Anisotropic Full Waveform Inversion

Source Estimation and Rock Physics Preconditioning

Huy Le

SEP168

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Source estimation: Benefits

- Seismic modeling often assumes simple physics, e.g. acoustic, constant density, no surface waves, or absorbing boundaries...
- This leads to amplitude mismatch between modeled and observed data.
- Source estimation by directly minimizing FWI objective function can help reduce amplitude mismatch.

Source estimation: Derivation

$$f(\mathbf{m}, s) = \frac{1}{2}\|d(\mathbf{m}, s) - d_0\|_2^2.$$

- $\mathbf{m}$: velocity model
- s: wavelet
- d: modeled data
- d_0: observed data

$$d = \mathbf{RPQ}s.$$

- **Q**: injection of the source function at shot locations
- **P**: forward propagation
- **R**: recording of wavefields at receivers

Source estimation: Derivation

$$\frac{\partial f}{\partial s} = \mathbf{Q}^T \mathbf{P}^T \mathbf{R}^T (d - d_0).$$

- $\mathbf{R}^T$: injection of receiver locations
- $\mathbf{P}^T$: backward propagation operator
- $\mathbf{Q}^T$: recording at source locations
- Note: **no cross-correlation**

Source estimation: Example

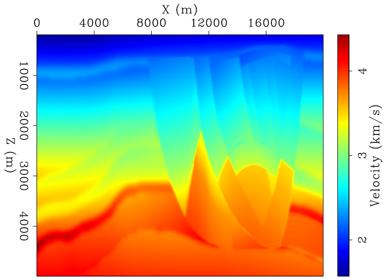

Figure 1: True velocity

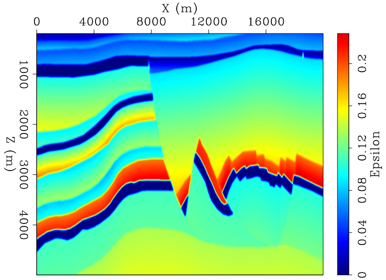

Figure 2: True ϵ

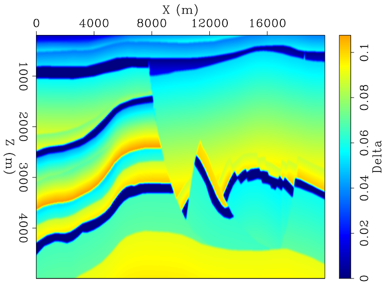

Figure 3: True δ

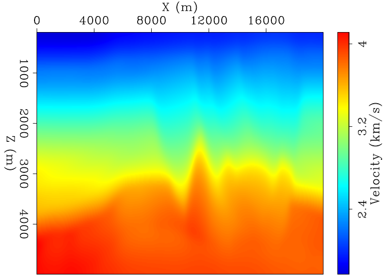

Figure 4: Background velocity

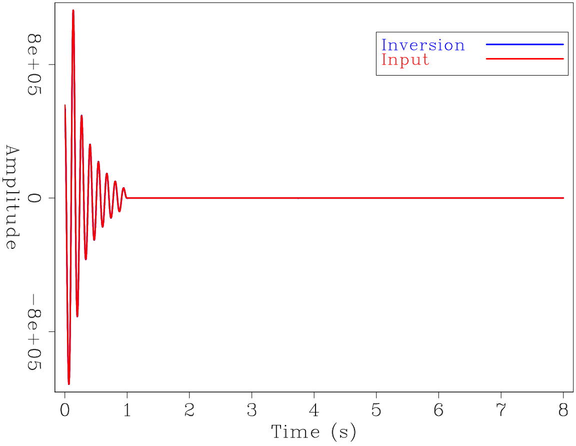

Figure 5: Input and inverted wavelets

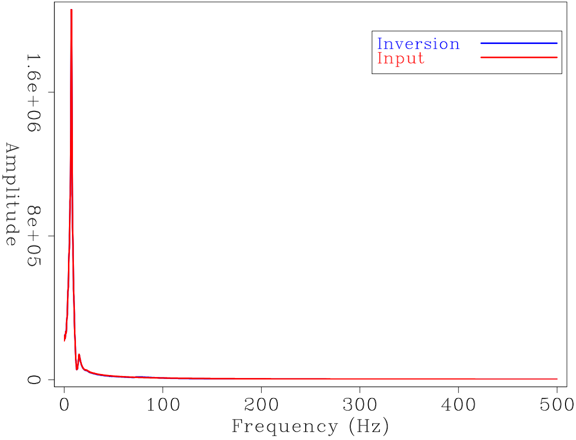

Figure 6: Input and inverted spectra

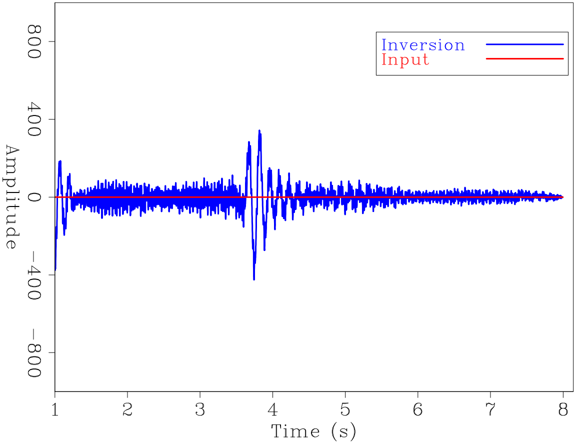

Figure 7: Input and inverted wavelets

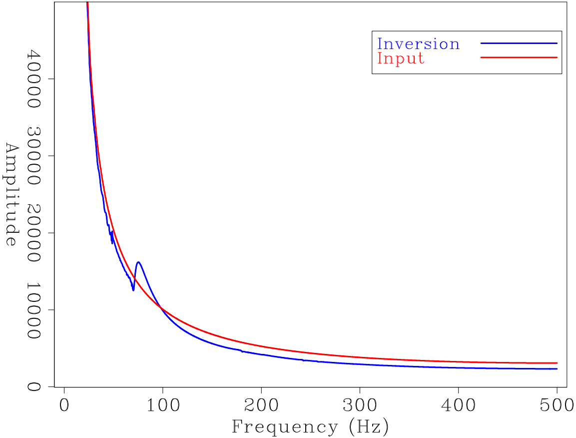

Figure 8: Input and inverted spectra

Source estimation: Example

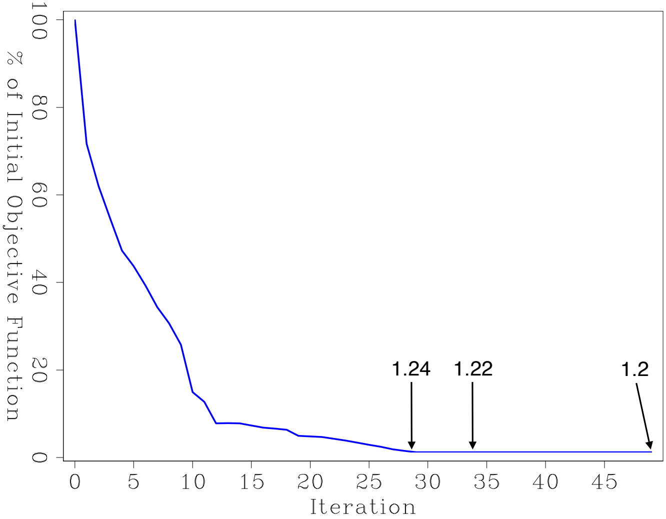

Figure 9: Objective function

Rock physics to precondition anisotropic FWI

- Parameters have different physical interpretations, dimensions, magnitudes, and sensitivities.
- Tradeoff and crosstalk can lead to unrealistic results.
- The Hessian can help reduce crosstalk and speedup convergence but **expensive**.
- Rock physics is another way to obtain model covariances.

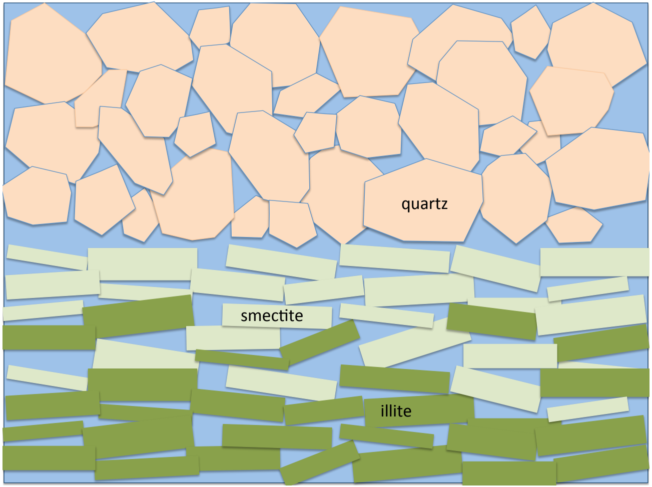

Figure 10: Sand-shale layers typical for Gulf of Mexico

- Shale volume: V_{shale}
- Temperature increases with burial/depth, smectite transforms into illite.
- Temperature determines illite percentage: $P_{\text{illite}}(T)$.

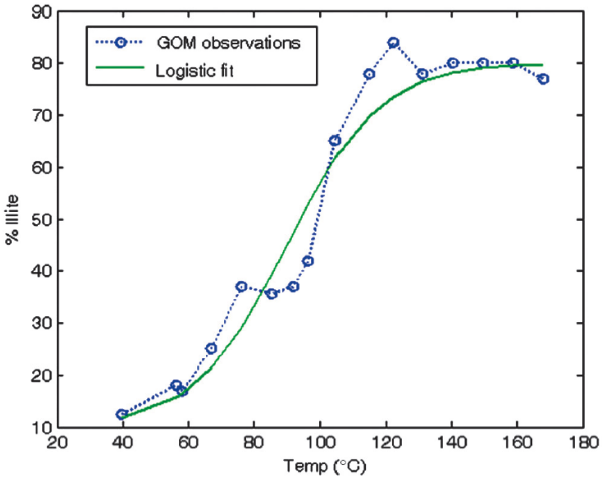

Figure 11: Smectite-illite transition (Bachrach, 2011)

Compaction

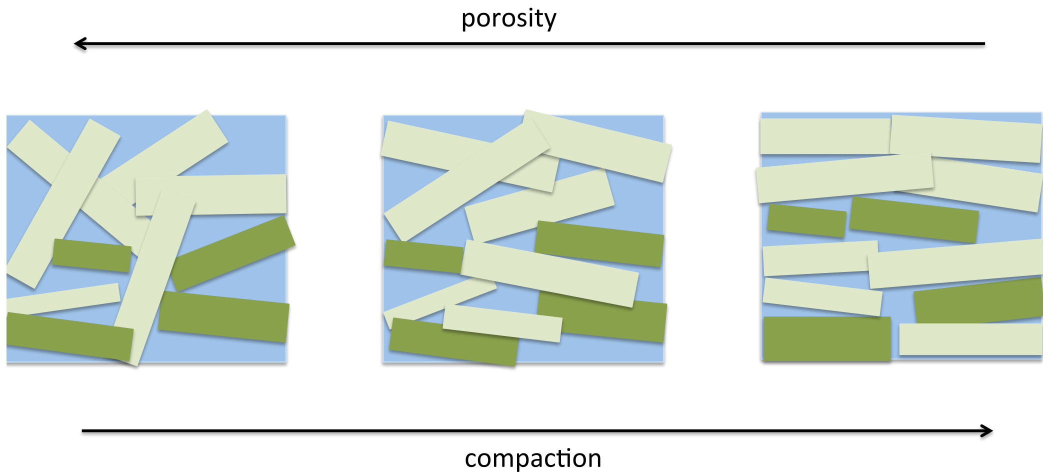

Figure 12: Compaction model for shale: porosity decreased while anisotropy increases as increasing compaction

Compaction model

- Porosity: $\phi = ae^{bz} + ce^{dz}$ (Dutta et al, 2009)
- Average stiffnesses of clay: $c_{ij}(c_{ij}^{\text{particle}}, W)$ (Brandyopadhyay, 2009)
- Orientation distribution: $W(\phi)$

Rock physics model: Differential Effective Medium

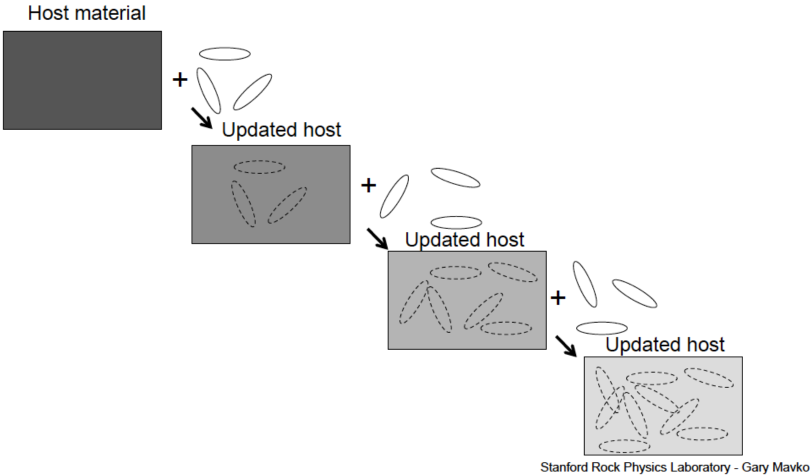

Figure 13: Differential Effective Medium (DEM) model adds inclusions in small increments and updates.

Rock physics model: Differential Effective Medium

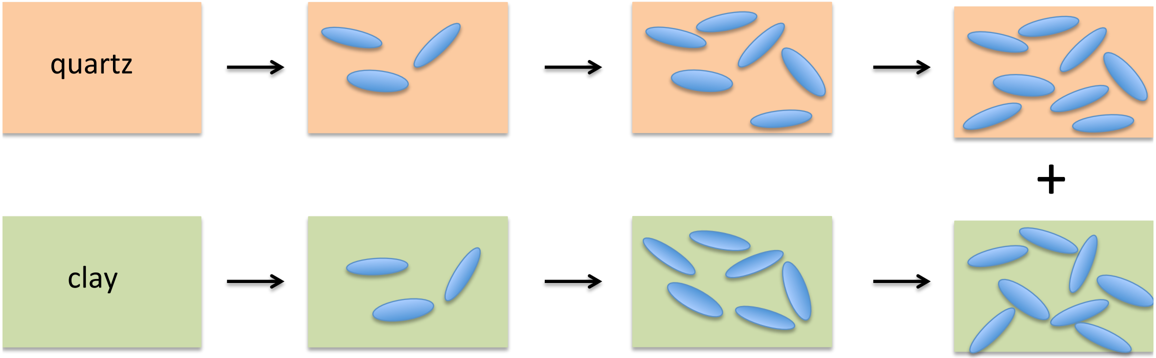

Figure 14: Model sand and shale layers separately, calibrate, and add.

Workflow

1. From uniform distributions, randomly select values for parameters like reaction temperatures, clay orientation parameters, critical porosity, and aspect ratio.
2. Calibrate porosity-depth trends for sand and shale and the total porosity.
3. Model sand and shale using DEM.
4. Compute the average stiffnesses of sand-shale layers.
5. Repeat to calibrate with well data and generate many earth models.
6. Compute the mean models and covariances.

Field application: sand-shale selection

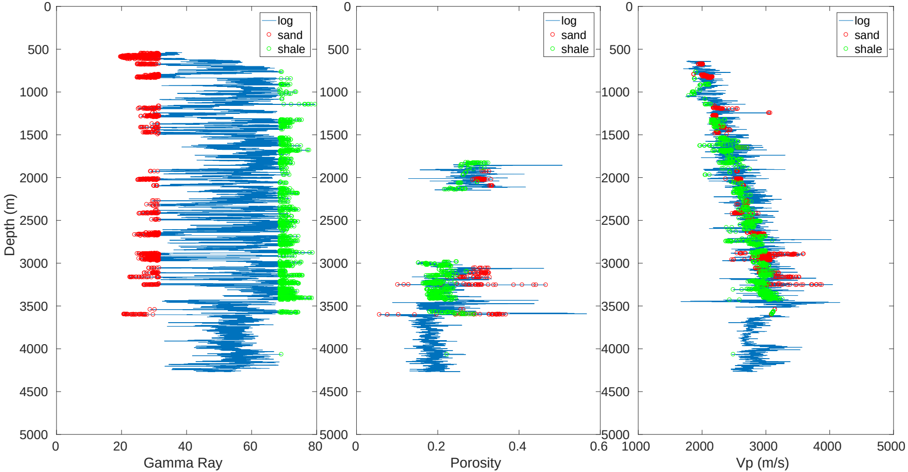

Figure 15: Gamma ray as indication of sand-shale[1]

[1]Includes data supplied by IHS Energy Log Services, Copyright 2017, IHS Energy Log Services Inc.

Field application: porosity calibration

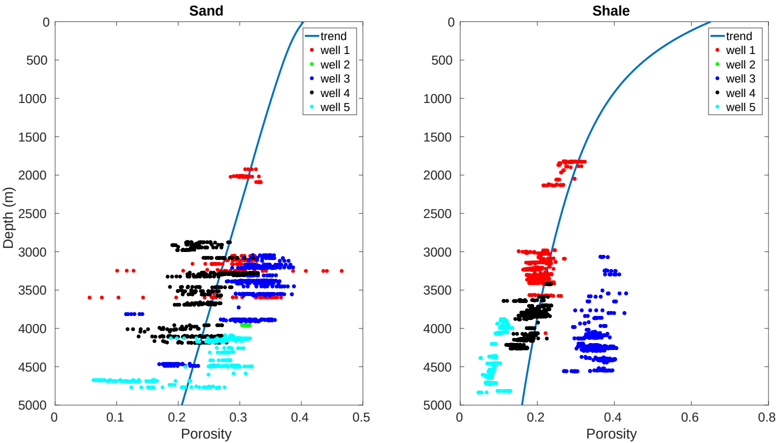

Figure 16: Calibration of porosity[2]: $\phi = ae^{bz} + ce^{dz}$

[2]Includes data supplied by IHS Energy Log Services, Copyright 2017, IHS Energy Log Services Inc.

Field application: velocity calibration

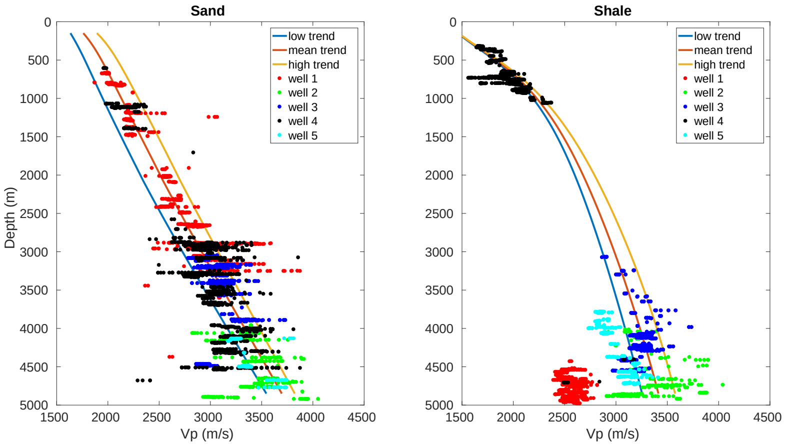

Figure 17: Calibration of velocity[3]

[3]Includes data supplied by IHS Energy Log Services, Copyright 2017, IHS Energy Log Services Inc.

Field application: distributions

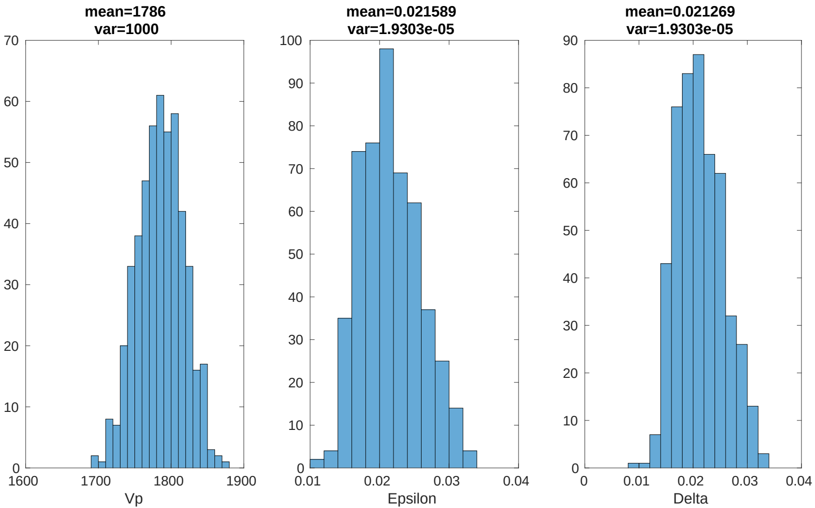

Figure 18: Shallow sandy shale (more shale than sand)

Field application: distributions

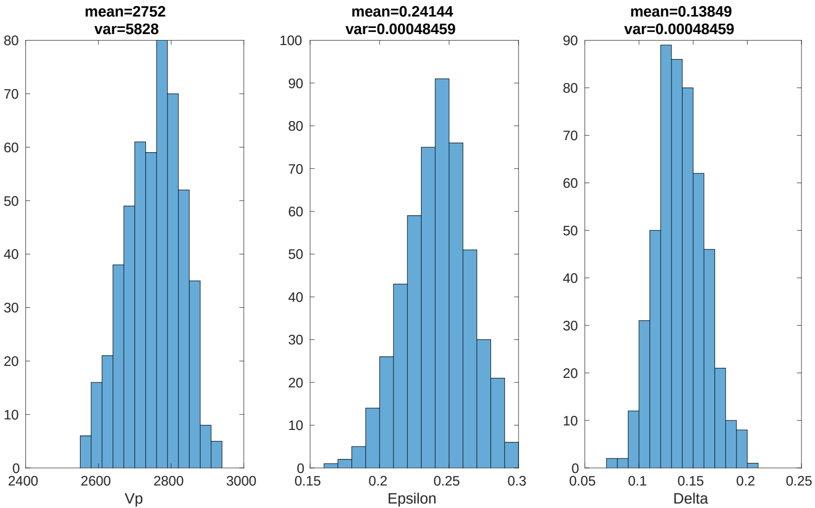

Figure 19: Deep sandy shale

Field application: distribution

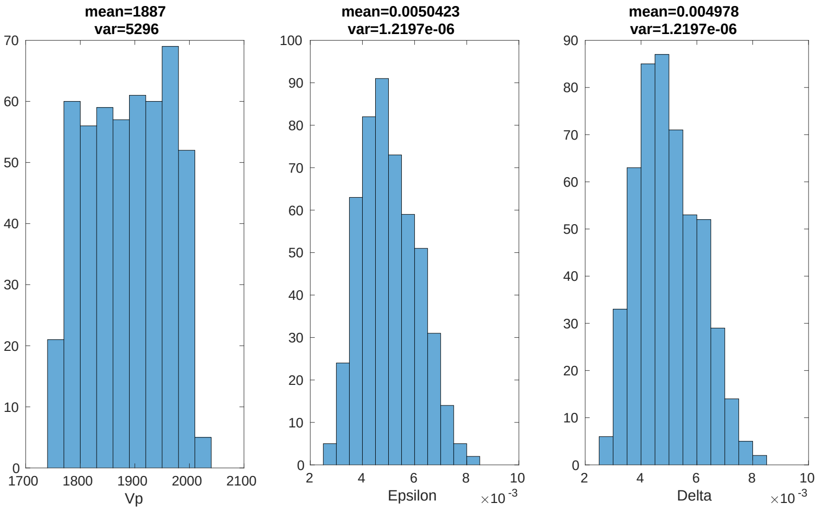

Figure 20: Shallow shaly sand (more sand than shale)

Field application: distributions

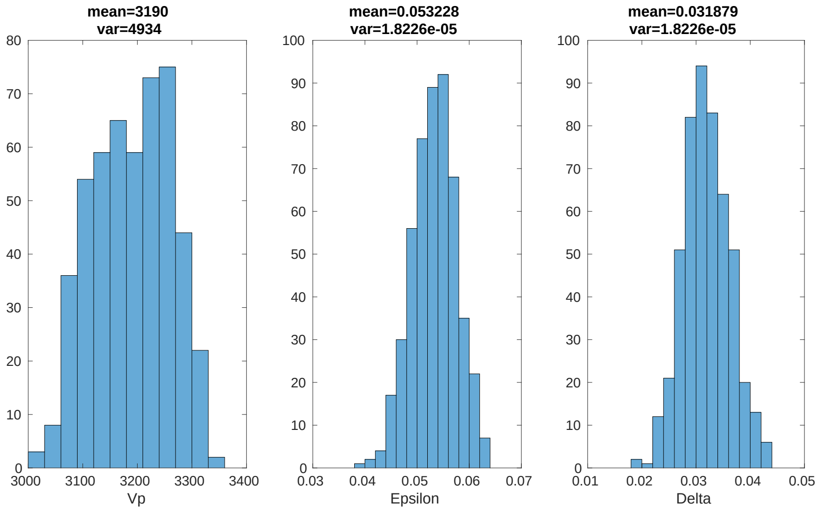

Figure 21: Deep shaly sand

Field application: correlations

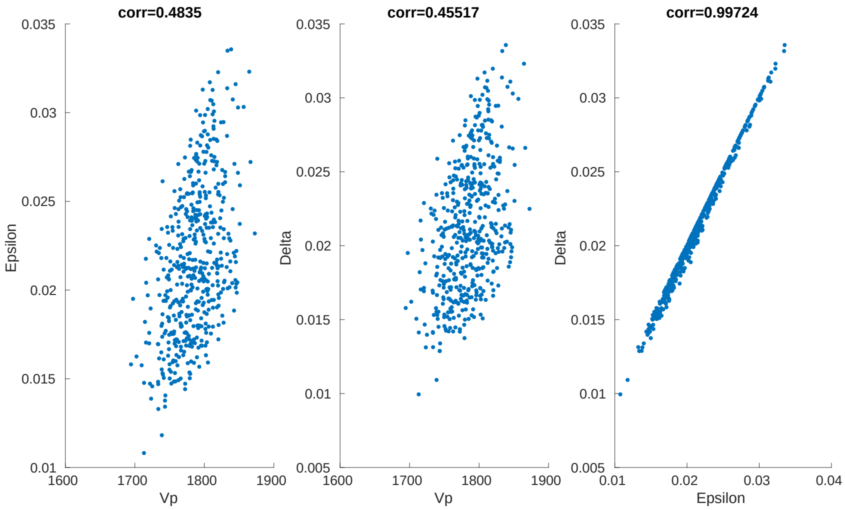

Figure 22: Shallow sandy shale

Field application: correlations

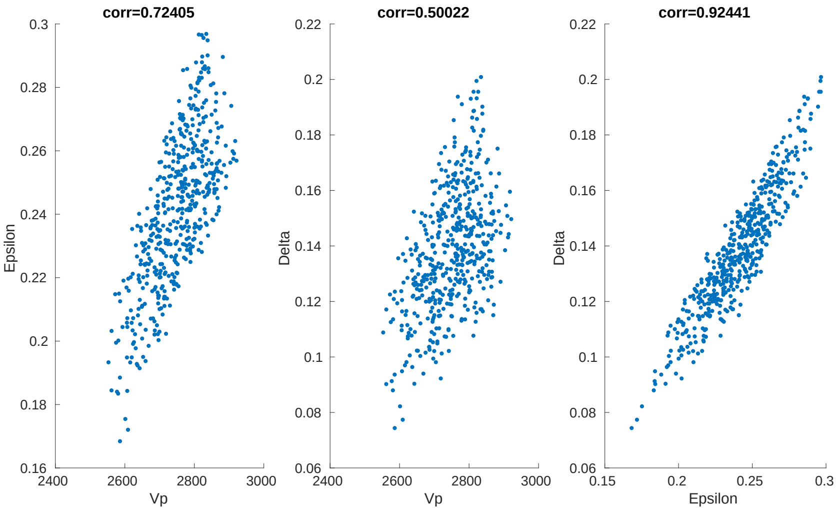

Figure 23: Deep sandy shale

Field application: correlations

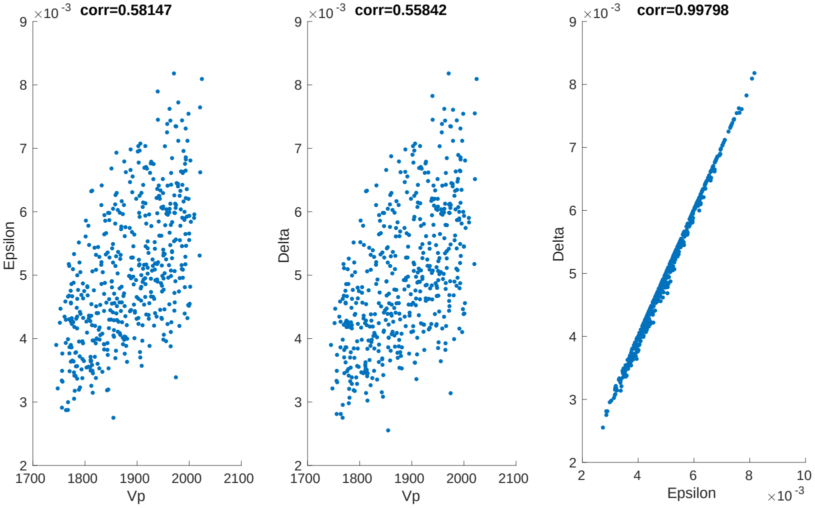

Figure 24: Shallow shaly sand

Field application: correlations

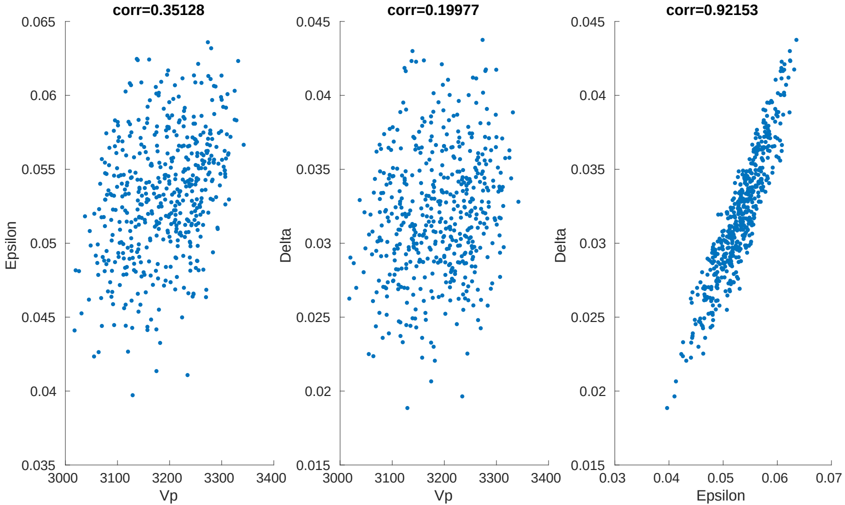

Figure 25: Deep shaly sand

Field application: mean models

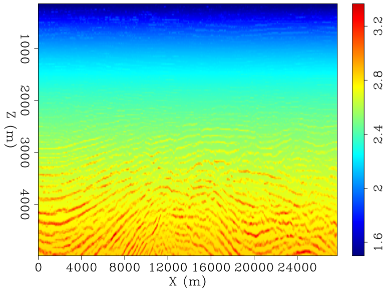

Figure 26: Velocity

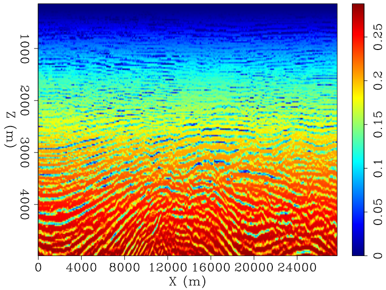

Figure 27: ϵ

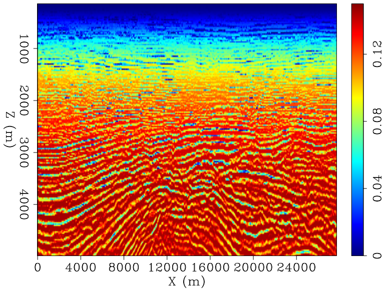

Figure 28: δ

Field application: model variances

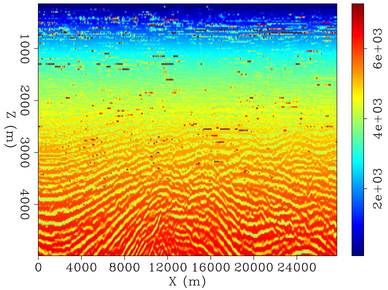

Figure 29: Velocity

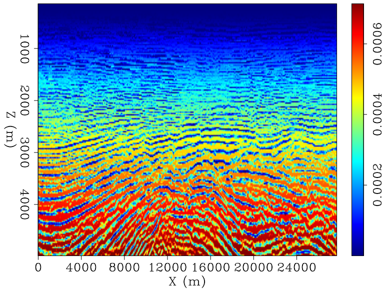

Figure 30: ϵ

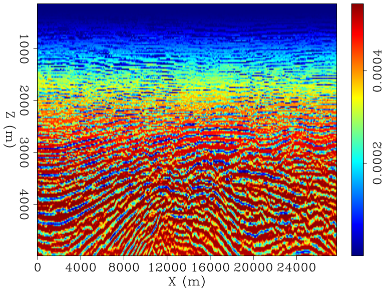

Figure 31: δ

Field application: model covariances

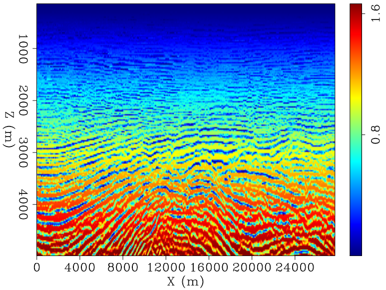

Figure 32: Velocity and ϵ

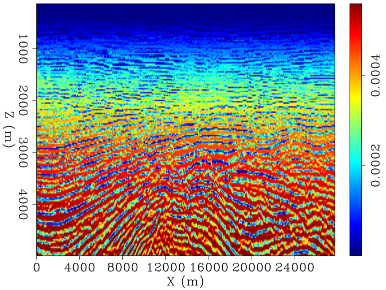

Figure 33: ϵ and δ

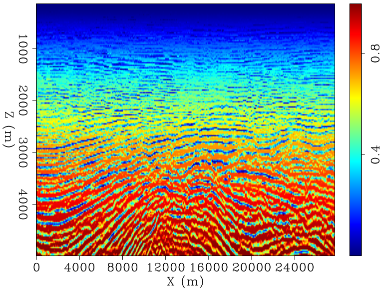

Figure 34: Velocity and δ

Conclusions

- Source estimation can help reduce amplitude mismatch between modeled and observed data.
- Simple synthetic example validates our derivation.
- Rock physics is one approach to obtain model covariance and precondition FWI.
- Parameters tuning and calibration are important.
- Future work: apply source estimation and rock physics preconditioning on field data.

Acknowledgements

- We thank WesternGeco for donating the shale volume.
- We thank IHS Energy Log Services Inc. for the well logs.