BBS 2015 Workshop

New developments in coal seismology

Shaun Strong & Steve Hearn

Velseis
Integrated Seismic Technologies

UQ
EXPLORATION GEOPHYSICS

BBS 2015 Workshop

New developments in coal seismology

This file contains a subset of images used in the workshop presentation.
It is not intended as a standalone document.

The document is intended solely as a personal reference for attendees at BBS2015.
Please do not distribute this document, or use images in any other context.

Velseis
Integrated Seismic Technologies

UQ
EXPLORATION GEOPHYSICS

New developments in coal seismology

Acquisition modelling of seismic resolution

Seismic anisotropy and stress prediction

Exploitation of seismic noise

Velseis
Integrated Seismic Technologies

UQ
EXPLORATION GEOPHYSICS

New developments in coal seismology

Acquisition modelling of seismic resolution

Seismic anisotropy and stress prediction

Exploitation of seismic noise

Velseis
Integrated Seismic Technologies

UQ
EXPLORATION GEOPHYSICS

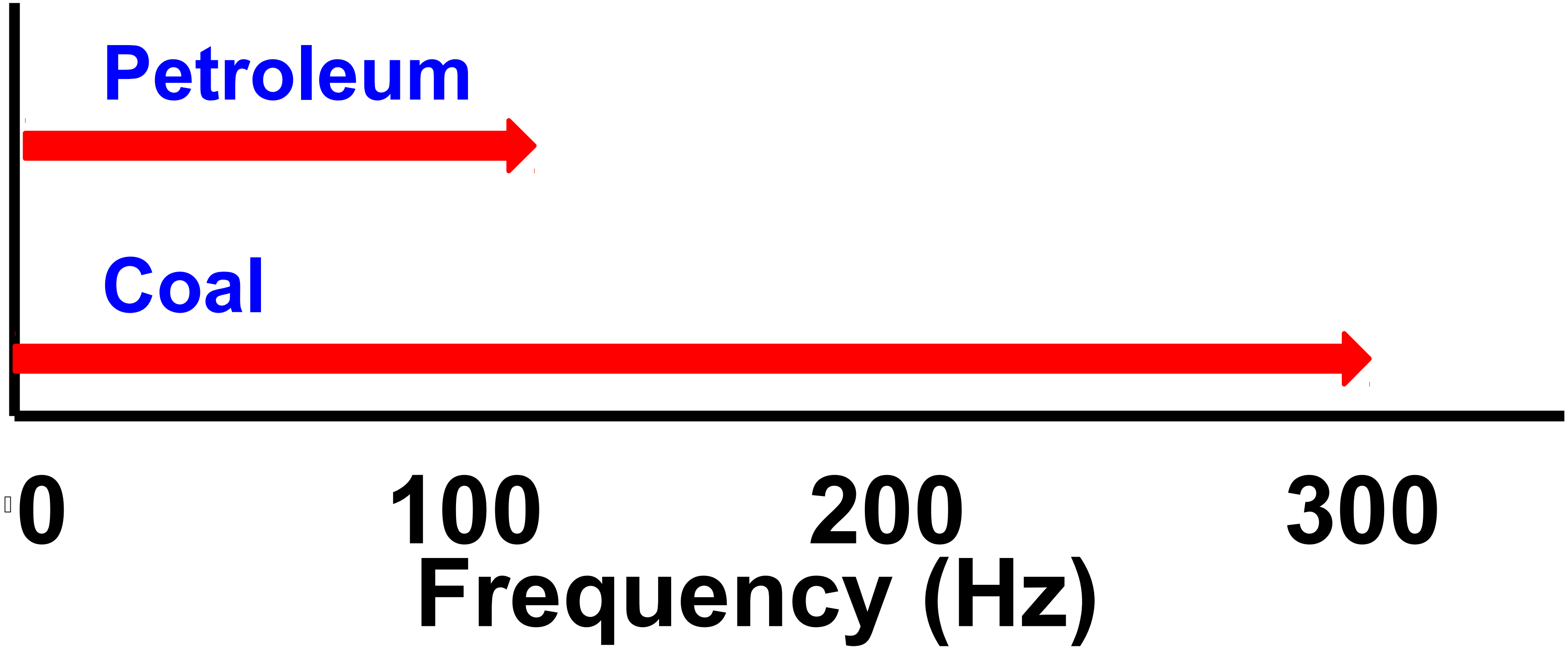
Seismic Resolution

Desirable frequency characteristics

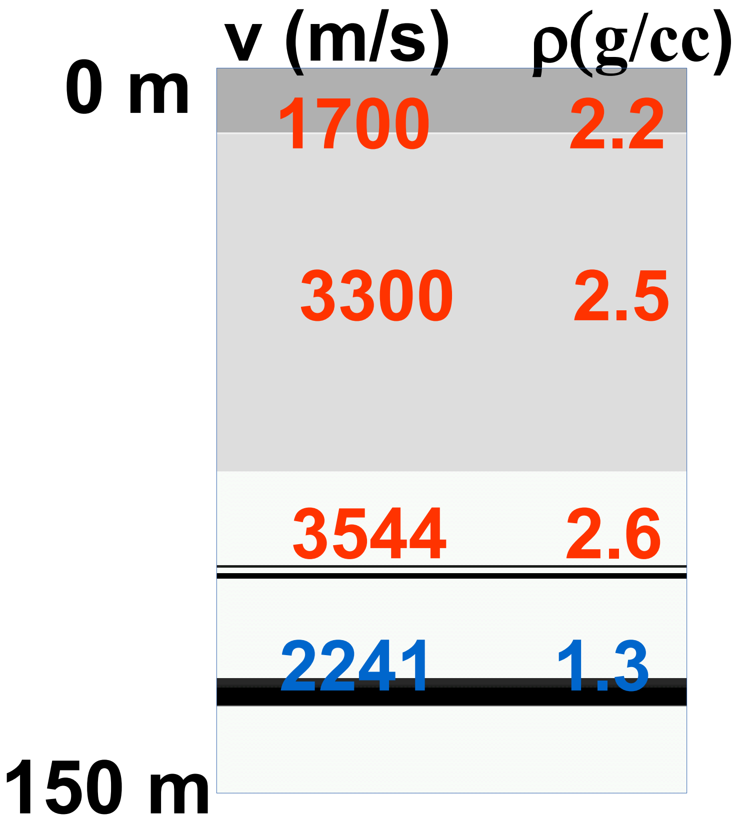
broad bandwidth → stable pulse

high dominant frequency → short wavelength → good resolution

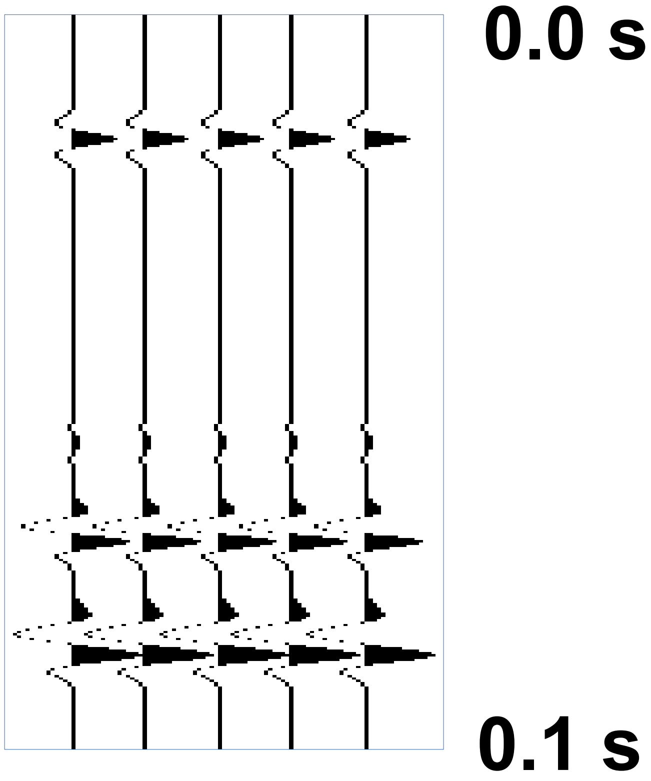
Earth Scattering Limit



Simple Resolution Modelling

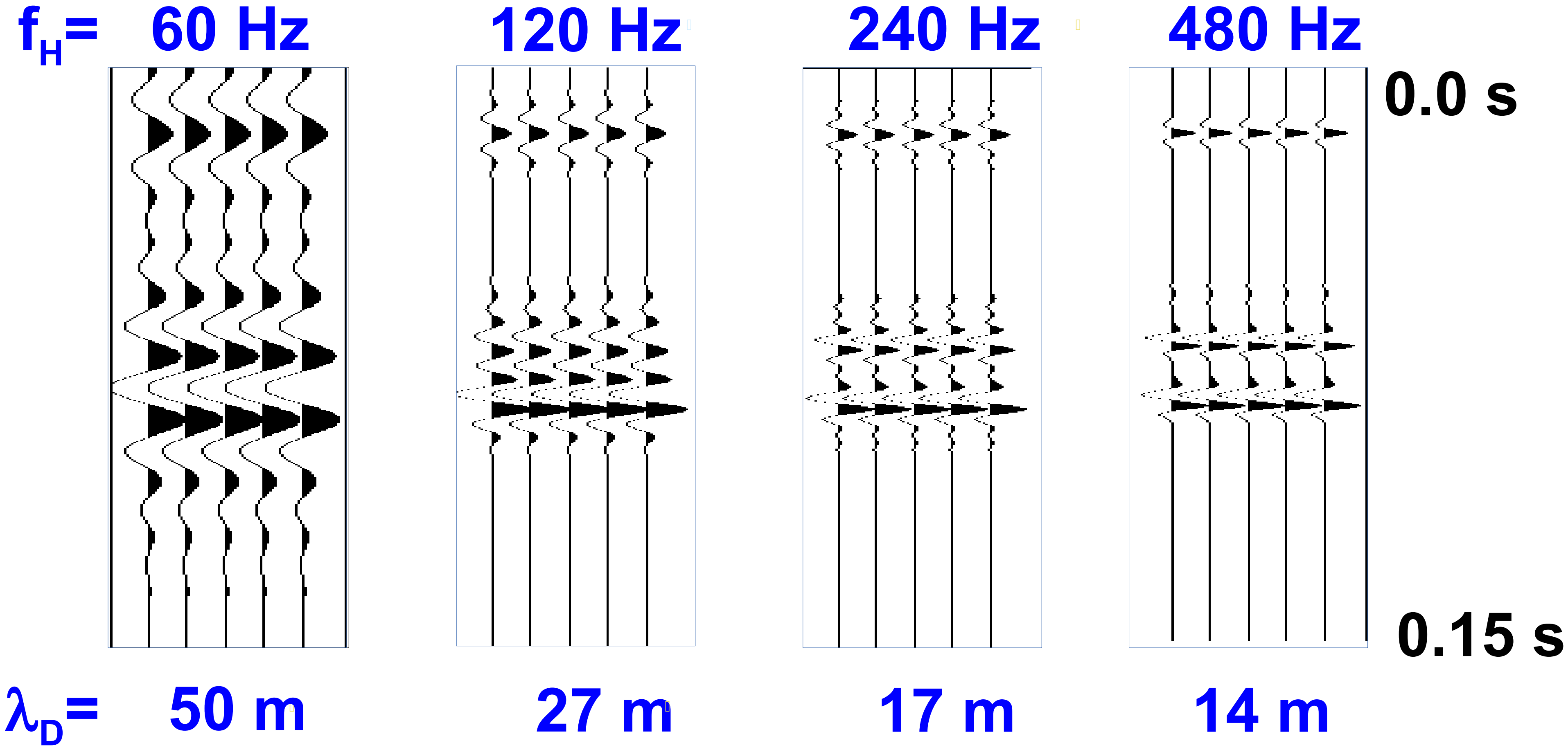


Bowen Basin Model

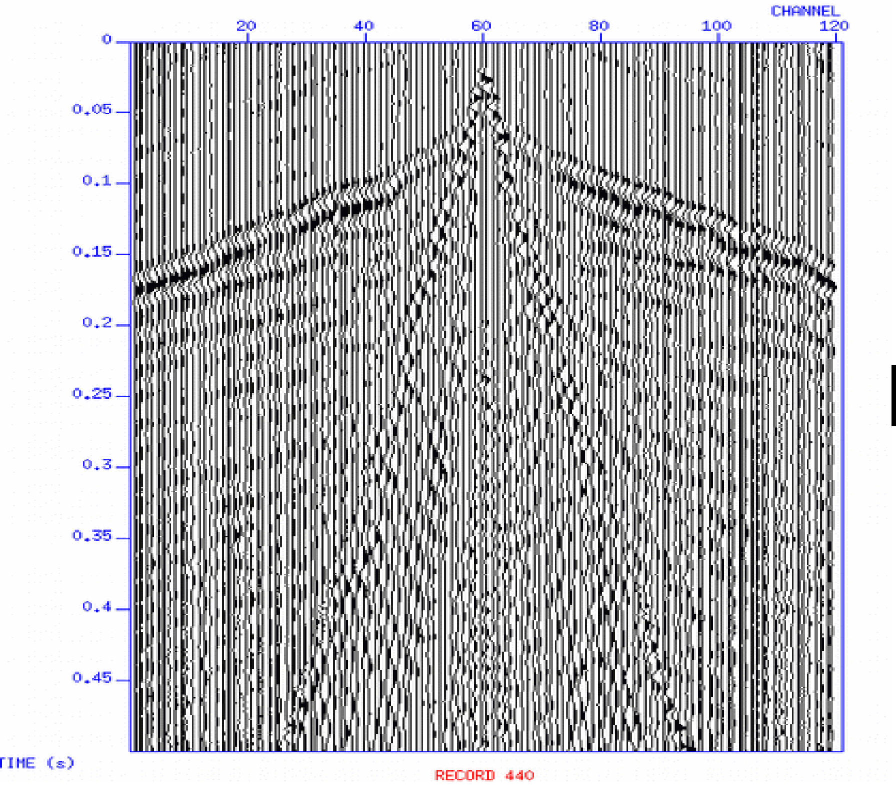


Seismic Section

Influence of High Frequencies

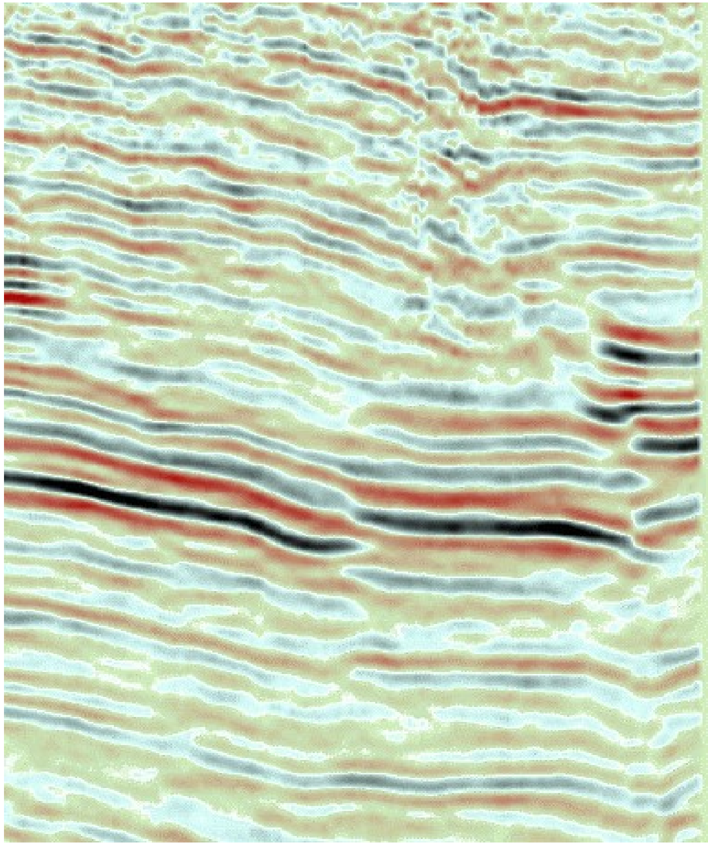


Real seismic exploration



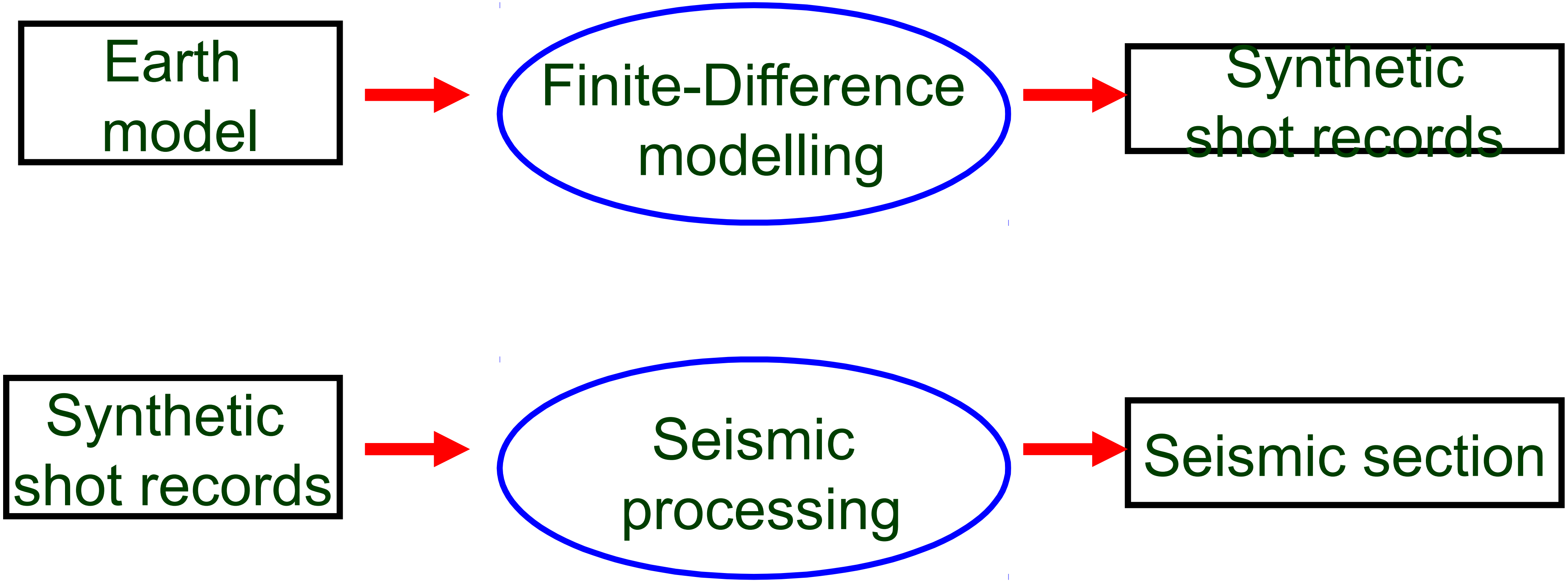
Many Shot Records

Seismic Processing

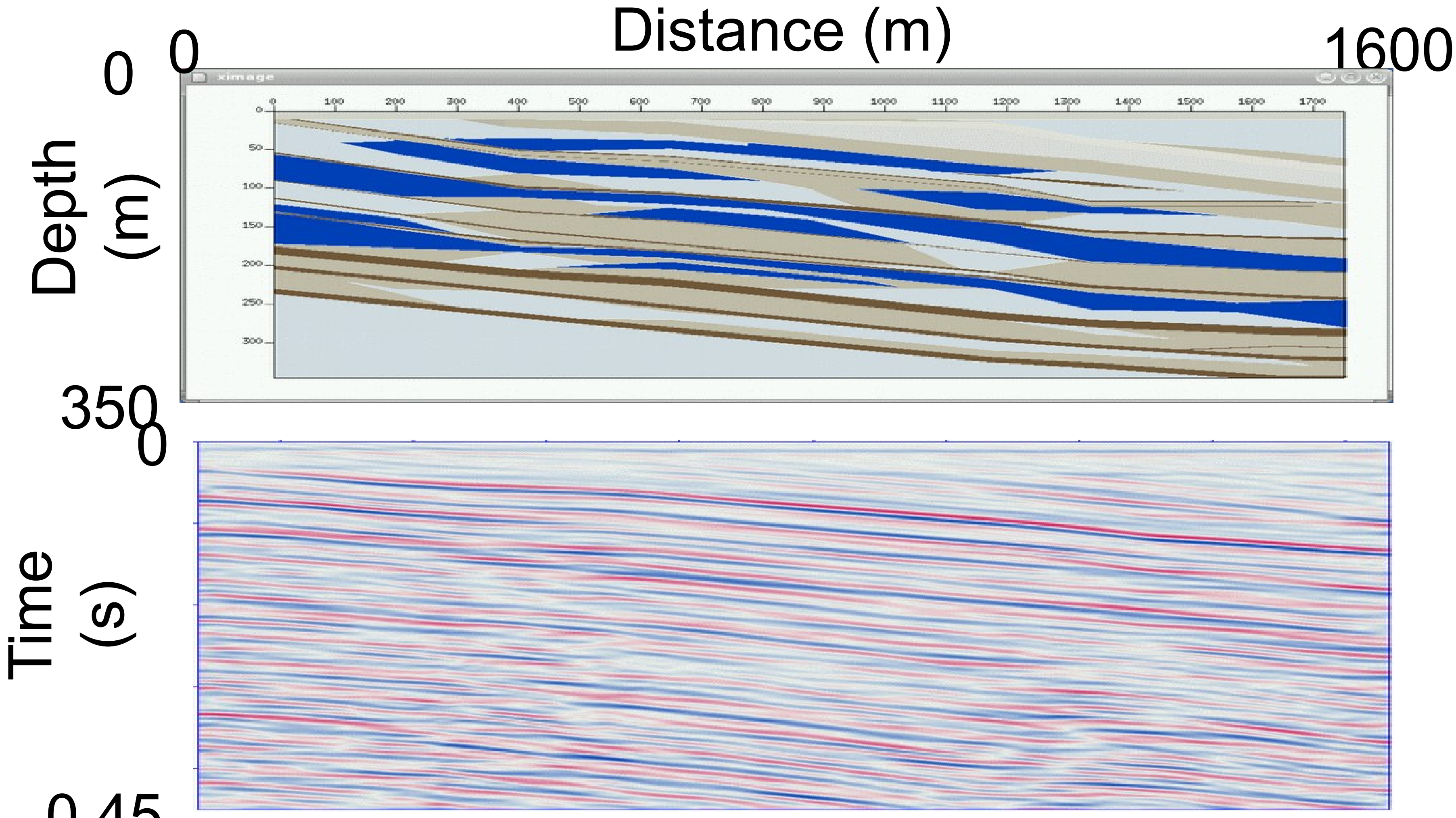


Stacked Image

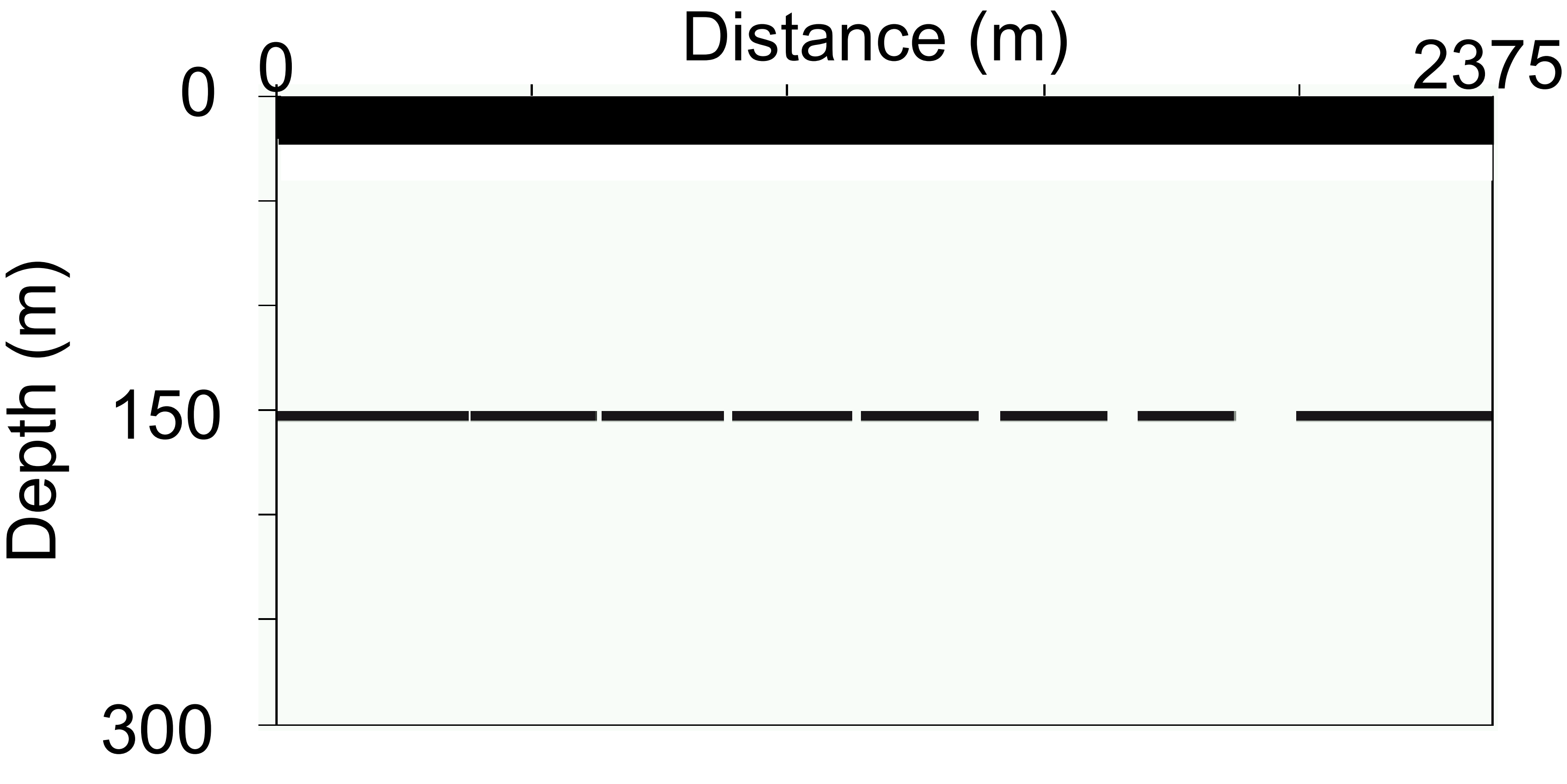
“Acquisition Modelling”



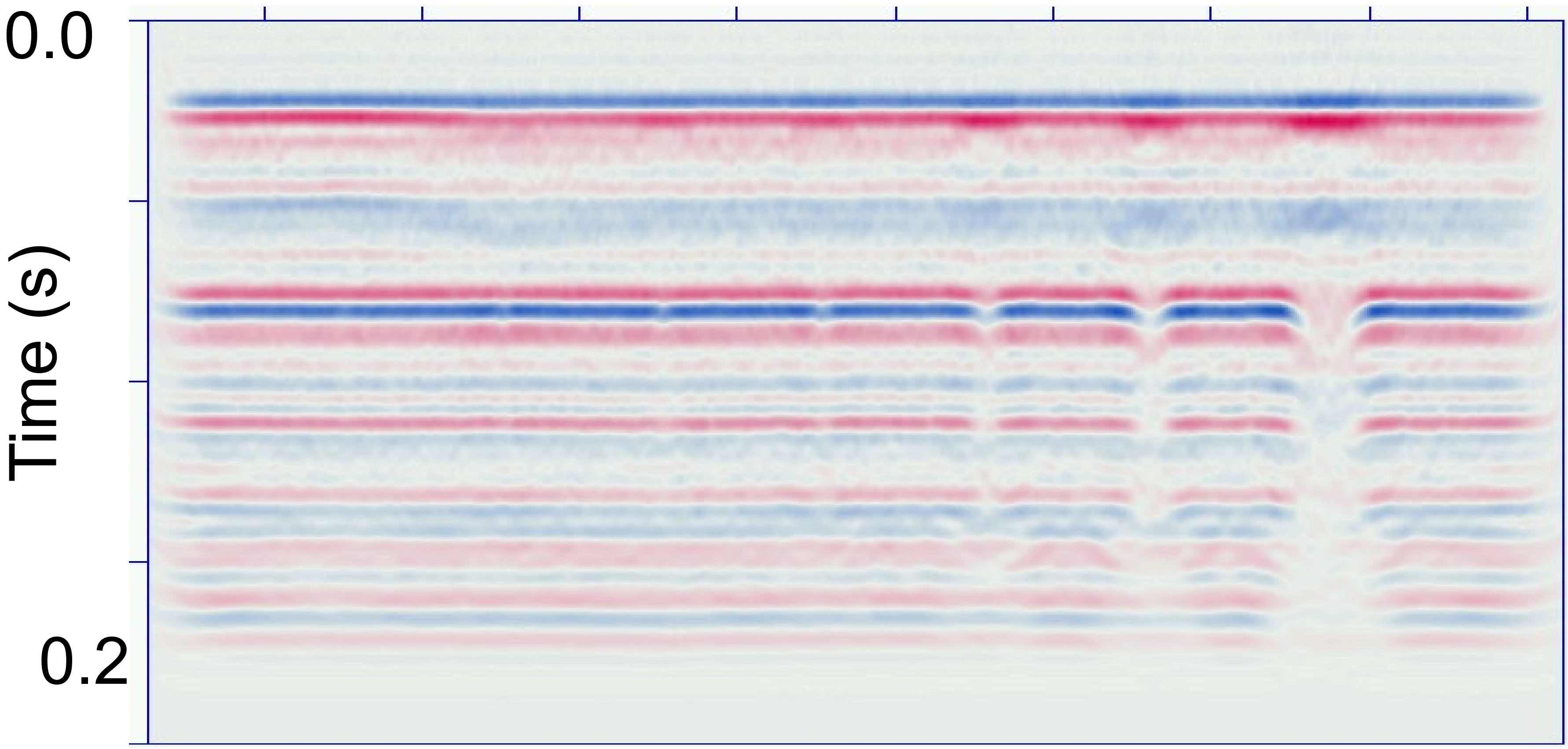
Acquisition modelling example



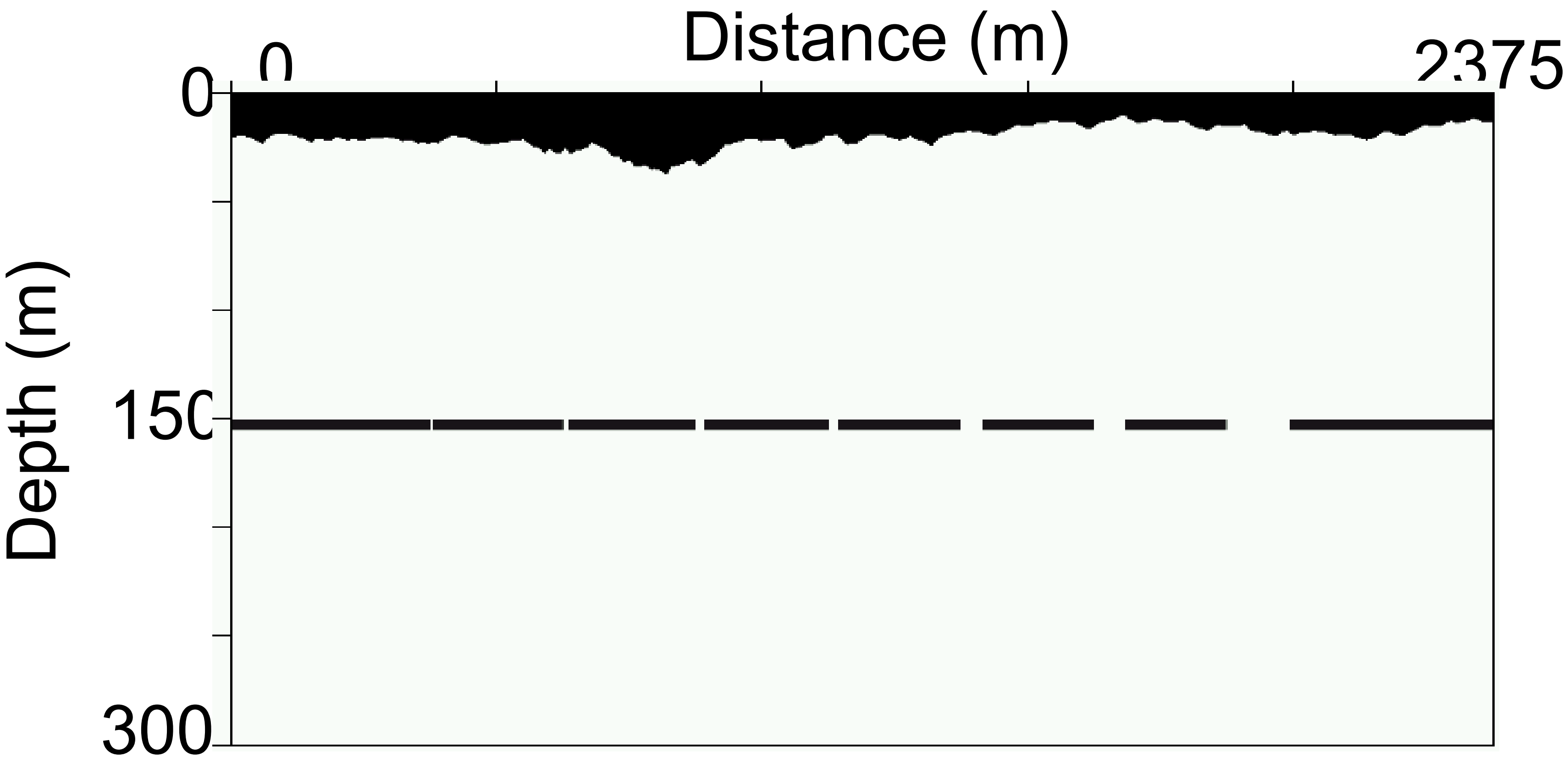
Barren-zone modelling



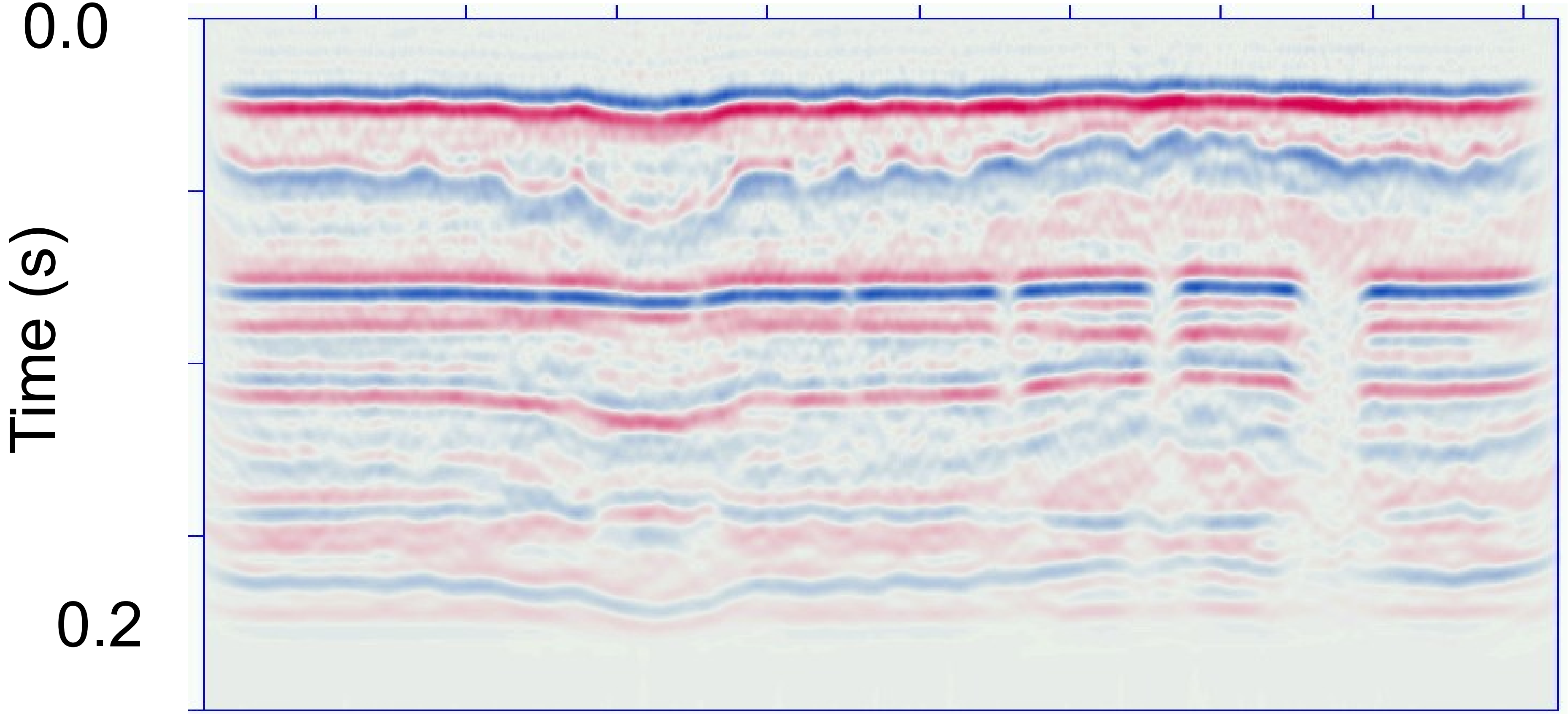
Barren-zone modelling



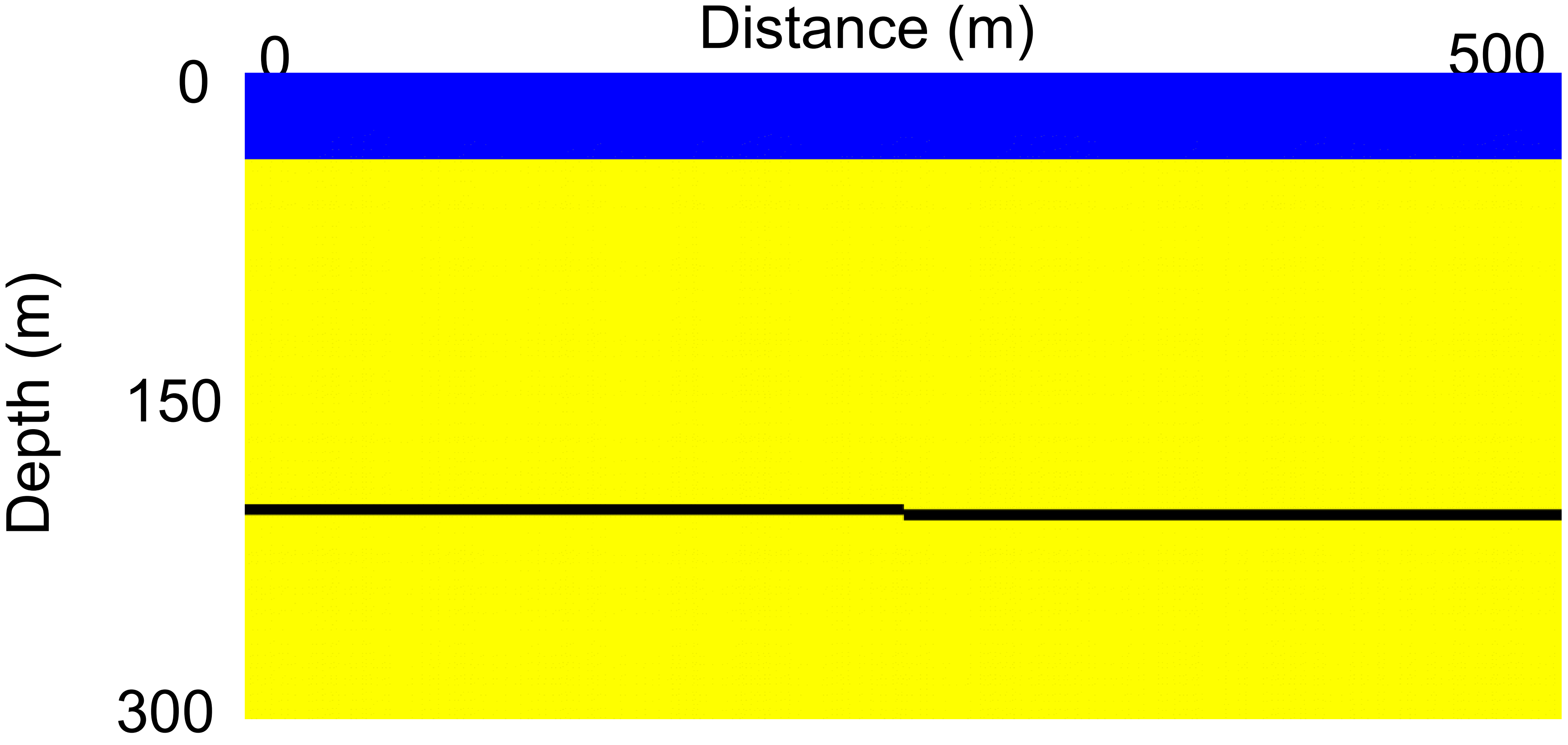
Barren-zone modelling



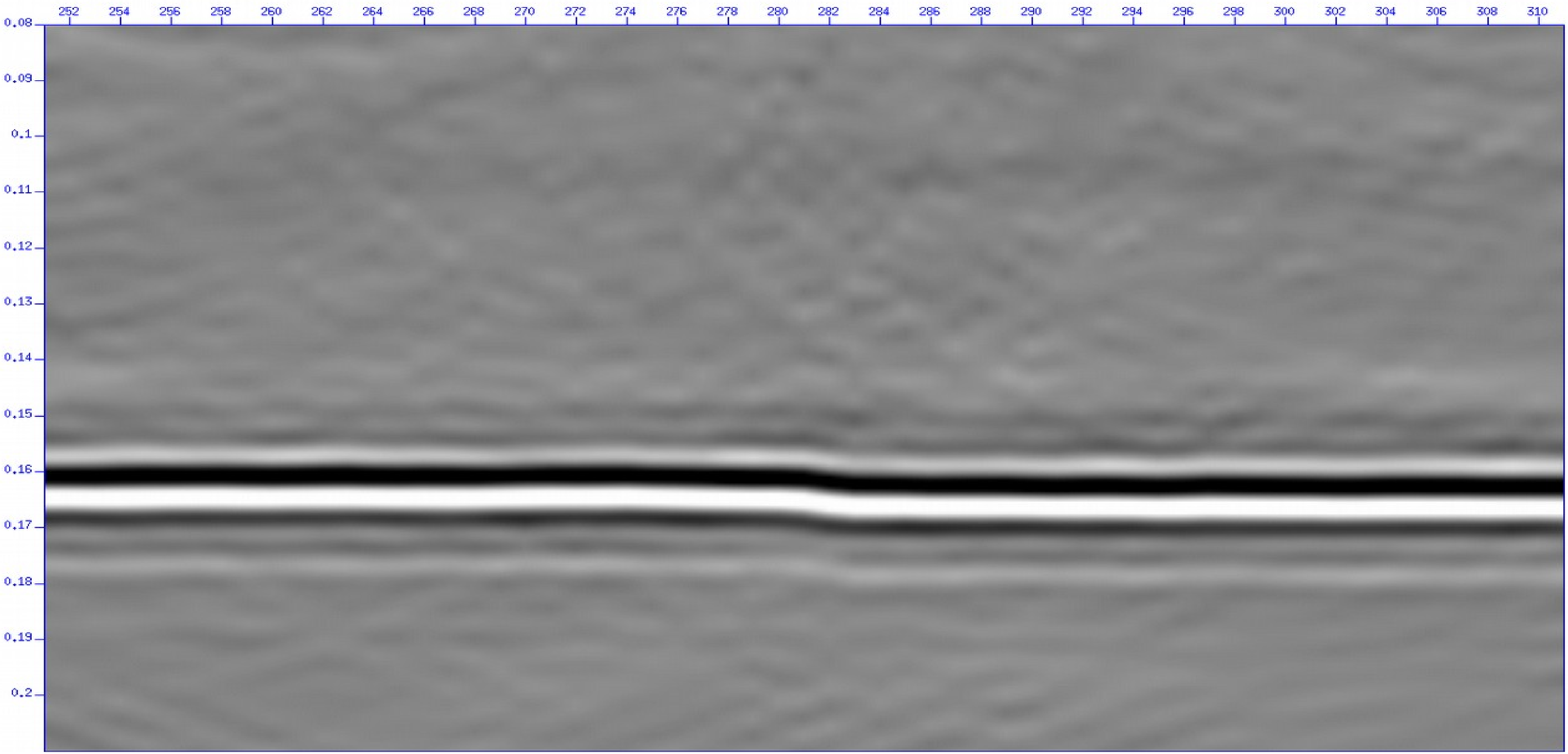
Barren-zone modelling



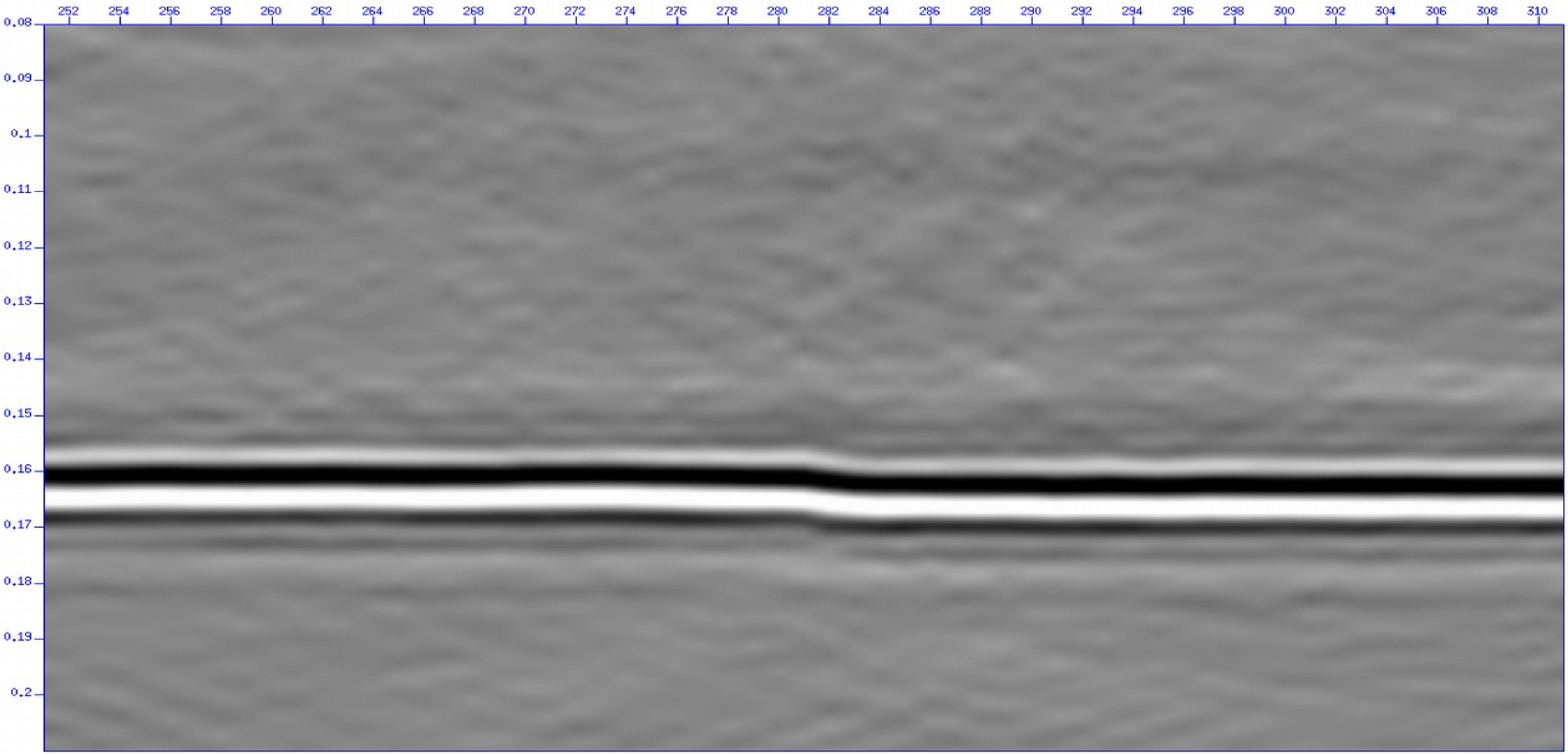
Seismic source modelling



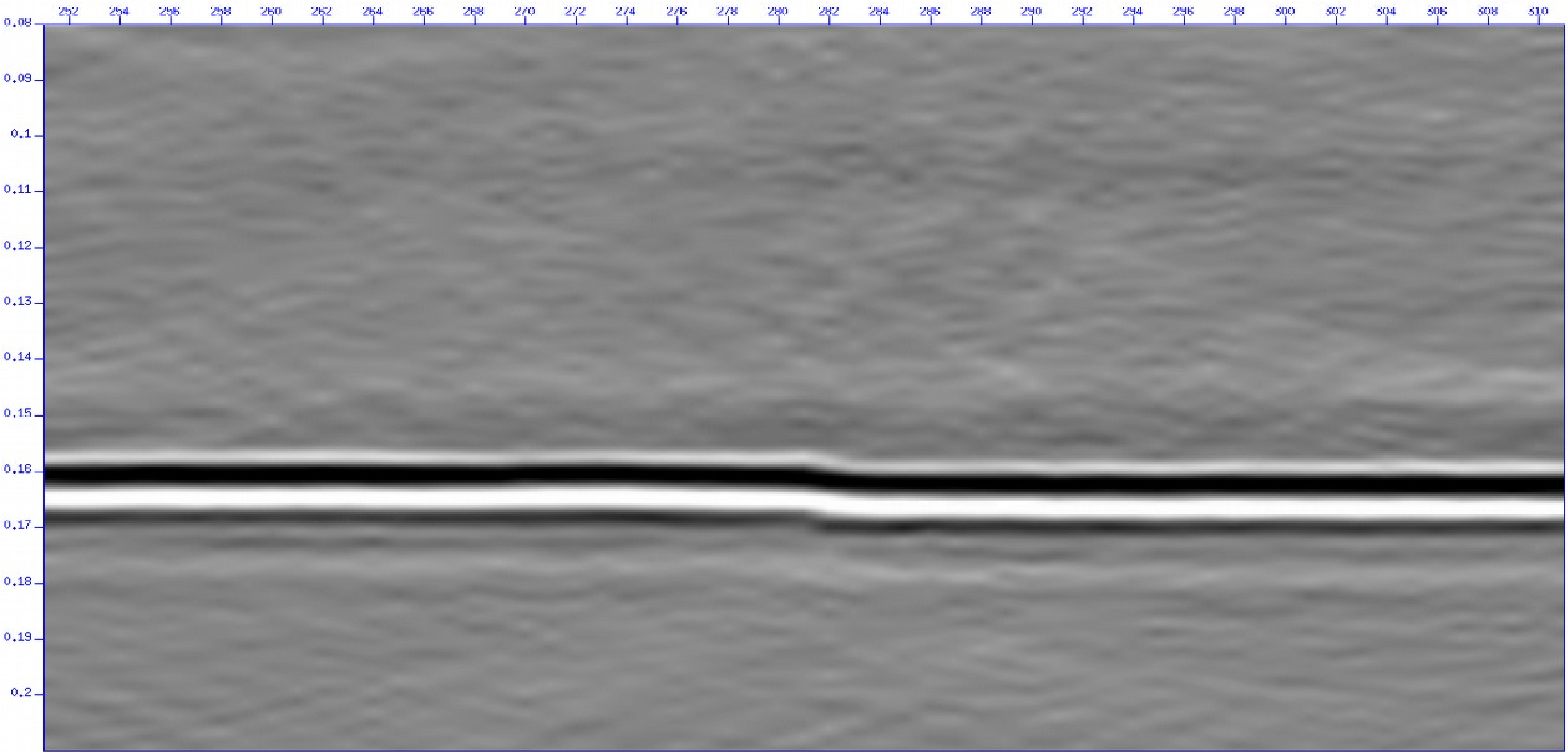
Vibroseis (10-200 Hz)



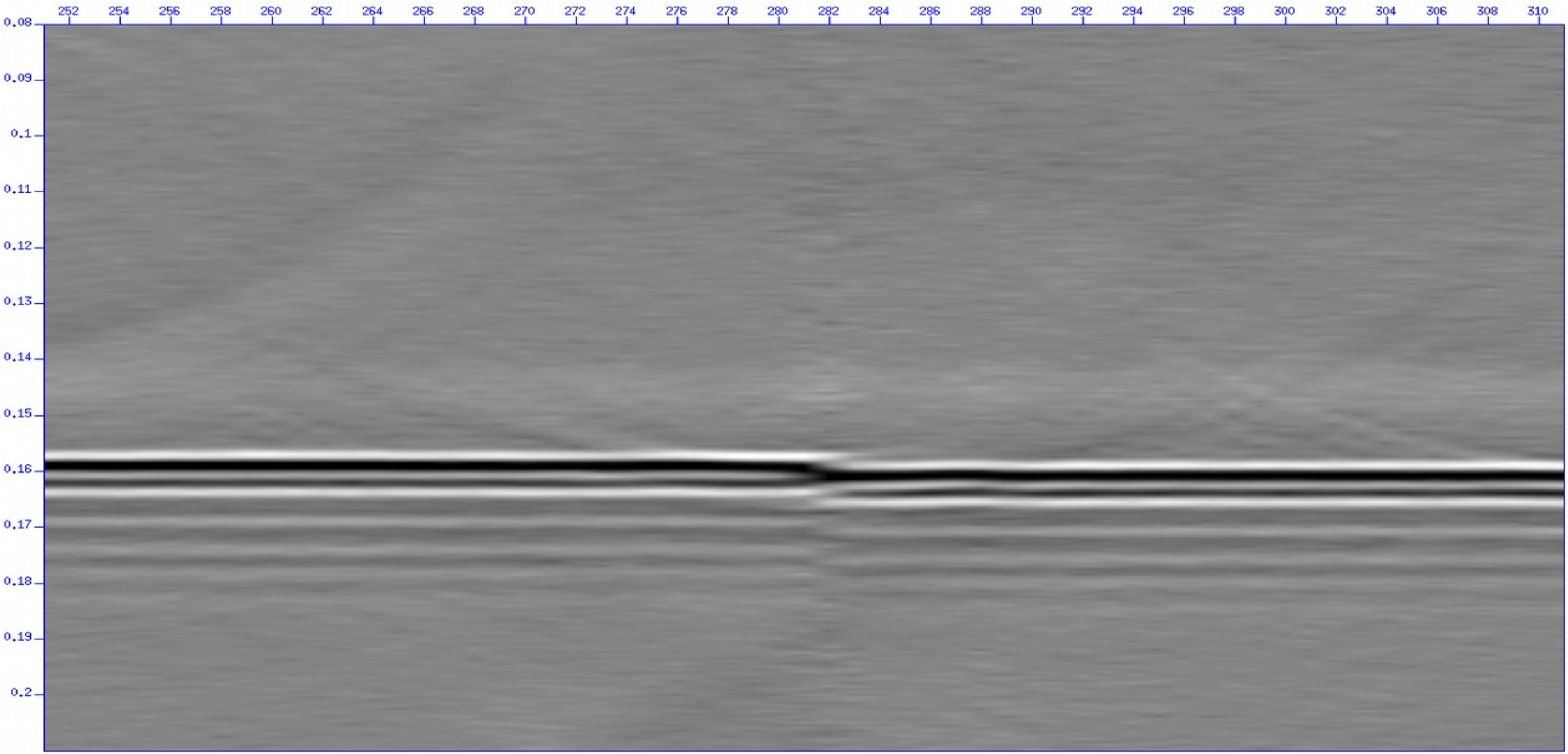
Vibroseis (10-250 Hz)



Vibroseis (10-350 Hz)

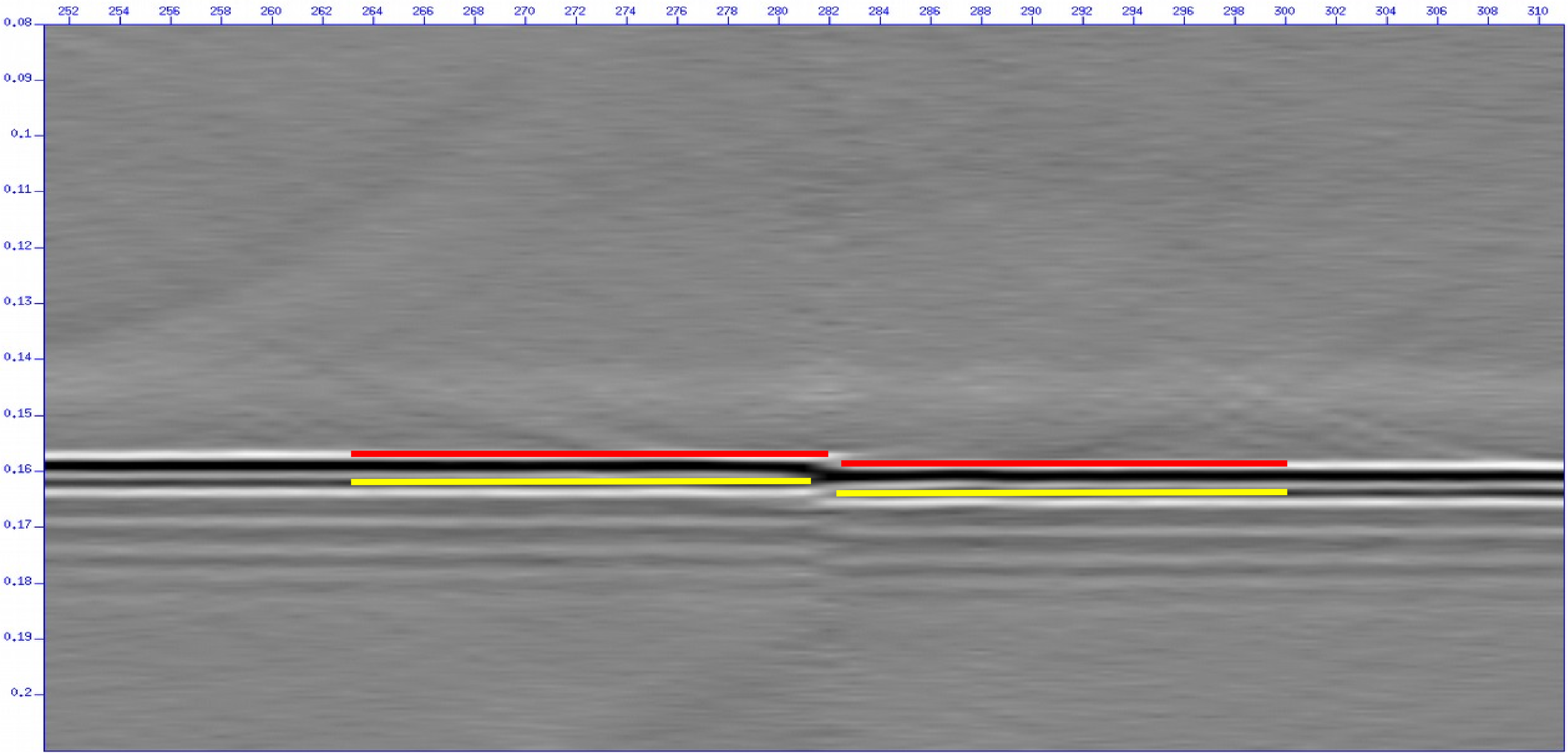


Dynamite



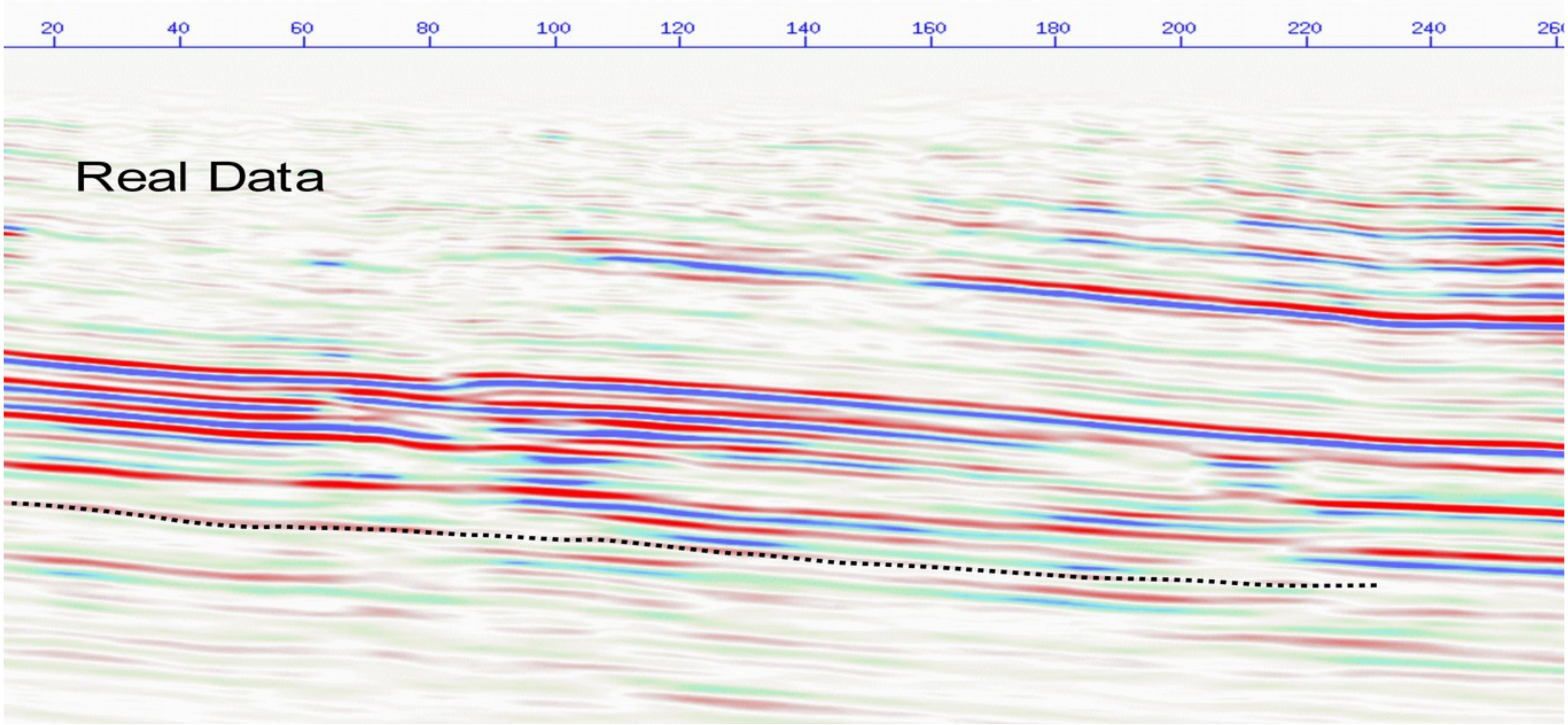
252 254 256 258 260 262 264 266 268 270 272 274 276 278 280 282 284 286 288 290 292 294 296 298 300 302 304 306 308 310
0.08 0.09 0.1 0.11 0.12 0.13 0.14 0.15 0.16 0.17 0.18 0.19 0.2

Dynamite

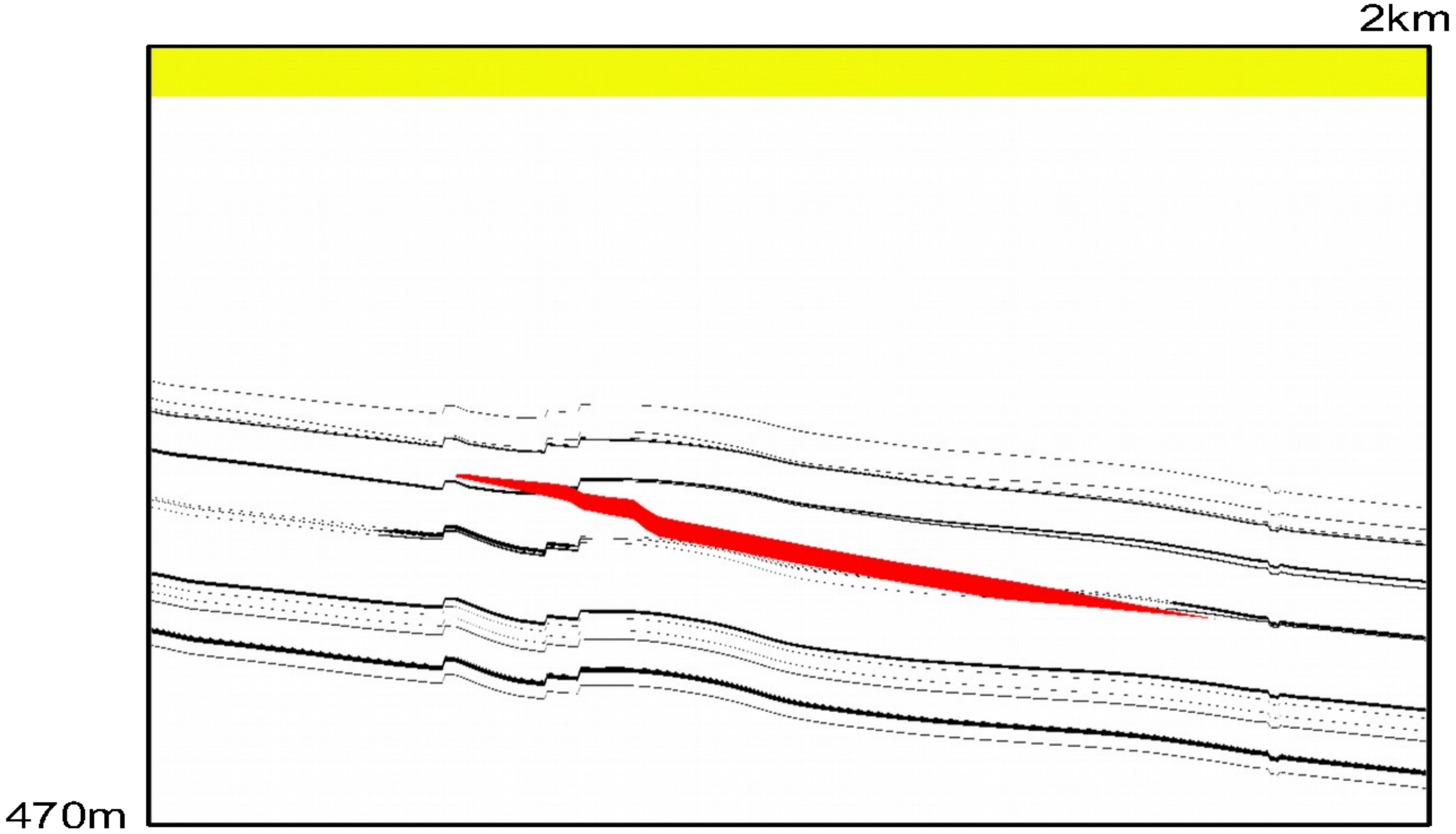


252
254
256
258
260
262
264
266
268
270
272
274
276
278
280
282
284
286
288
290
292
294
296
298
300
302
304
306
308
310
0.08
0.09
0.1
0.11
0.12
0.13
0.14
0.15
0.16
0.17
0.18
0.19
0.2

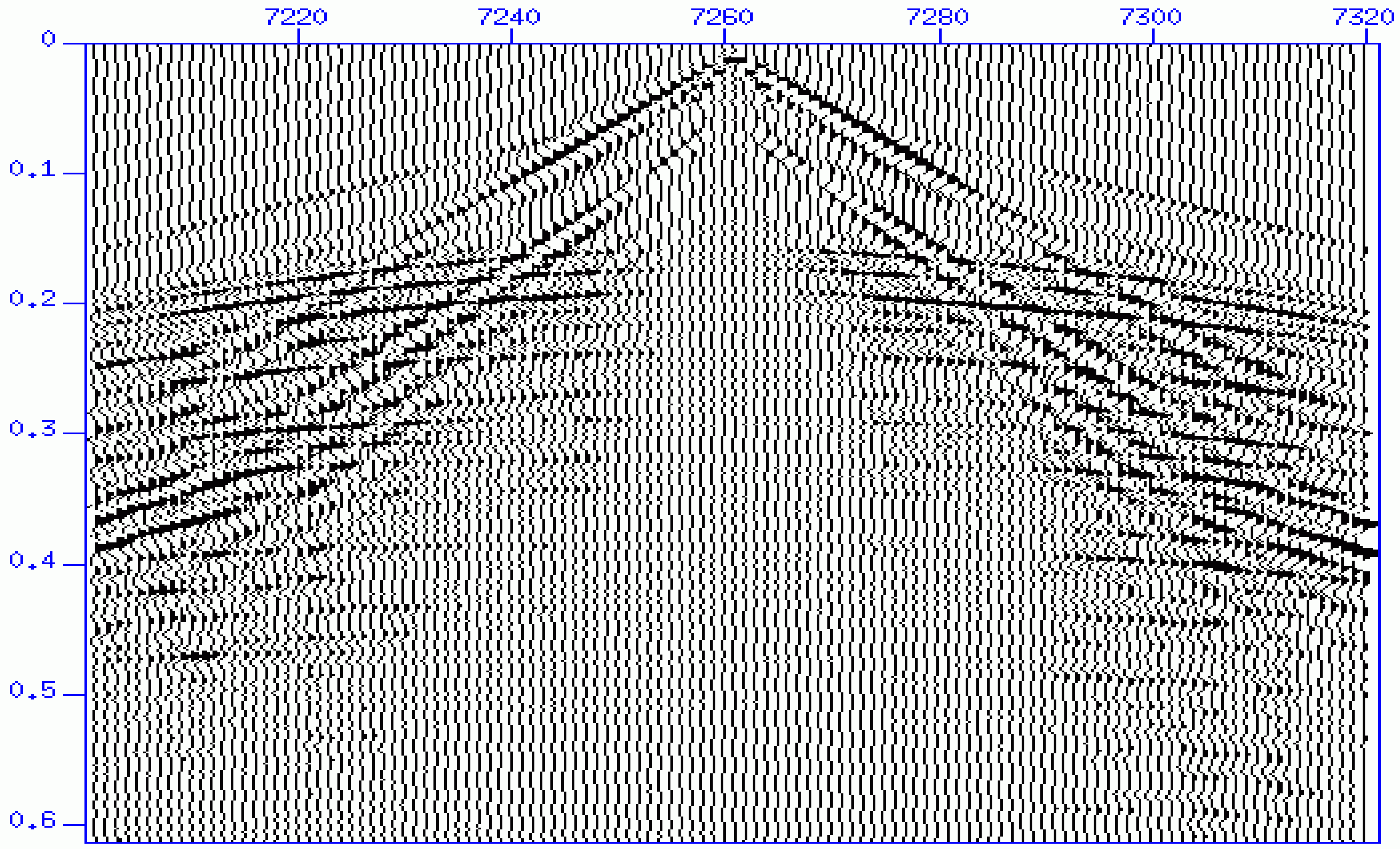
Acquisition modelling as an interpretational aid



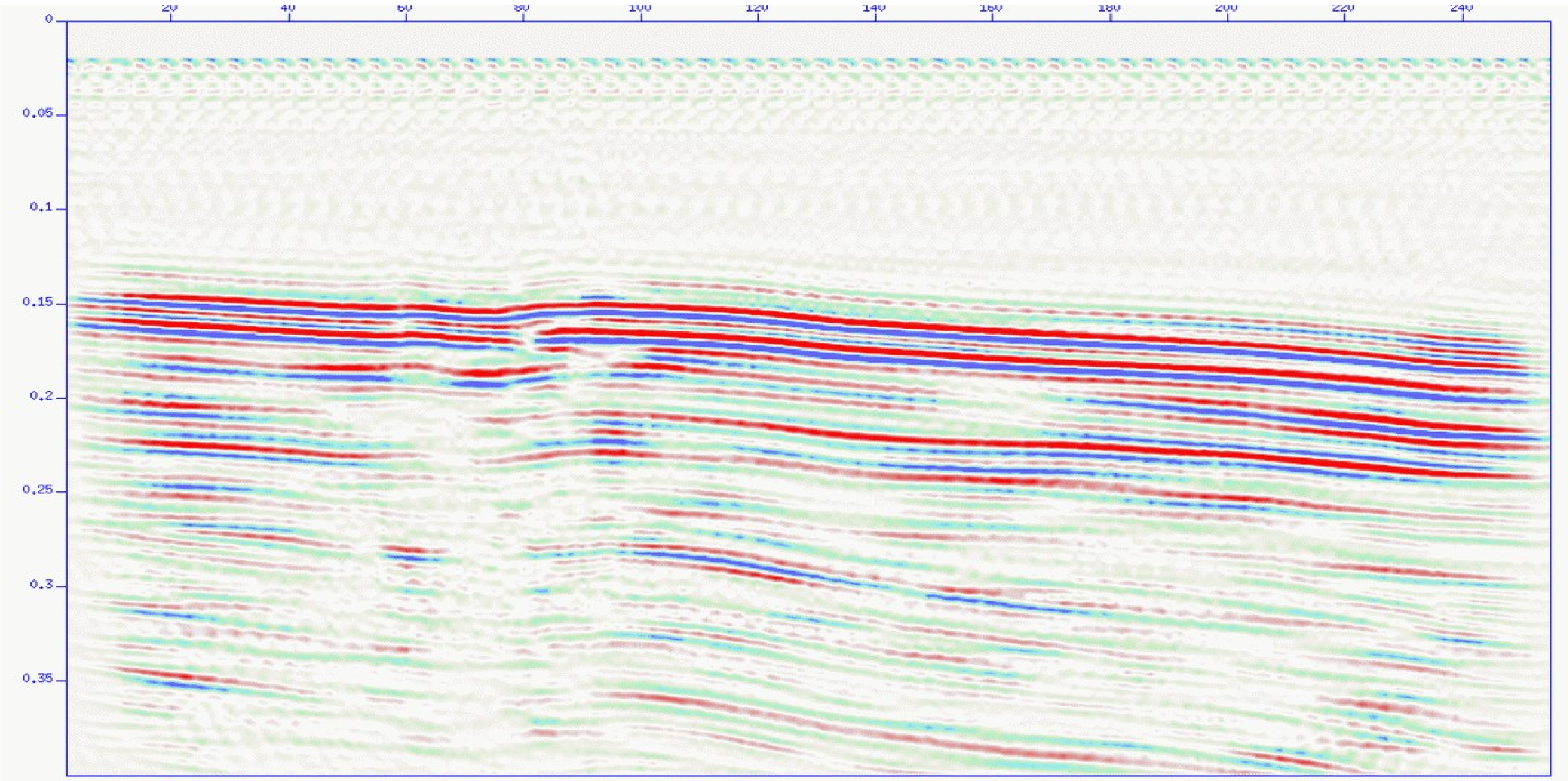
Model 1 – Geological model

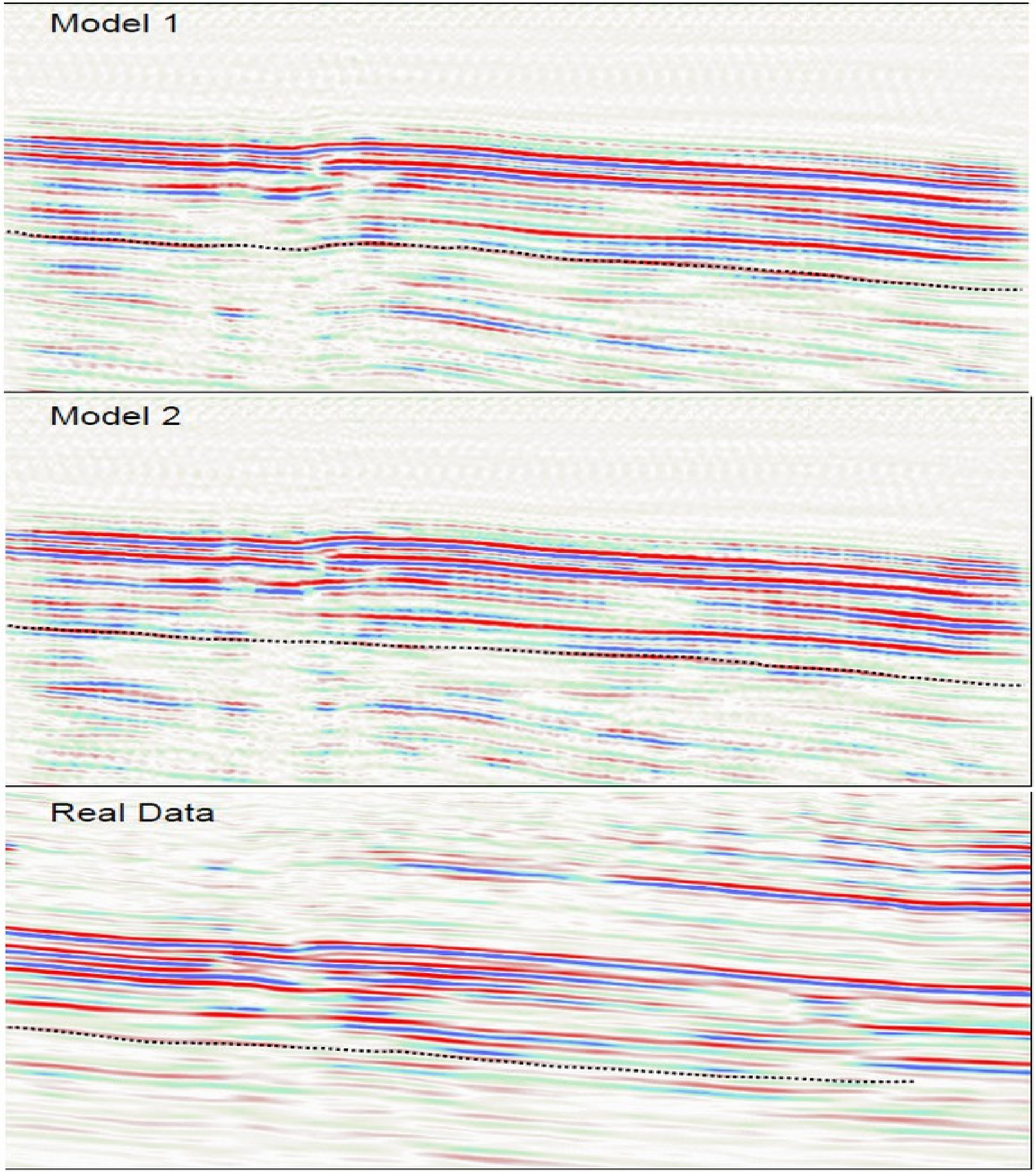


Model 1 – Finite Difference Record



Model 1 – Processed Section




Model 1
Model 2
Real Data

Thursday 11am

Seismic Geophysics B

Shaun Strong

Applications of finite-difference modelling to coal-scale seismic exploration

Acquisition Modelling

Helps understanding of factors affecting seismic resolution

Valuable tool for survey planning and image interpretation

New developments in coal seismology

Acquisition modelling of seismic resolution

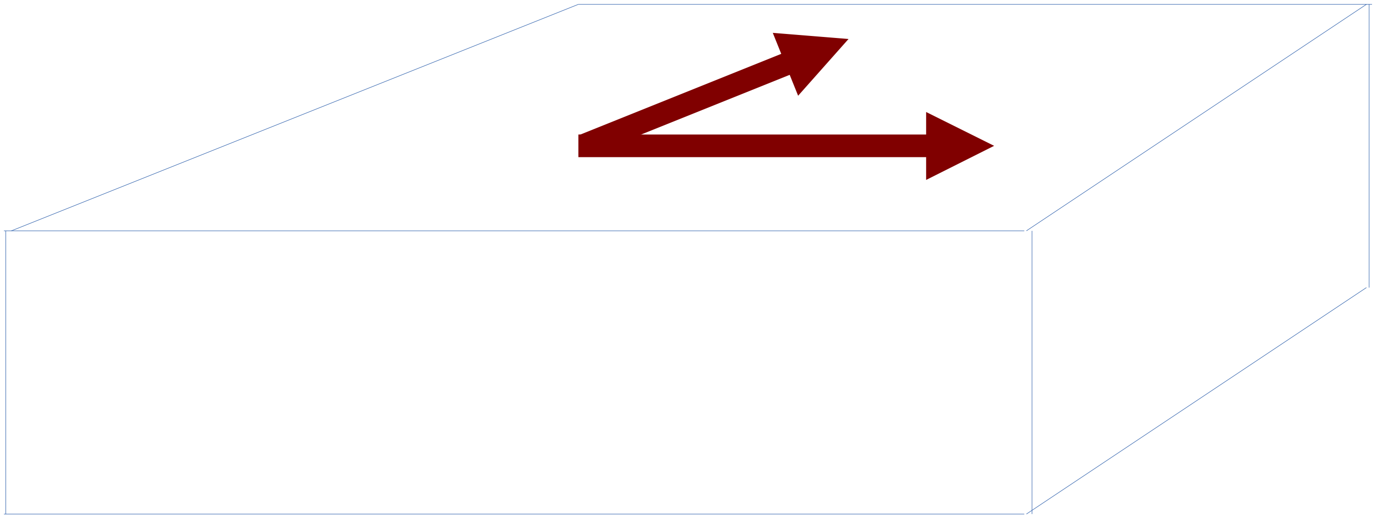
Seismic anisotropy and stress prediction

Exploitation of seismic noise

Velseis
Integrated Seismic Technologies

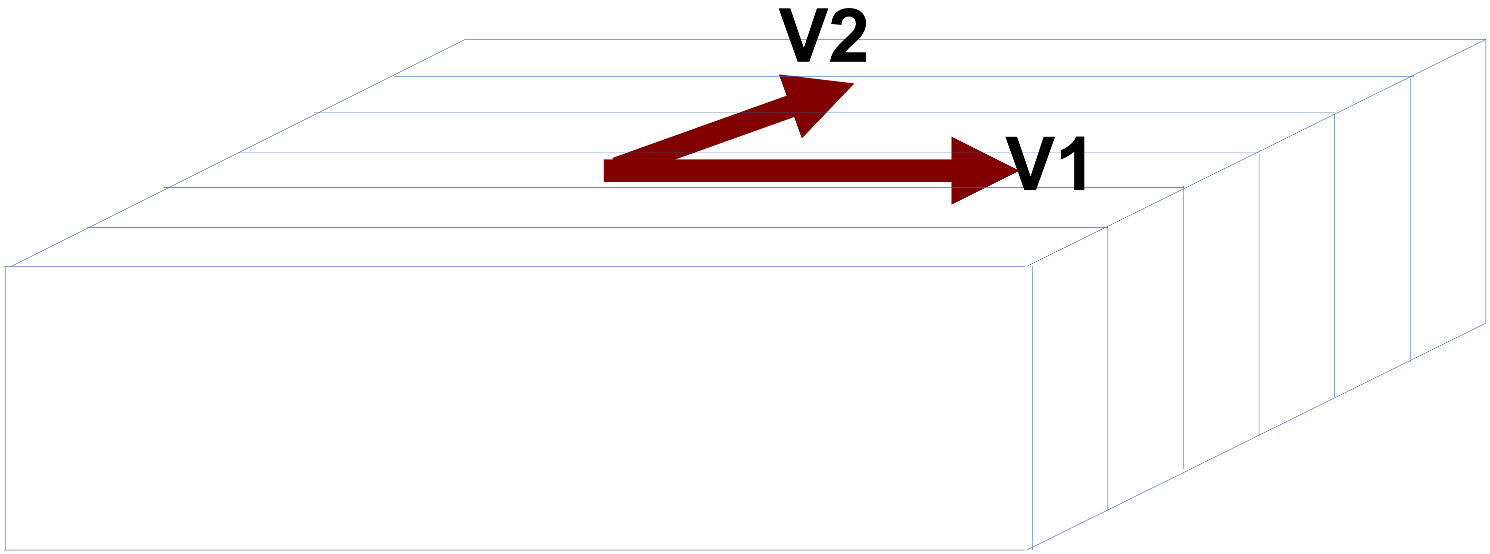
UQ
EXPLORATION GEOPHYSICS

Azimuthal Anisotropy (HTI)



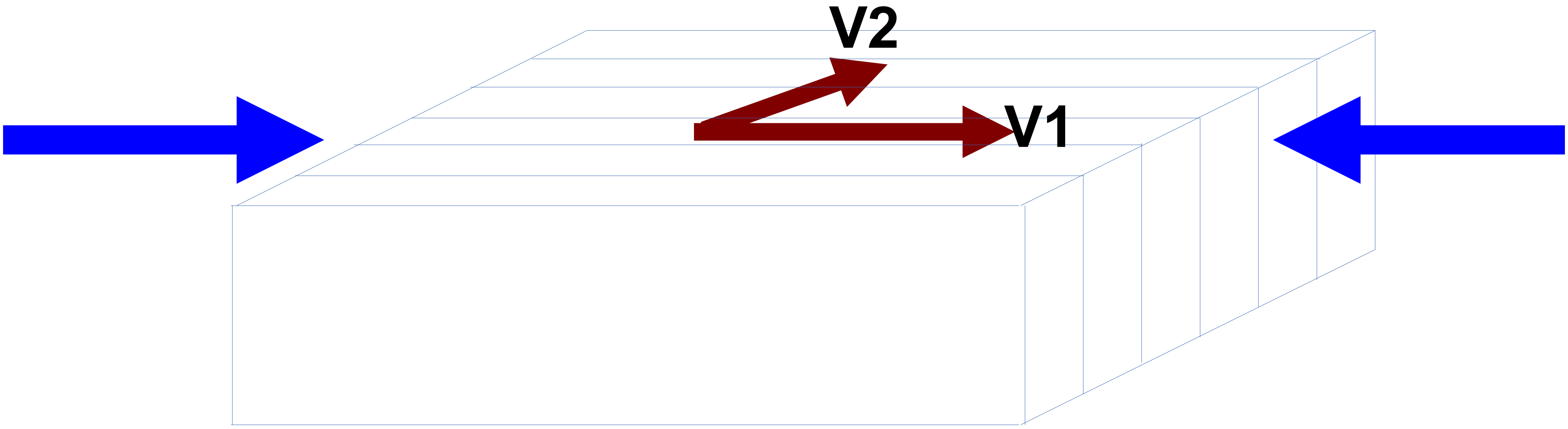
V1 ≠ V2

Azimuthal Anisotropy (HTI)



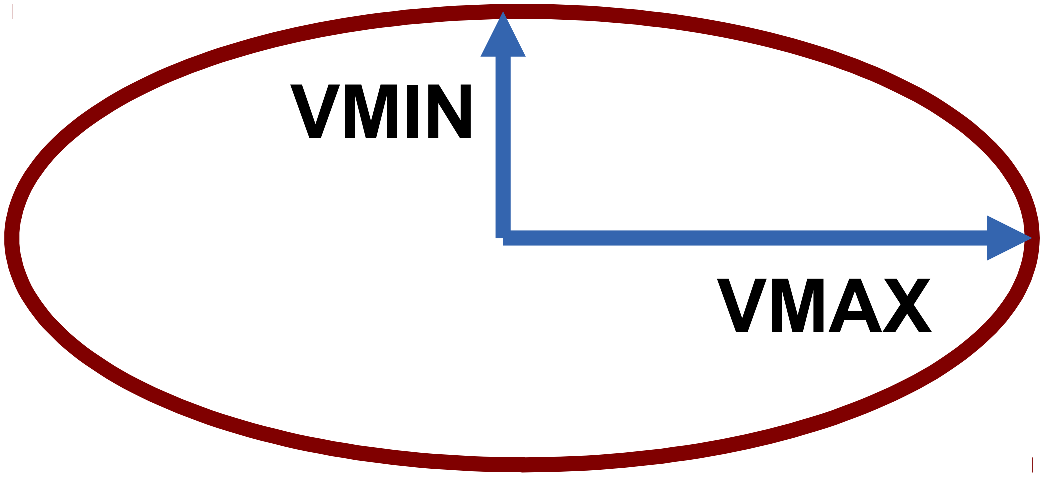
V1 > V2

Maximum horizontal stress



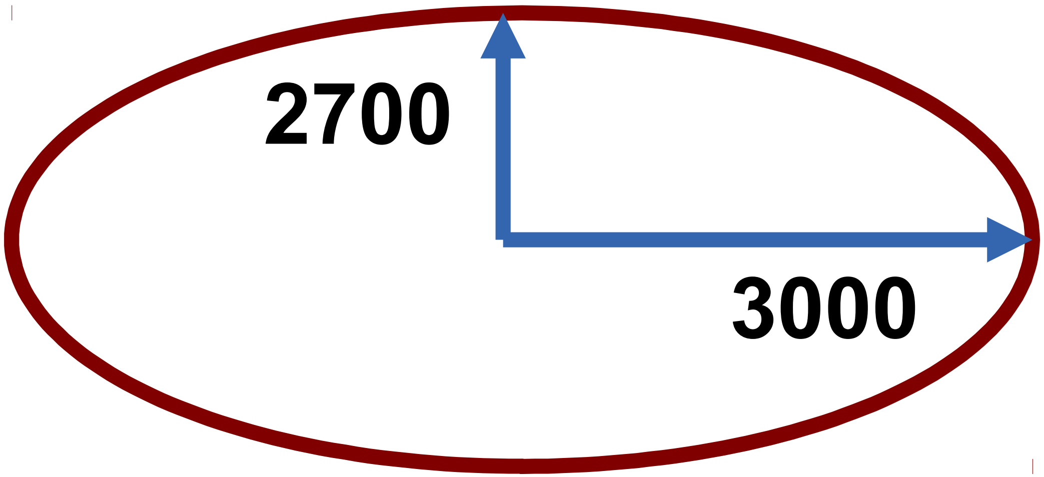
V1 > V2

Azimuthal velocity variation



Flatness = 1 - VMIN / VMAX

Azimuthal velocity example



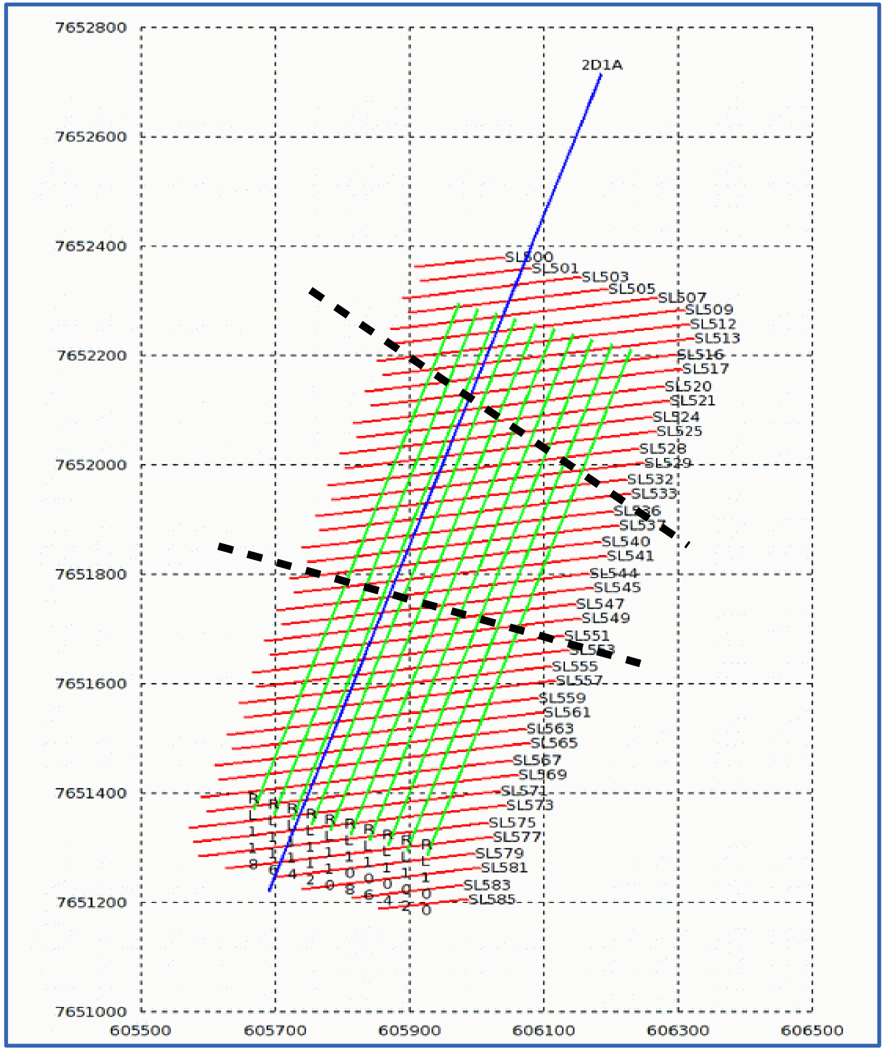
Flatness = 1 - 2700 / 3000
= 0.1

10% Azimuthal anisotropy

ACARP Project C17029

- Acquire a 3D Multi-Component Data Set with the aim of imaging a shallow (~100m) coal target
- Assess the complexities of processing the converted-wave (PS) volume
- Assess degree of image variation due to ray-azimuth in the P and PS volumes

ACARP Project C17029

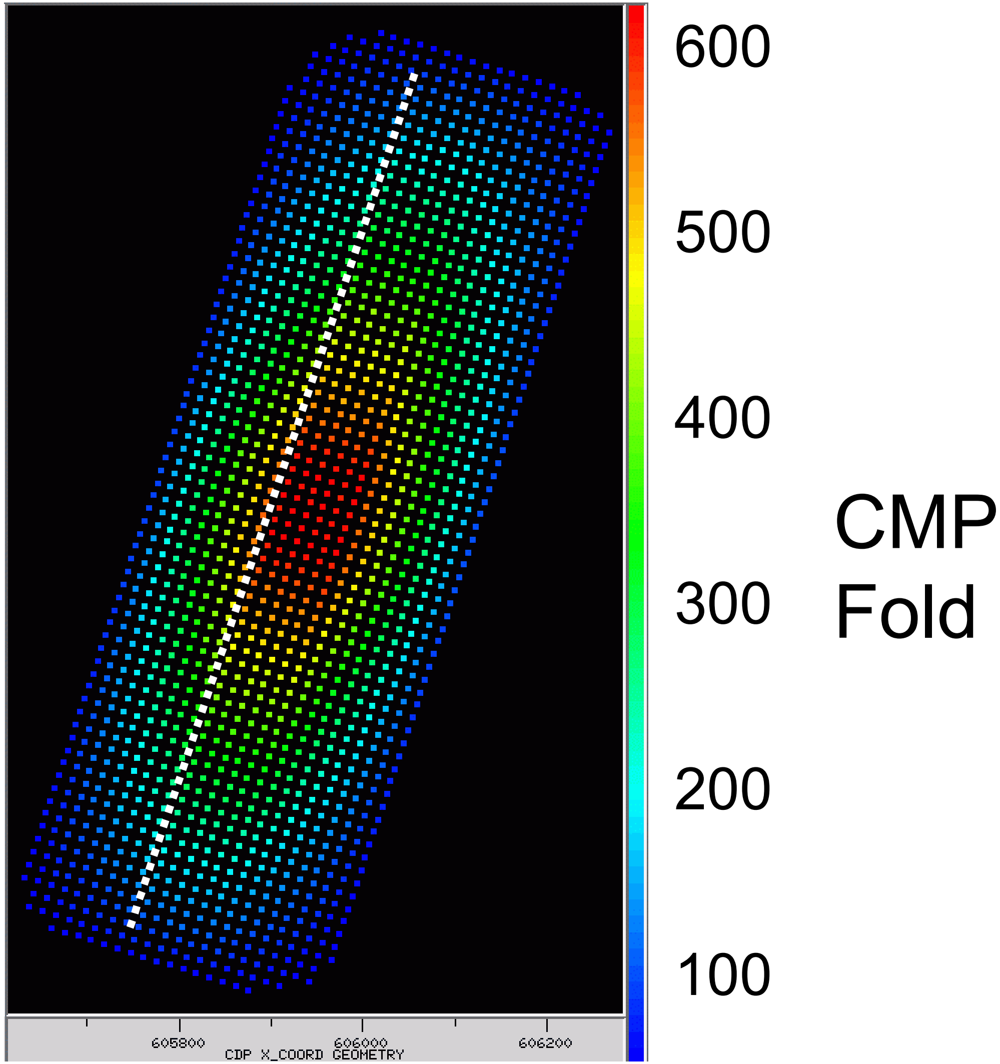


Legend

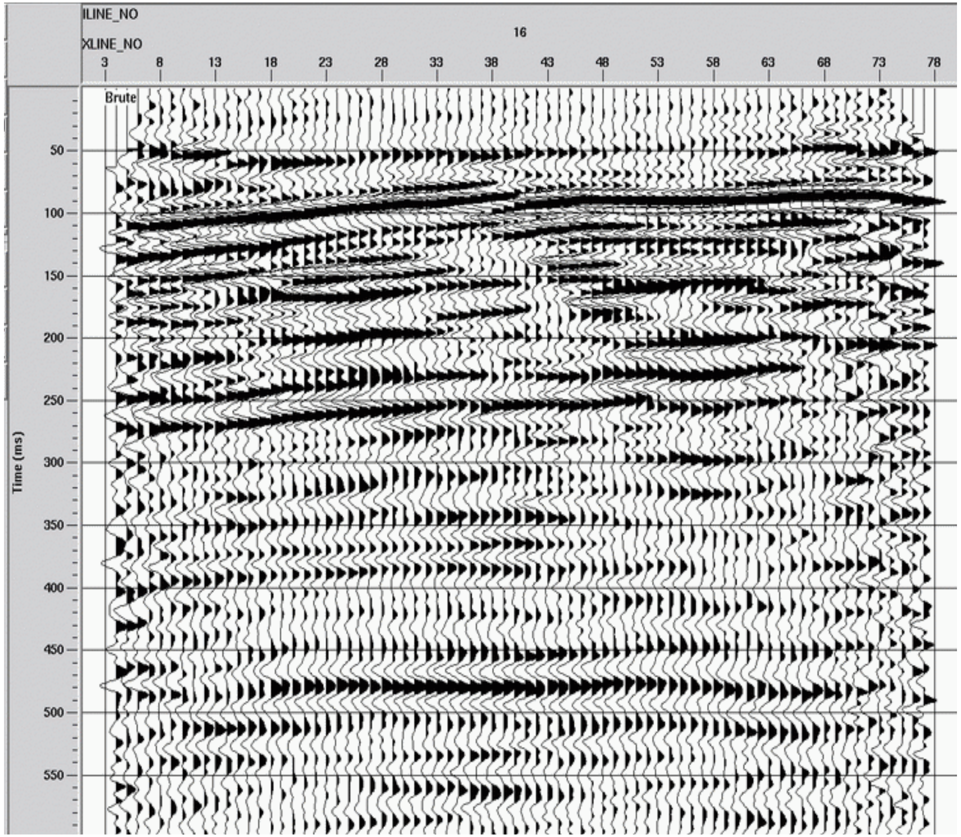
2D P Survey
Source Lines
Receiver Lines
Possible Fault

Target depth:	70-120m
Target Thickness:	5m
Source:	Vibroseis
Line Spacing:	30m
Rec Stn Spacing:	15m
Src Stn Spacing:	30m

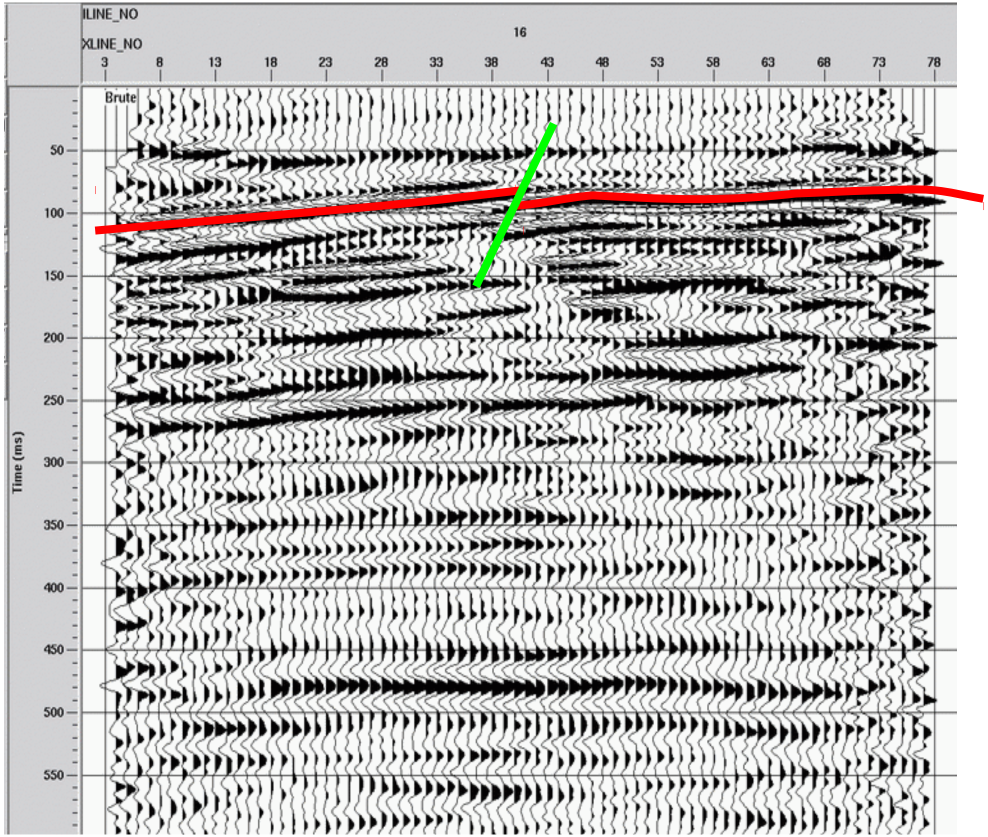
P-Wave Fold Plot



Test Swath – P-Wave Volume

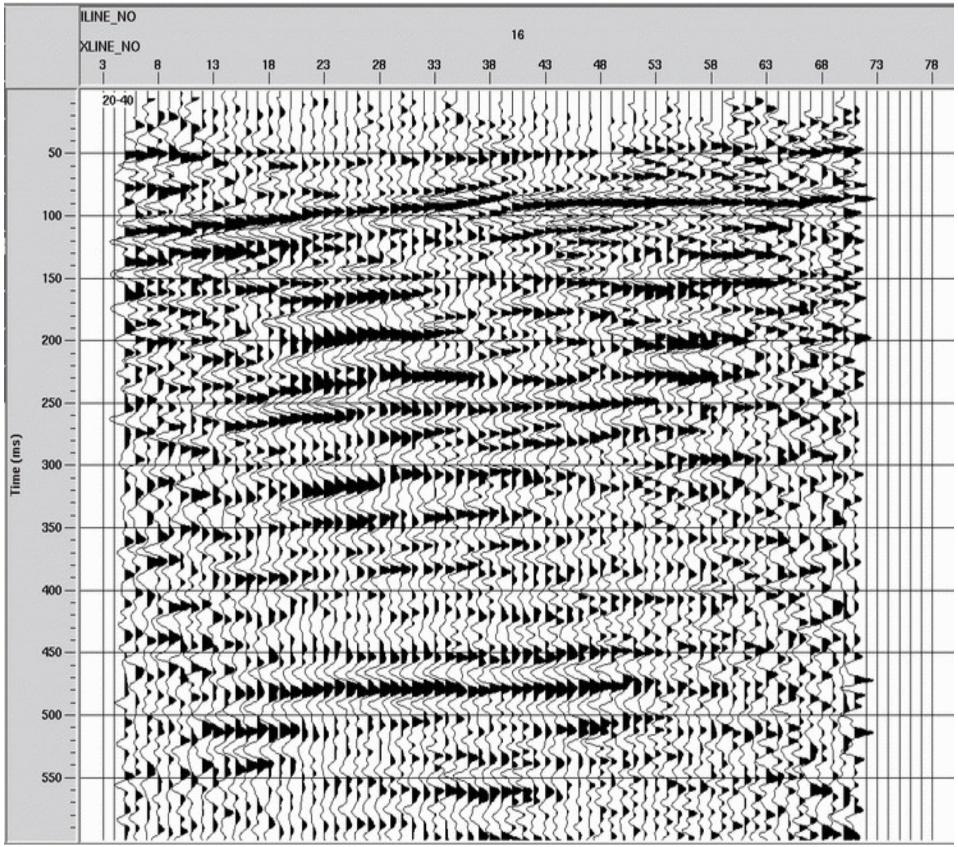


Test Swath – P-Wave Volume

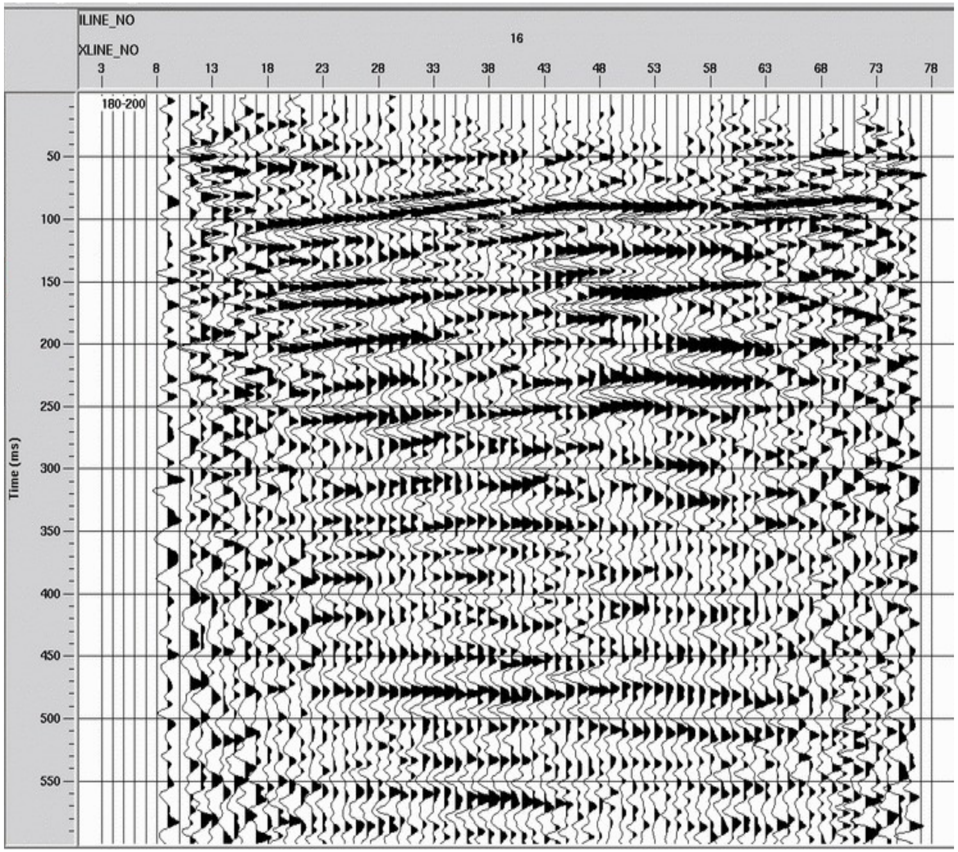


P-Wave Ray-Azimuth Volumes

20-40 Degrees

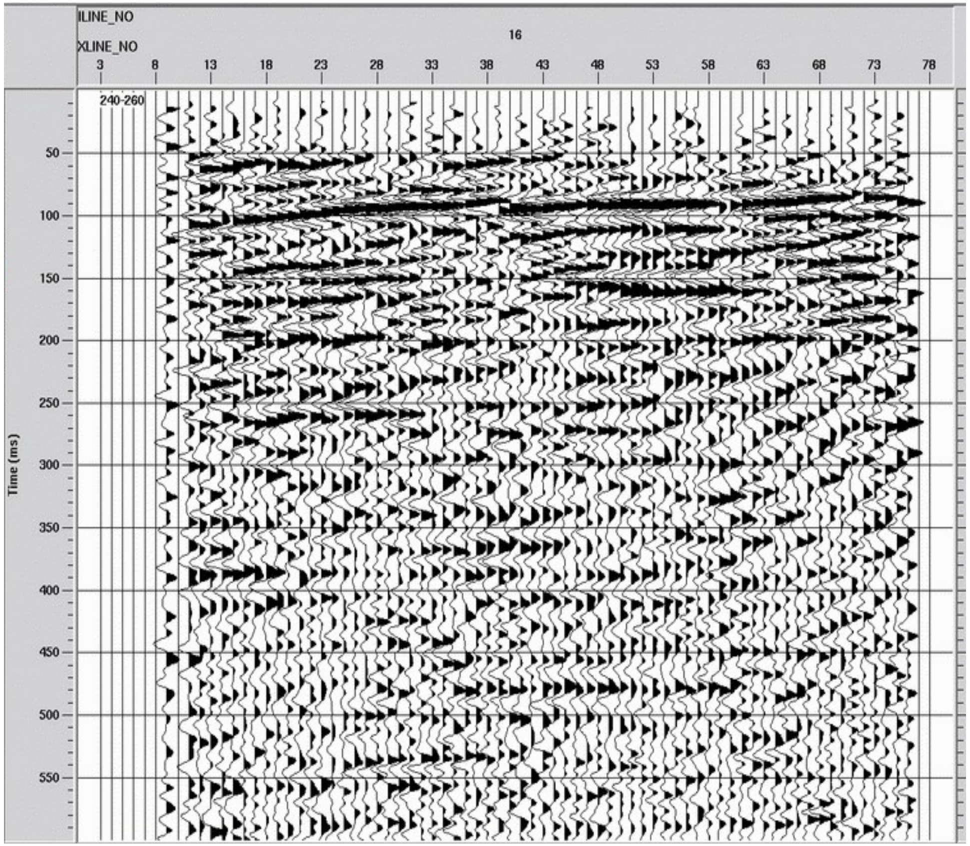


180-200 Degrees

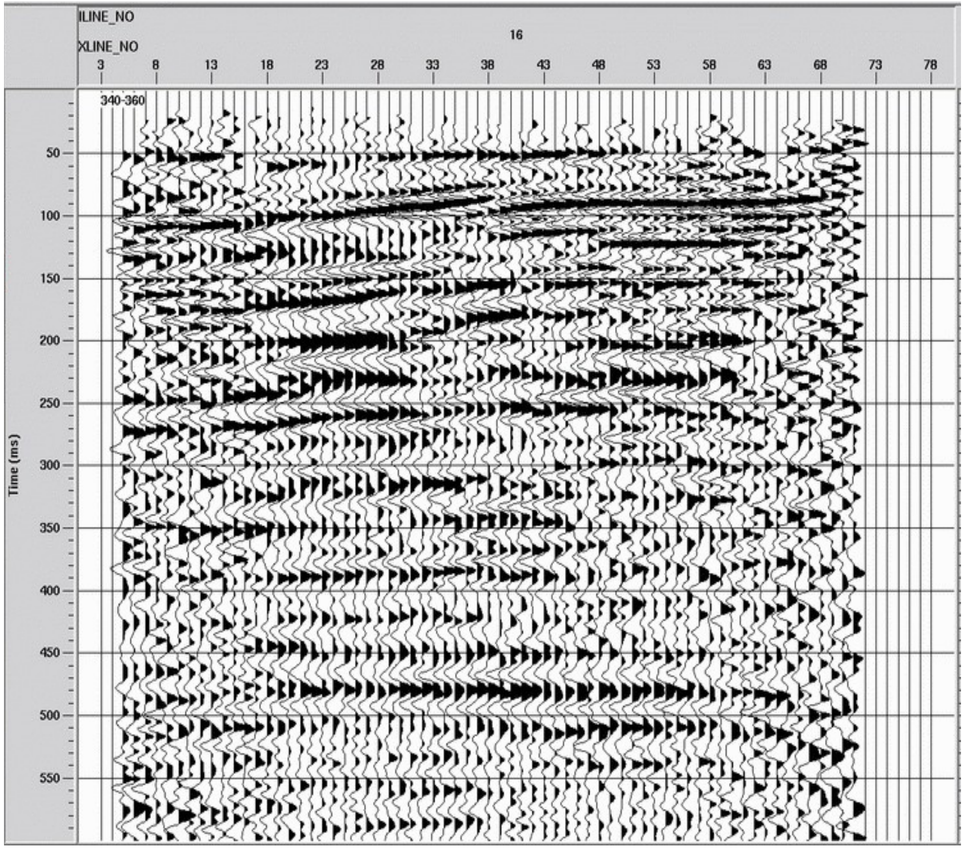


P-Wave Ray-Azimuth Volumes

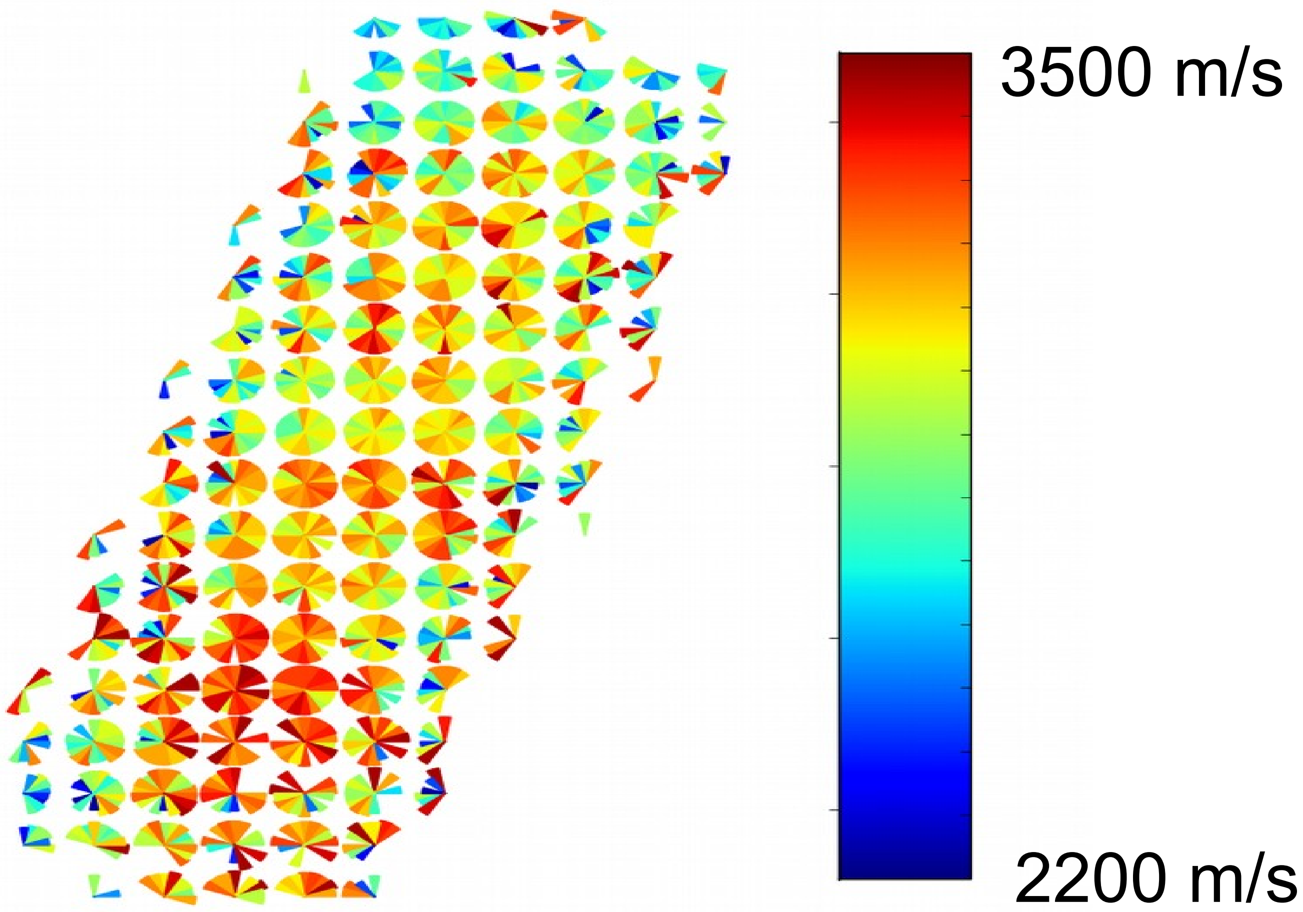
260-280 Degrees



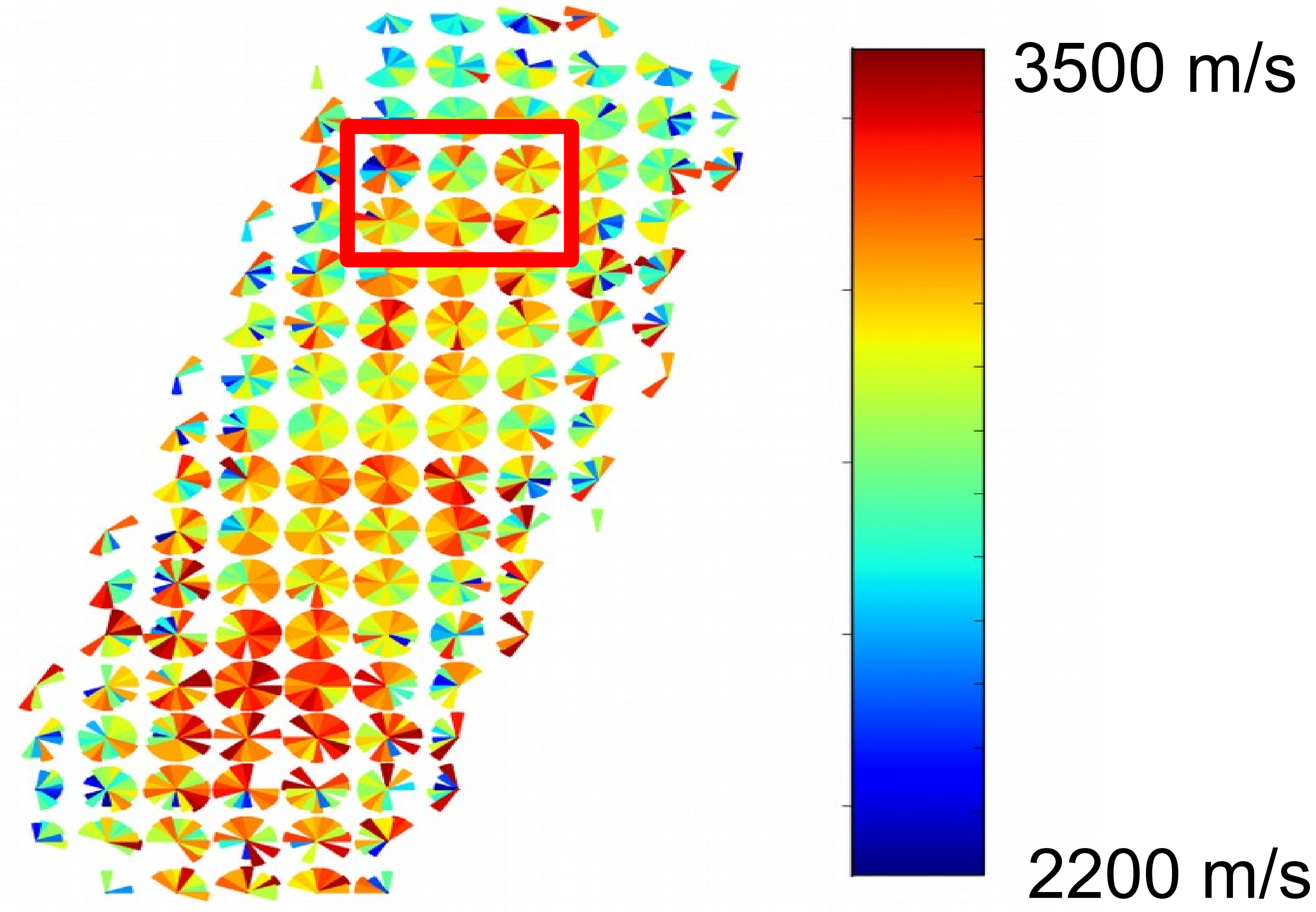
340-360 Degrees



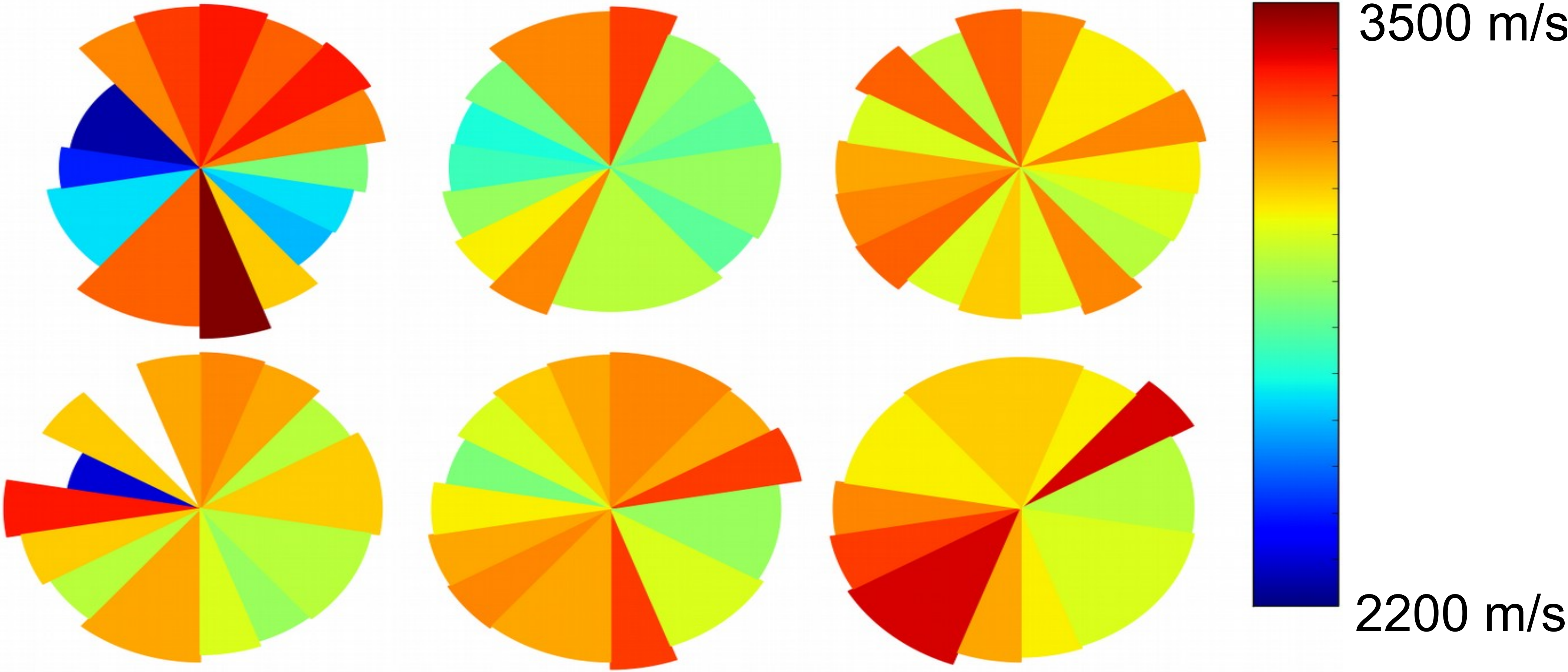
P-Wave azimuthal velocity analysis



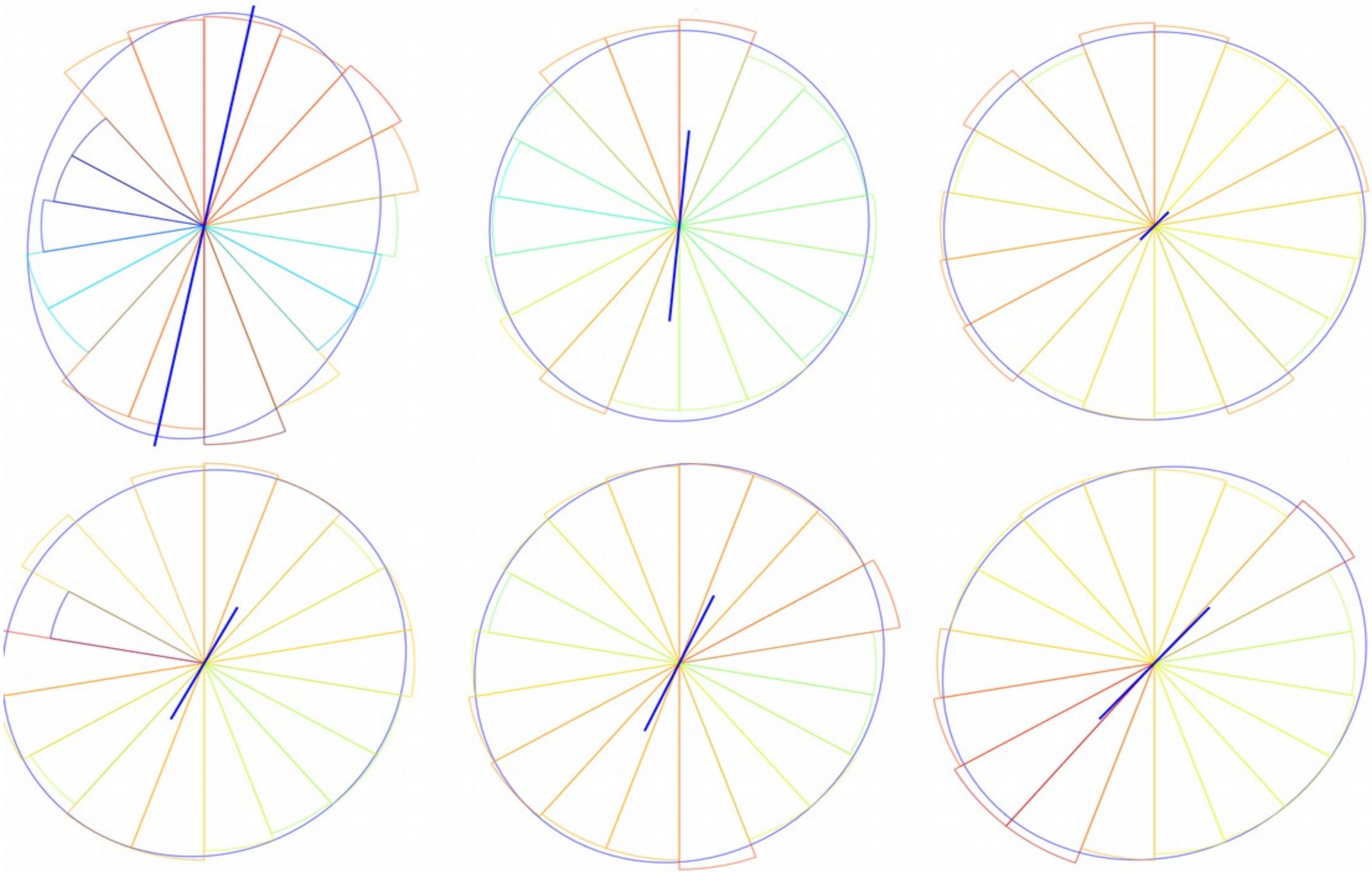
P-wave azimuthal velocity analysis



P-wave azimuthal velocity analysis

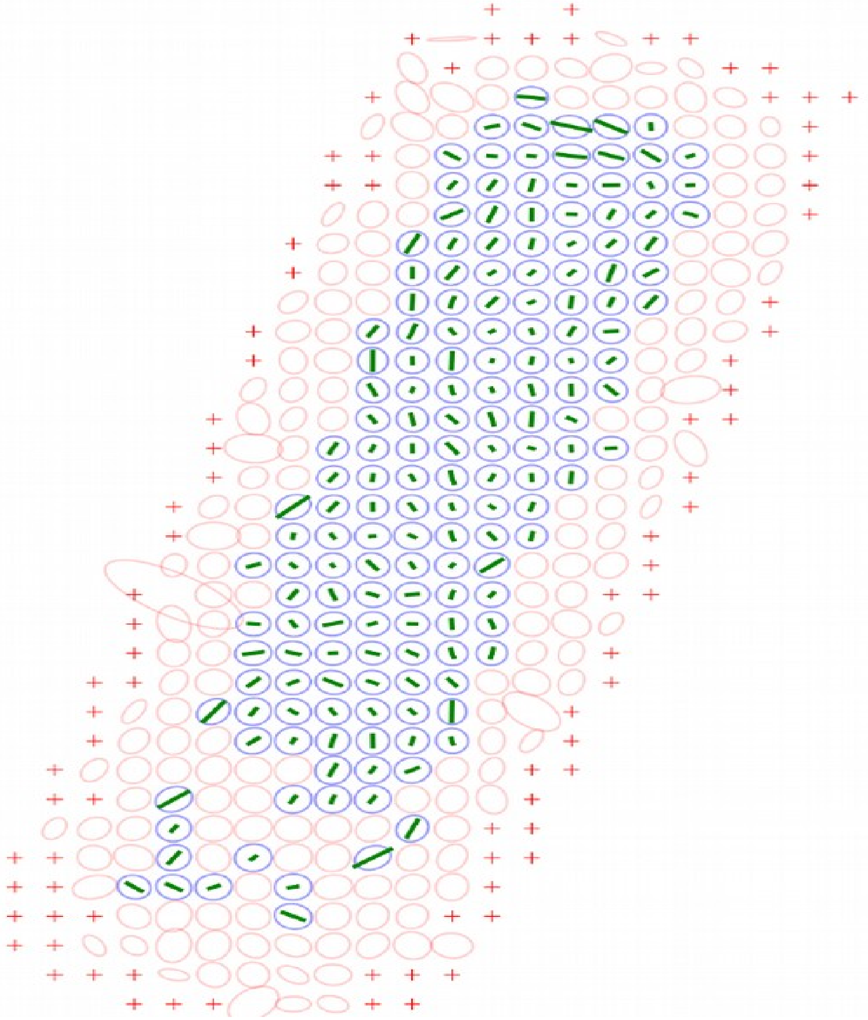


P-wave ellipse fitting



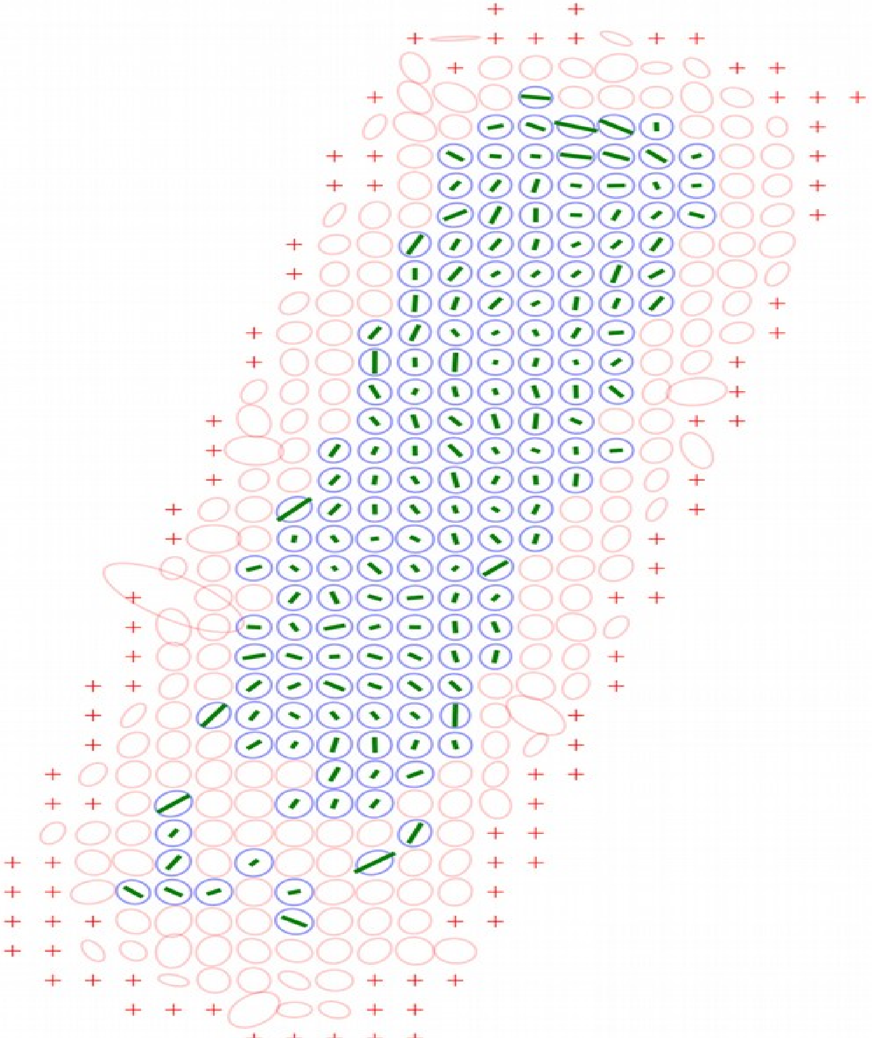
P-wave velocity ellipses

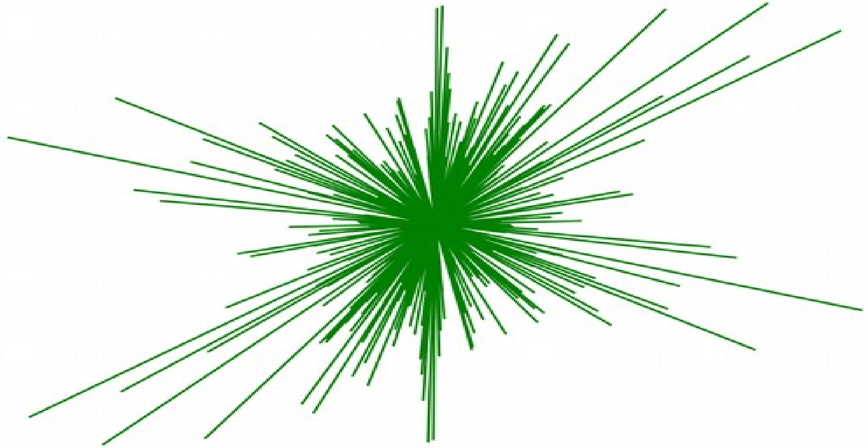
30m bins



P-wave velocity ellipses

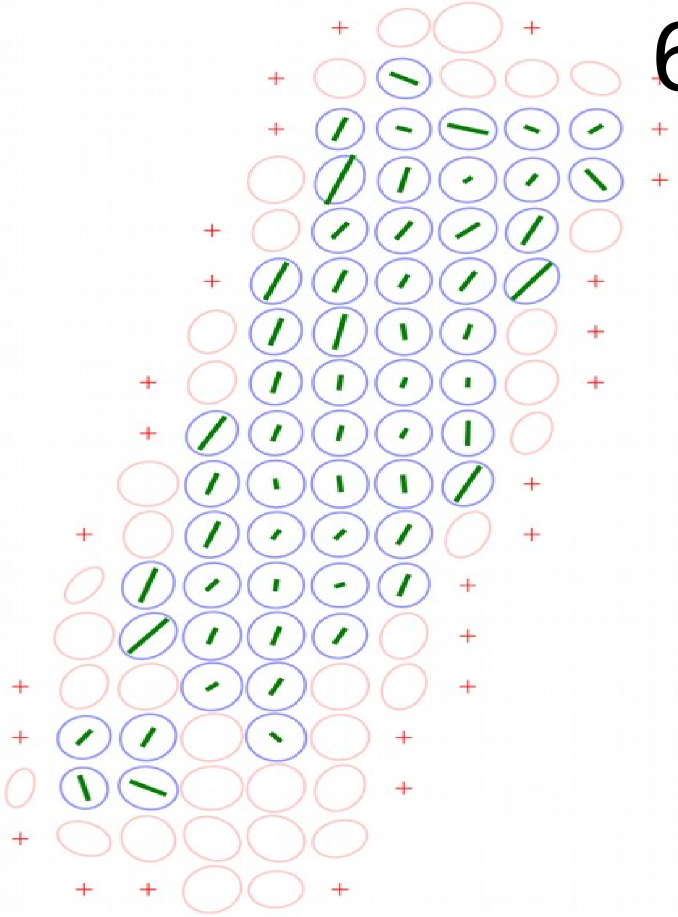
30m bins

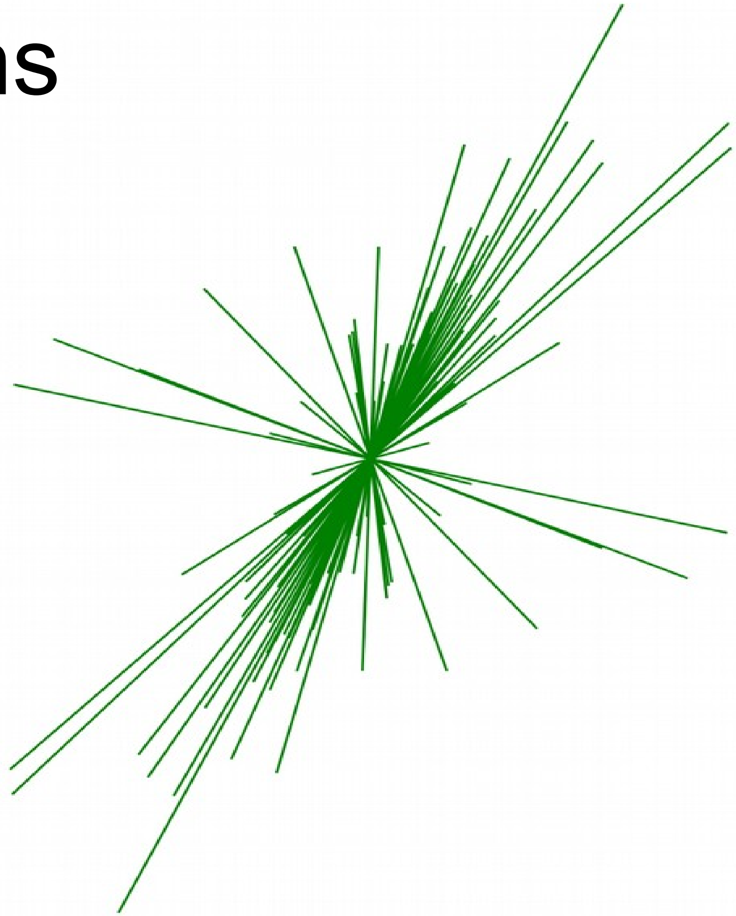




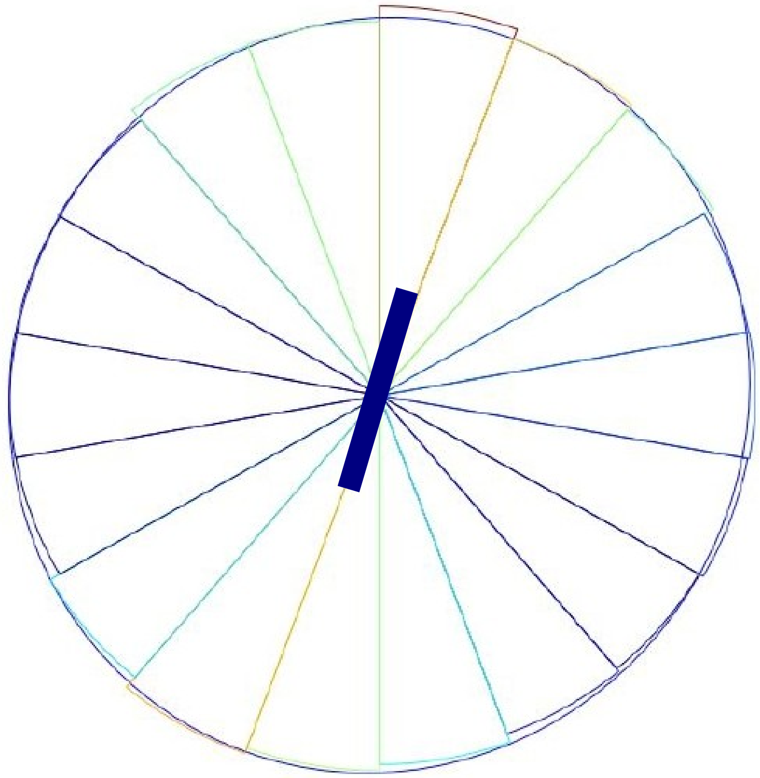
P-wave velocity ellipses

60m bins





Global P-wave velocity ellipse

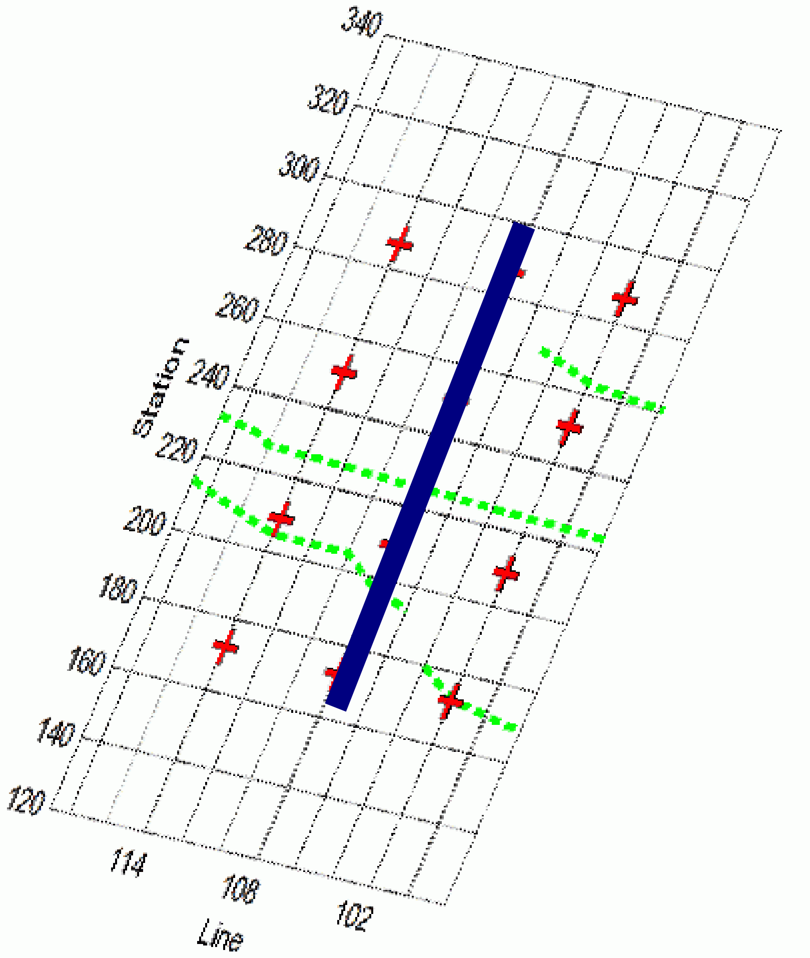


$f = 0.06$

$\phi = 17\ ^o$

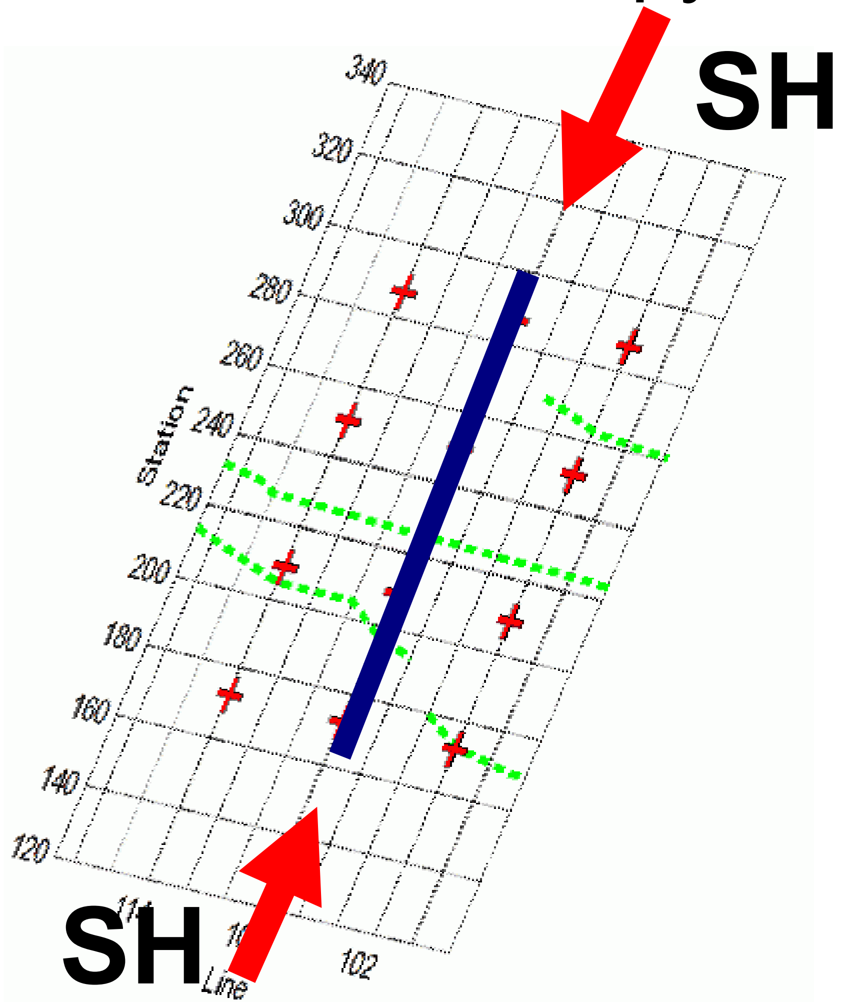
Average P-wave azimuthal anisotropy

Magnitude = 6 %
Fast Azimuth = 17 º

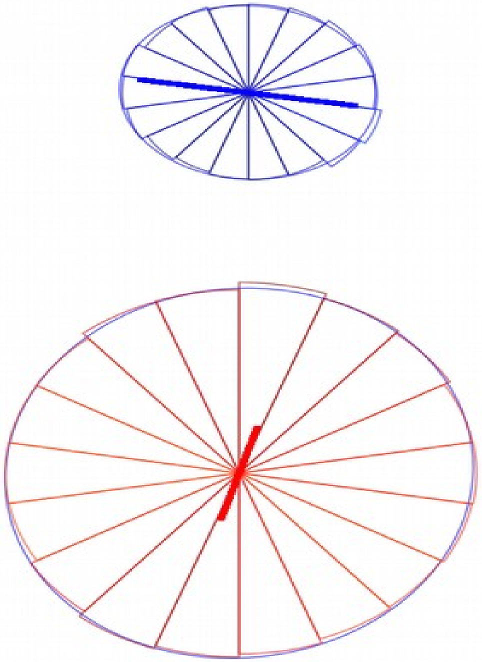


Average P-wave azimuthal anisotropy

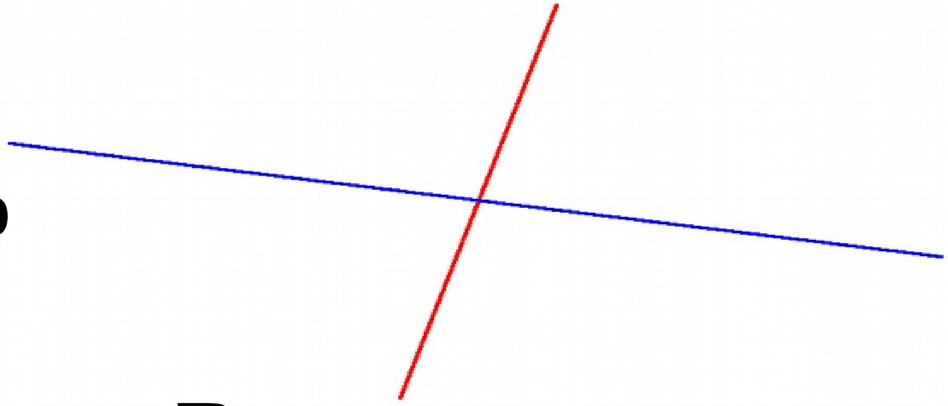
Magnitude = 6 %
Fast Azimuth = 17 º



Comparison of P and S azimuthal analyses



S:
10.5 %
99 º



P:
6 %
17 º

ACARP Trial: Conclusions

P-wave azimuthal anisotropy

- Averaged anisotropy 6%
- VMAX perpendicular to thrust fault
- Consistent with maximum stress direction

ACARP Trial: Conclusions

S-wave azimuthal anisotropy

- Averaged anisotropy 10.5%
- Greater variability in orientation
- Average VMAX-S perpendicular to VMAX-P

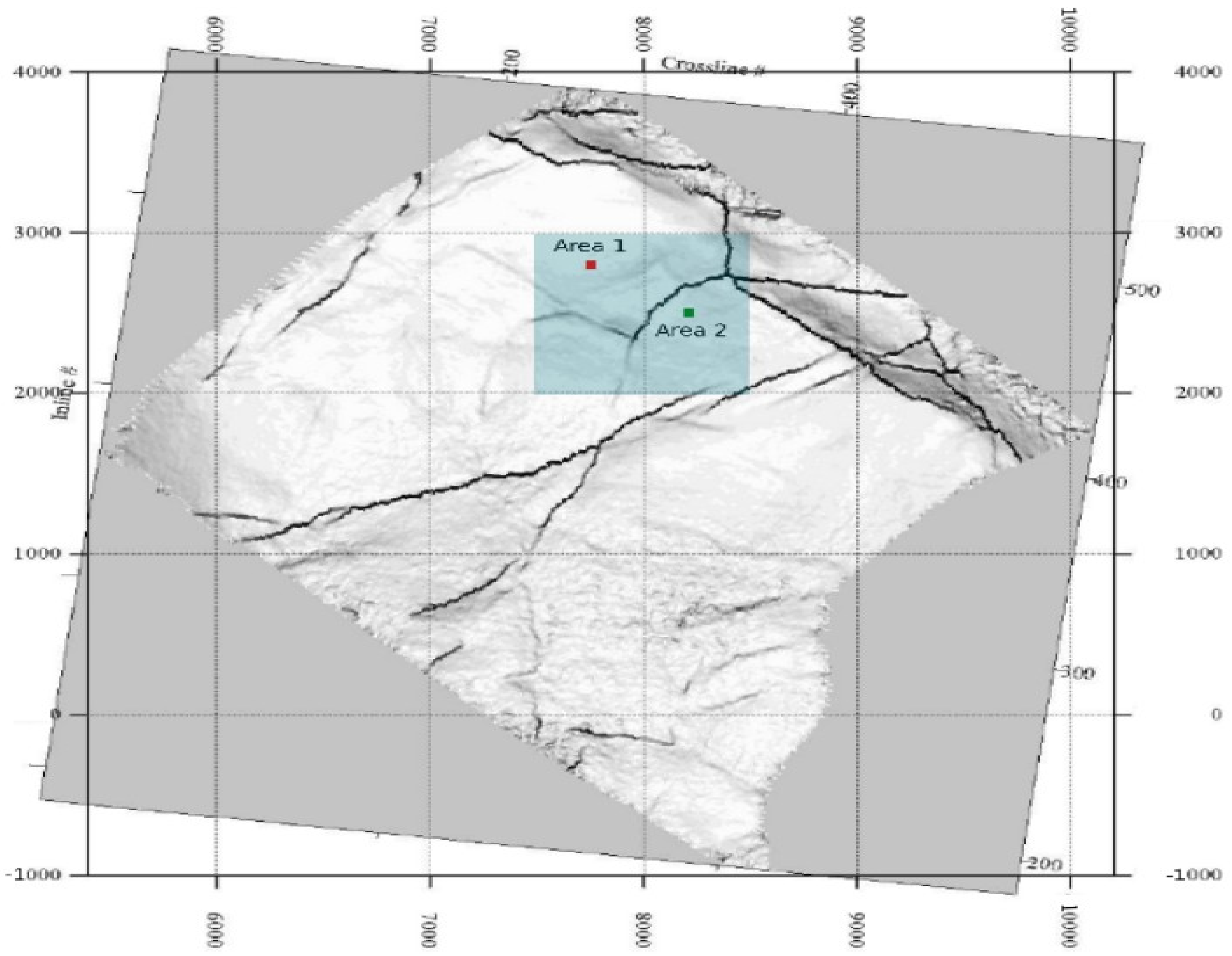
ACARP Trial: Conclusions

- Evidence that P and S anisotropy respond to different elements of the geological fabric.
- P-wave responding to maximum stress / micro-fractures
- S-wave responding to features perpendicular to maximum stress (shale foliation, jointing ...)

Production 3D
Mini-SOSIE

Central Bowen
Basin

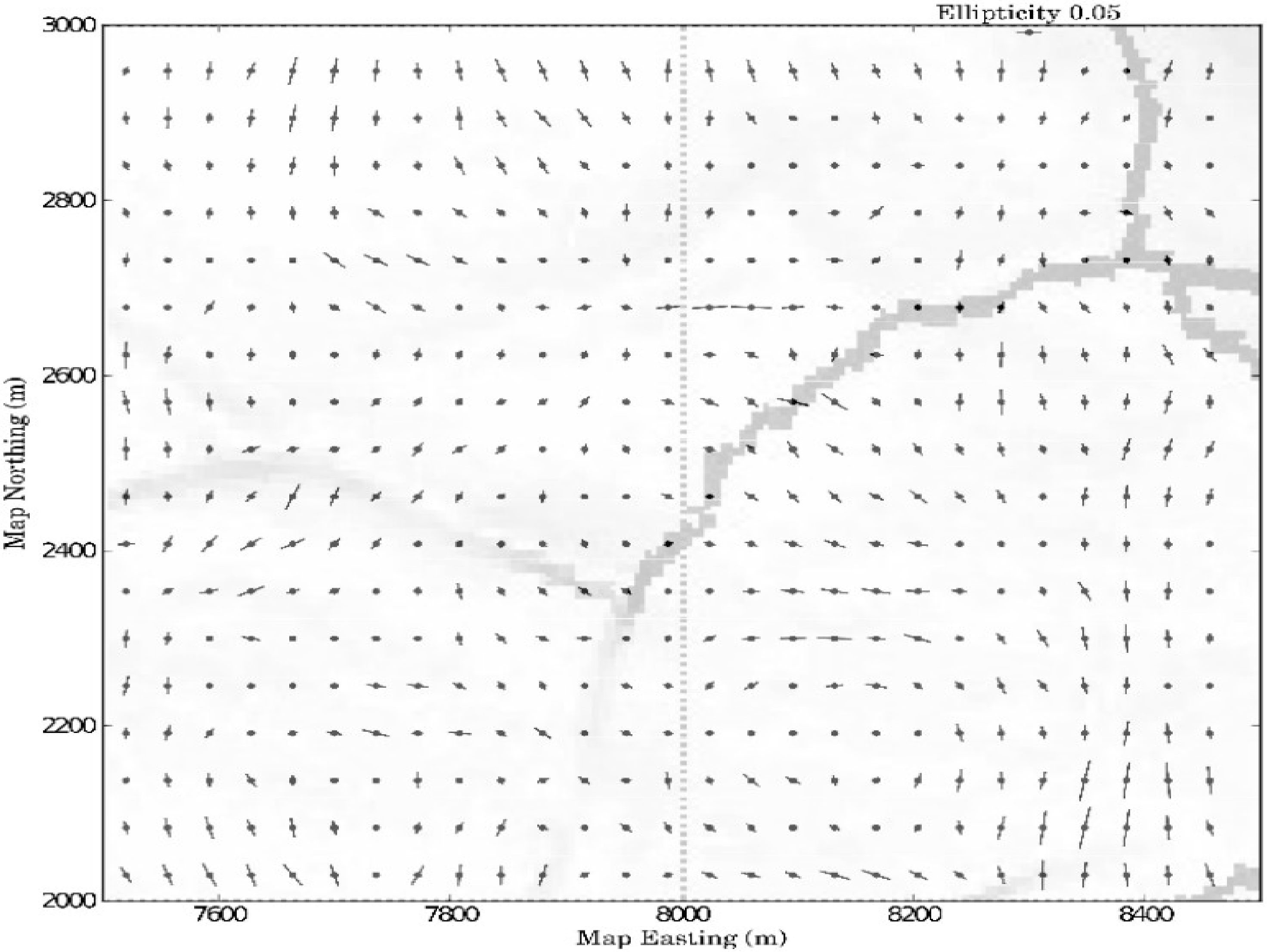
15 square km



Production 3D Mini-SOSIE

Central Bowen Basin

P-wave Anisotropy



Production 3D: Conclusions

- Consistent patterns of anisotropy across the survey area
- P-wave anisotropy up to 10 %
- Appears to be a relationship to faulting

New developments in coal seismology

Acquisition modelling of seismic resolution

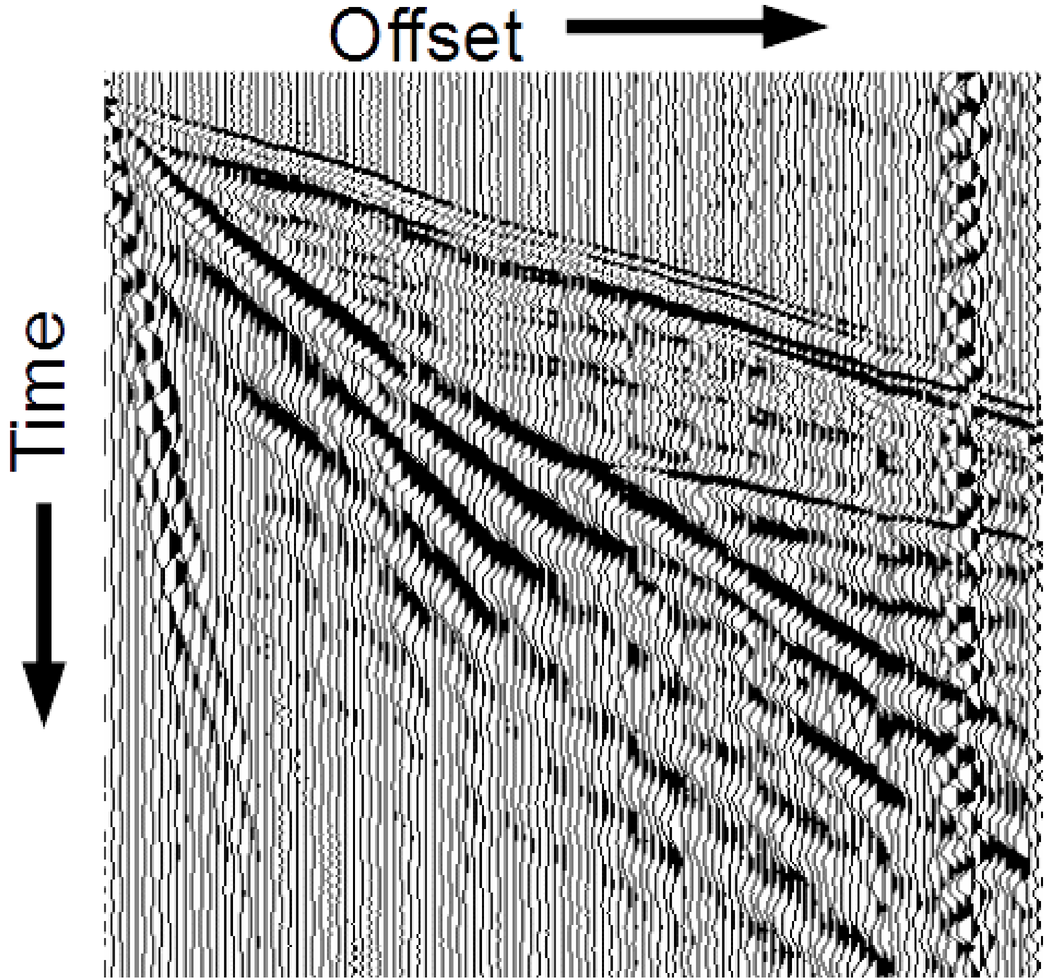
Seismic anisotropy and stress prediction

Exploitation of seismic noise

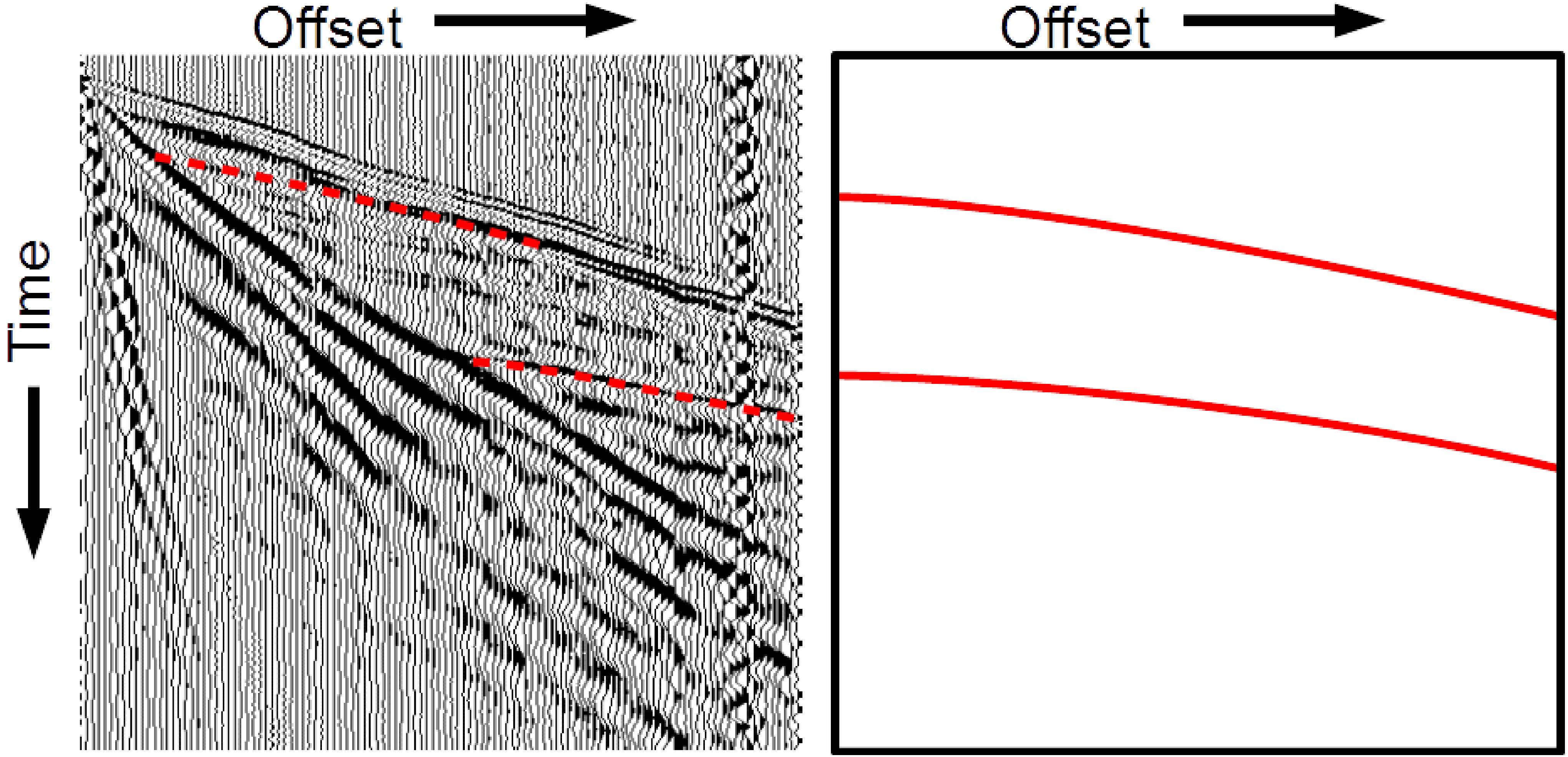
Velseis
Integrated Seismic Technologies

UQ
EXPLORATION GEOPHYSICS

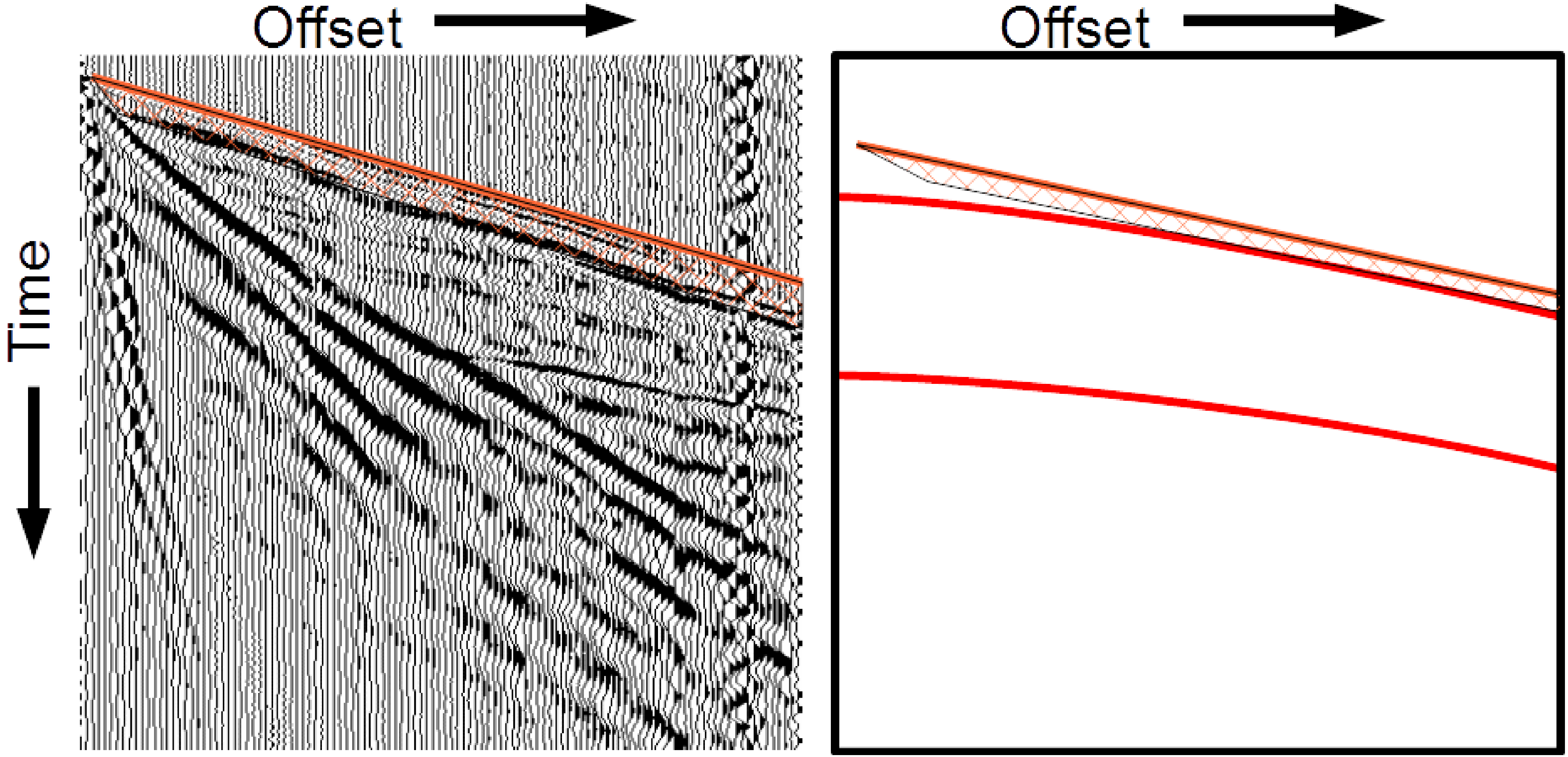
Seismic Record



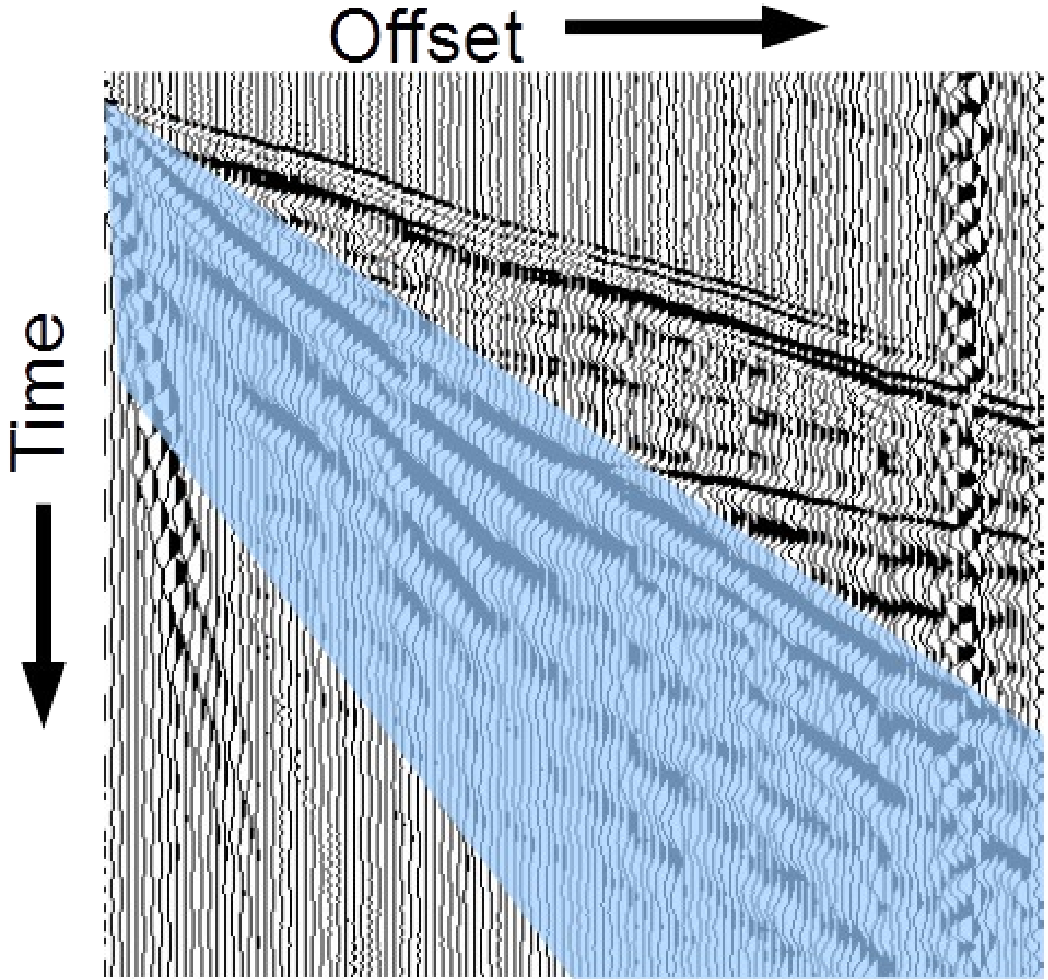
"Signal" - P-wave Reflections

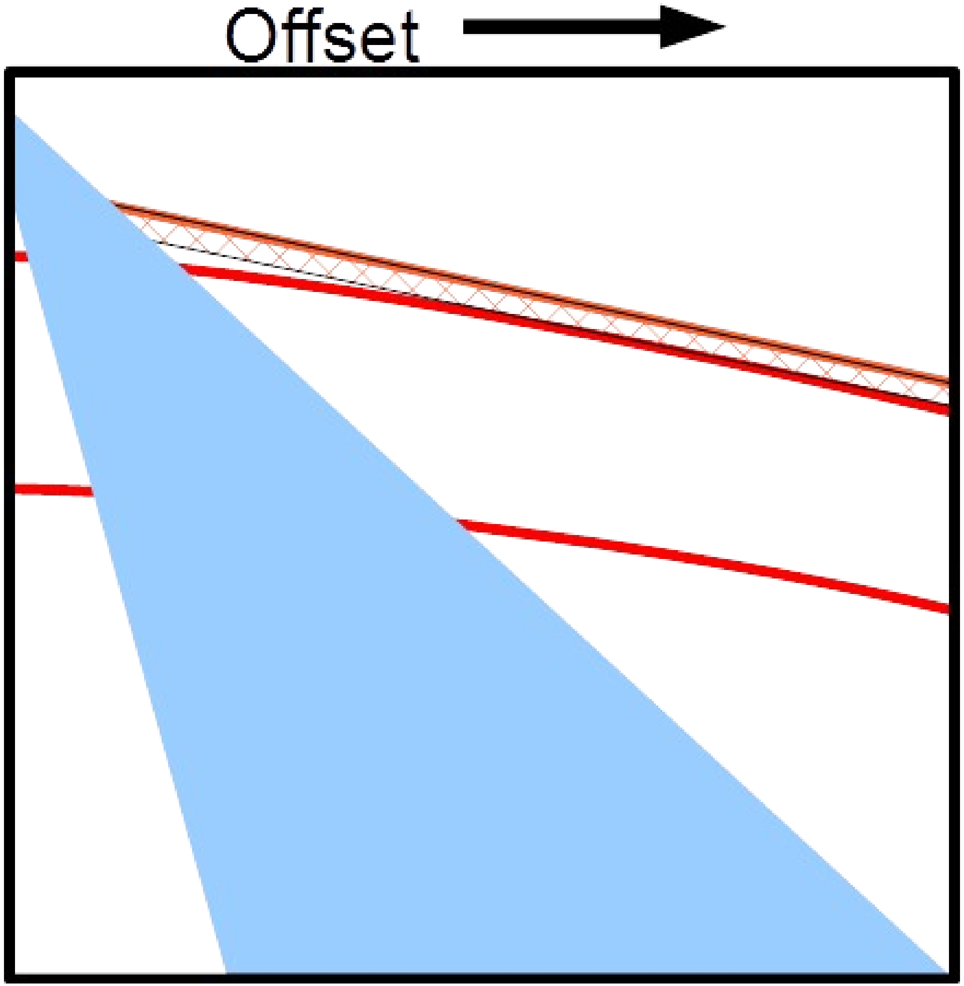


“Signal/Noise” - Refractions

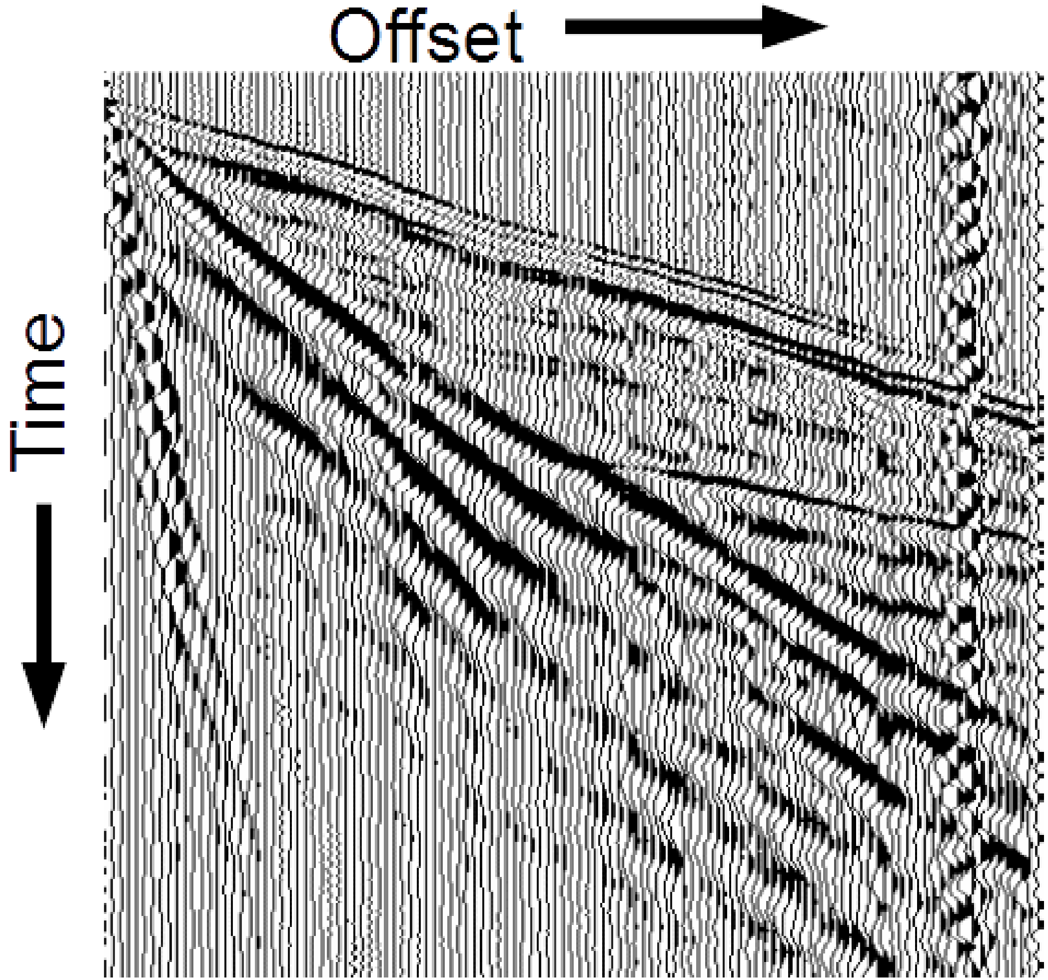


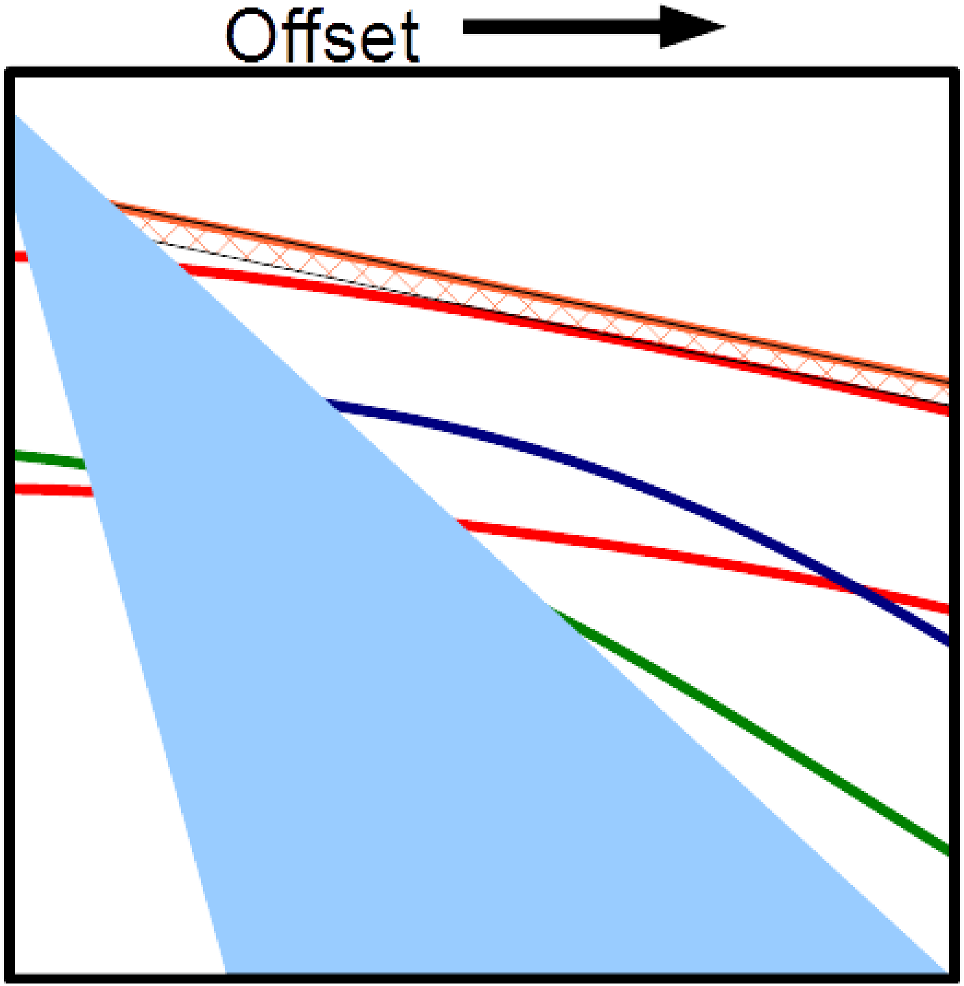
“Noise” - Surface waves



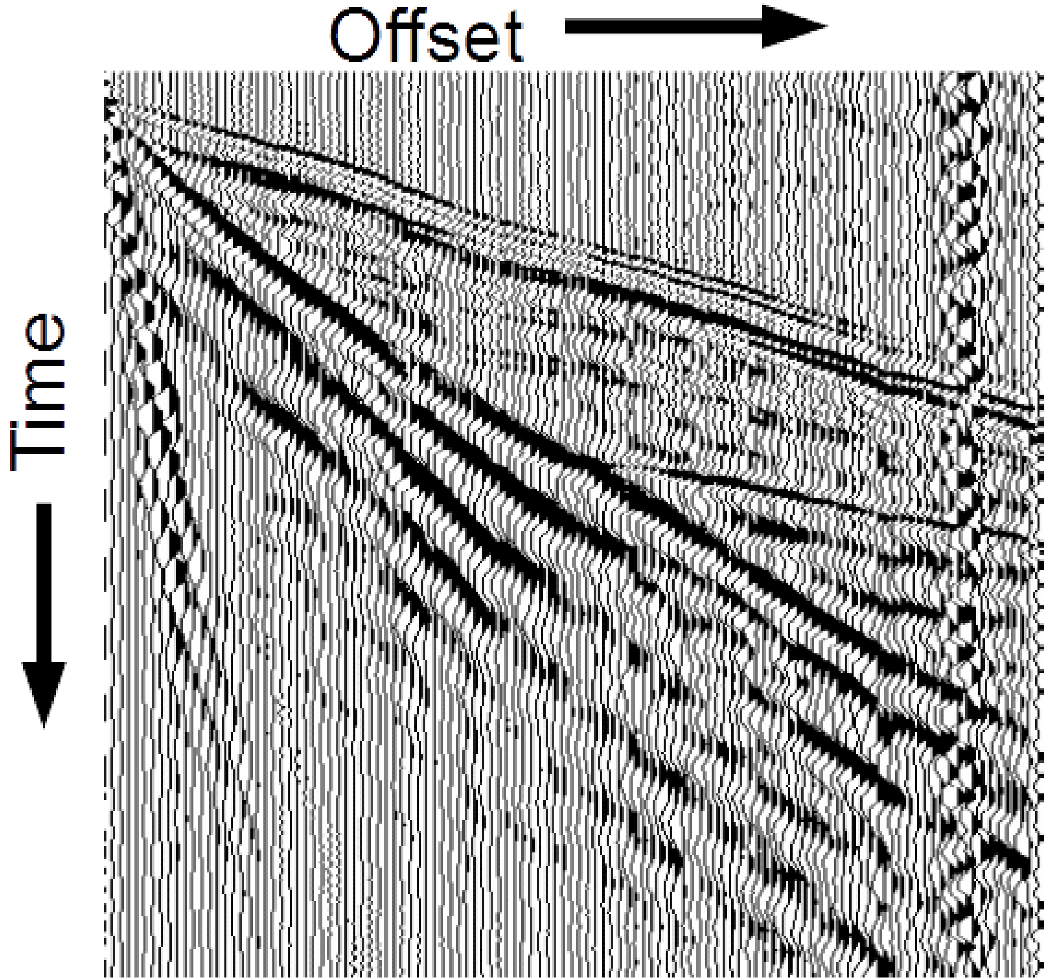


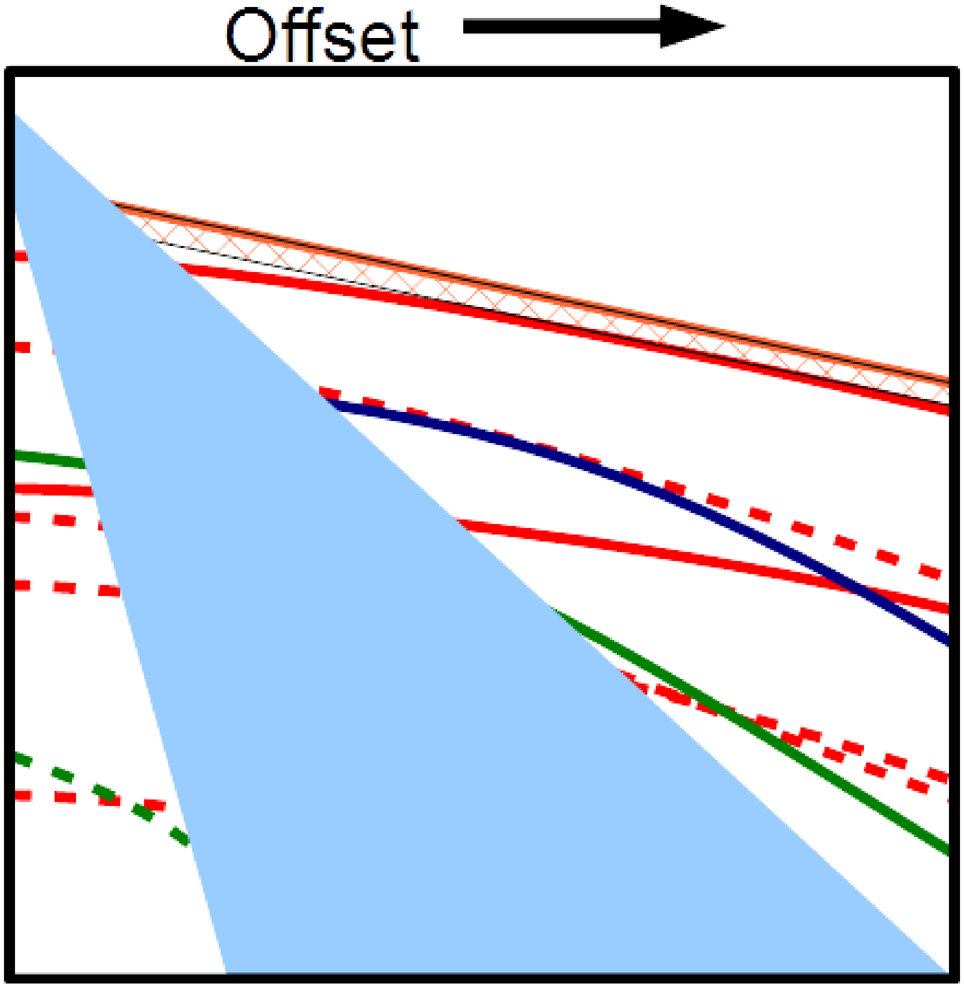
"Noise" - S-waves & PS-waves



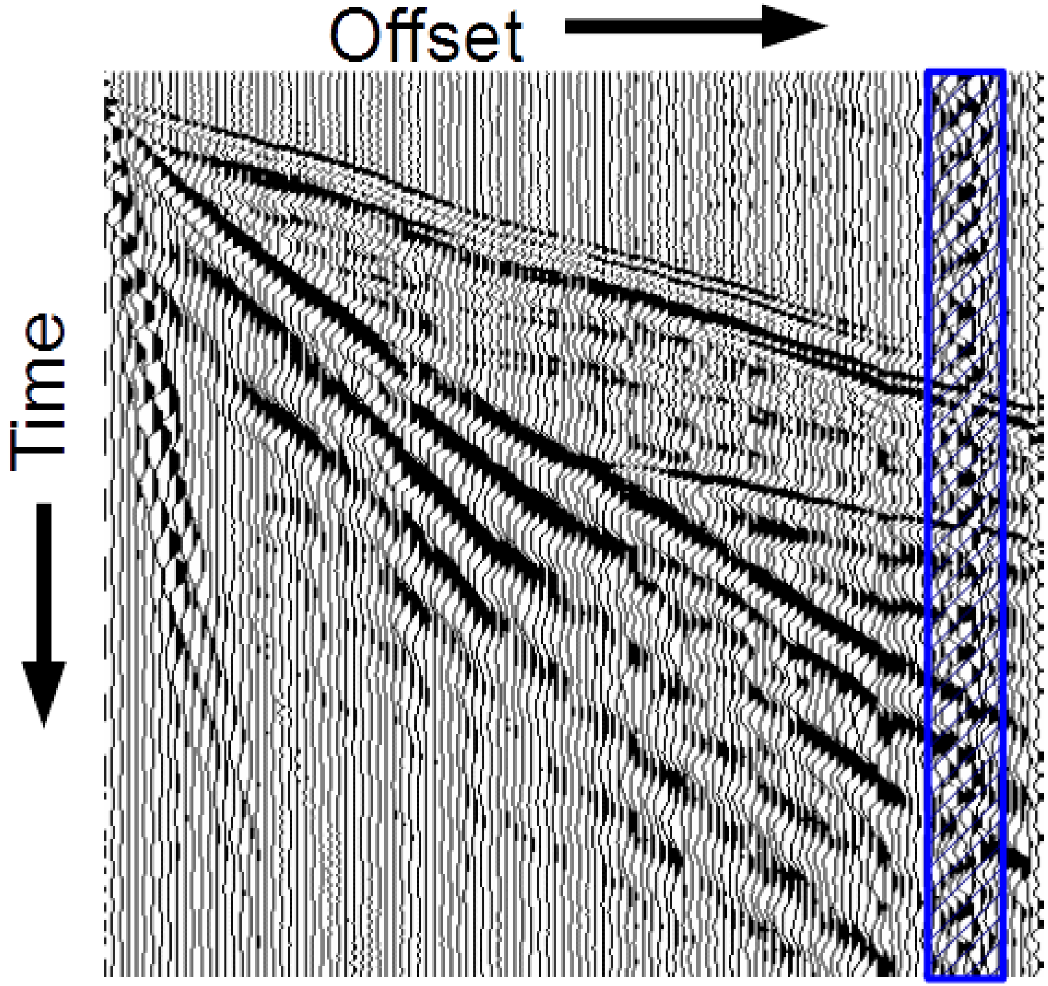


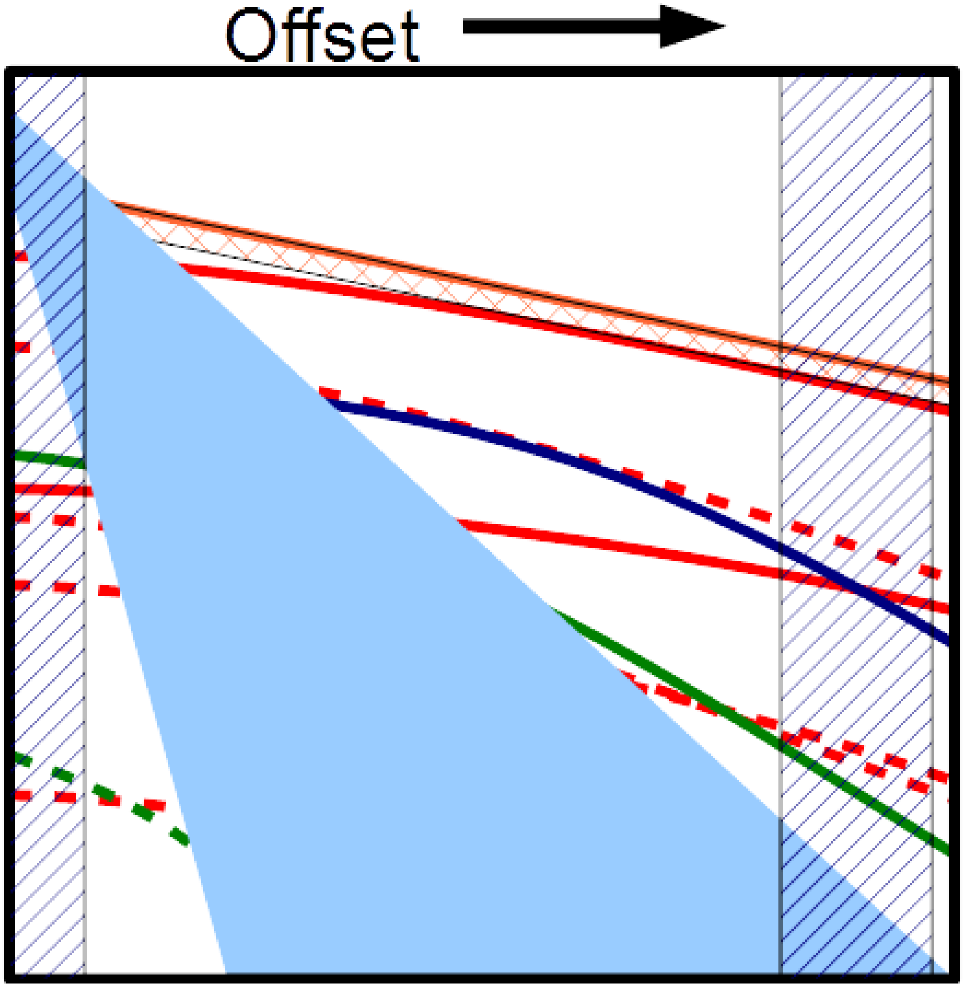
“Noise” - Multiples





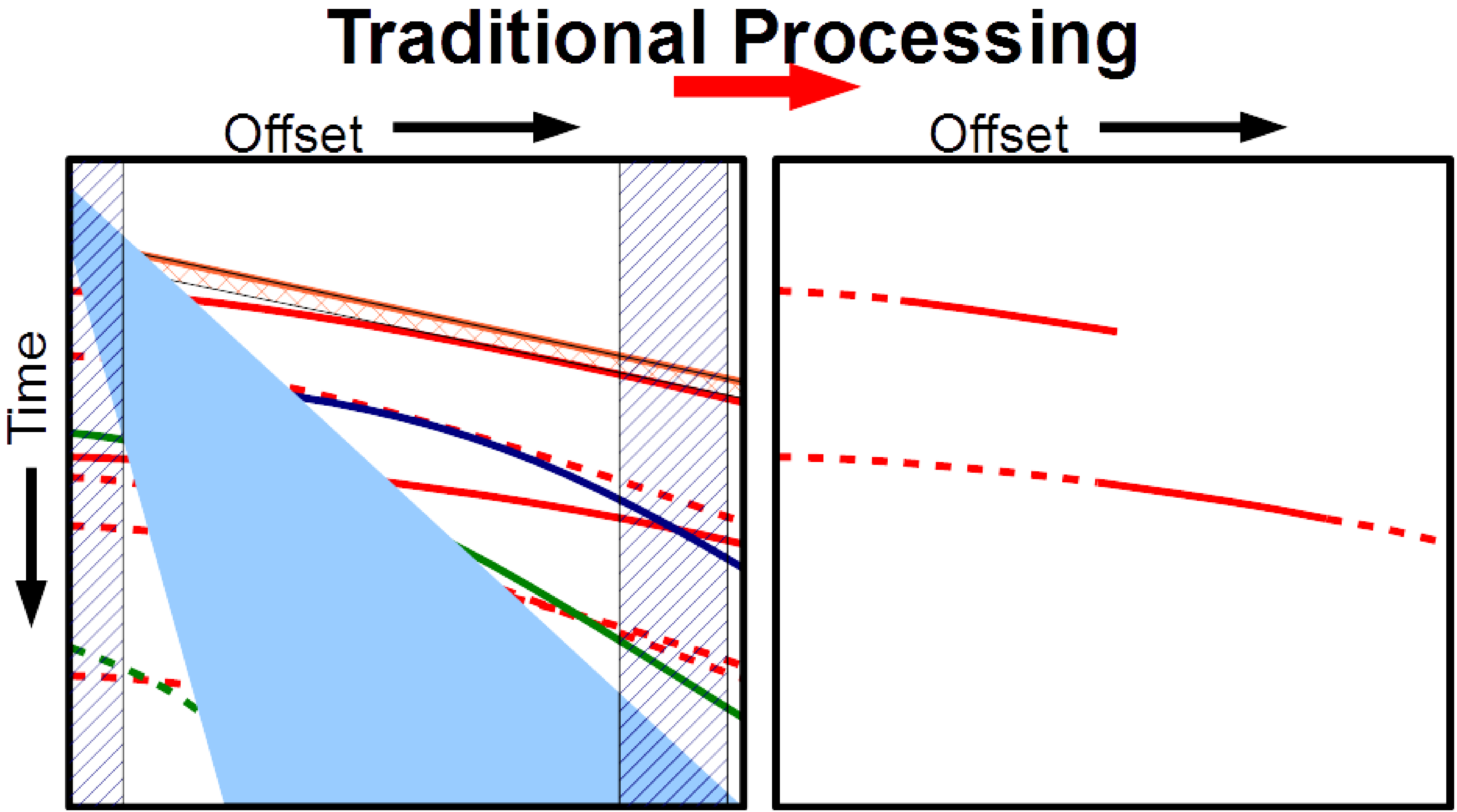
“Noise” - Other Random/Coherent





Traditional “Noise” Removal

- Refractions – Top Mute
- Surface waves – FK Filtering
- Multiples – Predictive Deconvolution
- PS & S Waves – NMO, FK Filtering, EWD
- Random Noise – TFD Noise Filter, CDP Stacking

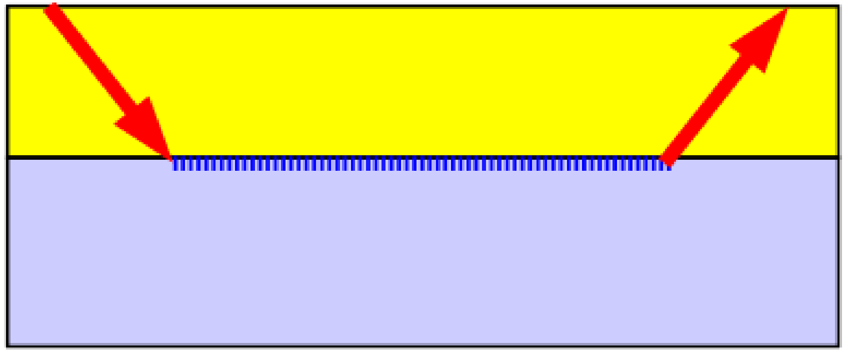


Traditional Processing
Offset
Offset
Time

Refraction & Surface-Wave “Noise”

- Tend to “image” near-surface structures
- How could near-surface information be utilised?
  - Improved statics calculations leading to improved reflection data.
  - Identification of Lox zones.
  - Engineering/rock competency information for infrastructure placement or site development.

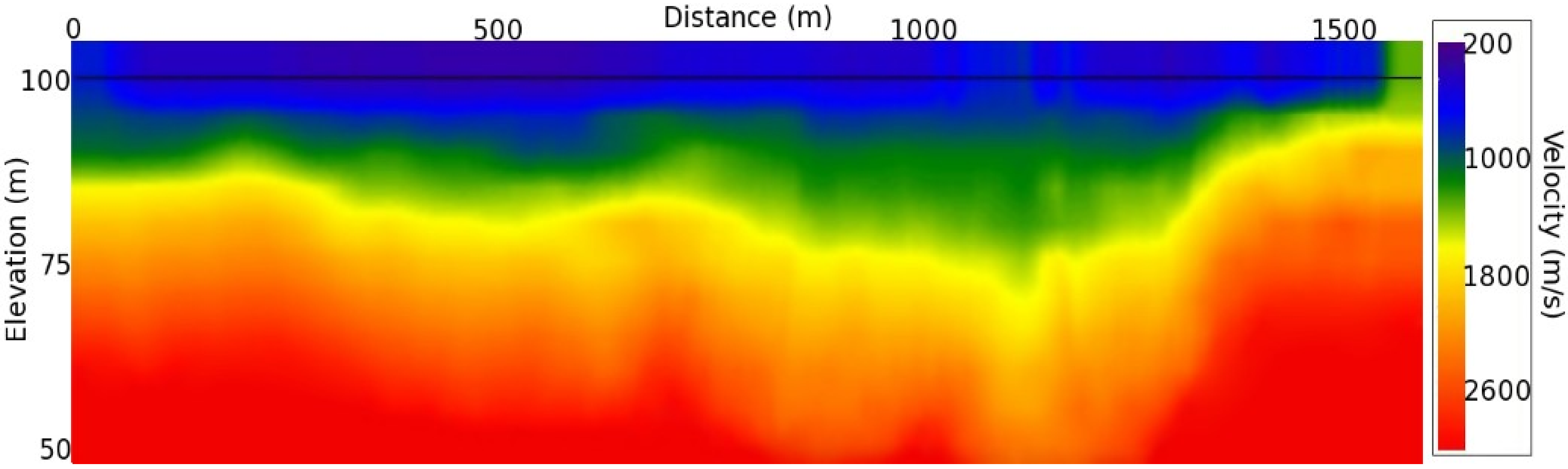
Refractions



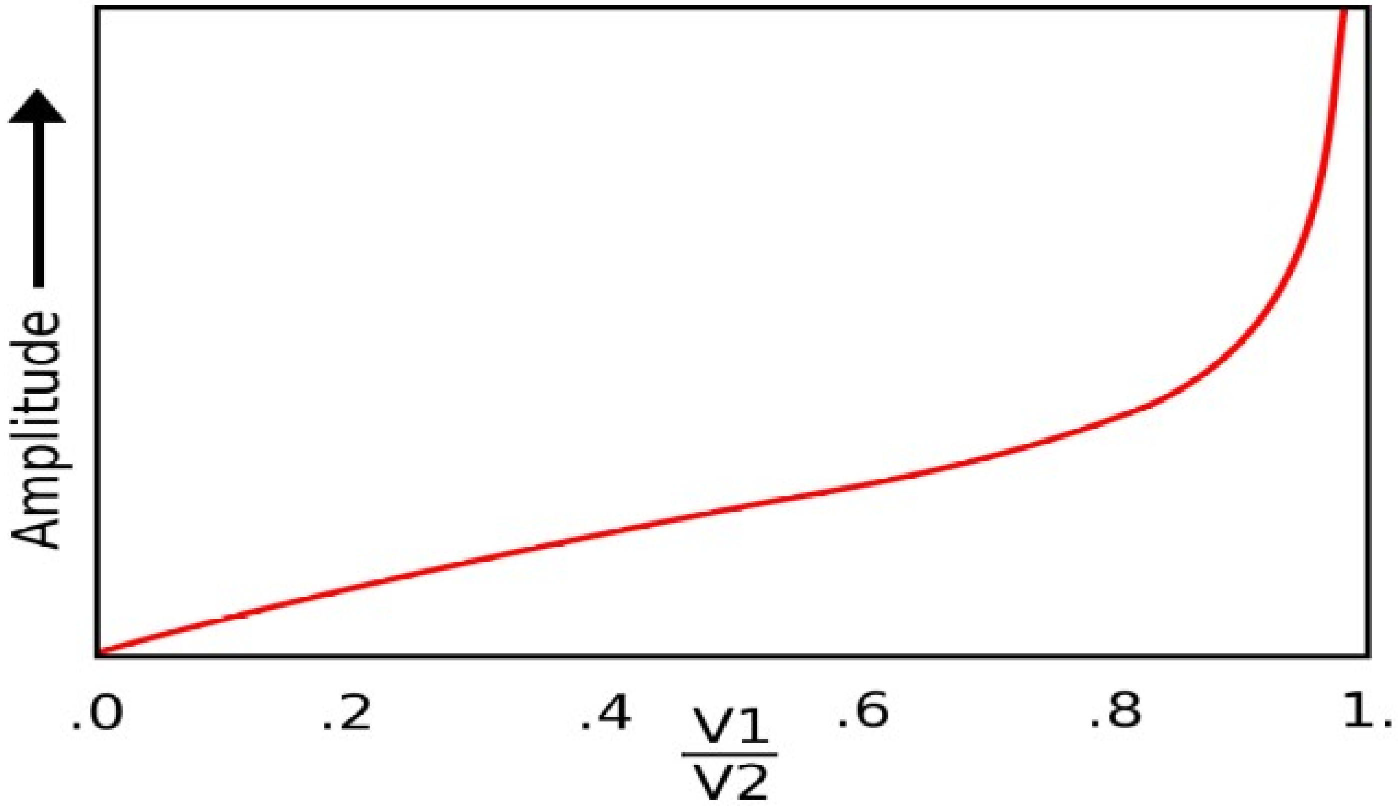
Advantages:

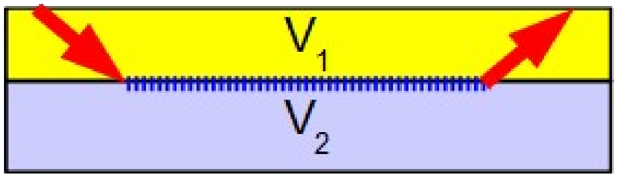
- Strong energy.
- Often first arrival on the seismic record.
- Already a useful tool that has more potential.

Refractions - Tomography

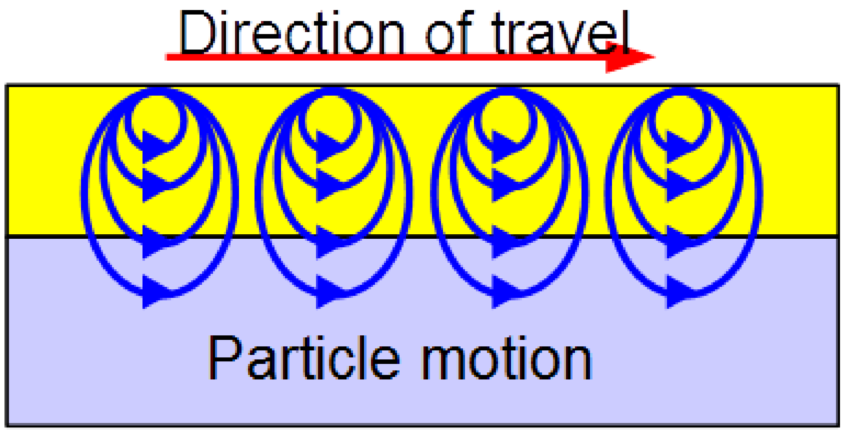


Refractions - Amplitude



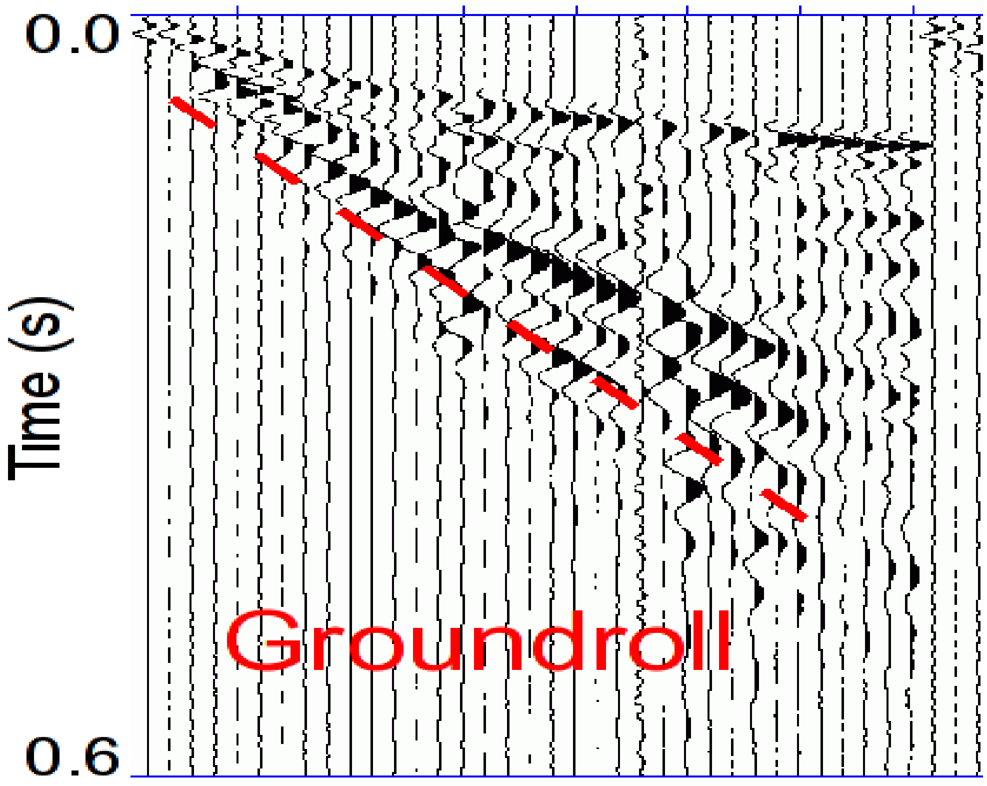


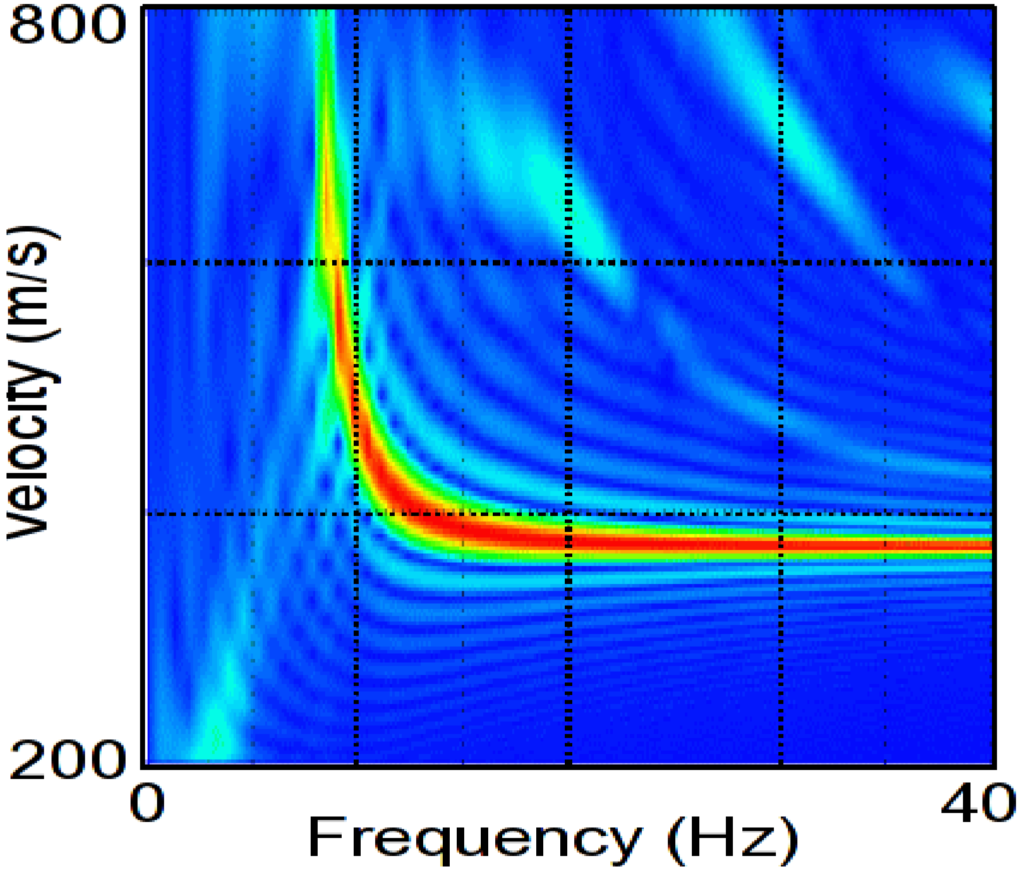
Surface Waves / Ground Roll



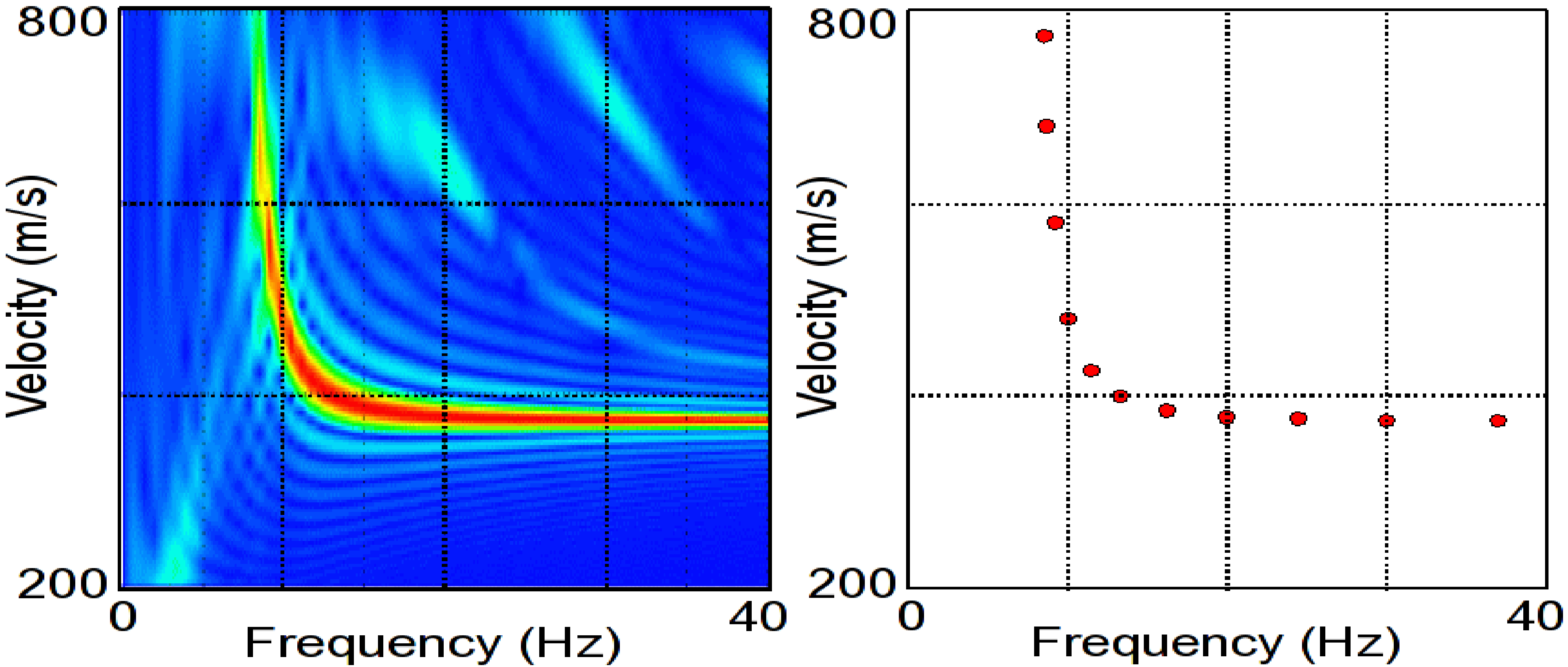
- Usually the strongest event when using surface sources.
- Have a dispersive ("ringy") nature.
- Dispersive behaviour dominated by S-wave properties.

Ground Roll - Method

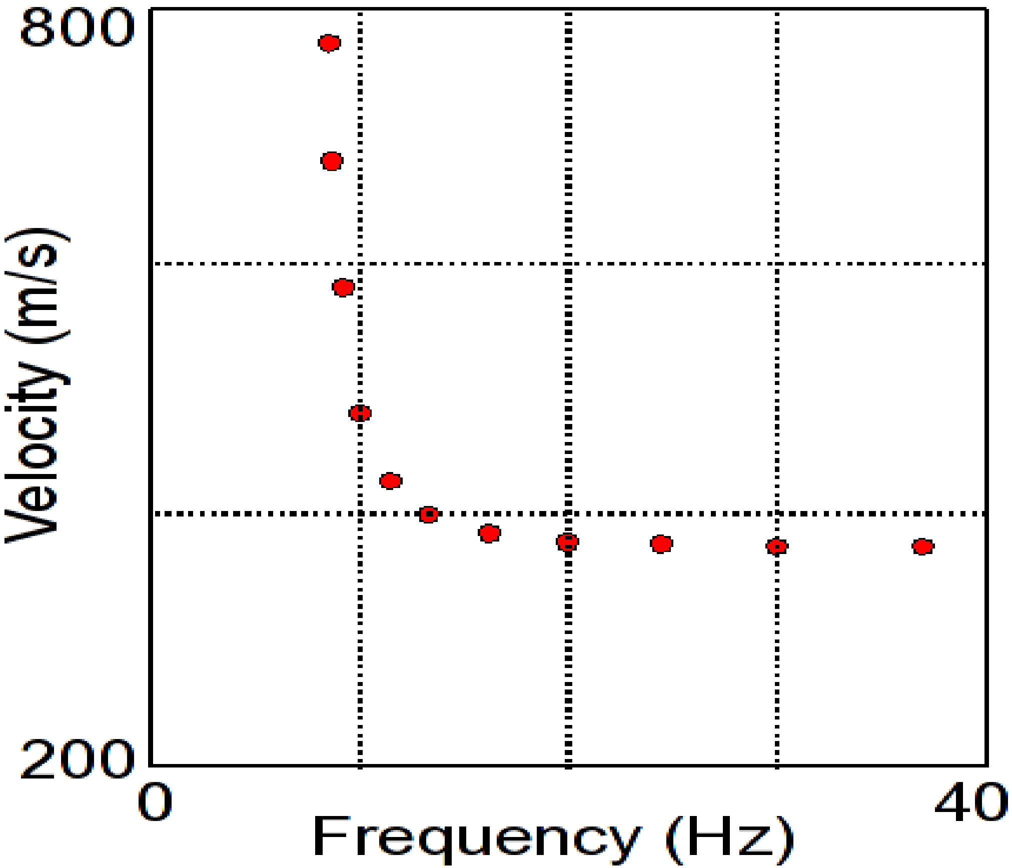


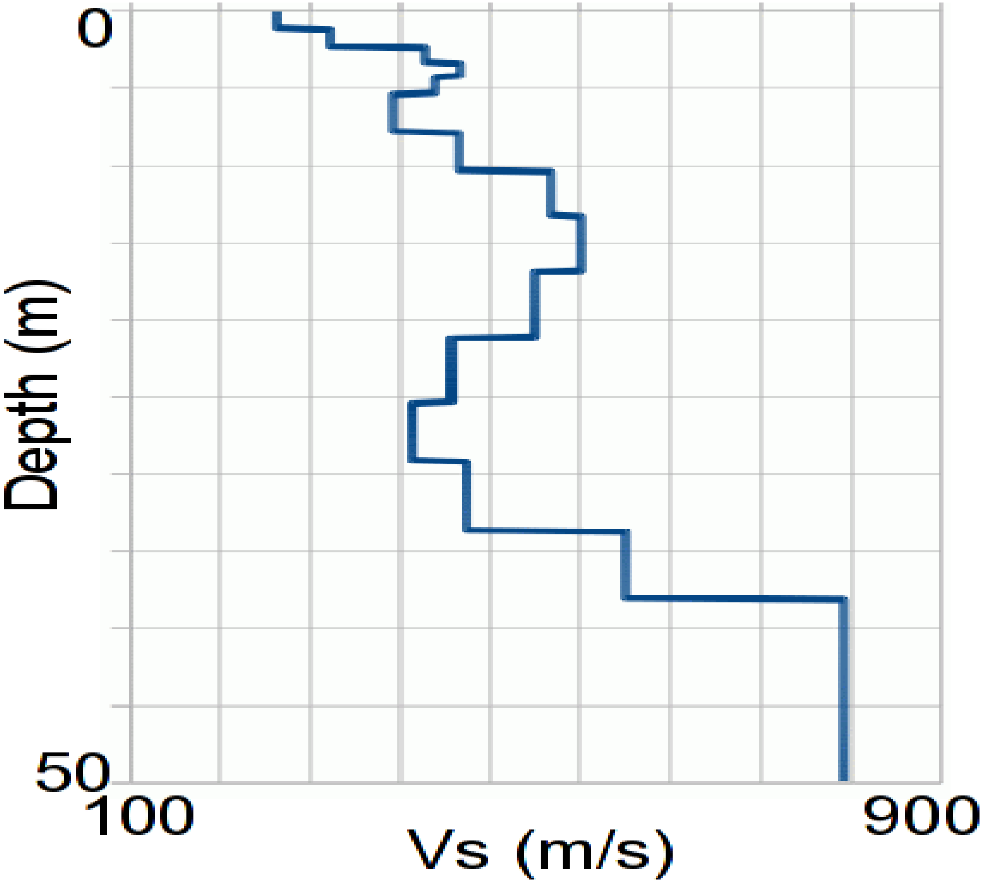


Ground Roll - Method



Ground Roll - Method

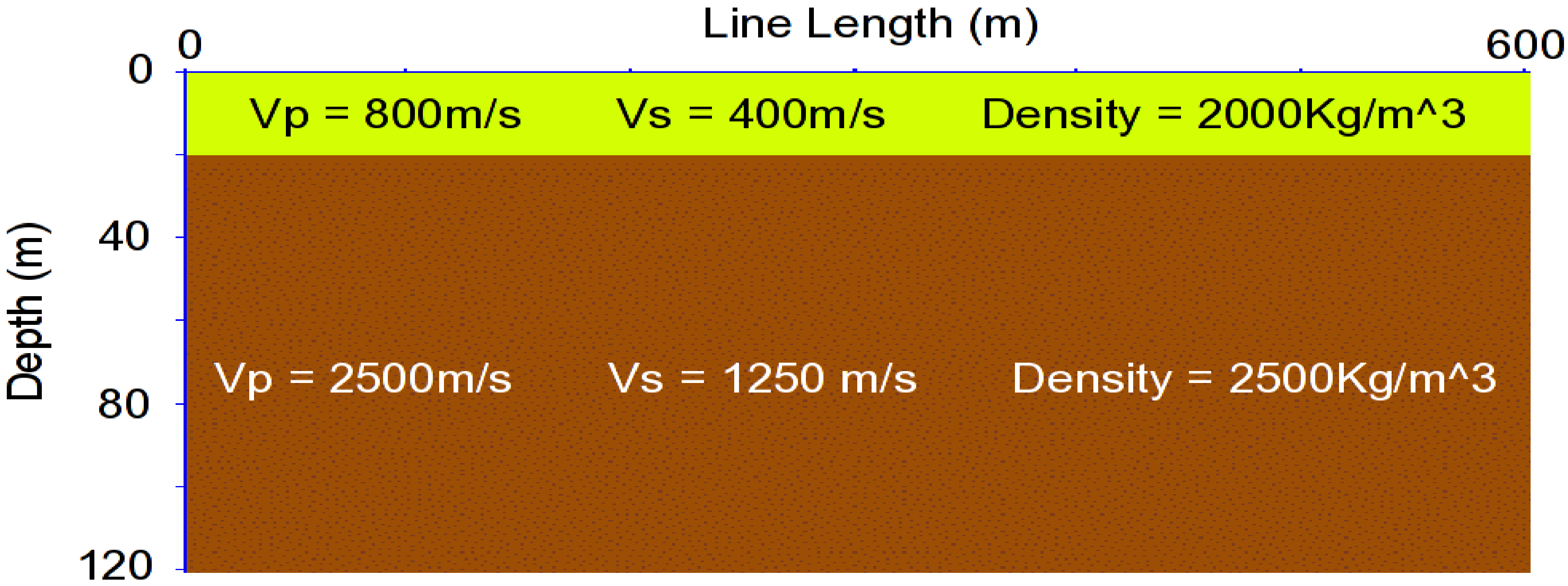




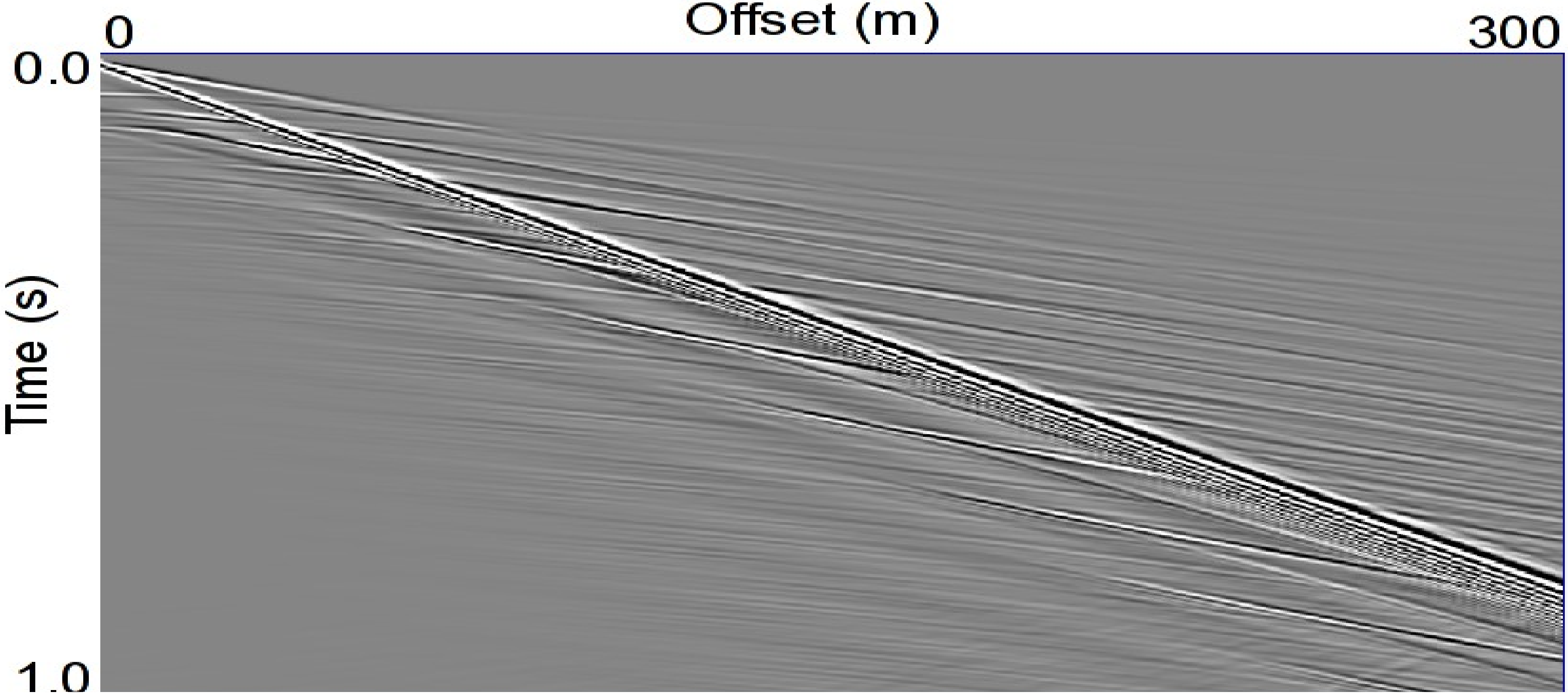
Survey Parameters

	Engineering	Exploration
Natural Frequency	<10Hz	>10Hz
Spacing	~0.25-3m	~4-10m
Number	2-50	50-300
Near offset	10-30m	2-5m
Far offset	30-100m	100-400m

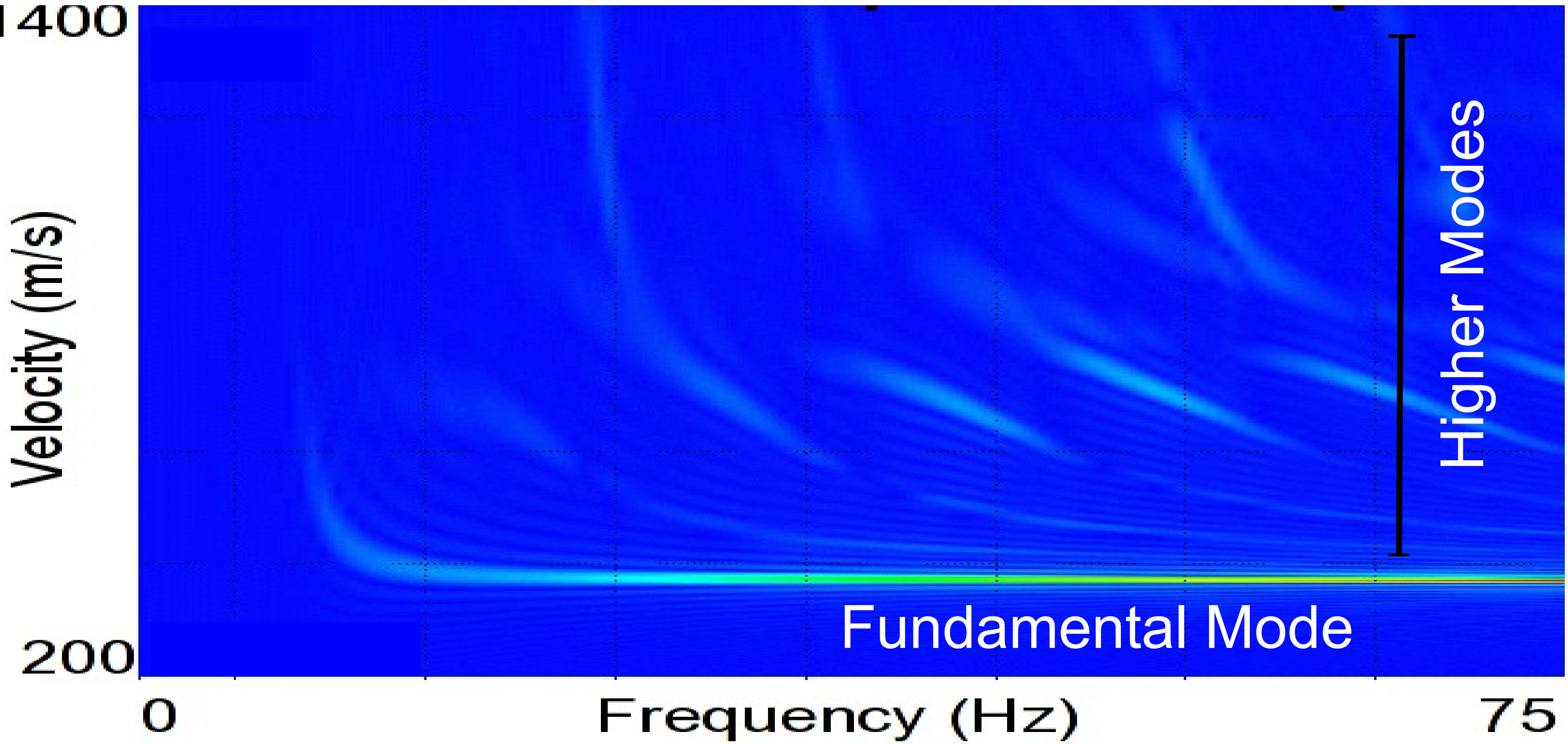
Dispersion Analysis



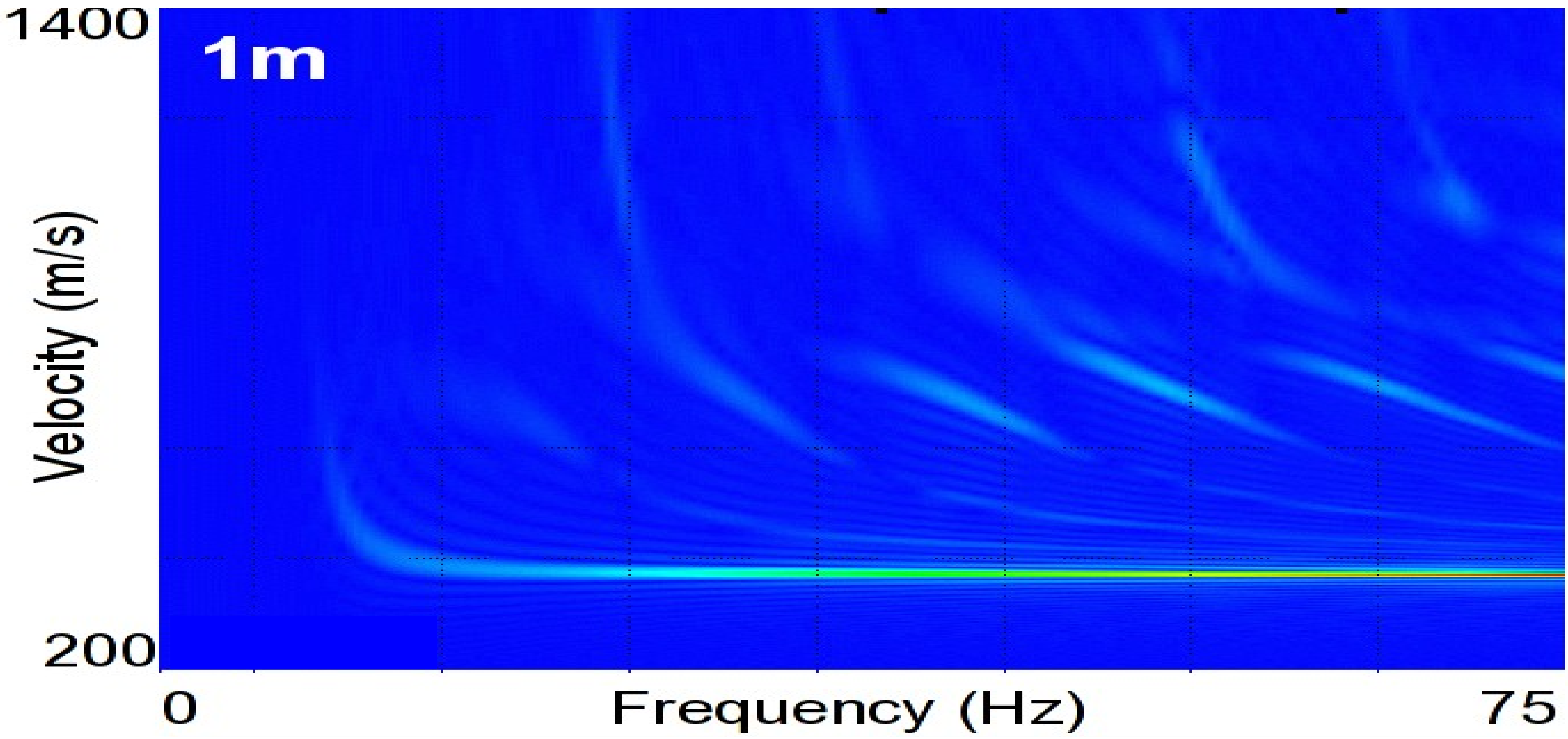
Dispersion Analysis



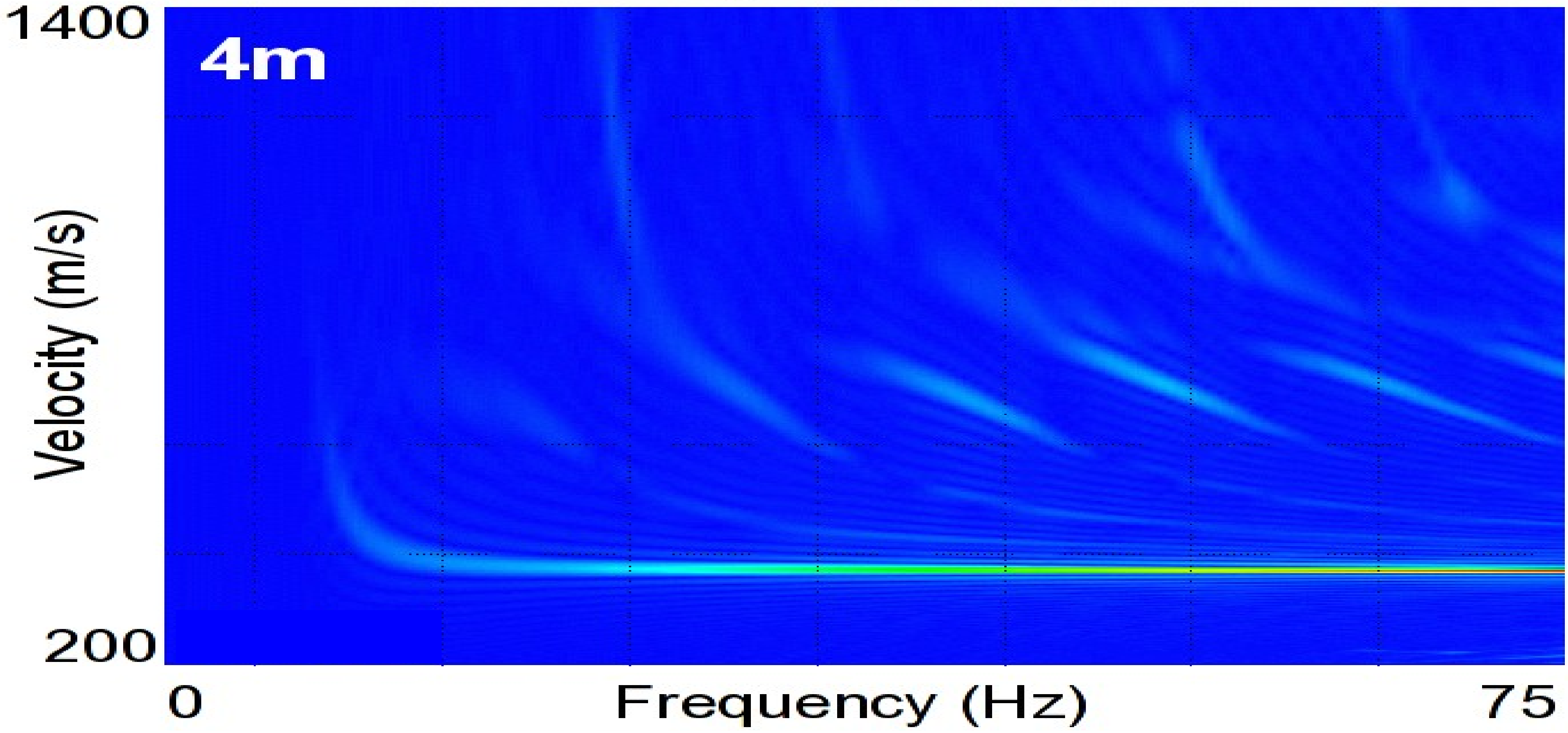
Dispersion Analysis



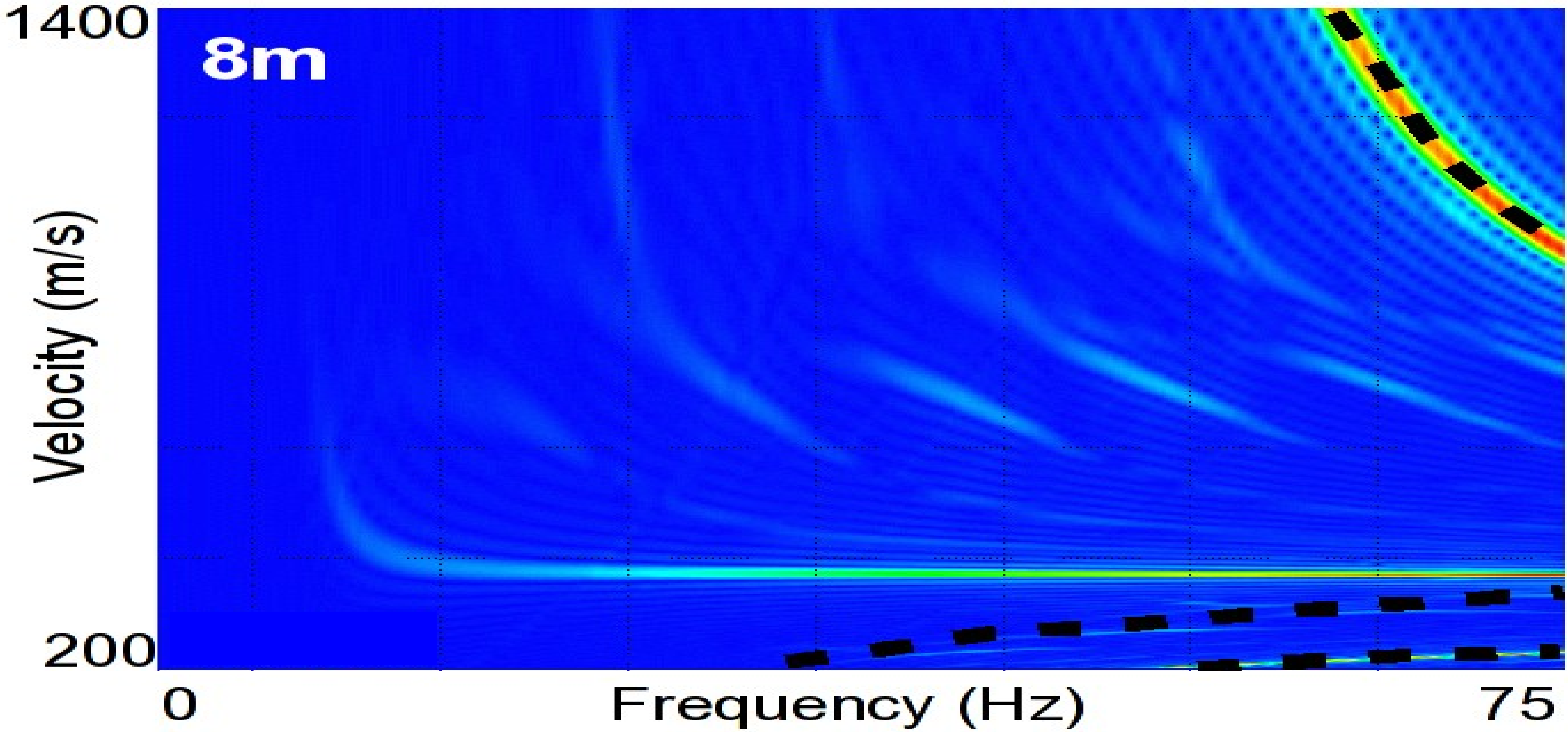
Geophone Spacing - 1m



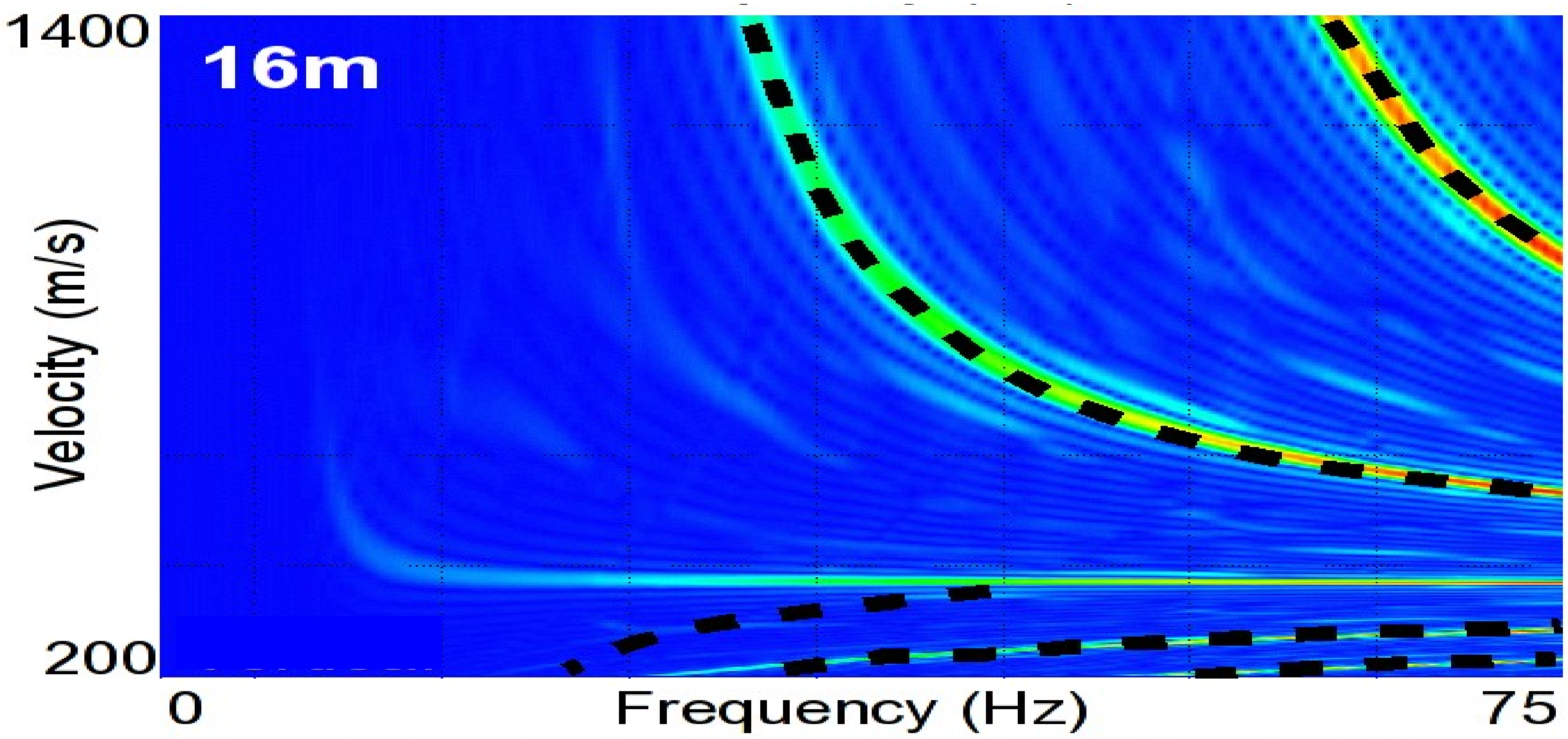
Geophone Spacing - 4m



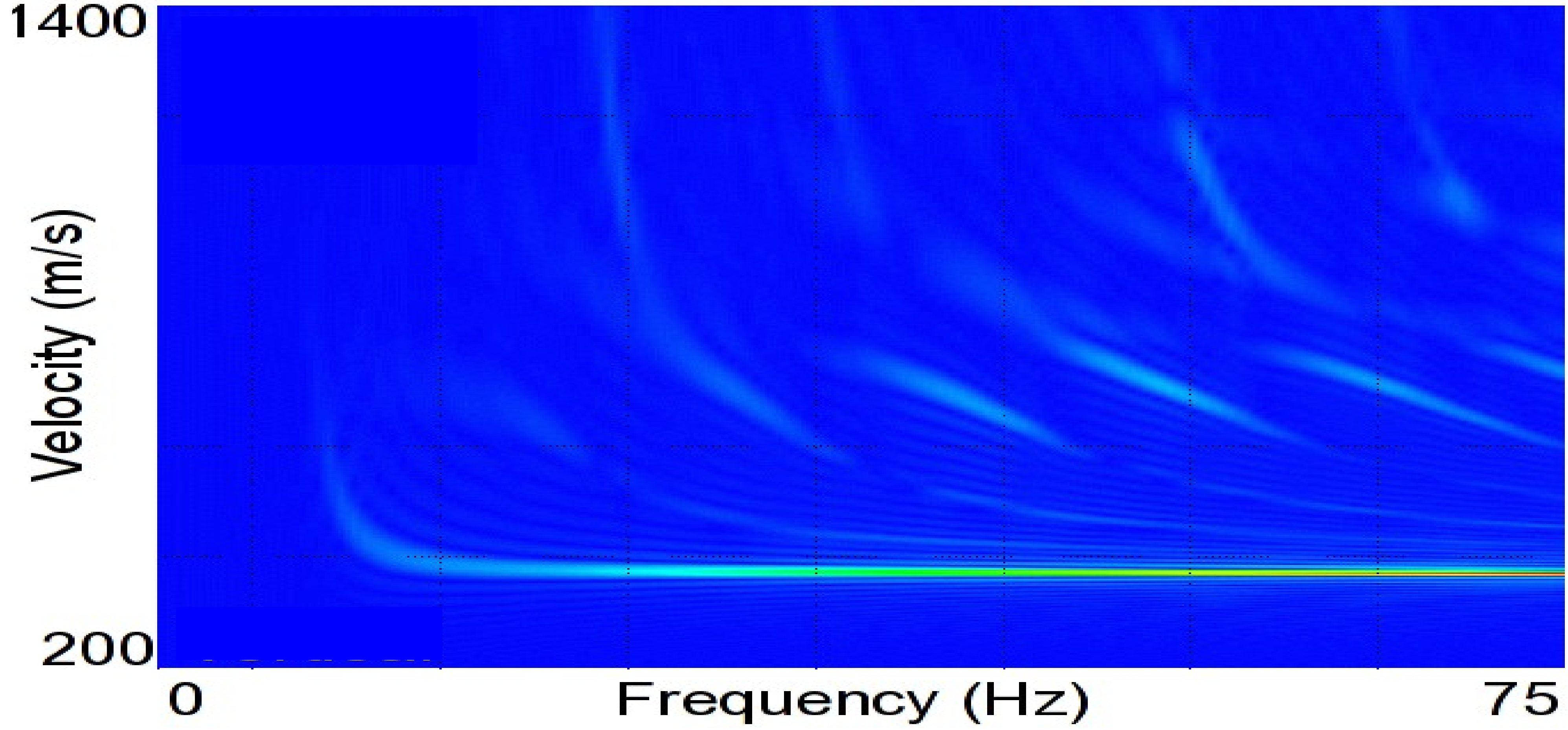
Geophone Spacing - 8m



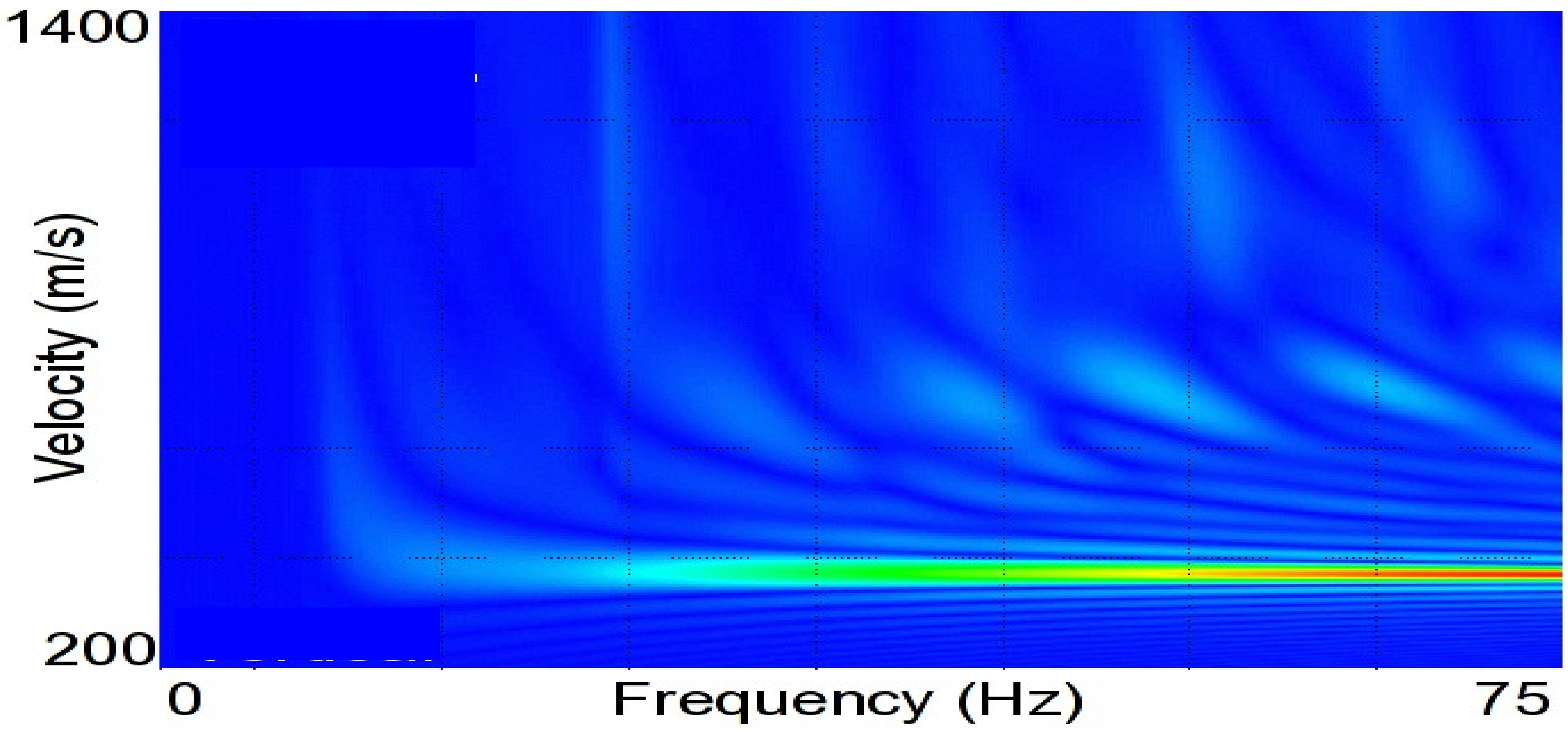
Geophone Spacing - 16m



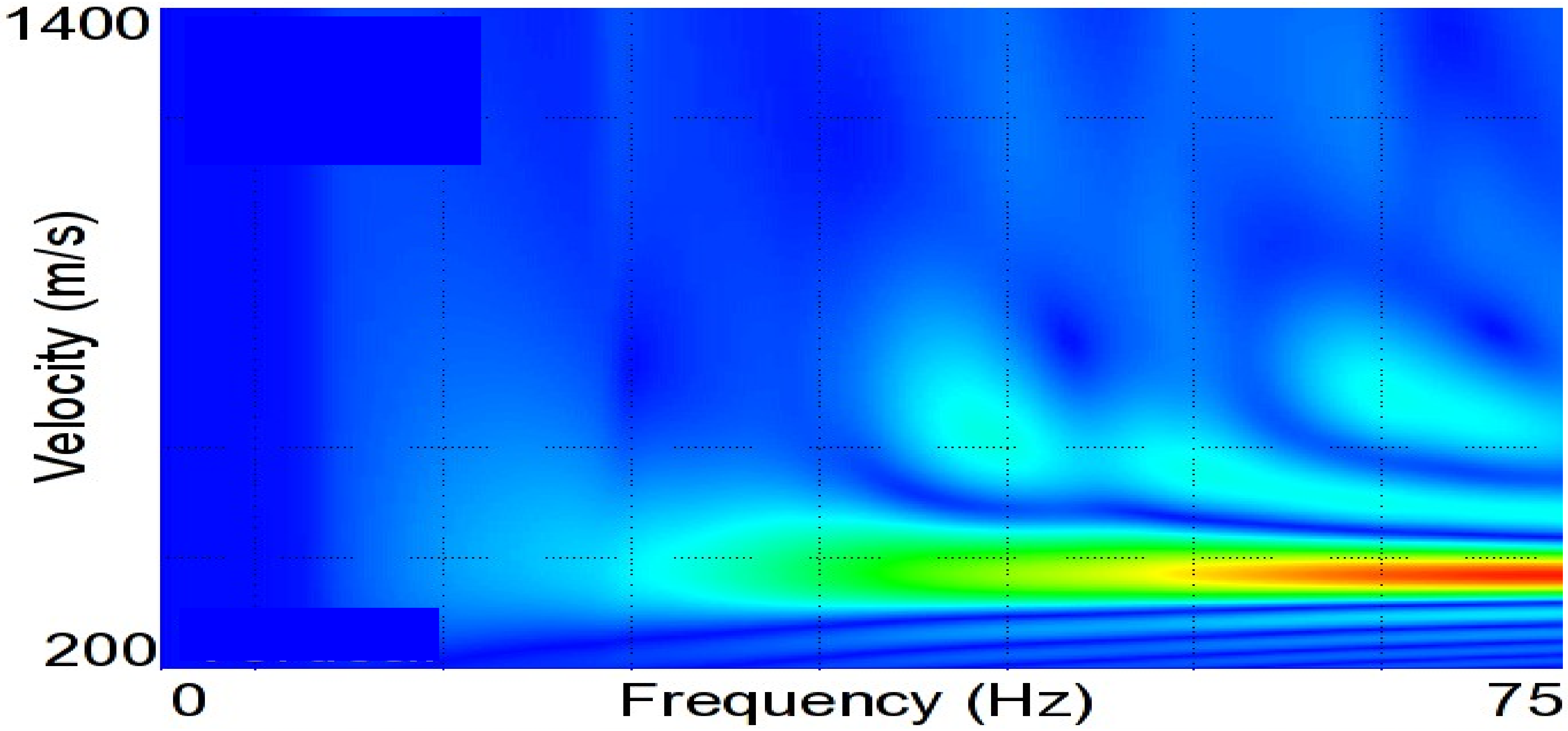
Max Offset - 300m



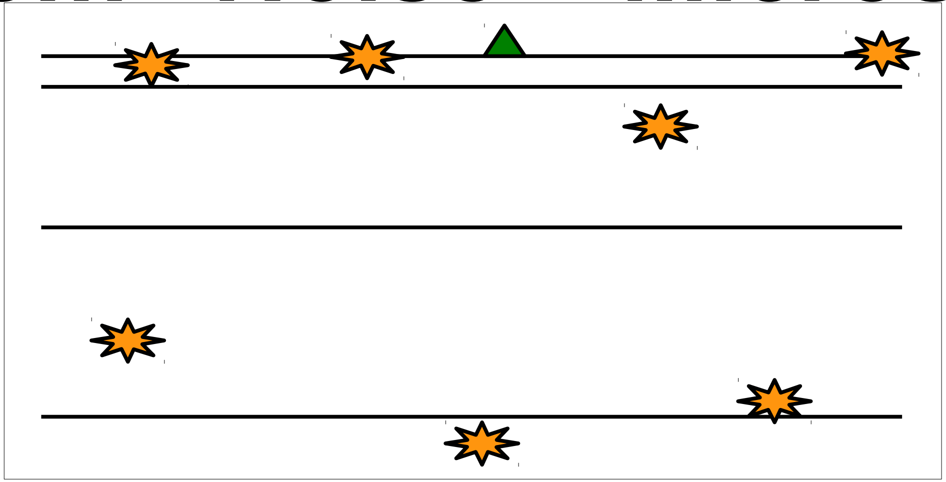
Max Offset - 100m



Max Offset - 30m

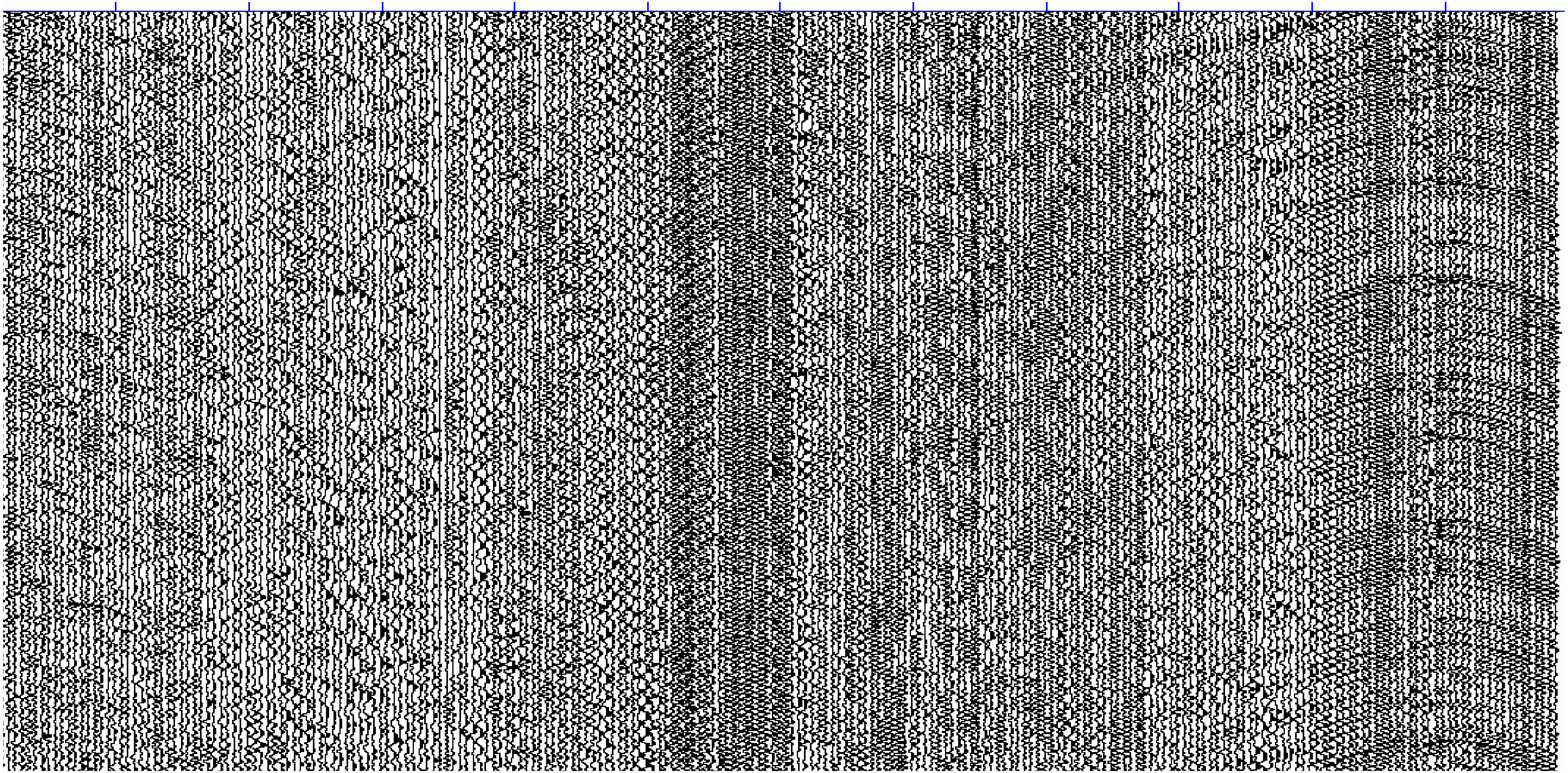


"Random" Noise – Microseismic

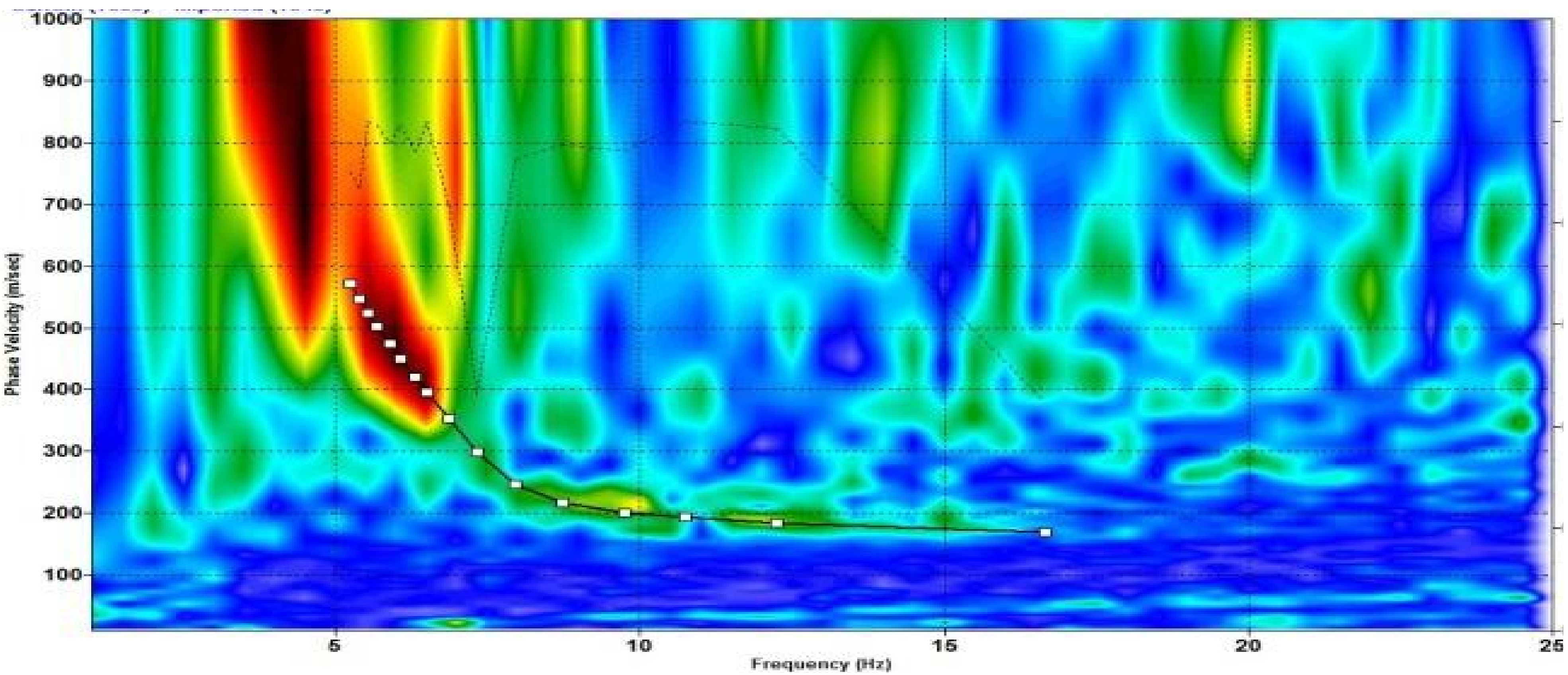


- Present in all seismic surveys.
- Often a mixture of random and coherent noise.
- Don't require costly source equipment.
- Requires long recording times.

“Random” Noise – Microseismic

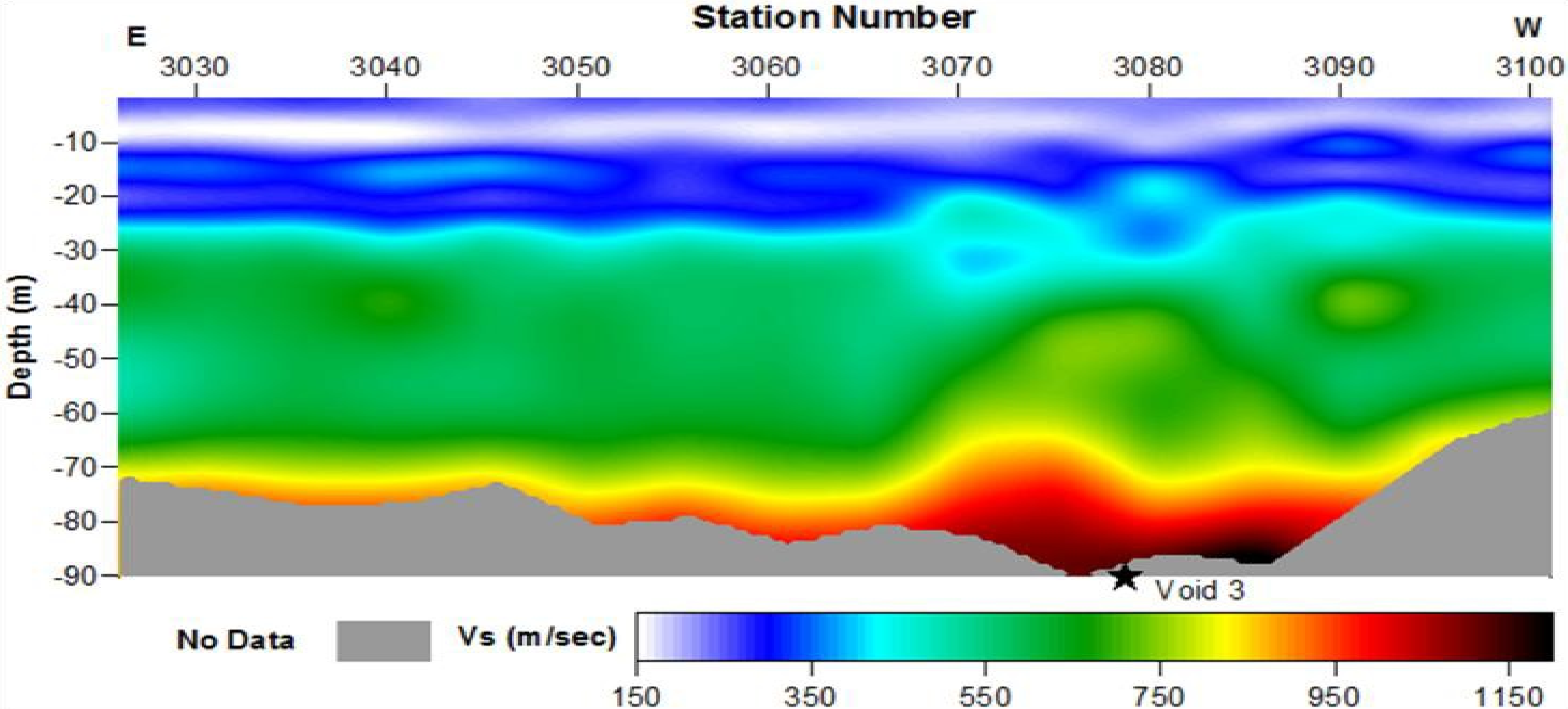


“Random” Noise – Microseismic



Nolan, J.J. et. al. 2013

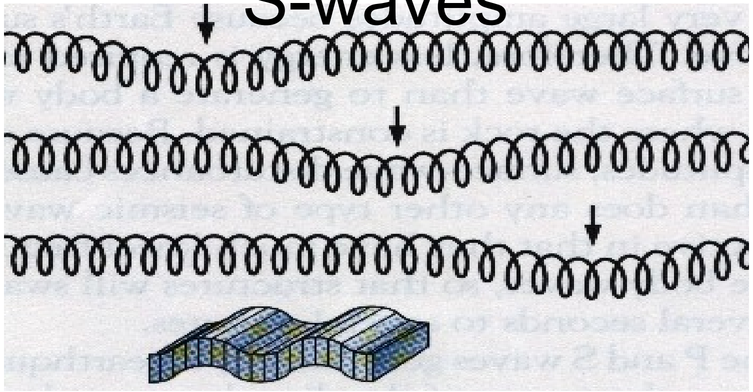
“Random” Noise – Microseismic



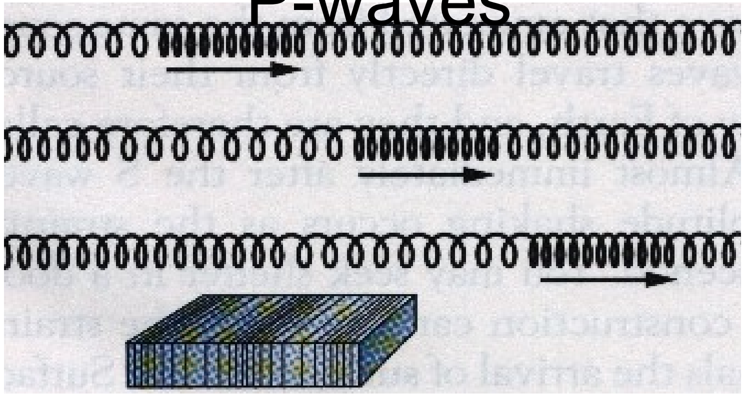
Nolan, J.J. et. al. 2013

S-waves

S-waves



P-waves



- Slower than P-waves: events occur a different times on seismic records.
- Geology presents in different ways on P-wave and S-wave data.
- Usually acquired via multicomponent surveys.

Multicomponent Receivers

Traditional 3C Geophone

Velseis
Integrated Seismic Technologies

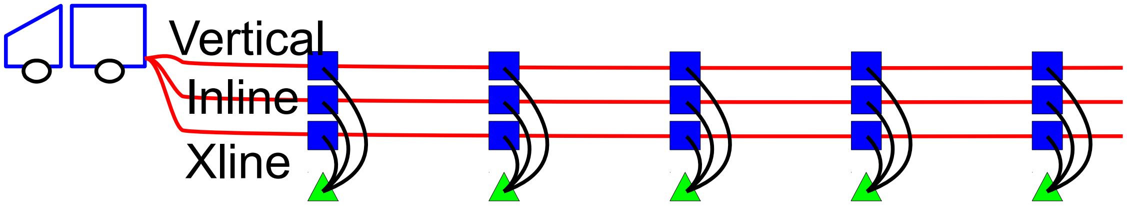
Multicomponent Receivers

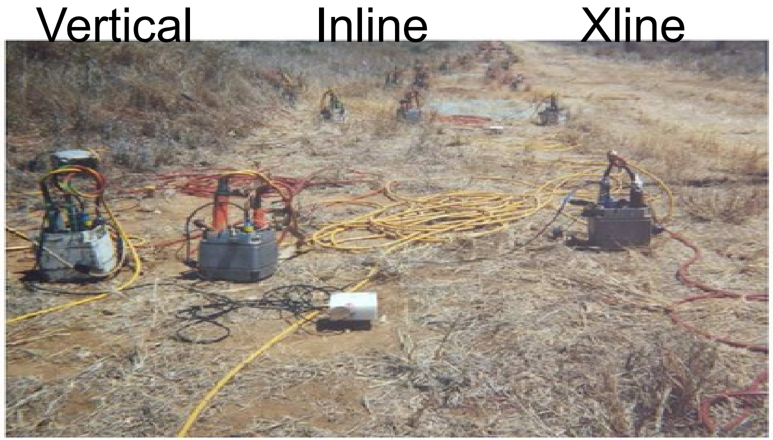
Traditional 3C Geophone

MEMS 3C Geophone

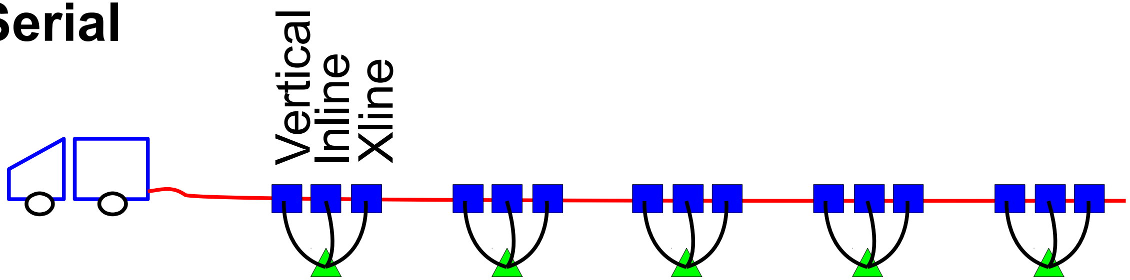
Multicomponent Survey Layout

Parallel



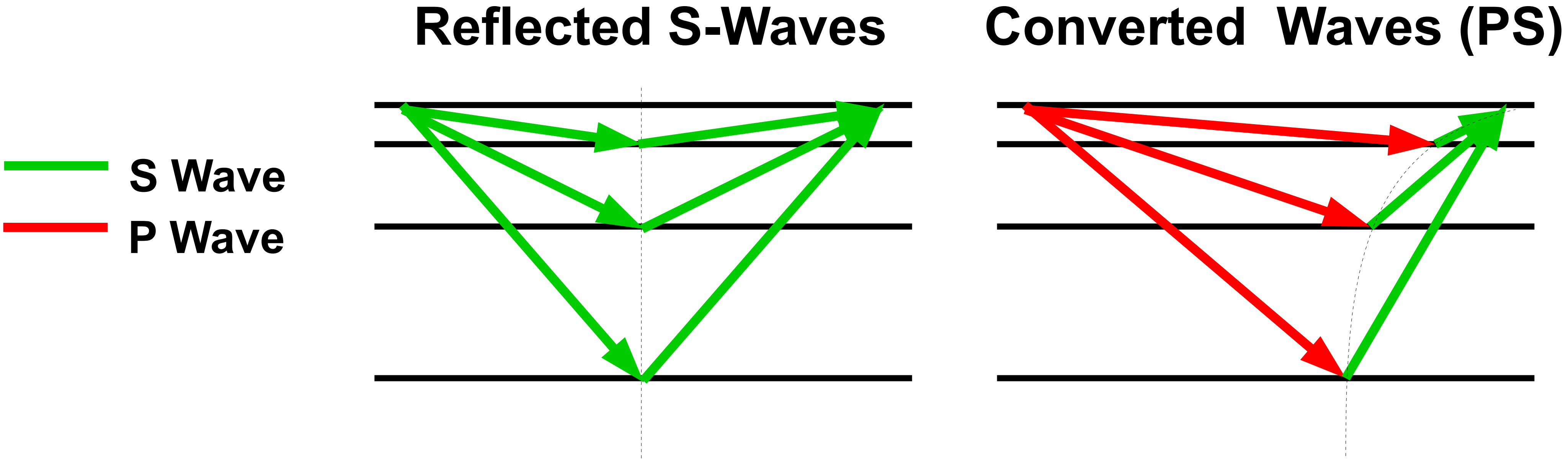


Serial



Receiver line direction →

Reflected Waves vs Converted Waves

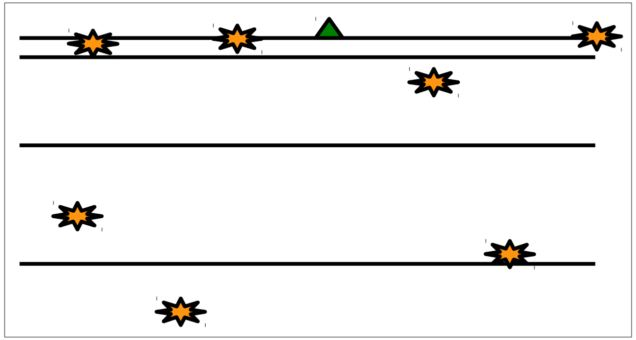


Raypath	Symmetric	Asymmetric
Source	S wave	P wave
Advantage	Easier to process Greater separation of events	Less attenuation Easier to acquire

Sources

Impulsive

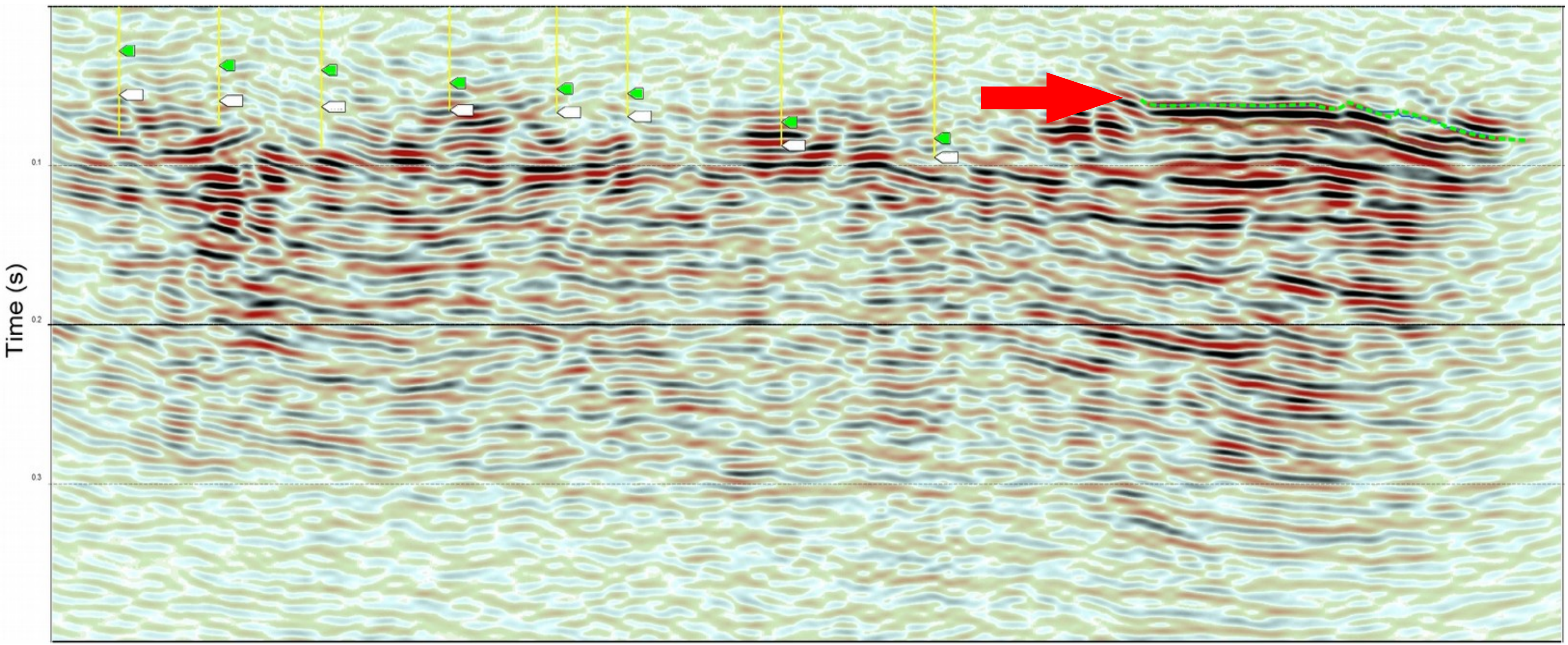
Correlation



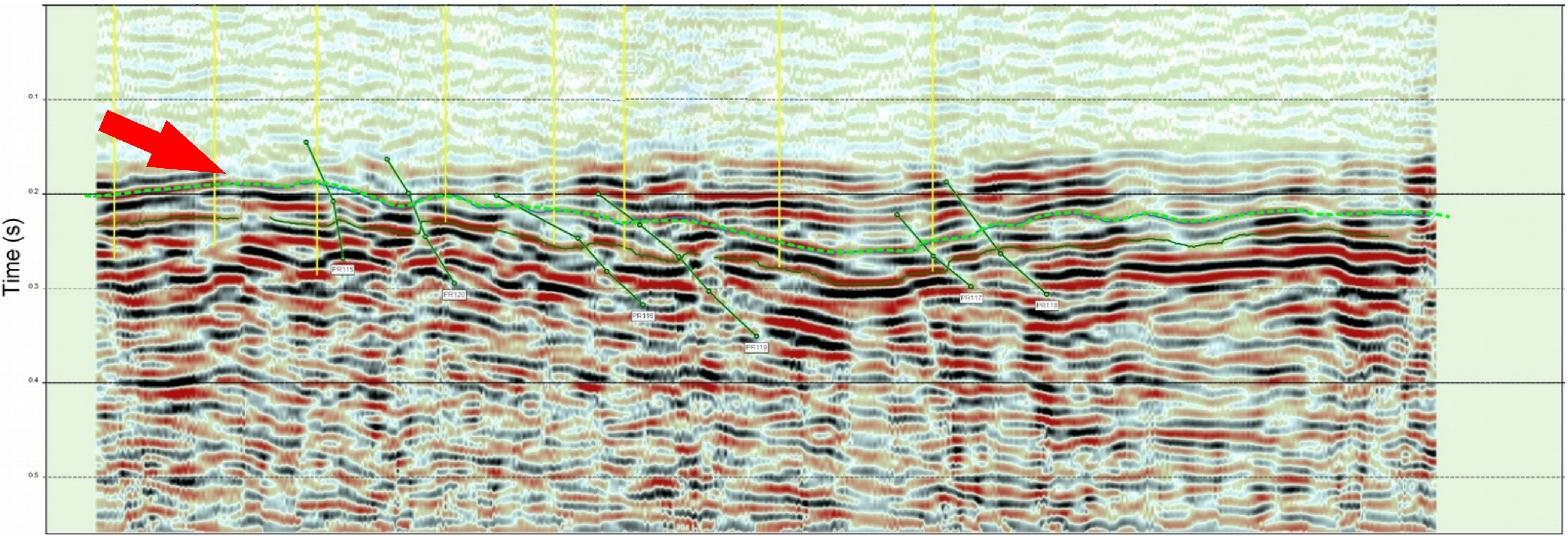
Microseismics

S-wave sources

Imaging Shallow Structures – P-wave Stack

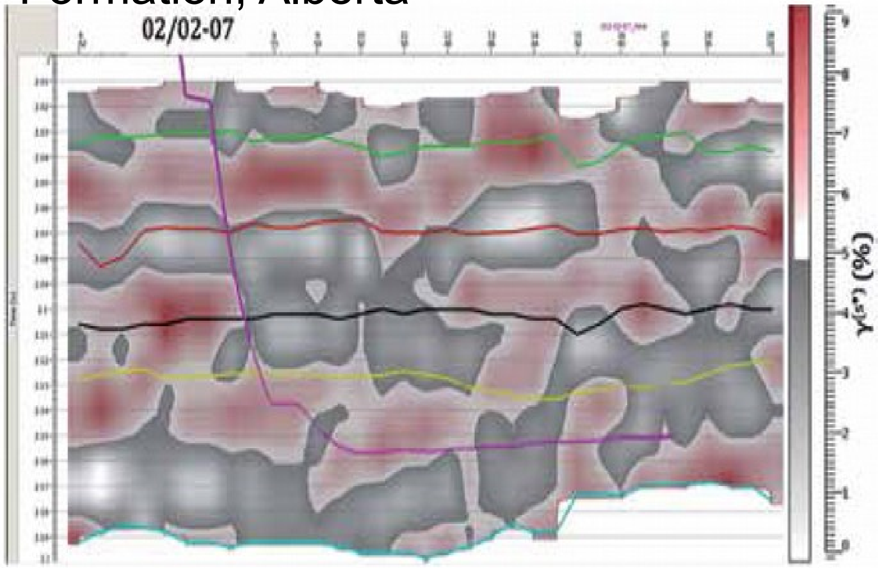


Imaging Shallow Structures – PS-wave Stack



Why Multicomponent? – Geology Identification
Gamma (Vp/Vs)

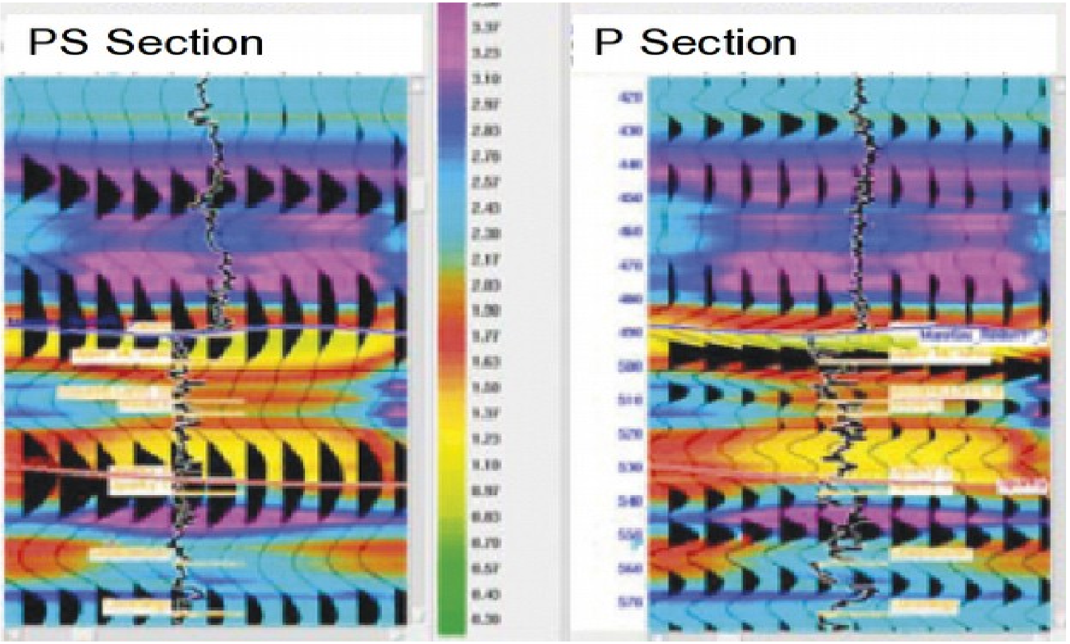
Gamma analysis from the Montony Formation, Alberta



Larger values (red) suggest regions of higher fracture density

MacFarlane & Davis (2015)
Anadarko Petroleum Corporation.
Colorado School of Mines.

Gamma analysis (colours) for heavy oil reservoirs

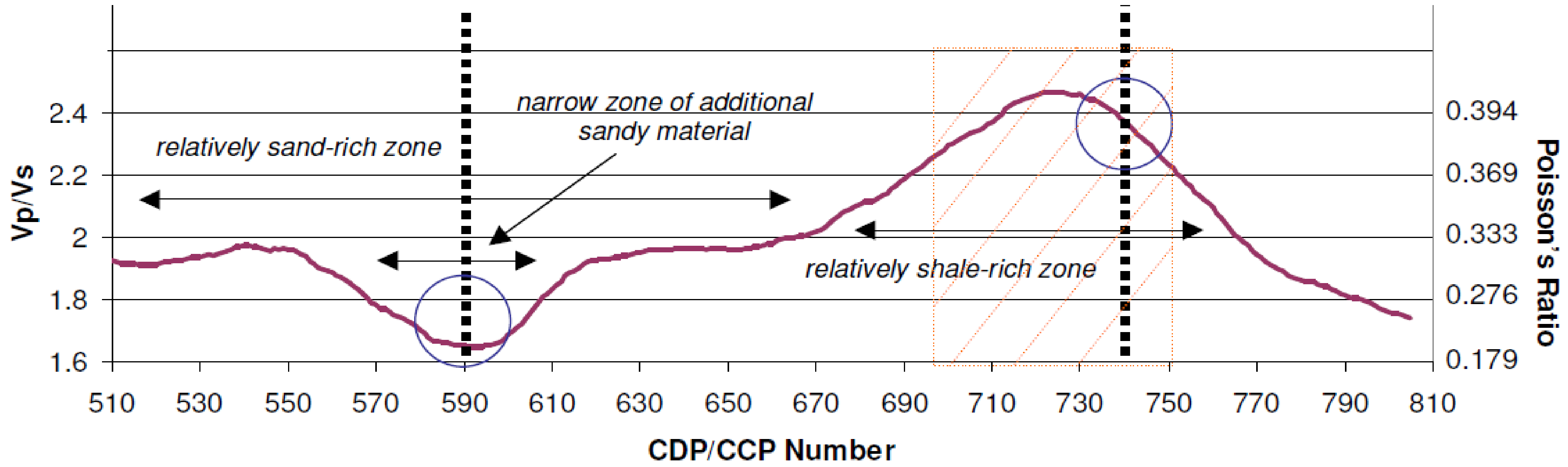


Yellow (low Vp/Vs) indicate sand rich zones

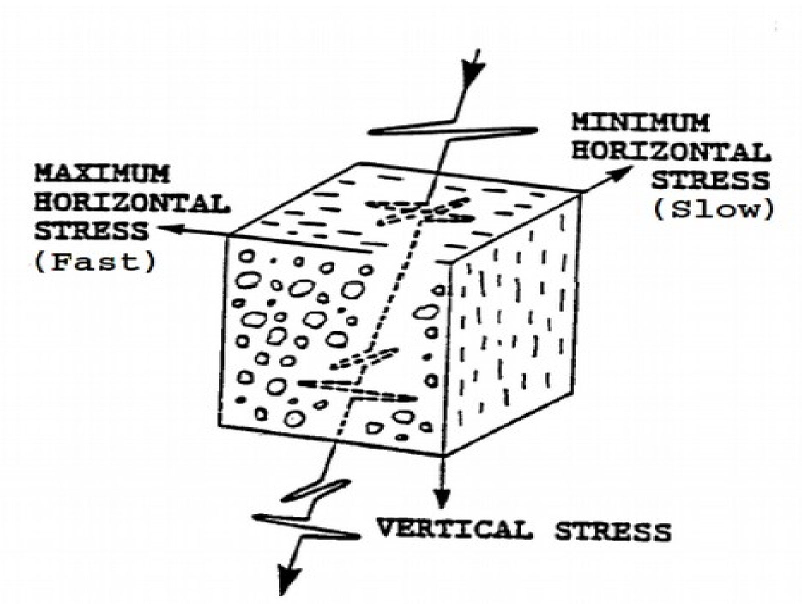
Stewart (2009)
University of Houston, University of Calgary.

Why Multicomponent? – Geology Identification
Gamma (Vp/Vs)

Gamma analysis to determine interburden strength for mine safety.

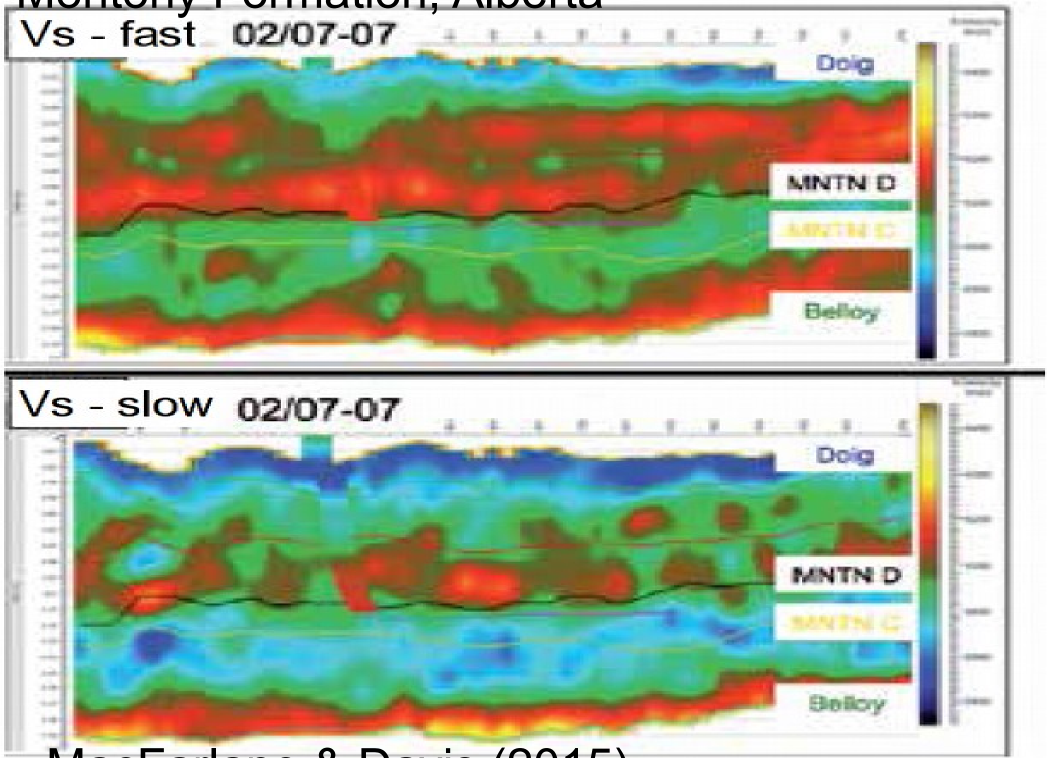


Why Multicomponent? – Fracture Identification
(S-wave splitting)



Crampin (1997)
Department of Geology and Geophysics, University of Edinburgh

Shear-wave splitting analysis from the Montony Formation, Alberta

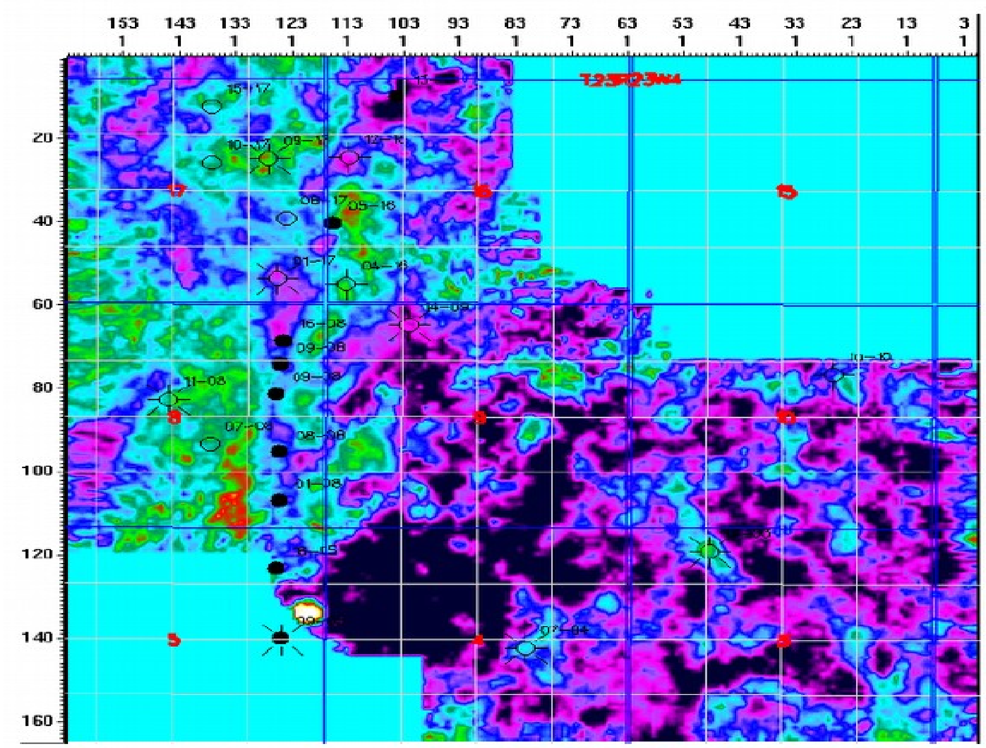


MacFarlane & Davis (2015)
Anadarko Petroleum Corporation.
Colorado School of Mines.

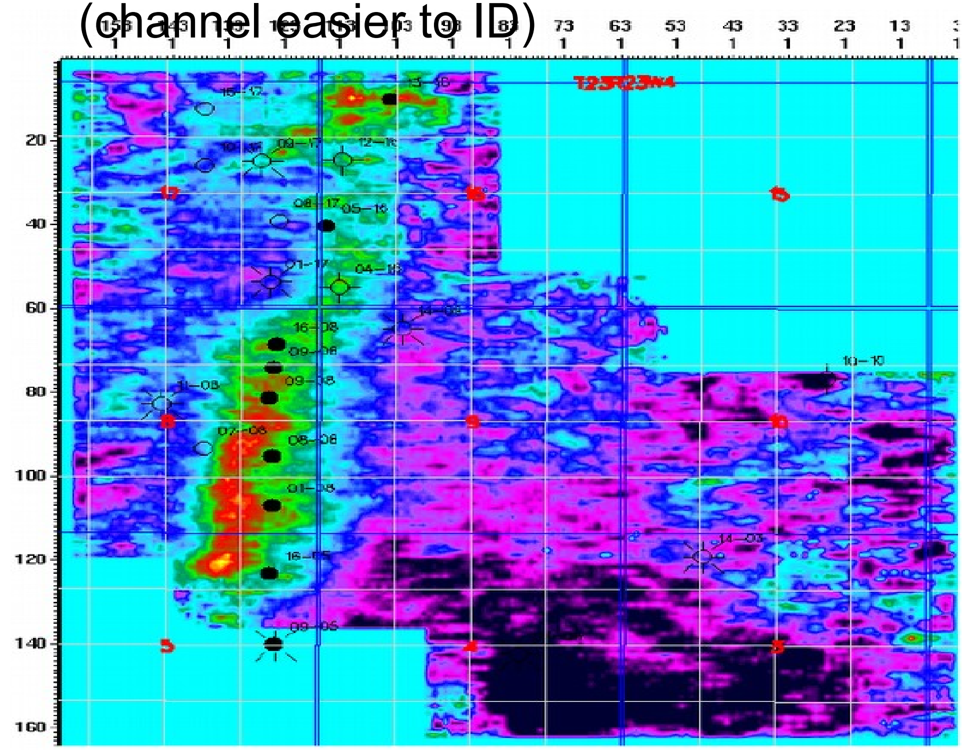
Why Multicomponent? – Structural Interpretation

Blackfoot 3D3C Survey

PP time slice of 3D volume

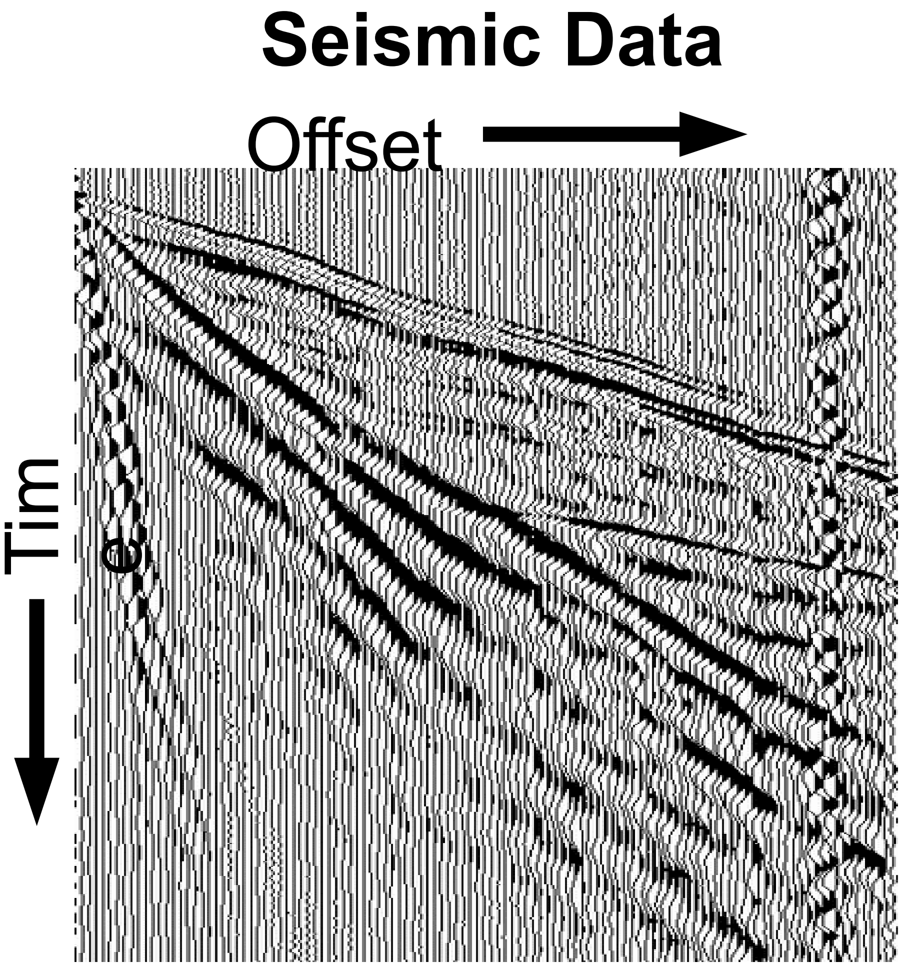


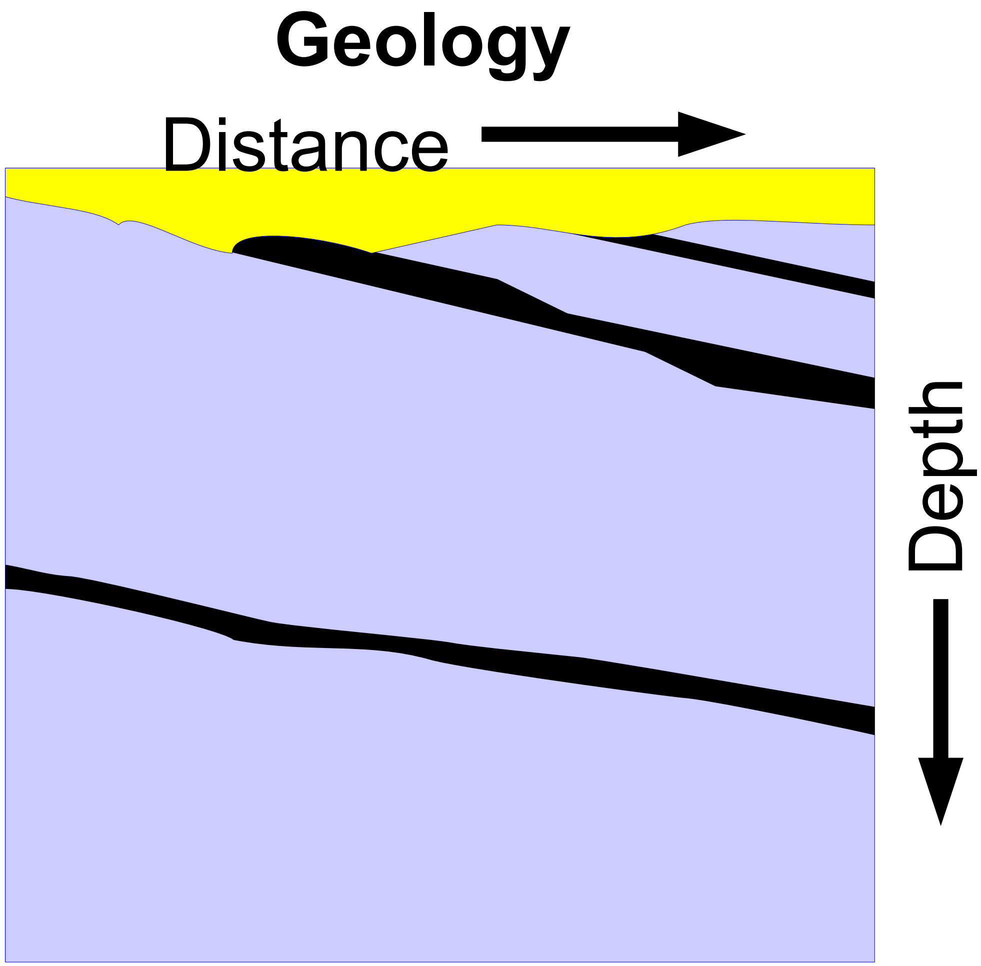
PS time slice of 3D volume
(channel easier to ID)



Stewart et al. (1999)
The CREWES Project, University of Calgary

Future – Full Waveform Inversion?





Full Waveform Inversion

Broadband Anisotropic Viscoelastic Inversion

Increasing:

- →Detail
- →Computational effort
- →Cost
- →Non uniqueness

Anisotropic Viscoelastic Inversion

Viscoelastic Inversion

Anisotropic Elastic Inversion

Elastic Inversion

Acoustic Inversion

Travel-time tomography

Seismic "Noise" Conclusions

- "Noise" is a significant percentage of the energy on a seismic record
- Includes:
  - Refractions
  - Surface waves
  - S-waves & Converted waves
  - Multiples
  - "Random" Noise

Seismic “Noise” Conclusions

- Refractions & Surface waves can provide added information about the near surface.
    - Useful for site development and resource estimate.

- S-waves provide extra information about the geological properties of the earth.

- Full waveform inversion has the potential to use all the energy of a seismic record but is extremely computationally expensive at this stage.

New developments in coal seismology

Acquisition modelling of seismic resolution

Seismic anisotropy and stress prediction

Exploitation of seismic noise

Velseis
Integrated Seismic Technologies

UQ
EXPLORATION GEOPHYSICS

Further Reading

Crampin, S, (1997) Going APE: I - Modeling the inherent anisotropy of intact rock. SEG Technical Program Expanded Abstracts 1997. January 1997, 952-955

Gaiser J., Strudley A., 2005, Acquisition and application of multicomponent vector wavefields: are they practical?, First Break volume 23, 2005

Hendrick N., (Velseis), 2007, Integrated P-wave/PS-wave seismic imaging for improved geological characterisation of coal environments, ACARP Project C13029.

Hoffe B.H., Bland H.C., Margrave G.F., Manning P.M., 1999, Analysis of the effectiveness of 3-C receiver arrays for converted wave imaging, SEG Abstracts 1999.

Kendall R., 2006, Advances in Land Multicomponent Seismic: Acquisition, Processing and Interpretation. CSEG Recorder 2006.

MacFarlane T.L., Davis T.L., 2015, Fracture characterization of the Montney Formation using amplitude inversion of converted wave seismic, First Break volume 33, 2015

Nolan, J. J., Miller, R., Ivanov, J., Peterie, S., & Lindgren, E. (2013). Near-Surface Salt Dissolution Void Identification Using Passive MASW. In 2013 SEG Annual Meeting. Society of Exploration Geophysicists.

Stewart R.R., 2009, The measure of full-wave motion: An overview of multicomponent seismic exploration and its value. CSEG Recorder 2009.

Stewart R.R., Gaiser J.E., Brown R.J., Lawton D.C., 1999, Converted-wave seismic exploration: a tutorial, CREWES Research Report, 11.

Strong S., Hearn S., (Velseis), 2011, Towards 3D, integrated P+PS seismic imaging of coal targets, ACARP Project C17029.