Seismic elastic double-beam characterization of faults and fractures for CO_2 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
2023 Project Review Meeting, Pittsburgh
08/31/2023

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 CO_2 Storage Technologies: Optimizing Performance Through Minimization of Seismicity Risks and Monitoring Caprock Integrity

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

Announcement Type: Amendment 1[1]

CFDA Number: 81.089

Emerging CO_2 Storage Technologies: Optimizing Performance Through Minimization of Seismicity Risks and Monitoring Caprock Integrity

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

AOI 1a - Fault Detection, Characterization, and Hazard Assessment.

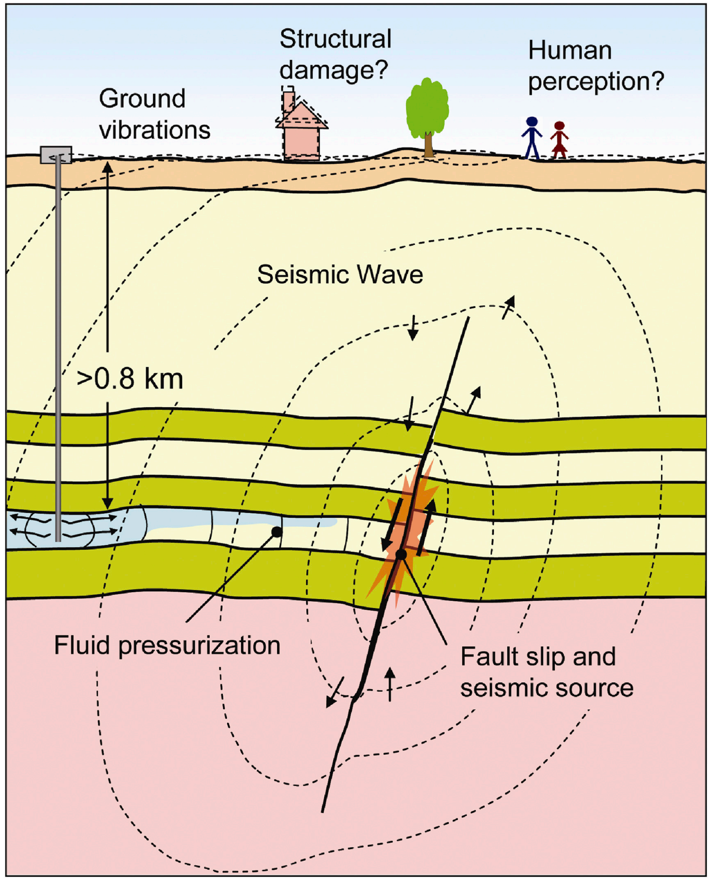
No field work. Novel method development. Final deliverable: a software package for subsurface analysis for Gigatonne storage scenarios.

Motivation: induced seismicity is quite common in operating CCS sites

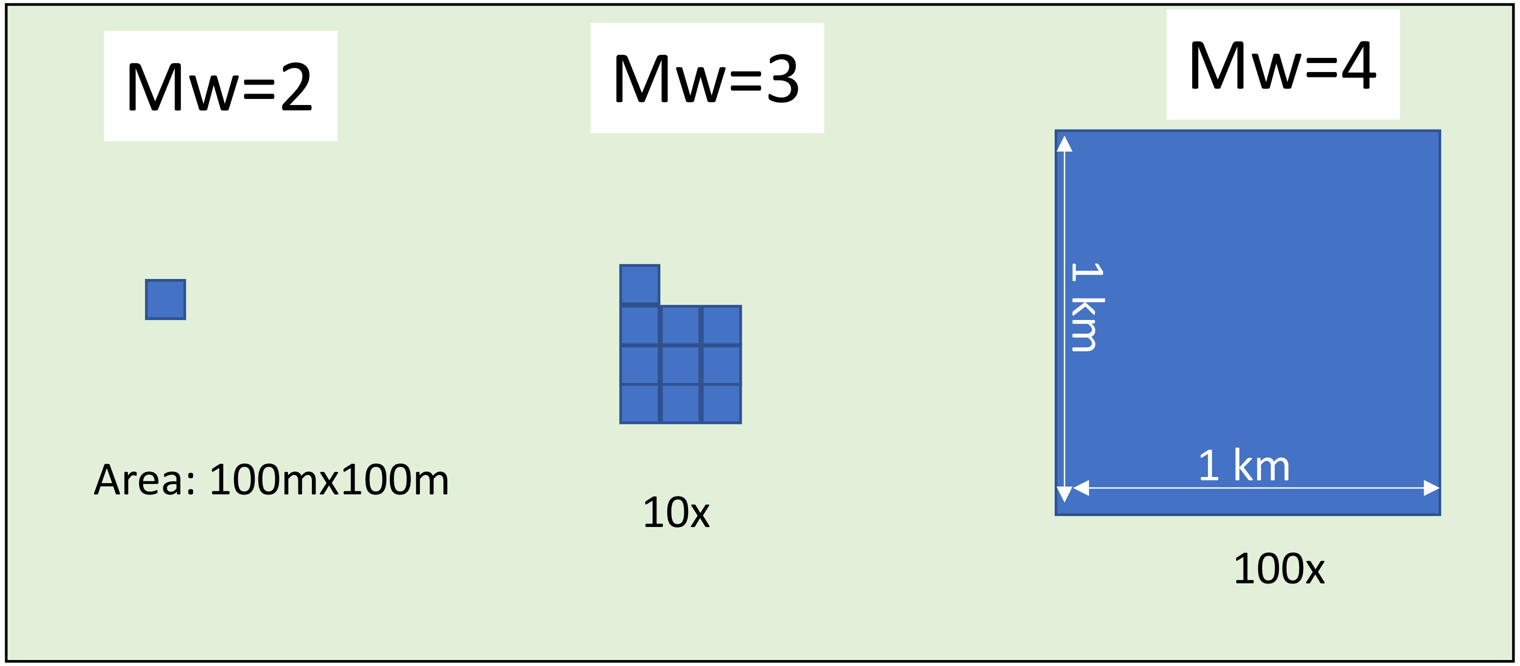
CCS Sites	Start Time	End Time	Injection Amount	Seismic Monitoring (Y/N)	Max Magnitude	Distance from injection	Rock Type	Injection Depth
Decatur, USA	2012	-	2.8Mt	Y	1.55	400m	Sandstone	2140m
In Salah, Algeria	2004	2011	3.8Mt	Y	**1.6**	1100m	Sandstone	1950m
Otway Australia	2007	--	30000t	Y	0.5	450m	Sandstone/Calcite/Kaolinite	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



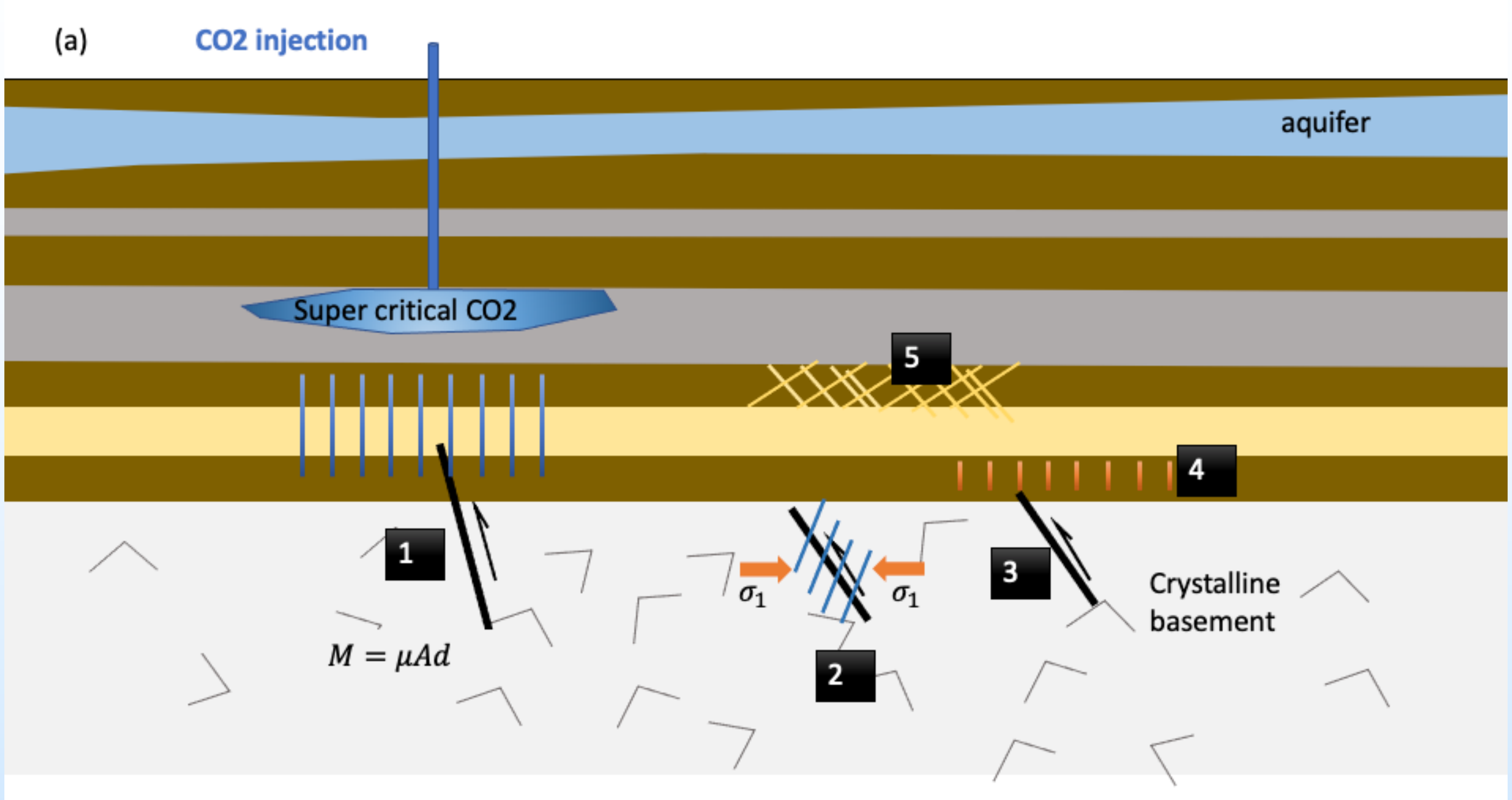
$$Mw = (2/3)\ Log_{10}(mu*Area*slip) - 6.0$$



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

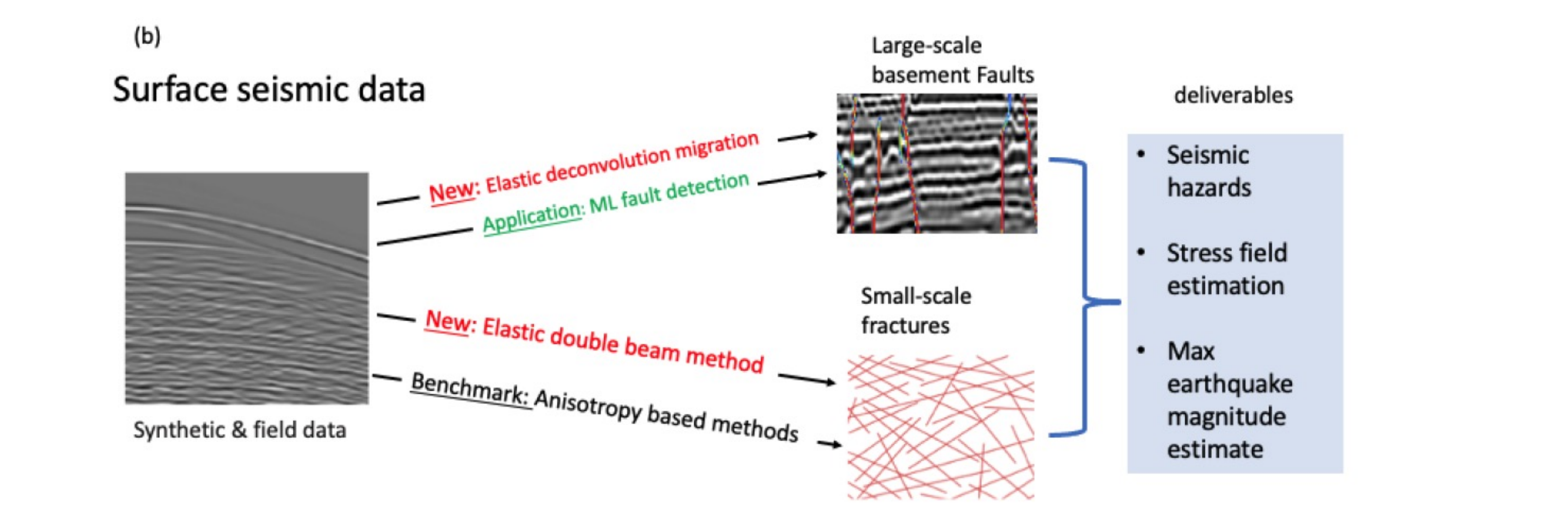
Objectives budget periods (BP)

- **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)

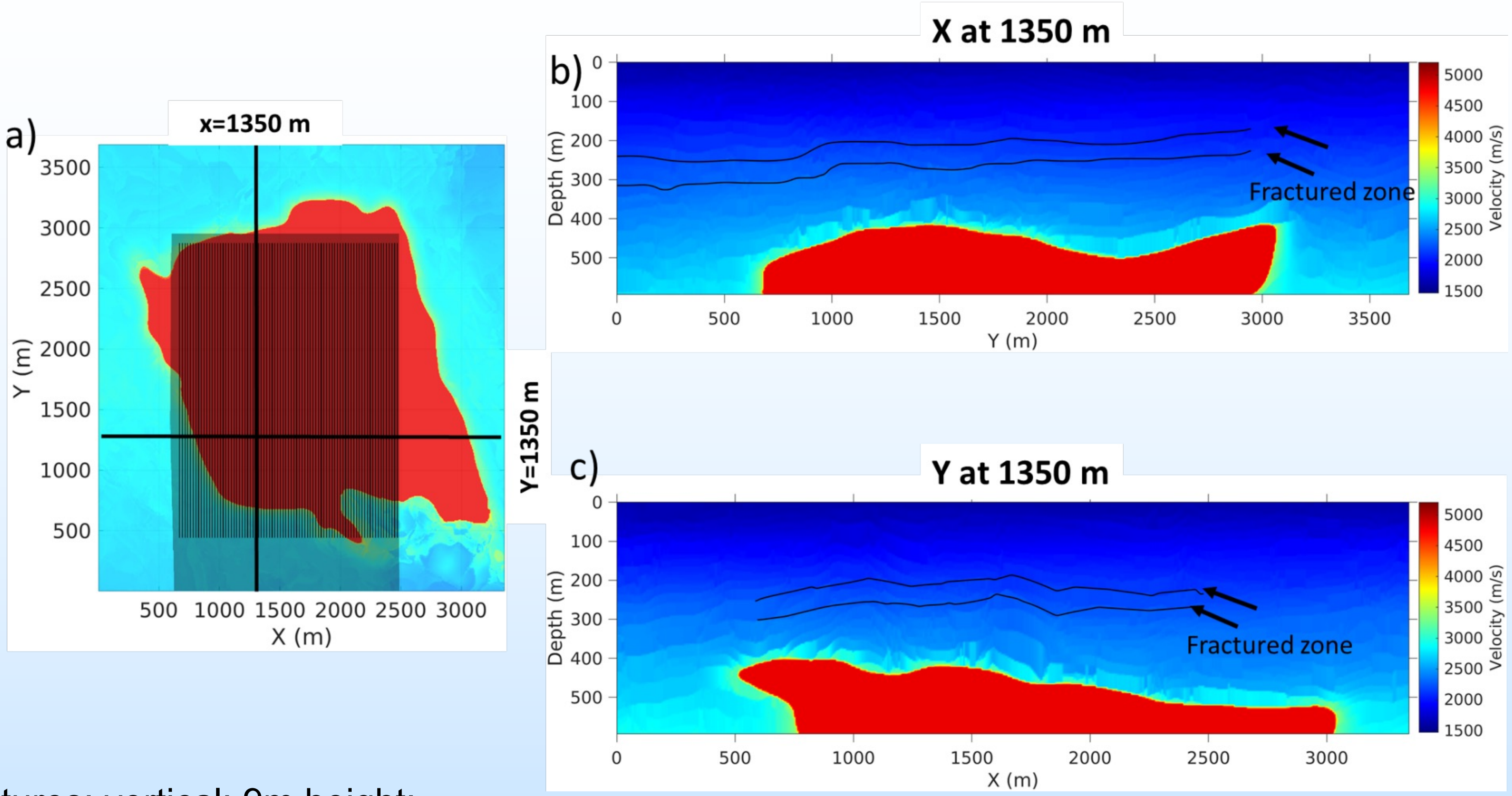
Technology Roadmap



Why another method for fracture characterization?

- Can seismic migration see the small-scale fractures?

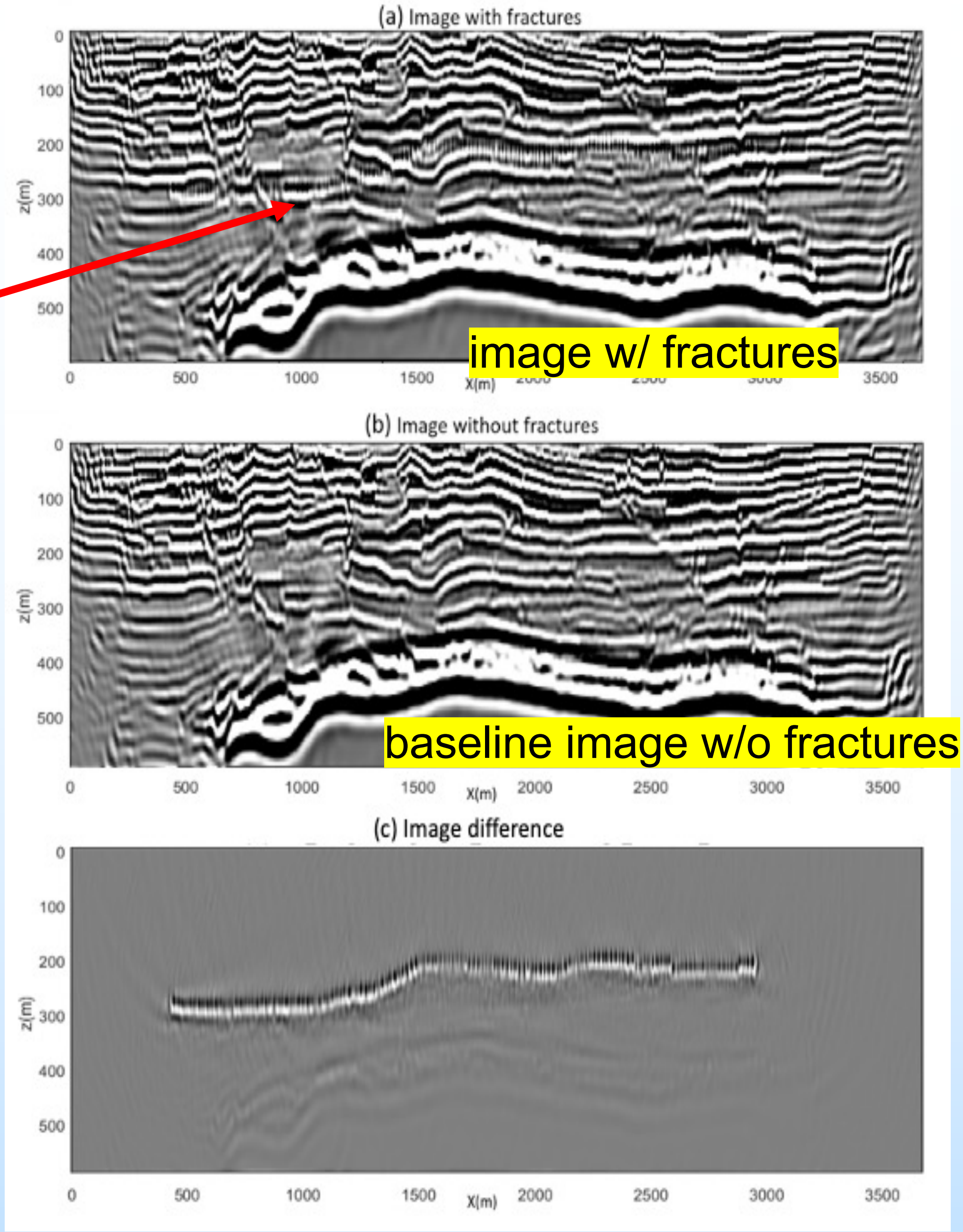
Motivational example: fractures are hard to see



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

Finite difference modeling: Coates and Schoenberg (1995)

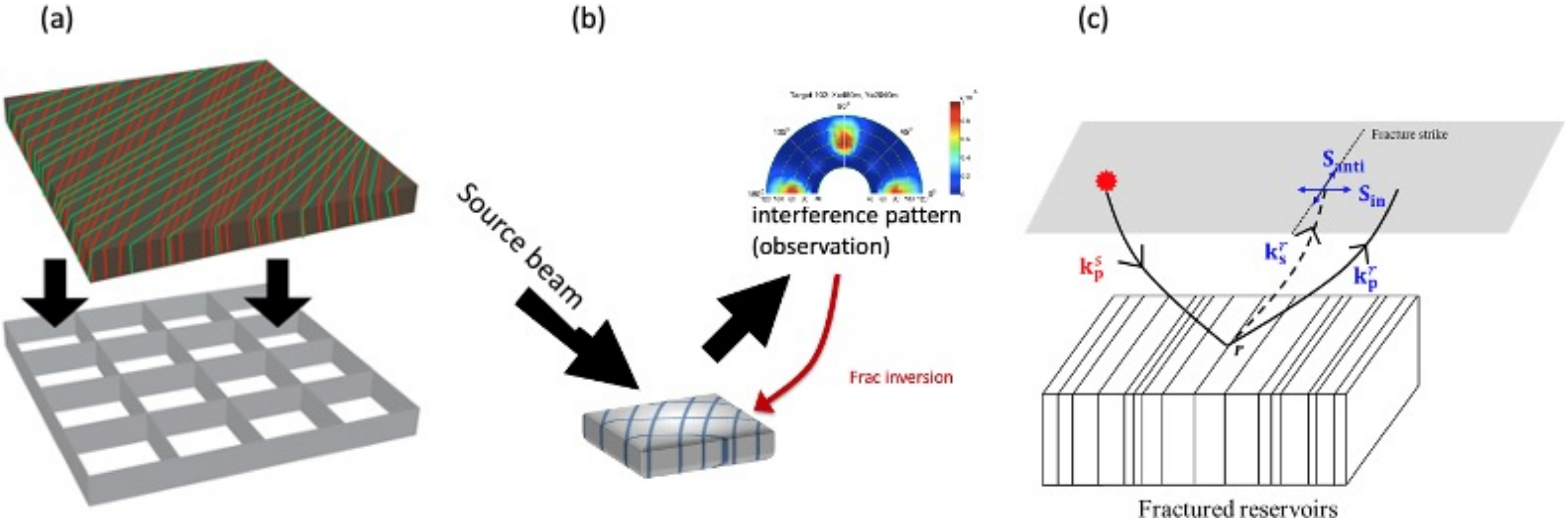
Hard to see fractures in traditional seismic migrated images



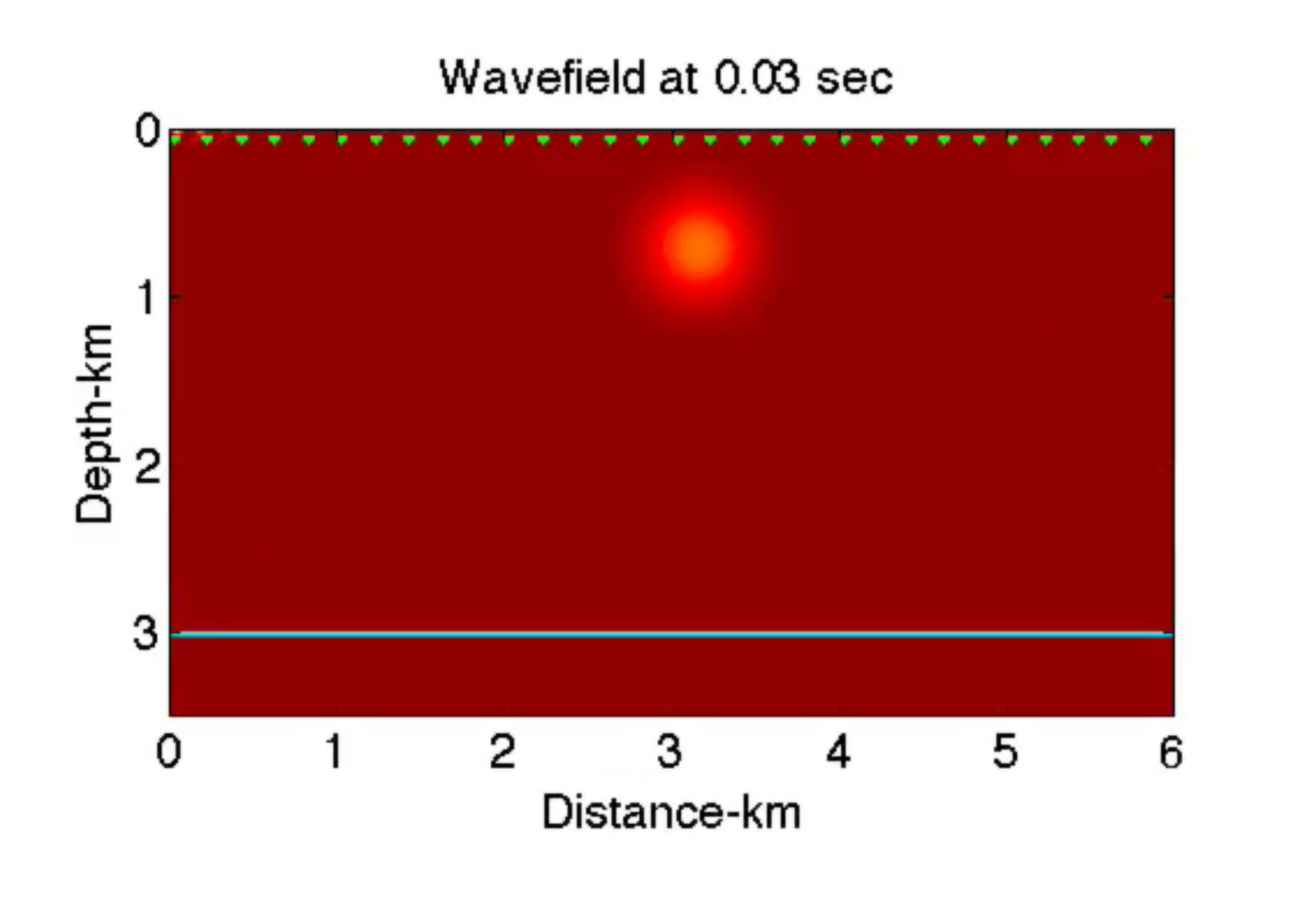
Seismic double-beam method

to characterize small-scale fractures

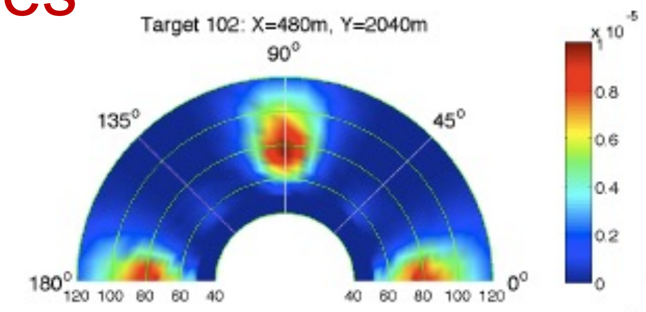
Basic idea of double-beam method



A directional seismic packet can selectively image

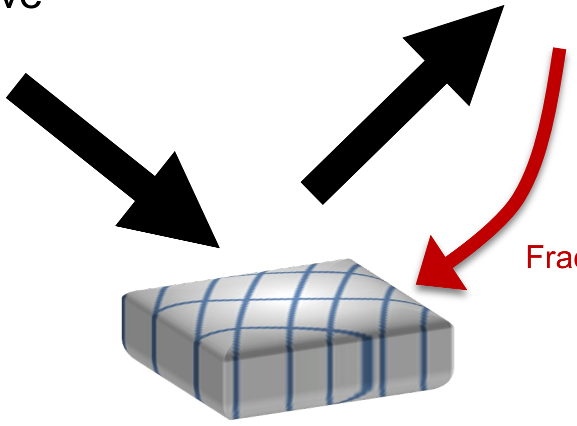


Interference pattern → fractures



interference pattern
(observation)

Directional wave
incidence



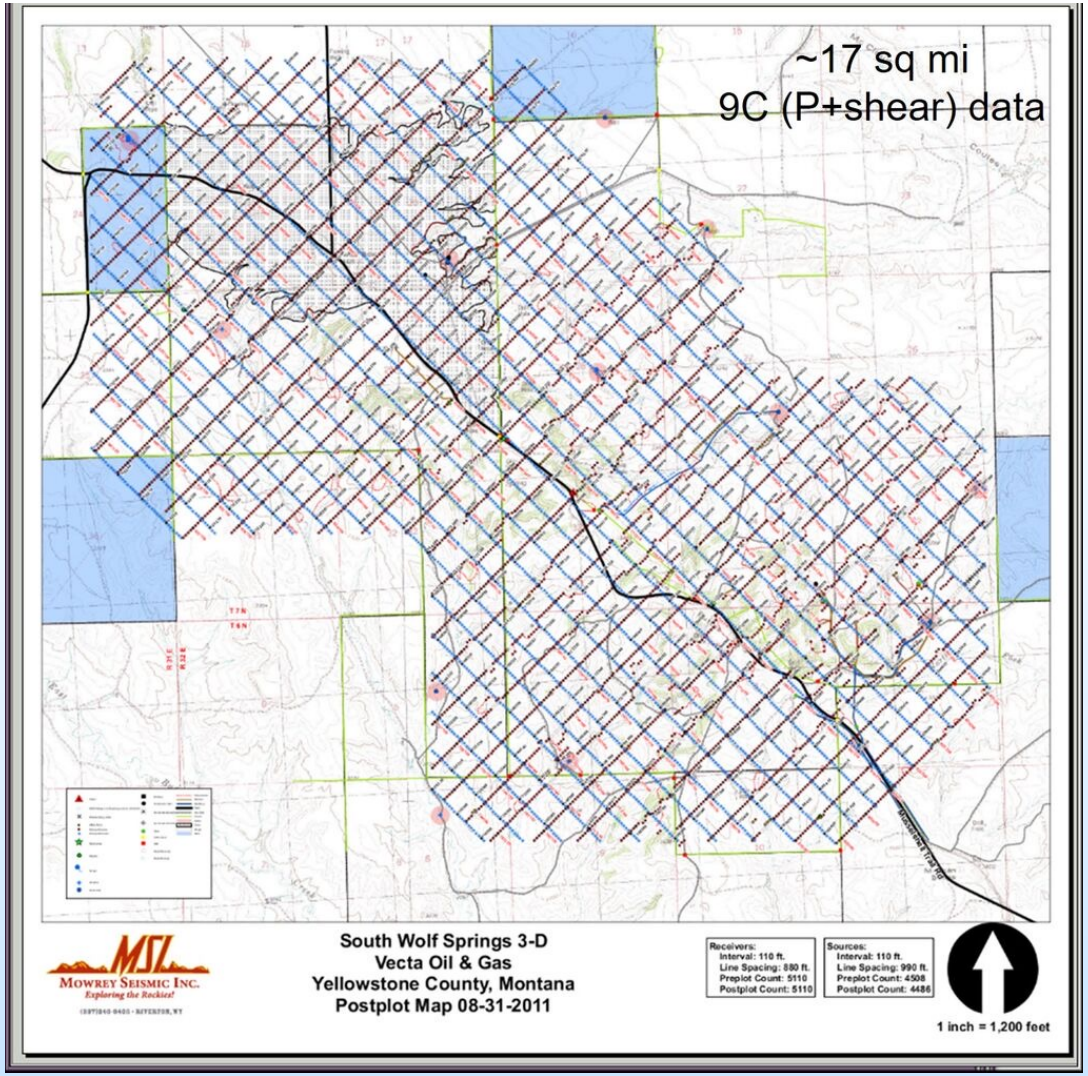
Frac parameter inversion

Fractured reservoir

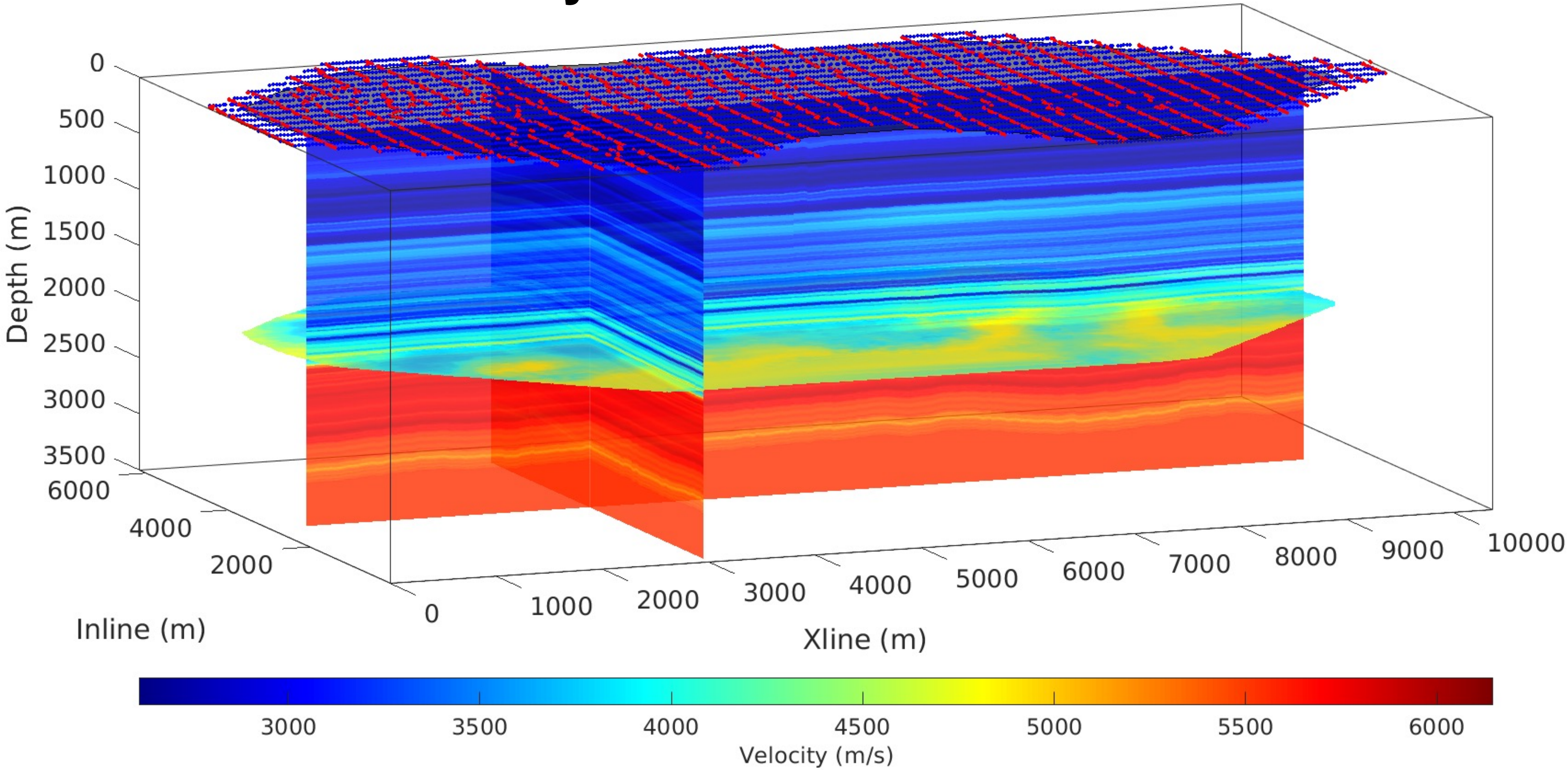
- Fracture orientation
- Density
- Compliance

Build the synthetic elastic model from the field data

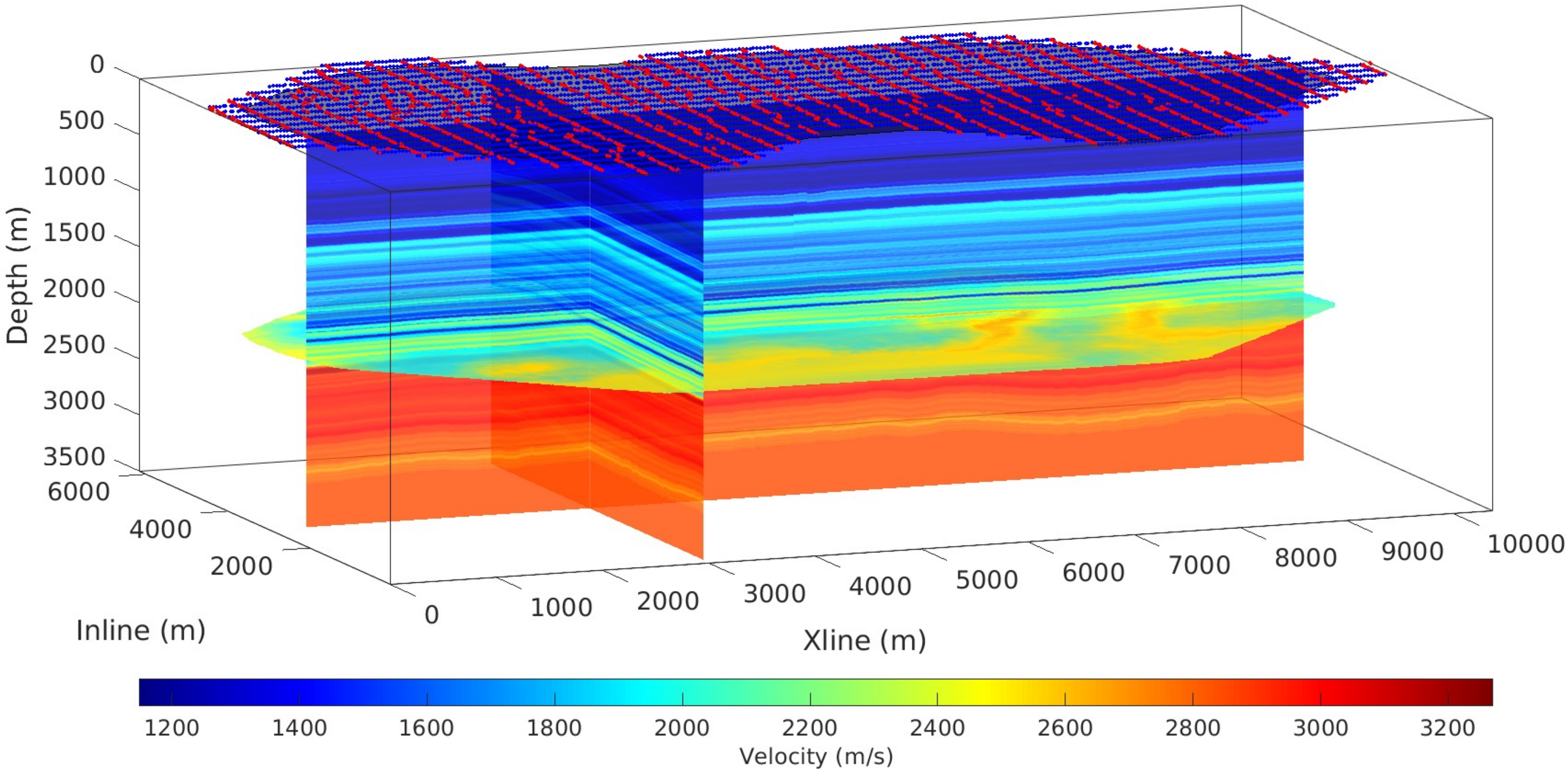
Field seismic data (9C) in Montana



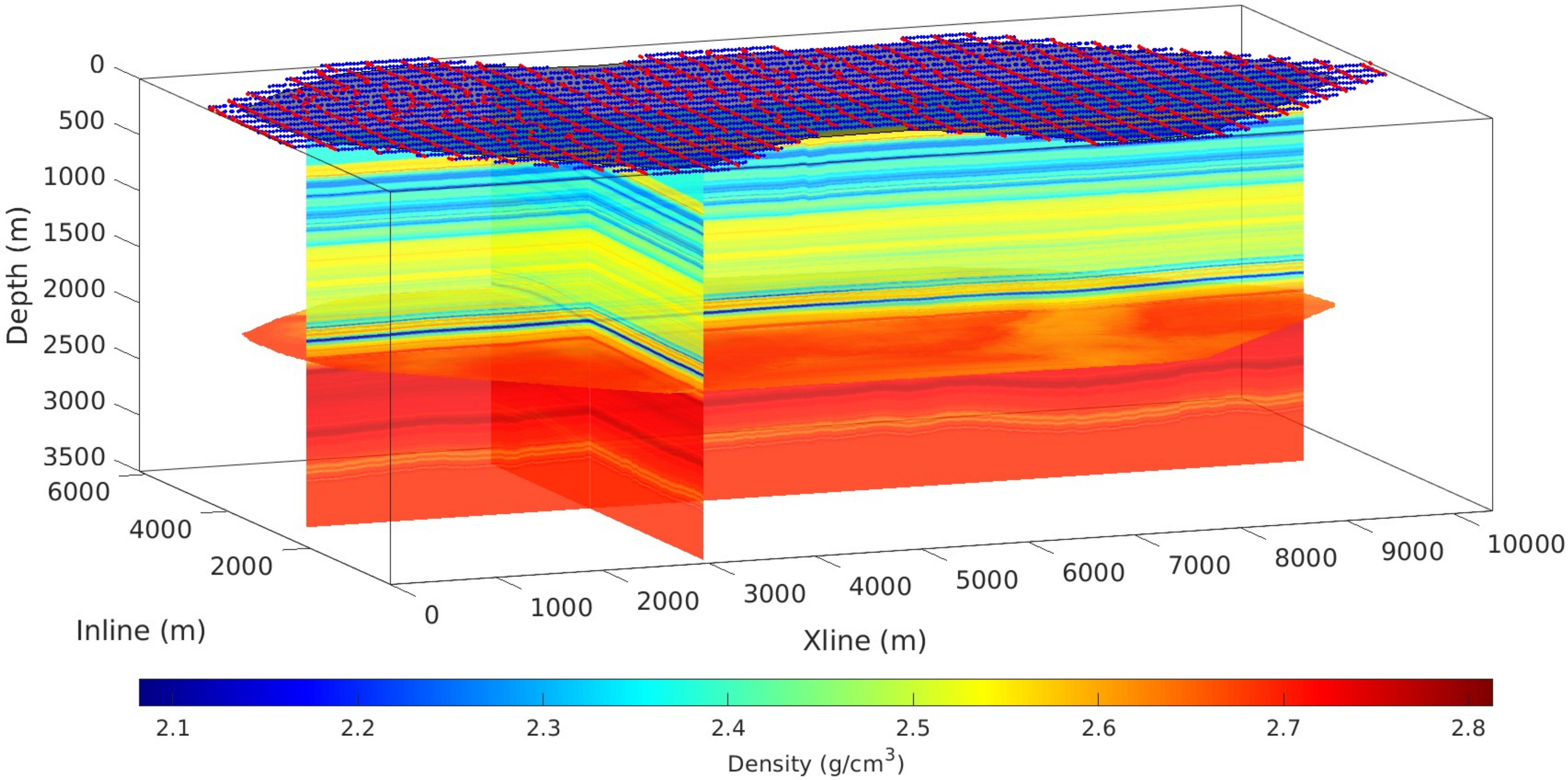
P-wave velocity model from the field Vecta data



Shear-wave velocity model from the field Vecta data

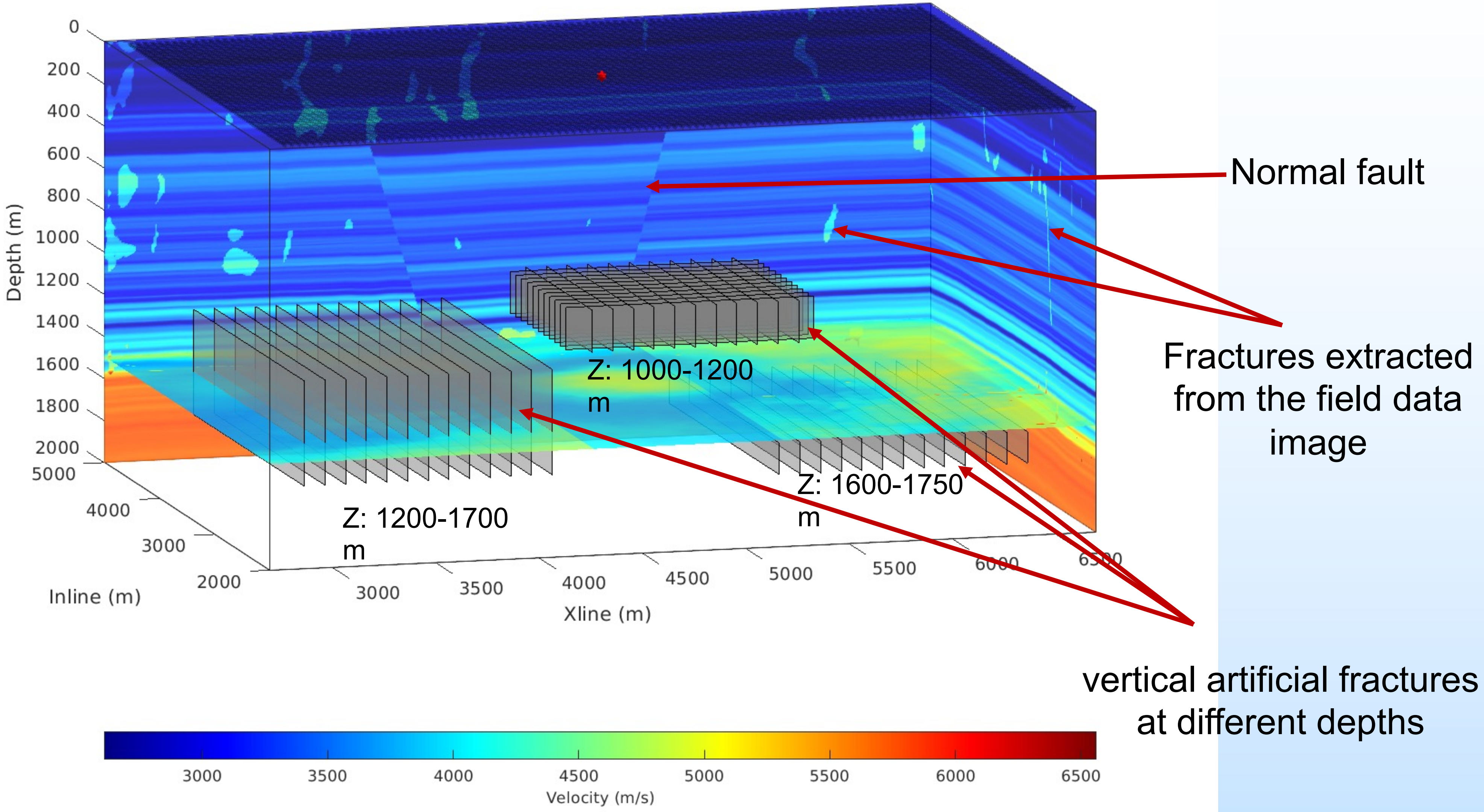


Density model from the field Vecta data

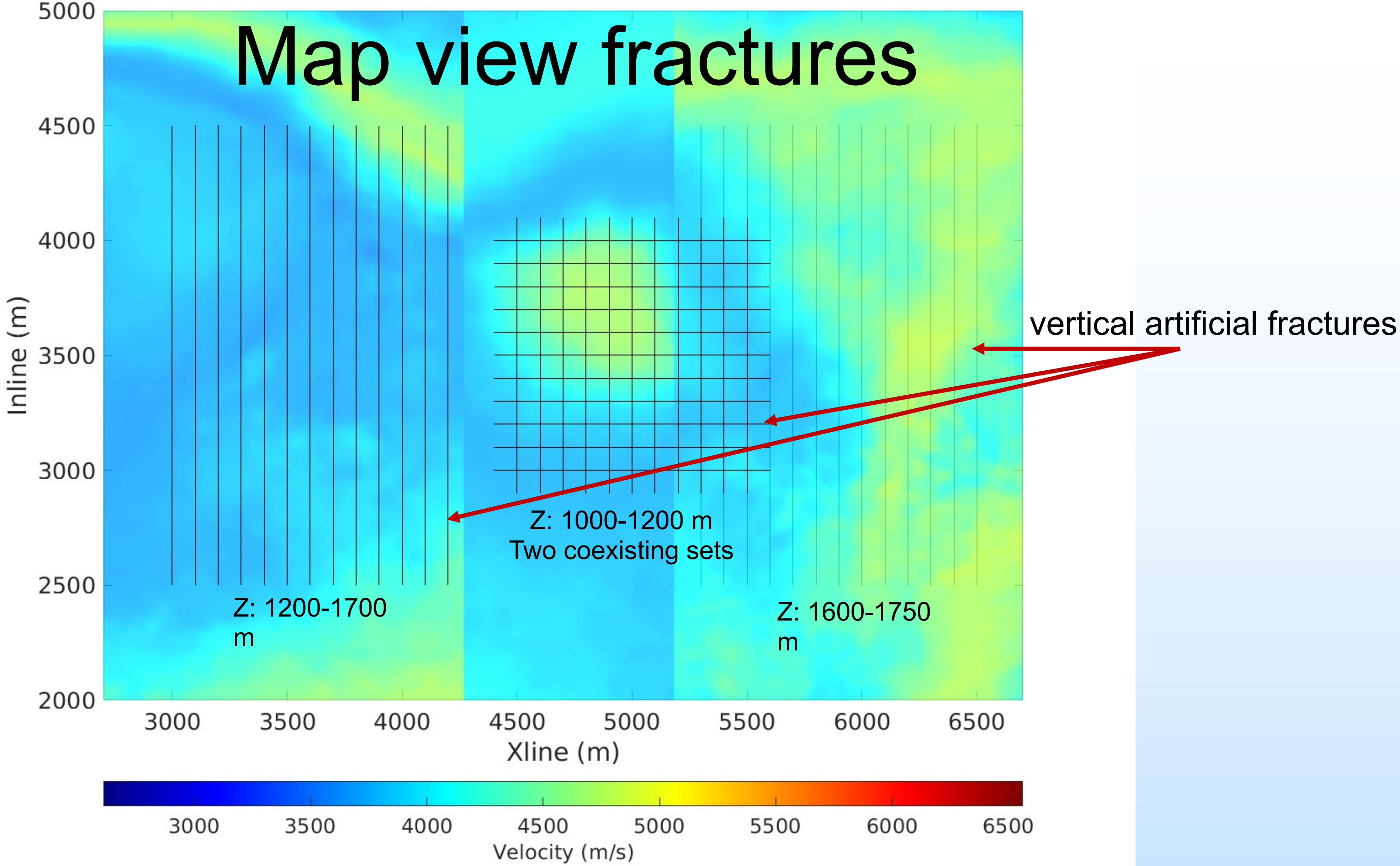


Detection Results: small-scale fractures

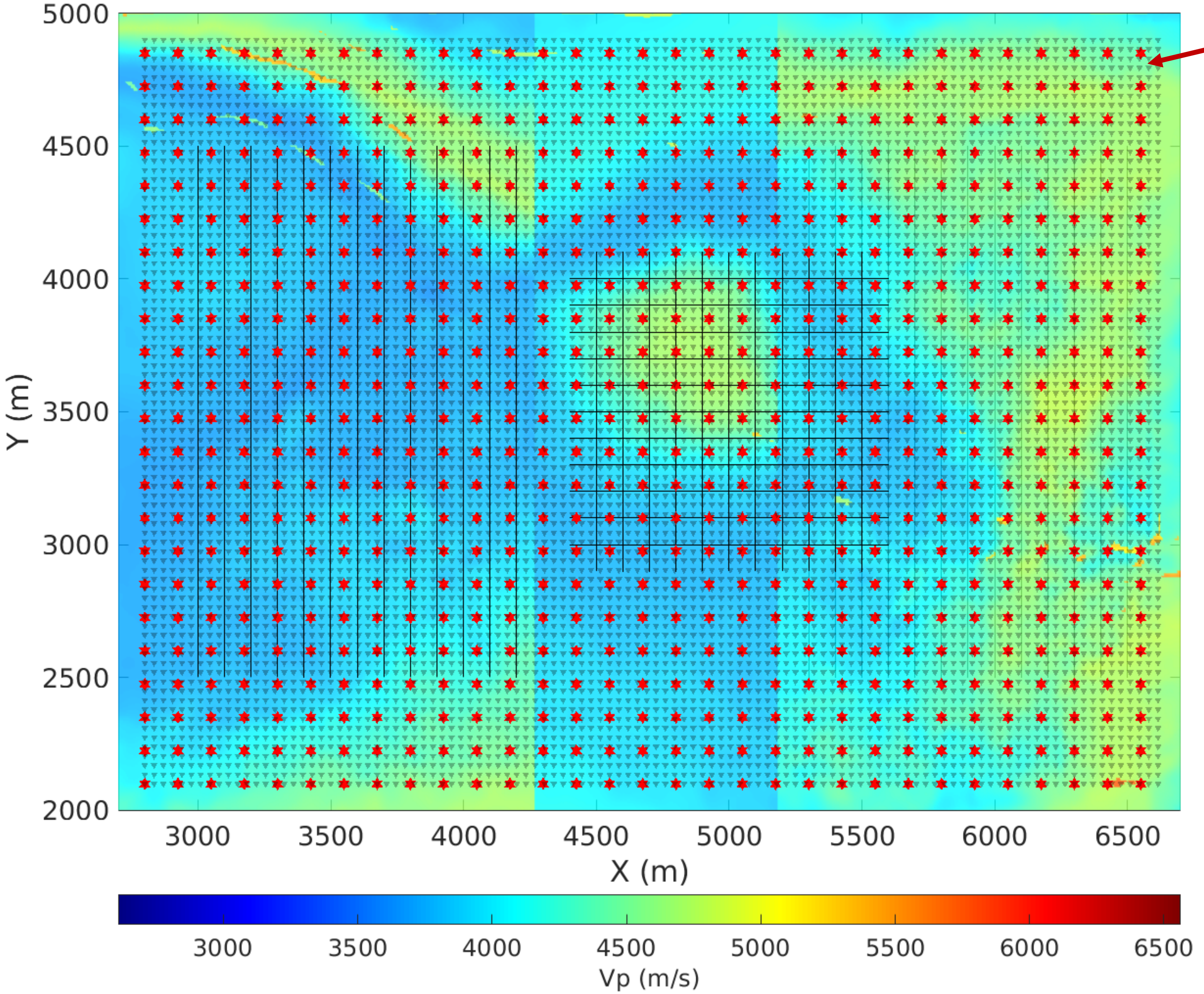
Synthetic Vp model with
: a normal fault
: vertical artificial fracture sets
: small fractures extracted from field data image



Map view fractures



Acquisition geometry



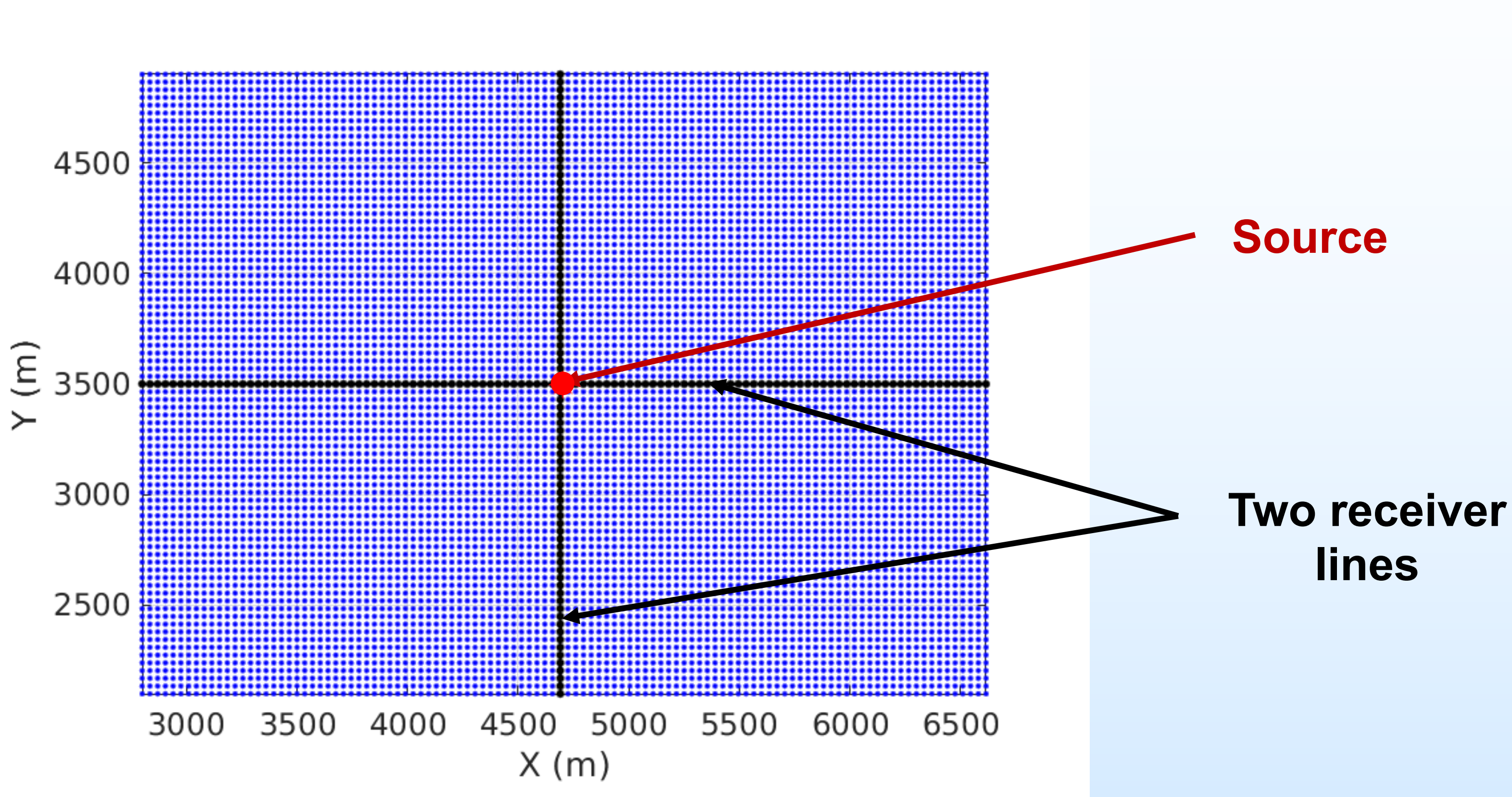
Source
Receiver

Sources:
X: 2800:125:6550 m
Y: 2100:125:4850 m
Total: 31*23=**713**

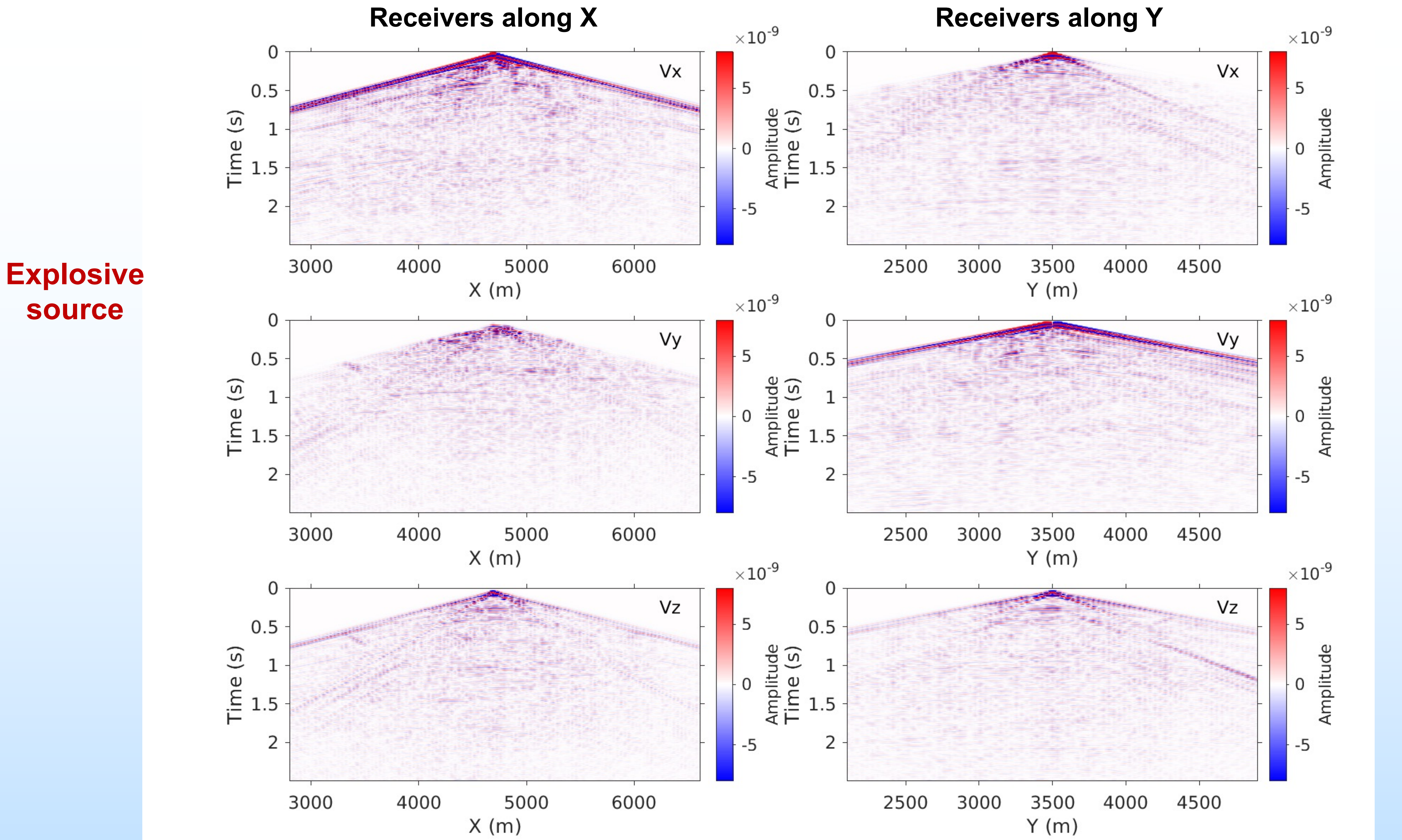
Receivers:
X: 2800:35:6615 m
Y: 2100:35:4900 m
Total: 110*81=**8910**

Both Source and receivers are at surface

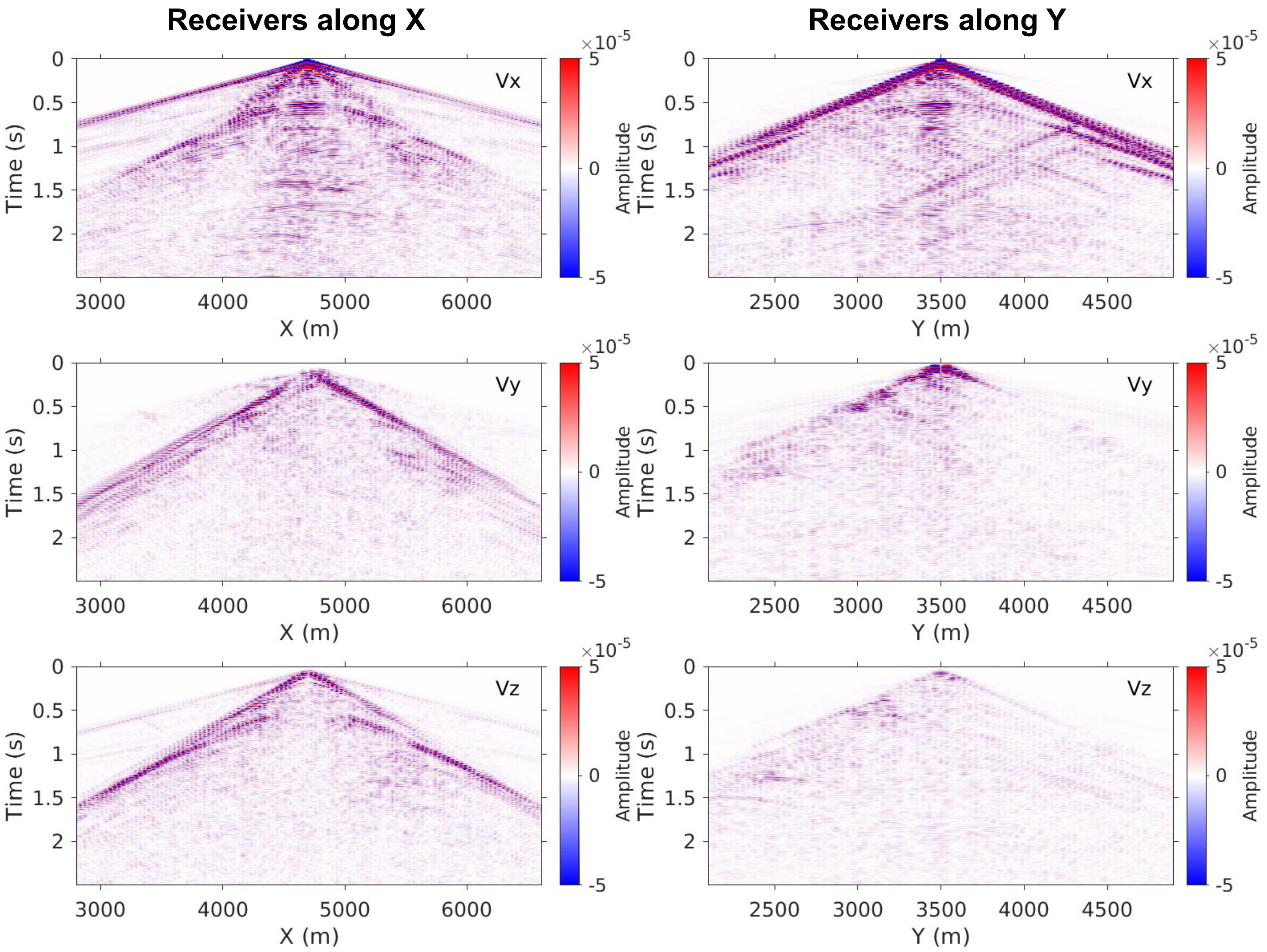
Modeled common-shot gathers at one location with different types of source.



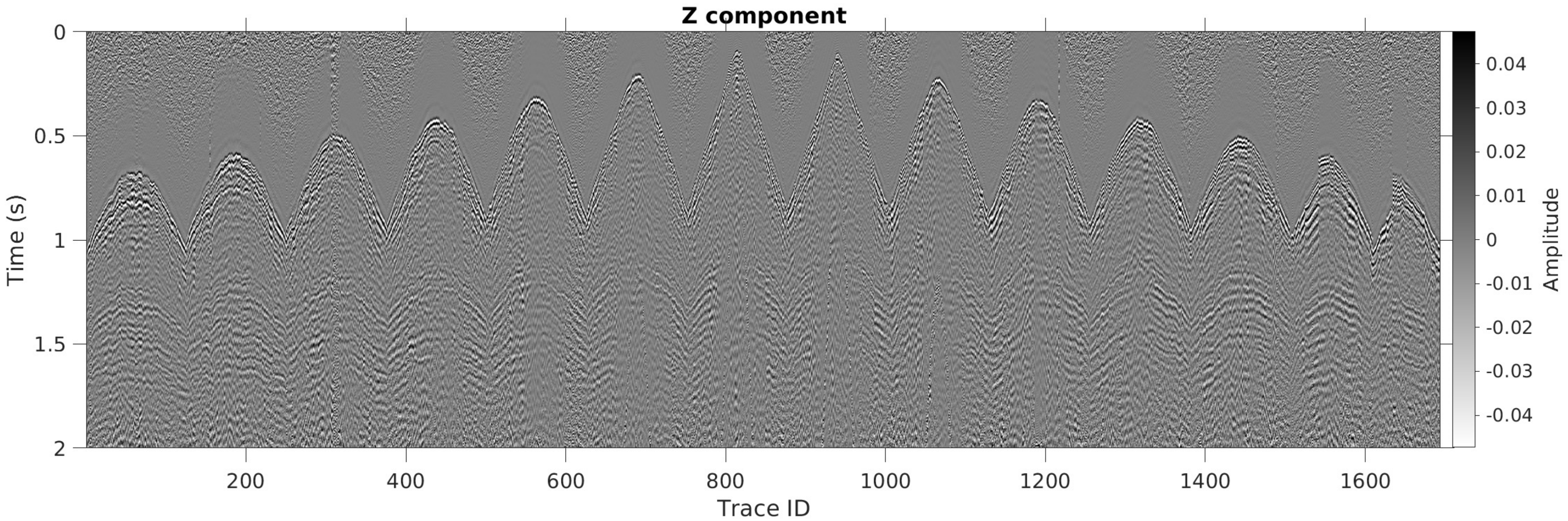
Source wavelet: 20 Hz Ricker


Receivers along X
Receivers along Y
Explosive source
Vx
Vy
Vz
Time (s)
X (m)
Y (m)
Amplitude
×10^-9
0
0.5
1
1.5
2
3000
4000
5000
6000
2500
3500
4500
5
-5

Single force-X



Field data

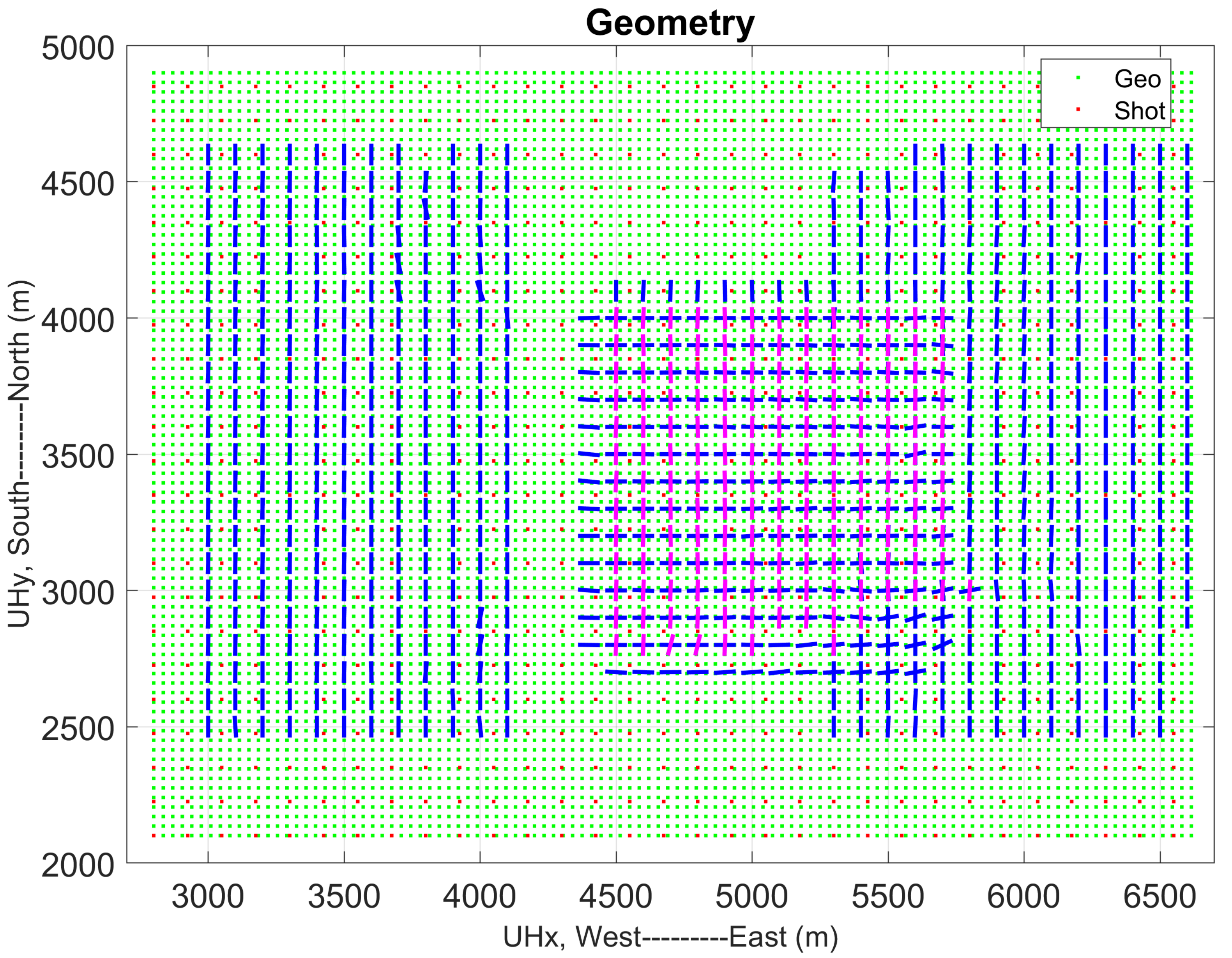


Vertical vibreseis

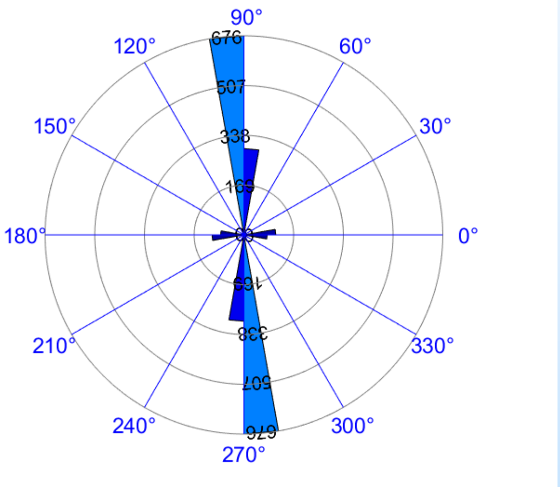
Fracture detection results using Seismic Double-Beam method

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

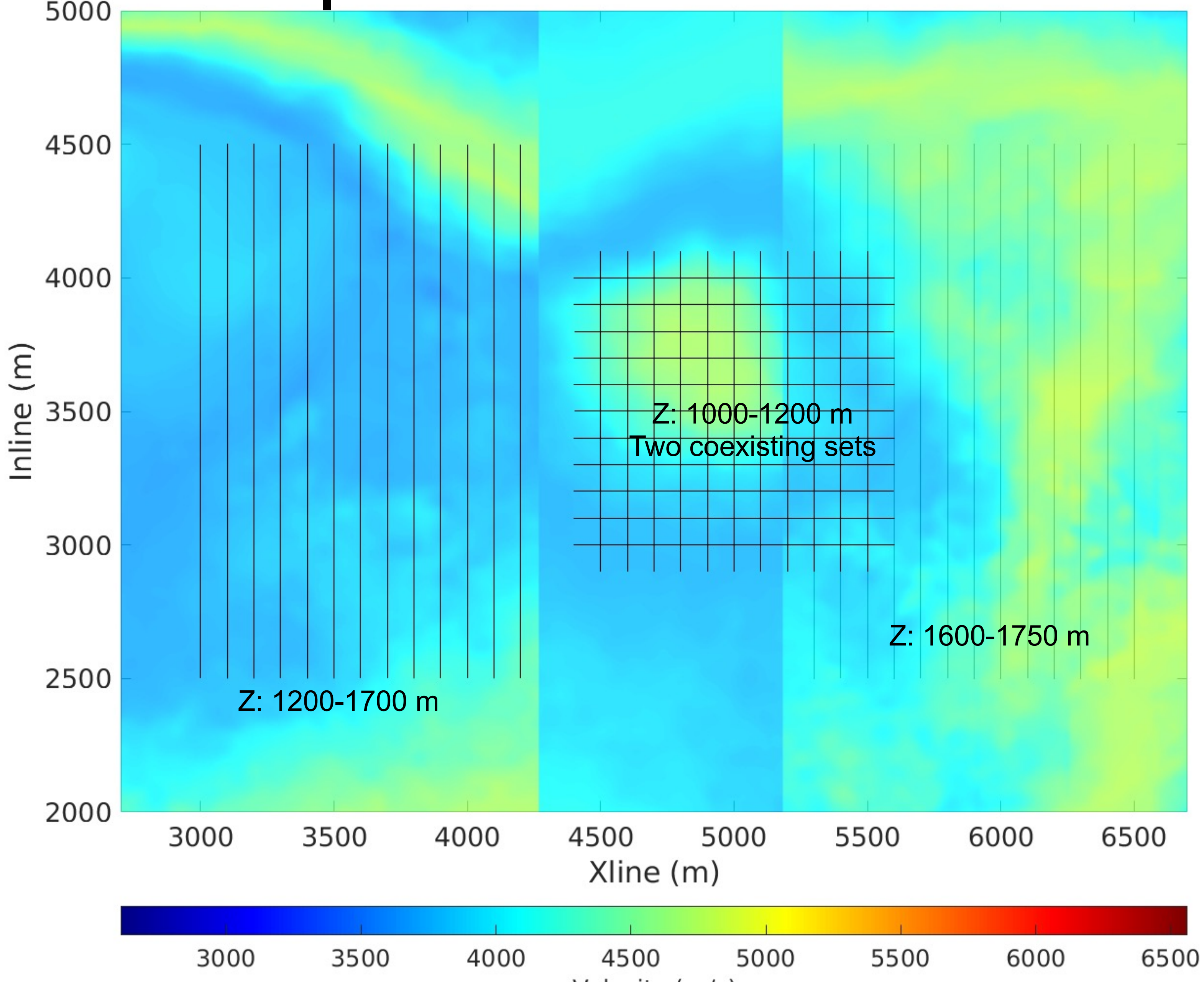
Results: top view of double-beam detected fractures



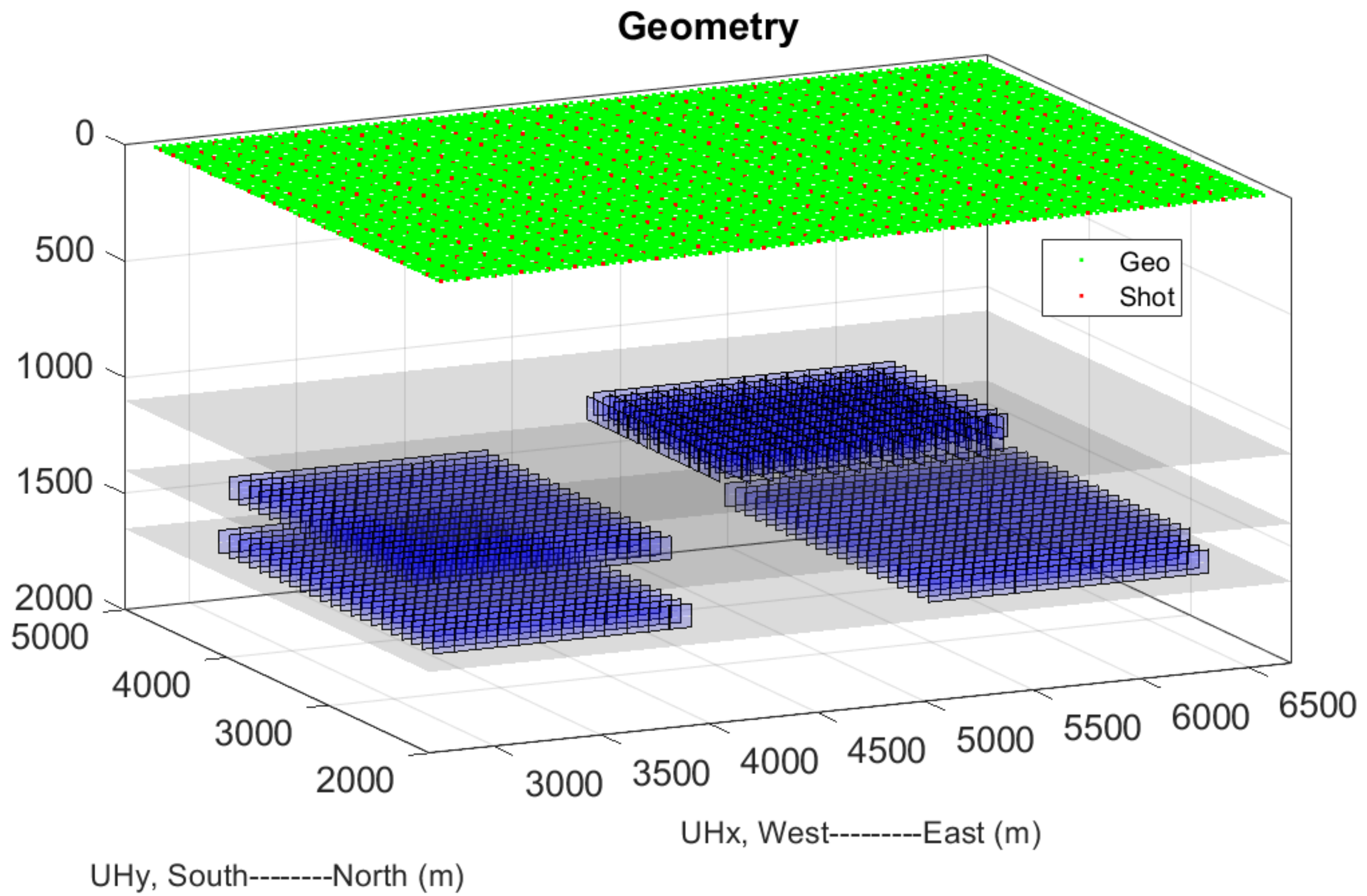
At three depths (1100 m, 1400 m and 1650 m) from frequencies 15 Hz, 20 Hz, 30 Hz and 40 Hz



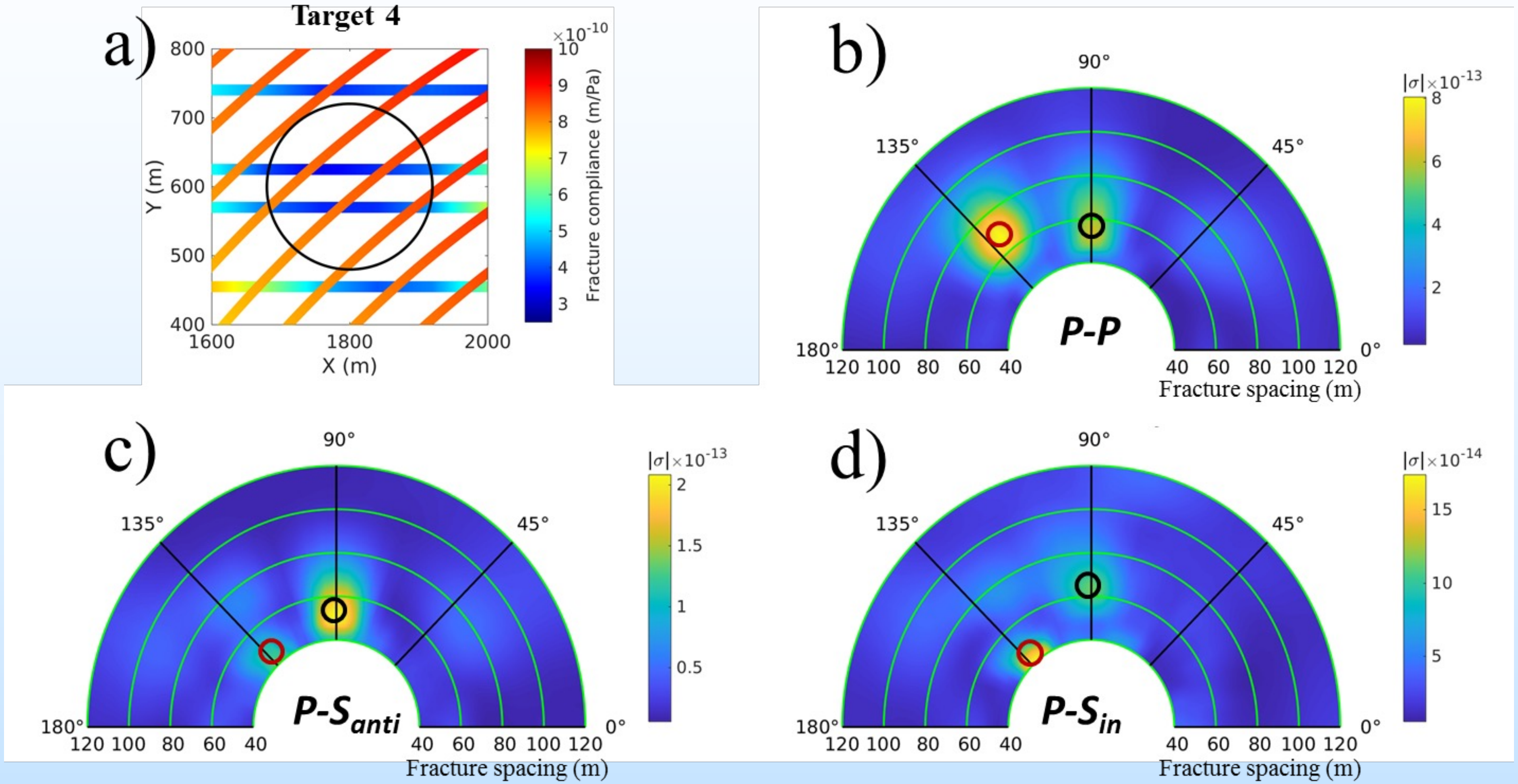
Map view of true fractures



3D view of detected fractures

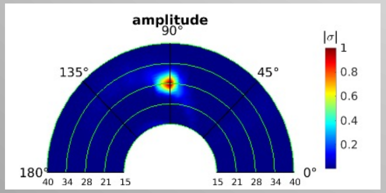


Next steps: discrete fracture network using Machine learning & field data

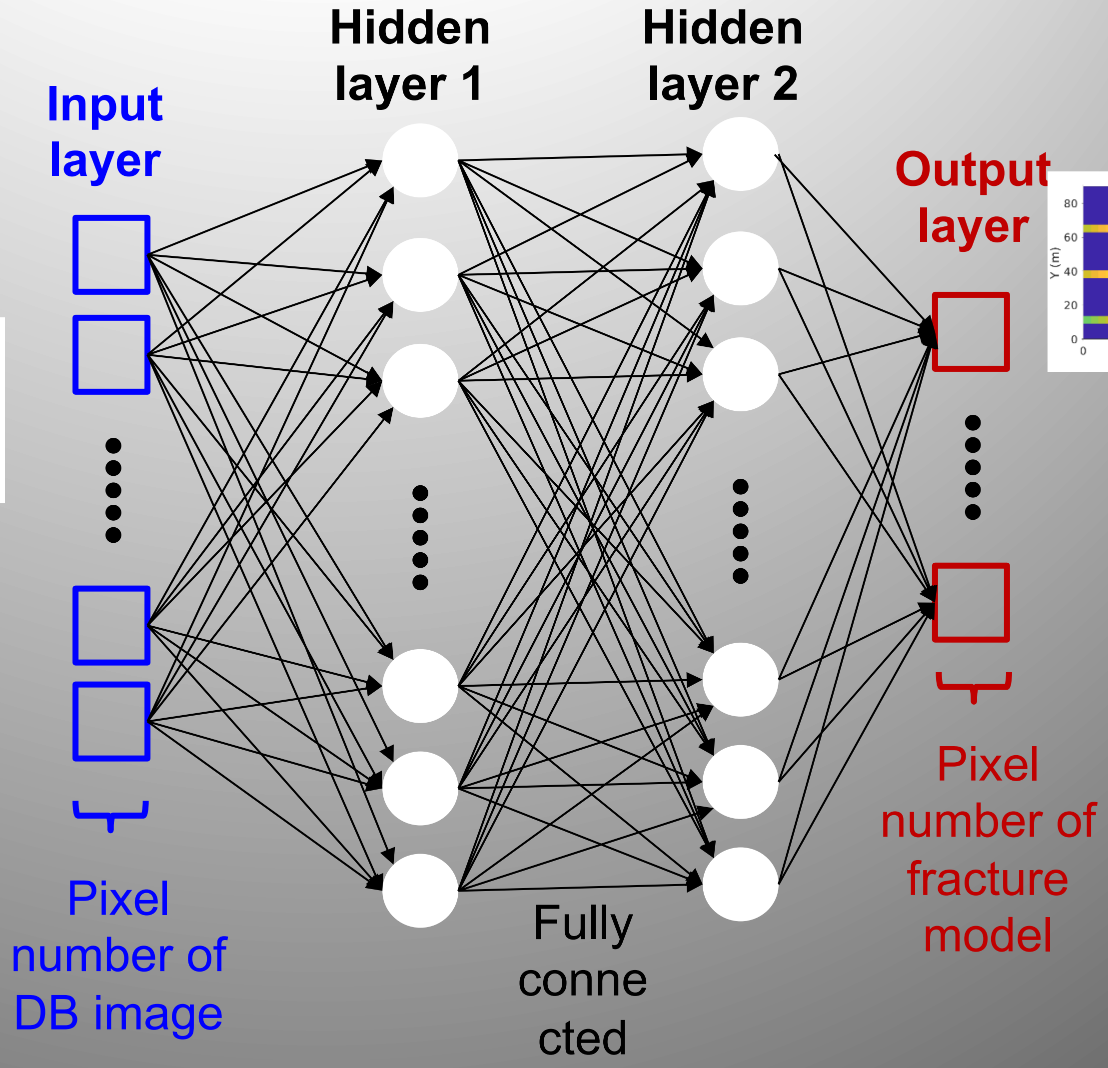


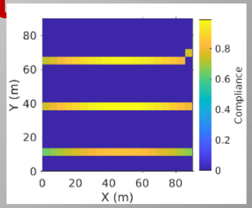
(Zheng et al., 2023 SGW)

Elastic double-beam neural network (DBNN) machine learning



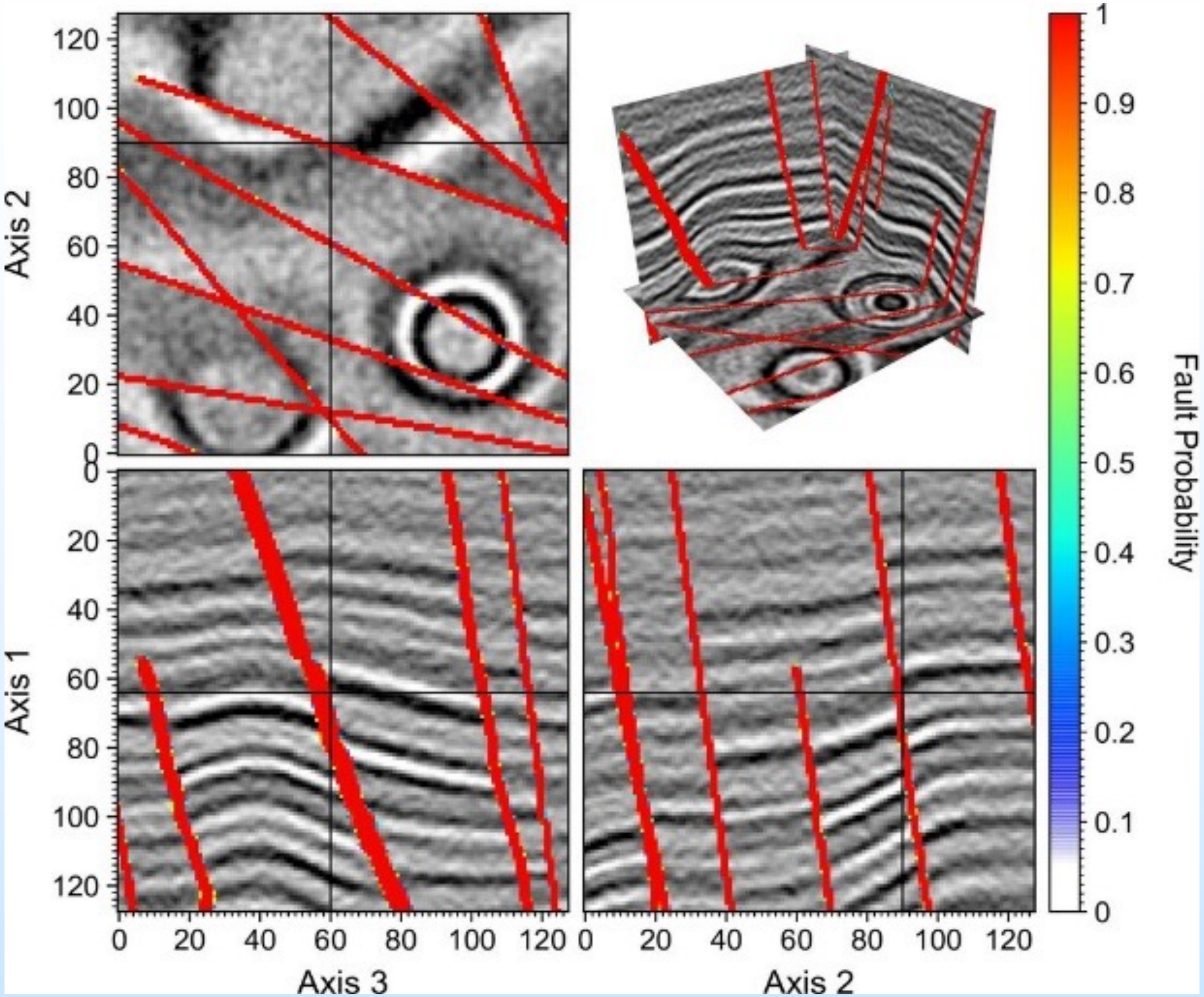
The architecture of our fully-connected neural network including two hidden layers.





Large-scale fault detection using machine learning (LANL)

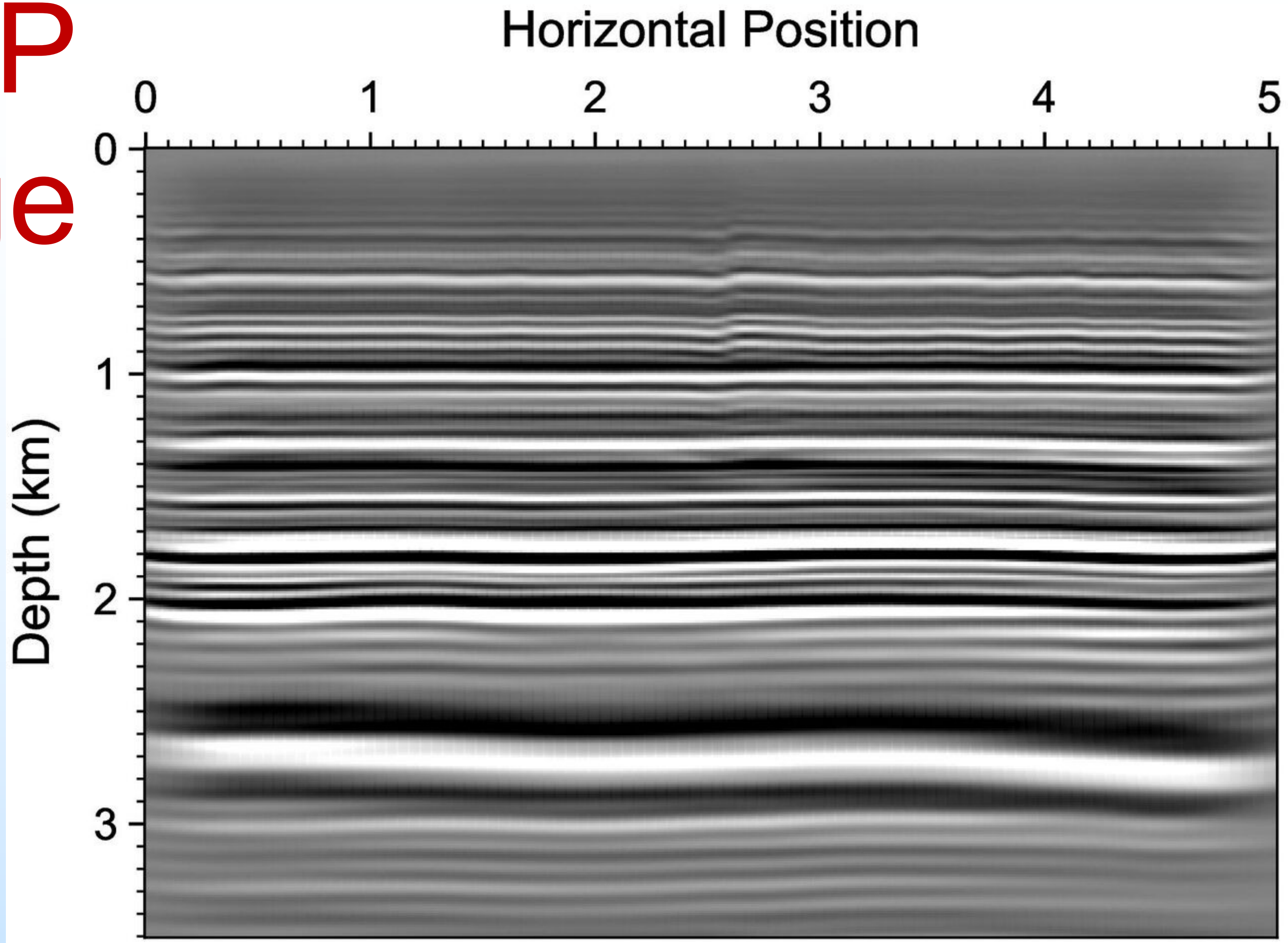
Large-scale faults detected using LANL's new NRU



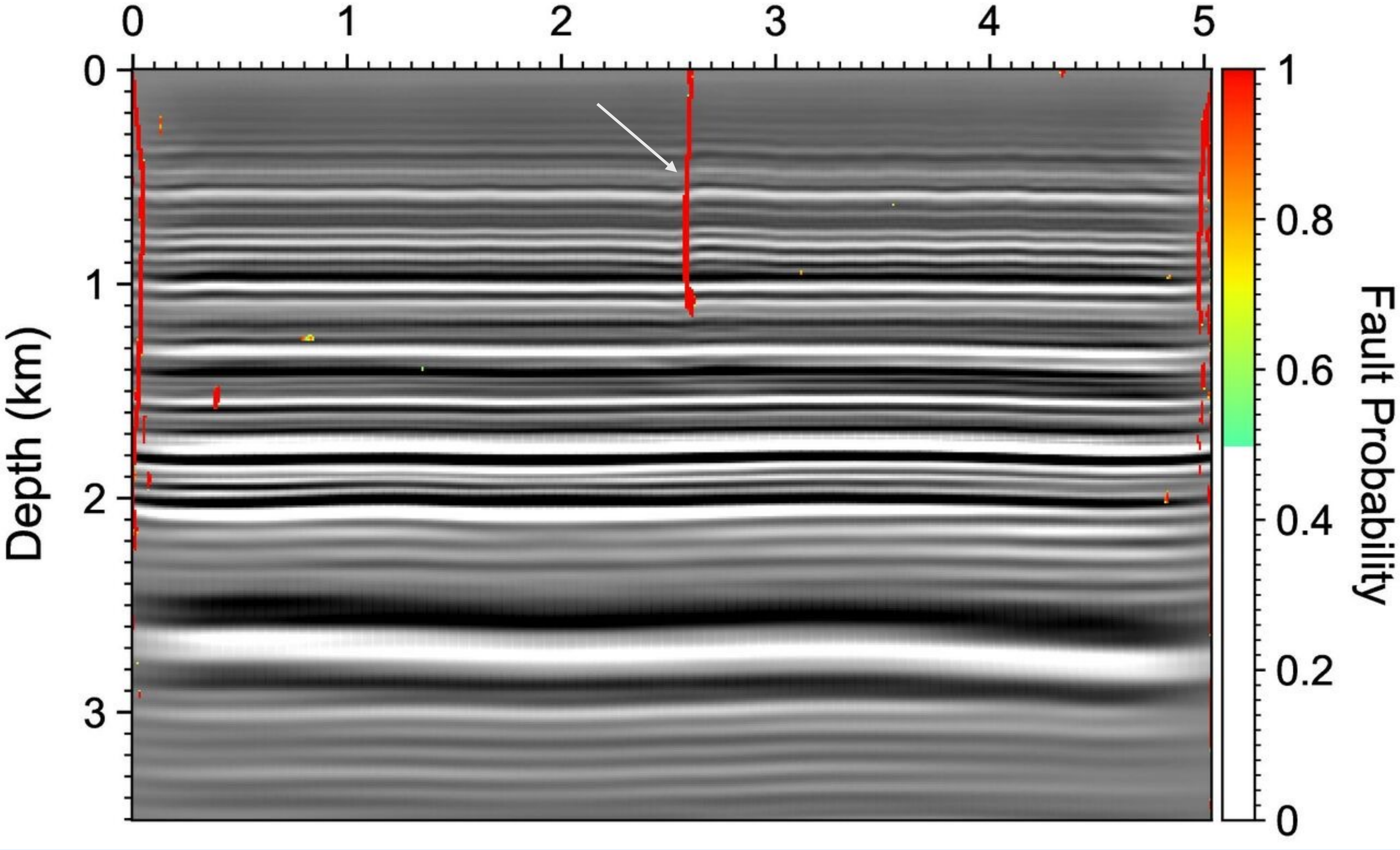
(Gao, Huang, Zheng 2022; IEEE TGRS)

Nested Residual U-shaped convolutional neural network (NRU)

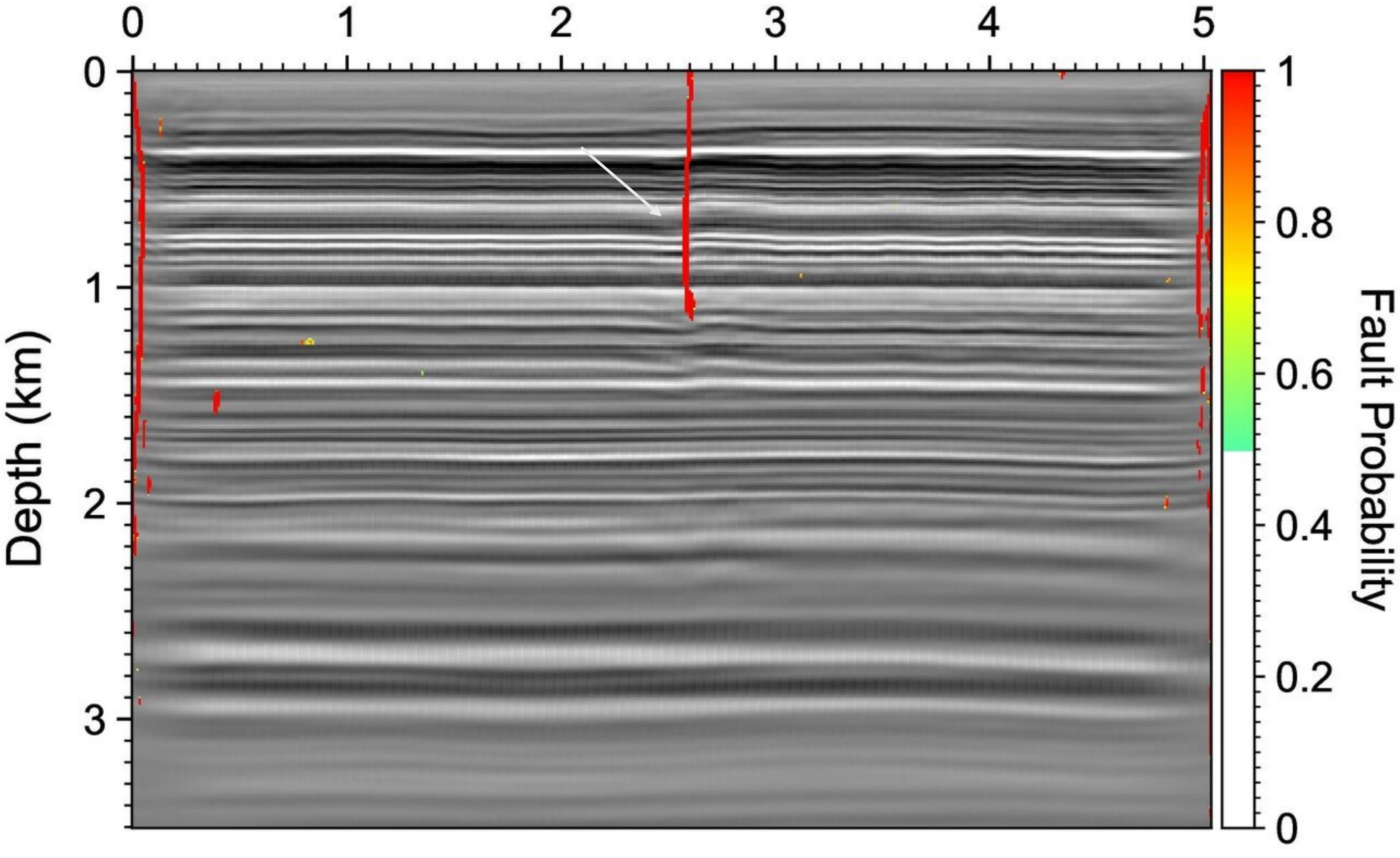
Fz PP image



Detected large scale faults using P-P data

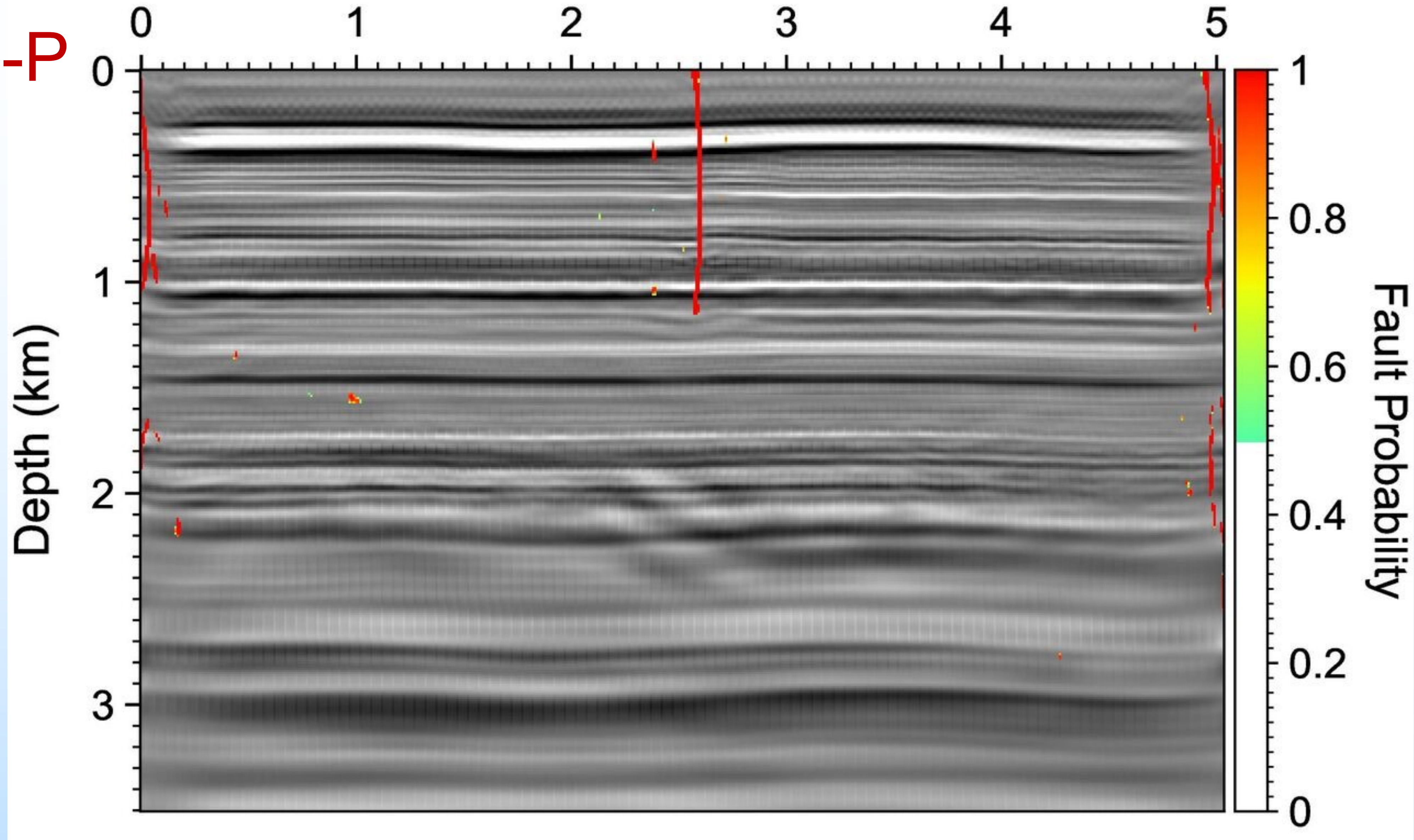


Detected large scale faults using P-S data

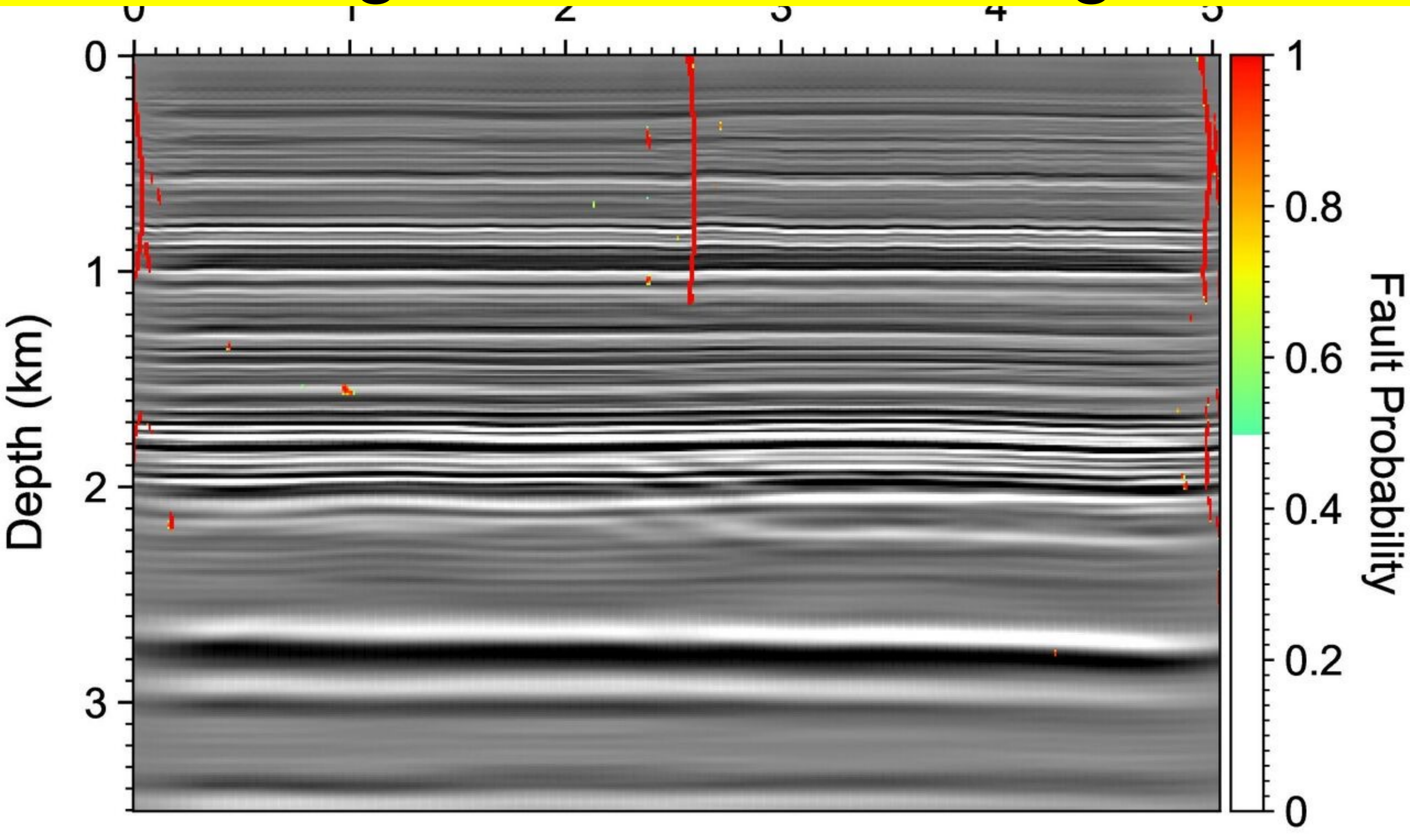


Detected large scale faults using S-P data

Fx: S-P



Detected large scale faults using S-S data

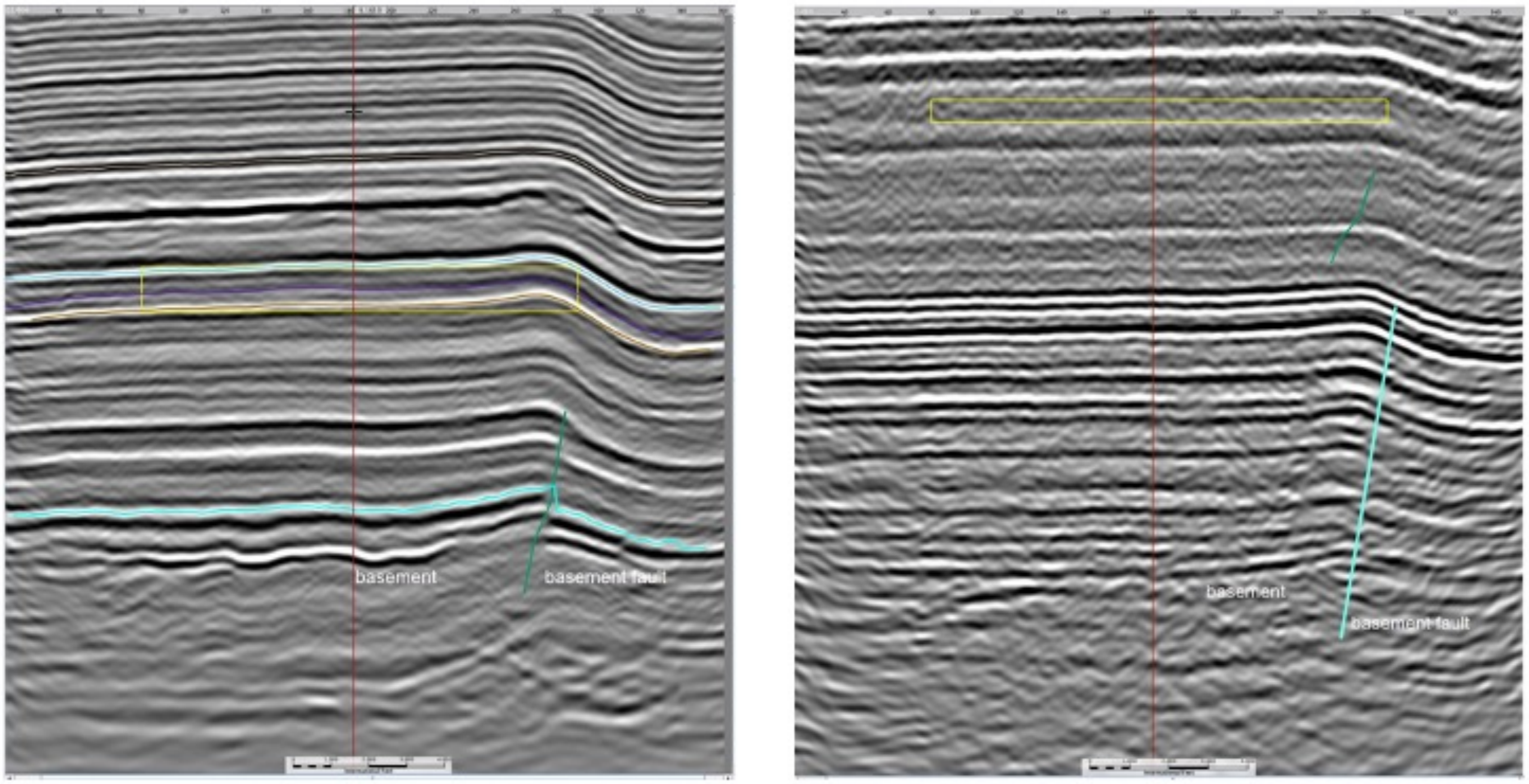


Lessons from: large-scale fault and small-scale fracture detection

- Different modes (P-P, P-S, S-P, S-S) give consistent results

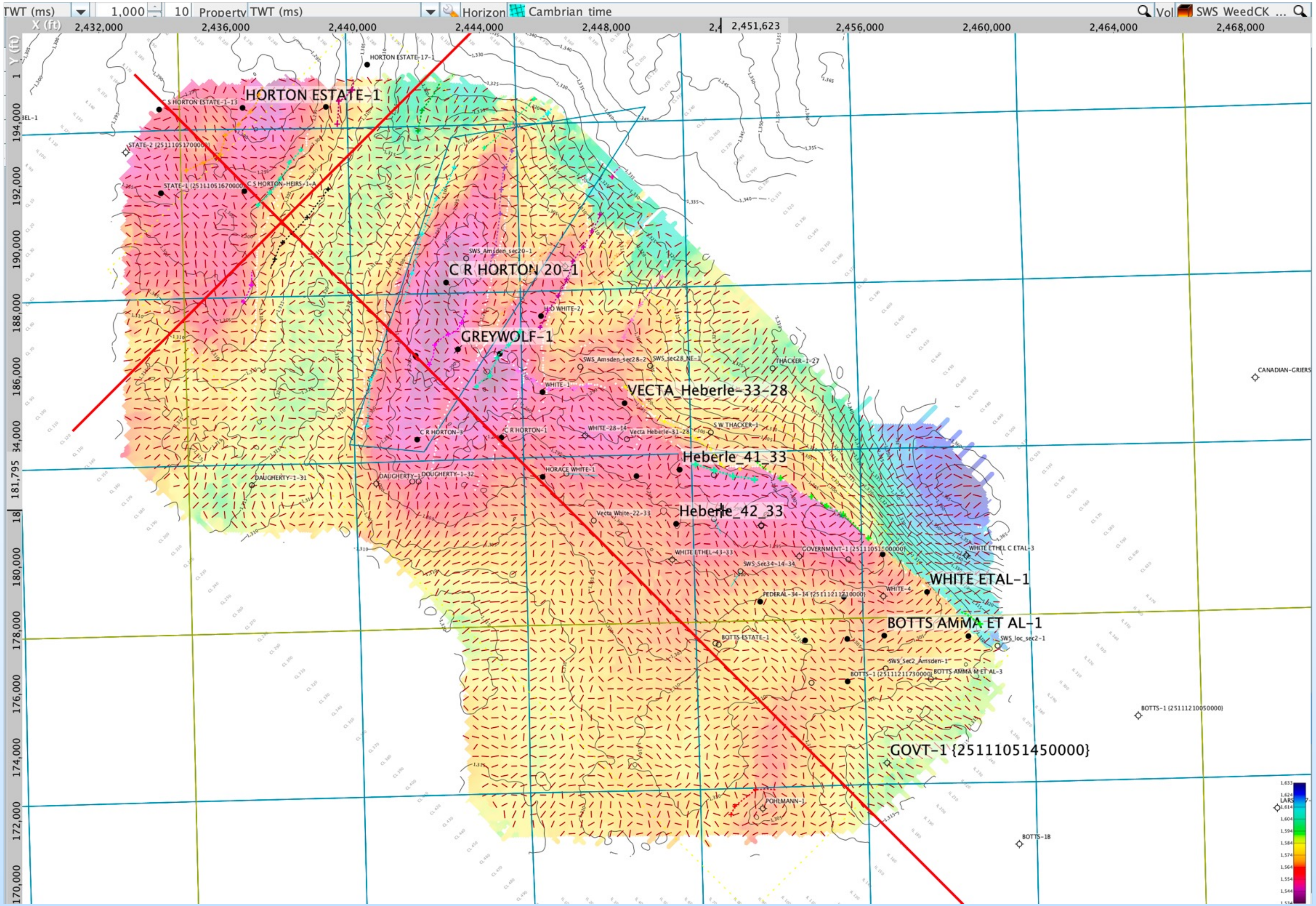
- The consistency reduces uncertainties & yields high confidence in the results.

Field data: 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



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.

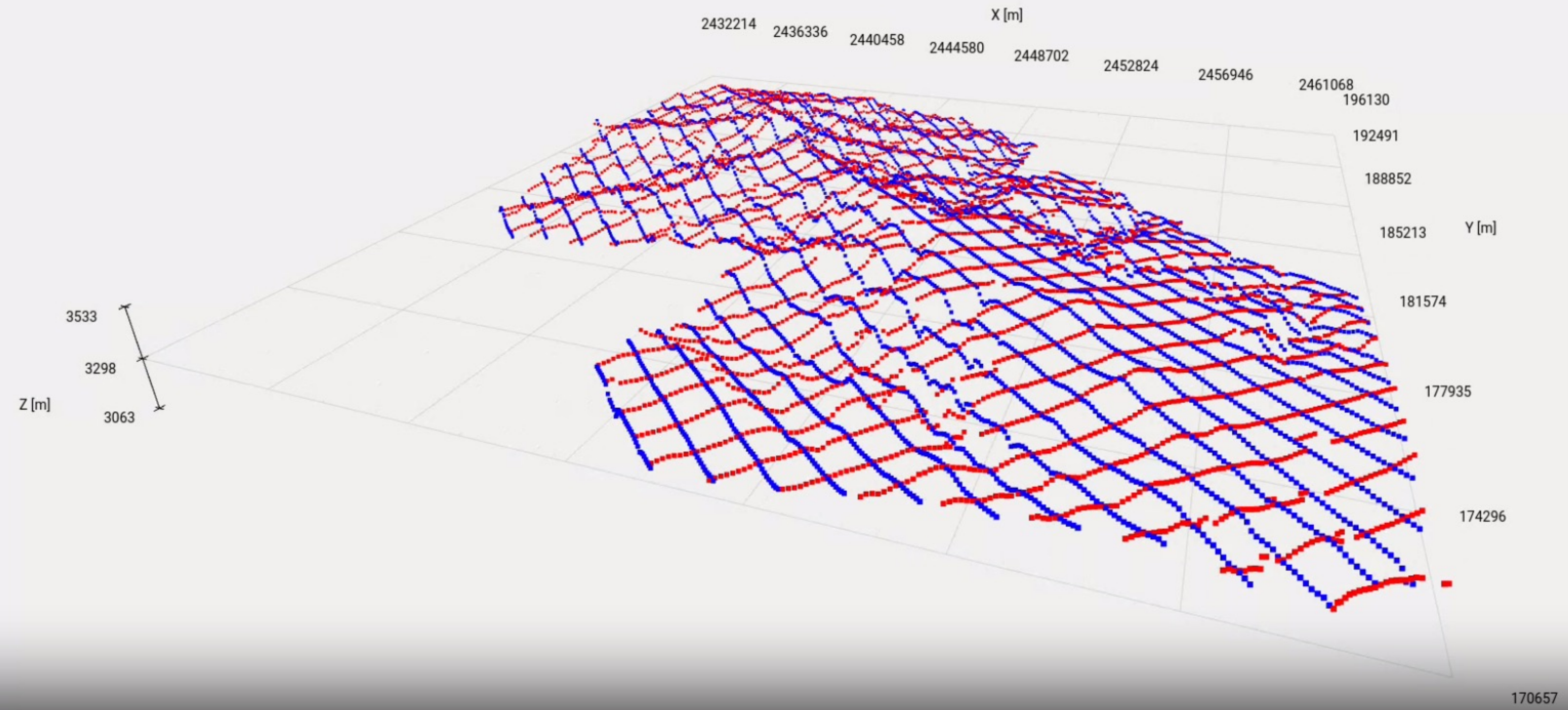
•Subtask 3.5 – (LANL) Fault detection using machine learning (M16-M24)

Deliverable: Software development

- Web browser for seismic model/data visualization

Find at UH Libraries | Gmail | uhwork | Google | DuckDuckGo | Find at UH Lib | Capture Reference | uhxfrac | Google Scholar | dictionary | Other Favorites

FILE | EDIT | VIEW | APPLICATIONS | HELP | ABOUT



GEOMETRY | TRACES

Scene Controls

Geometry Controls

Show Sources ✓

Show Receivers ✓

Show CMPs

Show Faults/Fractures ✓

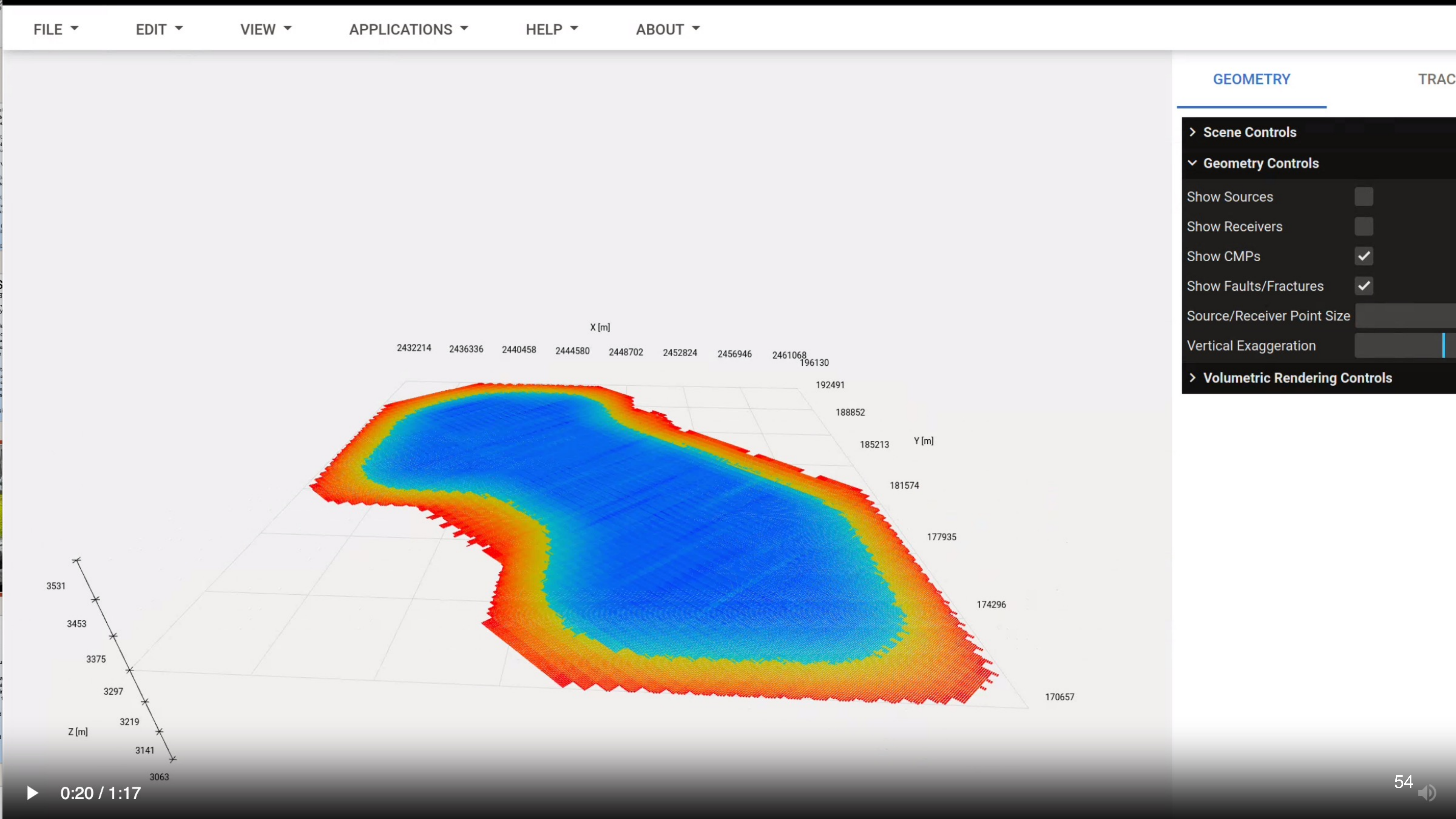
Source/Receiver Point Size 10

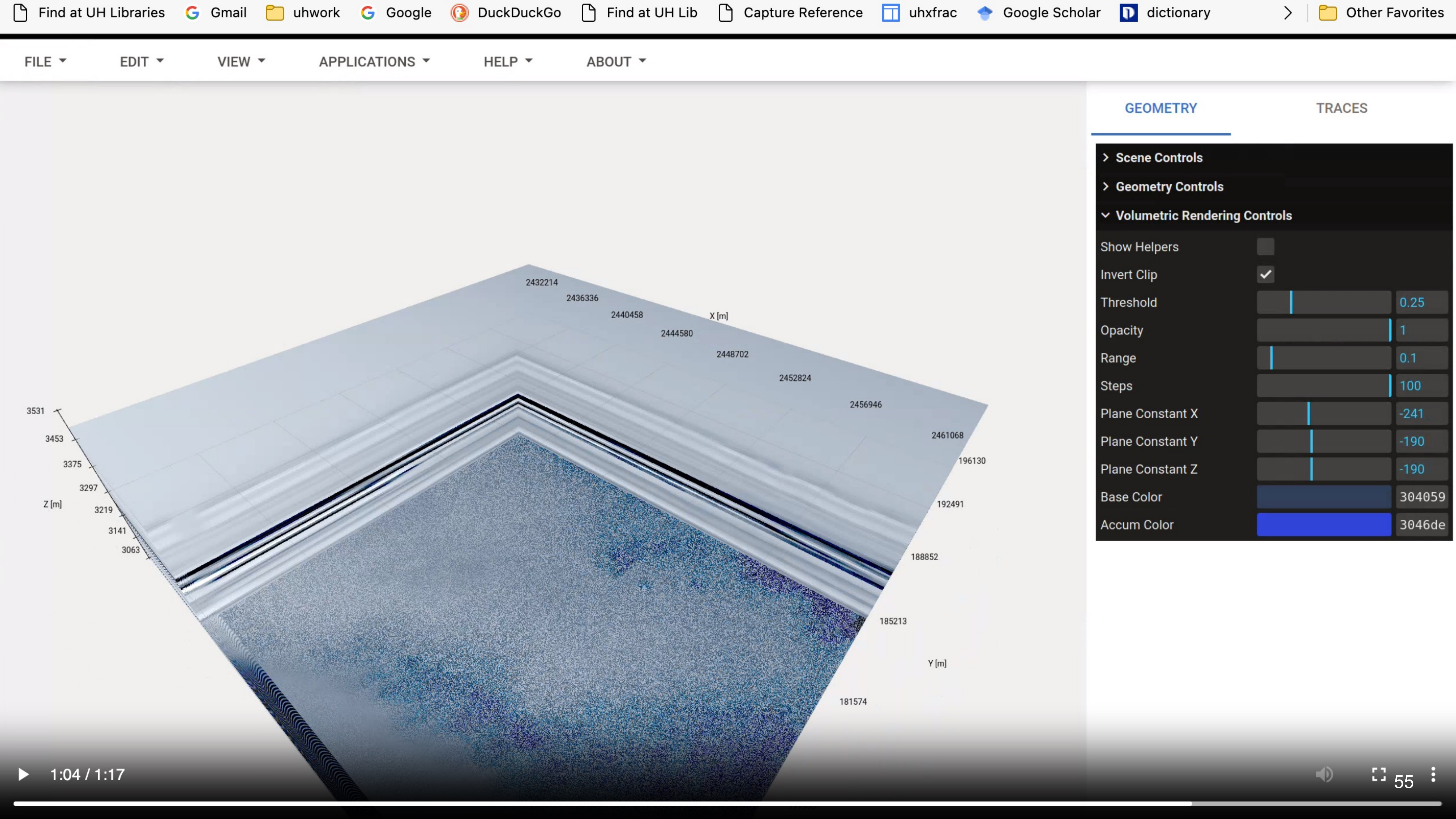
Vertical Exaggeration 1

Volumetric Rendering Controls

0:14 / 1:17

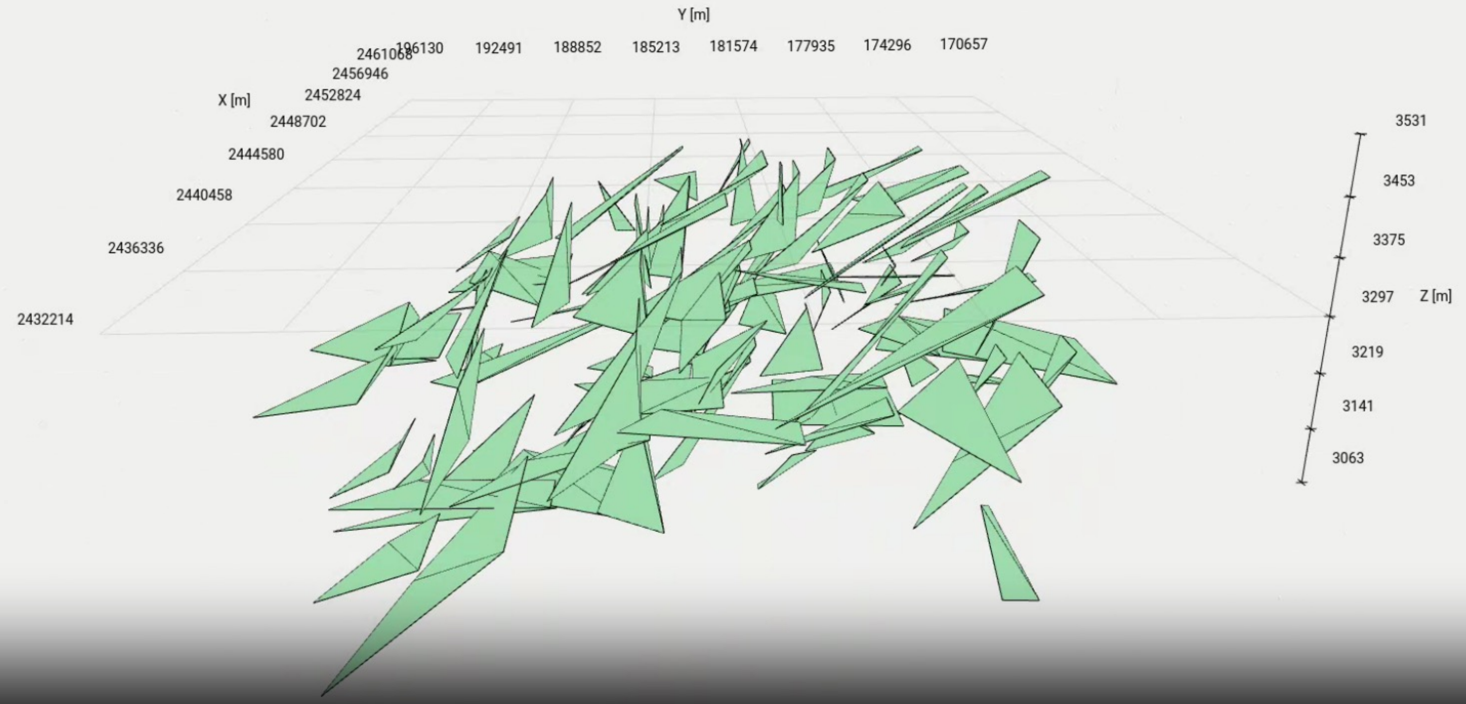
53


FILE
EDIT
VIEW
APPLICATIONS
HELP
ABOUT
GEOMETRY
TRAC
Scene Controls
Geometry Controls
Show Sources
Show Receivers
Show CMPs
Show Faults/Fractures
Source/Receiver Point Size
Vertical Exaggeration
Volumetric Rendering Controls
X [m]
2432214
2436336
2440458
2444580
2448702
2452824
2456946
2461068
196130
192491
188852
185213
Y [m]
181574
177935
174296
170657
3531
3453
3375
3297
3219
Z [m]
3141
3063
0:20 / 1:17
54


Find at UH Libraries
Gmail
uhwork
Google
DuckDuckGo
Find at UH Lib
Capture Reference
uhxfrac
Google Scholar
dictionary
Other Favorites
FILE
EDIT
VIEW
APPLICATIONS
HELP
ABOUT
GEOMETRY
TRACES
Scene Controls
Geometry Controls
Volumetric Rendering Controls
Show Helpers
Invert Clip
Threshold
0.25
Opacity
1
Range
0.1
Steps
100
Plane Constant X
-241
Plane Constant Y
-190
Plane Constant Z
-190
Base Color
304059
Accum Color
3046de
2432214
2436336
2440458
2444580
2448702
2452824
2456946
2461068
X [m]
196130
192491
188852
185213
181574
Y [m]
3531
3453
3375
3297
3219
3141
3063
Z [m]
1:04 / 1:17
55

Find at UH Libraries | Gmail | uhwork | Google | DuckDuckGo | Find at UH Lib | Capture Reference | uhxfrac | Google Scholar | dictionary | Other Favorites

FILE | EDIT | VIEW | APPLICATIONS | HELP | ABOUT



GEOMETRY | TRACES

Scene Controls

Geometry Controls

Show Sources

Show Receivers

Show CMPs

Show Faults/Fractures ✓

Source/Receiver Point Size 10

Vertical Exaggeration 3.1

Volumetric Rendering Controls

0:38 / 1:17

56

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 on 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)
  - State-of-the-art oil/gas industry methods (shear wave splitting) **DONE**
  - Shear wave splitting **DONE**;
  - Double-beam neural network (DBNN); with preliminary results. Overall status: in progress
  - Faults detection; with preliminary results; overall status: in progress

- 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