Enhancing Subsurface Imaging and Reservoir Characterization in the Marcellus Through Advanced Reprocessing of Wide Azimuth 3D Seismic*

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Abstract

The Marcellus Shale sits in a geologically complicated region, characterized by faults, and salt cored compressional folds. Large lateral velocity variations associated with this complex geology makes seismic imaging difficult. Recently acquired 3D seismic with wide azimuth and long offset has poorly imaged folds and faults within the Marcellus Shale. Wells drilled utilizing the existing 3D seismic volumes often present incorrect bed dips, and folds mistakenly interpreted as faults, or vice versa, due to the poor imaging quality.

After careful examination of each processing step a few key drivers were identified that could potentially provide improvements to subsurface imaging. Starting from field seismic records geometry errors were identified and corrected. Improved noise attenuation practices including land surface related multiple elimination (LSRME) were applied to improve S/N. An extensional patch was carefully tested and validated in the 5D interpolation which improved the offset coverage in the narrow direction. Furthermore, orthorhombic prestack time migration (PSTM) was performed. An orthorhombic velocity model fits the data better than the traditional VTI model for layered subsurface due to a dominant set of orthogonal fracture sets prevalent in the basin. Significant improvement of the subsurface imaging was obtained by implementation of these processing steps. The new orthorhombic PSTM correctly images steeply dipping (75° and above) faults which were previously elusive or absent. Additionally, former interpreted faults are now clearly imaged as folds, small and large in scale. These imaging improvements have enabled the accurate drilling of laterals in the target zone which otherwise would have been drilled out of zone. Some large faults are well imaged which pass through the Marcellus, Mahantango, and Tully, previously barely visible. The revelation of such large faults effectively helps avoid geohazard. The dramatic improvement in the subsurface imaging and amplitude friendly processing enhance the reservoir description of the Marcellus Shale.

References Cited

Engelder, T. G. Lash, and R. Uzcategui, 2009, Joint Sets that Enhance Production from Middle and Upper Devonian Gas Shales of the Appalachian Basin: American Association of Petroleum Geologists Bulletin, v. 93/7. p. 857-889. DOI:10.1306/03230908032.

Verschuur, D.J., A.J. Berkhout, and C.P.A. Wapenaar, 1992, Adaptive Surface-Related Multiple Elimination: Geophysics, v. 57/9, p. 1166-1177.

ENHANCING SUBSURFACE IMAGING AND RESERVOIR CHARACTERIZATION IN THE MARCELLUS THROUGH ADVANCED REPROCESSING OF WIDE AZIMUTH 3D SEISMIC

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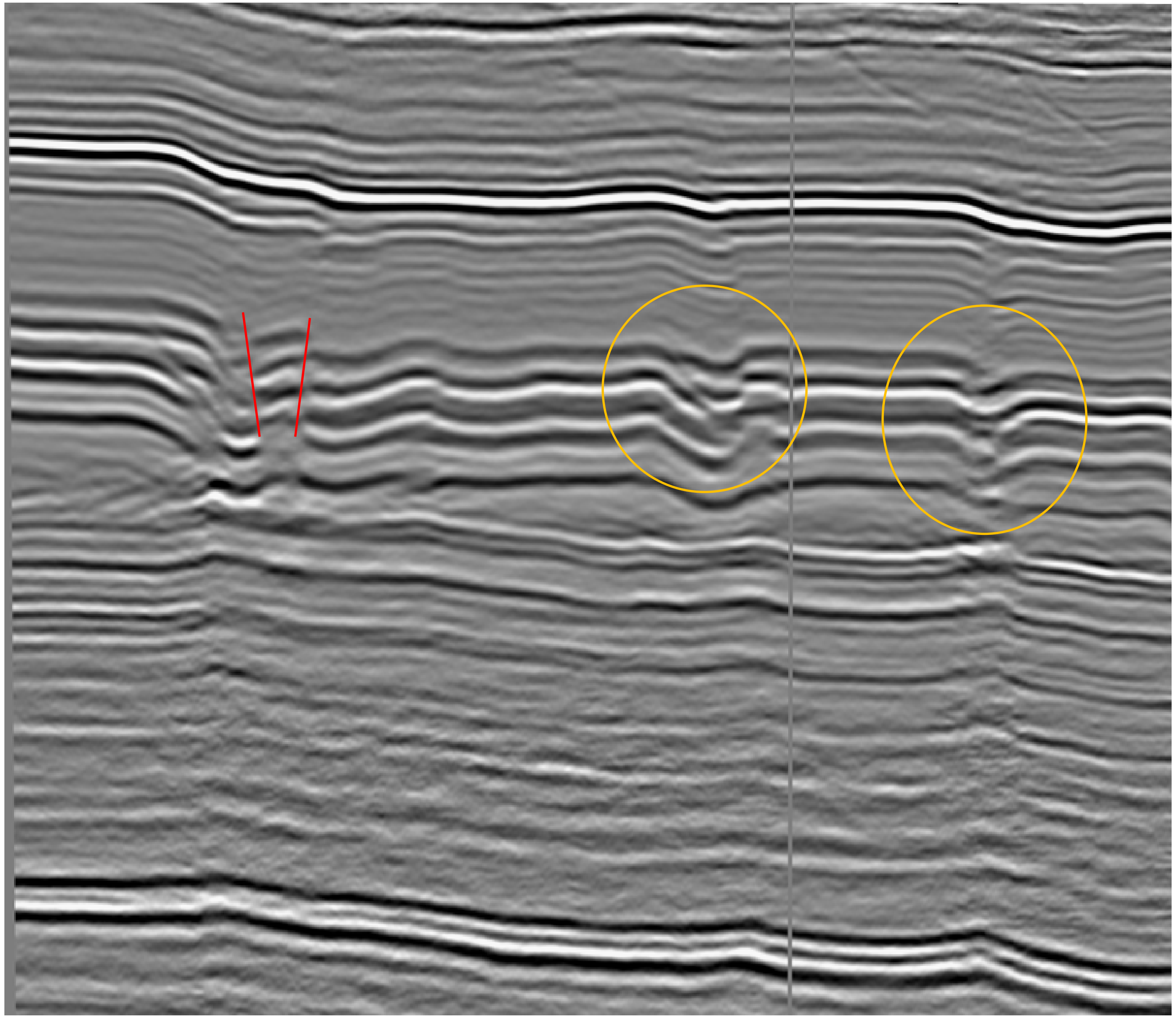
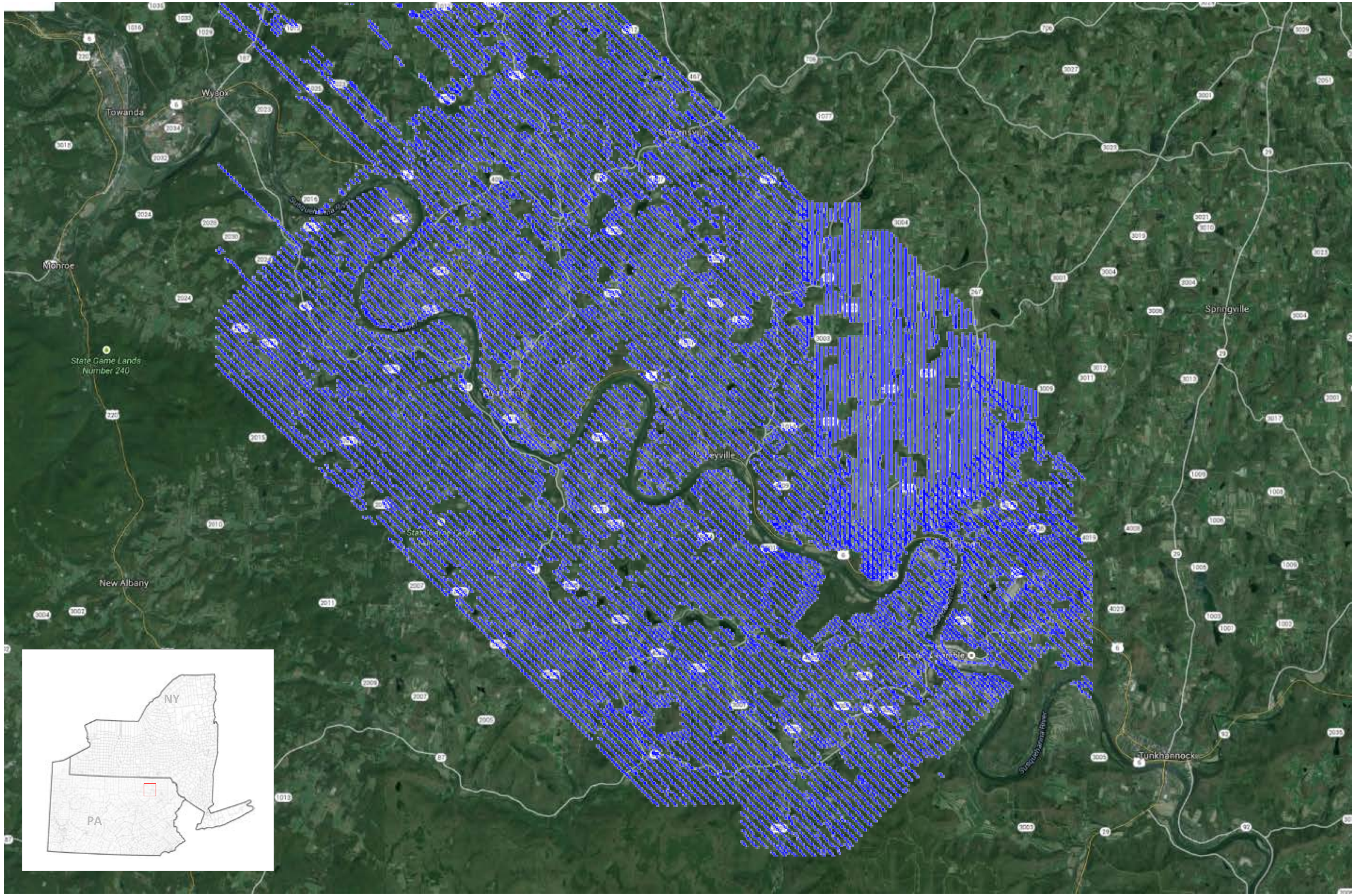
<u>Challenges</u>: A typical section from the 2013 PSTM



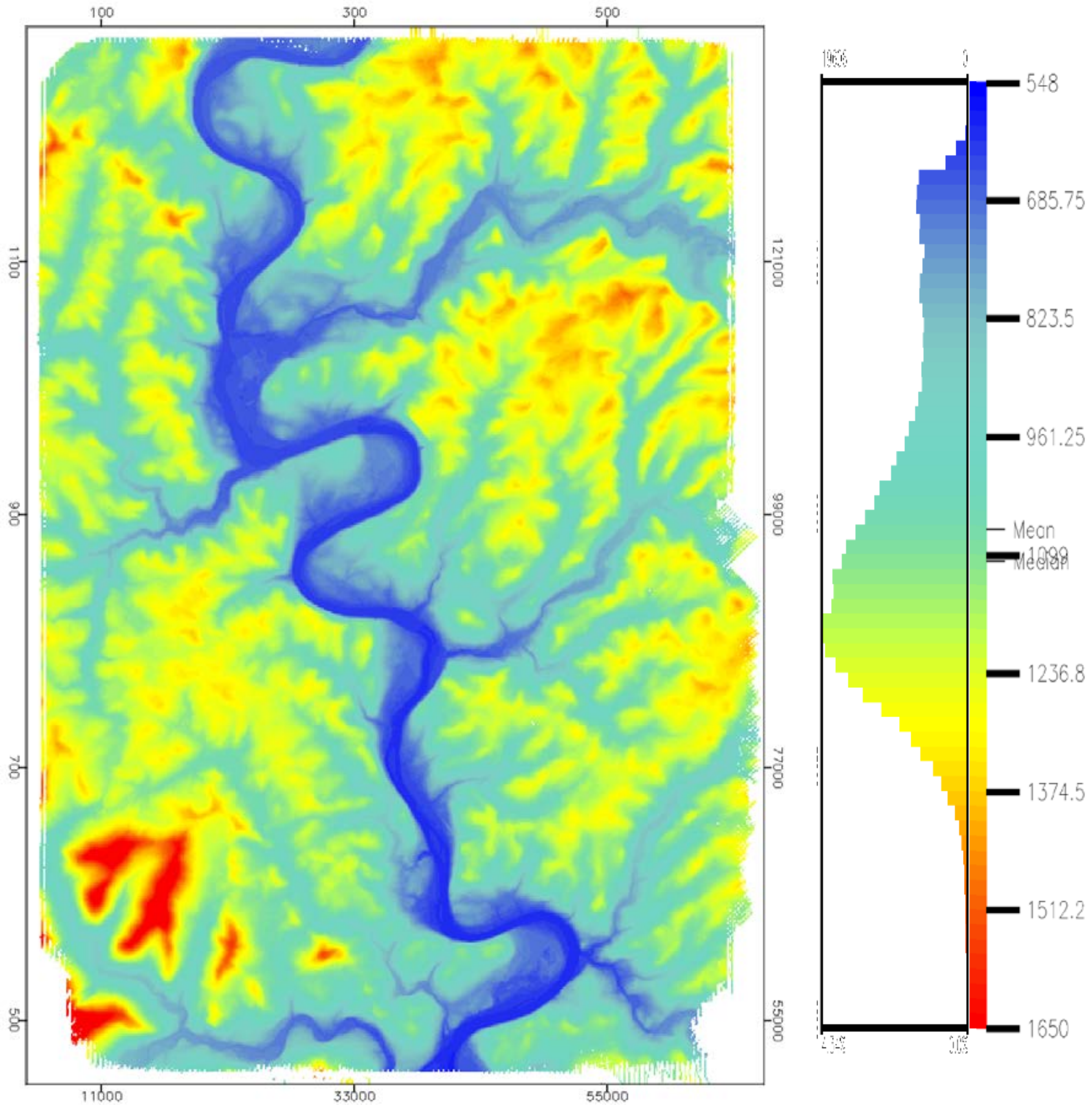
- *The upper Marcellus is shown to be thrusted about* 150-200 ft *in the faults interpreted in the left side section, but the drilling found it's a tight fold*
- Uncertainties about the faults and folds shown in the circled areas

Piot project area



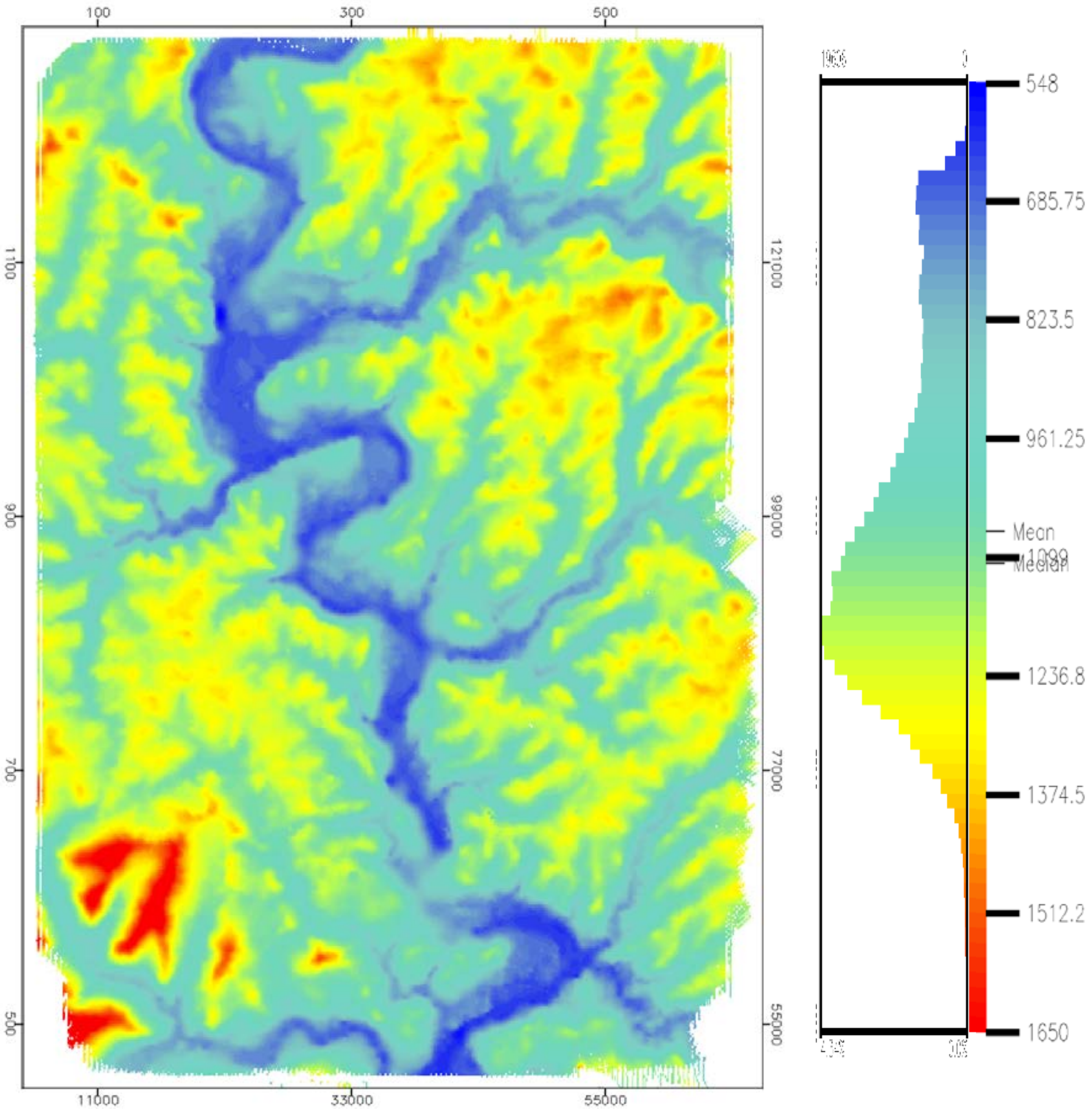
- Red square is pilot location
- *The blue lines are the receiver positions*
- *Mehoopany survey receiver lines in NS direction while the other 2 surveys w/ the same NW-SE receiver line direction*
- Susquehanna River cuts through

Elevation map from LIDAR: 3x3 ft grid



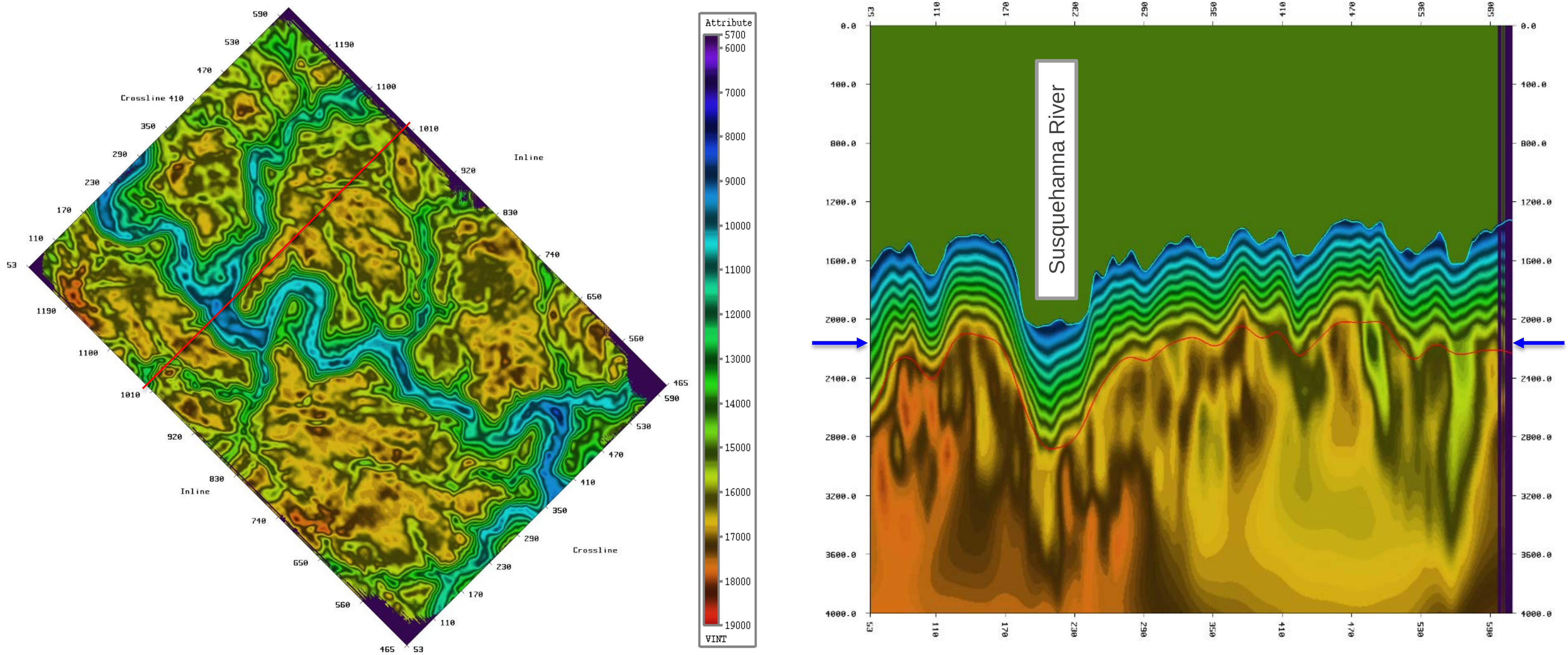
- LIDAR: light detection and ranging data
- High resolution, available through the state of Pennsylvania
- It provides the key information in no-access and no-permit zones
- Notice the high resolution definition of the Susquehanna River and the mountain ranges

Elevation map from shot and receiver elevations



- Inaccuracies introduced due to the inaccessibility of the river and also to the rough terrain changes
- Large elevation errors close to 200 ft.

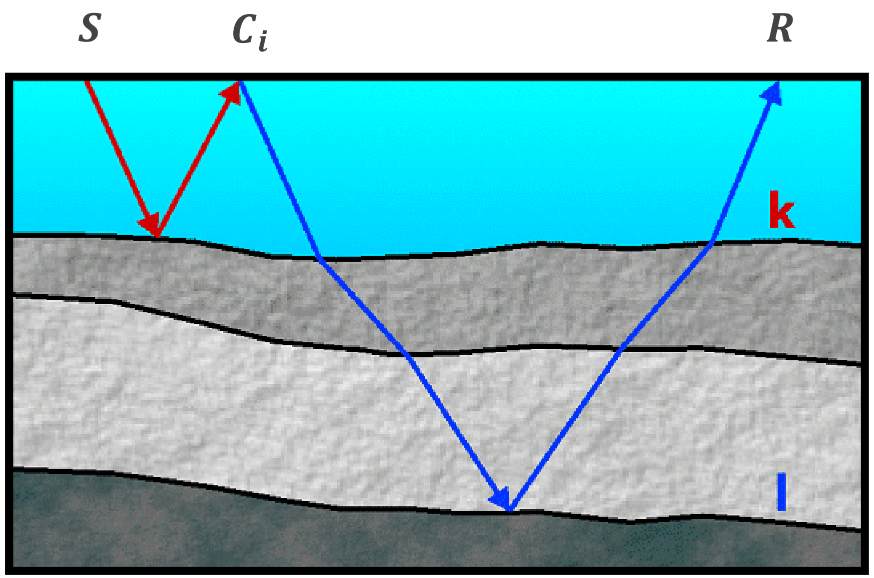
Depth slice through near-surface tomo model at 2165 ft below 2700 ft datum



- It's high resolution model, built from refraction tomography & LIDAR
- The Susquehanna River is clearly observable running through the survey
- The river is accurately modeled near surface

LSRME for removal of surface related multiples

- *SRME: Surface related multiple elimination (Verschuur et al., 1992)*
- *Developed primarily for deep water environment for removal of water bottom multiples*
- *A surface multiple reflection point can be considered to have both a shot and a receiver at that exact location where the multiple reflects back into the earth.*
- *The convolution of trace SC_i and trace C_iR is one possible multiple recorded at trace SR. Contributions from all the possible C_i locations constitute the multiples related to the free surface*
- *It is data driven, does not need a model*
- *The removal of the predicted multiples is an adaptive process.*

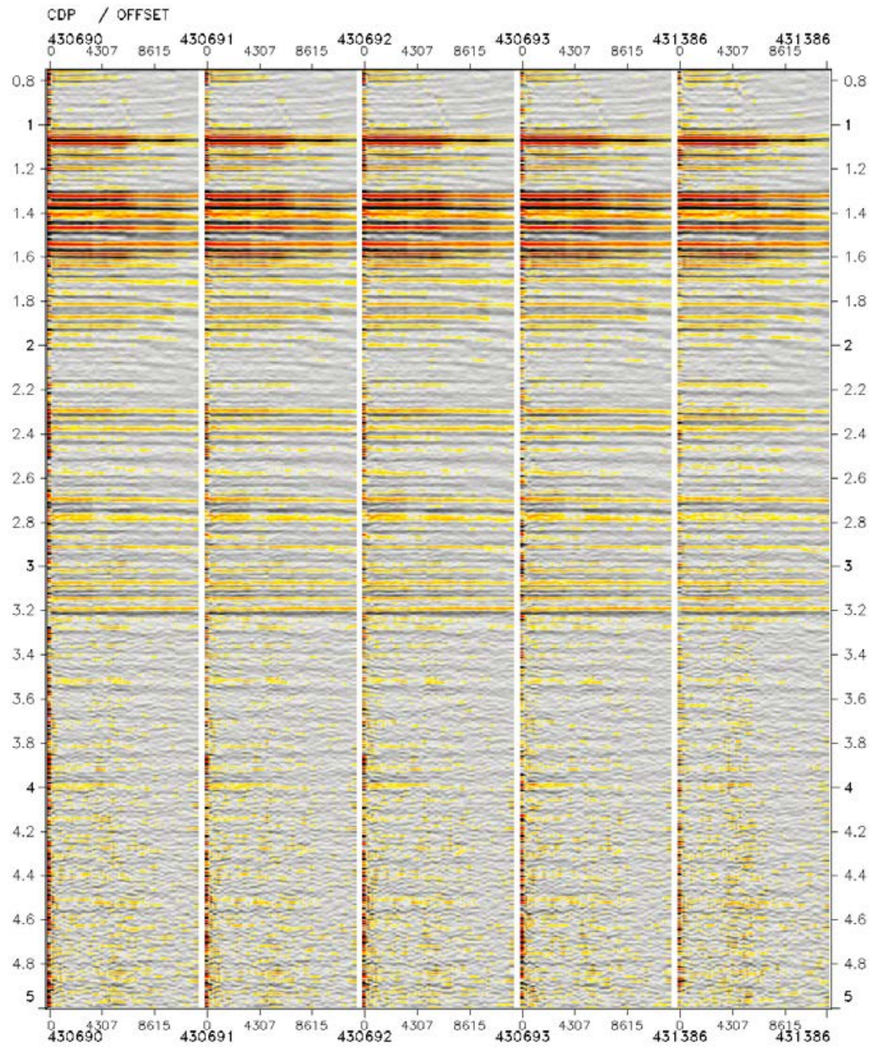


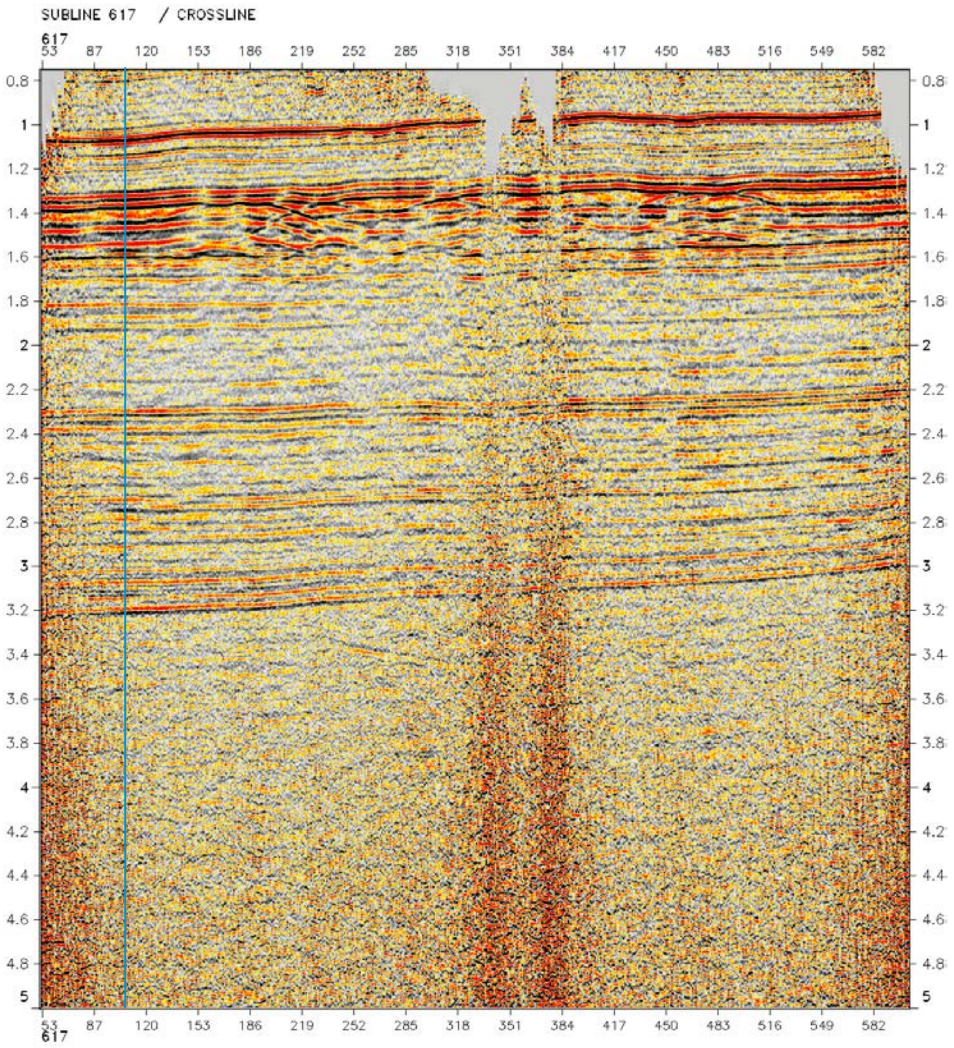
$$M_{SR} = \sum_i (SC_i * C_iR)$$

Challenges for Land SRME

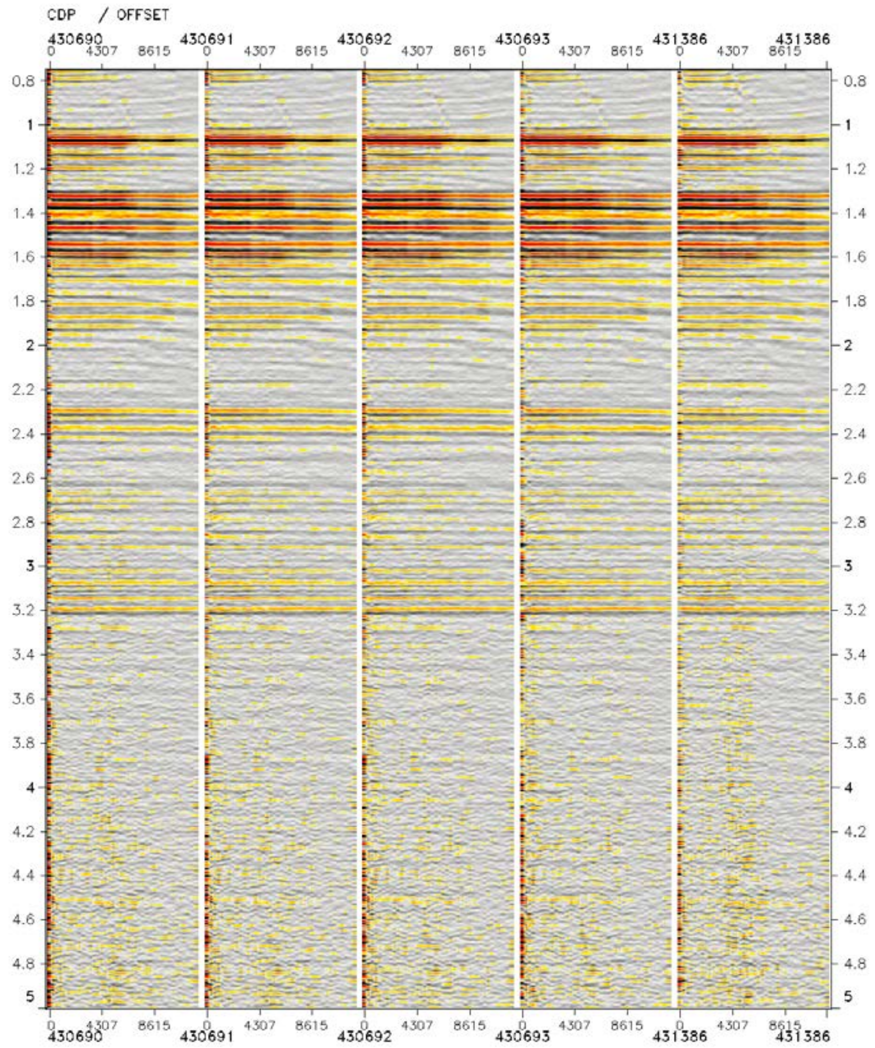
- *Low S/N*
- *The surface is rugose*
  - *Rugose surface can scatter reflections off the surface, outside of the live patch.*
  - *Variability of multiple scattering power in the surface*

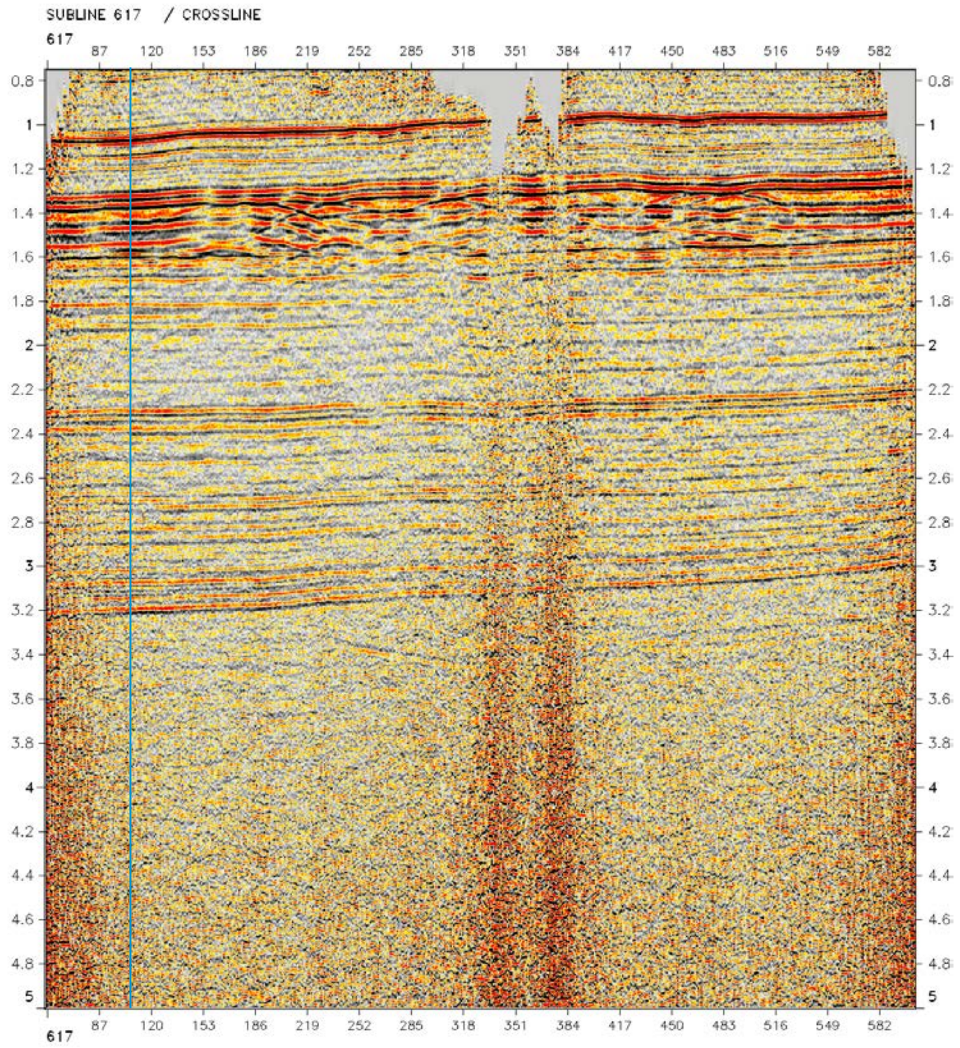
Gathers and stack: pre LSRME



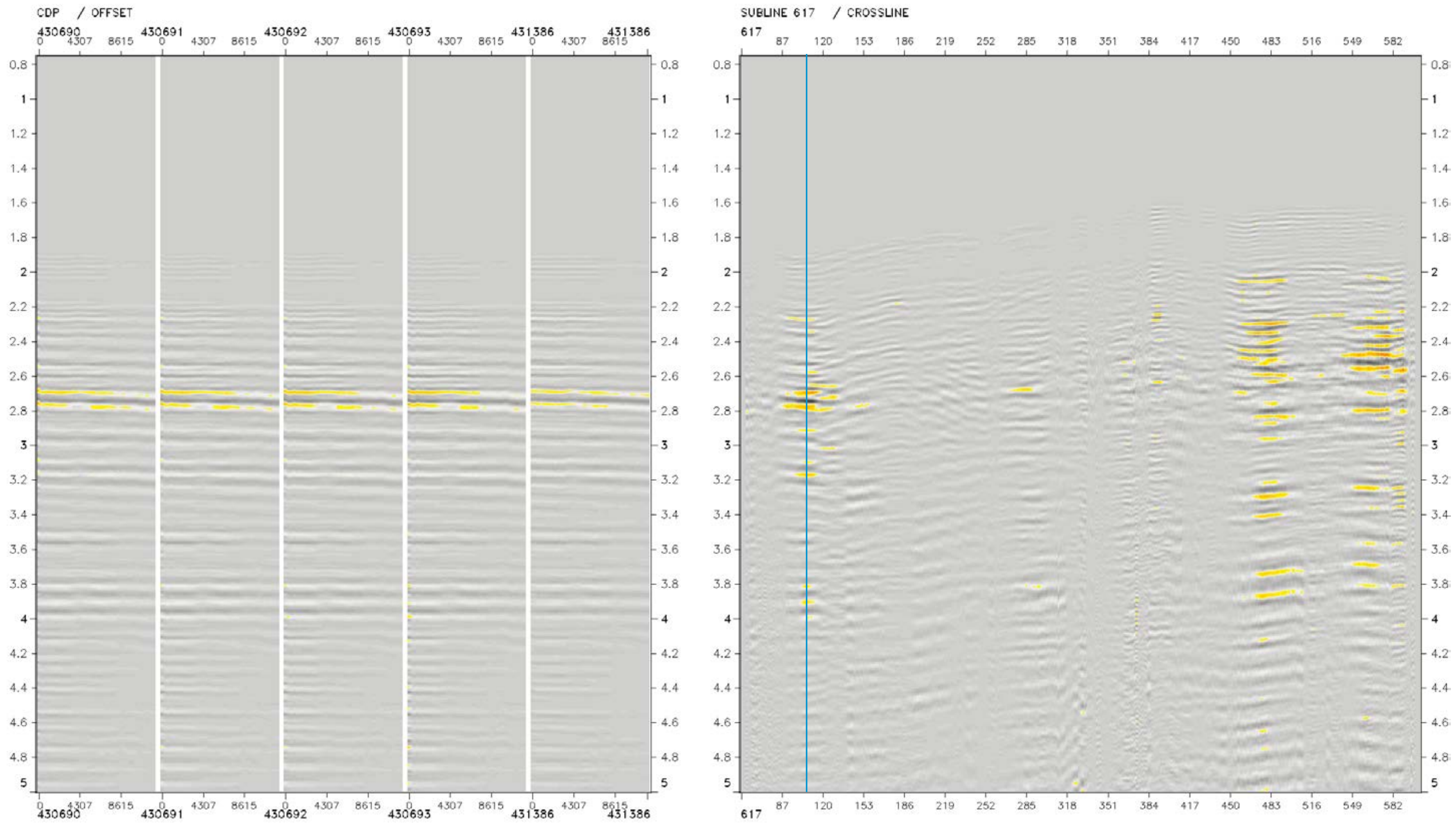


Gathers and stack: post LSRME



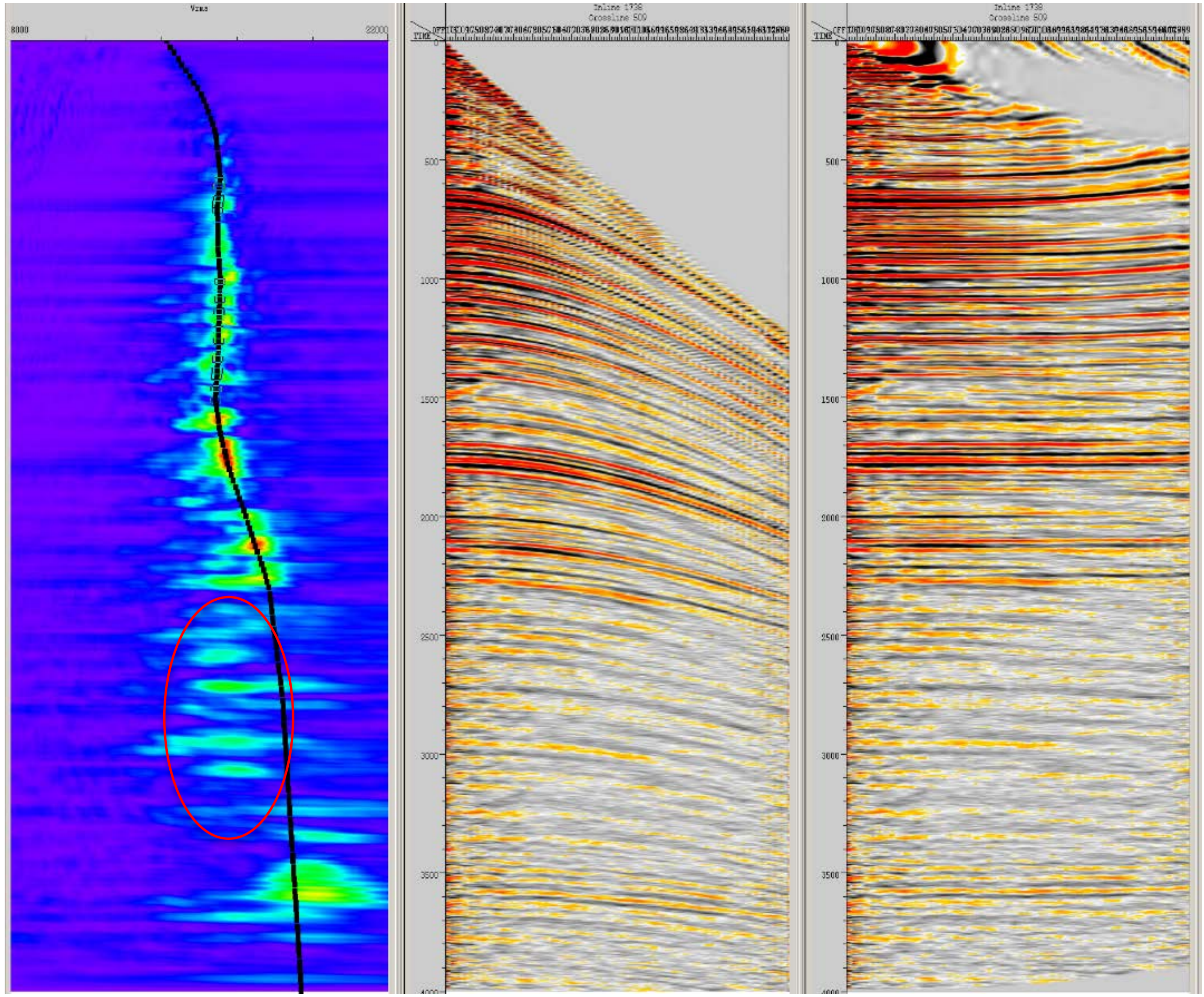


Gathers and stack: What was taken out by LSRME



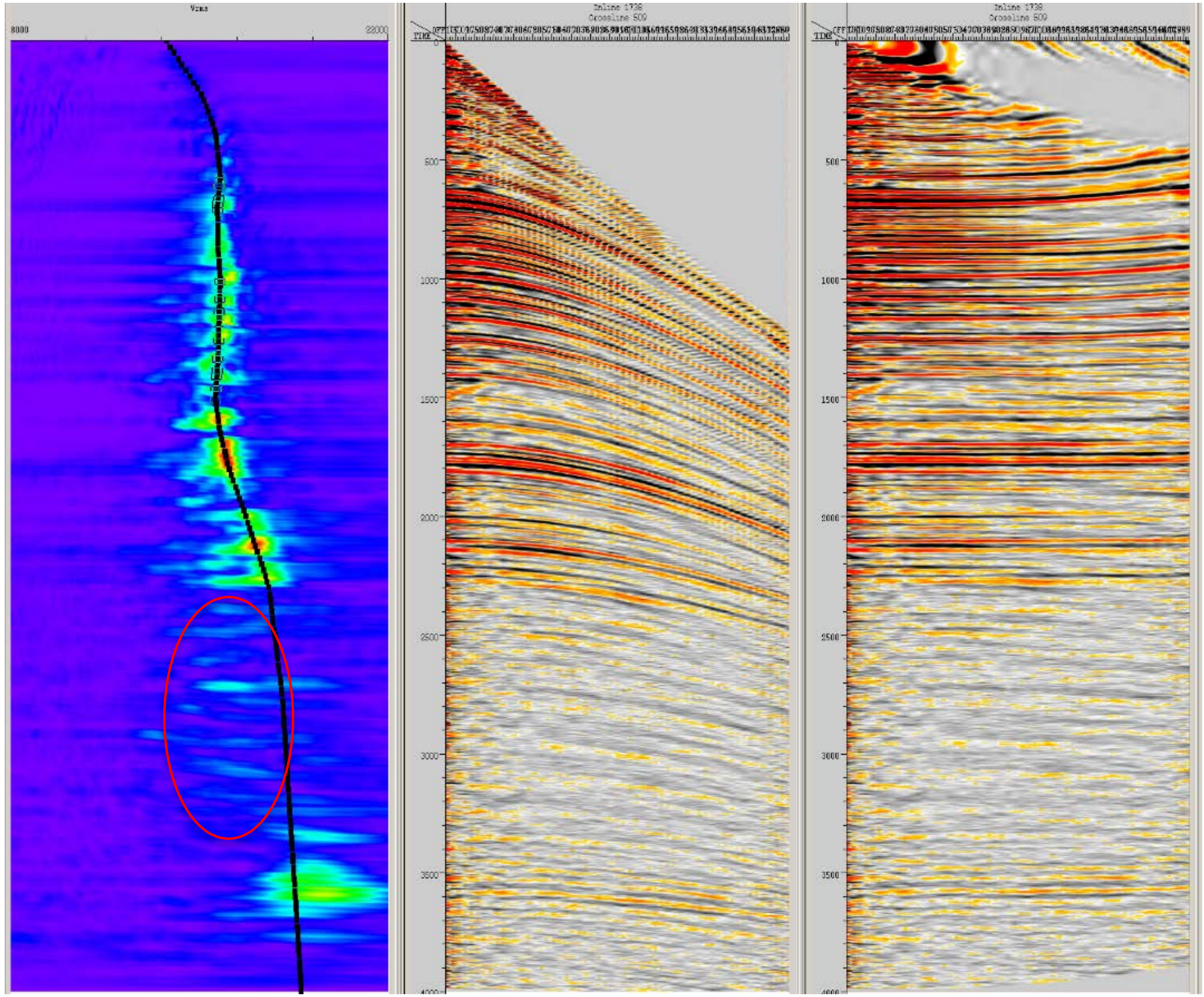
- The multiples have little moveout which defies other demultiple processes
- The multiple generators are quite variable spatially

LSRME effects on velocity semblance: pre LSRME



- Notice the energy highlighted
- Is the energy primaries?

LSRME effects on velocity semblance: post LSRME



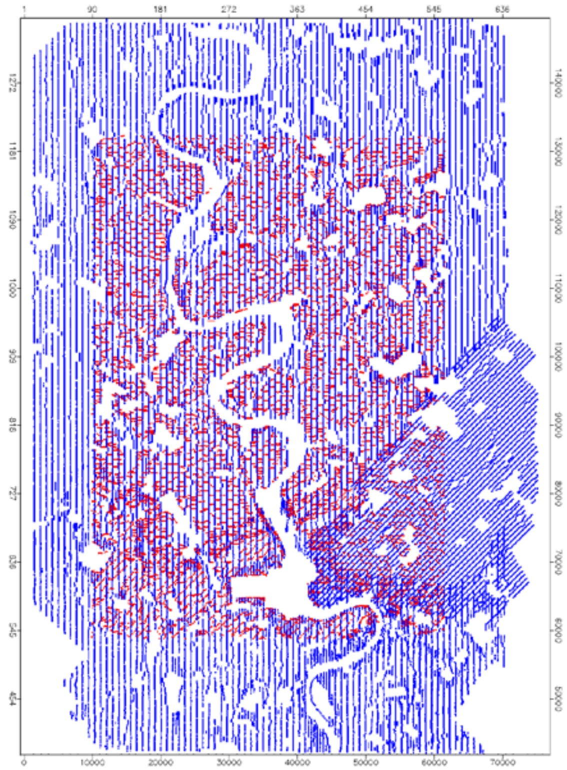
- The highlighted energy is basically removed by the LSRME
- The energy is from surface related multiples with small moveout
- Automatic velocity picking algorithms and inexperienced interpreters could mistakenly pick the energy as primaries

5D interpolation

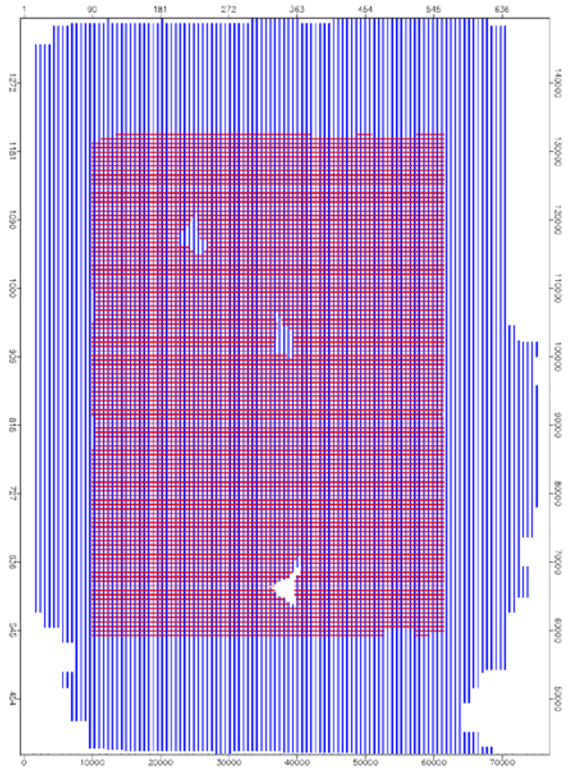
- Our acquired 3D seismic is often irregular, with holes
- Many key techniques such as migration and AVAZ require regular sampling of data in space & time. Otherwise, undesired artifacts could be introduced
- 5D interpolation: time, plus 4 spatial dimensions:

  inline, xline, offset and azimuth
- 5D interpolation reconstructs the missing traces at any spatial position from the adjacent present data assuming,

  the spatial spectra at a location is consistent with neighboring data's spatial spectra

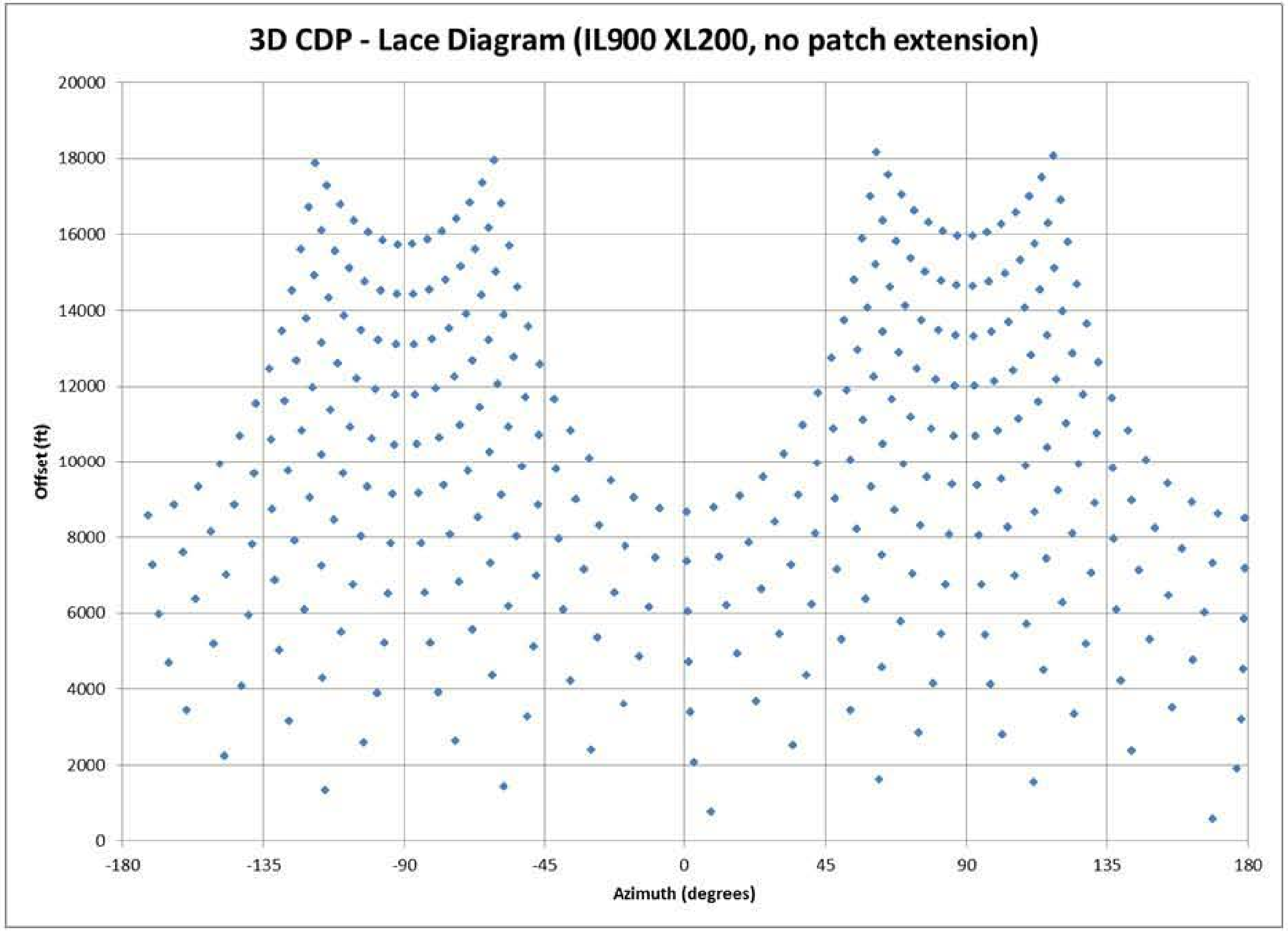


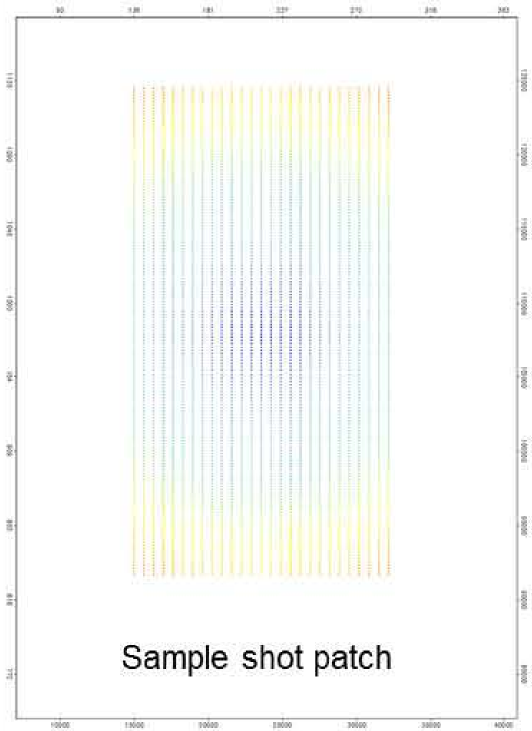
3D Shots & Receivers



5D Shots & Receivers

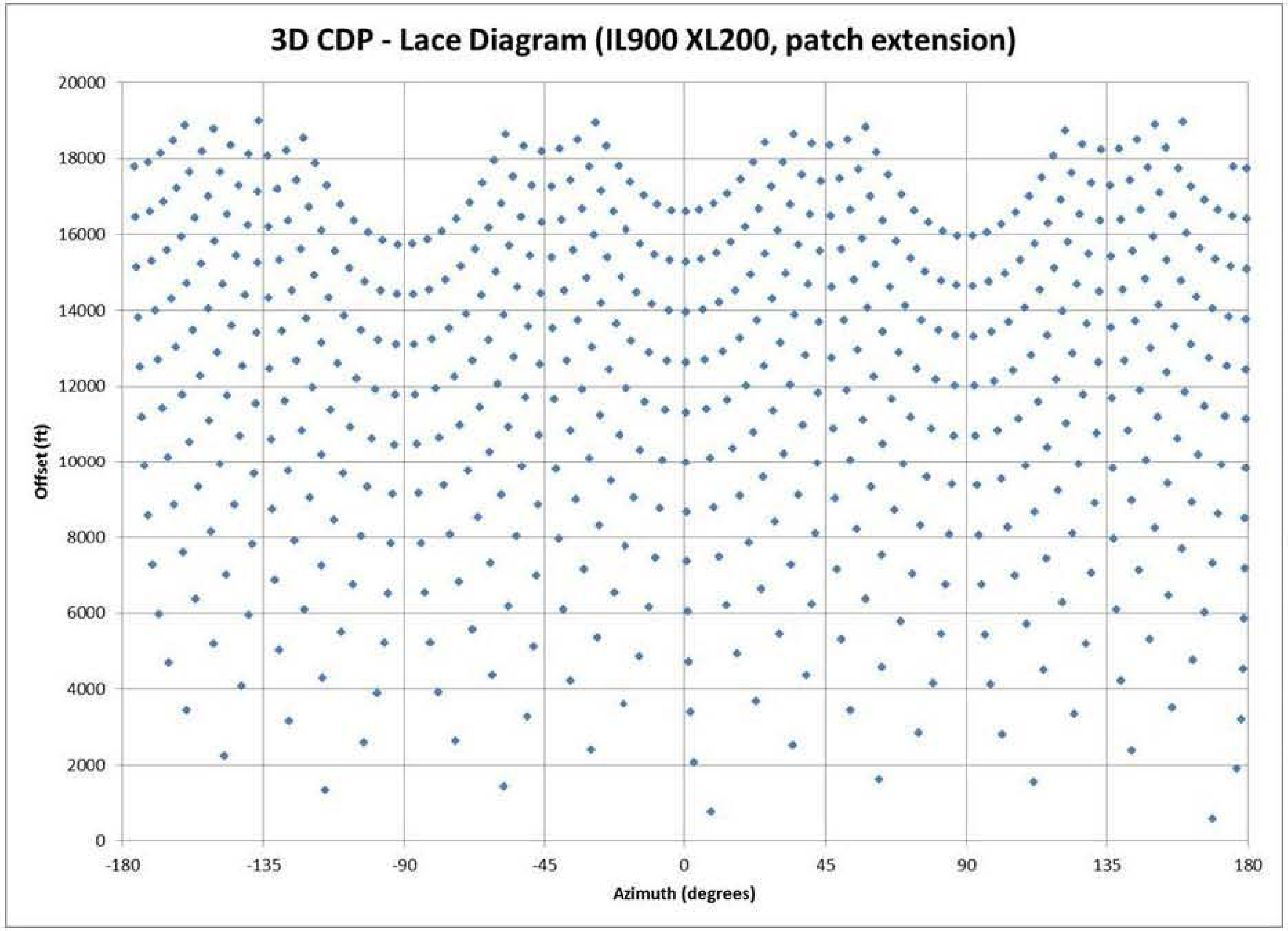
Offset-azimuth distribution of a CDP – typical 5D

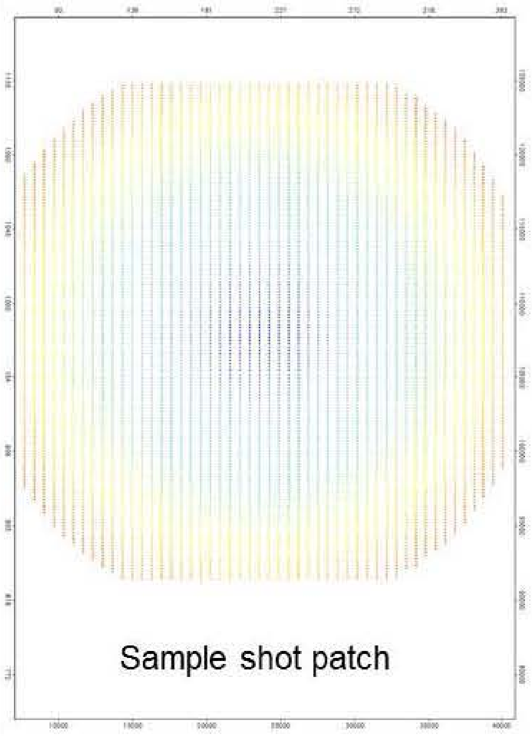




- Still limited offset at some azimuths
- For azimuth around 0 degrees here, the offset only covers to ~9000’
- Not ideal yet for AVAZ

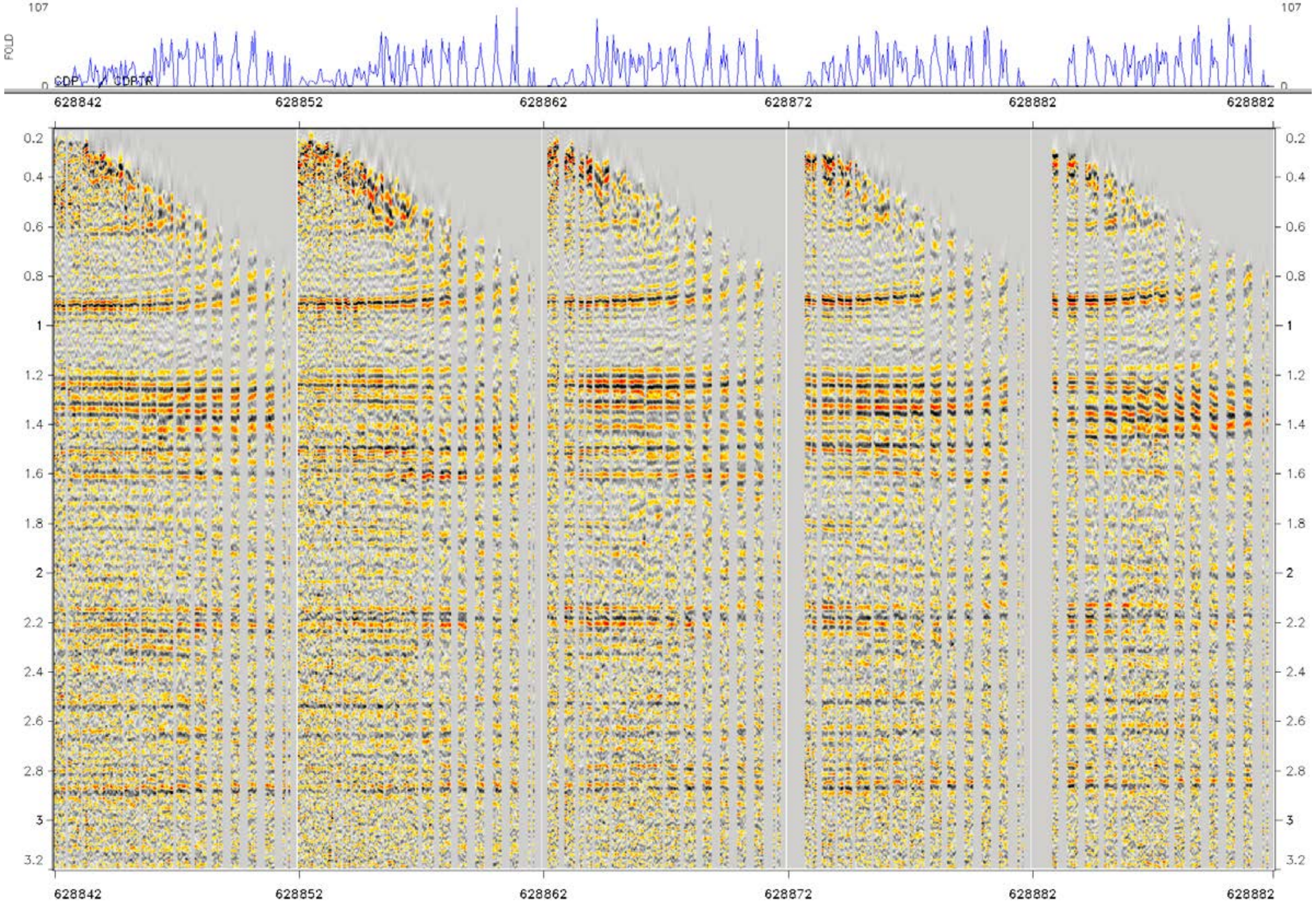
Offset-azimuth distribution of a CDP – Patch Extension 5D

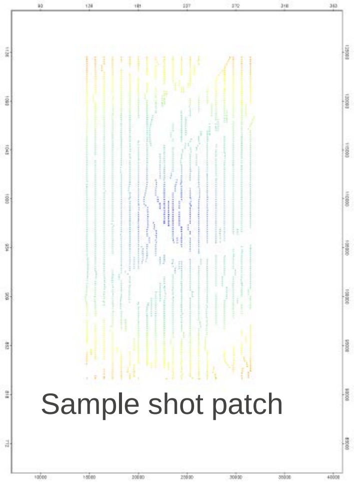




- All azimuths have data at least to 16000' offset
- Is it safe?

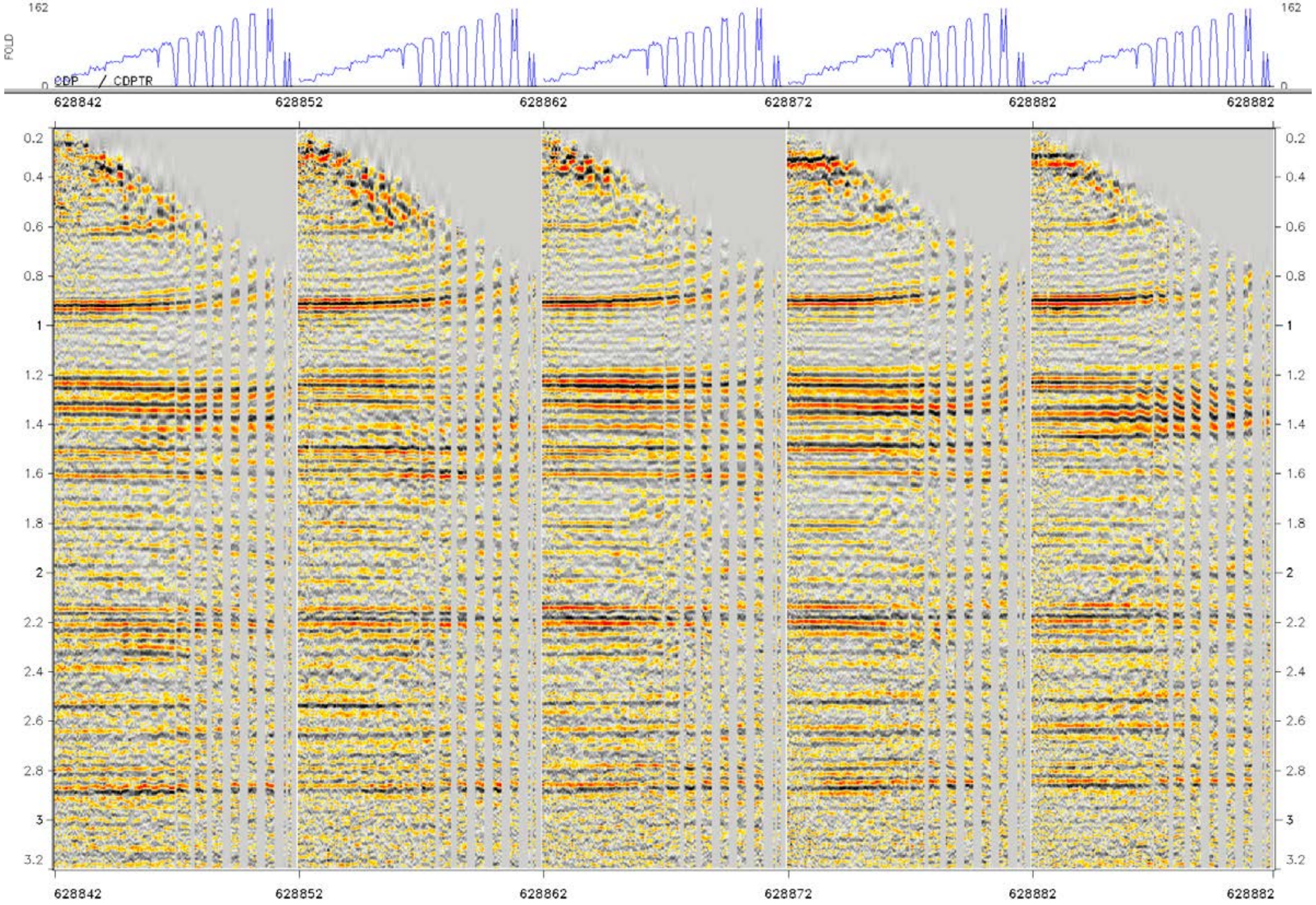
3D COCA gather

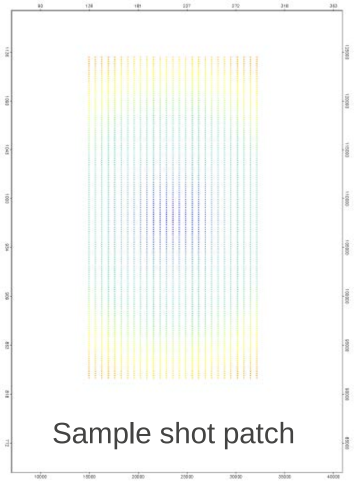



Sample shot patch

- 5x5, 15 offsets, 12 azimuths
- Notice the many missing traces, in all offsets/azi.

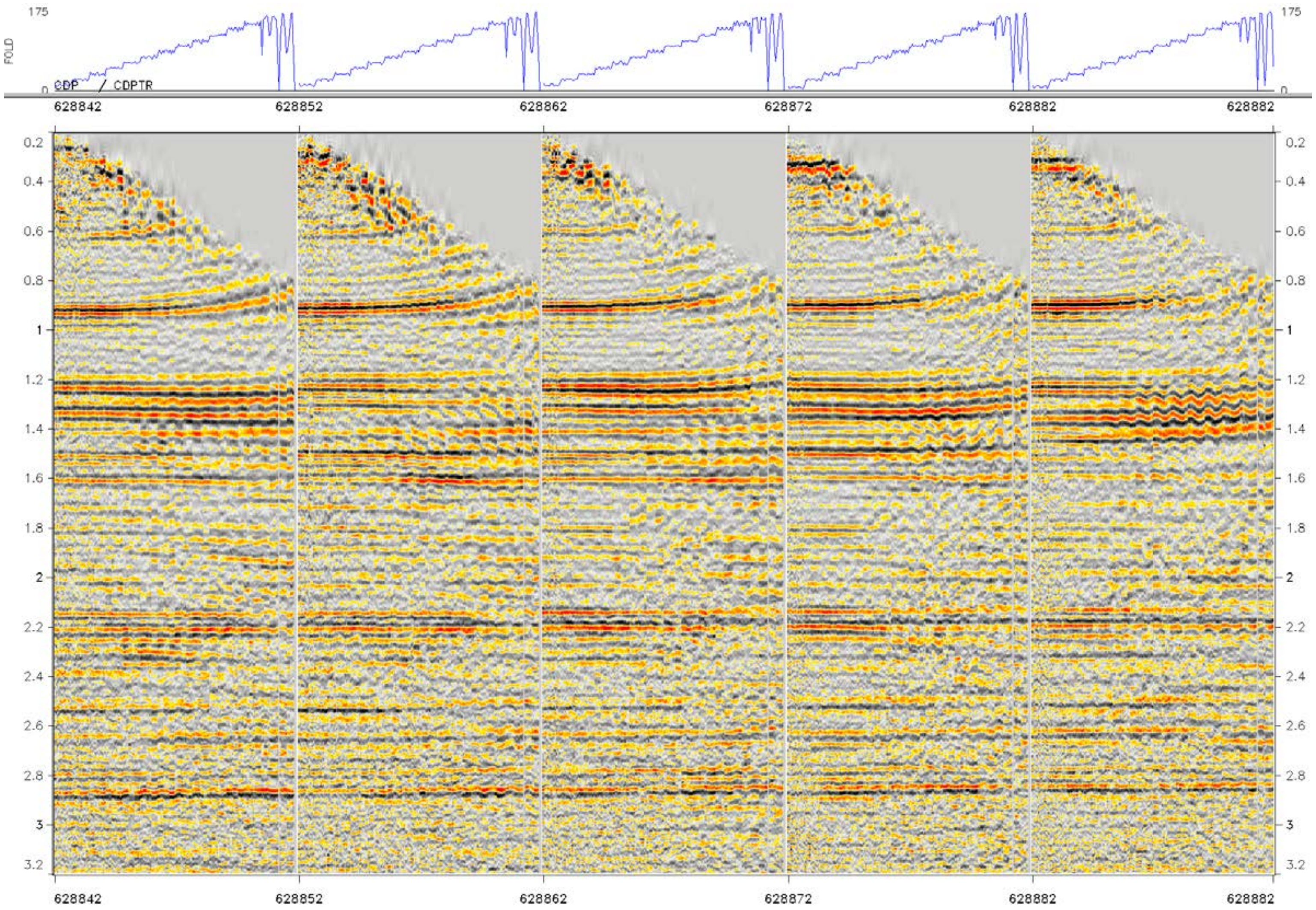
5D COCA gather – No patch extension

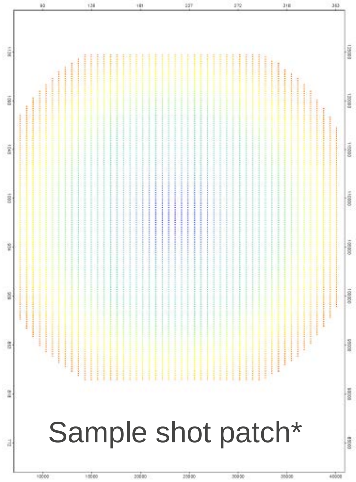




- 5x5, 15 offsets, 12 azimuths
- Standard 5D fills most holes in near and mid offsets, but leaves lots of holes in large offsets
- Sinusoidal features are not as obvious or missing in large offsets

5D COCA gather – Patch Extension

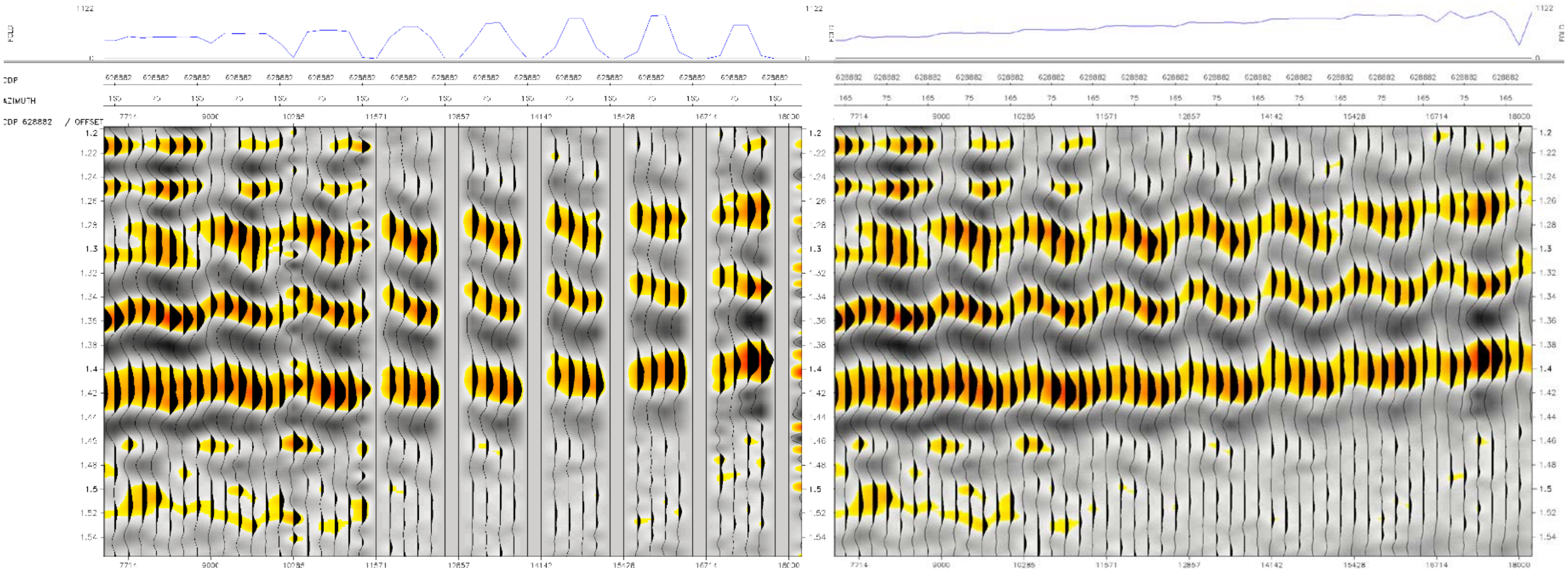




Sample shot patch*

- 5x5, 15 offsets, 12 azimuths
- Patch extension 5D fills almost all holes, even at large offsets
- Sinusoidal features are clear in mid and large offsets

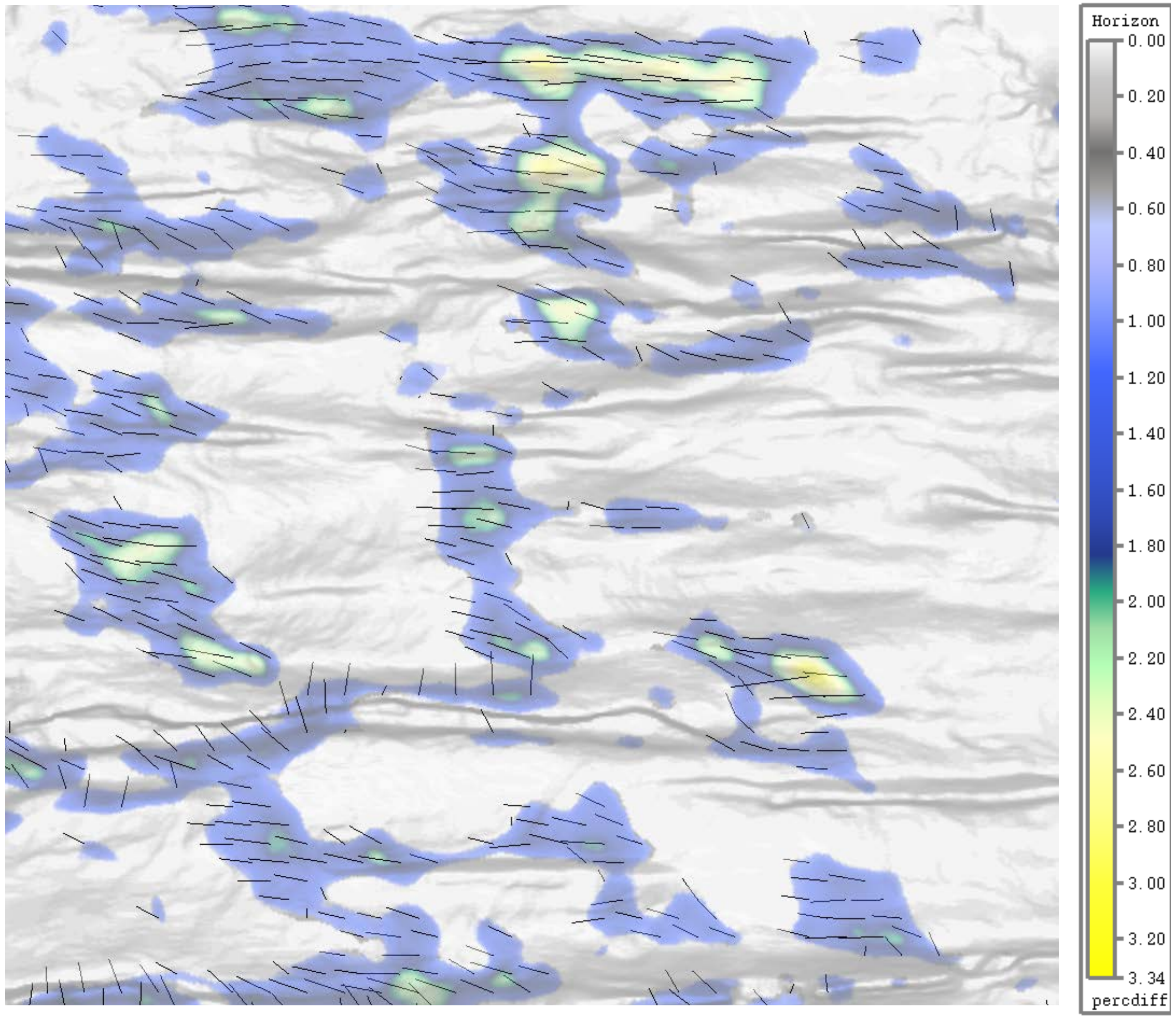
Zoomed comparison of a COCA gather at far offsets after 5D



Typical 5D **Patch extension 5D**

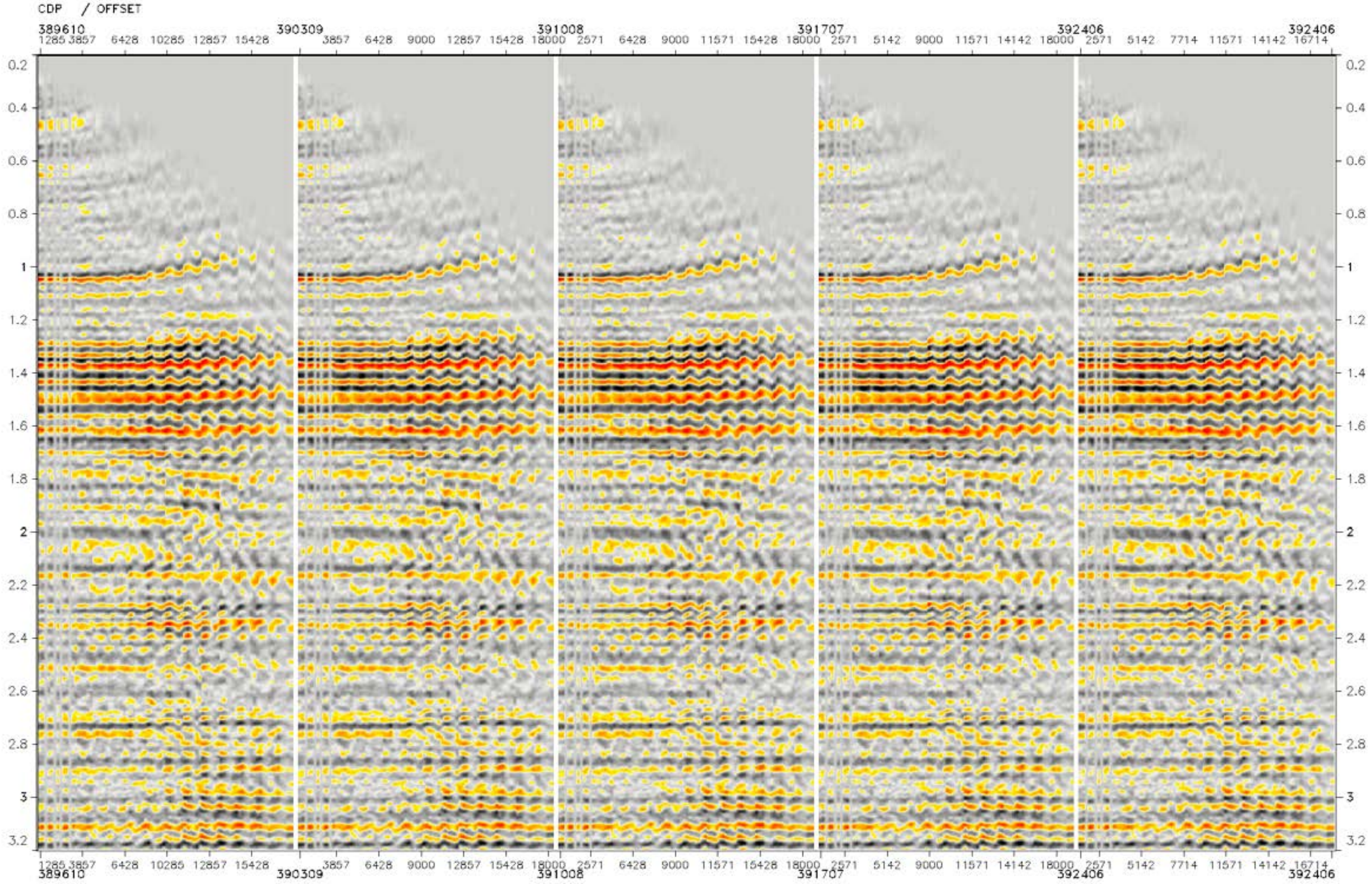
- Patch extension 5D fills almost all holes at large offsets
- Clear sinusoidal phenomenon at large offsets in the right panel

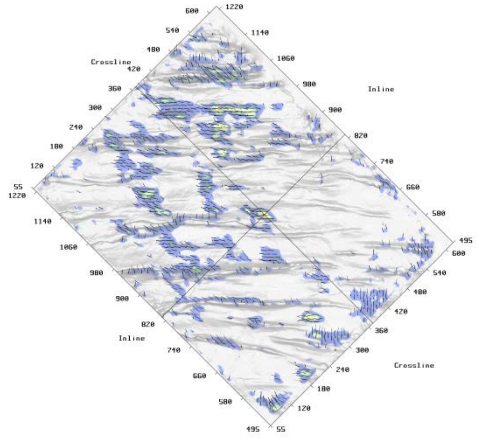
Difference of V_{fast} and V_{slow} at a time slice above Onondaga



- Difference of V_{fast} and V_{slow} as a ratio of V_{fast}
- Difference of less than 1% masked off
- The line segment represents the azimuth direction of the fast velocity plane
- The dominant direction of V_{fast} is N75E. It is almost the presumed regional direction of the J1 joints (Engelder et al., 2009)

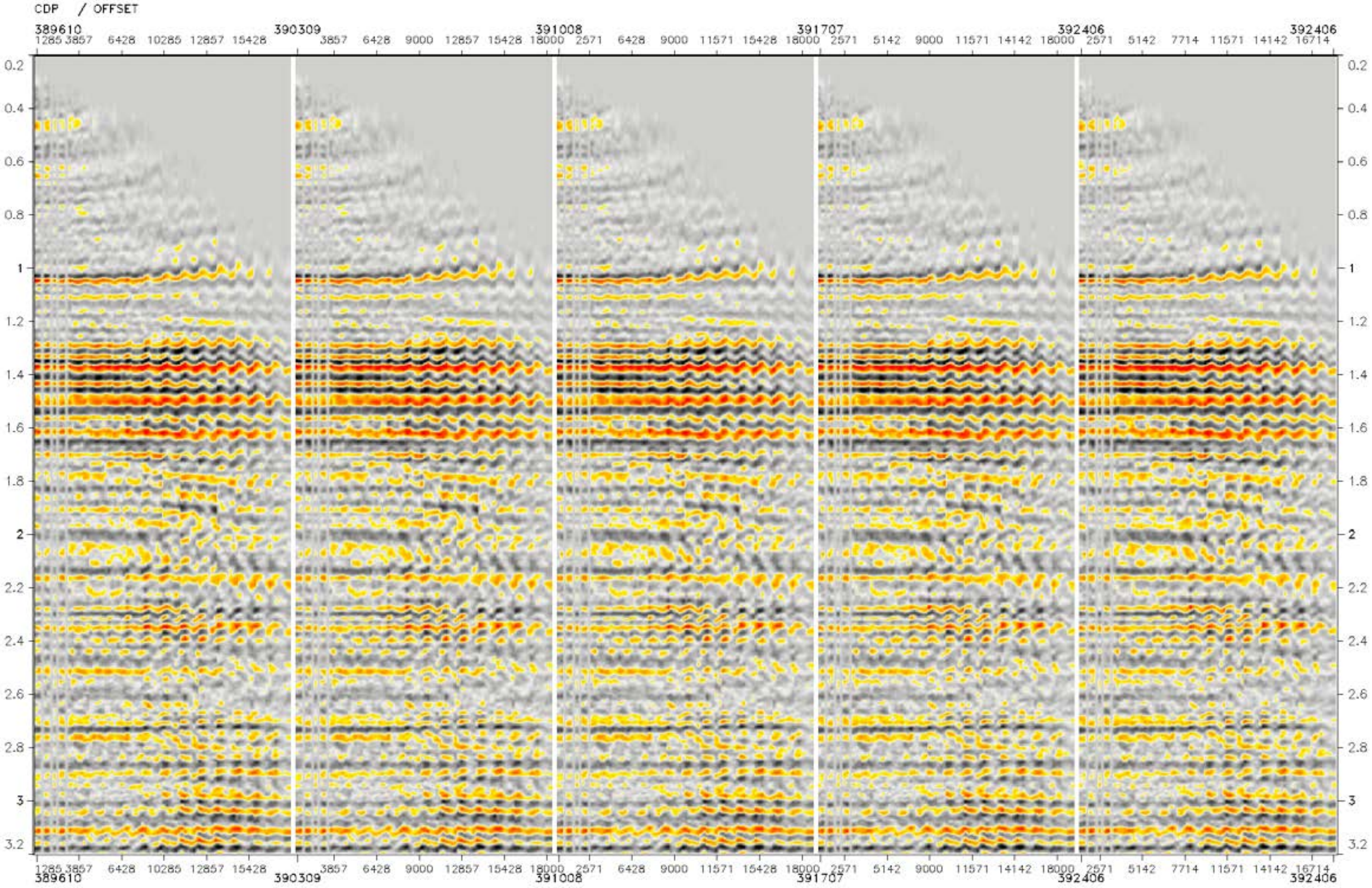
Isotropic PSTM COCA

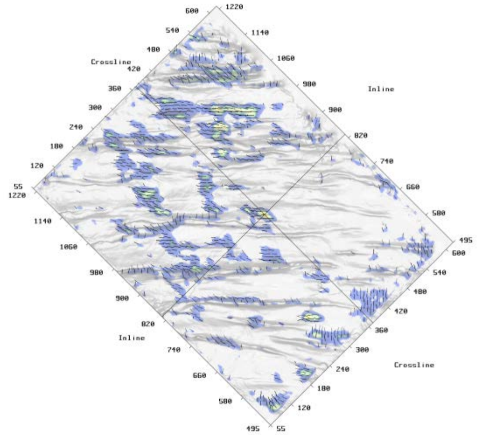




- Residual moveout in mid & far offsets
- Sinusoidal moveout in mid and far offset

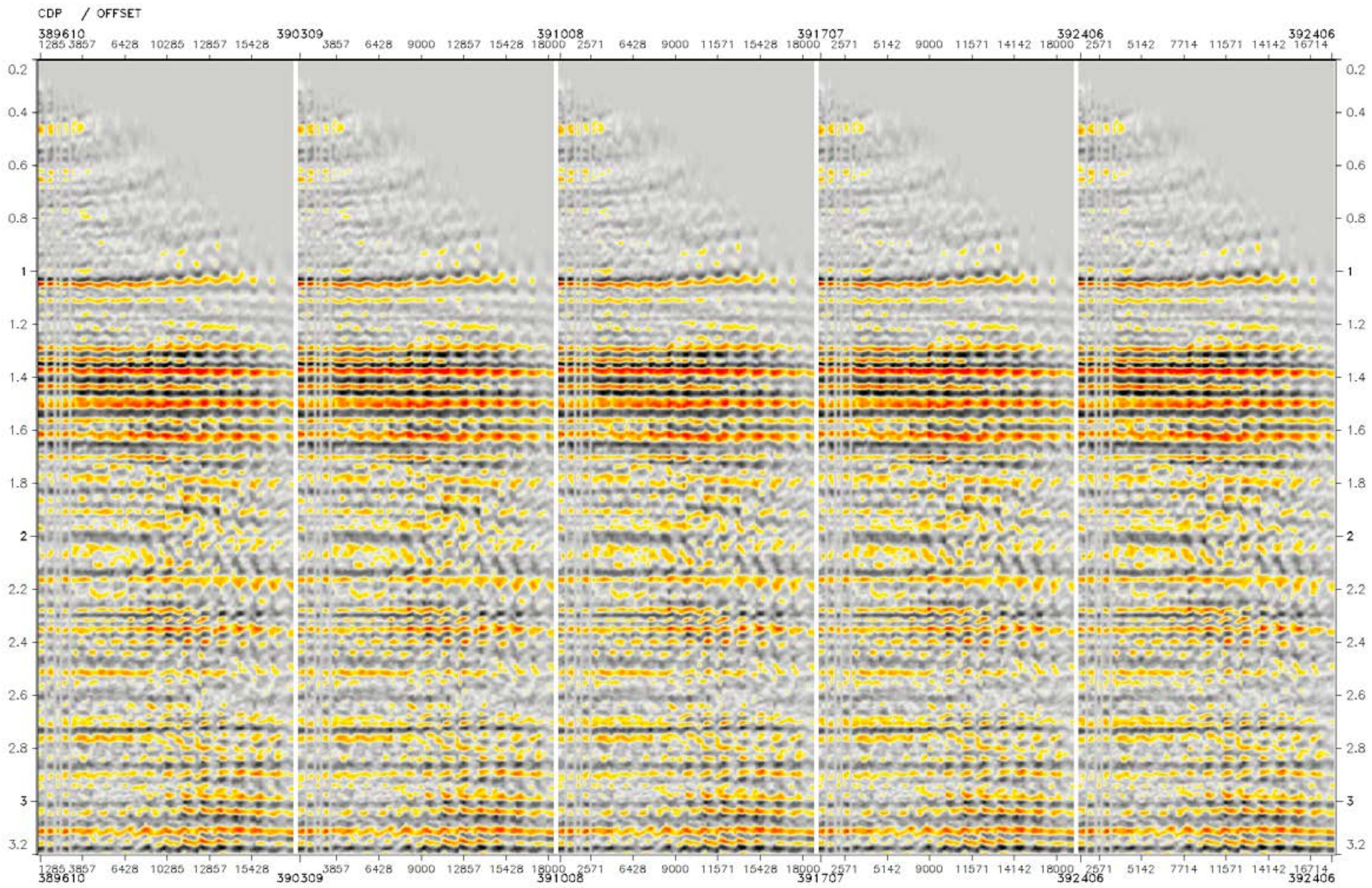
VTI PSTM COCA

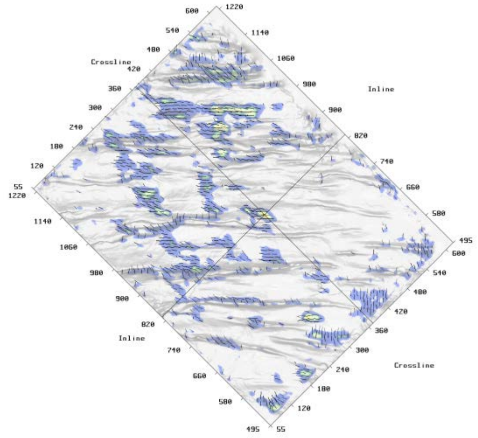




- Generally flat along offsets
- Sinusoidal moveout in mid and far offset

Orthorhombic PSTM COCA



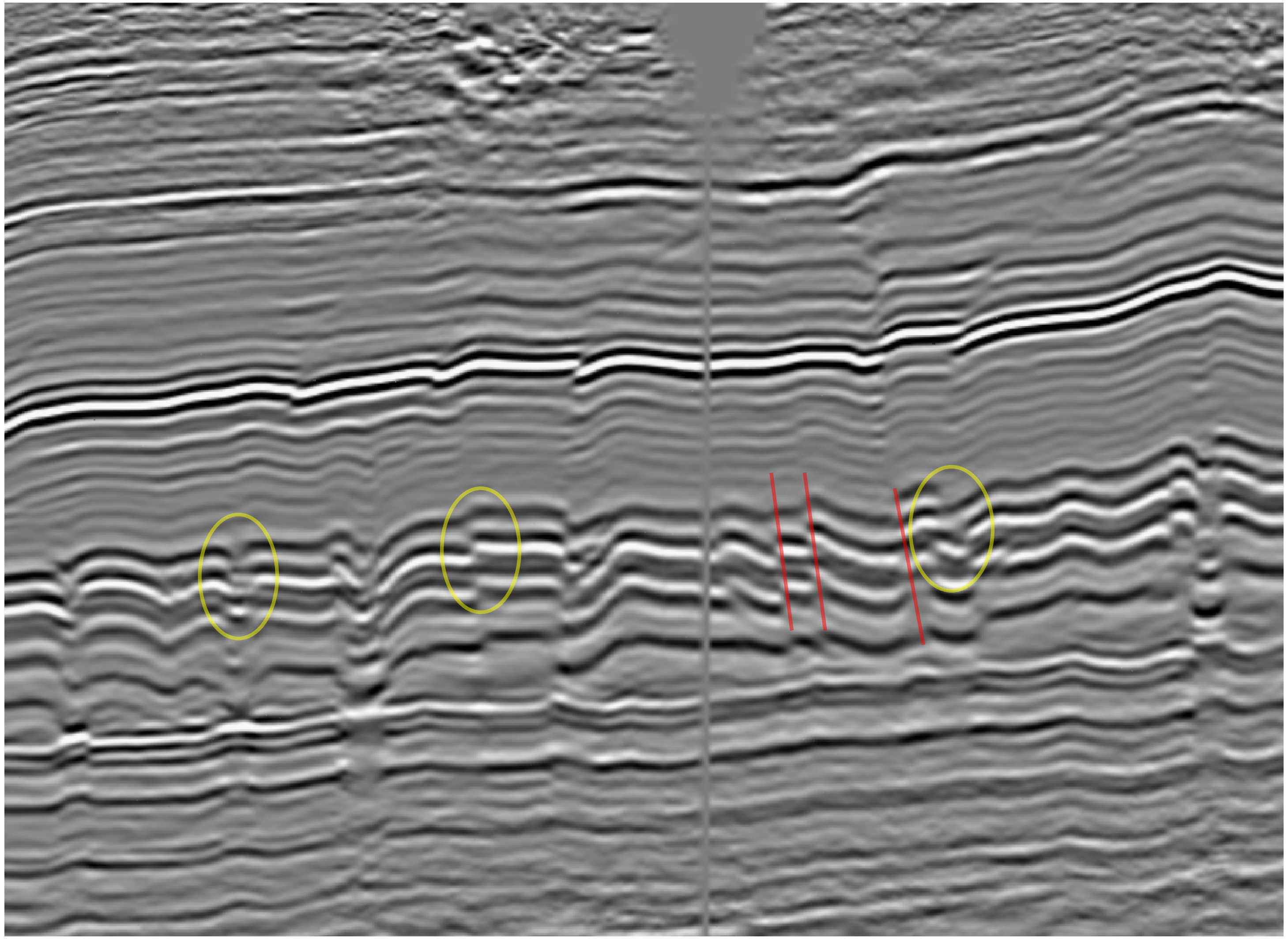


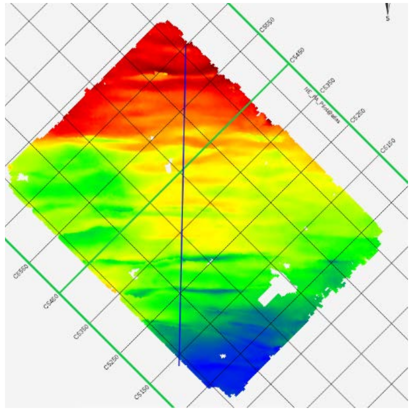
- No sinusoidal phenomenon in mid and far offset
- Flat along all offsets

Outline

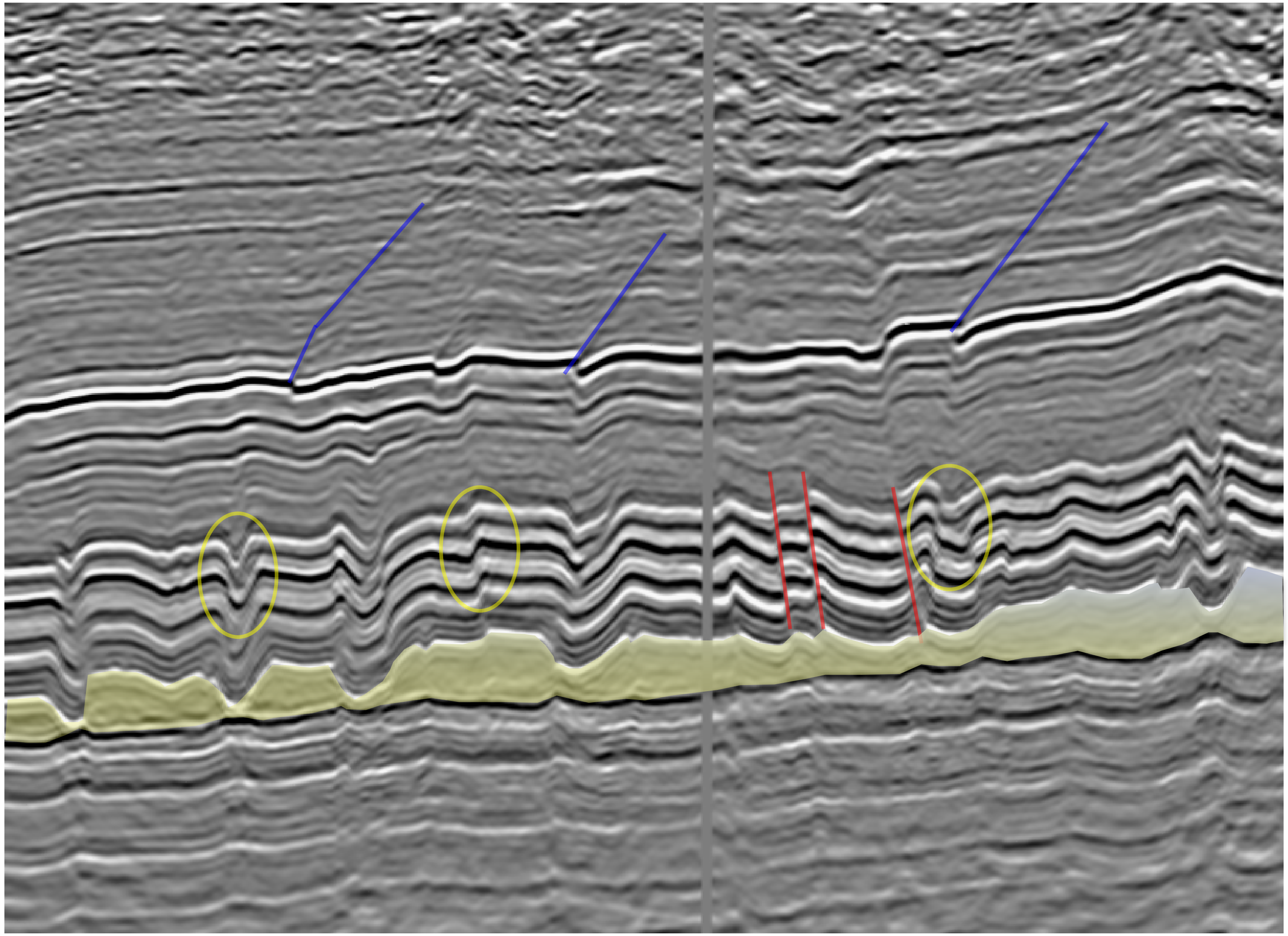
- ✓ What is the challenge?
- ✓ Key processes in the pilot study
  - o Geometry and near surface modeling
  - o Noise attenuation: LSRME
  - o Patch Extension 5D interpolation
  - o Orthorhombic prestack time migration
- ✓ Results
  - o Imaging comparison
  - o Drilling
  - o Prestack inversion
- ✓ Conclusions

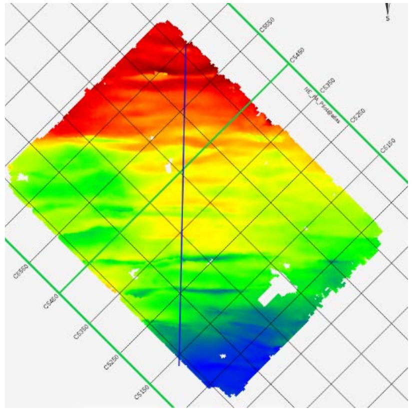
Pilot oPSTM vs. Legacy PSTM: N-S line: Legacy





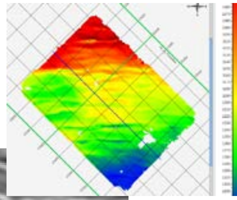
Pilot oPSTM vs. Legacy PSTM: N-S line: Pilot

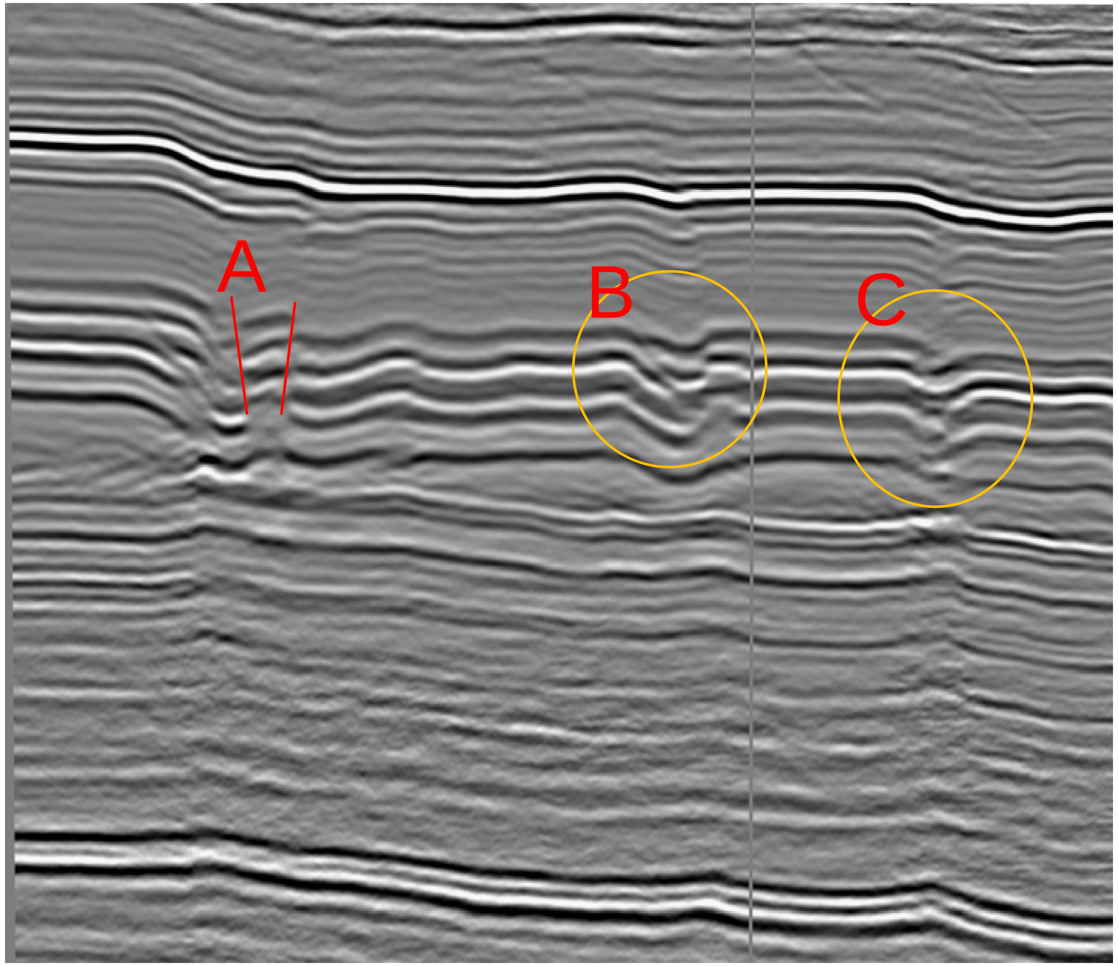


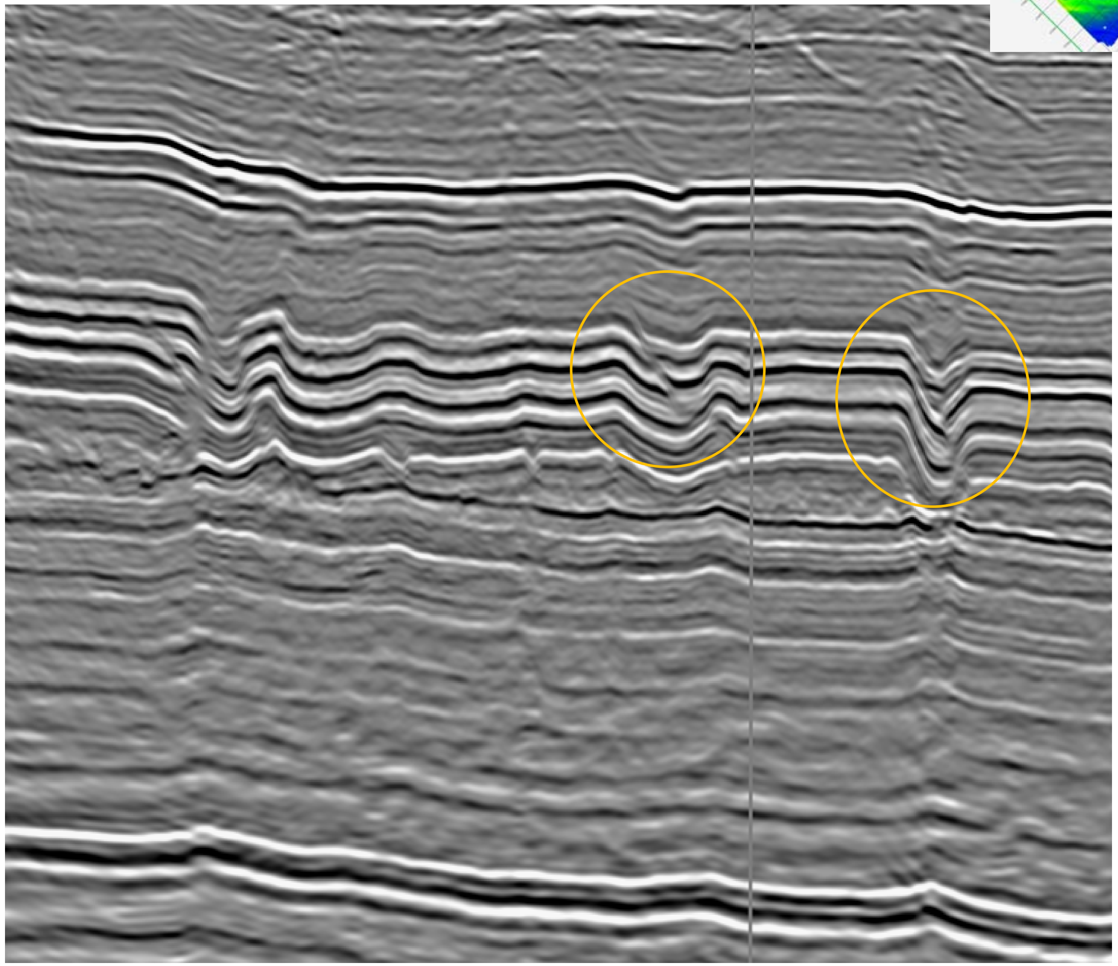


- oPSTM sharpens the thrusts
- Resolves the uncertainties of faults and folds
- Better imaged the shallow fault plans, helping avoiding geohazard
- Salina Salt shaded

What the Pilot reveals about the subsurface

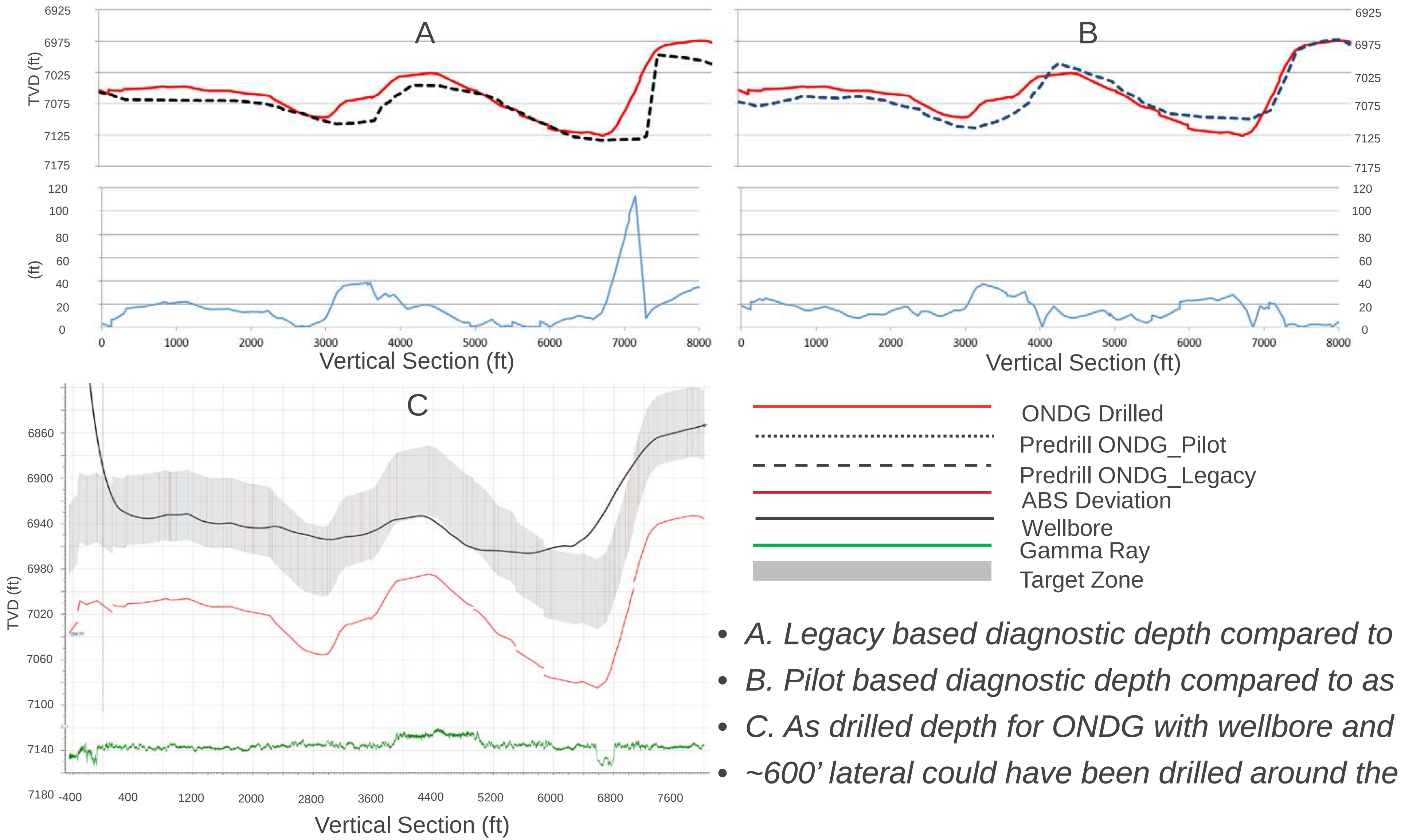






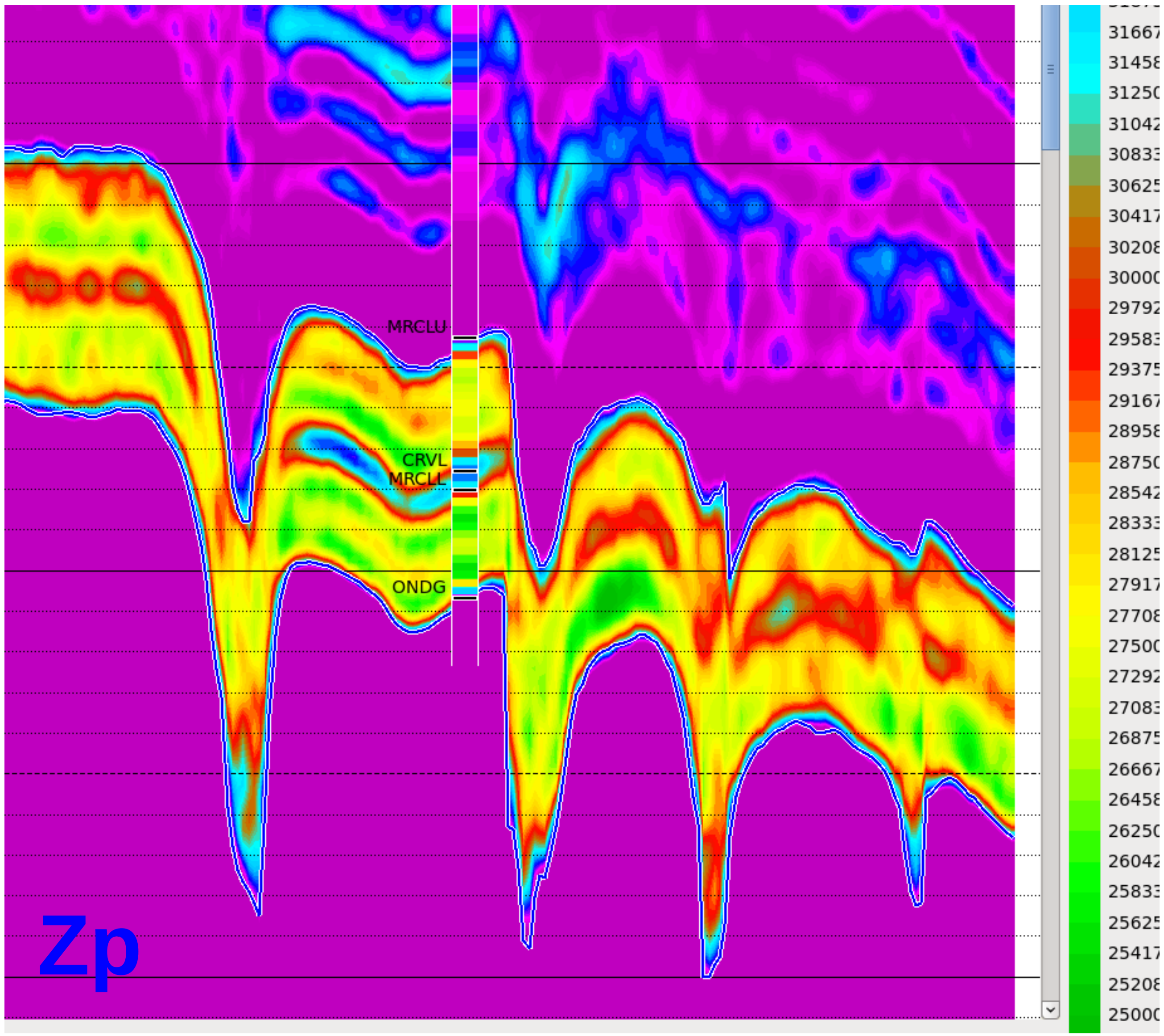
A: Thrusted ~150-200’ | Tight Fold
B: Fault? | 2 tight folds, thrust fault in between
C: Fault? | Withdrawn syncline

Diagnostic vs. drilled ONDG depth along wellpath



- *A. Legacy based diagnostic depth compared to as drilled depth*
- *B. Pilot based diagnostic depth compared to as drilled depth*
- *C. As drilled depth for ONDG with wellbore and optimum target window*
- *~600' lateral could have been drilled around the 7000 ft lateral position*

Prestack seismic inversion properties



- Good match to the log
- The Cherry Valley limestone is very well defined as high impedance and high density
- The CRVL is quite variable spatially, but seems to be consistently present over the area
- CRVL seems thick enough to act as a barrier

Conclusions

- ✓ LIDAR data helped build accurate near surface models, in addition to assisting in geometry QC and correction
- ✓ LSRME was very effective in removing small moveout surface multiples which otherwise interfere with primaries
- ✓ Patch extension 5D enhanced regularity of offset-azimuth distribution
- ✓ The orthorhombic PSTM produced significantly better imaging of the subsurface
- ✓ Some previously interpreted faults got significantly enhanced in resolution, many were clearly imaged as tight fold
- ✓ The new processed products allow us to drill more laterals in the zone, and help avoid geohazard
- ✓ The new product provides more appropriate seismic data for effective reservoir description of the Marcellus Shale

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Chesapeake Energy & CGG:

Permission to publish the work

GPI & Geokinetics:

Permission to present their multi-client data