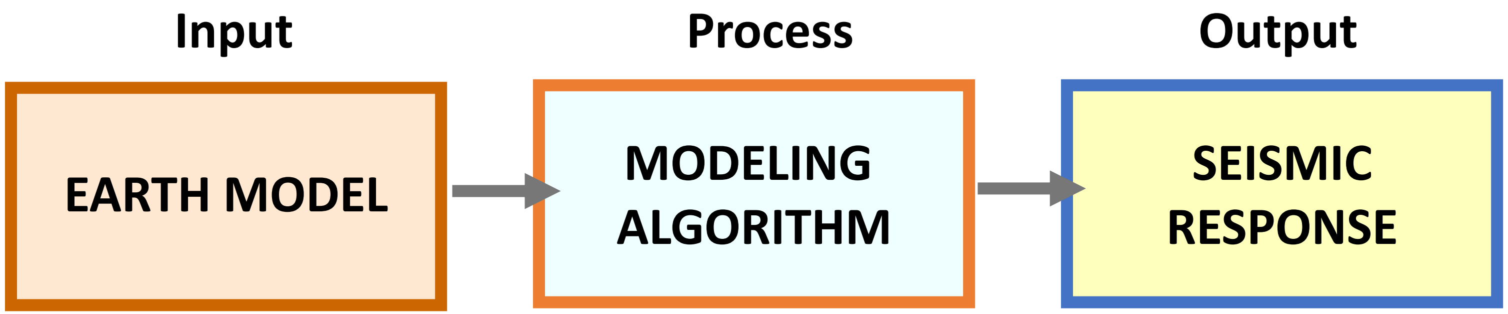
Chapter 3

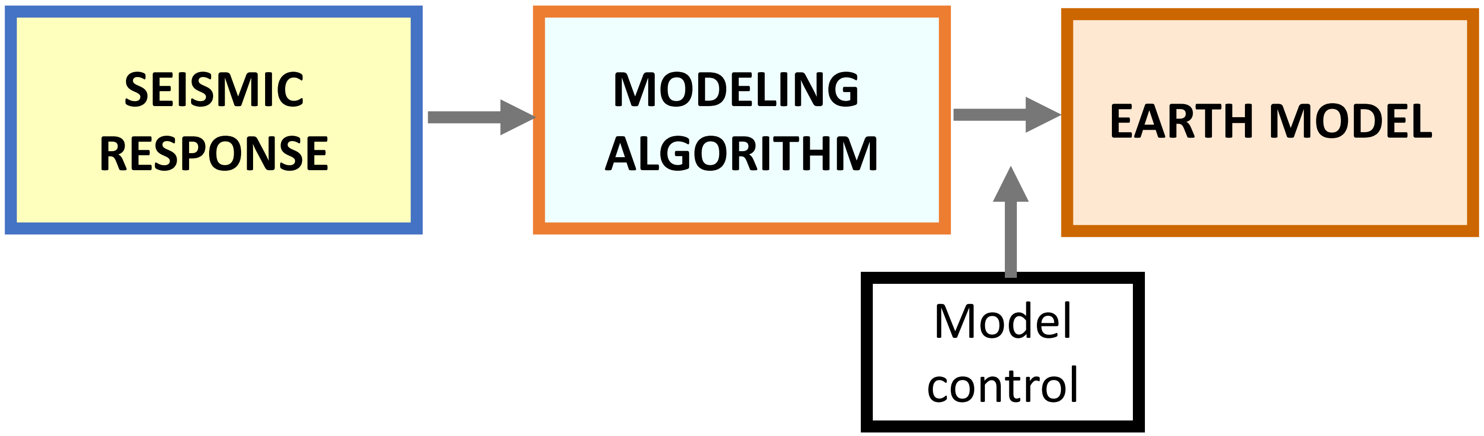
INVERSION THEORY

What is Inversion?

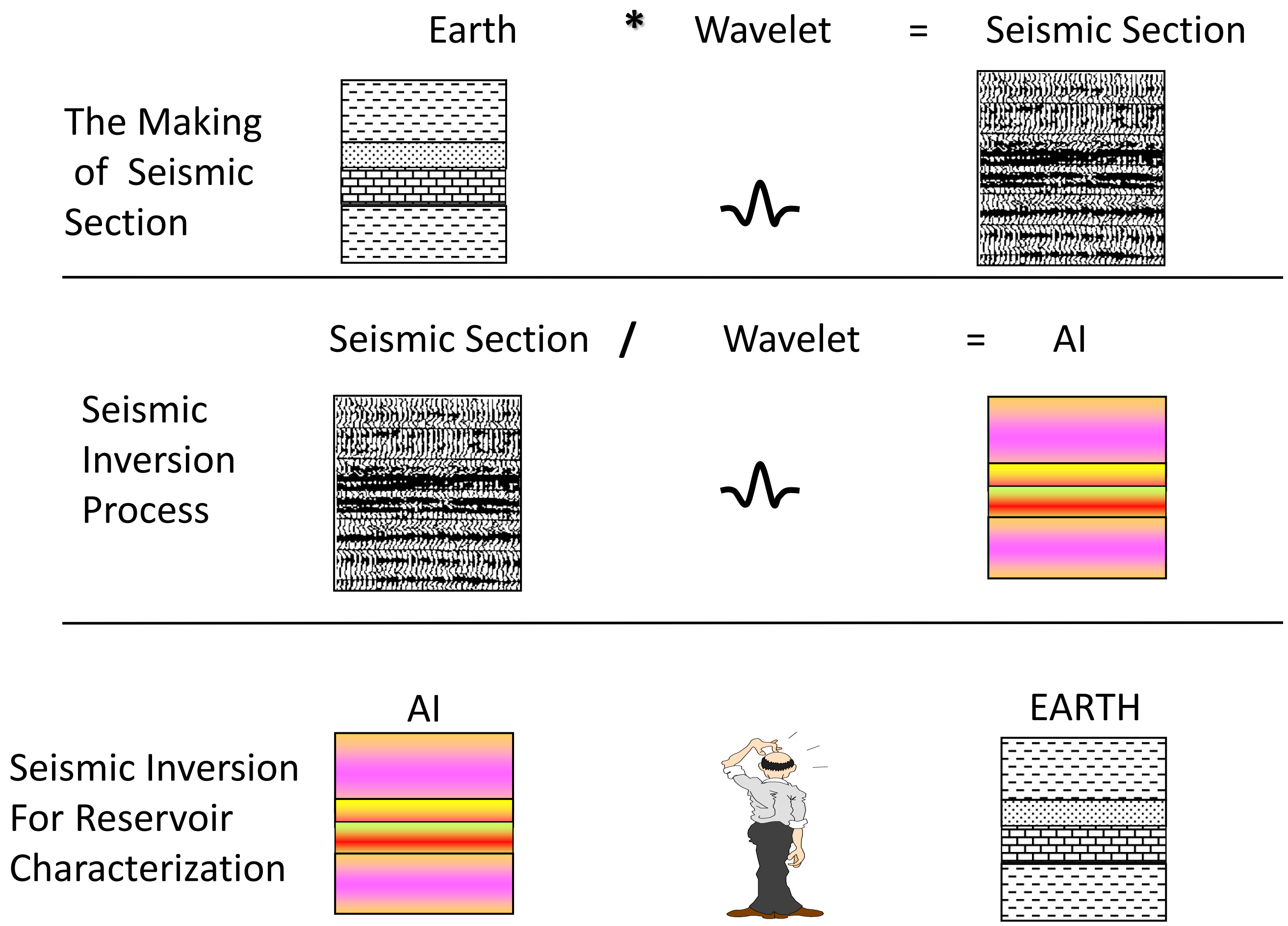
Forward modeling



Inverse modeling



What is Inversion?



Inversion Methods

- Post-Stack:
  - Trace Integration
  - Colored Inversion
  - Band-limited
  - Sparse Spike
  - Model based
- Pre-Stack:
  - AVO Inversion
  - Sparse Spike
  - Model based
- Neural nets
- Stochastic Inversion

Classic approach of seismic trace based inversion

Reflectivity R at interface of two layers denoted as 1 and 2 is related to the Acoustic Impedance I of these layers:

- $R = (I_2 - I_1)/(I_1 + I_2)$

If the acoustic impedance of the first layer is know the acoustic impedance of the subsequent layers can be calculated recursively from the reflectivity:

- $I_{n+1} = I_n * (1 + R_n)/(1 - R_n)$

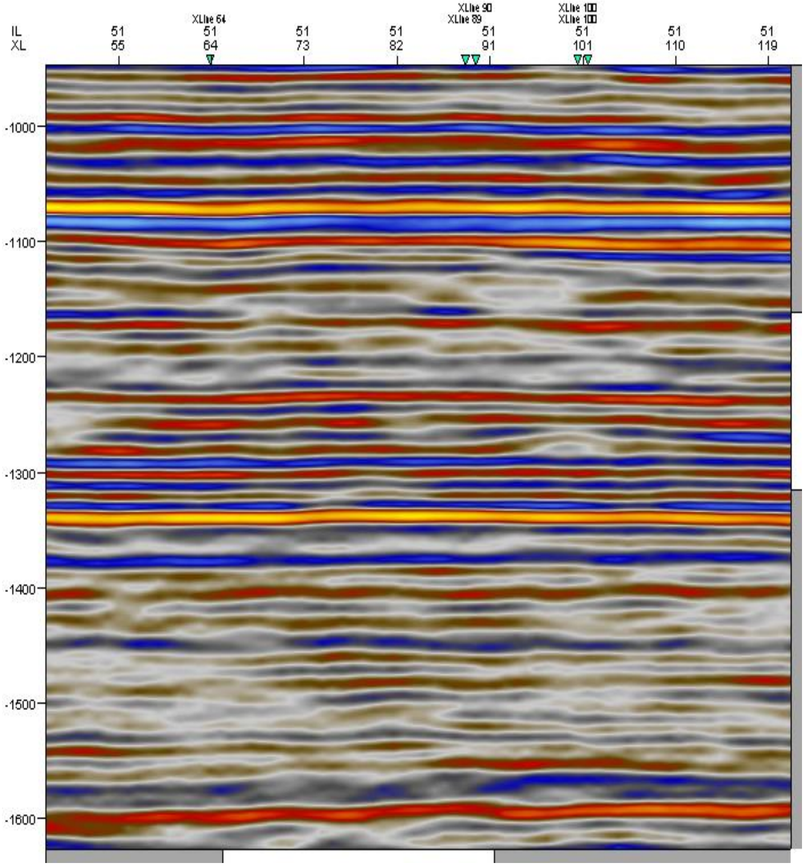
After some manipulation you get

$$\boxed{I_n = I_0 \exp[2\int_0^t R(t)dt]}$$

Inversion Methods

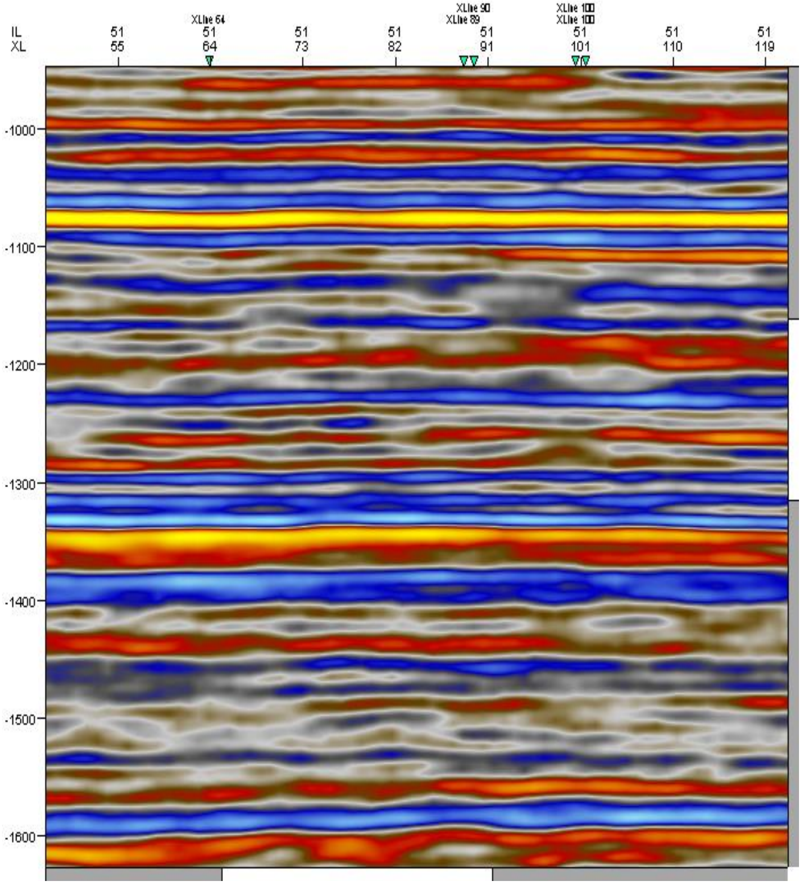
Trace Integration

Input seismic data



Amplitude

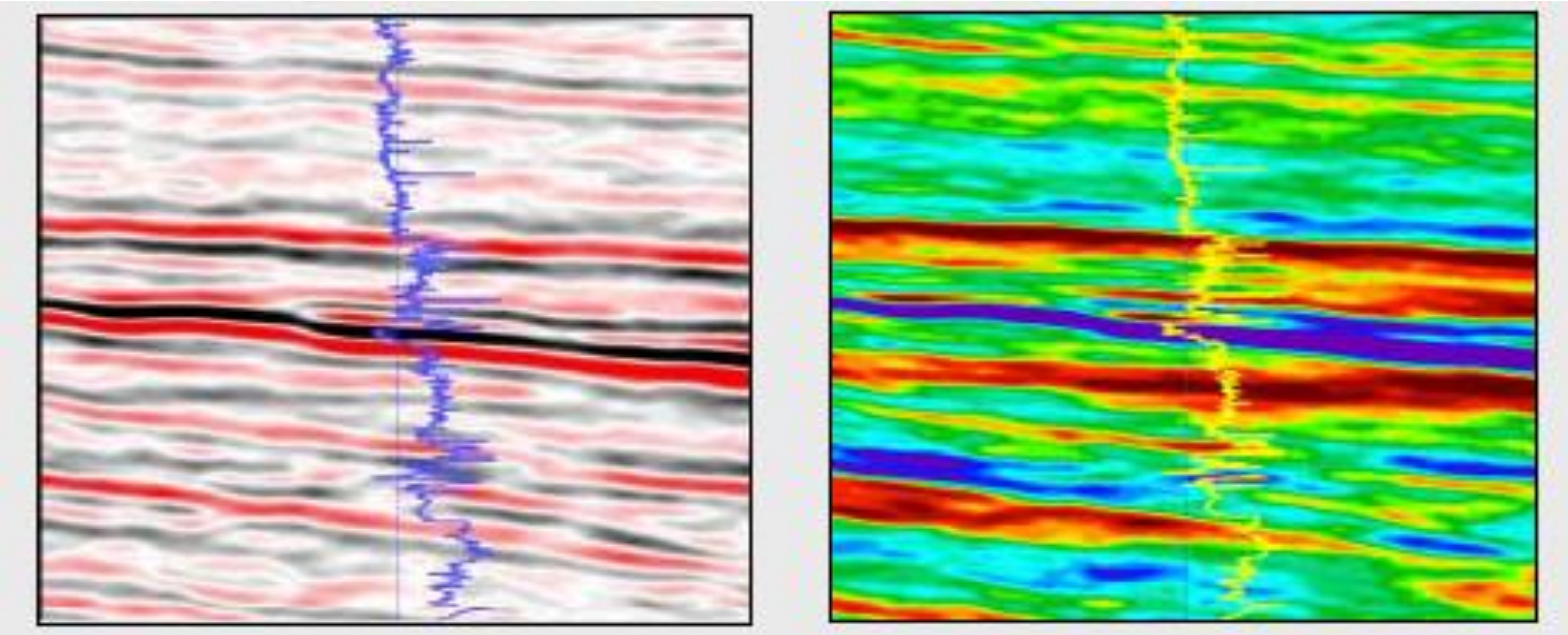
Trace integration inversion



Relative Acoustic Impedance (RAI)

Inversion Methods

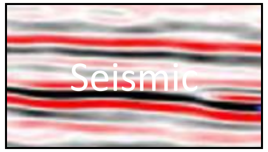
Colored Inversion

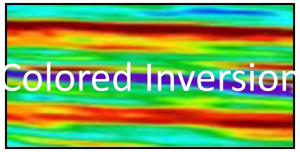


Amplitude Spectrum of well log

compared

Amplitude Spectrum of seismic





Colored inversion

Principle:

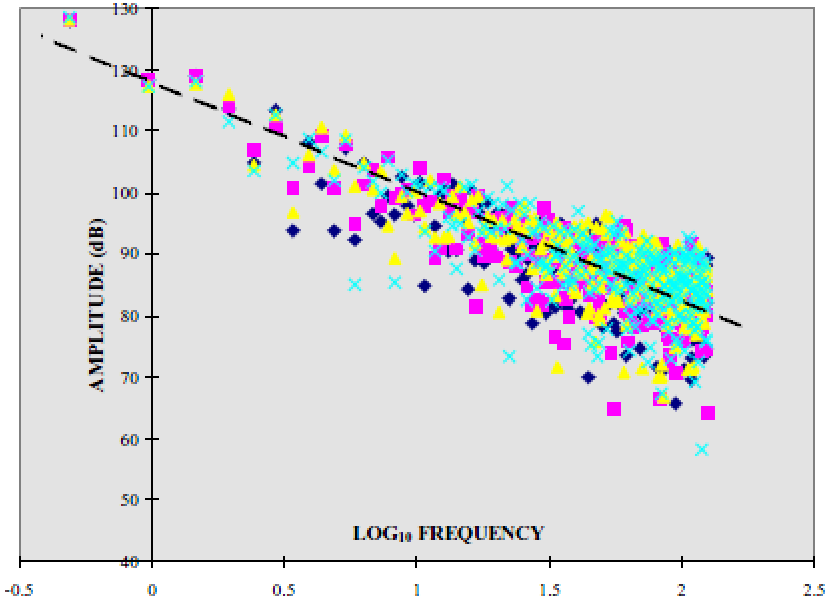
The various seismic and well log spectra are analysed to define an operator that shapes the average seismic trace spectrum to that of a fitted smooth curve which is representative of the average Reflectivity log spectrum. This defines the amplitude spectrum of the required operator. Theory tells us that a 90 degree phase rotation is also required.

The assumption is that the input seismic data is zero phase. The Coloured Inversion operator is converted to the time domain and simply applied to the seismic volume using a convolution algorithm.

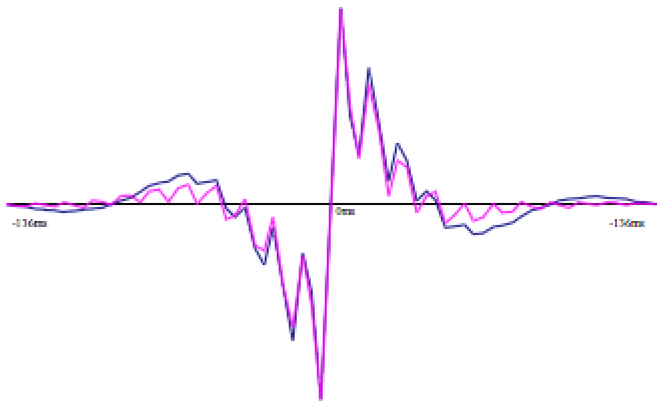
Colored Inversion

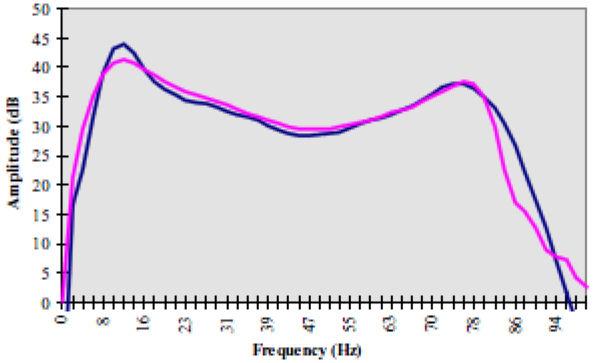
- Colored Inversion enables the rapid inversion of 3D data.
- A single convolutional inversion operator is derived that optimally inverts the data and honours available well data in a global sense.
- The process is inherently stable and broadly consistent with known AI behaviour in the area.
- Construction of the operator is a simple process
- No explicit wavelet is required other than testing for a residual constant phase rotation as the last step since zero phase wavelet is assumed

Colored inversion – match logs and seismic



Four AI logs from a North Sea field are displayed on a log-frequency axis to demonstrate the linear trend, equivalently exponential on a linear frequency axis. The gradient of the linear fit determines α.

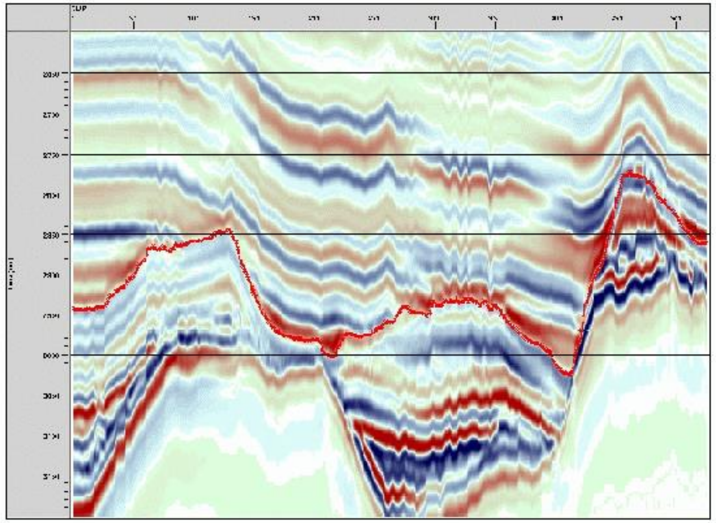




Comparison of the matching operator (pink) and the Coloured Inversion operator (dark blue).

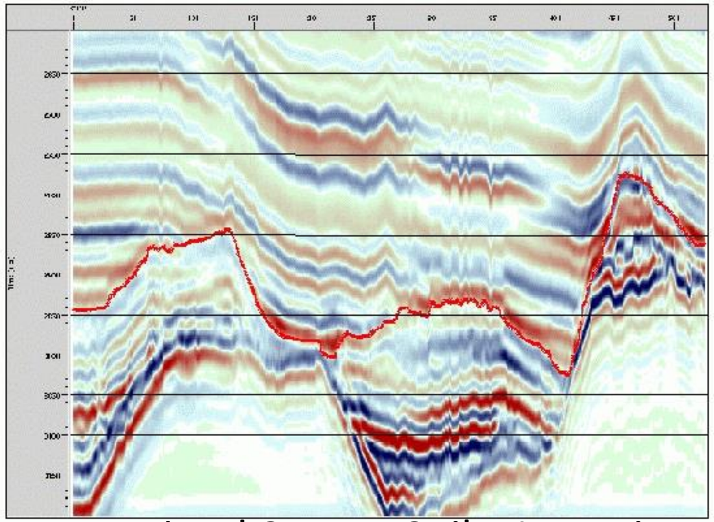
Lancaster & Whitcombe, 2000

Comparison between synthetic, sparse spike and colored inversion

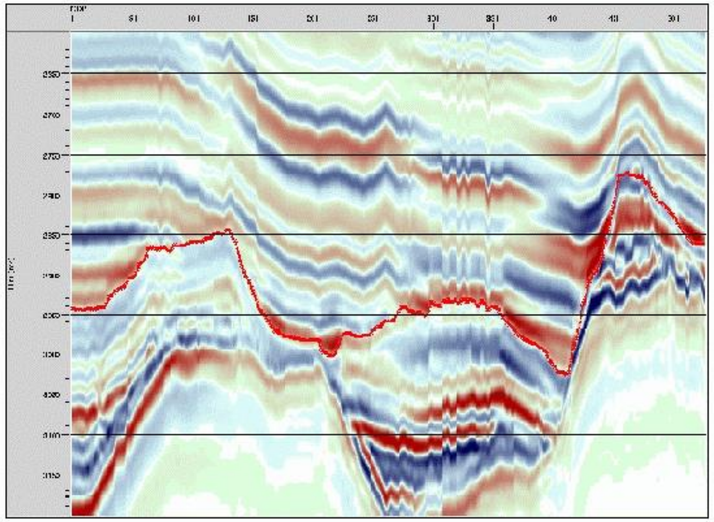


Benchmark dataset - ‘the answer’

Lancaster & Whitcombe, 2000

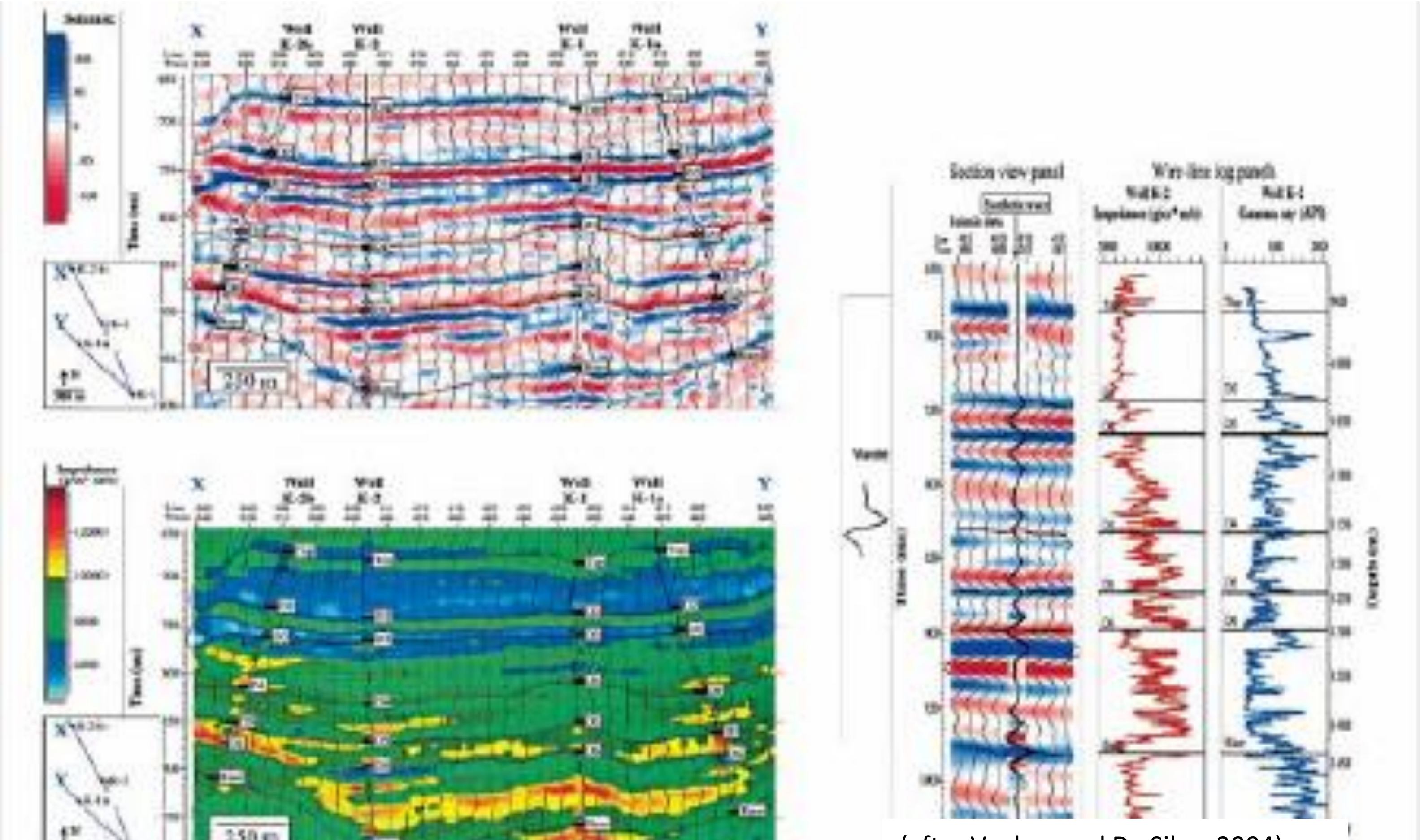


Unconstrained Sparse-Spike Inversion



Coloured Inversion

Sparse-Spike Inversion Method



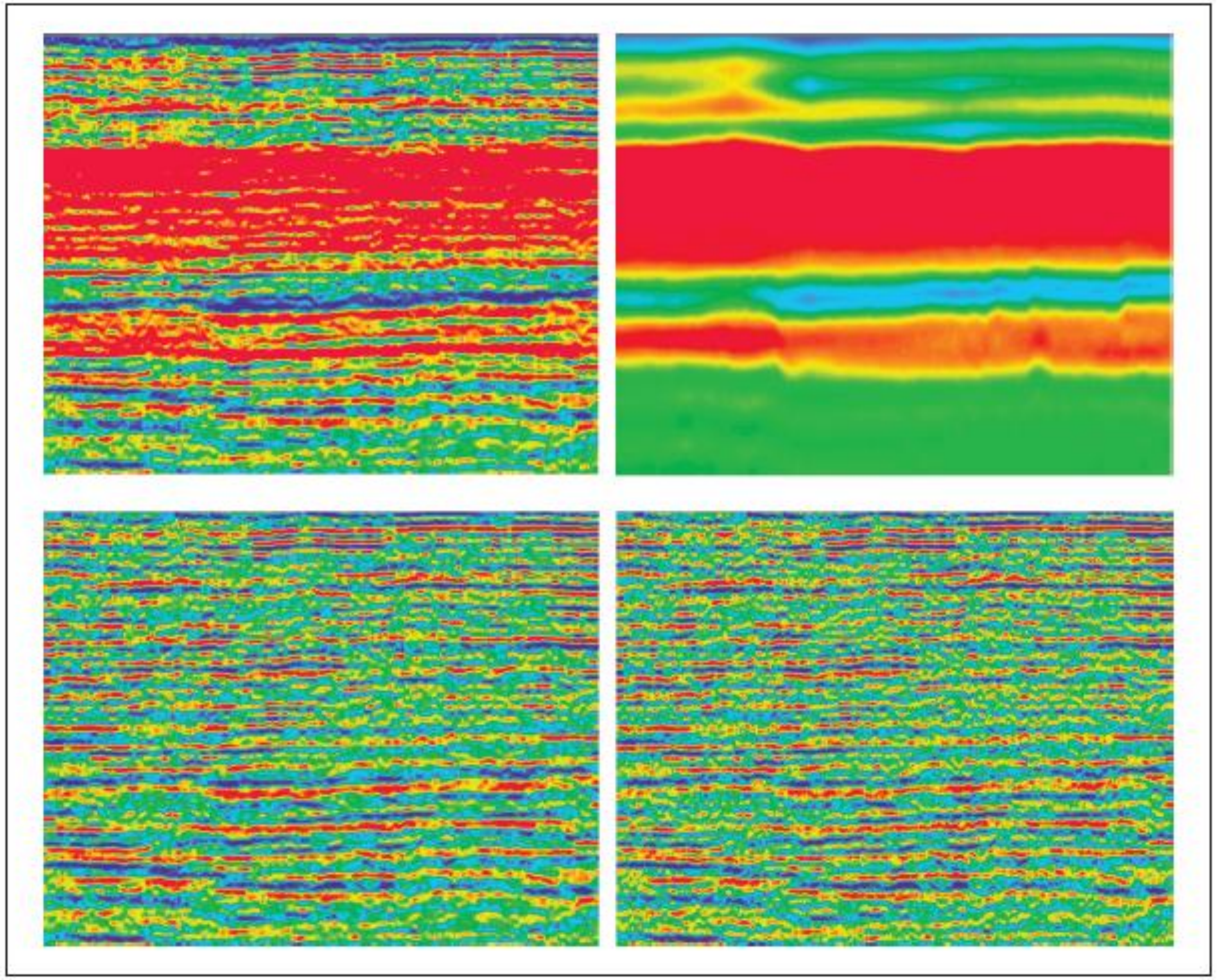
(after Veeken and Da Silva, 2004)

The sparse-spike method assumes a certain model of the reflectivity (based on spikes) and makes a wavelet estimate based on this model assumption.

Sparse-Spike Inversion Method

- Sparse-spike inversion assumes that only the big/significant spikes are important.
- Reflectivity series reconstruct one spike each at a time. The spike are added until the trace is modeled accurately.
- The sparse-spike inversion use the same parameter as the model-based inversion with constraint.

Example of sparse spike inversion *(Francs 2006)*
How to QC the sparse spike inversion



Top left: Sparse spike inversion

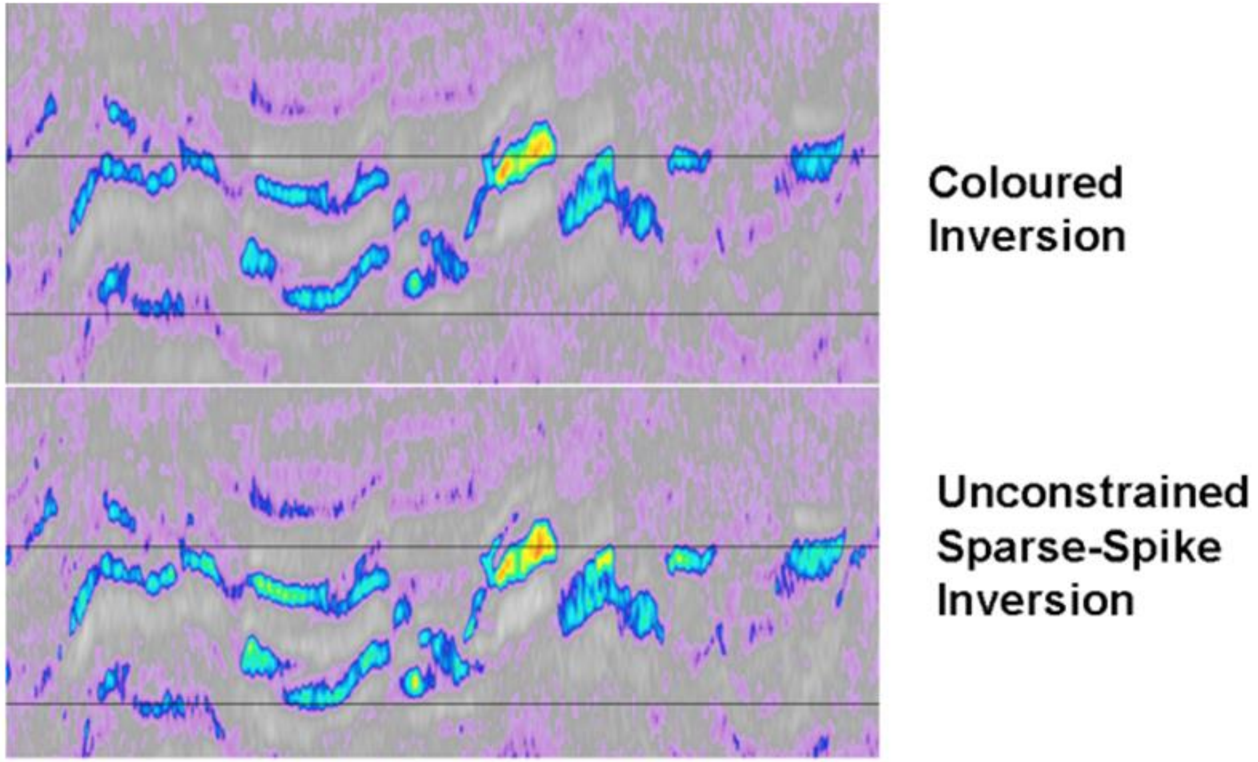
Top right: Low pass filtered sparse spike inversion

Low left: High pass filtered inversion

Low right: Relative acoustic impedance

Note: high frequency component of sparse spike inversion similar to relative acoustic impedance

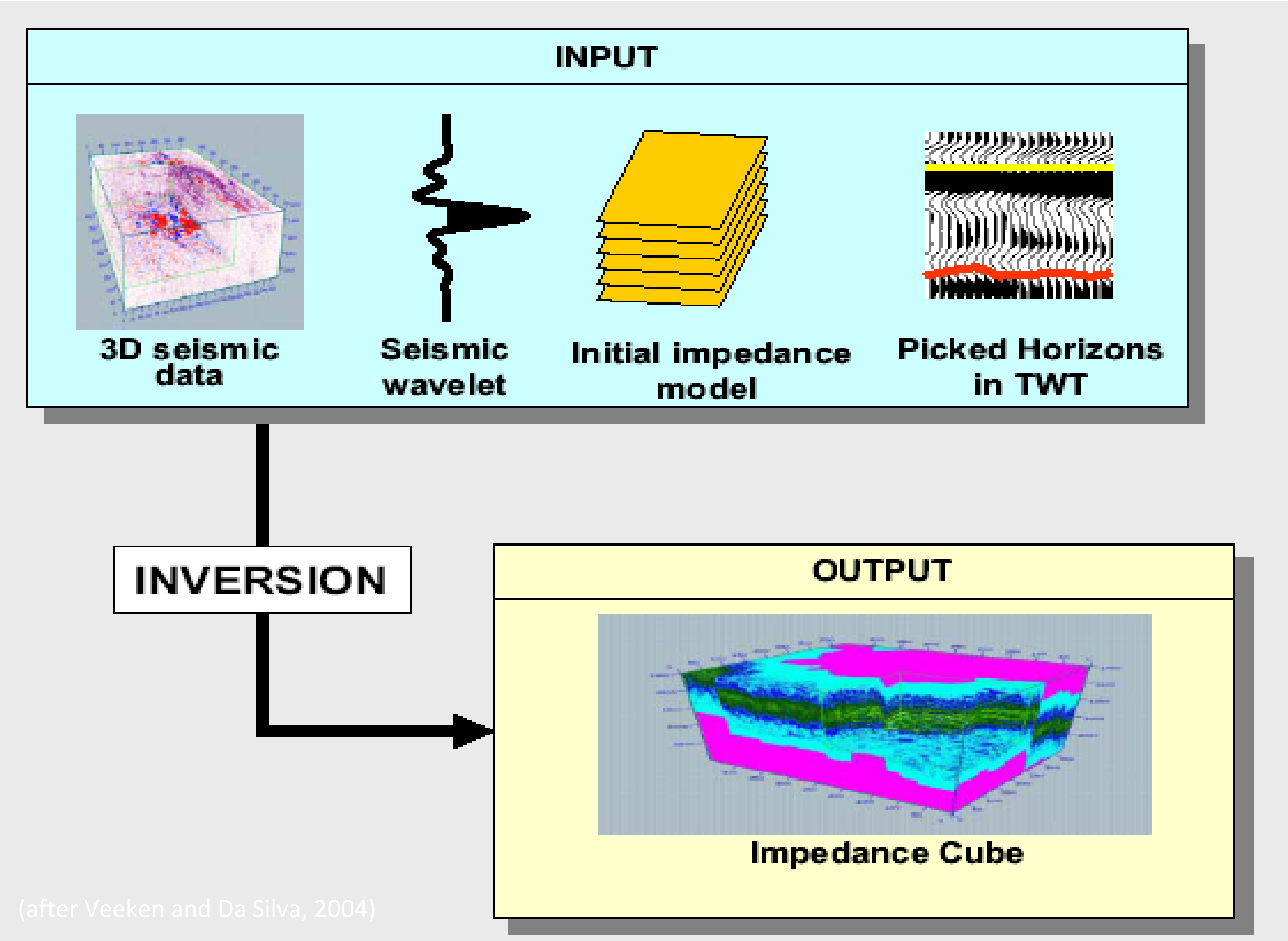
Comparison Sparse-spike inversion - Colored inversion



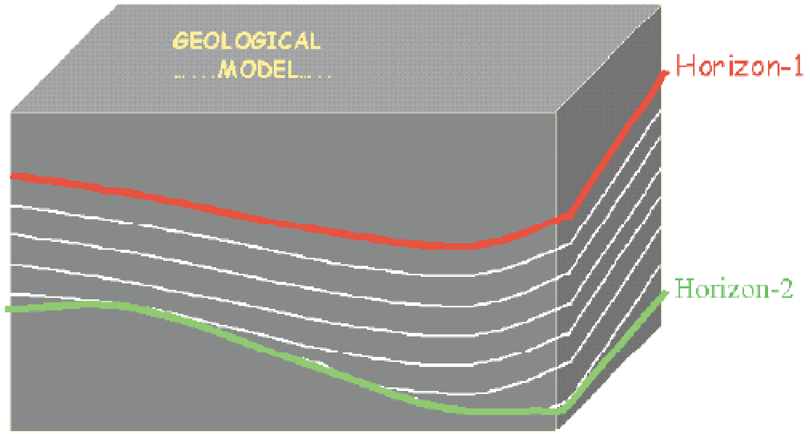
Results are very similar (in this case).

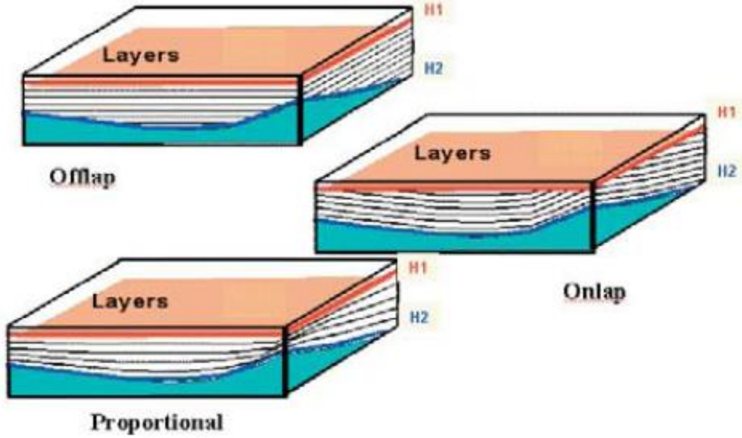
Advantage of colored inversion: results achieved within hours. Sparse spike inversion may take much longer.

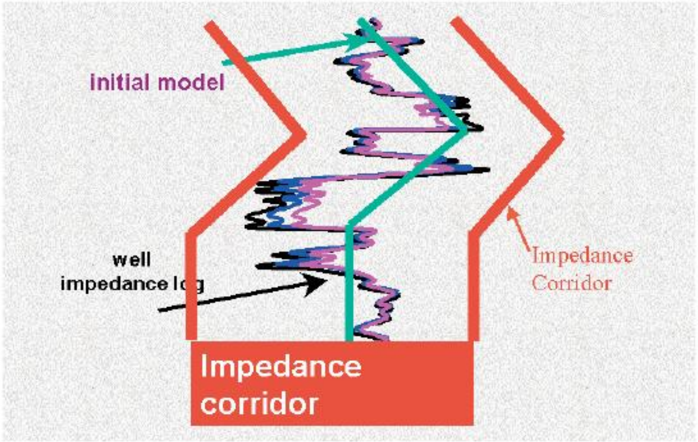
Model-Based Inversion



How to build the impedance models (Walia 2001)

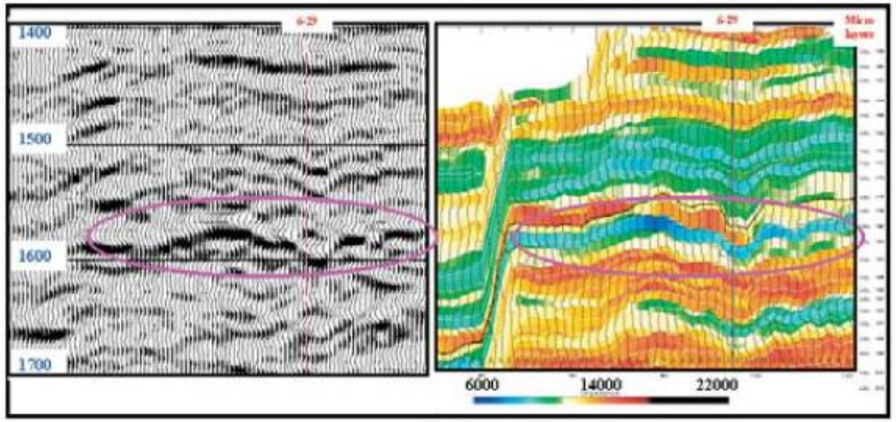




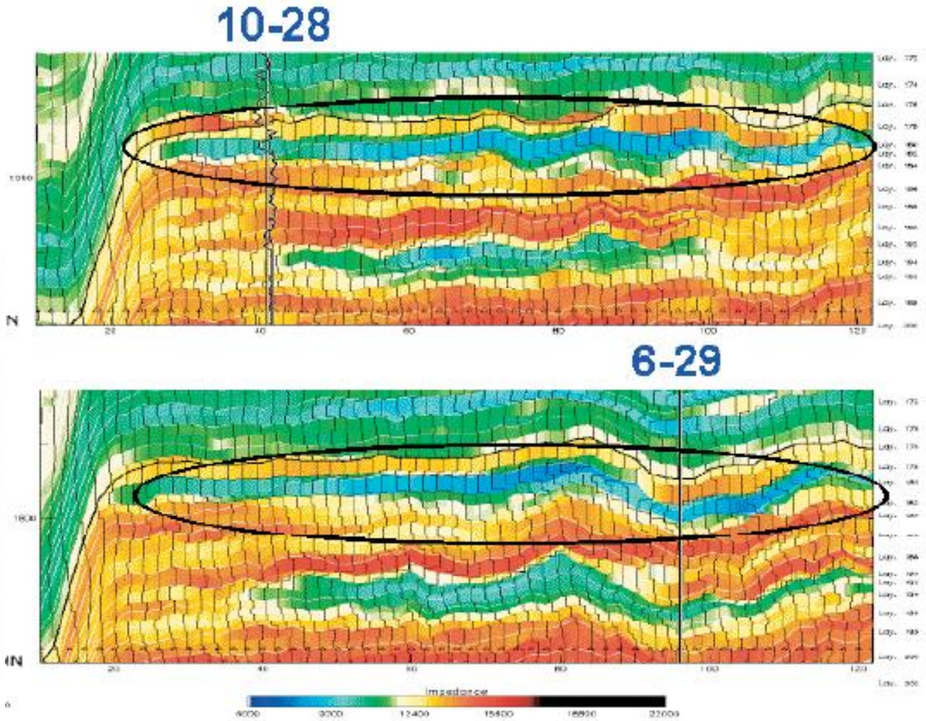


- Setup initial model with impedance layers limited by seismic horizons.
- Stochastic thin layer creation within each seismic layer
- Impedance range defined by well

Results from Walia (2001)



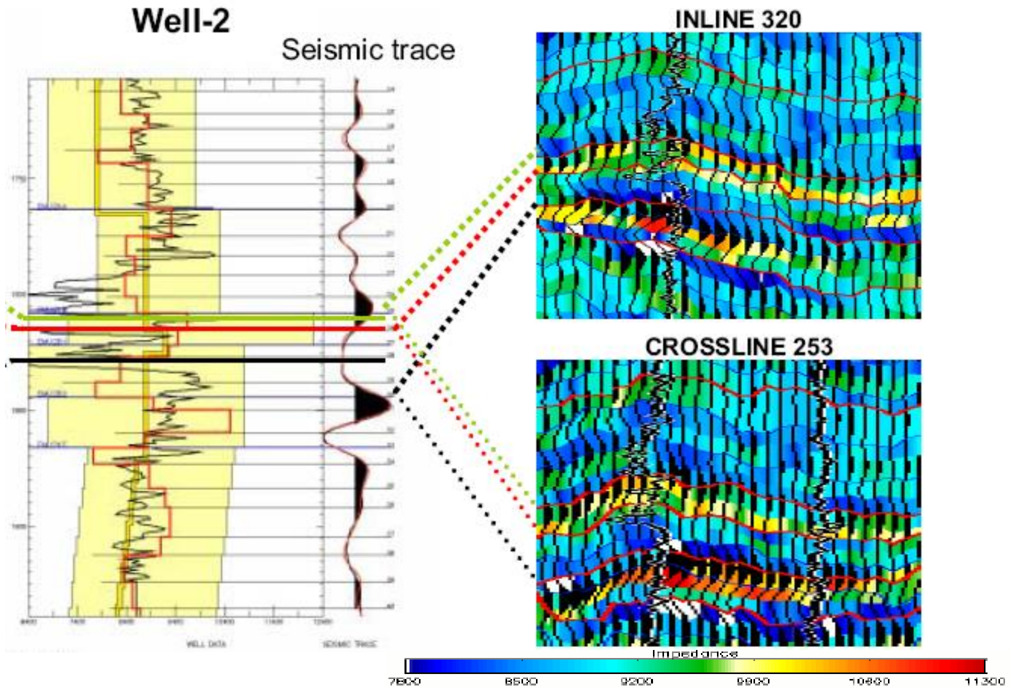
Seismic shows lower resolution compared to AI cube



High acoustic impedance (green) at the well 10-28 of top sand confirmed by low gas production of well.

Advantages of model driven AI

- Modeling guided by stratigraphic (seismic) horizons (reduces the number of possible models)
- Tuning effects resulting from thin layers have no significant effect on the acoustic impedance result
- **Higher resolution compared to seismic**
- Well logs not explicitly input to inversion process (Seismic does not need to match synthetics)
- <u>BUT: result is non-unique</u>



Black: well AI trace

Red: inversion AI

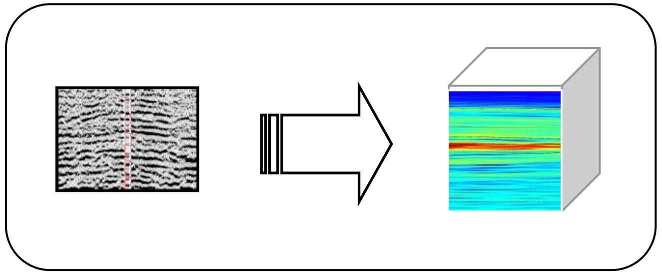
Yellow: AI model and corridor

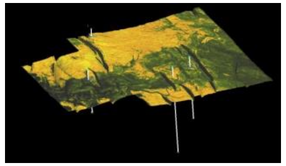
Colour: acoustic impedance

Varwiggle: seismic amplitude

Post-stack vs pre-stack inversion

Limited Outputs

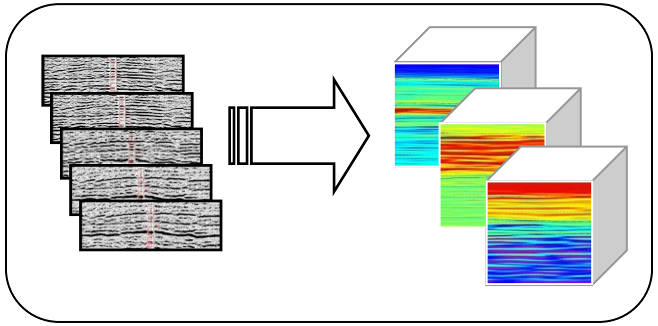


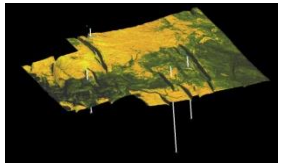


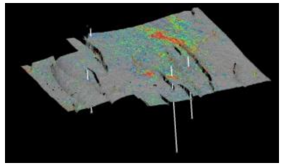
- **AI**
- **Porosity**
- **Lithology “indicator”**

“Dry” rock props

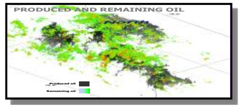
Reservoir/flui d properties



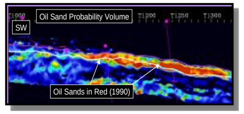




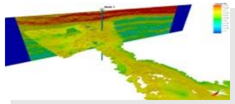
- **AI/Porosity**
- **Hydrocarbon probability**



- **4D produced vs remaining oil**



- **Litho-probability cubes**



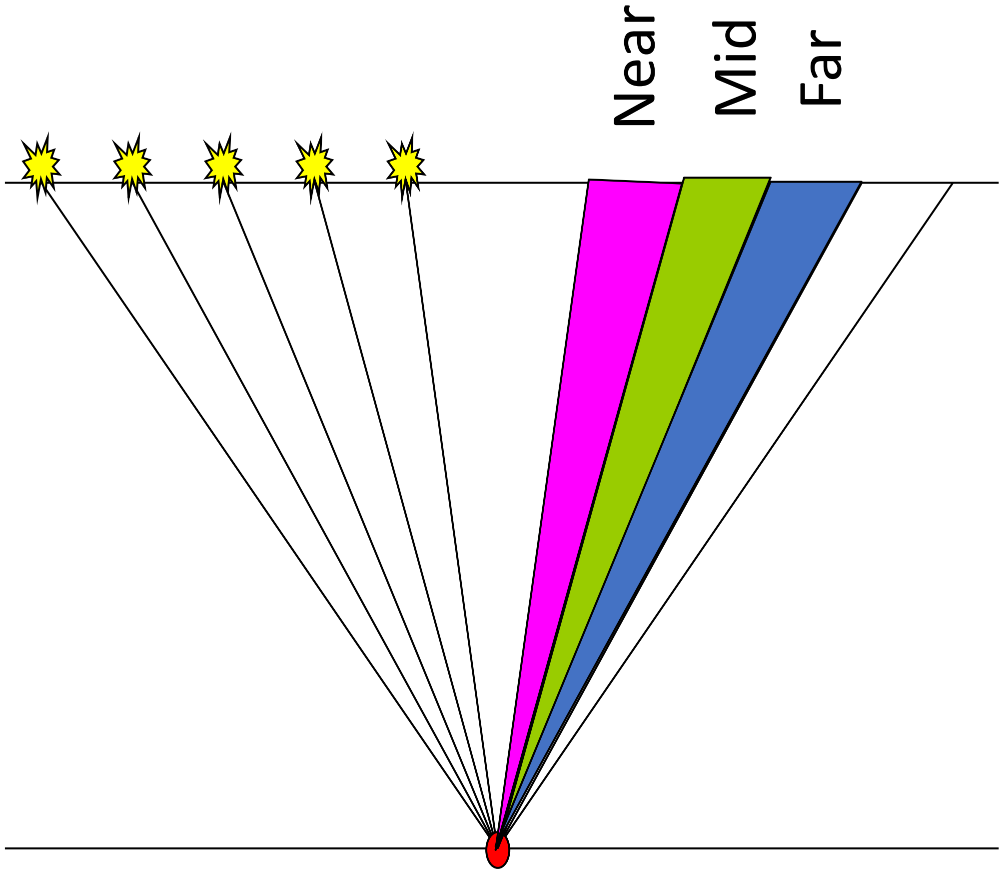
- **Reservoir geobodies**

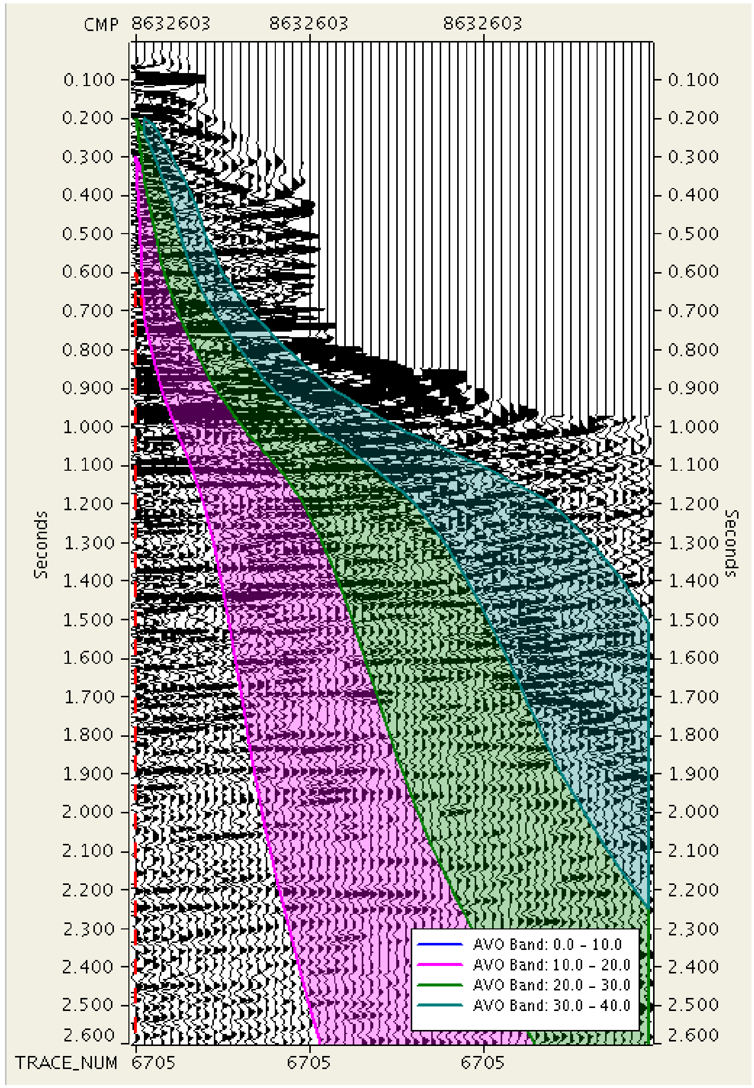
AVO INVERSION

INPUT - Relative Elastic Impedances (NEAR - MID - FAR)

- Standard 2-term (Shuey) based on $R = P + \sin^2\theta * G$
  - RAI ~ P
  - RSI ~ P - G
  - Relative PRatio ~ P + G
- 3-term inversion based on full Aki-Richards equation
  - RAI (relative acoustic impedance)
  - RSI (relative shear impedance)
  - RRHO (relative density)

Input to pre-stack seismic inversion





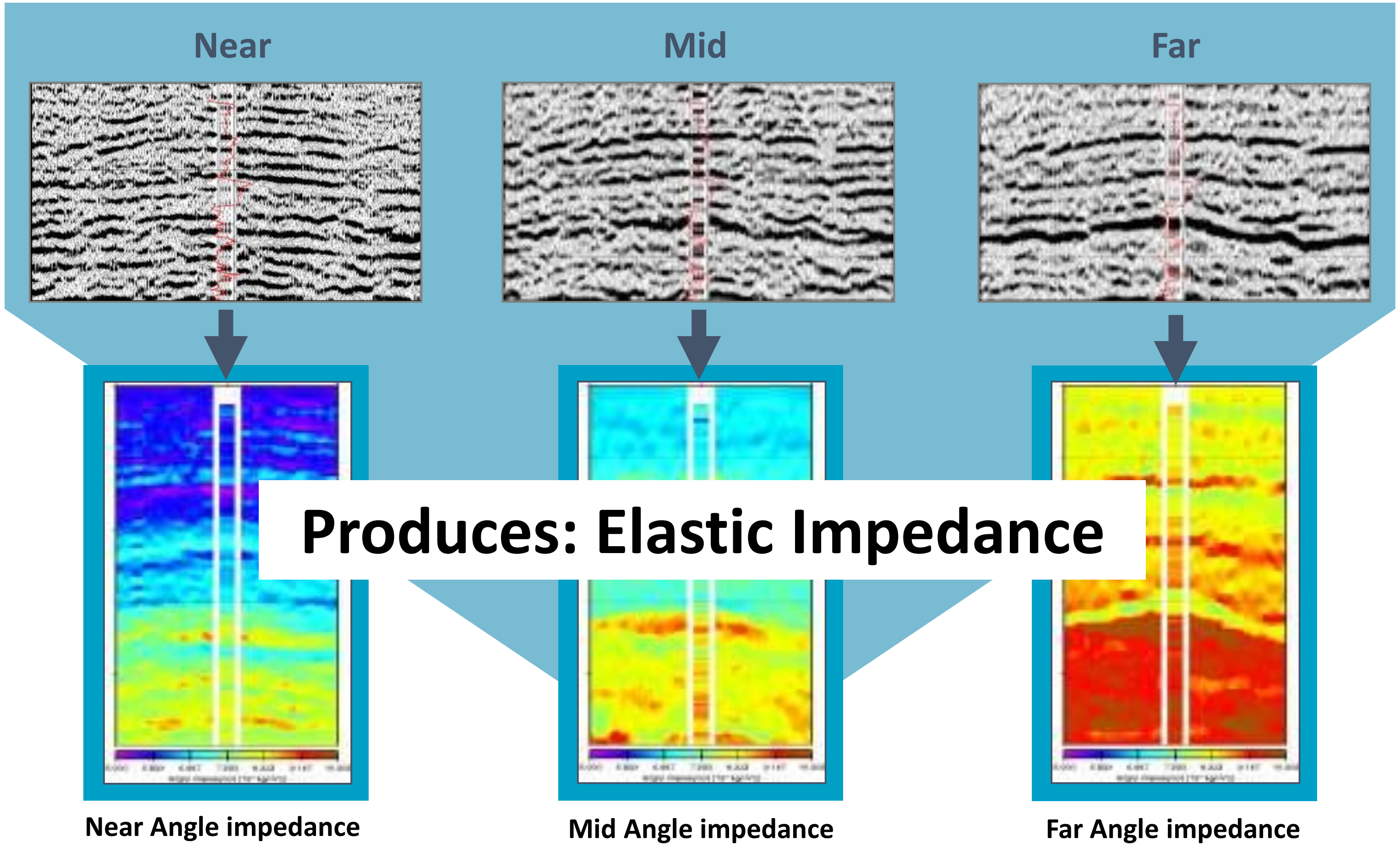
Angle stack bands

Simultaneous Inversion vs Separate Inversion

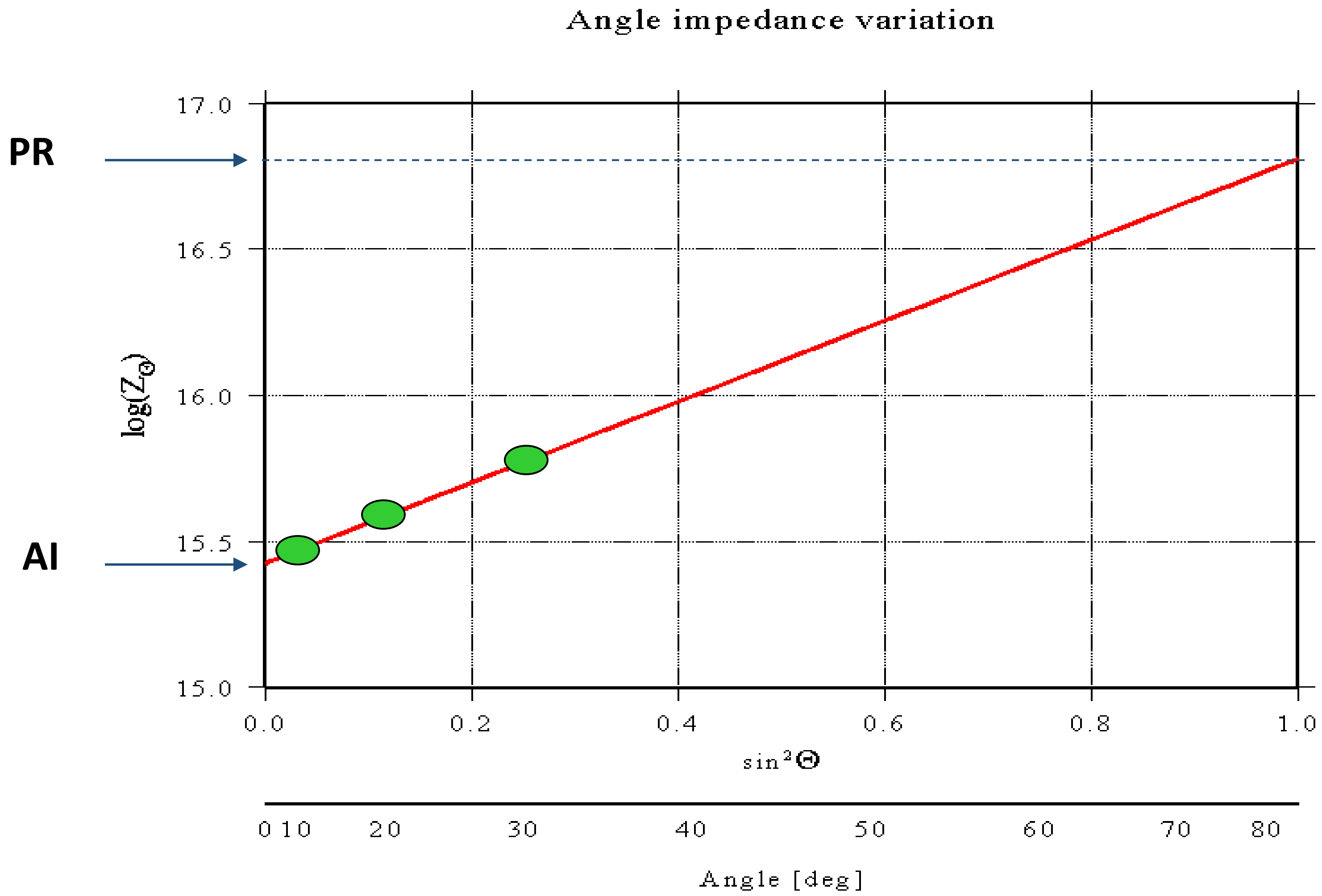
Advantages of Simultaneous Inversion

- Noise cancellation
- Inversion directly for physical parameters
- Combined inversion run

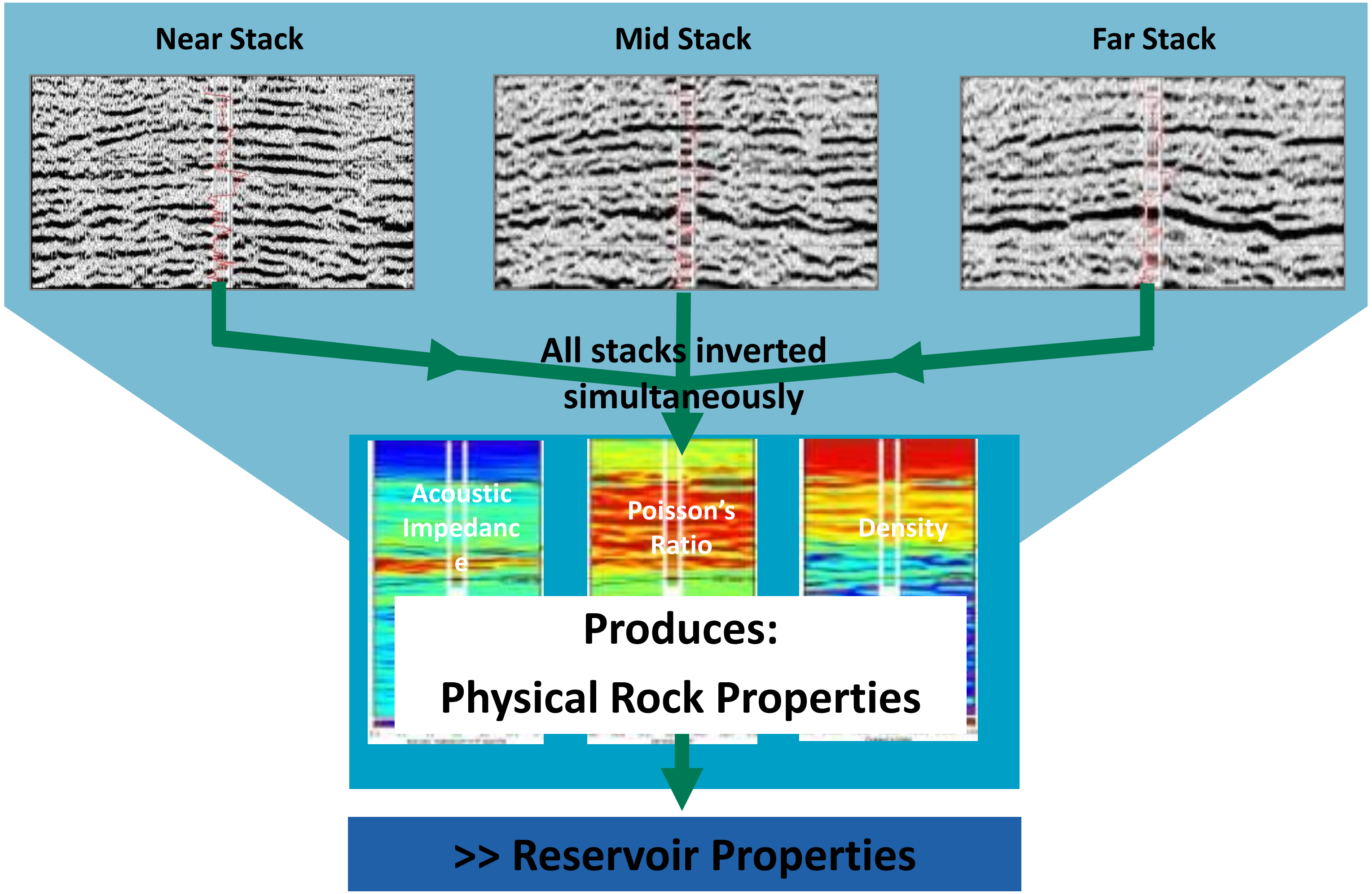
SEPARATE AVO INVERSION (”ELASTIC INVERSION”)



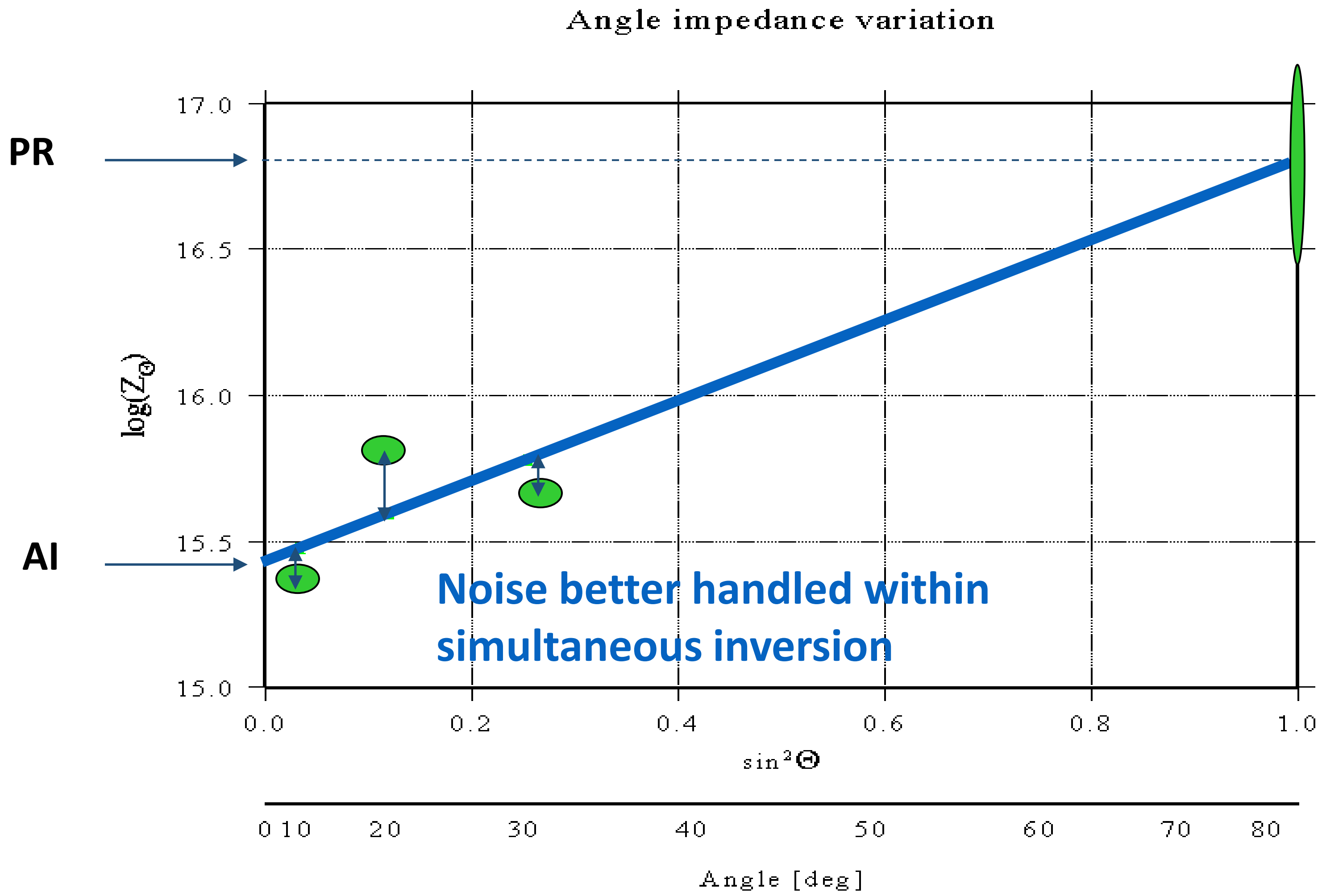
Separate AVO inversion



GLOBAL SIMULTANEOUS INVERSION



Simultaneous AVO inversion



SSI Simultaneous AVO Inversion

S/N ratio Seismic (incl. wavelet)

S/N ratio Seismic (incl. wavelet)

S/N ratio Seismic (incl. wavelet)

Prior model

Deviation AI

Deviation PR

Deviation Dens

SSI inversion kernel

Continuity for each result

Significant reflector

Result AI Result PR Result dens

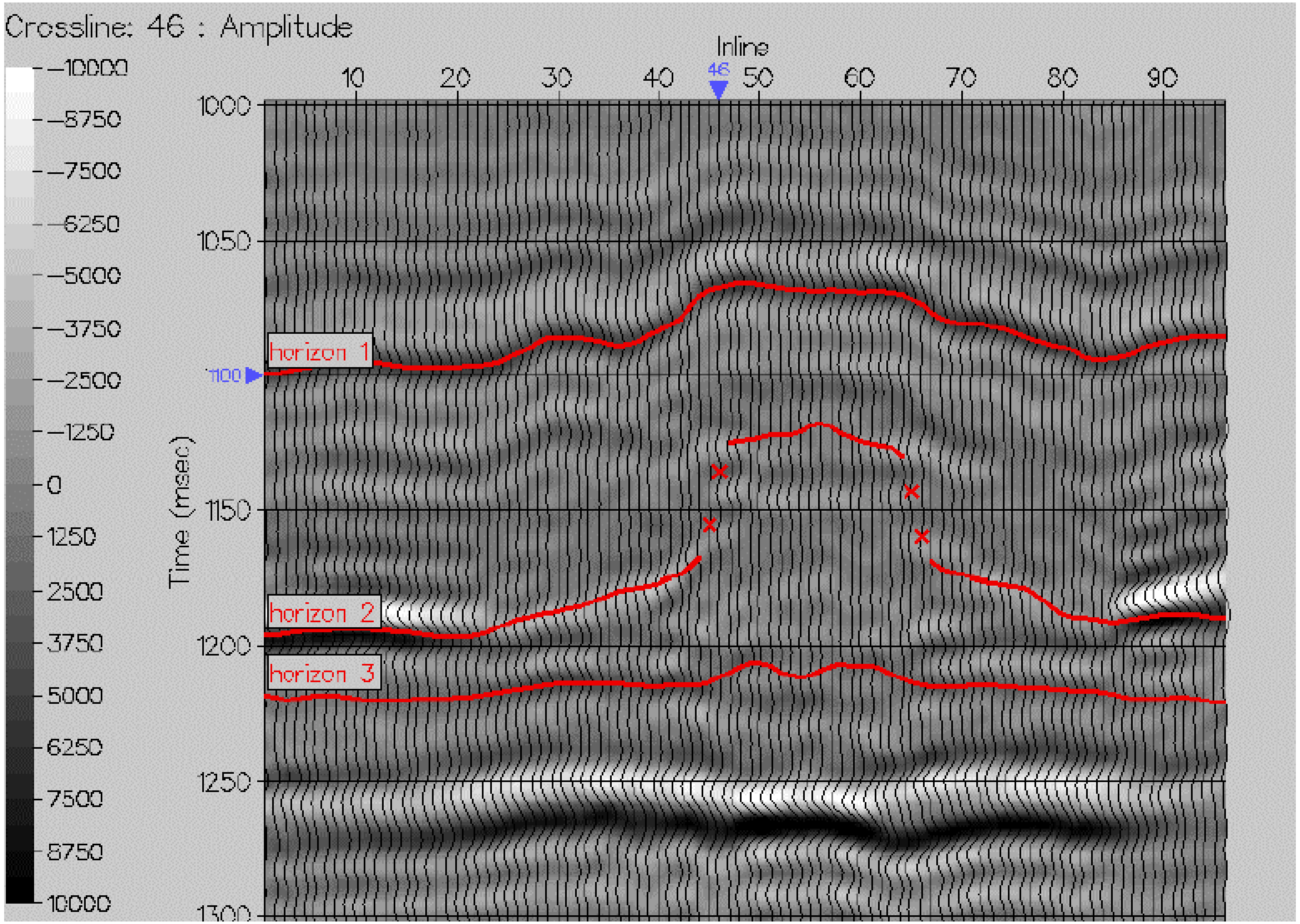
Seismic inversion techniques

Inversion techniques can be divided into two main classes:

- Those employing global optimization, such as SSI Global Seismic Inversion.
- Those employing local optimization, such as sparse-spike based methods.

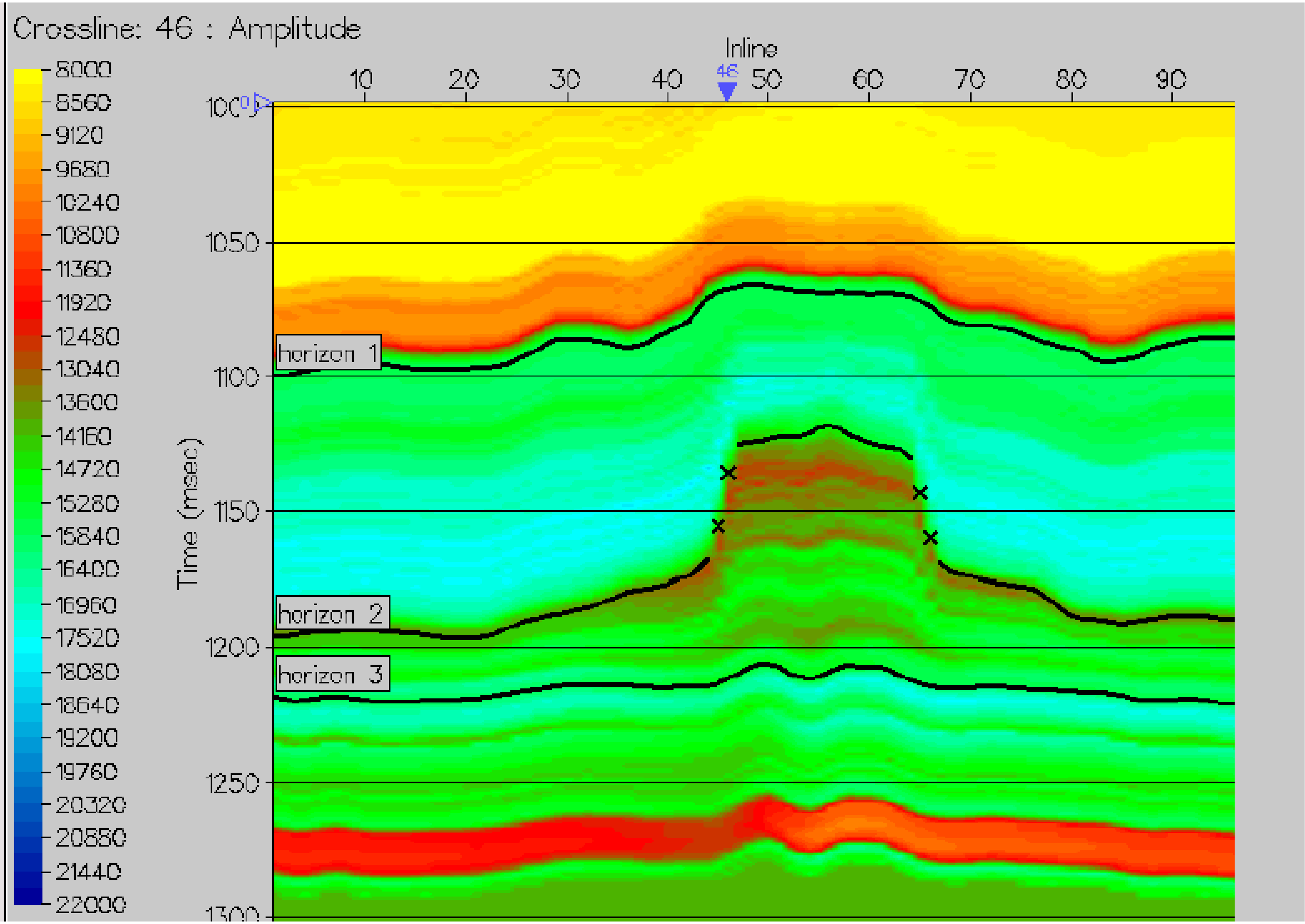
Inversion Methods

Seismic Input Data



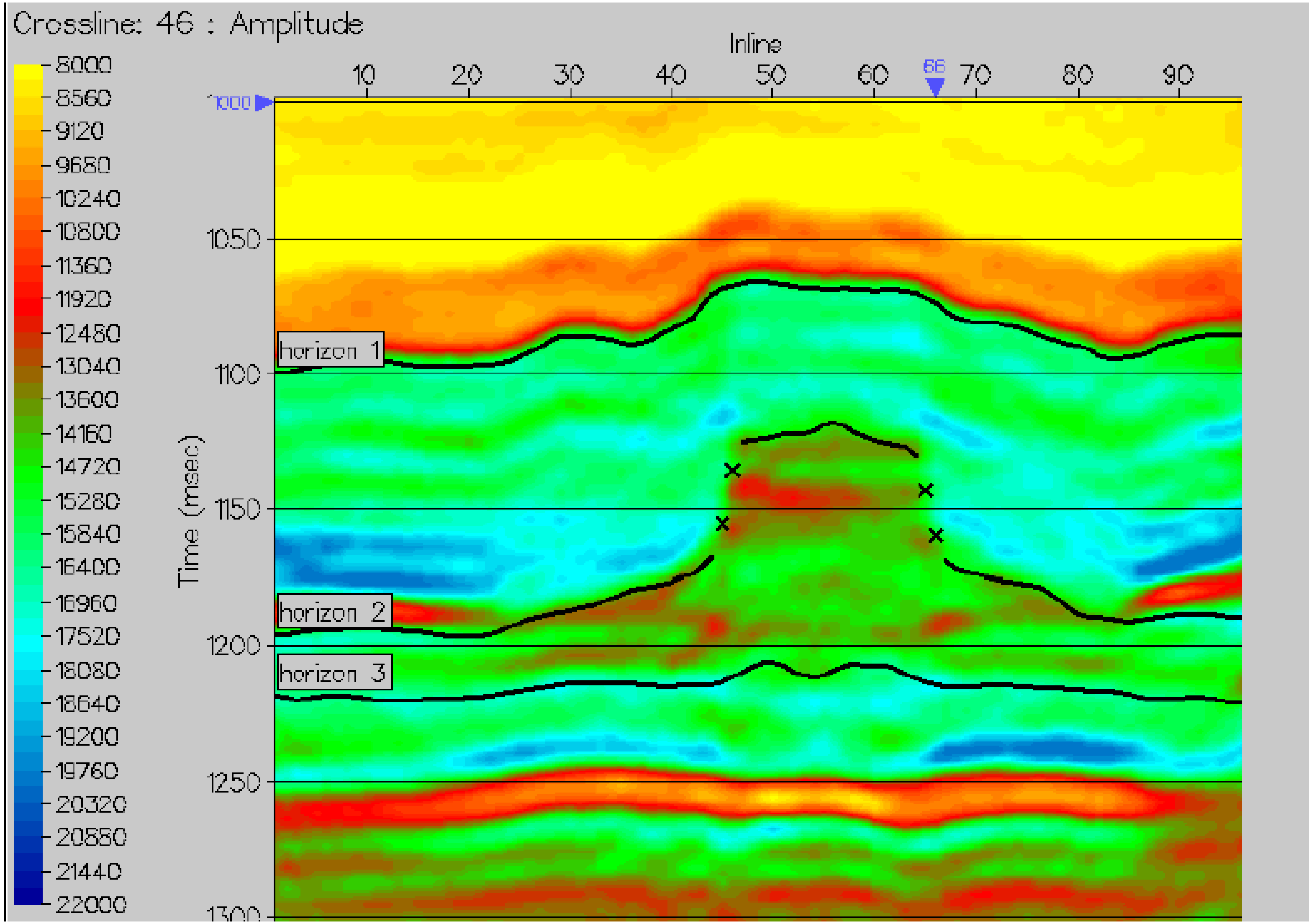
Inversion Methods

Relative Acoustic Impedance by Colored Inversion



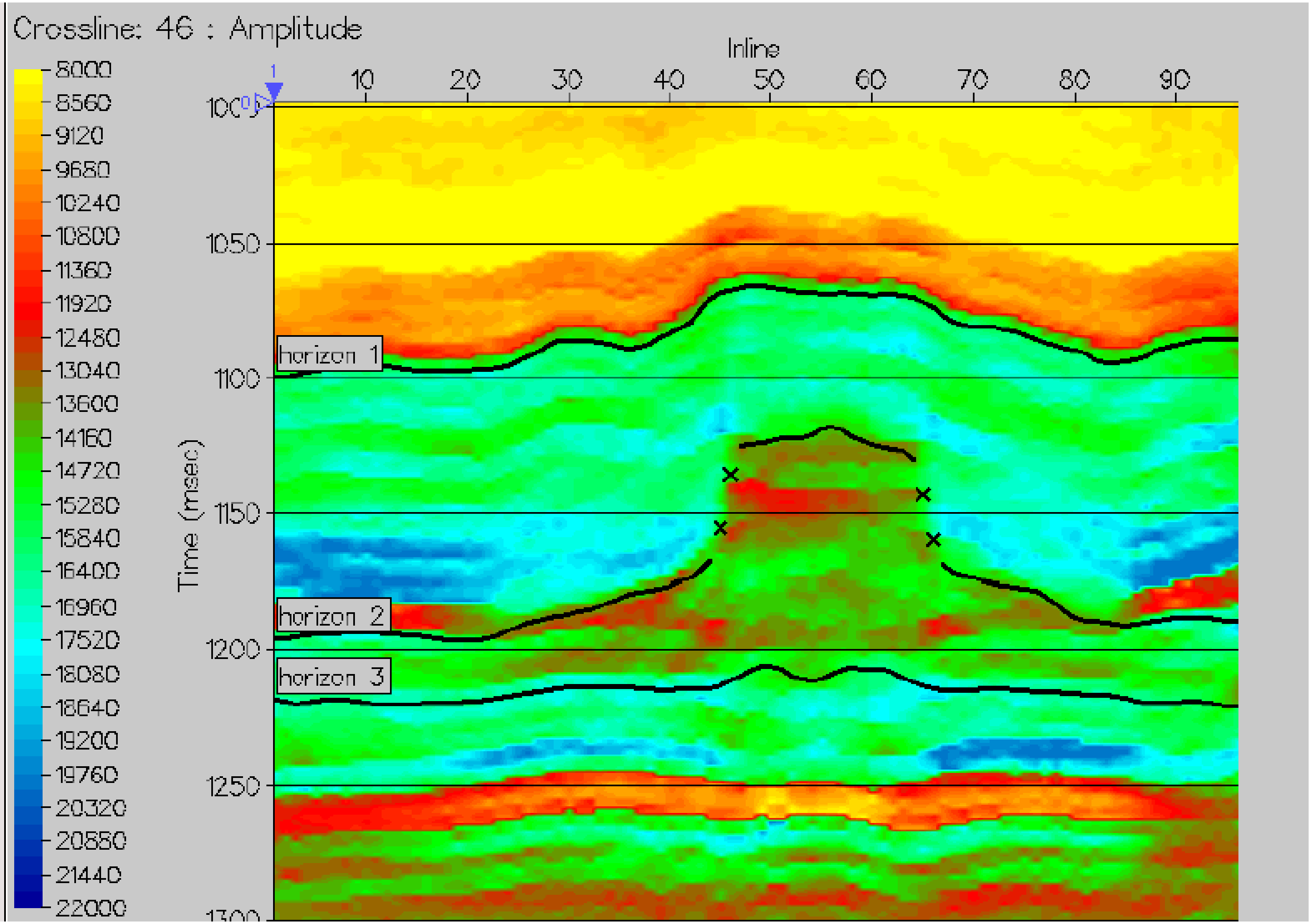
Inversion Methods

Model-Based Acoustic Impedance



Inversion Methods

Discrete Spike Impedance

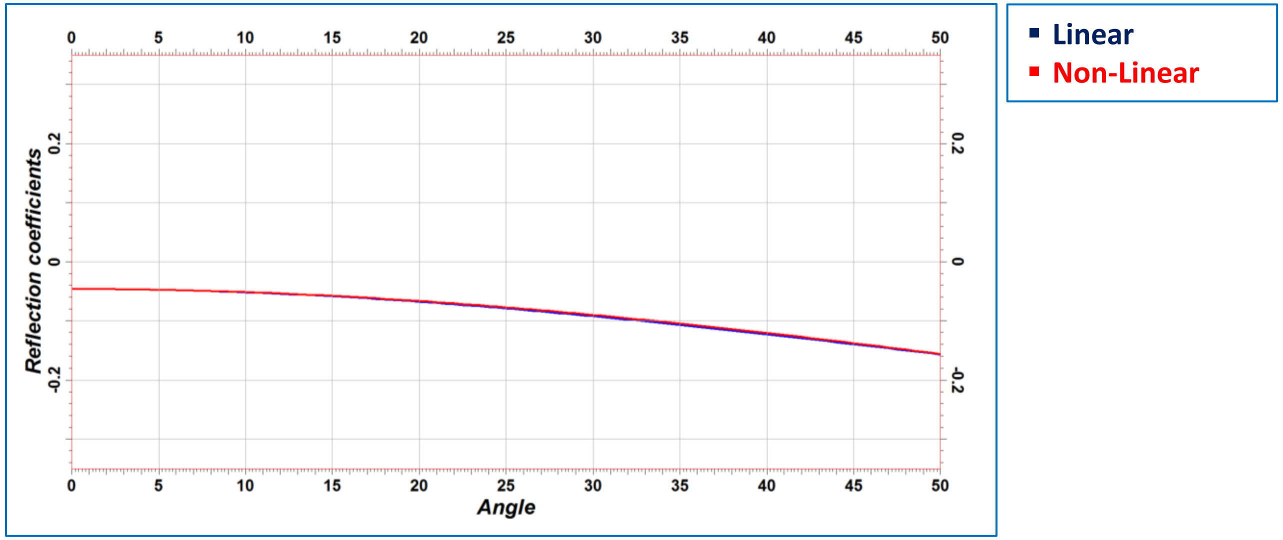


Why Non-Linear, Anisotropic AVO Inversion?

- Linearized AVO approximations assume:
  - small contrasts
  - narrow reflection angles (<30deg)

and are not valid in presence of **strong contrasts**

	Vp	Vs	den	ε	δ	γ
Layer 1	2625	1548	2.173	0	0	0
Layer 2	2600	1800	2	0	0	0



Non-linear orthorhombic AVAZ inversion workflow

E.Gofer, R.Bachrach, R.Fletcher, M.Vie - 86th SEG International Annual Meeting, 2016

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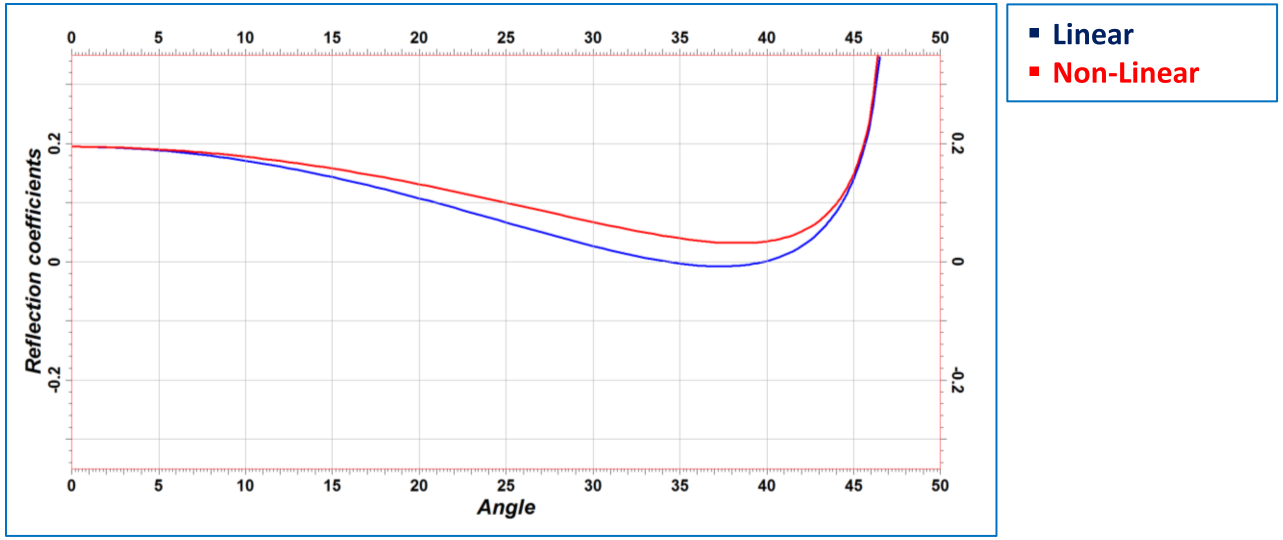
)

	Vp	Vs	den	ε	δ	γ
Layer 1	2625	1548	2.173	0	0	0
Layer 2	3600	2400	2.35	0	0	0



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Why Non-Linear, Anisotropic AVO Inversion?

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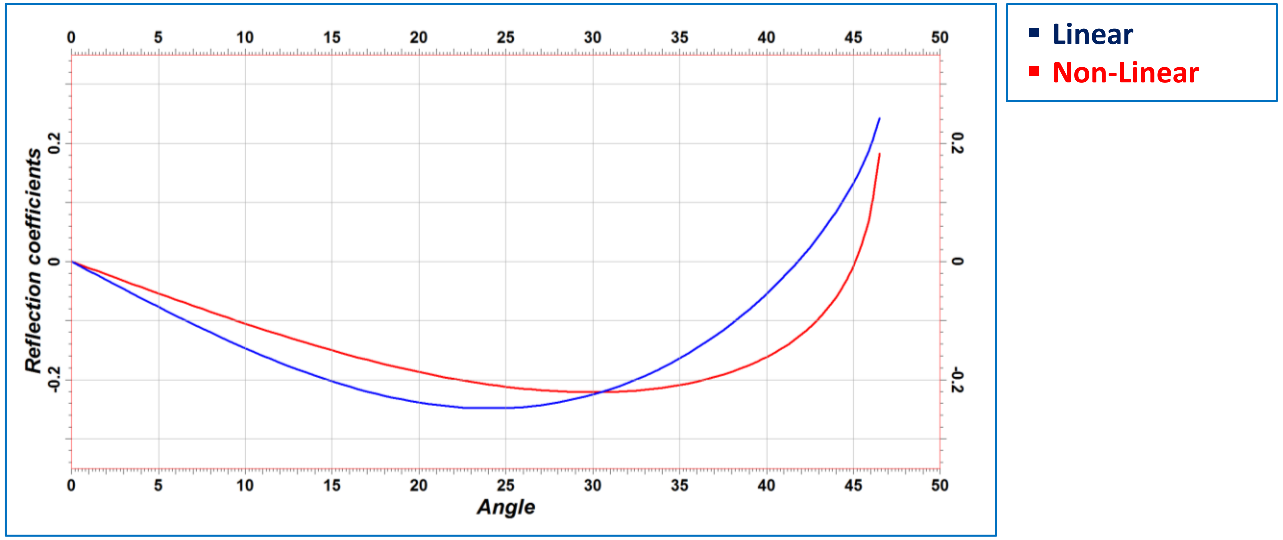
  - narrow reflection angles (<30deg)

  and are not valid in presence of **strong contrasts**

- This is even more important for **PS data**

	Vp	Vs	den	ε	δ	γ
Layer 1	2625	1548	2.173	0	0	0
Layer 2	3600	2400	2.35	0	0	0



Non-linear orthorhombic AVAZ inversion workflow

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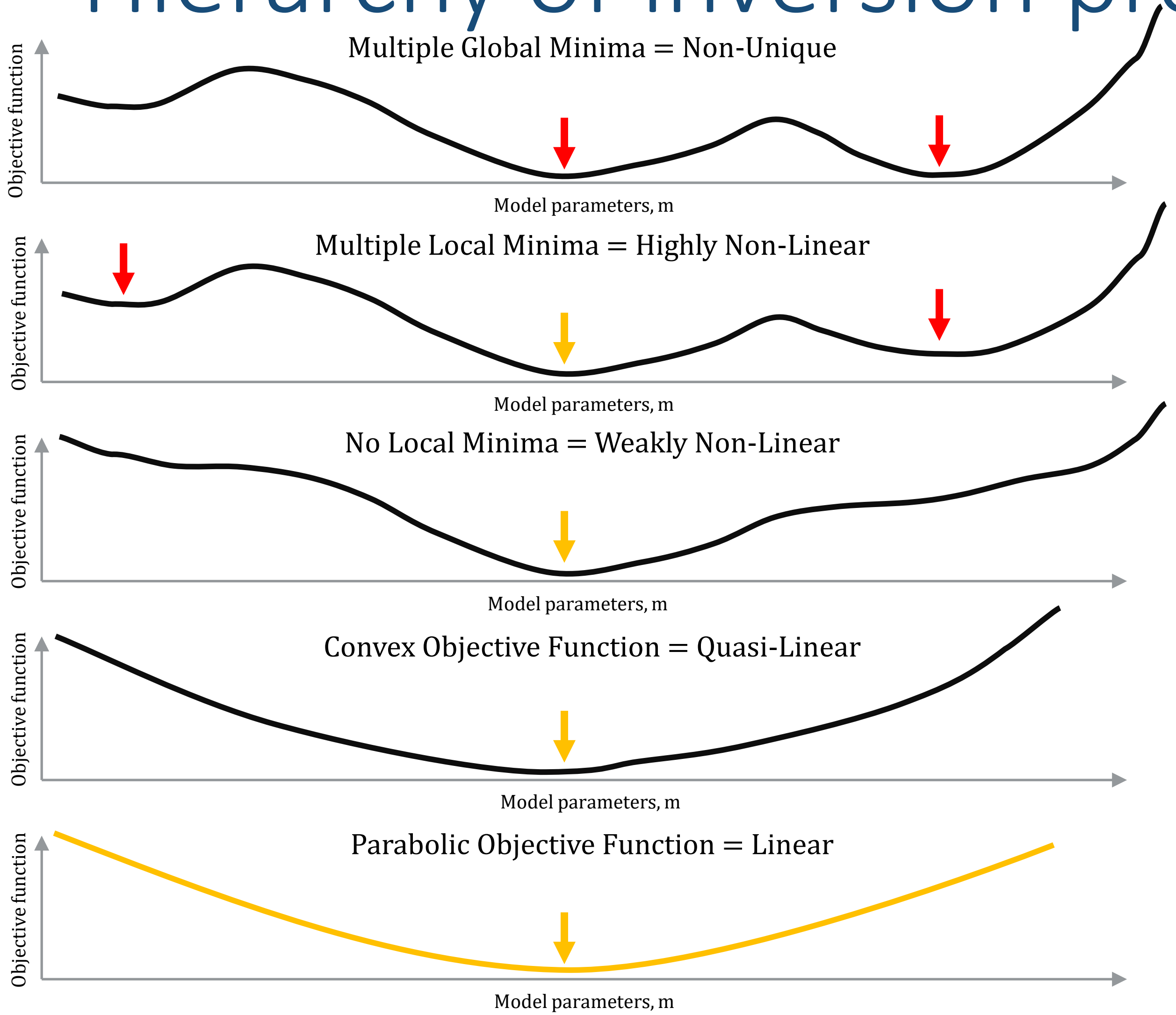
Hierarchy of inversion problems



Seismic inversion is **non-unique** because of **limited bandwidth of seismic signal**, amplitude errors and noise

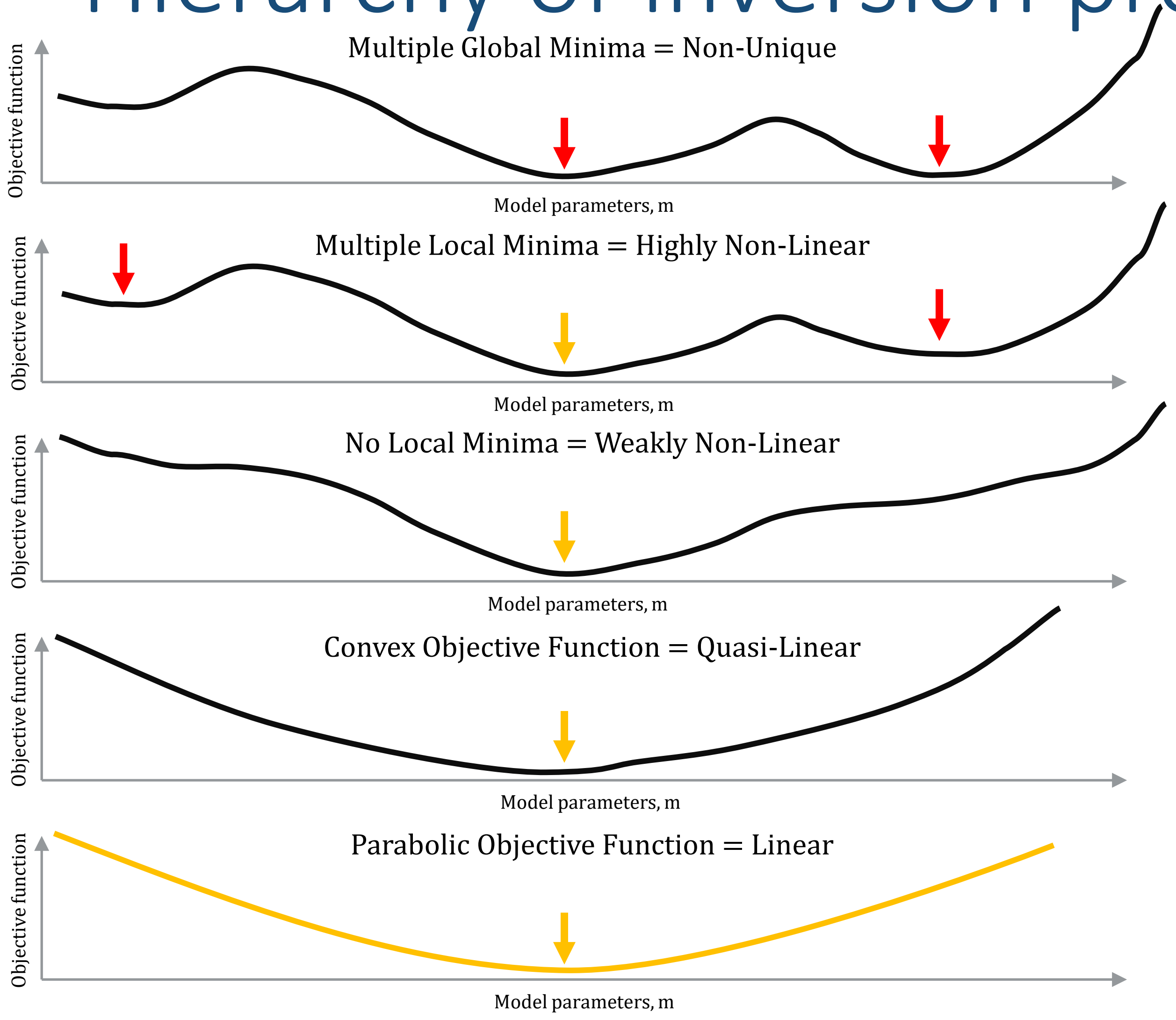
***'a priori'* constraints** to reduce the non-uniqueness

Types of inversion methods:

- global inversion (GA, simulated annealing, …)
- local search (Simplex, Taboo, …)
- descent type or linearized inversion (Newton, Gradient based)

Inspired by Earthworks Environment & Resources Ltd – A practical guide to inversion and stochastic modelling

Hierarchy of inversion problems

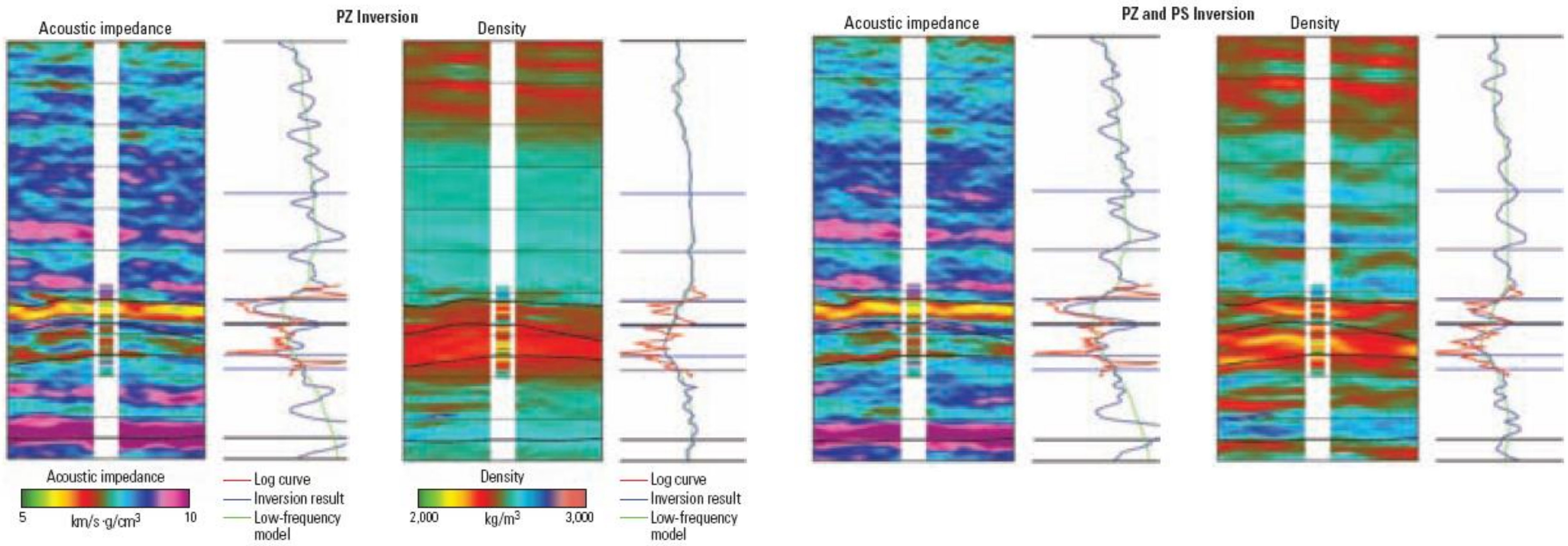


Waveform Inversion of

- pre-stack seismic data using Finite Difference Modelling
- pre-stack seismic data using Dynamic Ray-tracing
- pre-stack seismic data using 1D Reflectivity Modelling
- **multiple angle stacks using (Linearized) Zoeppritz equation and convolution**
- Single stack using convolution

Inspired by Earthworks Environment & Resources Ltd – A practical guide to inversion and stochastic modelling

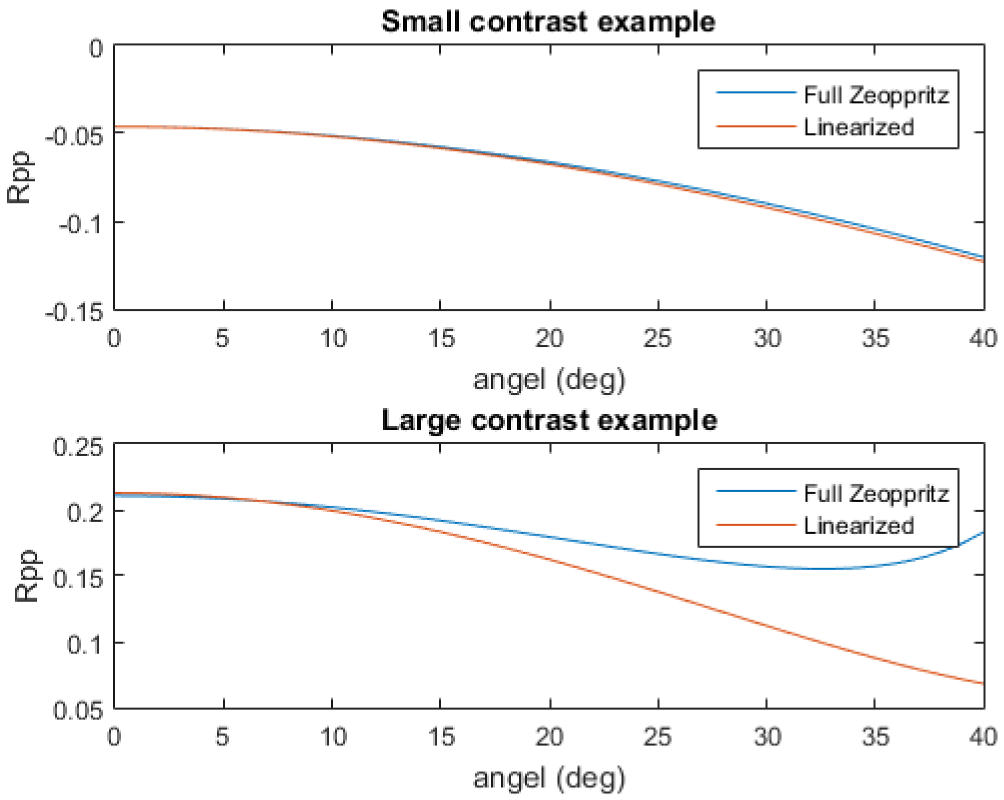
Comparison post-stack - pre-stack inversion



Left: Acoustic impedance cube and density cube based on P-seismic only.

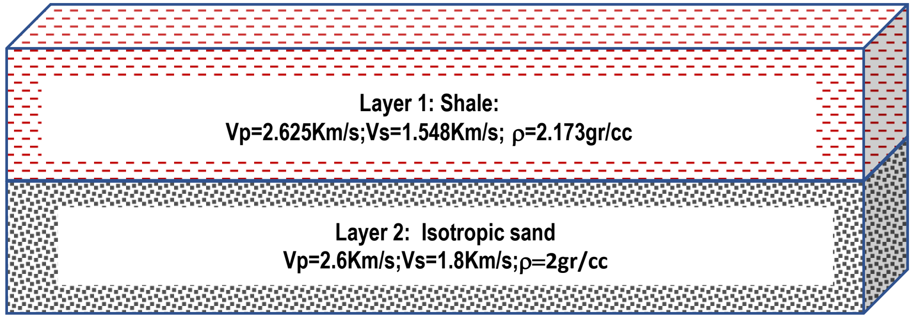
Right: Inversion based on P- and S-seismic. Note the higher resolution of the density section.

Linearized vs non linear PP example

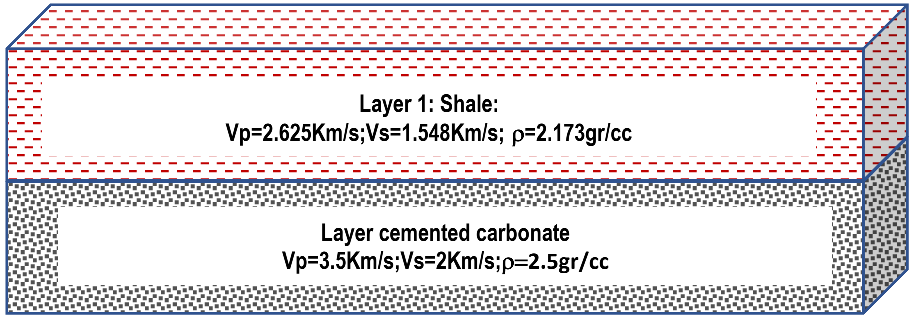


Large contrast and high angles…

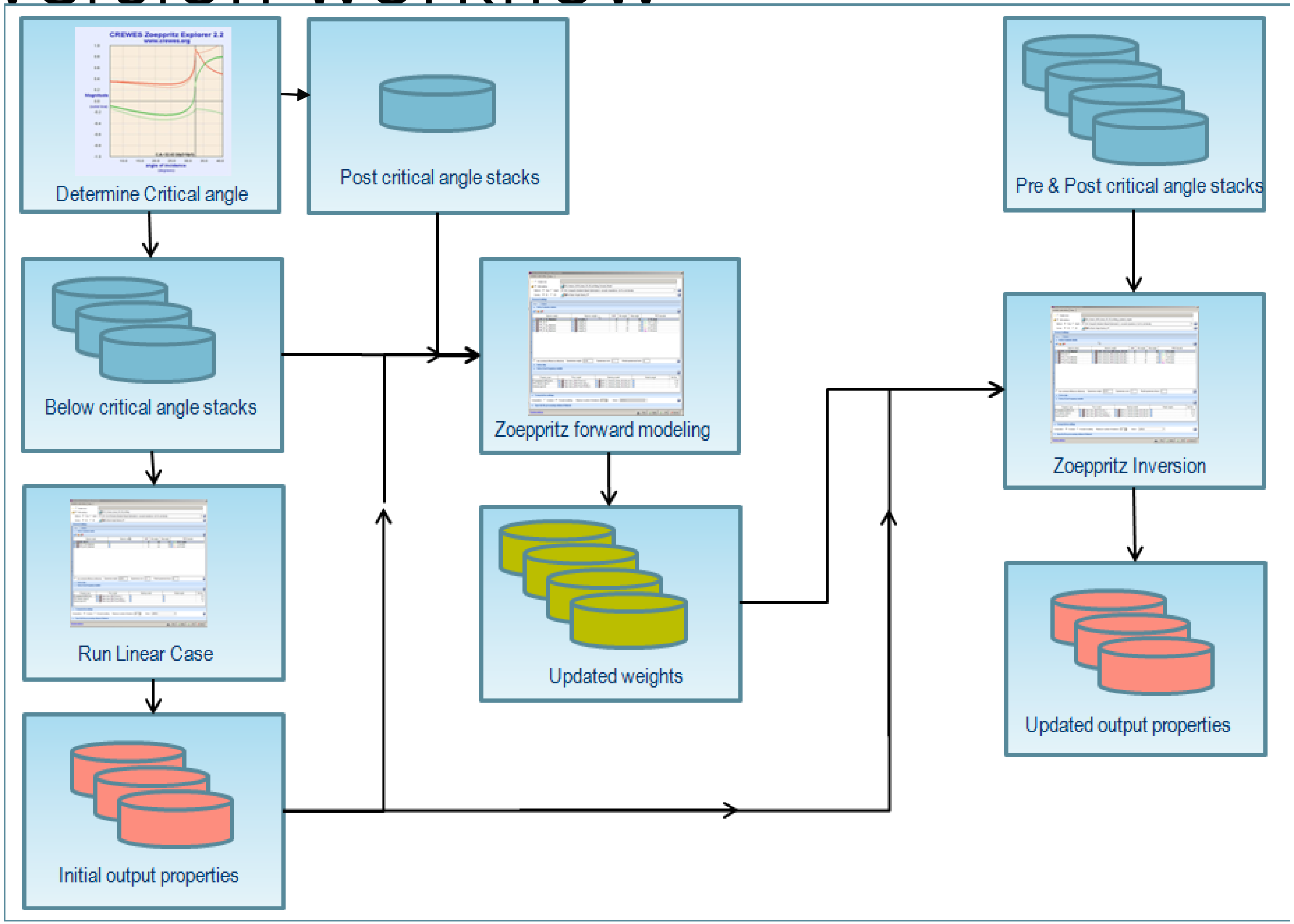
Small contrast



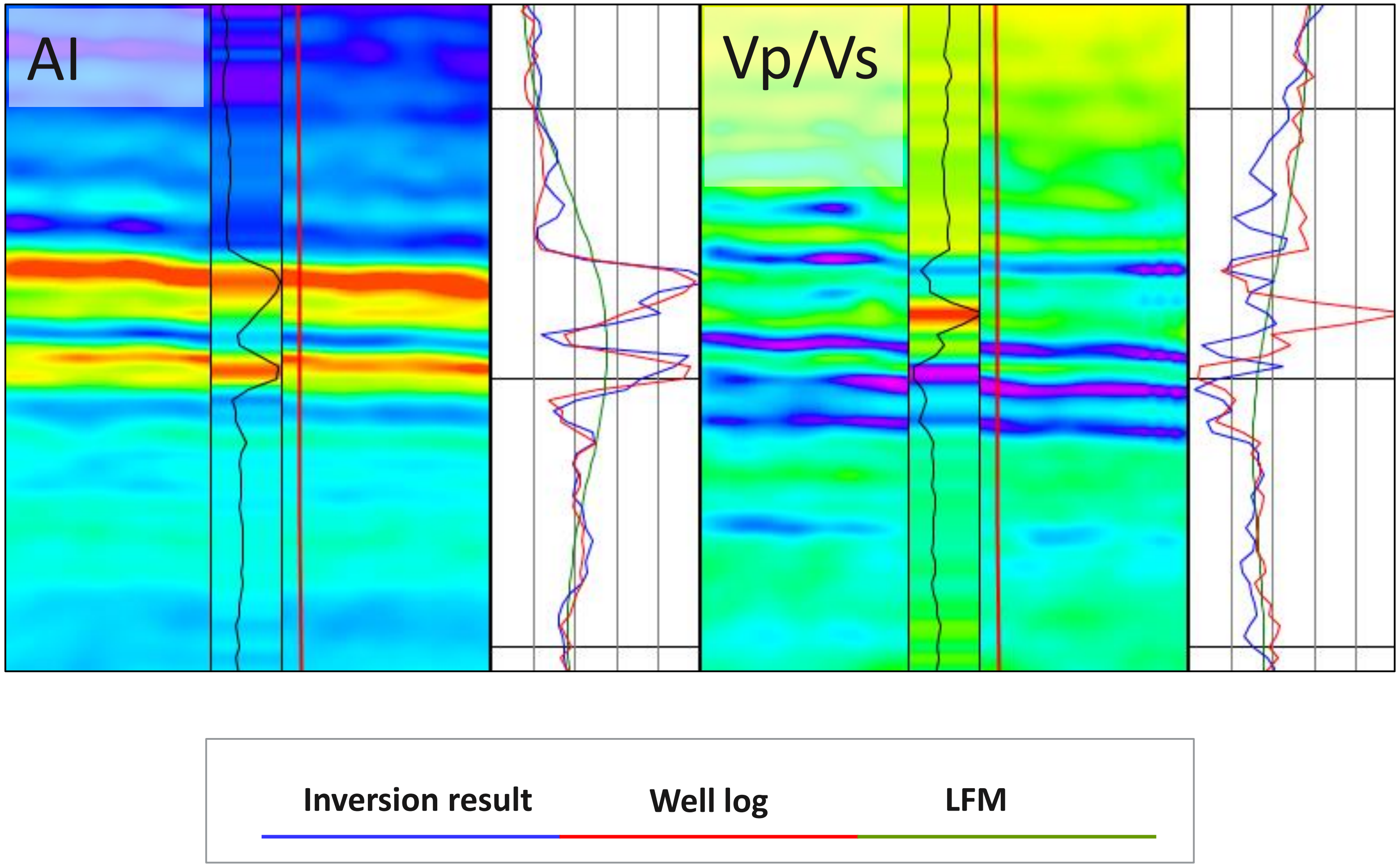
Large contrast



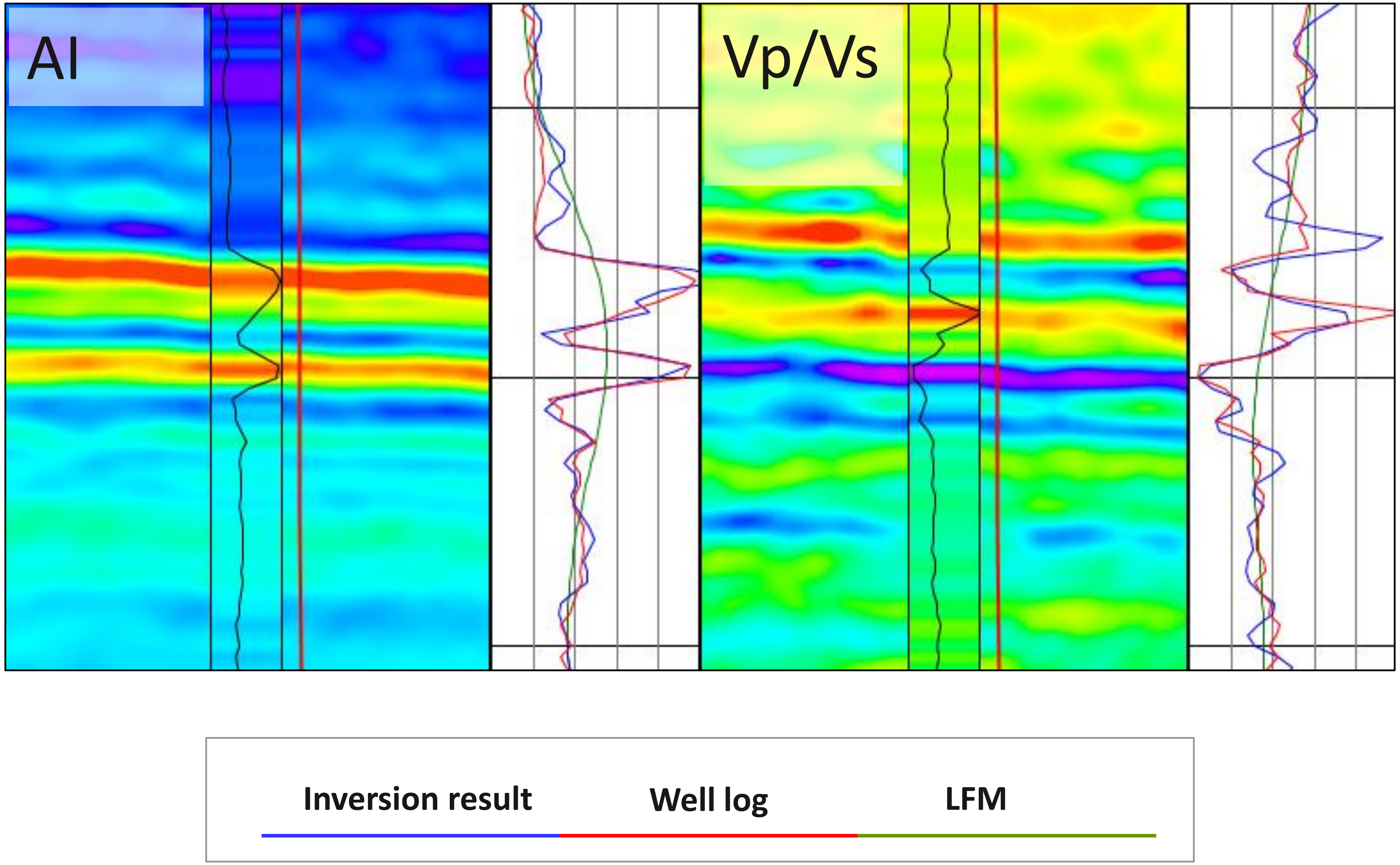
GBO inversion workflow



Conventional Aki&Richards Linear Inversion



Zoeppritz Non-Linear Inversion



Summary:
Why seismic inversion

- ***Direct link to reservoir parameters***
  - Option to invert seismic cube directly to reservoir parameters who have a strong influence on the acoustic impedance (porosity, shaliness, density etc)
- ***AVO inversion: direct link to rock properties***
- Output of geological layers rather than reflection edges
- Better image of the stratigraphy
- Higher resolution compared to seismic
- Reduction of wavelet tuning effect

Summary on Seismic Inversion

- Impedance inversion allows fluid determination in the reservoir rocks: Gas or water (oil with gas in solution)
- Well log conditioning is the key for constraining inversion
- Seismic inversion is not a unique process. Several AI models can generate similar synthetic traces when convolved with the wavelet. The number of possible solutions is significantly reduced by putting constraints on the modeling.
- Stratigraphic interpretation is improved

Summary on Seismic Inversion

- Seismic impedance volume allows the integration of seismic amplitudes for reservoir characterization.
- The analysis of 3D seismic data in terms of acoustic impedance provides rock parameter estimation: porosity, permeability, shale volume, net sand, etc.
- 3D acoustic impedance “soft data” for geostatistical model of rock properties

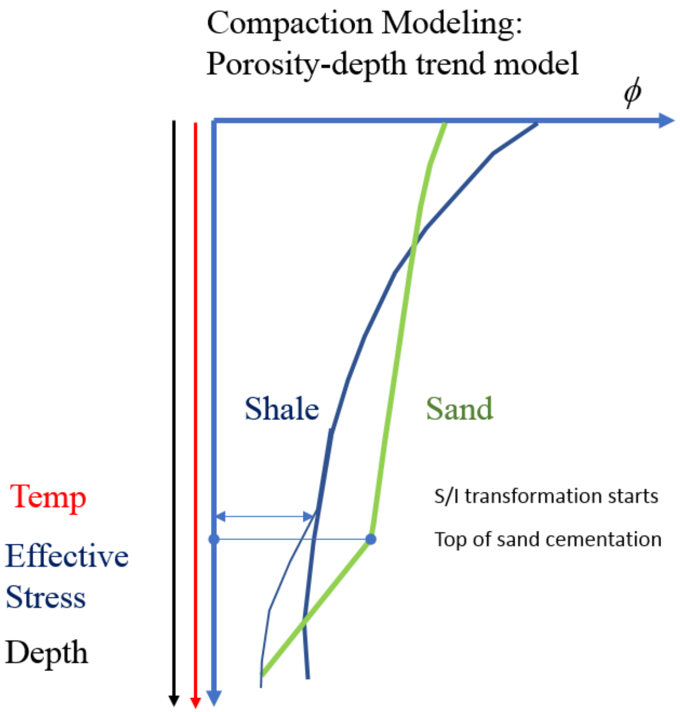
Seismic Inversion
A Word of Caution

- Other techniques, such as multi-component inversion, elastic inversion and AVO should be used to better discriminate fluid content and lithology.

- Seismic velocities are sensitive to the presence of gas in a rock sequence. A 5-10% gas saturation has already a tremendous impact on the seismic response. It will lead to AVO and AI anomalies, but these are non-commercial.

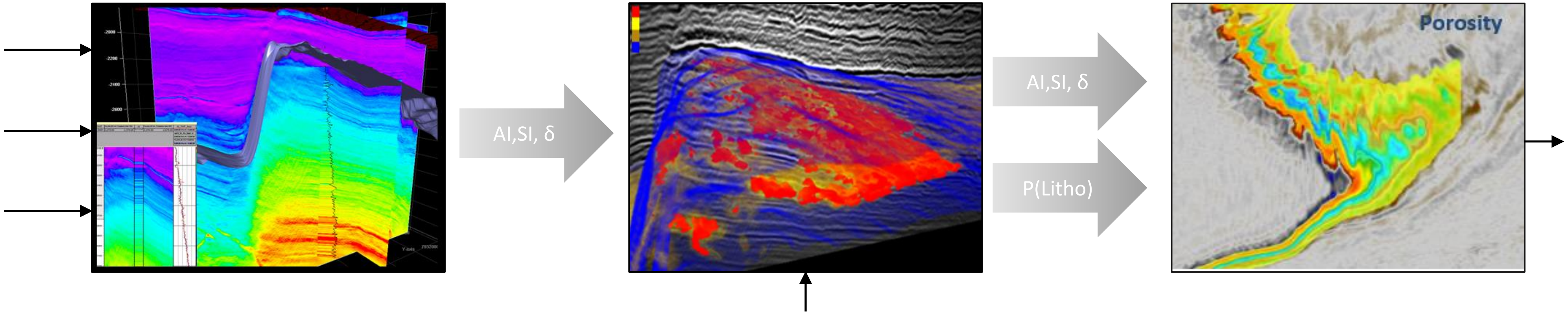
Rock physics trend driven single loop inversion

- Building accurate low frequency prior models is often very challenging
    - Frontier exploration areas, channelized systems, structurally complex areas
- Low frequency trends are governed by geological processes
    - Mechanical compaction, geochemical alteration, cementation, etc.
- Rock Physics modelling and compaction trend analysis of the basin enable t amplitudes to lithology units and elastic properties



LPE | Litho-Petro-Elastic inversion

Conventional 3-steps reservoir characterization workflow



LPE | Litho-Petro-Elastic inversion

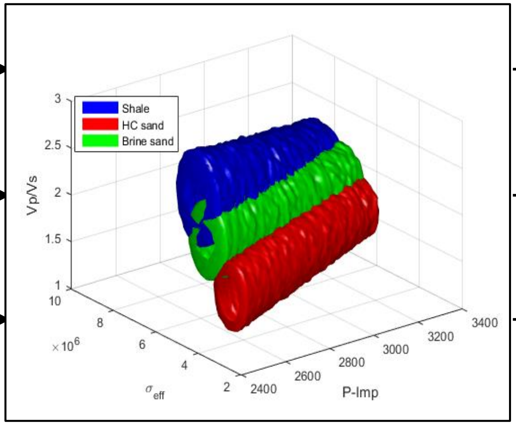
Single-loop approach to seismic reservoir characterization

Single-Loop Litho-Petro-Elastic inversion

Seismic →

Wavelets →

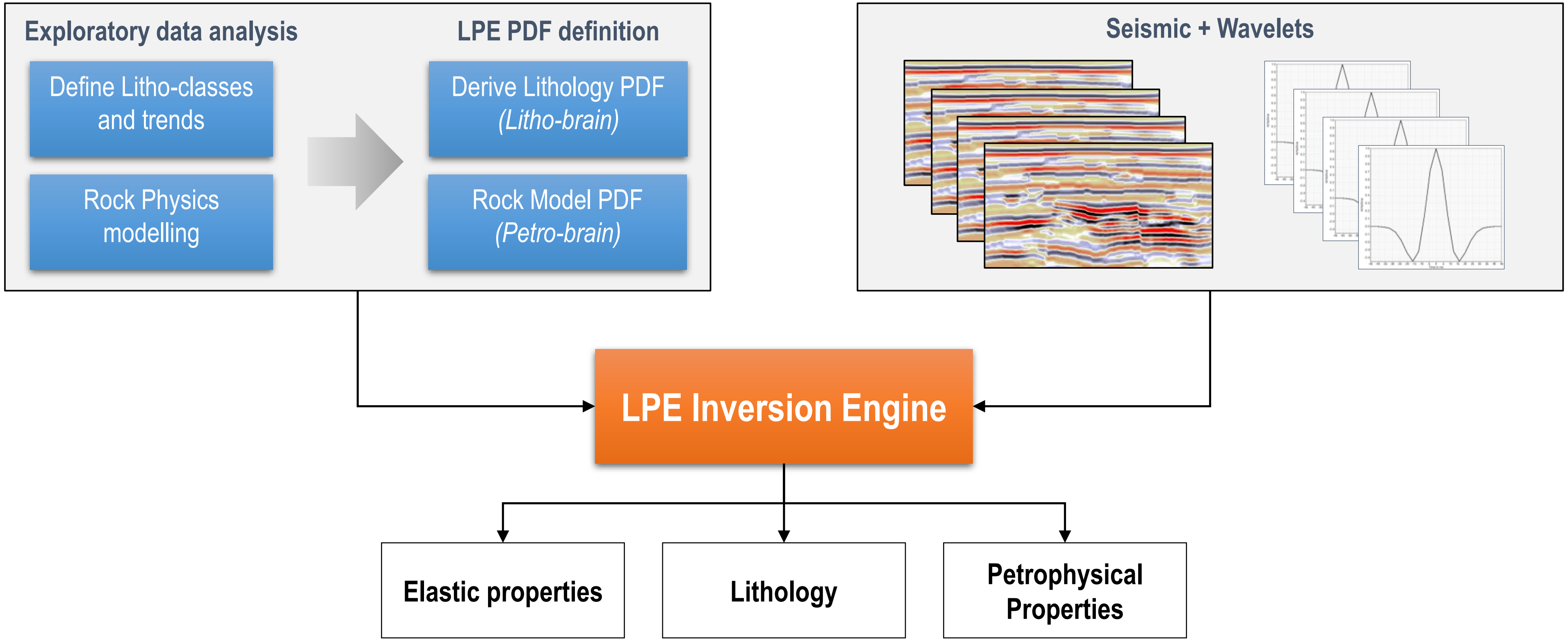
Rock Physics Trends →

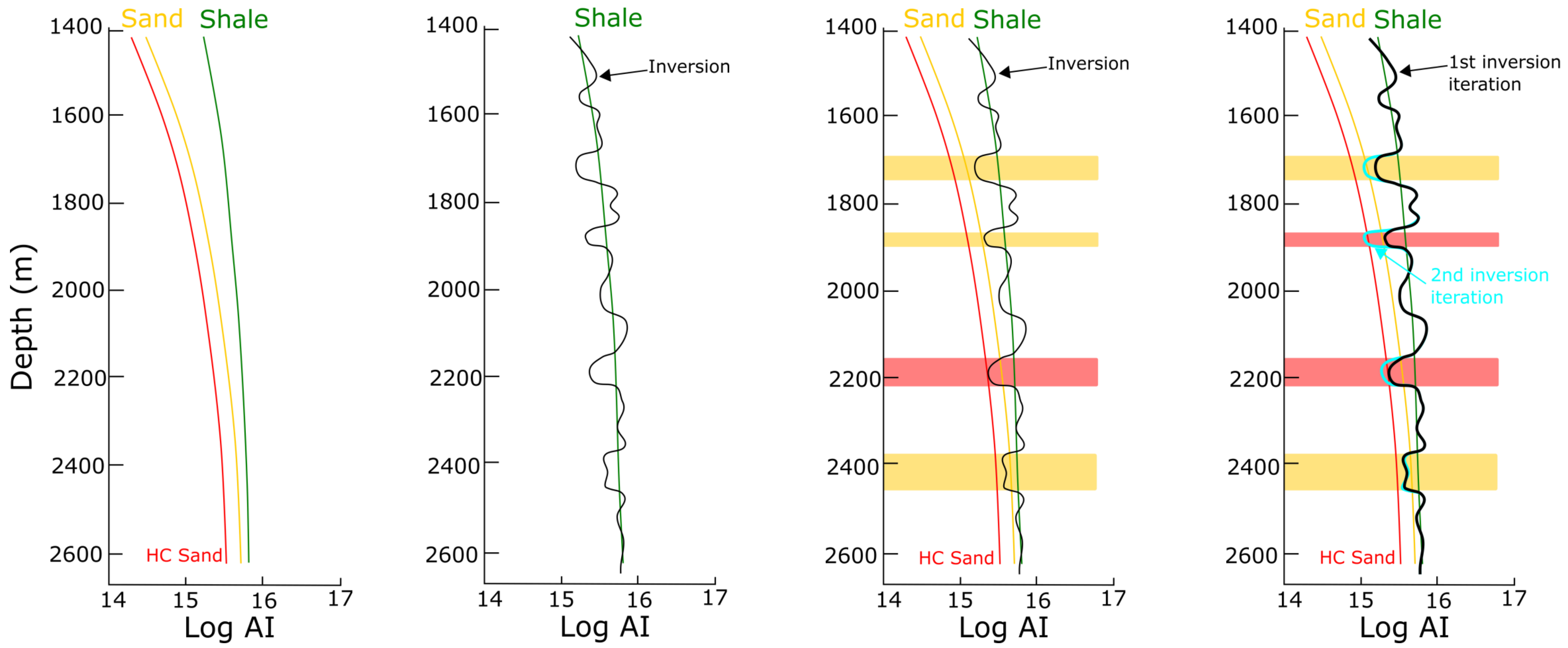


→ AI,SI, δ

→ P(Litho)

→ Φ, Sw, Vcl

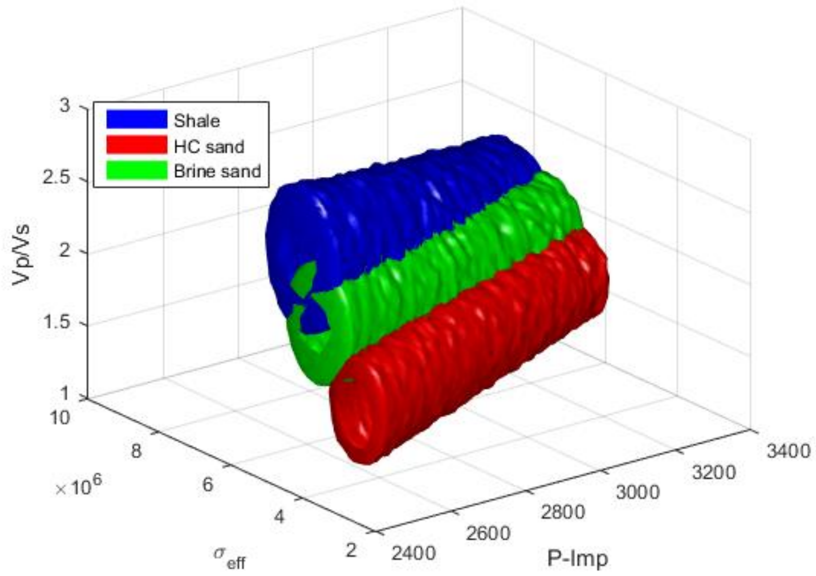

Exploratory data analysis
Define Litho-classes and trends
Rock Physics modelling
LPE PDF definition
Derive Lithology PDF (Litho-brain)
Rock Model PDF (Petro-brain)
Seismic + Wavelets
LPE Inversion Engine
Elastic properties
Lithology
Petrophysical Properties



Sand
Shale
Inversion
1st inversion iteration
2nd inversion iteration
HC Sand
Depth (m)
Log AI
1400
1600
1800
2000
2200
2400
2600
14
15
16
17

- 1D prior as opposed to 3D LFM
  - No horizons used. No interpolation of well logs
- Prior based on rock physics/ compaction trends per f
  - Inversion choses which prior to use based on facies estimates.
- Trends built using available wells in region
  - No need for wells to be within the survey
  - Quantity of wells much less crucial
- 3D LFM is an output as opposed to an input

P(Facies | P-Impedance ,Vp/Vs, Effective stress trend)

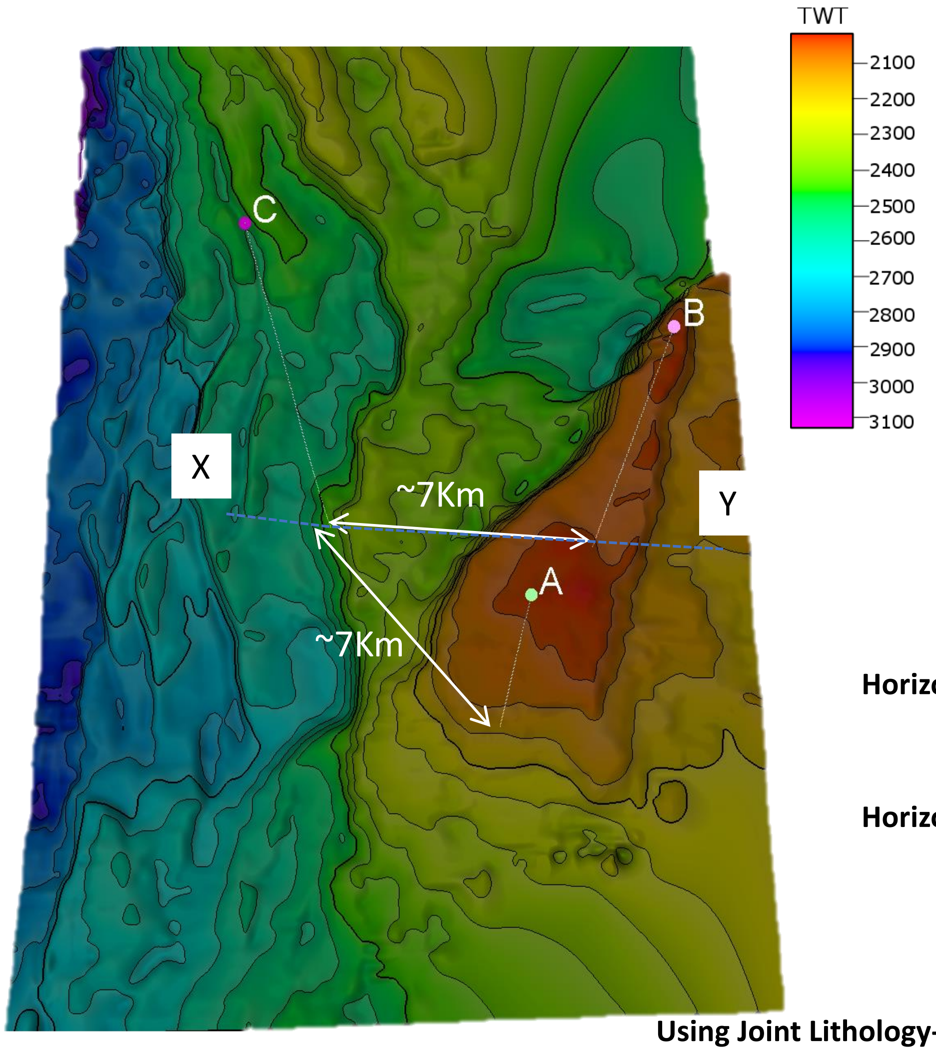


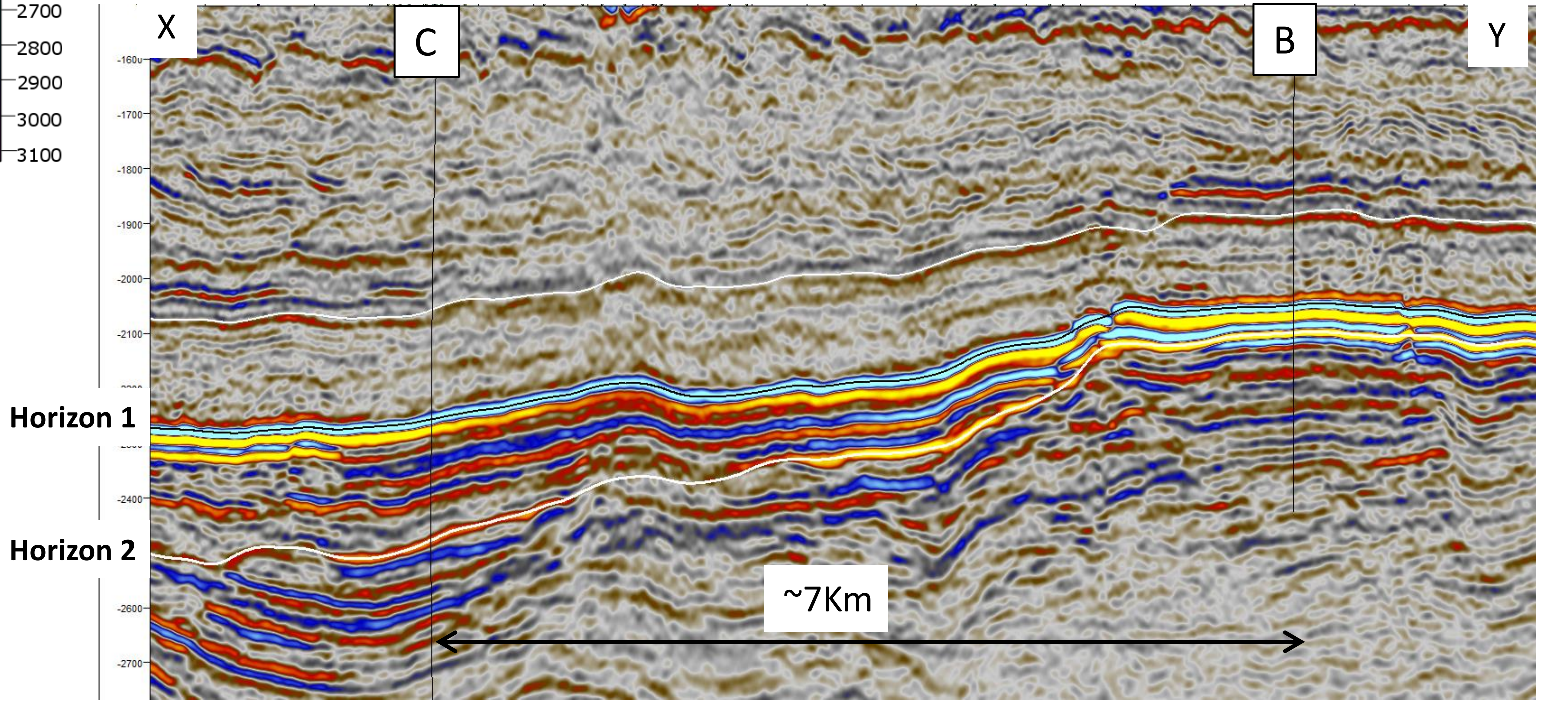
- Data assimilation framework - using sequential filters as inversion engine
    - Can easily integrate other models and measurements (PS data, AVAz etc.)
    - Linear and Non-Linear, anisotropic reflectivity operators

- Joint estimation of *lithologies*, *elastic* and *petrophysical* properties
  - Compaction trend modelling – no explicit definition of LFM
    - From simple 1D depth trends (based on depth and thermal gradients)…
    - …to more complex scenarios (handles effective stress variations, estimated from seismic velocities or 3D basin modelling)
  - Rock physics modelling for petrophysical response
    - Stochastic modelling to estimate non parametric PDFs
    - Handles anisotropy (i.e. VTI shale anisotropy)

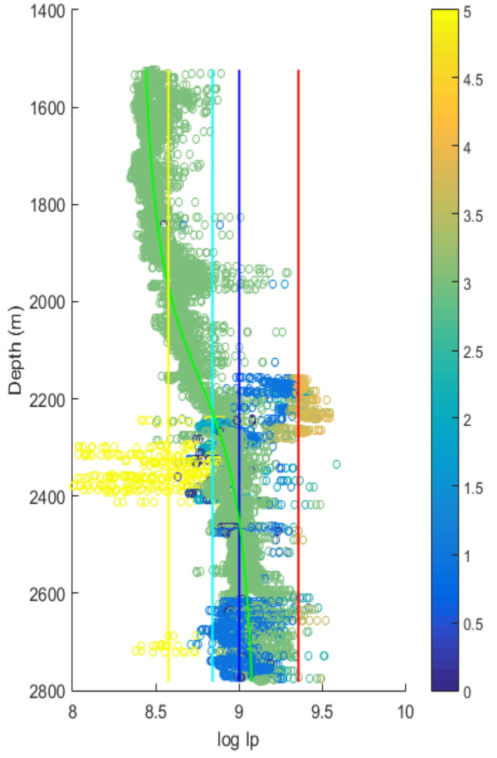
Scenario assumptions:

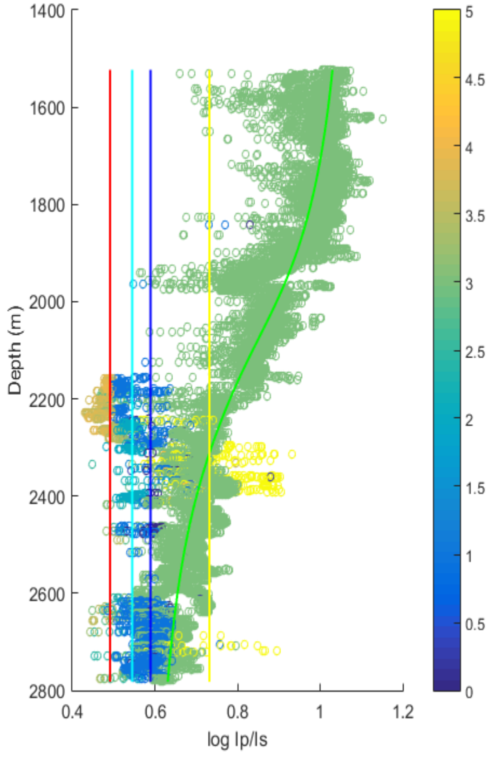
- Only wells A and B exist.
- Well C is blind

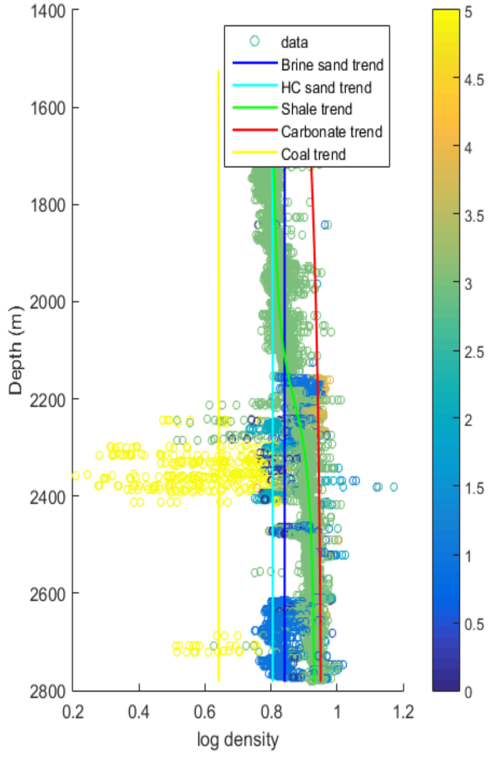


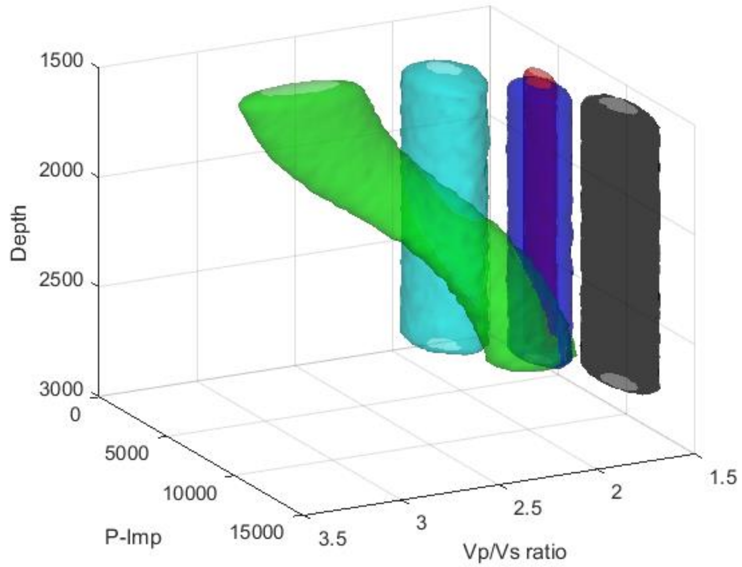


Using Joint Lithology-Elastic Inversion to Enhance Earth Model Building Workflows
Barling, T., Bachrach, R., Leone, C., Chen, S. - 2nd EAGE/PESGB Workshop on Velocities, London 2019









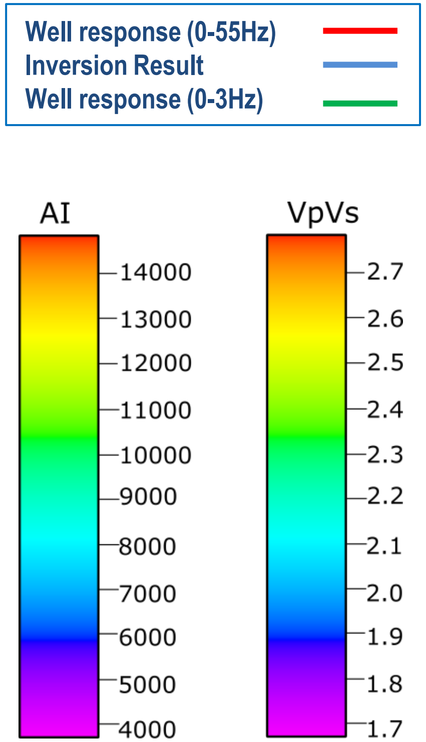
Shale

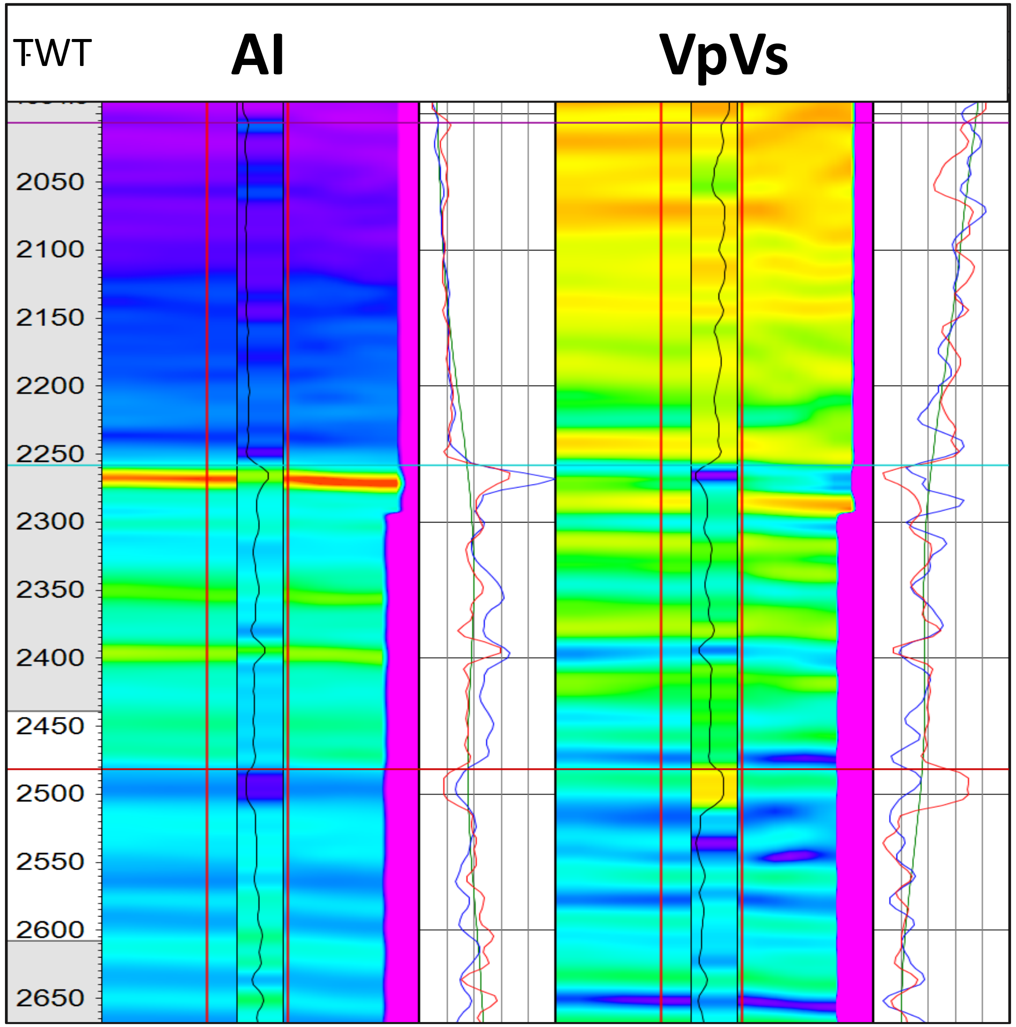
Brine sand

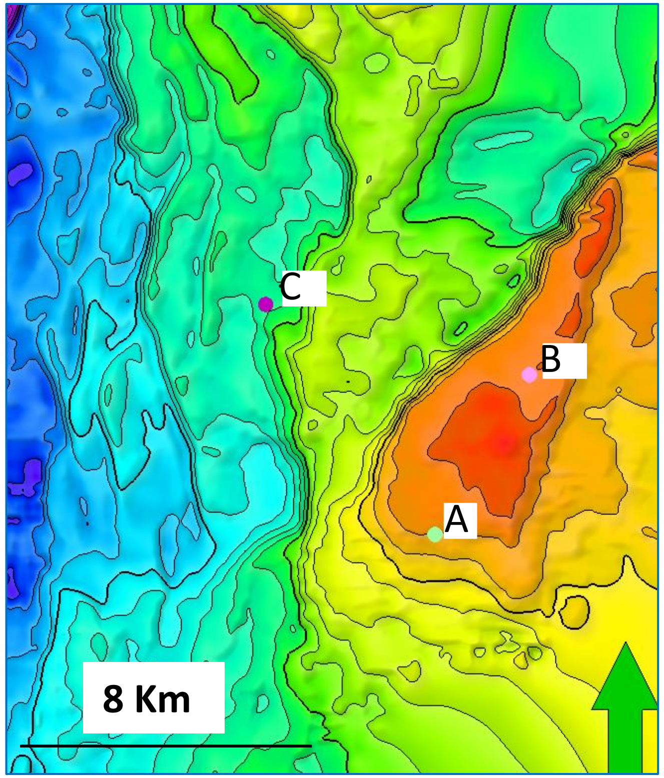
HC sand

Carbonate

Coal

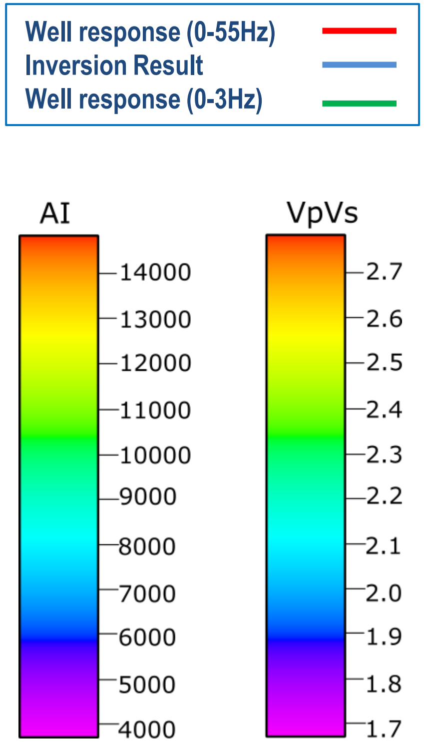




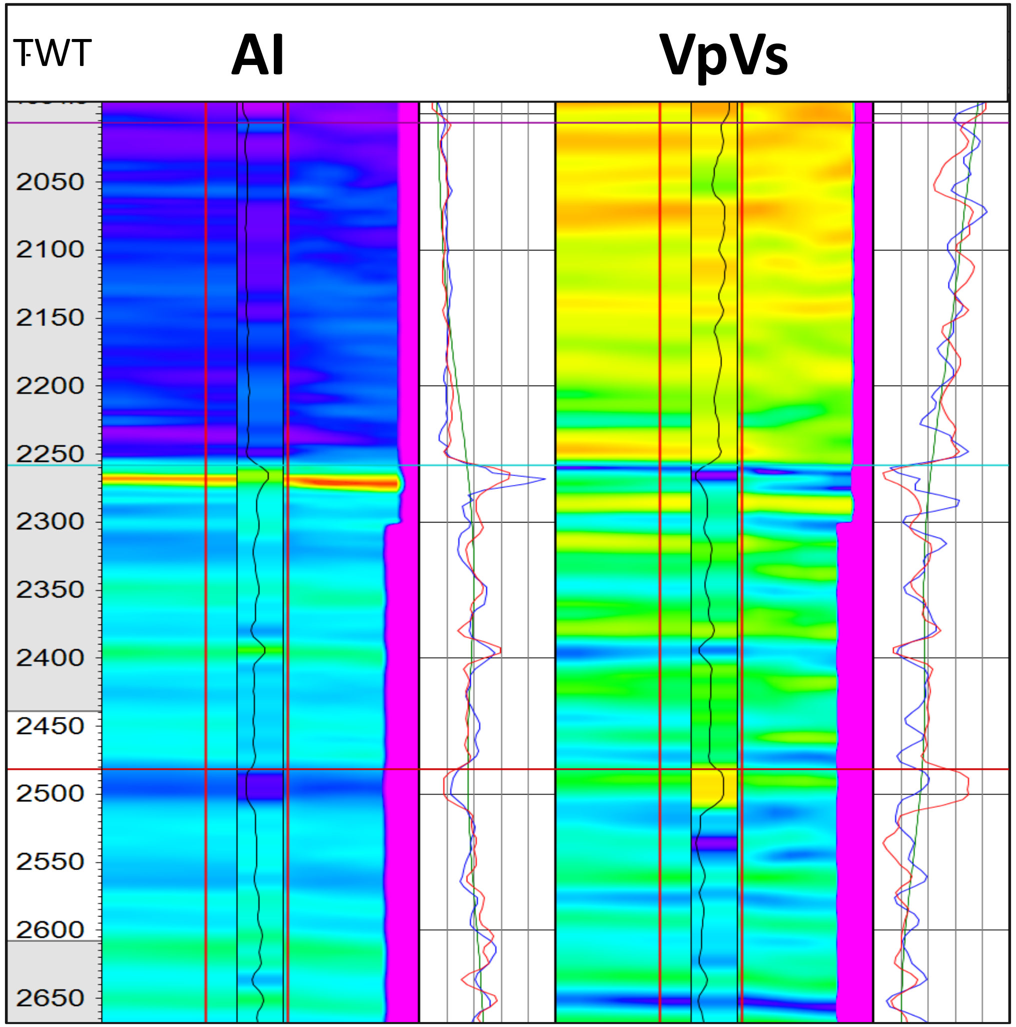


Using Joint Lithology-Elastic Inversion to Enhance Earth Model Building Workflows

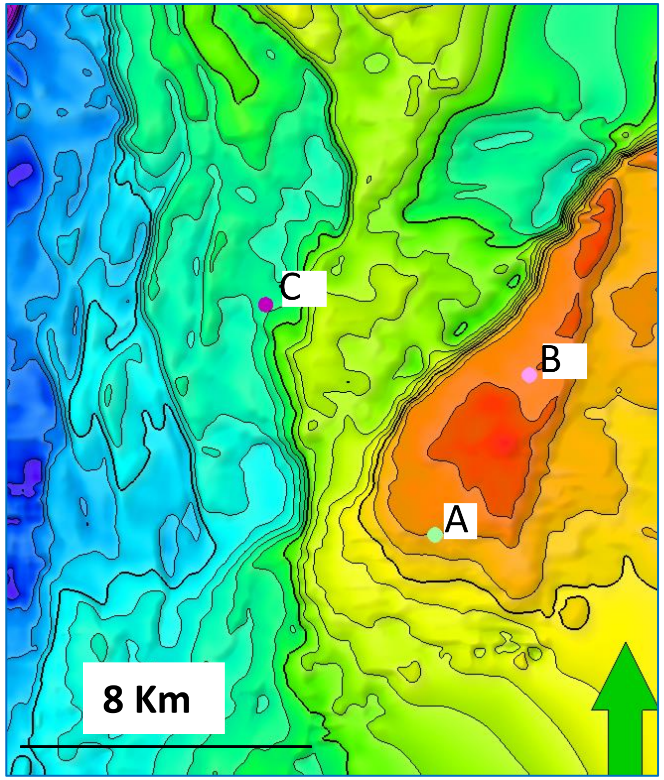
Barling, T., Bachrach, R., Leone, C., Chen, S. - 2nd EAGE/PESGB Workshop on Velocities, London 2019



Well response (0-55Hz)
Inversion Result
Well response (0-3Hz)
AI
14000
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
VpVs
2.7
2.6
2.5
2.4
2.3
2.2
2.1
2.0
1.9
1.8
1.7

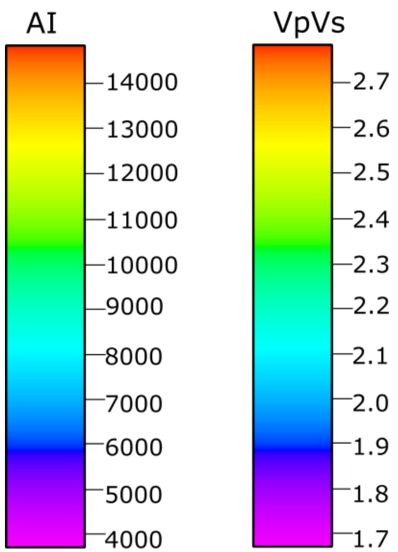


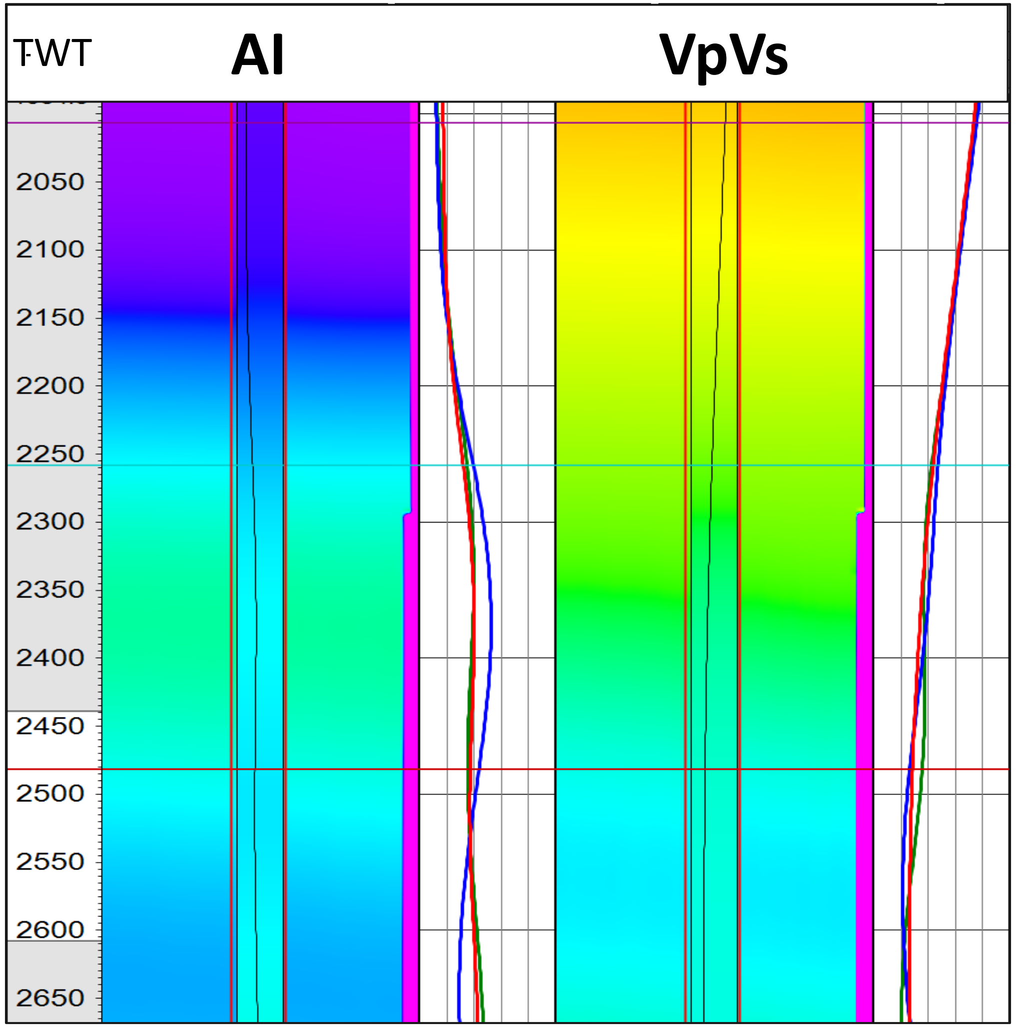
TWT
AI
VpVs
2050
2100
2150
2200
2250
2300
2350
2400
2450
2500
2550
2600
2650

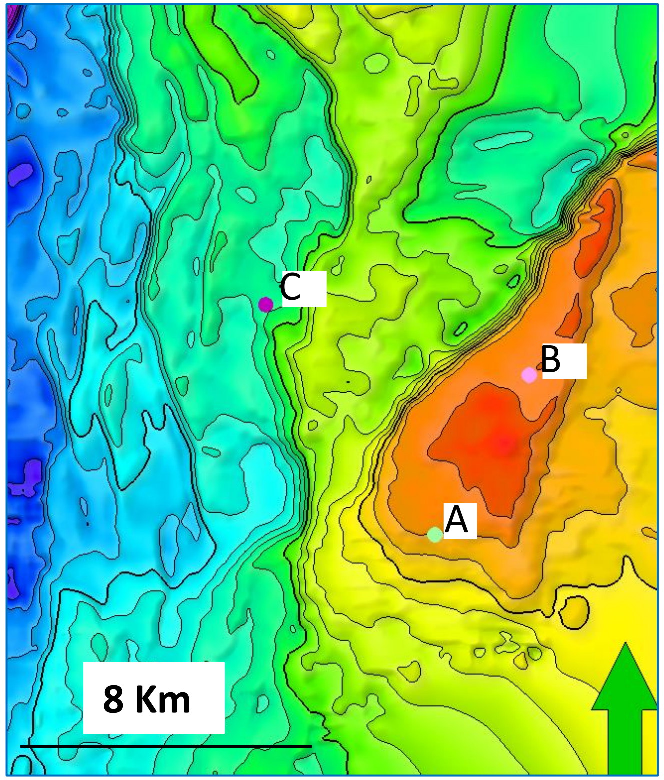


C
B
A
8 Km

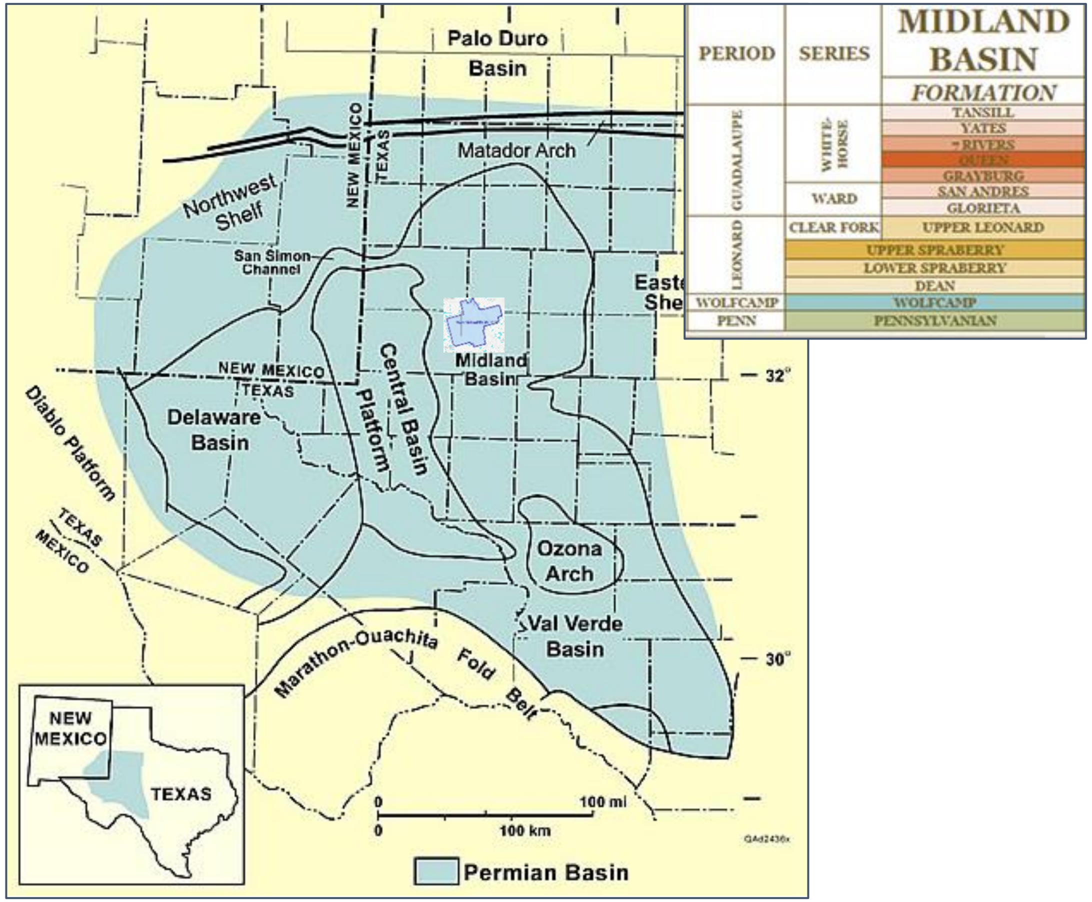
Well response (0-55Hz)
Inversion Result
Well response (0-3Hz)

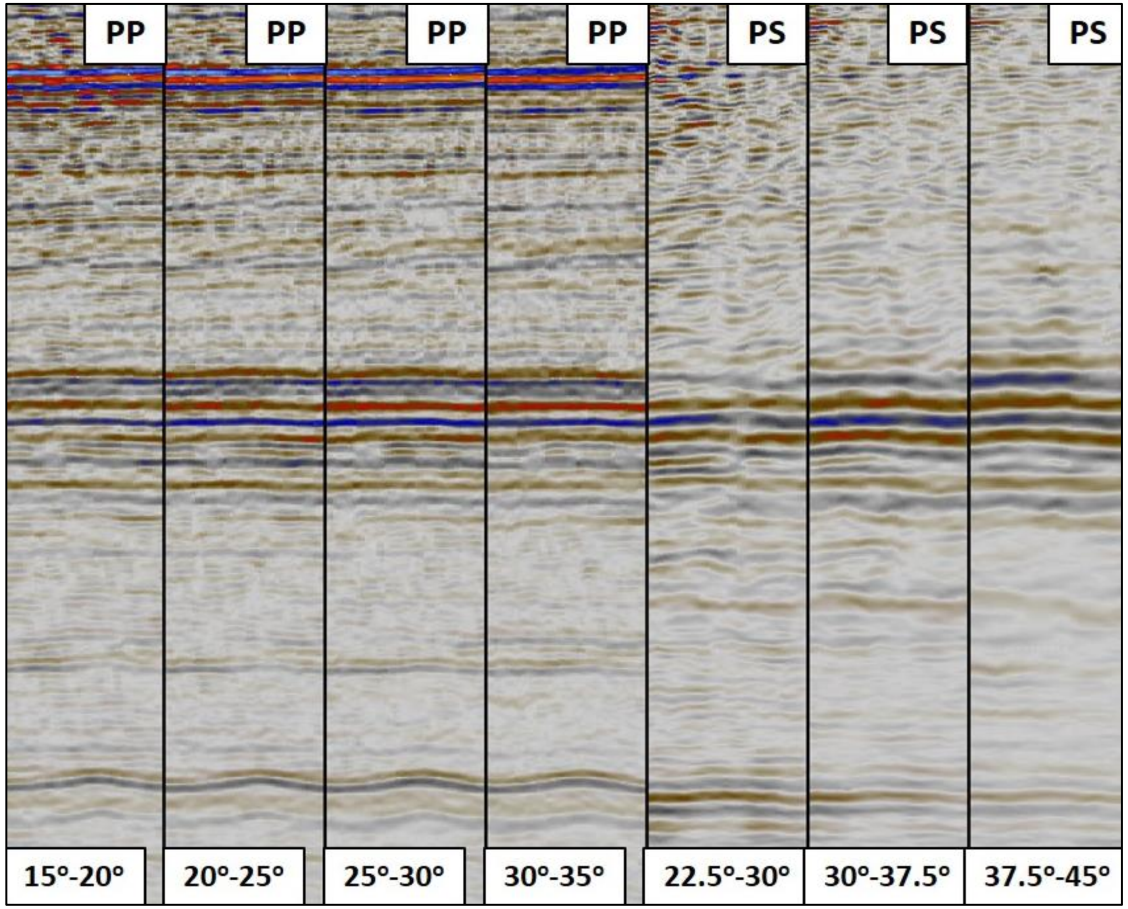






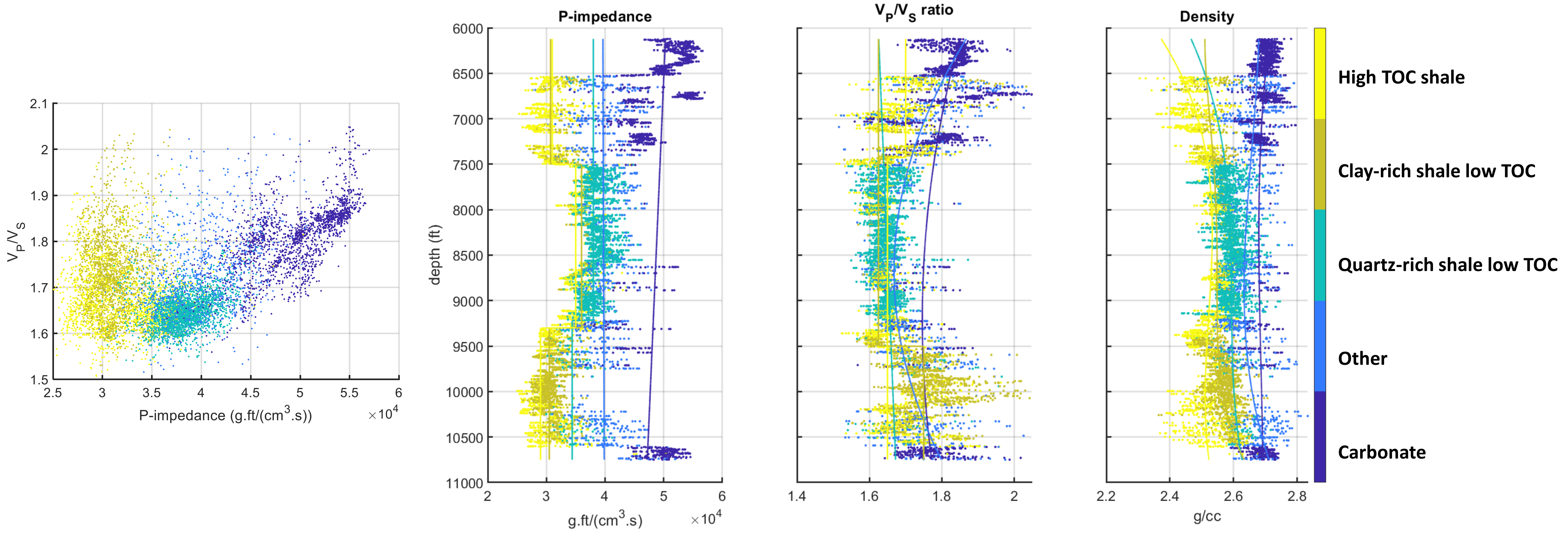
LPE result filtered to 3Hz
LFM extrapolated from wells A and B (0-3Hz)
Well response (0-3Hz)



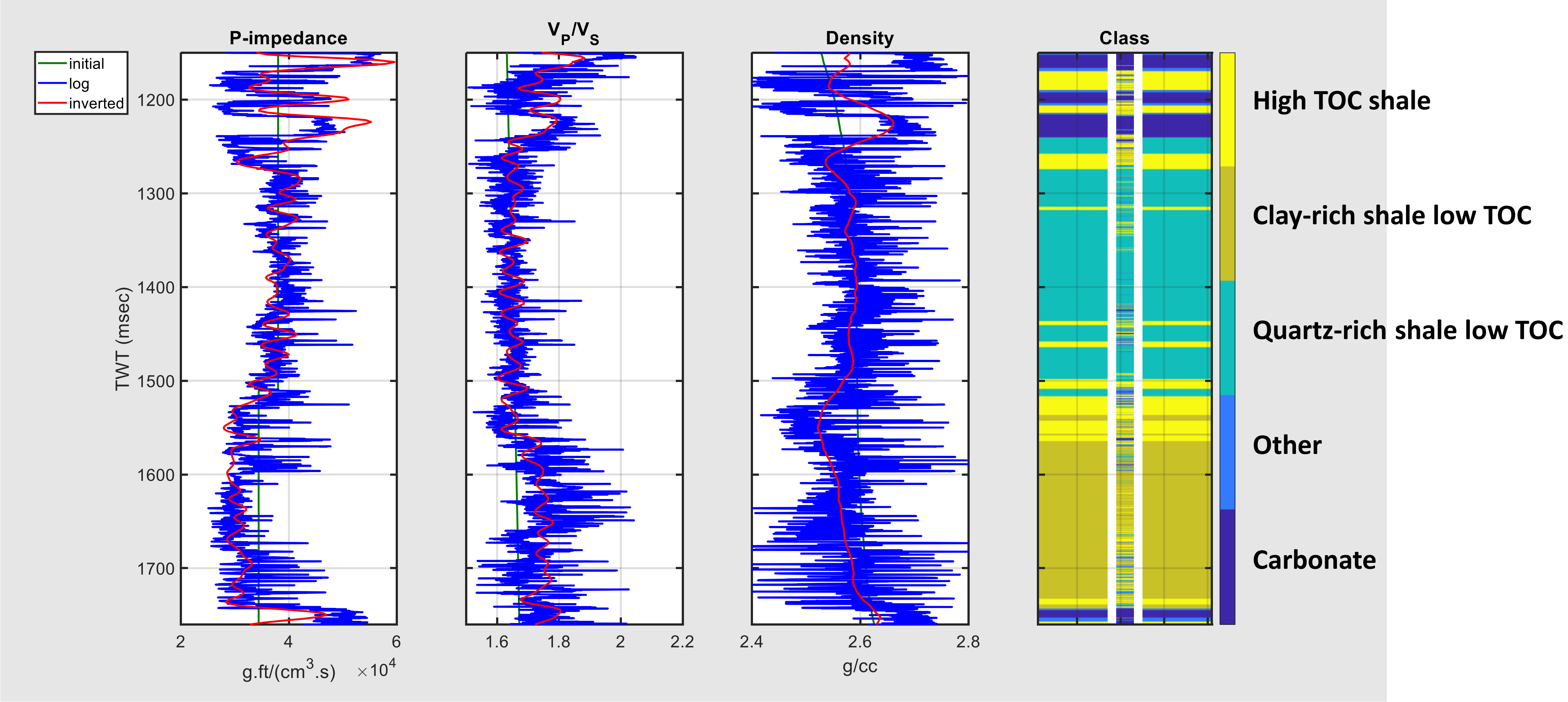


- 3D-3C survey, 844 km^{2}; PP is depth migrated; PS is Time migrated
- Ref: Brzostowski et al., 2019; Johns, 2018

E. Gofer, R. Bachrach, S. Re, F. Golfre Andreasi (2019) **Joint PP-PS litho-elastic AVA inversion: Example from Midland Basin**; SEG Annual Conference



E. Gofer, R. Bachrach, S. Re, F. Golfre Andreasi (2019) **Joint PP-PS litho-elastic AVA inversion: Example from Midland Basin**; SEG Annual Conference



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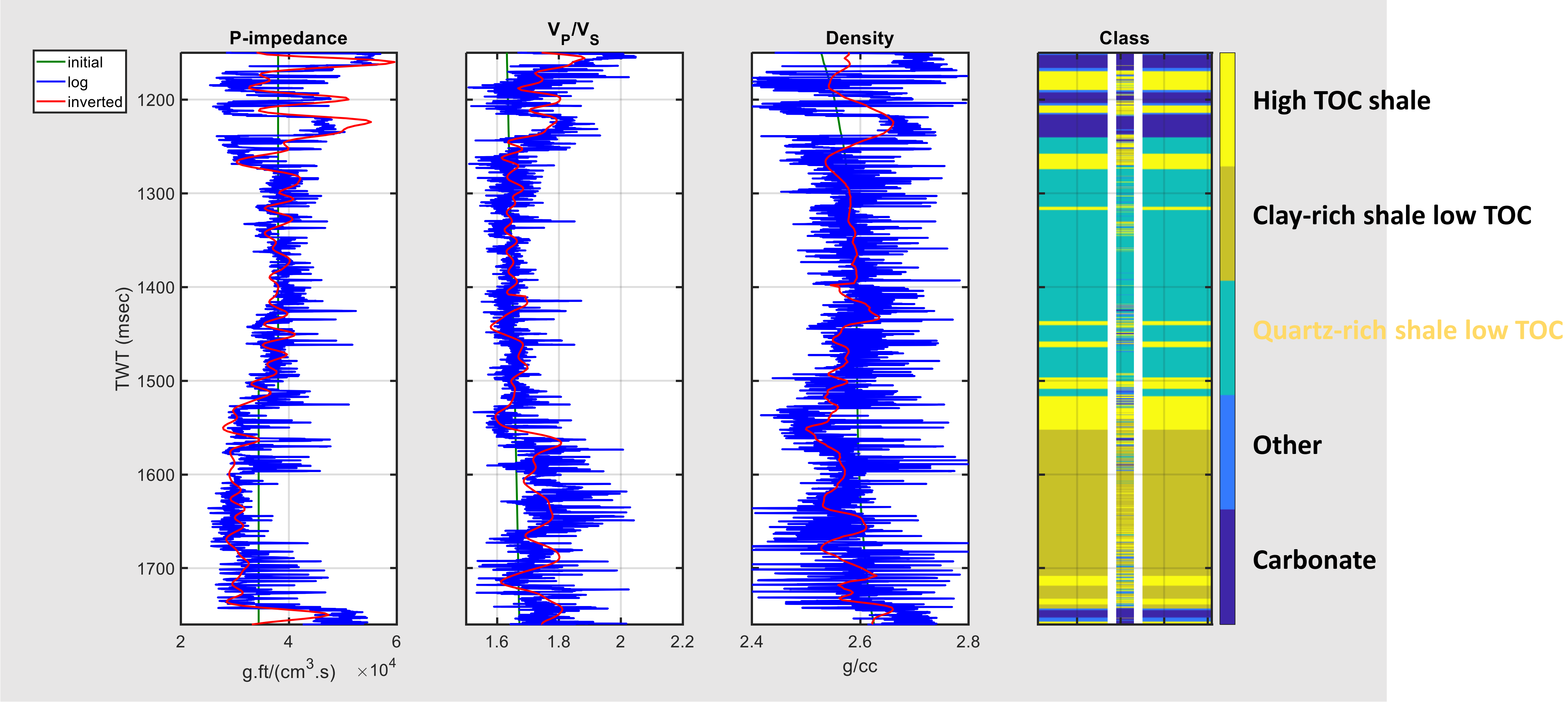
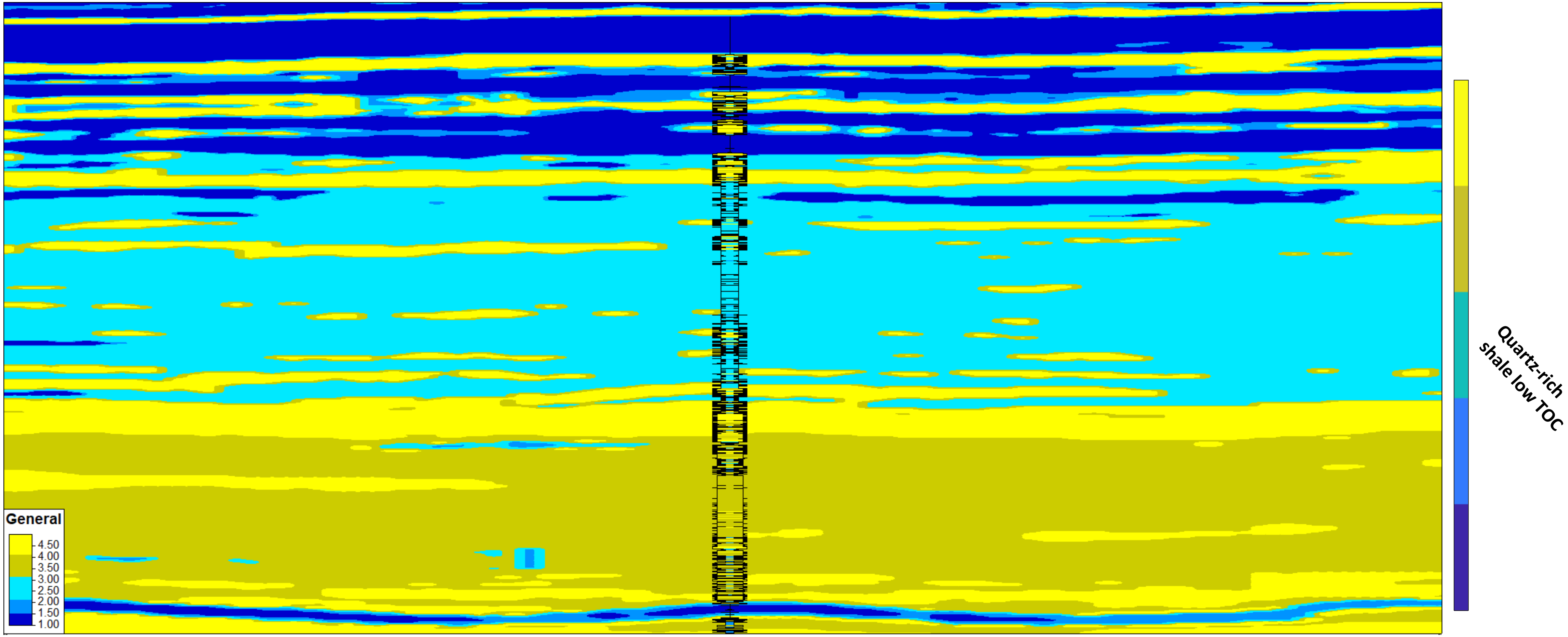


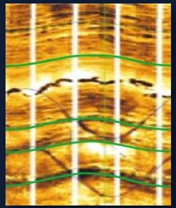
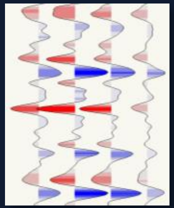
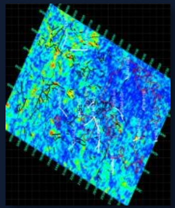
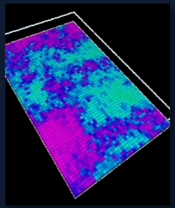
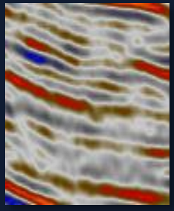
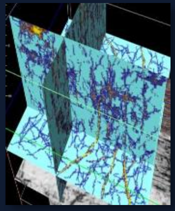
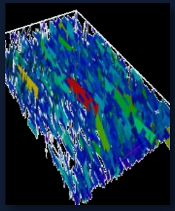
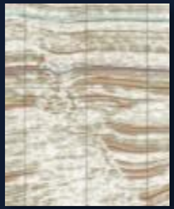
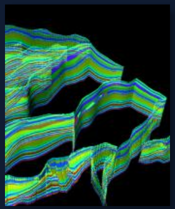
E. Gofer, R. Bachrach, S. Re, F. Golfre Andreasi (2019) **Joint PP-PS litho-elastic AVA inversion: Example from Midland Basin**; SEG Annual Conference



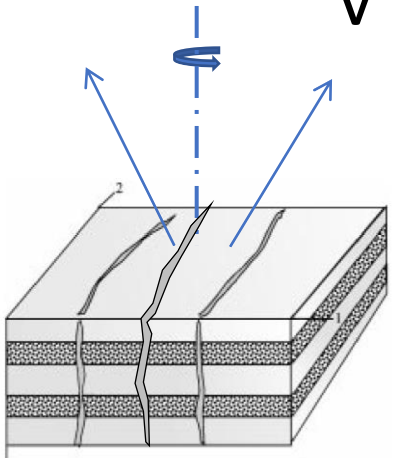
E. Gofer, R. Bachrach, S. Re, F. Golfre Andreasi (2019) **Joint PP-PS litho-elastic AVA inversion: Example from Midland Basin**; SEG Annual Conference

Anisotropic Inversion for fracture estimation

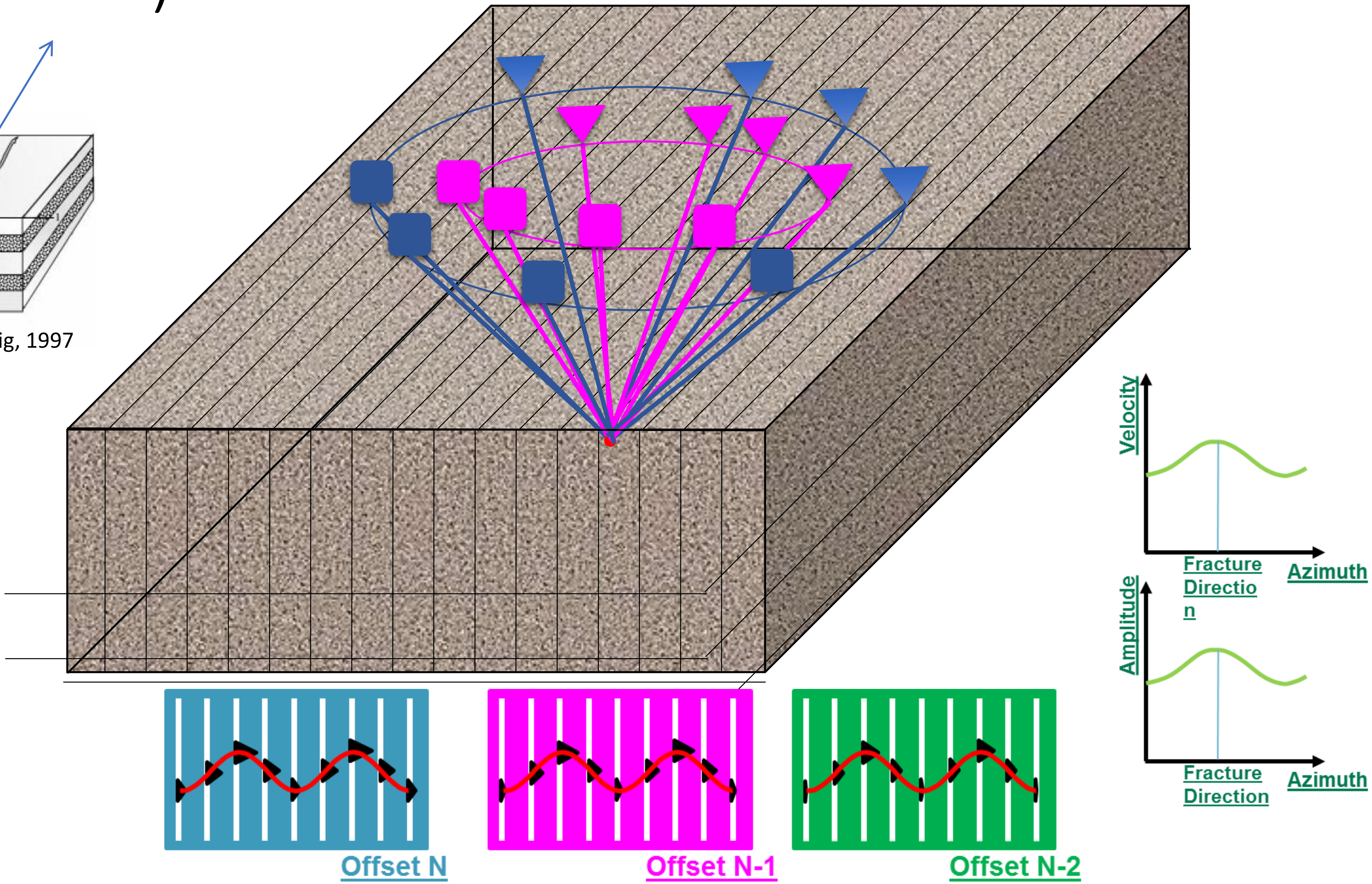
Fracture Characterization: From Seismic to Simulation

	Geological Features	Seismic Observations	Data Analysis	Model Representations
Micro-Scale	 **Diffuse Fractures**	 **Seismic Anisotropy**	 **Anisotropy Analysis & Inversion**	 **Implicit Fracture Model / DFN**
Meso-Scale	 **Fracture Corridors**	 **Subtle Discontinuities & Scattering**	 **Fracture Cluster Mapping**	 **Fracture Patch Sets**
Macro-Scale	 **Faults**	 **Dislocated Horizons**	 **Ant Tracking, Fault Transmissivity**	 **Structural Faults**

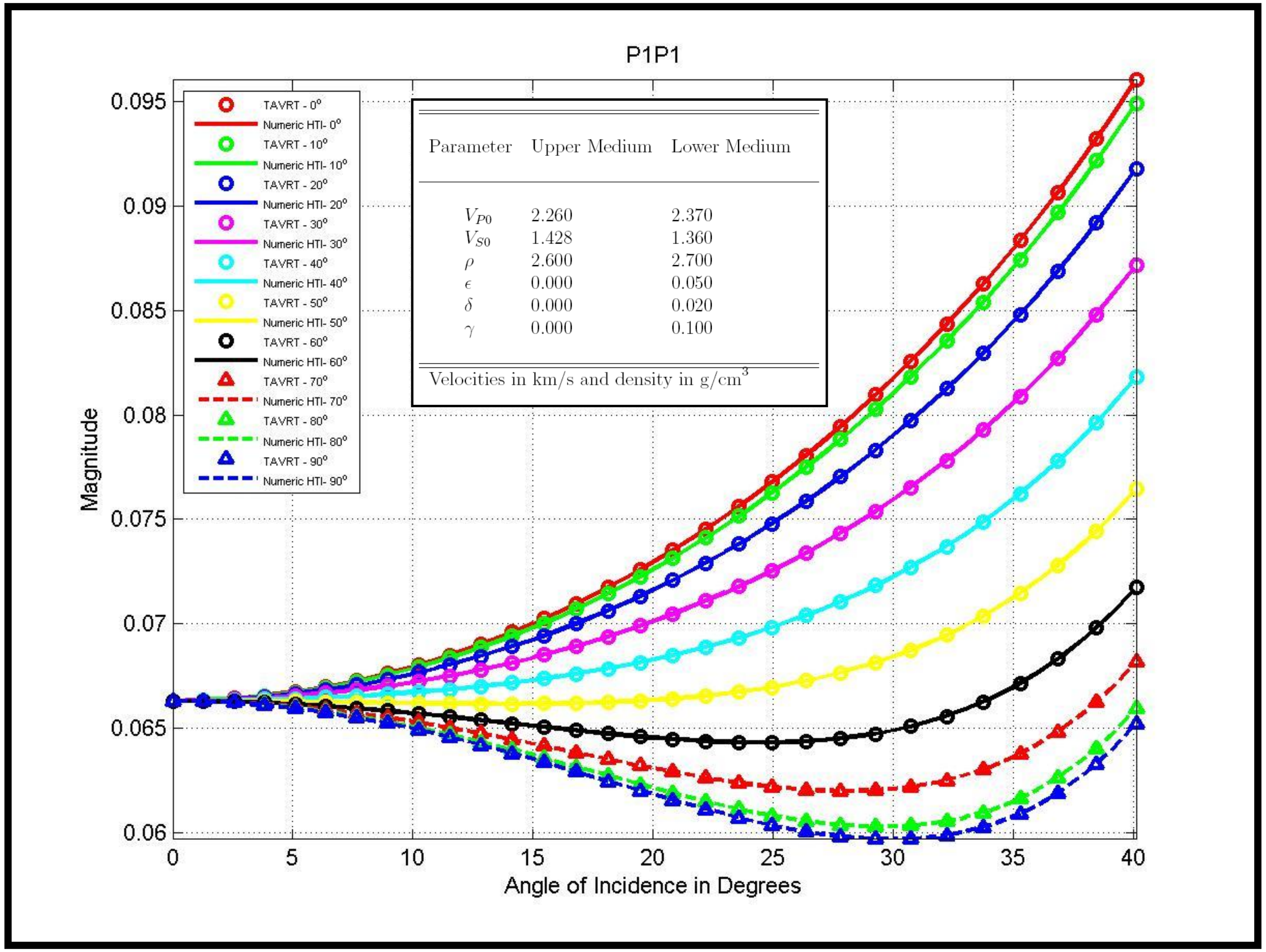
PP Seismic - Anistropic Medium (HTI + VTI)



Schoenberg and Helbig, 1997



PP-Reflection Coefficients in HTI Medium

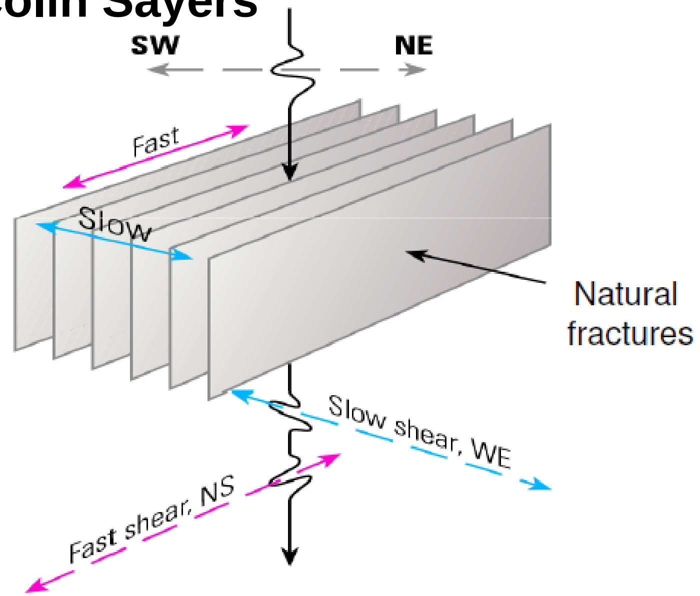


Parameter	Upper Medium	Lower Medium
V_{P0}	2.260	2.370
V_{S0}	1.428	1.360
ρ	2.600	2.700
ϵ	0.000	0.050
δ	0.000	0.020
γ	0.000	0.100

Velocities in km/s and density in g/cm^3

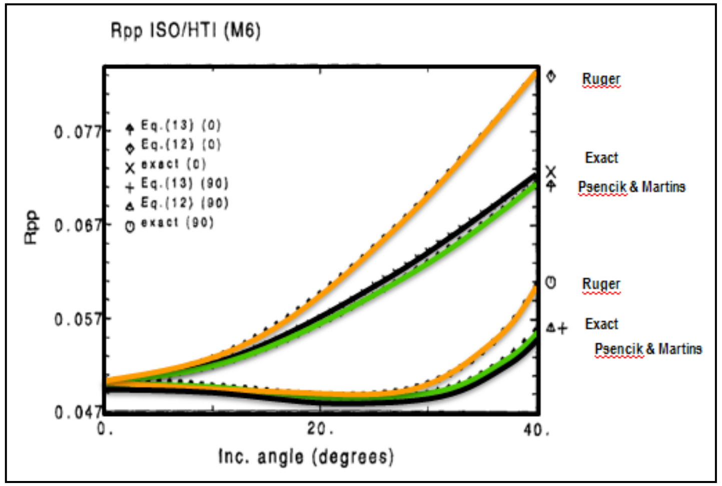
Petrel Simultaneous PP Azimuthal AVO Inversion

Colin Sayers



Theory / Concept

- Stress and fractures combine to provide an azimuthally anisotropic velocities, and AVO response.
- Shear-Wave Splitting in Anisotropic Medium
- Shear wave polarized parallel to fractures is FAST
- Shear wave polarized perpendicular to fractures is SLOW



- Extend Petrel simultaneous AVO inversion to AVOaz for fracture characterization
- Use seismic azimuth dependent effective shear velocity in standard isotropic workflow
- Utilize fast and slow shear from SS/DSI
- Results in "SS/DSI-domain"
- Using the Psencik and Martins (2001) C_{ij} – based rather than Ruger (1997) Thomson parameter-based approximation

$$V_{s,eff} \approx \sqrt{\cos^2(\phi - \phi_{fast})V_{s,fast}^2 + \sin^2(\phi - \phi_{fast})V_{s,slow}^2}$$

Petrel Simultaneous PP Azimuthal AVO Inversion (HTI)

Multiple Azimuths/Sectors of Angle Stacks

Far-angle Seismic (and wavelet)

Mid-angle Seismic (and wavelet)

Near-angle Seismic (and wavelet)...

Prior model

Shear Impedance

Density

Petrel inversion kernel

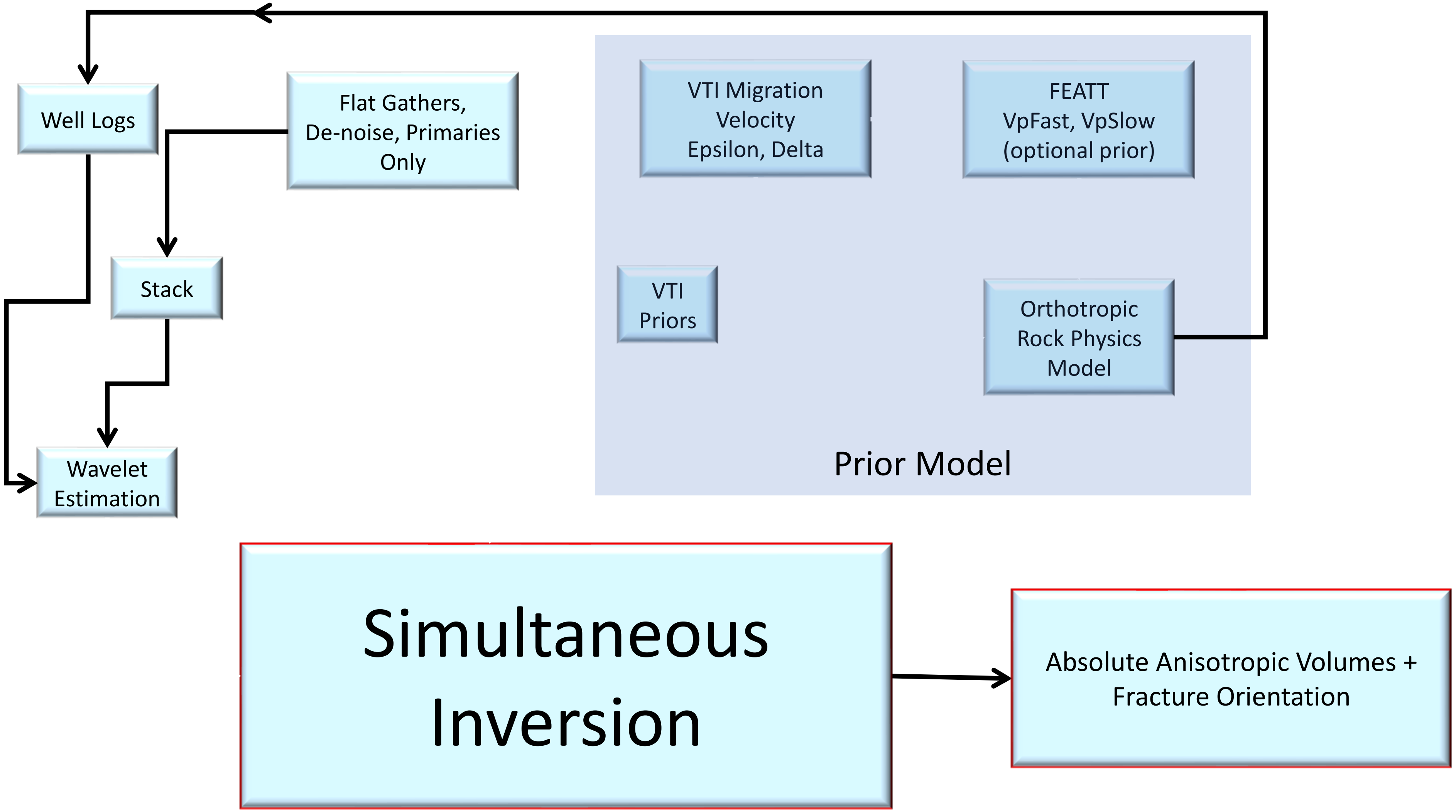
Result AI

Result Shear Impedance

- Fast shear impedance, Poisson's ratio, Lambdarho, Murho
- Slow shear impedance, Poisson's ratio, Lambdarho, Murho
- Slow/fast shear ratio (fracture intensity)
- Fast shear azimuth (fracture orientation)

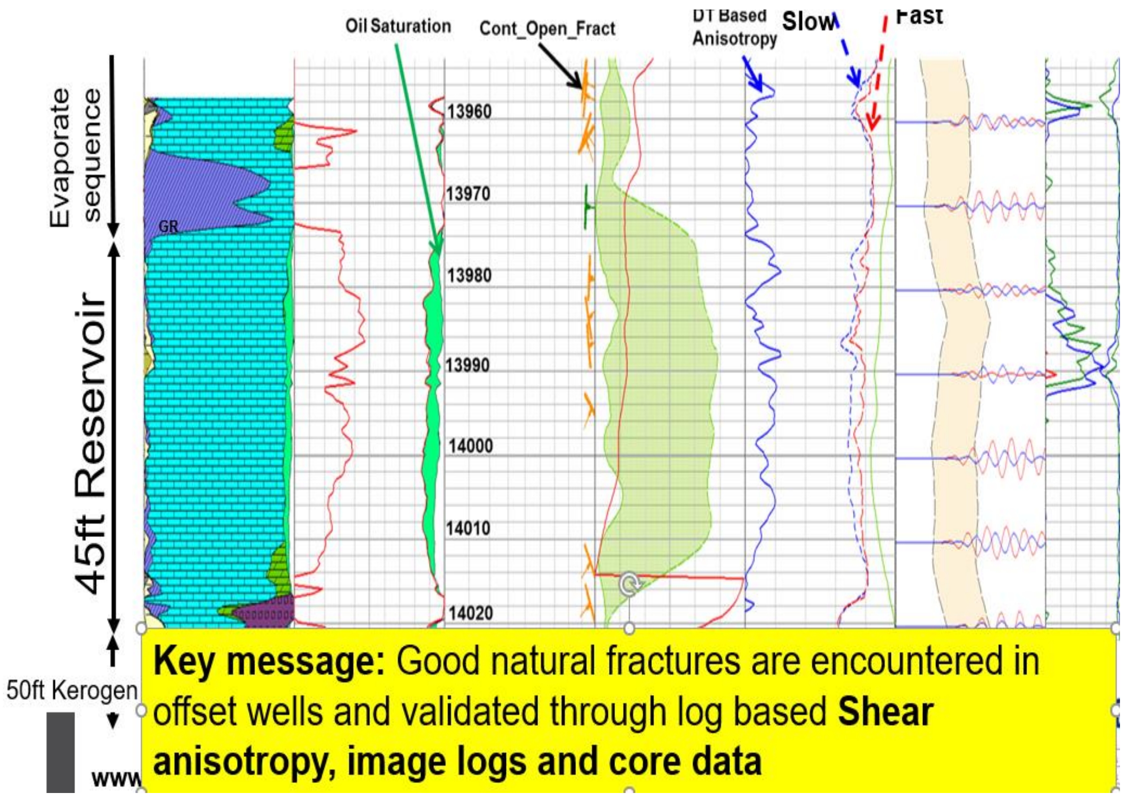
Result Density

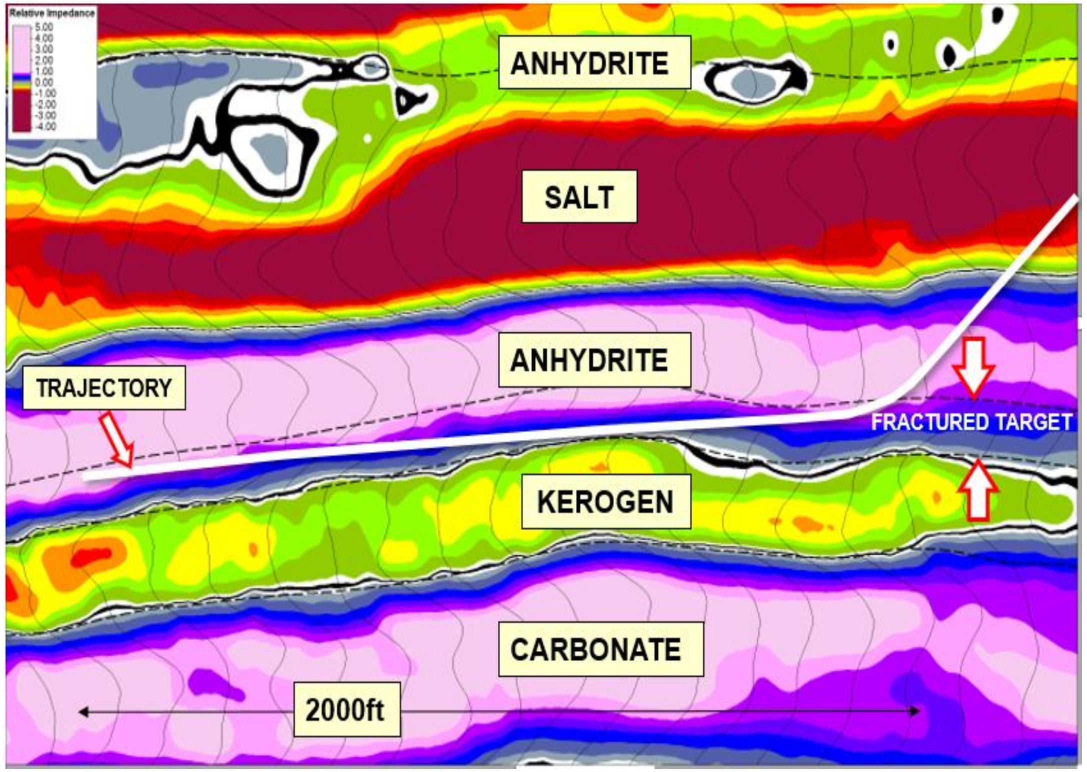
Workflow Orth. SimInv



Bachrach et al (2013) inversion workflow suitable for layered media with vertically aligned fractures

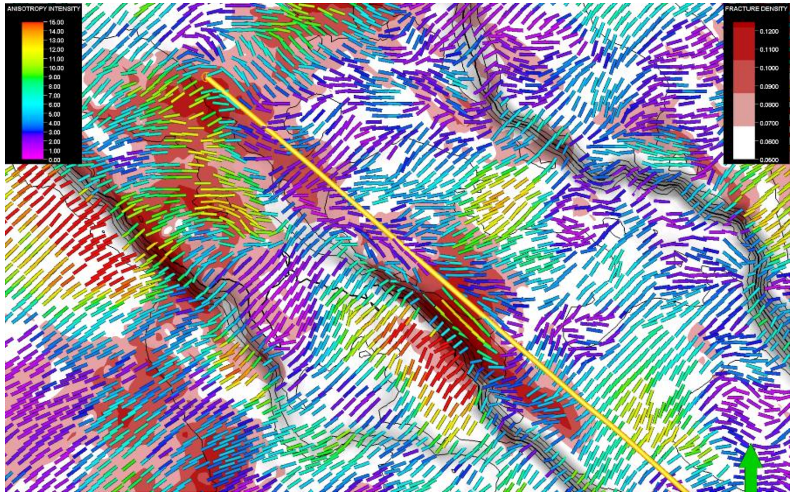
Shear wave anisotropy indicating presence of open fractures: offset well

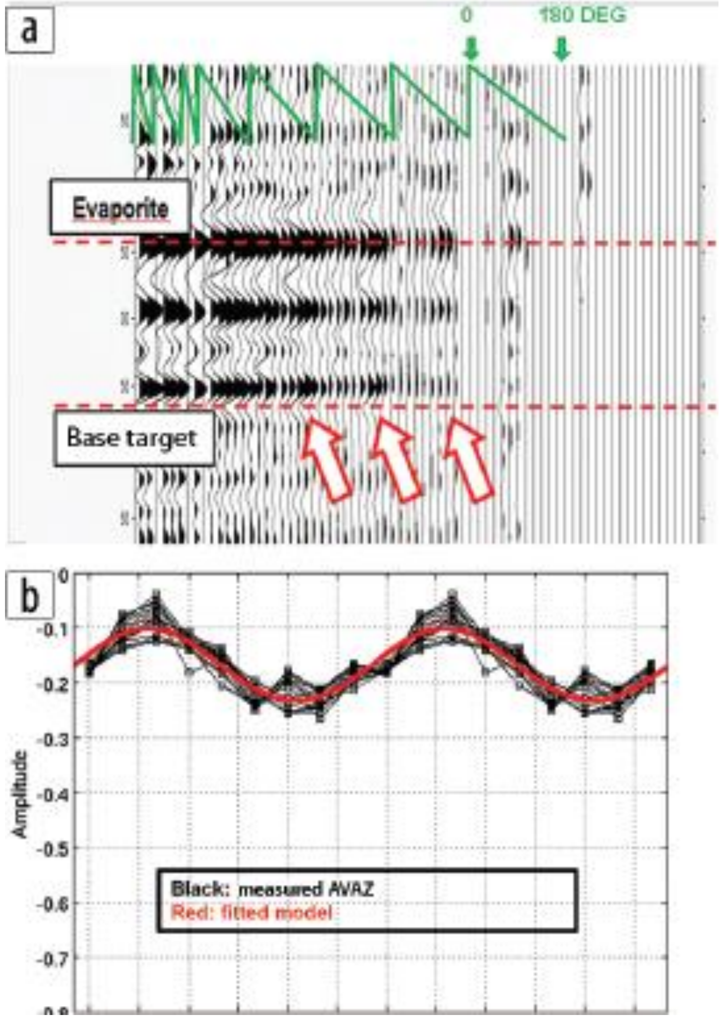


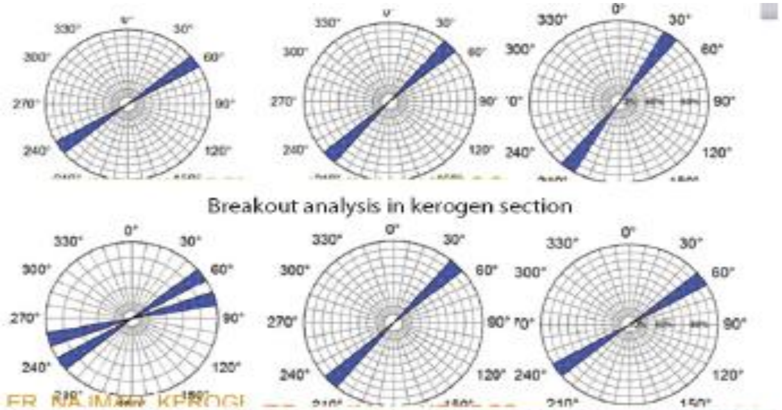


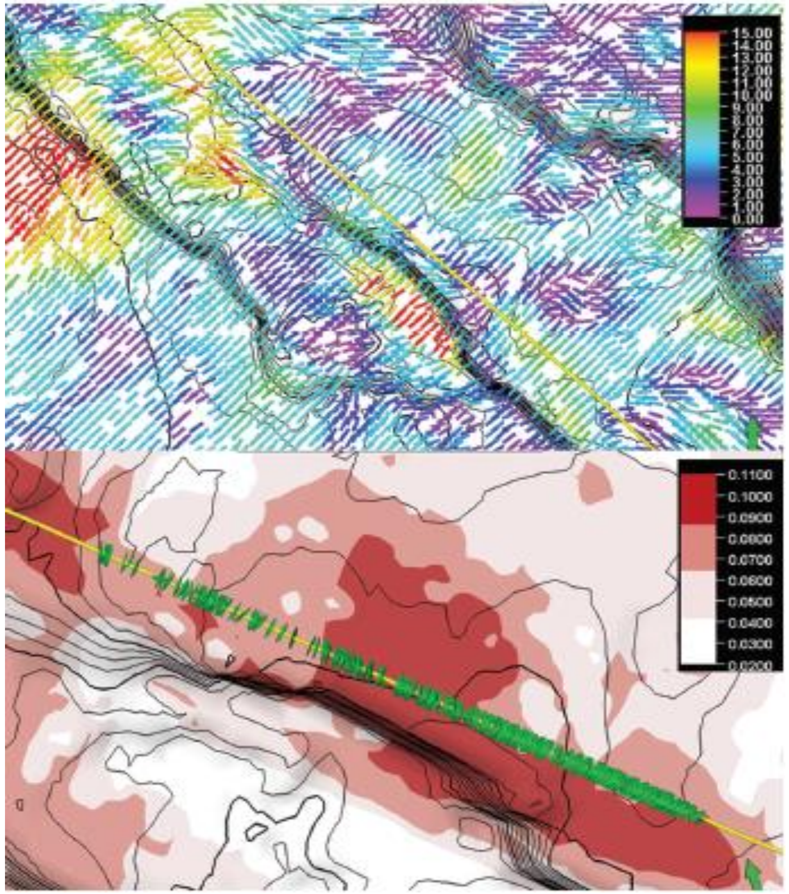
Narhari et al., The Leading Edge, Dec. 2015

Natural Fracture Density
Fracture Orientation with Anis
Contrast





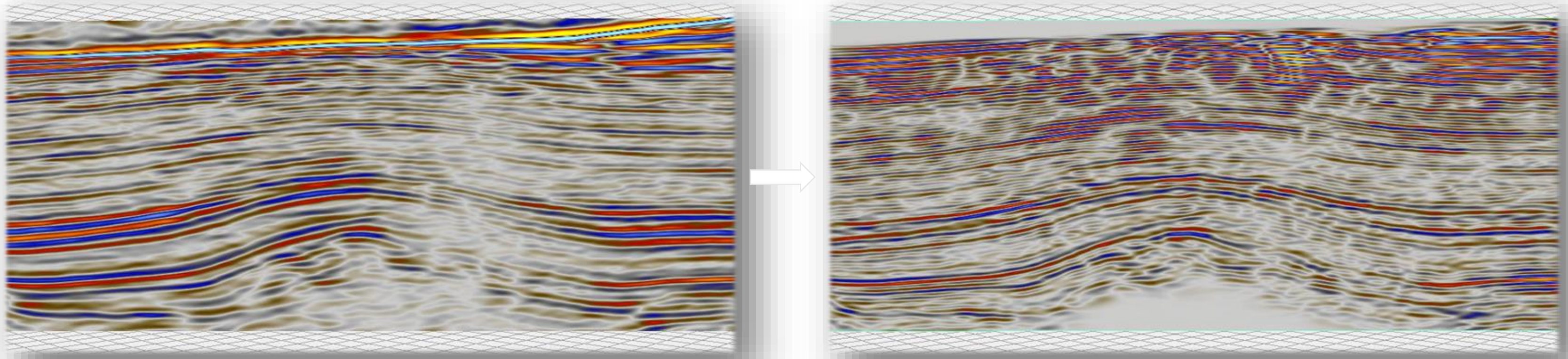




Depth Domain Inversion

Introduction

- ❑ Finite acquisition geometries and overburden complexity cause variable illumination effects in the depth-migrated images and gathers
  - ✓ negative impact on both qualitative (structural) and quantitative interpretation



- ❑ DDI can help mitigate the imprint of variable illumination

Deriving earth properties through image-domain LSM

- ❑ Image-domain LSM:

$$I = H\,r \quad \textit{with} \quad H = M_{mig} M_{mod}$$

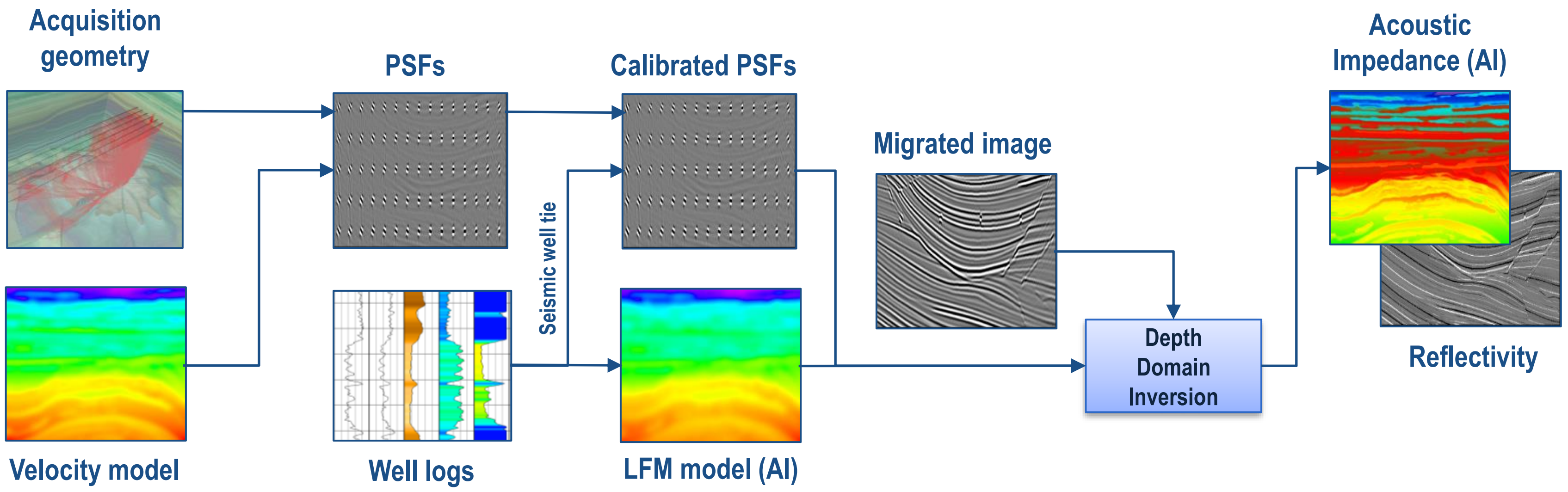
- ❑ Depth-domain inversion (Fletcher et al, 2012):

$$I = \ H R(m)$$

  - ✓ *R* : reflectivity operator (prestack, poststack, linear, non-linear..)
  - ✓ *m* : earth properties (acoustic impedance, Vp/Vs, density)

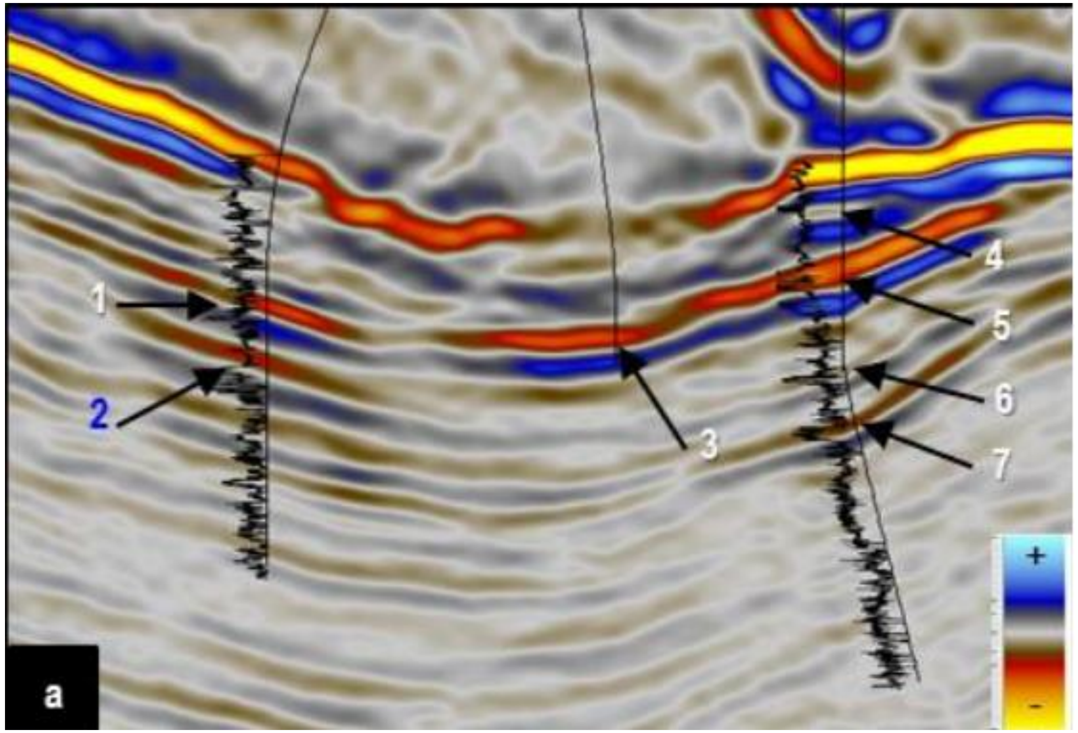
- ❑ Iterative deconvolution (with constraints)

General workflow (poststack)



Example 1 | Mississippi Canyon, Gulf of Mexico

RTM image

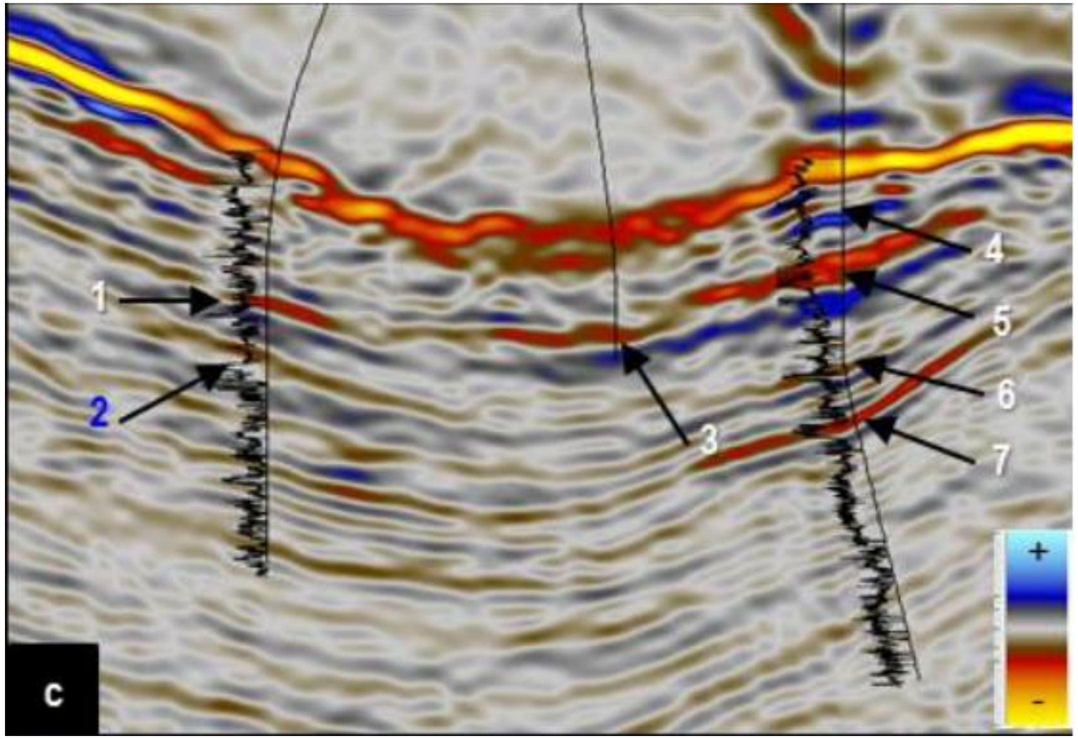


- ✓ Thin sands located just below salt structure
- ✓ Arrows denote hydrocarbon sands except #2 (brine sands)

REF: *Leon, L., Inyang, C., Hegazy, M., Hydal, S., Hargrove, K., Pasch, K. and Hollins, J. 2018. Least-squares migration in the image domain and depth-domain inversion: A Gulf of Mexico case study. 88th Annual International Meeting,SEG, Expanded Abstracts.*

Example 1 | inverted reflectivity

LSMi with calibration

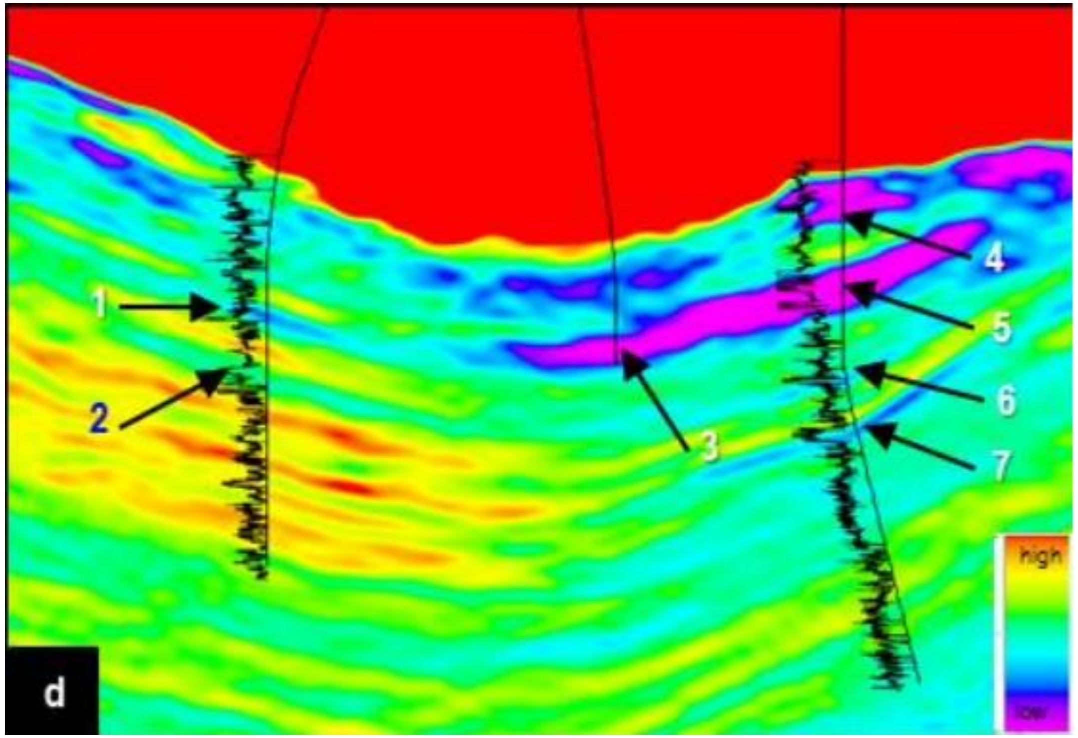


- ✓ much-enhanced amplitude balancing
- ✓ higher resolution

REF: *Leon, L., Inyang, C., Hegazy, M., Hydal, S., Hargrove, K., Pasch, K. and Hollins, J. 2018. Least-squares migration in the image domain and depth-domain inversion: A Gulf of Mexico case study. 88th Annual International Meeting,SEG, Expanded Abstracts.*

Example 1 | acoustic impedance

Depth Domain Inversion



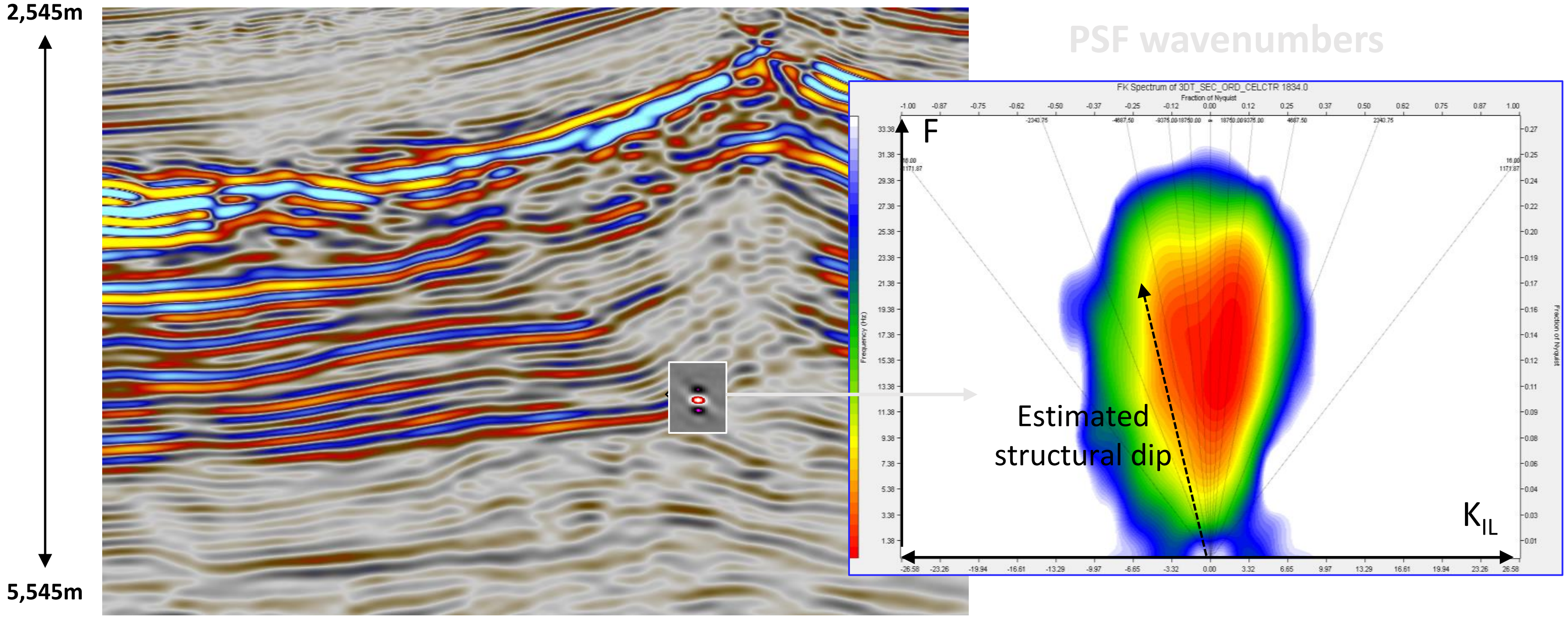
✓ acoustic impedance at brine sands (#2) much more reliable!

REF: *Leon, L., Inyang, C., Hegazy, M., Hydal, S., Hargrove, K., Pasch, K. and Hollins, J. 2018. Least-squares migration in the image domain and depth-domain inversion: A Gulf of Mexico case study. 88th Annual International Meeting,SEG, Expanded Abstracts.*

Example 2 | Brazil Santos Basin

RTM image

PSF wavenumbers

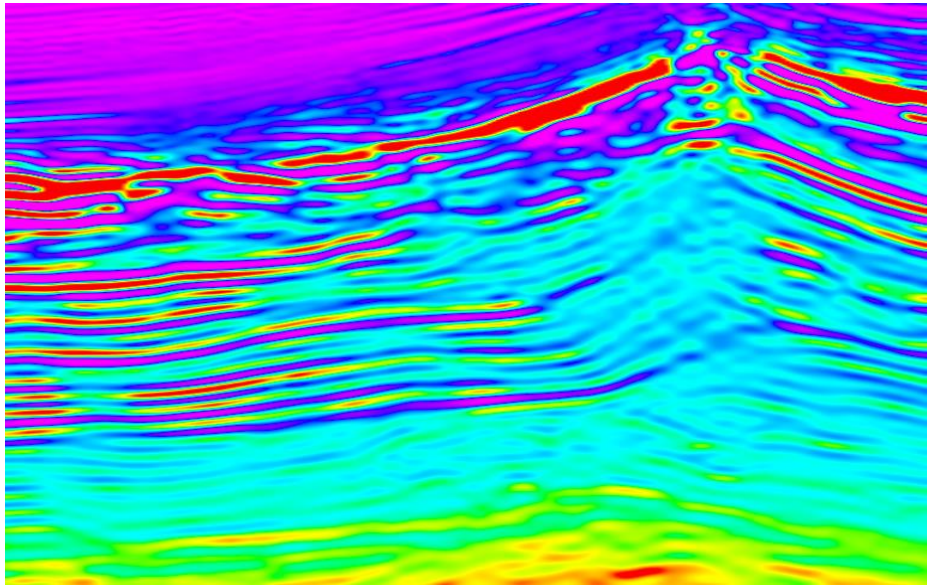


- ✓ Thick and layered salt body
- ✓ Significant dip-dependent illumination variations

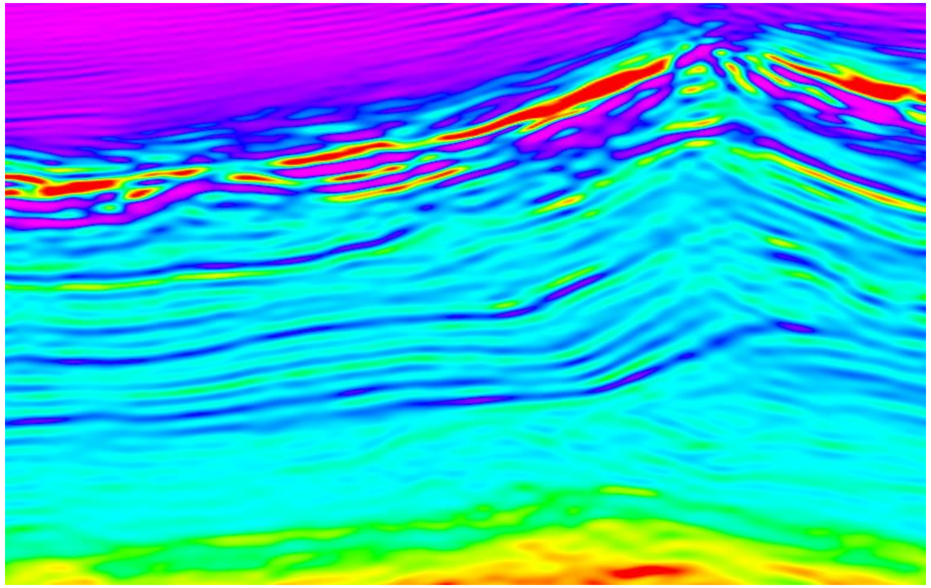
REF: *Letki, L., Darke, K., and Araujo Borges, Y. 2015b. A comparison between time domain and depth domain inversion to acoustic impedance. 85th Annual International Meeting, SEG, Expanded Abstracts.*

Example 2 | acoustic impedance

CONVENTIONAL TIME-DOMAIN INVERSION



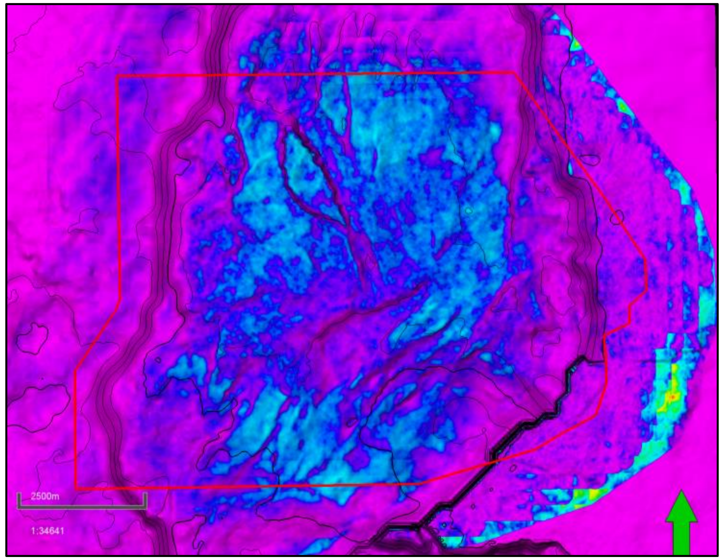
DEPTH-DOMAIN INVERSION



✓ 3D PSFs capturing space and dip-dependent illumination effects, leading to more continuous and reliable acoustic impedance

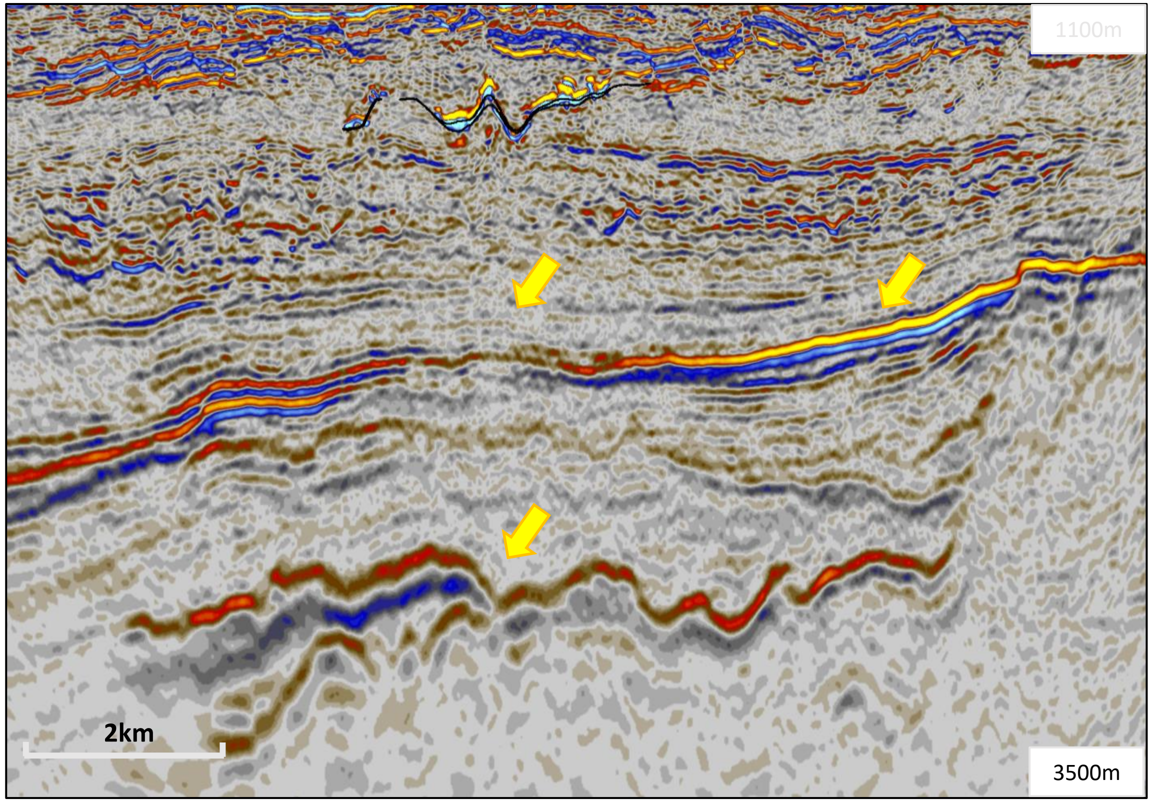
REF: *Letki, L., Darke, K., and Araujo Borges, Y. 2015b. A comparison between time domain and depth domain inversion to acoustic impedance. 85th Annual International Meeting, SEG, Expanded Abstracts.*

Example 3 | Ivar Aasen Field, North Sea



RMS amplitude map

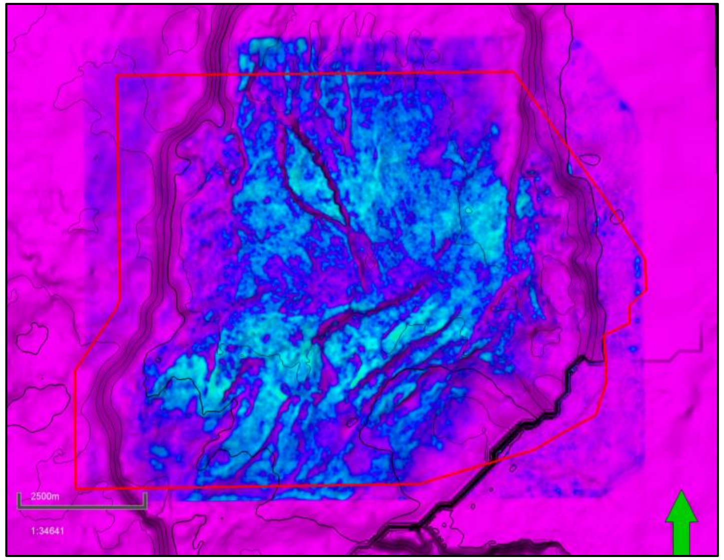
Kirchhoff image



✓ Sand injectites creating strong illumination imprint on the reservoirs underneath

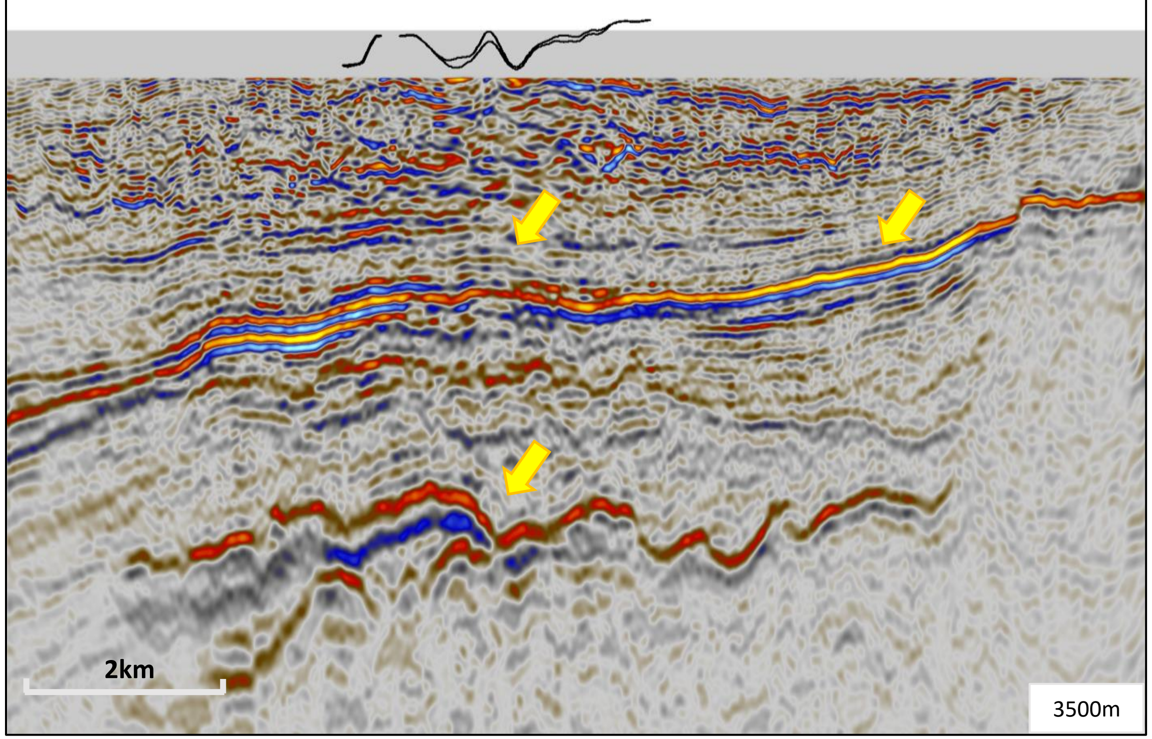
REF: *Leone, C., Osen, A., Cavalca, M., Fletcher, R.P. and Ferriday, M. 2018a. Improving Quantitative Interpretation beneath Sand Injectites: A North Sea Case Study. 80th EAGE Conference & Exhibition, Extended Abstracts*

Example 3 | inverted reflectivity (poststack)



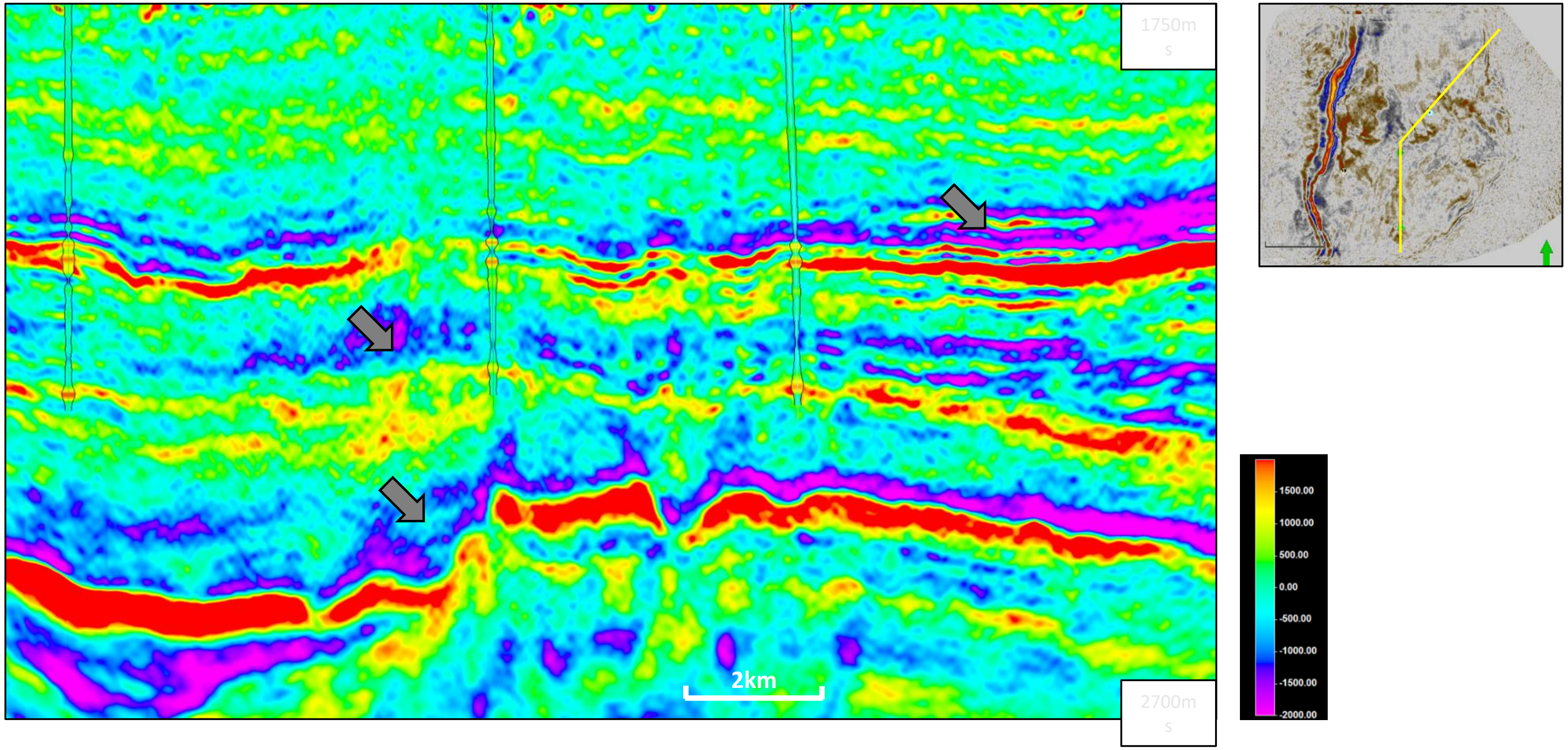
RMS amplitude map

Depth-domain inversion



REF: *Leone, C., Osen, A., Cavalca, M., Fletcher, R.P. and Ferriday, M. 2018a. Improving Quantitative Interpretation beneath Sand Injectites: A North Sea Case Study. 80th EAGE Conference & Exhibition, Extended Abstracts*

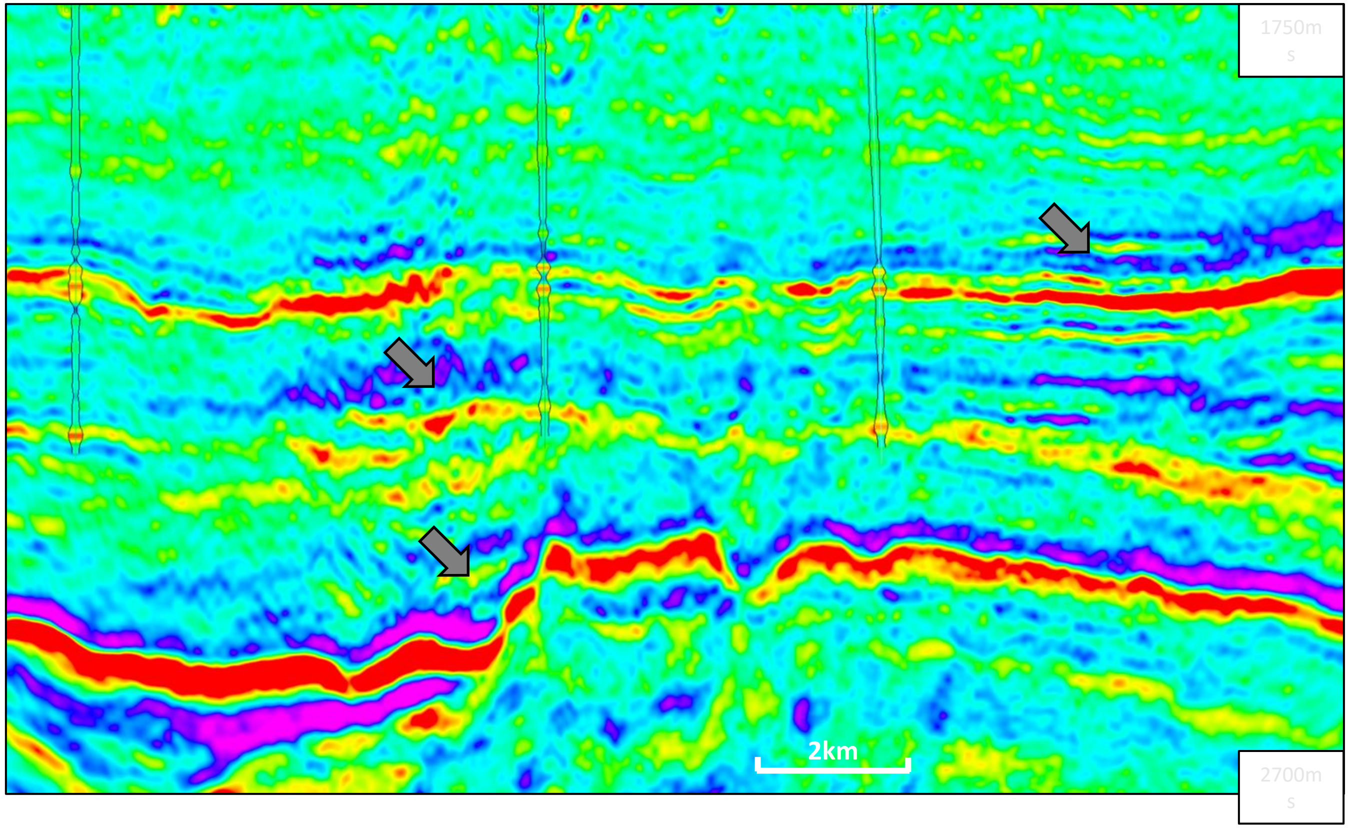
Example 3 | Relative AI: time-domain inversion

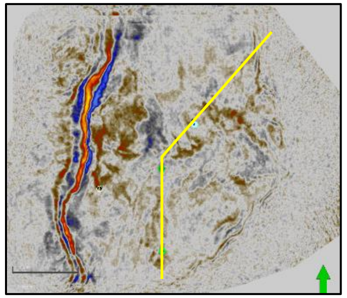


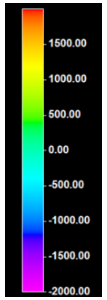
REF: *Leone, C., Osen, A., Cavalca, M., Fletcher, R.P. and Ferriday, M. 2018a. Improving Quantitative Interpretation beneath Sand Injectites: A North Sea Case Study. 80th EAGE Conference & Exhibition, Extended Abstracts*

WesternGeco

Example 3 | Relative AI: DDI





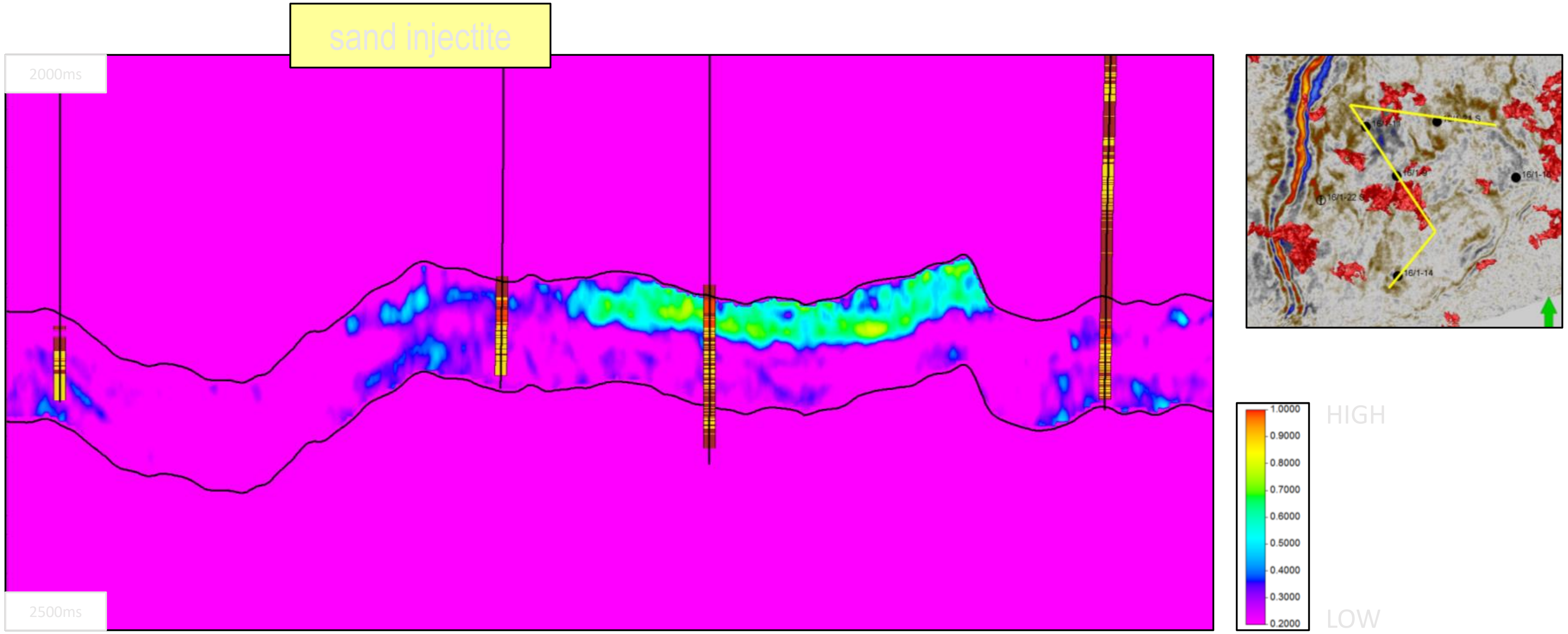


REF: *Leone, C., Osen, A., Cavalca, M., Fletcher, R.P. and Ferriday, M. 2018a. Improving Quantitative Interpretation beneath Sand Injectites: A North Sea Case Study. 80th EAGE Conference & Exhibition, Extended Abstracts*

WesternGeco

Example 3 | hydrocarbon sand probability

Conventional prestack time-domain inversion



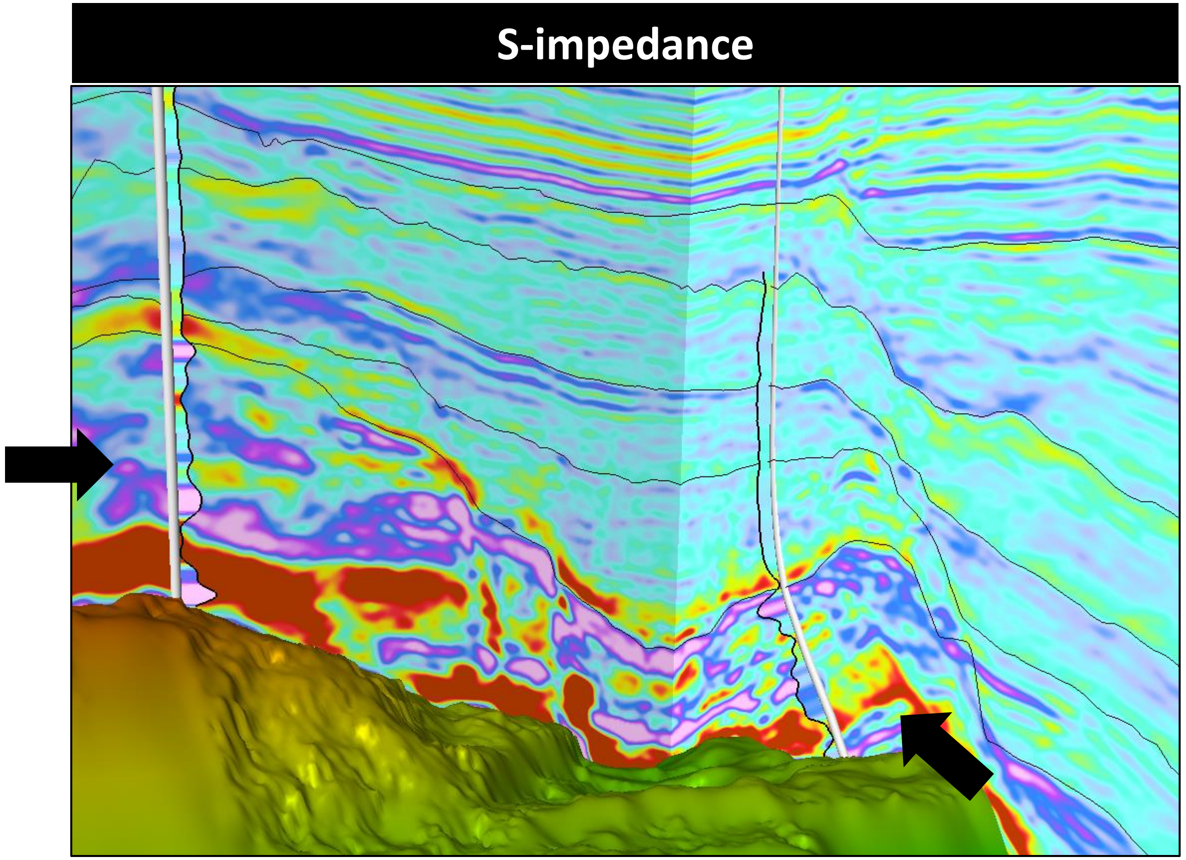
REF: *Leone, C., Osen, A., Cavalca, M., Fletcher, R.P. and Ferriday, M. 2018a. Improving Quantitative Interpretation beneath Sand Injectites: A North Sea Case Study. 80th EAGE Conference & Exhibition, Extended Abstracts*

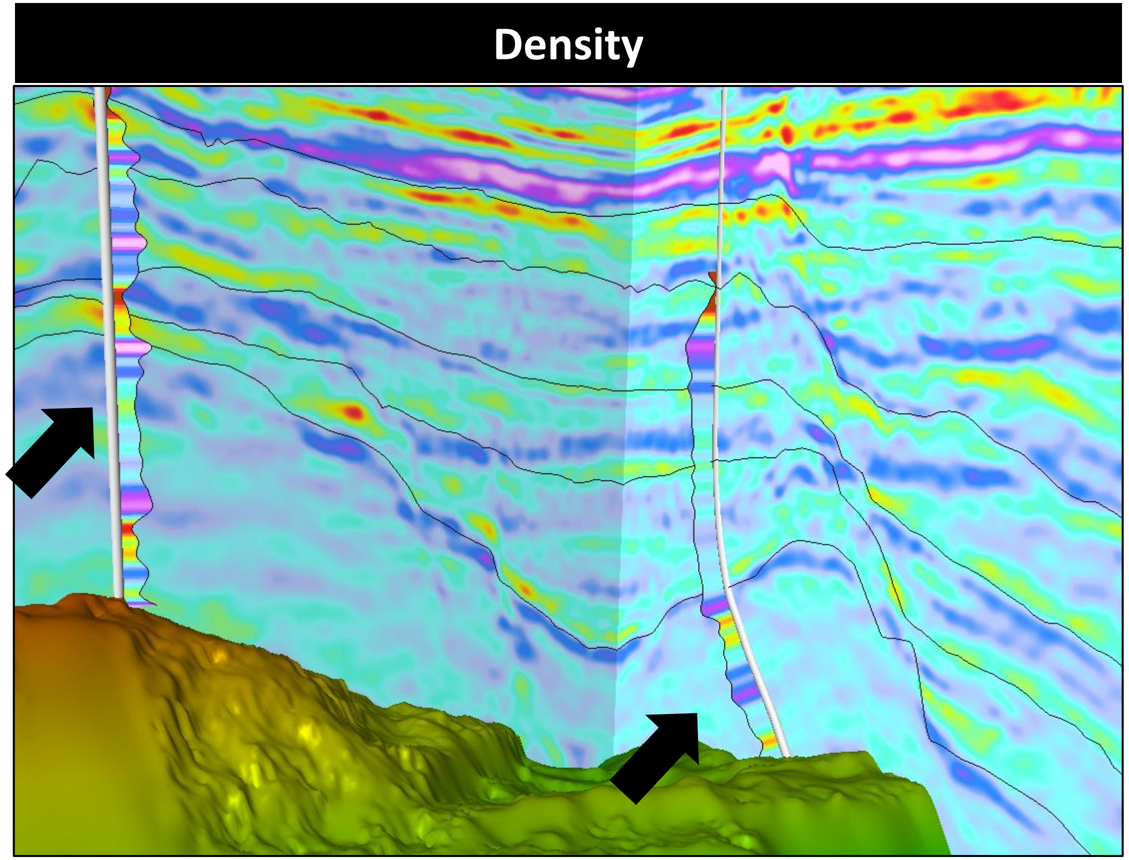
Multi-component Seismic Inversion

Outline

- **PP-PS inversion | Key updates**
- Non-Linear inversion
- Litho-elastic
  - Sequential filtering
  - Anisotropy
- Iterative PP-PS event matching

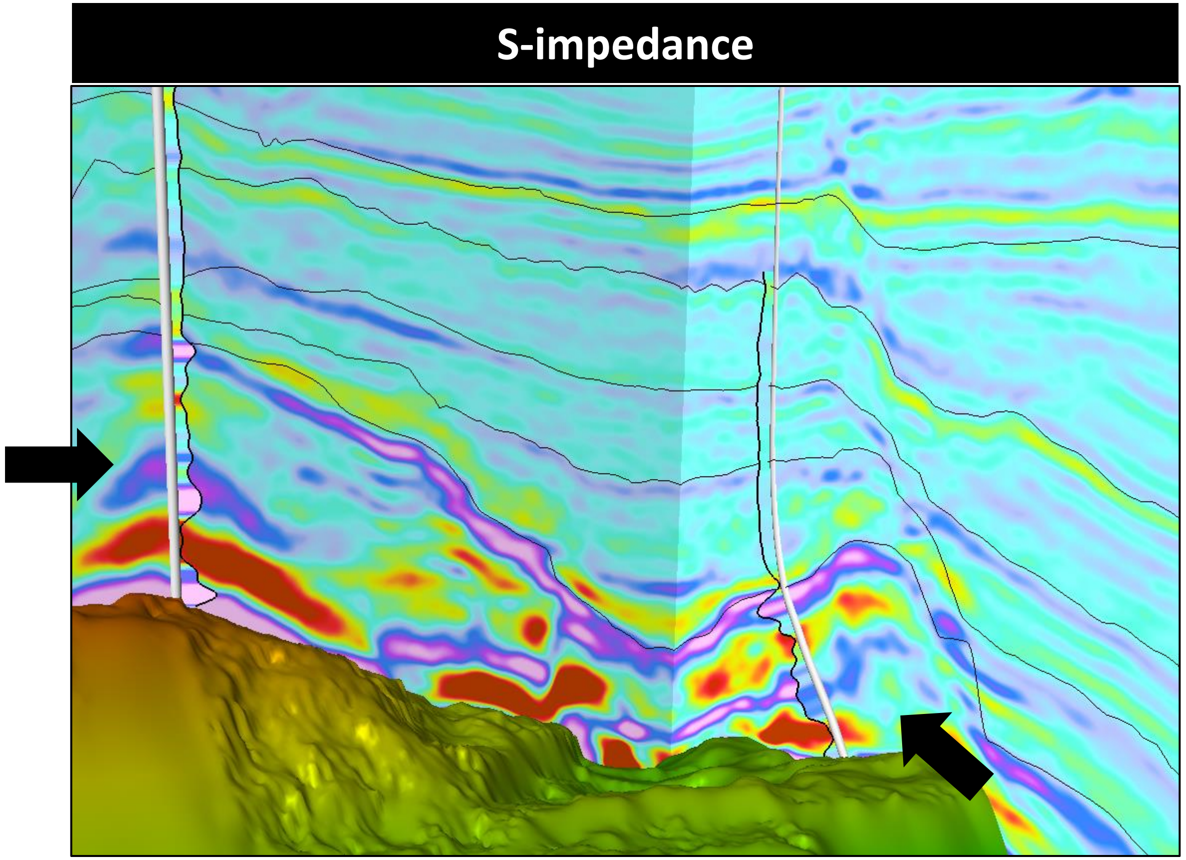
Case study | PP AVO Inversion

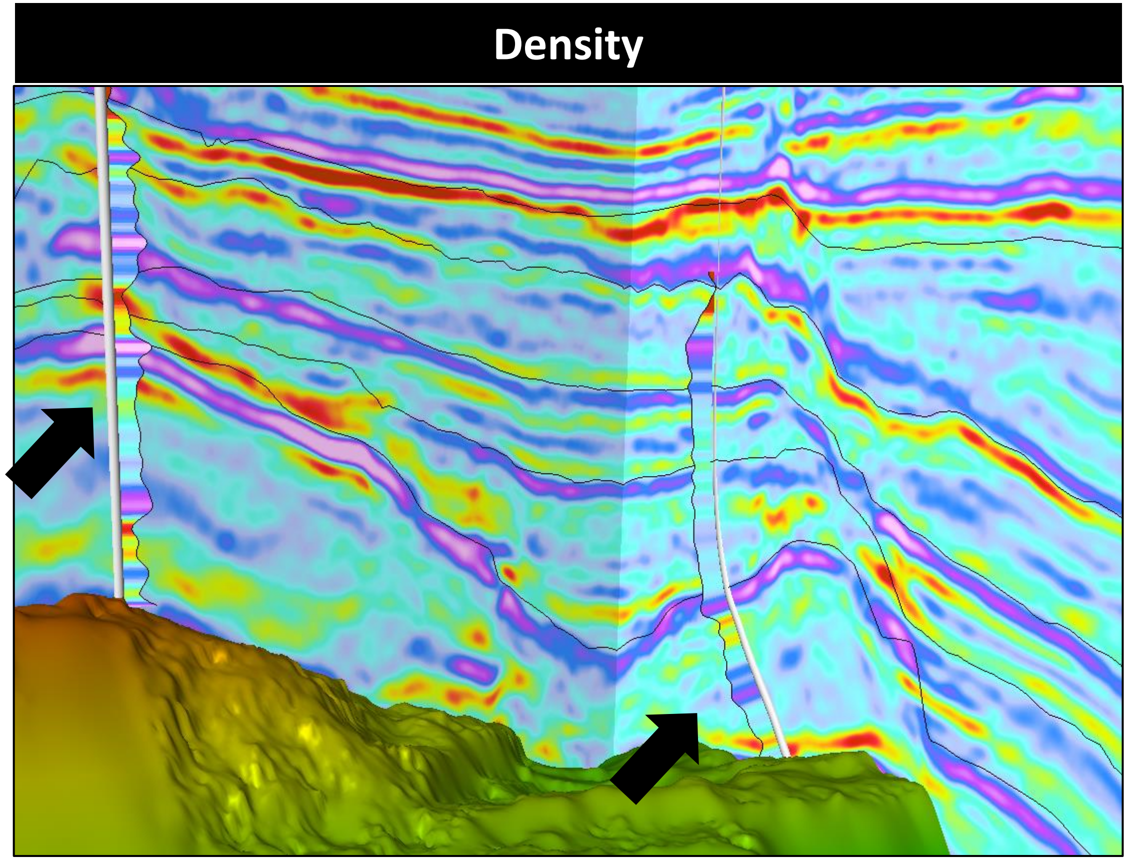




Converted wave AVO QC and joint PP-PS density inversion at Clair Ridge
Bullock, A.D., Aviles, J., Leone, C., and Butt, J. (2019) 81st EAGE Conference and Exhibition

Case study | Joint PP-PS AVO Inversion





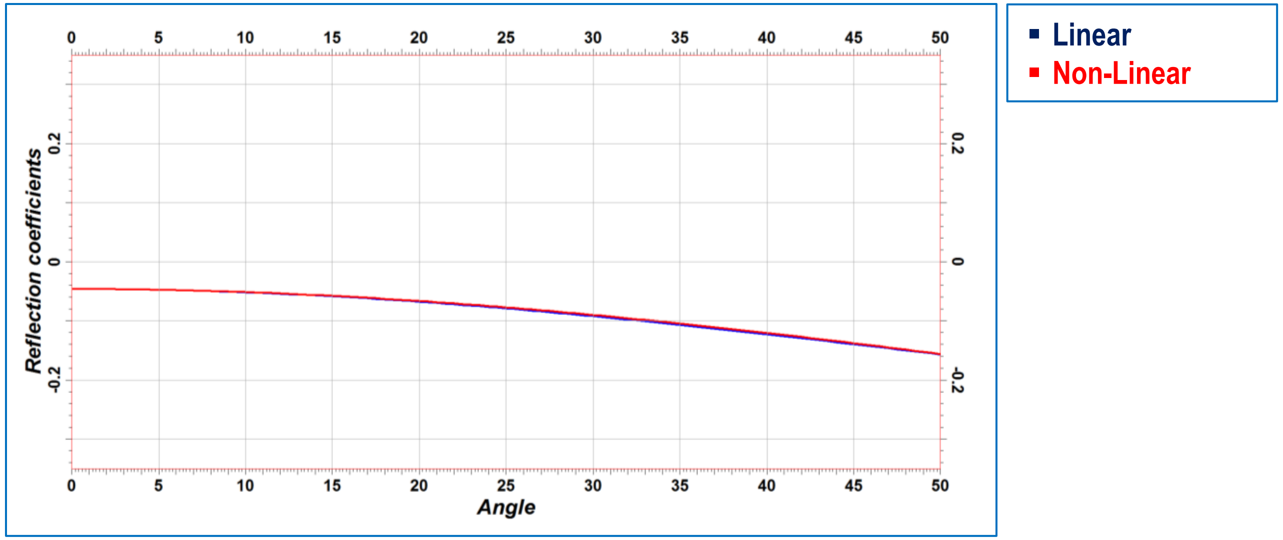
Converted wave AVO QC and joint PP-PS density inversion at Clair Ridge
Bullock, A.D., Aviles, J., Leone, C., and Butt, J. (2019) 81st EAGE Conference and Exhibition

Why non-linear AVO inversion

- Linearized AVO approximations assume:
  - small contrasts
  - narrow reflection angles (<30deg)

  and are not valid in presence of **strong contrasts**

	Vp	Vs	den	ε	δ	γ
Layer 1	2625	1548	2.173	0	0	0
Layer 2	2600	1800	2	0	0	0



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	Vp	Vs	den	ε	δ	γ
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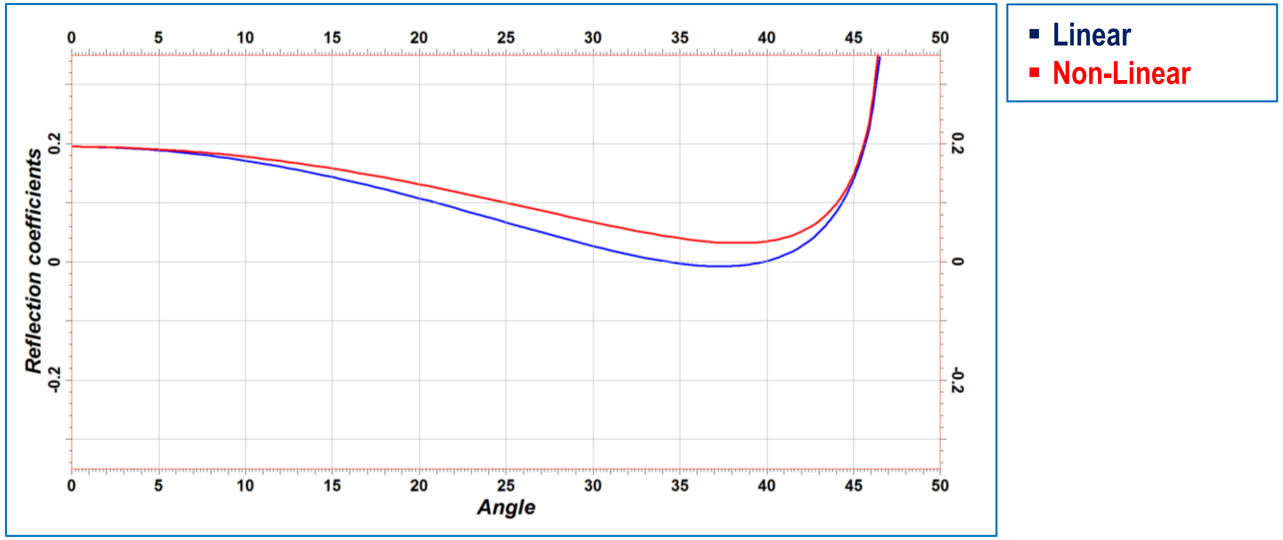
Layer 2	3600	2400	2.35	0	0	0



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- This is even more important for **PS data**

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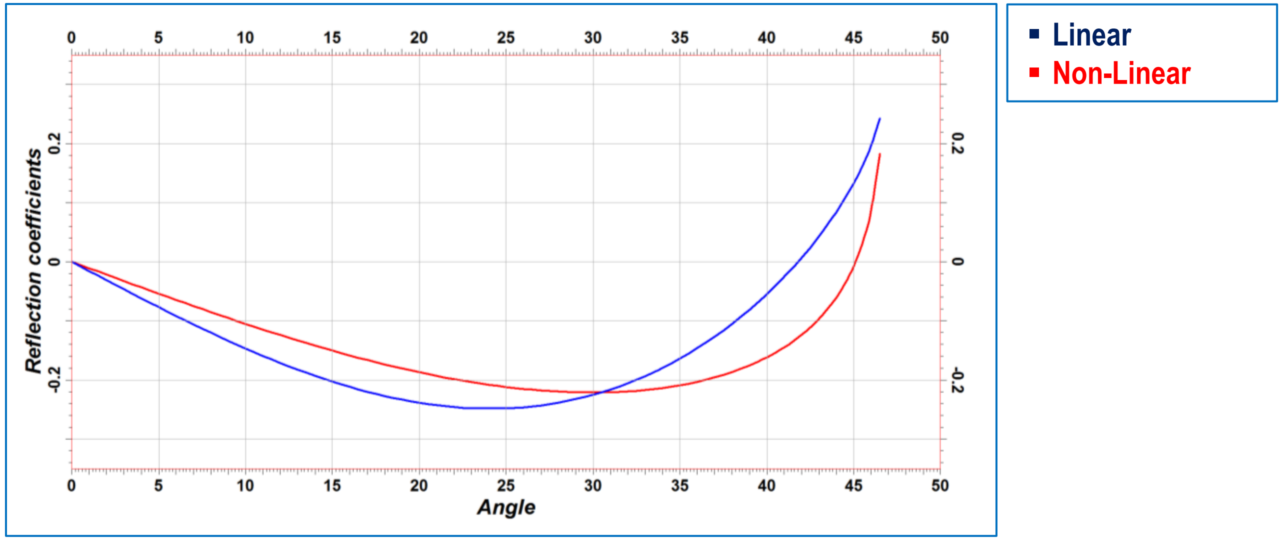

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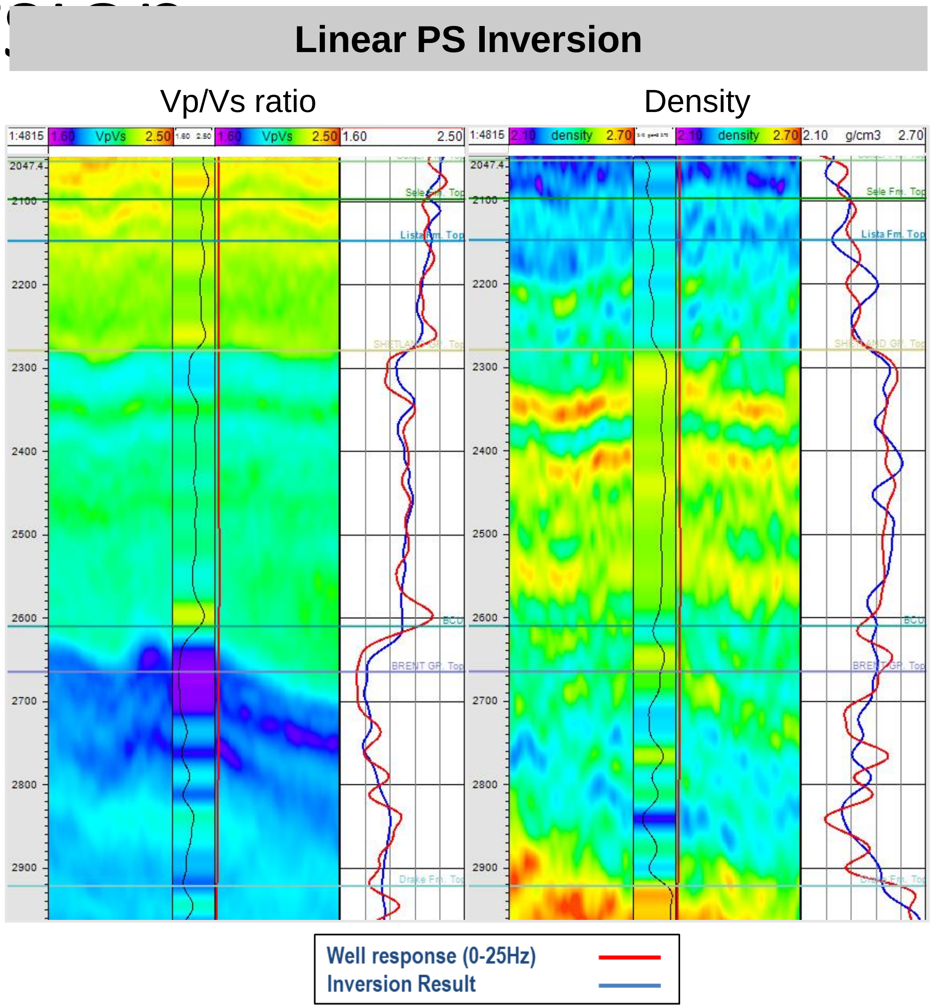

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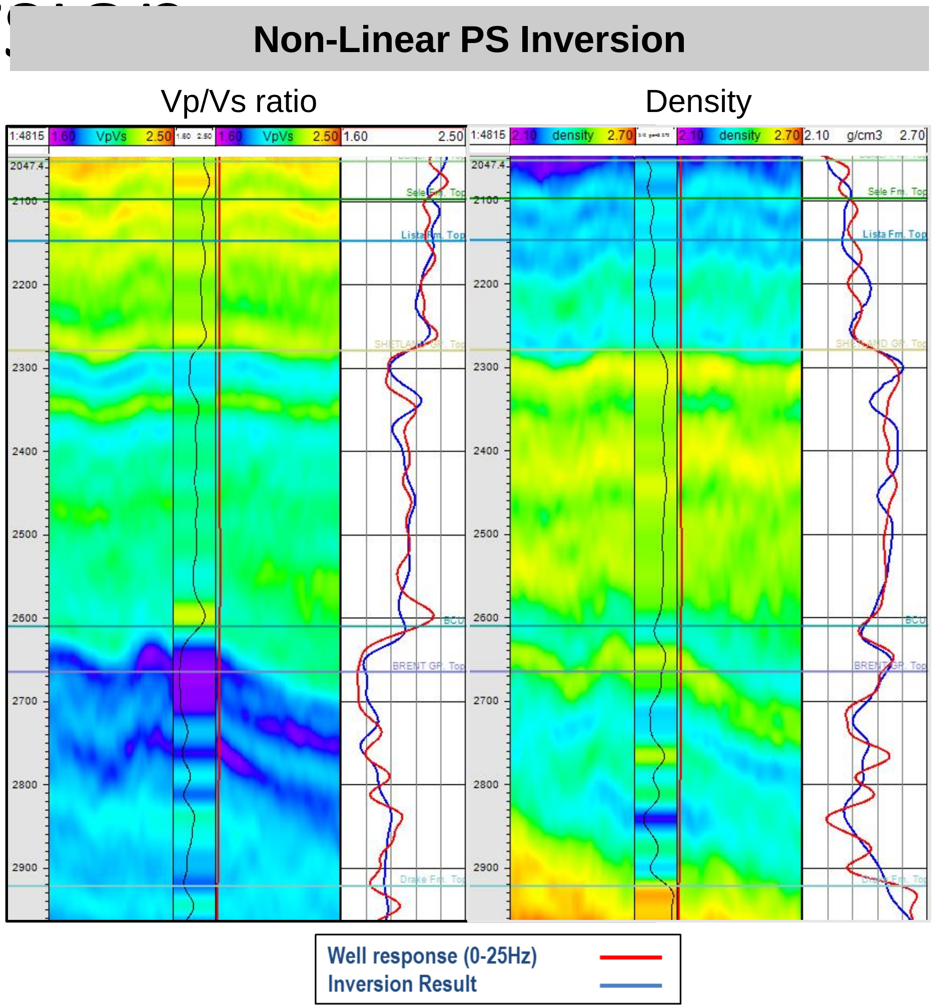
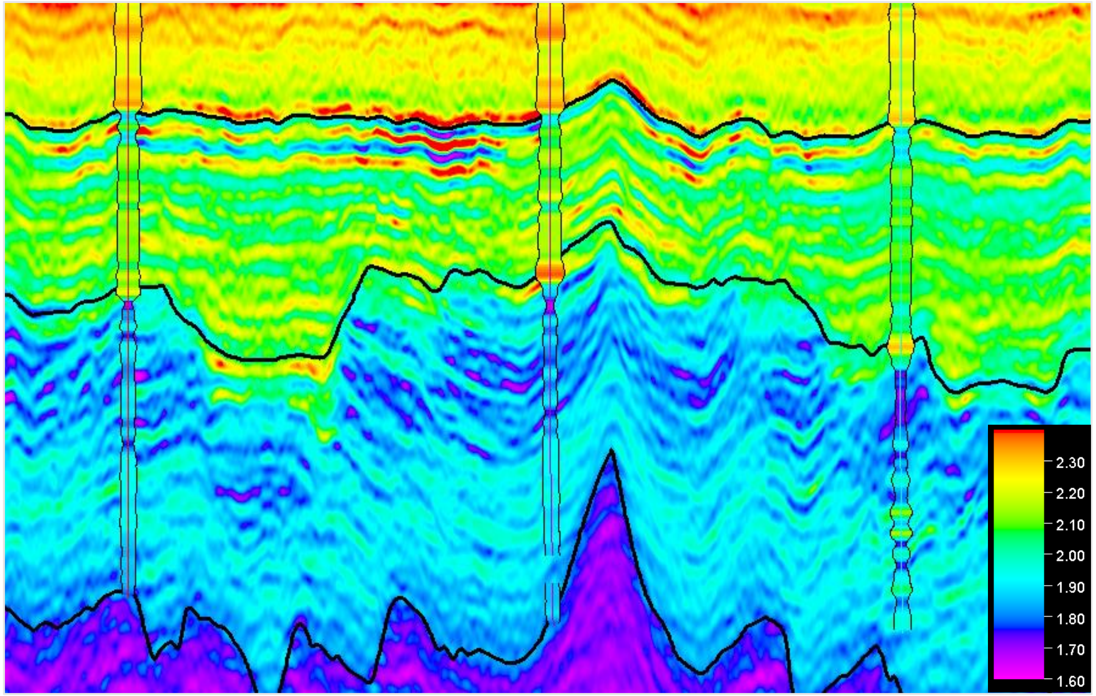


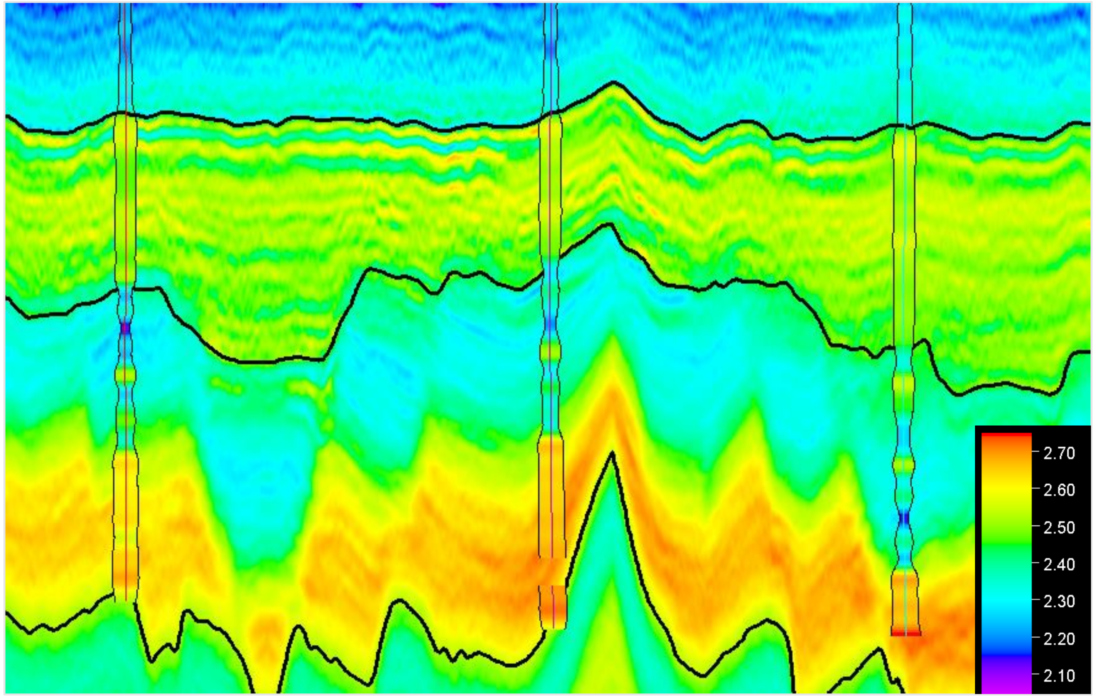
Norway example | PP-PS Inversion

PP AVO Inversion

Vp/Vs ratio



Density

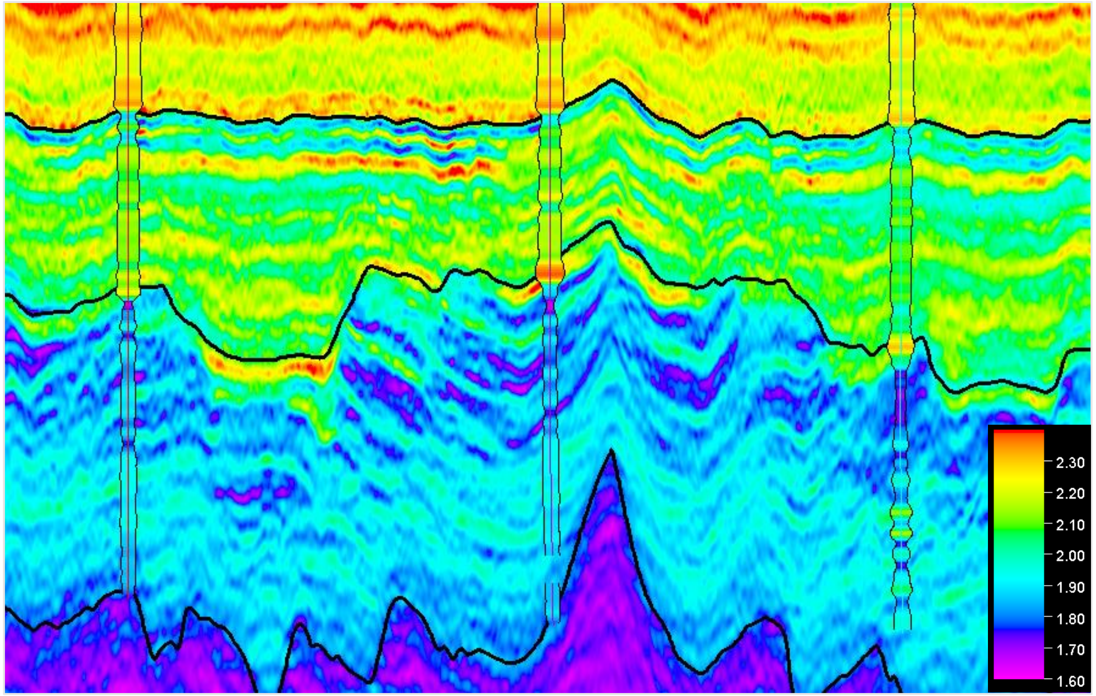


The value of PS seismic and non-linear inversion for reservoir characterization: Oseberg South case study
Thomas Barling*, James Butt, Maria Shadrina and Claudio Leone, Schlumberger; Hugo Sese, Equinor

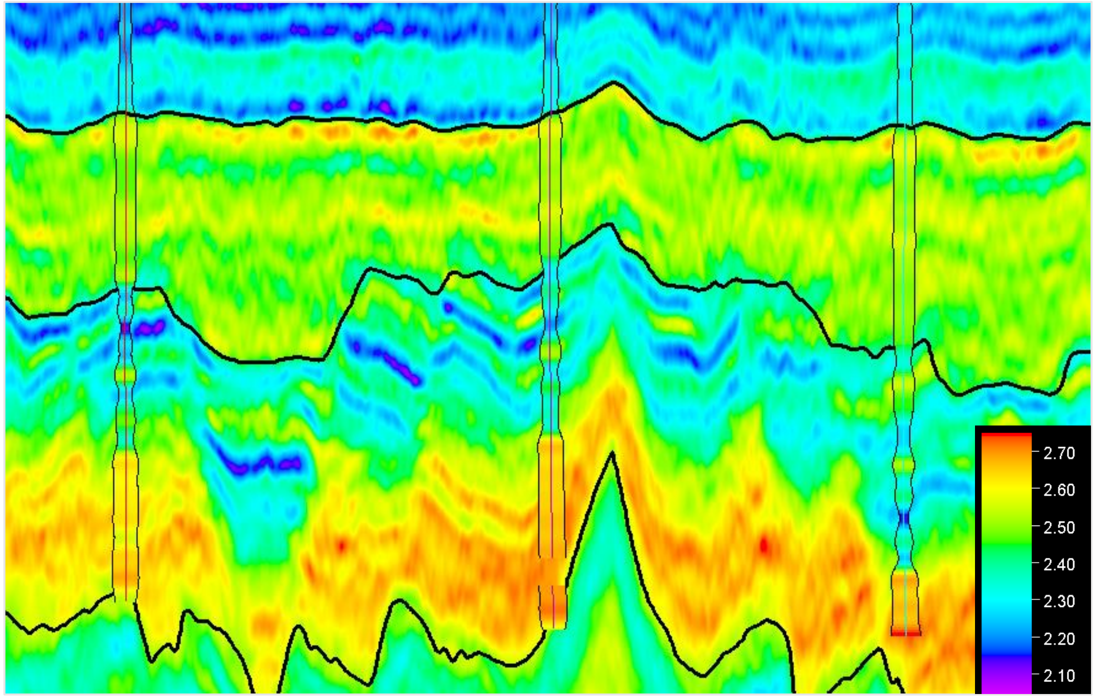
Norway example | PP-PS Inversion

PP-PS AVO Inversion

Vp/Vs ratio



Density



The value of PS seismic and non-linear inversion for reservoir characterization: Oseberg South case study

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Why anisotropic AVO inversion

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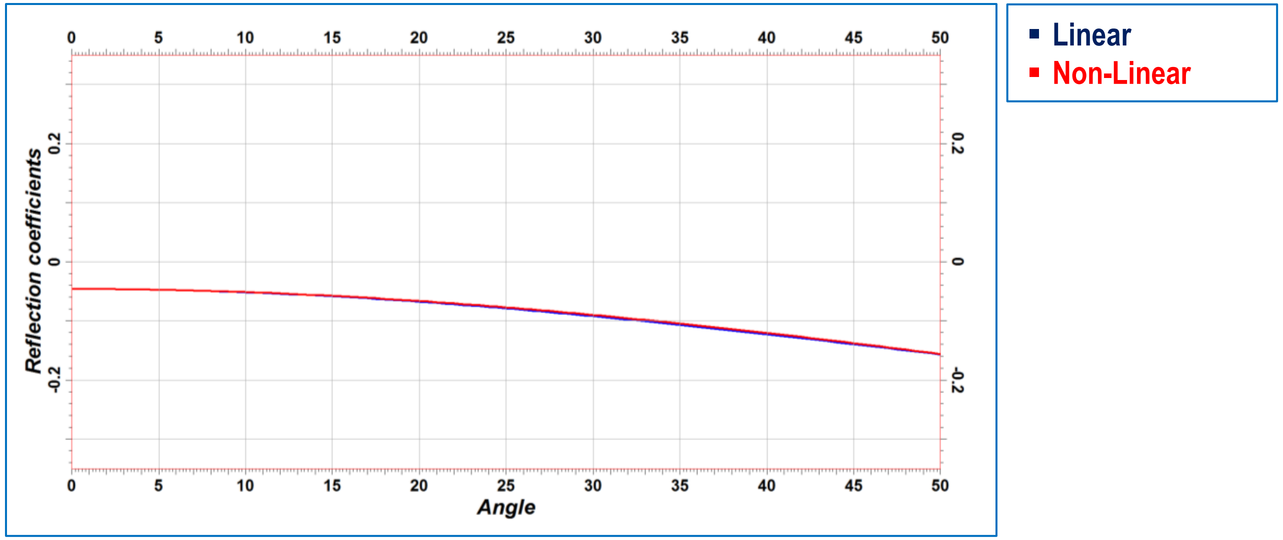
	Vp	Vs	den	ε	δ	γ
Layer 1	2625	1548	2.173	0	0	0
Layer 2	2600	1800	2	0	0	0



Non-linear orthorhombic AVAZ inversion workflow

E.Gofer, R.Bachrach, R.Fletcher, M.Vie - 86th SEG International Annual Meeting, 2016

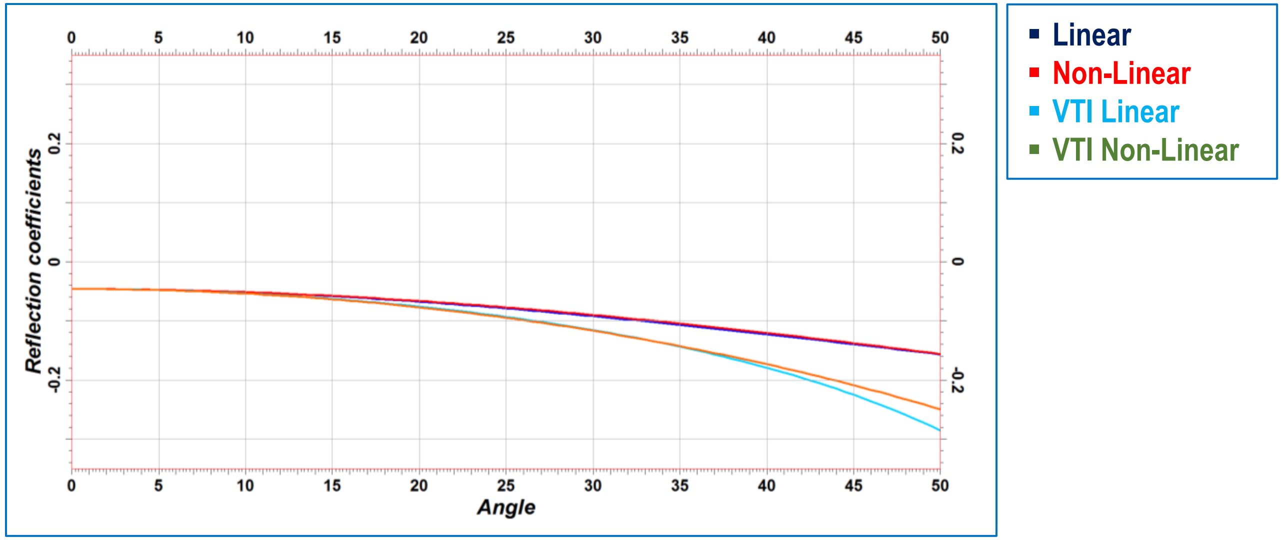
Why anisotropic AVO inversion

- Linearized AVO approximations assume:
  - small contrasts
  - narrow reflection angles (<30deg)

  and are not valid in presence of **strong contrasts**

- Similarly, AVO is affected by contrasts in **anisotropy**, related to:
  - shales (VTI)
  - Fractured or stressed media (HTI, VFTI, ORT)

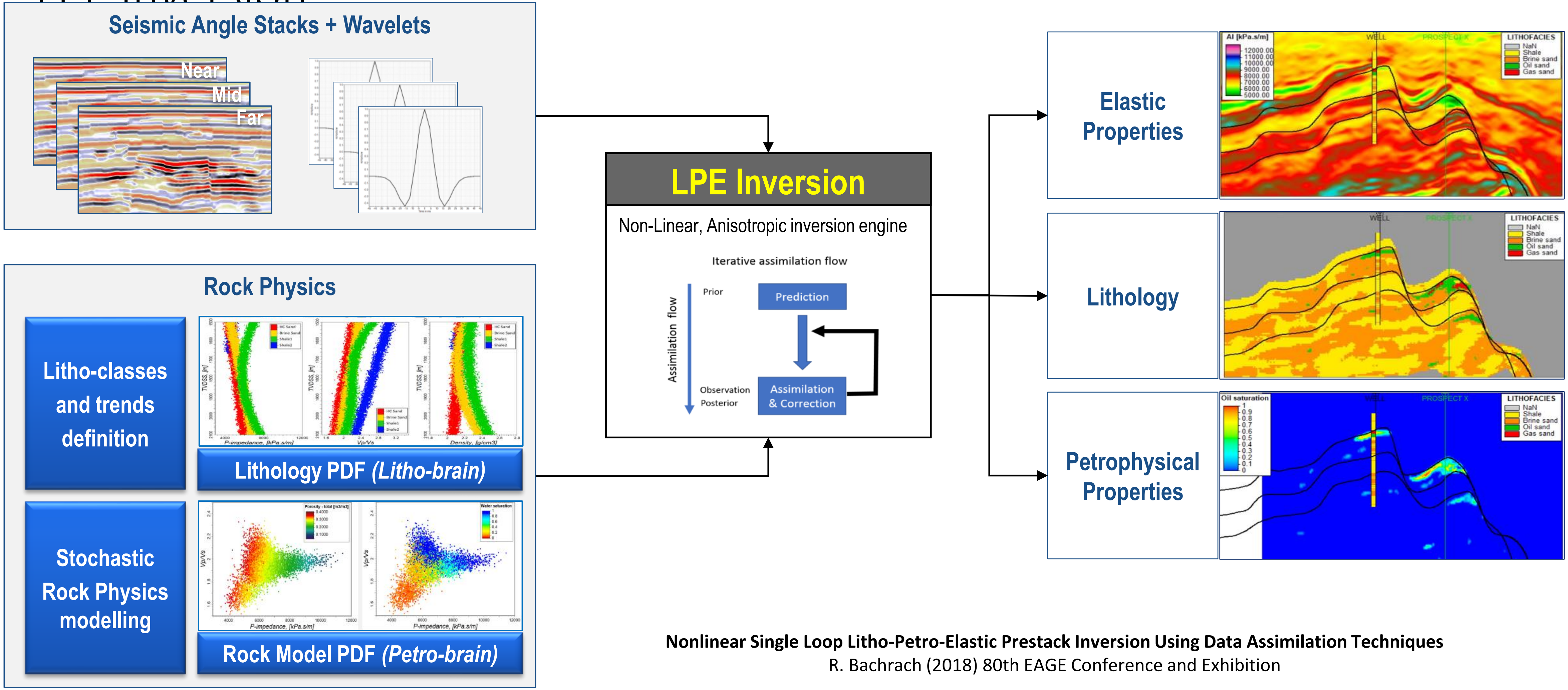
	Vp	Vs	den	ε	δ	γ
Layer 1	2625	1548	2.173	0.24	0.12	0.24
Layer 2	2600	1800	2	0	0	0



Non-linear orthorhombic AVAZ inversion workflow

E.Gofer, R.Bachrach, R.Fletcher, M.Vie - 86th SEG International Annual Meeting, 2016

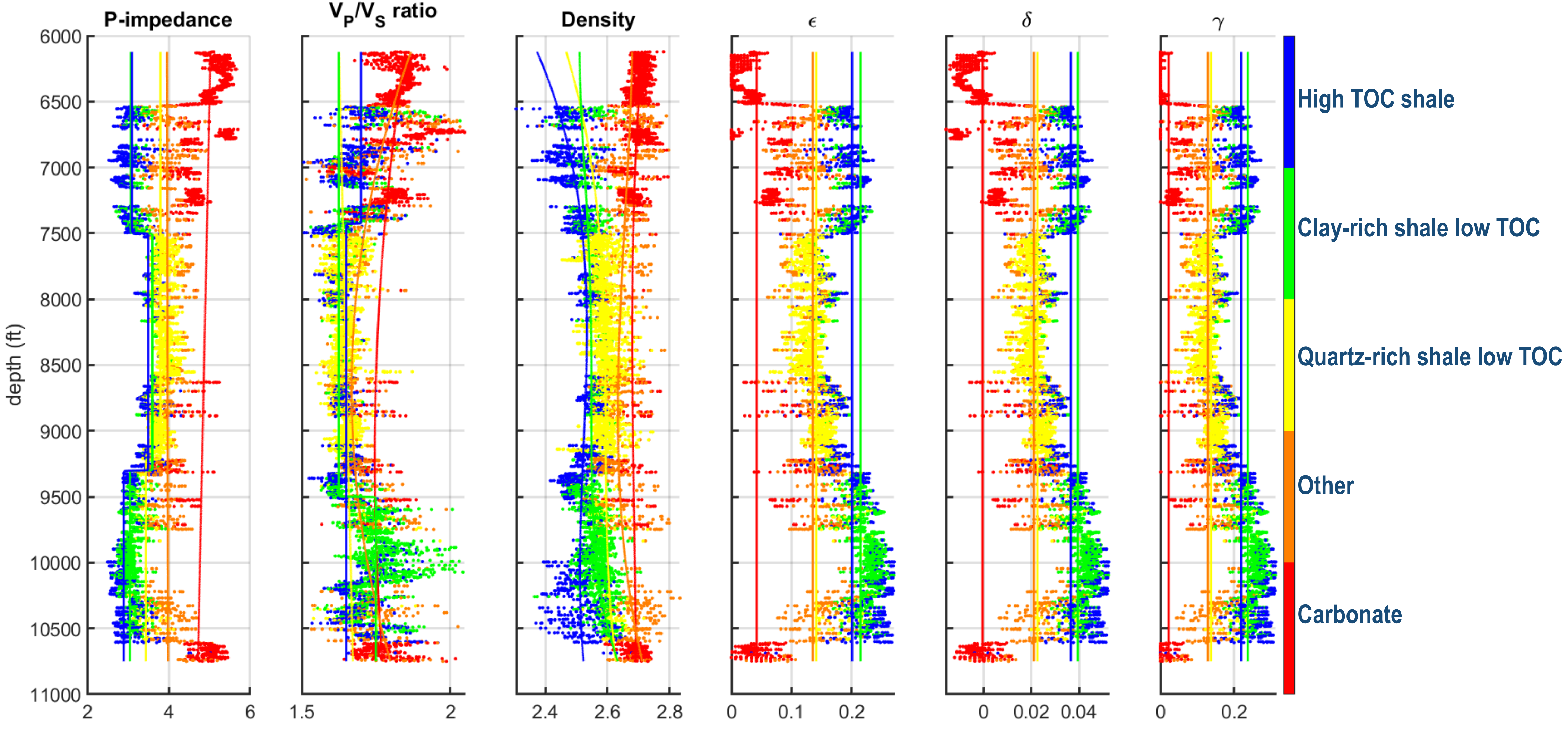
LPE Inversion



Nonlinear Single Loop Litho-Petro-Elastic Prestack Inversion Using Data Assimilation Techniques
R. Bachrach (2018) 80th EAGE Conference and Exhibition

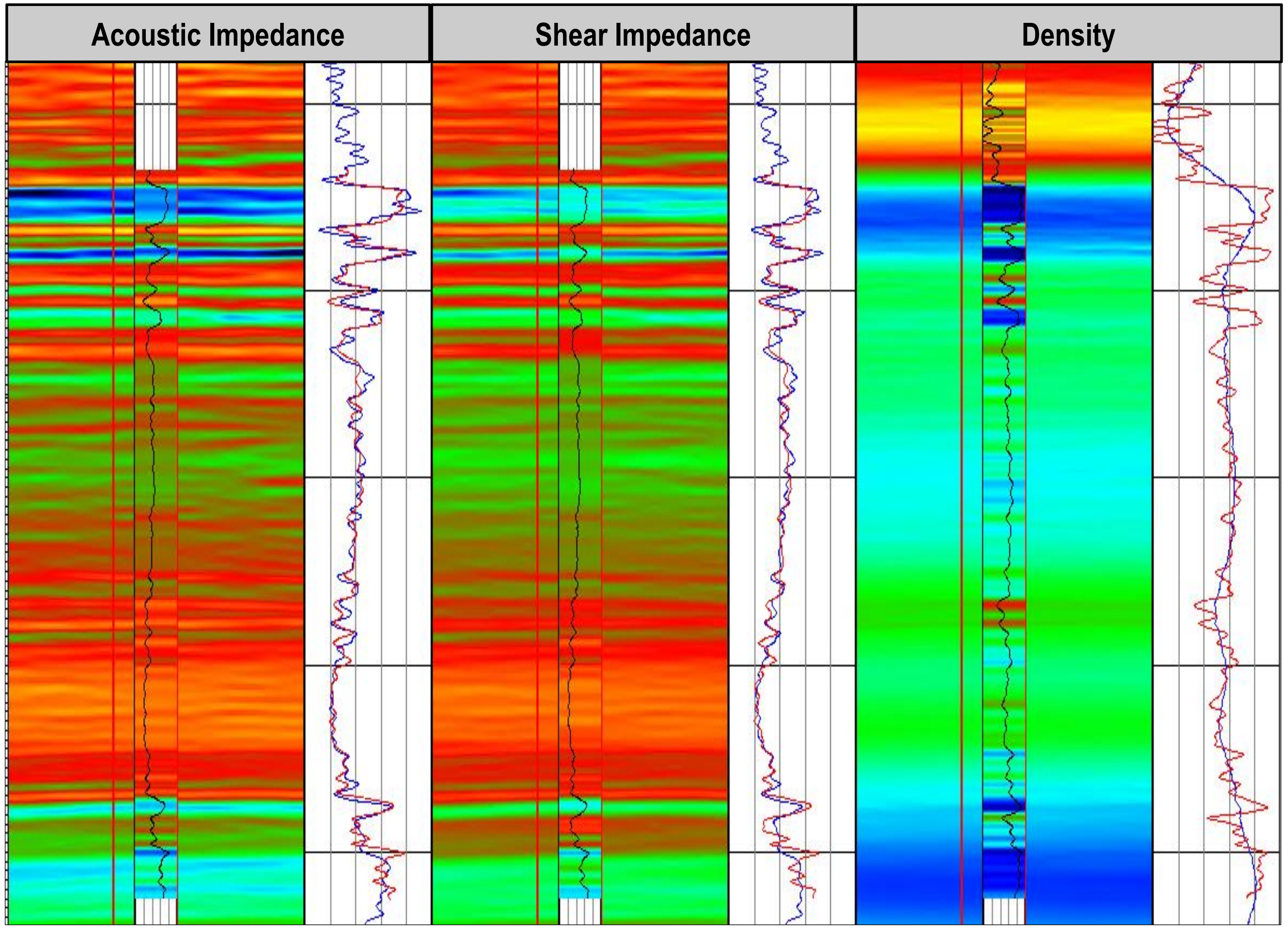
PP-PS case study | VTI Trends

Note: *Transverse isotropy parameter values estimated using Leaney and Jocker (2018) tensor completion approach*



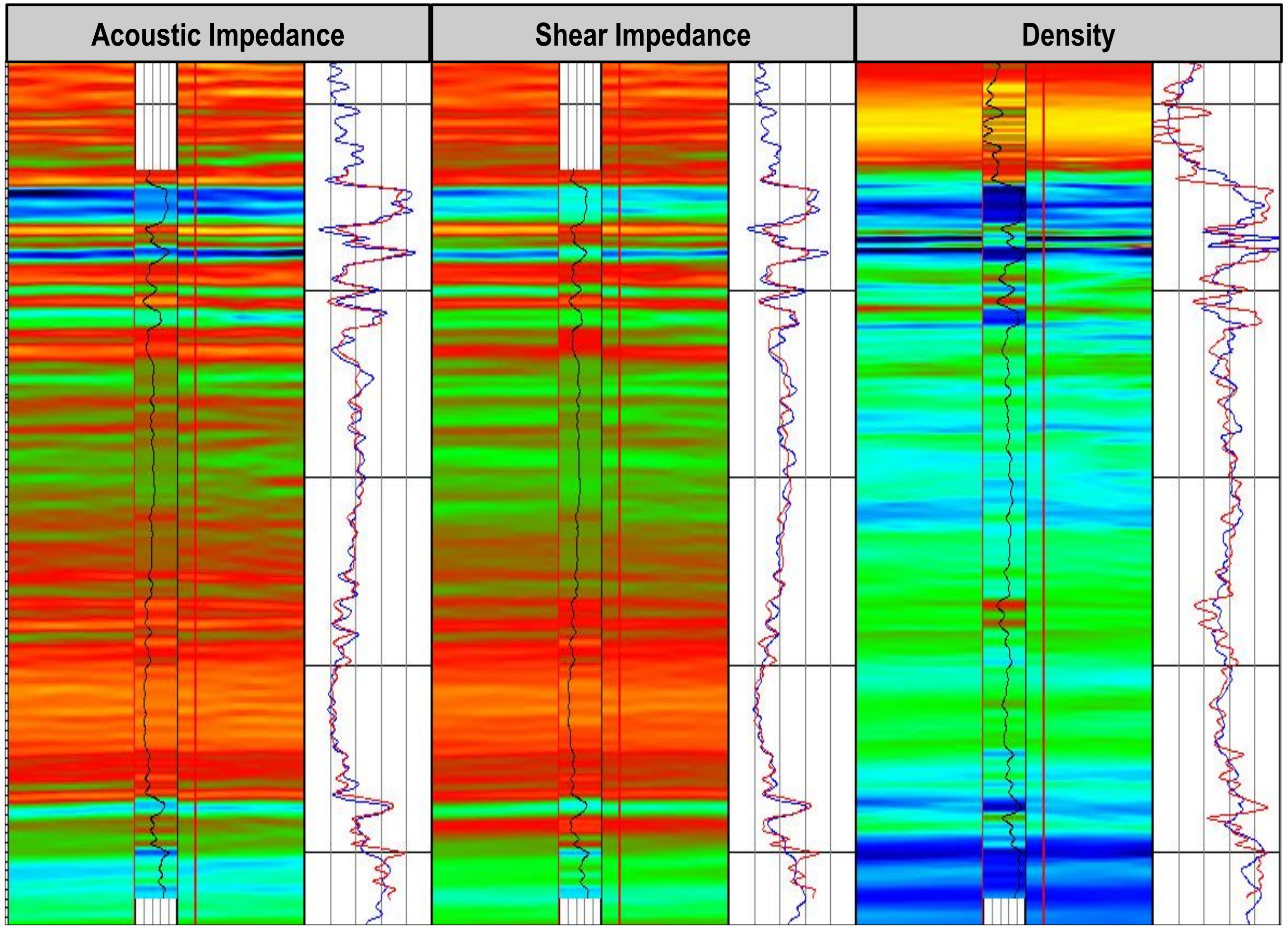
REF: Bachrach, R., Gofer, E., Nonlinear Anisotropic Joint Pp-Ps Litho-Elastic Inversion: Example from Midland Basin (2019)

PP-PS case study | PP AVO Inversion



Joint PP-PS litho-elastic AVA inversion: Example from Midland Basin
Gofer, E, Bachrach, R., Golfre Andreasi, F., Re, S. (2019) SEG Annual Meeting

PP-PS case study | PP-PS AVO Inversion



Joint PP-PS litho-elastic AVA inversion: Example from Midland Basin
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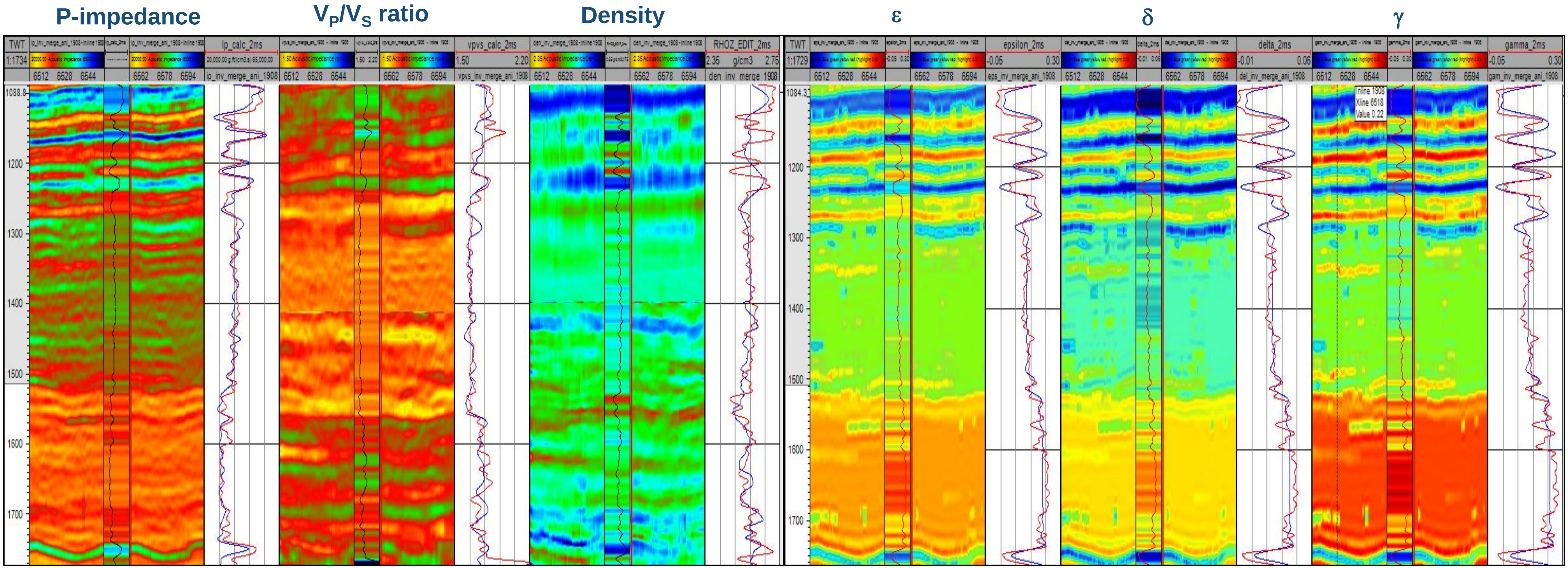
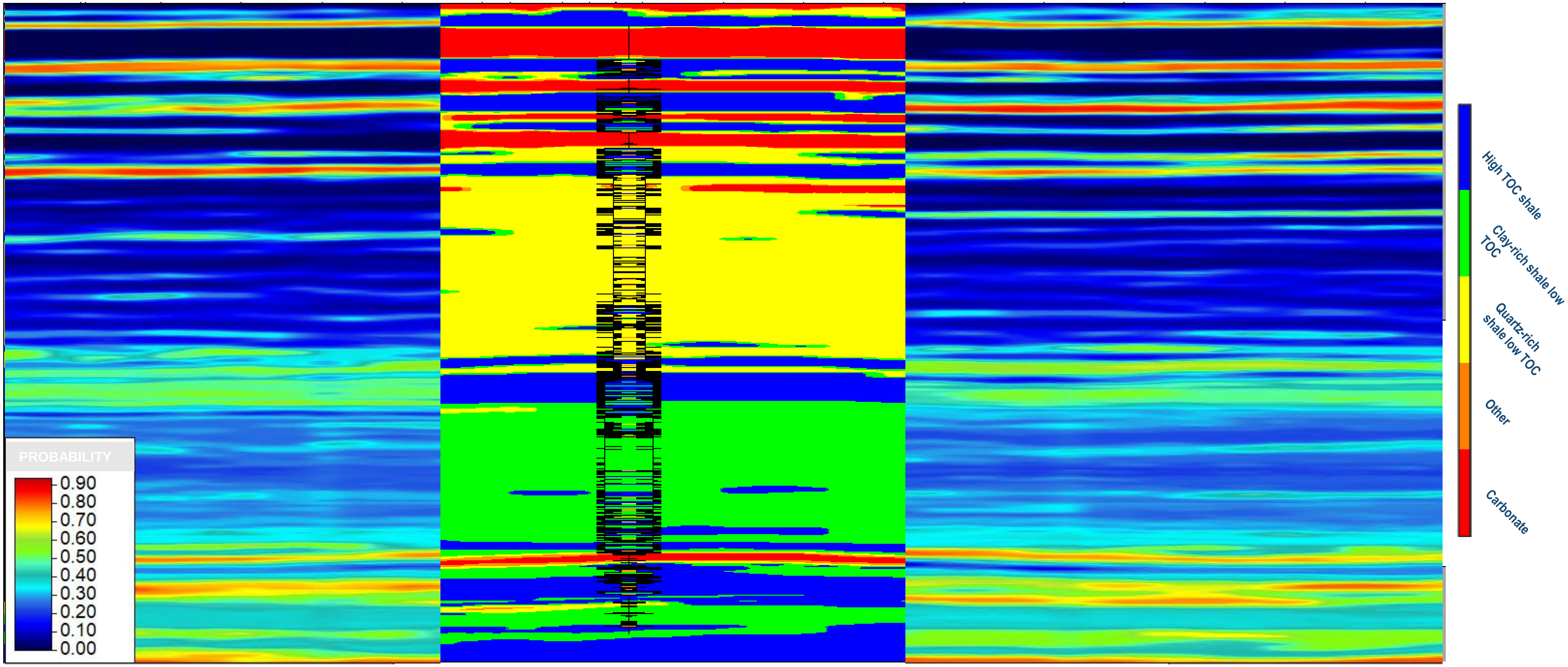
PP-PS case study | PP-PS AVO inversion

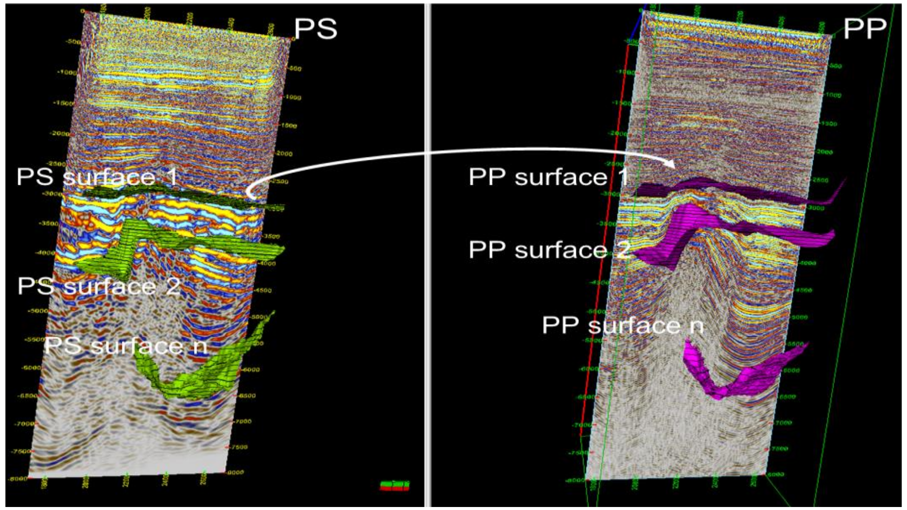


Estimated Litho-Class and Probability of High TOC Shale



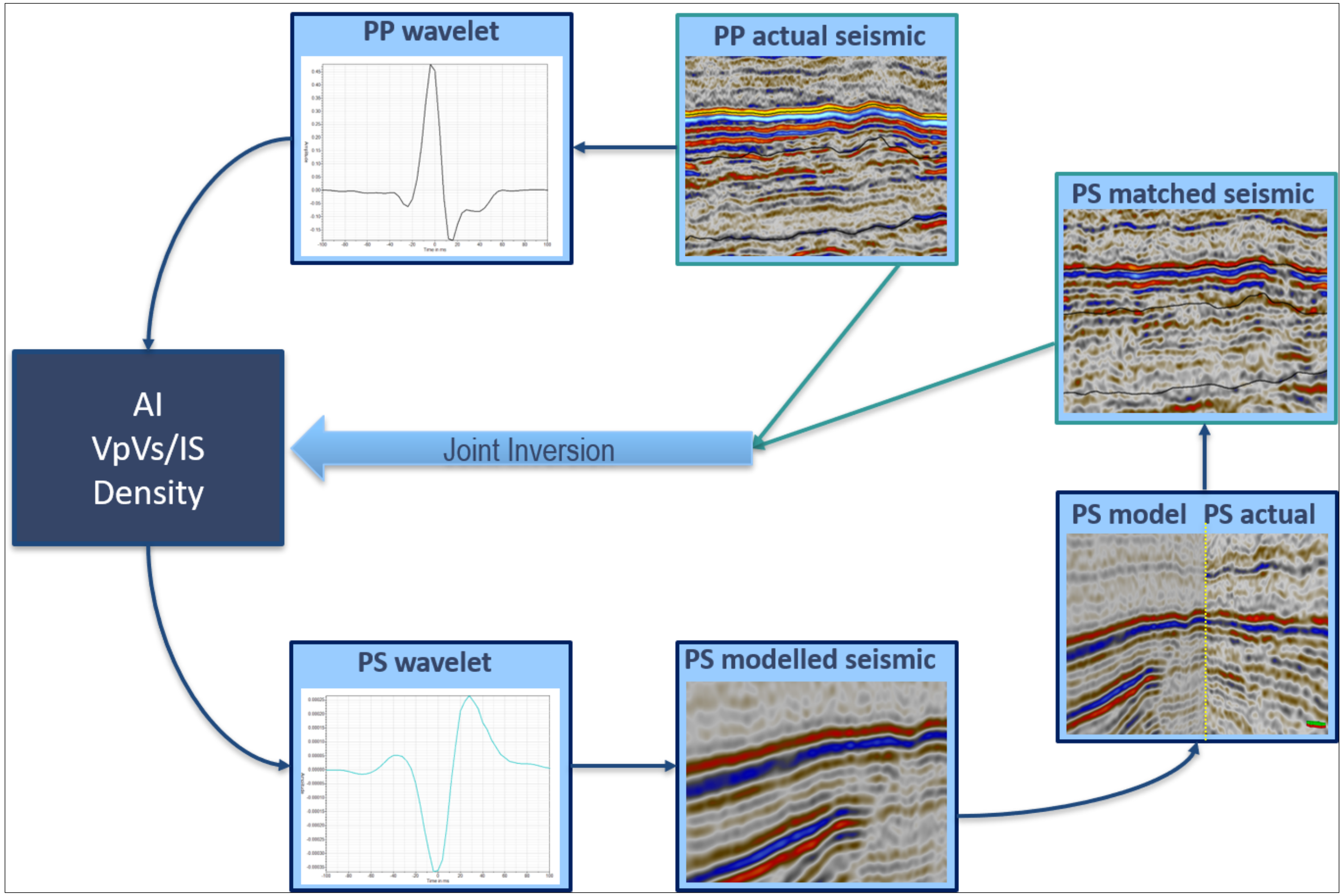
PP-PS event matching

- **For model building:**
  - Create displacement fields for Joint PP-PS Tomography
  - Need to handle large displacements
  - Manual, semi-automated and automated methods
  - Dynamic Image Warping technique with Vel update QC
- **For inversion:**
  - Residual alignment prior to inversion (small displacements)
  - Need to handle differences in <u>reflectivity</u>, <u>frequency content</u>, <u>phase</u>



PP-PS Event Matching - Workflow

Residual alignment prior to AVO inversion



Summary

- Recent advanced in inversion technology allowed to extract more value out of PS amplitudes
- Case studies were presented where this had a key impact on the understanding of the reservoir

References

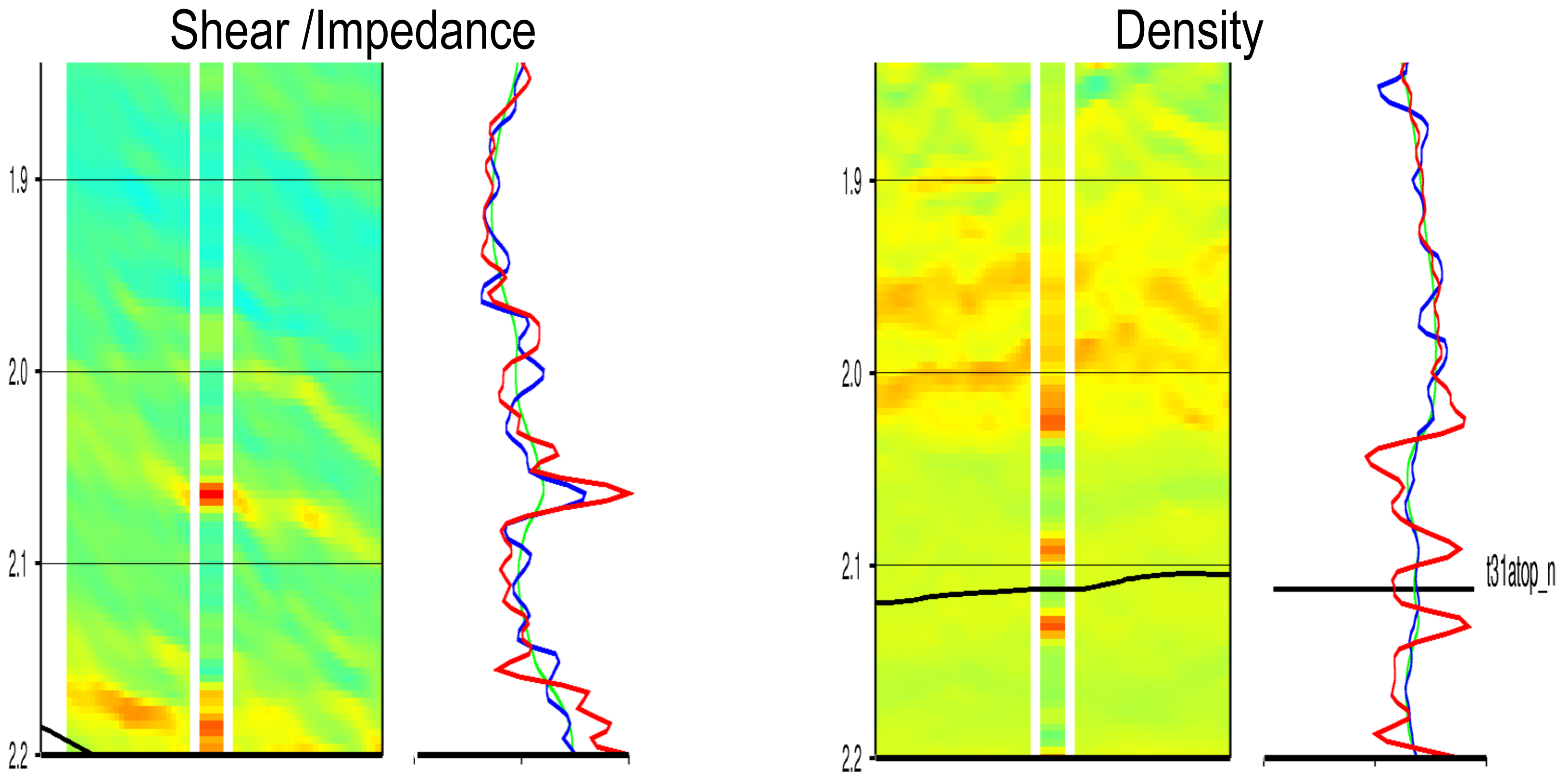
- Barling, T., Butt, J., Shadrina, M., Paxton, A., Leone, C., Sese, H., Patriarca, C. (2021) **The Value of PS Seismic and Non-linear Inversion for Reservoir Characterization: Oseberg South North Sea Case Study**, SEG annual meeting 2021
- Bullock, A.D., Aviles, J., Leone, C., and Butt, J. (2019) **Converted wave AVO QC and joint PP-PS density inversion at Clair Ridge**. 81st EAGE Conference and Exhibition
- Gofer, E, Bachrach, R., Golfre Andreasi, F., Re, S. (2019) **Joint PP-PS litho-elastic AVA inversion: Example from Midland Basin.** SEG Annual Meeting
- M Paydayesh, M Leathard, J Mathewson, **The synergy between PP and PS for reservoir definition,** 76° EAGE Conference and Exhibition 2014
- A.Barnola, M.Ibram, **3D simultaneous joint PP-PS pre-stack seismic inversion at Schiehallion field, United Kingdom Continental Shelf,** Geophysical Prospecting, 2014, 62, 278–292
- A. Murineddu, A.Rasmussen, F.R. Mohamed, A.S. Wendt, M.Nickel , **PZPS Event Matching and Simultaneous Inversion - A Critical Input to 3D Mechanical Earth Modeling,** 70° EAGE Conference and Exhibition

Older case studies

Case study: Simultaneous Joint PP-PS Inversion

Improved Shear Impedance and density estimation

PP AVO Inversion

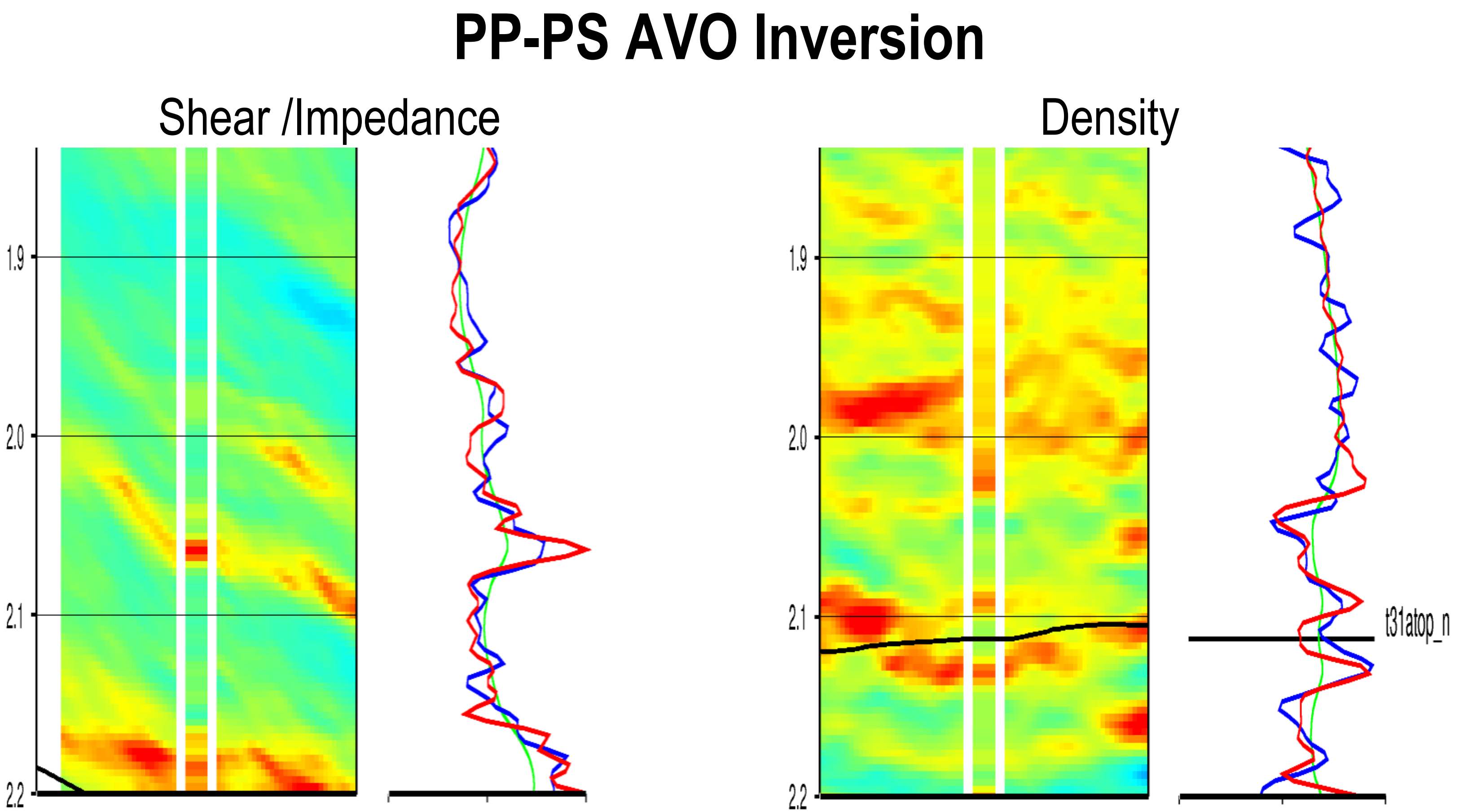


3D simultaneous joint PP-PS pre-stack seismic inversion at Schiehallion field, United Kingdom Continental Shelf

A.Barnola, M.Ibram - Geophysical Prospecting, 2014, 62, 278–292

Case study: Simultaneous Joint PP-PS Inversion

Improved Shear Impedance and density estimation



3D simultaneous joint PP-PS pre-stack seismic inversion at Schiehallion field, United Kingdom Continental Shelf

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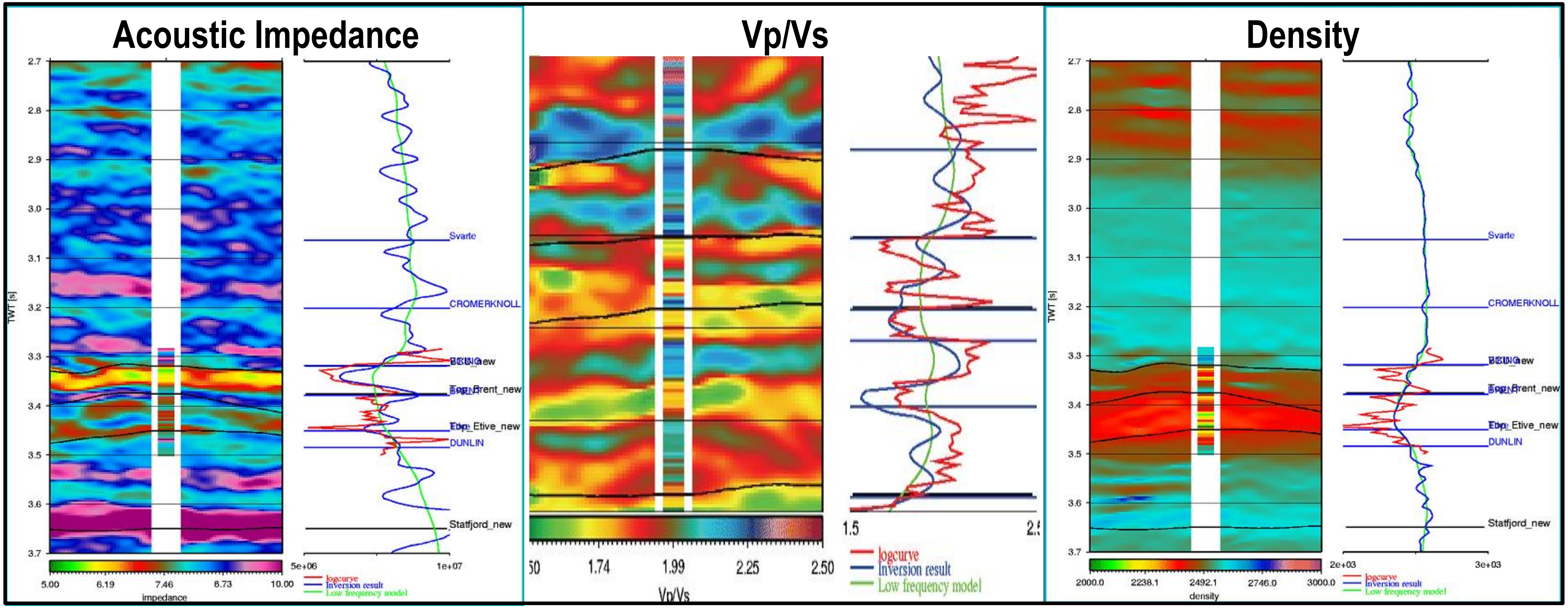
Case study: Simultaneous Joint PP-PS Inversion

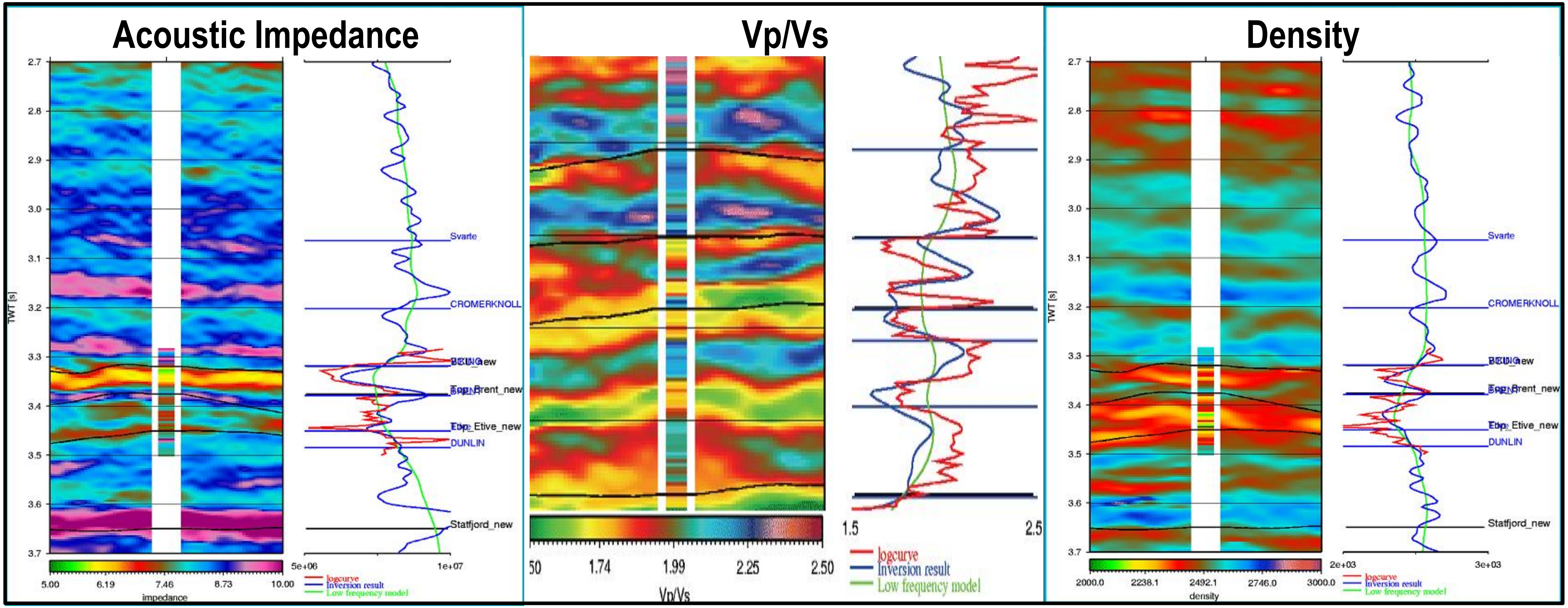
PP AVO Inversion



PZPS Event Matching and Simultaneous Inversion - A Critical Input to 3D Mechanical Earth Modeling
A. Murineddu, A.Rasmussen, F.R. Mohamed, A.S. Wendt, M.Nickel - 70° EAGE Conference and Exhibition

Case study: Simultaneous Joint PP-PS Inversion

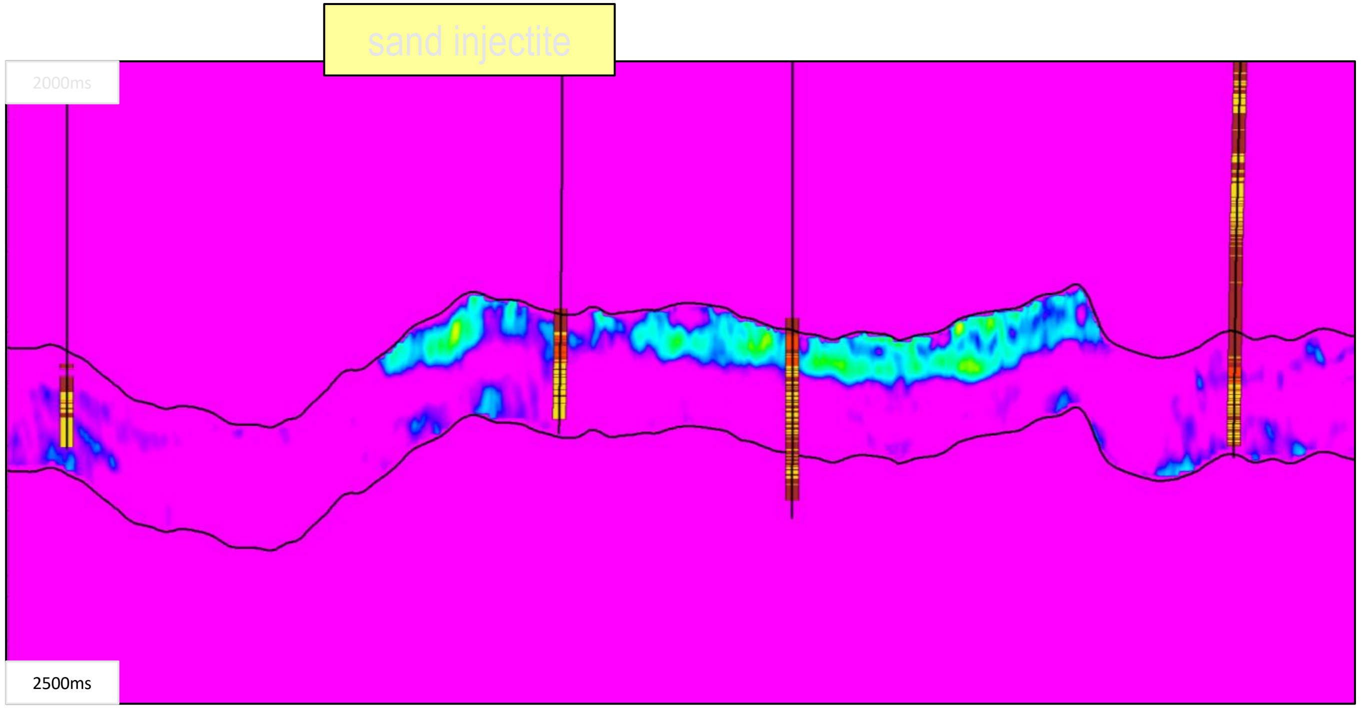
PP-PS AVO Inversion

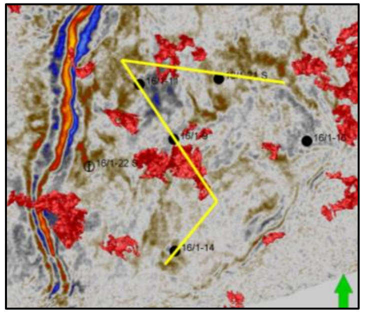


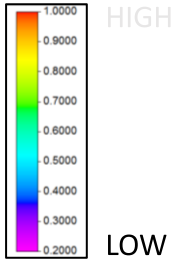
PZPS Event Matching and Simultaneous Inversion - A Critical Input to 3D Mechanical Earth Modeling
A. Murineddu, A.Rasmussen, F.R. Mohamed, A.S. Wendt, M.Nickel - 70° EAGE Conference and Exhibition

Example 3 : Hydrocarbon sand probability

Prestack depth-domain inversion





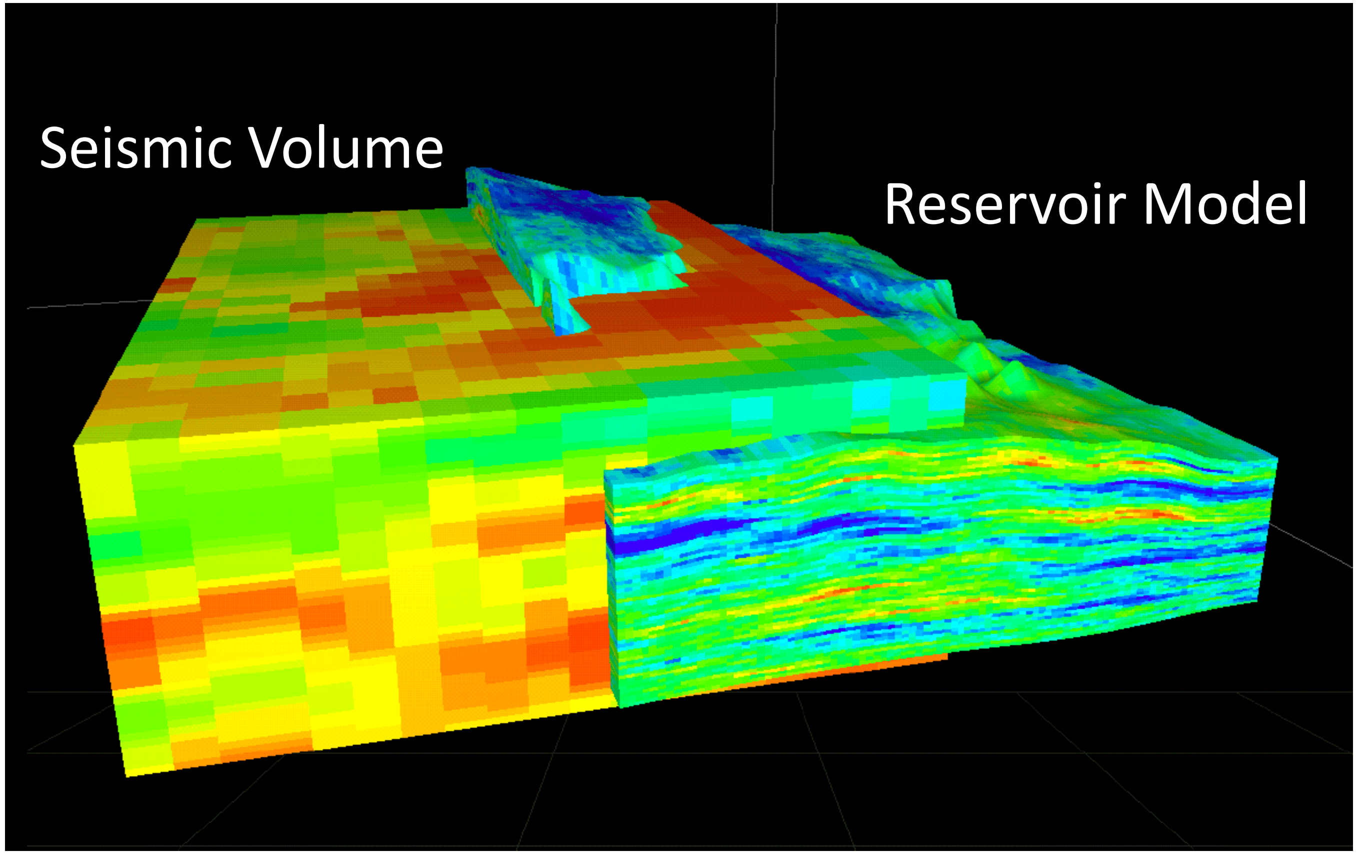


✓ Sand injectites imprint mitigated -> more reliable lithology classification

REF: *Leone, C., Osen, A., Cavalca, M., Fletcher, R.P. and Ferriday, M. 2018a. Improving Quantitative Interpretation beneath Sand Injectites: A North Sea Case Study. 80th EAGE Conference & Exhibition, Extended Abstracts*

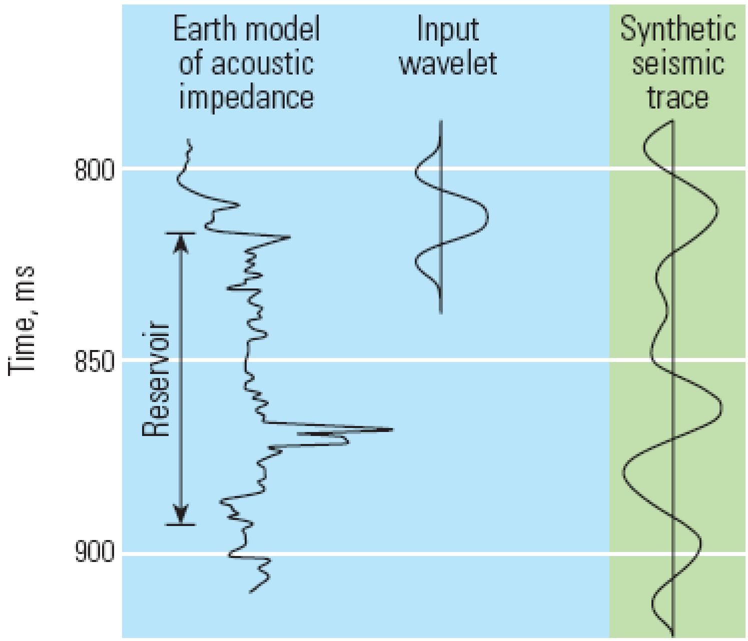
Stochastic Seismic Inversion

Issues of Scale in Reservoir Modelling

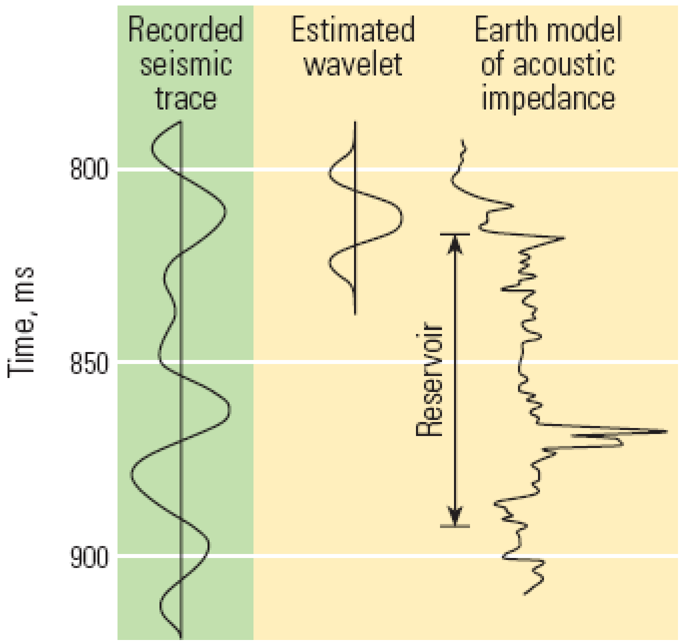


Forward Modelling & Inversion*

Forward Modelling

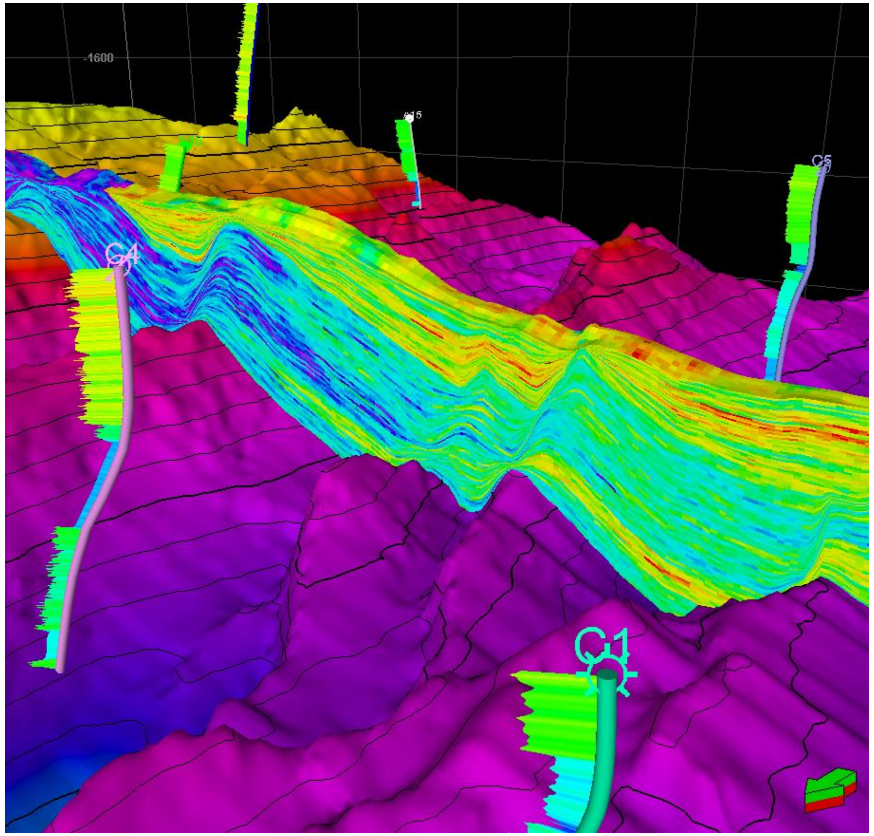


Inversion



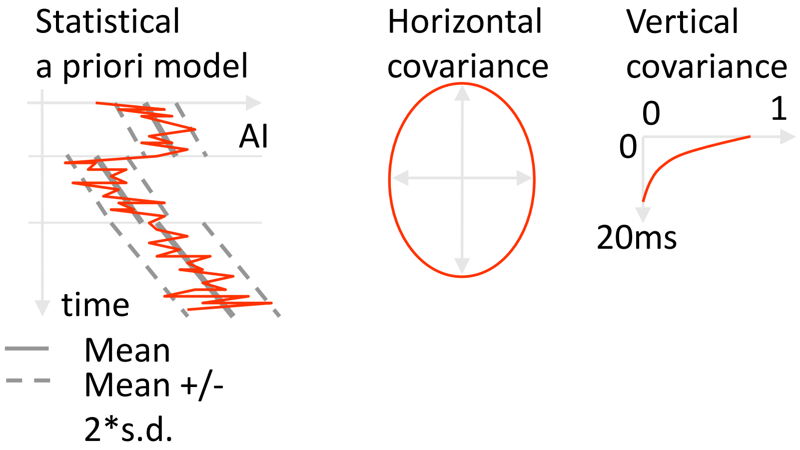
*Seismic Inversion: Reading Between the Lines, Oilfield Review, Spring 2008

Post-stack Stochastic Inversion

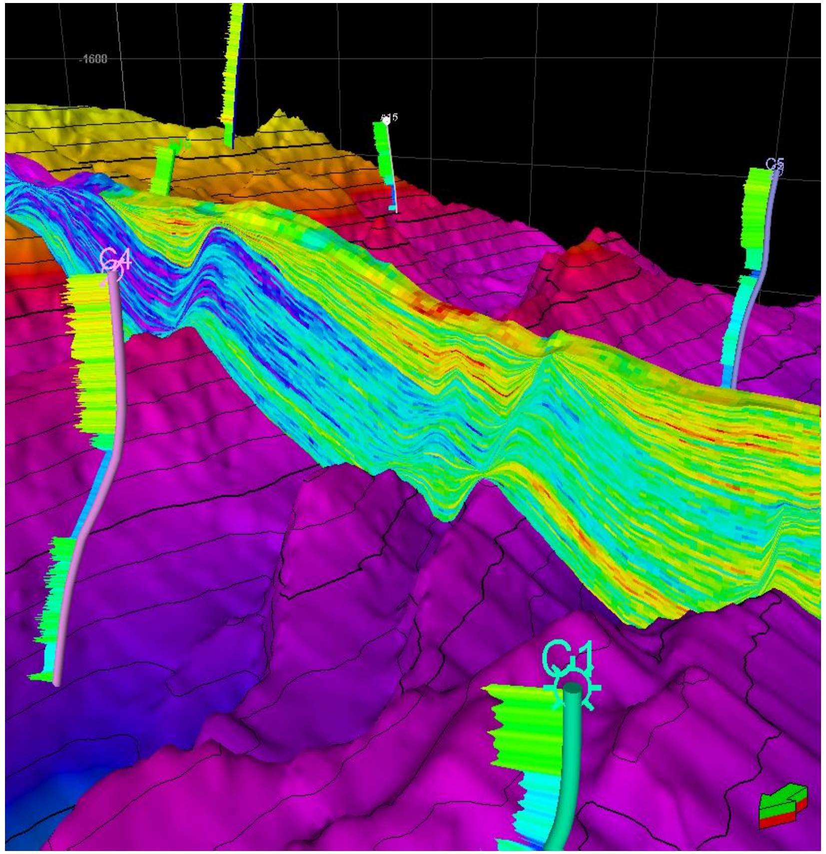


Impedance models constrained to:

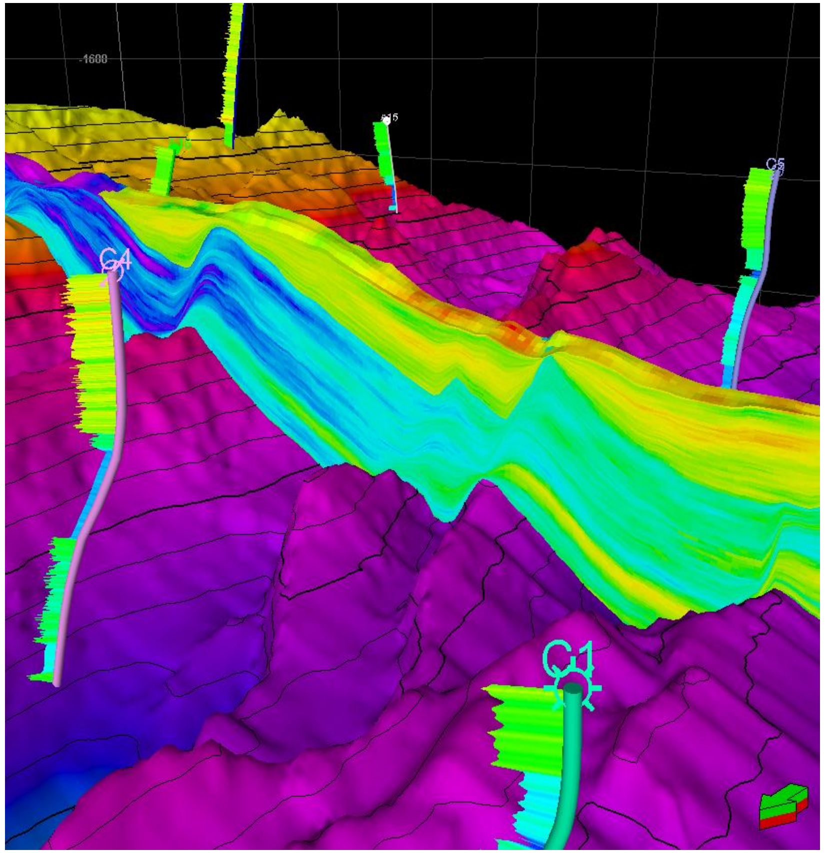
- Seismic amplitudes
- Geological model (Petrel pillar grid)
- 3D a priori model
- 3D heterogeneity model



Stochastic Inversion - Products



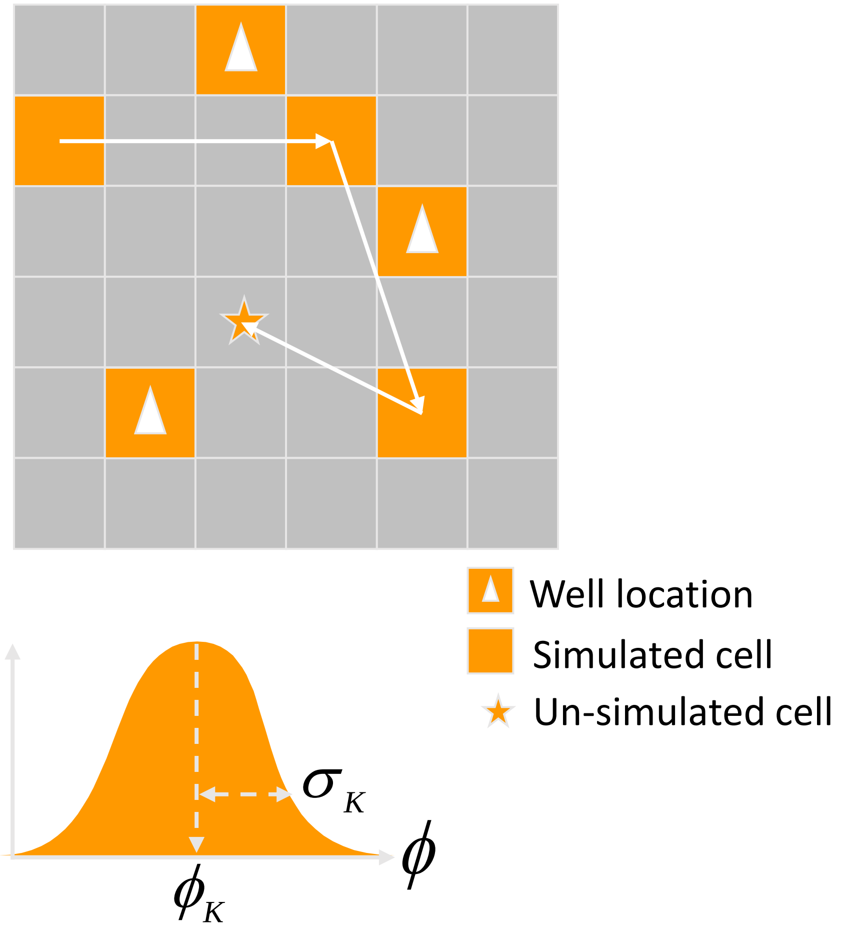
Acoustic Impedance Realizations



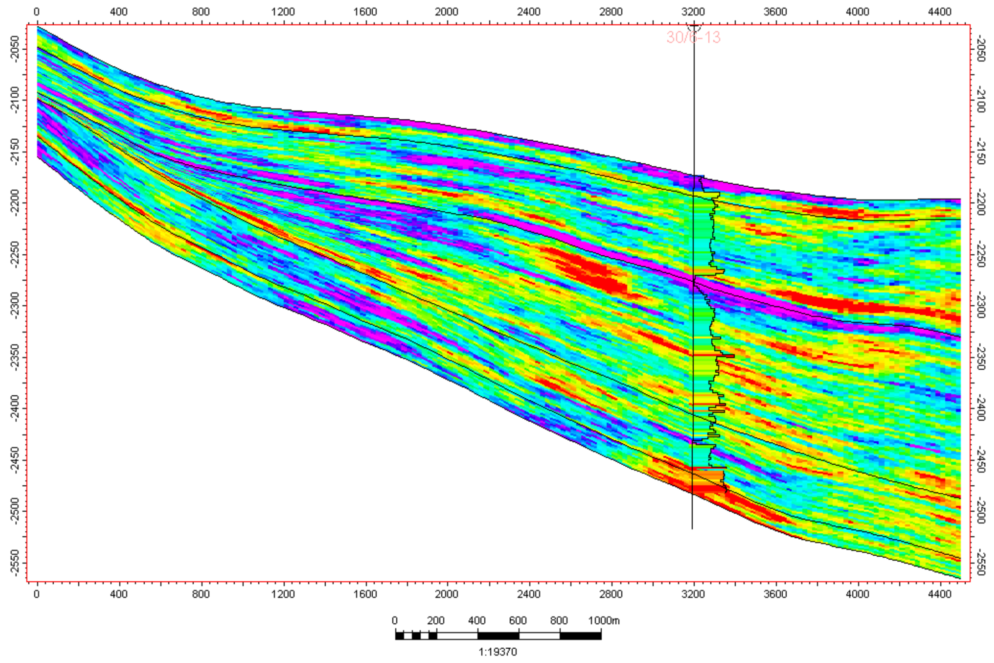
Mean of 20 realizations

Sequential Gaussian Simulation

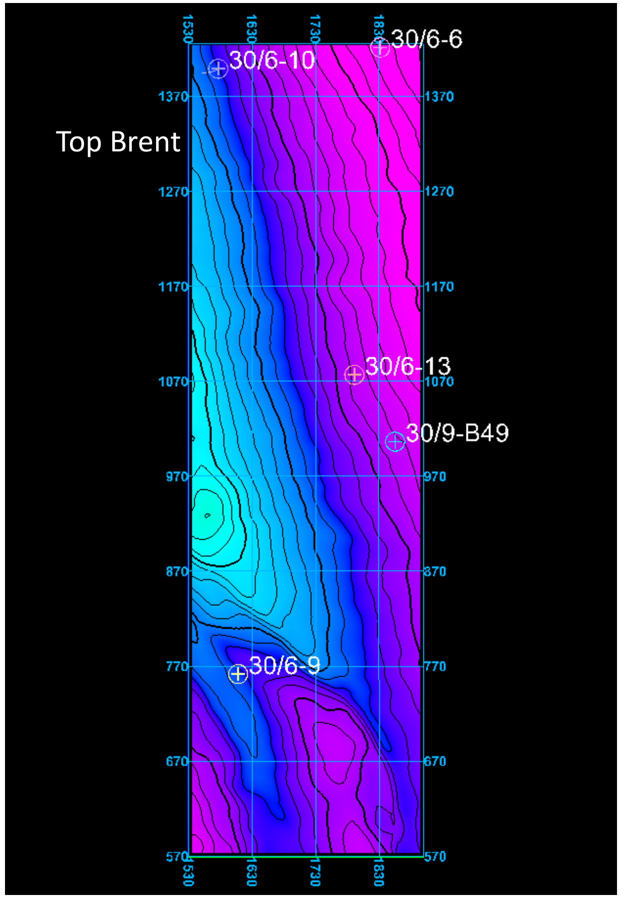
1. Pick un-simulated cell at random
2. Compute kriging estimate and variance
3. Draw simulated value at random from conditional distribution
4. Treat simulated value as additional control point
5. Repeat until full grid is simulated



Section 3.
Post-Stack Stochastic Inversion of the Oseberg Field



Area of Interest



- Cropped seismic survey:
    - IL range 570-1425
    - IL length 4627m (18.75m)
    - XL range 1530-1900
    - XL length 16032m (12.5m)
- Well data:
    - 30/6-6, 30/6-9, 30/6-10, 30/6-13, 30/9-B49

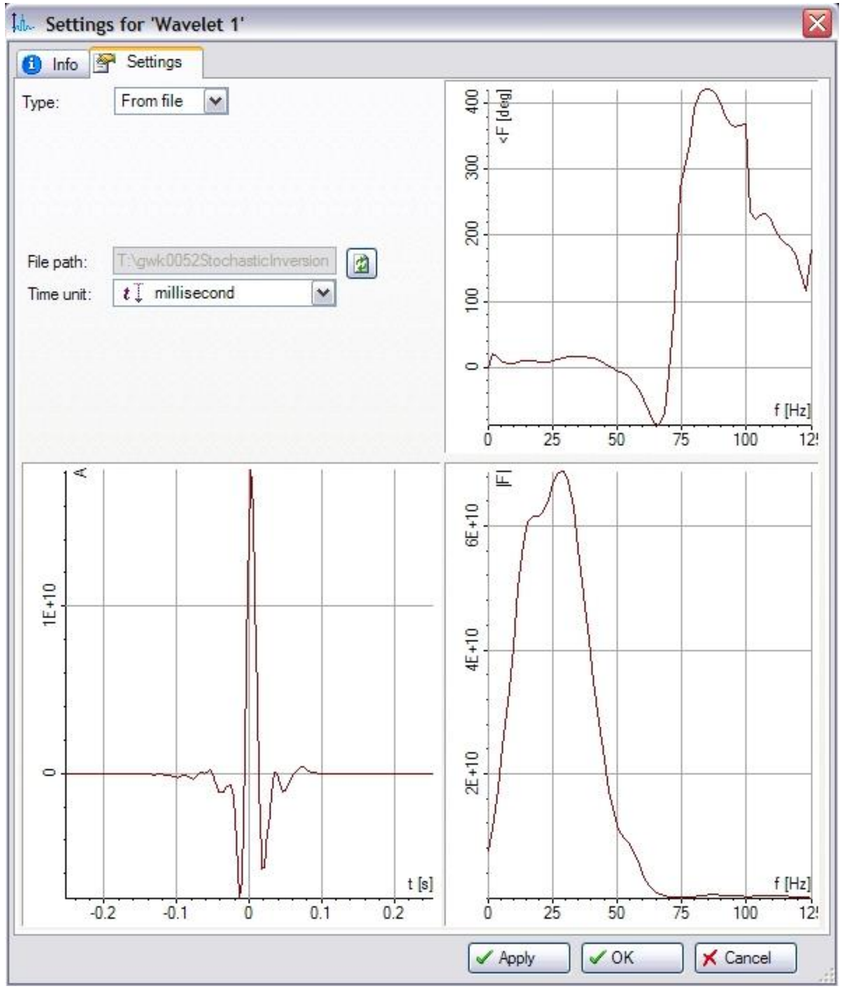
Workflow - 1

- Input data
  - Post-stack seismic amplitude volume
  - Extracted wavelet
  - Interpreted seismic horizons
  - Well logs
  - Time-depth curves

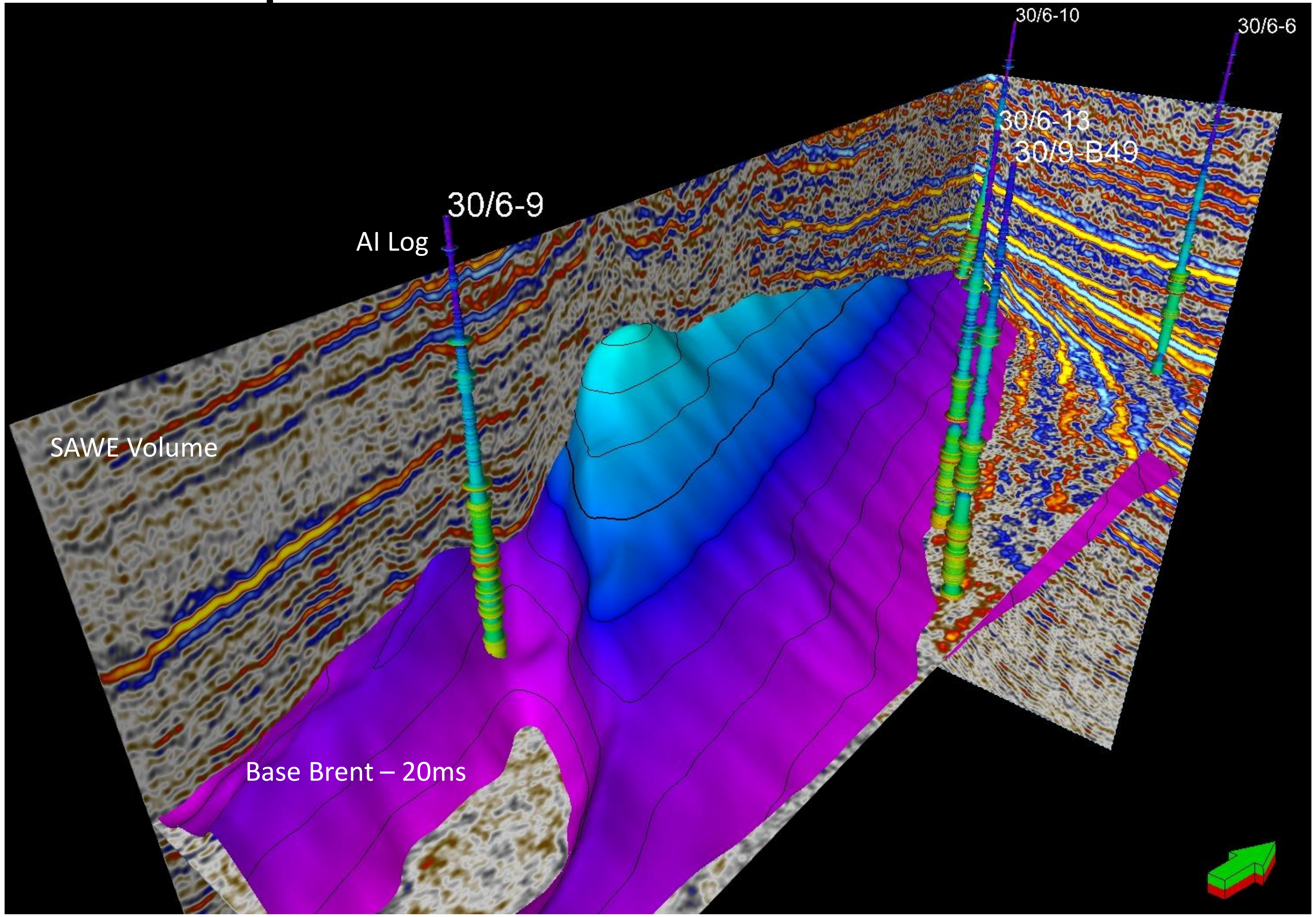
Workflow - 2

- Structural model building (time domain)
  - Fault modelling, create zones and layering
- Upscaling well log AI into structural model
- Variogram analysis and modelling
- Prior model building
- Inversion QC

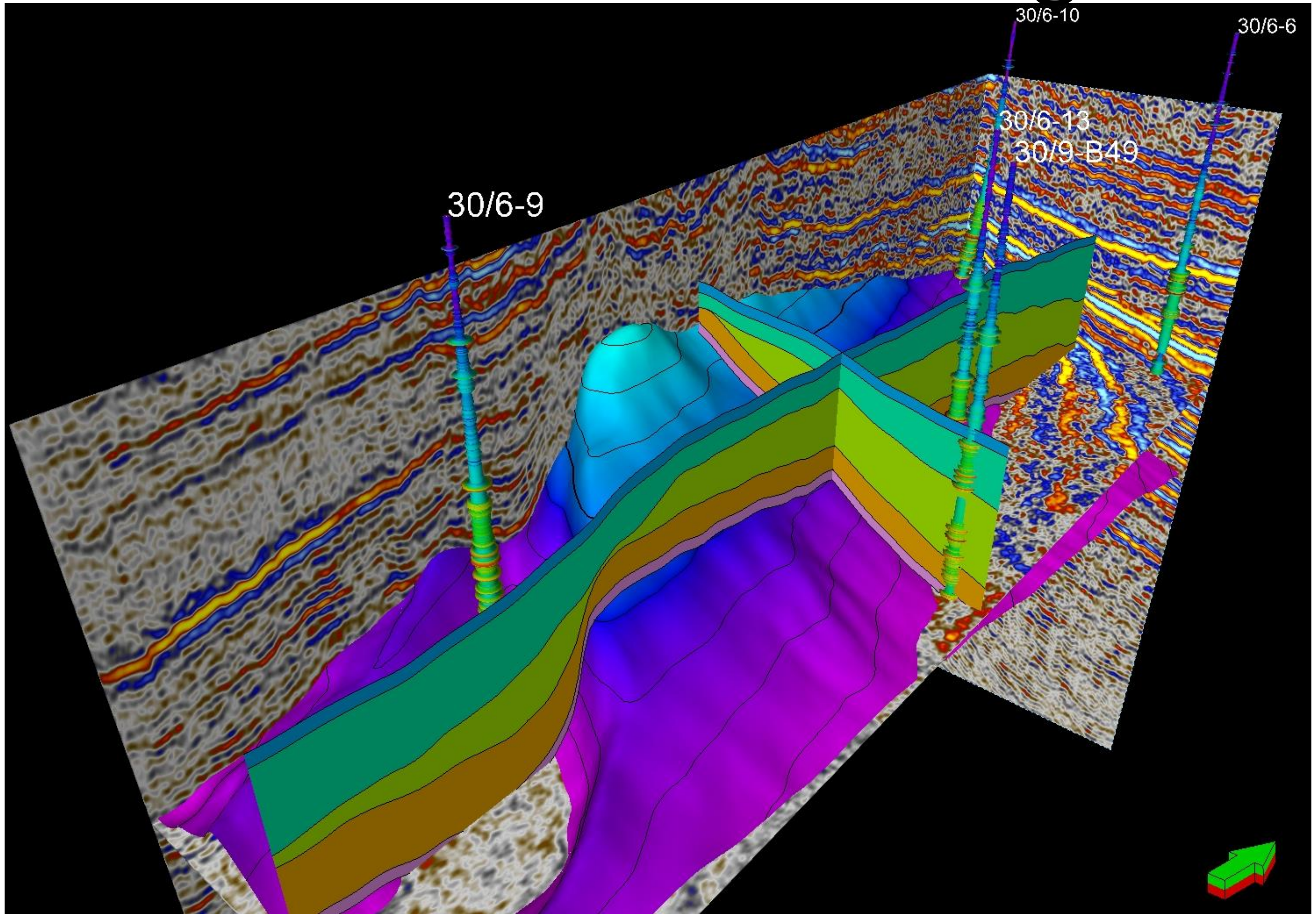
Workflow – Input Wavelet



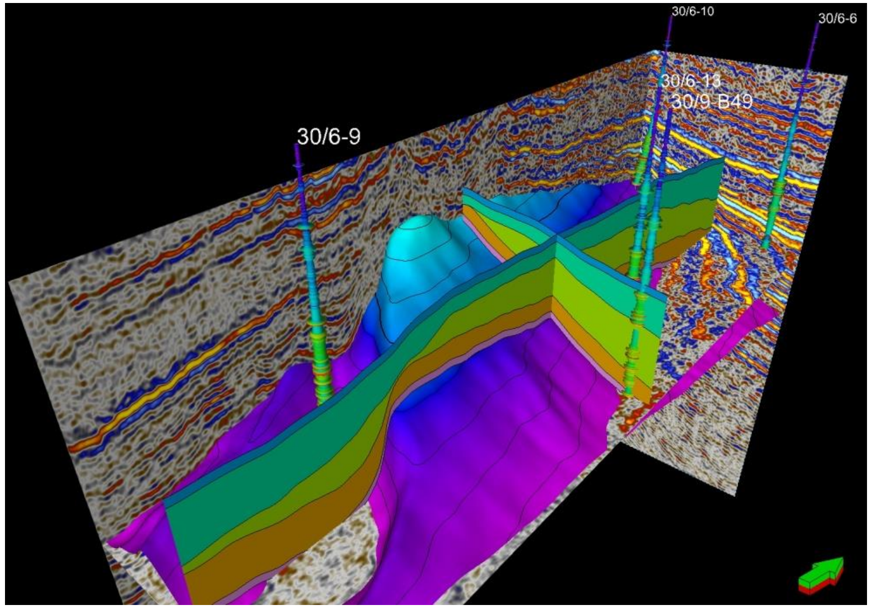
Workflow - Input Data



Workflow – Structural Modelling

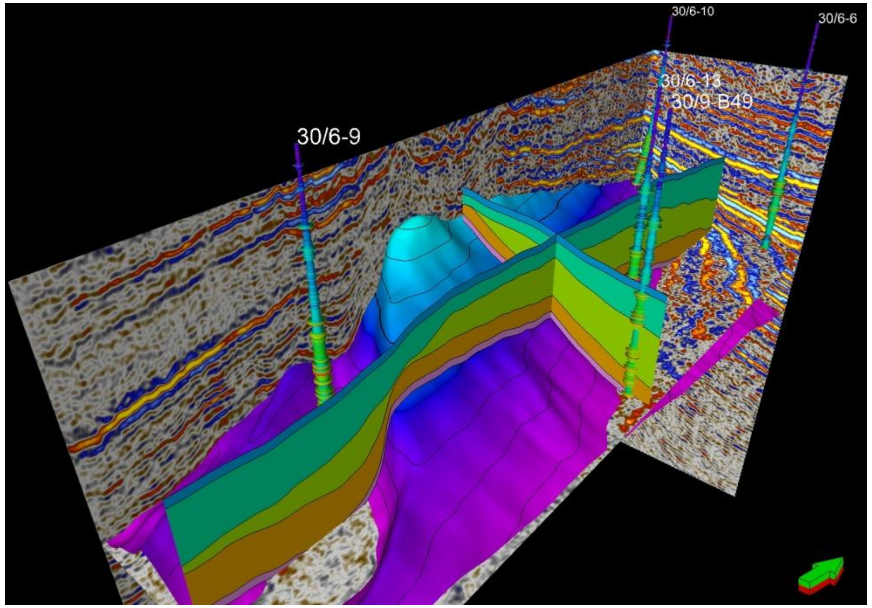


Workflow – Grid Zonation



- Five zones:
  - TCRET+20 to TCRET
  - TCRET to BCRET
  - BCRET to TBRENT
  - TBRENT to BBRENT
  - BBRENT to BBRENT-20

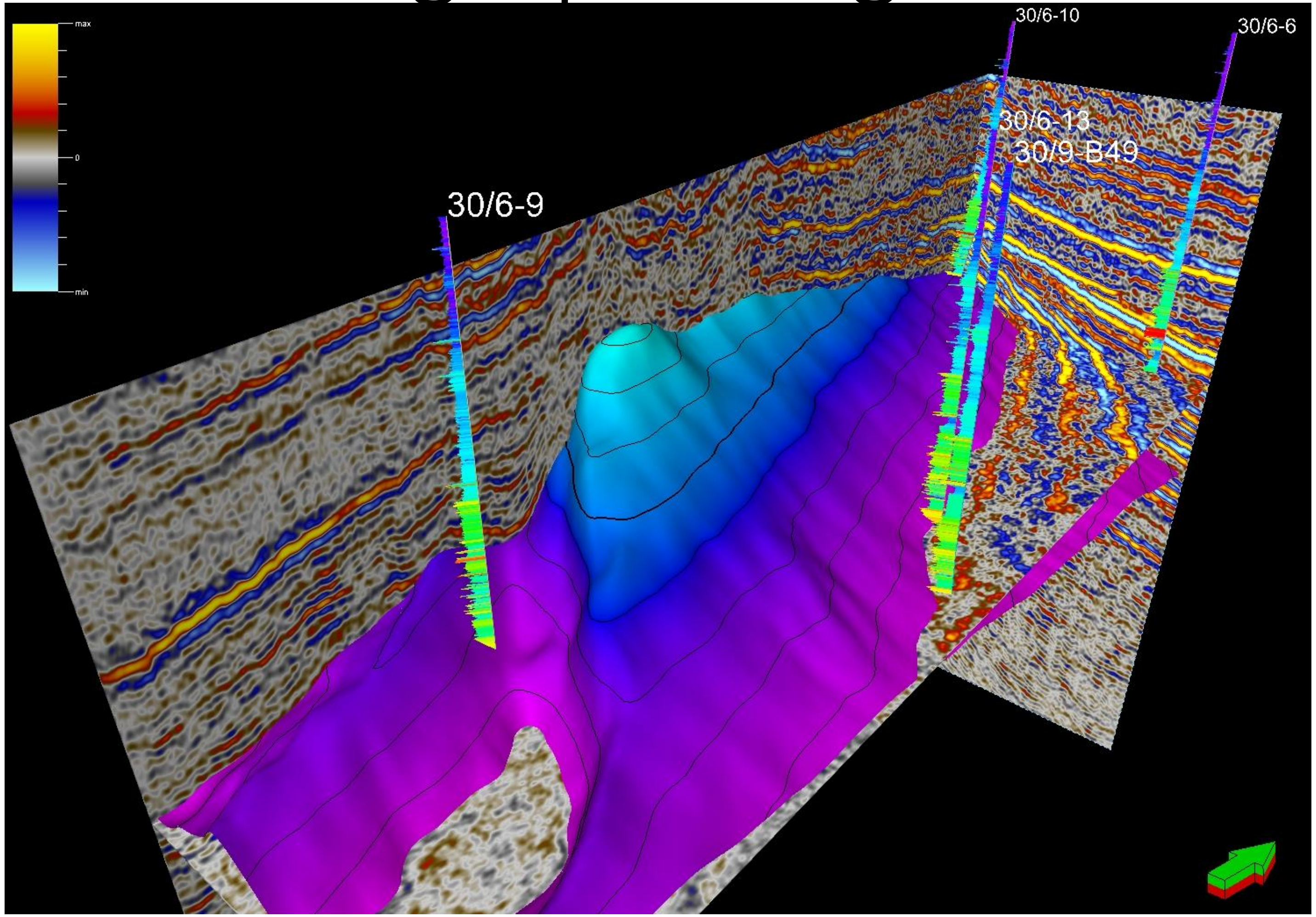
Workflow – Grid Layering



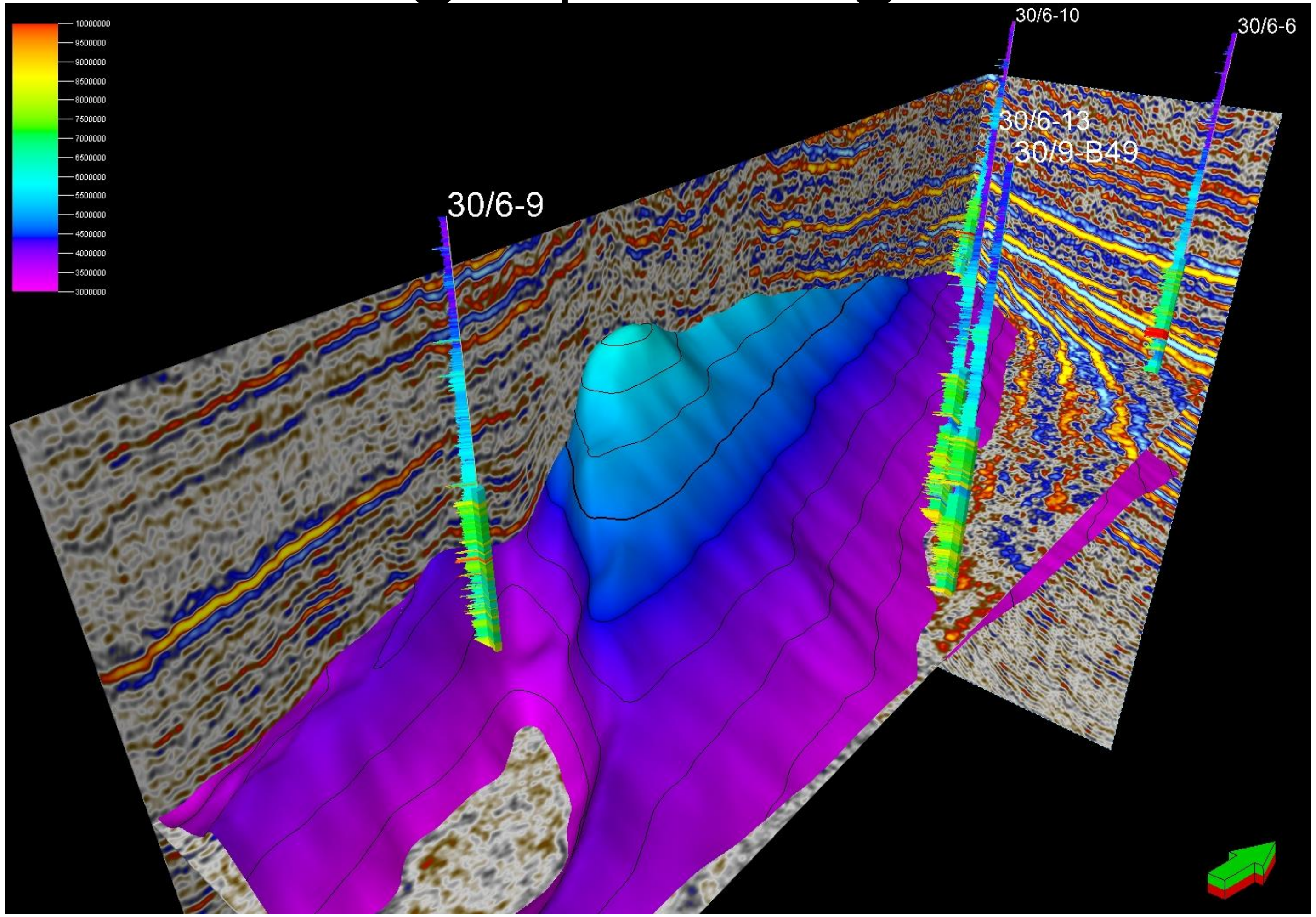
	Name	Color	Calculate	Zone division		
	Zone 1		Yes	Proportional	Number of layers:	10
	Zone 2		Yes	Proportional	Number of layers:	40
	Zone 3		Yes	Proportional	Number of layers:	60
	Zone 4		Yes	Follow base	Cell thickness:	2.00
	Zone 5		Yes	Proportional	Number of layers:	10

- Number of cells:
  NI x NJ x NK =
  180 x 638 x 180 = 20671200
- Cell size:
  25m x 25m x 1.785ms

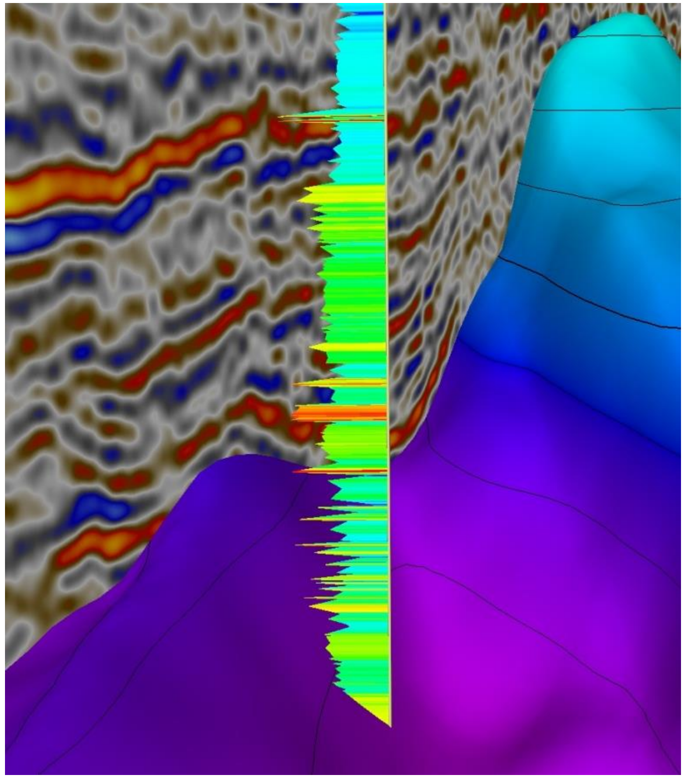
Workflow – AI Log Upscaling



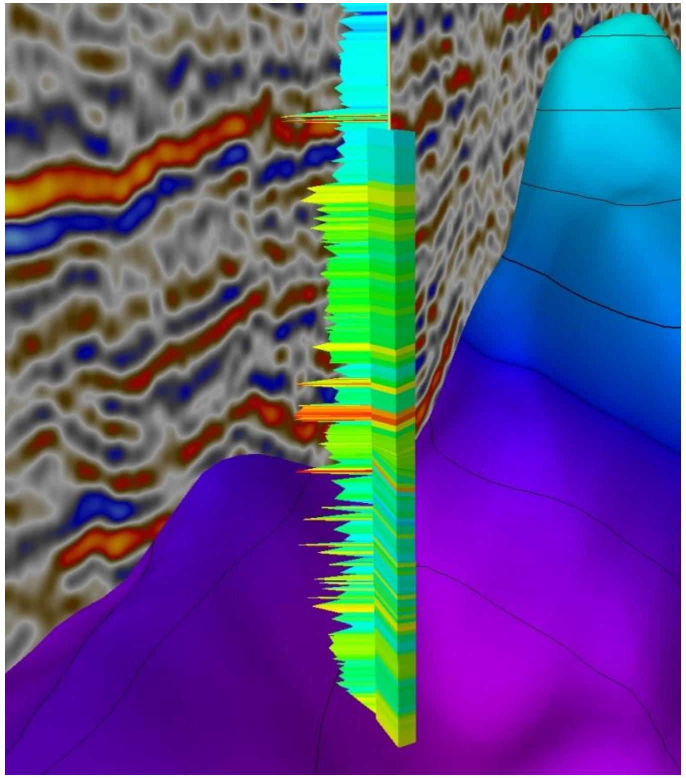
Workflow – AI Log Upscaling



Workflow – AI Log Upscaling

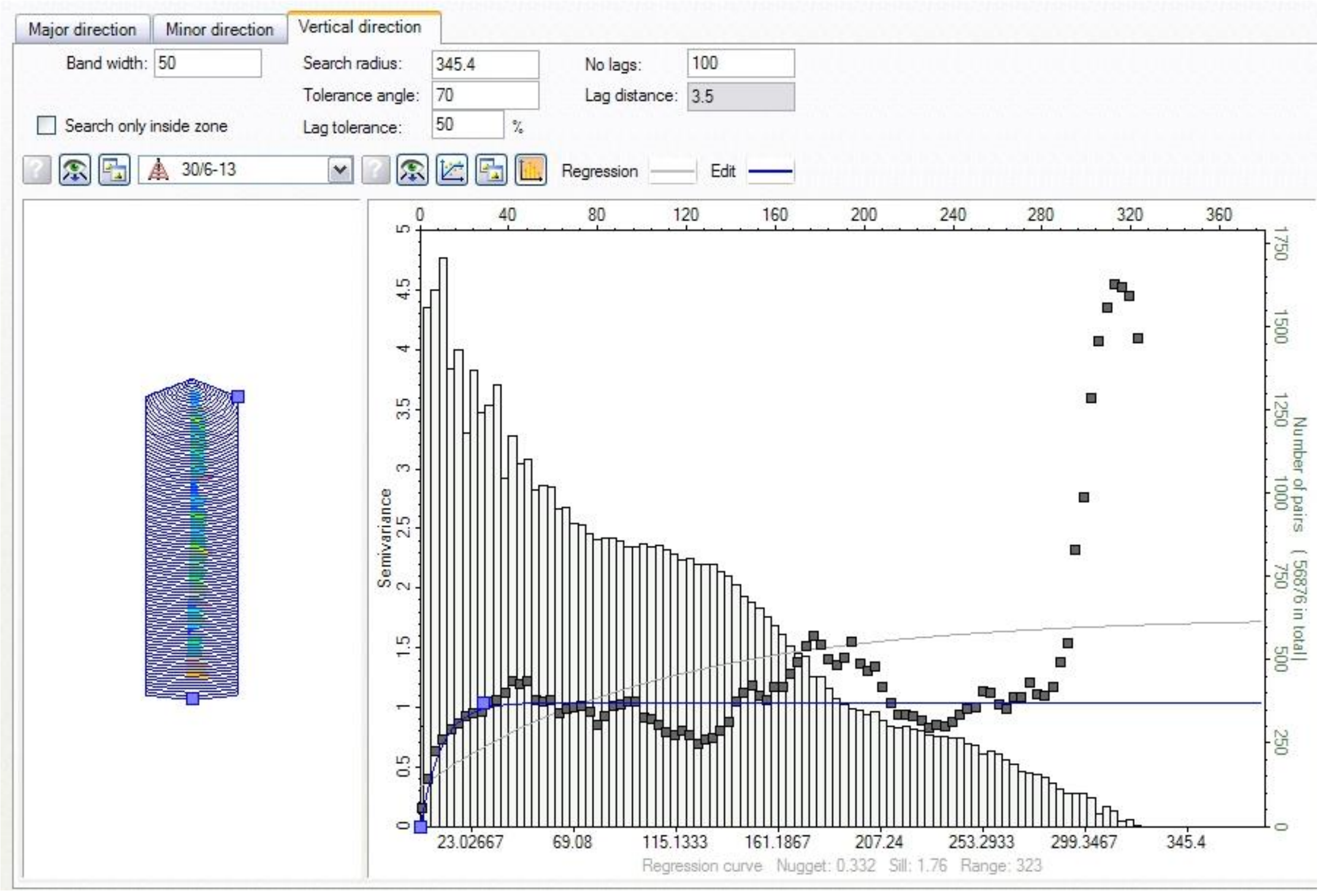


AI Log



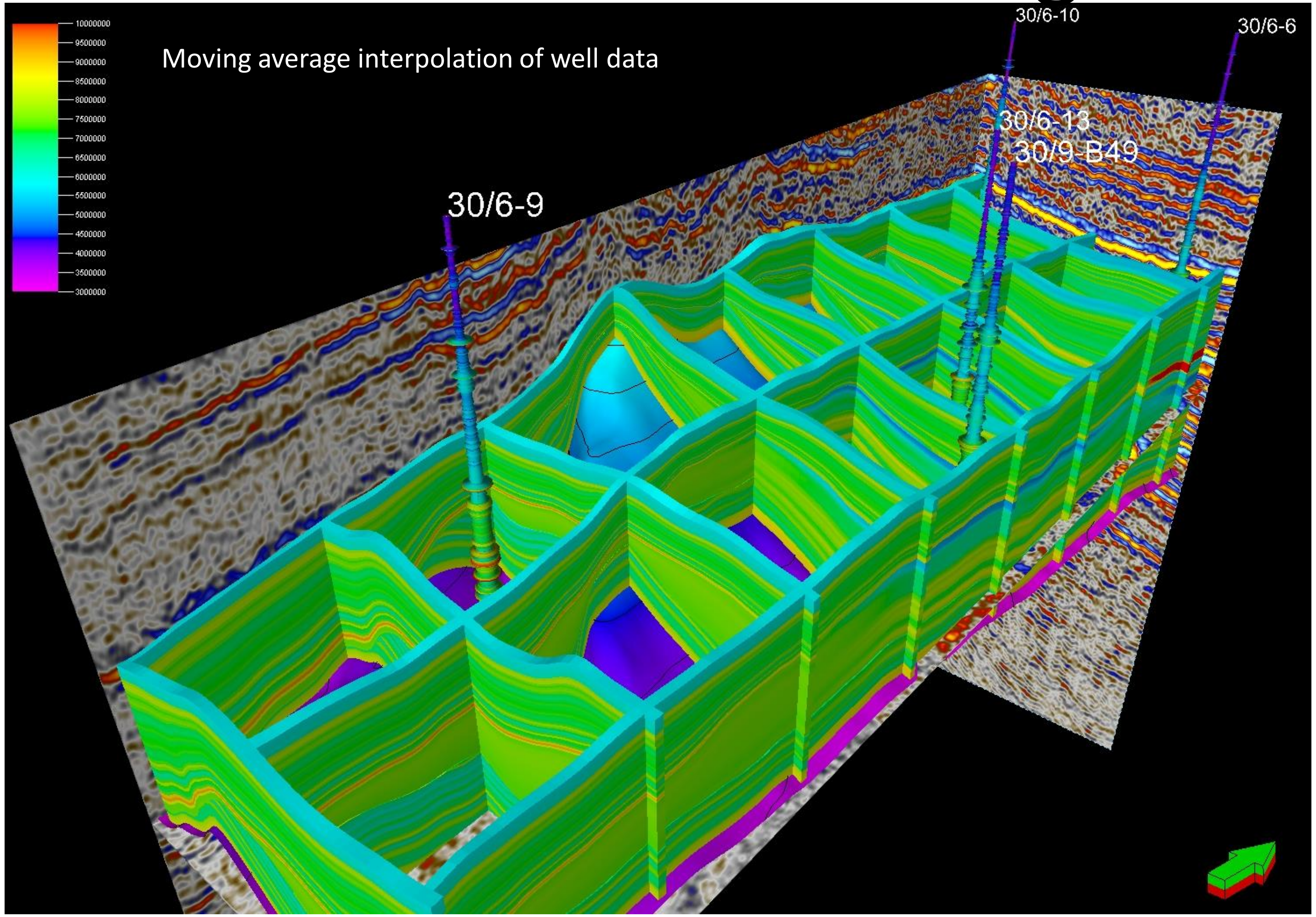
Upscaled AI Log

Workflow – Variogram Modelling

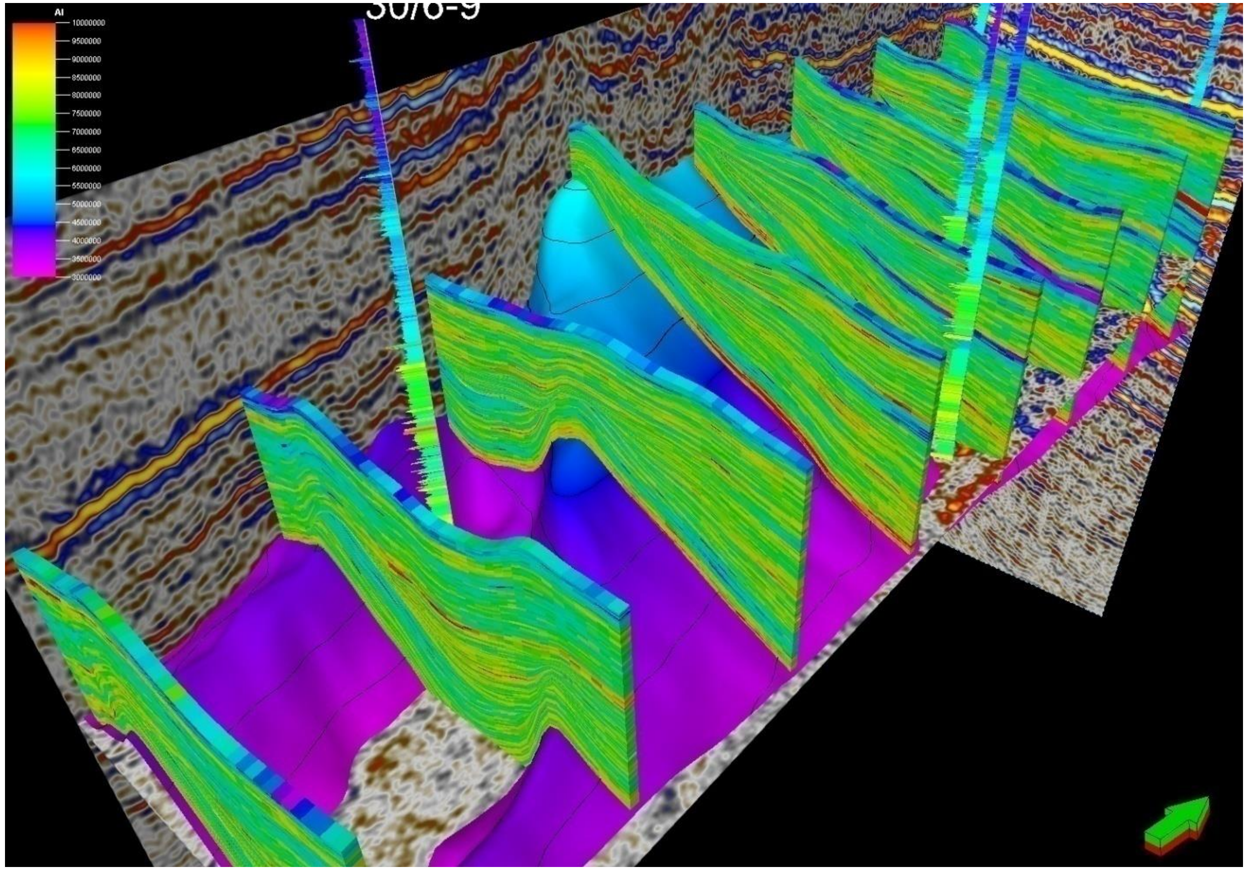


Vertical direction

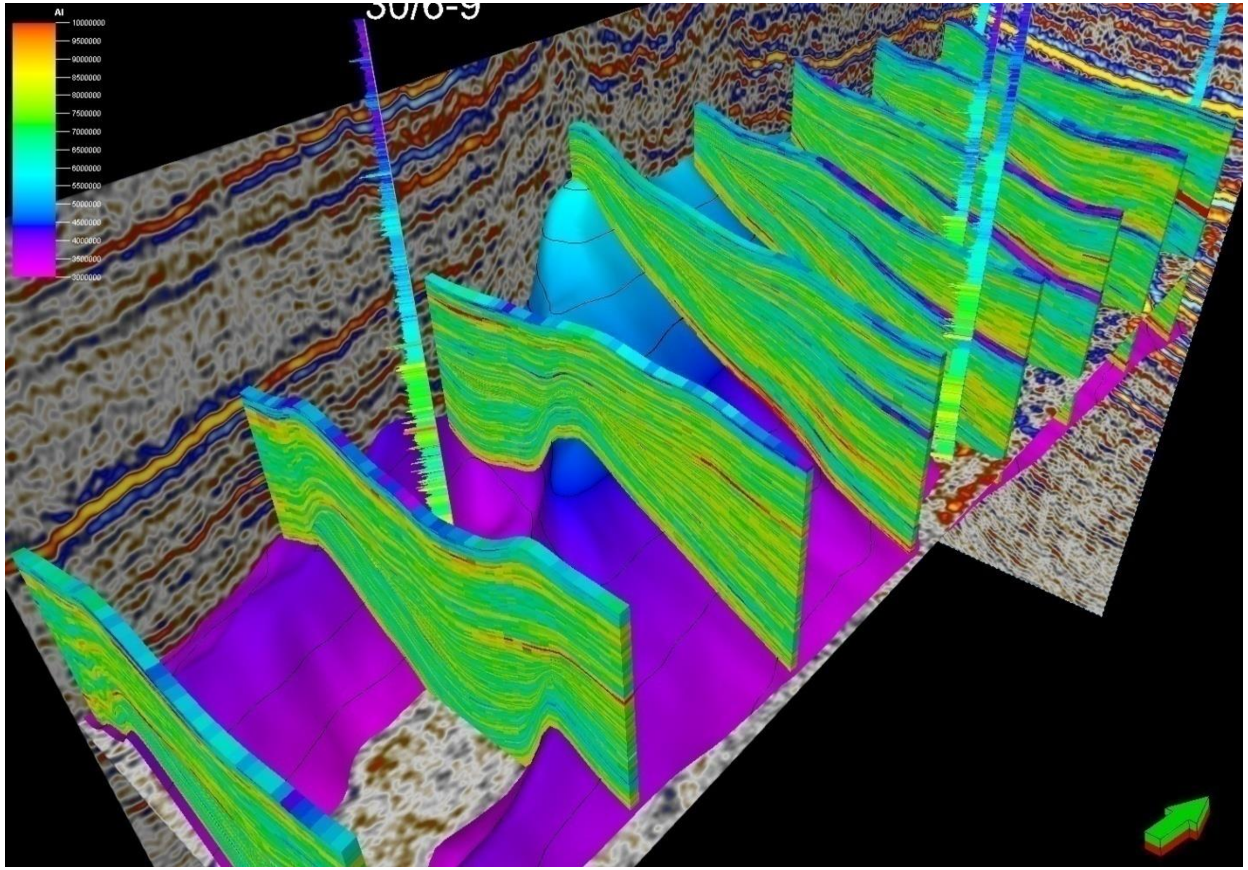
Workflow – Prior Model Building



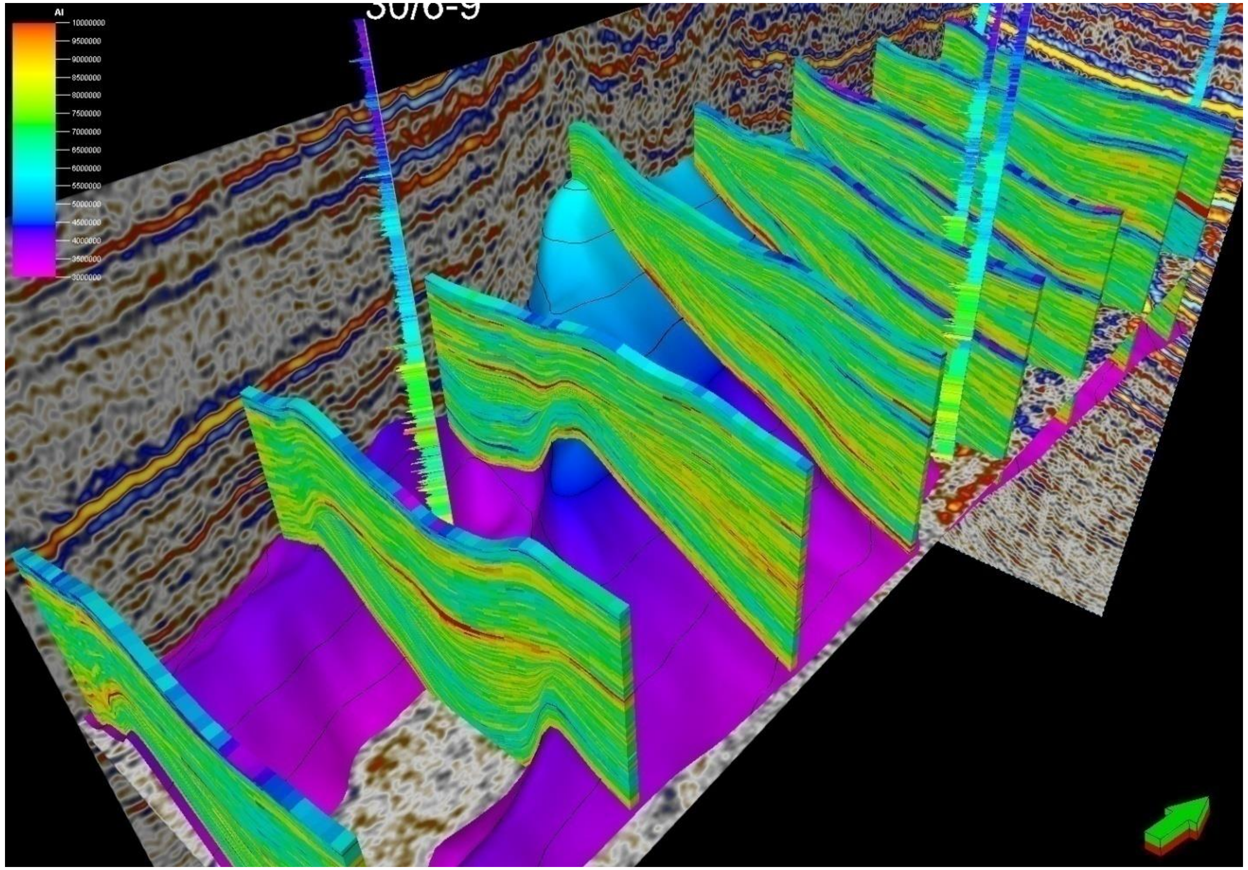
Workflow – Realization #1



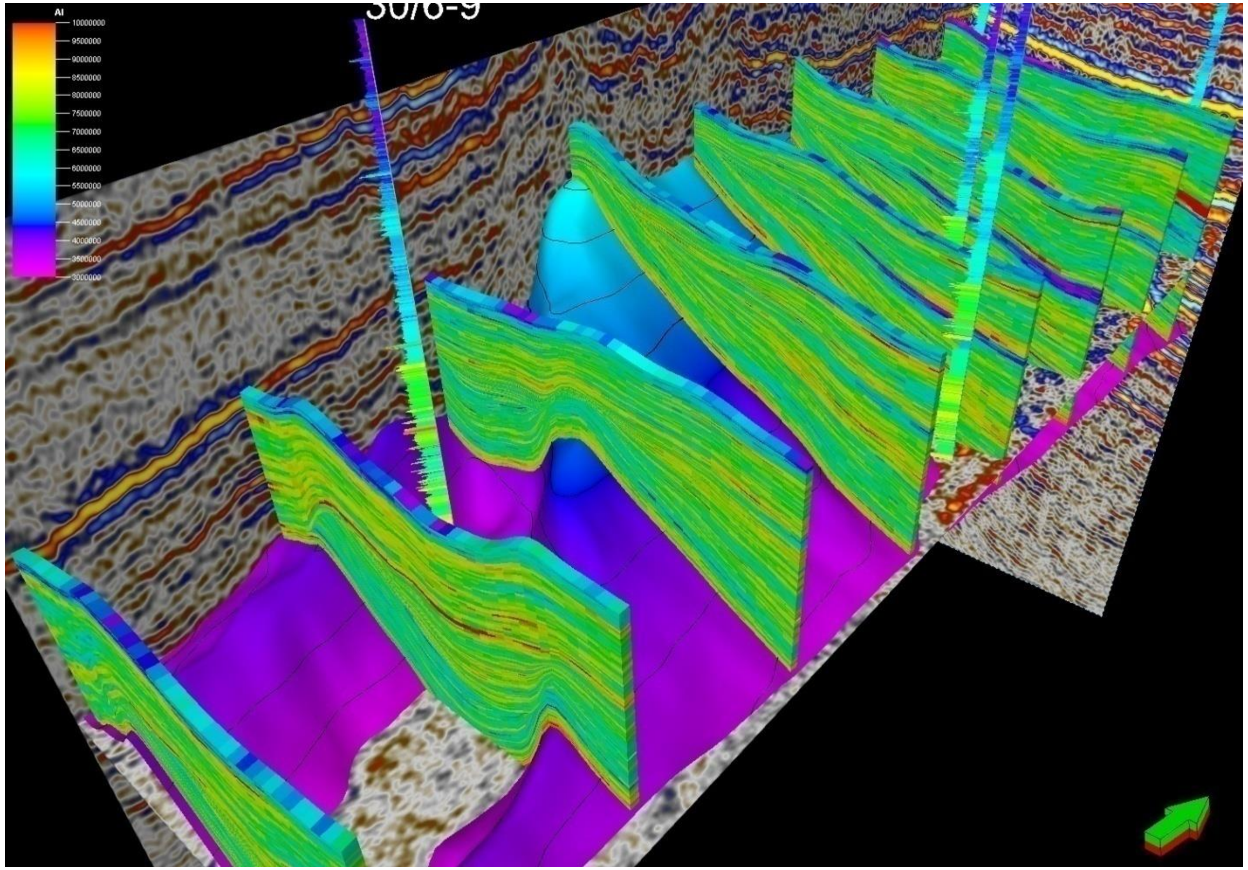
Workflow – Realization #2



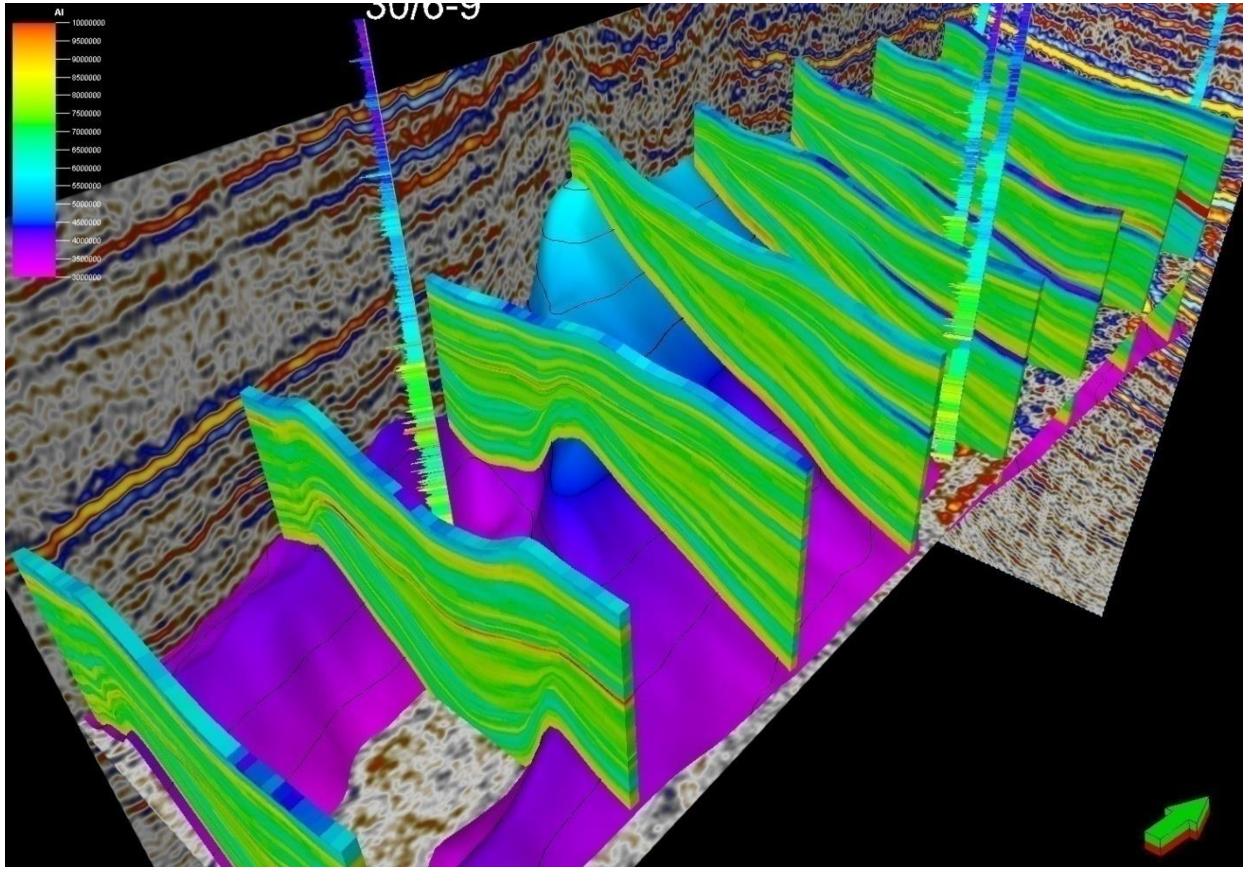
Workflow – Realization #3



Workflow – Realization #4

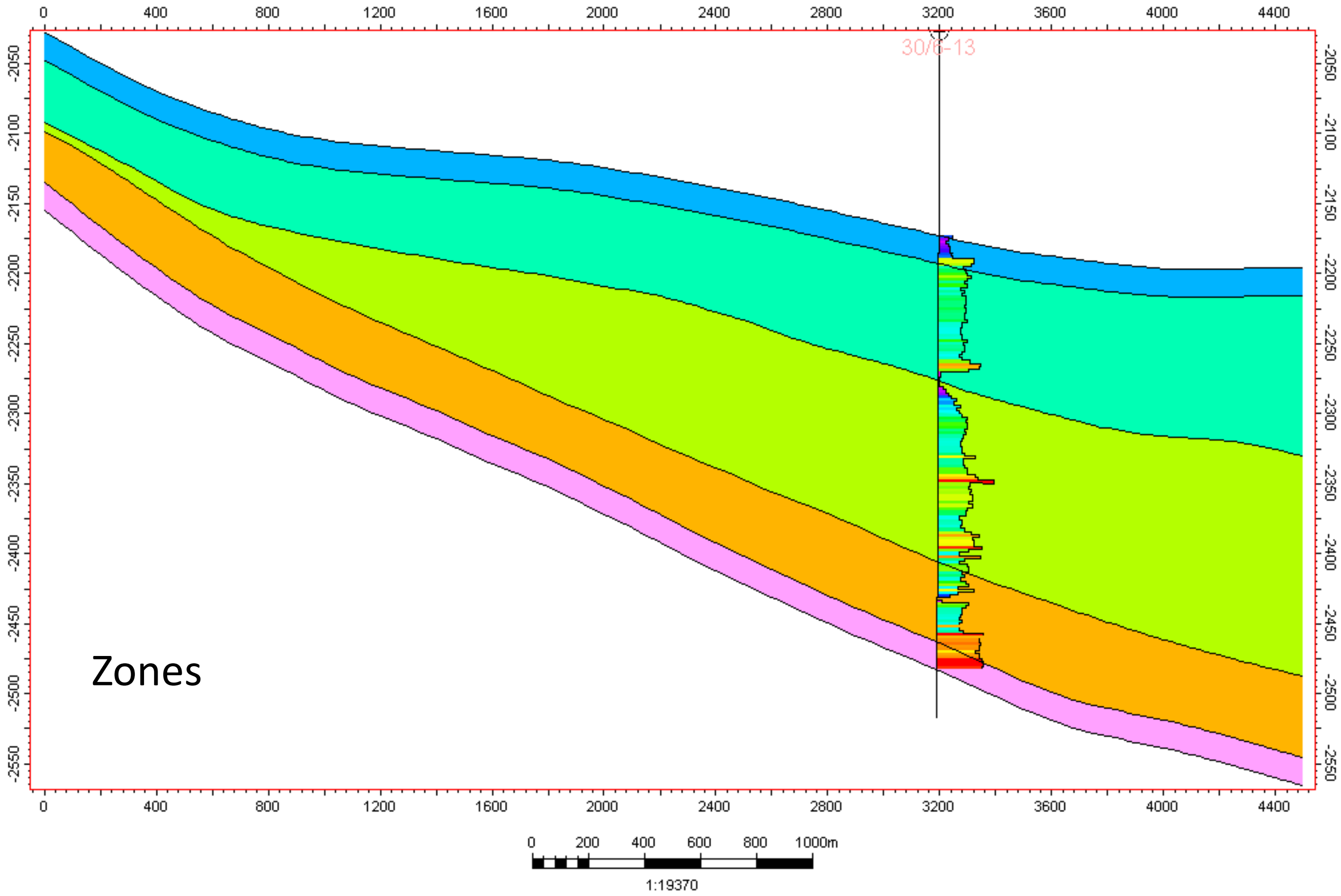


Workflow – Mean of 100 Realizations

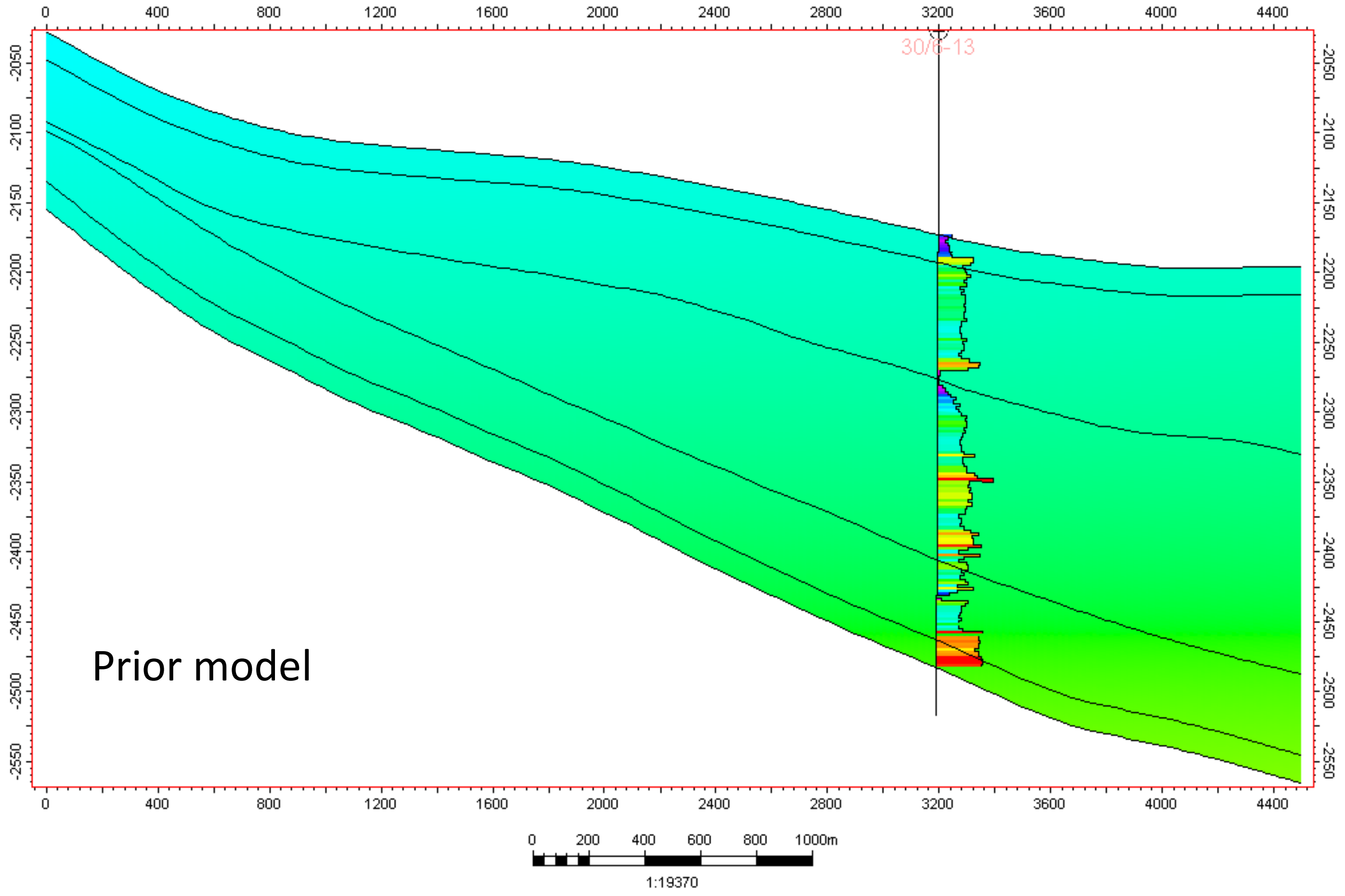


Cross-sections through 30/6-13

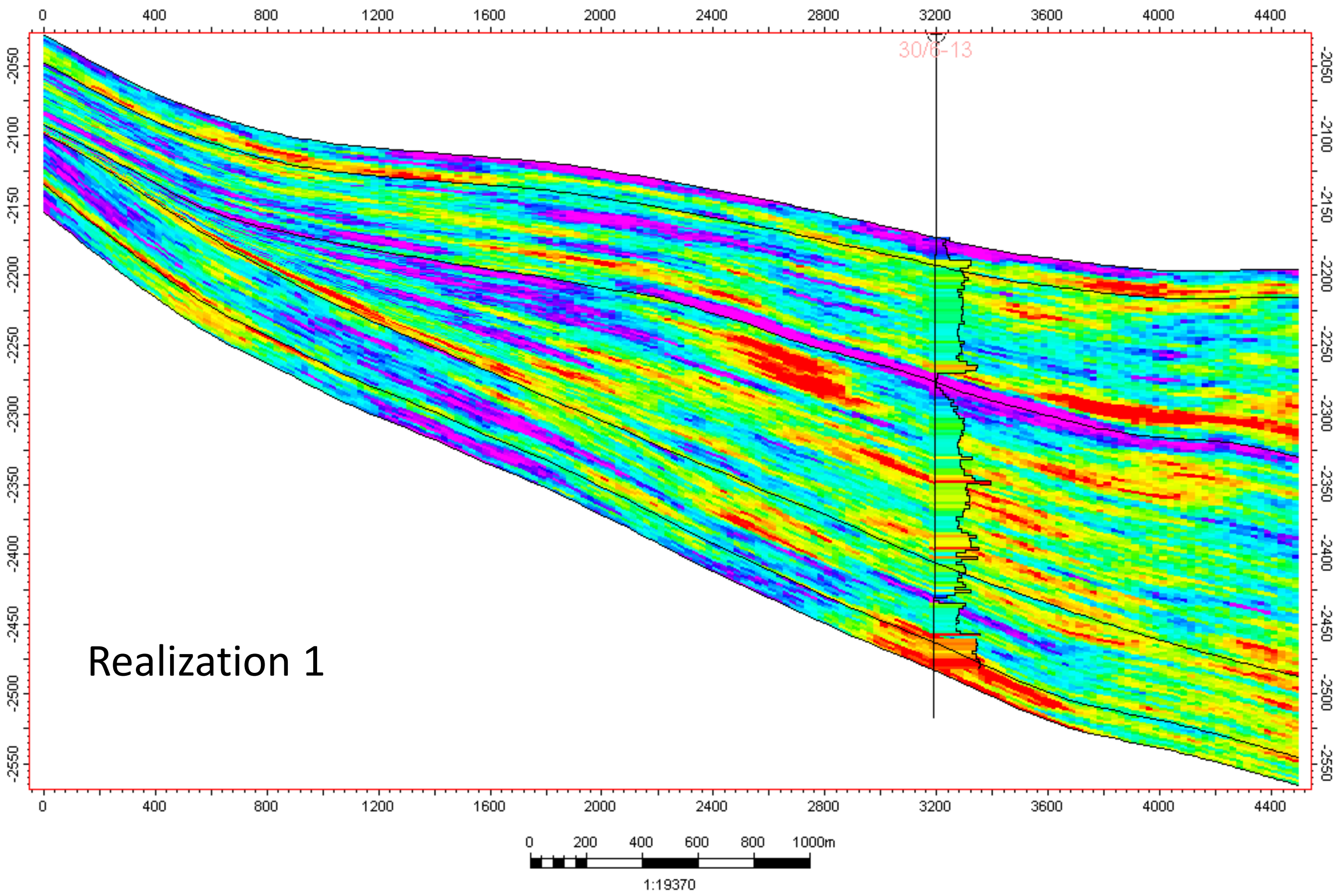
Cross-Section – 30/6-13



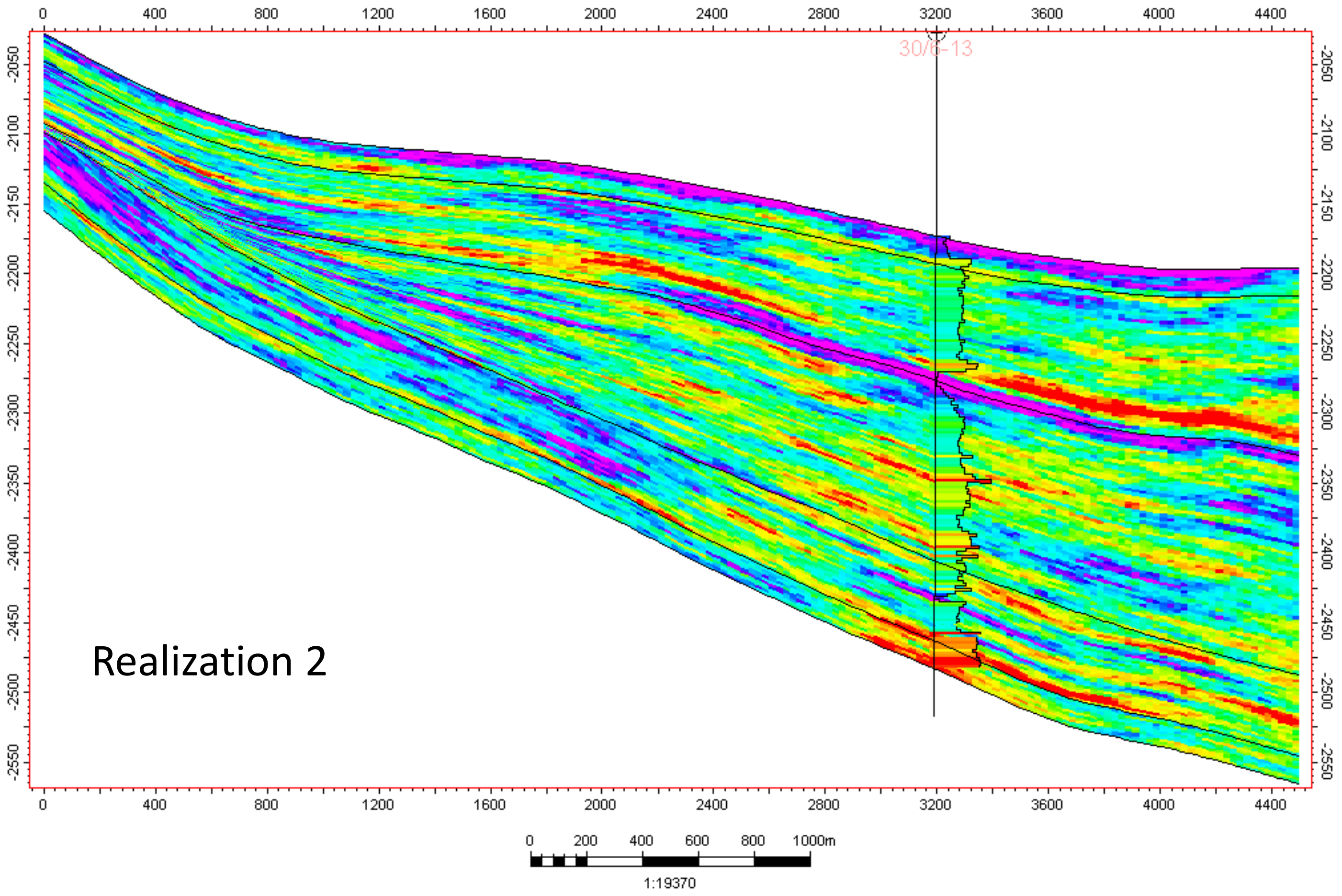
Cross-Section – 30/6-13



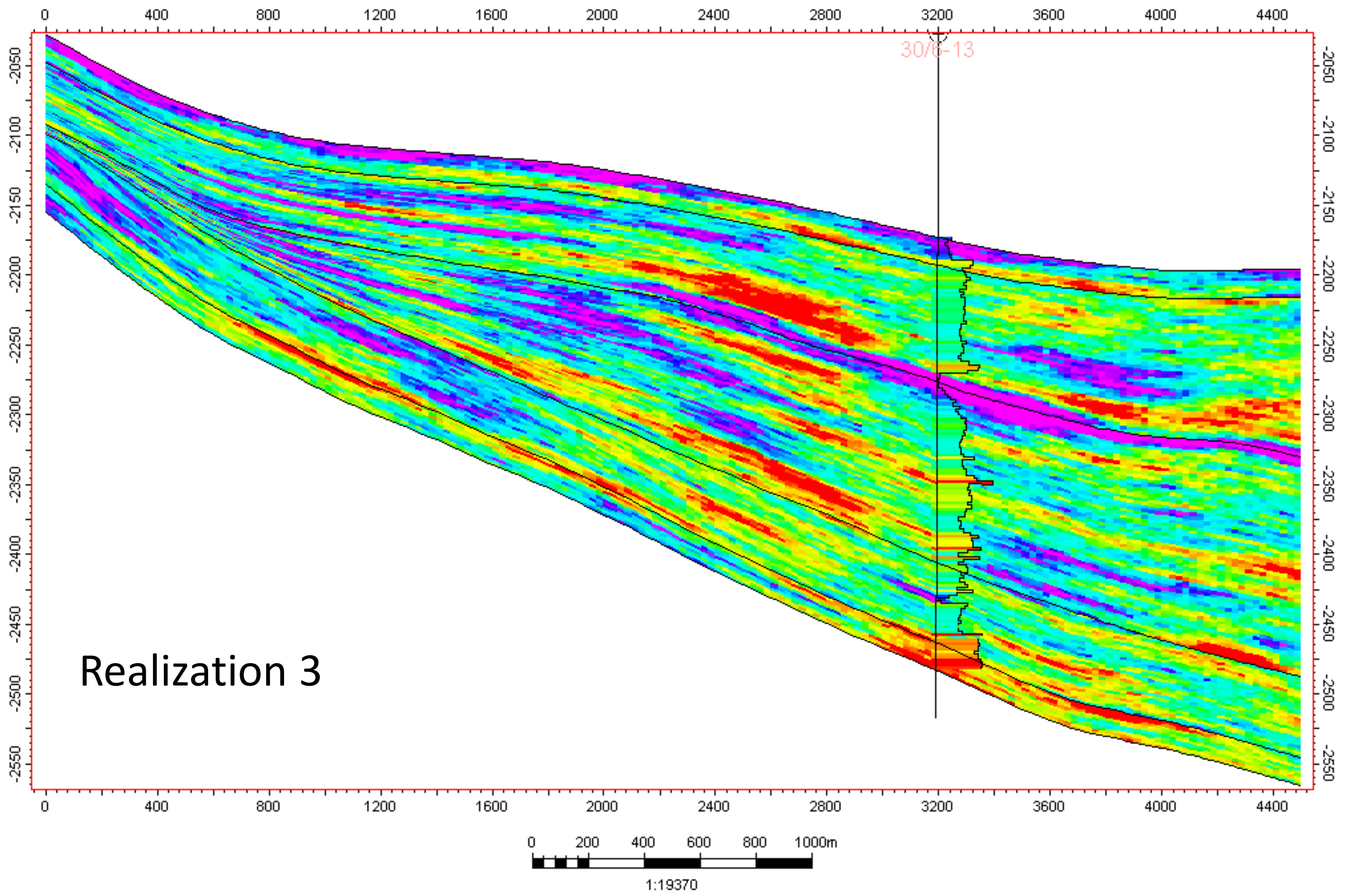
Cross-Section – 30/6-13



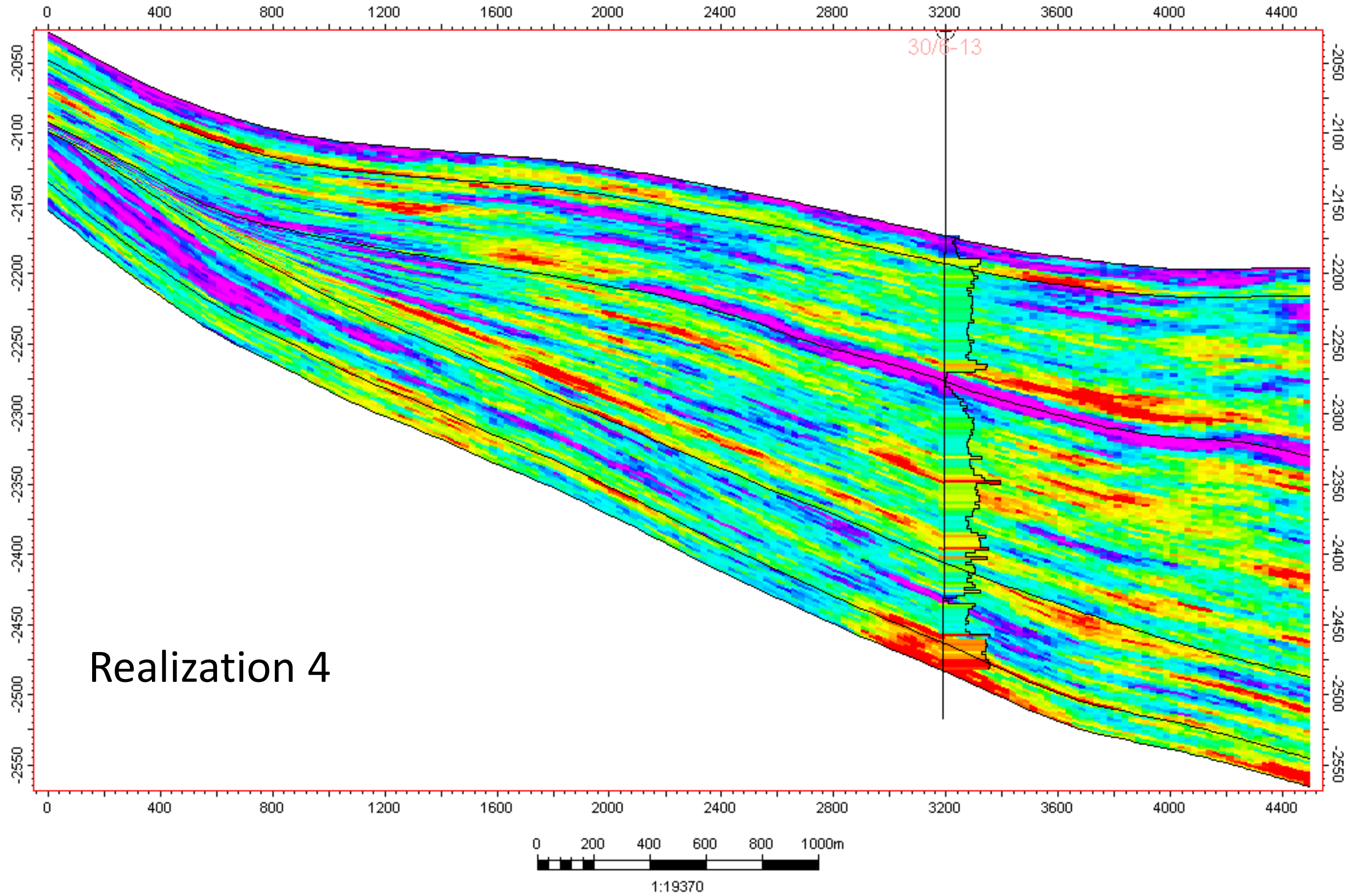
Cross-Section – 30/6-13



Cross-Section – 30/6-13

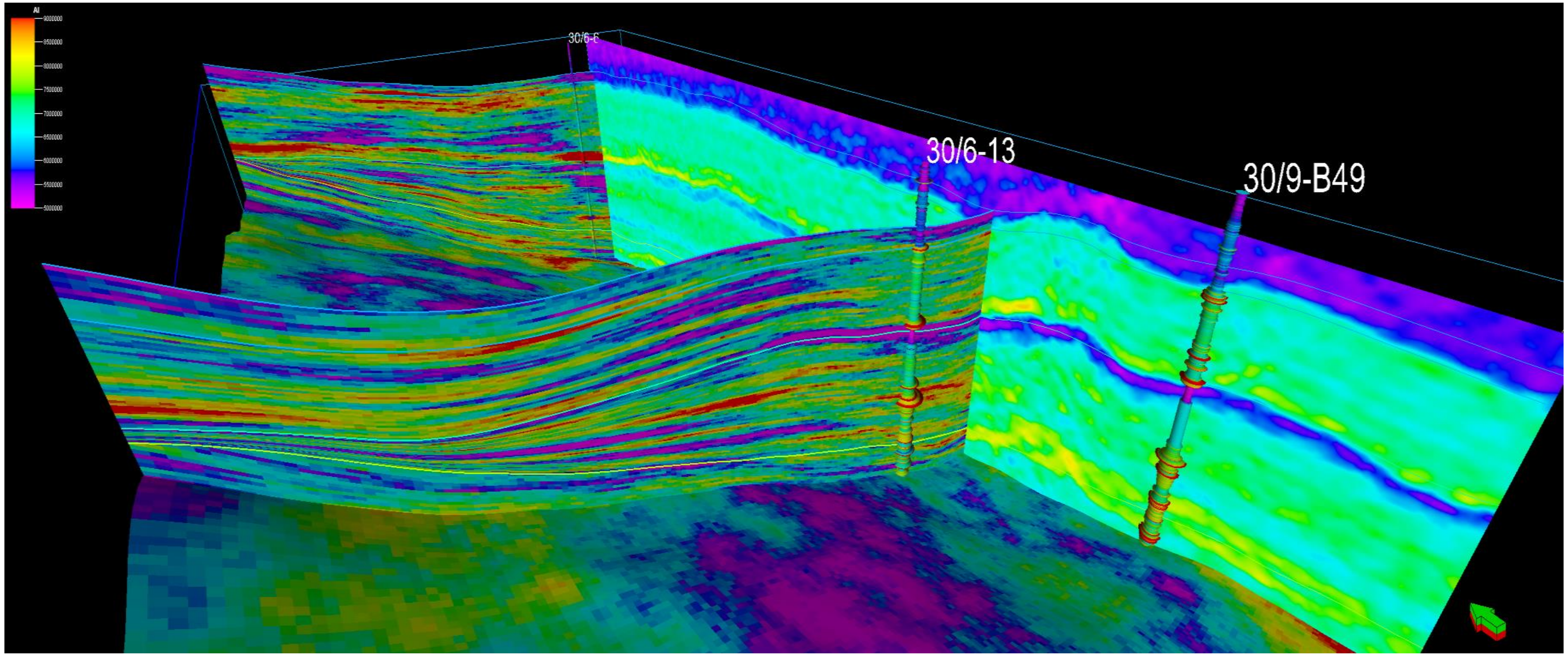


Cross-Section – 30/6-13

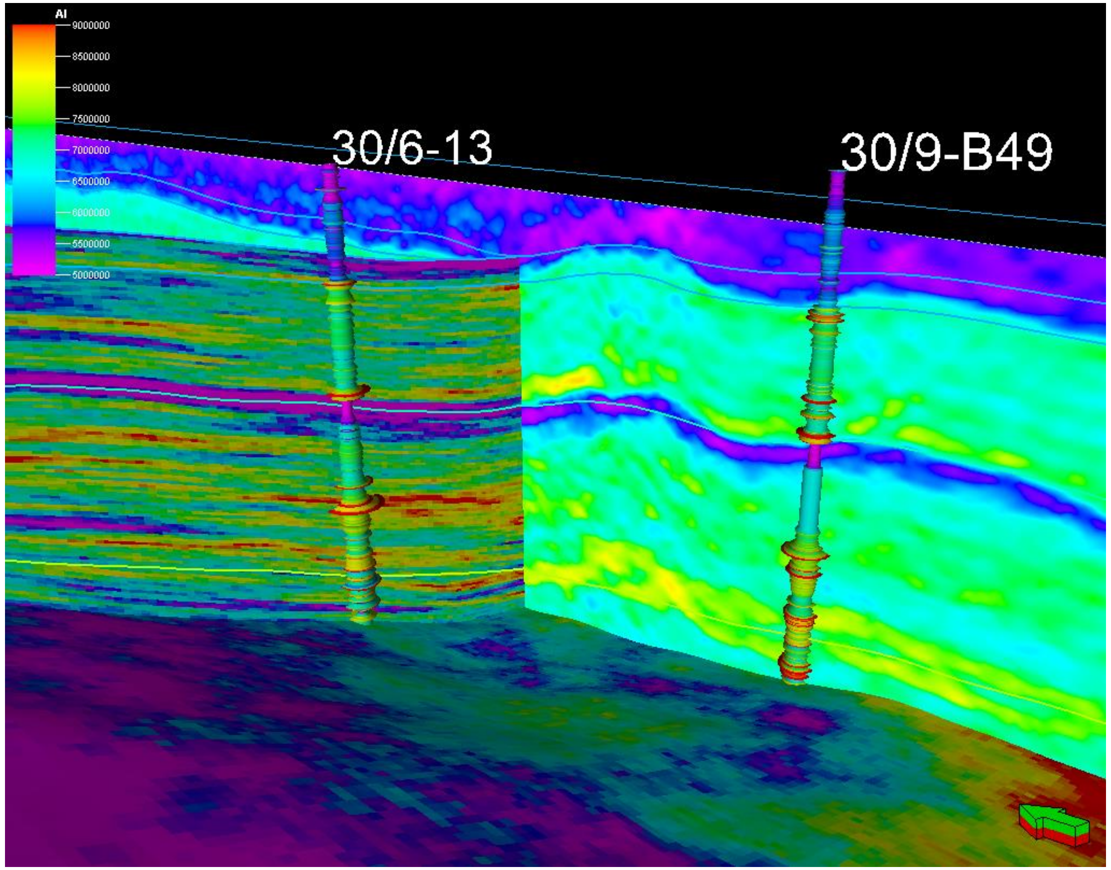


Section 4.
Comparing stochastic and deterministic inversions

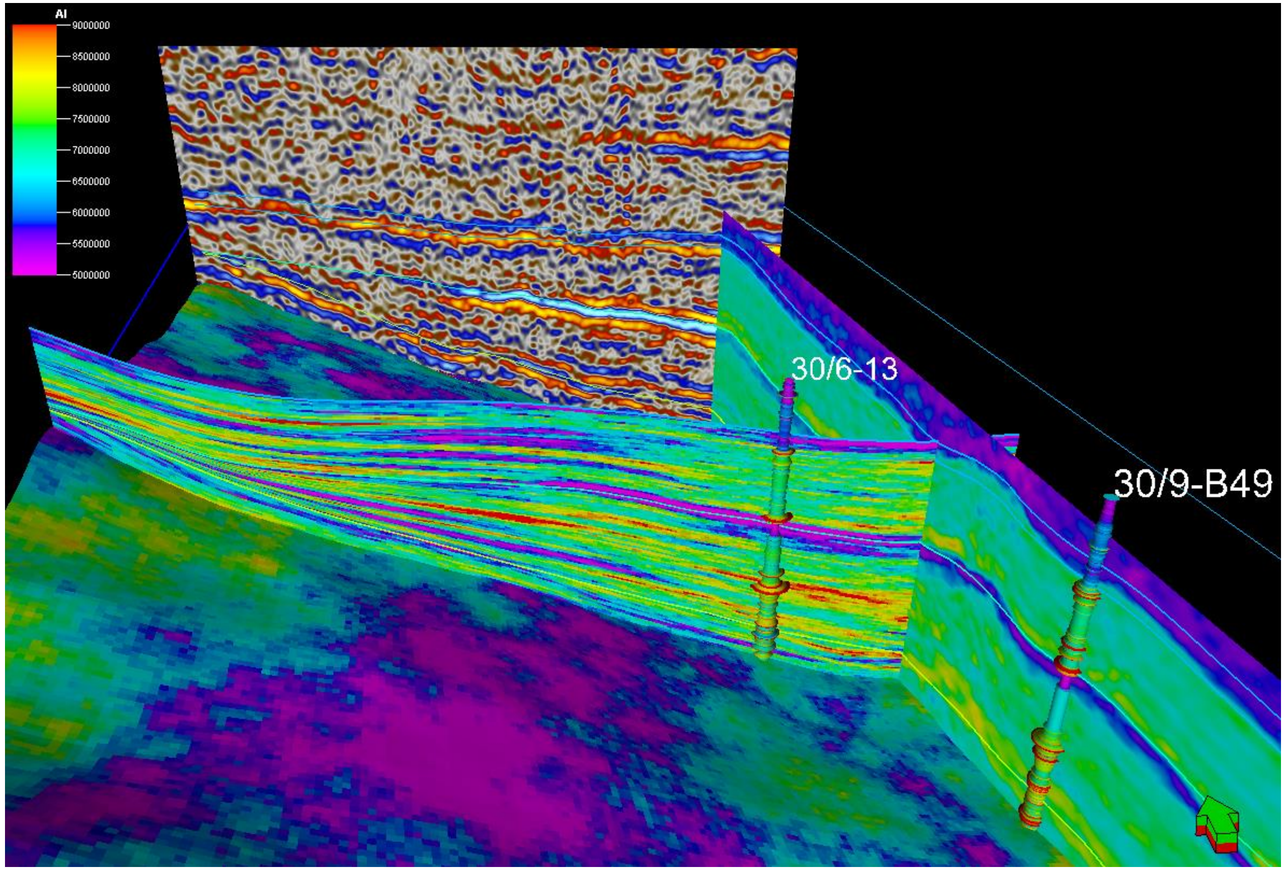
Stochastic-Deterministic Comparison



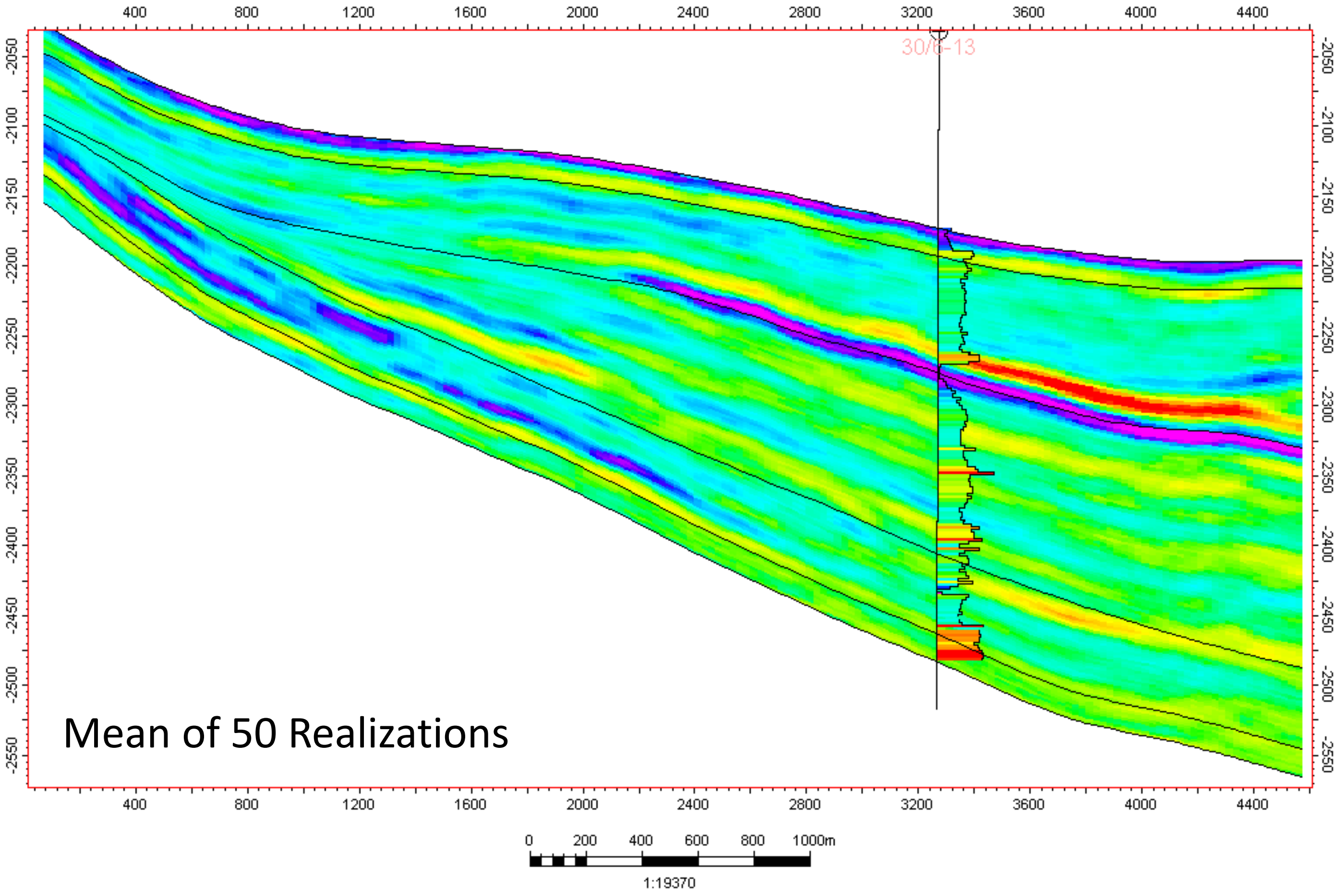
Stochastic-Deterministic Comparison



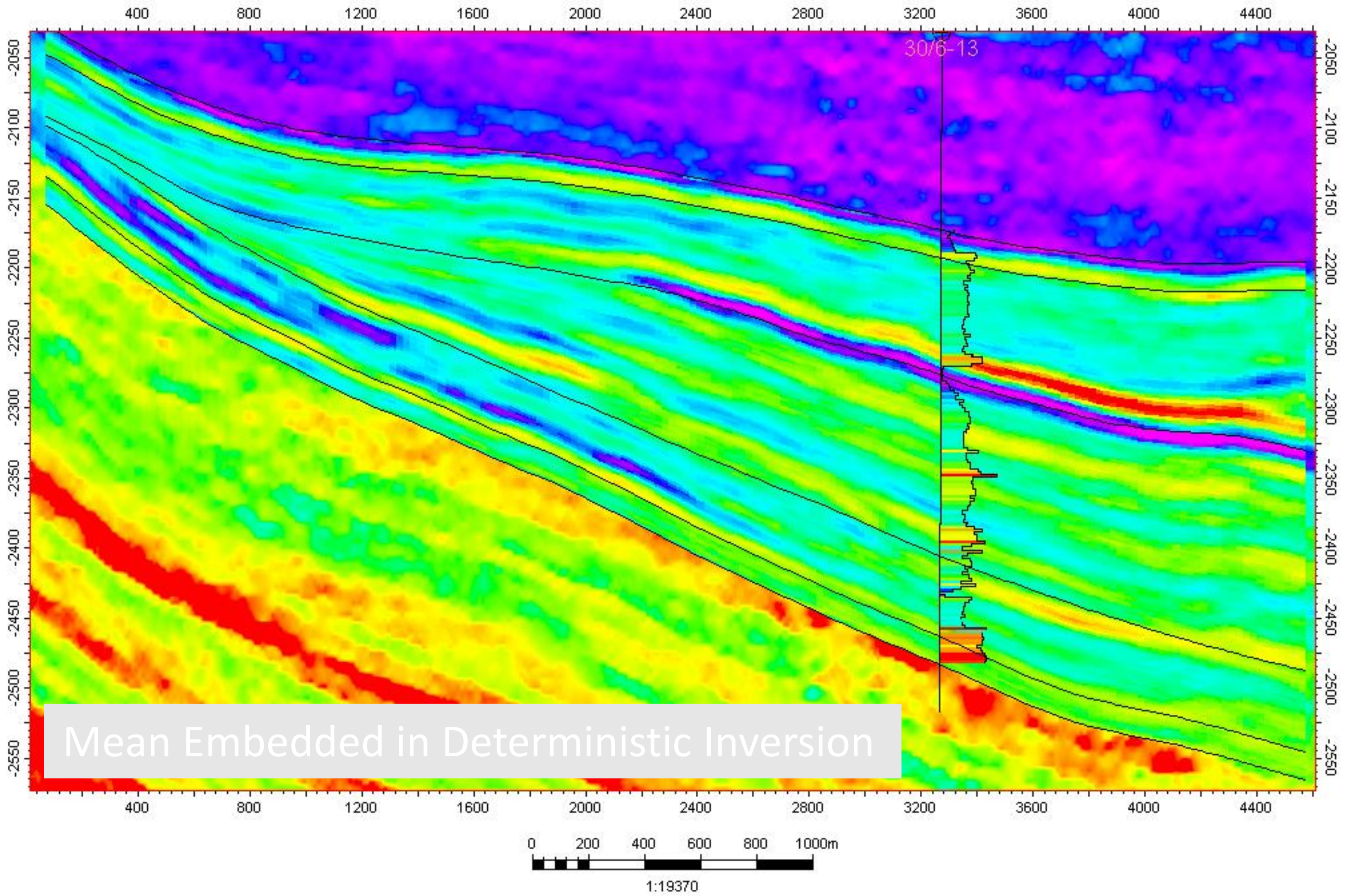
Stochastic-Deterministic Comparison



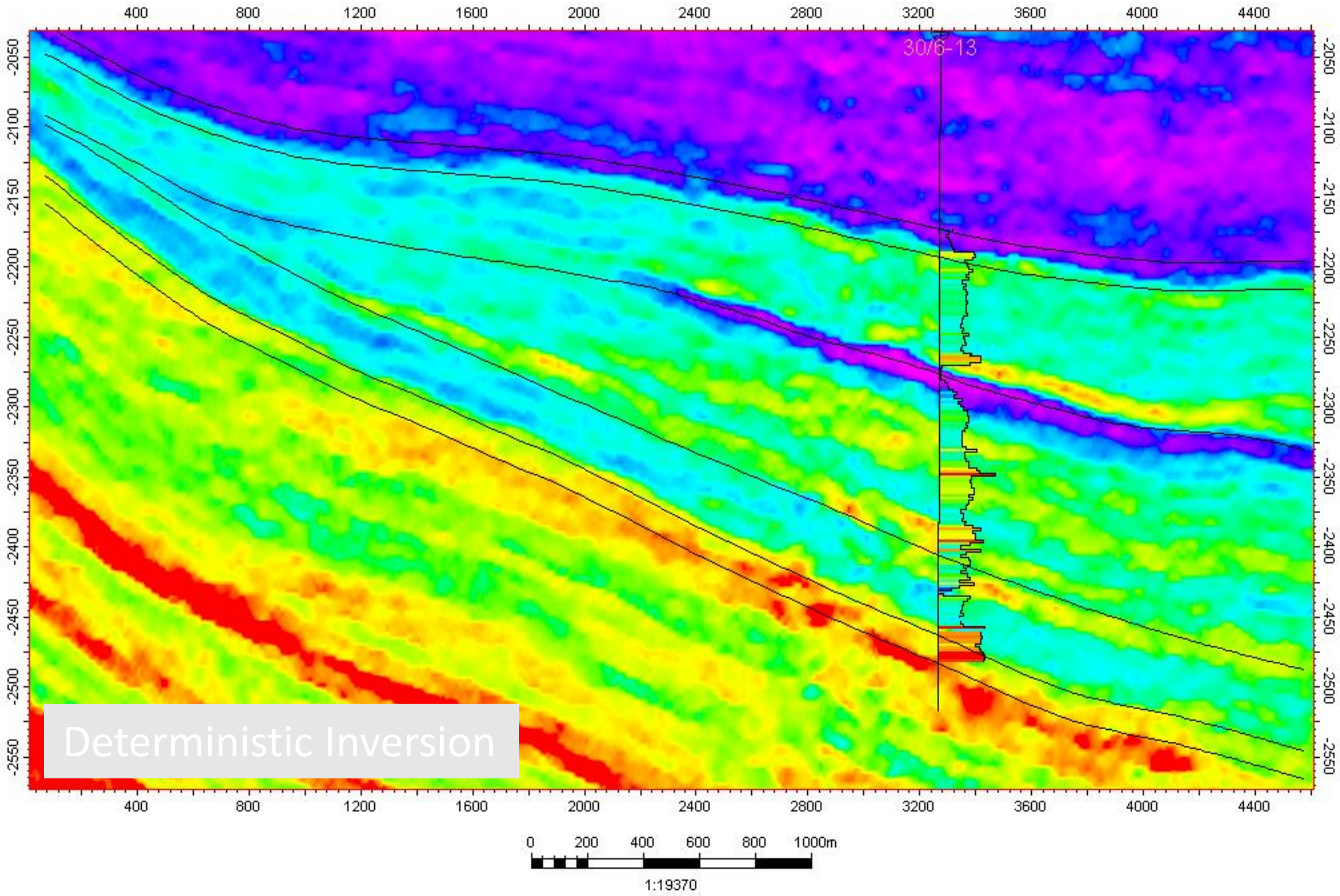
Cross-Section – 30/6-13



Cross-Section – 30/6-13

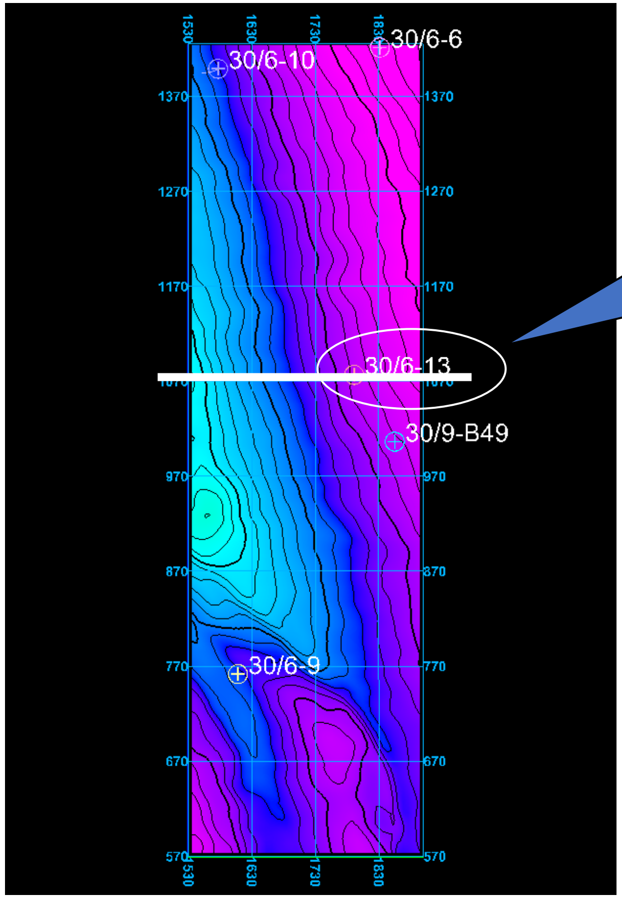


Cross-Section – 30/6-13



Section 5.
Validating stochastic inversion at blind wells

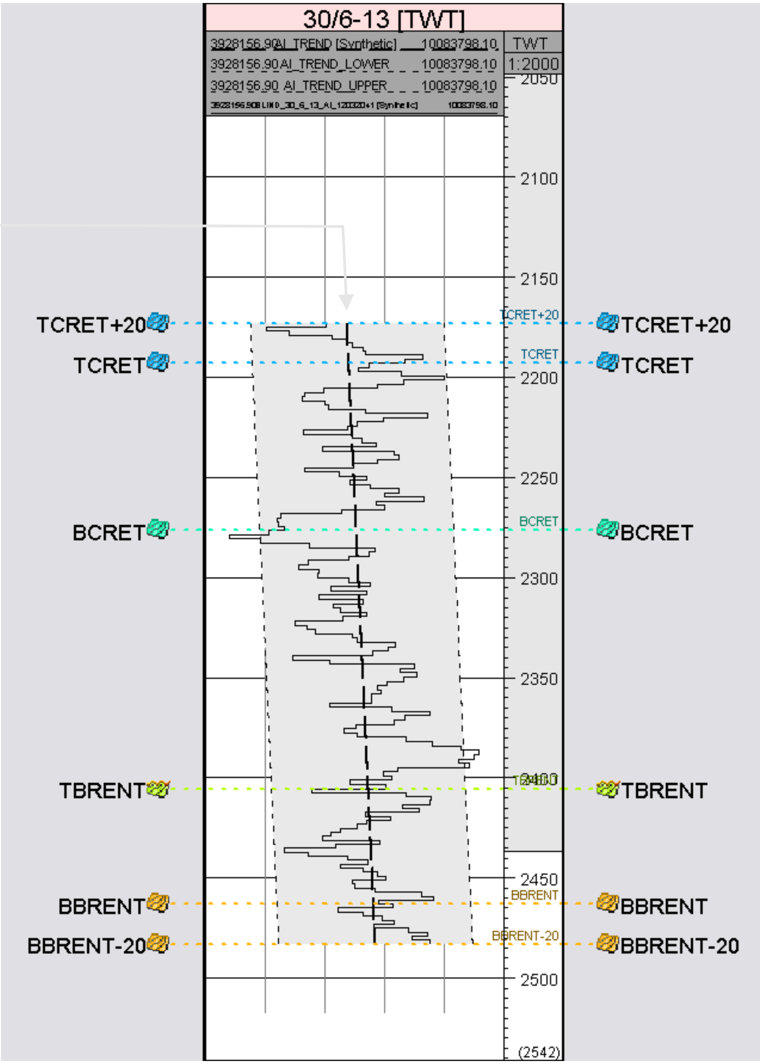
Blind Well Validation



well 30/6-13 not used in this example

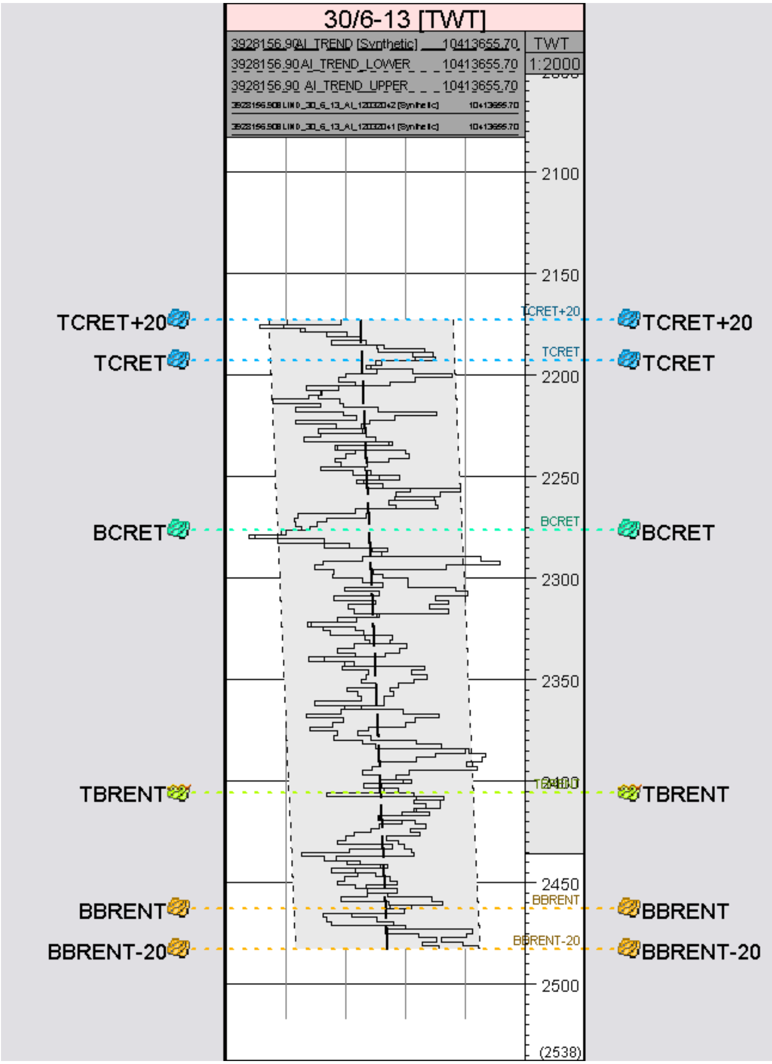
Blind Well Validation – 30/6-13

Slight, constant background trend



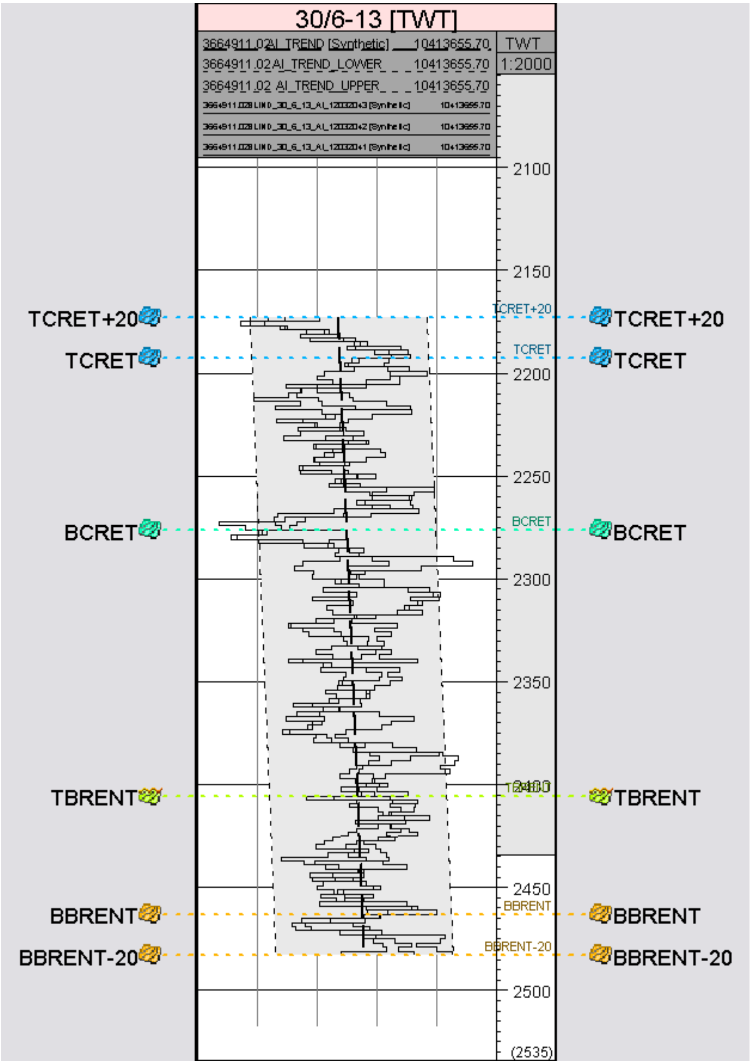
Single realization plotted

Blind Well Validation – 30/6-13



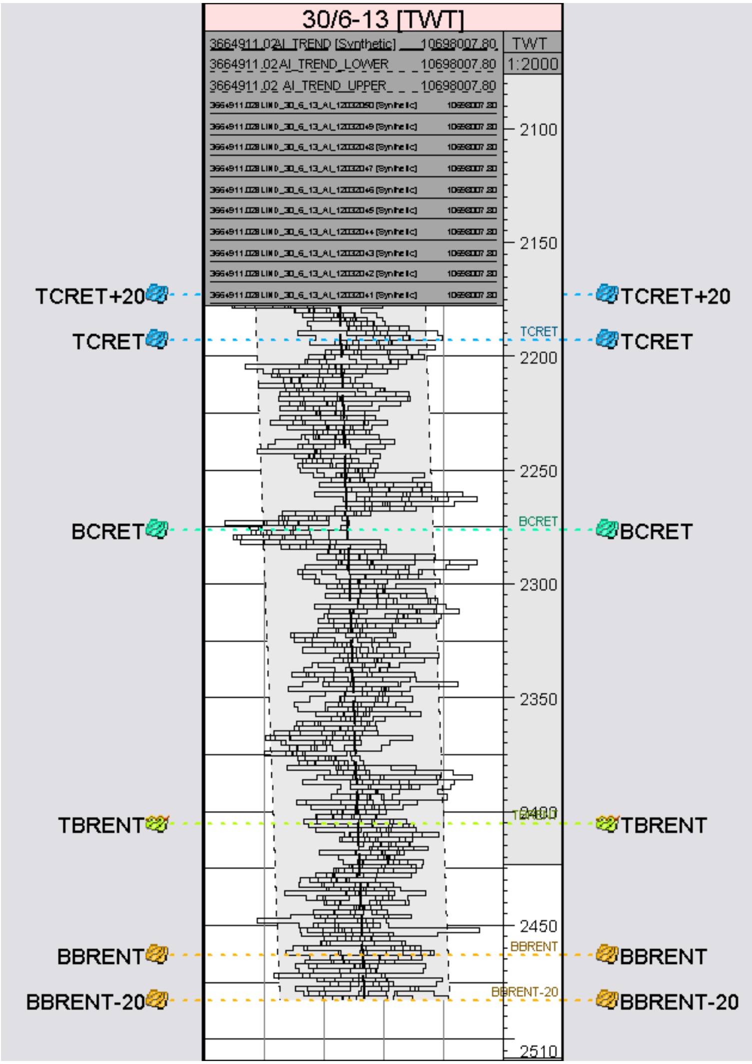
Two realizations plotted

Blind Well Validation – 30/6-13



Three realizations plotted

Blind Well Validation – 30/6-13



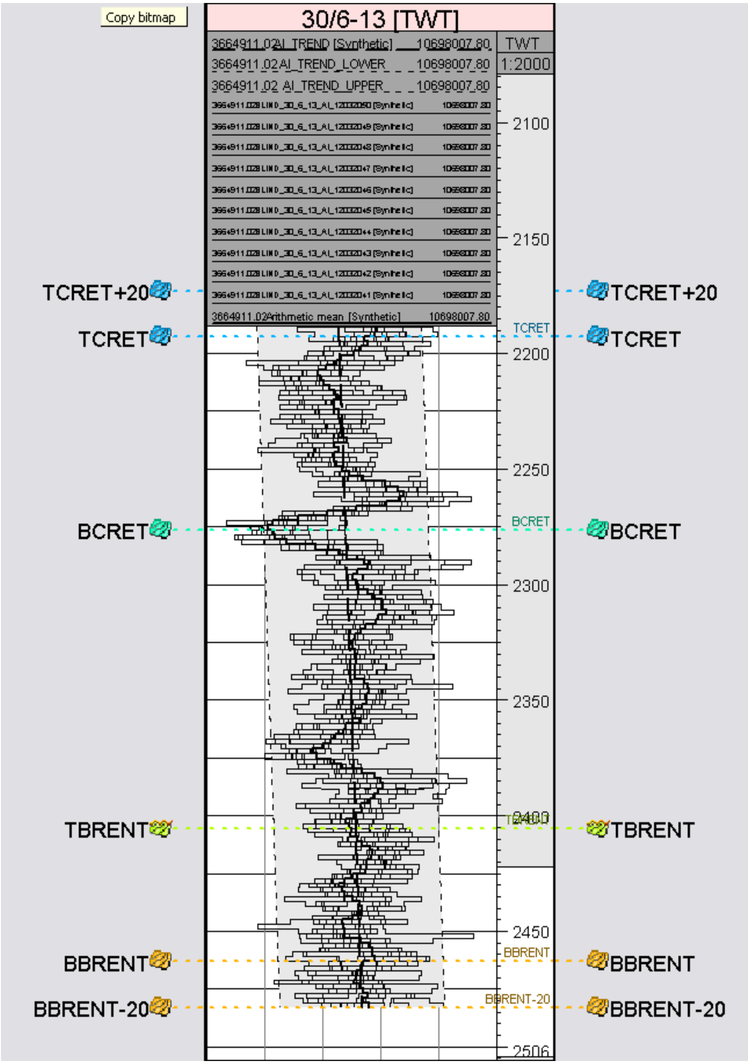
Ten realizations plotted

All realizations different but overall trend similar

All match input data within defined limits

~95% of predicted points lie within +/- 2 x std dev.

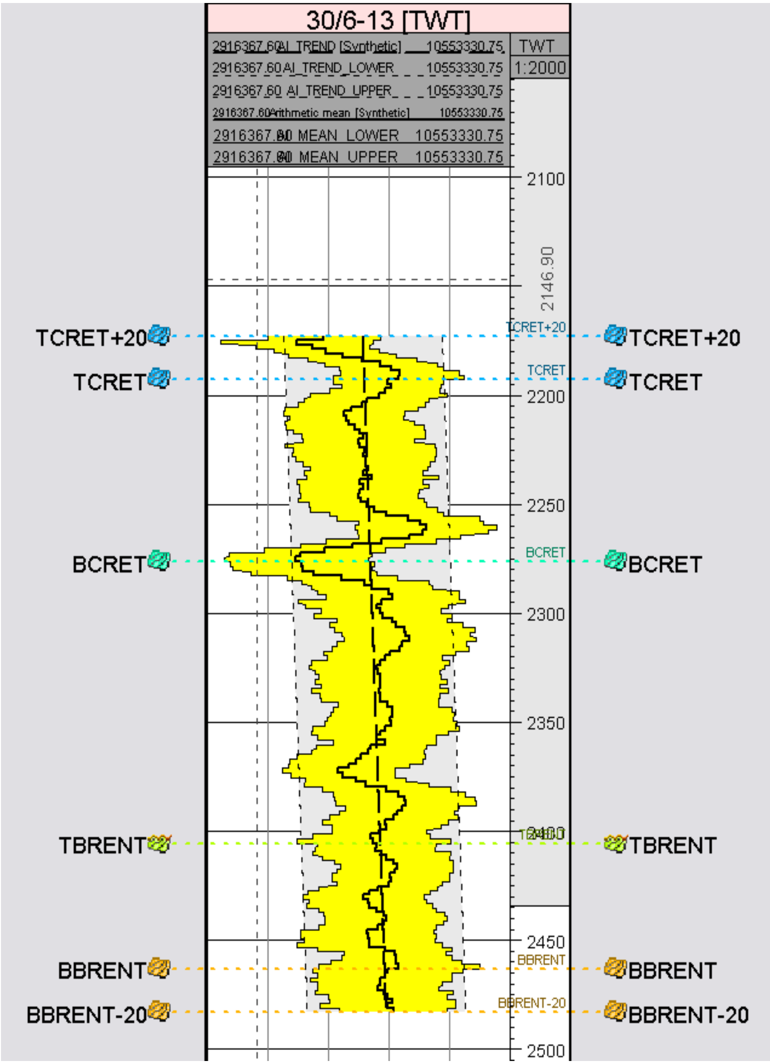
Blind Well Validation – 30/6-13



Bold black curve = mean of all realizations

Mean is smoother but still shows overall "character" of geology

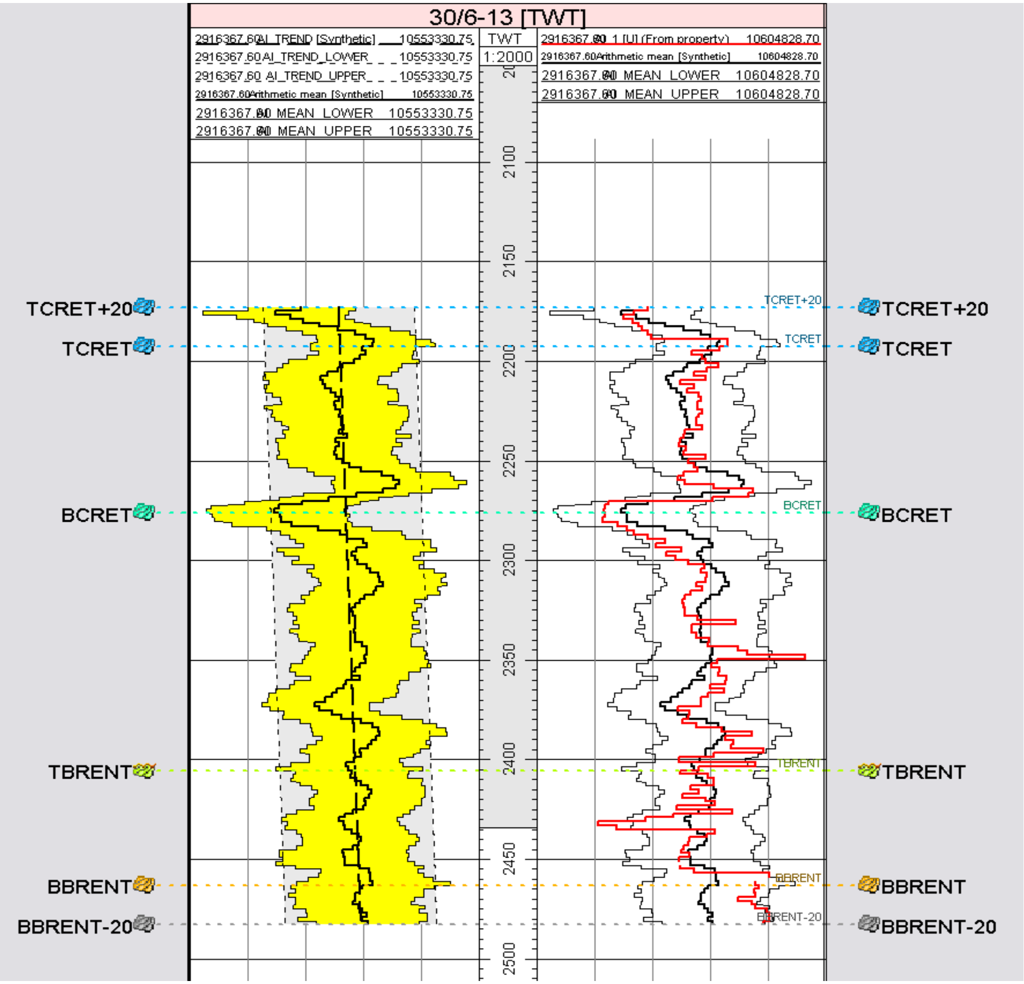
Blind Well Validation – 30/6-13



Bold black curve = mean of all realizations

Yellow = upper & lower limits of all realizations

Blind Well Validation – 30/6-13



Key to R.H.Log Panel

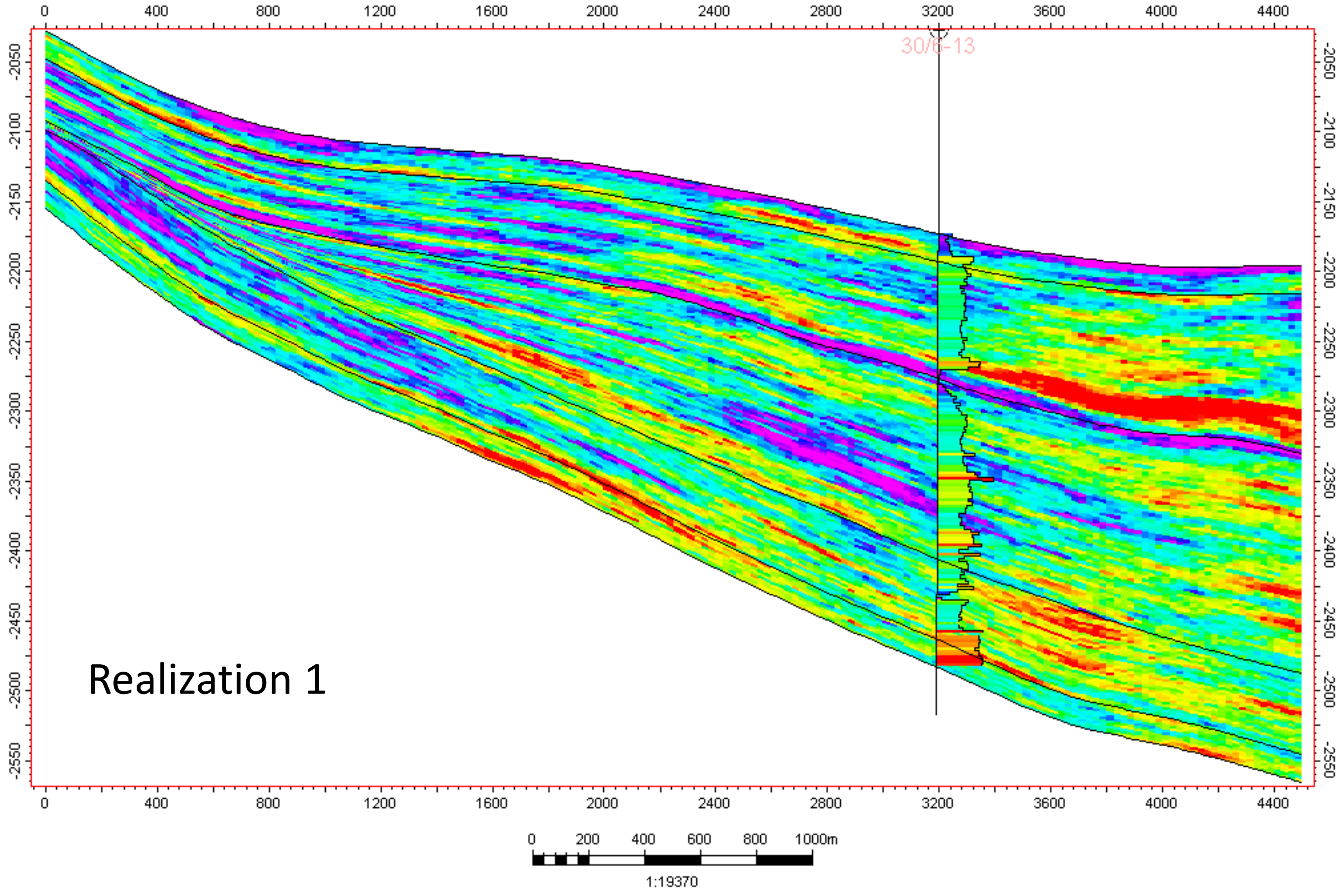
Actual AI from well

Mean of all realizations

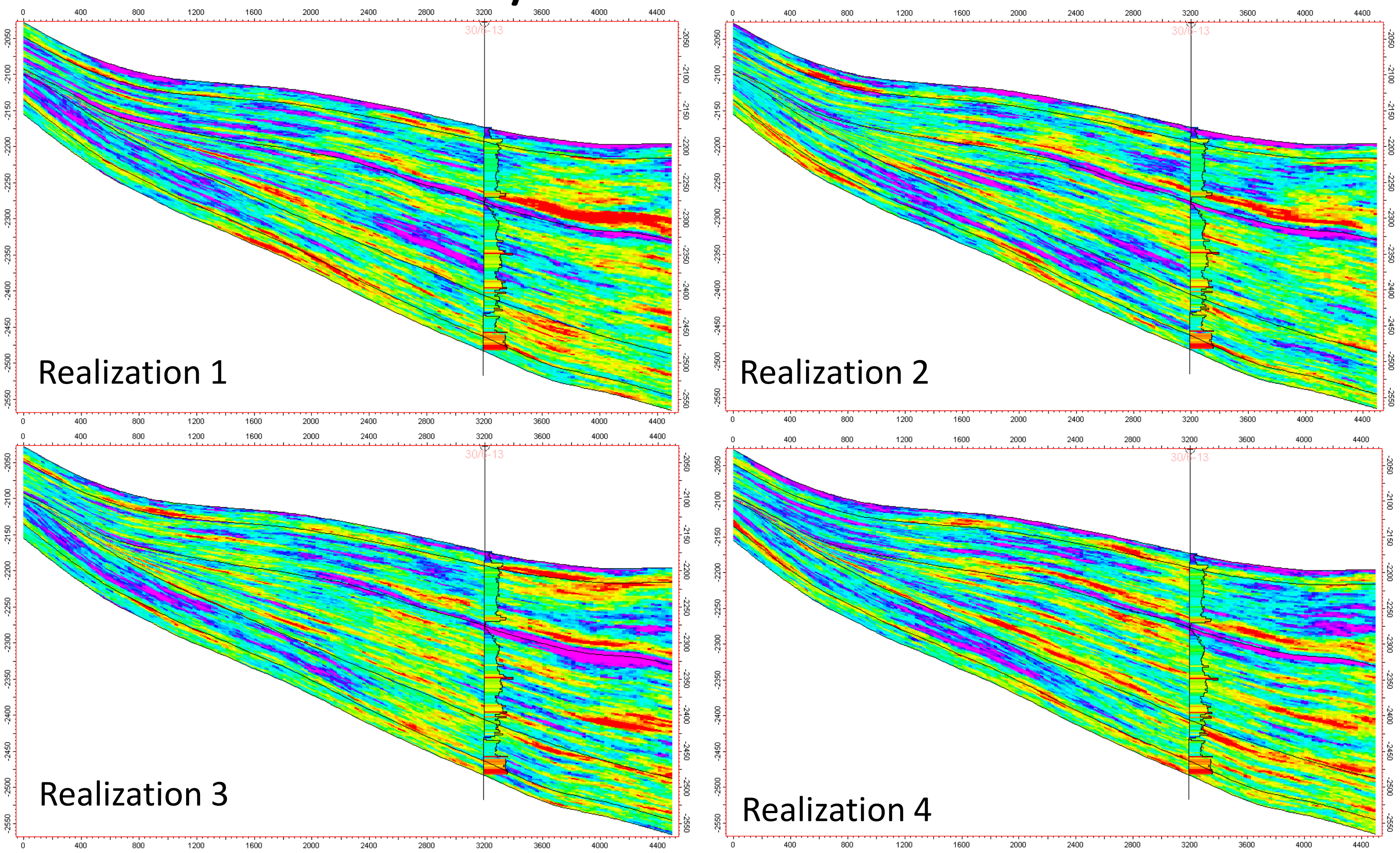
+/- 2 x std deviations

- **Mean is smoothed but still shows close tie to actual well results**
- **Realizations cover 95+% of actual log results even though well not used in this example**
- **Demonstrates predictive power of the realizations**

Cross-Section – 30/6-13

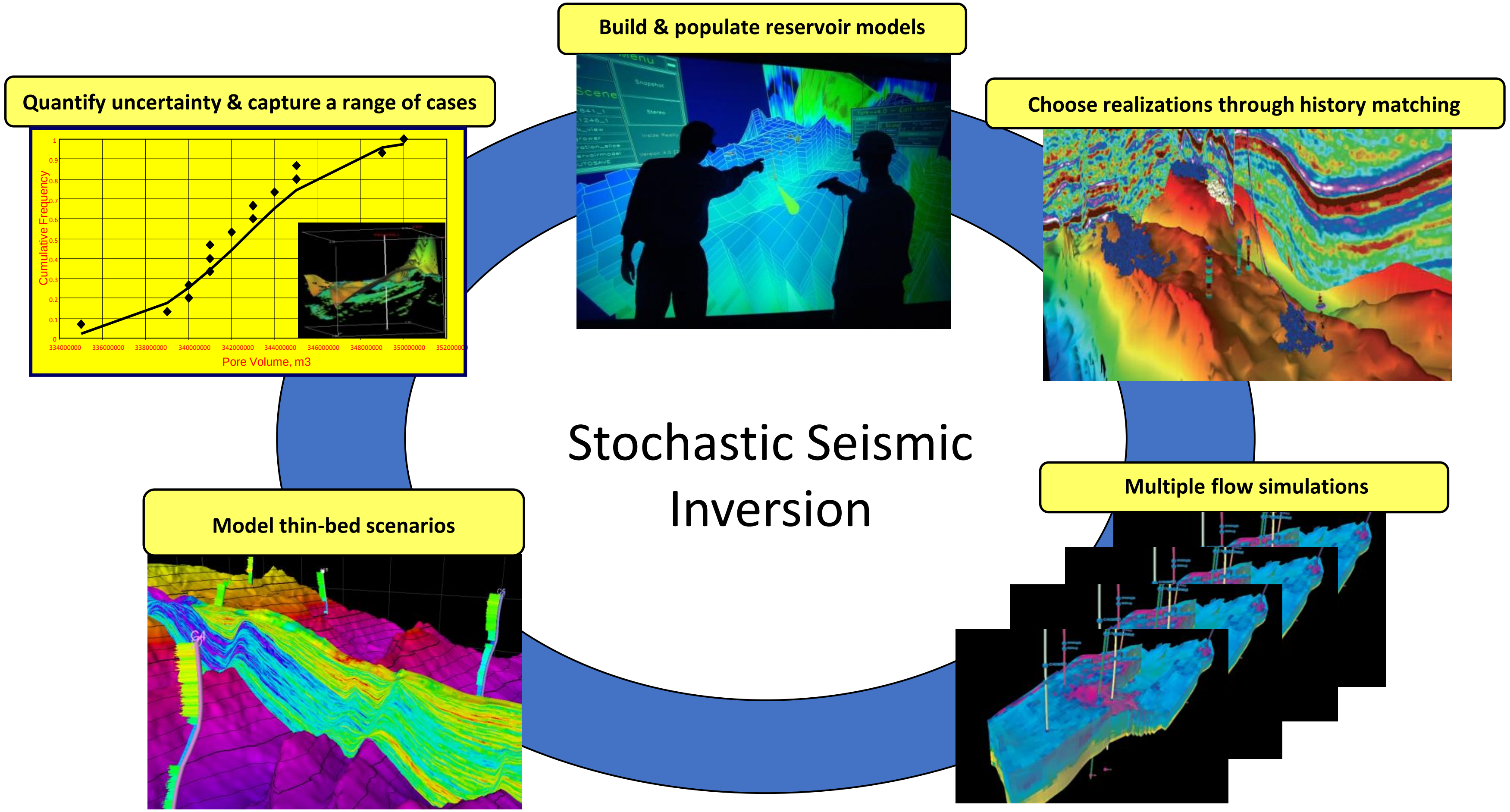


Cross-Section – 30/6-13



Section 6.
Stochastic inversion in seismic-to-simulation workflows

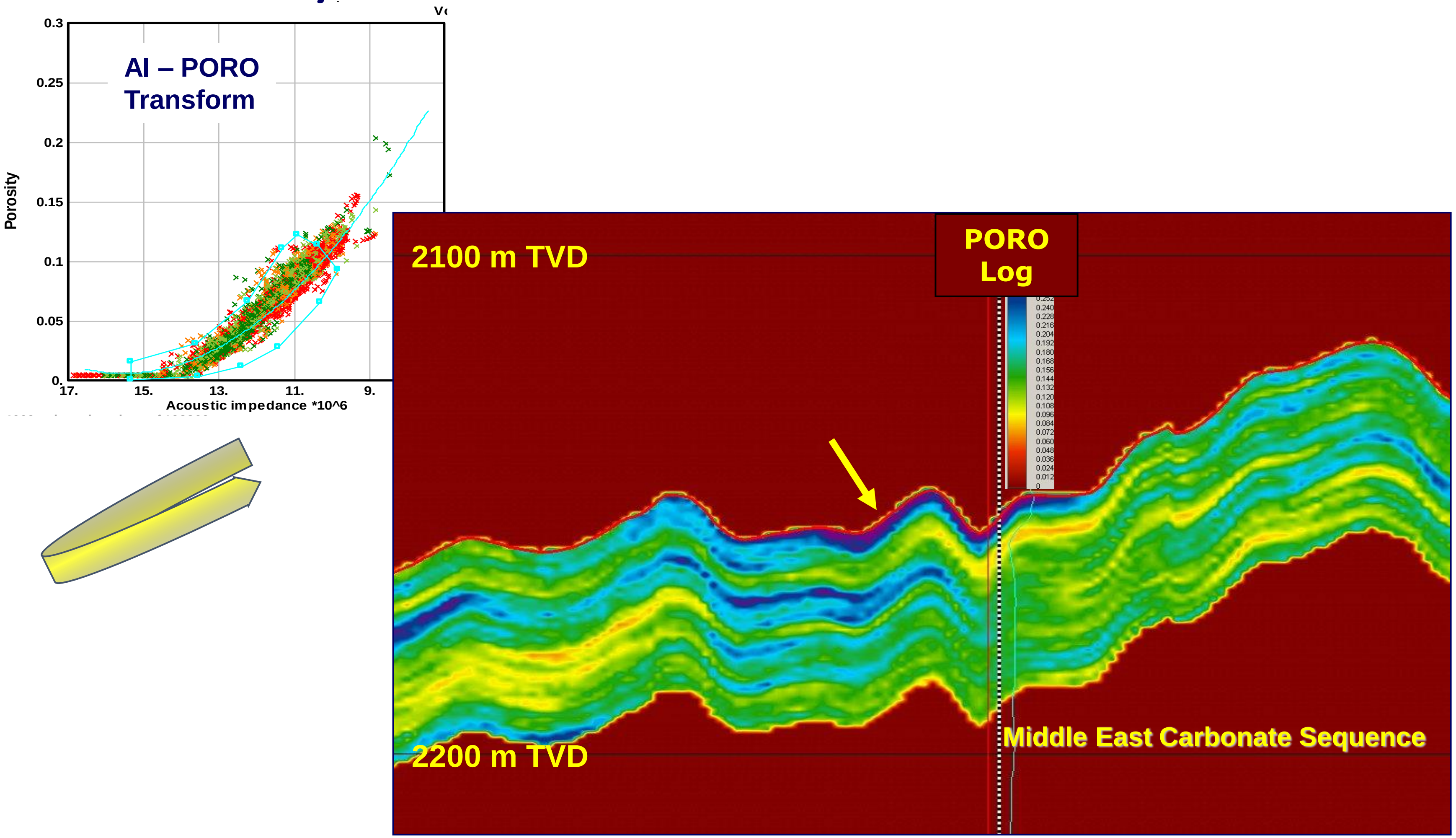
Exploiting Stochastic Inversion



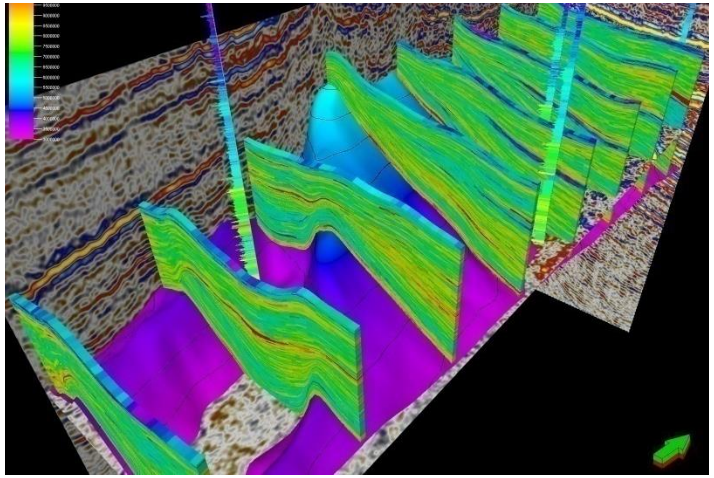
Exploiting Stochastic Inversion

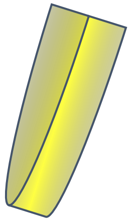
- Exploitation of stochastic inversion results:
  - Petrophysical property modelling
  - Volumetrics
  - Dynamic flow simulation (streamlines)
  - Well planning
  - Well connectivity
  - Connected volumes

Transform Impedance Volumes to Porosity

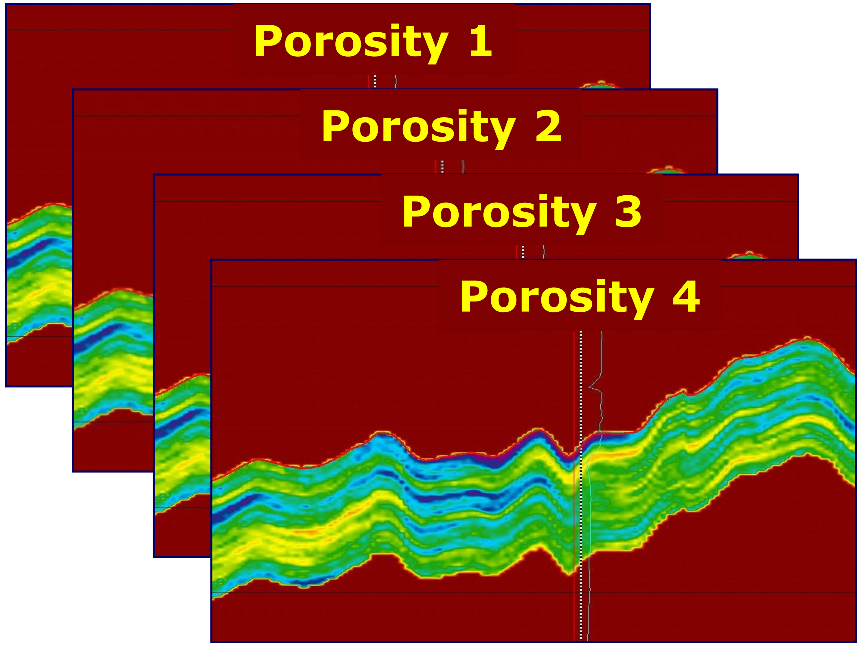


Create Multiple Pore Volume Realizations



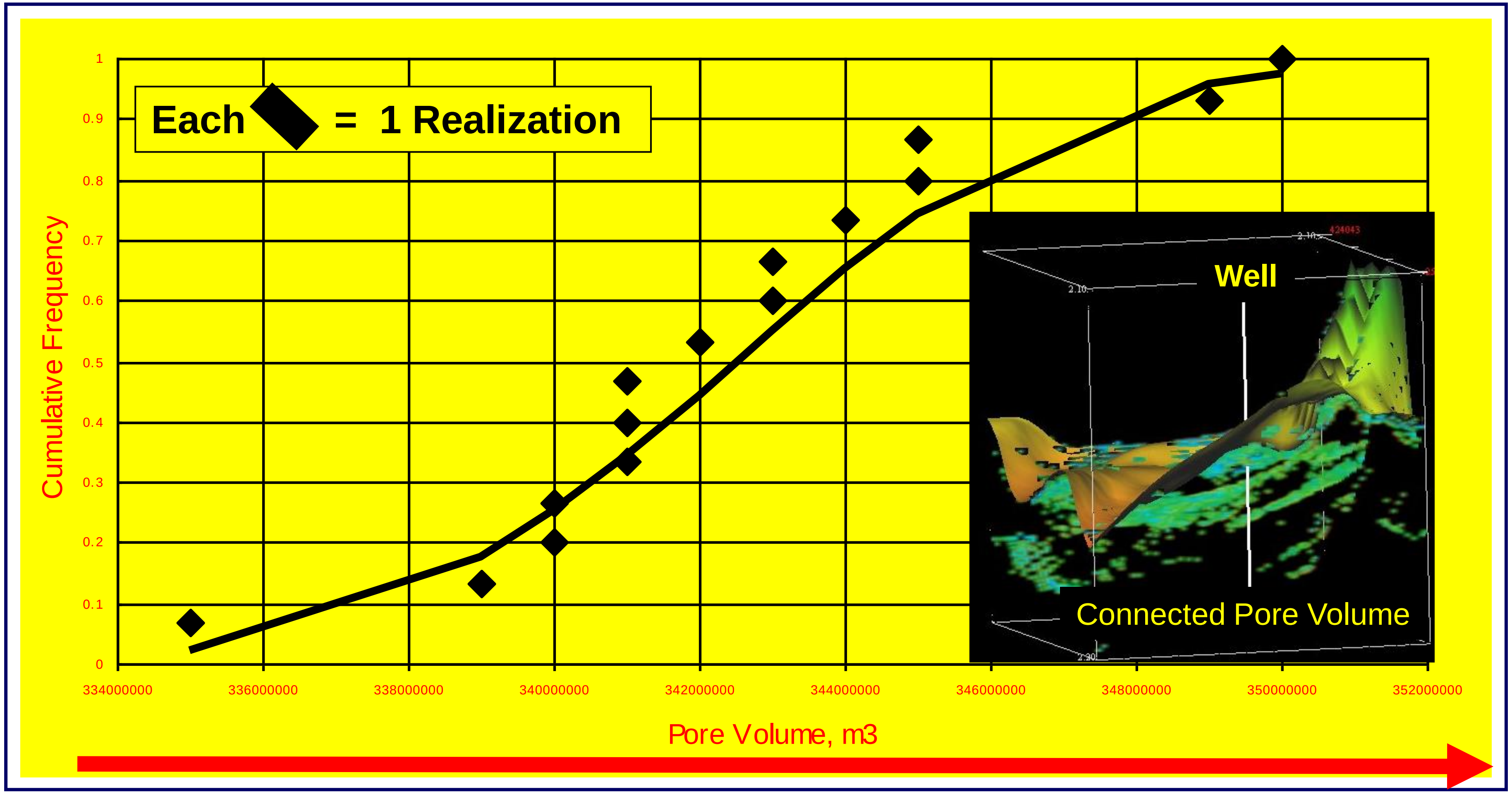


Hi-Res, Equiprobable
Stochastic Simulations



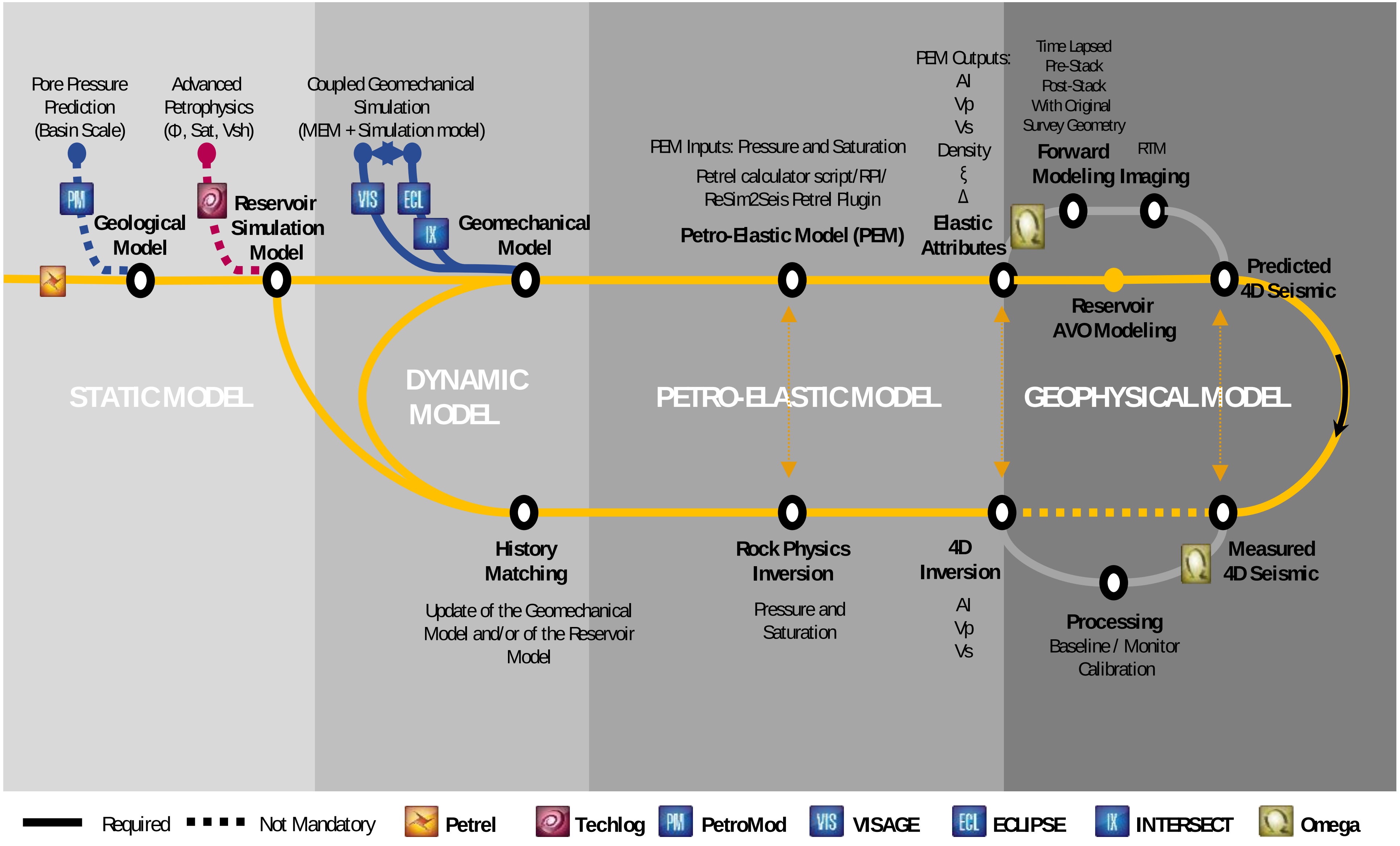
Depth Volumes

Rank models for P10, P50, P90 etc

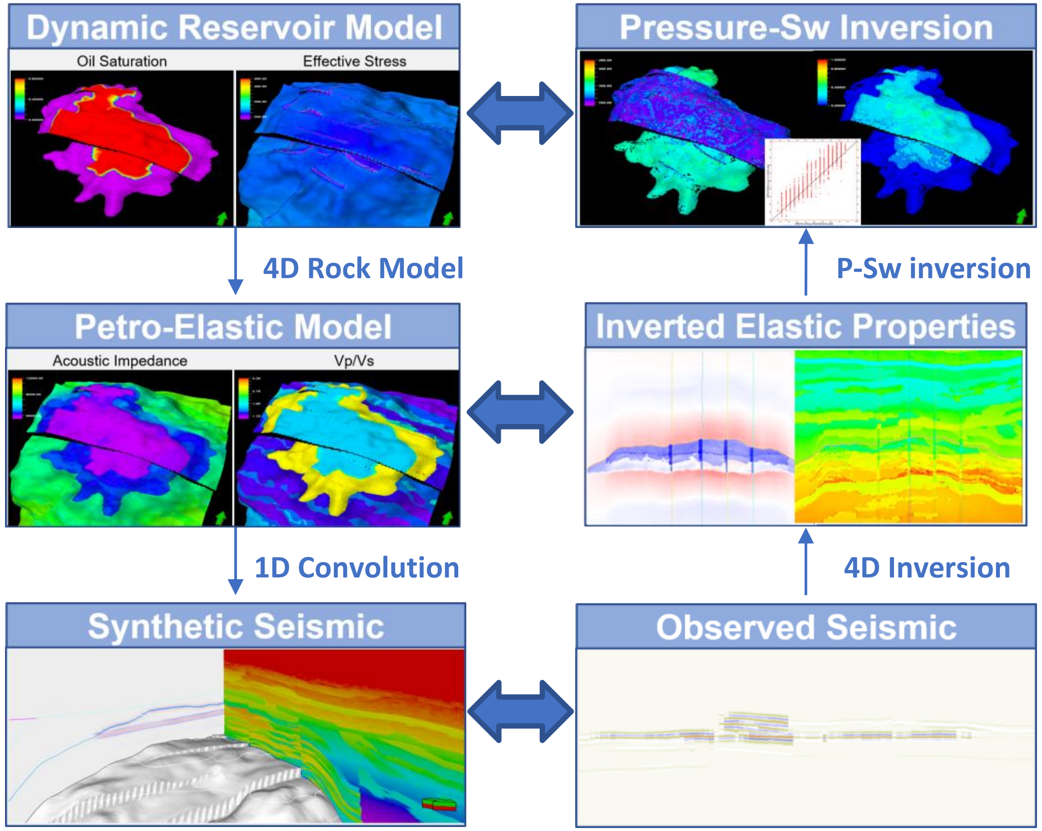


4D Interpretation Strategies

Closed-Loop Seismic Reservoir Monitoring



4D Interpretation strategies | From qualitative to quantitative



At which level should the matching be attempted?

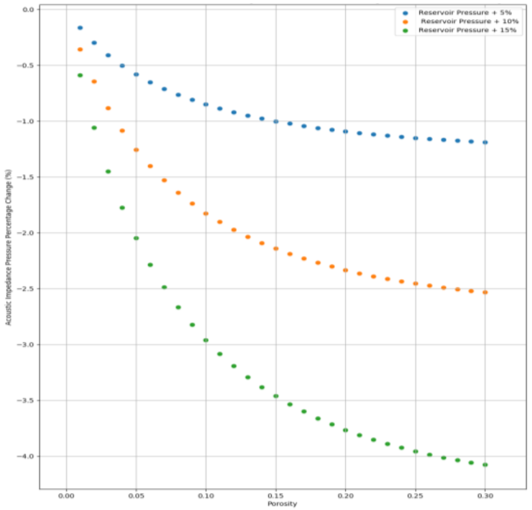
- seismic amplitudes
- elastic properties
- petrophysical properties

Driven by sensitivity analysis of the 4D rock model

- Upfront testing to streamline the seismic history matching process when data becomes available

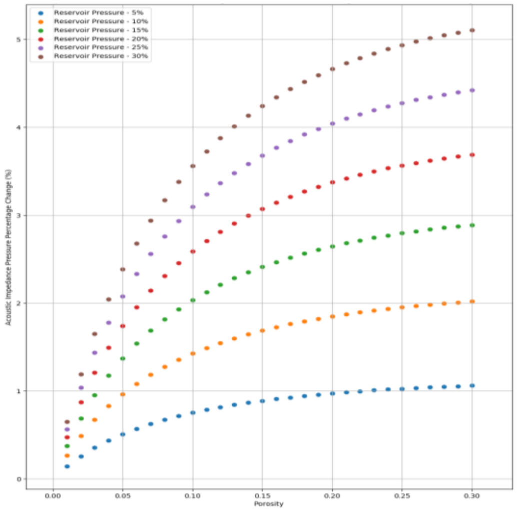
Rock model sensitivity analysis

Pressure increase scenario

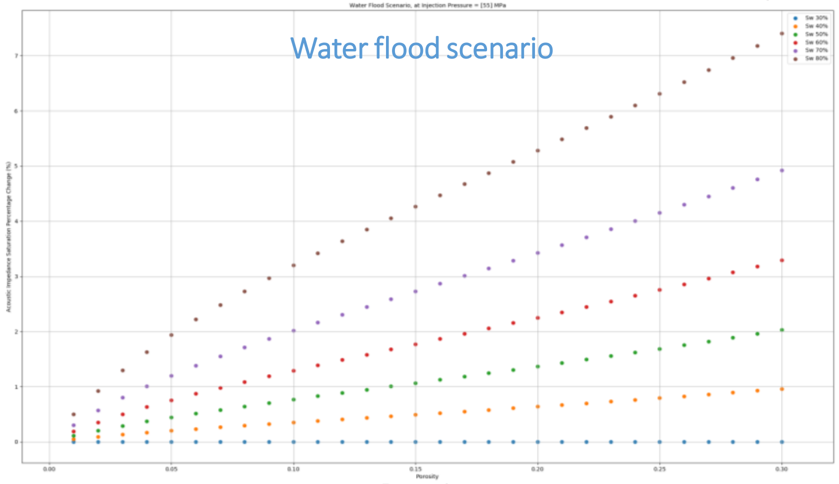


Porosity

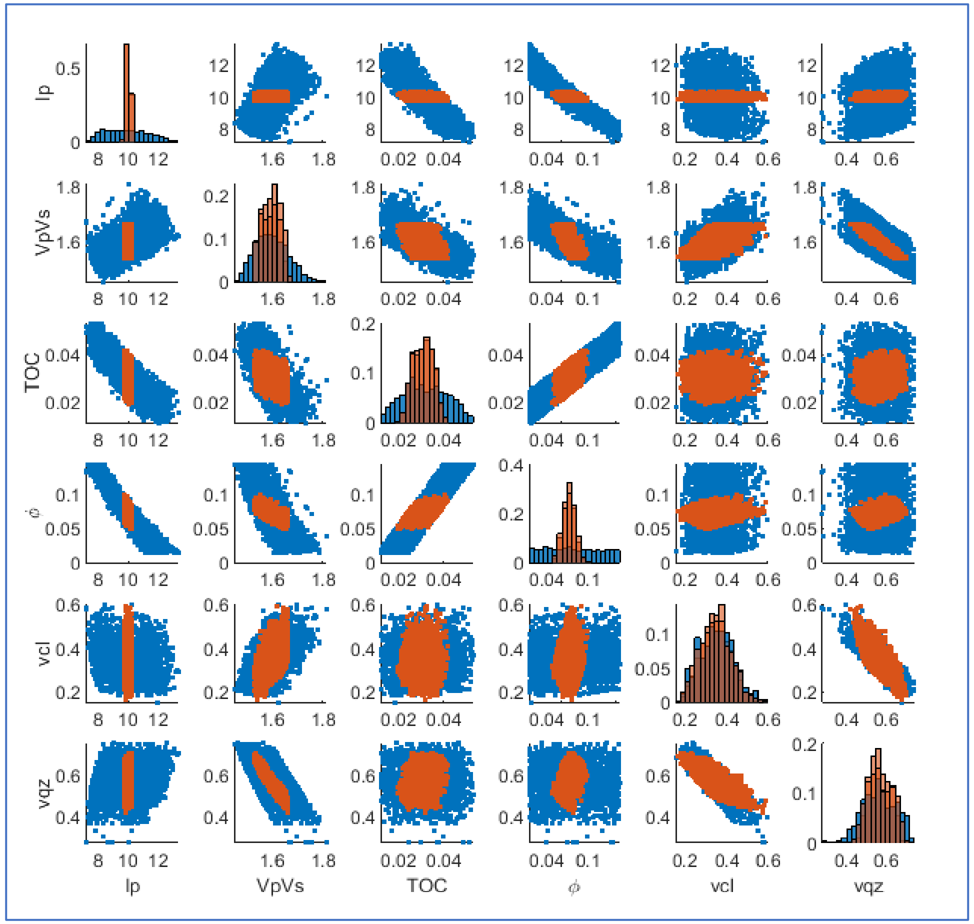
Depletion scenario



Porosity

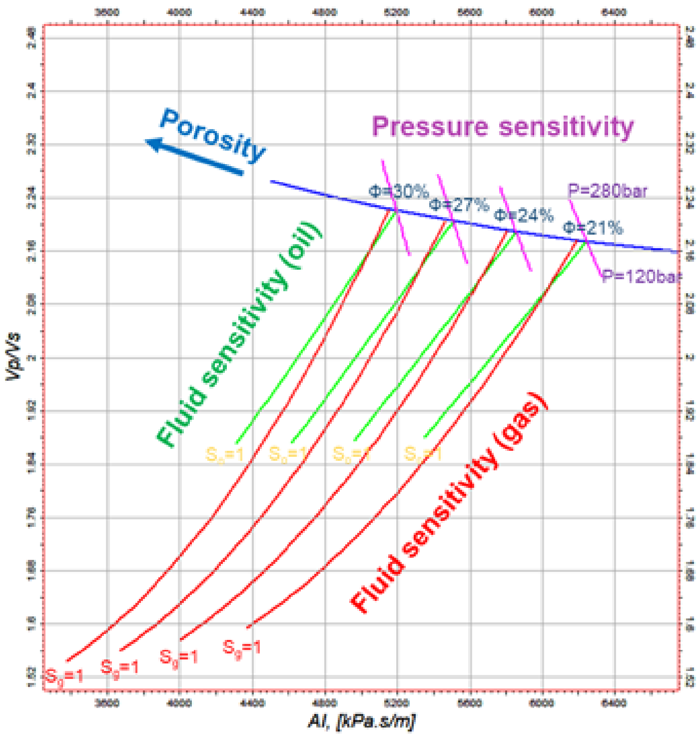


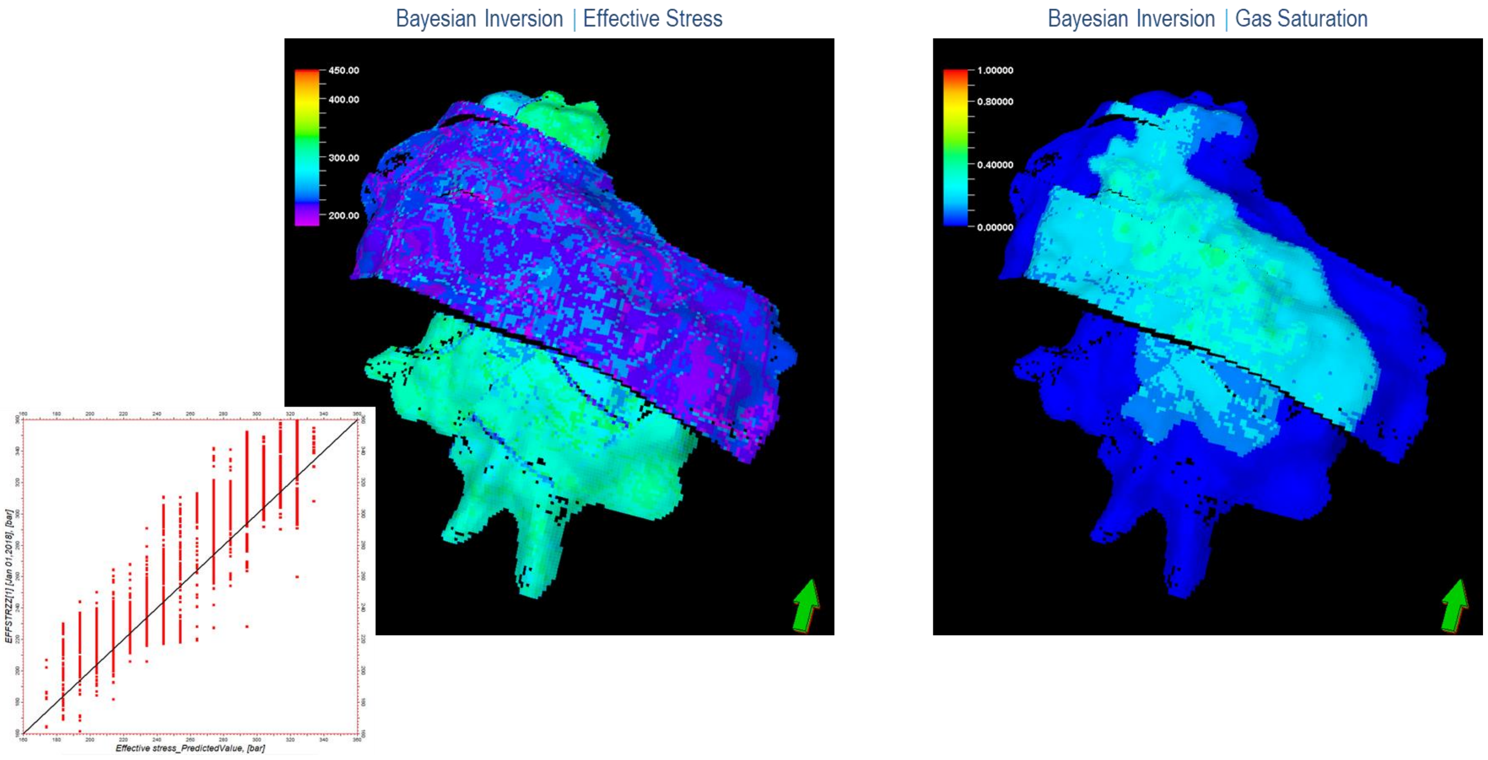
Porosity



Rock model sensitivity analysis | P-Sw inversion

- Pressure-Saturation inversion can be seen as a tool to understand sensitivity and our ability to recover and discriminate information even in absence of noise





Increasing complexity (and effort) of analysis

Qualitative

Difference, hardening / softening

Acoustic

Post-stack amplitude analysis only

Acoustic + Time-shifts

Post-stack amplitude analysis and time-shifts computation

4D AVO

Pre-stack amplitude analysis

4D AVO + Time-shifts

Pre-stack amplitude analysis and time-shifts computation

MEM integration

Pressure changes inversion from time shifts

Note: seismic data quality matters…

Case study | South Arne

Applying time-lapse seismic to reservoir management and field development planning at South Arne, Danish North Sea

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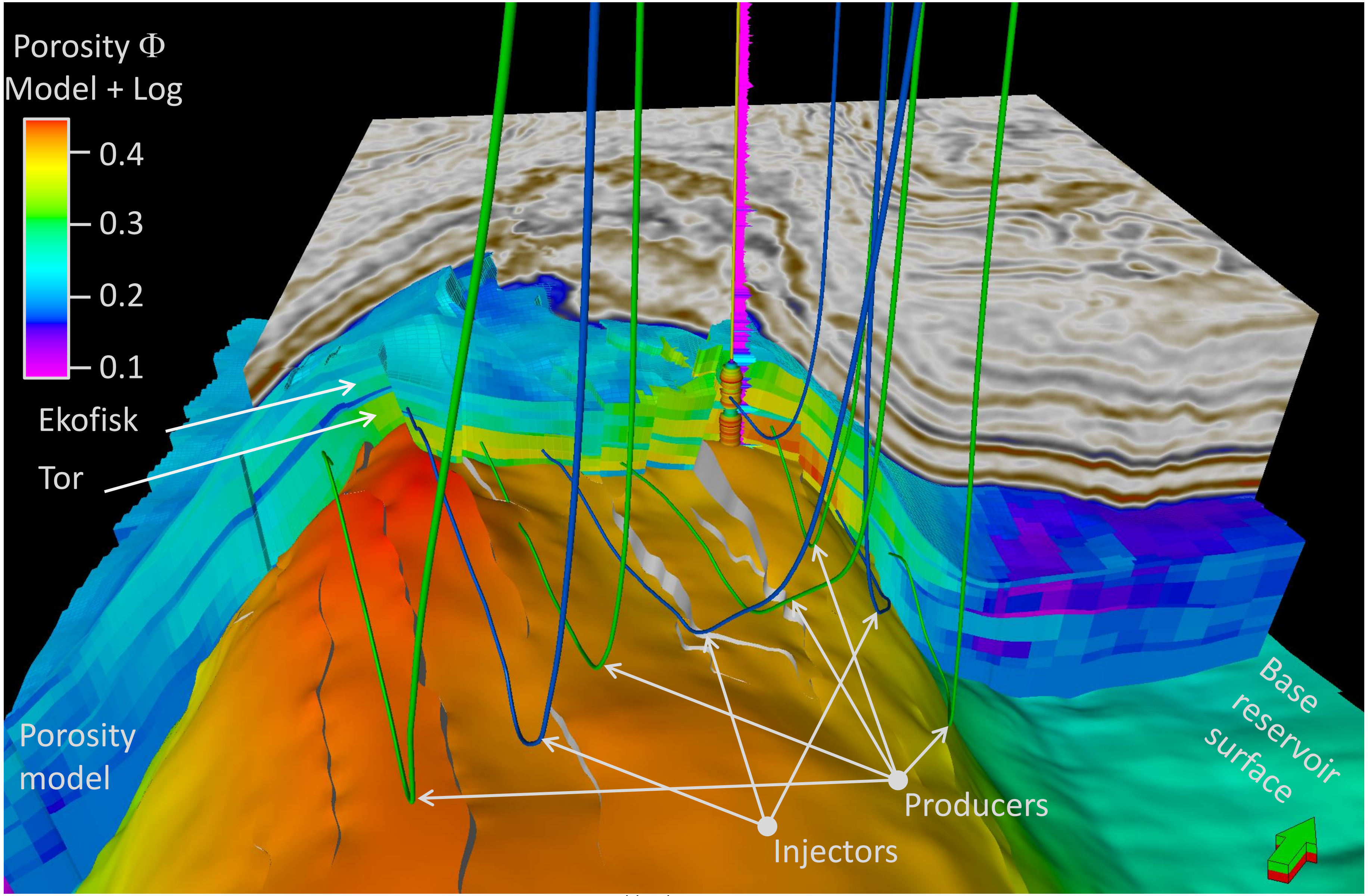
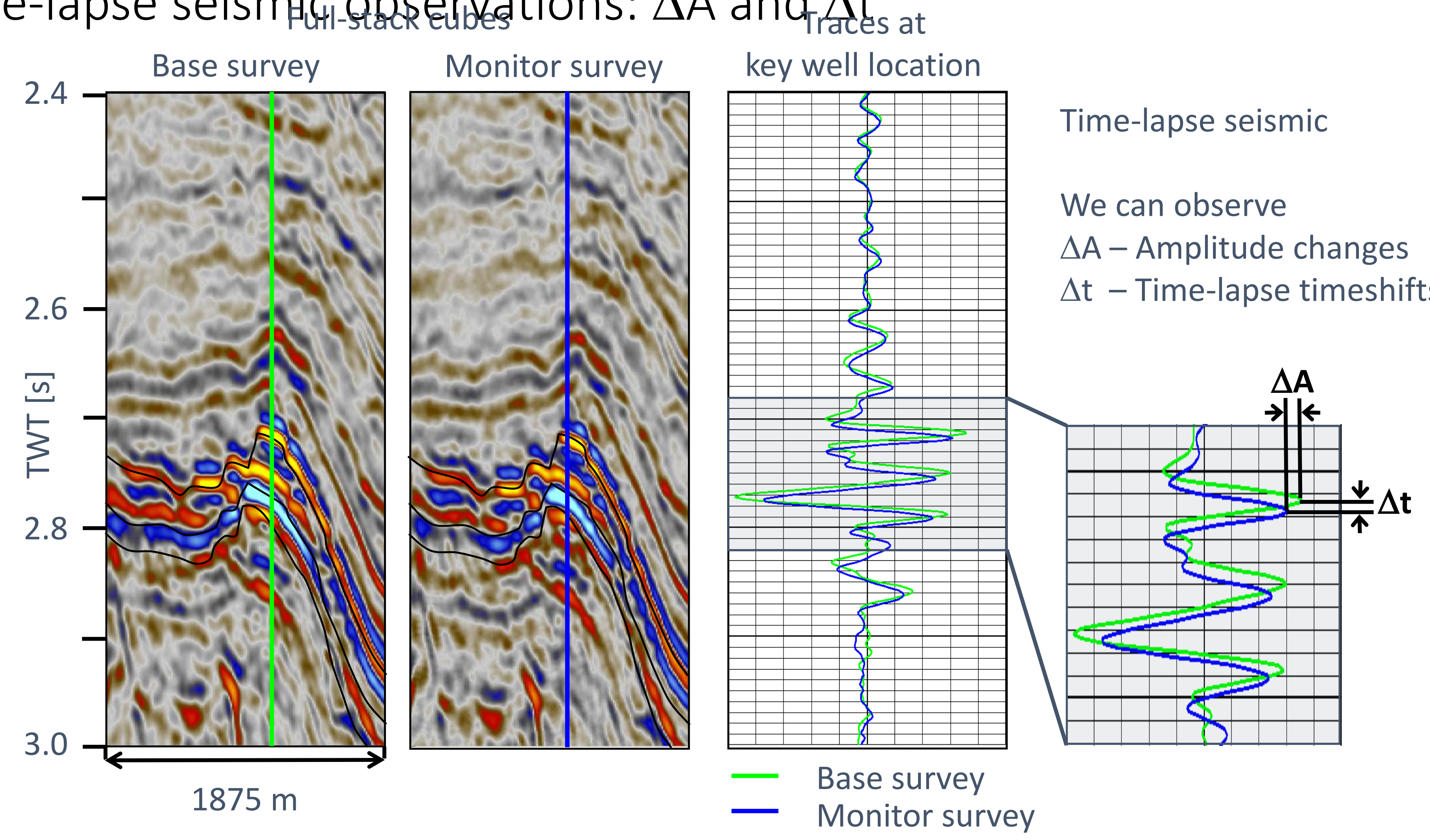
South Arne reservoir description



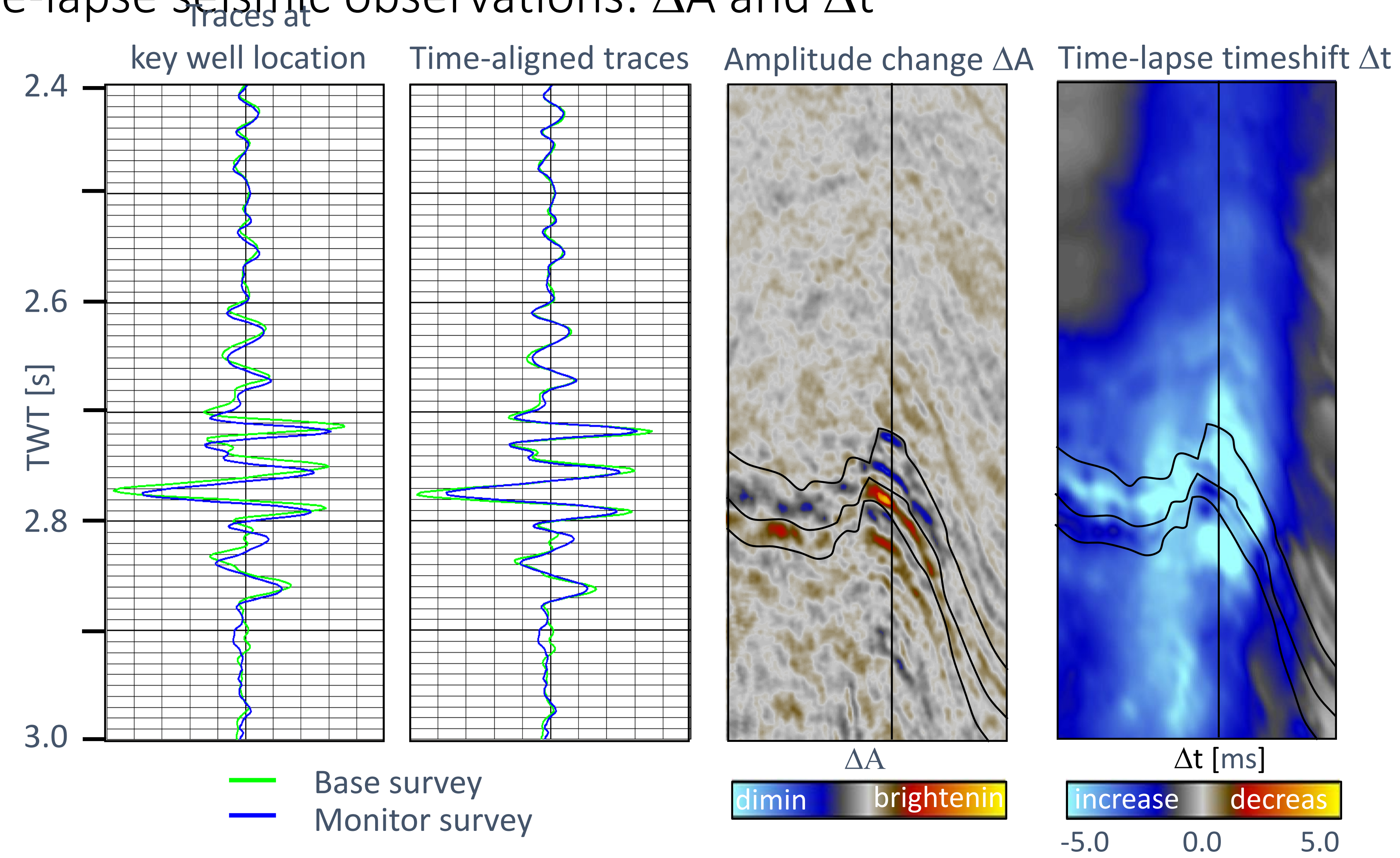
Time-lapse seismic observations: ΔA and Δt



Time-lapse seismic

We can observe
ΔA – Amplitude changes
Δt – Time-lapse timeshifts

Time-lapse seismic observations: ΔA and Δt

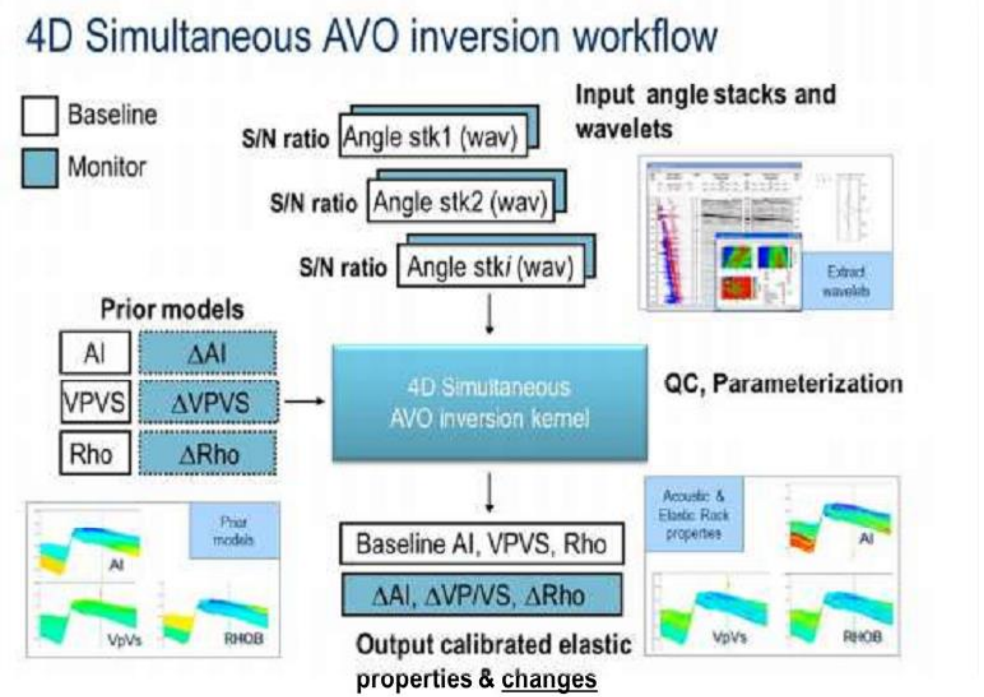


4D Simultaneous Inversion

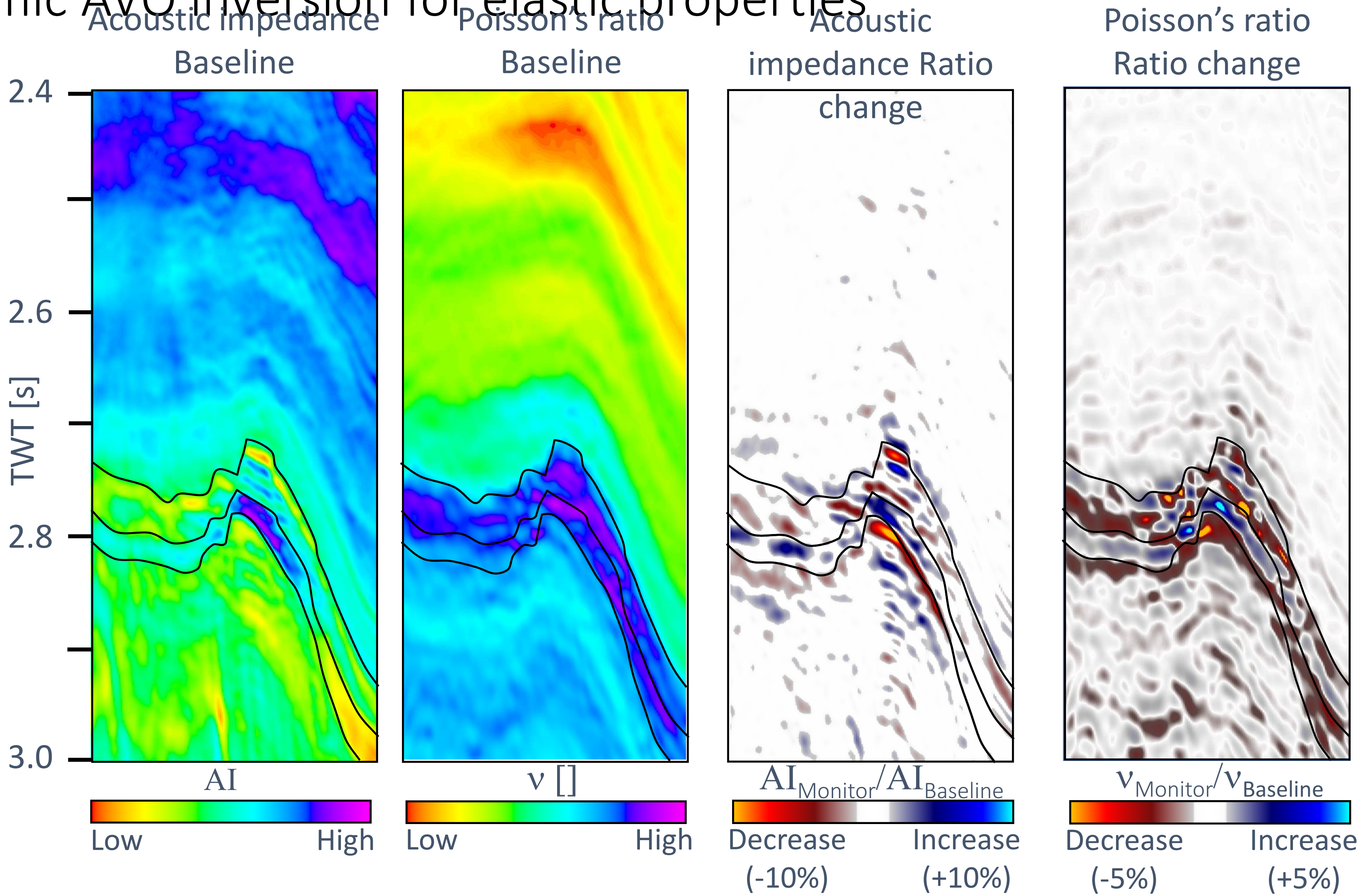
Global optimization technique
Solves for elastic properties and their changes with a global optimization technique.

Direct implementation of prior models
Low frequency models for different vintages using fluid substituted logs or ΔVP/VP attributes derived from estimated time shifts.

Joint 4D saturation-pressure inversion
The changes in reservoir properties can be estimated by combining lithology analysis and the joint 4D saturation-pressure inversion workflow based on stochastic simulation of the 4D rock model defined.



Seismic AVO inversion for elastic properties



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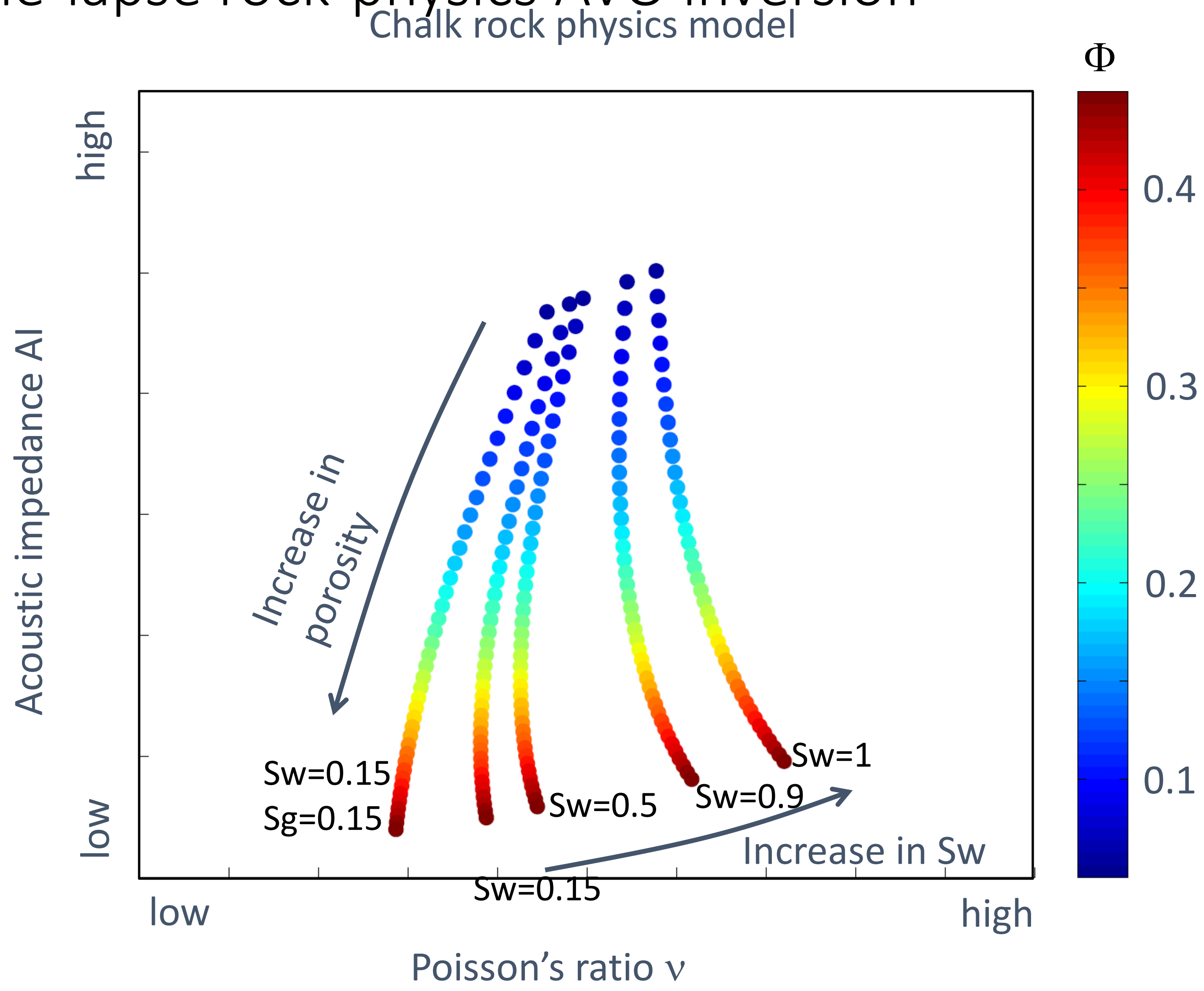
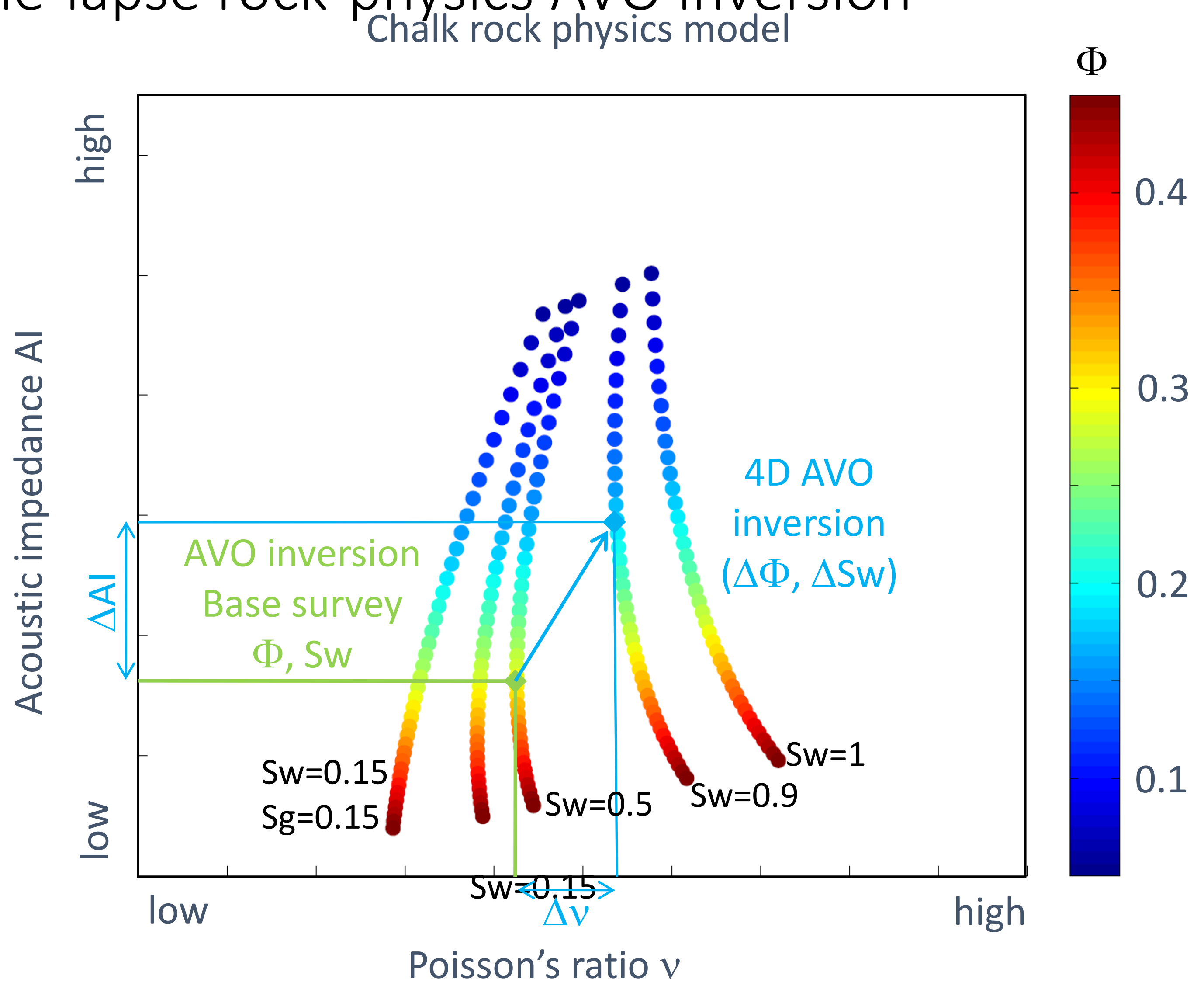
Time-lapse rock-physics AVO inversion



Rock physics AVO inversion:

Translate elastic properties (Acoustic impedance AI and Poisson's ratio ν) to petrophysical properties (Porosity Φ and Water saturation Sw) by using a rock physics model

Time-lapse rock-physics AVO inversion



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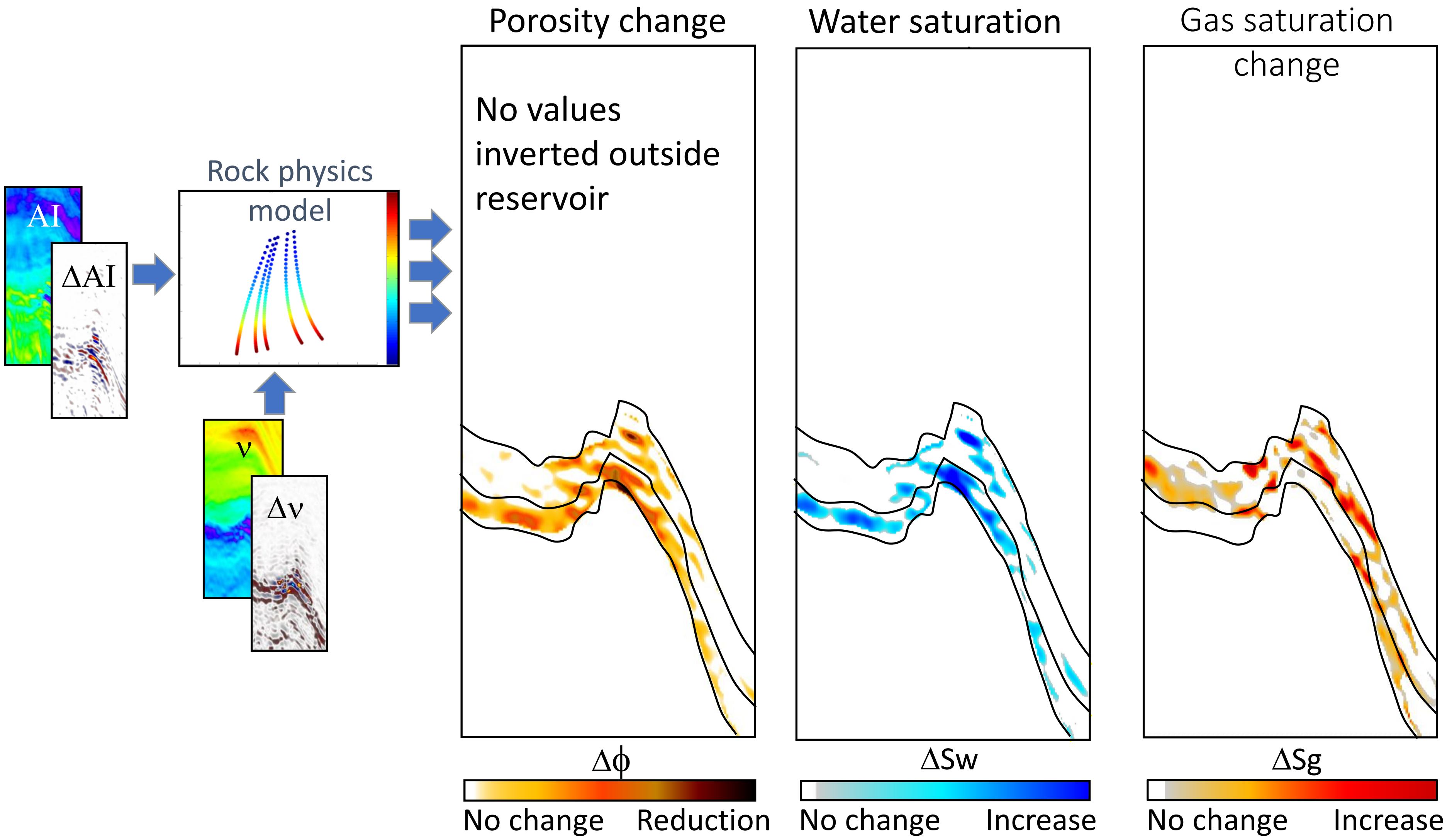
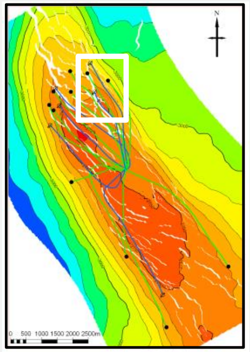
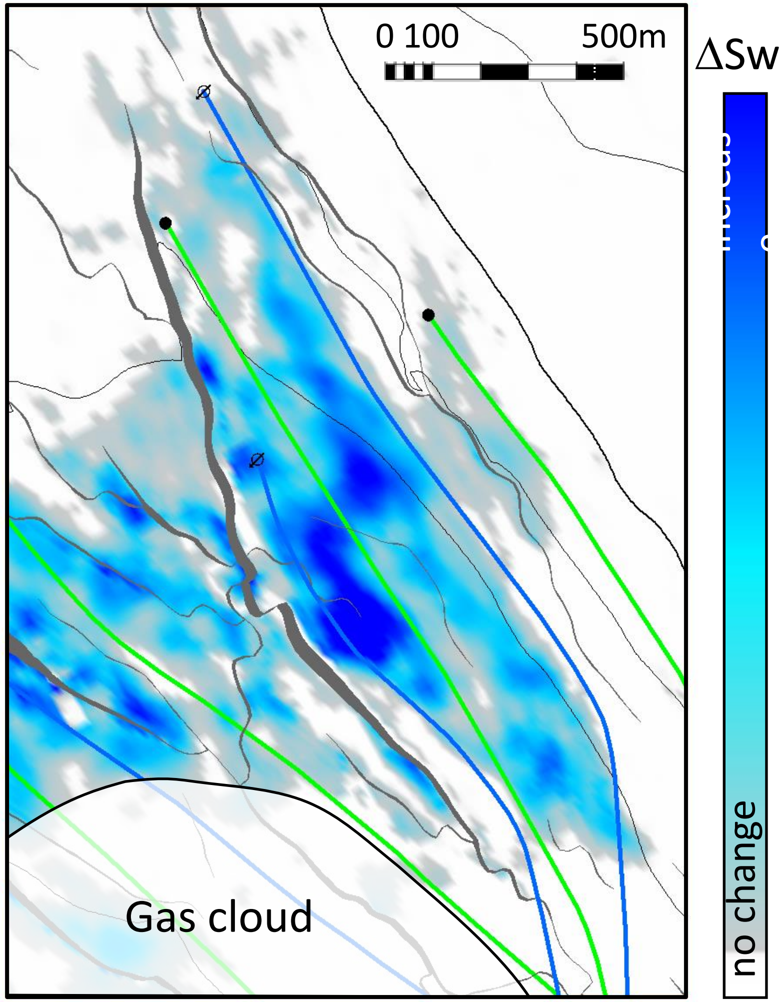
Time-lapse rock physics AVO inversion

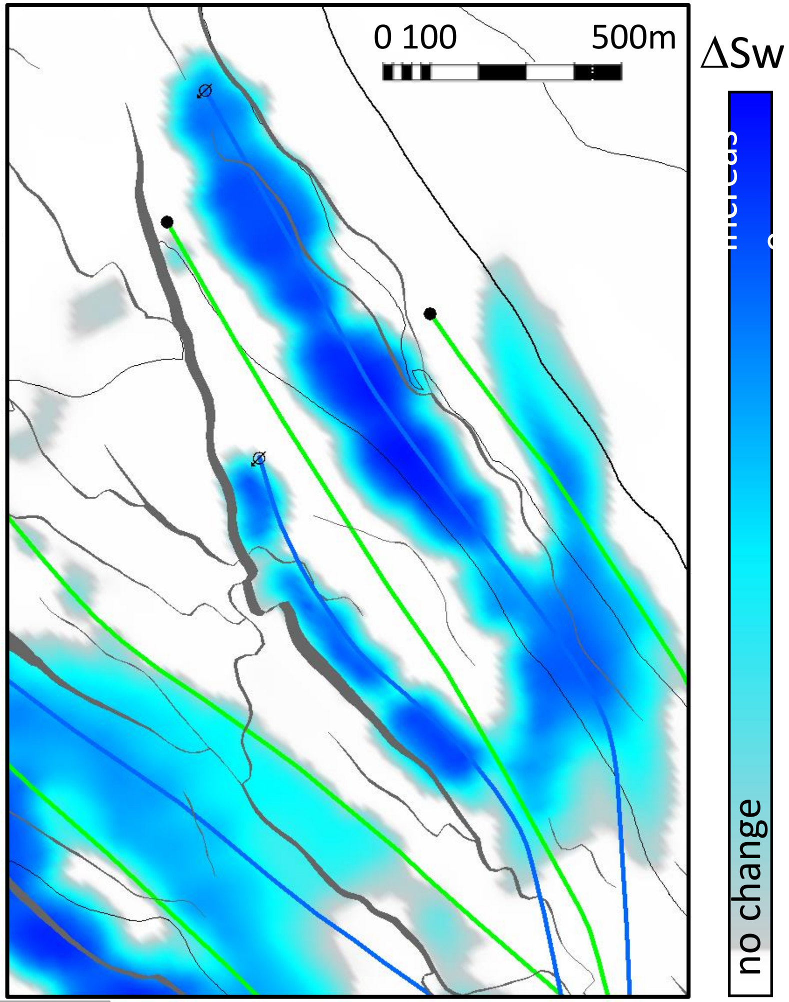


ΔSw from reservoir simulator

ΔSw from 4D AVO





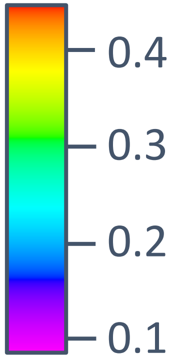


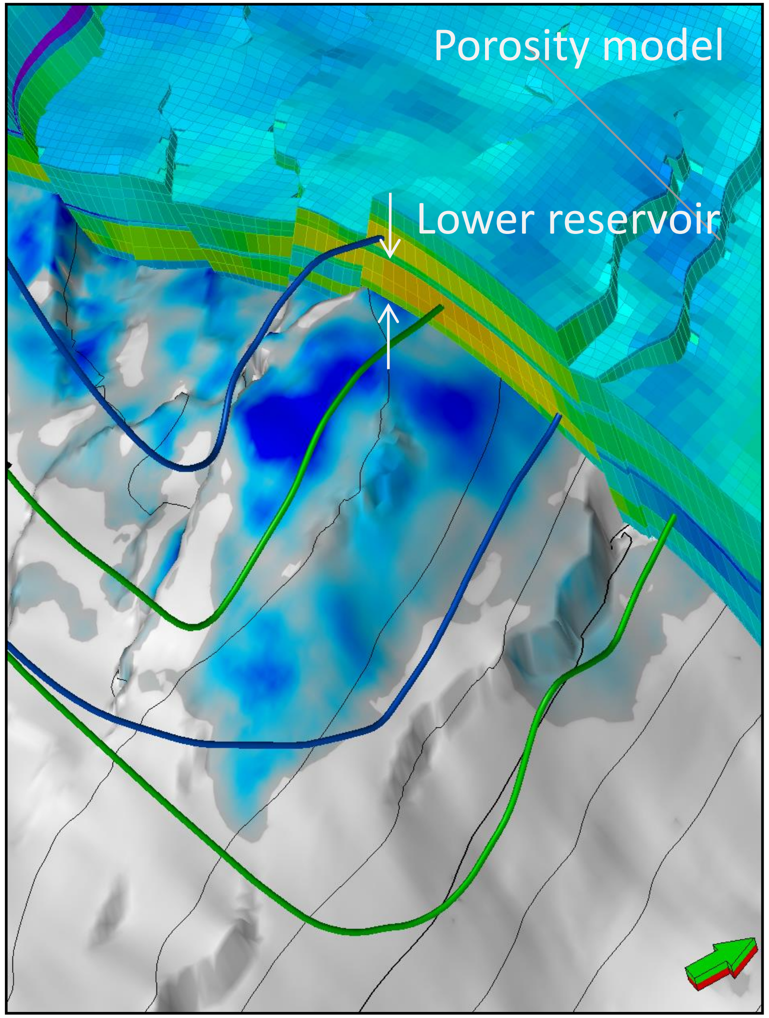
Average water saturation change in lower reservoir (Tor)

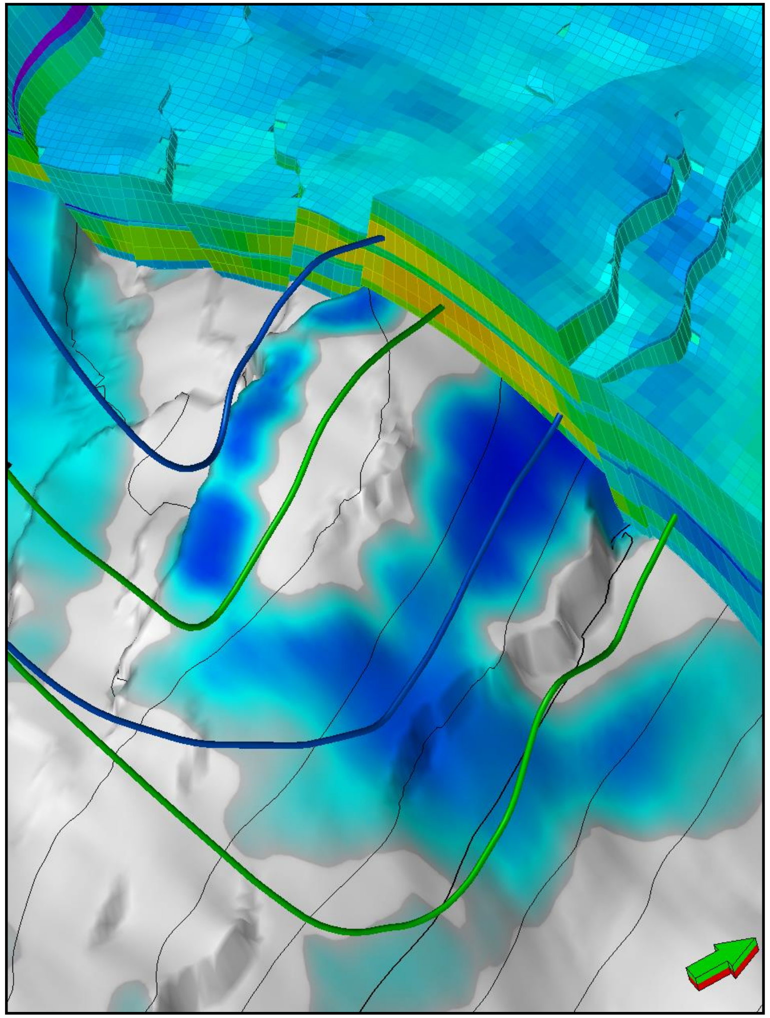
ΔSw from reservoir simulator

ΔSw from 4D AVO

Porosity Φ
Sim. Model



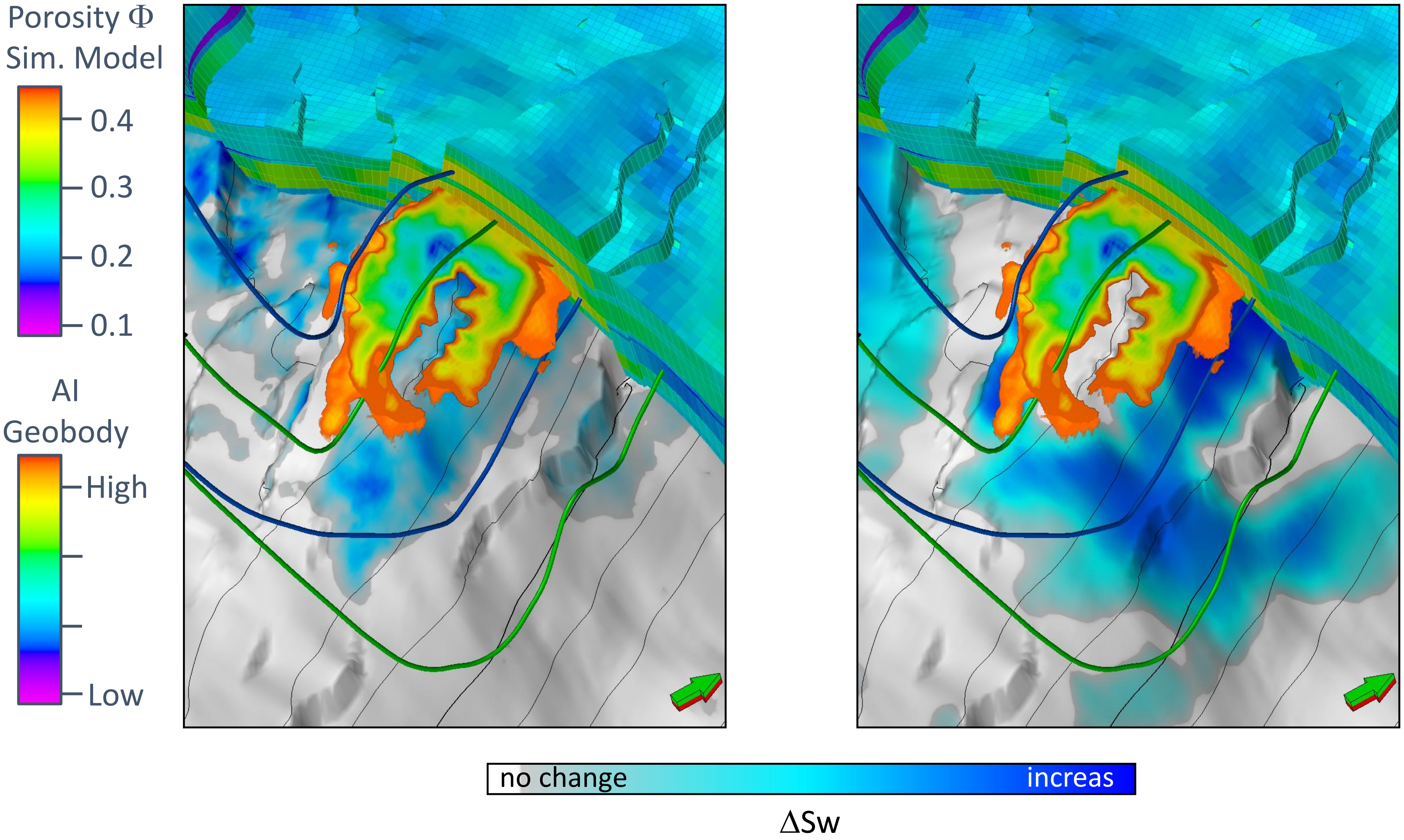




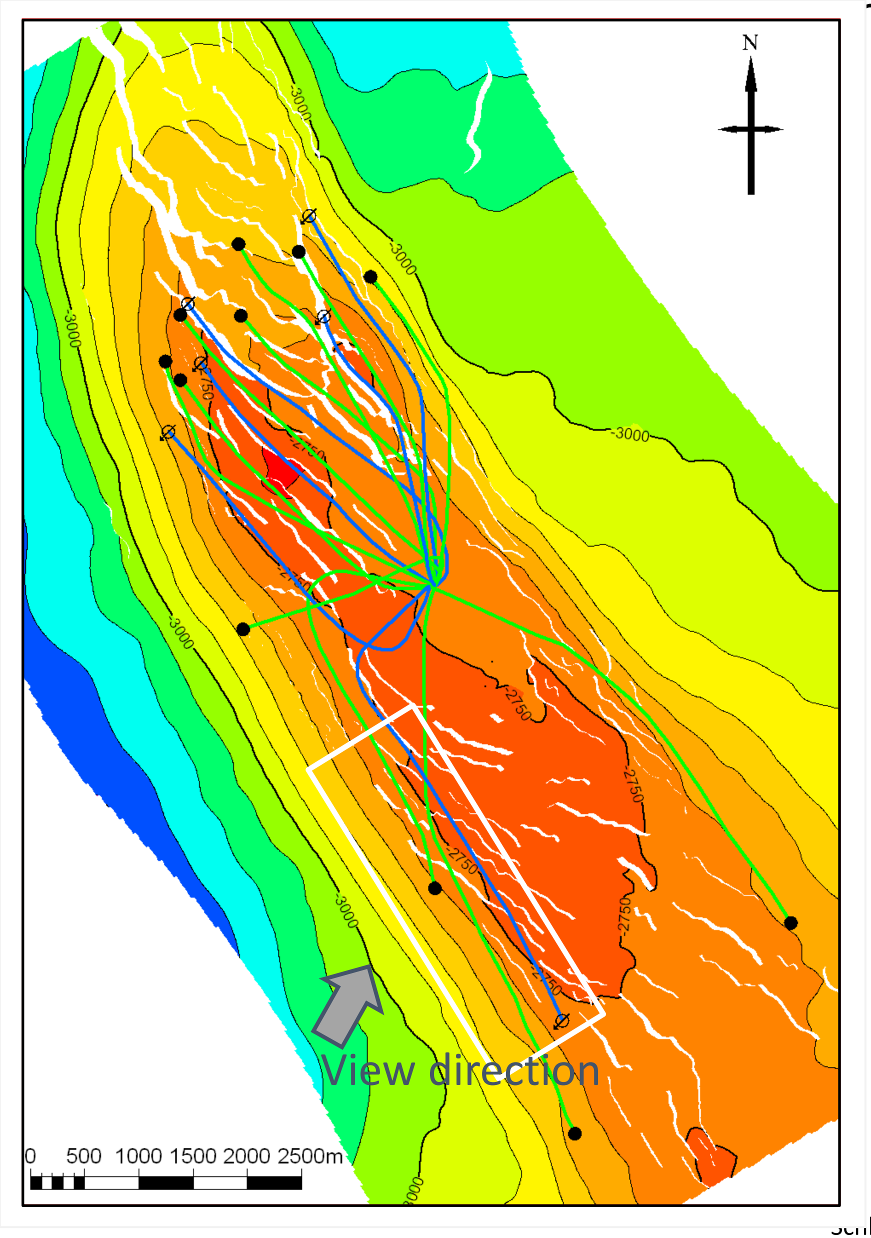
ΔSw

ΔSw from reservoir simulator

ΔSw from 4D AVO



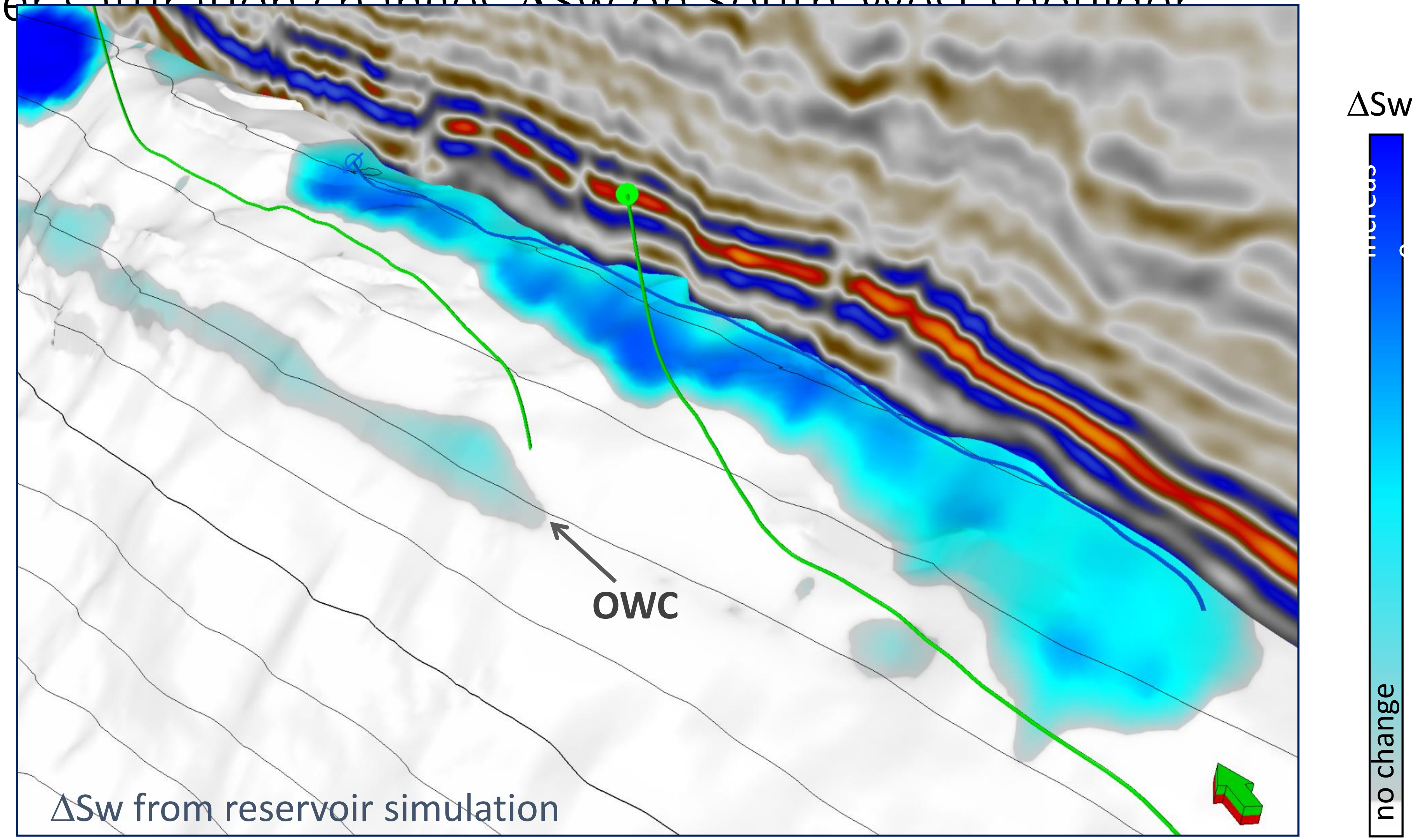
Wat… South-West shoulder



Compare water saturation changes derived from 4D AVO inversion and reservoir model

- Compare average water saturation in lower reservoir (Tor) interval
- Fault control on flow pathways

Water saturation changes ΔSw on South-West shoulder



ΔSw from reservoir simulation model

Water saturation changes ΔSw on South-West shoulder