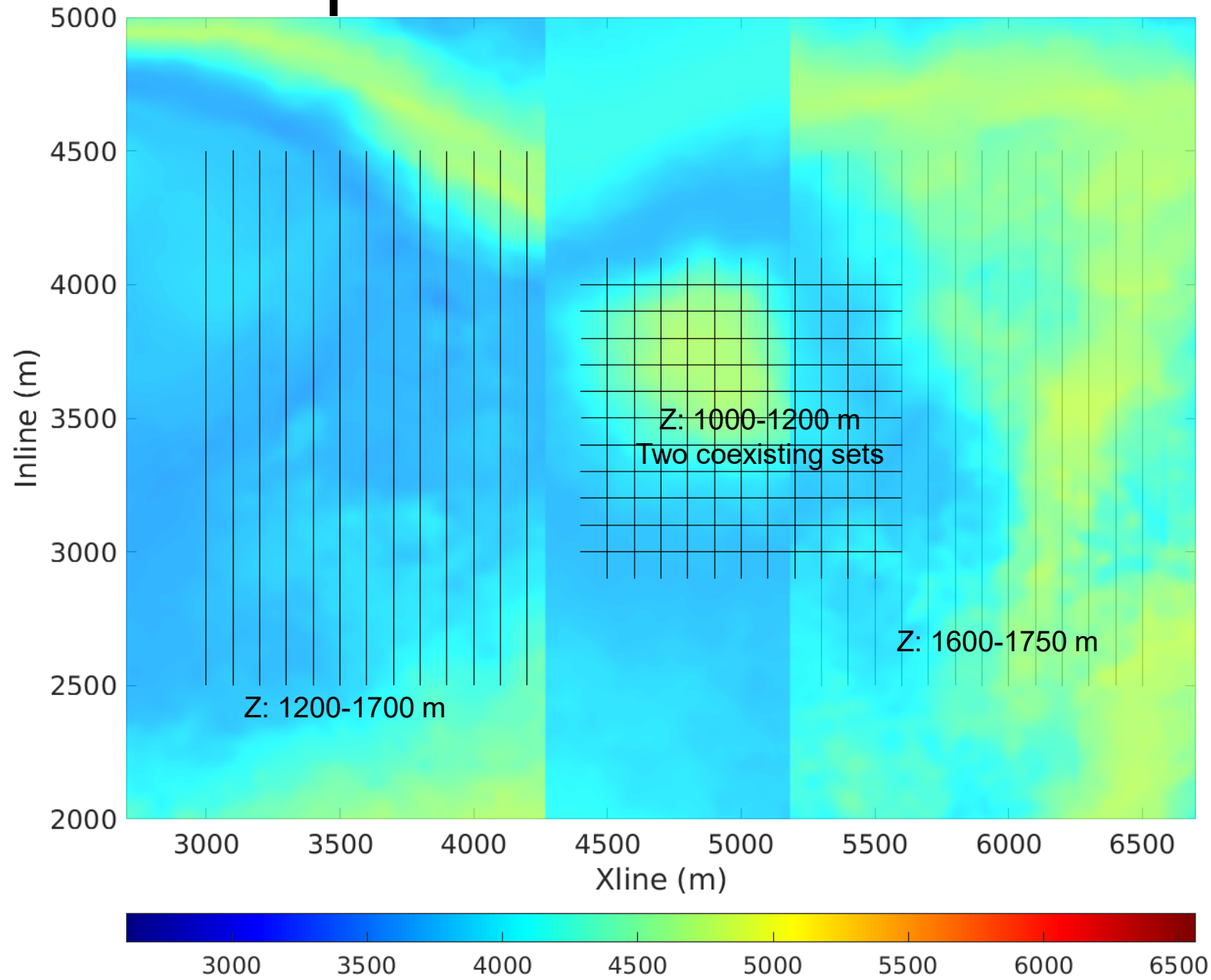
Results: top view of double-beam detected fractures



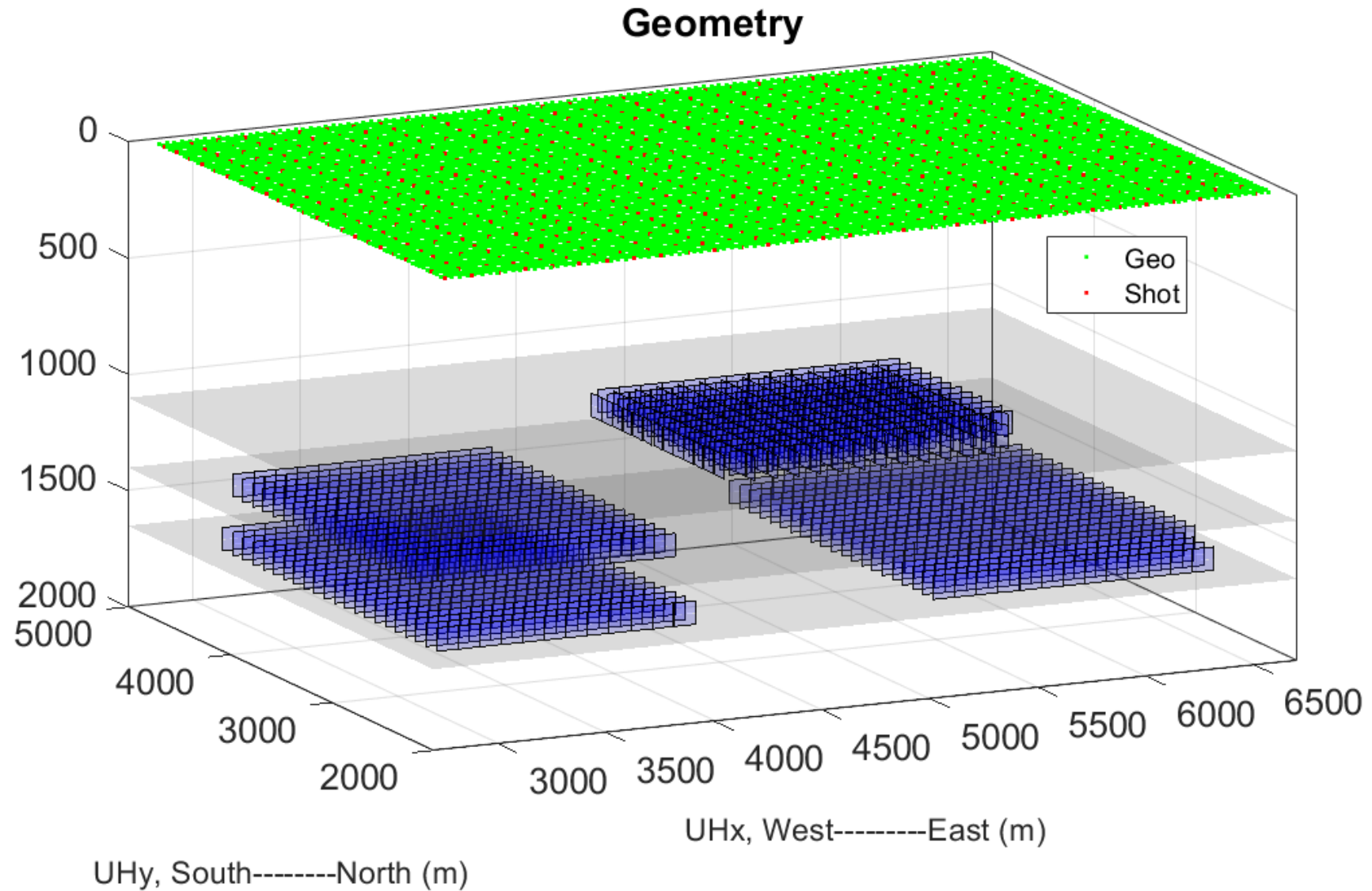
At three depths (1100 m, 1400 m and 1650 m) from frequencies 15 Hz, 20 Hz, 30 Hz and 40 Hz



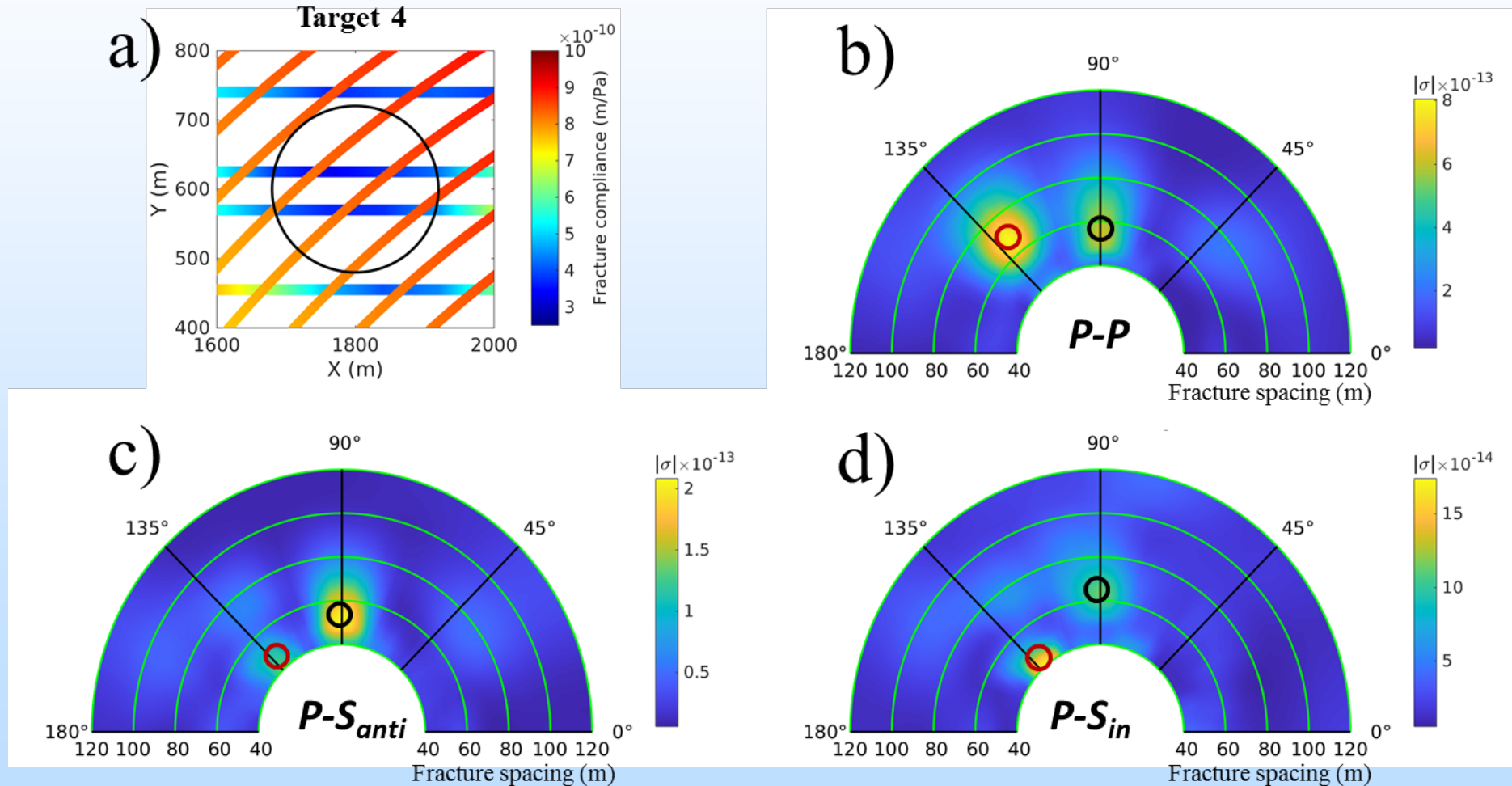
Map view of true fractures



3D view of detected fractures

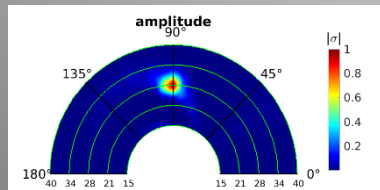


Next steps: discrete fracture network using Machine learning & field data

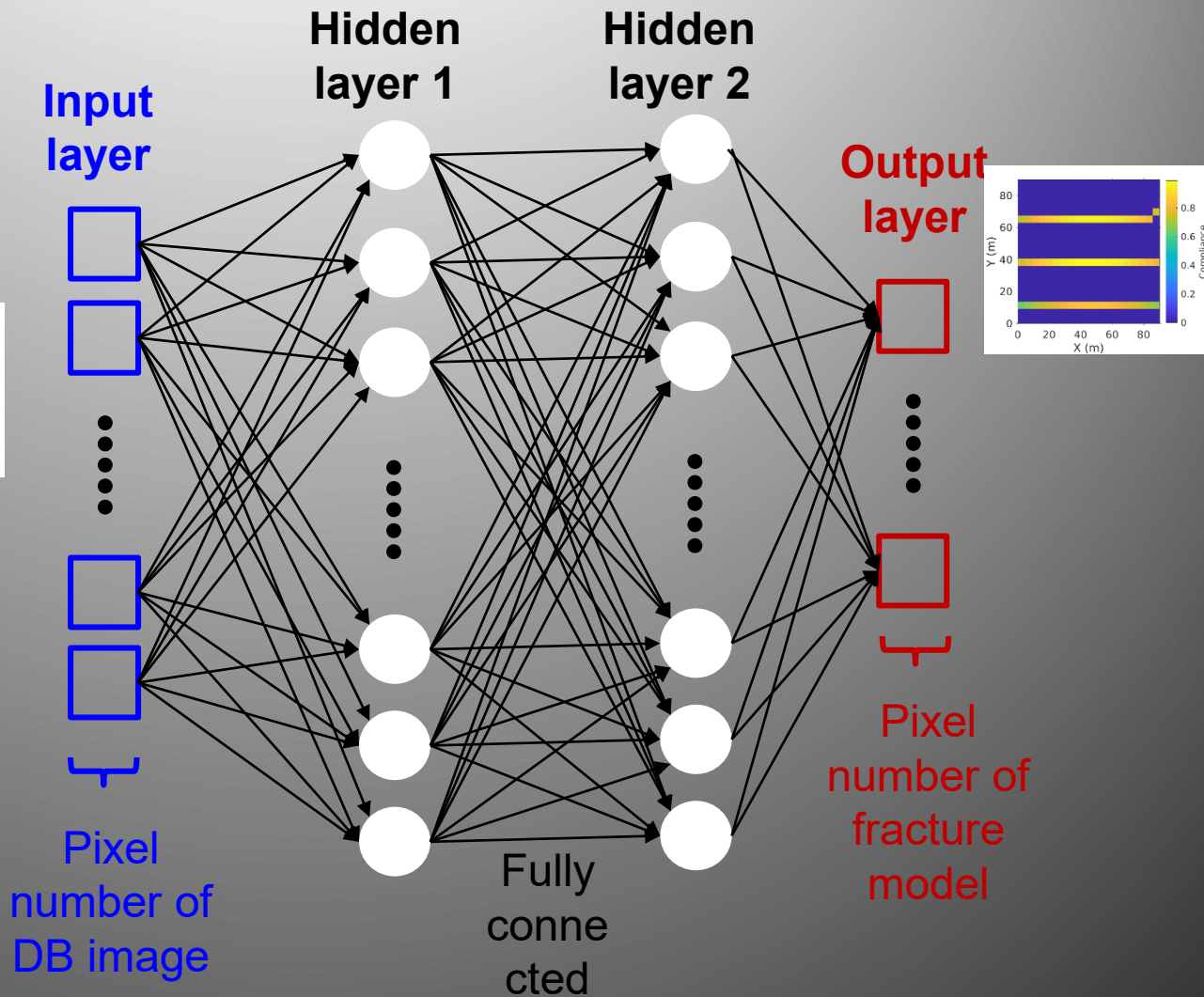


(Zheng et al., 2023 SGW)

Elastic double-beam neural network (DBNN) machine learning

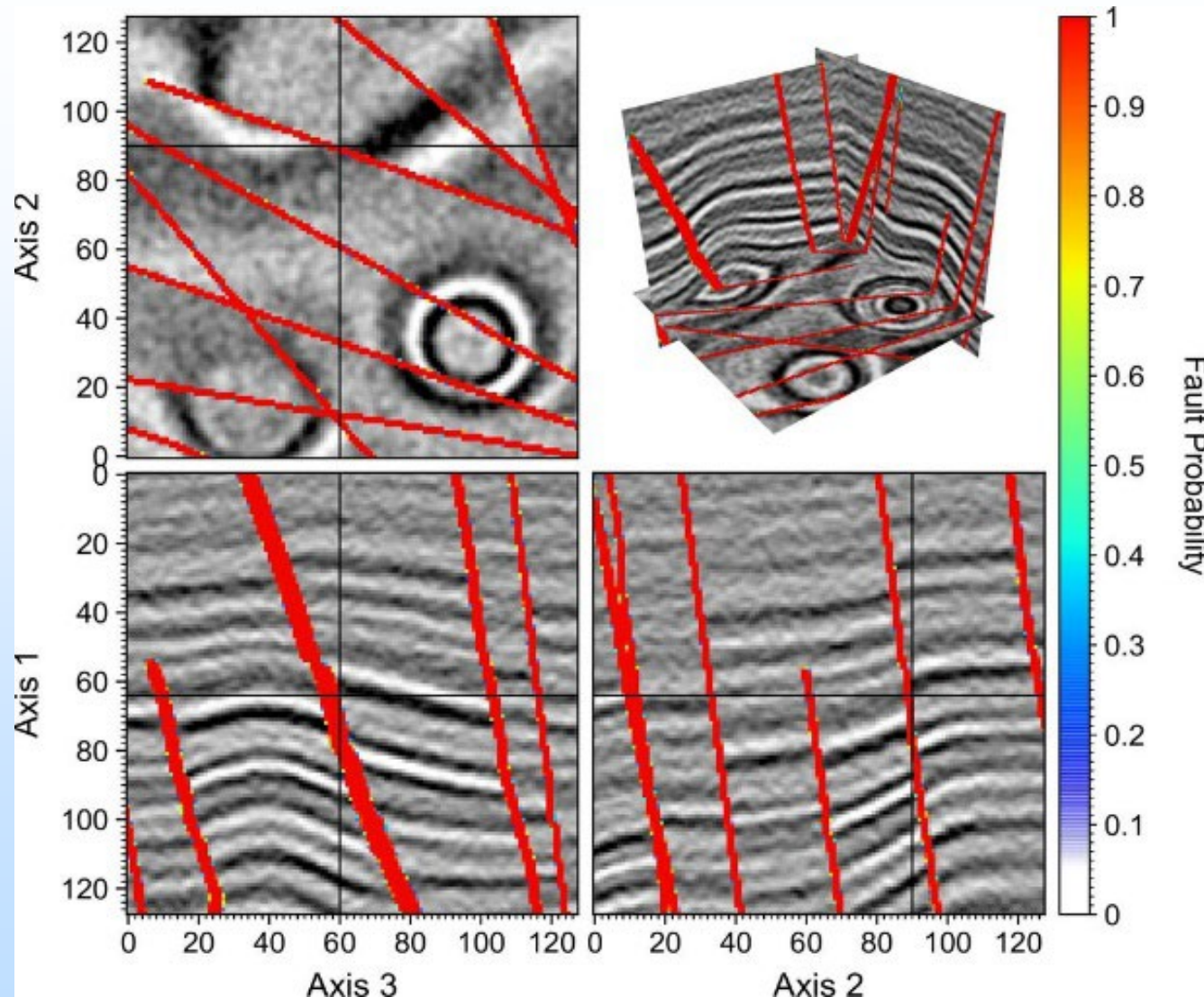


The architecture of our fully-connected neural network including two hidden layers.



Large-scale fault detection using machine learning (LANL)

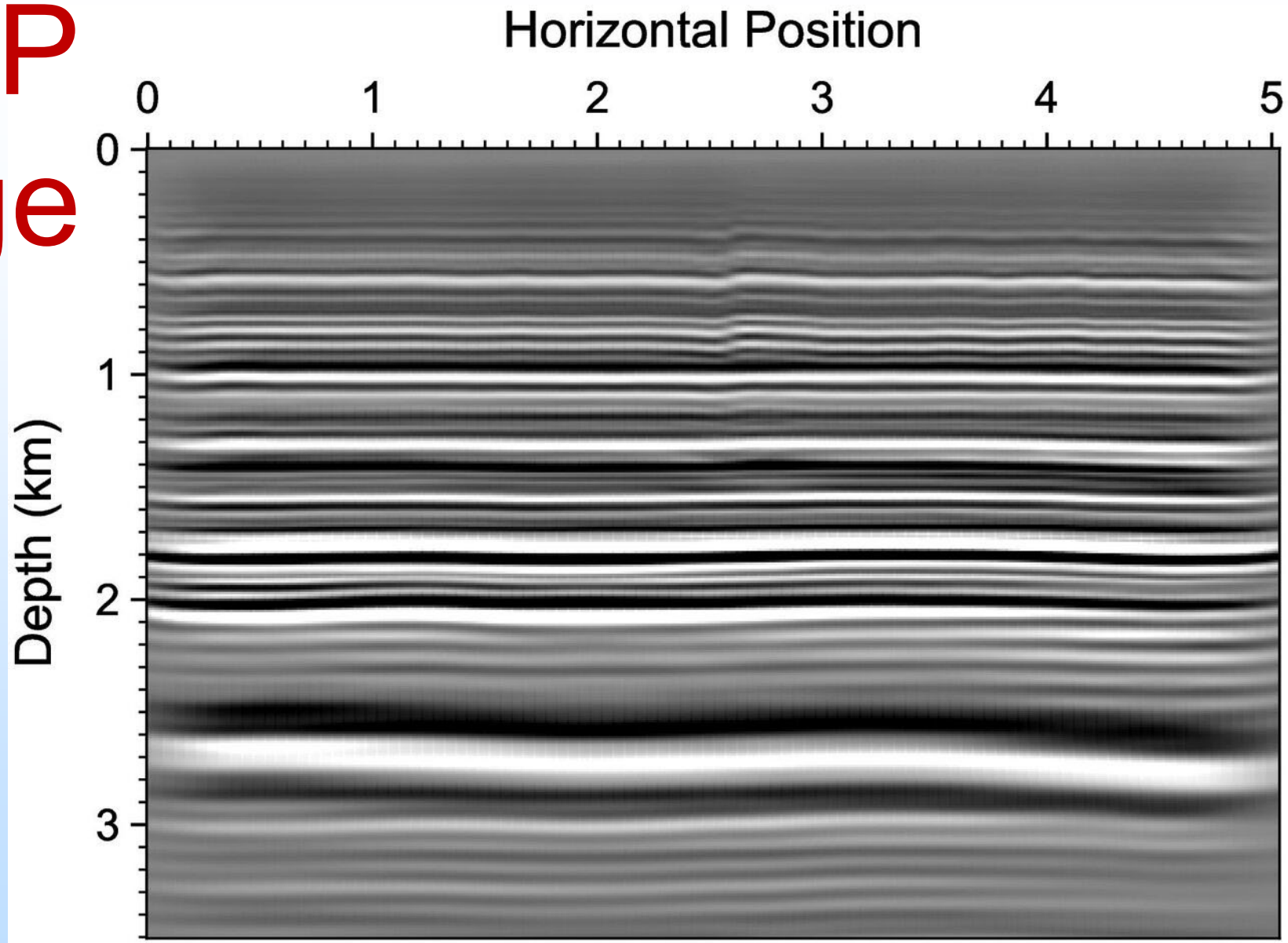
Large-scale faults detected using LANL's new NRU



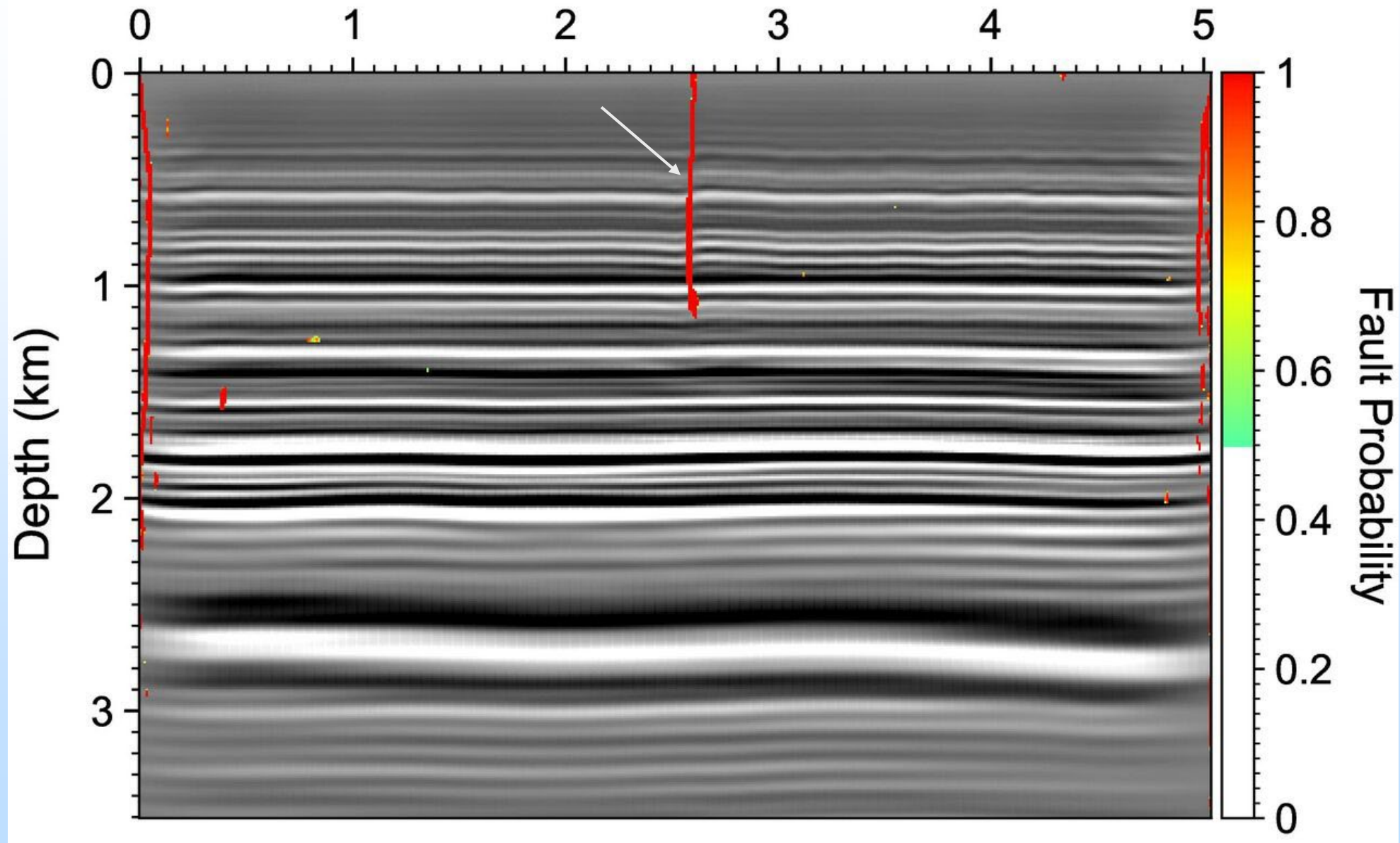
(Gao, Huang, Zheng 2022;
IEEE TGRS)

Nested Residual U-shaped convolutional neural network (NRU)

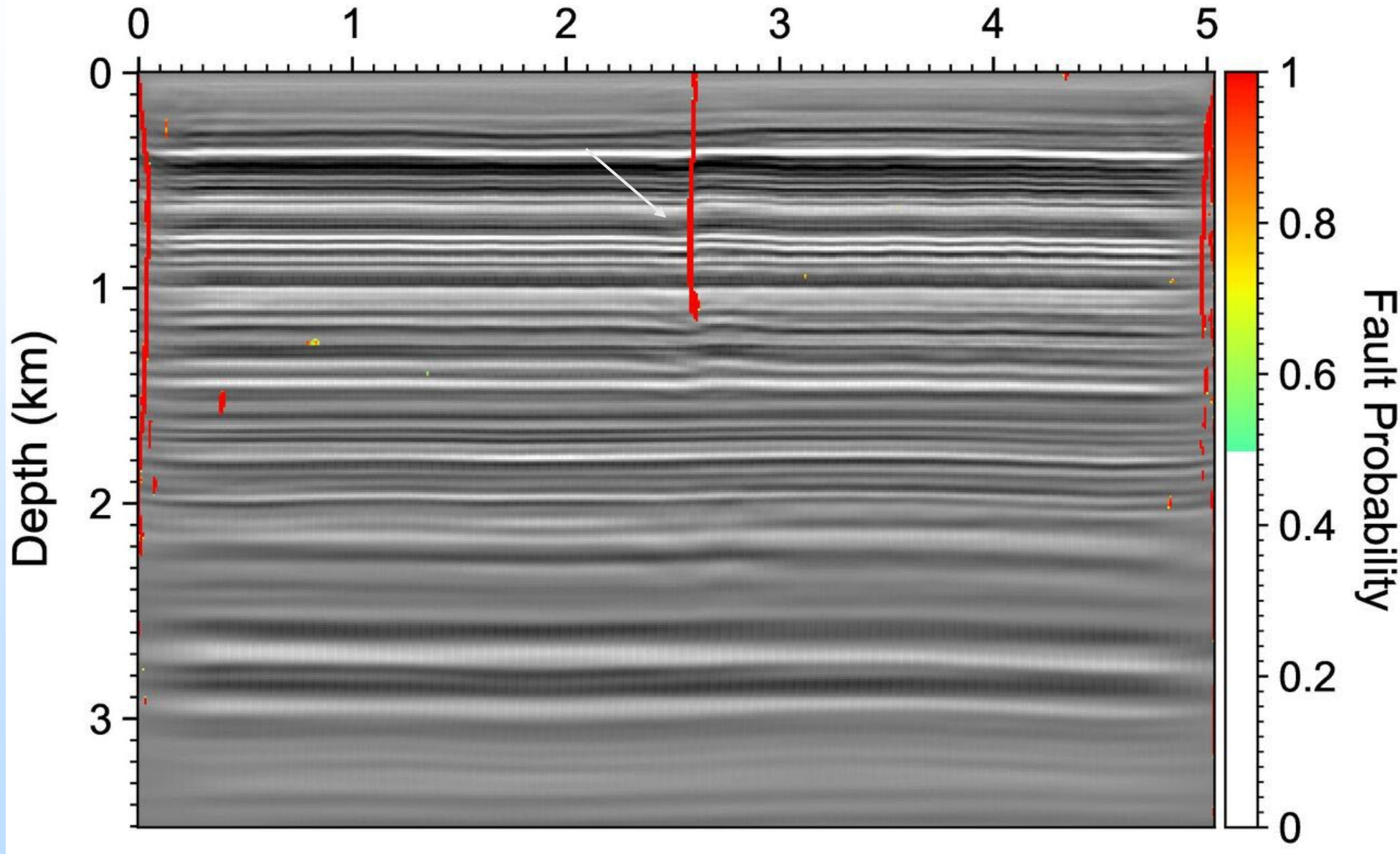
Fz PP image



Detected large scale faults using P-P data

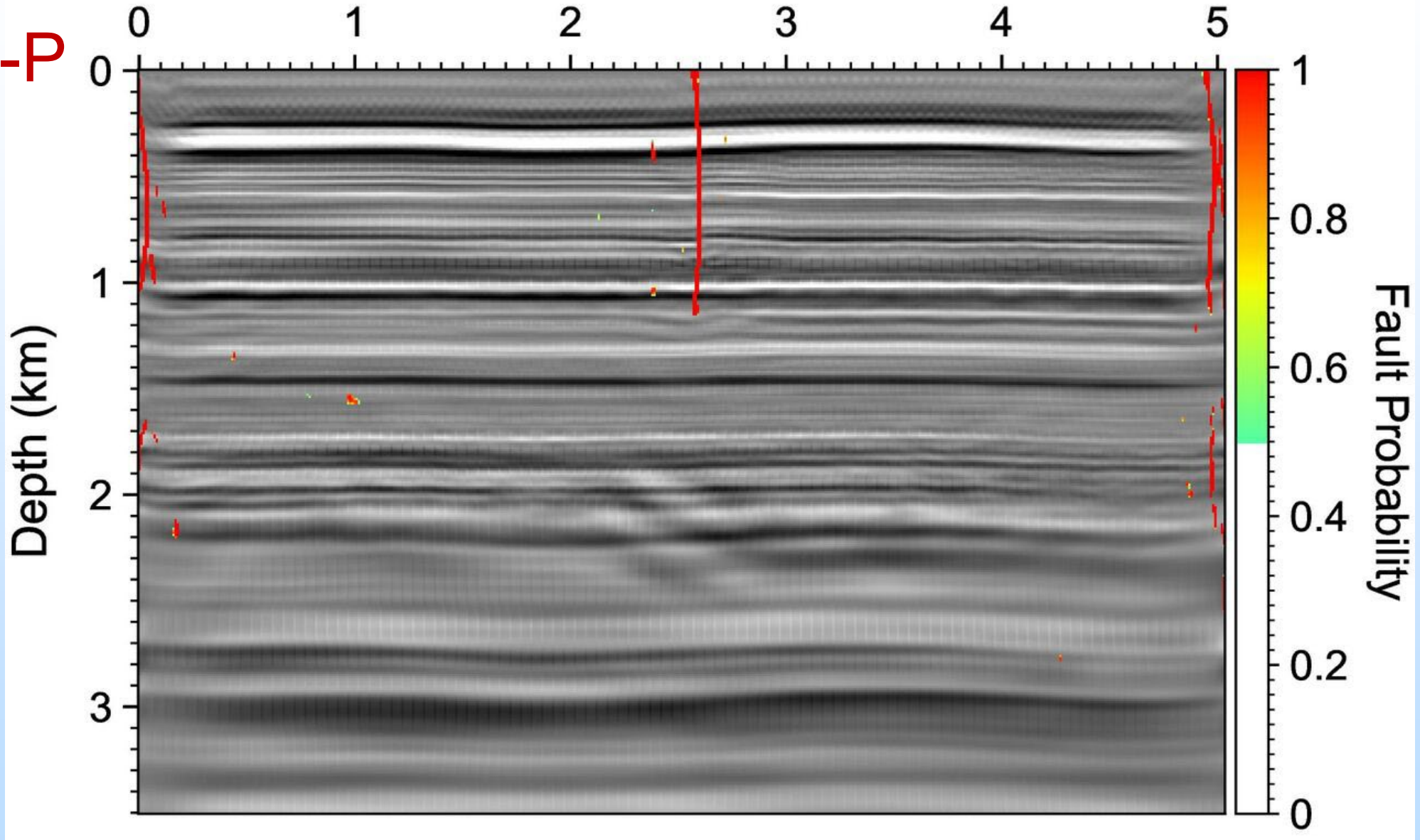


Detected large scale faults using P-S data

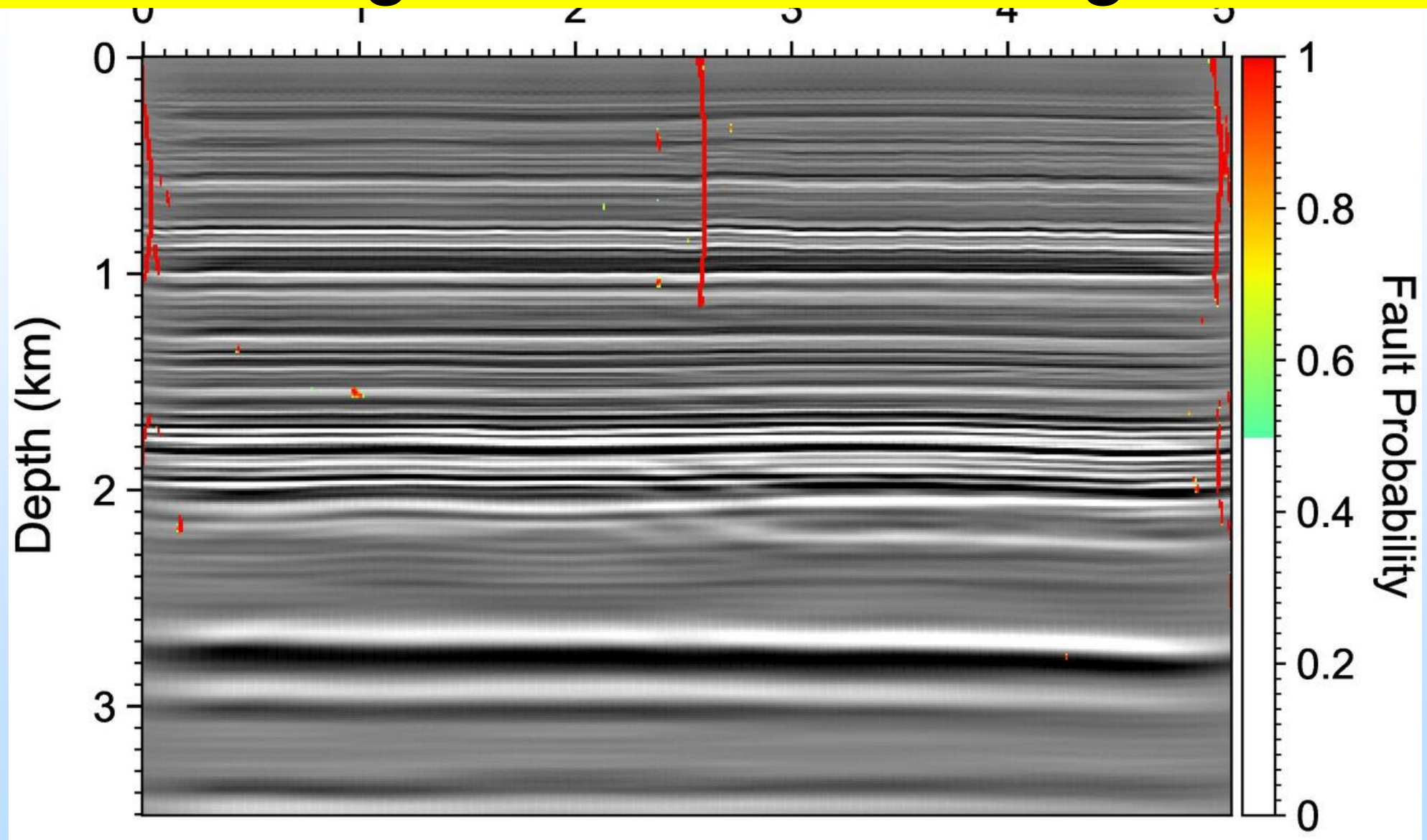


Detected large scale faults using S-P data

Fx: S-P



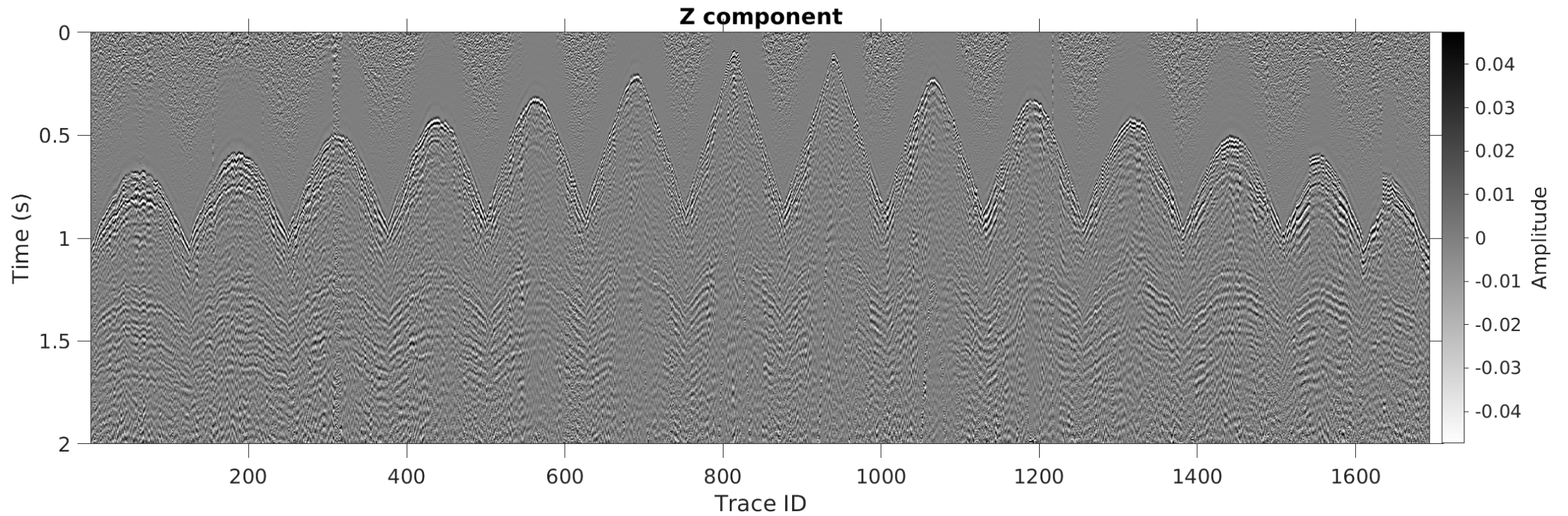
Detected large scale faults using S-S data



Lessons from: large-scale fault and small-scale fracture detection

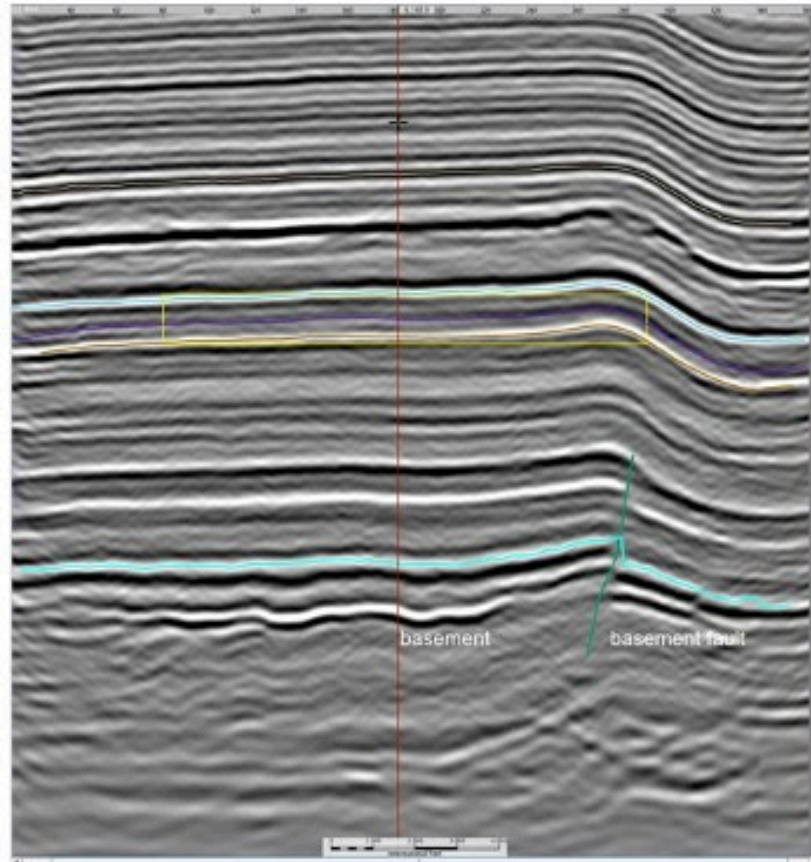
- Different modes (P-P, P-S, S-P, S-S) give consistent results.
- The consistency reduces uncertainties & yields high confidence in the results.

Field data

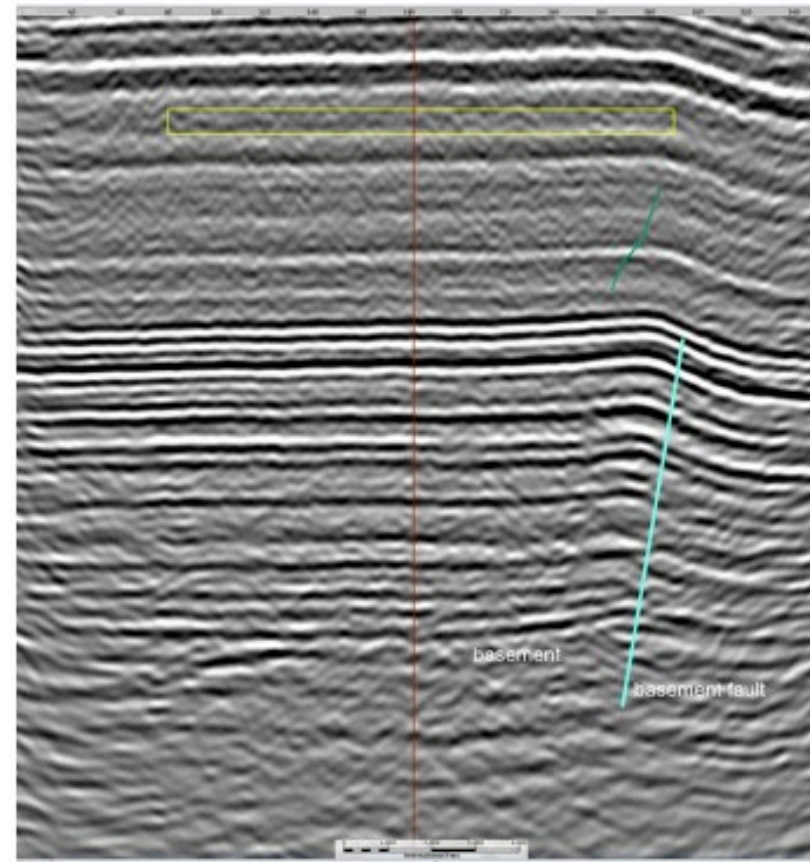


Vertical vibreseis

Field data: Fractures and Basement faults (Vecta processing)

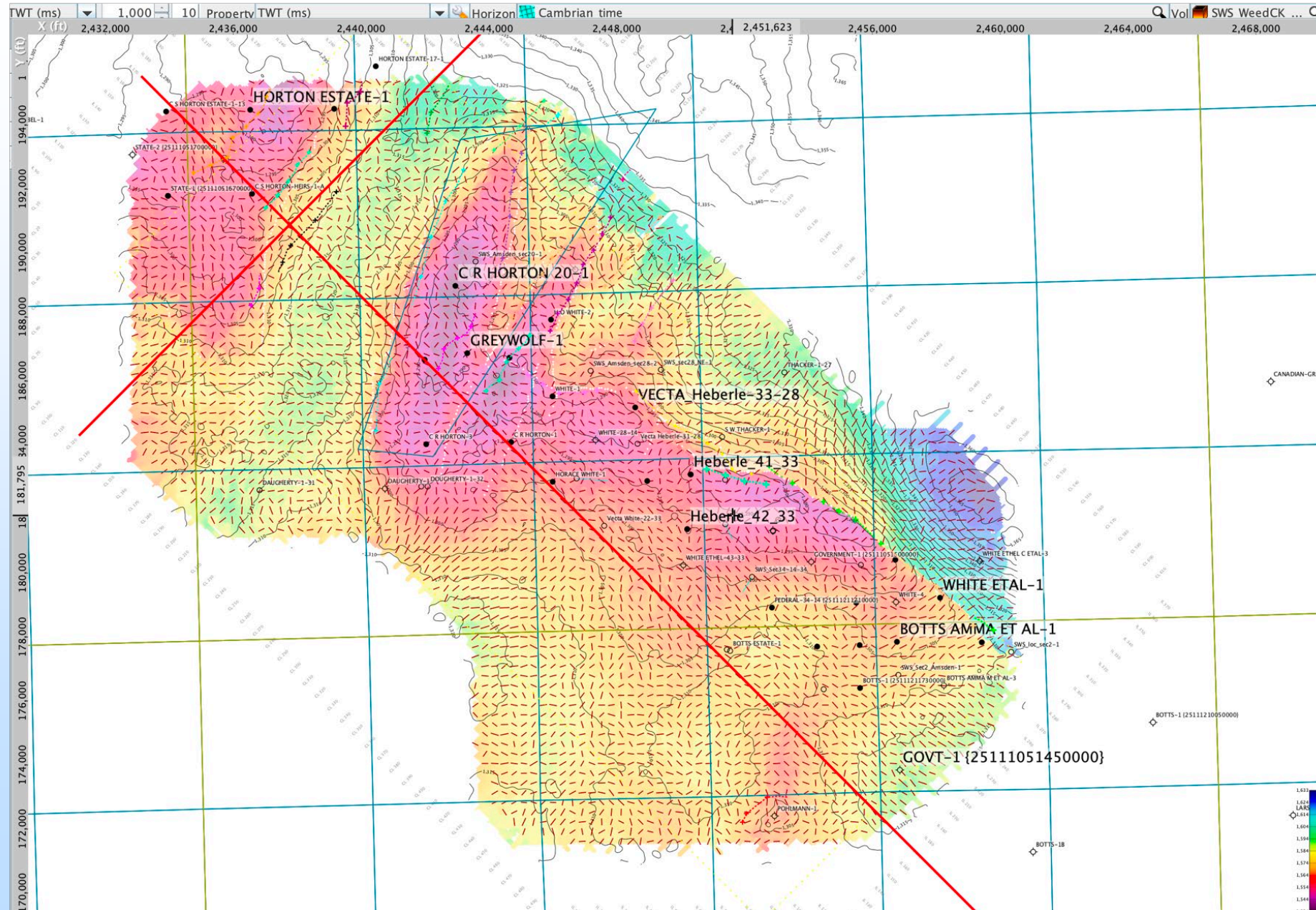


(a) PP image



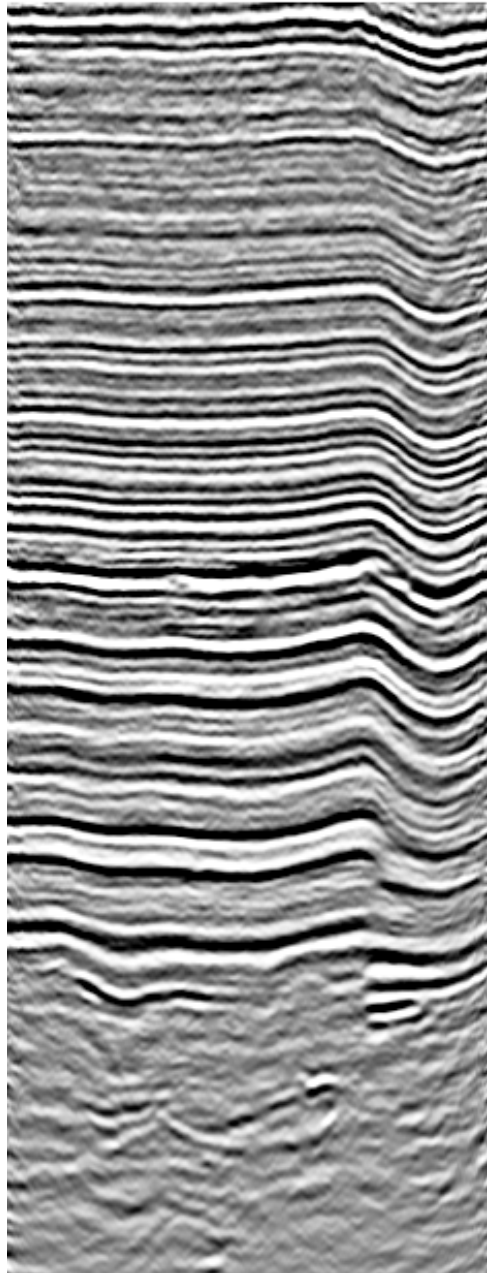
(b) SP image

Fast azimuths from Bani corendered with Cambrian time structure: this will be compared with directions from splitting analysis in future

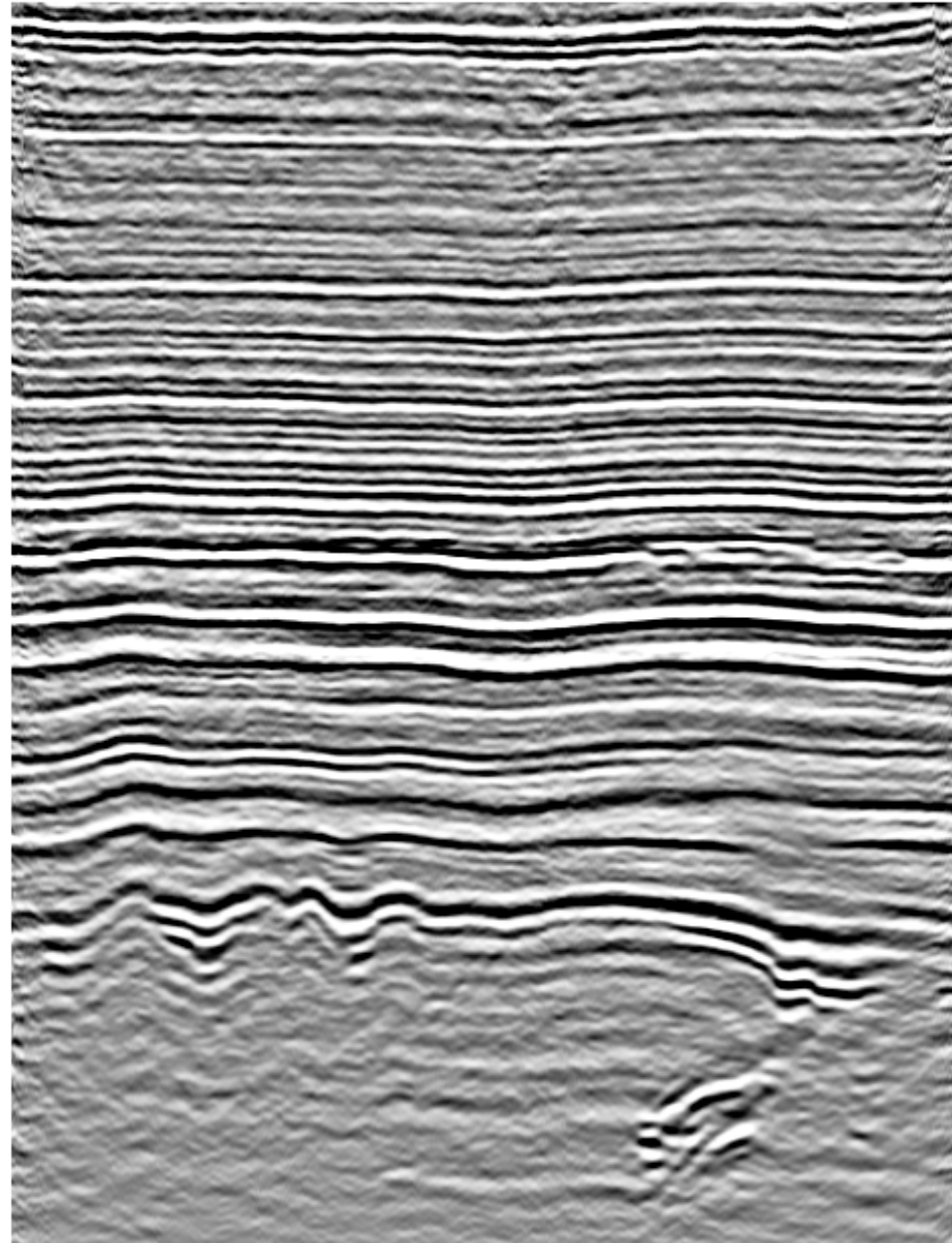


PP Images

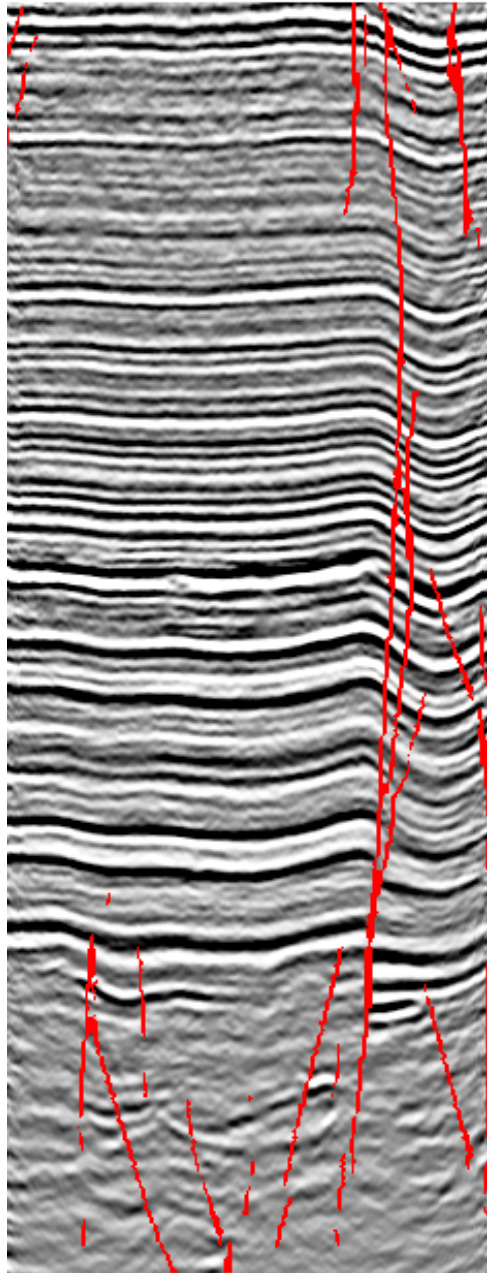
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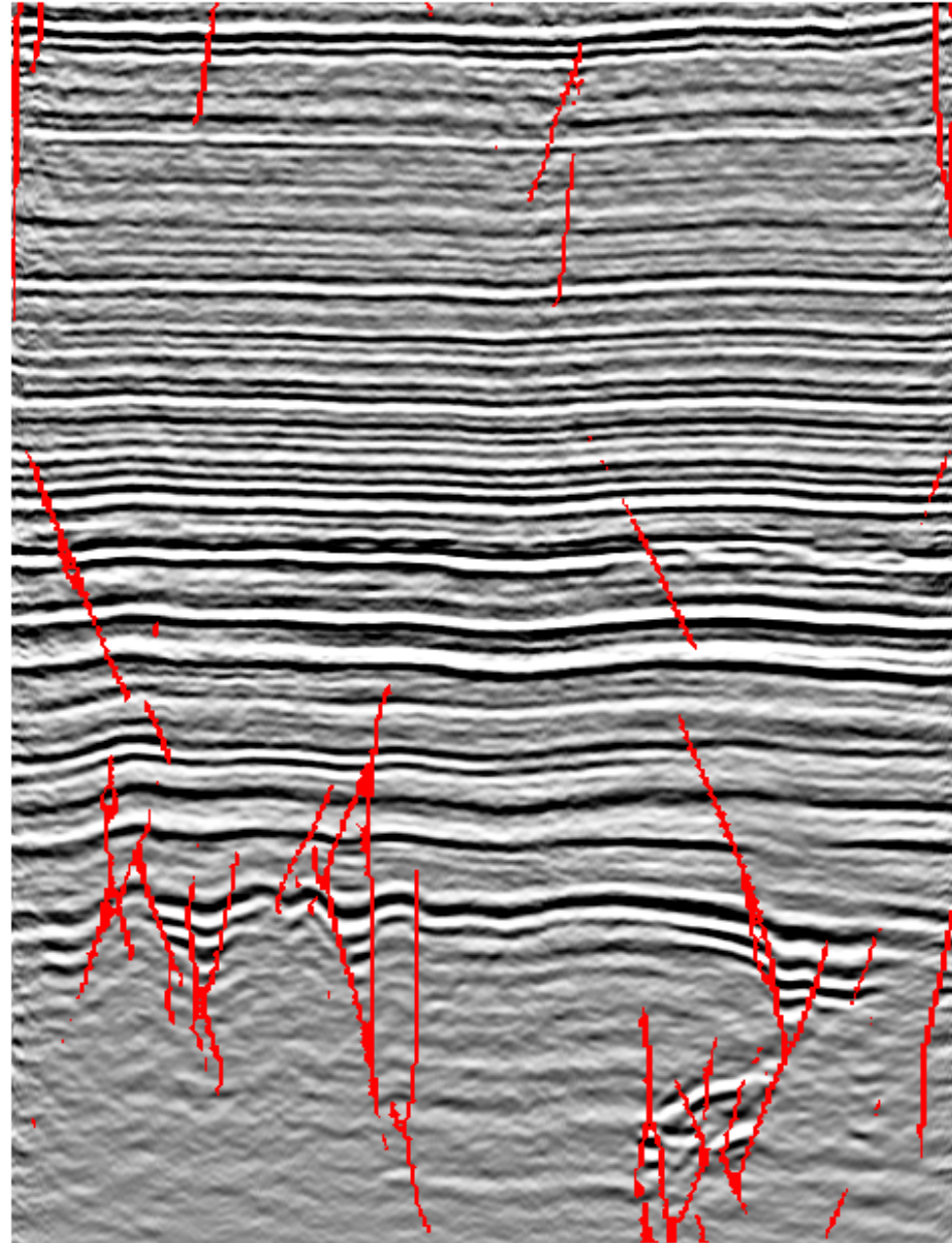
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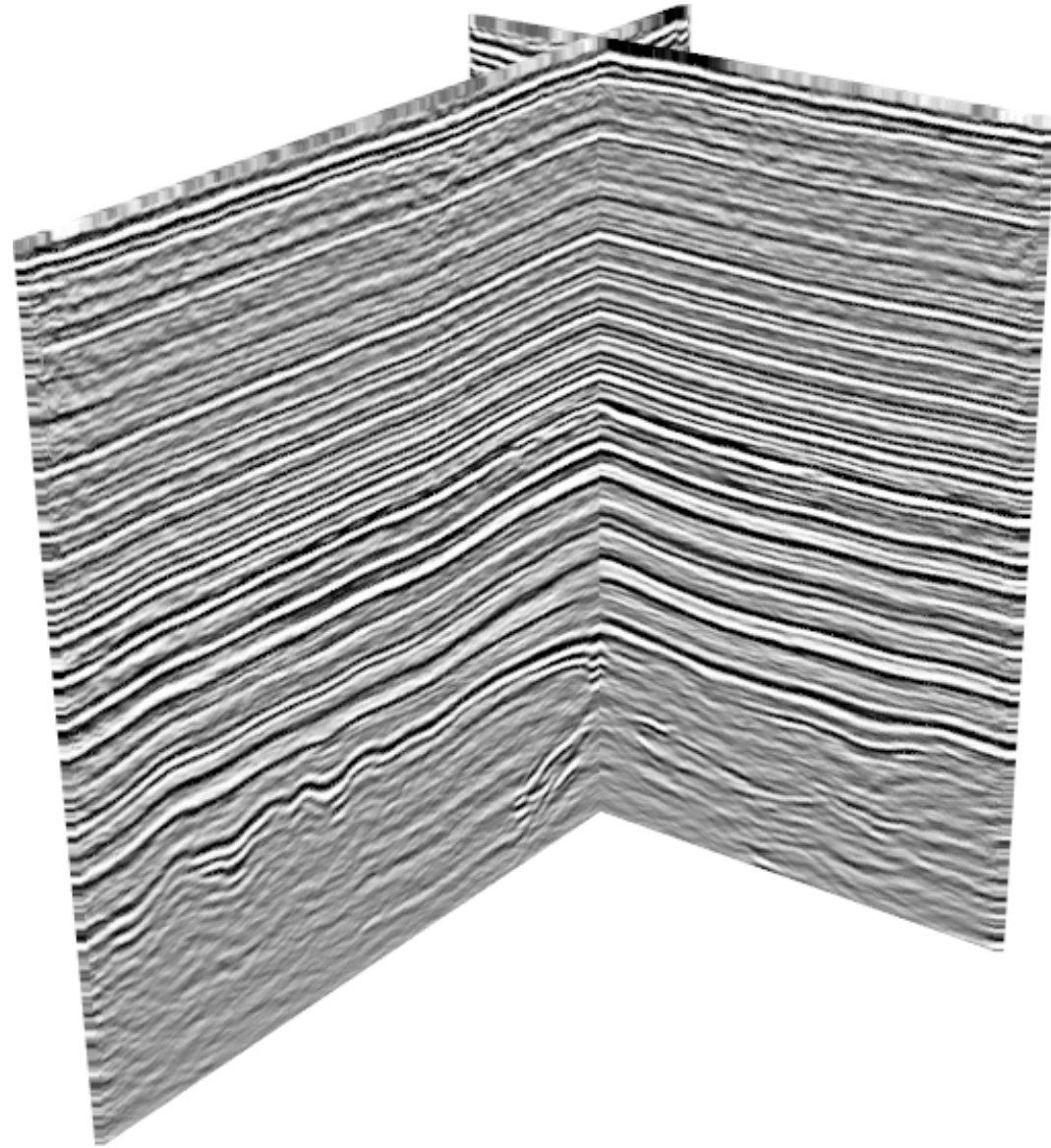


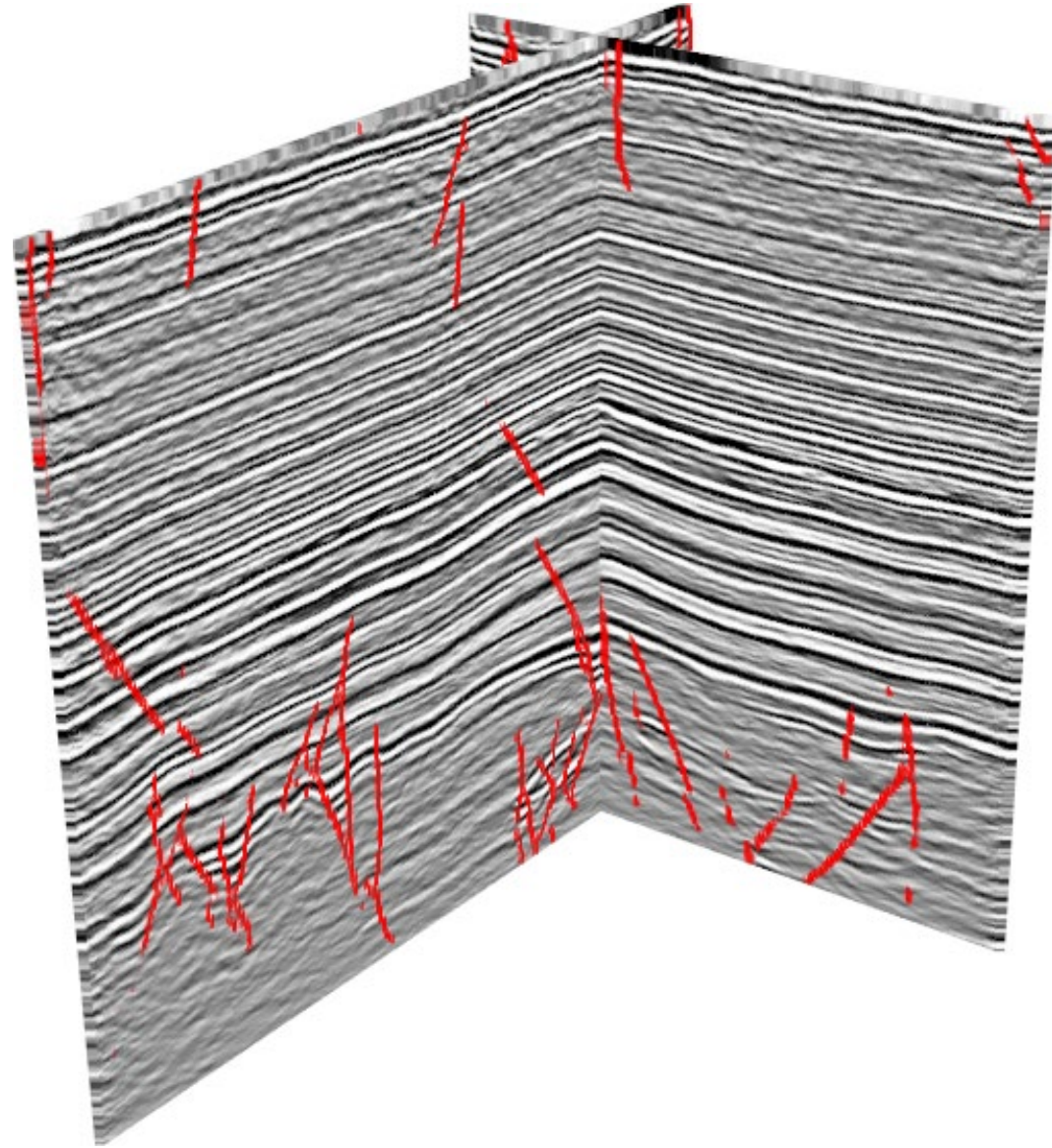
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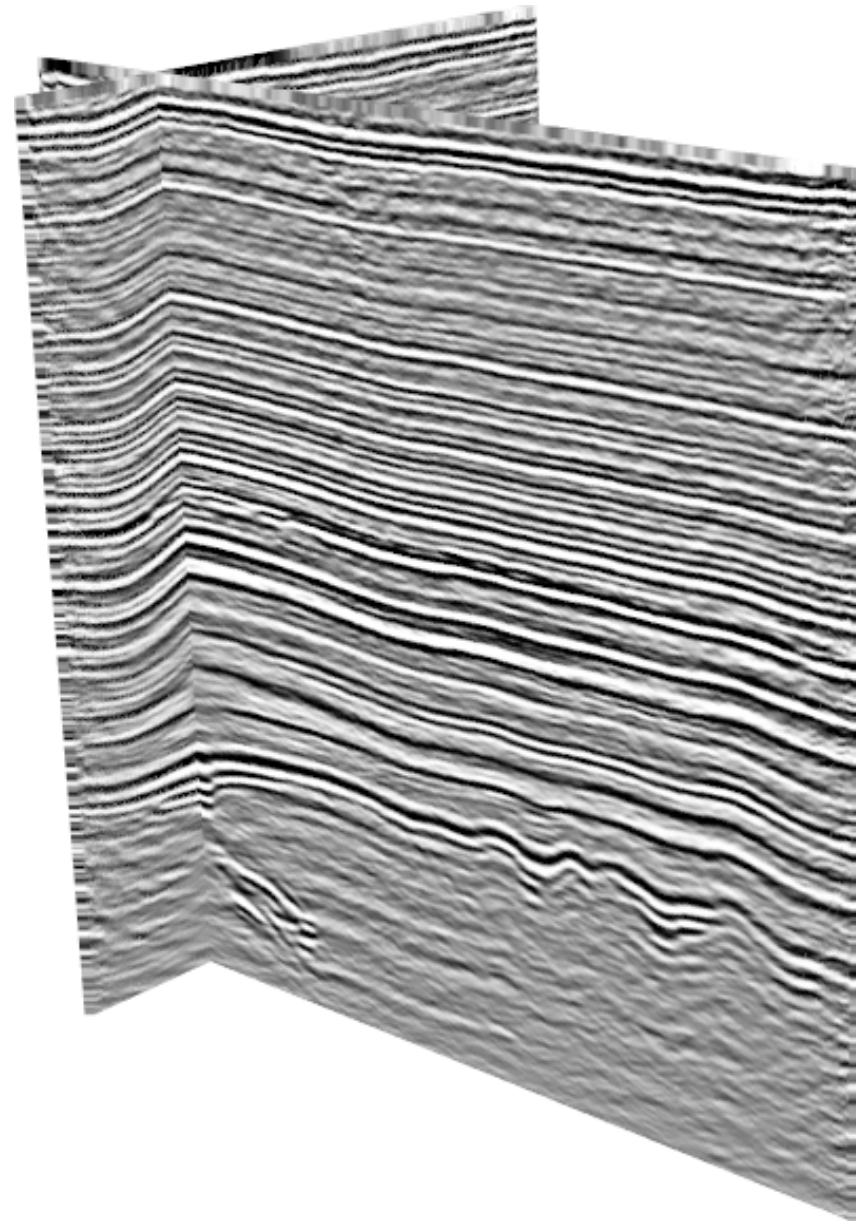


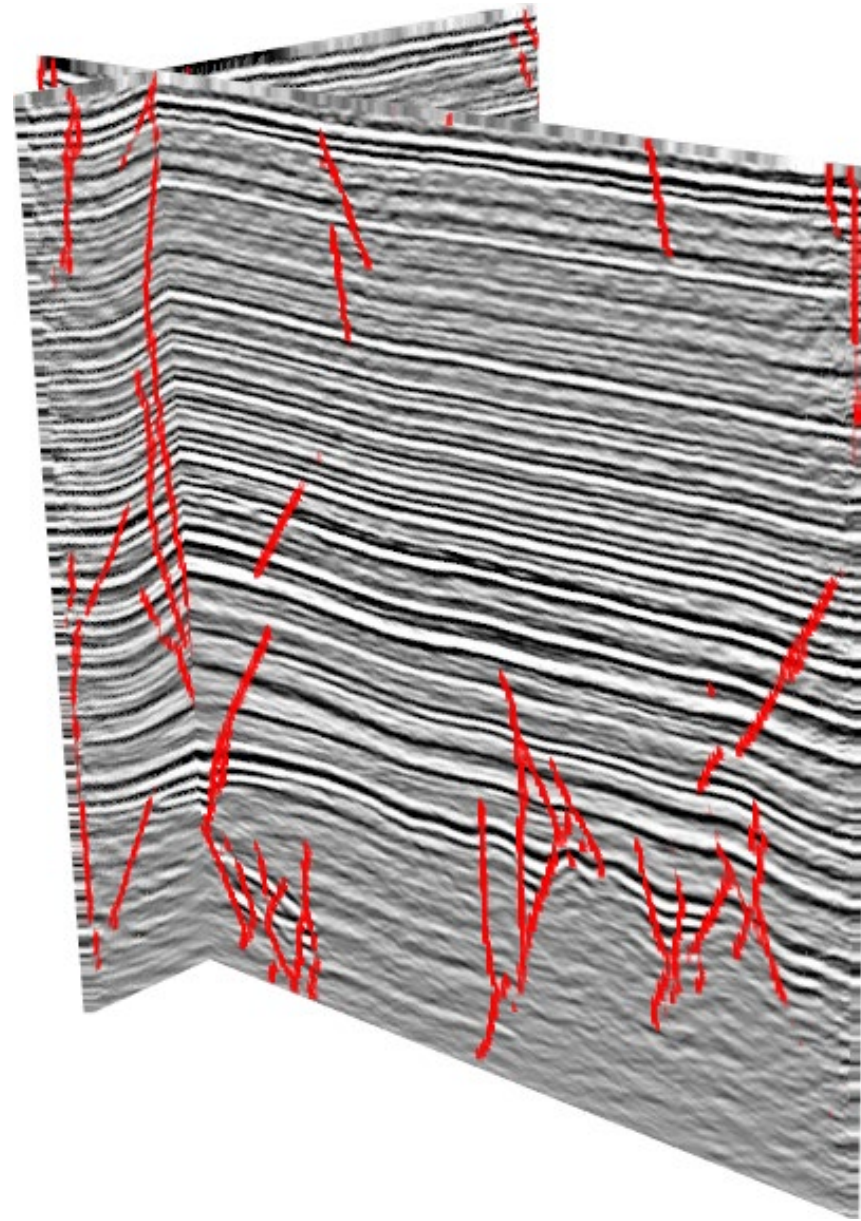
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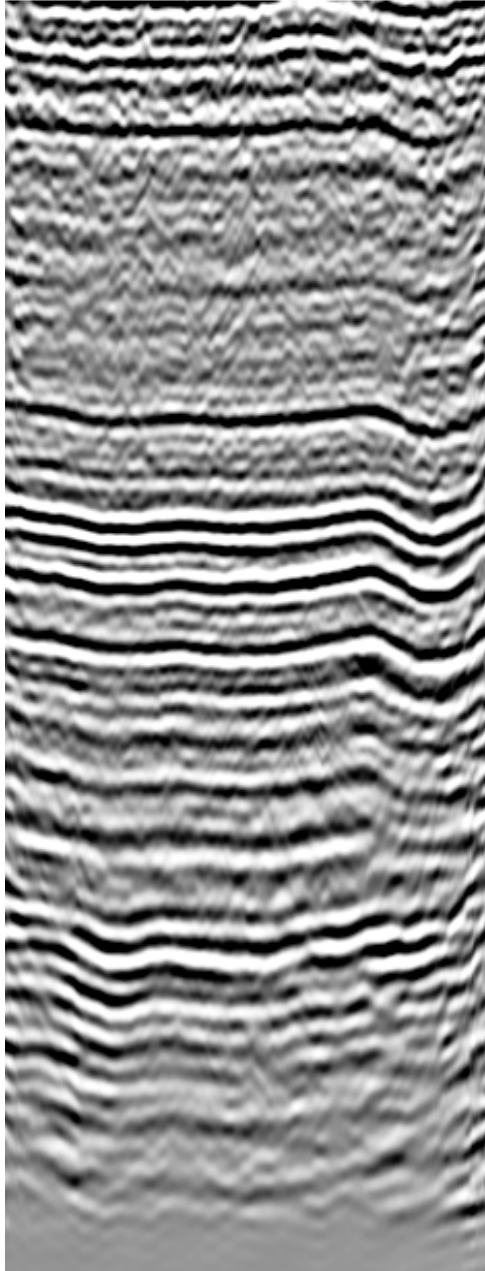




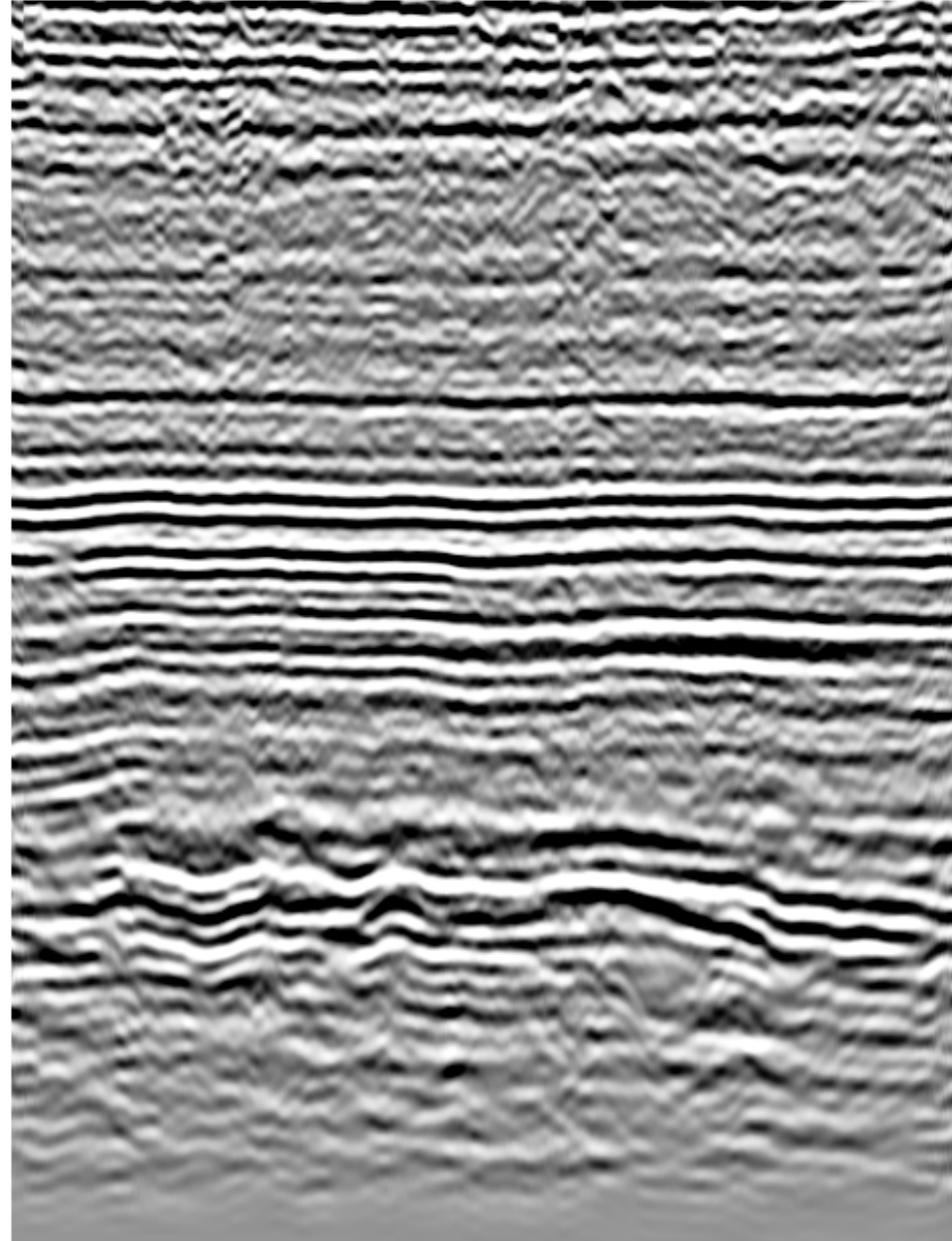


TT Images

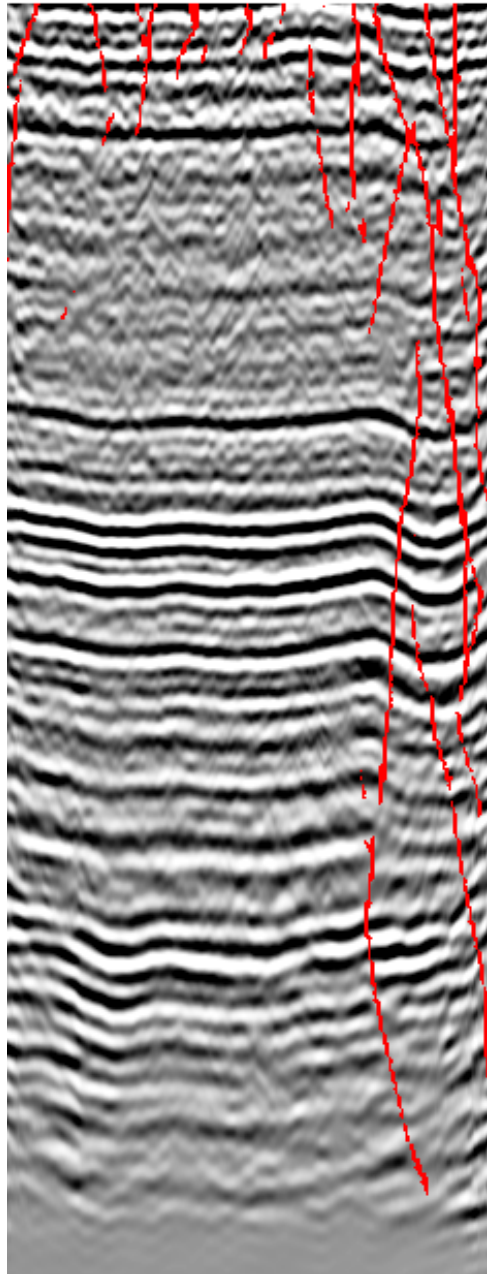
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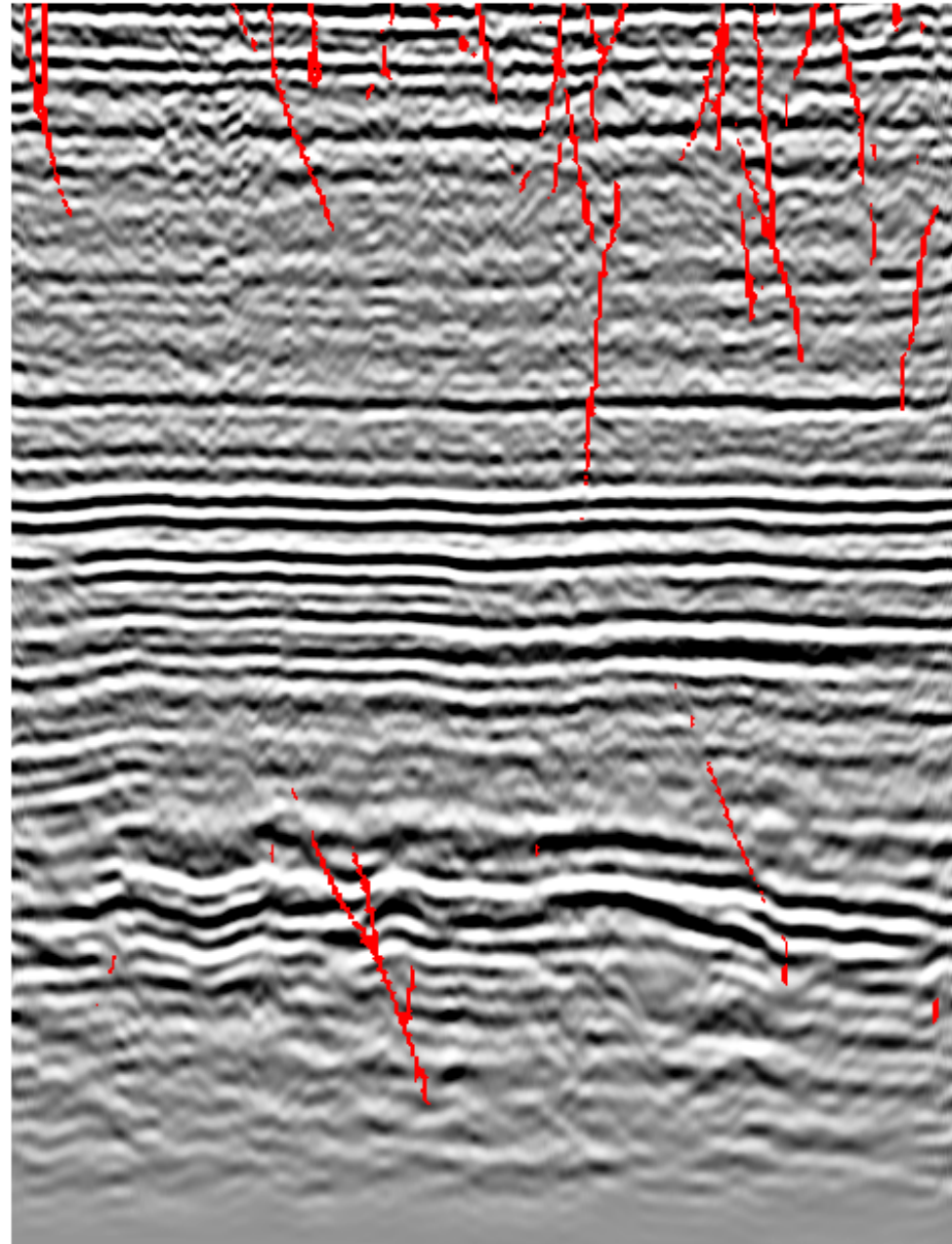
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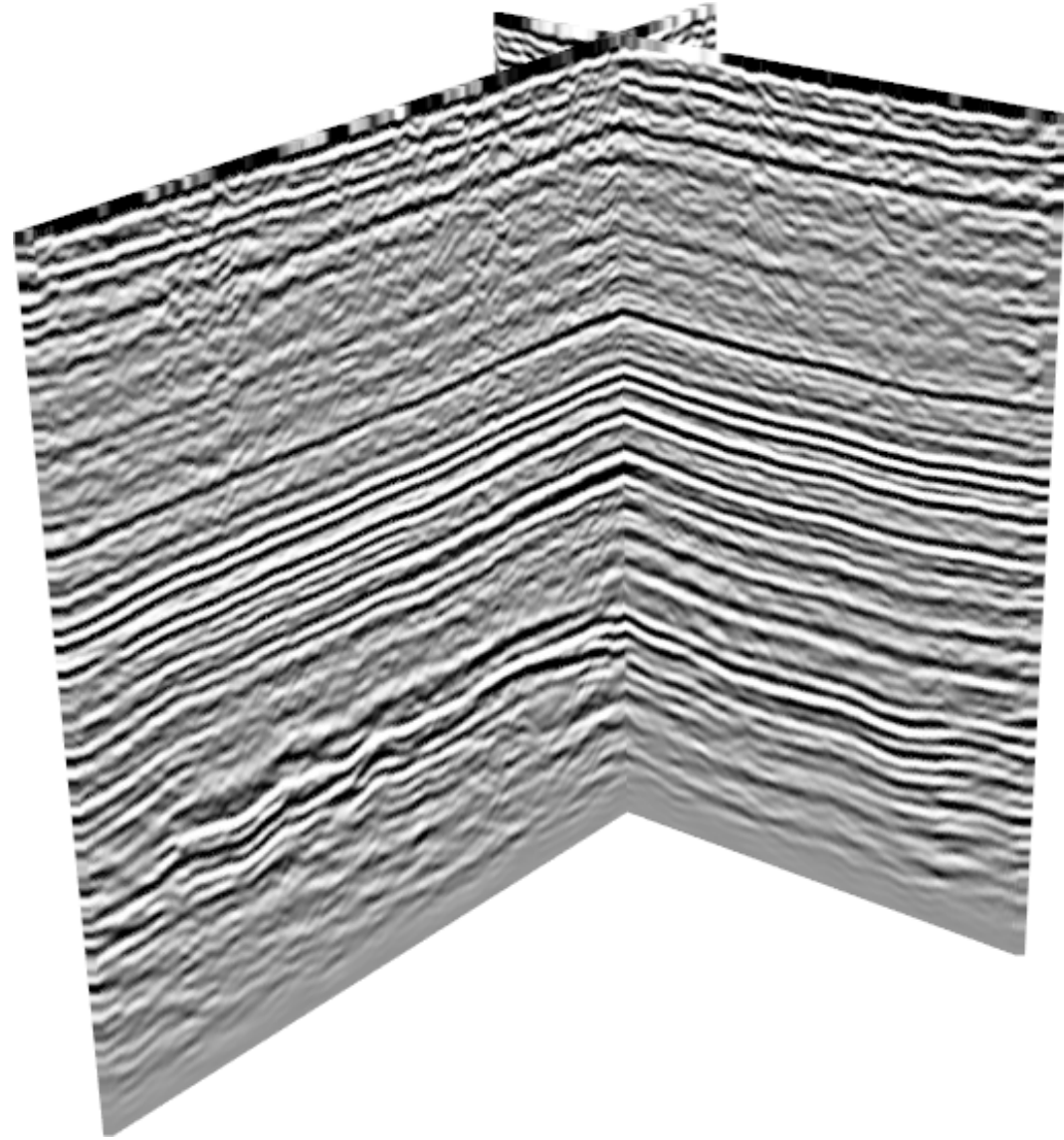


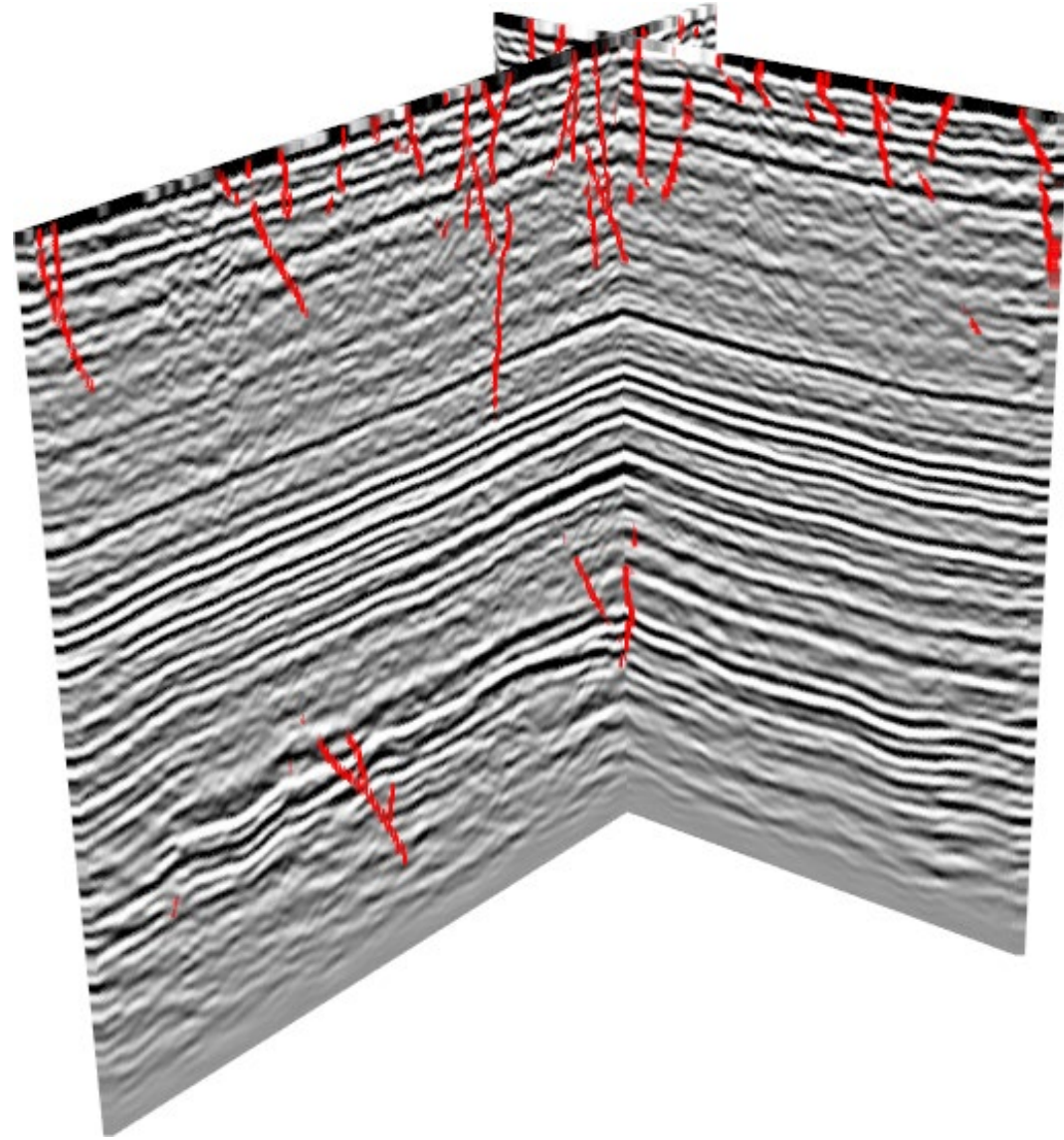
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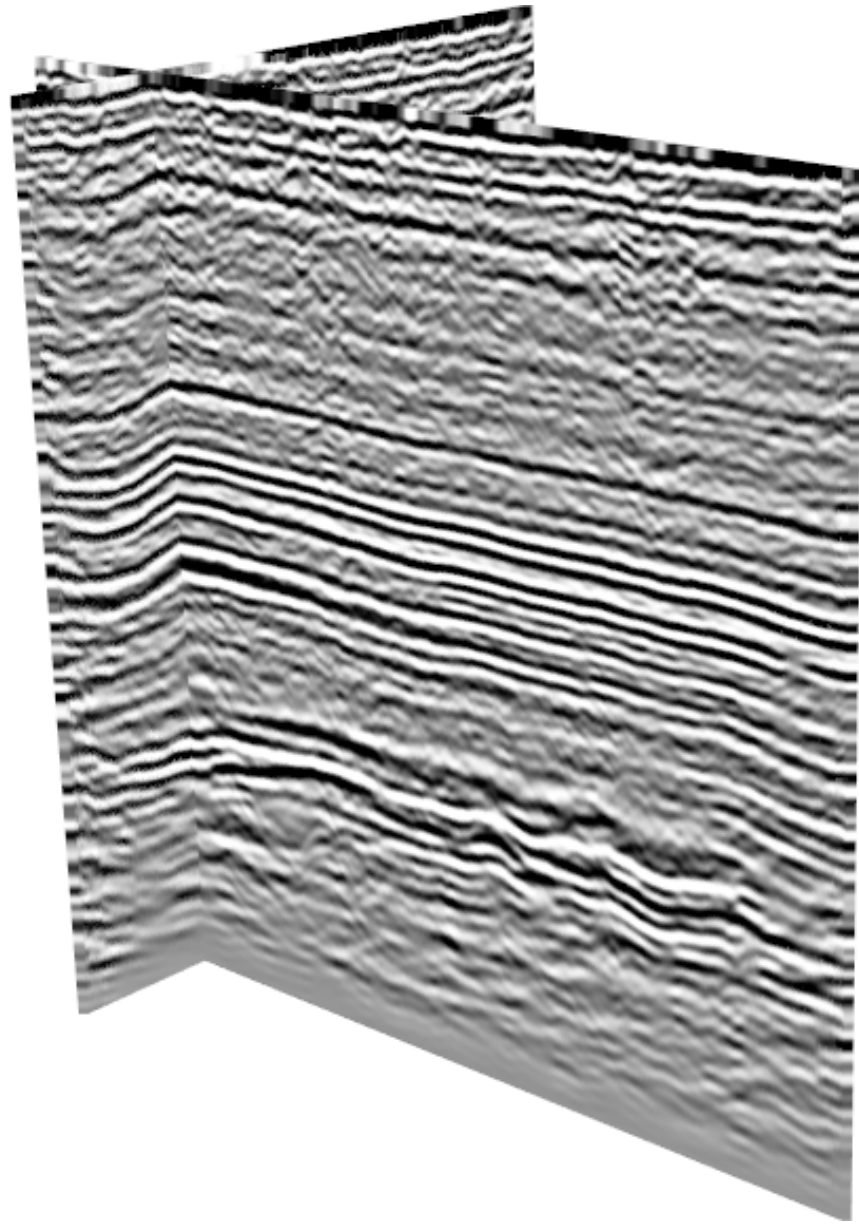


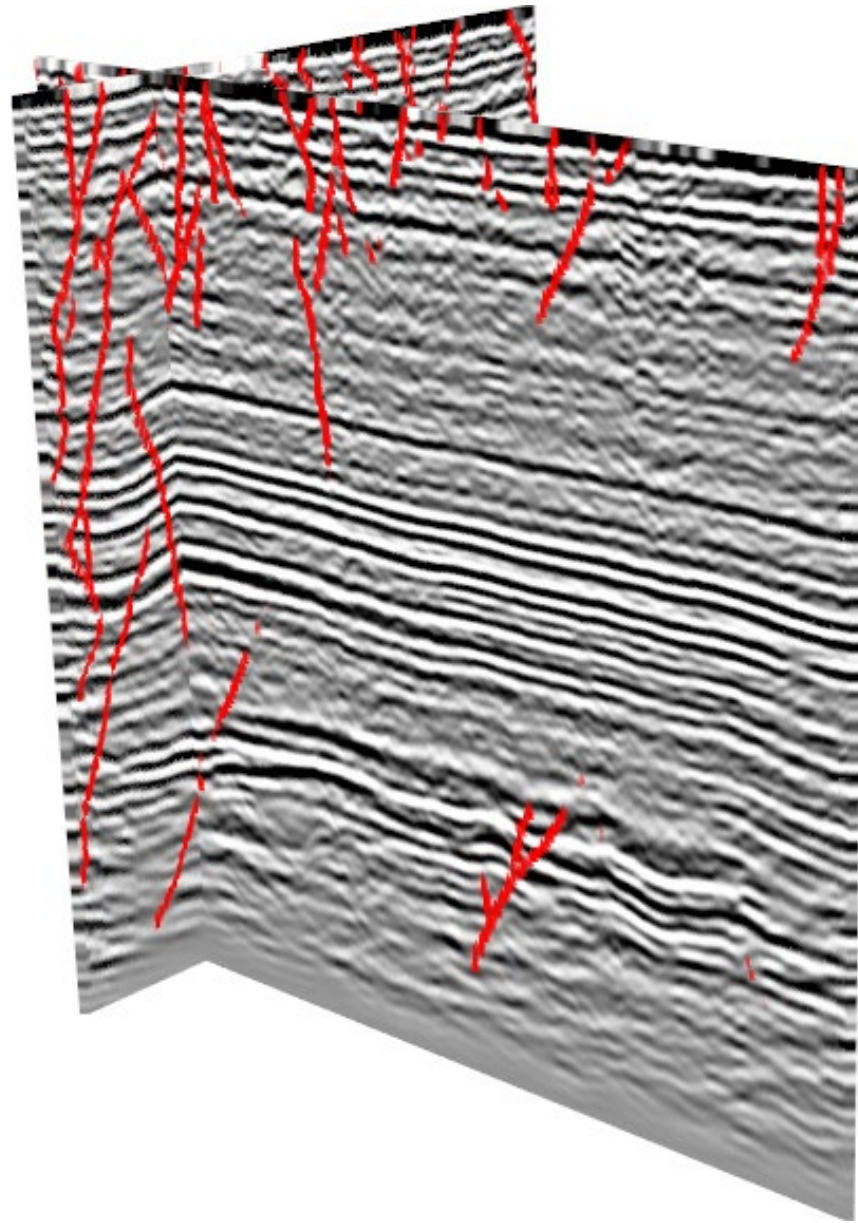
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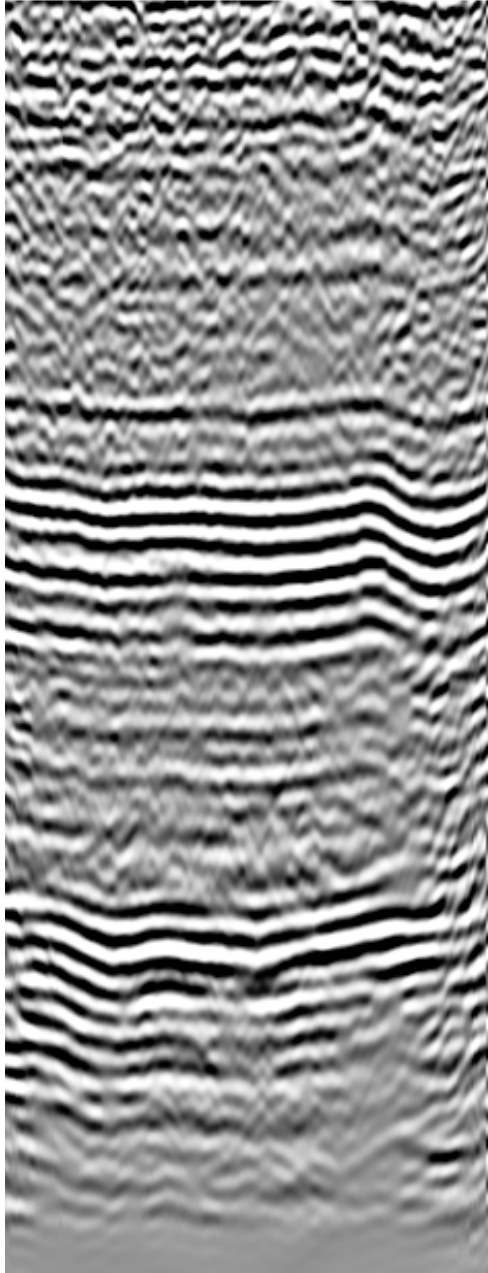




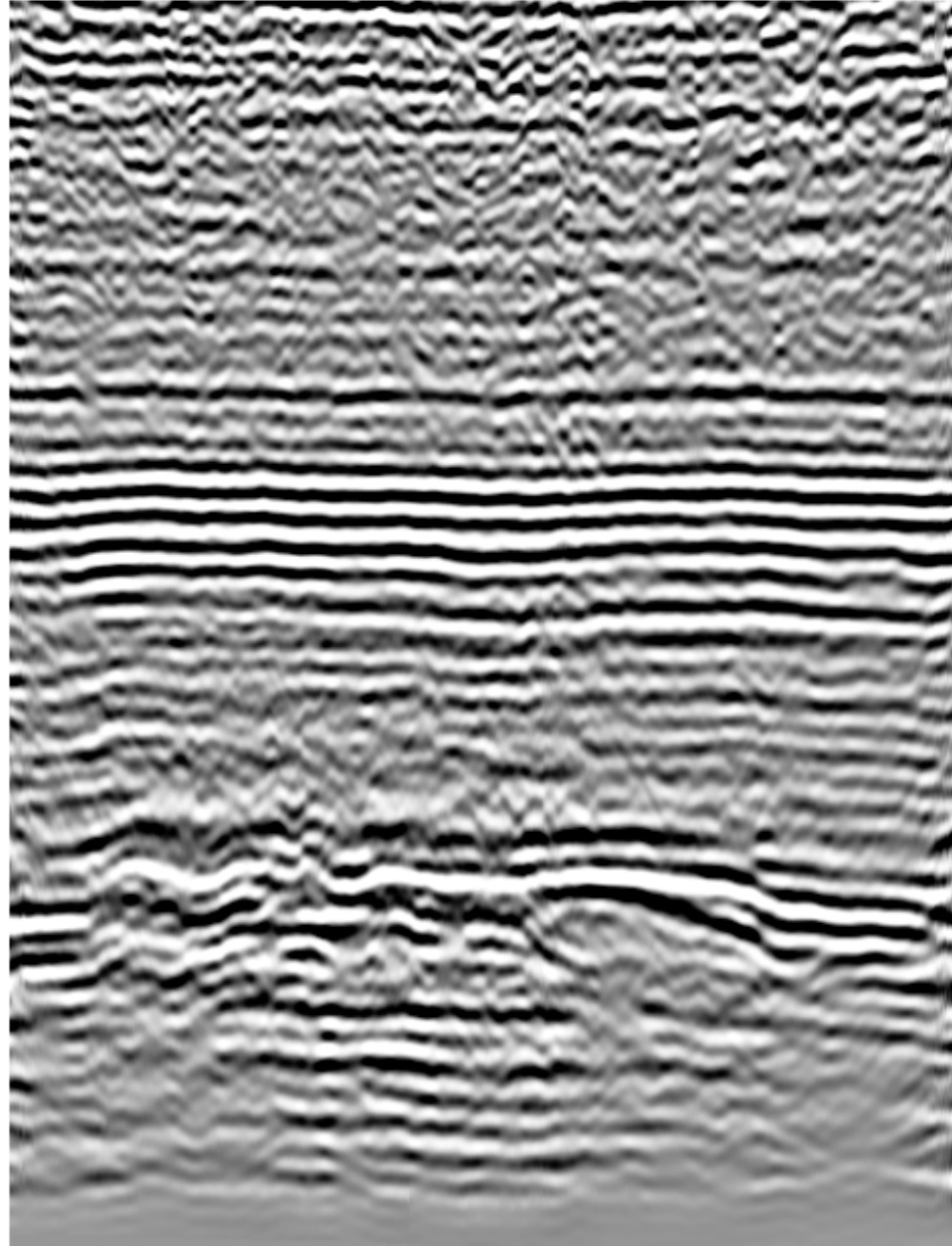


RR Images

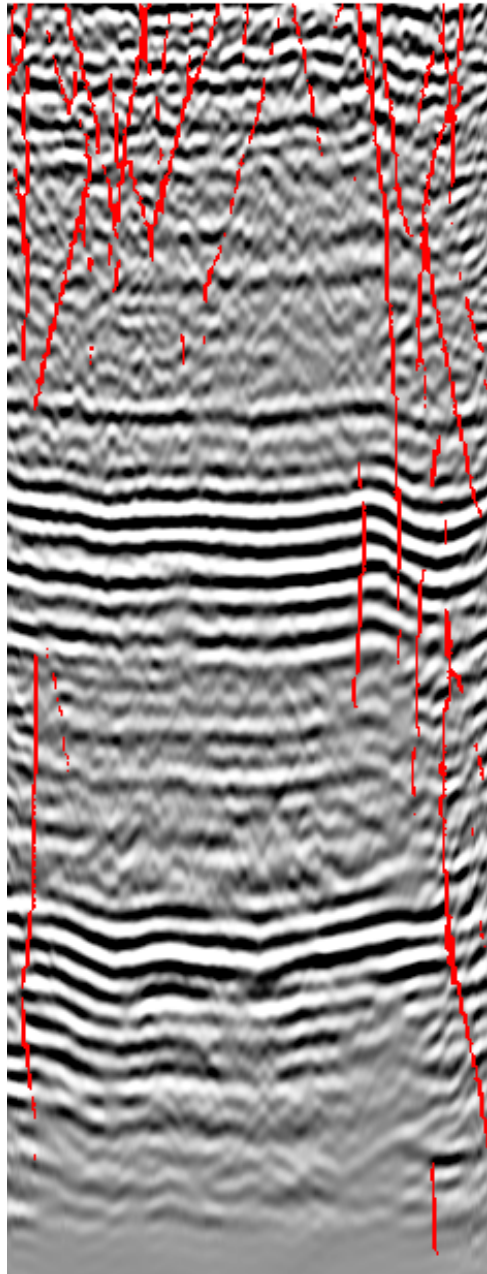
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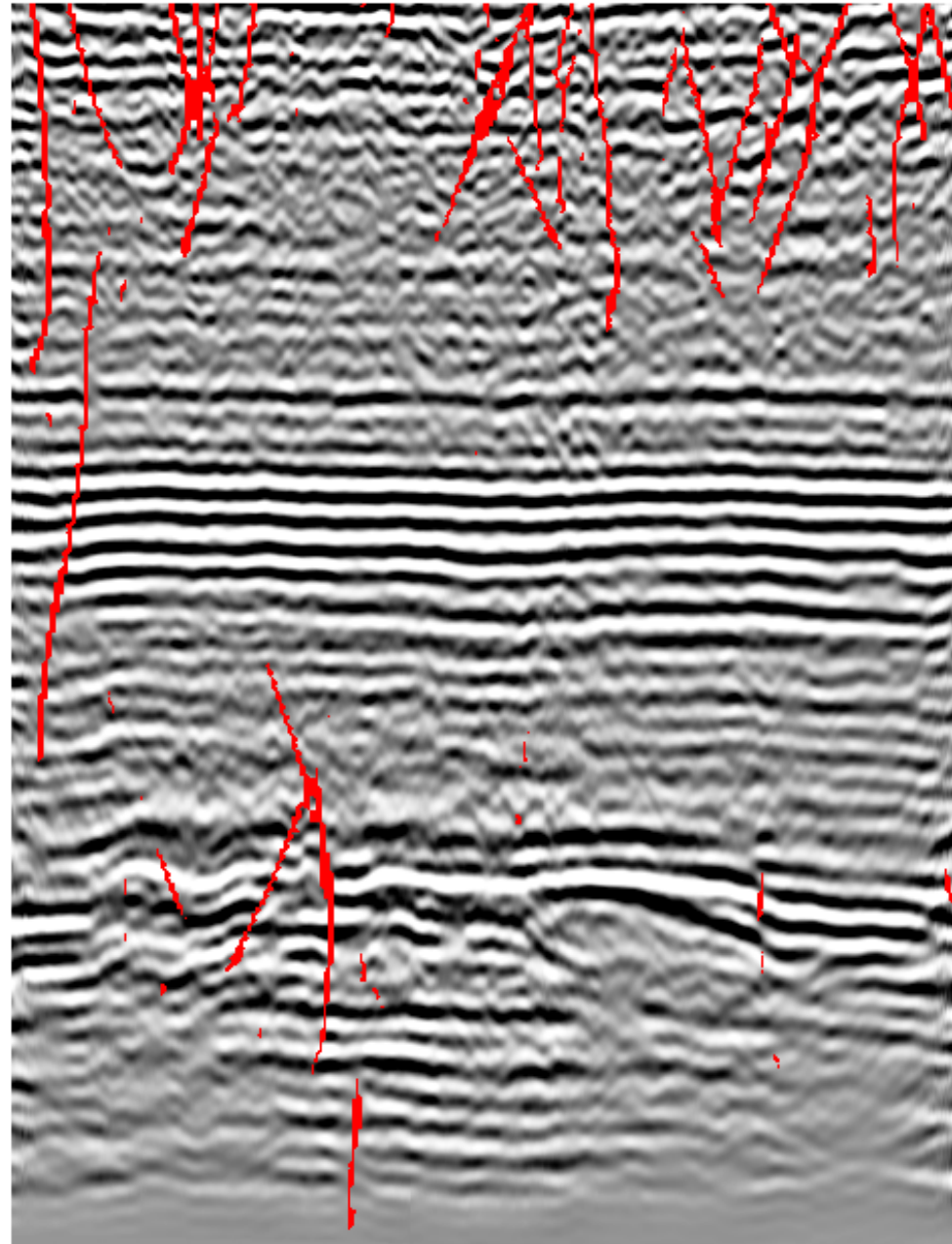
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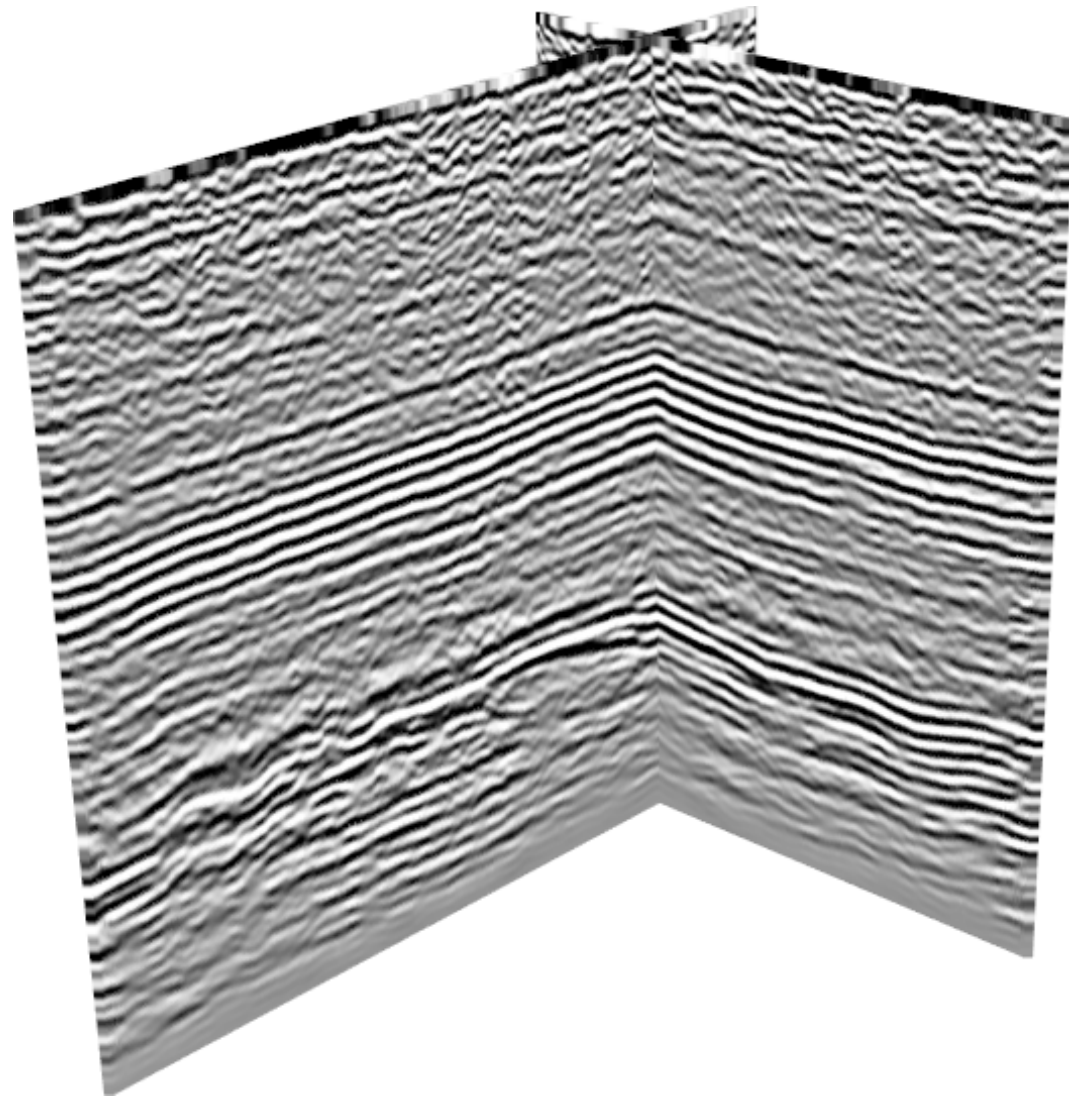


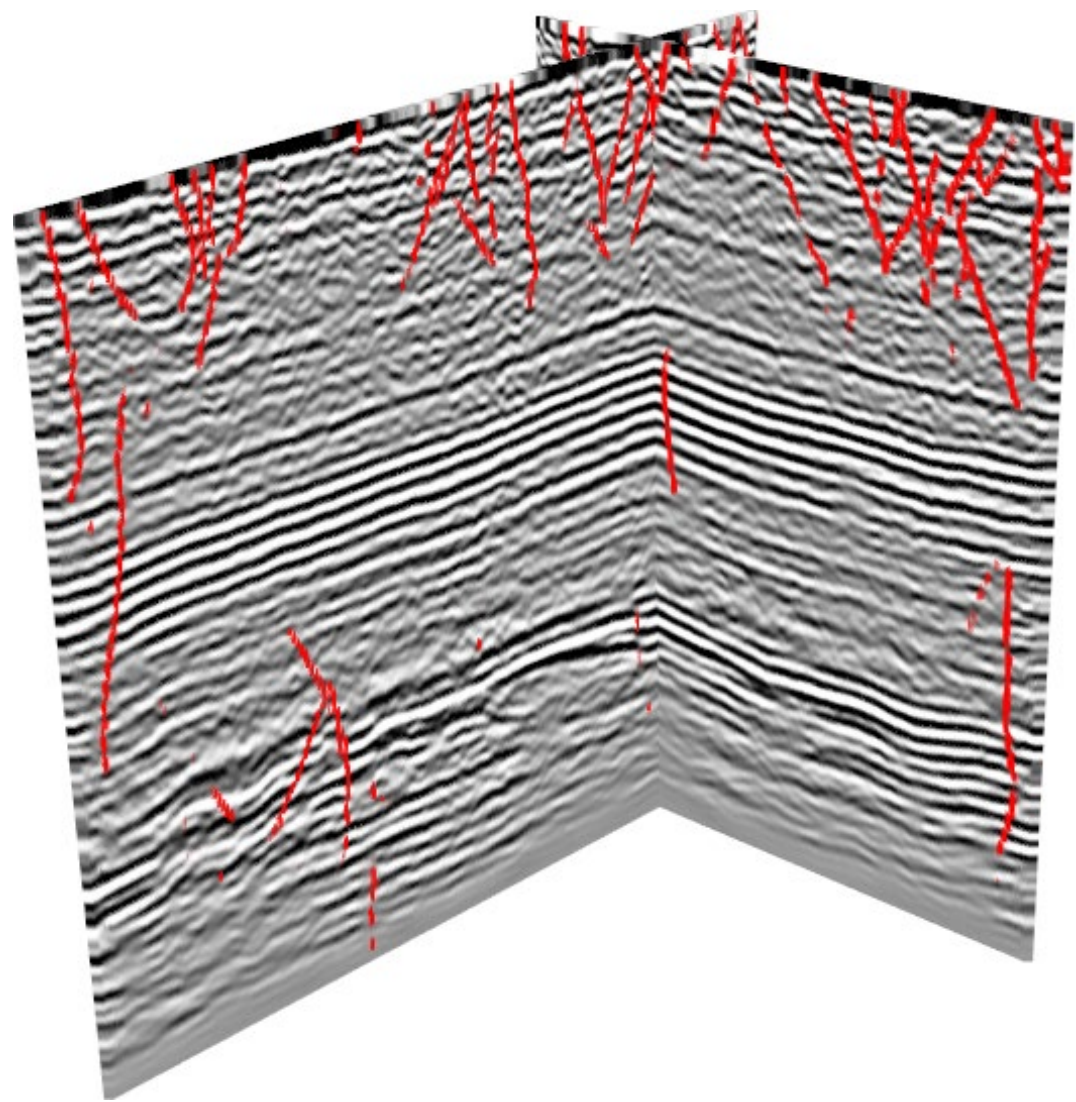
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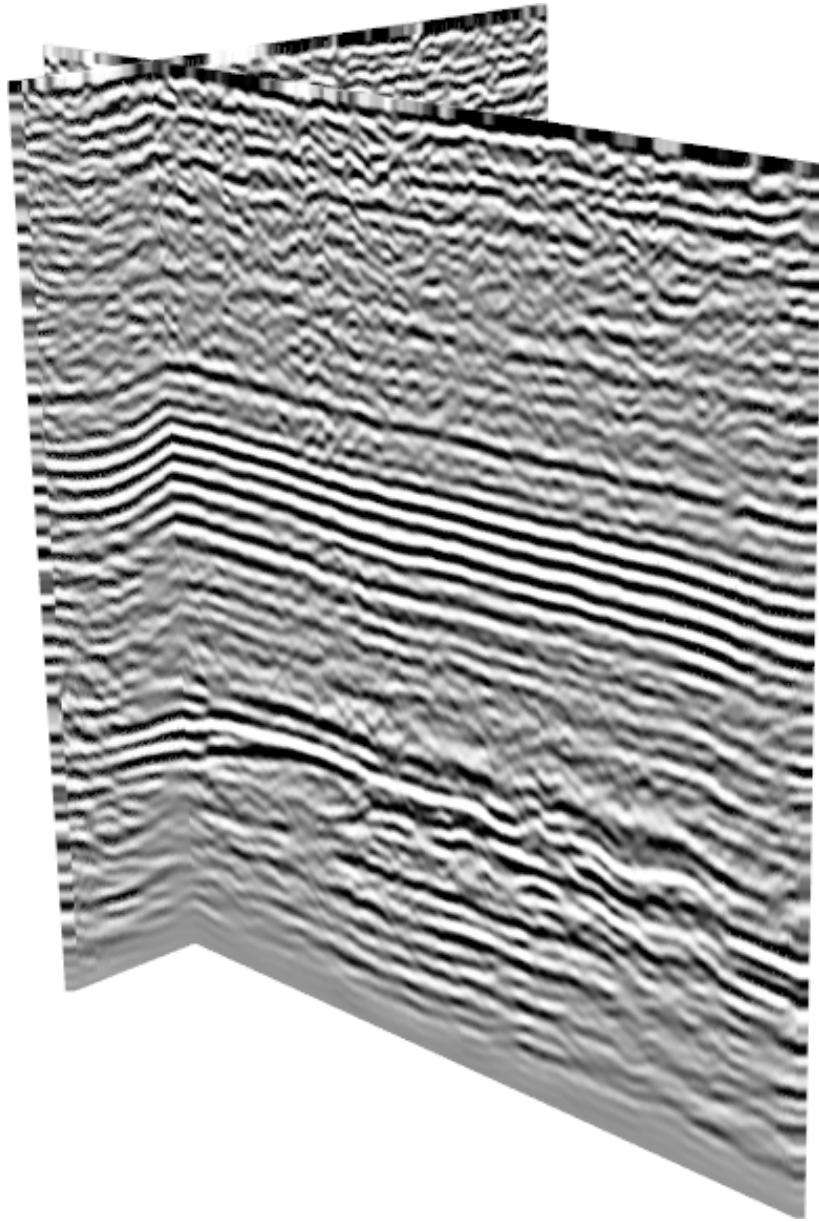


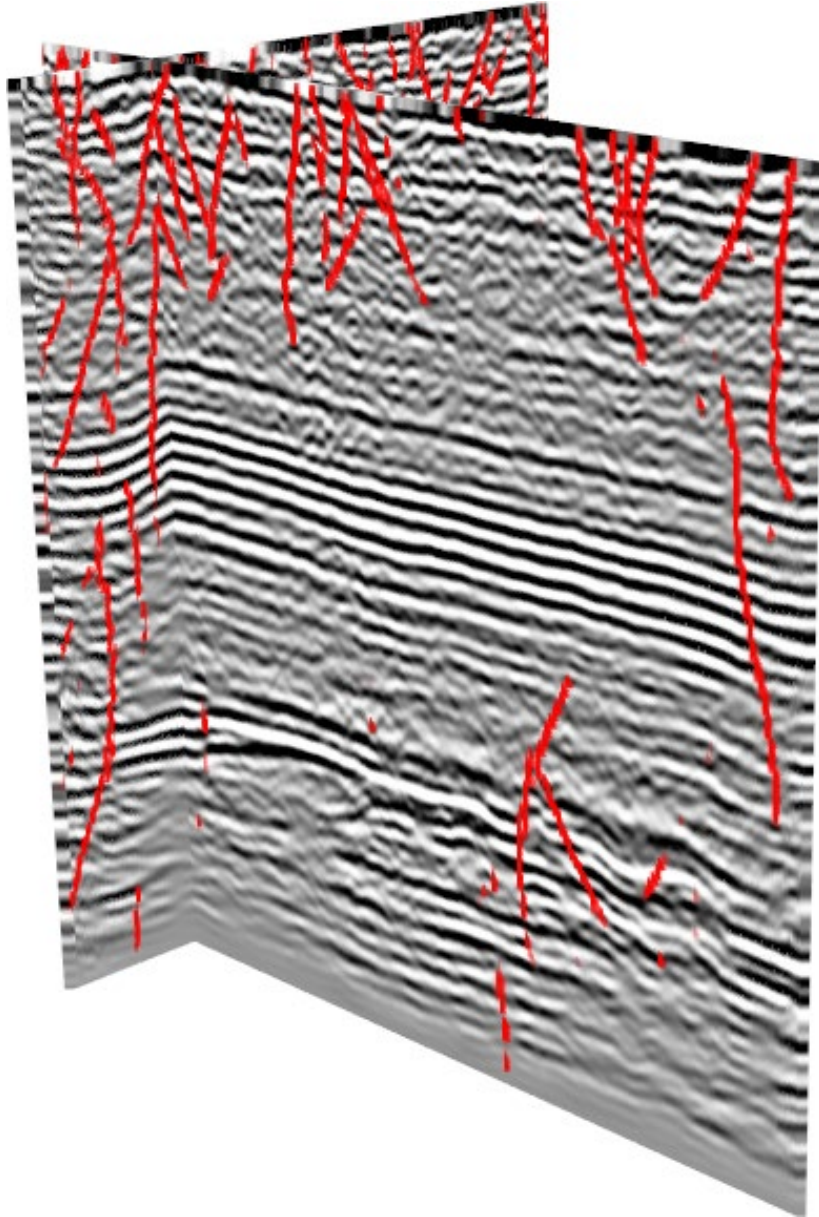
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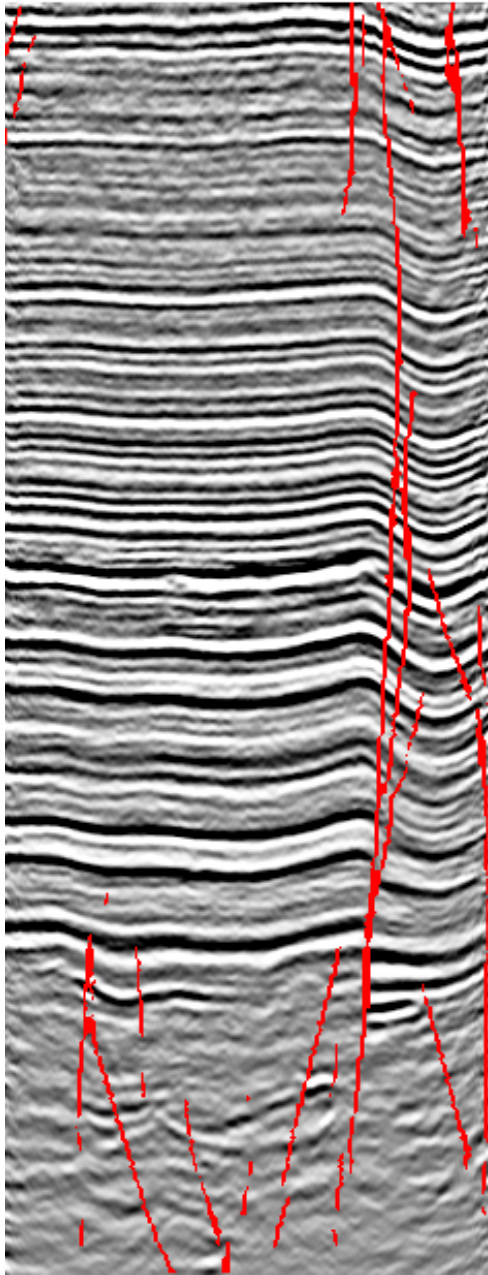




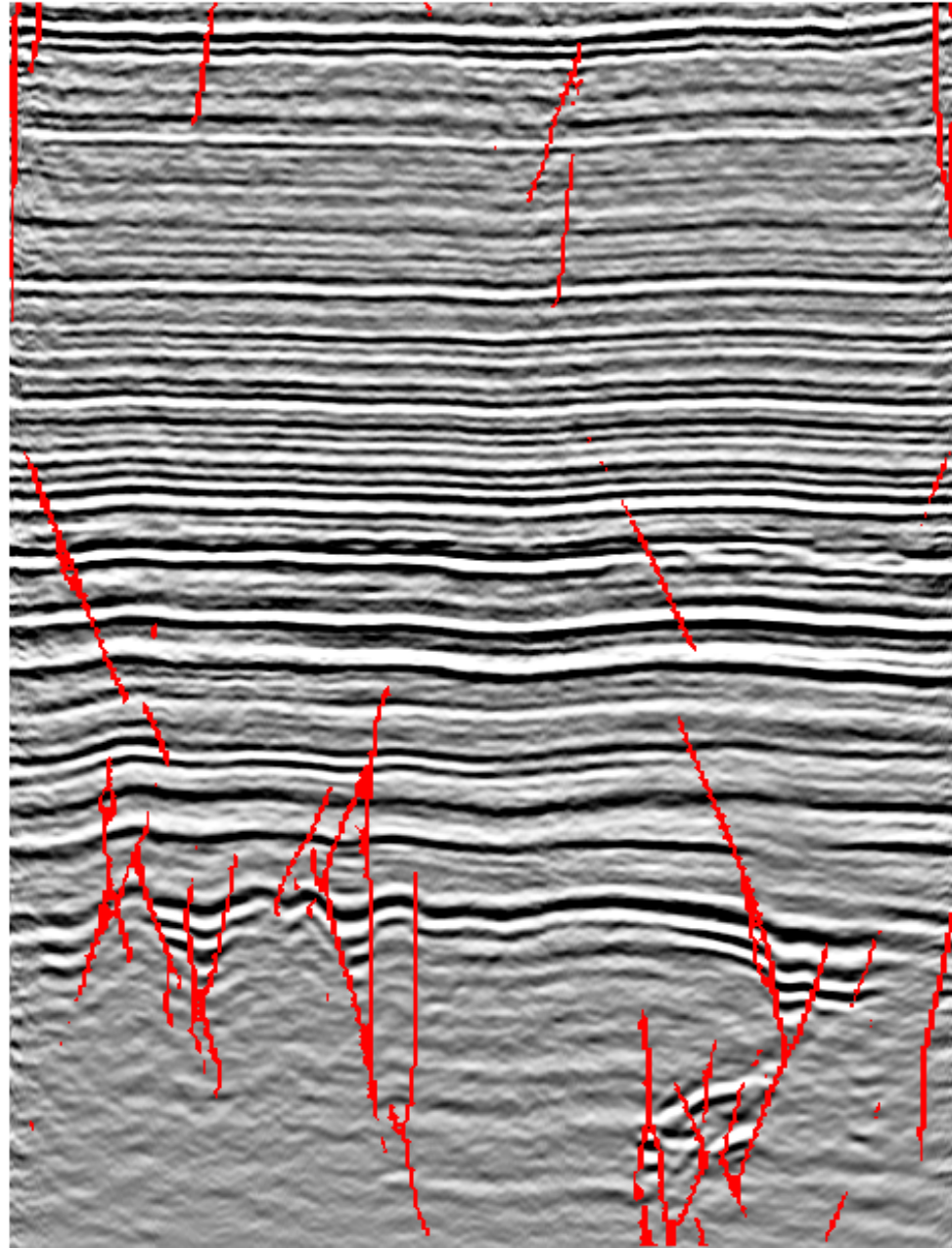
Comparison

PP

Xline: 111

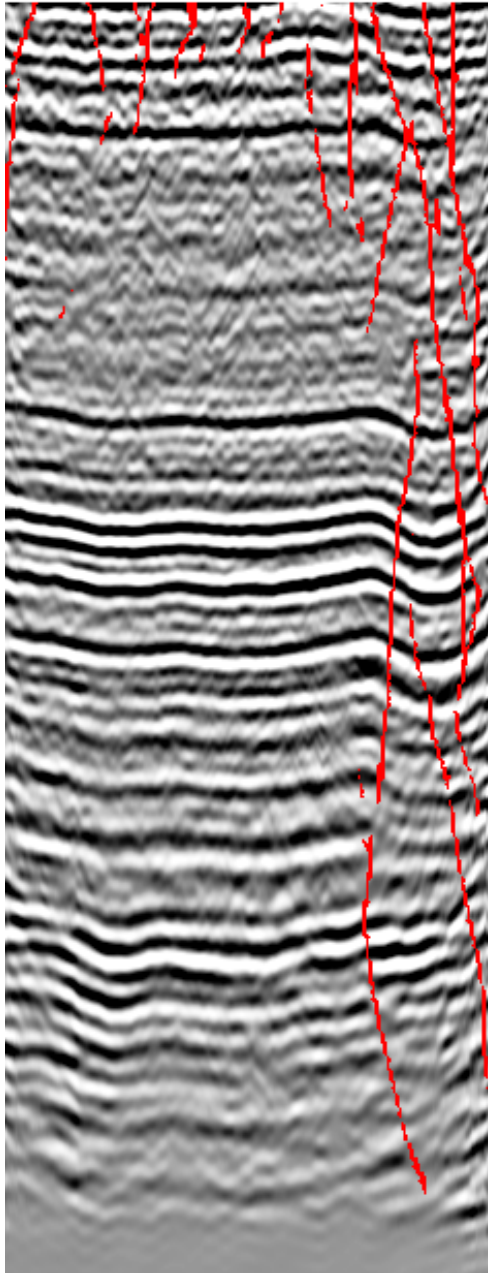


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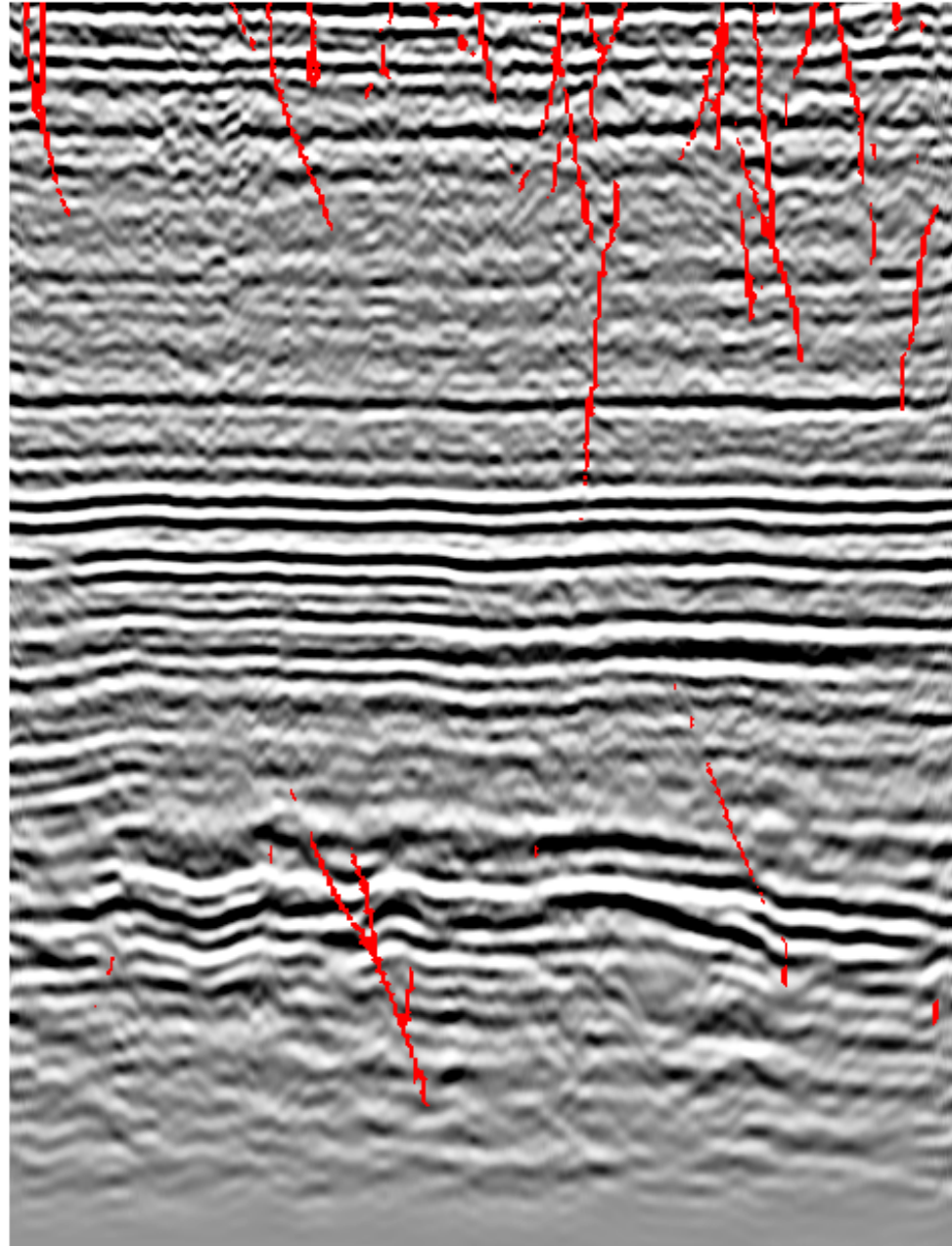


TT

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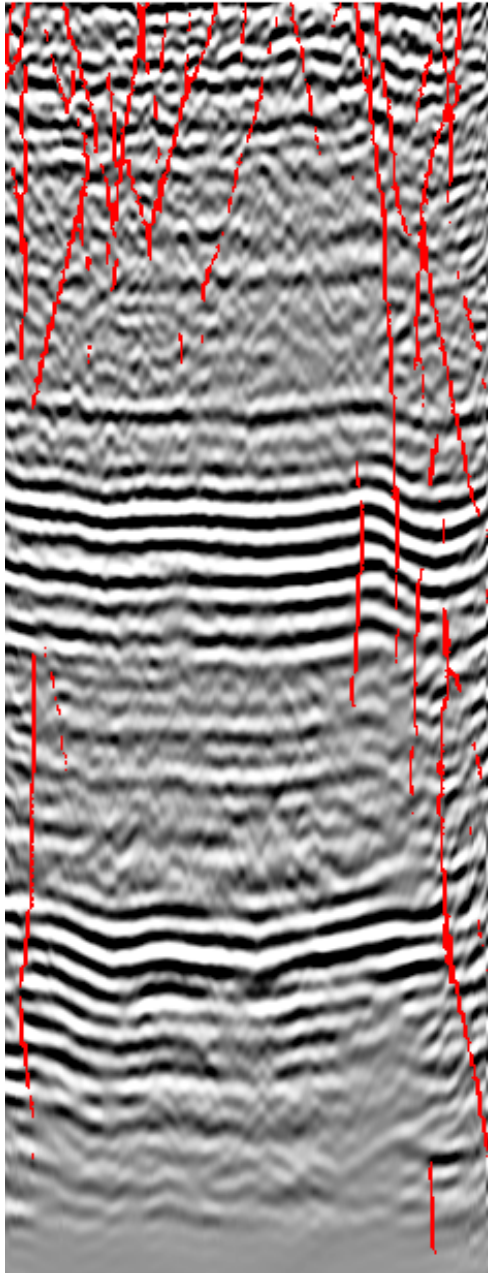


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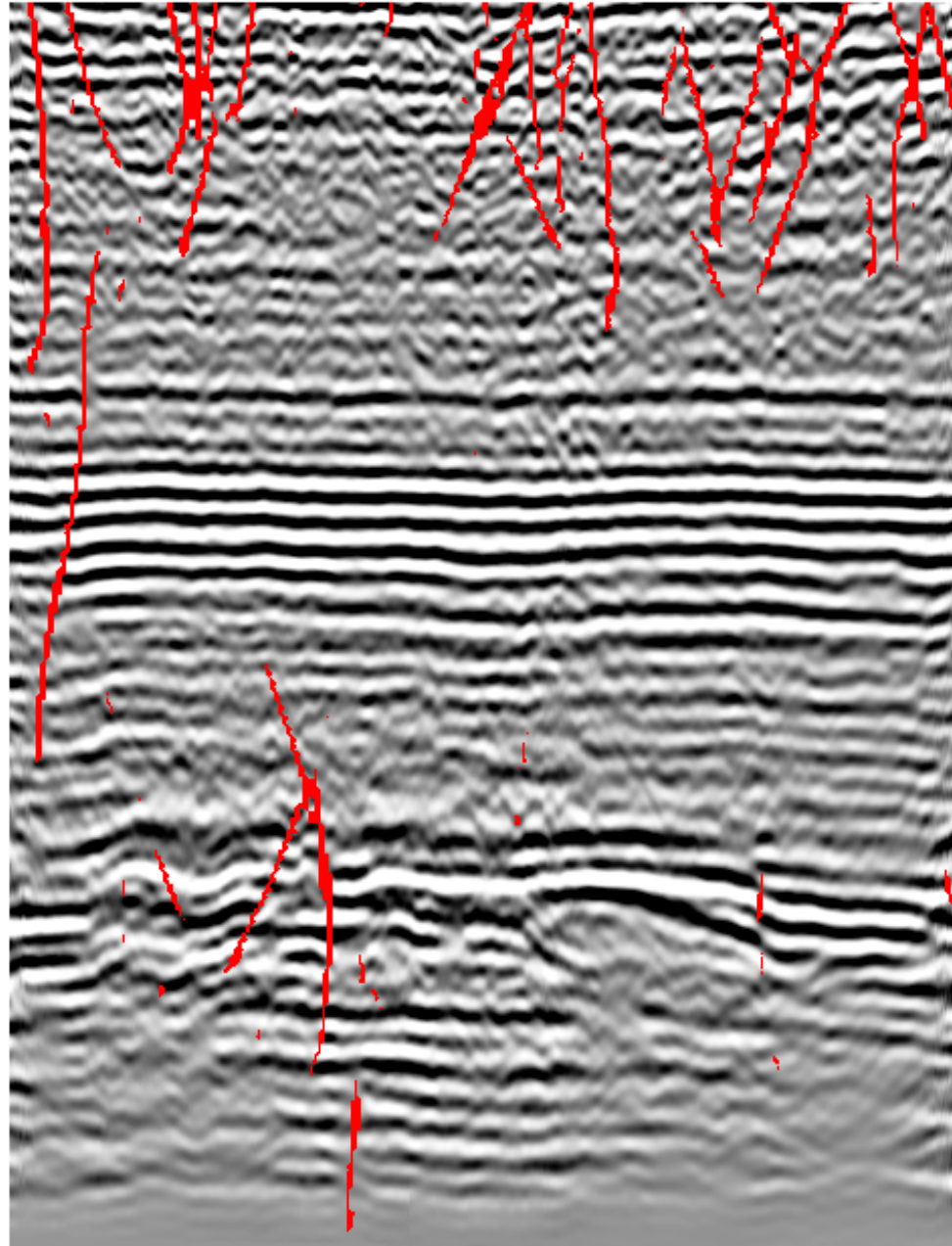


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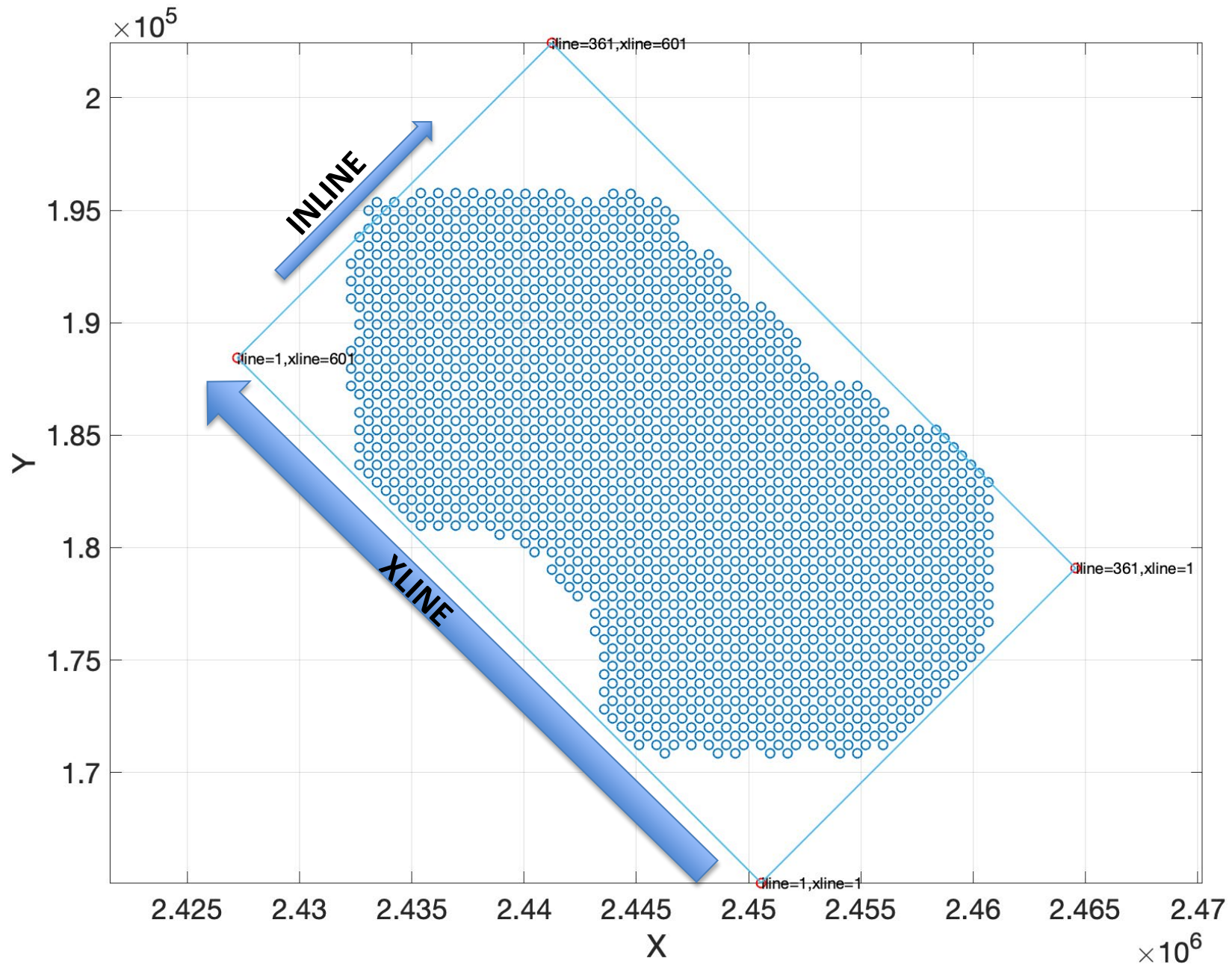
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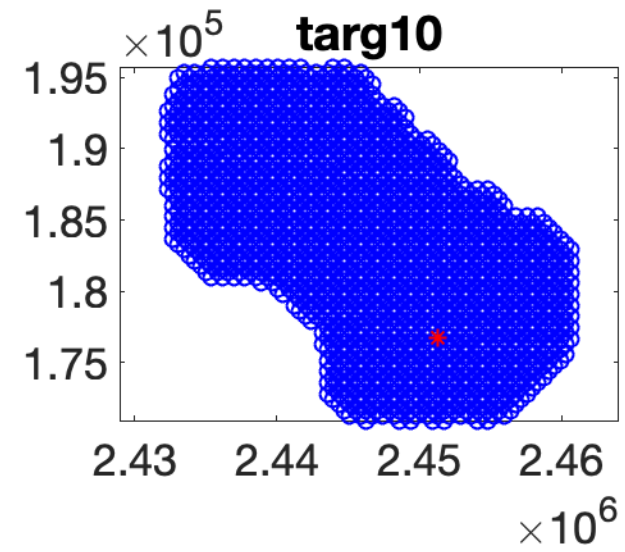
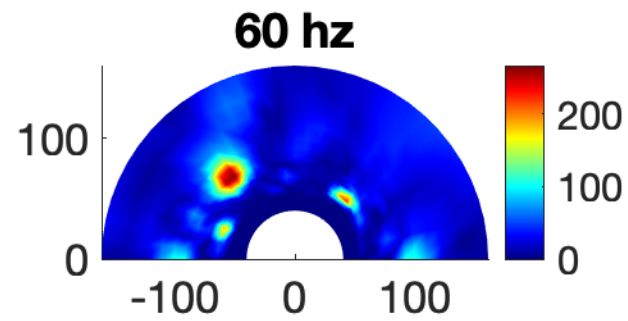
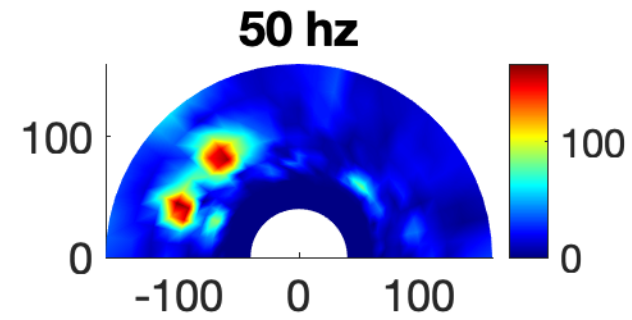
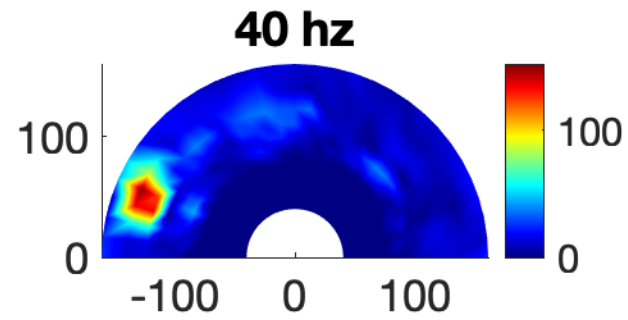


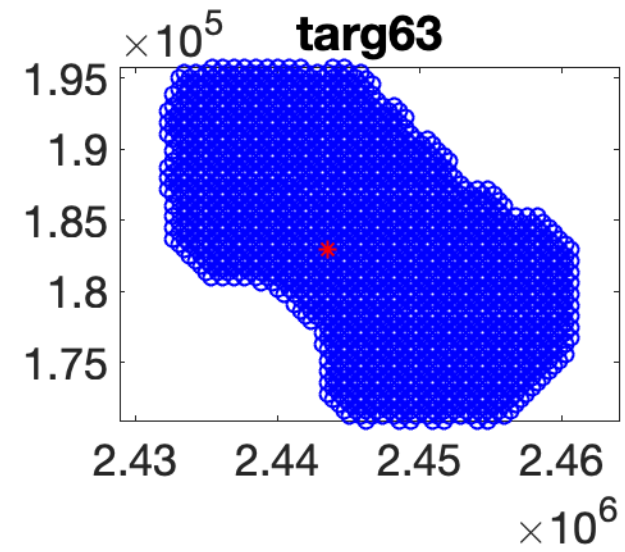
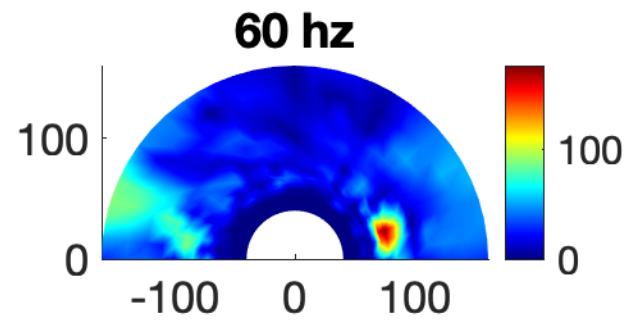
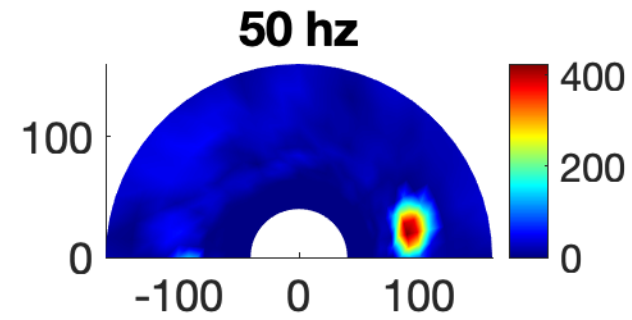
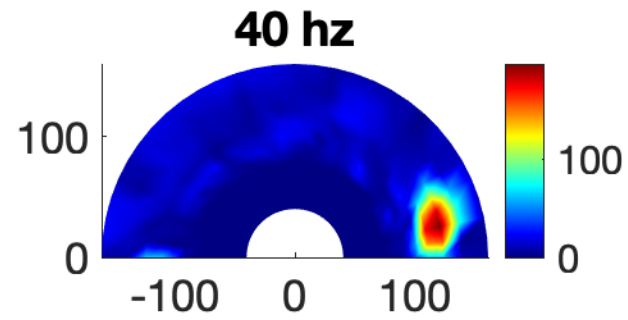
Inline: 292

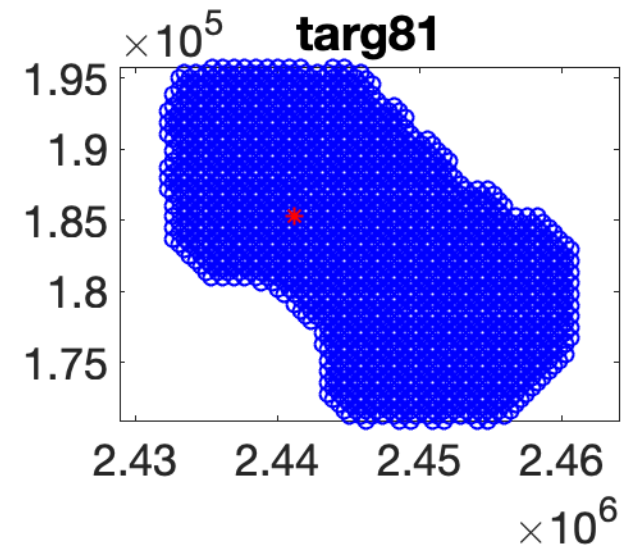
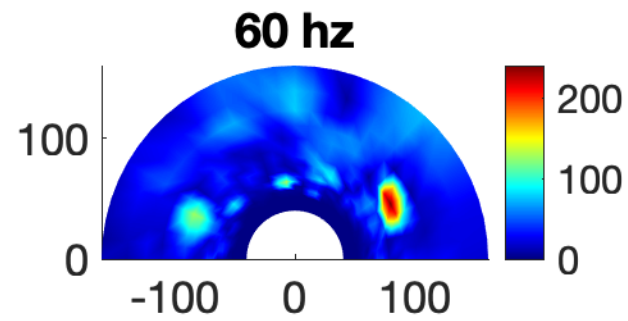
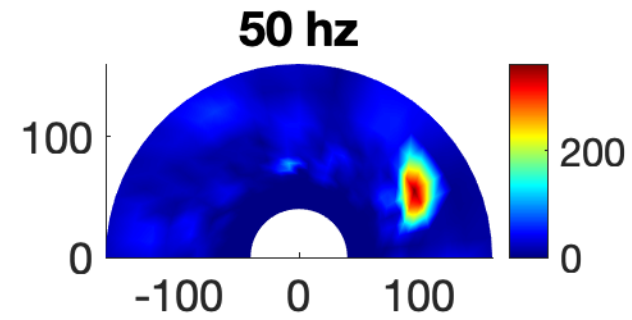
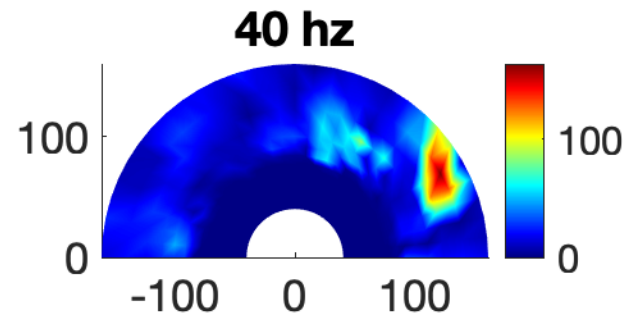


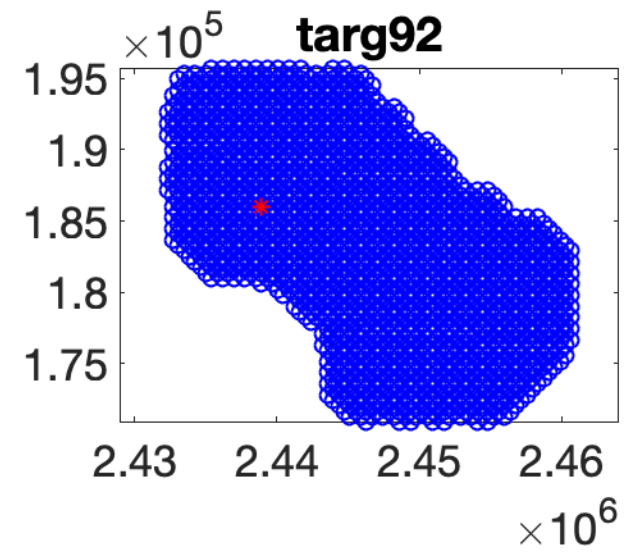
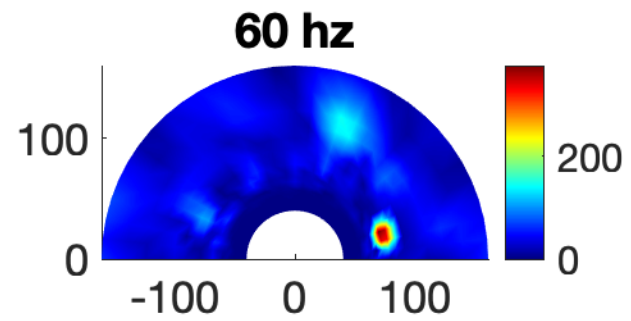
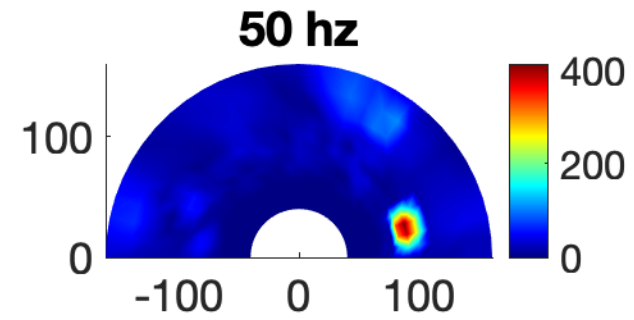
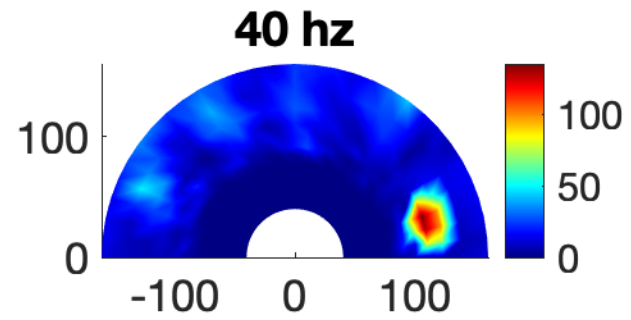
Double-beam fracture detection on field data

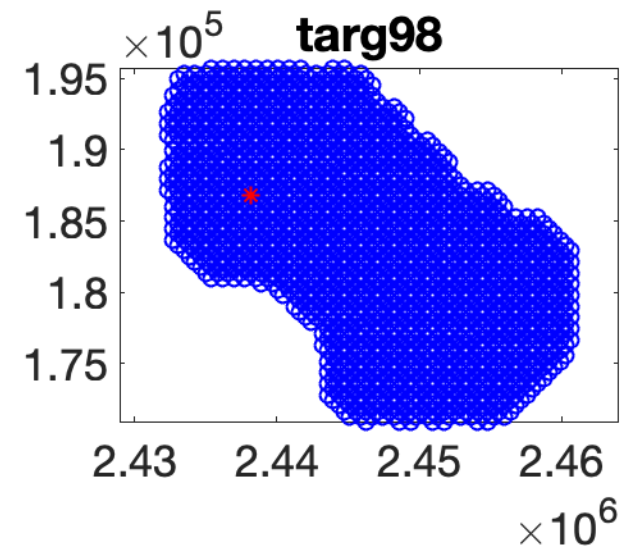
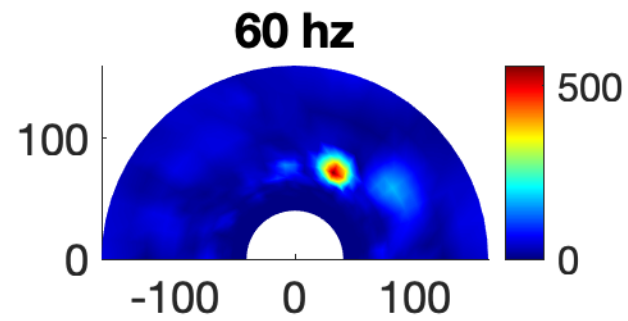
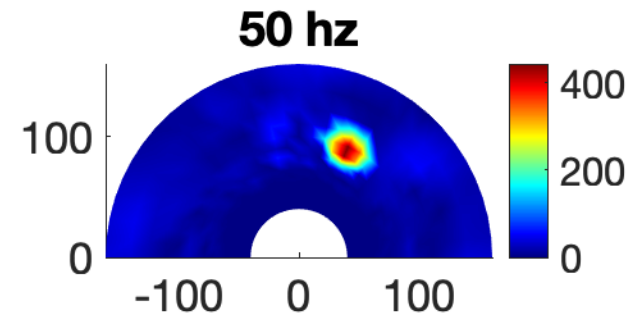
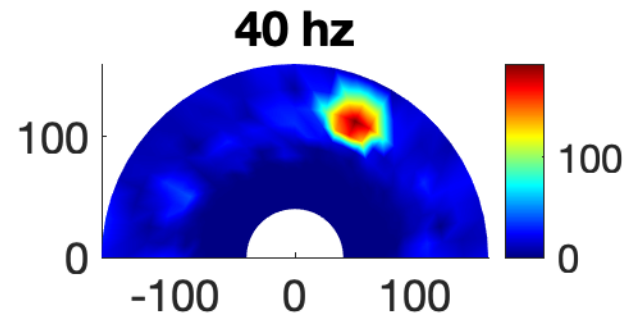












Task/Subtask Breakdown

Task 2.0 - Fault detection and fracture characterization in the basement using synthetic 9C surface seismic data

This task will be in Year-1 which is the budget period 1. The work will focus on synthetic dataset based on a model with dimensions similar to the Wolf Springs field data.

- Subtask 2.1 – (UH/LANL/Vecta) Model building based on central Montana (M1-M3): Build a 3D elastic model using the Wolf Springs field geometry.
- Subtask 2.2 – (UH) Multicomponent synthetic seismic data modeling (M4-M6): Using the model and the locations of the sources and receivers in the field data, UH will run their elastic finite-difference code to generate the synthetic datasets. The computation will be done on PI's group cluster.
- Subtask 2.3 – (LANL) Migration imaging (M7-M9): LANL will conduct P-P, P-S, S-P, and S-S imaging on the synthetic dataset.
- Subtask 2.4 – (LANL) Machine learning fault detection (M10-M12): LANL will detect faults on P-P, P-S, S-P, and S-S images of the synthetic dataset.
- Subtask 2.5 – (UH) Fracture characterization using elastic double beam (M10-M12).

•**Task 3.0 – Fault detection and fracture characterization in the basement using field 9C surface seismic data**

This task will be in the budget period 2. The work will focus on the field 9C seismic dataset at Wolf Springs, Yellowstone County, Montana.

•Subtask 3.1 – (UH) Seismic data denoise such as the ground roll removal (M13-15).

Because the field data has ground coupling issues and different source strengths, UH will apply trace amplitude balance and ground roll removal to clean up the data.

•Subtask 3.2 – (Vecta Oil and Gas) Quality control of the field data and geologic interpretation of faults and fractures (M13-M15).

Vecta Oil and Gas will perform quality control of the field data and analyze geological and well log information for fault/fracture interpretation.

•Subtask 3.3 – (UH) eDB fracture characterization (M16-M24).

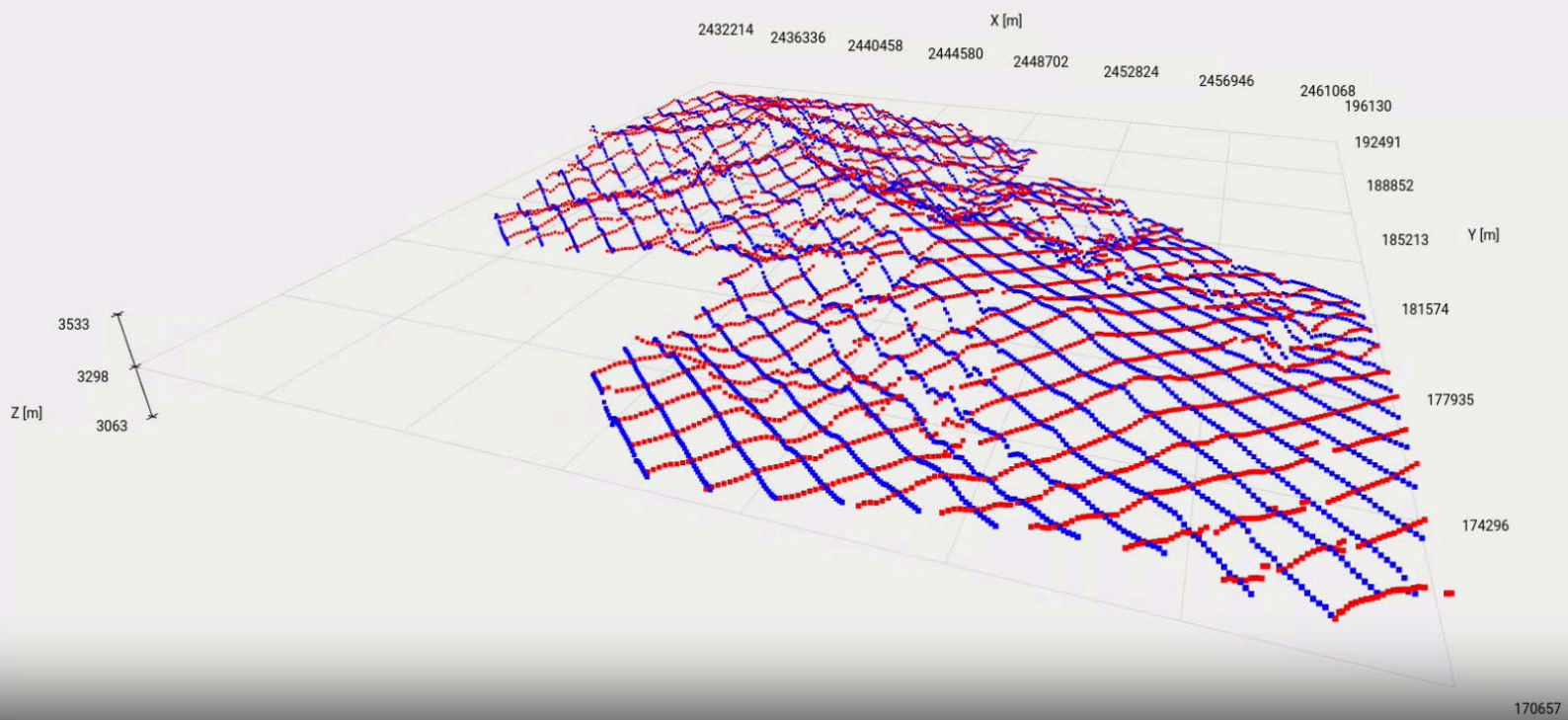
Perform eDB fracture characterization for P-P, P-S1, P-S2. Also use the neural network (DBNN) to obtain discrete fracture networks.

•Subtask 3.4 – (LANL) Enhancing images in the basement using elastic deconvolution migration imaging (M16-M24) LANL will perform P-P, P-S, S-P, and S-S imaging on the field dataset.

•Subtask 3.5 – (LANL) Fault detection using machine learning (M16-M24).

Deliverable: Software development

- Web browser for seismic model/data visualization



GEOMETRY TRACES

> Scene Controls

▼ Geometry Controls

Show Sources

Show Receivers

Show CMPs

Show Faults/Fractures

Source/Receiver Point Size

Vertical Exaggeration

> Volumetric Rendering Controls

> Scene Controls

▾ Geometry Controls

Show Sources

Show Receivers

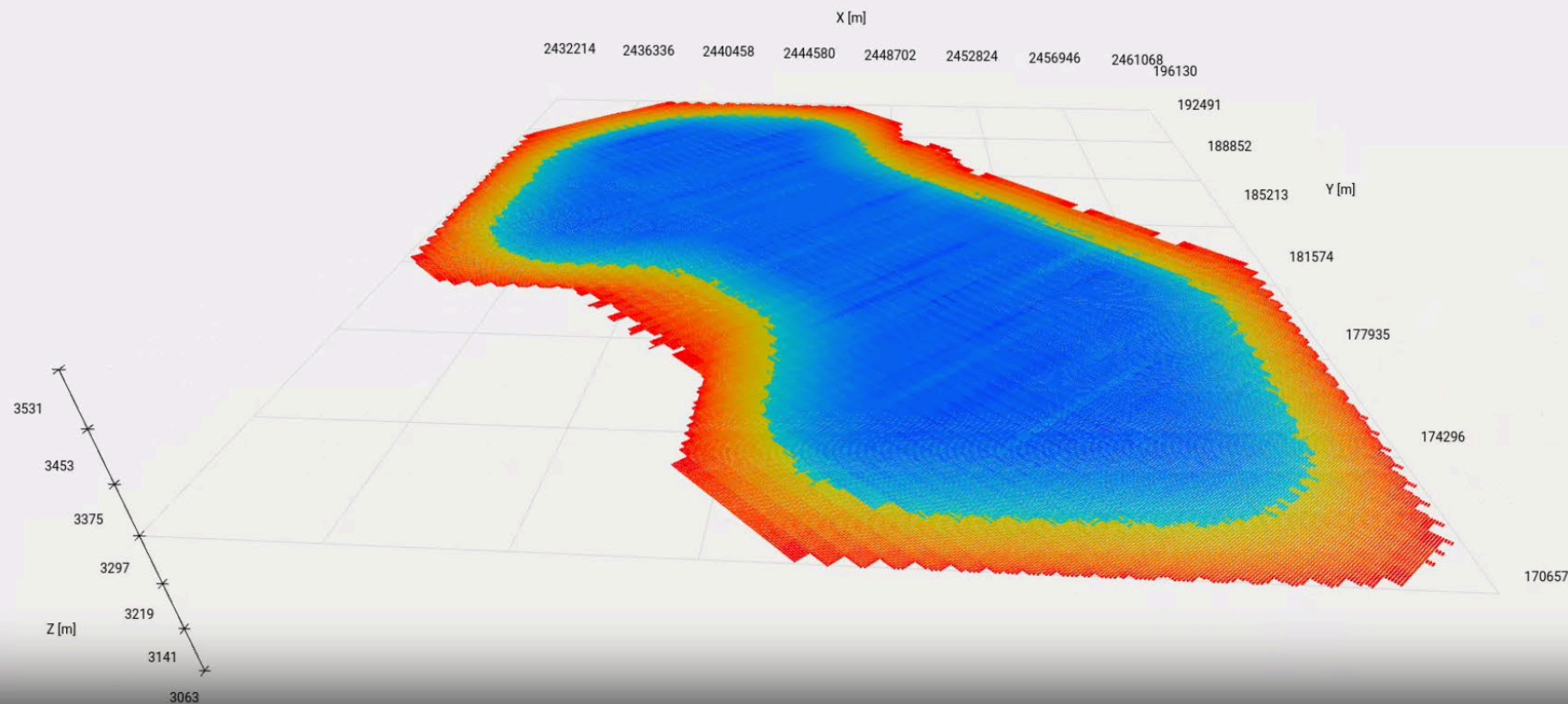
Show CMPs

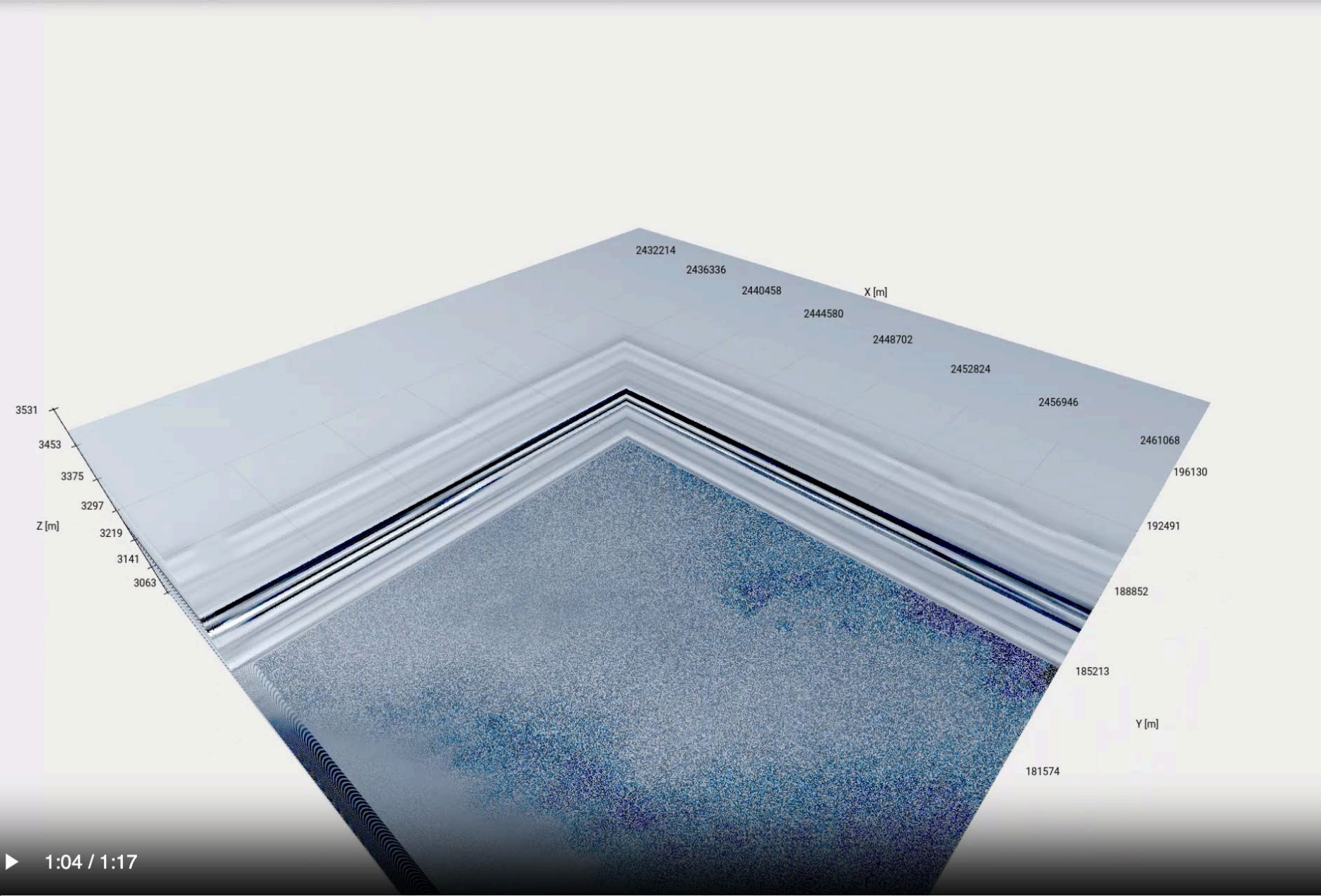
Show Faults/Fractures

Source/Receiver Point Size

Vertical Exaggeration

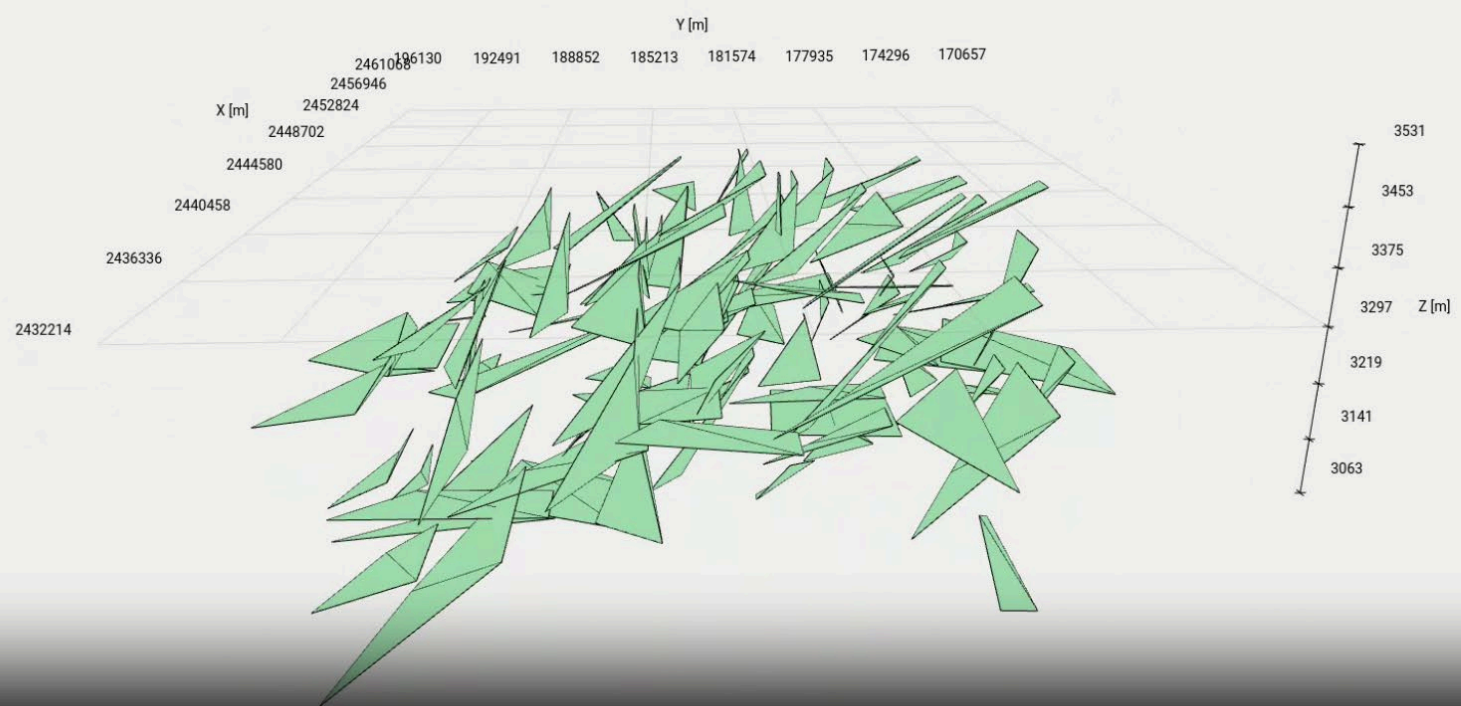
> Volumetric Rendering Controls





GEOMETRY TRACES

- > Scene Controls
- > Geometry Controls
- ▾ Volumetric Rendering Controls
 - Show Helpers
 - Invert Clip
 - Threshold
 - Opacity
 - Range
 - Steps
 - Plane Constant X
 - Plane Constant Y
 - Plane Constant Z
 - Base Color
 - Accum Color



GEOMETRY TRACES

> Scene Controls

▼ Geometry Controls

- Show Sources
- Show Receivers
- Show CMPs
- Show Faults/Fractures
- Source/Receiver Point Size
- Vertical Exaggeration

> Volumetric Rendering Controls

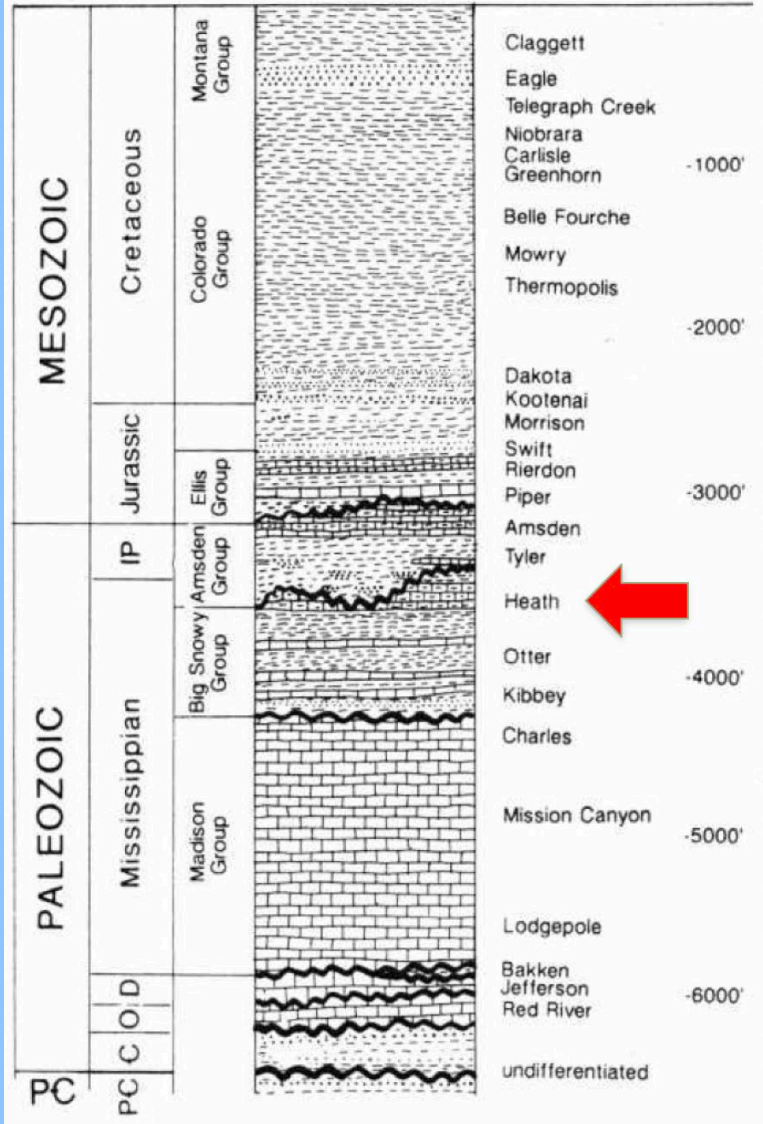
Summary of Accomplishments

- Synthetic model and data tests; **DONE**
 - UH, LANL, and Vecta Oil and Gas Ltd. worked together and built a 3d seismic model: Vp, Vs, density and spatially varying fracture networks including conjugate fracture sets **DONE**
 - We modeled 3d 9-c shot gathers **DONE**
 - We applied the double-beam method on the modeled datasets **DONE**
 - If there are fractures, DB can invert for the true fractures
 - If there is no fracture in the model, DB reports 'no fracture'
 - Different frequencies give consistent results → DB method is self-verifying
- BP-2: field data (Jan 1, 2023 - December 31, 2023, revised to June 2024)
 - State-of-the-art oil/gas industry methods (shear wave splitting) **DONE**
 - Shear wave splitting **DONE**;
 - Double-beam neural network (DBNN); with preliminary results
 - Faults detection; with preliminary results; overall status
- **BP-3: synthesis: fault stress state & activation potential**

Acknowledgments

- The work is funded by DOE with funding number DE-FE0032063.
- LANL is operated by Triad National Security, LLC, for the U.S. DOE National Nuclear Security Administration (NNSA) under Contract No. 89233218CNA000001. This research used computing resources provided by the LANL Institutional Computing Program supported by the U.S. DOE NNSA under Contract No. 89233218CNA000001.
- We also used computing facilities provided by the UHXfrac group at the University of Houston.
- Vecta Oil and Gas Ltd. provided field data.

CENTRAL MONTANA STRATIGRAPHIC COLUMN



Heath Is Well-Documented
as the Major Oil Source
Rock in Central Montana



Aram, 1993