

# Seismic elastic double-beam characterization of faults and fractures for CO<sub>2</sub> storage site selection

Project Number: DE-FE0032063

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Yingcai Zheng

University of Houston

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U.S. Department of Energy  
National Energy Technology Laboratory  
2022 Project Review Meeting, Pittsburgh  
08/16/2020 11am

# Teams

- University of Houston

- Yingcai Zheng (PI)
- Jake Parsons (graduate student)
- Sharmila Appini (graduate student)
- Yuesu Jin (graduate student)
- Hao Hu (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<sub>2</sub> 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<sup>1</sup>**

**CFDA Number: 81.089**

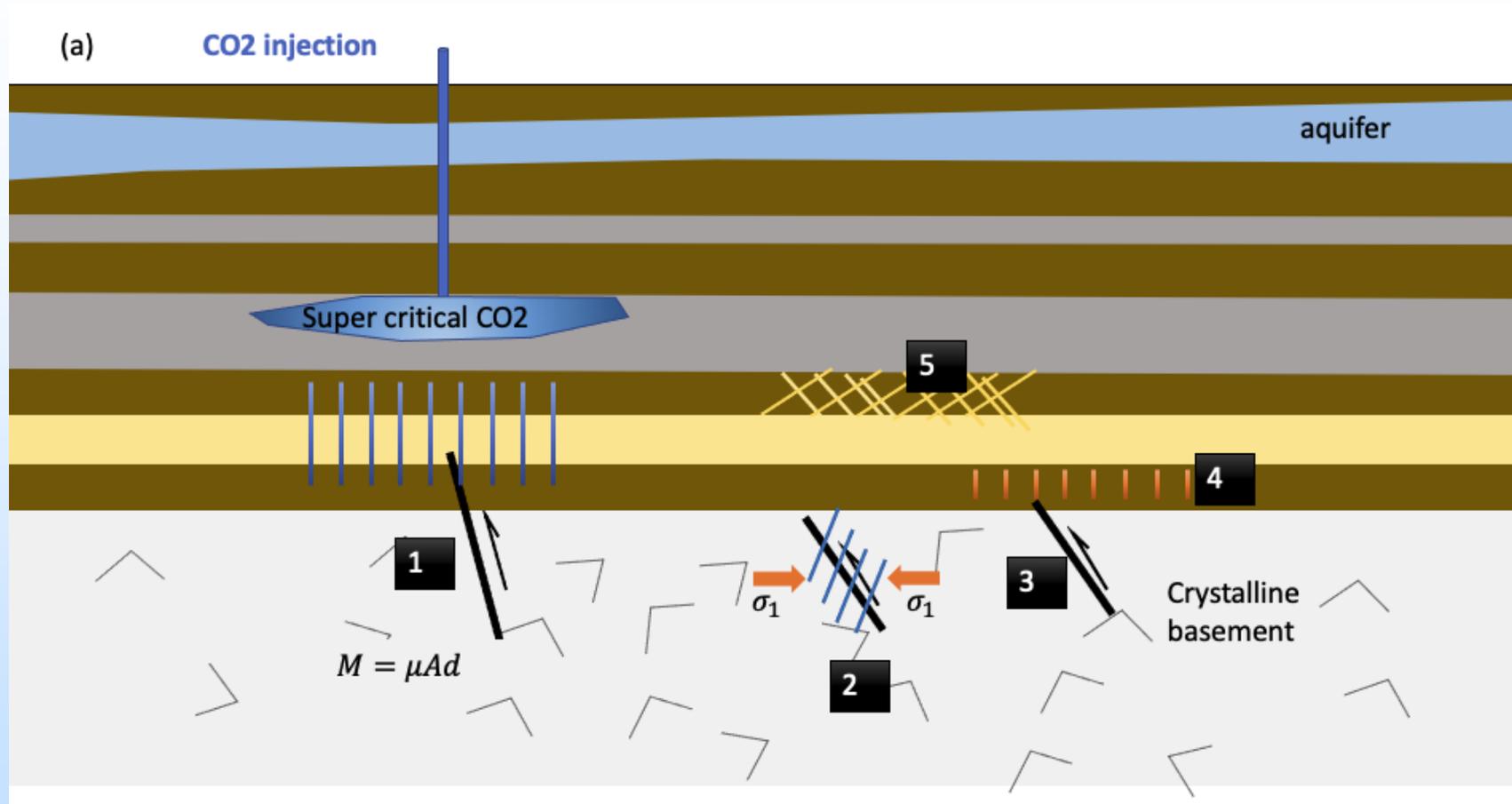
**EMERGING CO<sub>2</sub> STORAGE TECHNOLOGIES: OPTIMIZING PERFORMANCE  
THROUGH MINIMIZATION OF SEISMICITY RISKS AND MONITORING  
CAPROCK INTEGRITY**

**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.**

# Goals and Objectives for Gigatonne injection



# Methodology

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- Develop 9-component (9C) elastic double-beam method for small-scale fracture characterization (self validating)
- Develop large-scale fault detection method
- Synthesis:
  - fractures/faults in sedimentary layers and basement;
  - Stress
  - Estimating earthquake hazards
  - Estimating fluid pathways to basement faults
- Field data test: 9C seismic dataset from Wolf Springs in Central Montana

# Objectives budget periods (BP)

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

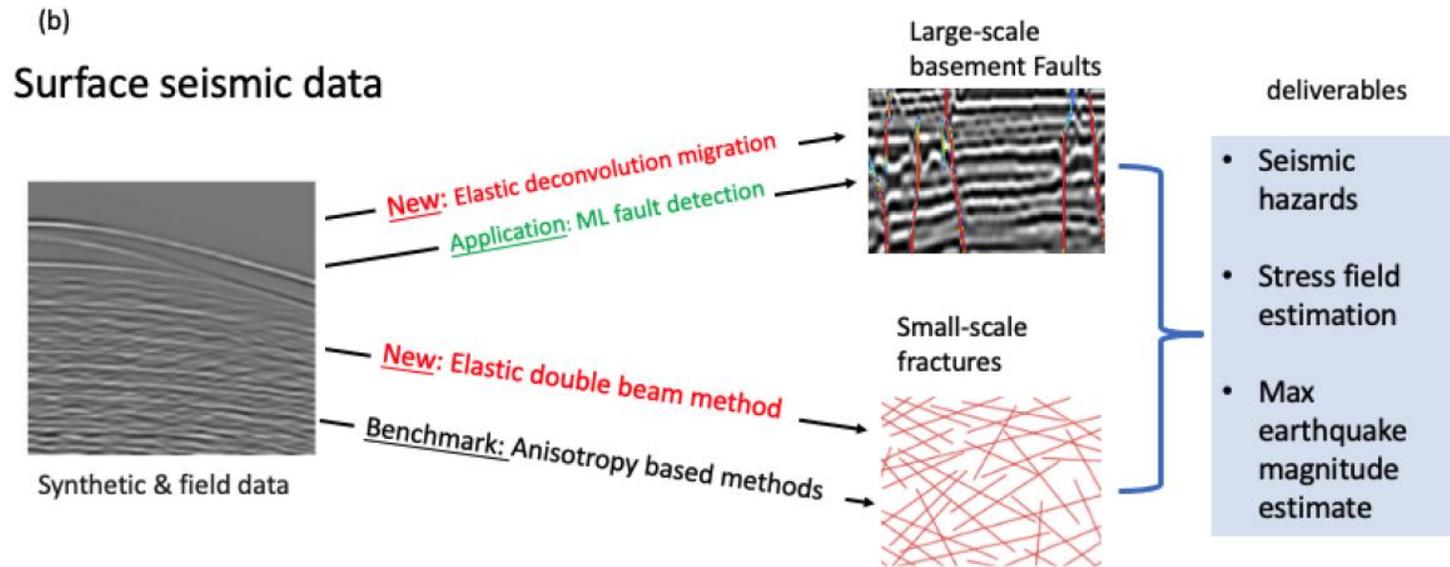
# Task/Subtask Breakdown

## **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)

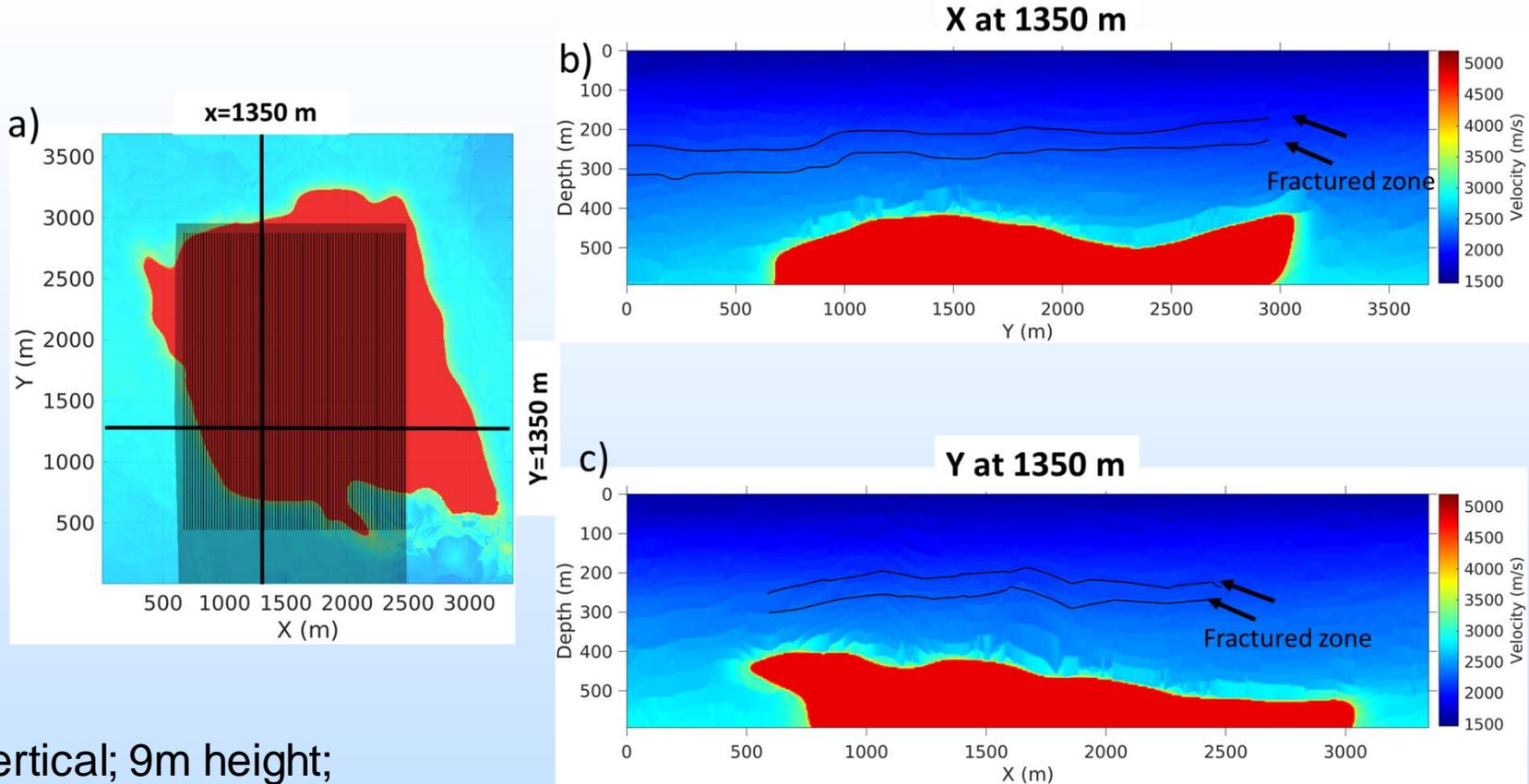
# Roadmap



# Why another method for fracture characterization?

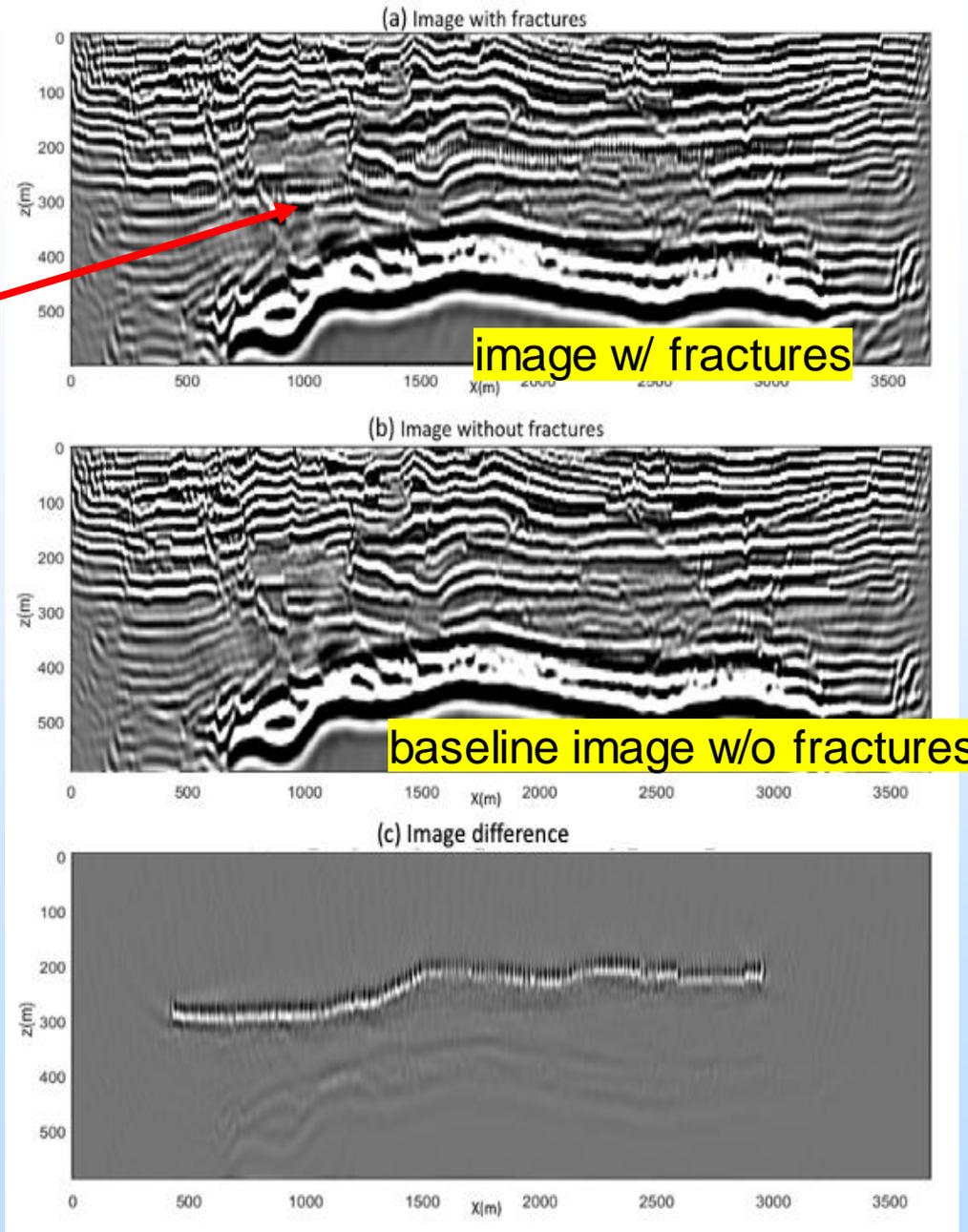
- Can seismic migration see the small-scale fractures?
  - No.

# Motivational example: fractures are hard to see

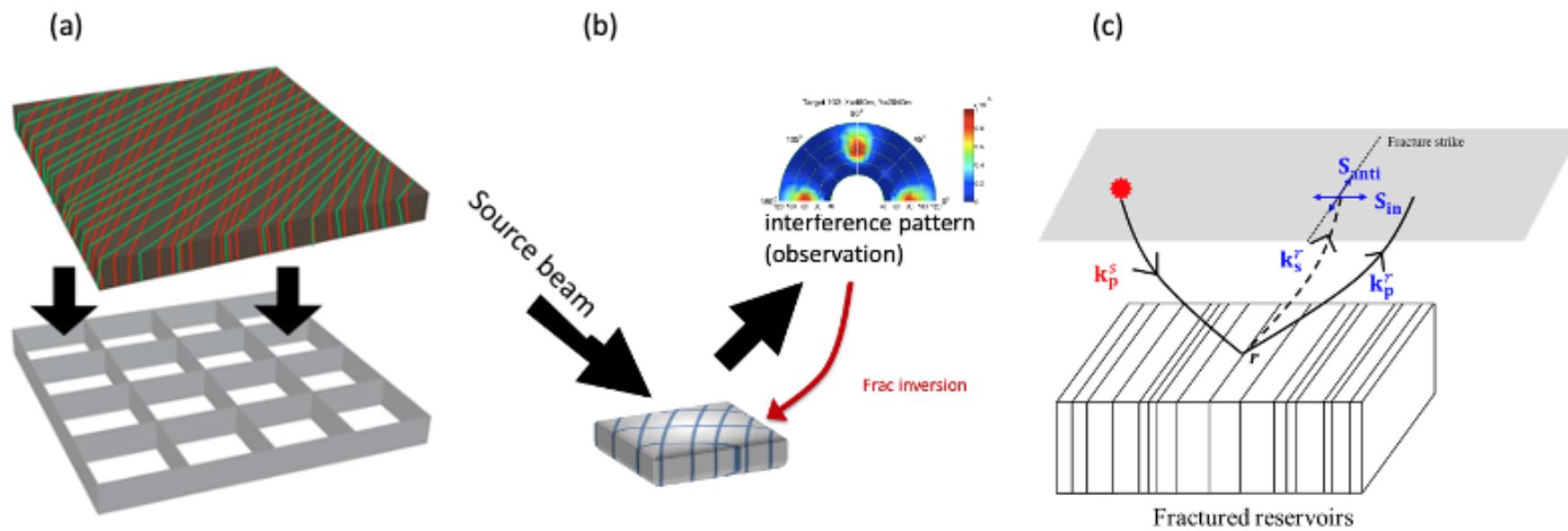


Fractures: vertical; 9m height;  
fracture compliance  $1e-10$  m/Pa

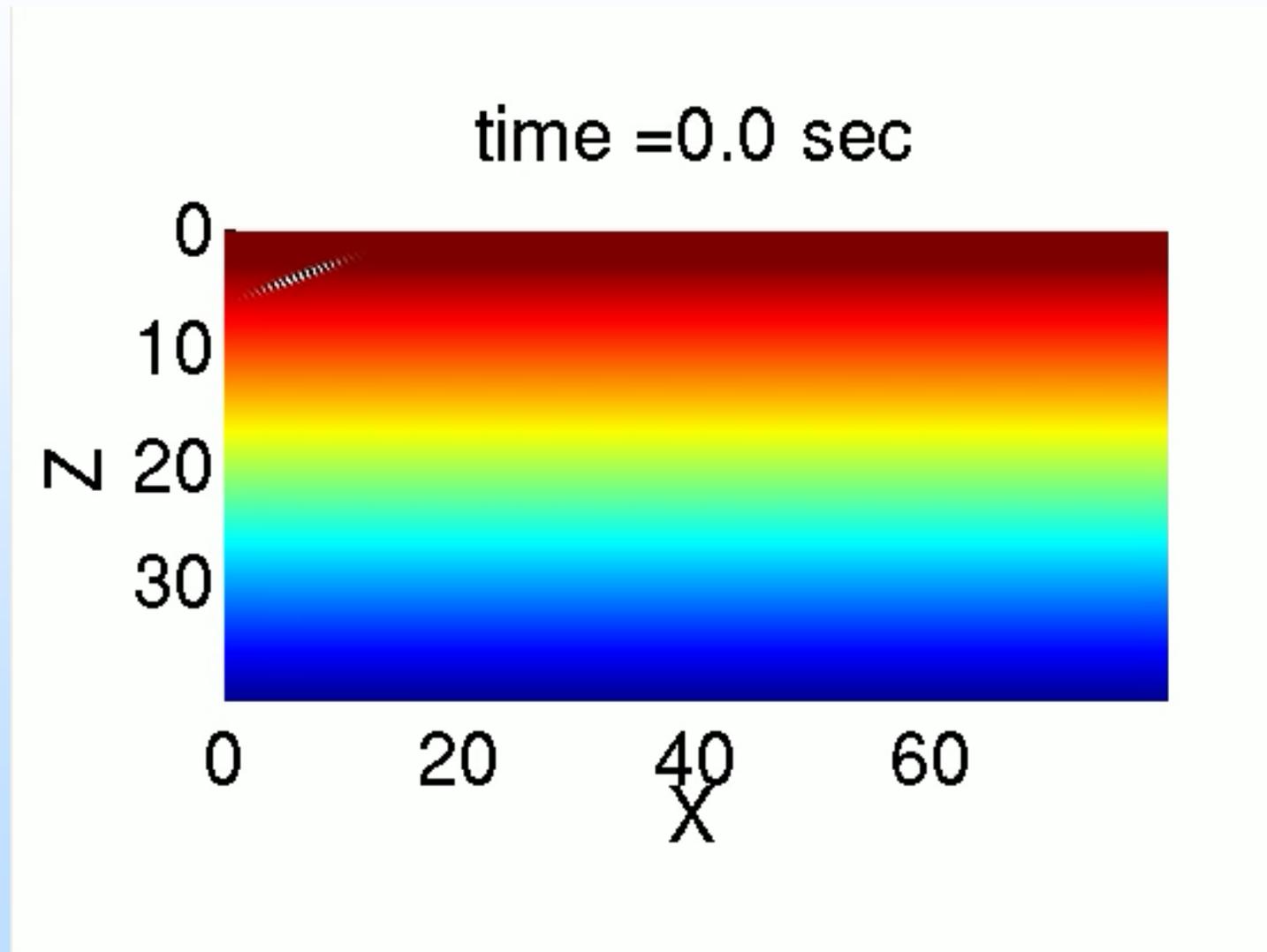
Hard to see fractures  
in traditional seismic  
migrated images



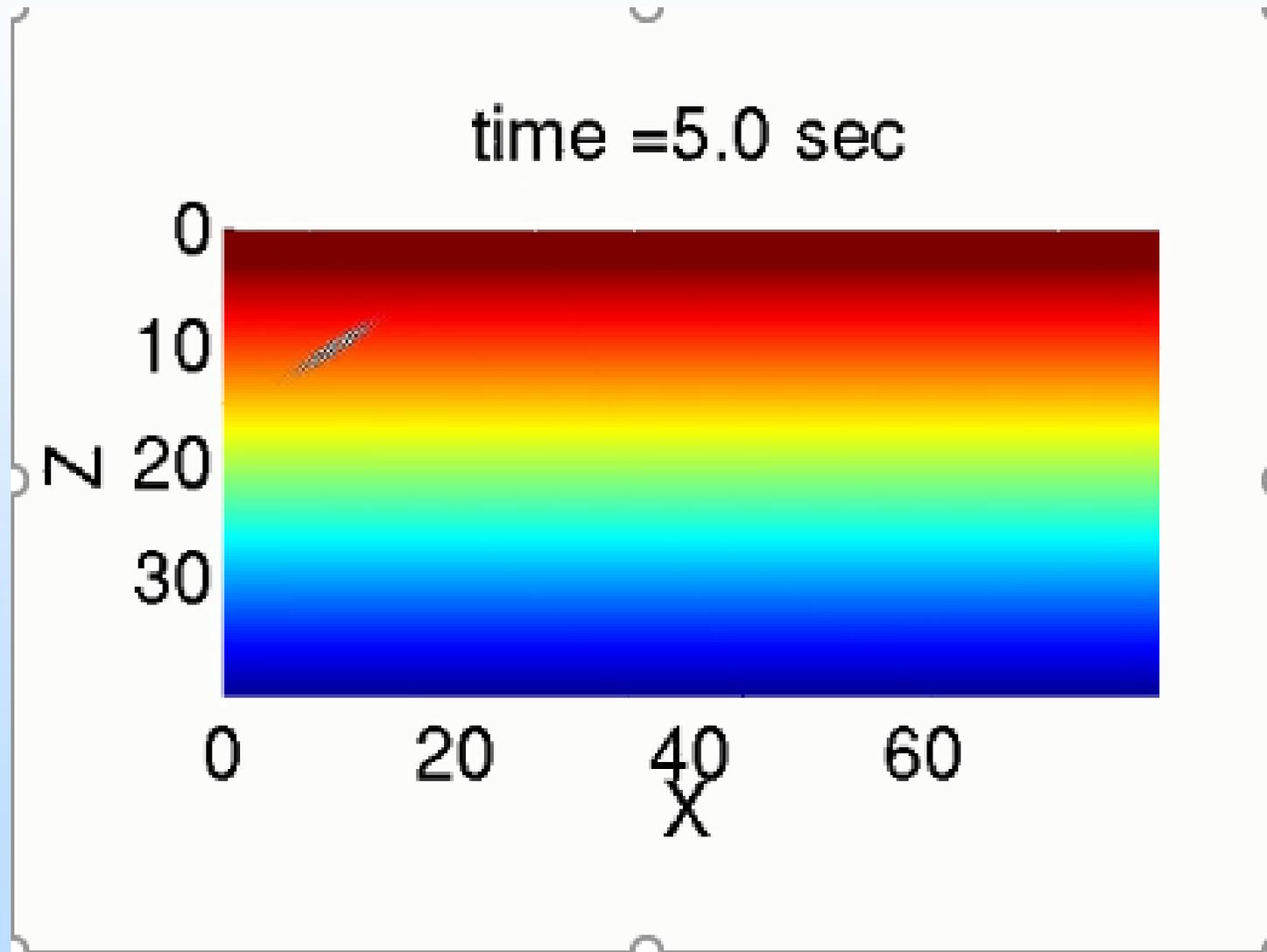
How does the seismic double-beam  
method characterize small-scale  
fractures



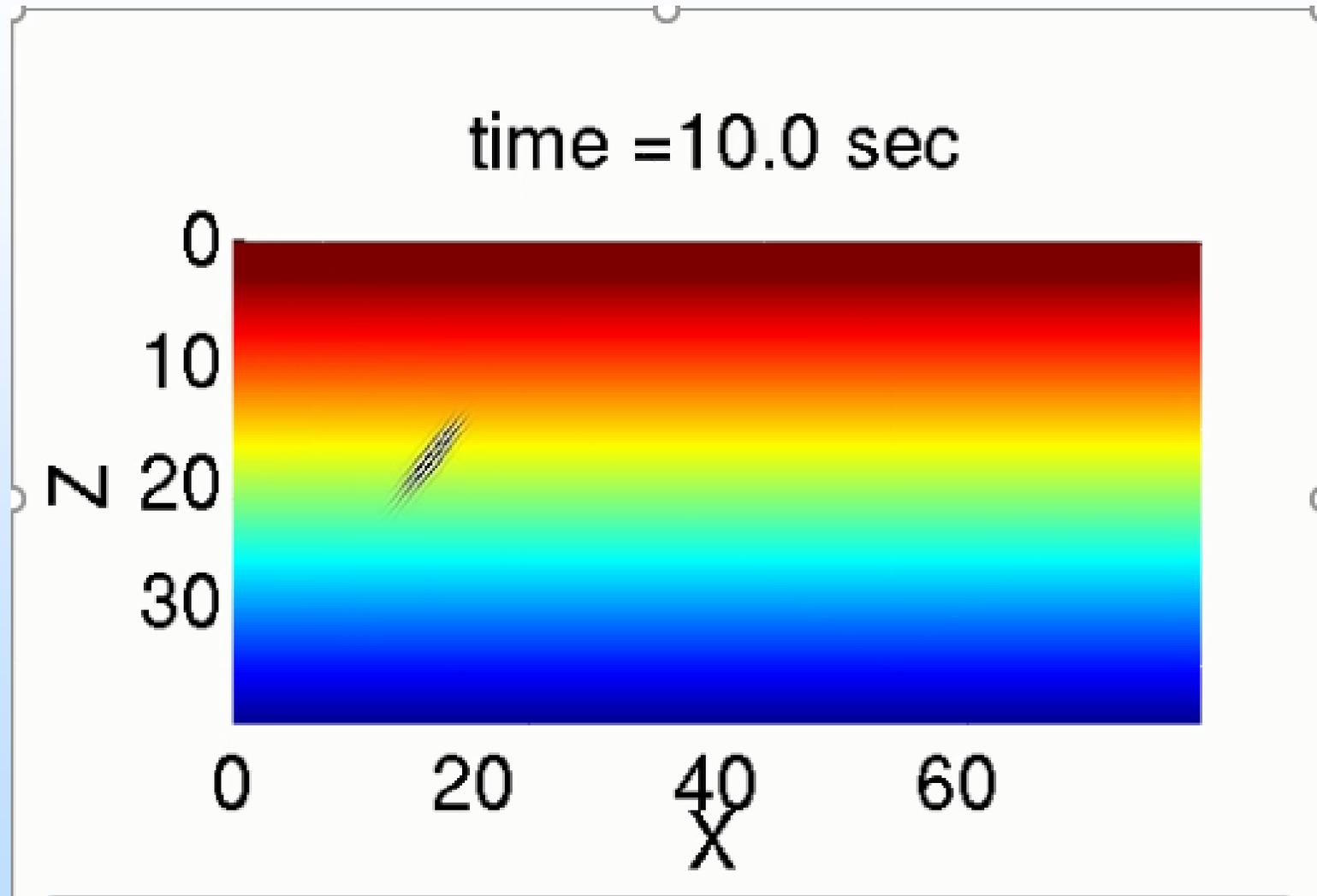
# From point sources to localized wave packet



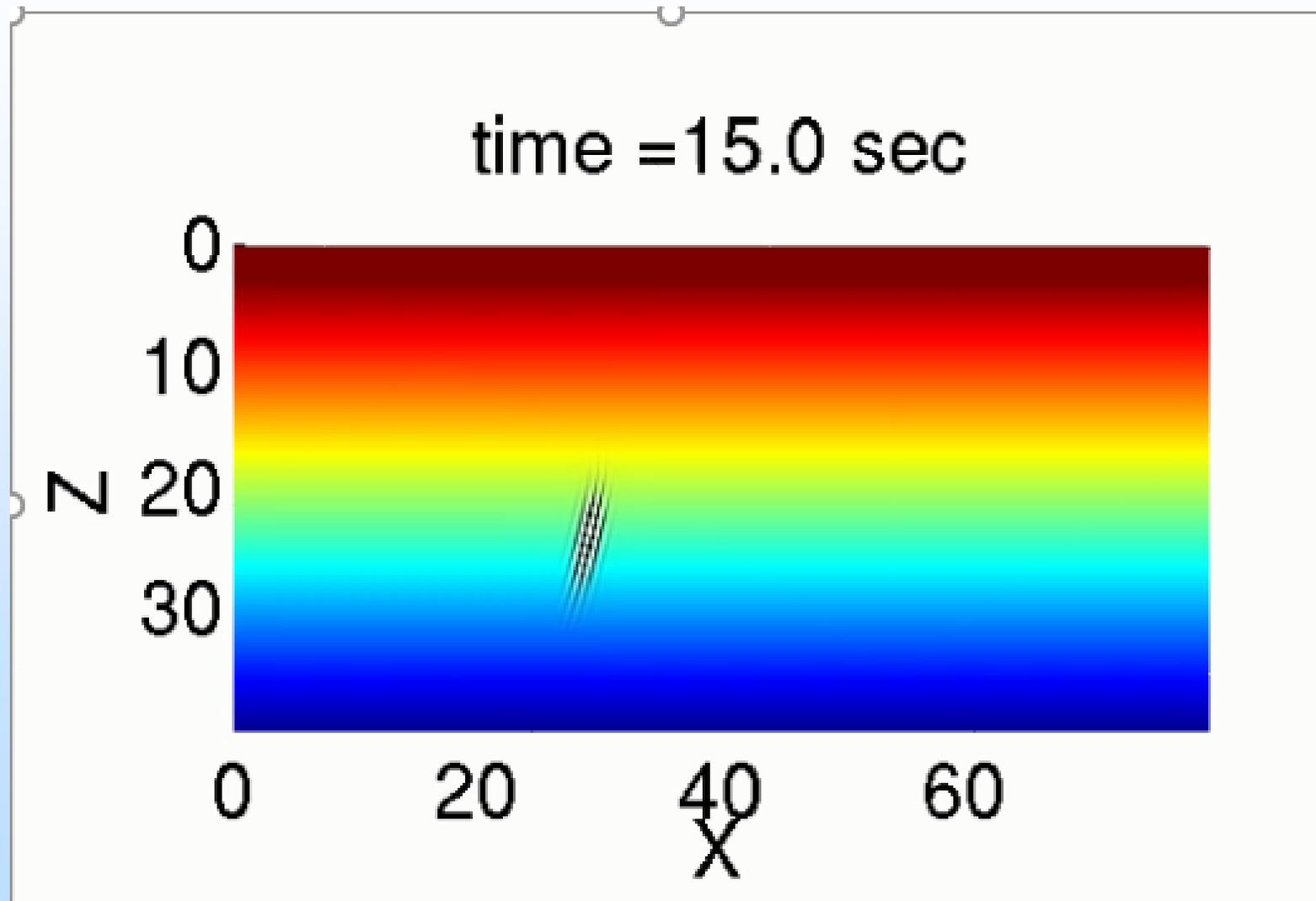
# From point sources to localized wave packet



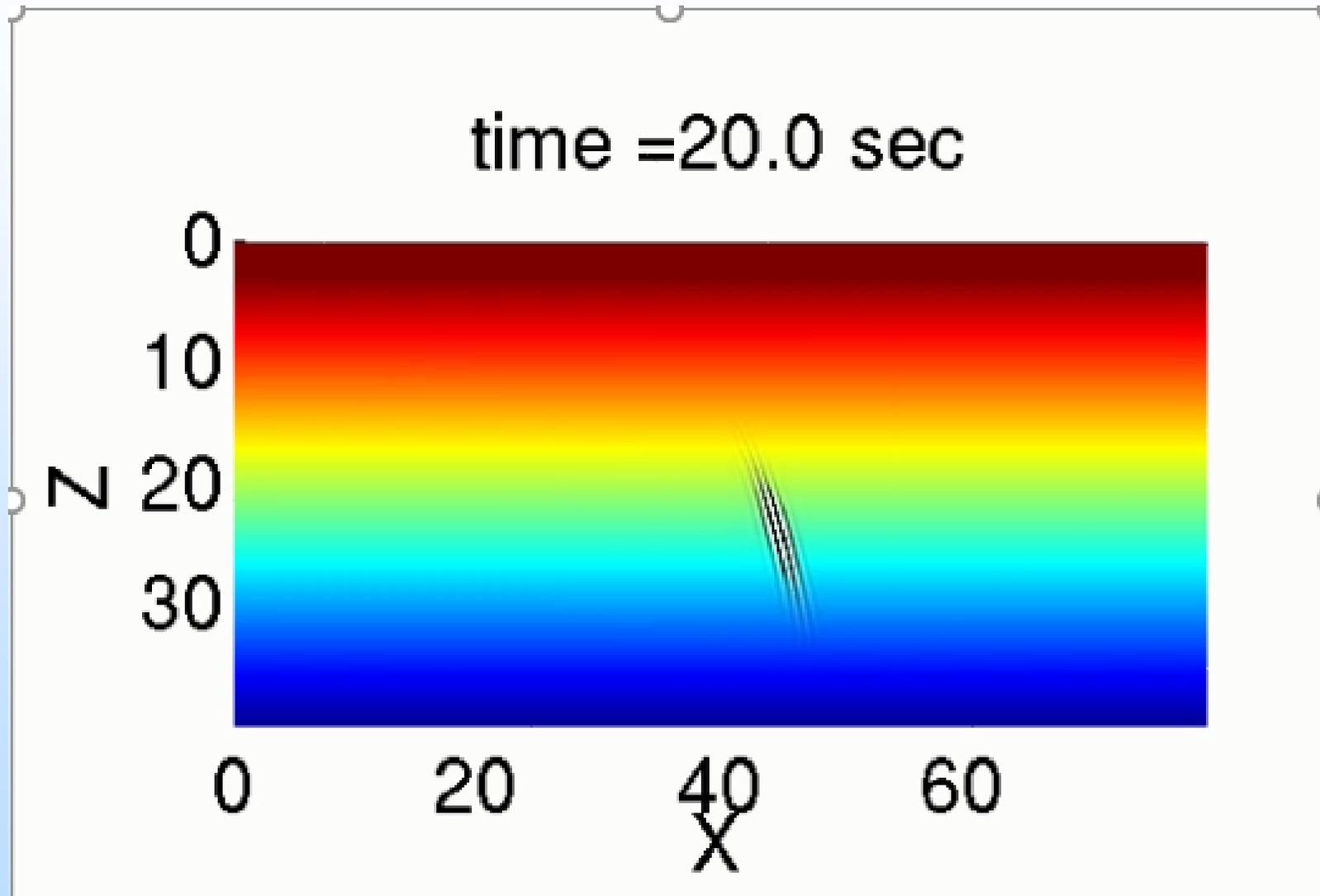
# From point sources to localized wave packet



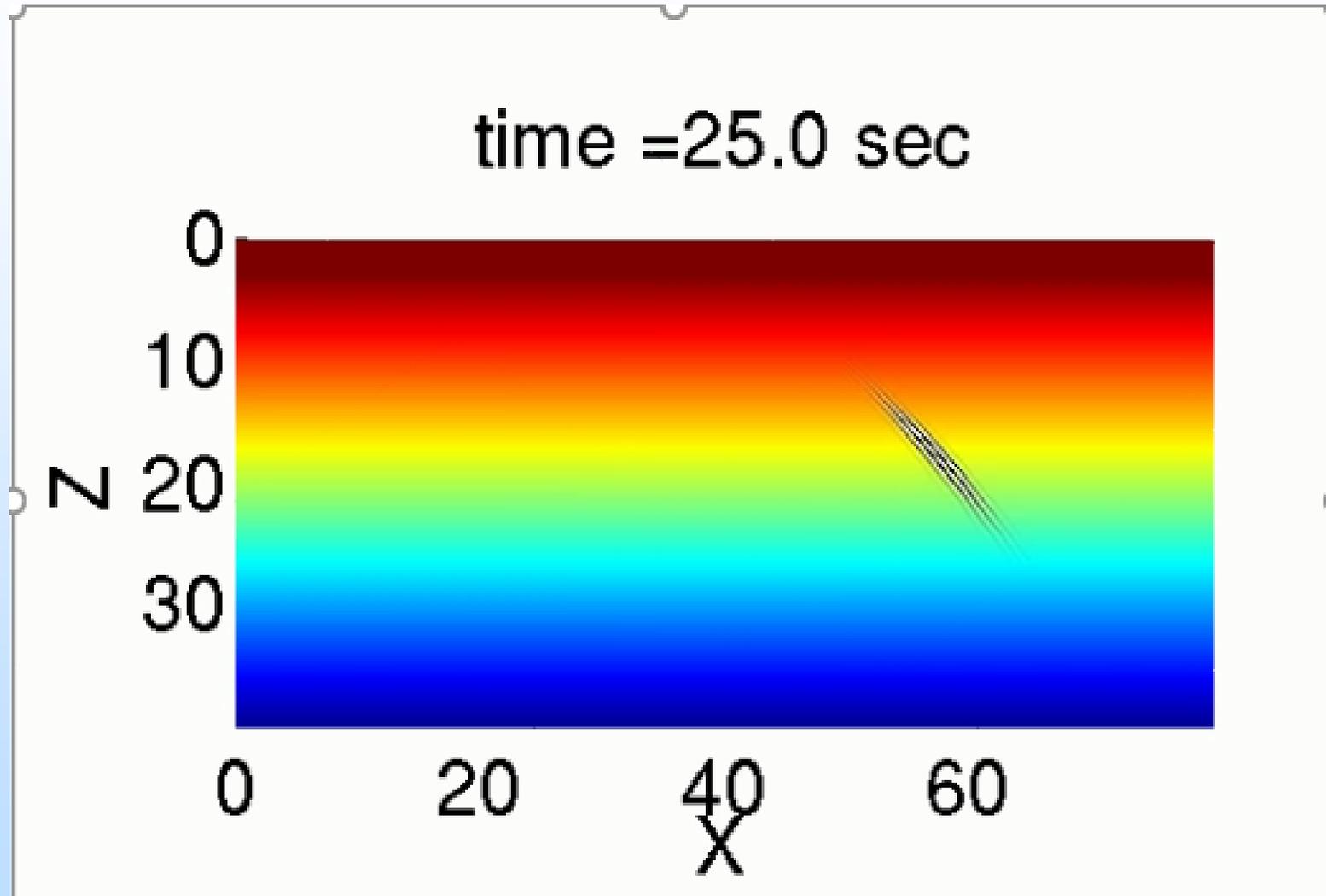
# From point sources to localized wave packet



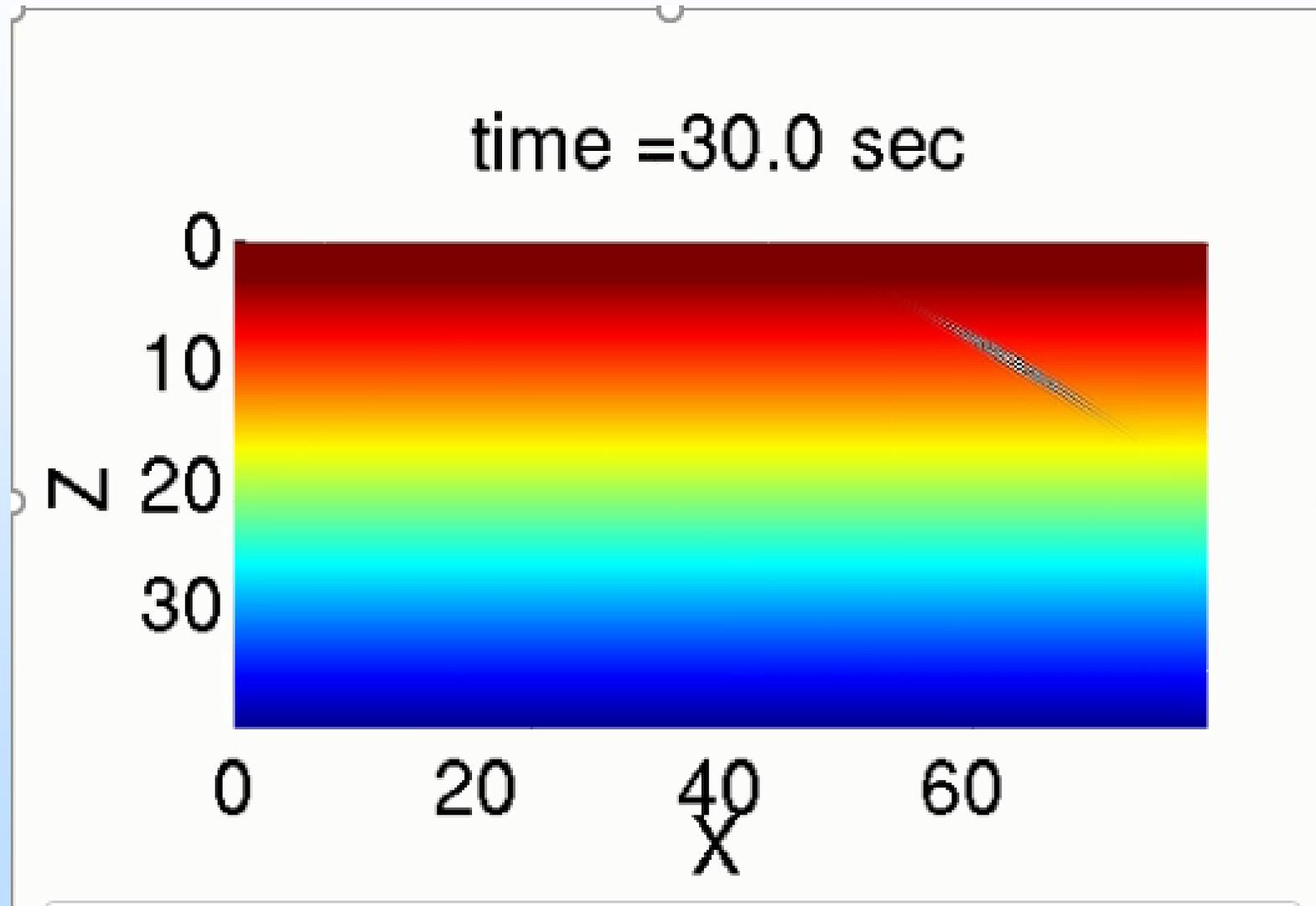
# From point sources to localized wave packet



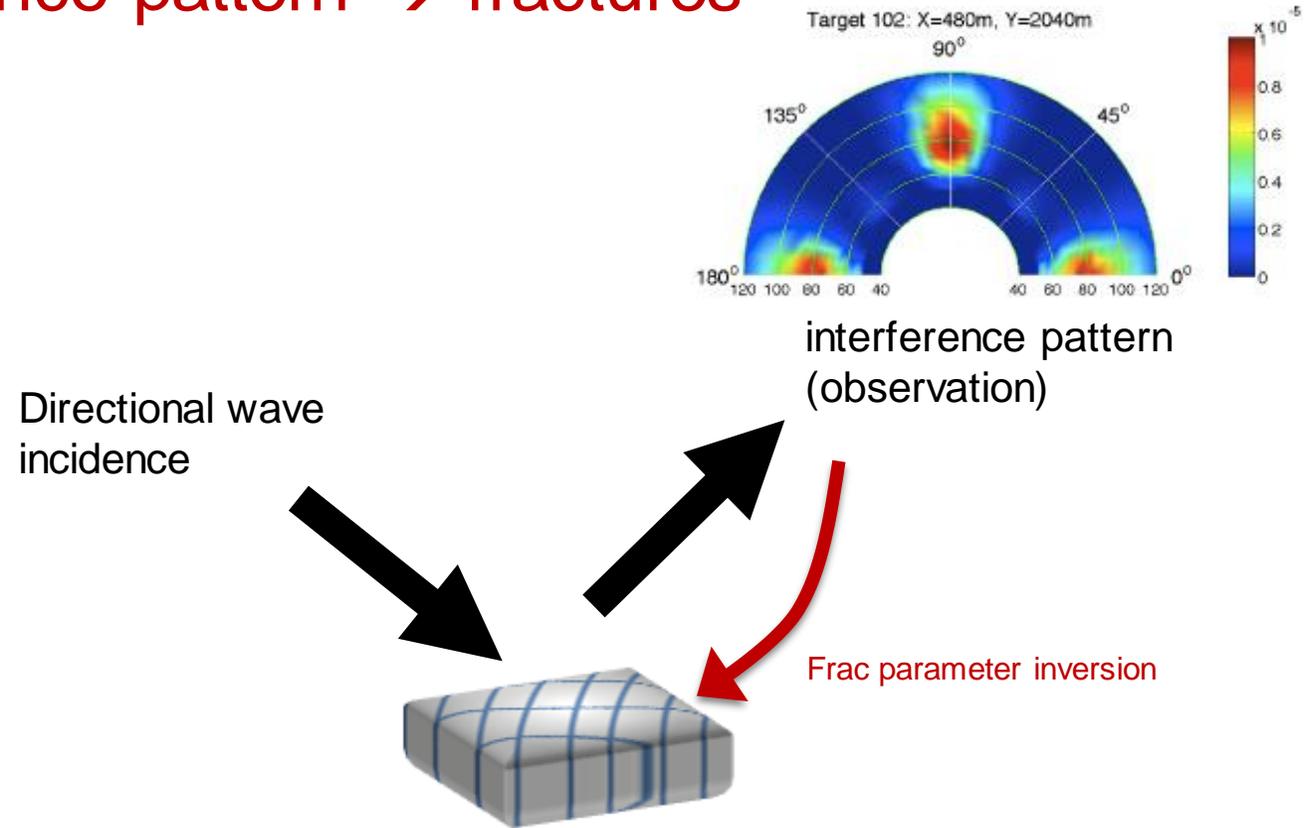
# From point sources to localized wave packet



# From point sources to localized wave packet



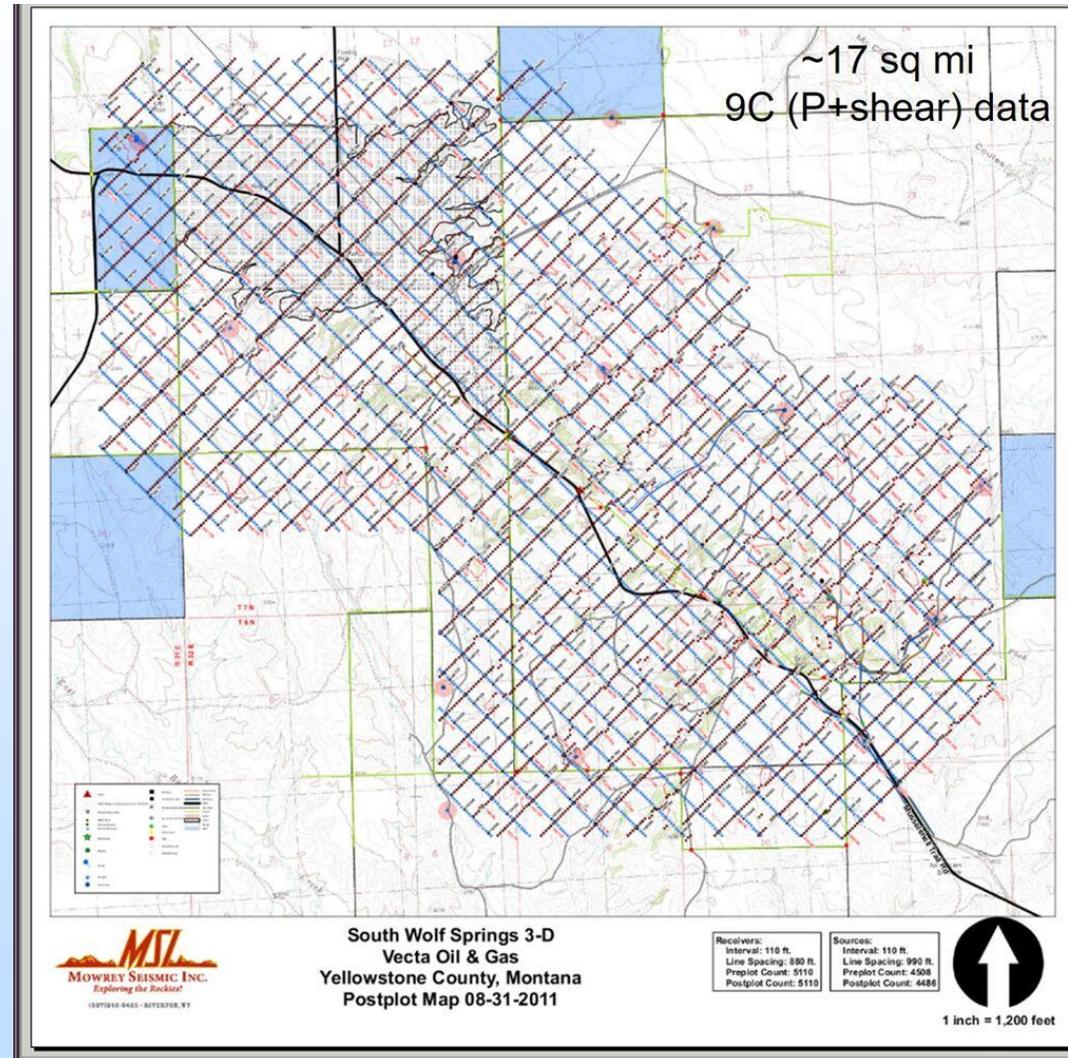
# Interference pattern → fractures

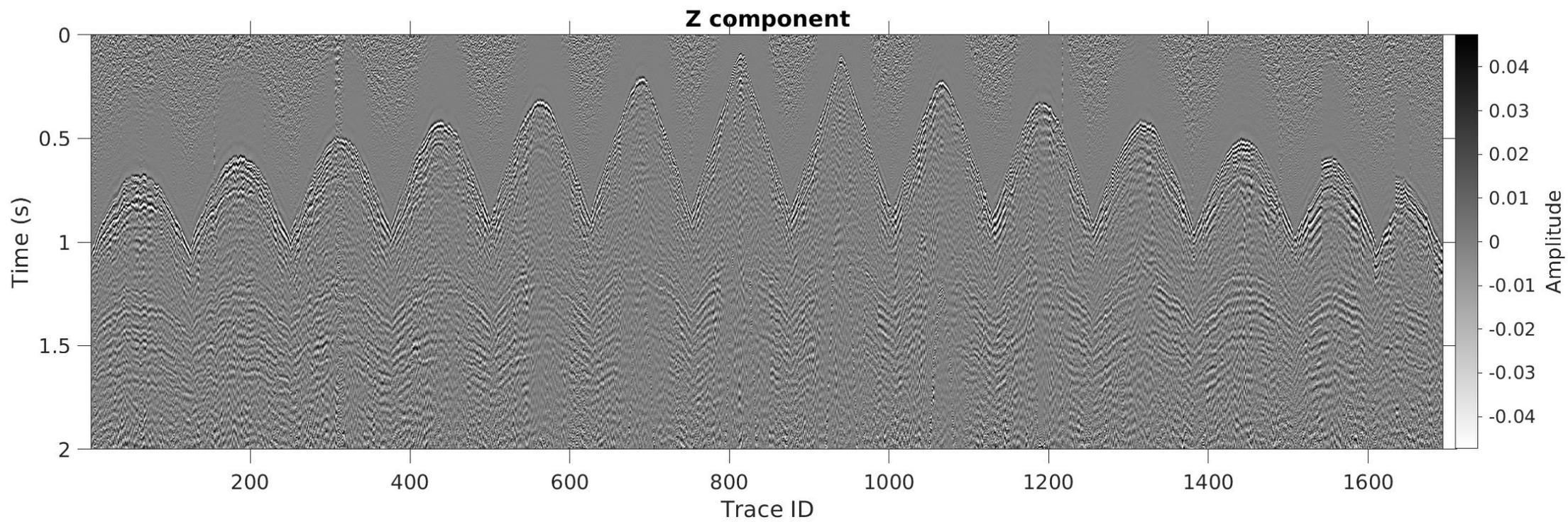


Fractured reservoir

- Fracture orientation
- Density
- Compliance → fluid permeability (Petrovitch et al., 2013)

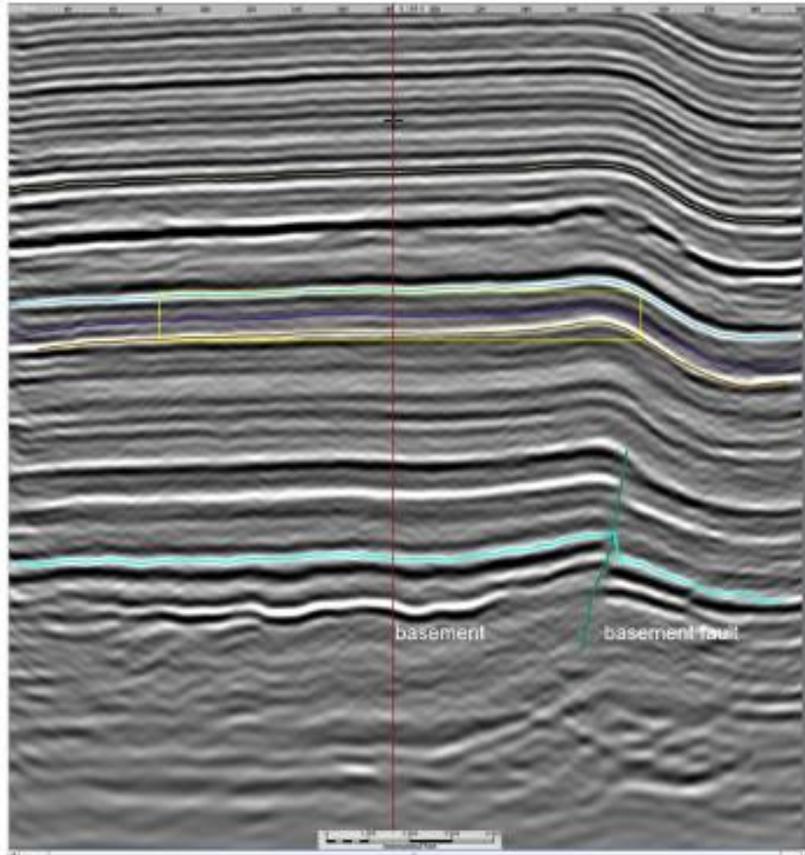
# Field seismic data (9C) in Montana



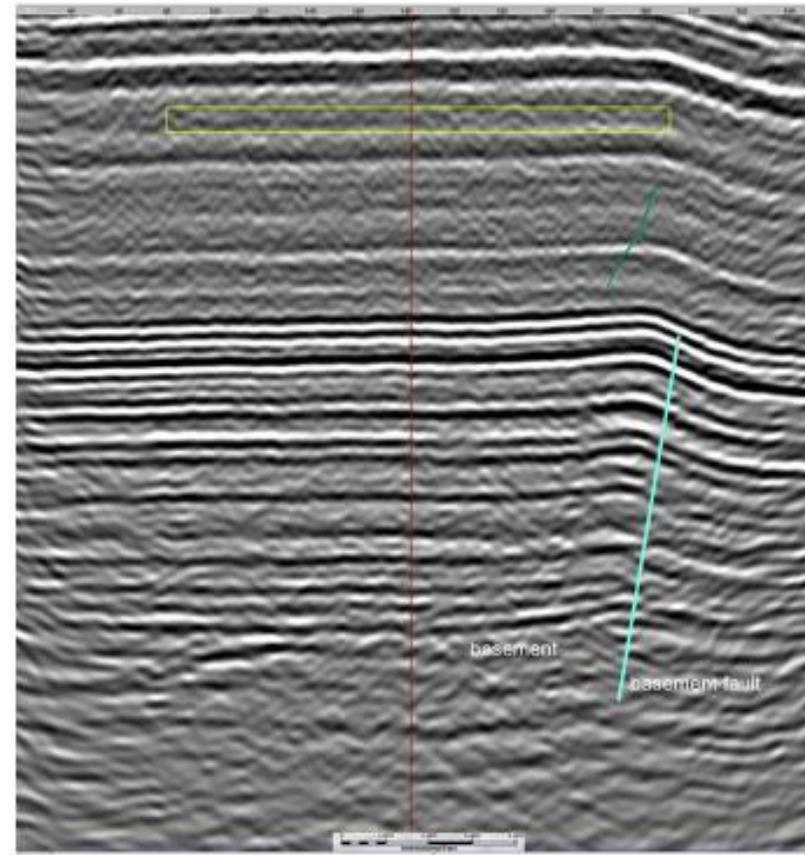


Vertical vibreseis

# Fractures and Basement faults



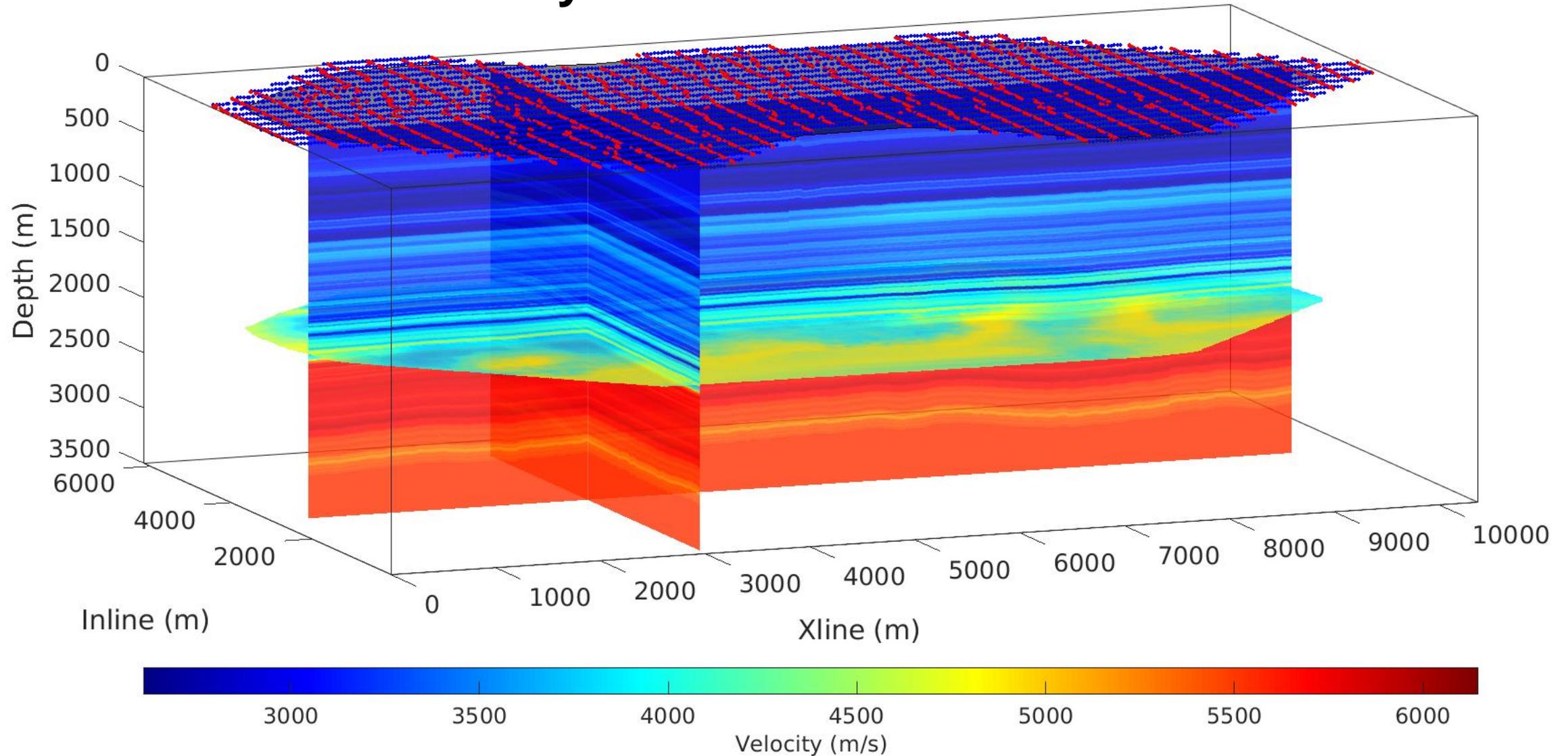
(a) PP image



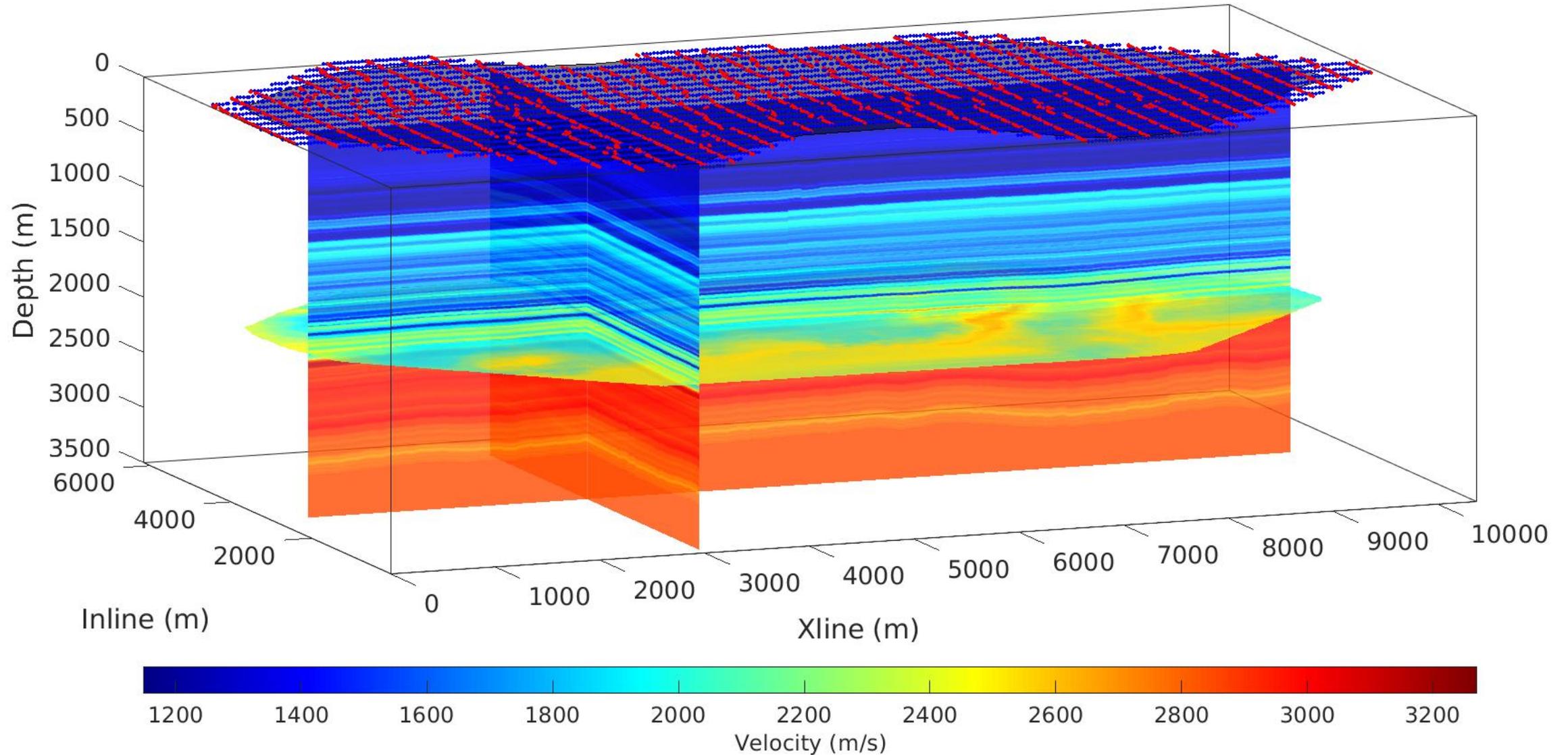
(b) SP image

Build the synthetic elastic model from the  
field data

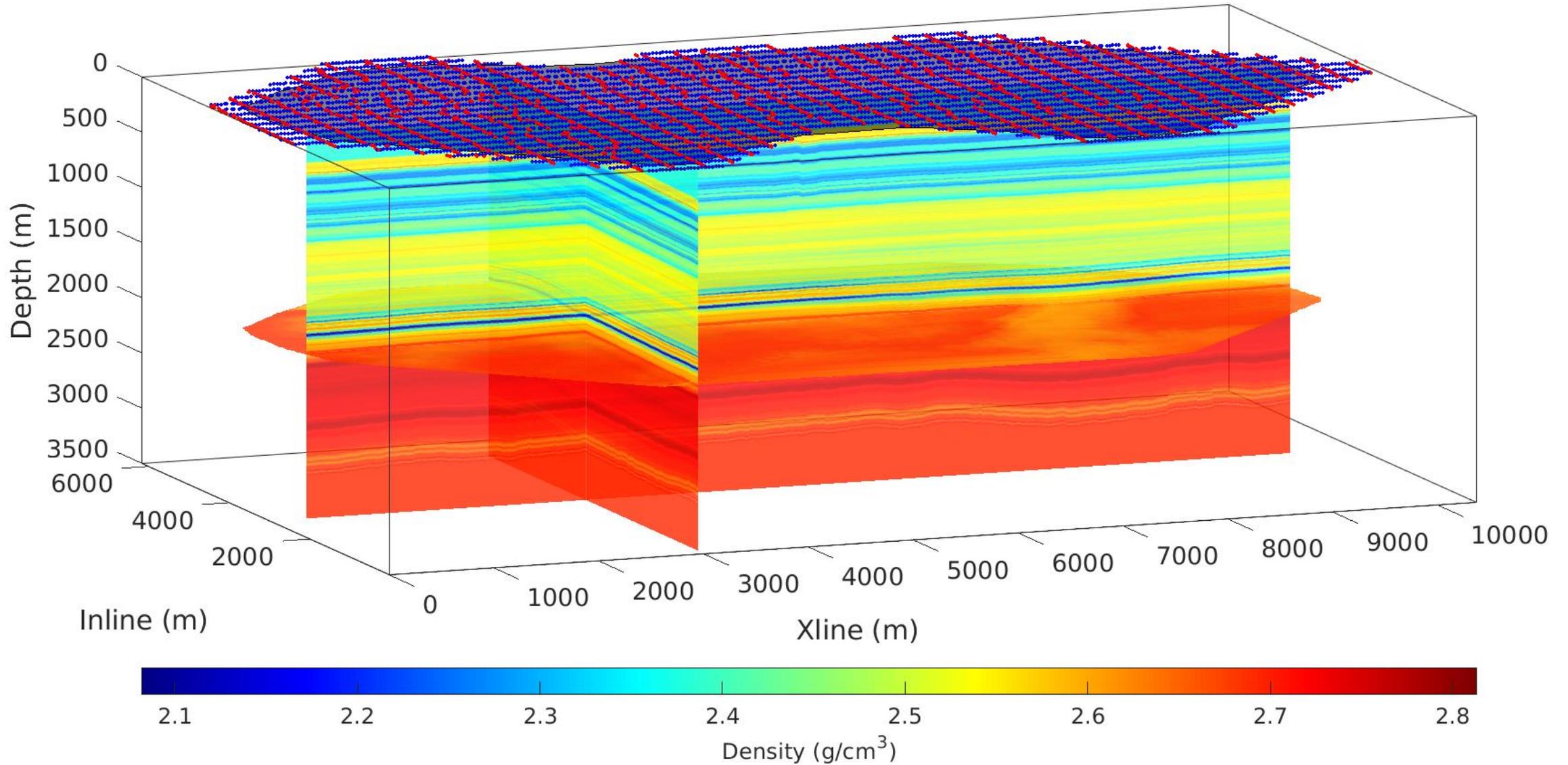
# P-wave velocity model from the field Vecta data



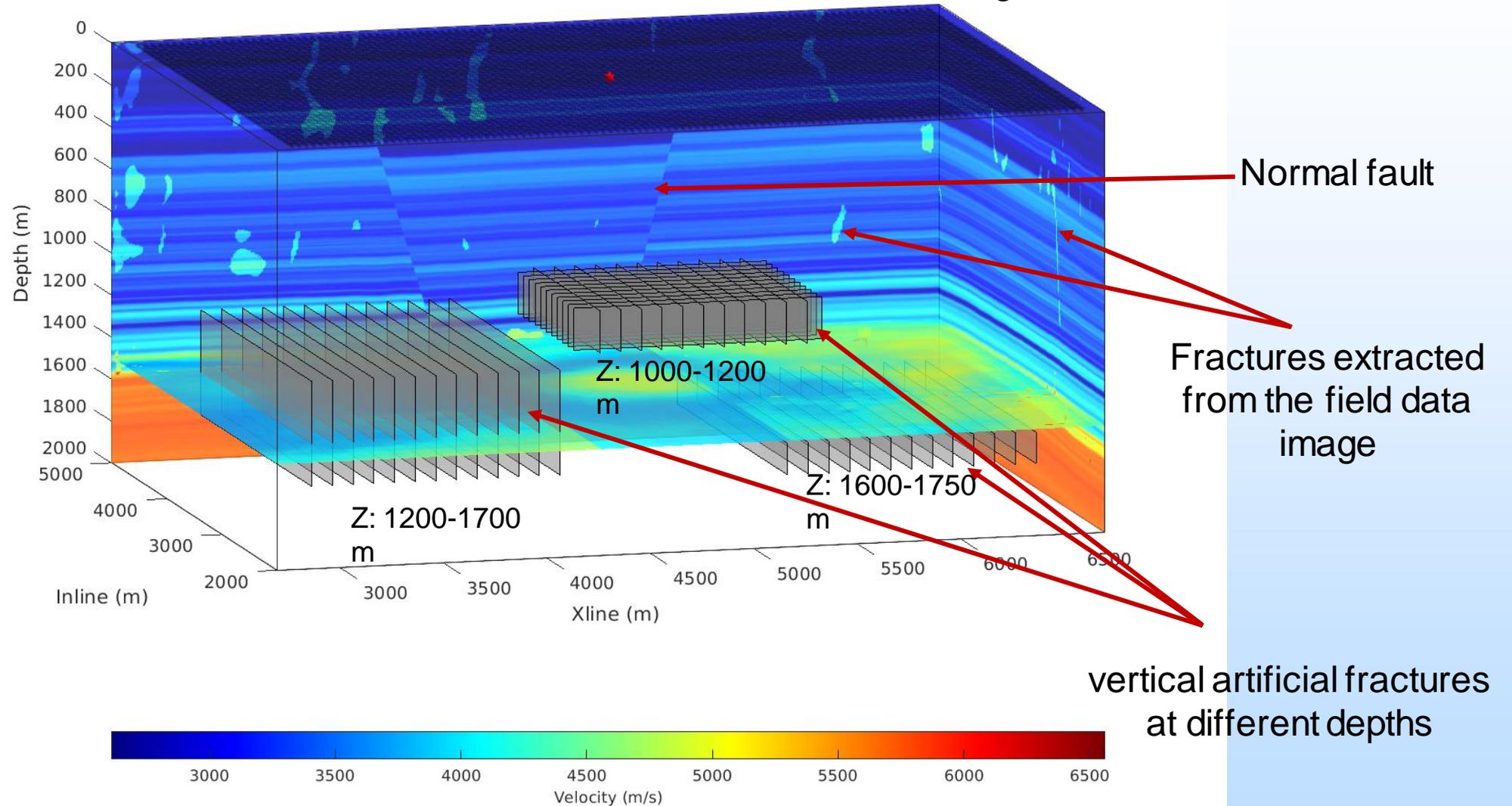
# Shear-wave velocity model from the field Vecta data

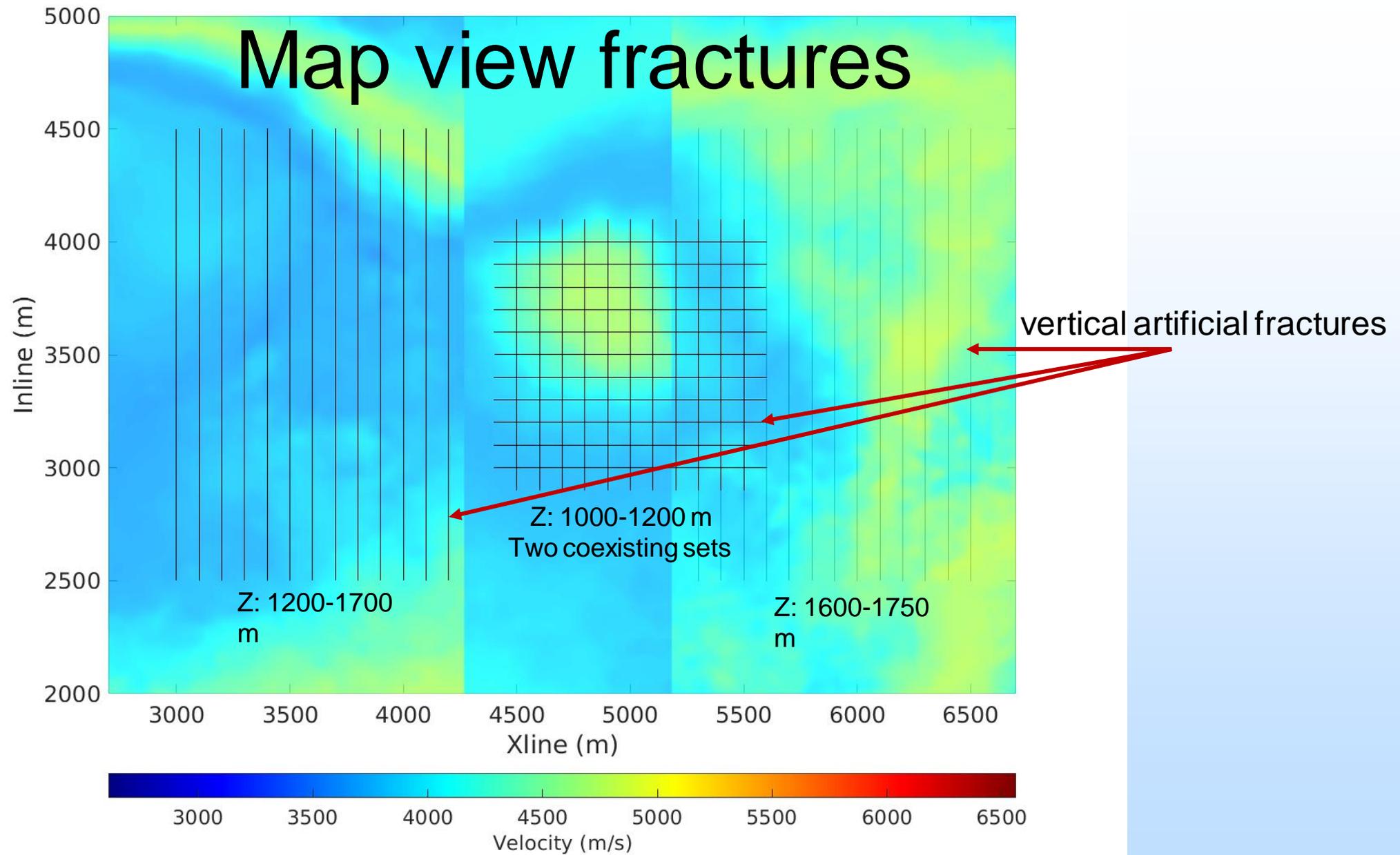


# Density model from the field Vecta data

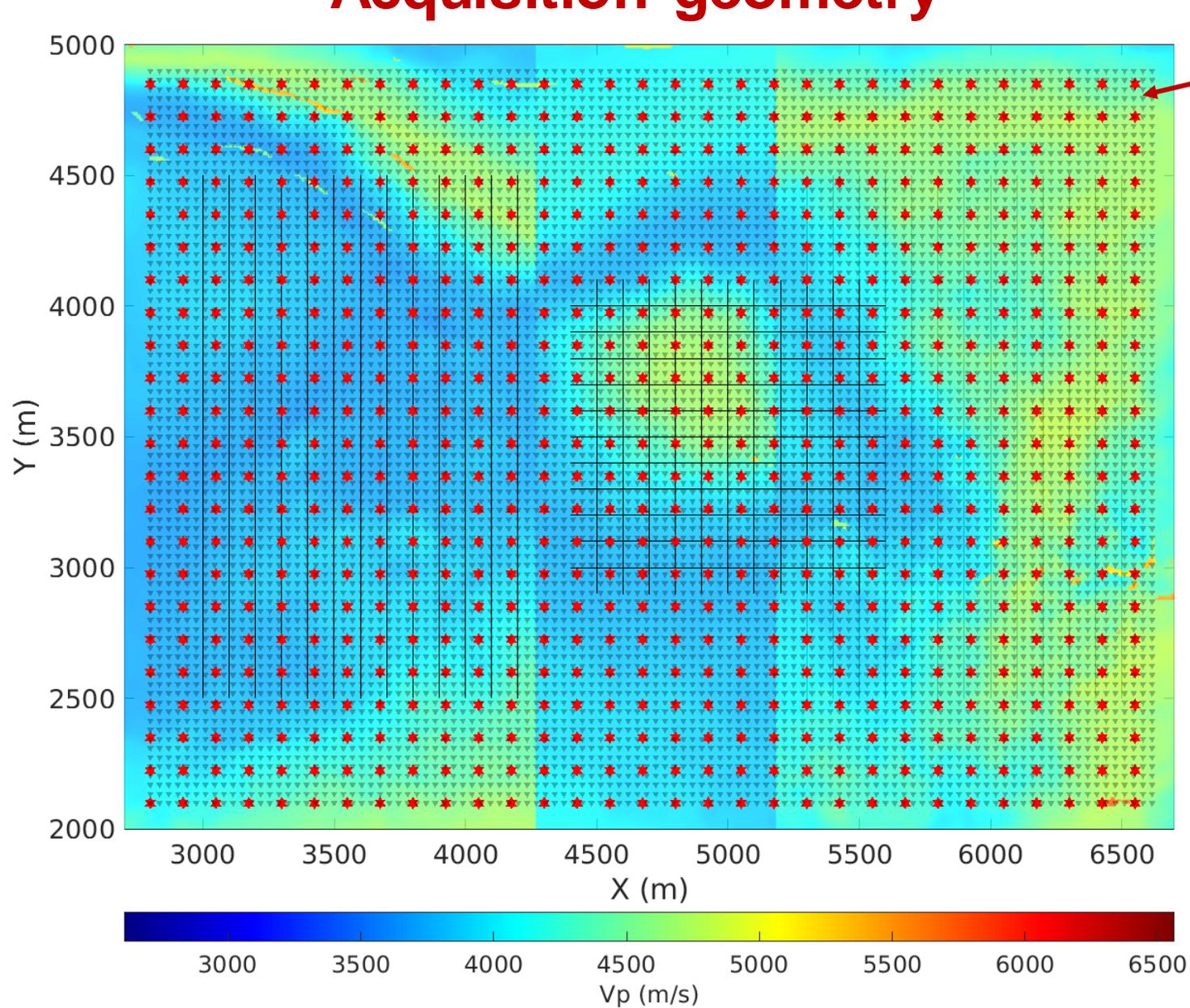


- Synthetic Vp model with
- : a normal fault
  - : vertical artificial fracture sets
  - : small fractures extracted from field data image





# Acquisition geometry



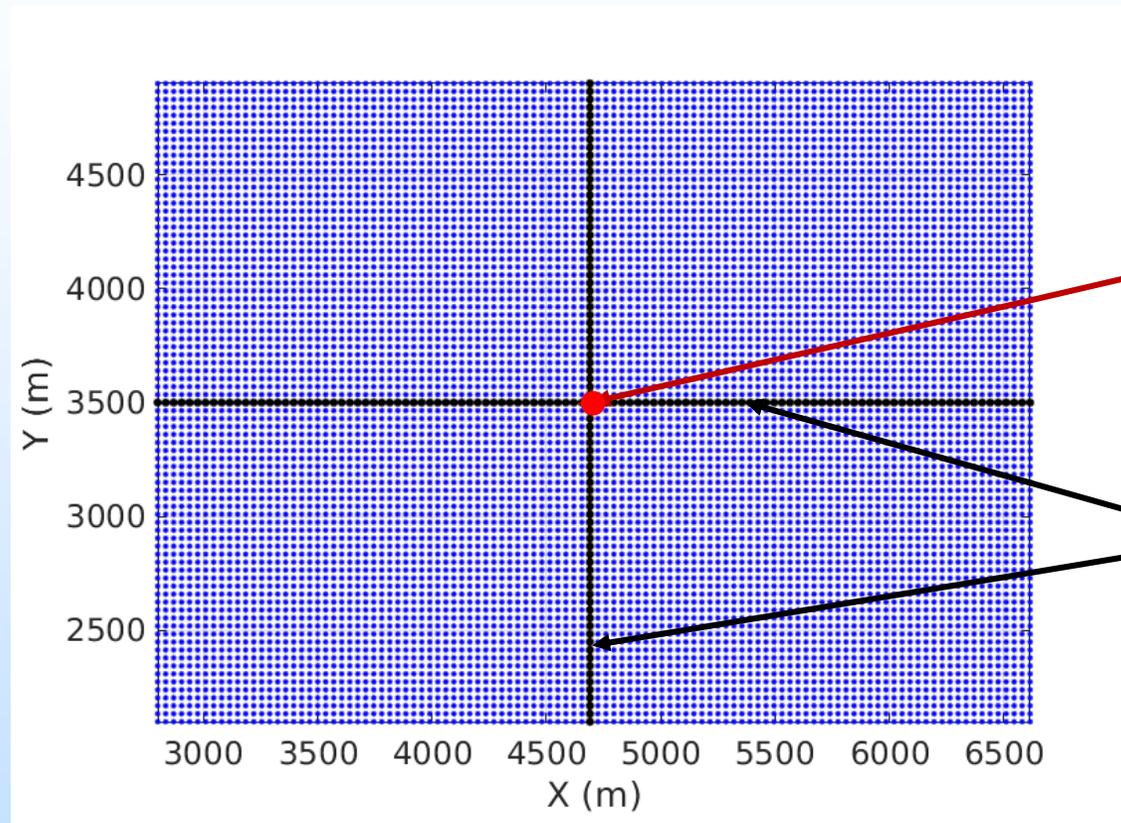
★ Source  
▼ Receiver

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.

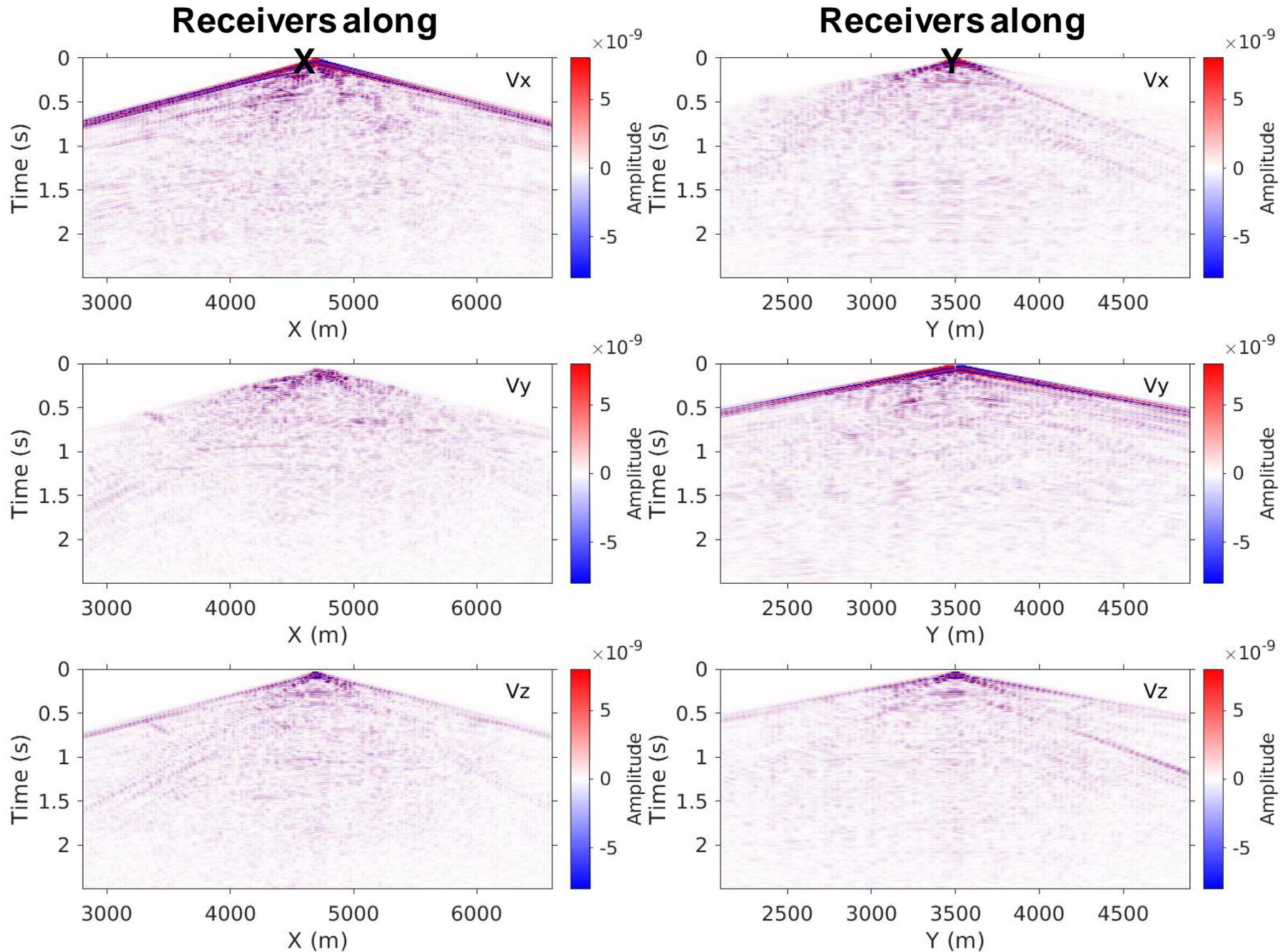


**Source**

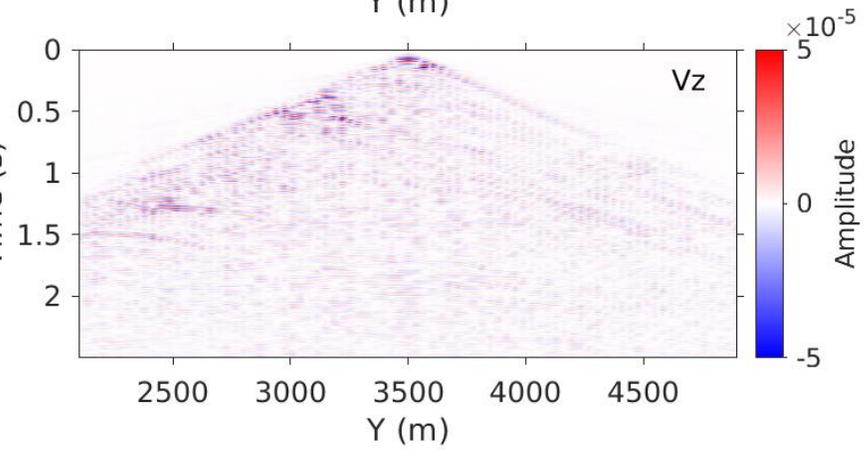
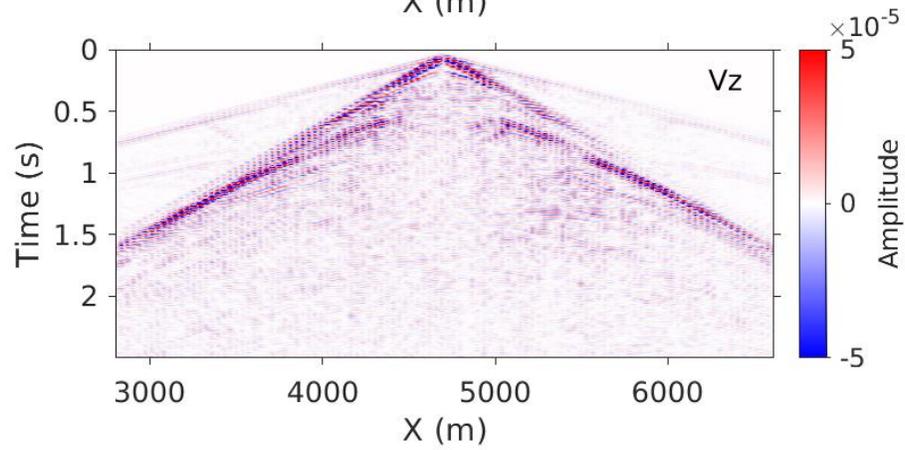
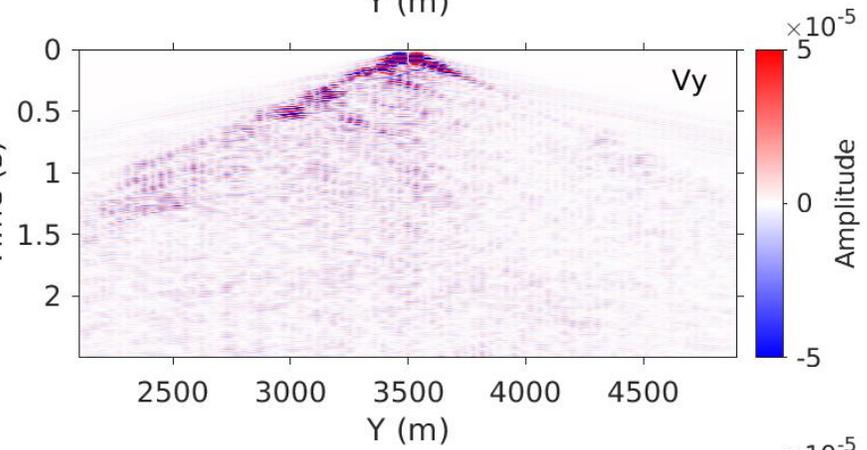
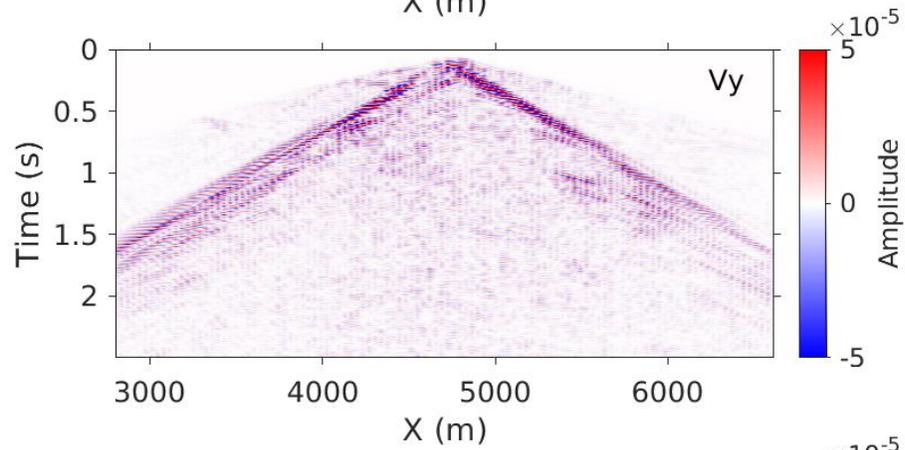
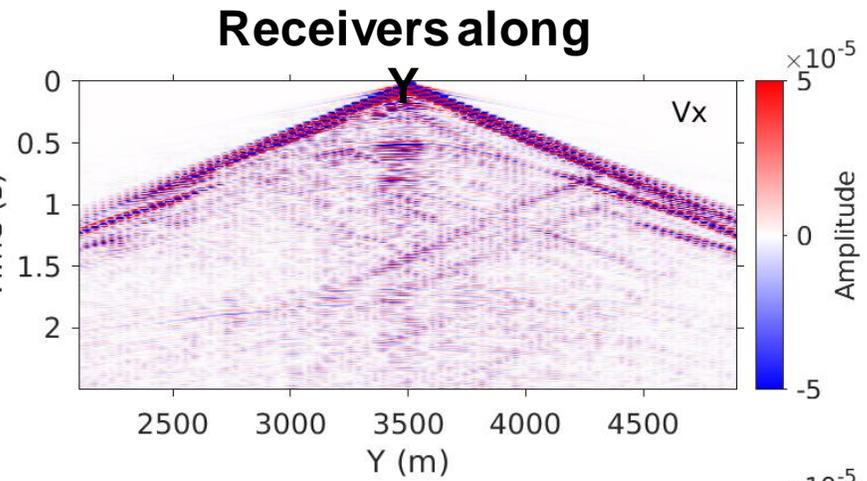
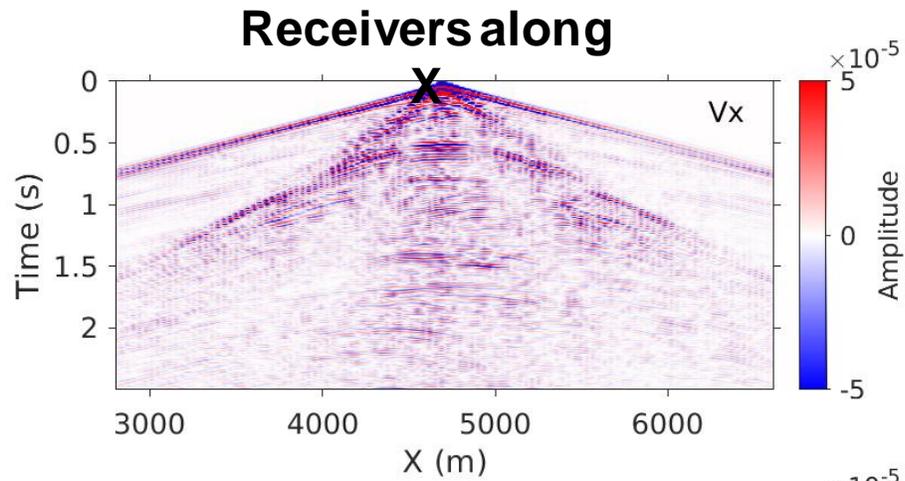
**Two receiver  
lines**

Source wavelet: 20 Hz Ricker<sub>34</sub>

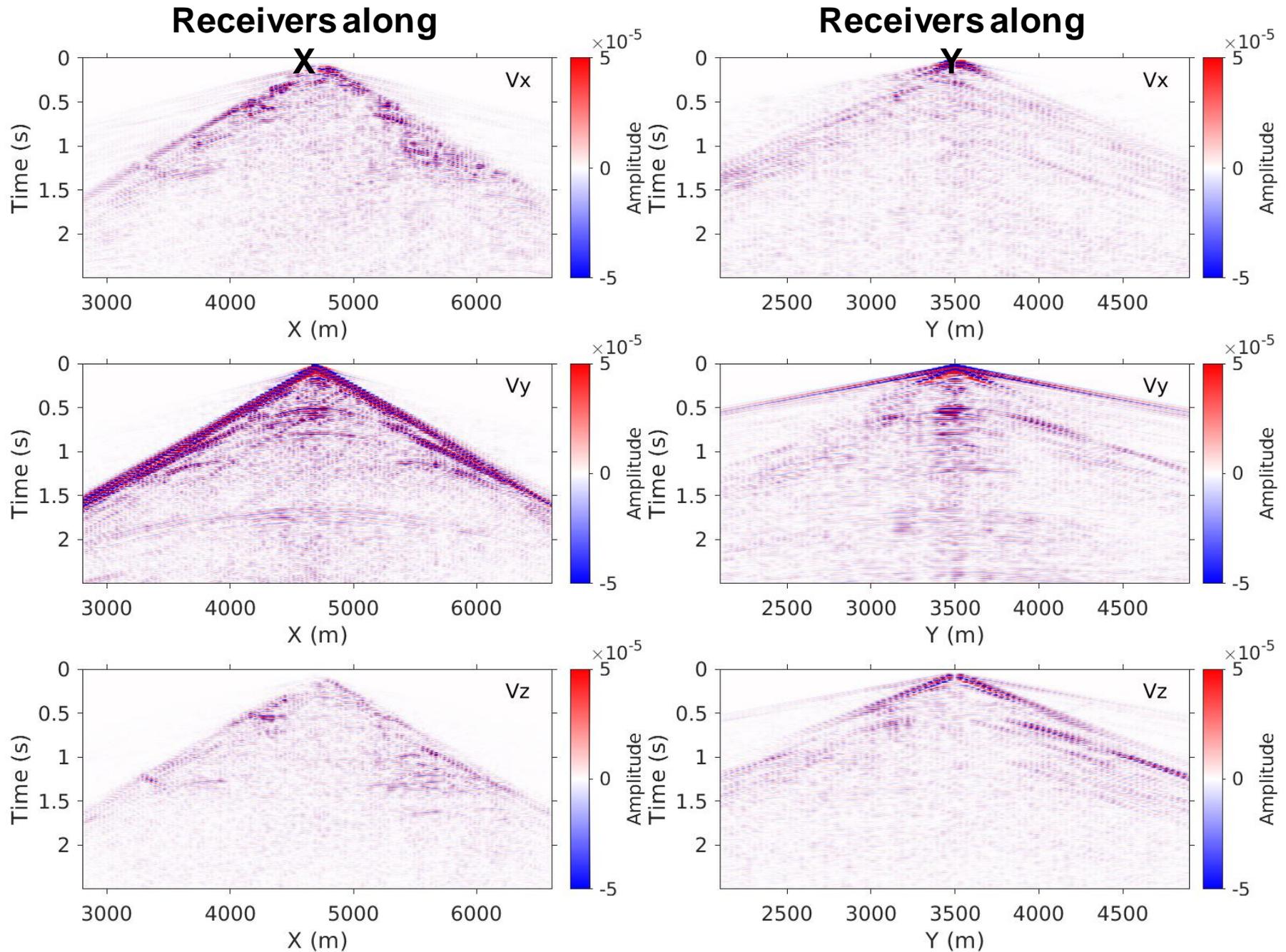
**Explosive  
source**



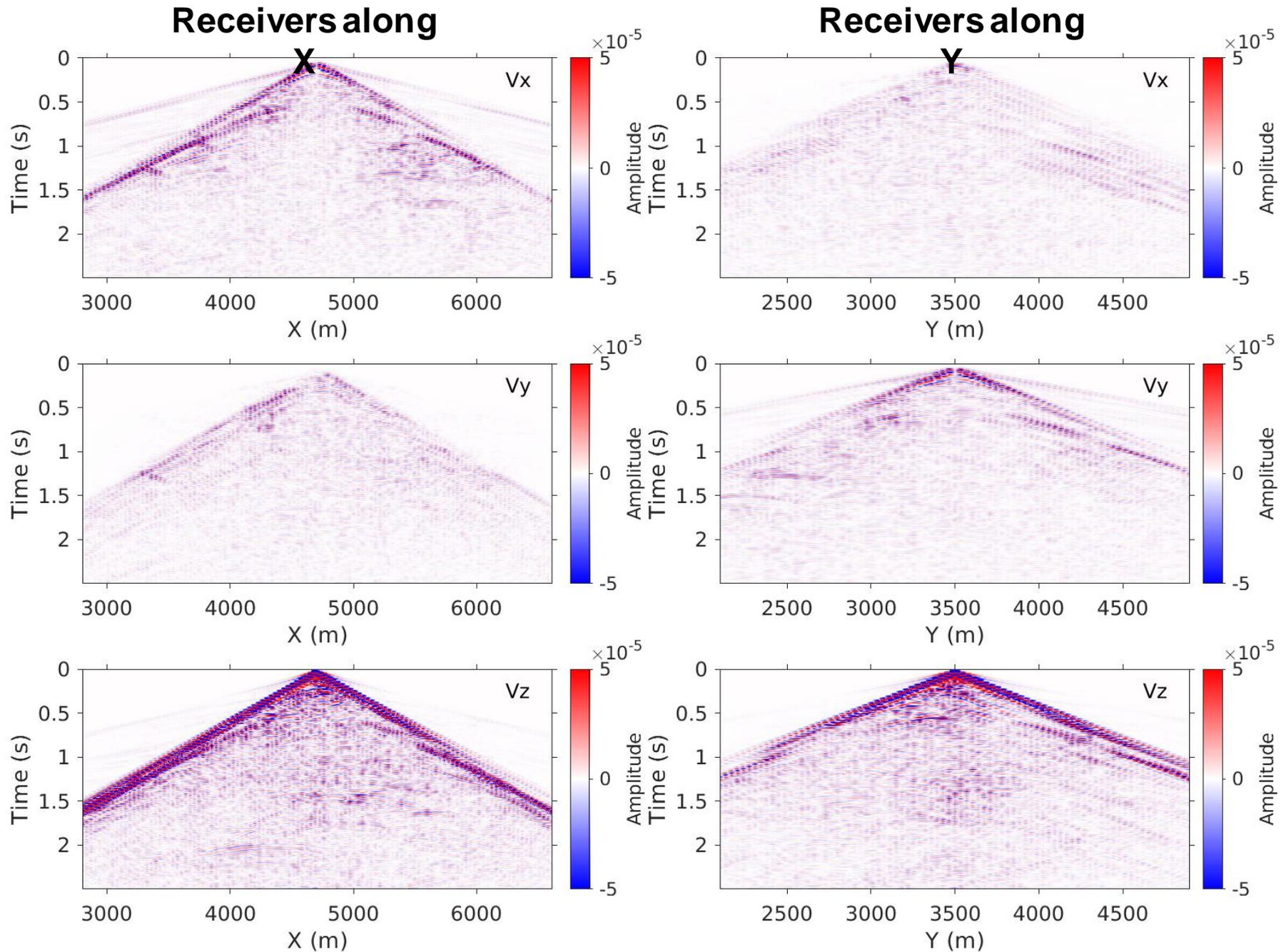
Single force:  
X



Single  
force:  
Y

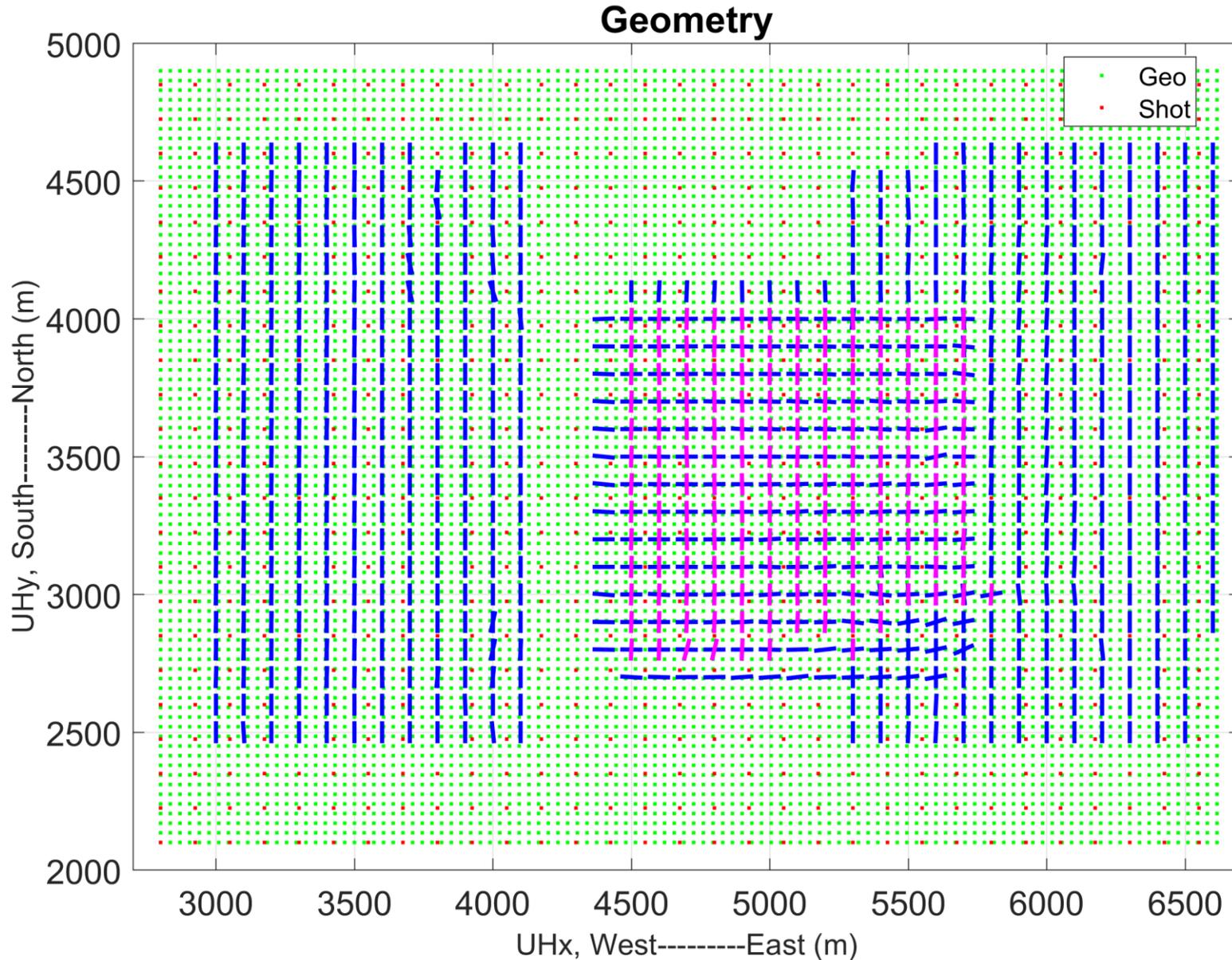


Single  
force:  
Z

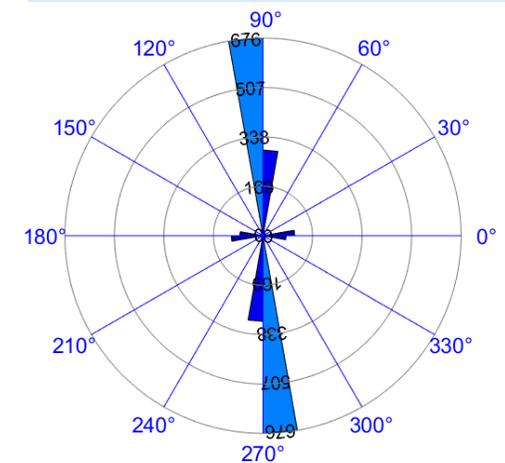


Fracture detection results  
using  
The Seismic Double-Beam method

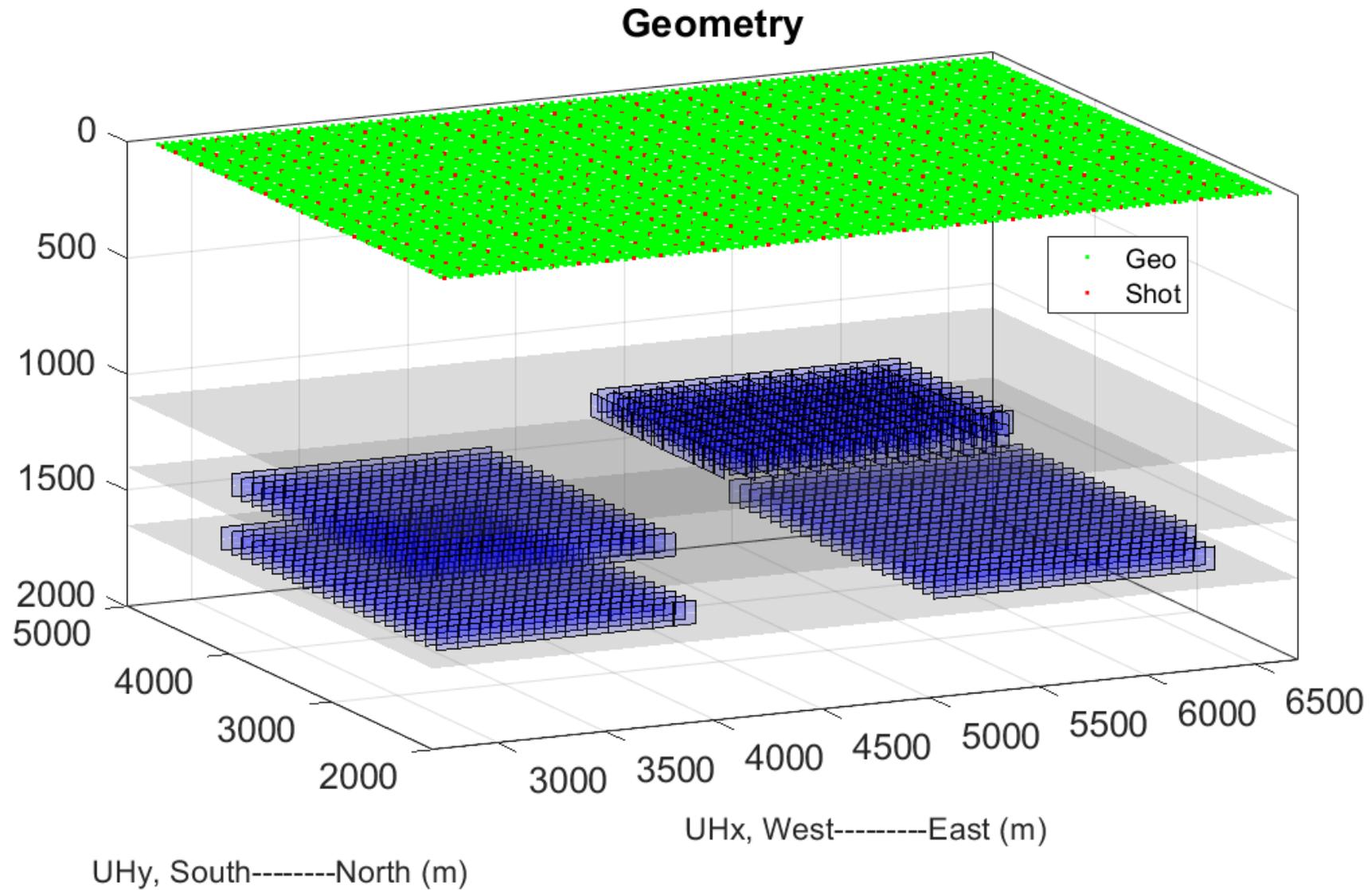
# Top view of detected fractures



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



# 3D view of detected fractures



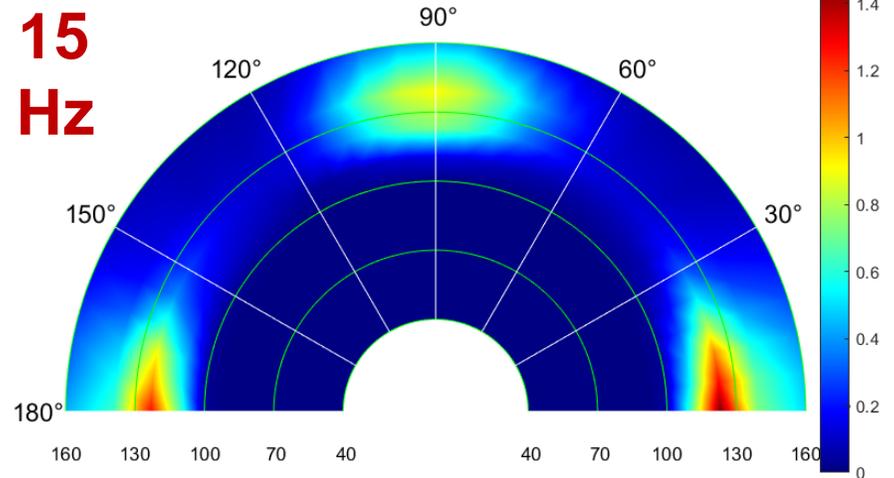
# Example of DB images

# Depth 1100 m: **Has** fractures

Azi=144  
Spa=154  
Amp=9.04e-10  
Hc = 9.97e+01

SS/HC: f 15 Hz tx 5000 ty 3400  
inline 340 xline 500

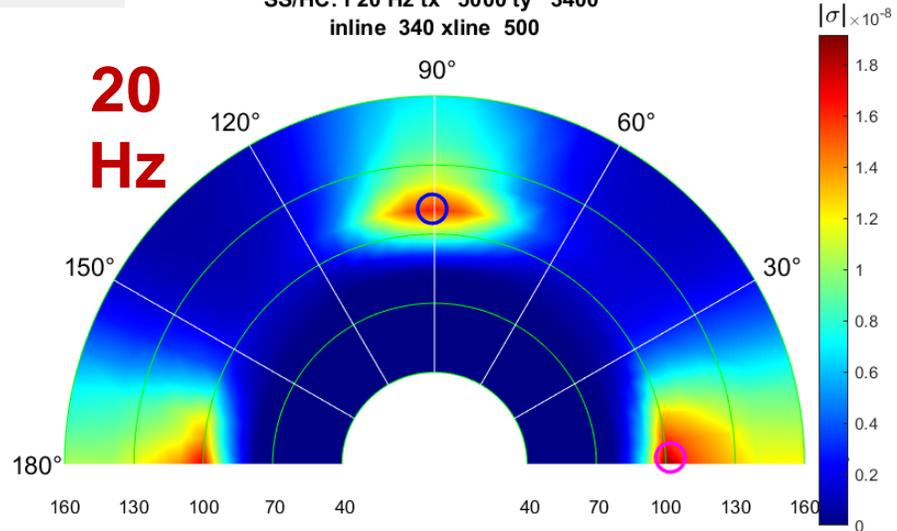
**15  
Hz**



Target: 728  
x=05000  
y=03400

SS/HC: f 20 Hz tx 5000 ty 3400  
inline 340 xline 500

**20  
Hz**

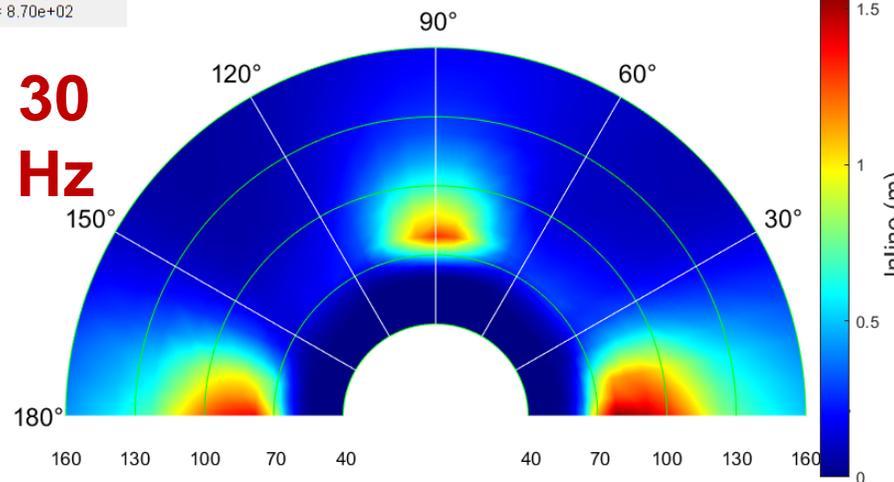


Picked:  
Azi=180  
Spa=098  
Amp=1.02e-08  
Hc = 81

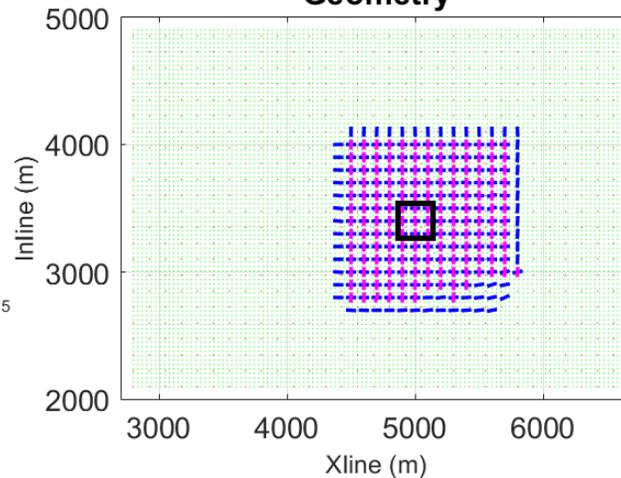
Azi=076  
Spa=136  
Amp=1.96e-09  
Hc = 8.70e+02

SS/HC: f 30 Hz tx 5000 ty 3400  
inline 340 xline 500

**30  
Hz**



## Geometry



```

0728: Inline00340,Xline00500
0729: Inline00350,Xline00500
0730: Inline00360,Xline00500
0731: Inline00370,Xline00500
0732: Inline00380,Xline00500
0733: Inline00390,Xline00500
0734: Inline00400,Xline00500
0735: Inline00410,Xline00500
0736: Inline00420,Xline00500
0737: Inline00430,Xline00500
0738: Inline00440,Xline00500
0739: Inline00450,Xline00500
0740: Inline00460,Xline00500
0741: Inline00470,Xline00500
0742: Inline00480,Xline00500
0743: Inline00490,Xline00500
0744: Inline00500,Xline00500
0745: Inline00200,Xline00510
0746: Inline00210,Xline00510
0747: Inline00220,Xline00510
0748: Inline00230,Xline00510
0749: Inline00240,Xline00510
0750: Inline00250,Xline00510
0751: Inline00260,Xline00510
    
```

f: forward  
b: back  
s: pick  
r: remove  
a: autopick

Previous -

Next +

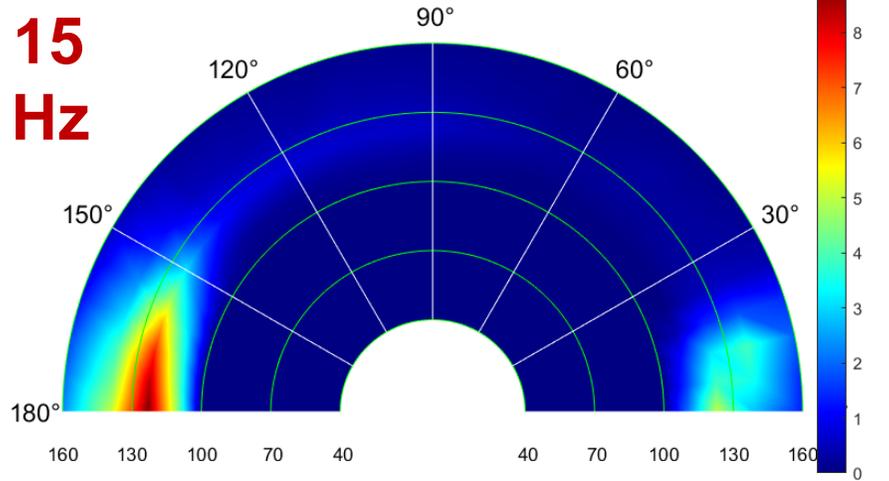
Save

# Depth 1400 m: **Has** fractures

Azi=117  
Spa=159  
Amp=1.34e-09  
Hc = 4.71e+01

SS/HC: f 15 Hz tx 4100 ty 4500  
inline 450 xline 410

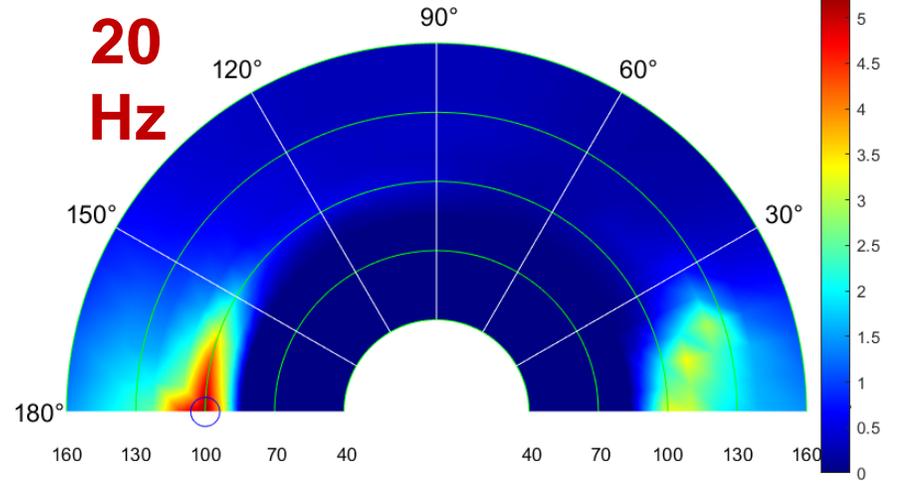
**15  
Hz**



Target:460:  
x=04100  
y=04500

SS/HC: f 20 Hz tx 4100 ty 4500  
inline 450 xline 410

**20  
Hz**

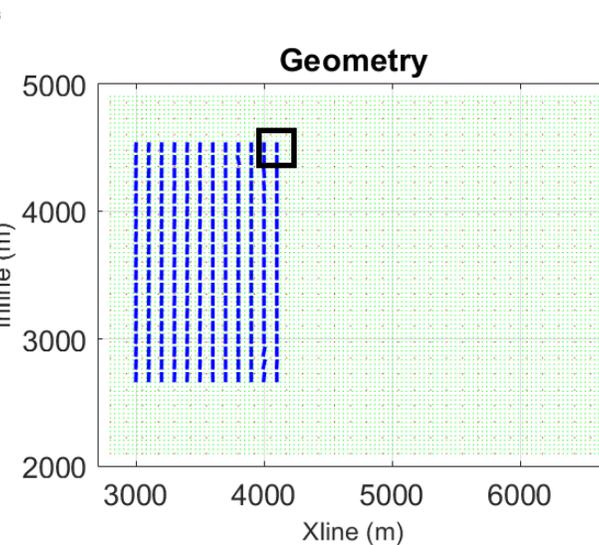
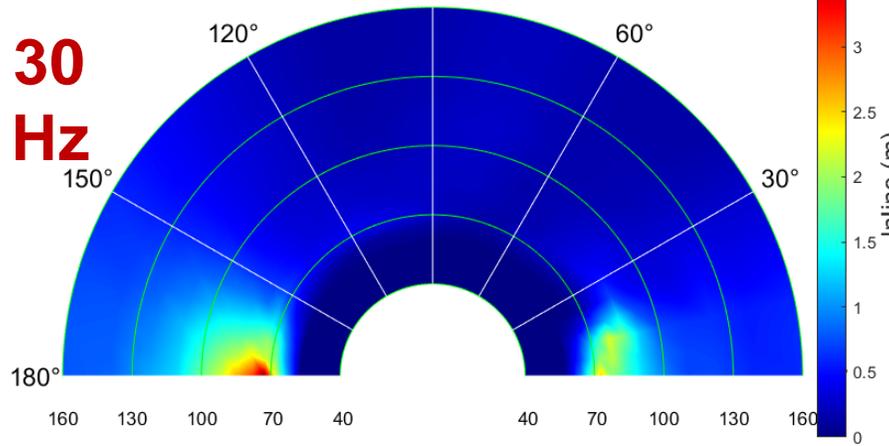


Picked:  
Azi=066  
Spa=156  
Amp=2.26e-09  
Hc = 22

Azi=076  
Spa=088  
Amp=5.63e-10  
Hc = 1.14e+02

SS/HC: f 30 Hz tx 4100 ty 4500  
inline 450 xline 410

**30  
Hz**



0437: Inline00220,Xline00410  
0438: Inline00230,Xline00410  
0439: Inline00240,Xline00410  
0440: Inline00250,Xline00410  
0441: Inline00260,Xline00410  
0442: Inline00270,Xline00410  
0443: Inline00280,Xline00410  
0444: Inline00290,Xline00410  
0445: Inline00300,Xline00410  
0446: Inline00310,Xline00410  
0447: Inline00320,Xline00410  
0448: Inline00330,Xline00410  
0449: Inline00340,Xline00410  
0450: Inline00350,Xline00410  
0451: Inline00360,Xline00410  
0452: Inline00370,Xline00410  
0453: Inline00380,Xline00410  
0454: Inline00390,Xline00410  
0455: Inline00400,Xline00410  
0456: Inline00410,Xline00410  
0457: Inline00420,Xline00410  
0458: Inline00430,Xline00410  
0459: Inline00440,Xline00410  
0460: Inline00450,Xline00410

f: forward  
b: back  
s: pick  
r: remove

Previous -

Next +

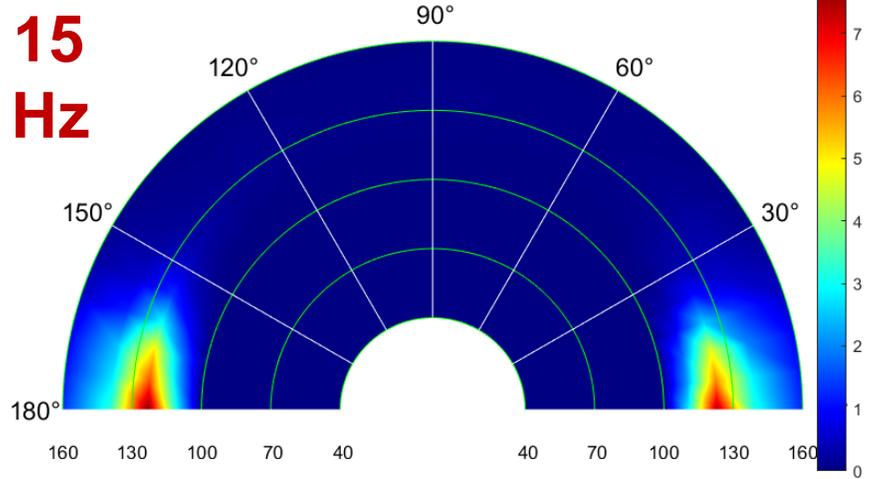
Save

# Depth 1400 m: **Has** fractures

Azi=096  
Spa=156  
Amp=2.60e-10  
Hc = 1.60e+01

SS/HC: f 15 Hz tx 3600 ty 3700  
inline 370 xline 360

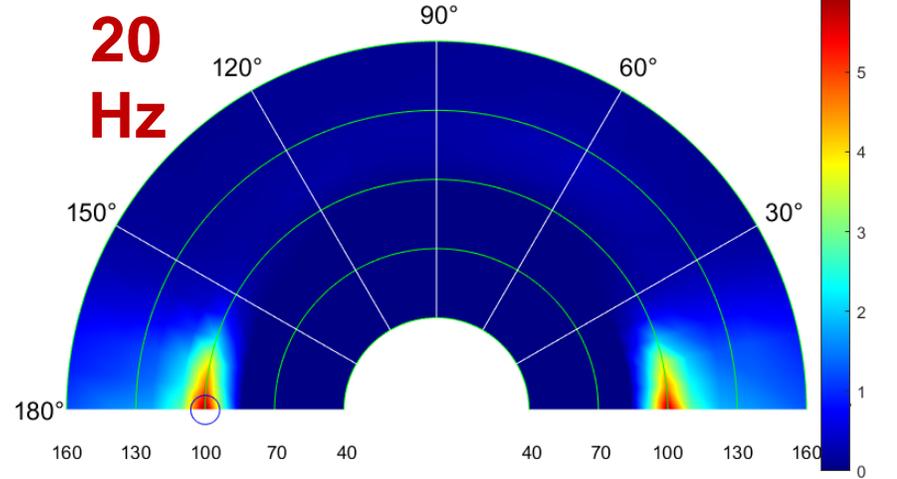
**15  
Hz**



Target:297:  
x=03600  
y=03700

SS/HC: f 20 Hz tx 3600 ty 3700  
inline 370 xline 360

**20  
Hz**

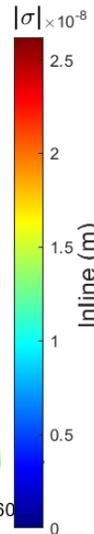
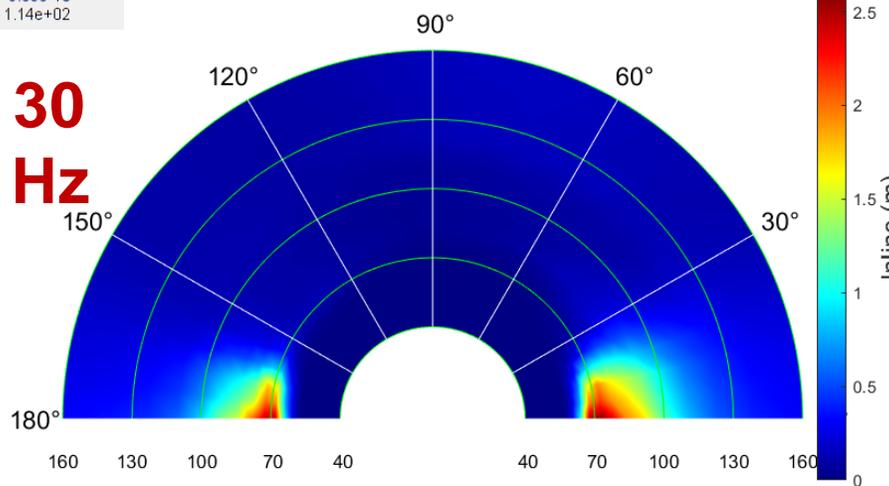


Picked:  
Azi=066  
Spa=156  
Amp=2.26e-09  
Hc = 22

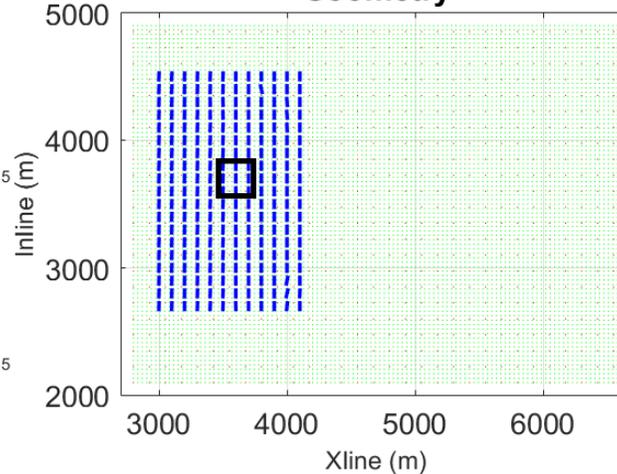
Azi=076  
Spa=088  
Amp=5.63e-10  
Hc = 1.14e+02

SS/HC: f 30 Hz tx 3600 ty 3700  
inline 370 xline 360

**30  
Hz**



## Geometry



```

0297: Inline00370,Xline00360
0298: Inline00380,Xline00360
0299: Inline00390,Xline00360
0300: Inline00400,Xline00360
0301: Inline00410,Xline00360
0302: Inline00420,Xline00360
0303: Inline00430,Xline00360
0304: Inline00440,Xline00360
0305: Inline00450,Xline00360
0306: Inline00460,Xline00360
0307: Inline00470,Xline00360
0308: Inline00480,Xline00360
0309: Inline00490,Xline00360
0310: Inline00500,Xline00360
0311: Inline00200,Xline00370
0312: Inline00210,Xline00370
0313: Inline00220,Xline00370
0314: Inline00230,Xline00370
0315: Inline00240,Xline00370
0316: Inline00250,Xline00370
0317: Inline00260,Xline00370
0318: Inline00270,Xline00370
0319: Inline00280,Xline00370
0320: Inline00290,Xline00370
    
```

f: forward  
b: back  
s: pick  
r: remove

Previous -

Next +

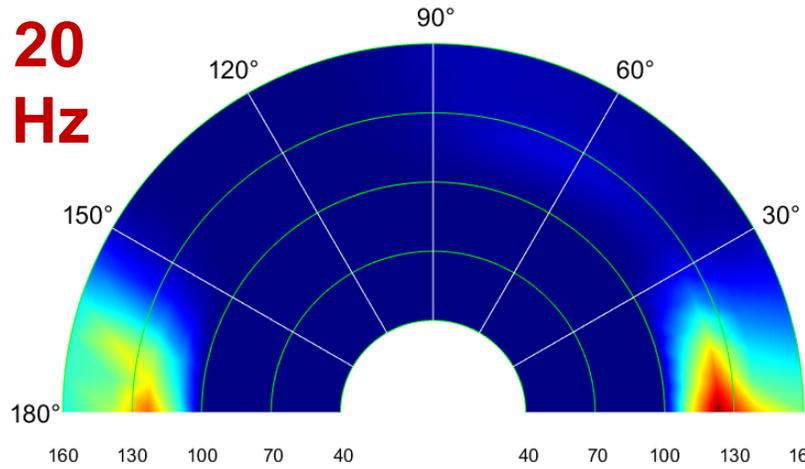
Save

# Depth 1650 m: **Has** fractures

Azi=175  
Spa=151  
Amp=1.18e-08  
Hc = 2.84e+01

SS/HC: f 20 Hz tx 6500 ty 4400  
inline 440 xline 650

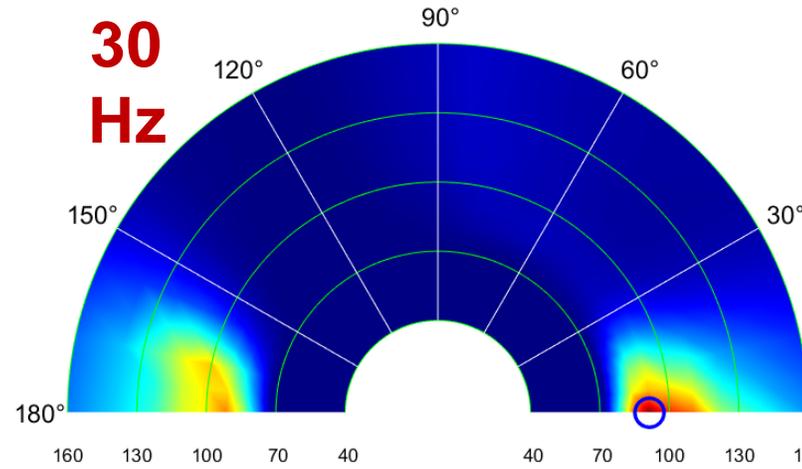
**20  
Hz**



Target: 1203:  
x=06500  
y=04400

SS/HC: f 30 Hz tx 6500 ty 4400  
inline 440 xline 650

**30  
Hz**

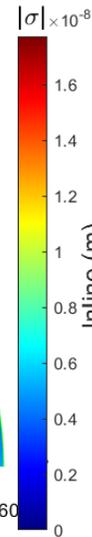
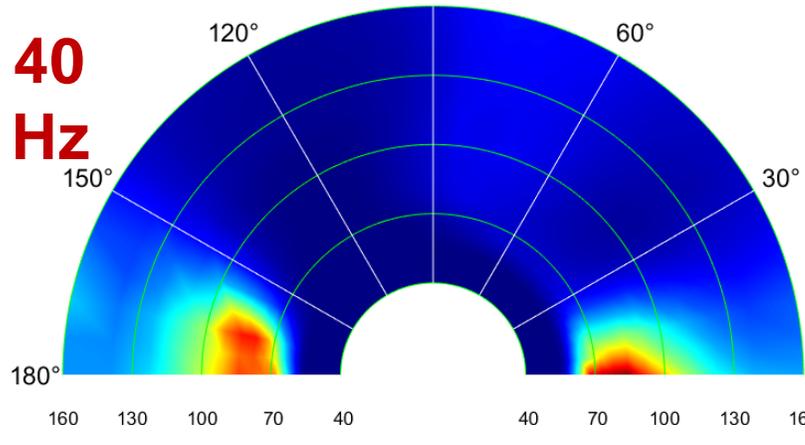


Picked:  
Azi=000  
Spa=091  
Amp=1.17e-08  
Hc = 35

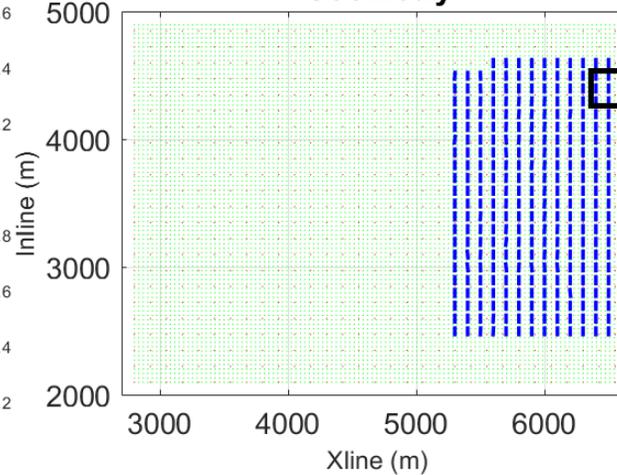
Azi=061  
Spa=126  
Amp=1.66e-09  
Hc = 2.13e+02

SS/HC: f 40 Hz tx 6500 ty 4400  
inline 440 xline 650

**40  
Hz**



## Geometry



- 1180: Inline00210,Xline00650
- 1181: Inline00220,Xline00650
- 1182: Inline00230,Xline00650
- 1183: Inline00240,Xline00650
- 1184: Inline00250,Xline00650
- 1185: Inline00260,Xline00650
- 1186: Inline00270,Xline00650
- 1187: Inline00280,Xline00650
- 1188: Inline00290,Xline00650
- 1189: Inline00300,Xline00650
- 1190: Inline00310,Xline00650
- 1191: Inline00320,Xline00650
- 1192: Inline00330,Xline00650
- 1193: Inline00340,Xline00650
- 1194: Inline00350,Xline00650
- 1195: Inline00360,Xline00650
- 1196: Inline00370,Xline00650
- 1197: Inline00380,Xline00650
- 1198: Inline00390,Xline00650
- 1199: Inline00400,Xline00650
- 1200: Inline00410,Xline00650
- 1201: Inline00420,Xline00650
- 1202: Inline00430,Xline00650
- 1203: Inline00440,Xline00650

f: forward  
b: back  
s: pick  
r: remove  
a: autopick

Previous -

Next +

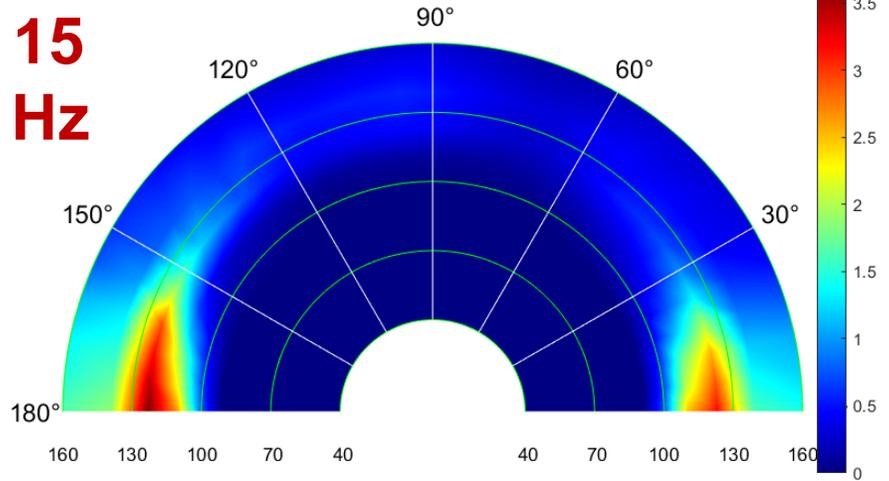
Save

# Depth 1100 m: No fracture

Azi=116  
Spa=159  
Amp=2.79e-10  
Hc = 5.48e+01

SS/HC: f 15 Hz tx 6100 ty 3500  
inline 350 xline 610

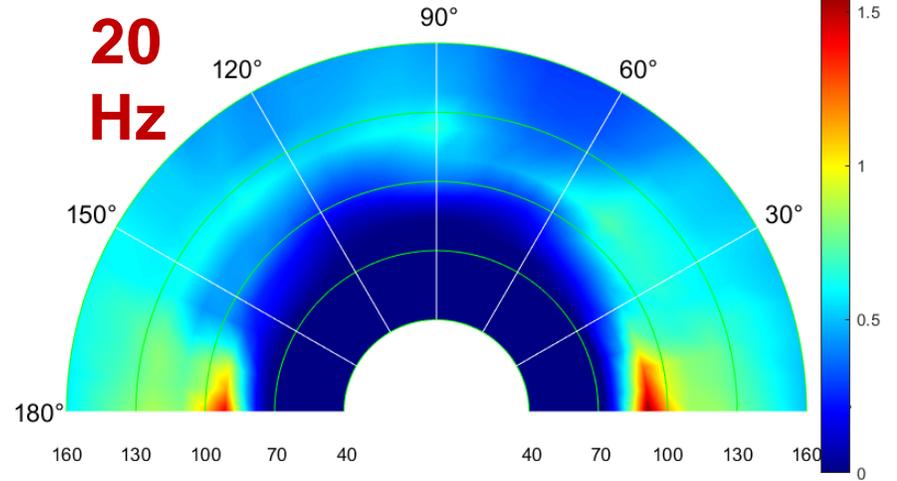
15  
Hz



Target 1070:  
x=06100  
y=03500

SS/HC: f 20 Hz tx 6100 ty 3500  
inline 350 xline 610

20  
Hz



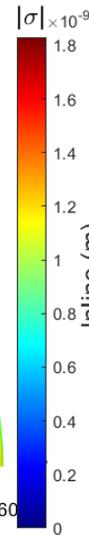
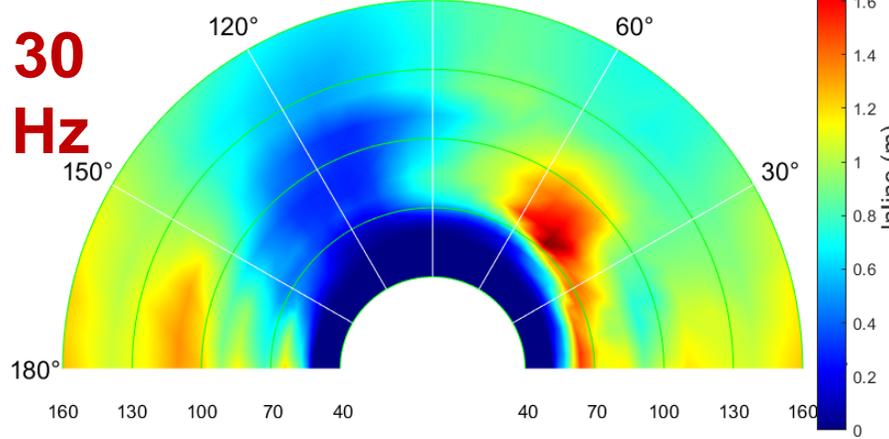
Picked:  
Azi=180  
Spa=098  
Amp=1.02e-08  
Hc = 81

No consistent focused "bright spot"

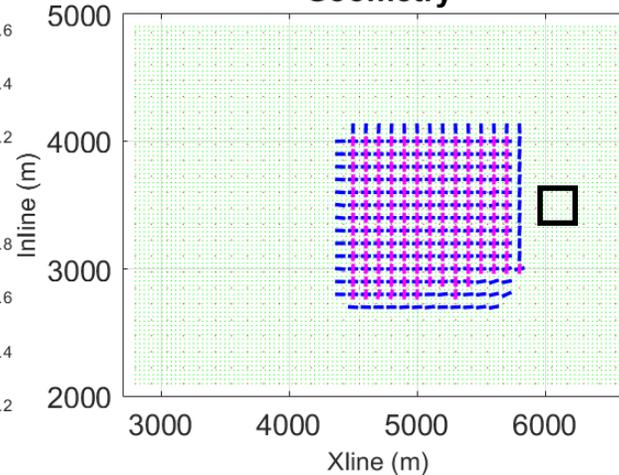
Azi=055  
Spa=143  
Amp=7.56e-10  
Hc = 5.50e+02

SS/HC: f 30 Hz tx 6100 ty 3500  
inline 350 xline 610

30  
Hz



Geometry



- 1048: Inline00440,Xline00600
- 1049: Inline00450,Xline00600
- 1050: Inline00460,Xline00600
- 1051: Inline00470,Xline00600
- 1052: Inline00480,Xline00600
- 1053: Inline00490,Xline00600
- 1054: Inline00500,Xline00600
- 1055: Inline00200,Xline00610
- 1056: Inline00210,Xline00610
- 1057: Inline00220,Xline00610
- 1058: Inline00230,Xline00610
- 1059: Inline00240,Xline00610
- 1060: Inline00250,Xline00610
- 1061: Inline00260,Xline00610
- 1062: Inline00270,Xline00610
- 1063: Inline00280,Xline00610
- 1064: Inline00290,Xline00610
- 1065: Inline00300,Xline00610
- 1066: Inline00310,Xline00610
- 1067: Inline00320,Xline00610
- 1068: Inline00330,Xline00610
- 1069: Inline00340,Xline00610
- 1070: Inline00350,Xline00610
- 1071: Inline00360,Xline00610

f: forward  
b: back  
s: pick  
r: remove  
a: autopick

Previous -

Next +

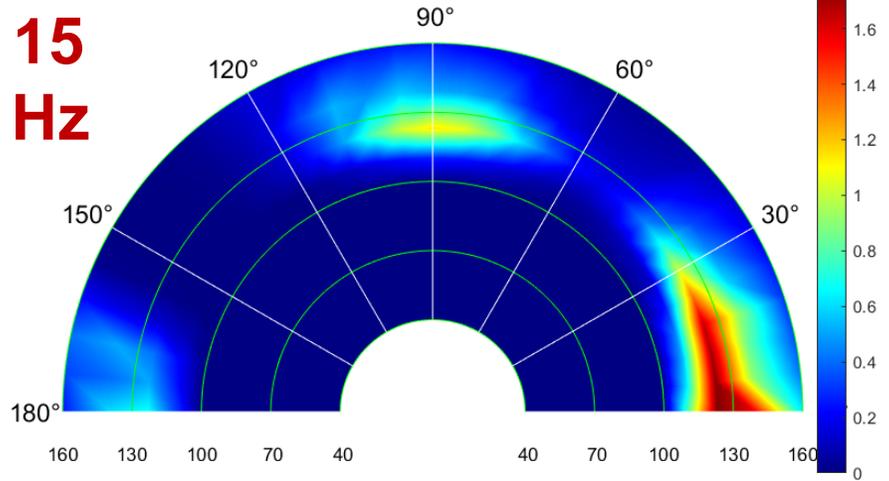
Save

# Depth 1400 m: No fracture

Azi=117  
Spa=150  
Amp=2.08e-09  
Hc = 6.98e+00

SS/HC: f 15 Hz tx 3500 ty 2400  
inline 240 xline 350

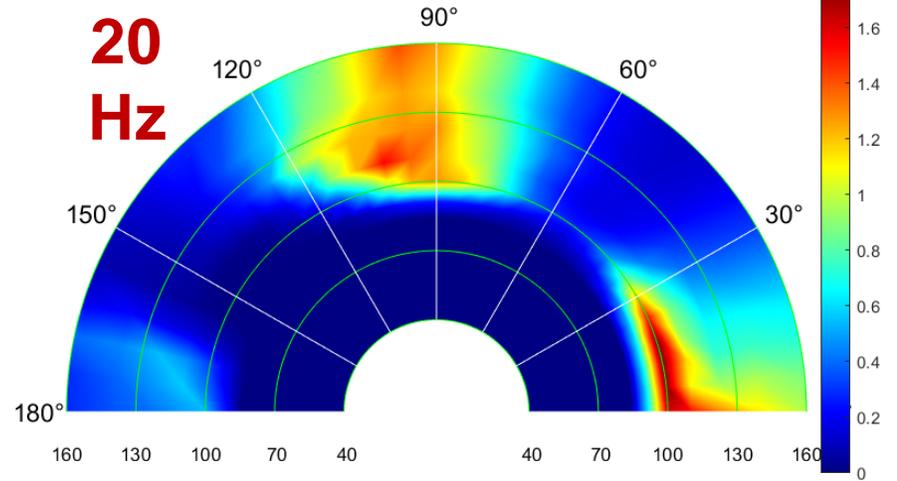
15  
Hz



Target:253:  
x=03500  
y=02400

SS/HC: f 20 Hz tx 3500 ty 2400  
inline 240 xline 350

20  
Hz

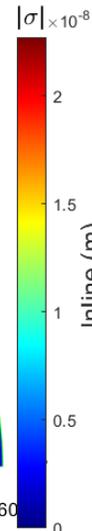
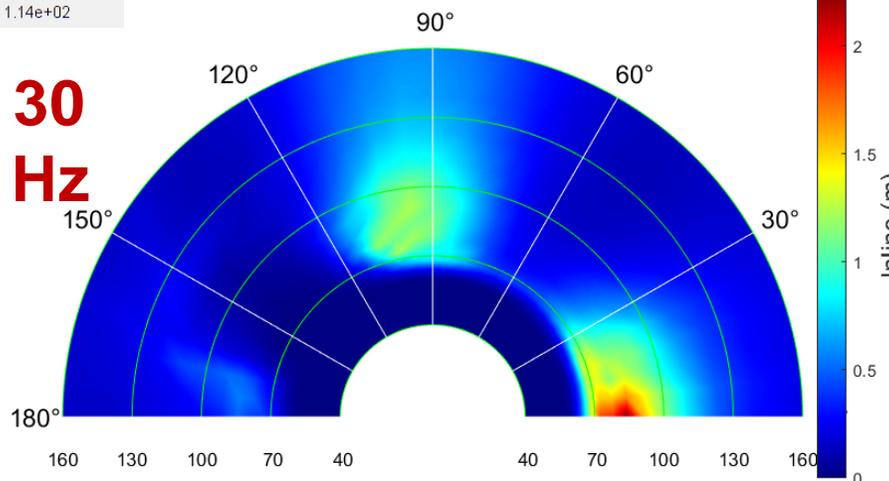


Picked:  
Azi=066  
Spa=156  
Amp=2.26e-09  
Hc = 22

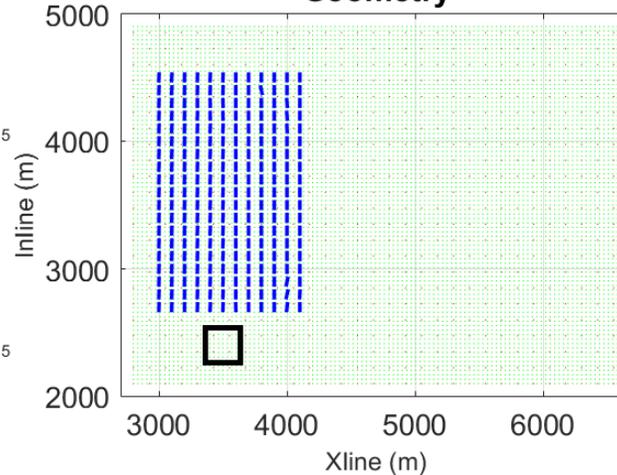
Azi=076  
Spa=088  
Amp=5.63e-10  
Hc = 1.14e+02

SS/HC: f 30 Hz tx 3500 ty 2400  
inline 240 xline 350

30  
Hz



## Geometry



0230: Inline00320,Xline00340  
0231: Inline00330,Xline00340  
0232: Inline00340,Xline00340  
0233: Inline00350,Xline00340  
0234: Inline00360,Xline00340  
0235: Inline00370,Xline00340  
0236: Inline00380,Xline00340  
0237: Inline00390,Xline00340  
0238: Inline00400,Xline00340  
0239: Inline00410,Xline00340  
0240: Inline00420,Xline00340  
0241: Inline00430,Xline00340  
0242: Inline00440,Xline00340  
0243: Inline00450,Xline00340  
0244: Inline00460,Xline00340  
0245: Inline00470,Xline00340  
0246: Inline00480,Xline00340  
0247: Inline00490,Xline00340  
0248: Inline00500,Xline00340  
0249: Inline00200,Xline00350  
0250: Inline00210,Xline00350  
0251: Inline00220,Xline00350  
0252: Inline00230,Xline00350  
0253: Inline00240,Xline00350

f. forward  
b. back  
s. pick  
r. remove

Previous -

Next +

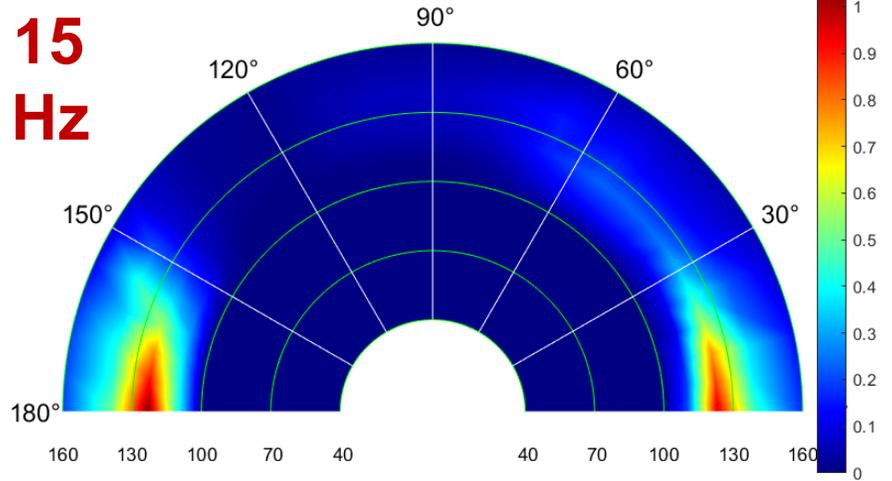
Save

# Depth 1400 m: No fracture

Azi=111  
Spa=157  
Amp=2.73e-10  
Hc = 8.30e+00

SS/HC: f 15 Hz tx 6000 ty 4000  
inline 400 xline 600

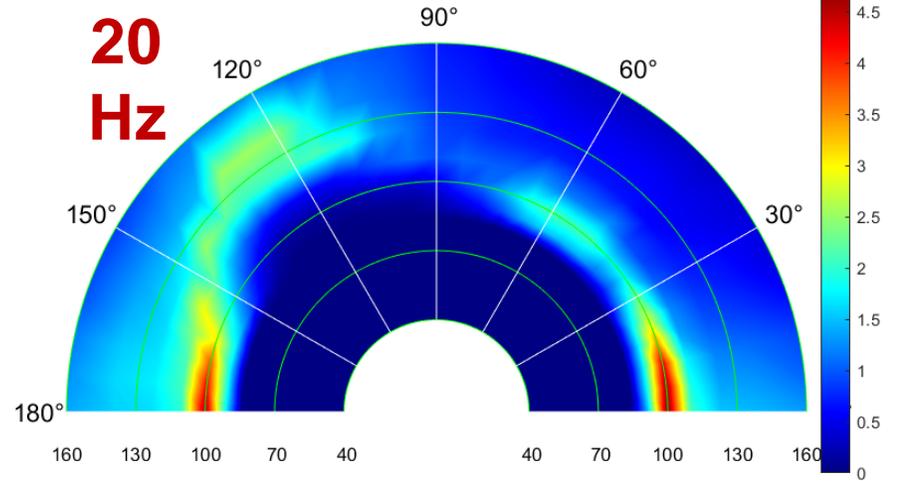
15  
Hz



Target 1044:  
x=06000  
y=04000

SS/HC: f 20 Hz tx 6000 ty 4000  
inline 400 xline 600

20  
Hz

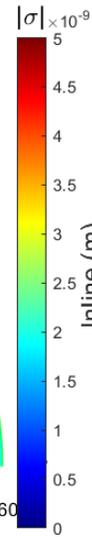
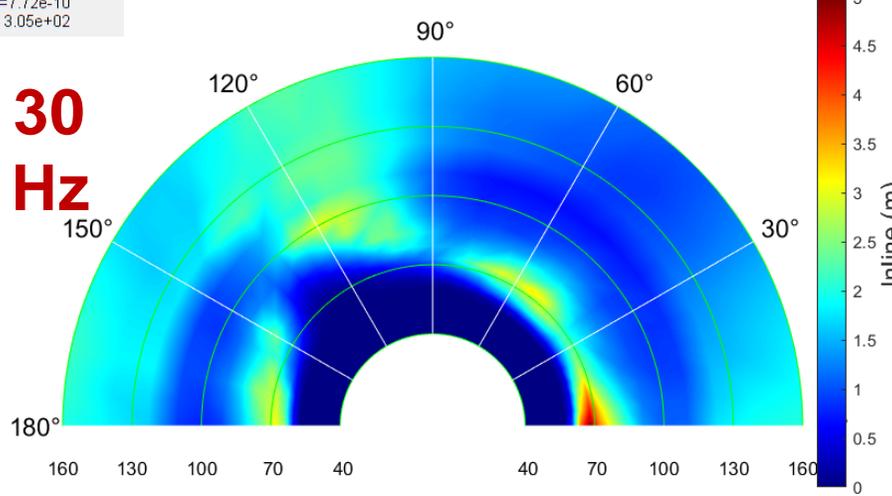


Picked:  
Azi=066  
Spa=156  
Amp=2.26e-09  
Hc = 22

Azi=062  
Spa=103  
Amp=7.72e-10  
Hc = 3.05e+02

SS/HC: f 30 Hz tx 6000 ty 4000  
inline 400 xline 600

30  
Hz



Geometry

- 1021: Inline00480,Xline00590
- 1022: Inline00490,Xline00590
- 1023: Inline00500,Xline00590
- 1024: Inline00200,Xline00600
- 1025: Inline00210,Xline00600
- 1026: Inline00220,Xline00600
- 1027: Inline00230,Xline00600
- 1028: Inline00240,Xline00600
- 1029: Inline00250,Xline00600
- 1030: Inline00260,Xline00600
- 1031: Inline00270,Xline00600
- 1032: Inline00280,Xline00600
- 1033: Inline00290,Xline00600
- 1034: Inline00300,Xline00600
- 1035: Inline00310,Xline00600
- 1036: Inline00320,Xline00600
- 1037: Inline00330,Xline00600
- 1038: Inline00340,Xline00600
- 1039: Inline00350,Xline00600
- 1040: Inline00360,Xline00600
- 1041: Inline00370,Xline00600
- 1042: Inline00380,Xline00600
- 1043: Inline00390,Xline00600
- 1044: Inline00400,Xline00600

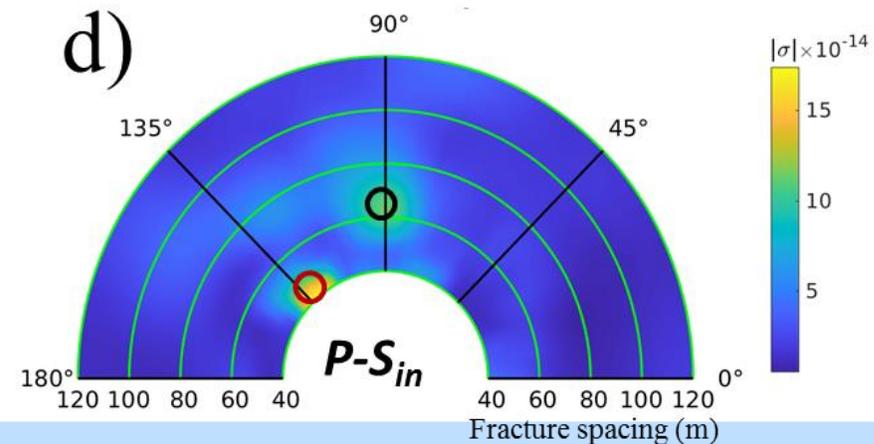
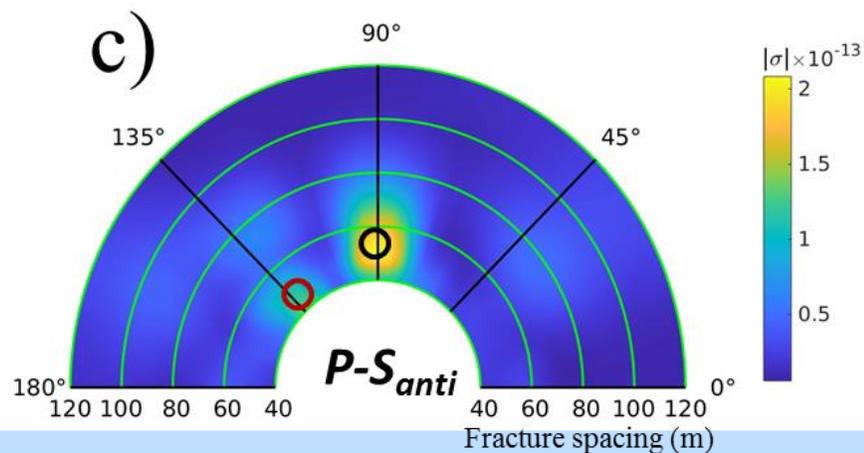
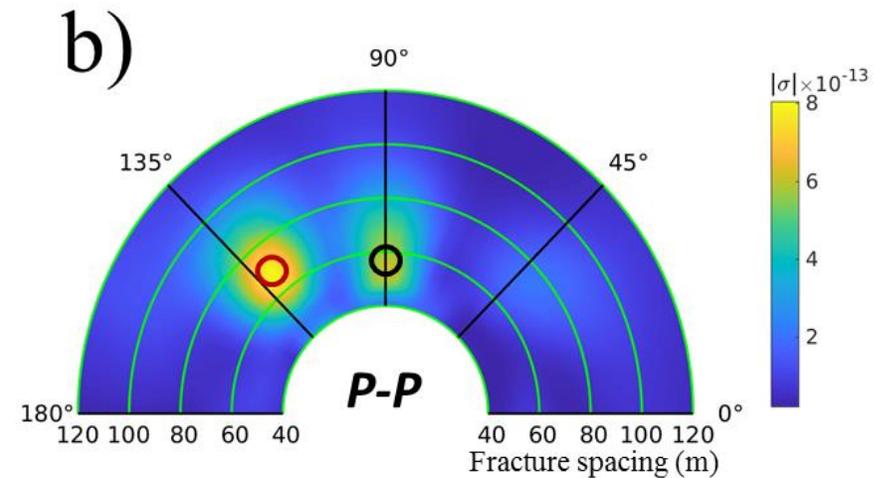
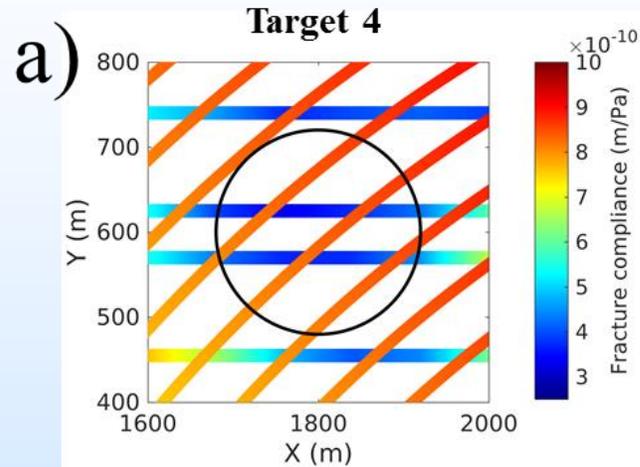
f. forward  
b. back  
s. pick  
r. remove

Previous -

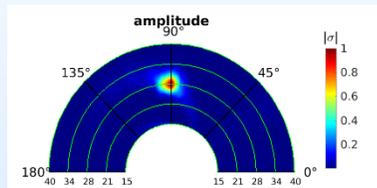
Next +

Save

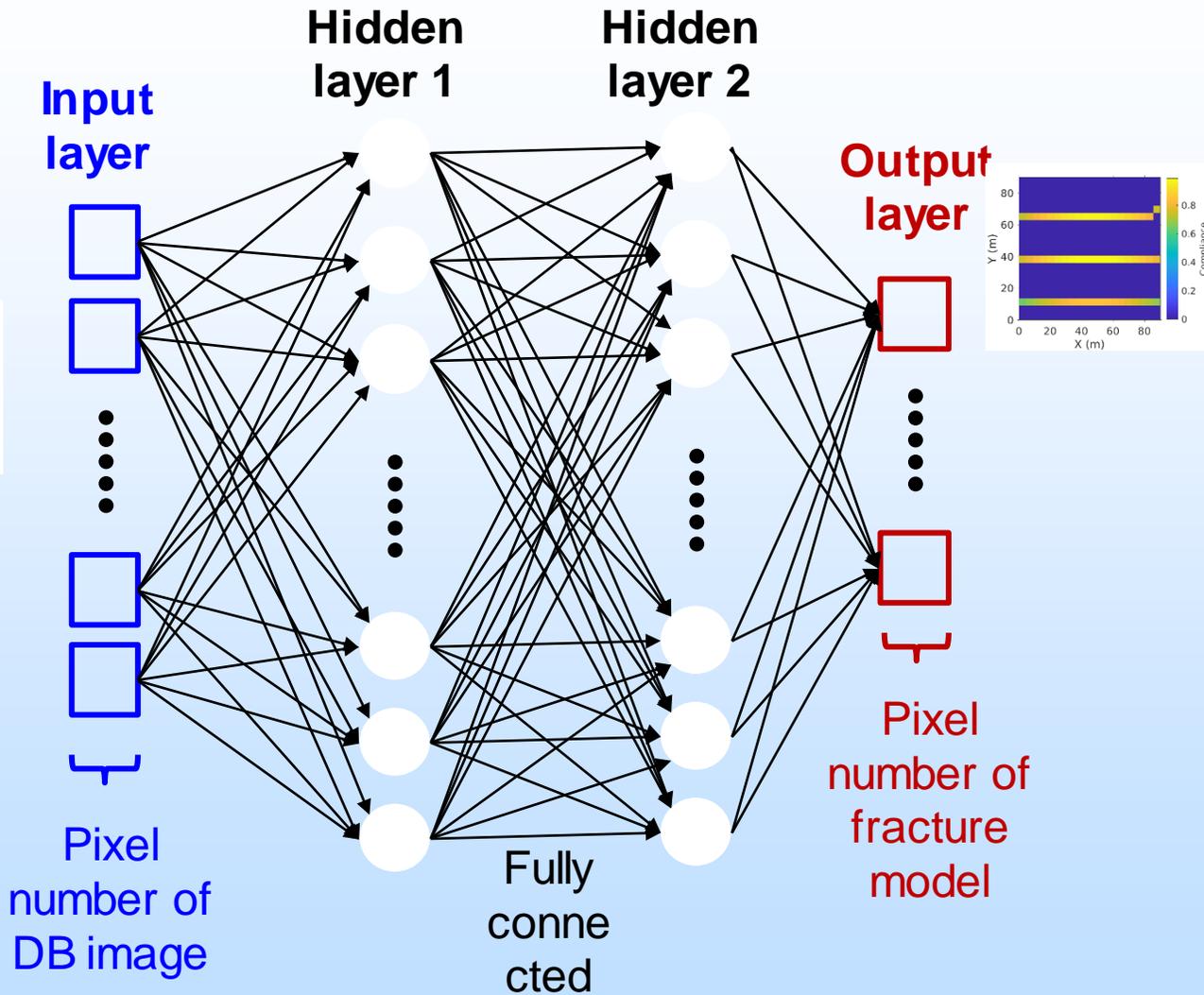
# Next steps: discrete fracture network using Machine learning



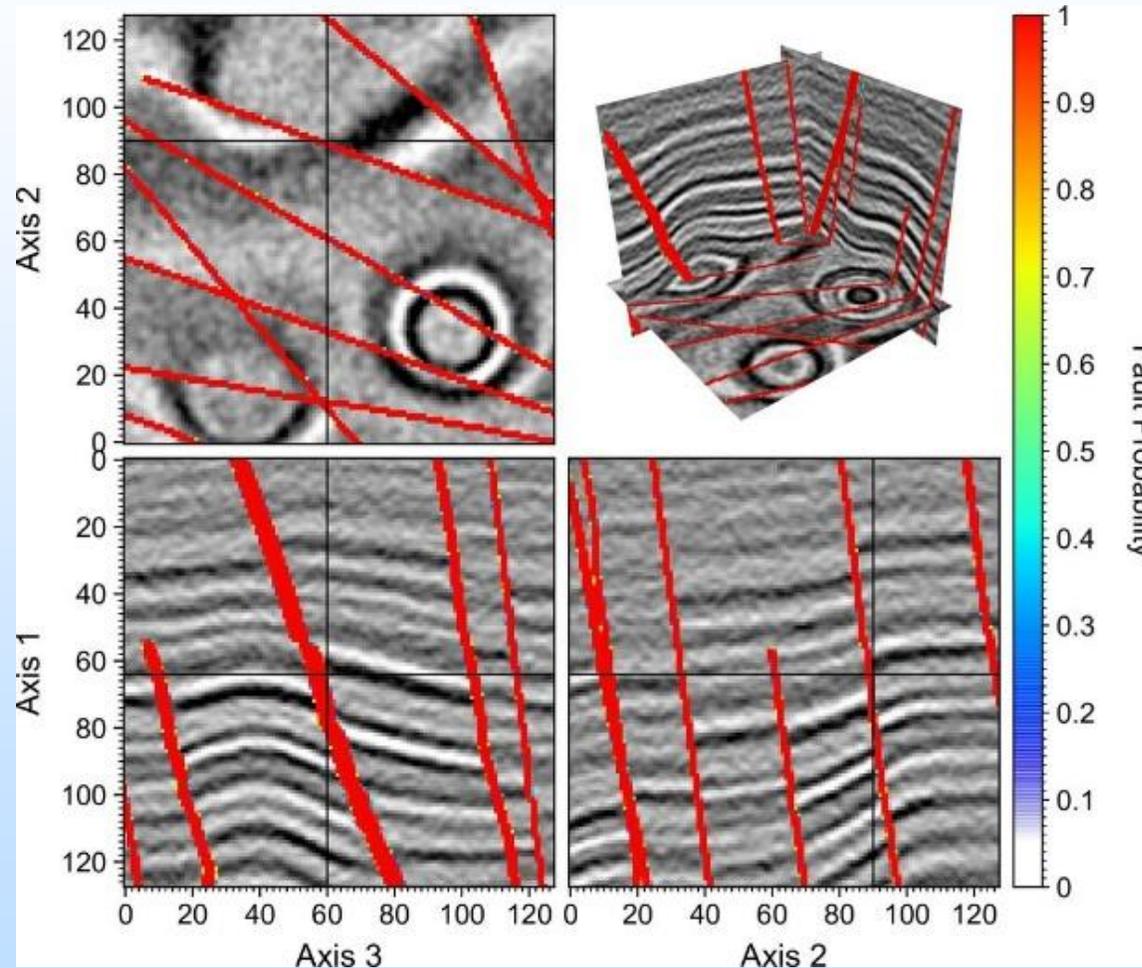
# Elastic double-beam neural network (DBNN) machine learning



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



## Large-scale faults detected using LANL's new NRU



Nested Residual U-shaped convolutional neural network (NRU)

# Summary

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- Year-1 focused on synthetic model and data tests
- 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
- We modeled 3d 9-c shot gathers
- We applied the double-beam method on the modeled datasets and found
  - 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
- In the Gigaton CO<sub>2</sub> injection scenario, our methods could be extremely useful in providing information: permeable fluid flow pathways, stress state, and earthquake hazards

# Acknowledgments

- The work is funded by DOE with funding number DE-FE0032063
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- We also used computing facilities provided by the UHXfrac group at the University of Houston.
- Vecta Oil and Gas Ltd. provided relevant field information