New Integrated Workflows for Improved Pore Pressure Prediction and Seismic Imaging*

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Abstract

As petroleum exploration has migrated towards poorly imaged often sub-salt reservoirs, it has become critical to develop new approaches that can be used to improve quality of pre-drill pressure predictions and seismic image. Seismic imaging typically attempts to account for either depth varying compaction driven velocity models or laterally varying velocity models constrained by so called HBI (horizon based interpolation) and use a generic background seismic anisotropy. Typically, utilized rock properties and horizons are "static", i.e., do not take into account geological, geomechanical and diagenetic history of rocks. This often results in a less comprehensive rock property distribution and resultant seismic image that is not focused. To overcome some of the drawbacks, it has become routine to integrate basin modeling with seismic velocities. Basin modeling that honors stratigraphy, evolution of rock properties, etc., provides effective stress that is used to compute velocities. In pre-stack depth migration such velocities typically lead to a better seismic image.

This presentation introduces new geologically constrained pressure and velocity workflows that integrate basin modeling, tomography, geomechanics, and petrophysics. They honor stratigraphy, depositional environment and account for the evolution of rock properties due to burial, changing pressure / temperature conditions, diagenesis, etc. Our workflows consist of several steps that include basin modeling, tomography, petrophysical and geomechanical data analysis, building hybrid effective stress and velocity models, inversion for new velocities / anisotropy, and pre-stack depth migration. The process starts in the shallow section where the image is typically better and iteratively proceeds downwards. Each iteration consists of building two hybrid cubes: 1. Hybrid Effective Stress (HES) cube from Basin Model (BM) results and Mechanical Earth Model, e.g., MEM

addressing shallow hazards, and 2. Hybrid Velocity cube (HV) from HES using petrophysics established Vertical Effective Stress – Velocity transforms. Step 1 is optional and depends on MEM availability. Based on our experience vertical Effective Stress (VES) from a properly calibrated basin model using measured pore pressure, logs, etc., may be sufficient.

Here are two examples of the HV hybrid model building: 1. When the measure of gather flatness for common image gathers satisfies a predefined error level, the region in the tomography velocity model is kept; when the measure of gather flatness does not satisfy the predefined error level, the region in the tomography velocity model is replaced with the corresponding region in the basin modeling derived velocity model. The hybrid model is then smoothed before being used further; 2. Use velocities from tomography in the shallow section and velocities from basin modeling in the deeper section, where tomography loses fidelity.

Proposed workflows allow simultaneous improvement of pore pressure predictions and seismic image and are especially useful in early stages of seismic processing, areas of poor image and sub-salt.

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Selected References

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Outline

- Calibration / validation of pore pressure models
- When pore pressure predictions and seismic imaging should be done together?
- Model building
- Workflows integrating tomography and pore pressure prediction
- Examples
- Conclusions

Calibration / validation of pore pressure models

Calibration

- Fit to measured pressure from wells
- Fit to pressure from seismic velocities
- Fit to ES derived from Sonic-ES transforms from petrophysics
- …

Validation

- Good fit to measured pressure?
- Good fit to sonic?
- Reproduced diagenetic observations- clay diagenesis, quartz cementation, etc.?
- “Improved” or “damaged” seismic image?
- Realistic seismic anisotropy?
- …

Should pressure prediction and imaging be done together?

Observations

- Both seismic velocities and predicted pore pressure should honor stratigraphy and rock property evolution
- Basin modeling and geomechanics provide first approximation effective stress and temperature that can be used in the velocity model building process

When and where is it beneficial to consider doing it together?

- Velocities are a function of effective stress
- Shale dominated Tertiary basins
- Sub-salt, e.g., Gulf of Mexico, West Africa, …
- Seismic tomography needs guidance (e.g., HBI)
- Where understanding diagenetic transitions are critical

Related work

Disciplines

- Stratigraphy
- Seismic tomography
- Basin modeling
- Geomechanics
- Anisotropy
- Petrophysics
- …

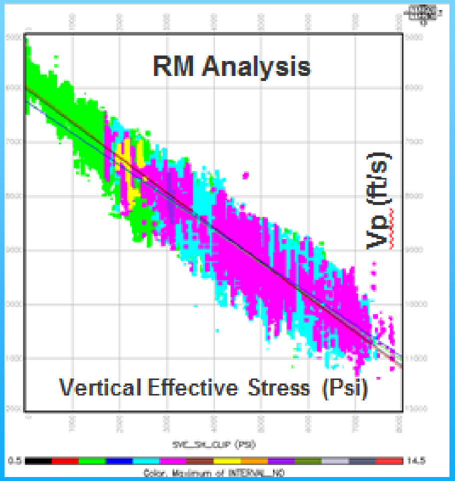
Example publications

- Sayers, 1995
- Lopez, et al., 2004
- Sayers, 2004
- Albertin, et al., 2006
- Williams, 2007
- Petmecky, et al., 2009
- Bachrach, 2010
- Kacewicz, et al., 2014
- …

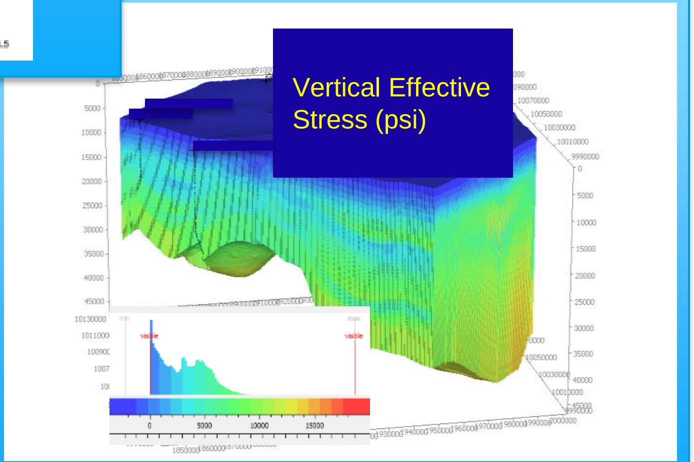
Improved methodology for pore pressure and seismic imaging

Improved pore pressure prediction and depth imaging are achieved through an integration of seismic tomography, geomechanics, petrophysics and basin modeling

Establish petrophysics and geomechanics derived transforms for different age rocks

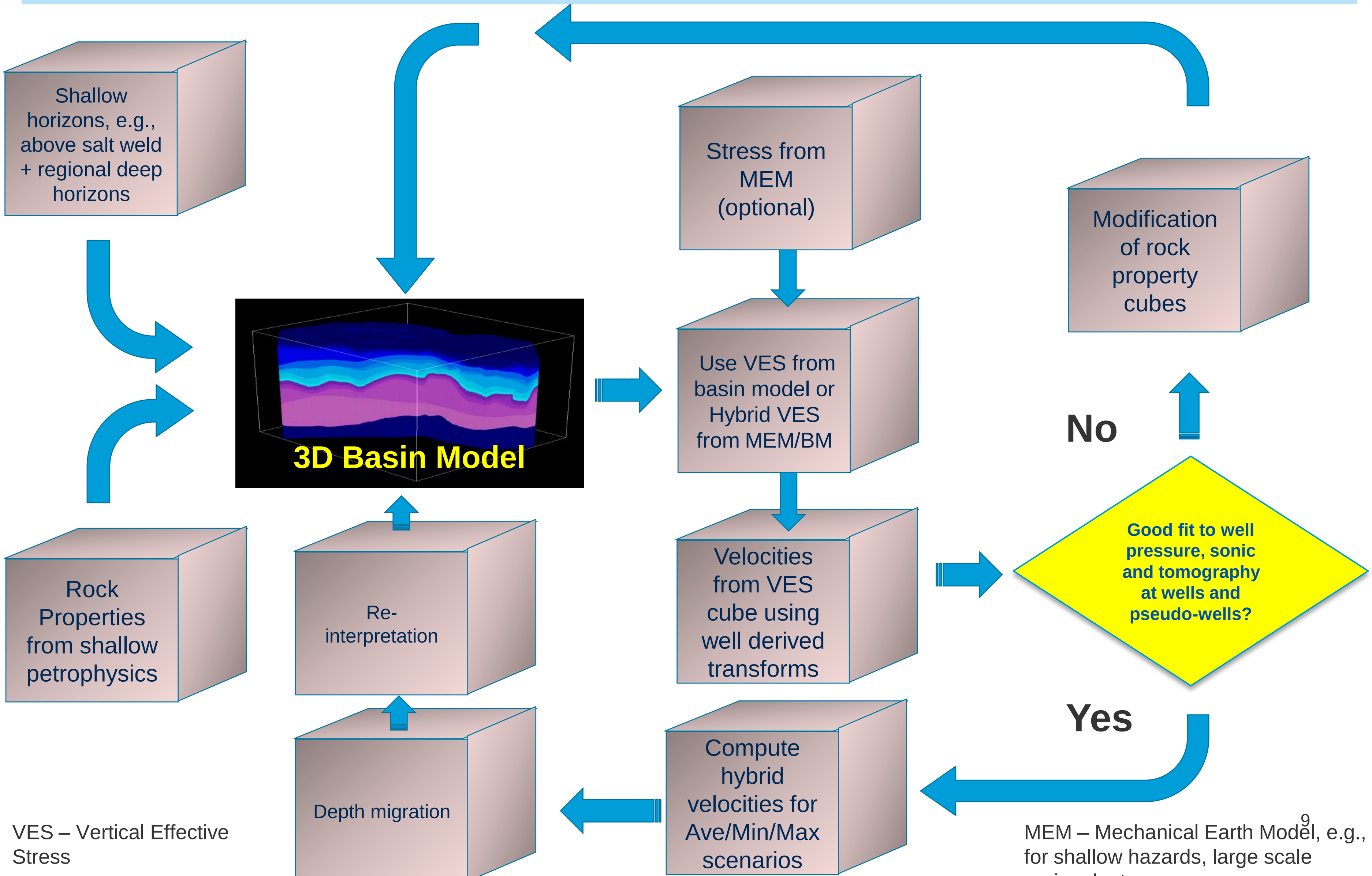


Hybrid VES cubes from BM and/or shallow MEM



Build hybrid velocities from hybrid VES cubes and tomography velocities
+
Migration

Basin modeling iterations

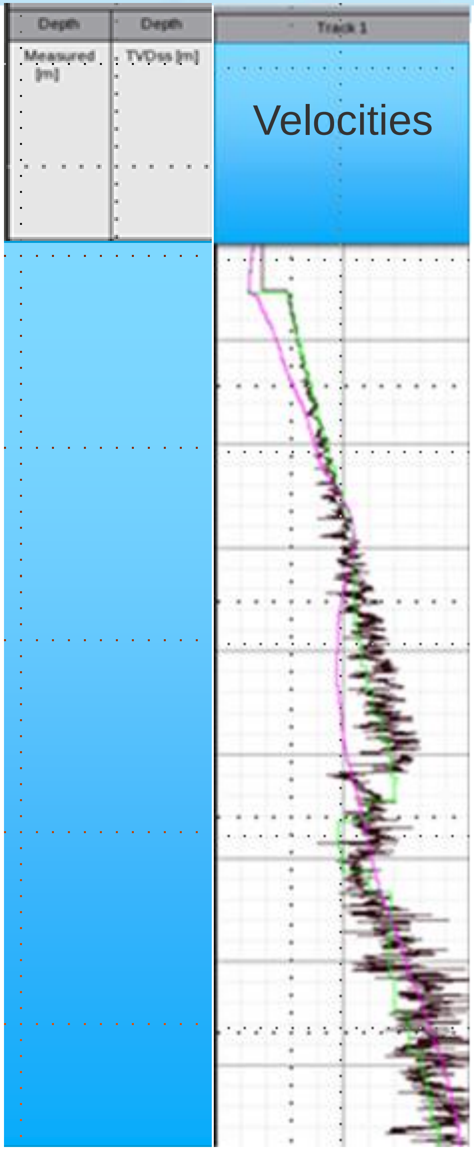


VES – Vertical Effective Stress

MEM – Mechanical Earth Model, e.g., for shallow hazards, large scale regional, etc.

Example Calibration Results – 1D velocity extracts

Tomography typically loses fidelity @ ~8000’-10000’, BM velocity better matches well results at depths



Tomography data provides with high resolution lateral velocity control but the vertical resolution is considerably less and results in a smeared out velocity profile.

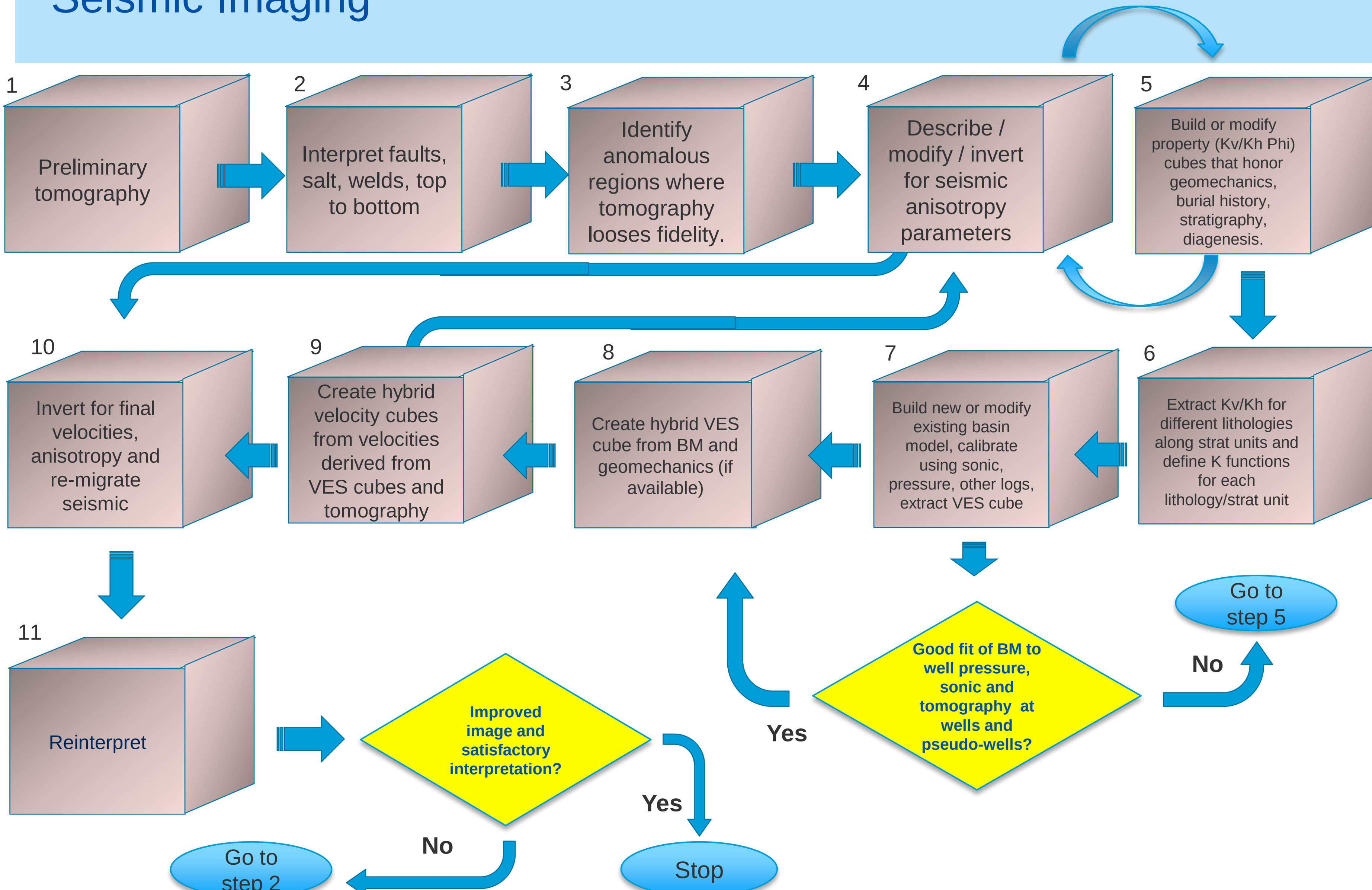
Diagram on the left is an 1D extract from velocity cubes derived from tomography and new hybrid velocities. It shows the improvement and added constraint on vertical velocity

Green – Hybrid velocities
Pink – Tomography velocities
Black – Sonic from well

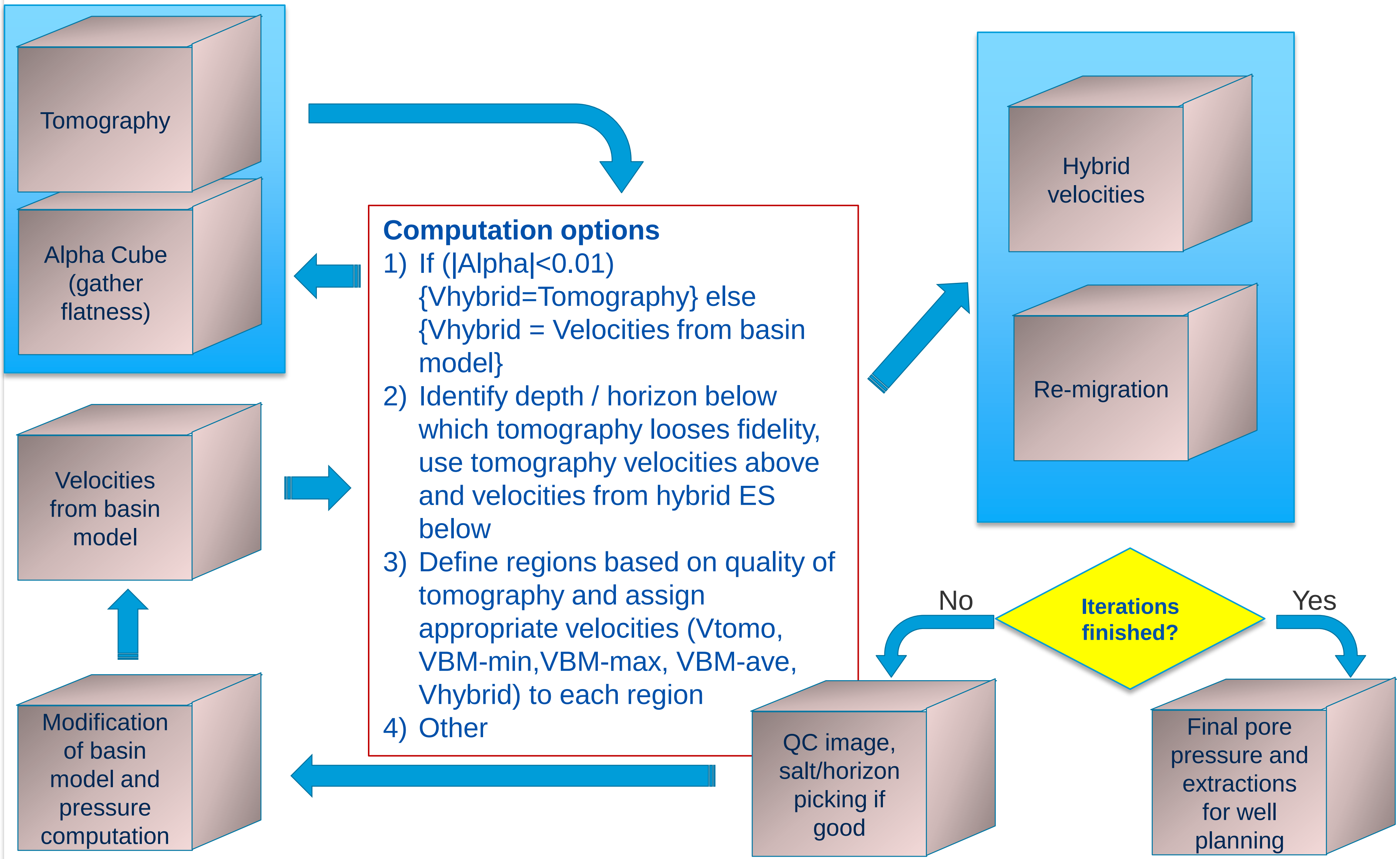
Workflow Summary for Improved Pore Pressure Prediction and Seismic Imaging

- Start from seismic tomography, shallow reflectors
- Build rock property cubes, e.g., from geomechanics, seismic inversion, analogs
- Establish Effective Stress (ES)/Velocity relationships / seismic anisotropy from wells
- Construct and calibrate 3D basin model using shallow interpretations, rock properties
- Construct Hybrid ES (HES) cubes from basin model and MEM (use ES cube from basin model if MEM not available)
- Compute Minimum, Average and Maximum velocity cubes (Vmin, Vave, Vmax) from HES
- Construct HVmin, HVave, HVmax Hybrid Velocity cubes from Tomography and Vmin, Vave, Vmax
- Iterative inversion for velocity / anisotropy or trade off calculation, e.g., based on NMO)
- Migrate seismic data
- Iterate tomography / basin modeling gradually improving image (shallow to deep)

Full workflow for Improved Pore Pressure Prediction and Seismic Imaging

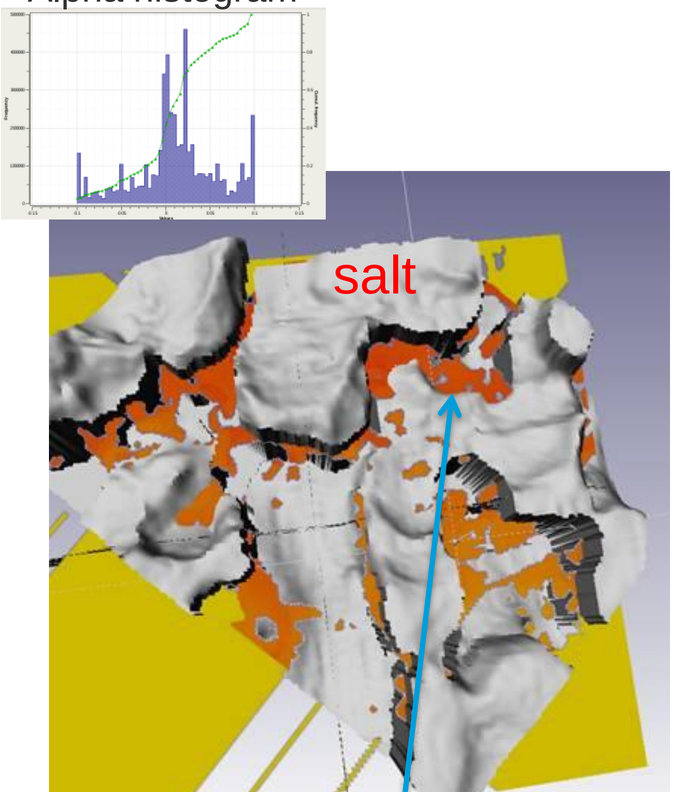


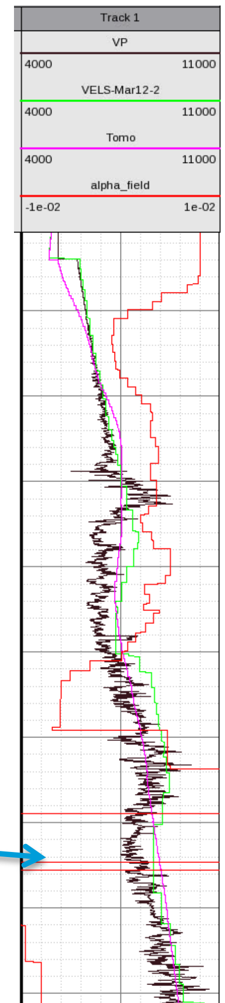
Pore pressure and velocity Workflow – creating hybrid velocities



Example hybrid model building - use of Alpha Cube for defining regions

Alpha histogram





ft/sec

Green - velocity from BM
Purple - Tomography
Black – Velocity from well
Red - Alpha

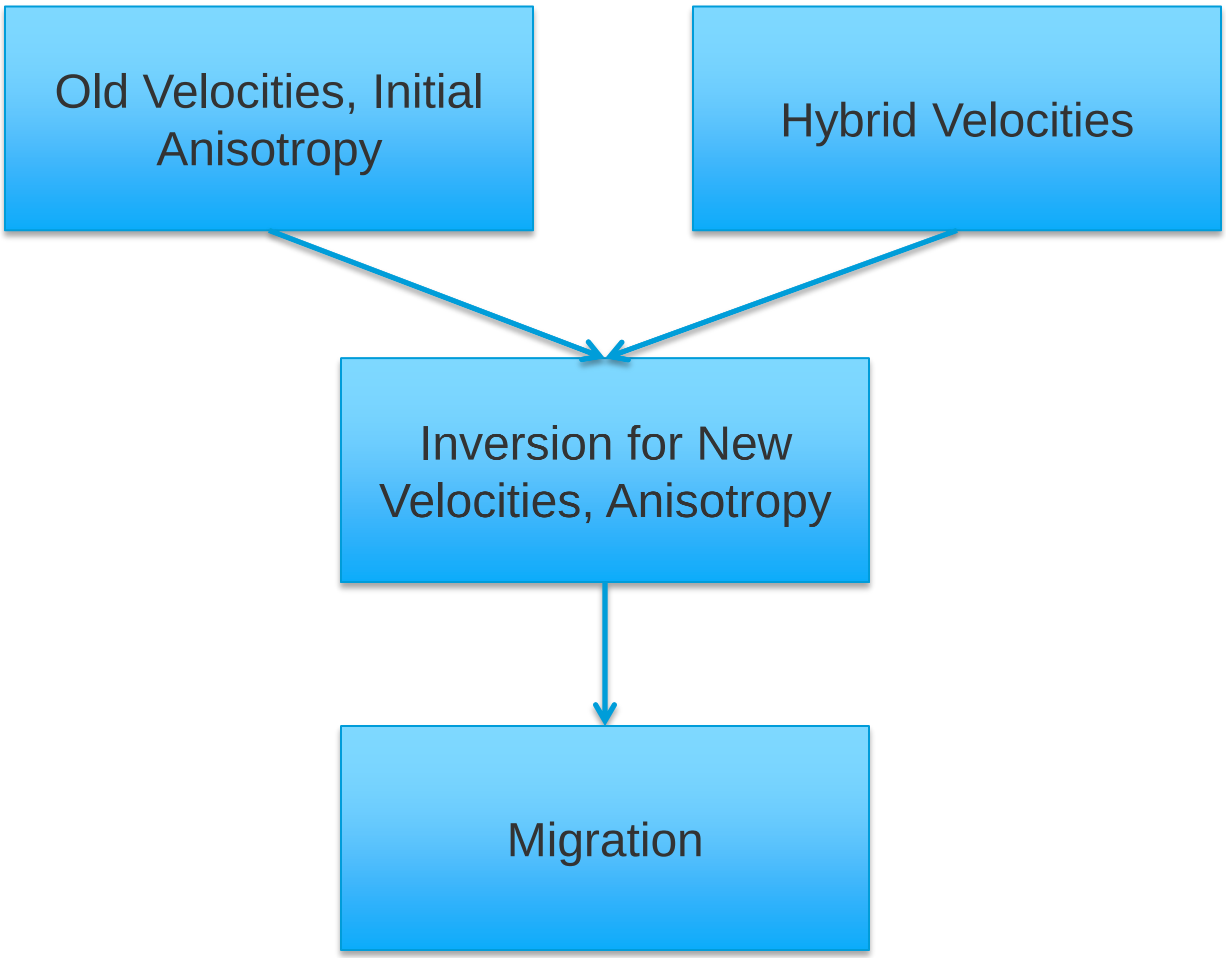
Alpha >0.005

Alpha <-0.005

Alpha <-0.01 OR Alpha>0.01

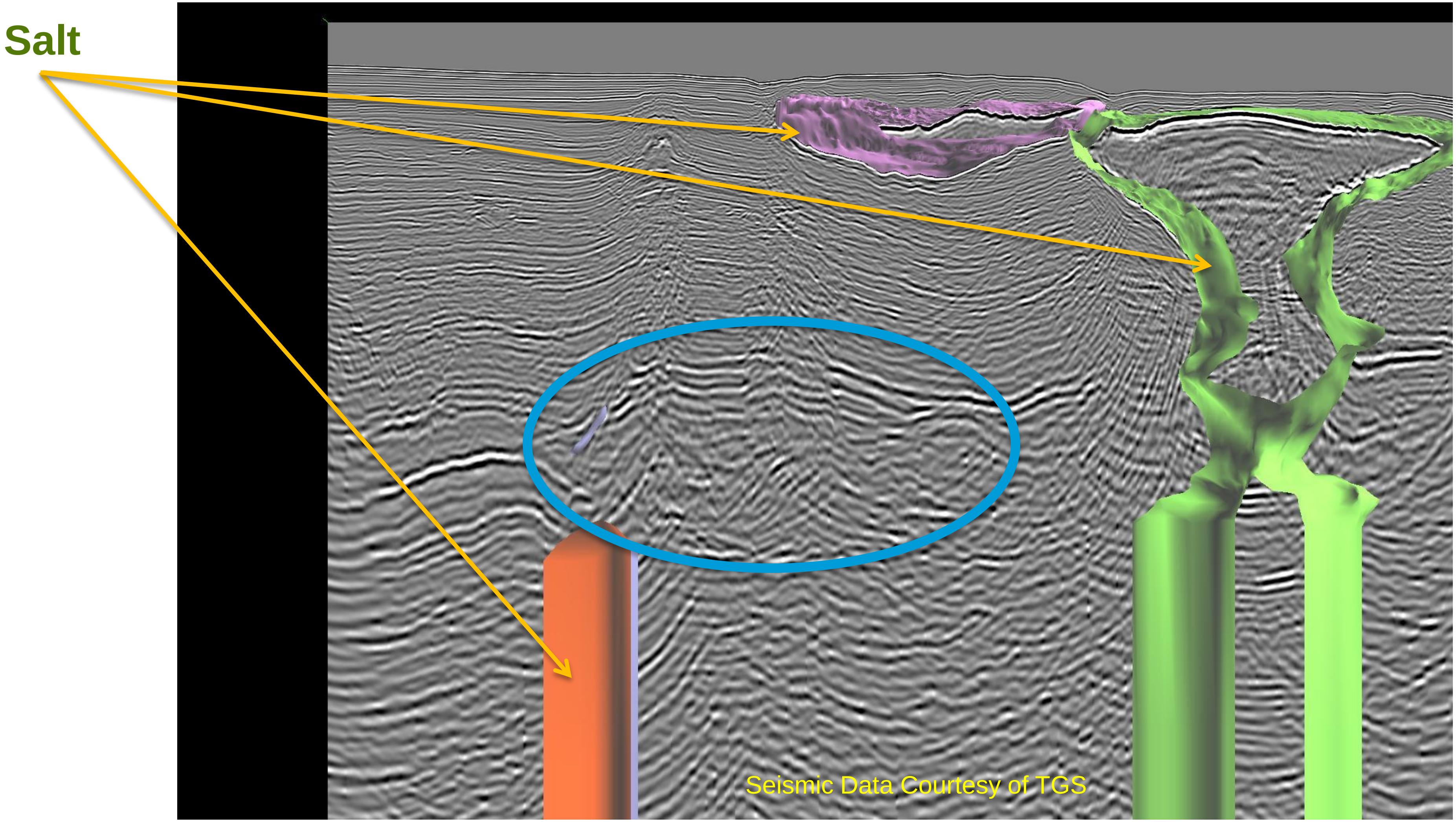
Alpha values > 0.01 (red) indicate poor quality tomography. Use velocities from hybrid VES in Orange/Red region

Inversion for Final Velocities from Tomography, Hybrid and Anisotropy



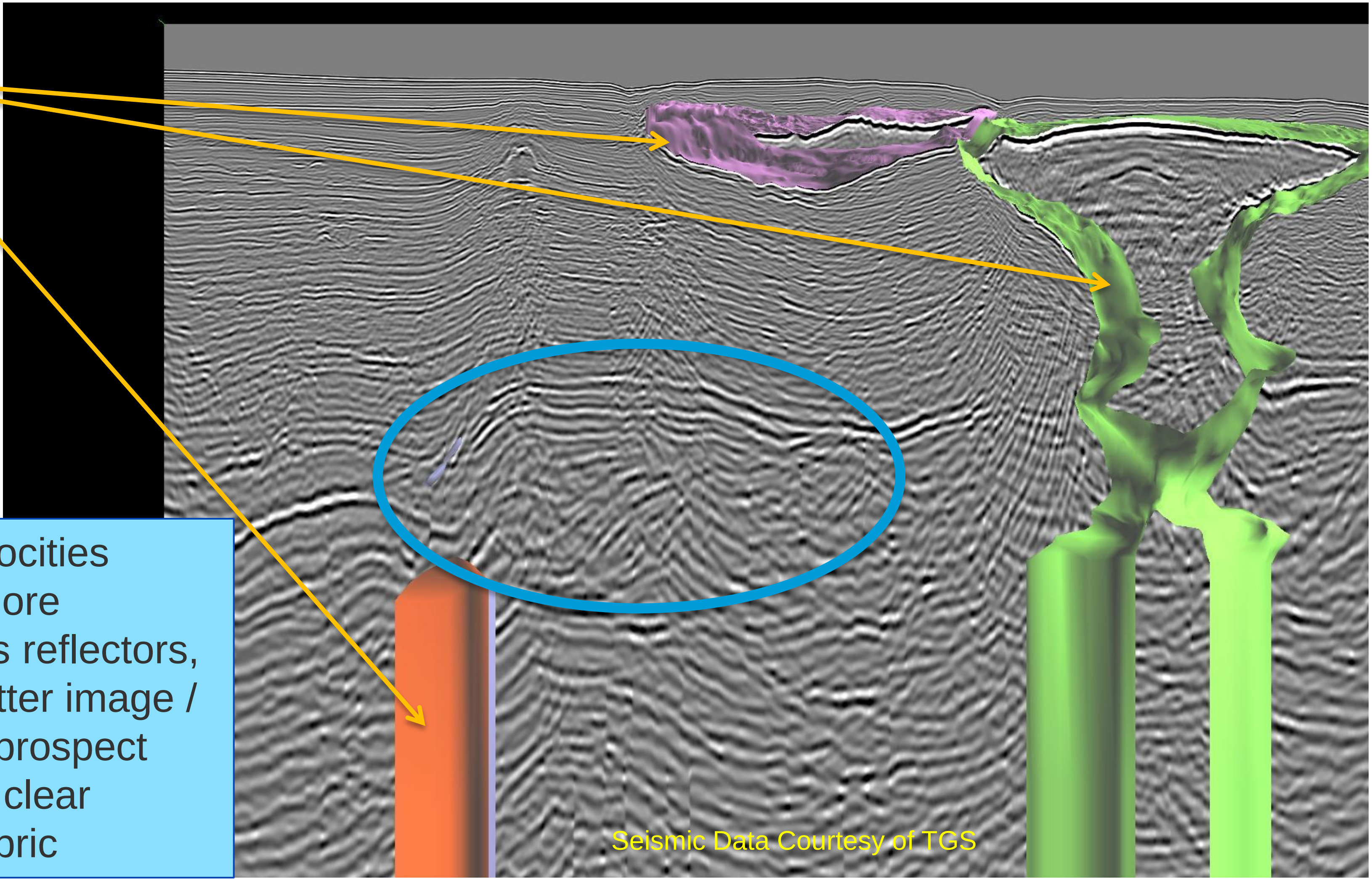
Examples

Example 1 - Improved Geometry / Internal Fabric of a Prospect



Before

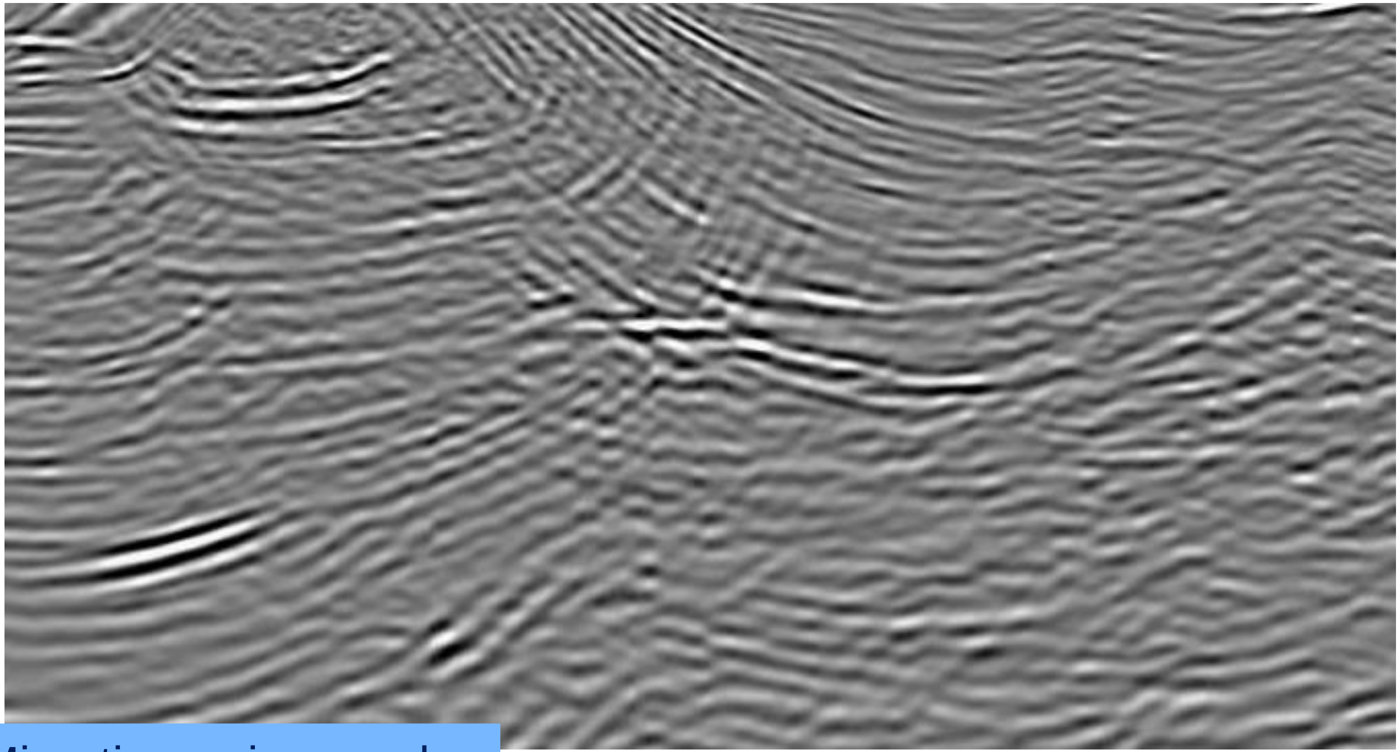
Example 1 - Improved Geometry / Internal Fabric of a Prospect



Hybrid velocities result in more continuous reflectors, slightly better image / improved prospect geometry, clear internal fabric

After

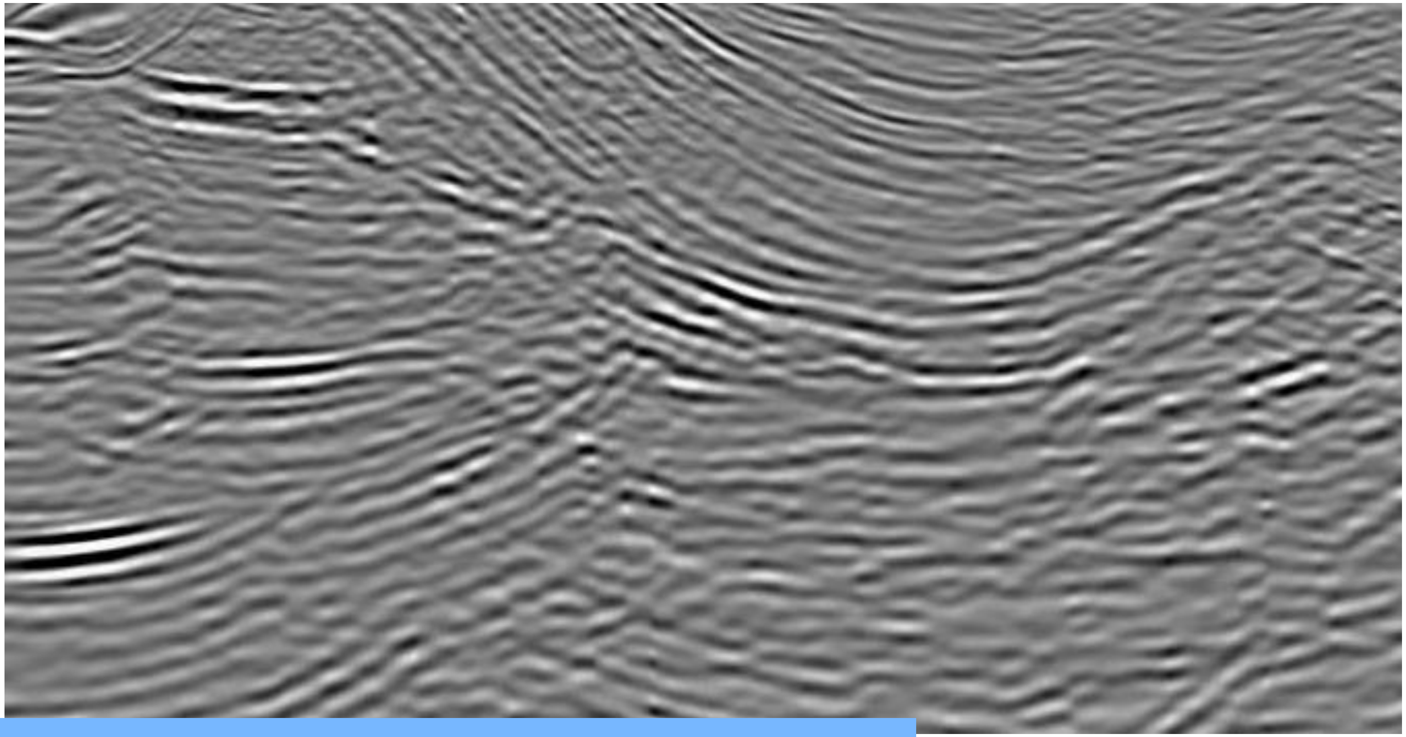
Example 2 - Better Image of Possible Salt Weld



Migration swings and sub-horizontal, discontinuous, high amplitude reflections

Before Re-migration

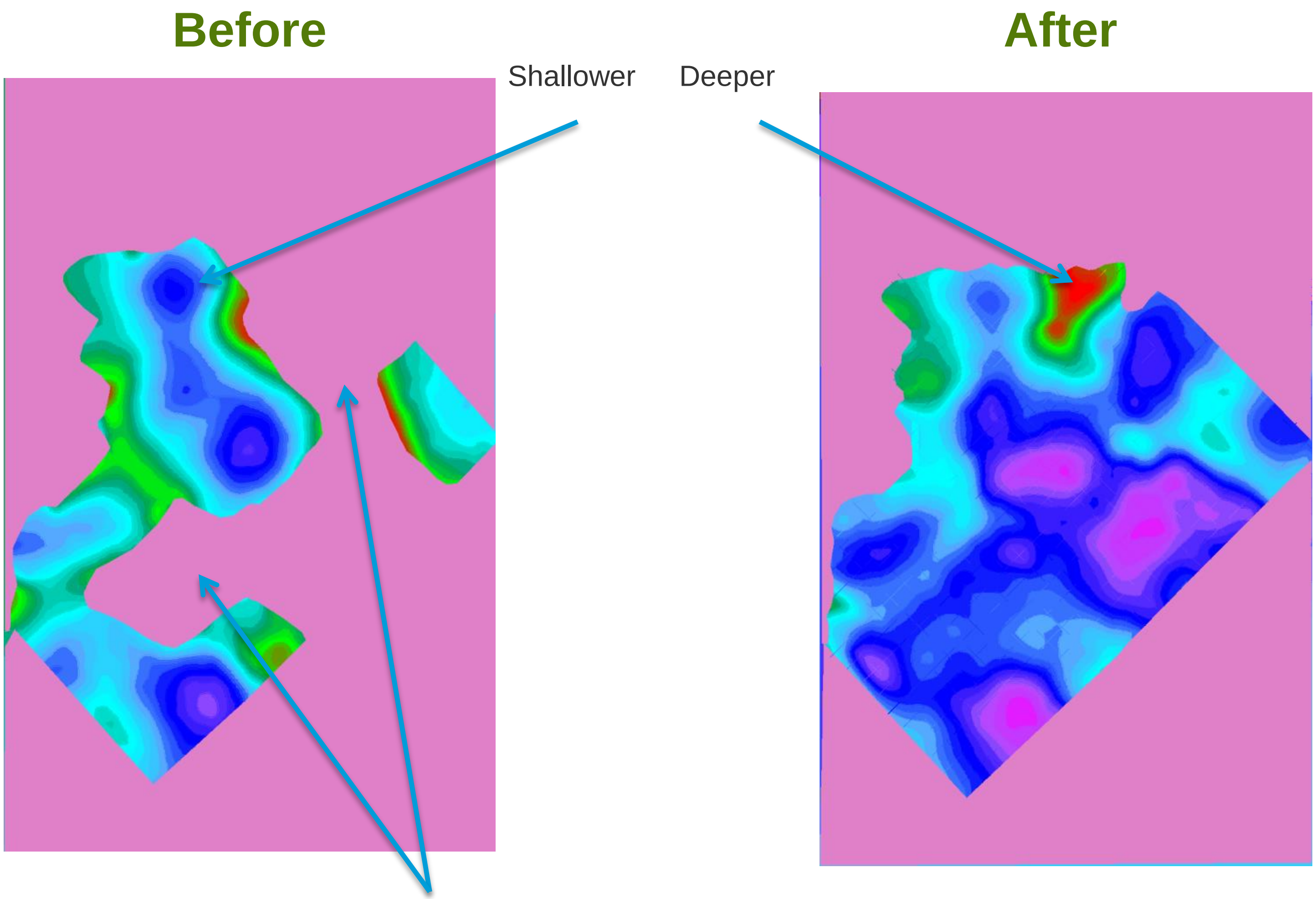
Example 2 - Better Image of Possible Salt Weld



Sub-vertical migration swings in before image has been subdued and sub-horizontal, discontinuous, high amplitude reflections have now coalesced into a more continuous possible weld surface connected to the upper allochtonous salt

After Re-migration

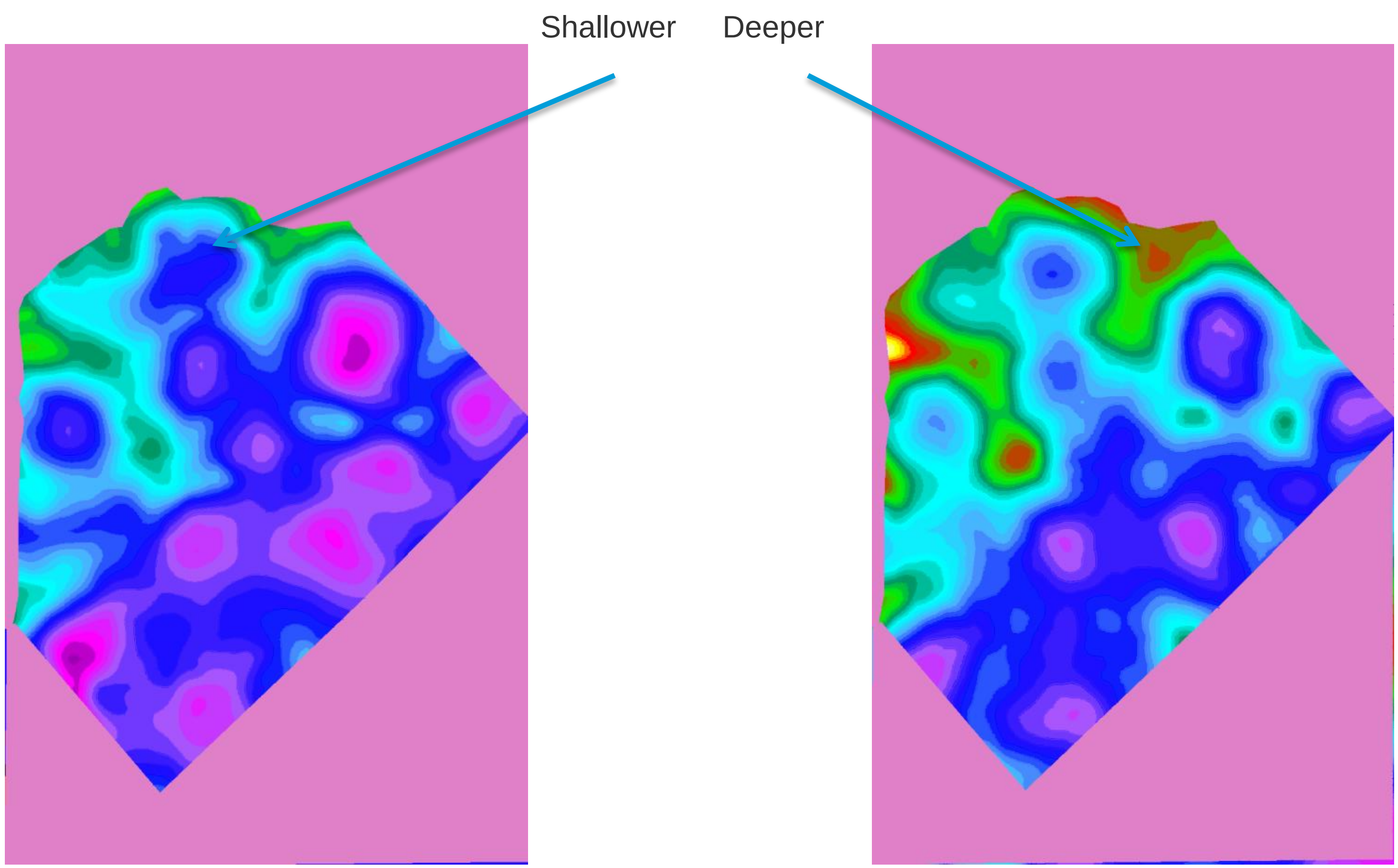
Example 3 - Improved Ability to Interpret Deep Section



Poor image, inability to interpret

Example 3 – top of source rock reflector before and after remigration

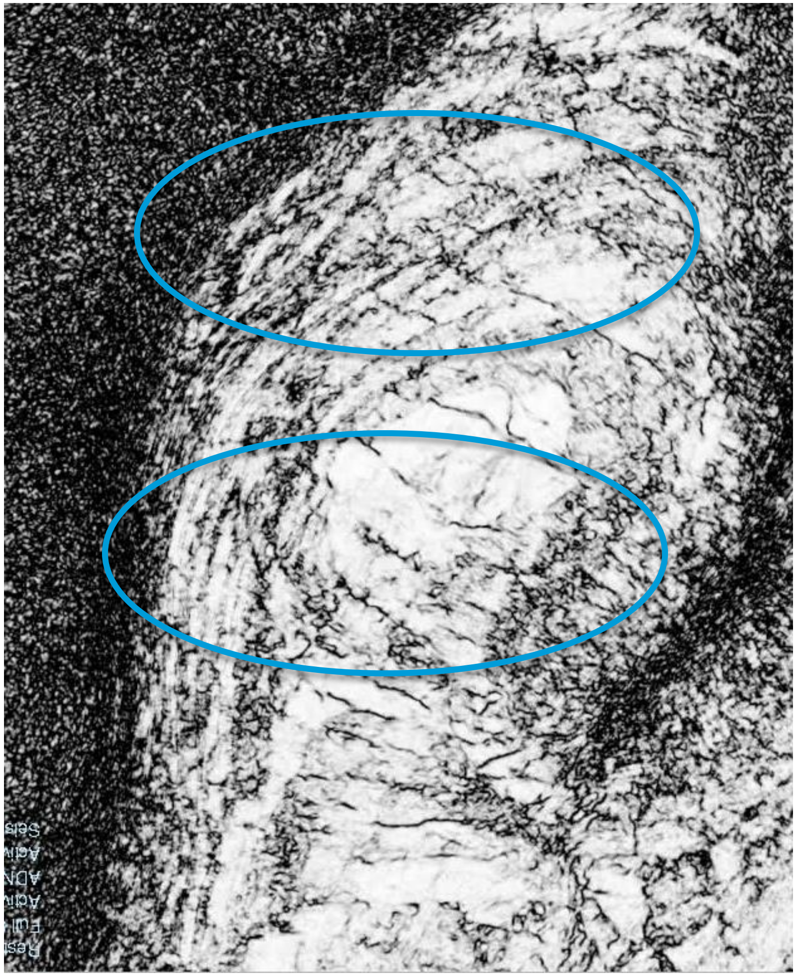
Before **After**



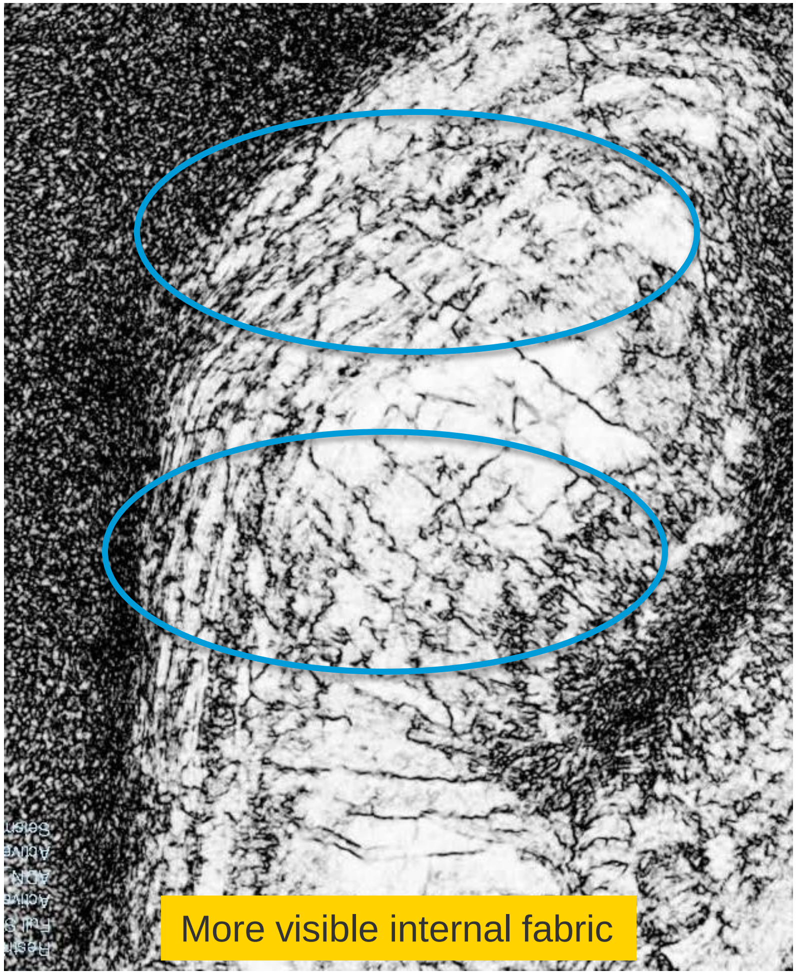
Exploration implication- source is deeper, more mature and generating more gas component

Example 4 – More Visible Prospect Fabric

Coherency Depth Slice at Depth1



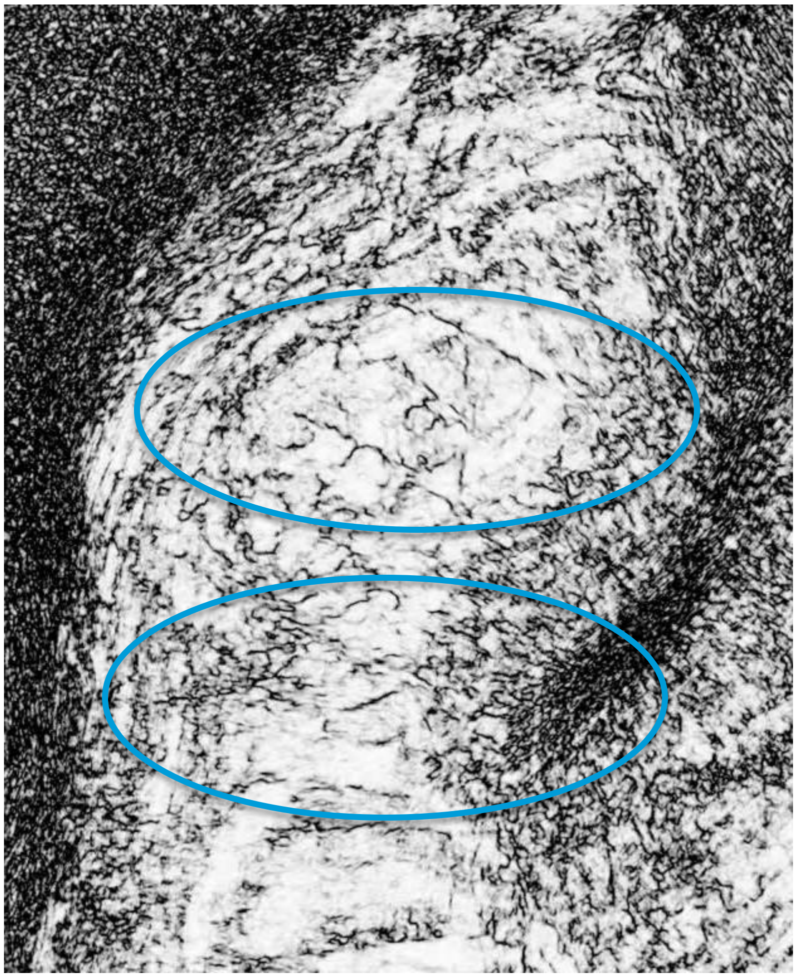
Before



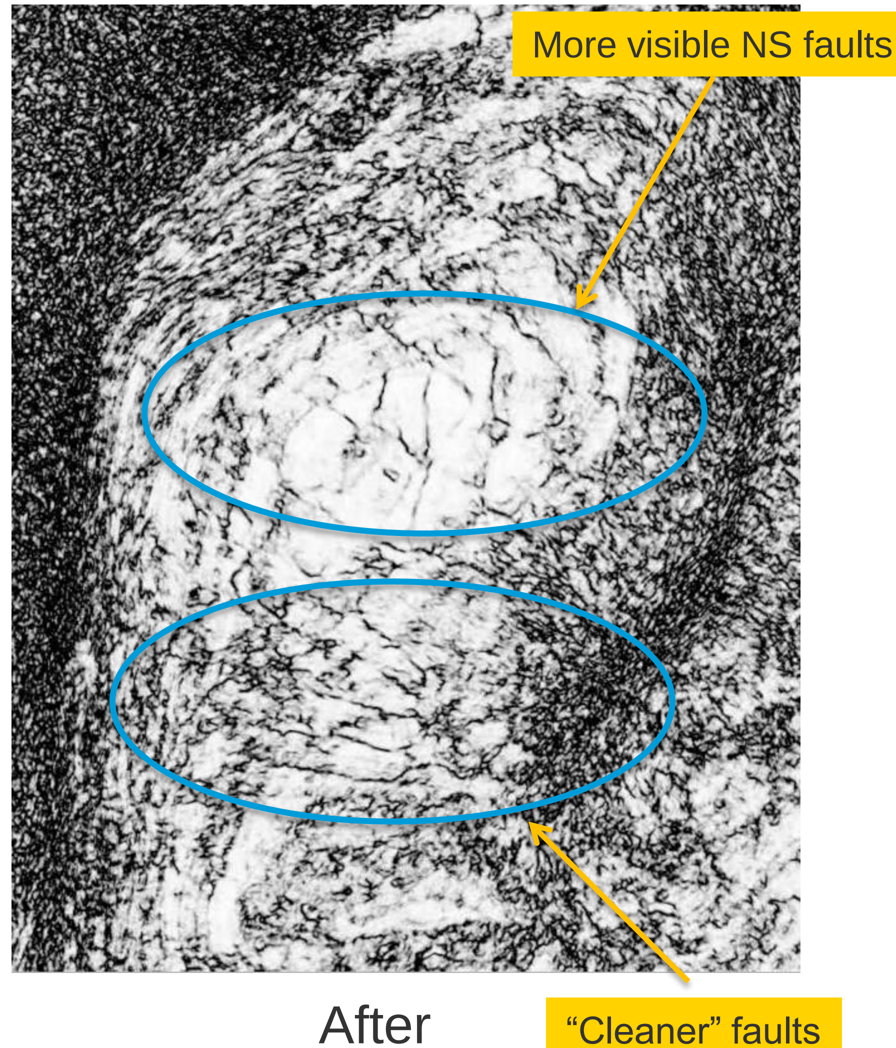
After

Example 4 – More Visible Prospect Fabric

Coherency Depth Slice at Depth2



Before



After

Conclusions

- Pore pressure predictions and seismic image can be iteratively improved through an integrated workflow combining seismic tomography basin modeling, geomechanics and petrophysics:
  - Defining rock properties and extracting trends from shallow petrophysics
  - Building basin model based shallow interpretations and rock properties
  - Building hybrid VES based on basin model results and geomechanics model (if available)
  - Building hybrid cube from tomography velocities and velocities computed from VES / petrophysics
  - Inverting for anisotropy parameters and velocities for processing
  - Iterative improvement of the image and pressure predictions top/down
- Presented examples demonstrate that the new approach can improve image, geometry and provide better understanding of prospect internal fabric.

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