Title
San Juan Fracture Characterization Project: Status and current results

Authors
Majer, E.L.
Daley, T.M.
Myer, L.R.
et al.

Publication Date
2001-02-26

San Juan Fracture Characterization Project: Status and Current Results

E.L. Majer, T.M. Daley, L.R. Myer, K. Nihei

Lawrence Berkeley National Laboratory

J. Queen, J. Sinton, J. Murphy, M. Fortuna - *Conoco, Inc*

H.B. Lynn

Lynn, Inc

M.A. Imhof and R. Wilson

Virginia Tech

Development and Validation of the Next Generation Seismic Imaging Methods for Quantifying Naturally Fractured Gas Reservoirs

Industry: Conoco Inc., Schlumberger-Doll Research, Schlumberger Reservoir Technologies, Lynn Inc.

University: Stanford University, Virginia Tech

Lawrence Berkeley National Laboratory

Statement of Problem

- Small fractures often control the permeability over a large area
- Fractured reservoirs often occur in heterogenous geologic environments
- Past advances in seismic imaging using surface methods identify anisotropy
- Anisotropy can be caused by geologic fabric as well as fractures
- Needed are methods/approaches to sort out the different effects in order to identify the fractures controlling flow and transport

Needs

- Today's technology can locate fracture patterns and general geometry, but there are no reliable methods to quantify fracture characteristics
  - Fracture density
  - Fracture spacing
  - Fracture interactions
  - Fracture fillings
  - Fracture permeability

Overall Objectives

- Extend current state-of-the-art 3-D imaging to extract the optimal information for fracture quantification
- Develop next generation capability in fracture imaging for true 3-D imaging of the static and dynamic fracture properties

Hypothesis Addressed

- Seismic waveforms contain the information to map and quantify the necessary fracture properties (detectability hypothesis)
- To obtain the necessary seismic data, larger band-widths, greater dynamic range and spatial coverage can only be provided with subsurface methods (high frequency hypothesis)
- Technology is available, or soon to be available, to obtain the necessary spatial coverage, band width, and dynamic range in a cost-effective fashion (technology hypothesis)

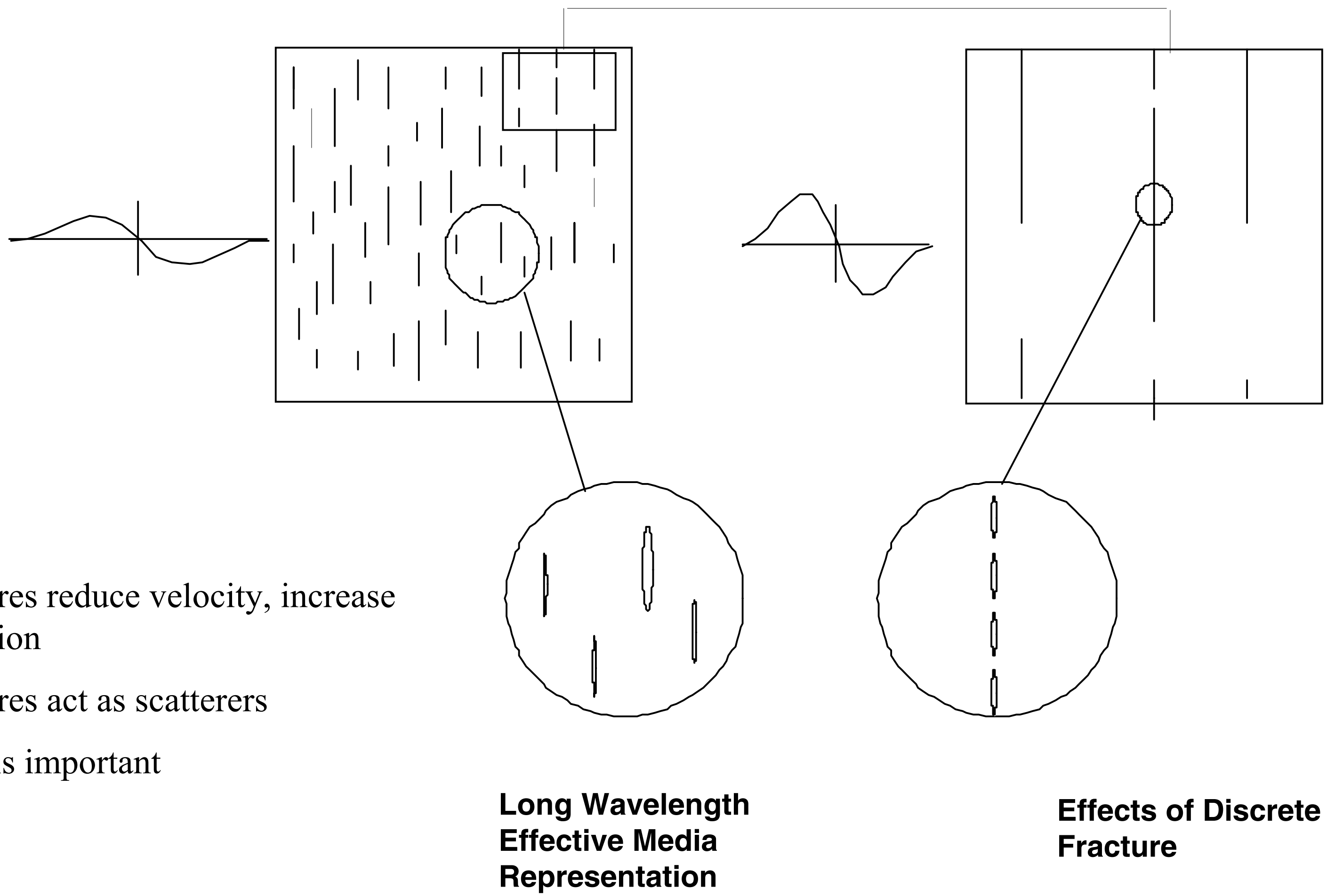
Tasks

- Modeling
- Field Measurements
- Processing and Interpretation
- Reservoir Simulation

Theoretical Background

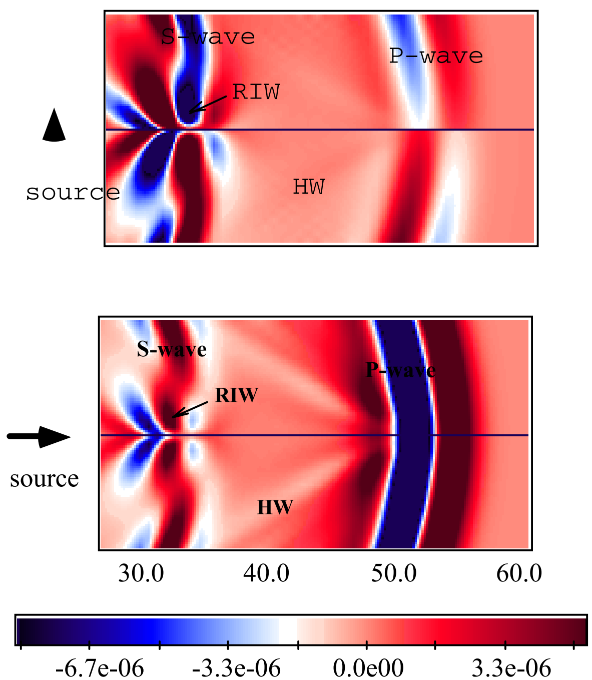
- Conventional model: fractured rock represented by effective anisotropic medium.
- State-of-the-art model: fractures represented by “point” scatterers.
- Explicit fracture model: fractures produce waves not predicted by either of above approaches.

Seismic Characteristics of Fractures

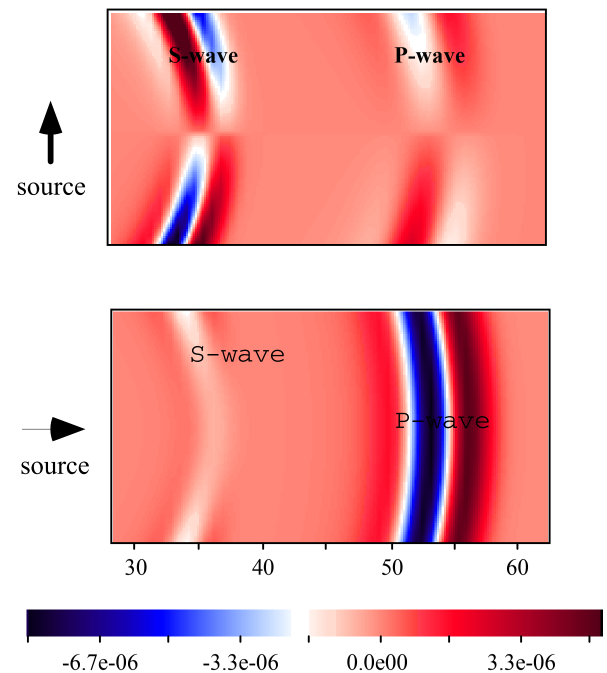


- Fractures reduce velocity, increase attenuation
- Fractures act as scatterers
- Scale is important

Wave Propagation in Fractured Rock



Homogeneous medium with one fracture

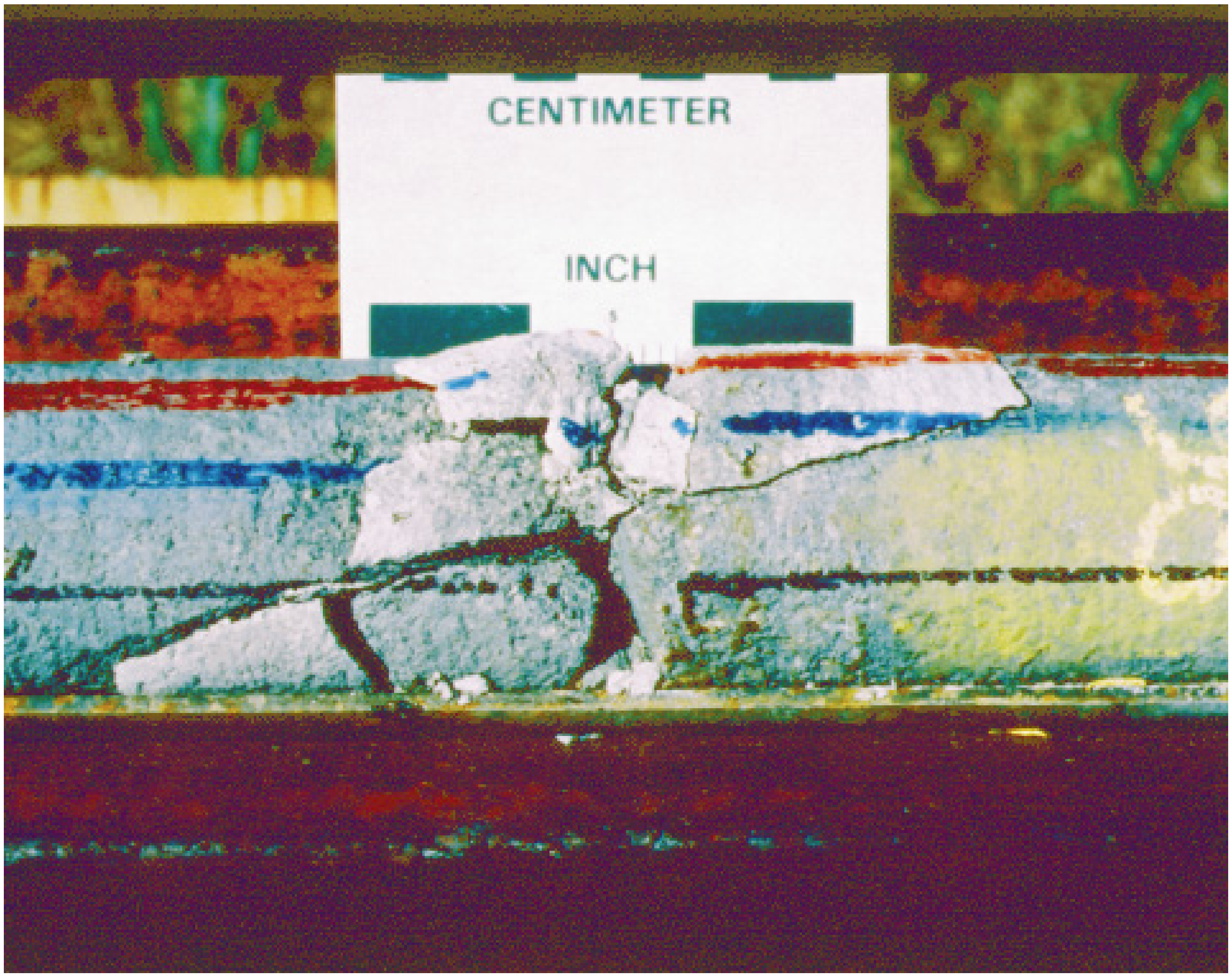


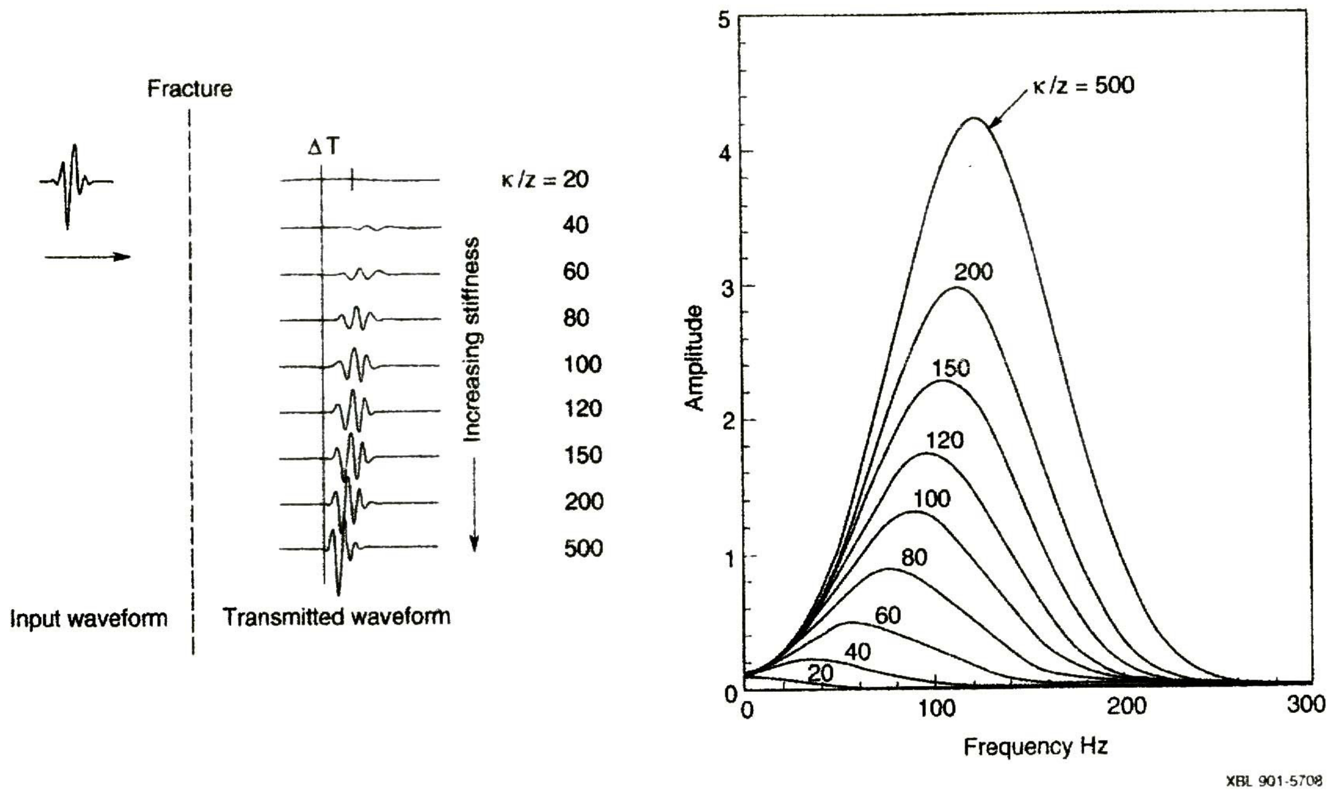
Equivalent homogeneous medium

?Energy partitioning affected by discrete fractures

?Fractures in an equivalent medium slow and attenuate and can result in effective anisotropic properties

Fracture Core Sample




Fracture
ΔT
κ/z = 20
40
60
80
100
120
150
200
500
Increasing stiffness
Input waveform
Transmitted waveform
Amplitude
0
1
2
3
4
5
κ/z = 500
200
150
120
100
80
60
40
20
0
100
200
300
Frequency Hz
XBL 901-5708

Approach

- Past work has been in smaller scale experiments, theory and laboratory work has supported high frequency and detectability hypothesis
- Now we are ready to scale up to field scale in production environment
- Develop methods in conjunction with users and implementation of technology for optimal technology transfer
- Today's economic environment requires cost sharing and leverage

Approach (cont.)

- Select field with following attributes
  - Economically viable
  - Well characterized with other information
  - Mature enough to test methodologies
  - Aggressive infill-drilling program
  - Cooperative operator with vision and resources to apply to problem, as well as be able to implement technology
- Conoco, San Juan meets all criteria

Modeling and Analysis

- Develop new processing methods to quantify fracture spacing, orientation and properties; develop new attributes.
- Utilize new understanding of properties of the diffracted wavefield.
- Apply to both surface seismic and high resolution single well, VSP, and crosswell data.
- Develop optimum acquisition geometries and frequencies, source receiver geometries.

Theory

1. Discrete fracture realization
2. Dynamic composite elastic medium theory
3. Mixing model of gas-fluids

Seismic Modeling of Fractures

- Development of a hybrid 3-D ray-finite difference wave propagation simulator for modeling seismic wave propagation in fractured reservoirs.

- Numerical 2-D and 3-D parametric studies examining the effects of finite length fractures embedded in sand-shale lithologies (e.g., effects of fracture spacing, dimensions, and stiffnesses) for surface seismic, vertical seismic, crosswell, and single well acquisition geometries and frequencies.

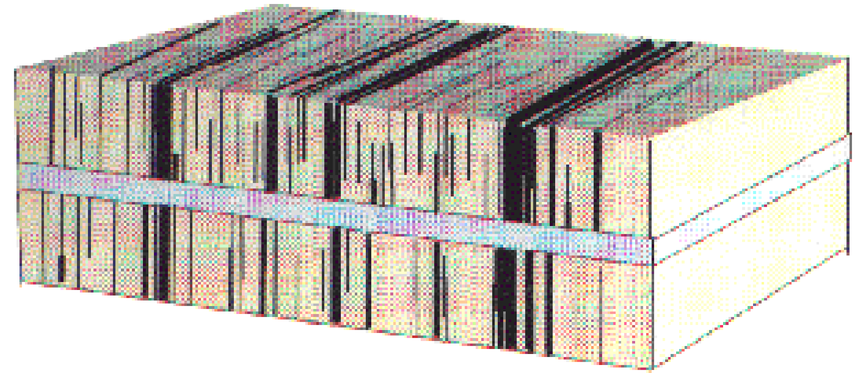
- Analysis of wavefields for frequency-dependent wave speeds, particle motions, and amplitudes. Analyses of the partitioning of incident P- and S-body waves into the various fracture-related waves and the subsequent radiation off the fracture back into body waves will be examined for both P- and S-wave sources.

- Modeling of the seismic data obtained from the VSP, crosswell, and single well surveys.

Modeling Approach

Phase I

- Build 3-D model.
- Forward model of surface seismic
- Compare with 3-D surface data.
- Refine and iterate.



A litho-mechanical model for Austin Chalk

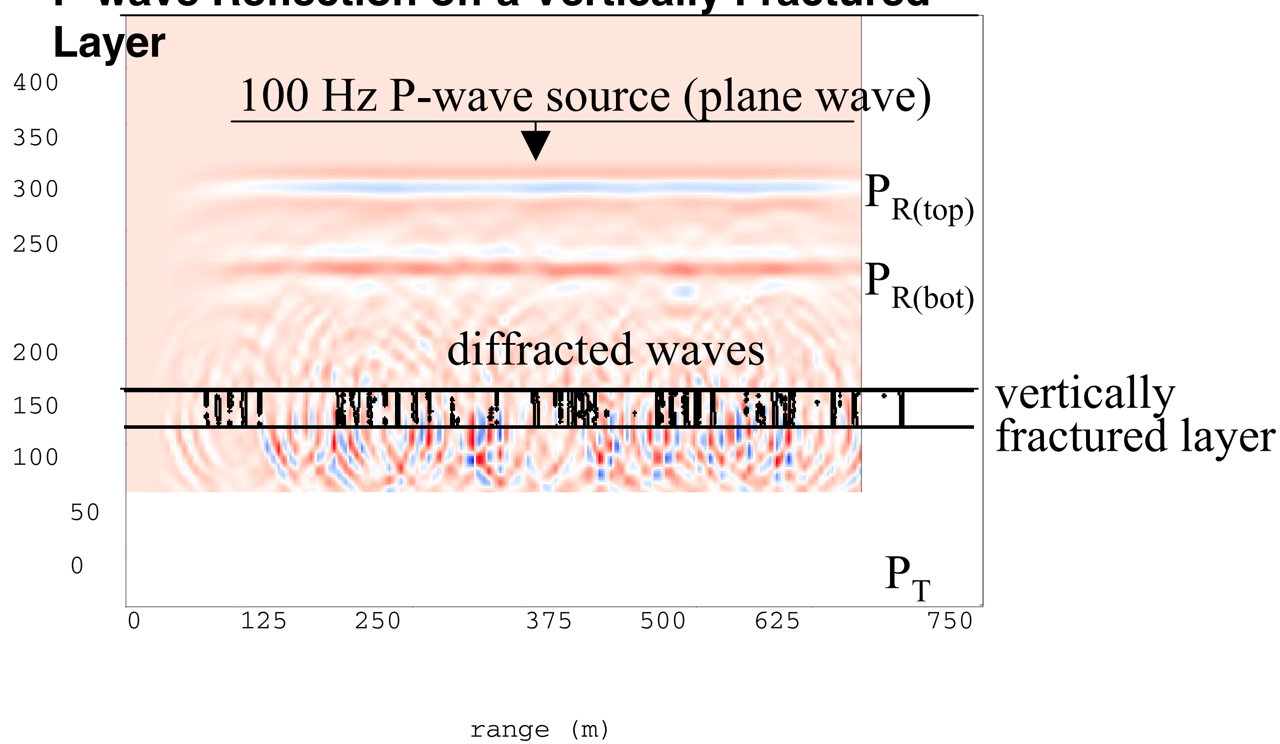
Phase II

- **Forward model for single well and crosswell configuration.**
- **Compare with observations.**
- **Refine and iterate.**

Example Model Results

- **2D**
- **Background: sandstone**
- **Fractured layer: sandstone with fractures**

P-wave Reflection off a Vertically Fractured Layer



3-D Model

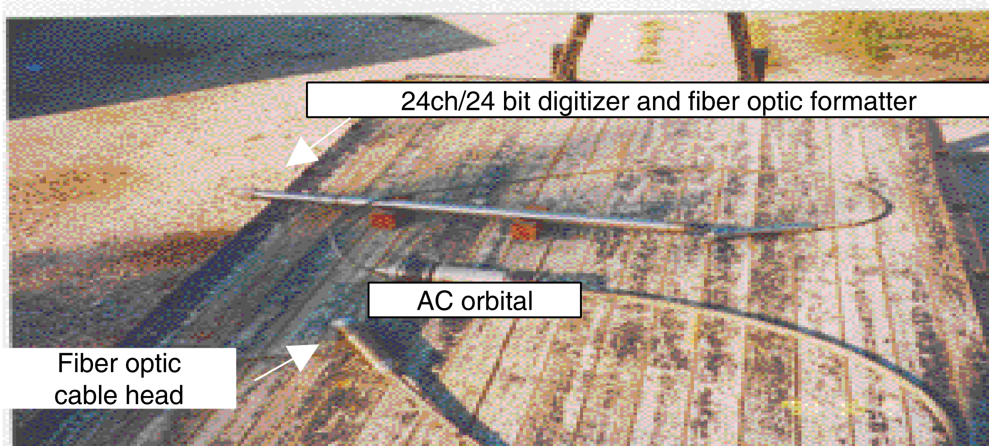
- Layered model above reservoir.
- Explicit representation of fractures in reservoir interval
  - Based on previous geophysical and geologic work; outcrop data.
- One approach: ray trace through upper layers;
  3-D finite difference for fractured reservoir.

Field Measurements

- 3-D seismic data (Conoco, Lynn Inc.)
  - P-waves
  - Multicomponent
- VSP multicomponent (LBNL, Schlumberger)
- Single well (LBNL, Schlumberger)
  - Orbital, far offset piezoelectric
  - High frequency
- Semi-permanent/permanent arrays
- Time lapse acquisition
- Manipulation experiments

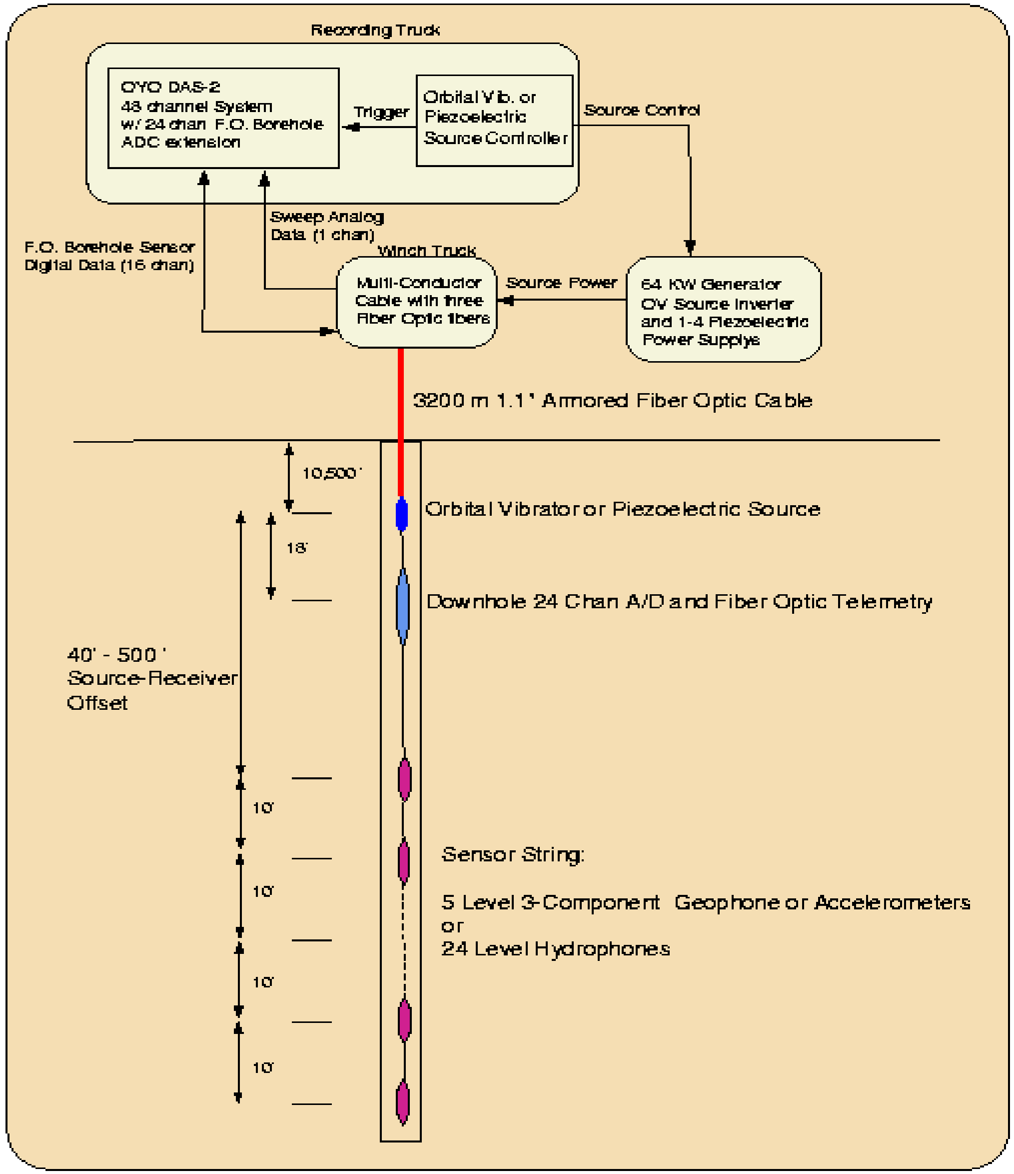
Deployment of LBNL Single Well System

Fiber optic/24 bit system with AC orbital source



AC orbital source with borehole (cushions)

LBNL Single Well Seismic Imaging System



Anticipated Products and Benefits

- Greatly advanced commercially available technology to quantify fracture properties in gas reservoirs (Schlumberger, Lynn Inc.)
- Advancement and optimization of current 3-D seismic technology
- Leap to true 3-D subsurface imaging using seismic methods
- Improved links with reservoir modeling technology for fracture characterization

Summary

- Joint Industry/University/Lab cooperative proposal that leverages resources and accelerates commercialization of technology
- Anticipated Products
  - Optimized methods for 3-D surface seismic for fracture quantification
  - Commercialization of current prototype/research borehole seismic methods
  - Birth of a new technology for true 3-D imaging

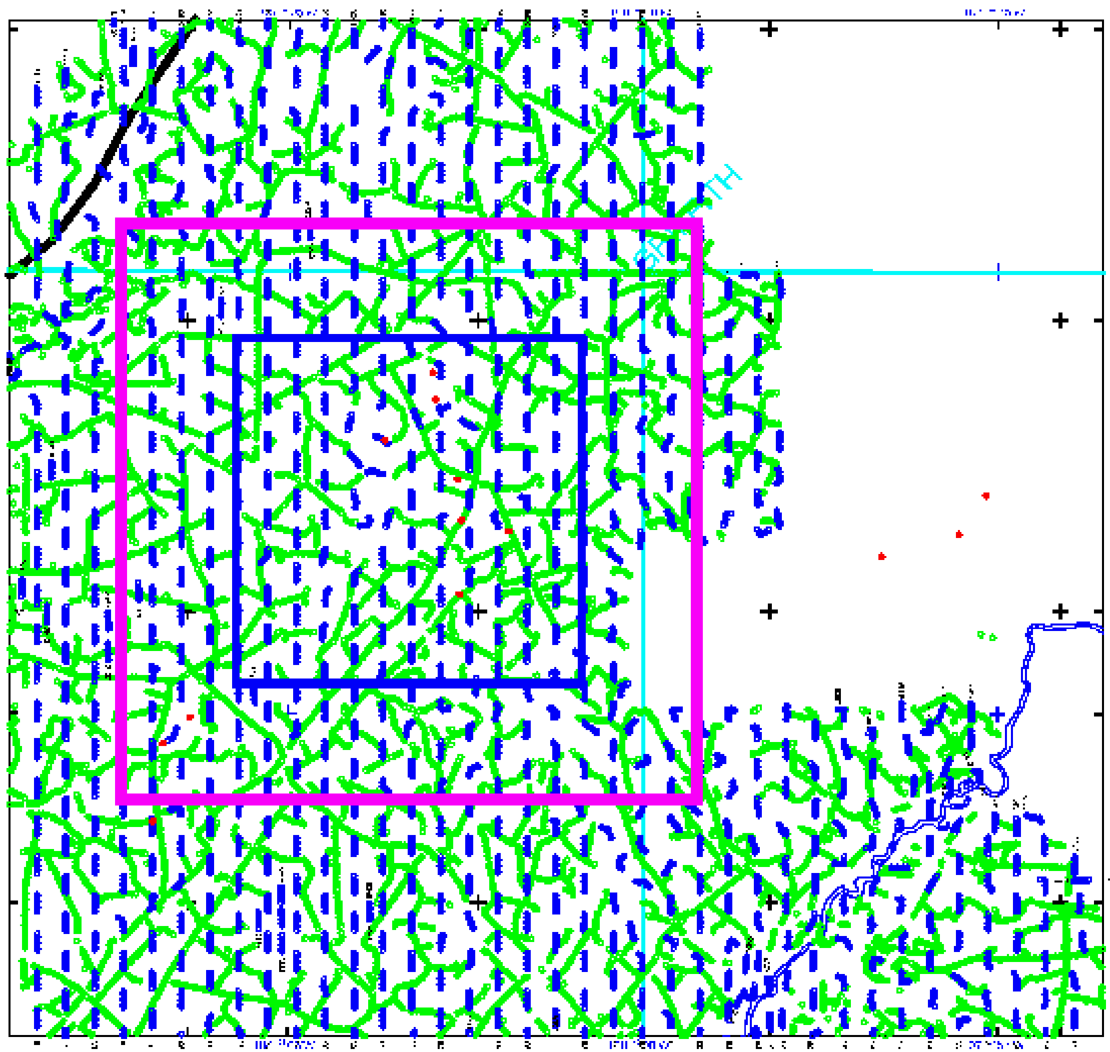
LBNL Fracture Quantification Project
Review of Seismic Processing

December, 2000

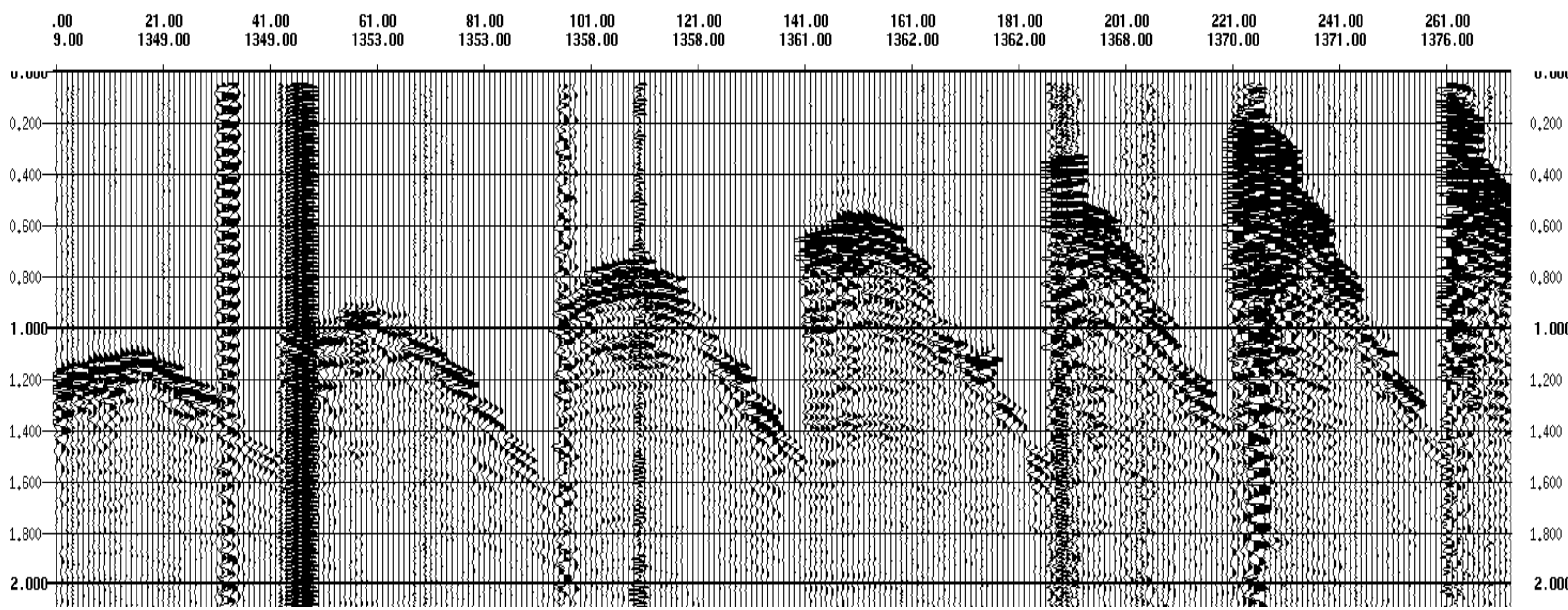
Processing Goals

- Process data from the San Juan Basin 3-D survey necessary to produce 20 square miles of fully imaged data, using the advanced seismic processing techniques selected by LBNL.
- Provide LBNL with data necessary to meet the goals of all partners.

Area of Interest



Raw Data



.00
9.00
21.00
1349.00
41.00
1349.00
61.00
1353.00
81.00
1353.00
101.00
1358.00
121.00
1358.00
141.00
1361.00
161.00
1362.00
181.00
1362.00
201.00
1368.00
221.00
1370.00
241.00
1371.00
261.00
1376.00
0.200
0.400
0.600
0.800
1.000
1.200
1.400
1.600
1.800
2.000

Processing Sequence

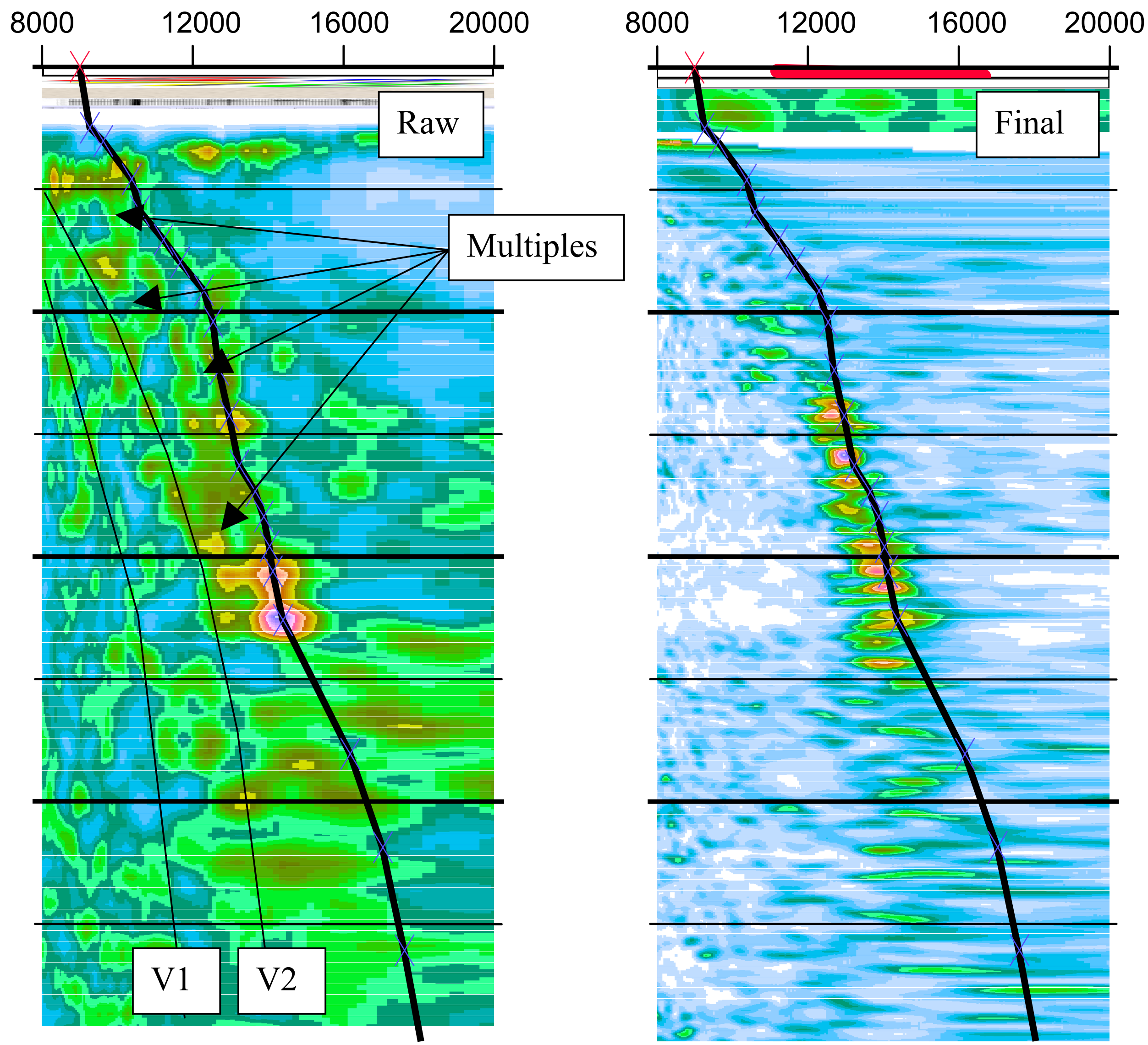
Preprocessing

- Edit traces, apply geometry
- Refraction statics & VA
- GD correction
- Source noise attenuation
- SCAC
- Noise despike
- Two passes of RS & VA
- Tau-P demultiple
- Gapped decon

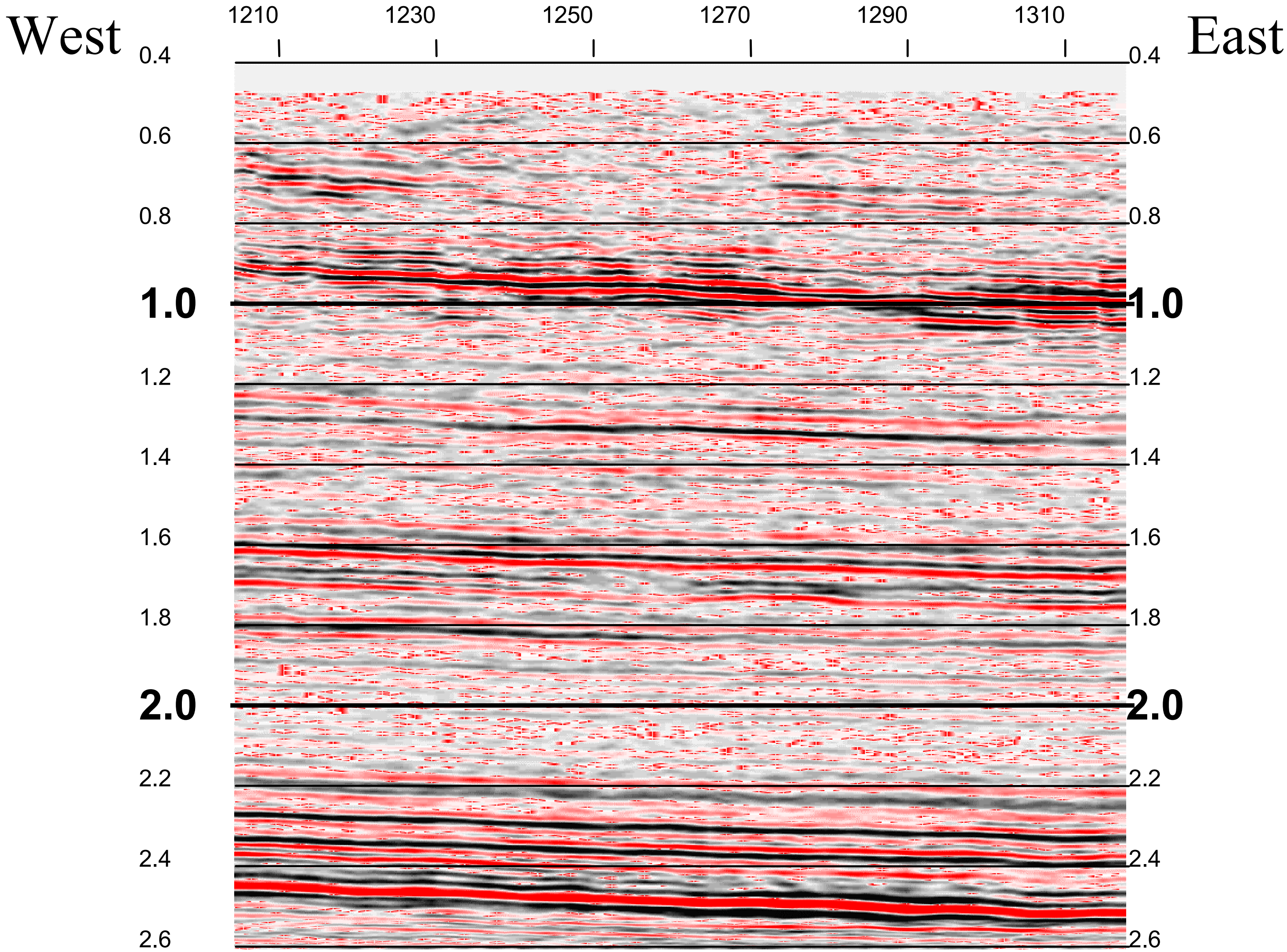
Imaging

- MVXP, CMP statics, Filter
  - 2-pass FK migration
  - KBSTM
  - Azimuthal KBSTM
- VA & Stack
- Post-processing & coherency enhancement.

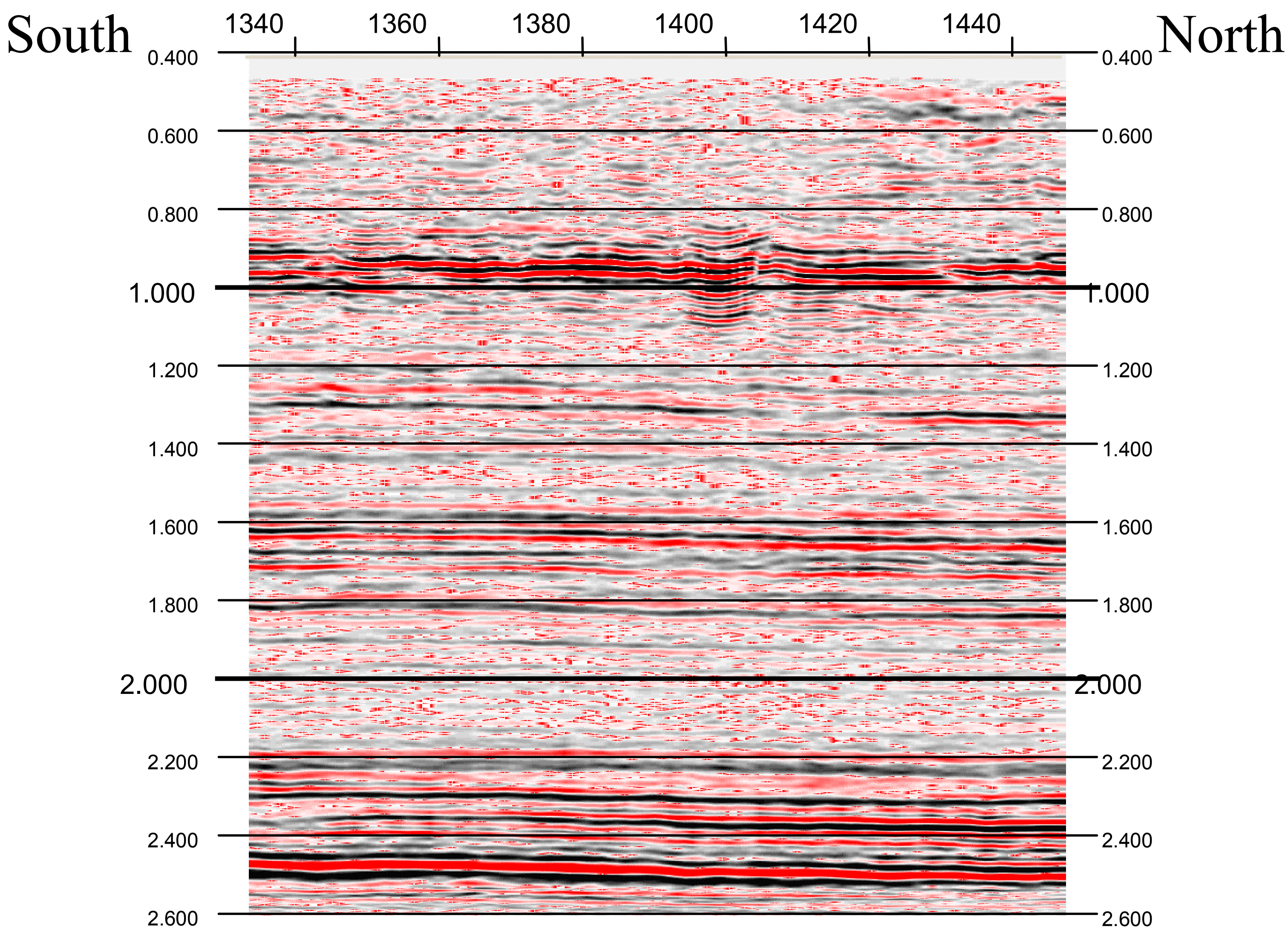
Typical Velocity Analysis



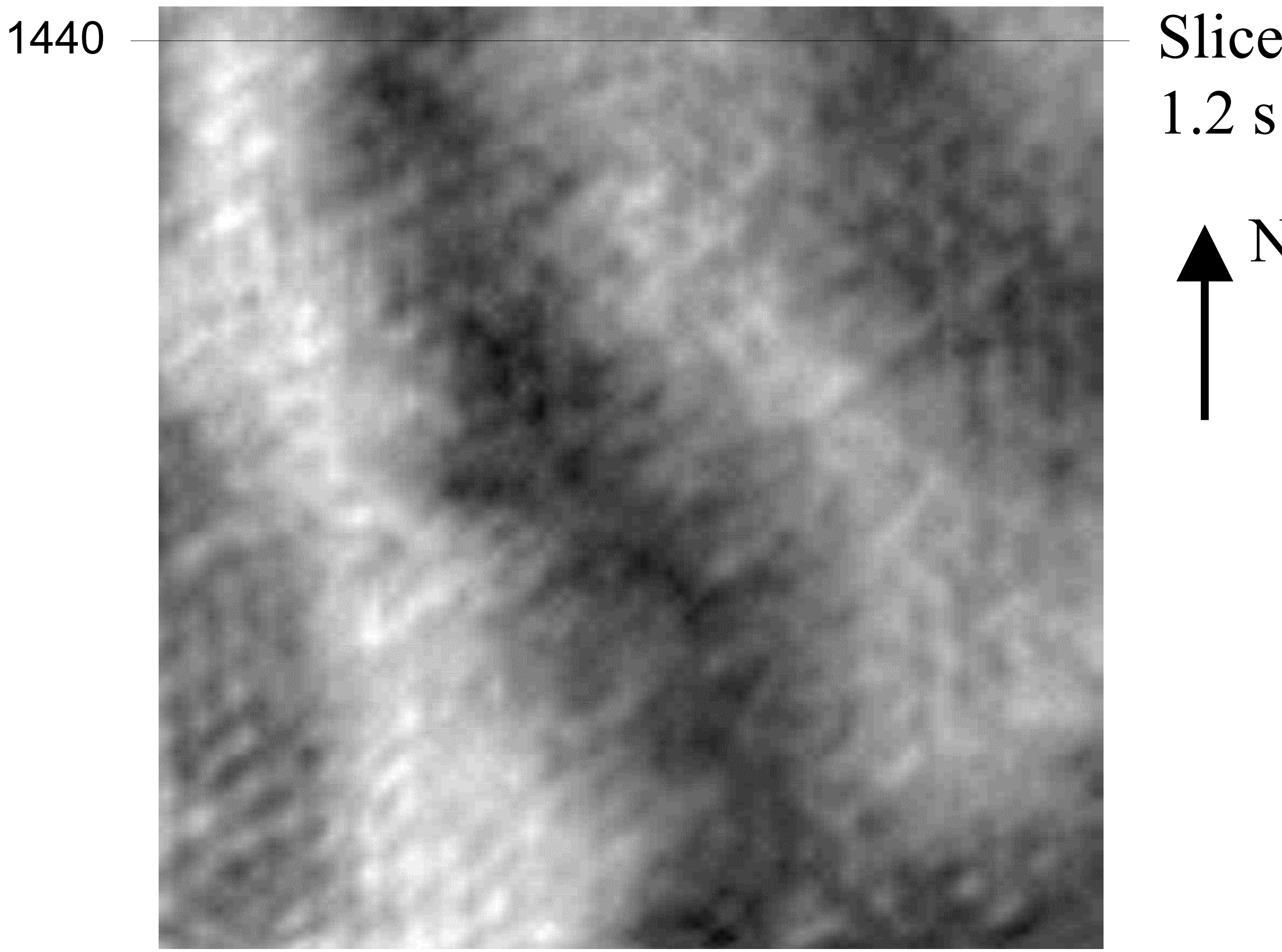
KBSTM Line 1390



KBSTM Xline1260



Acquisition Foot Print



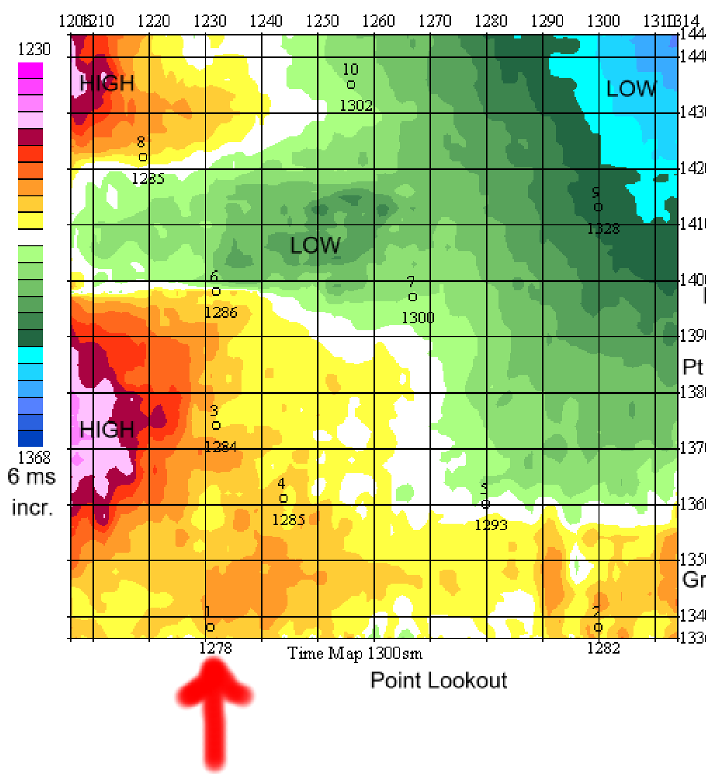
SUMMARY

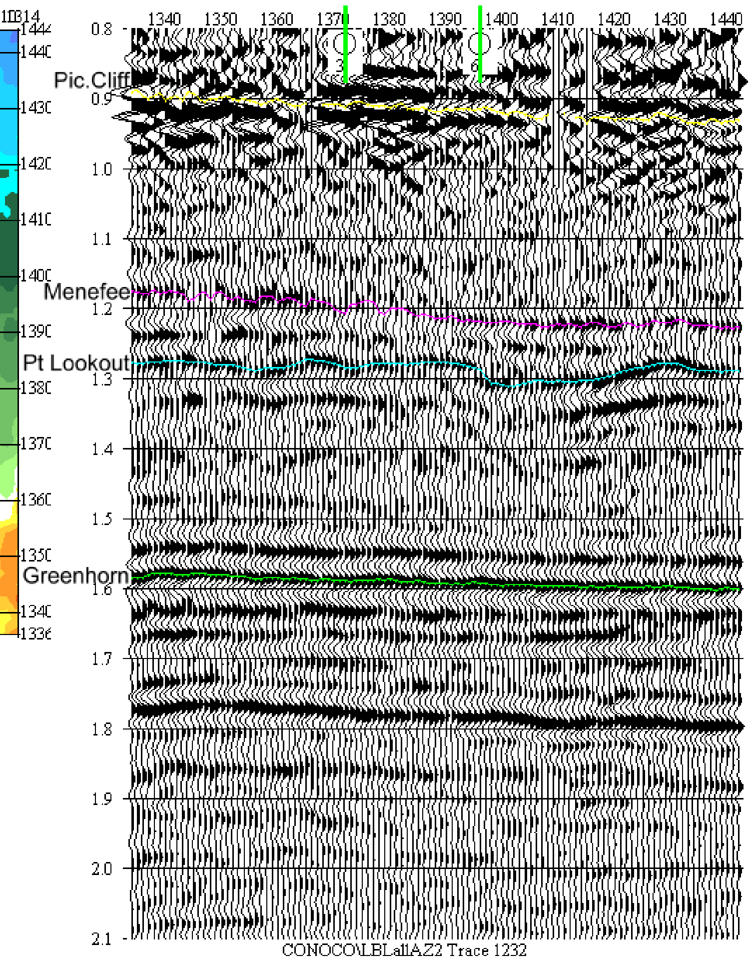
- Reprocessing significantly improved data quality.
  - Shallow data improved by order of magnitude.
  - New seismic volume is consistent with known geologic dip.
  - Reflections are more consistent and have apparently higher S/N.
- LBNL was provided with the following data.
  - SEGY tapes of edited “raw” data with geometry.
  - SEGY tapes of preprocessed data without deconvolution.
  - Several different types of fold of stack plots for anisotropy analysis.
  - SEGY tapes of KASTM volume.
  - SEGY tapes of final KBSTM volume.
  - Preliminary and final (in progress) processing reports.

Interpretation/Azimuth Gathers

H.B. Lynn, Lynn Inc.

Time Map – Pt. Lookout – Xline 1232

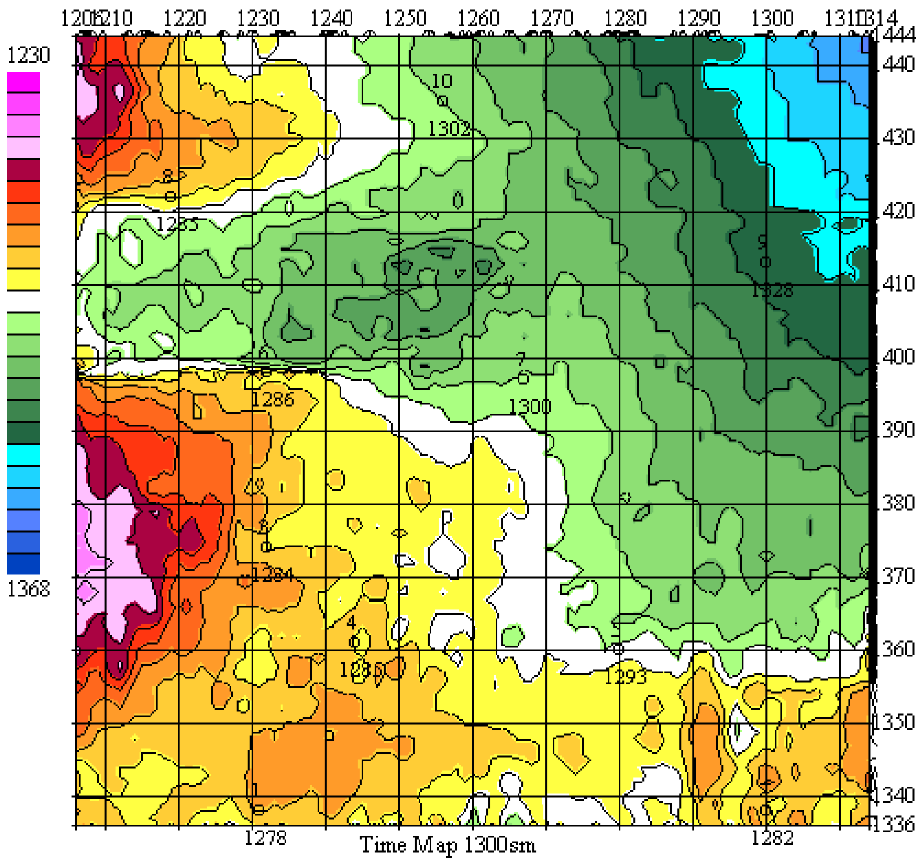




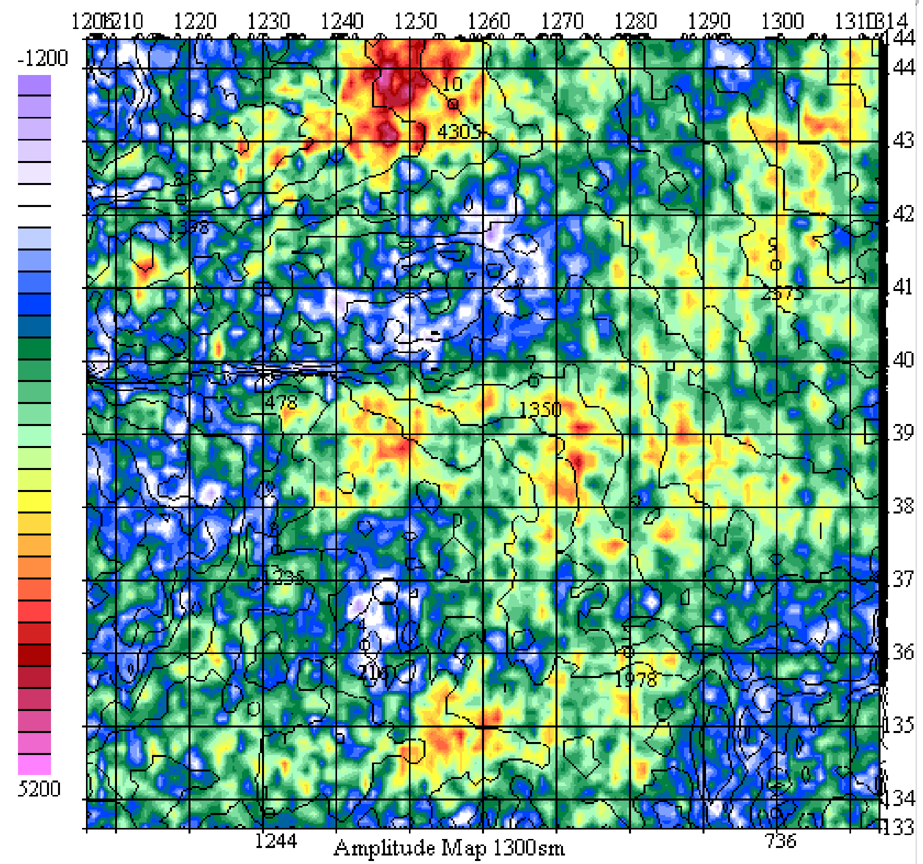
fn mIntro1

Pt. Lookout Time & Ampl. Map

3D (post stack) Time Migration

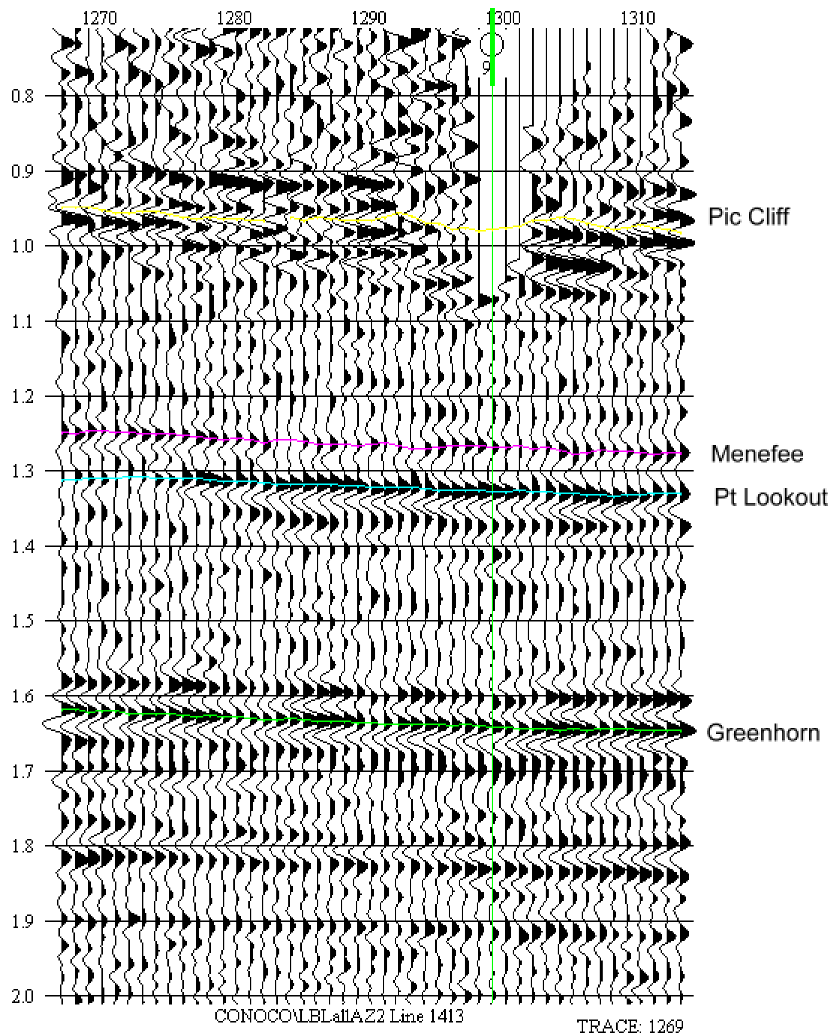


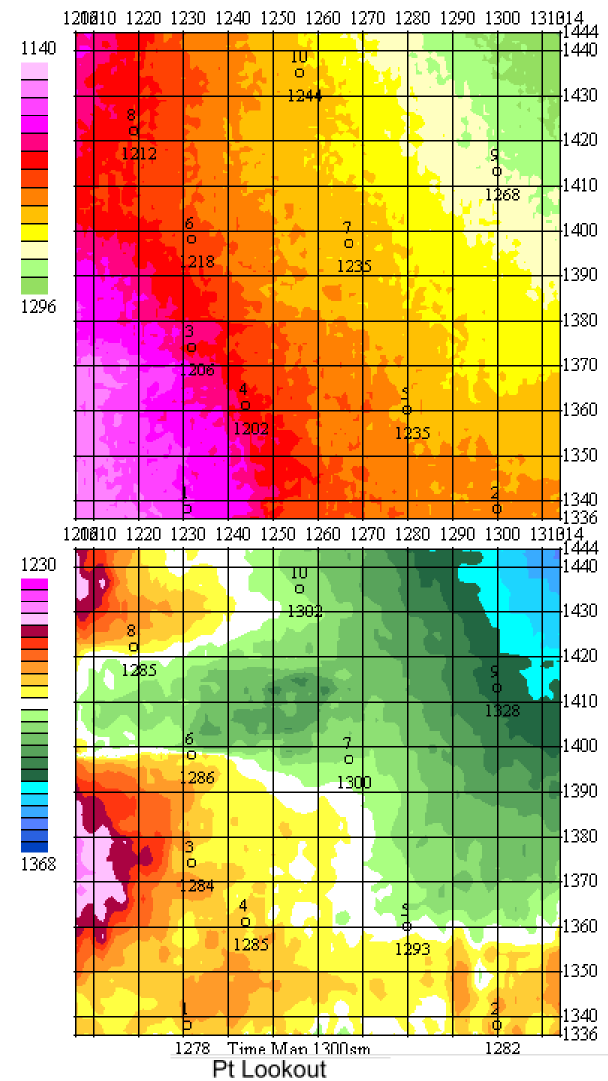
TIme map - Point Lookout



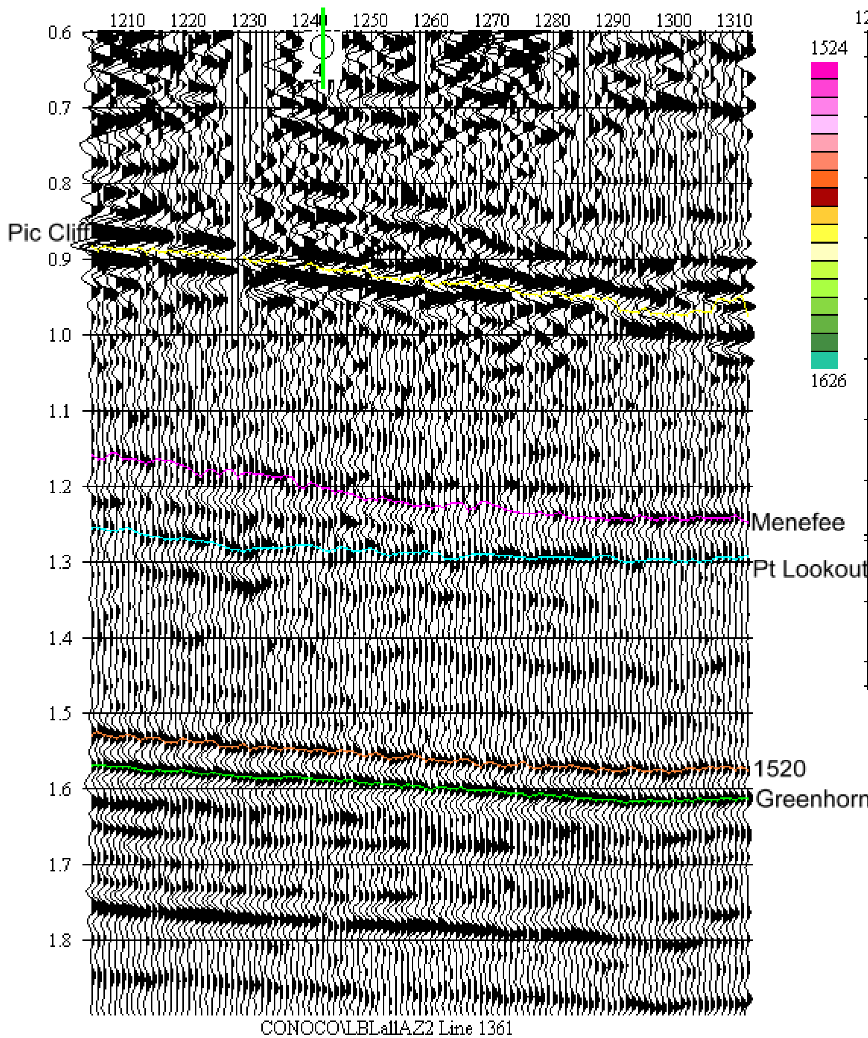
Ampl. map - Point Lookout

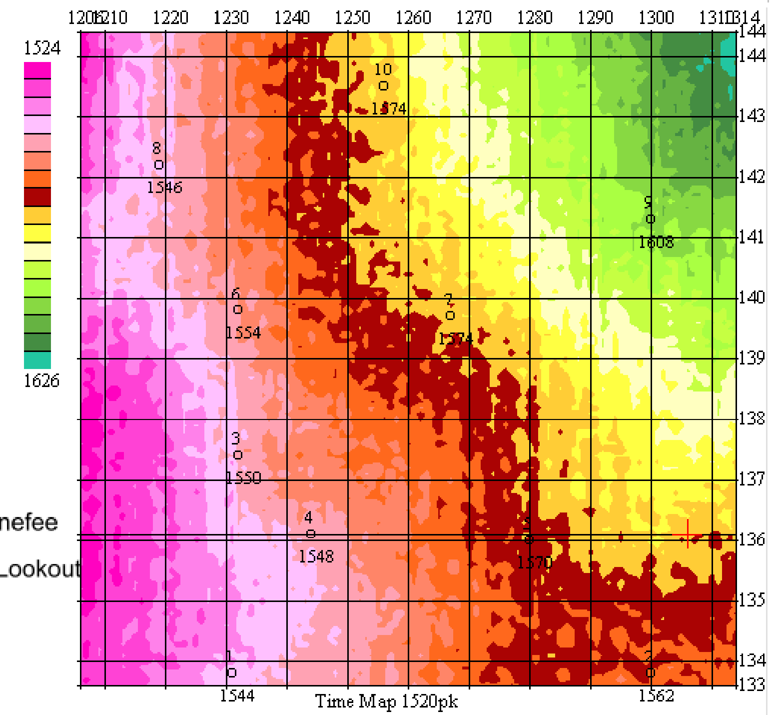
Line 1413 – Site 9 – Menefee, Pt. Lkout Time Maps





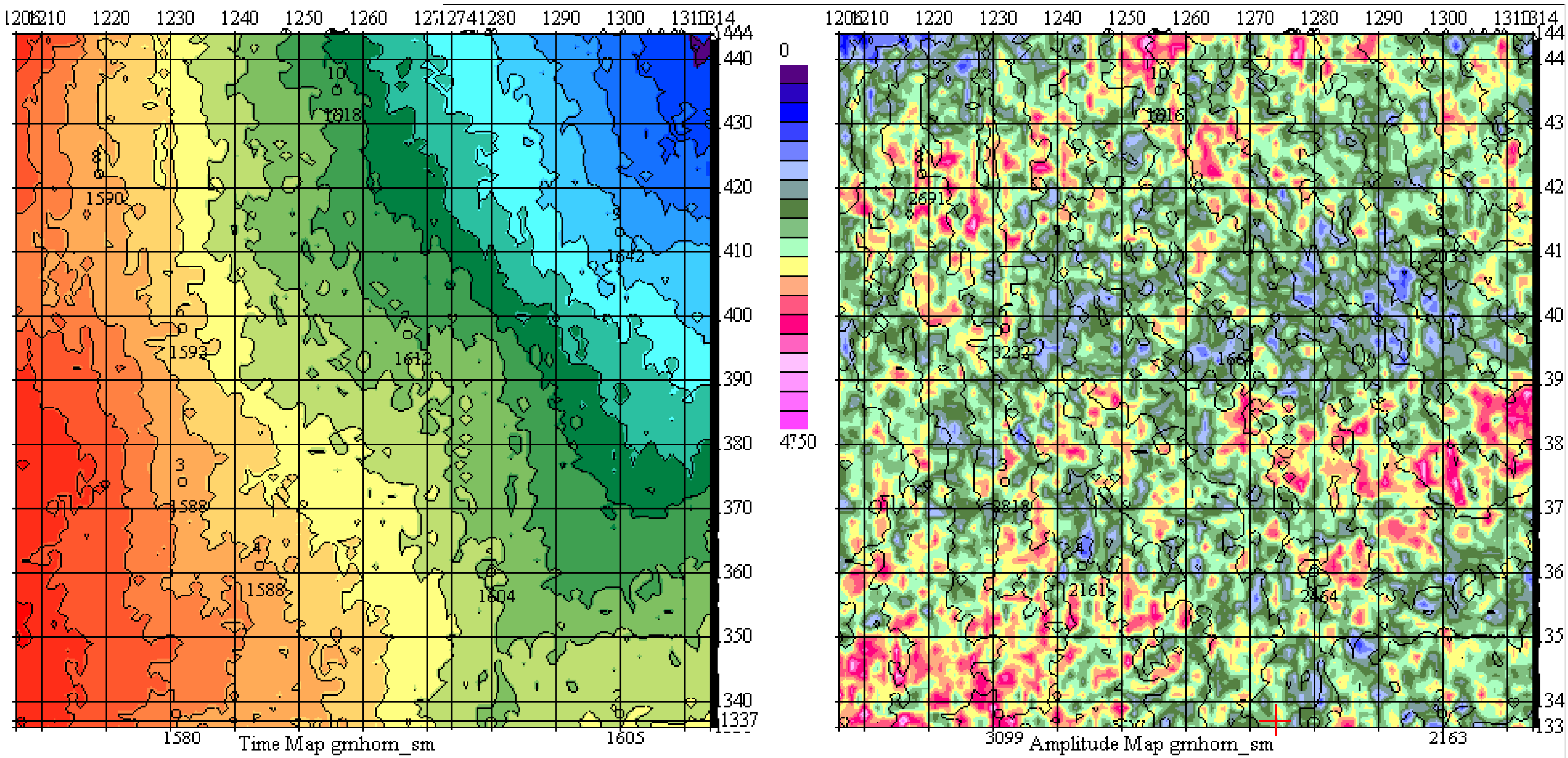
L-1361–time map event 1520





Time and Ampl. Maps: Greenhorn

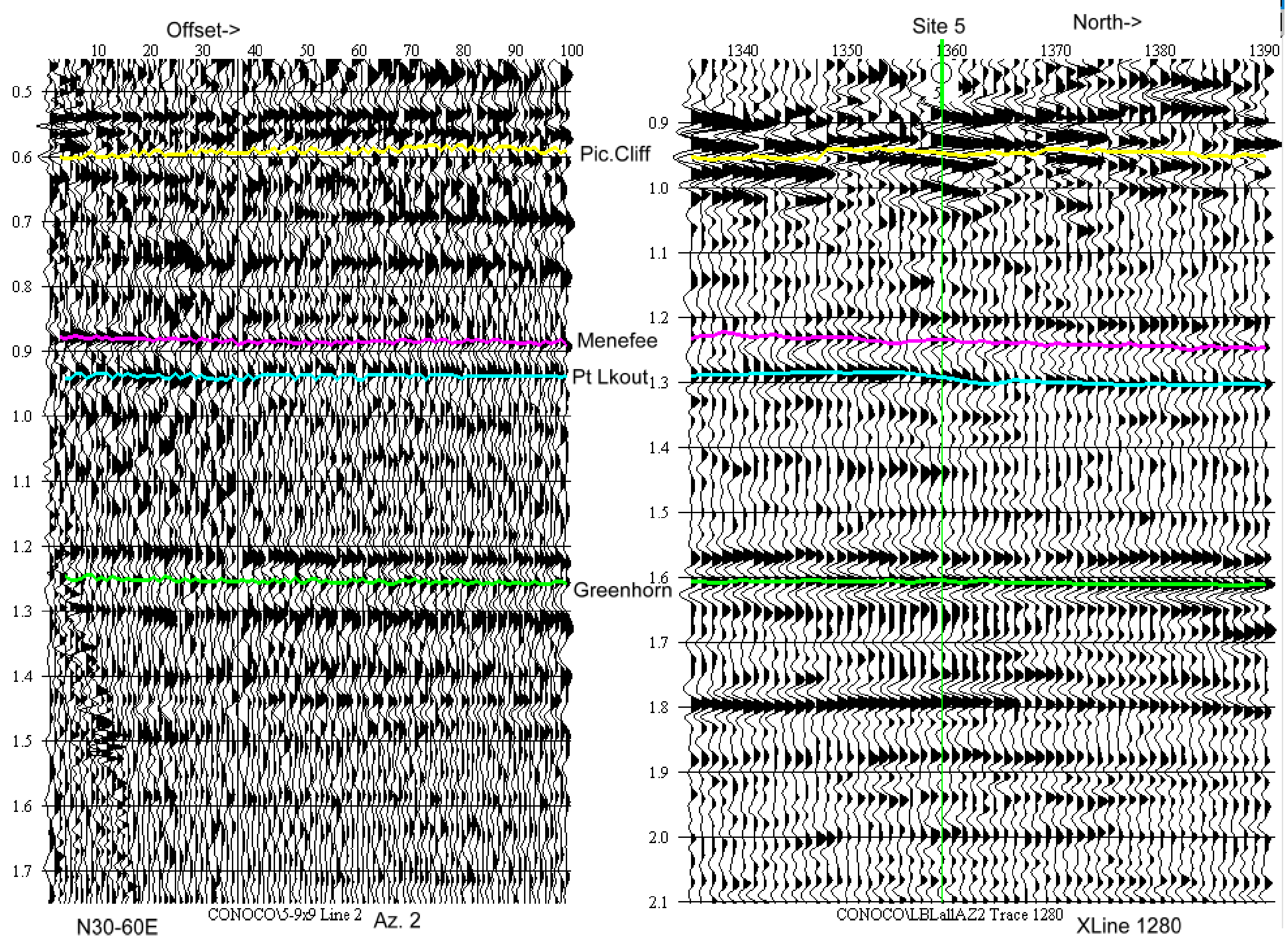
Greenhorn (post stack Time Migrated volume)



Time Map

Ampl. Map

Az. Gather Site 5 – XL 1280

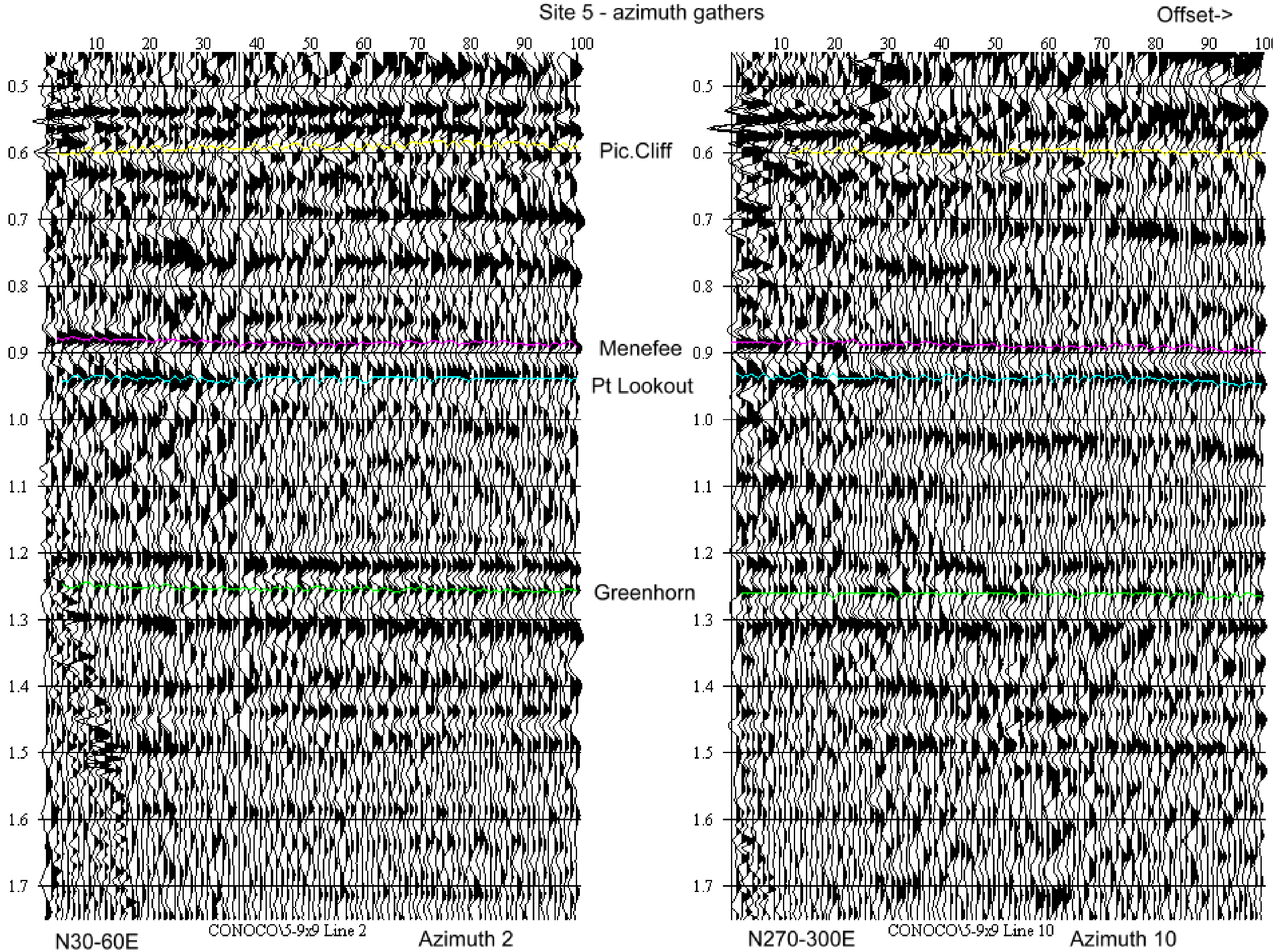


fn s5az2.bmp

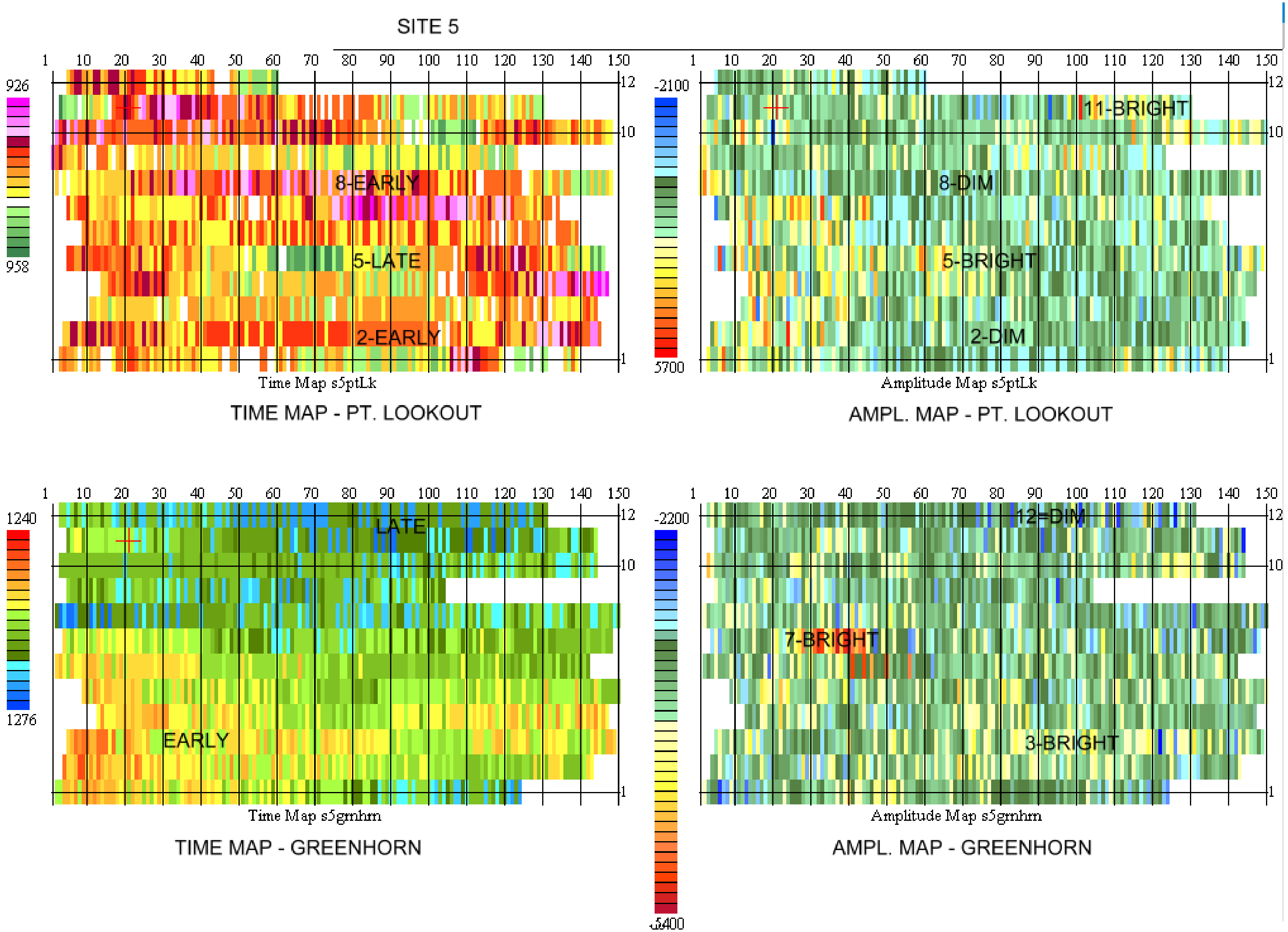
Azimuth Gathers

- 9x9 CMP bins joined to form a super-gather
- Data then sorted firstly by azimuth, 0-360^{o}, at 30^{o} increments: 12 azimuths to view
- Data sorted secondly by offset (0-10kft)
- 1-fold data to be shown: no binning (yet) to offset dimension, no demultiple; has 1 NMO function applied.

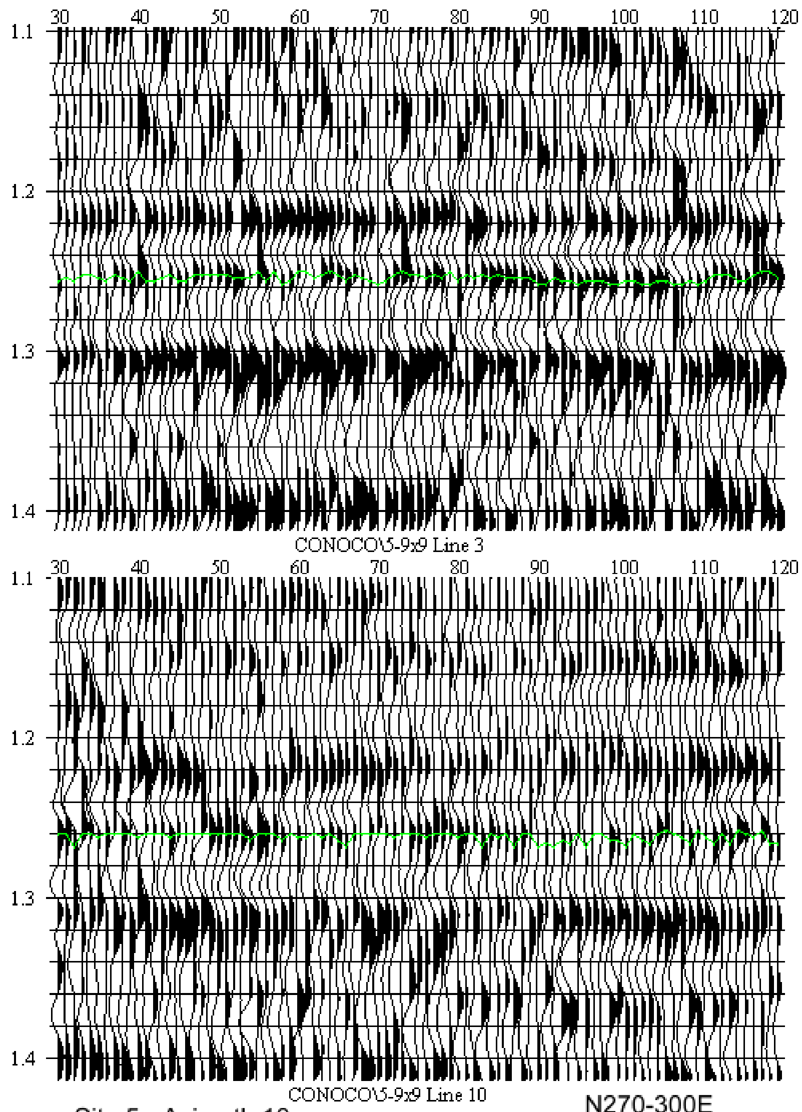
Site 5: N45E, N285E

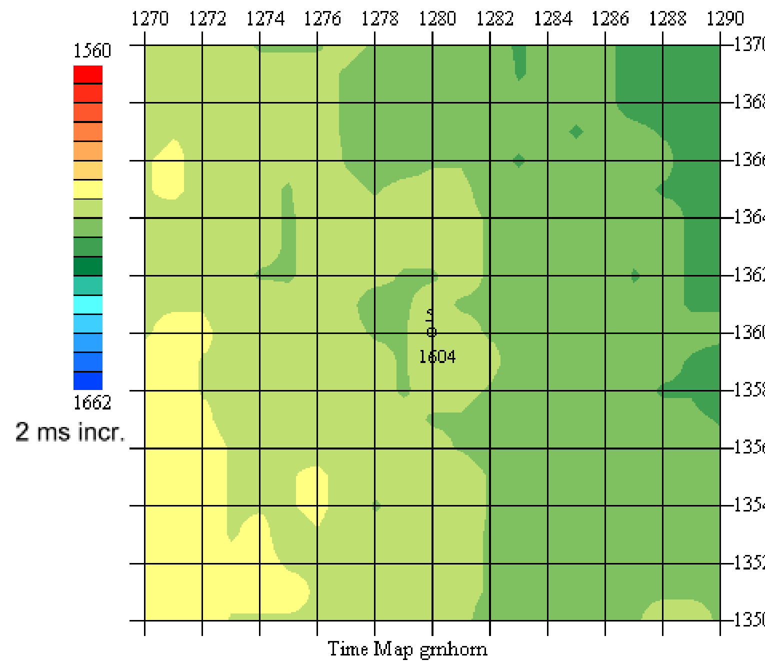


Site 5 – azimuth gathers’ times & ampl.s



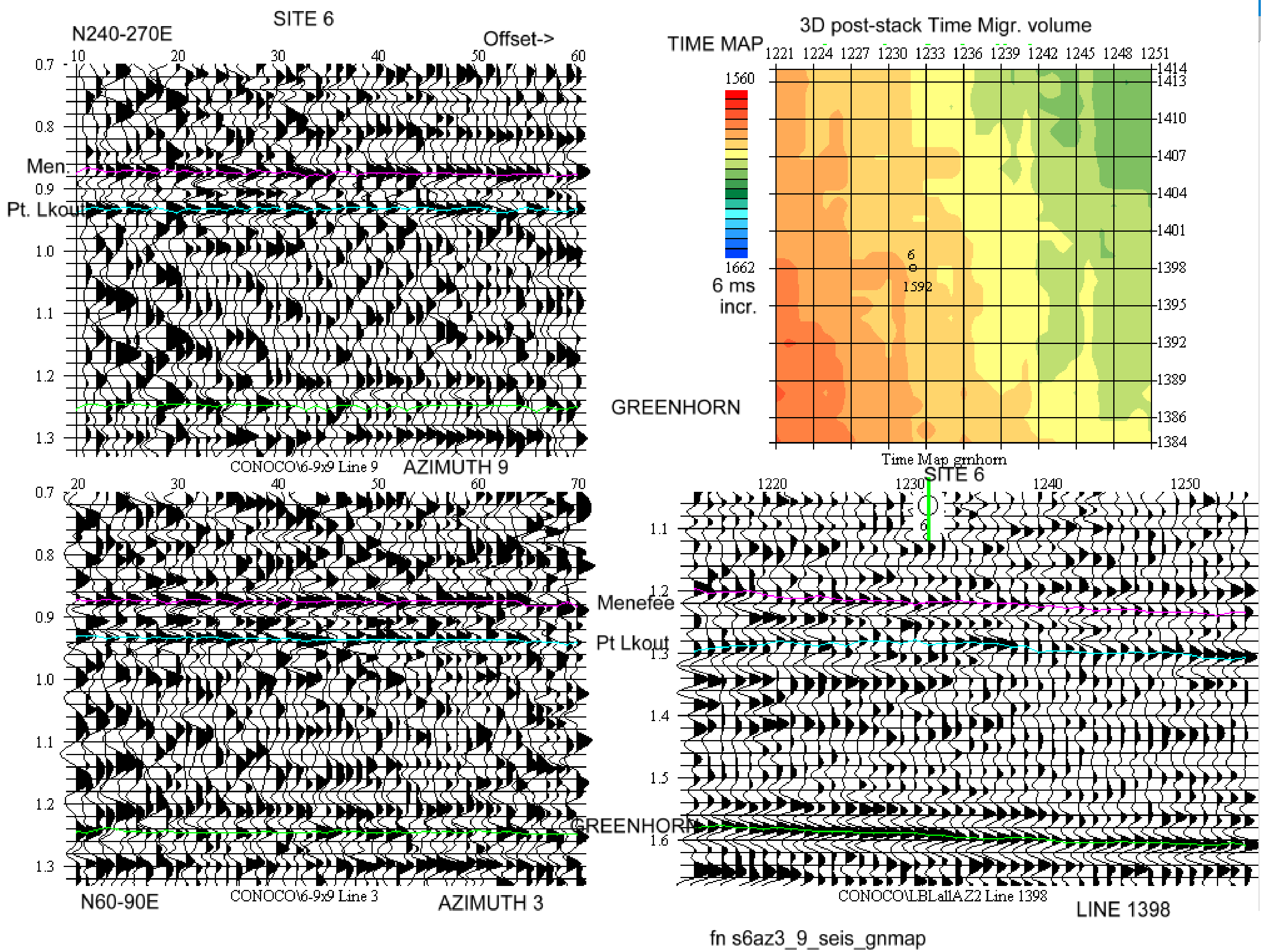
Site 5 – az. gathers- Time map 3D



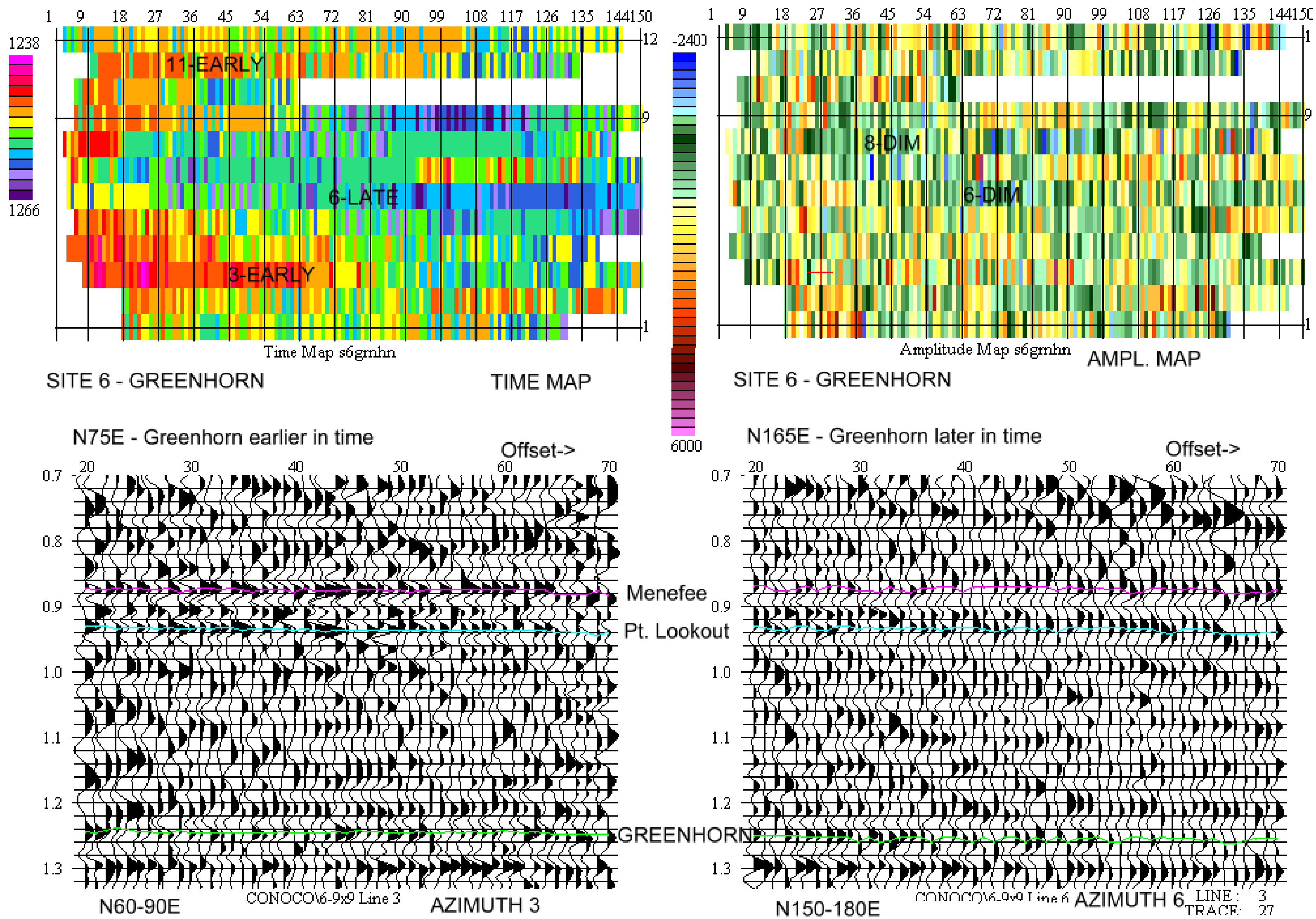


fn s5grnMapSeis

Site 6 – az gathers & 3D seismic



Site 6 – Greenhorn maps



fn s6GrnMapsAzgat3_6

Conclusions – Dec. 2000

- Azimuthal variations in traveltime & amplitude observed at several locations
- N45E (±45) earlier time at some az.gather locations
- N135E(+45) later time at some locations

2001 Work

- Interpret az. gathers with demultiple, and offset binning – Tom Daley's kind creation thereof
- Document az'l variations in target interval at ten locations supplied by the Conoco business unit (traveltime, amplitude, etc.)
- Evaluate / map limited-azimuth 3D volumes for az'l variations (time, ampl., etc.)
- Participate in modeling and development of new analysis methods for char. frac.s in refl. data
- 2D/3D multi-component survey / design acq.

Modeling and Analysis of San Juan Fractured Reservoir

Motivation

- Model reservoir scale effects of fracturing using a discrete fracture model (rather than an equivalent media model) to investigate fractures of varying scale lengths and mechanical properties.
- Obtain a field scale numerical CDP data set to constrain and guide the analysis of San Juan 3D surface seismic.

Method

- 2D Finite-difference, elastic, anisotropic code.
- Vertical fractures modeled as single column of grid points with anisotropic elastic parameters within an isotropic background.
- Implementation in fortran by Kurt Nihei
- Ref: Coates and Schoenberg, Geophysics 1995, Finite-difference modeling of faults and fractures.
- Ref: Schoenberg and Sayers, Geophysics, 1995, Seismic anisotropy of fractured rock.

Project History

- Material properties of Mesa Verde and other units taken from well logs with single layer used above the Mesa Verde.
- Initial 9-layer model developed, used for GX-II ray-tracing, then simplified for initial F-D models.
- FD models 101-103: 3-layers, 3 fractures, define F-D parameters, LBNL Report May, 2000.
- model 104 - single fracture - "reasonable" properties, in homogeneous background

History Continued

- Model 105 - multiple fractures (about 100 m spacing)
- Model 106: 5-layers with constant properties
- Model 107: 2 fracture sets with different properties in model 106
- Model 108: 2 fracture sets with different lengths and different properties
- Model 109: model 108 with 5-layer velocity structure. First CMP data generated!

Current Model Suite

- Model 110: Refine F-D parameters, establish baseline 5-layer model with no fractures.
- Model 111: Add fractures to Cliff House. Thin layer, small fracture spacing, higher fracture stiffness
- Model 112: Add "faults" to Mesa Verde. Thick layer, large fracture spacing, low fracture stiffness
- Model 113: Combine 111 and 112
- Generate VSP data sets for models 110-113.

Current Model Parameters

- Size: 2250 x 2250 m (7400 x 7400 ft) +boundary with datum: 150 m from top
- 5 Layers, 2 fracture sets
- Small fractures in Cliffhouse:

  Stiffness 8x10^9 Pa/m every 21 m
- Large faults in Mesa Verde:

  Stiffness 8x10^8 Pa/m every 650 m

Current Model Parameters Cont.

- Source and Receiver spacing: 60 m(~200ft), 38 total sources and receivers).
- Source center frequency: 50 Hz
- Wavelength: P-wave 75-90m, S-wave 43-53m
- Grid Size: 3m   Time sample: 0.4ms
- Calculated Output: Vertical and Horizontal componets of velocity, pressure

Arch Rock #1 VSP Acquisition

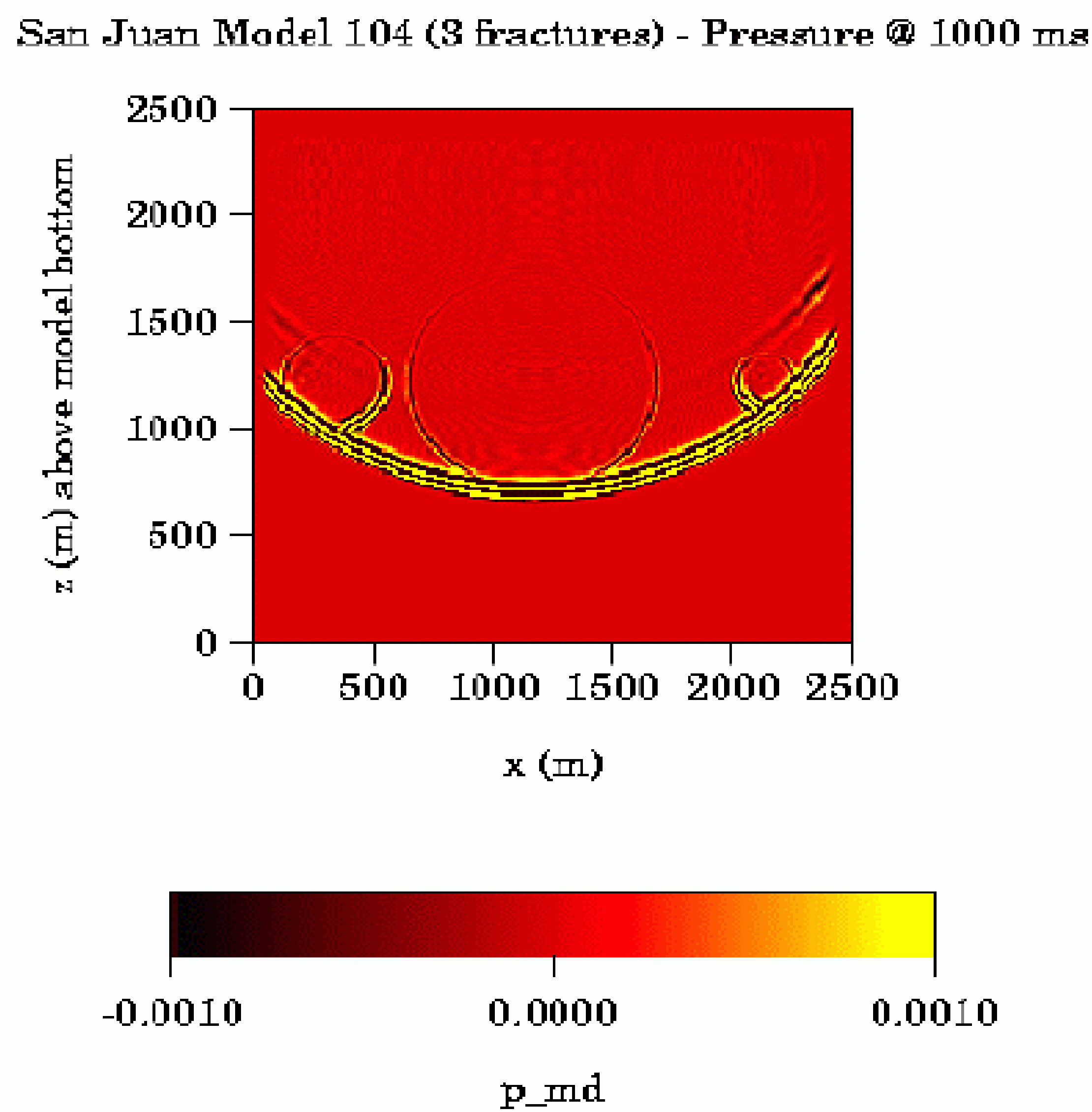
- Single Offset, 9-C VSP
- P- and S-Wave Vibroseis Sources
- 5-Level 3-Component Geophone String
- 265 Depths Recorded, 60 - 6160 ft.
- Offset P-wave Source for Sensor Orientation
- 8-80 Hz, 8s + 3 s sweep, 10 sweeps/source

Arch Rock #1 Single Well Survey

- Piezoelectric Source
- 24 Hydrophone Sensors @ 10 ft. spacing
- 260 ft. minimum offset
- 5000 ft. to 3300 @ 10 ft. source spacing

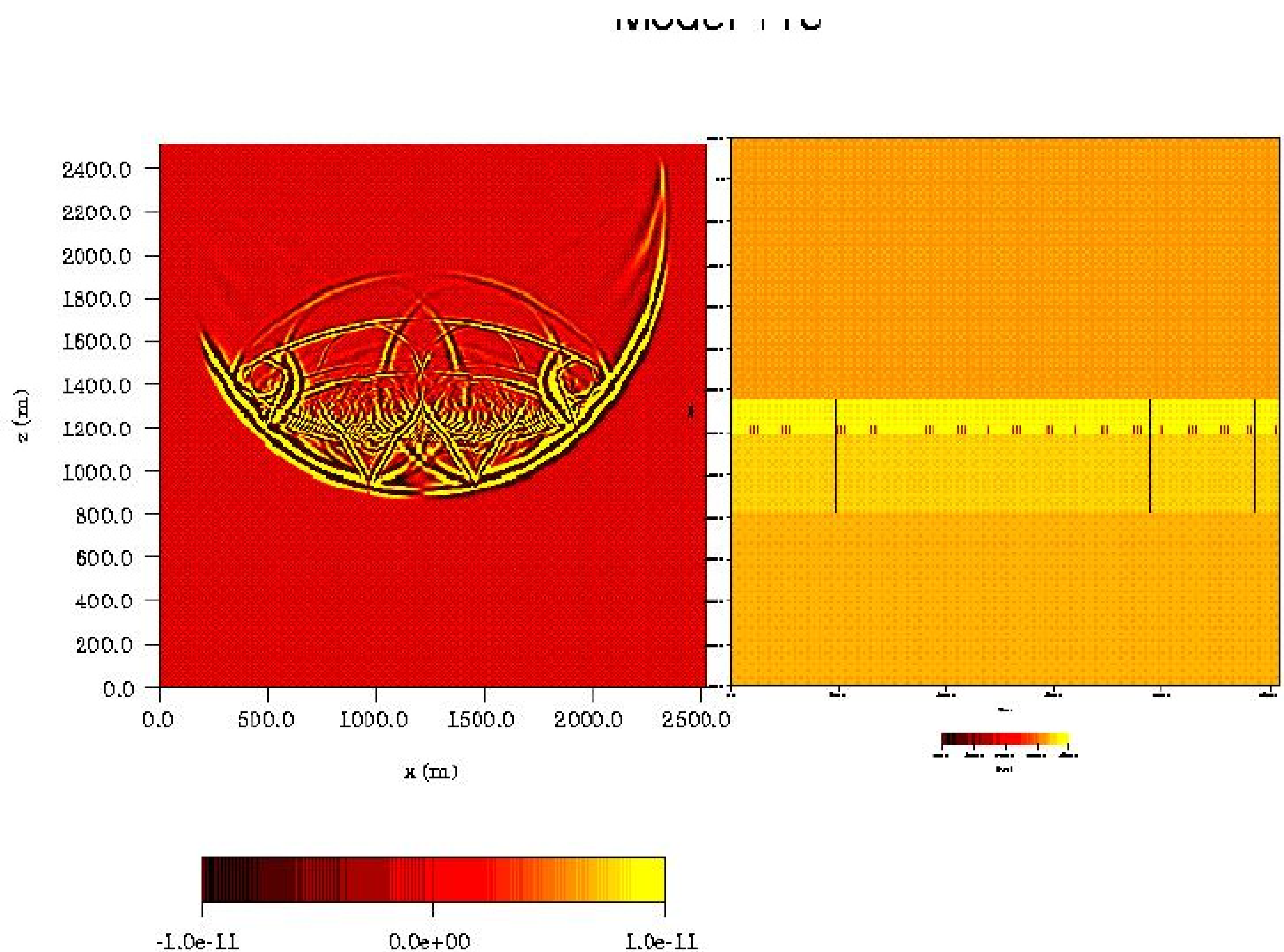
Recent Progress

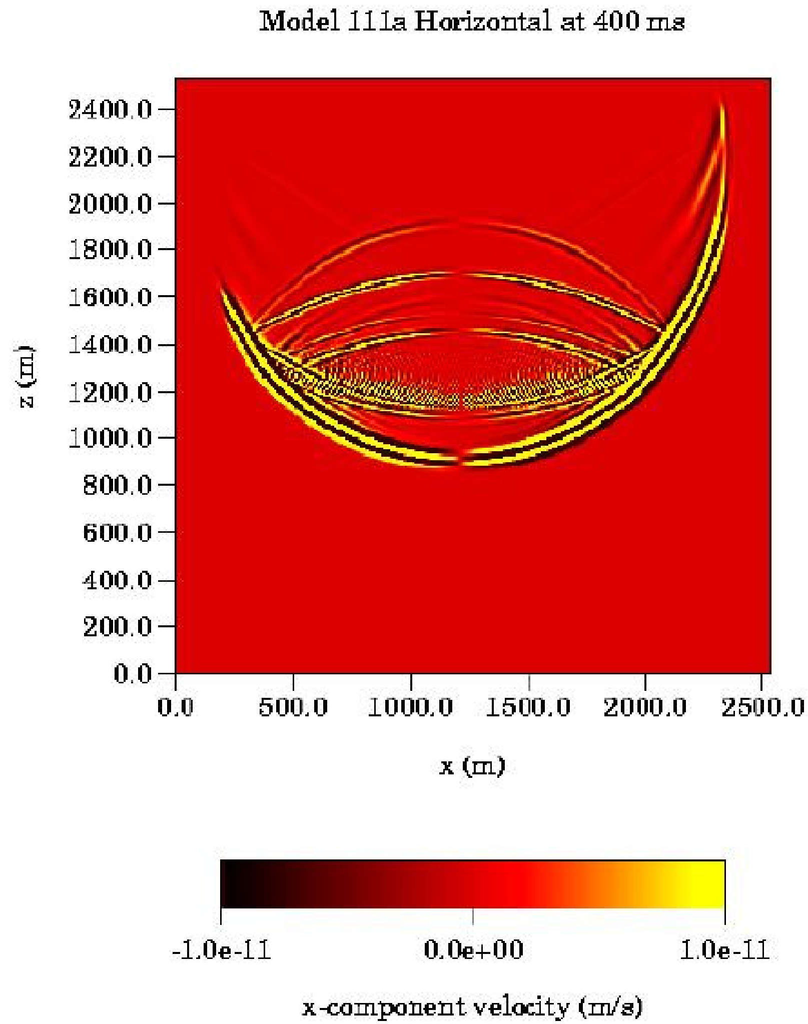
- Calculation of full CMP data set for models 110, 111, 112 and 113 using Conoco super-cluster
- Acquisition of 9-C VSP and Single Well surveys at Arch Rock #1 well
- Modeling of VSP in models 110, 111, 112, 113



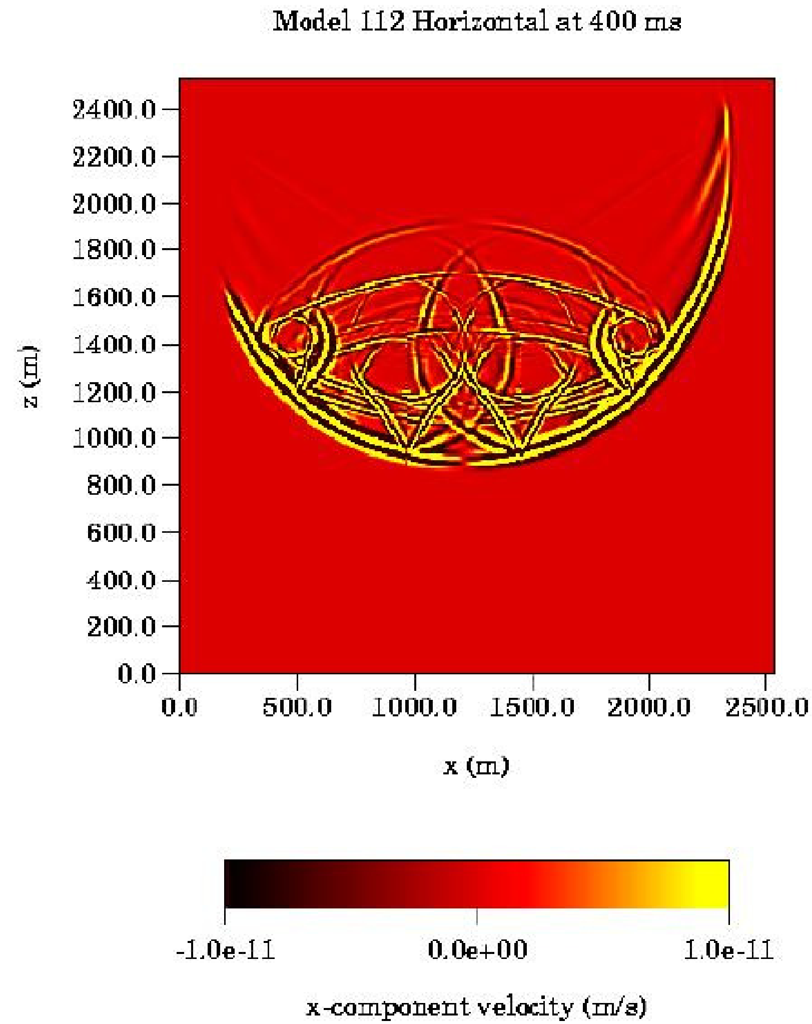
San Juan Model 104 (3 fractures) - Pressure @ 1000 ms
z (m) above model bottom
2500
2000
1500
1000
500
0
0
500
1000
1500
2000
2500
x (m)
-0.0010
0.0000
0.0010
p_md

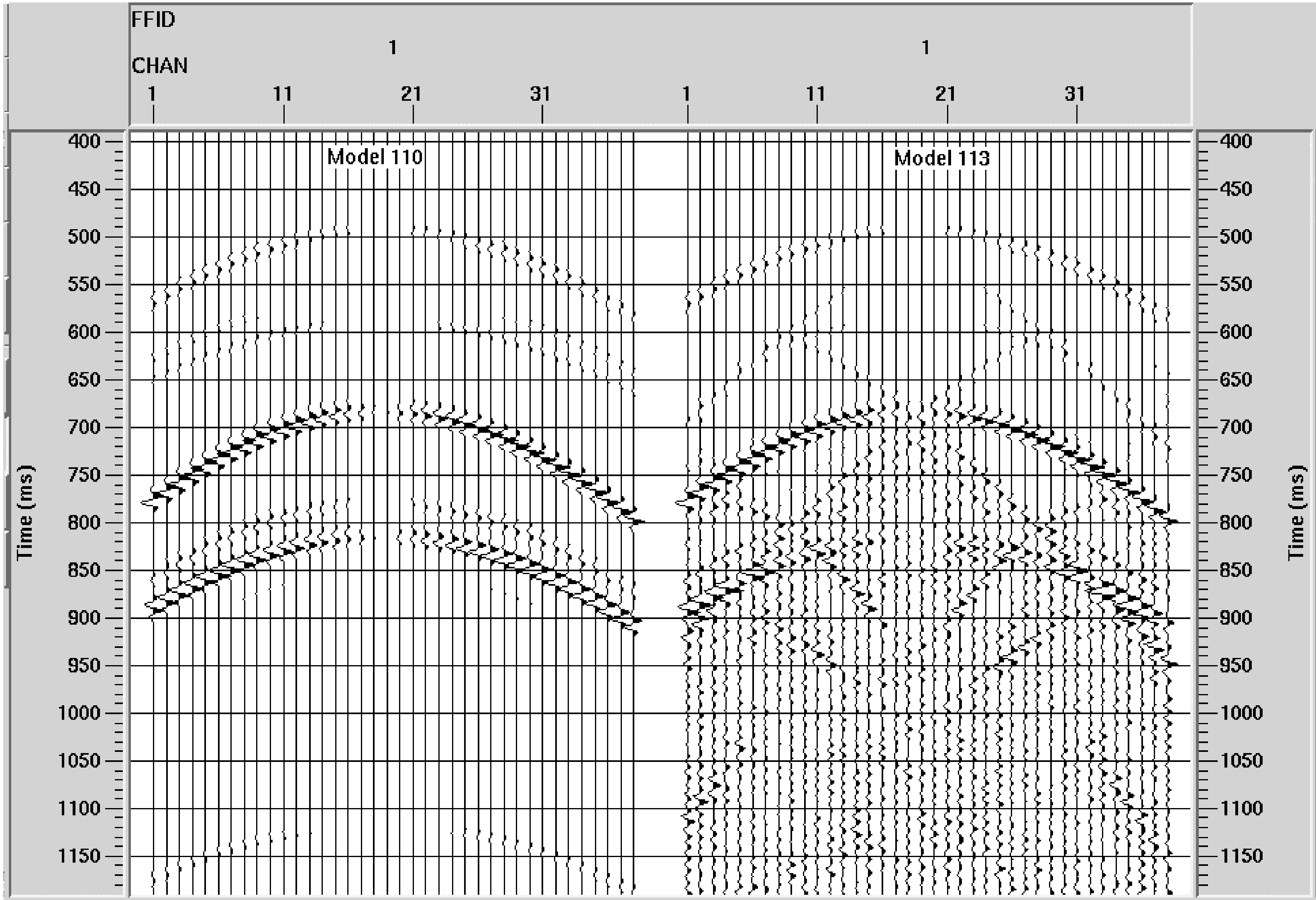
Wave Snapshot and Model 113 (two fracture sets)



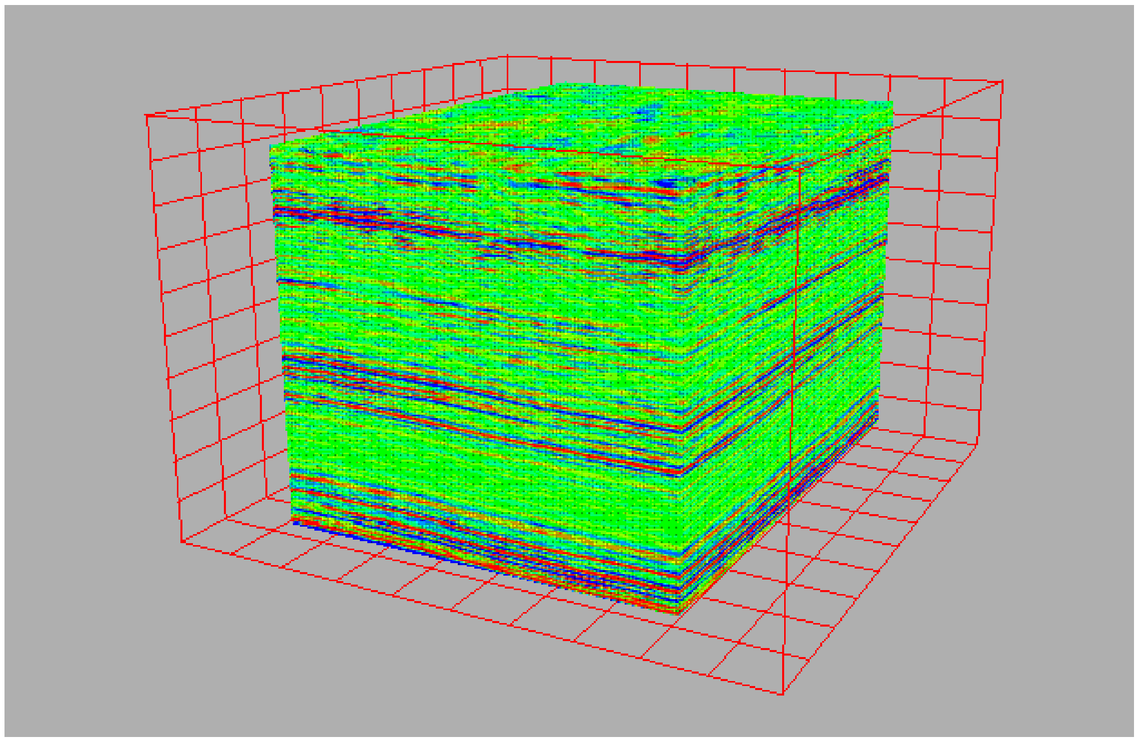


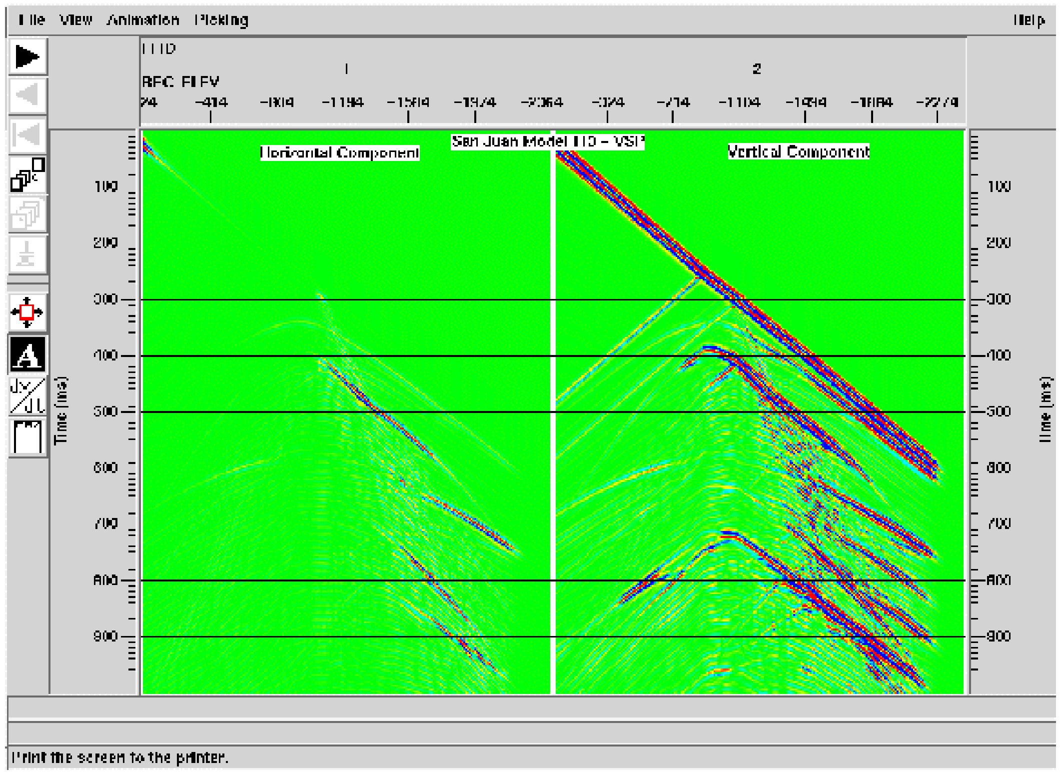
Model 111a Horizontal at 400 ms
z (m)
2400.0
2200.0
2000.0
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
0.0
500.0
1000.0
1500.0
2000.0
2500.0
x (m)
-1.0e-11
0.0e+00
1.0e-11
x-component velocity (m/s)


Model 112 Horizontal at 400 ms
z (m)
2400.0
2200.0
2000.0
1800.0
1600.0
1400.0
1200.0
1000.0
800.0
600.0
400.0
200.0
0.0
500.0
1000.0
1500.0
2000.0
2500.0
x (m)
-1.0e-11
0.0e+00
1.0e-11
x-component velocity (m/s)

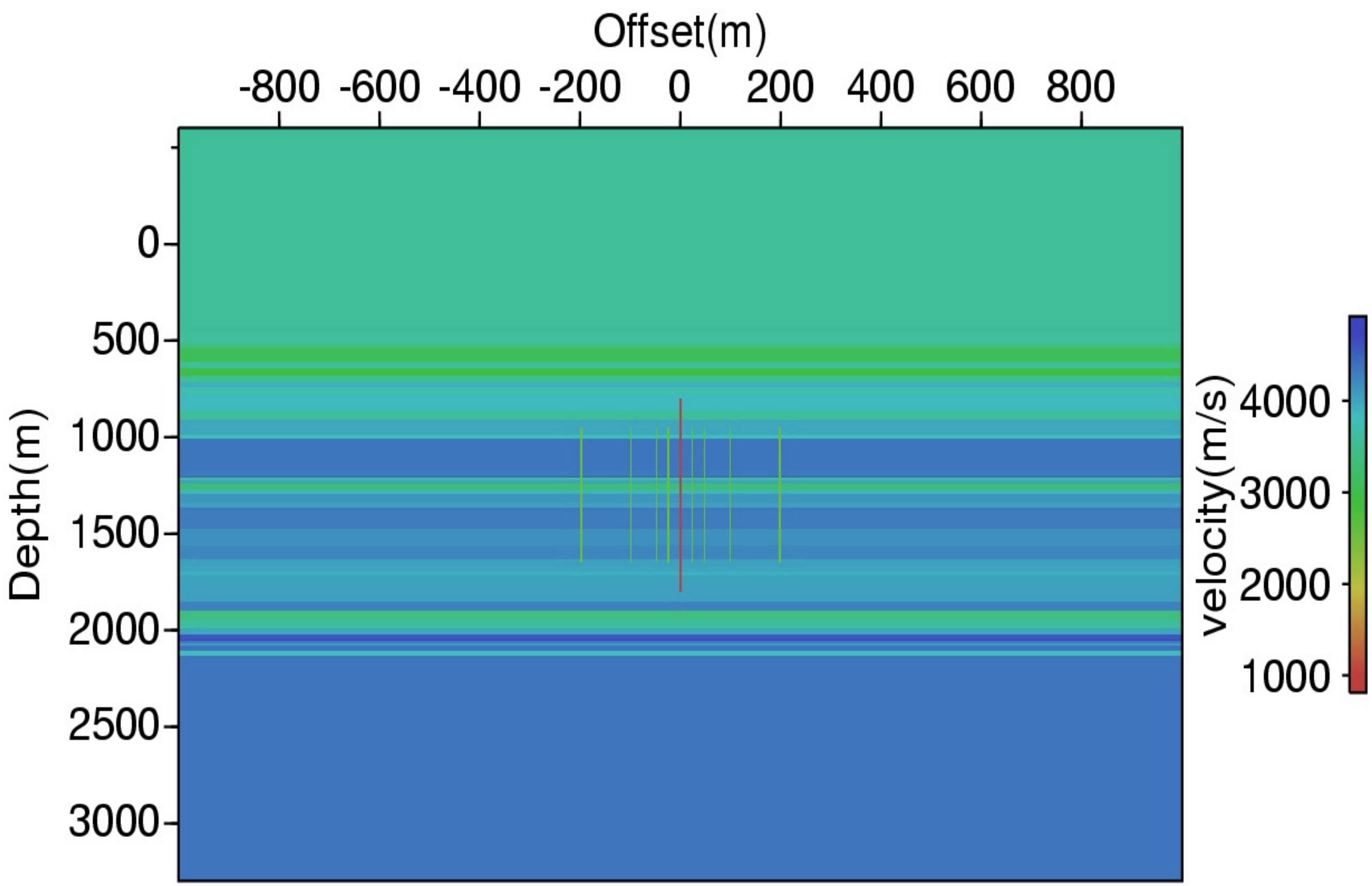

FFID
1
1
CHAN
1
11
21
31
1
11
21
31
Model 110
Model 113
Time (ms)
Time (ms)
400
450
500
550
600
650
700
750
800
850
900
950
1000
1050
1100
1150

3-3-D Data Cube - Arbitrary Datum



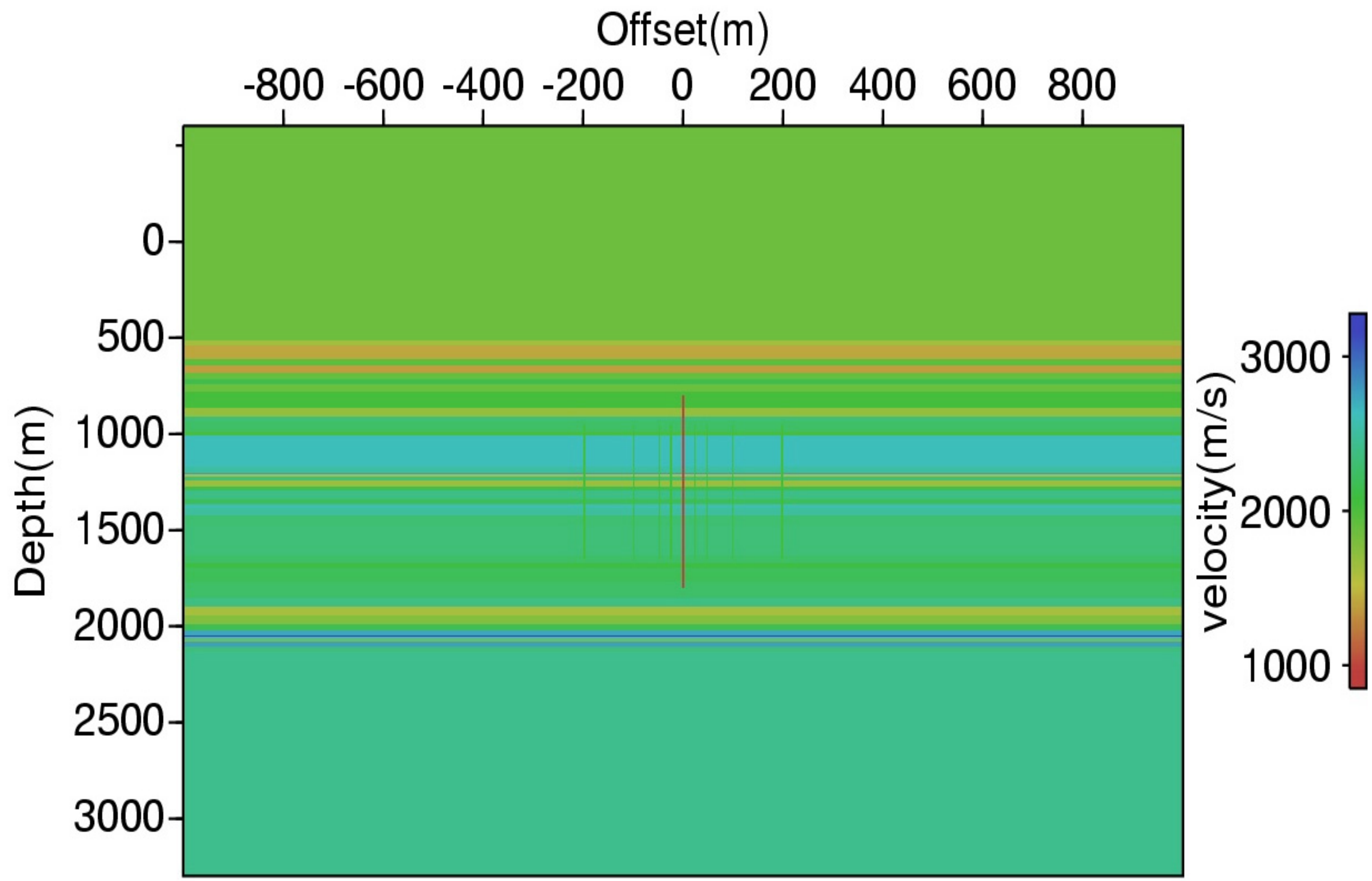

File View Animation Picking
Help
REC ELEV
Horizontal Component
San Juan Model IID - VSP
Vertical Component
Time (ms)
Print the screen to the printer.

CLOSEUP OF FRACTURES FOR MODEL 1



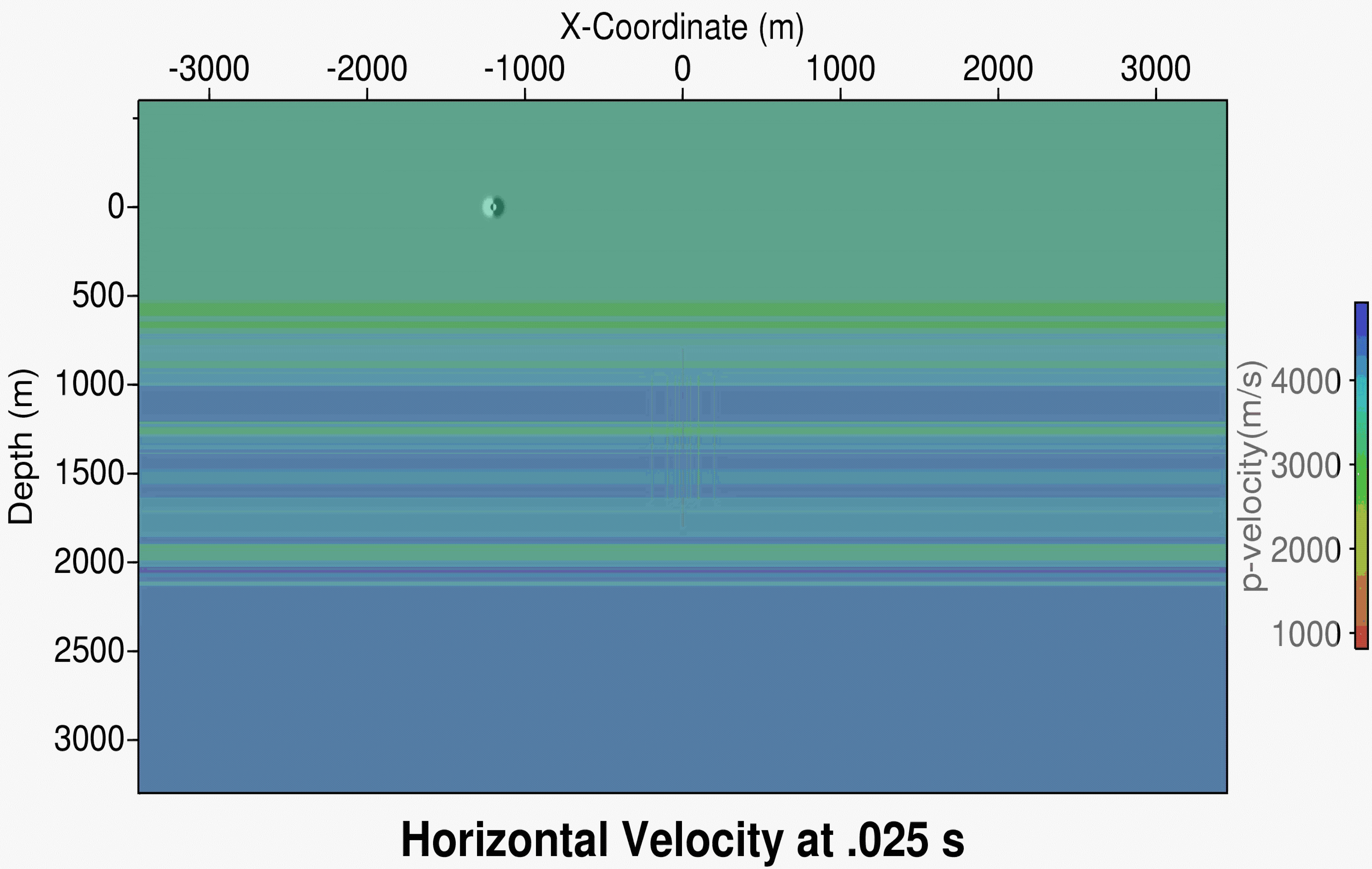
Compressional Velocity

CLOSEUP OF FRACTURES FOR MODEL 1

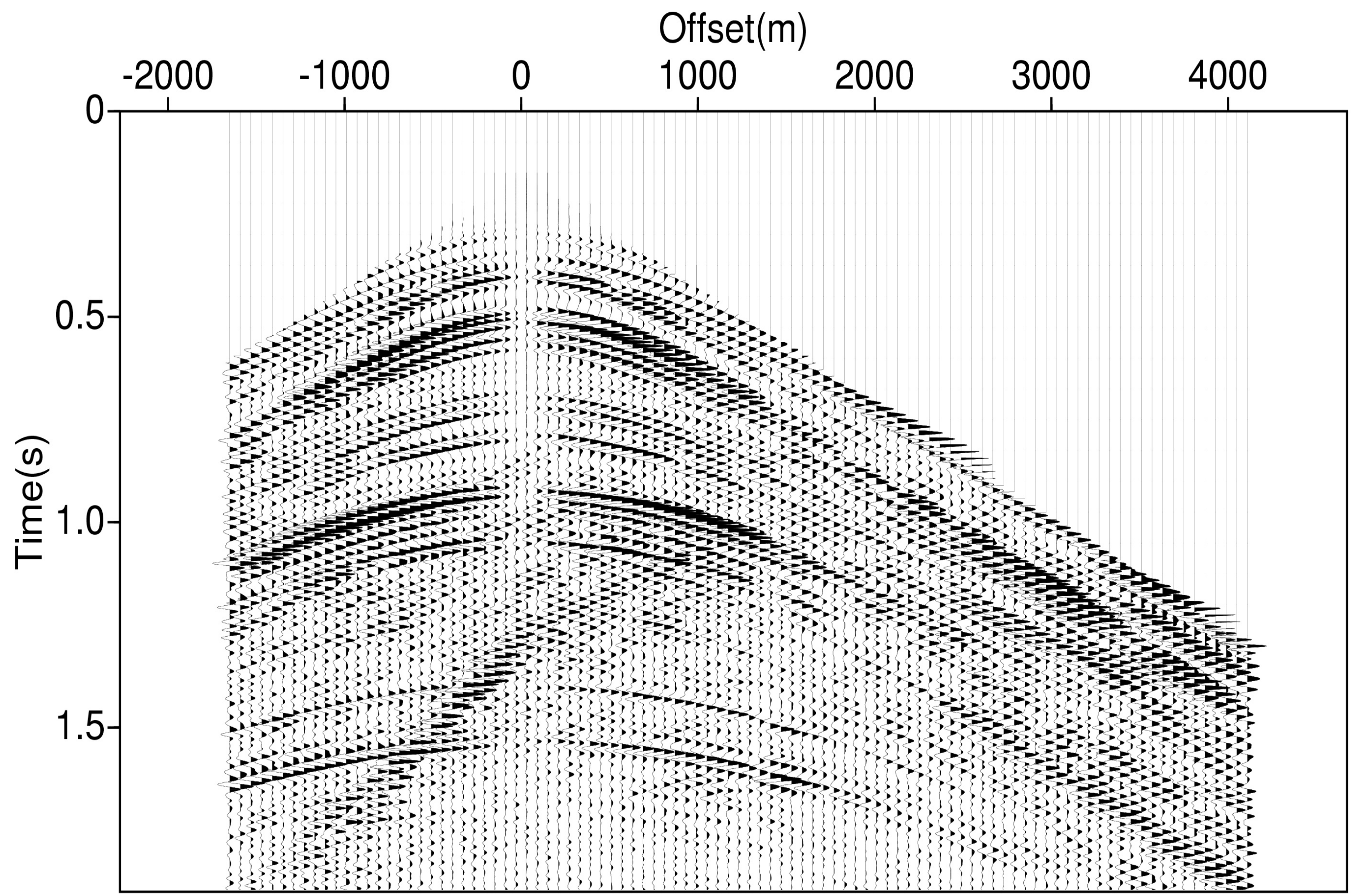


Shear Velocity

2-D FD SIMULATION MOVIE

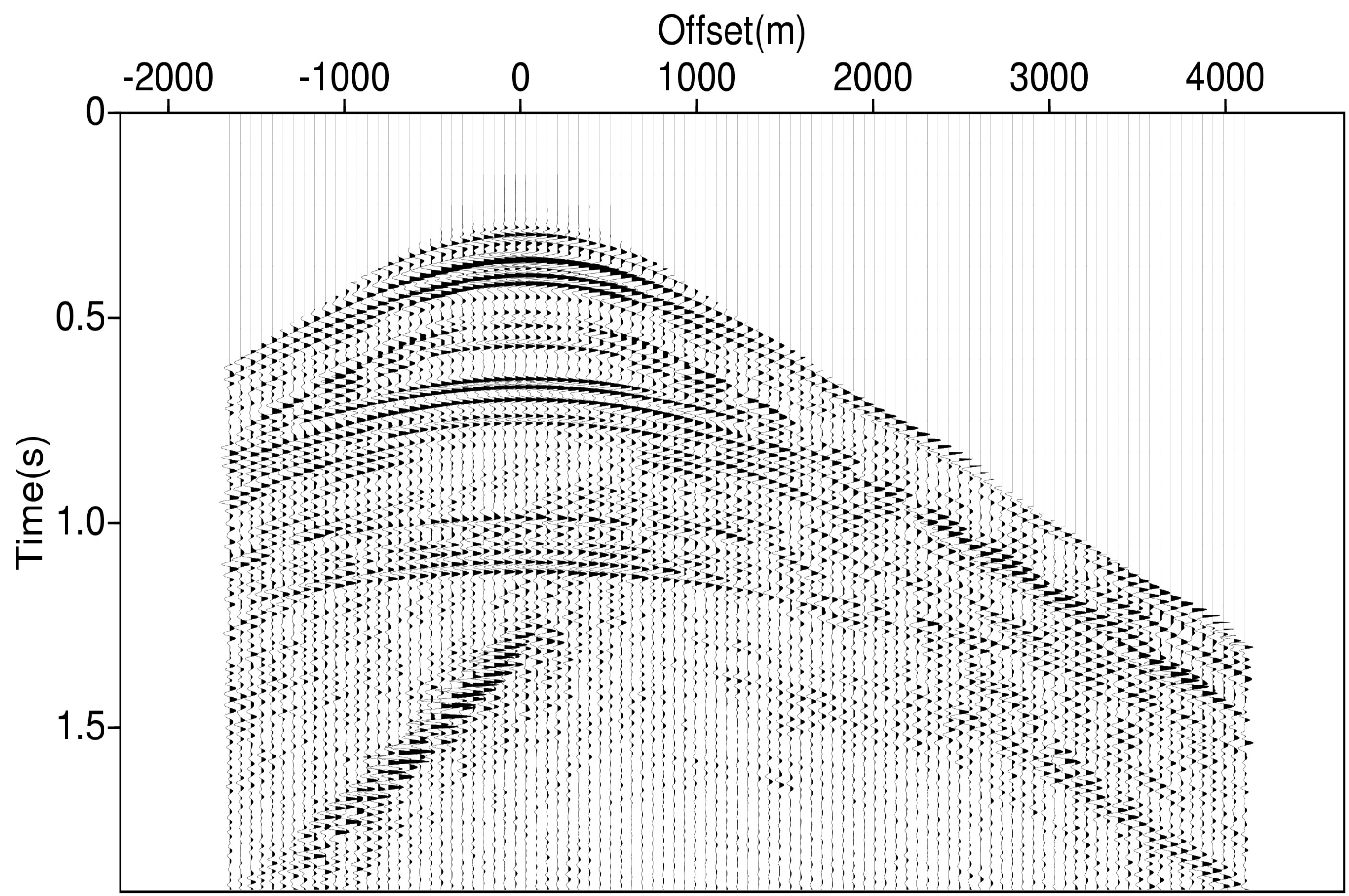


HORIZONTAL GEOPHONE



Horizontal

VERTICAL GEOPHONE



Vertical

Stratigraphic and/or Structural Heterogeneity in the San Juan Basin

Matthias G. Imhof and Rob Wilson

Department of Geological Sciences
Virginia Tech
Blacksburg, VA 24061-0420

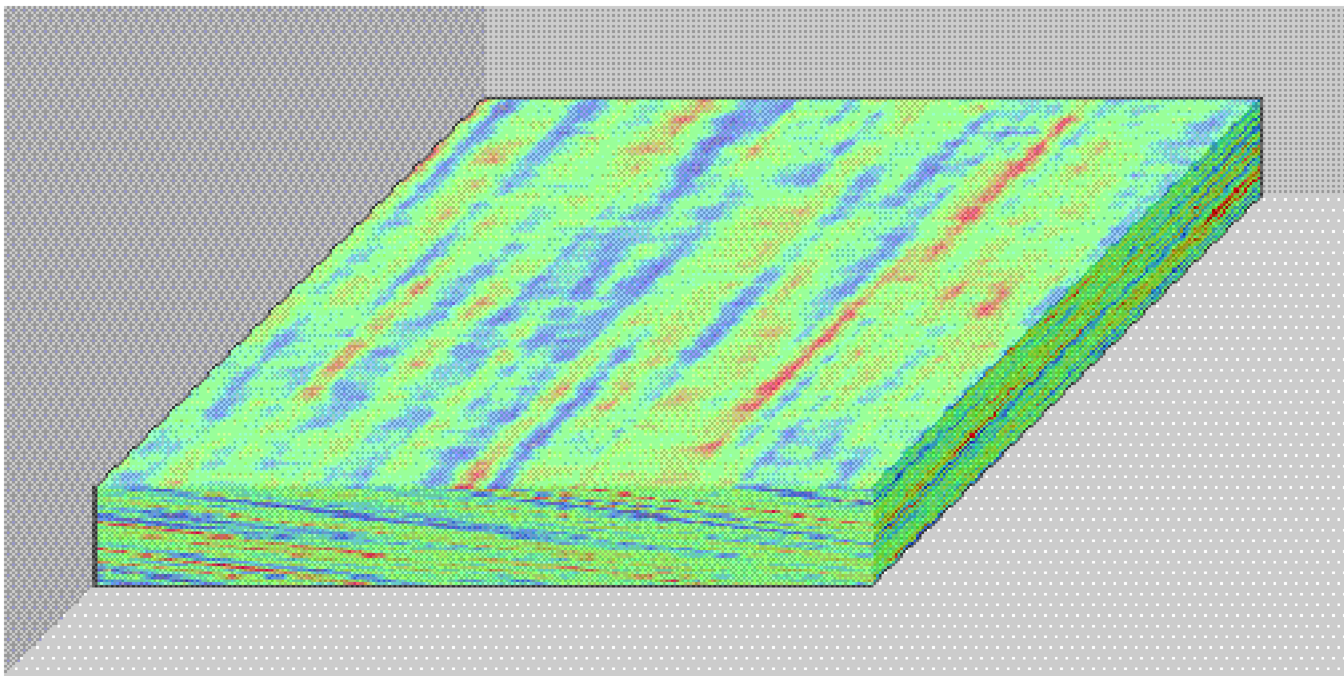
mgi@vt.edu

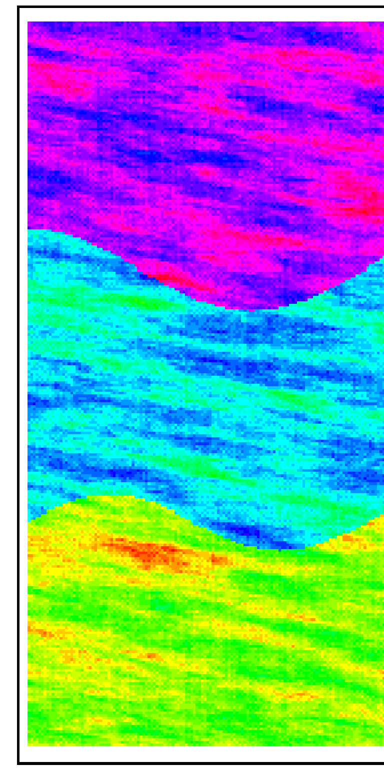
Overview of VT Activities:

- Modeling of Heterogeneity
  - ☞ What kind of heterogeneity is to be expected?
- Synthetic Data
  - ☞ How does heterogeneity affect seismic data?
- Seismic Field Data
  - ☞ Determination of stratigraphic and structural heterogeneity from field data.

Geostatistical Description: Autocorrelation or Variogram

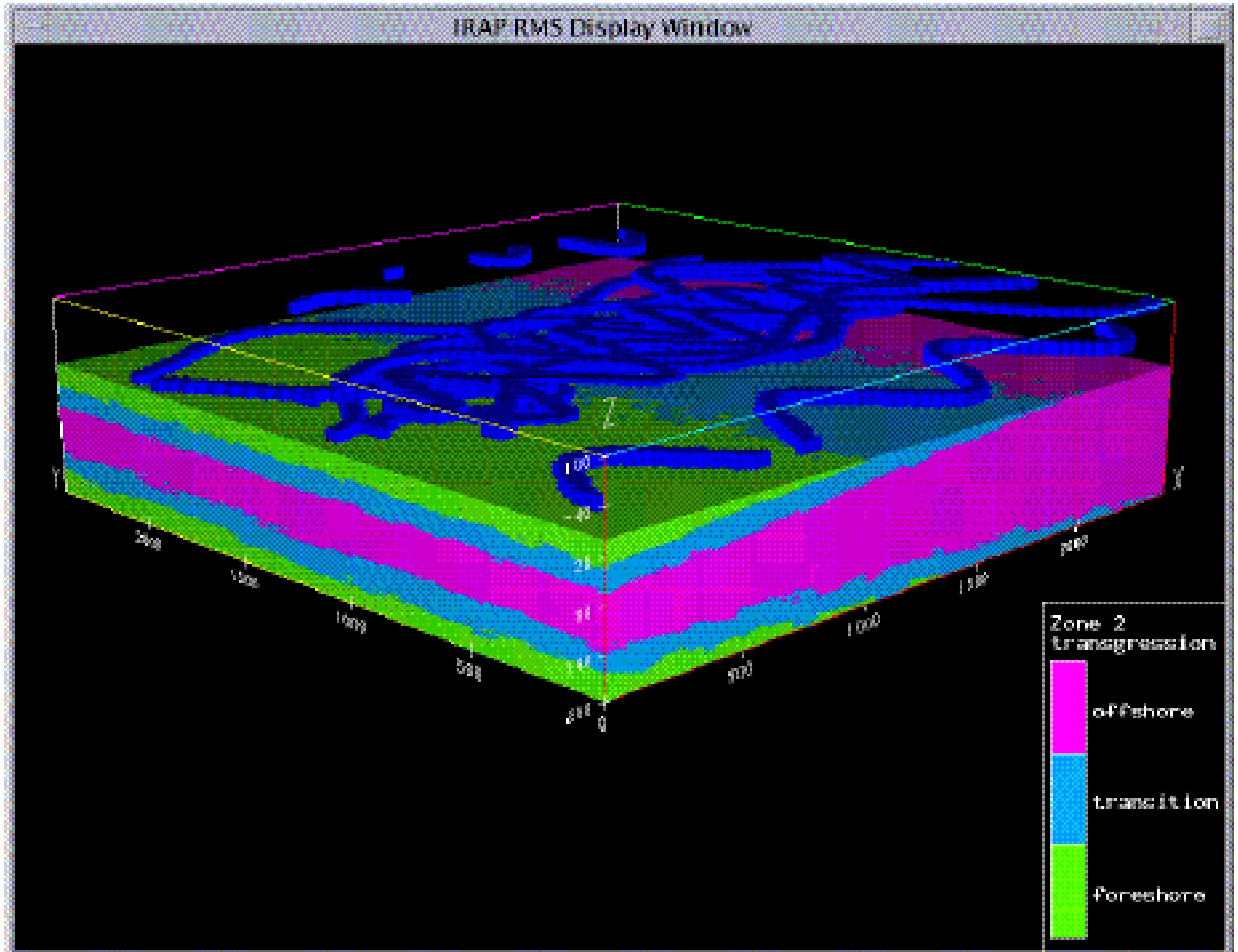
- Parameters: strength (variance), characteristic lengths, orientation



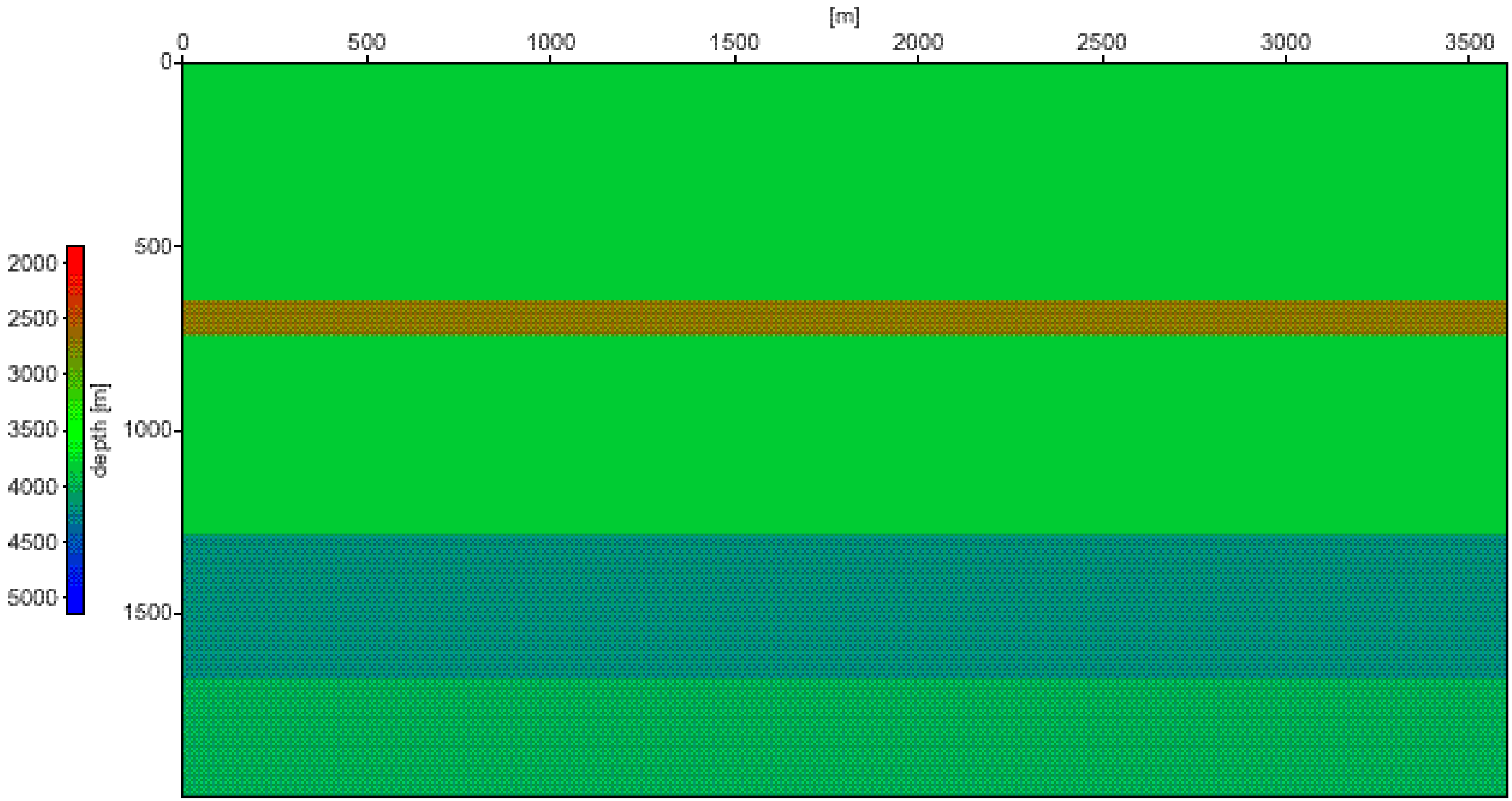


Object Based, e.g., Channels or Flooding/Erosion

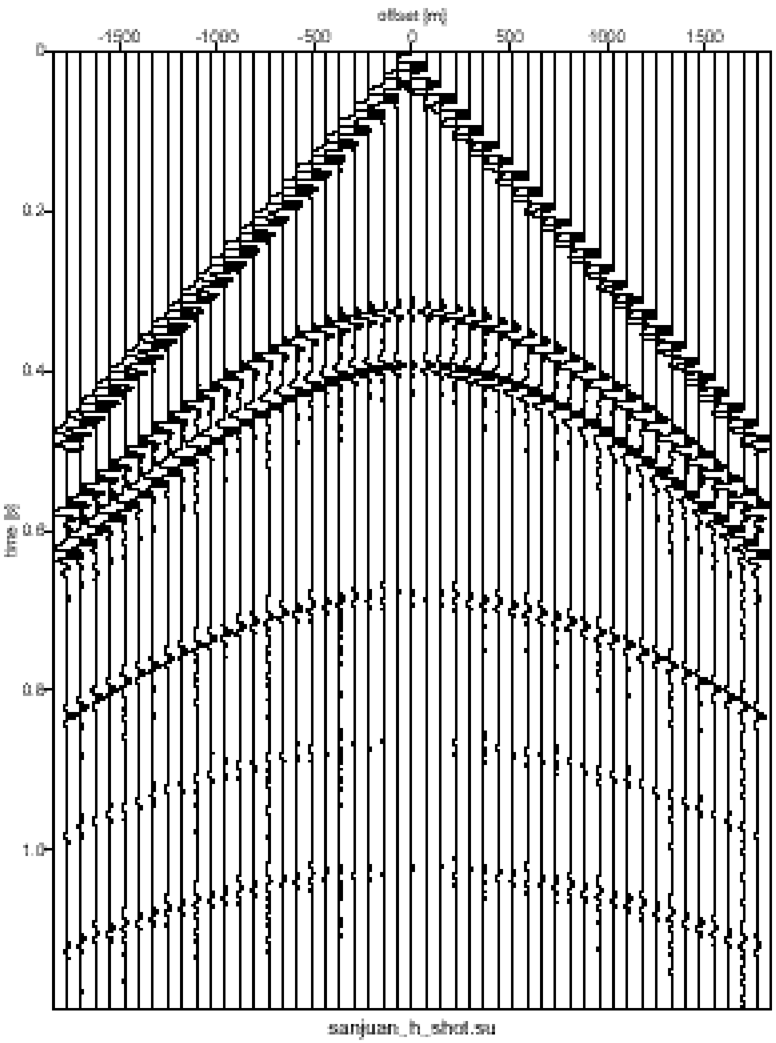
- Shape / Cross Section, Density, Sinuosity

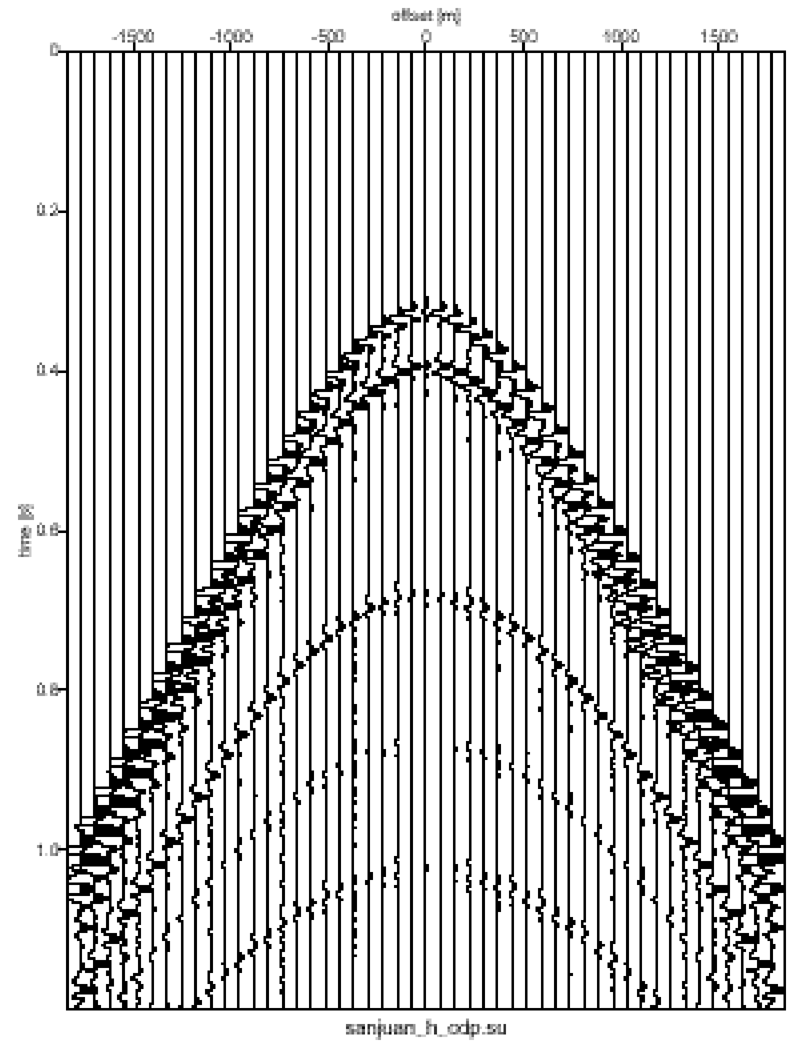


Synthetic Data: Homogeneous Reference Model

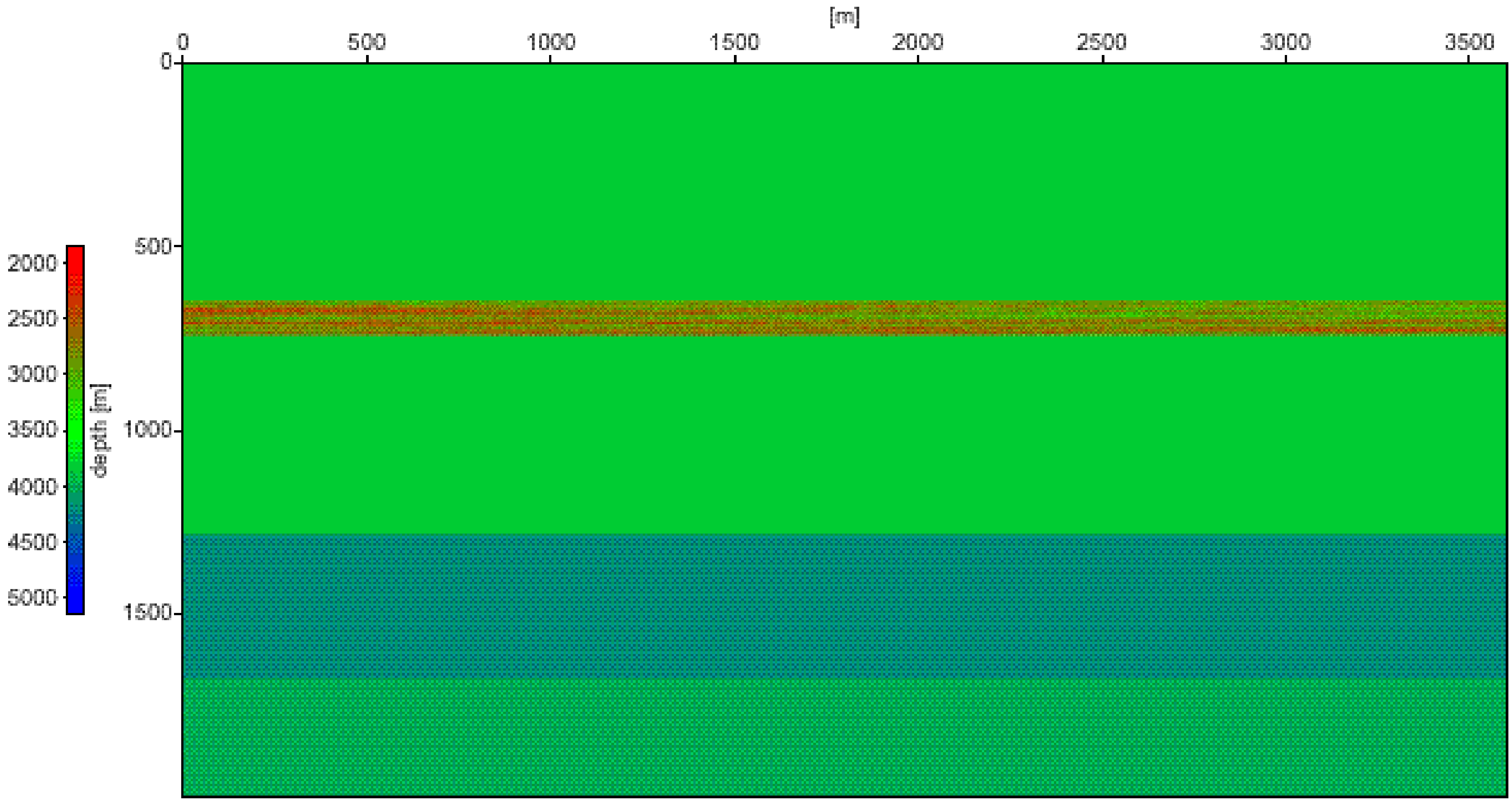


Synthetic Data: Homogeneous Reference Model

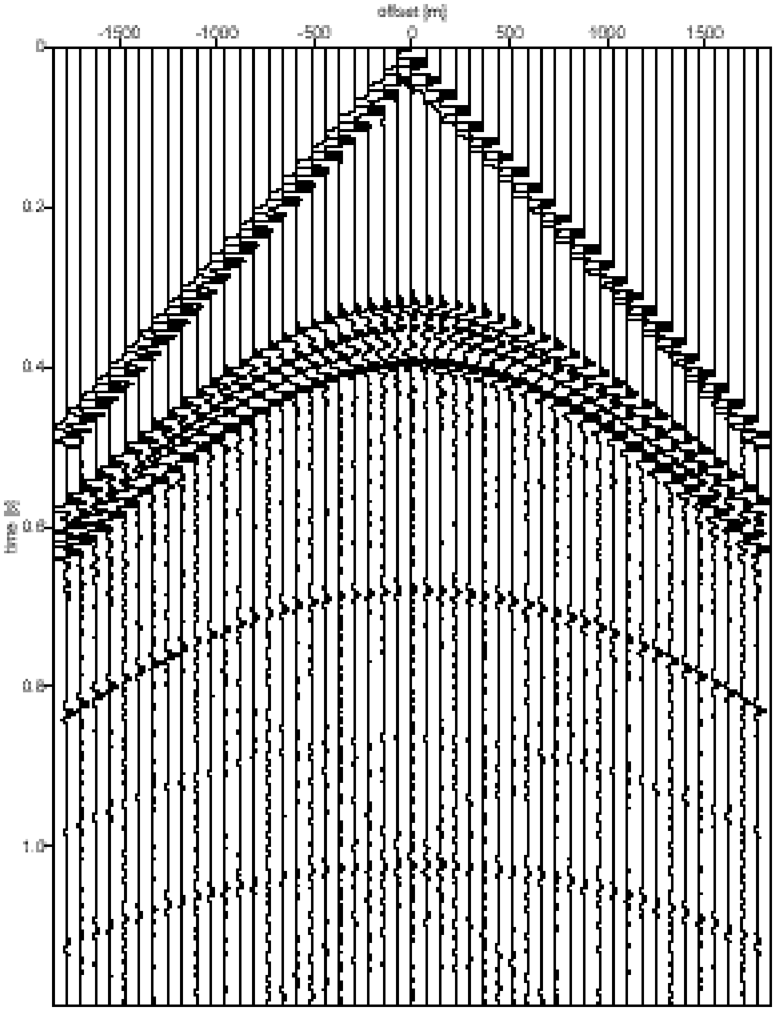




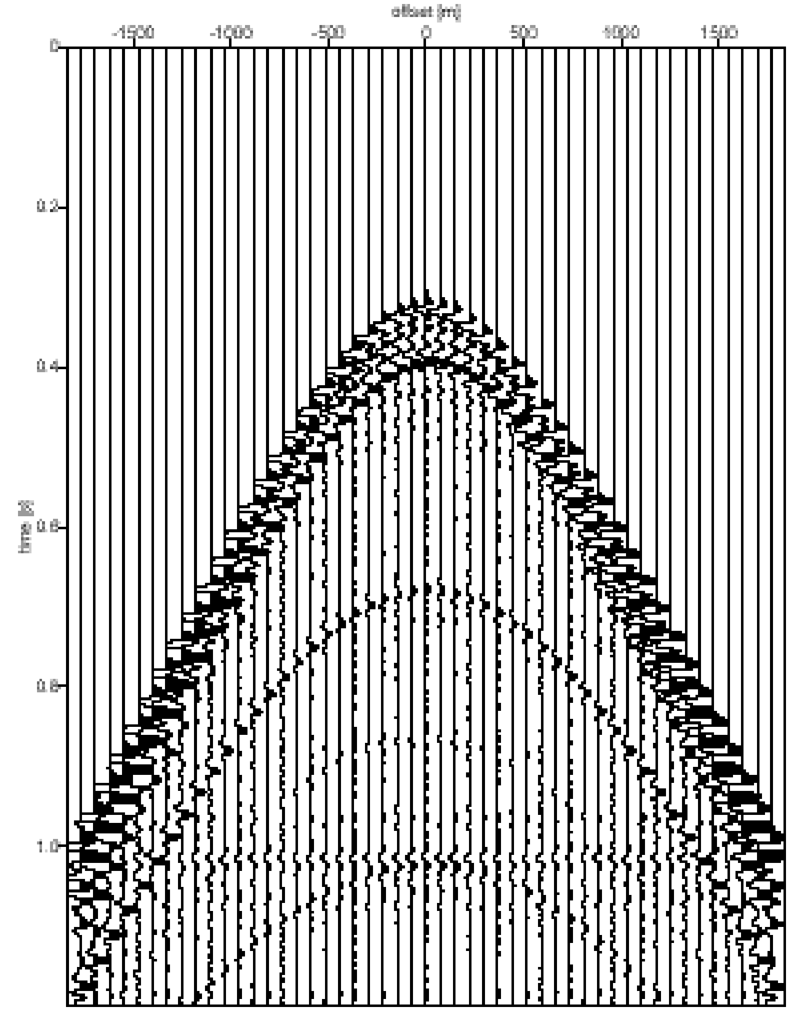
Synthetic Data: Heterogeneous Fruitland



Synthetic Data: Heterogeneous Fruitland



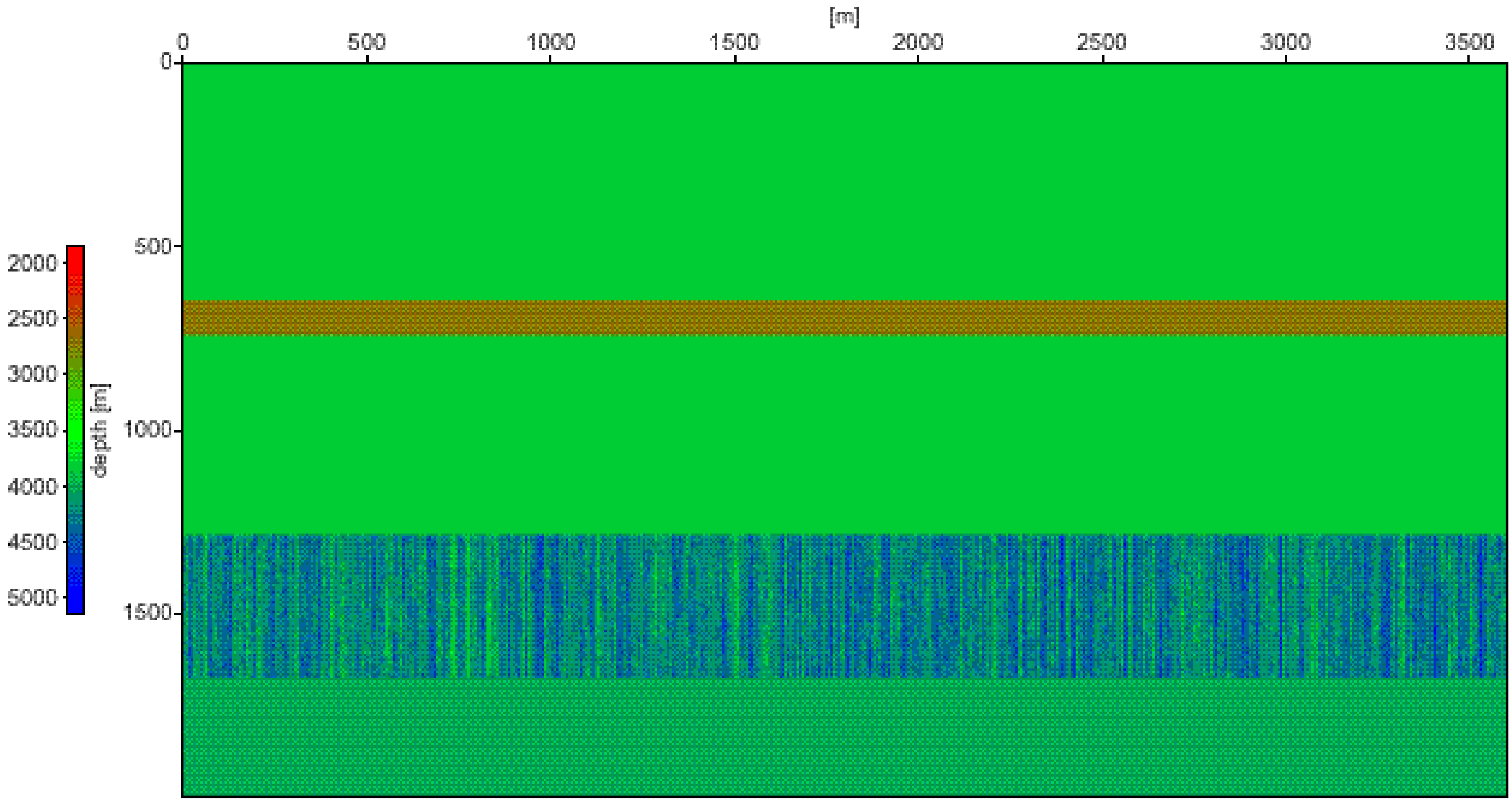
frtlnd_rand_shot.su



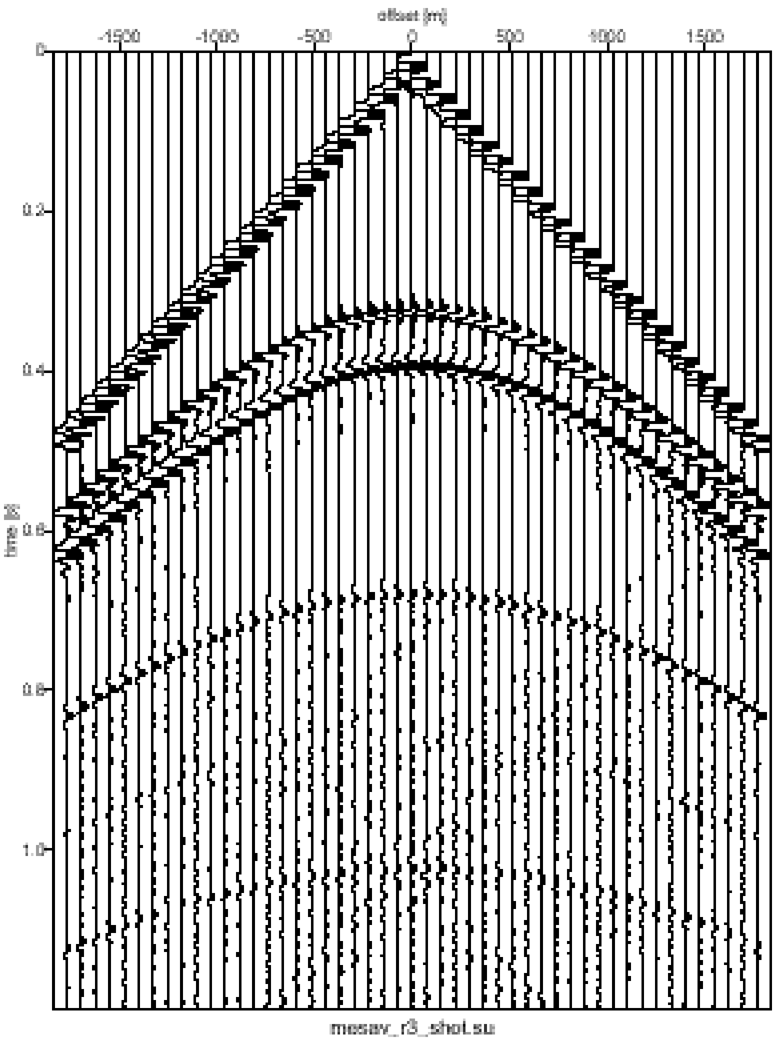
frtlnd_rand_cdp.su

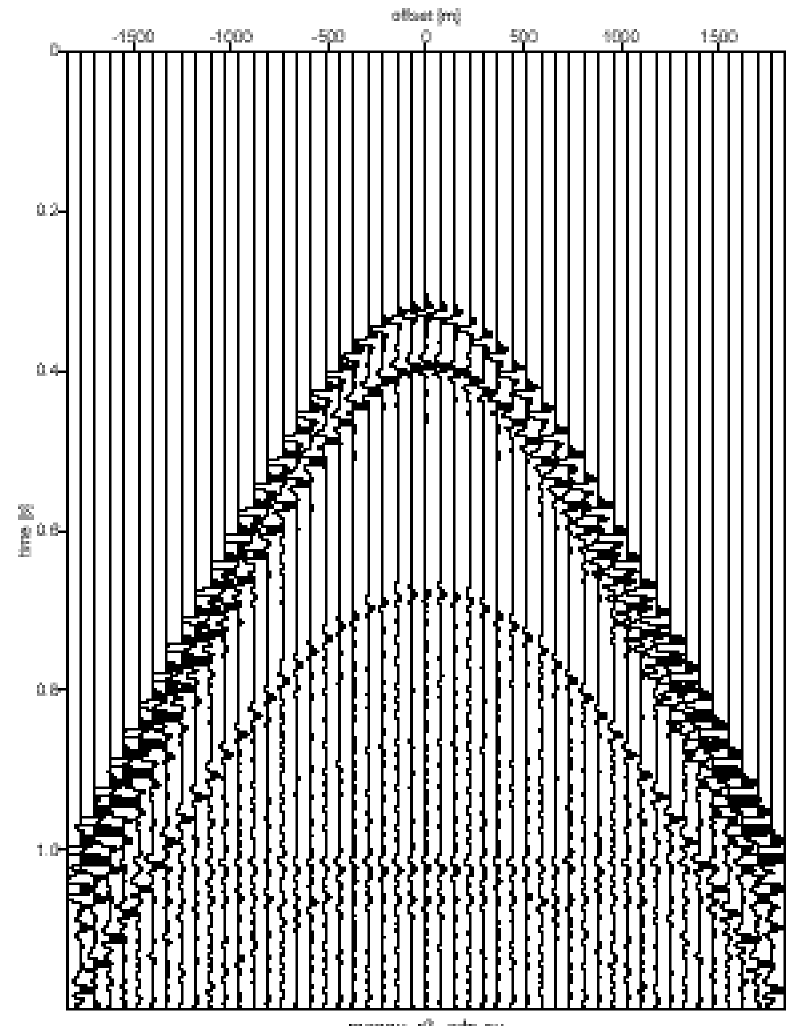
Seismic Reservoir Characterization Laboratory

Synthetic Data: Heterogeneous Mesa Verde

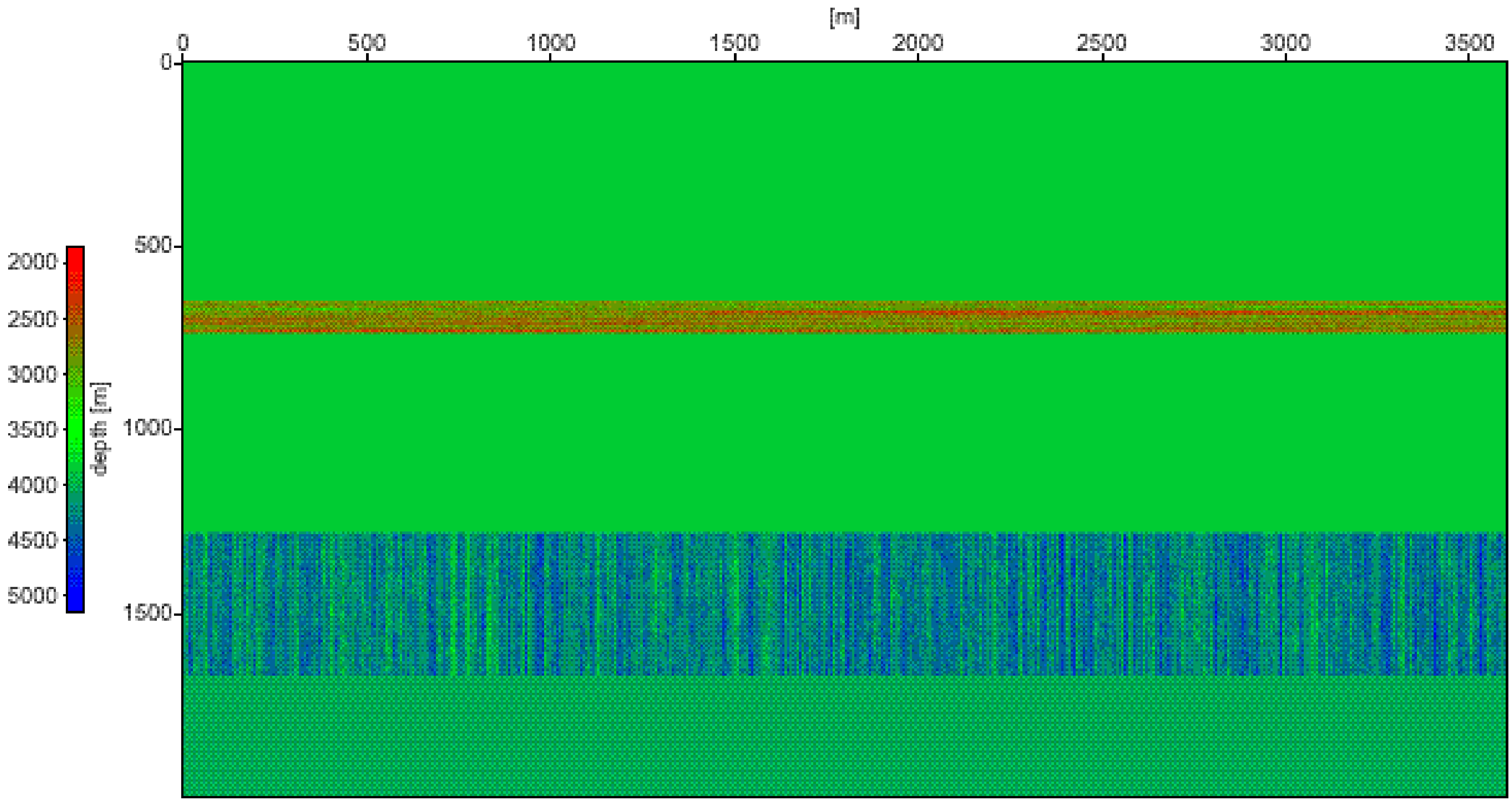


Synthetic Data: Heterogeneous Mesa Verde

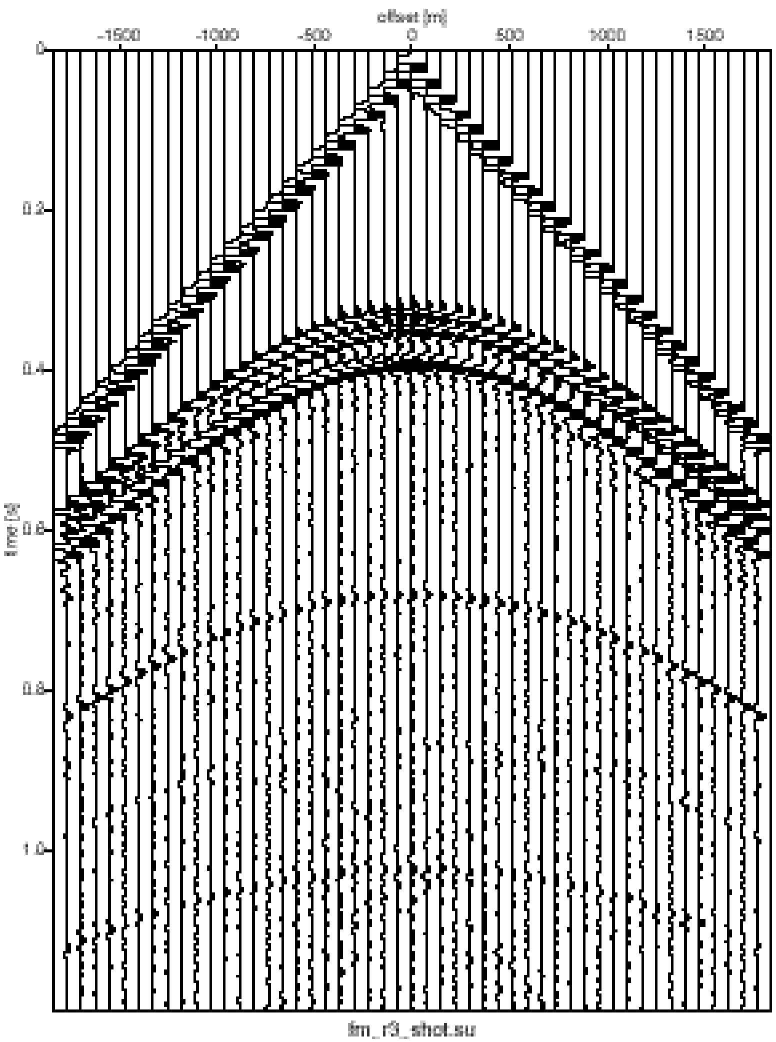


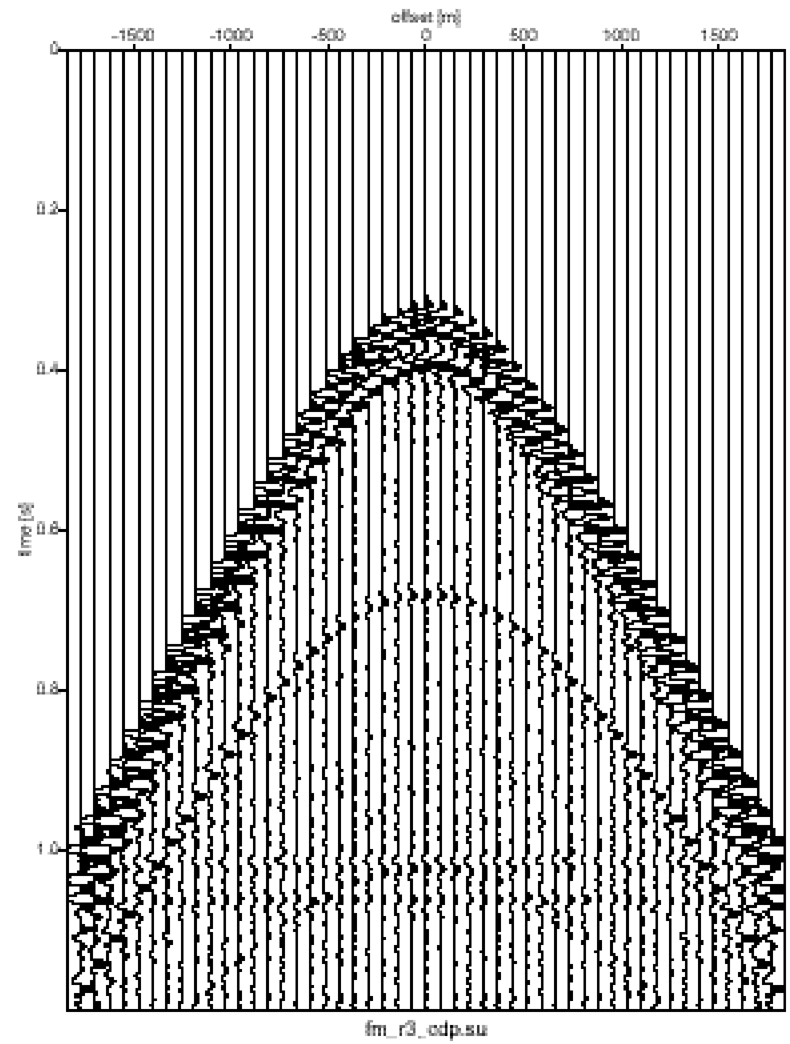


Synthetic Data: Heterogeneous Fruitland / Mesa Verde

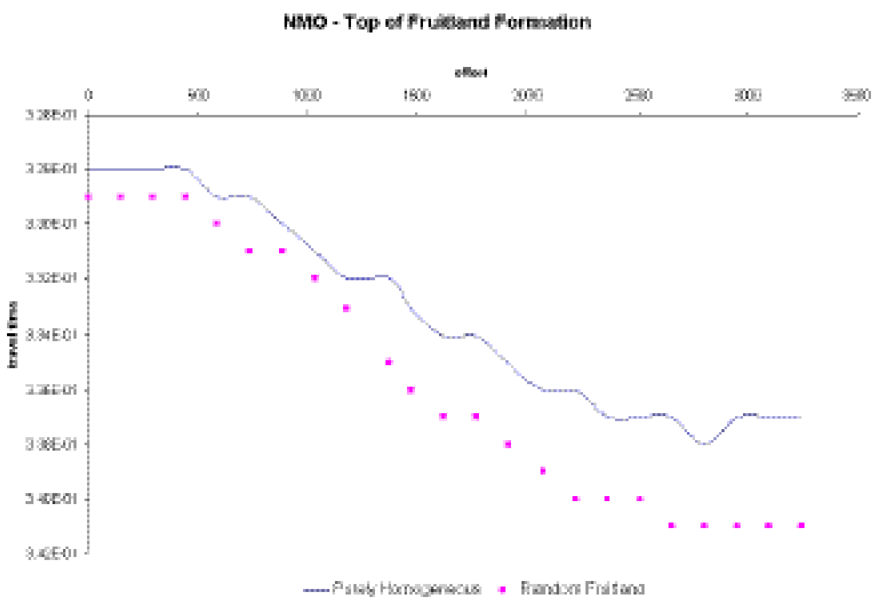


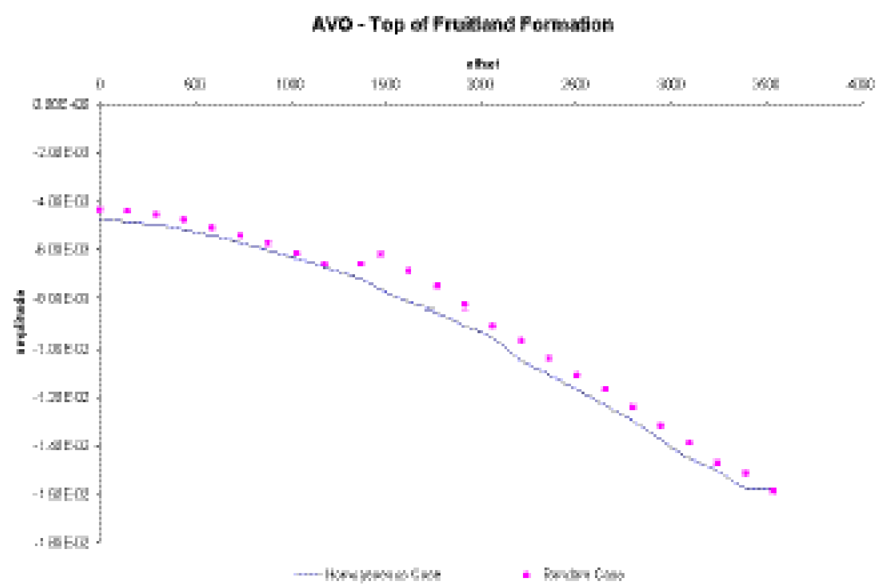
Synthetic Data: Heterogeneous Fruitland / Mesa Verde



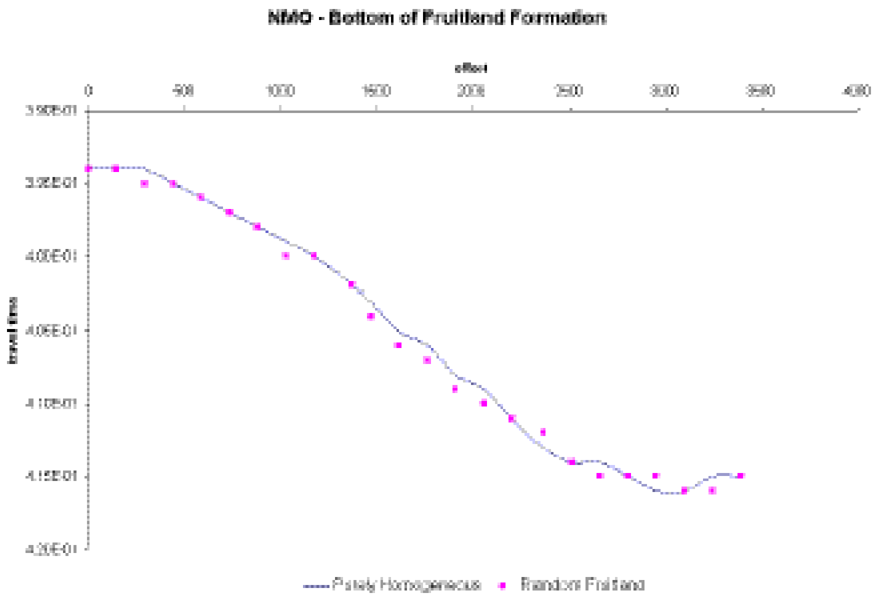


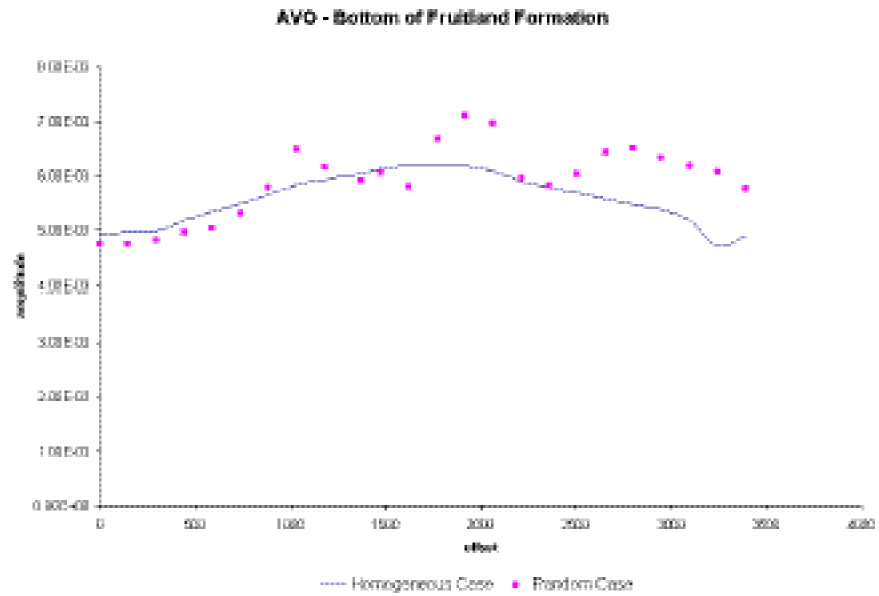
NMO / AVO: Top Fruitland



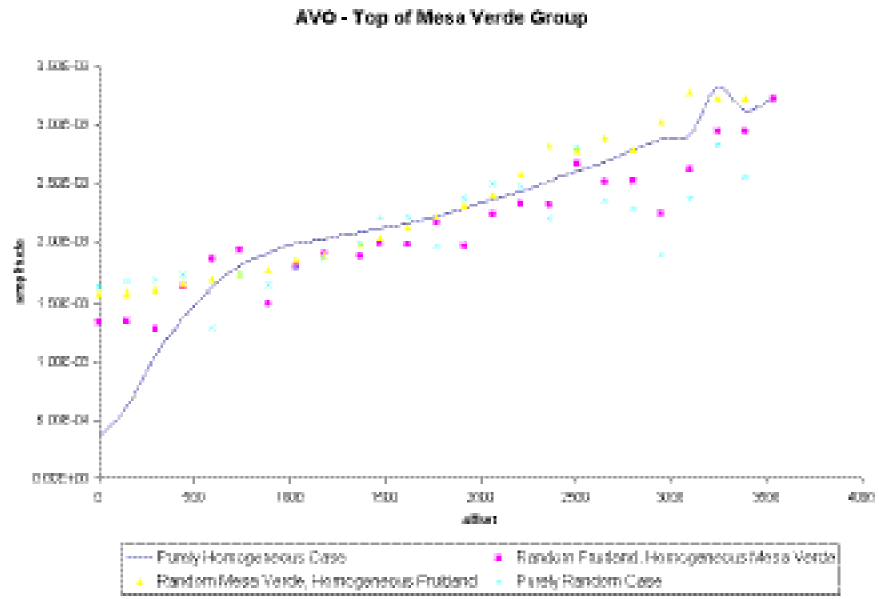


NMO / AVO: Bottom Fruitland

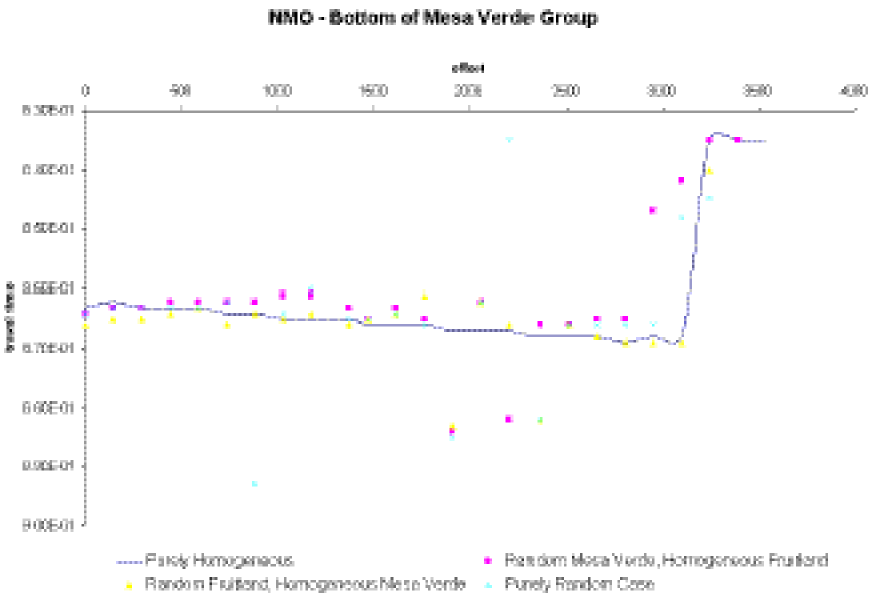


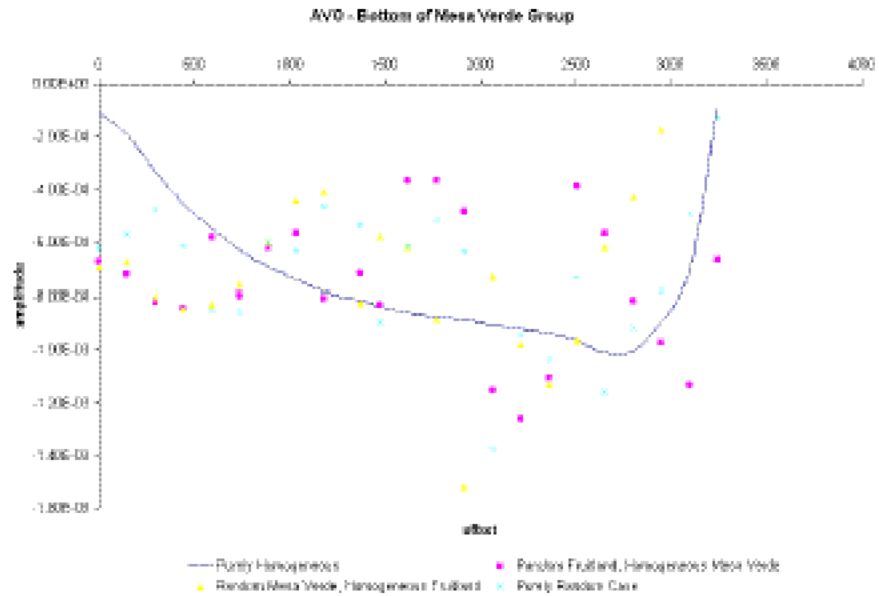


NMO / AVO: Top Mesa Verde

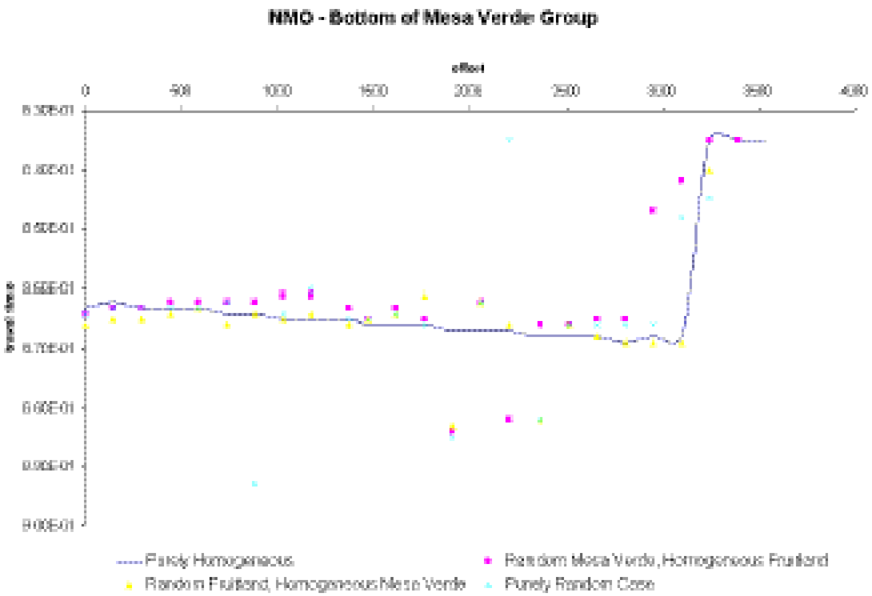


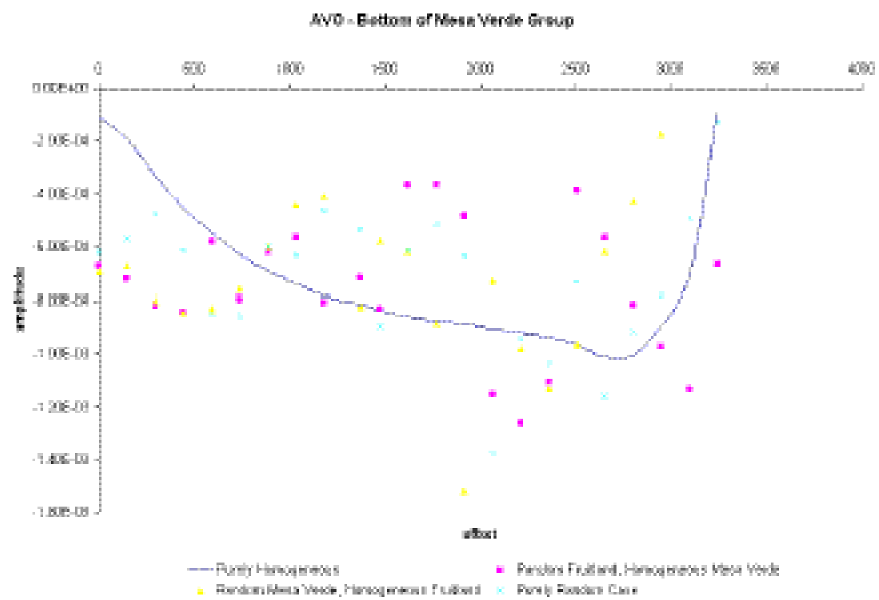
NMO / AVO: Bottom Mesa Verde



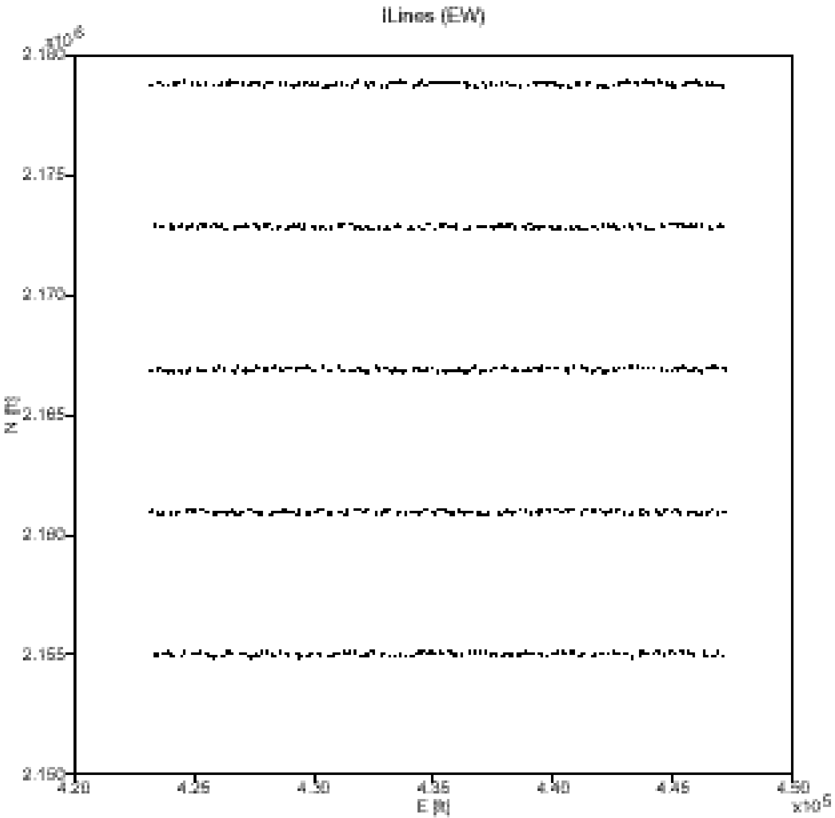


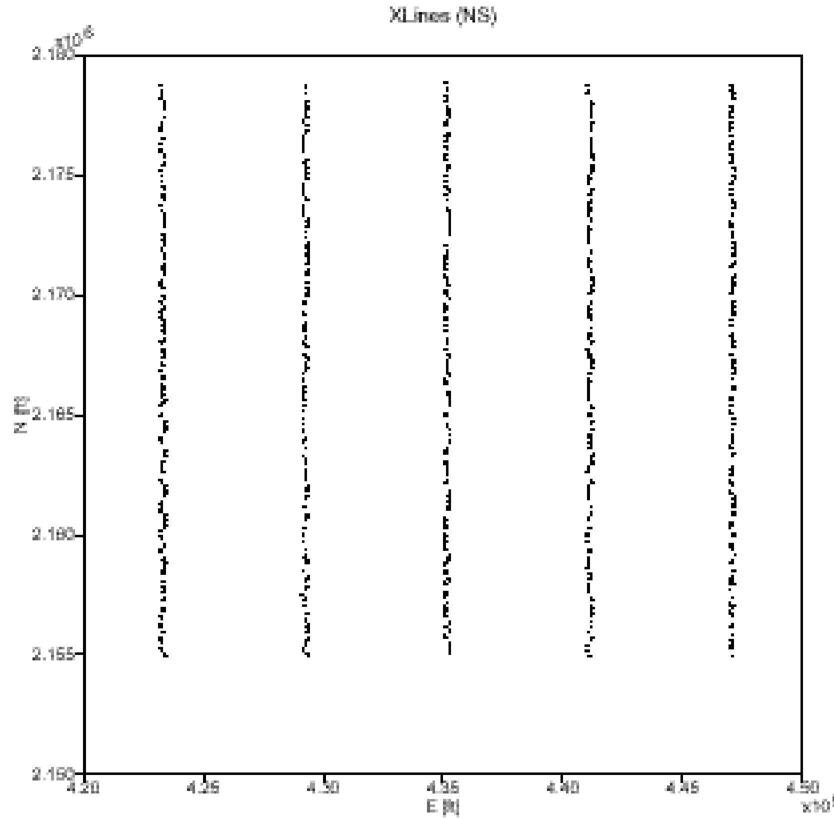
NMO / AVO: Bottom Mesa Verde



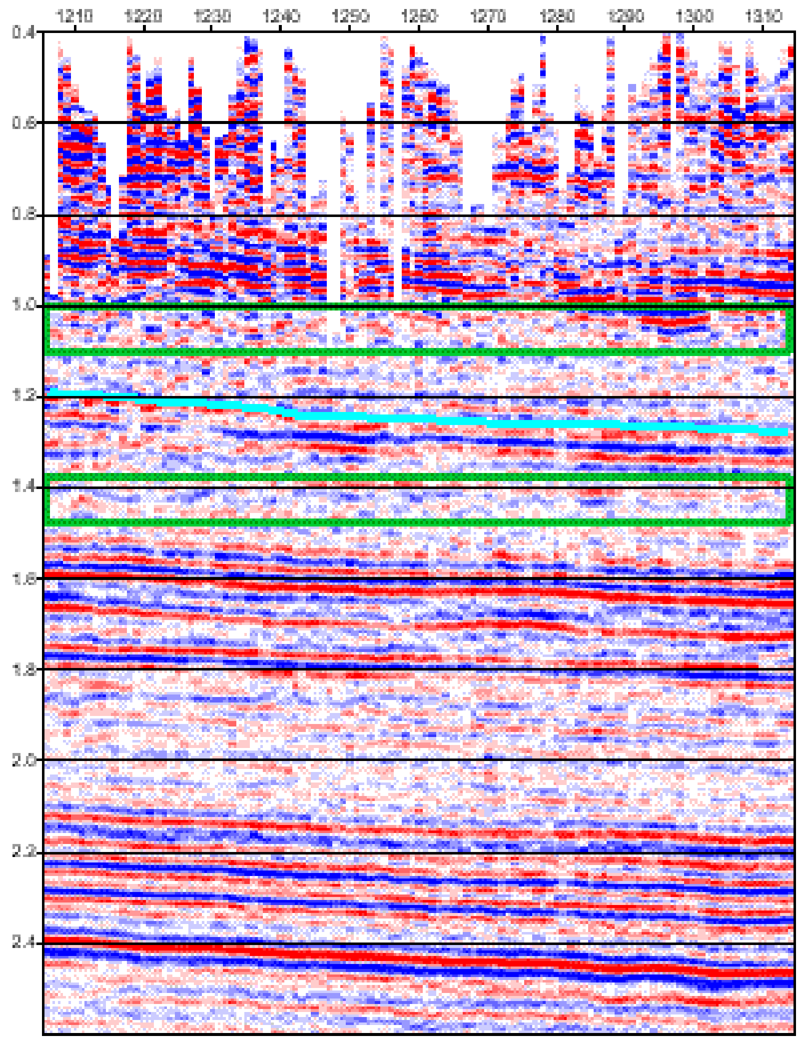


Field Data: Geometry

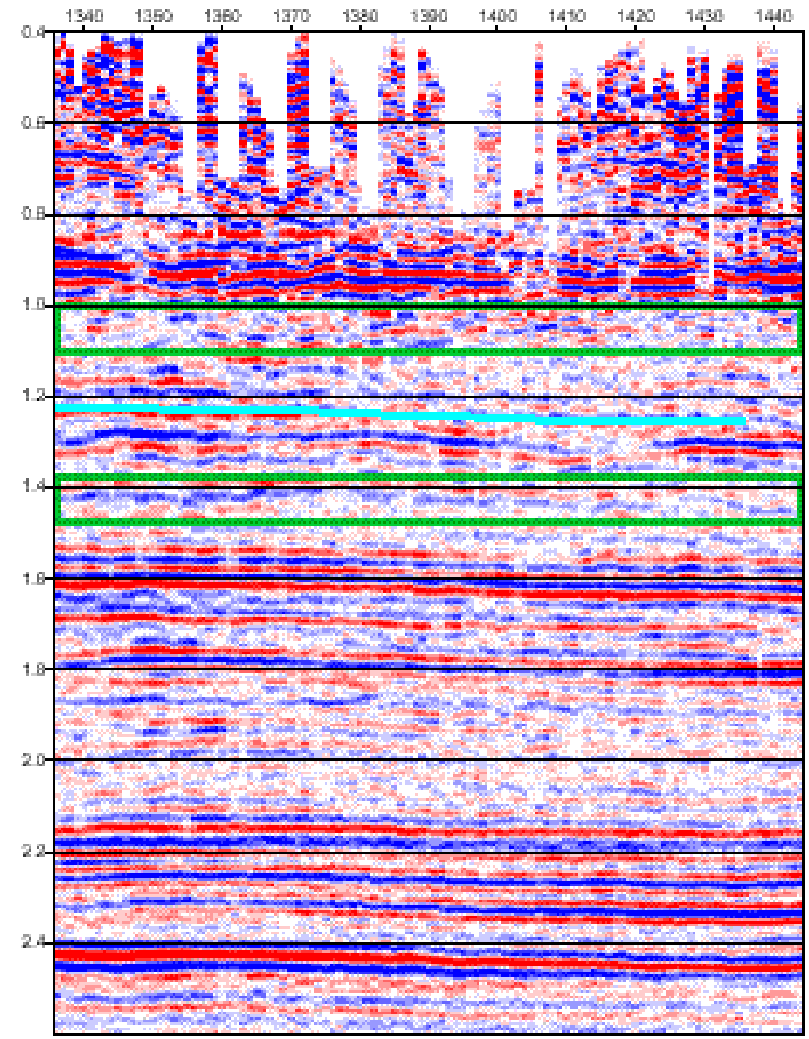




Field Data

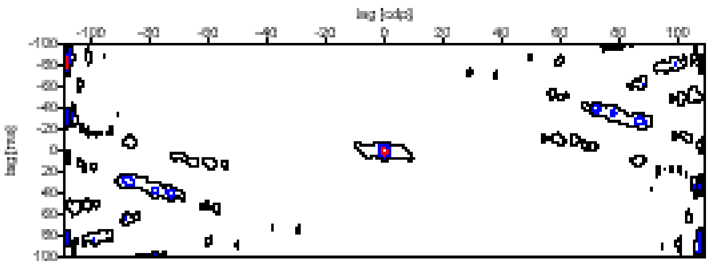


ILine 1390 (EW)

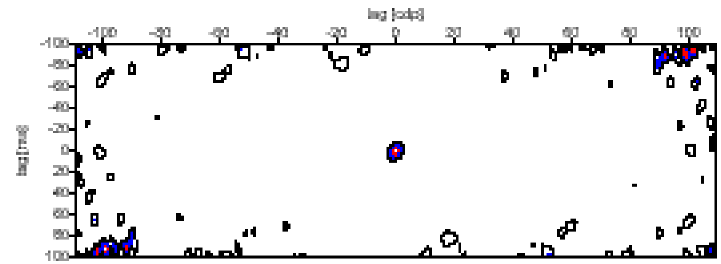


XLine 1260 (NS)

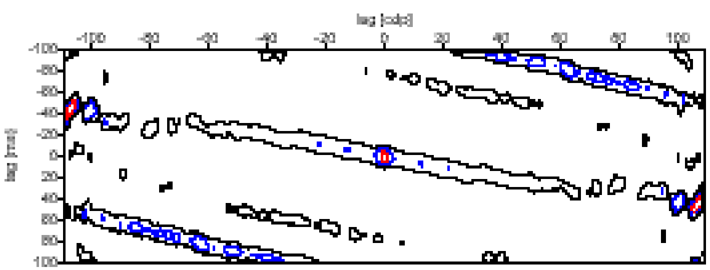
Autocorrelations



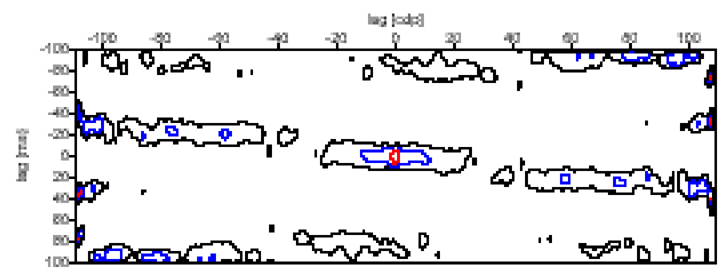
ILine 1390 (EW): 1000-1100ms raw



XLine 1260 (NS): 1000-1100ms raw

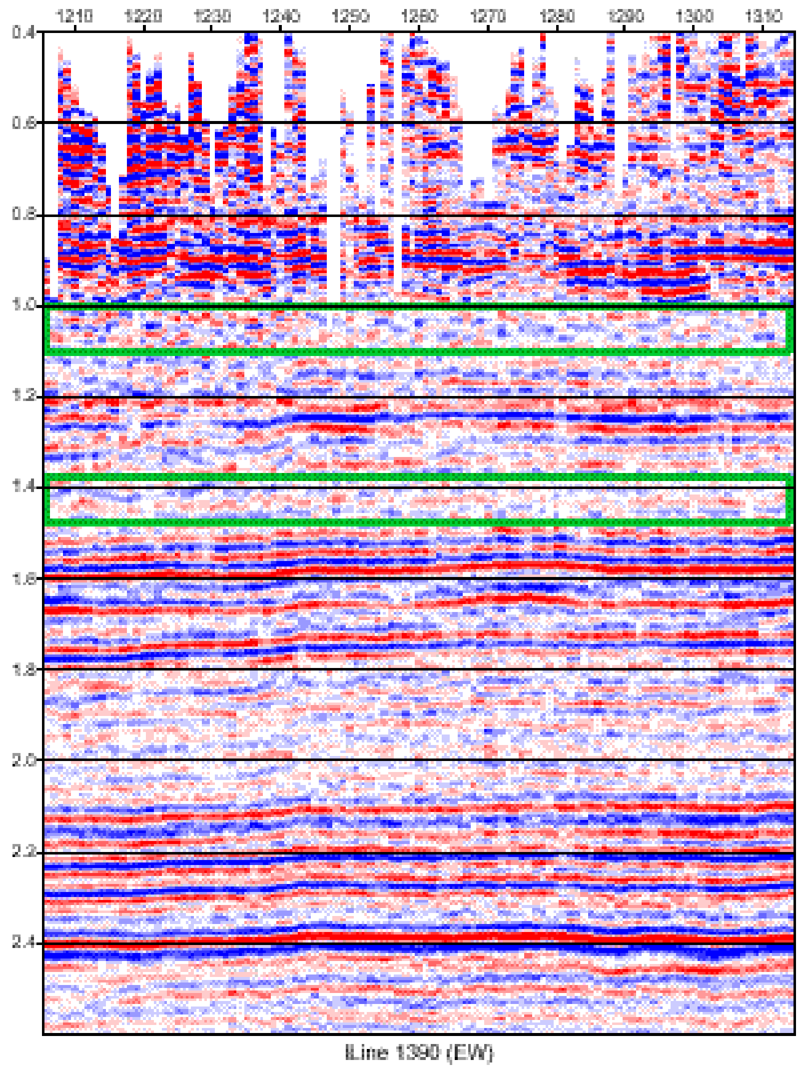


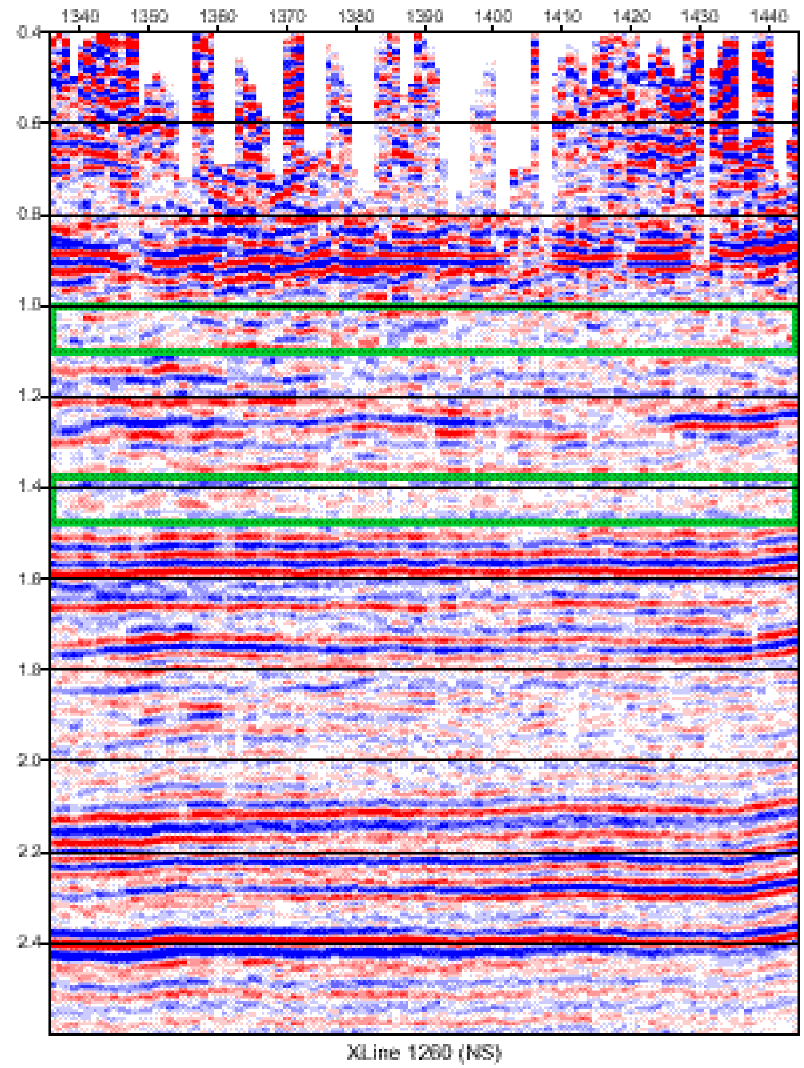
ILine 1390 (EW): 1375-1475ms raw



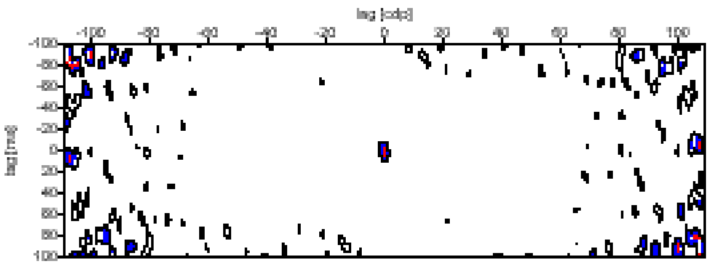
XLine 1260 (NS): 1375-1475ms raw

Field Data Flattened

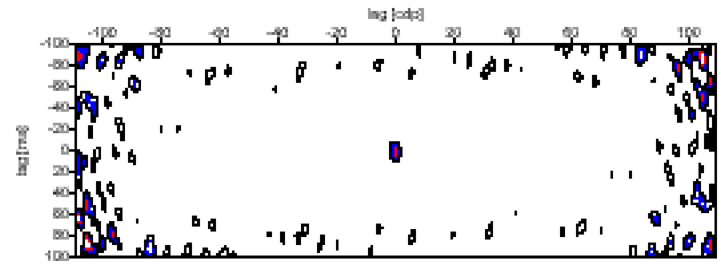




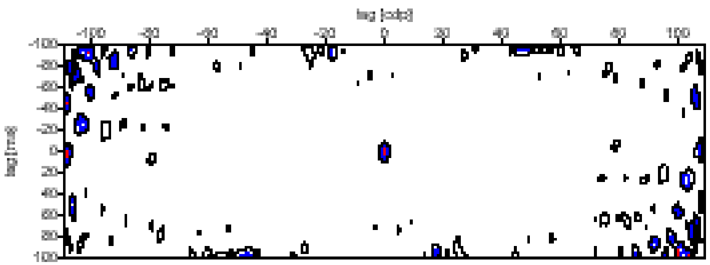
Lewis Shale Autocorrelations



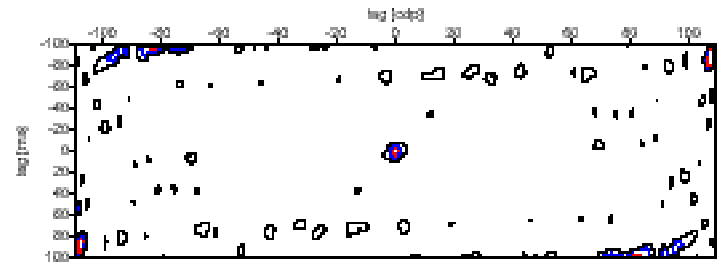
ILine 1336 (EW): 1000-1100ms.



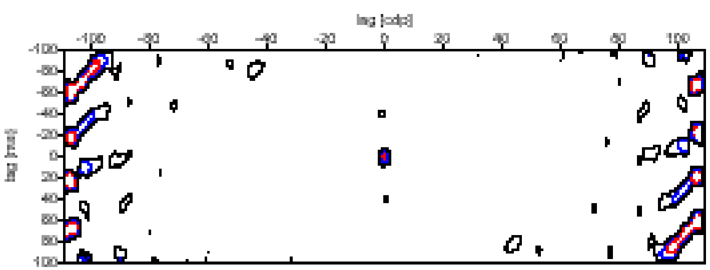
XLine 1206 (NS): 1000-1100ms



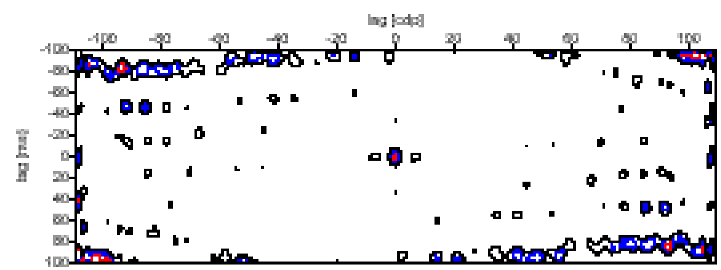
ILine 1390 (EW): 1000-1100ms.



XLine 1260 (NS): 1000-1100ms

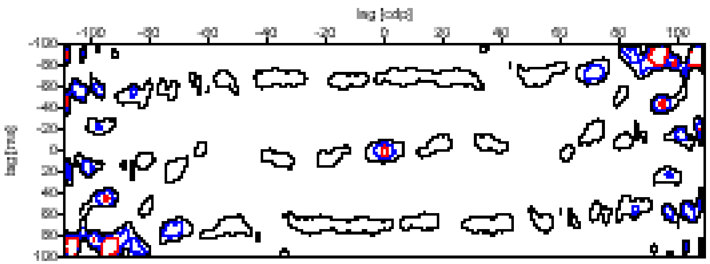


ILine 1444 (EW): 1000-1100ms.

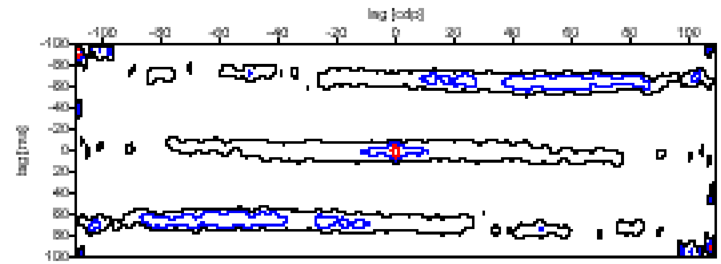


XLine 1314 (NS): 1000-1100ms

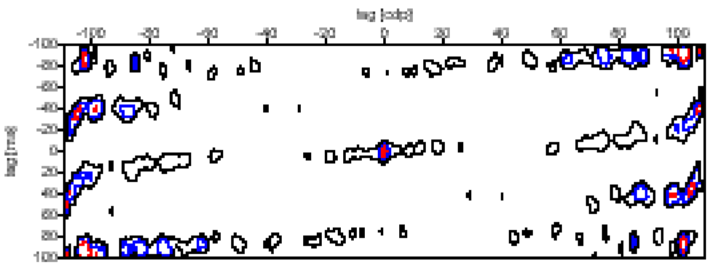
Mesa Verde Autocorrelations



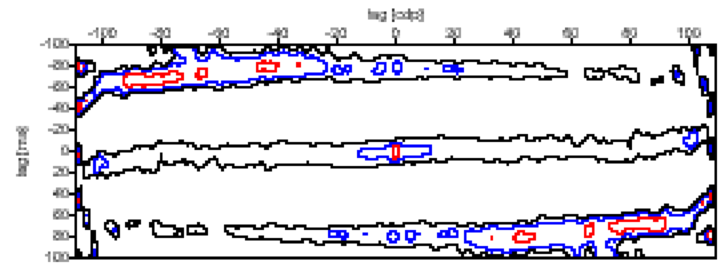
ILine 1336 (EW): 1375-1475ms.



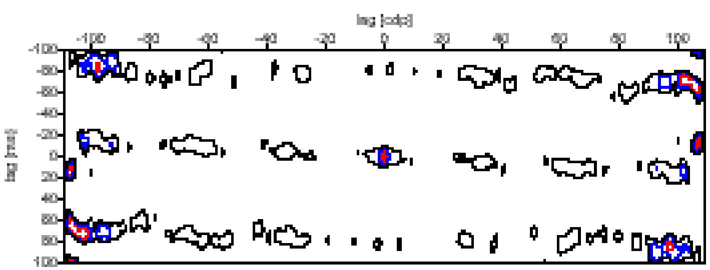
XLine 1206 (NS): 1375-1475ms



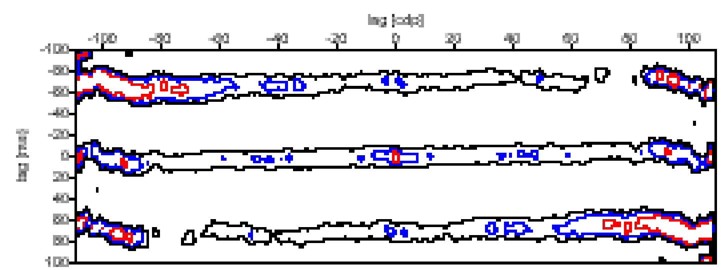
ILine 1390 (EW): 1375-1475ms.



XLine 1260 (NS): 1375-1475ms



ILine 1444 (EW): 1375-1475ms.



XLine 1314 (NS): 1375-1475ms

Acknowledgements

This work was supported by the assistant Secretary for Fossil Energy, National Energy Technology Laboratory. LBNL processing was performed at the Center for Computational Seismology, supported by the Director, Office of Science, Office of Basic Energy Sciences, Division of Engineering and Geosciences, of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098. We would like to thank NETL project managers Thomas Mroz and Frances Toro for their support.