Outline

- Motivation
- Theory
- Inversion examples:
  - Synthetic: VTI Marmousi
  - Field: MC311 from ExxonMobil
- Conclusions and future work

Motivation

- Anisotropic WEMVA
  - Anisotropy VS. isotropy
  - Wavefield VS. ray
  - Image space VS. data space

- Examples
  - Propagator: Two-way VS. one-way
  - Objective function test
  - Preconditioning

Theory

- Objective function

$$J = \frac{1}{2}\sum_{\mathbf{h}}\langle \mathbf{h}I_{\mathbf{h}}, \mathbf{h}I_{\mathbf{h}}\rangle$$

L: modeling operator
f : source wavelet
f': receiver data
I_h: image at subsurface offset h
S_{+h}: shifting operator by +h

- Constraints (State equations)

$$\mathbf{L}(s_n, \eta)\mathbf{p} = \mathbf{f}$$ Source wavefield

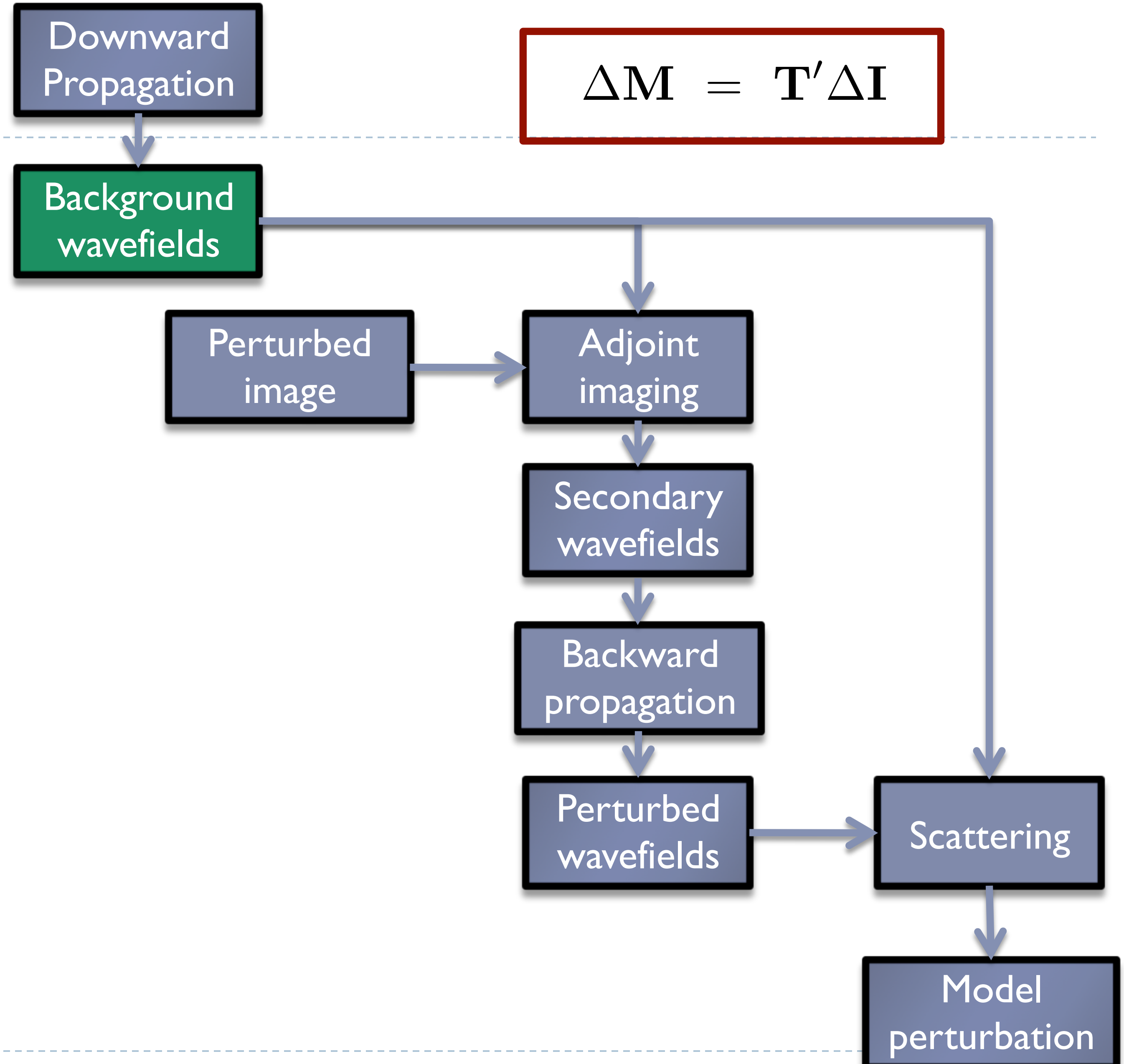
$$\mathbf{L}^*(s_n, \eta)\mathbf{q} = \mathbf{f}'$$ Receiver wavefield

$$I_{\mathbf{h}} = (S_{+\mathbf{h}}\mathbf{p})^*(S_{-\mathbf{h}}\mathbf{q})$$ Imaging condition

Theory

$$\mathbf{L}(s_n, \eta)\mathbf{p} = \mathbf{f}$$
$$\mathbf{L}^*(s_n, \eta)\mathbf{q} = \mathbf{f}'$$

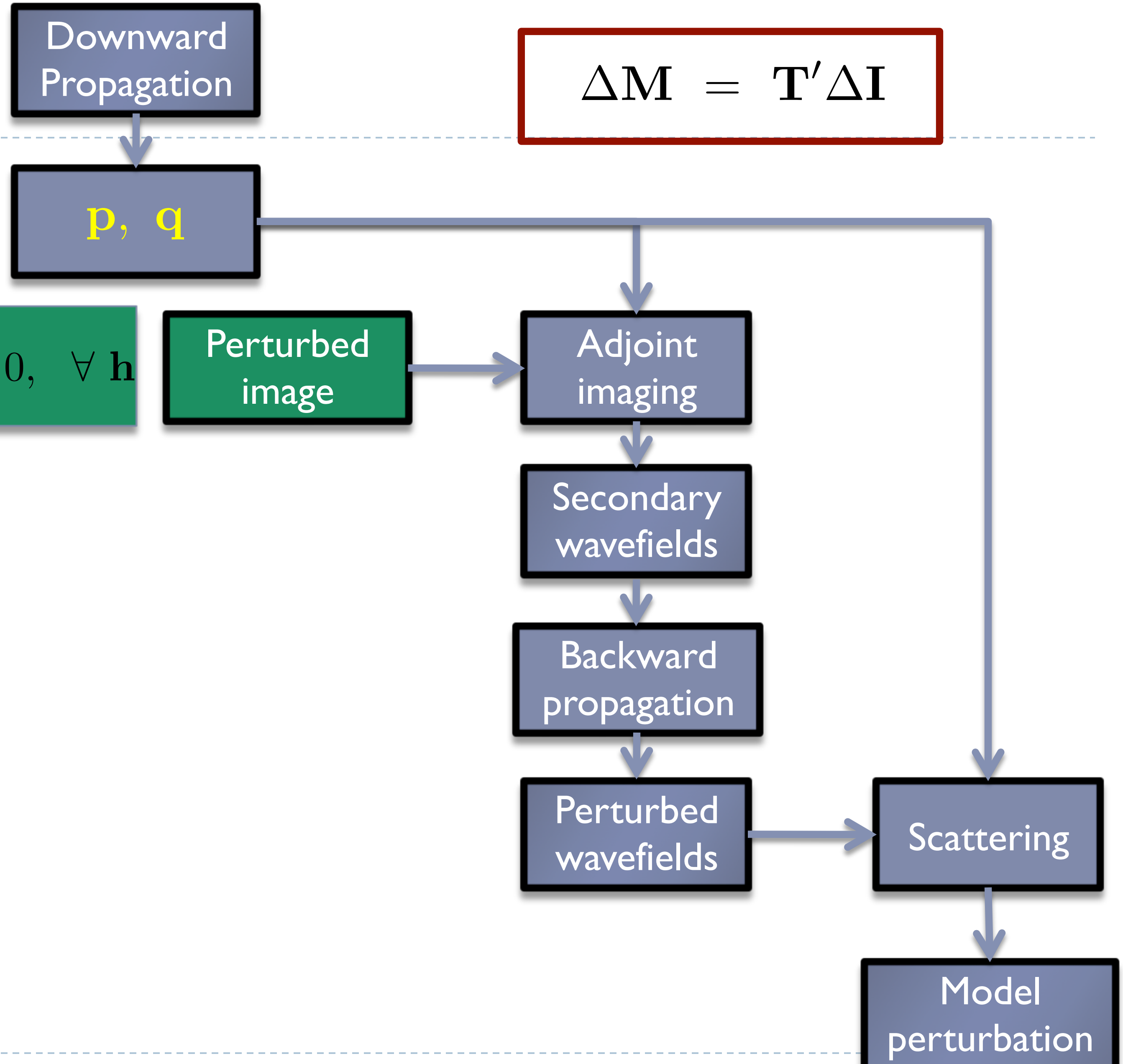
$$\Delta\mathbf{M} \;=\; \mathbf{T}'\Delta\mathbf{I}$$



Theory

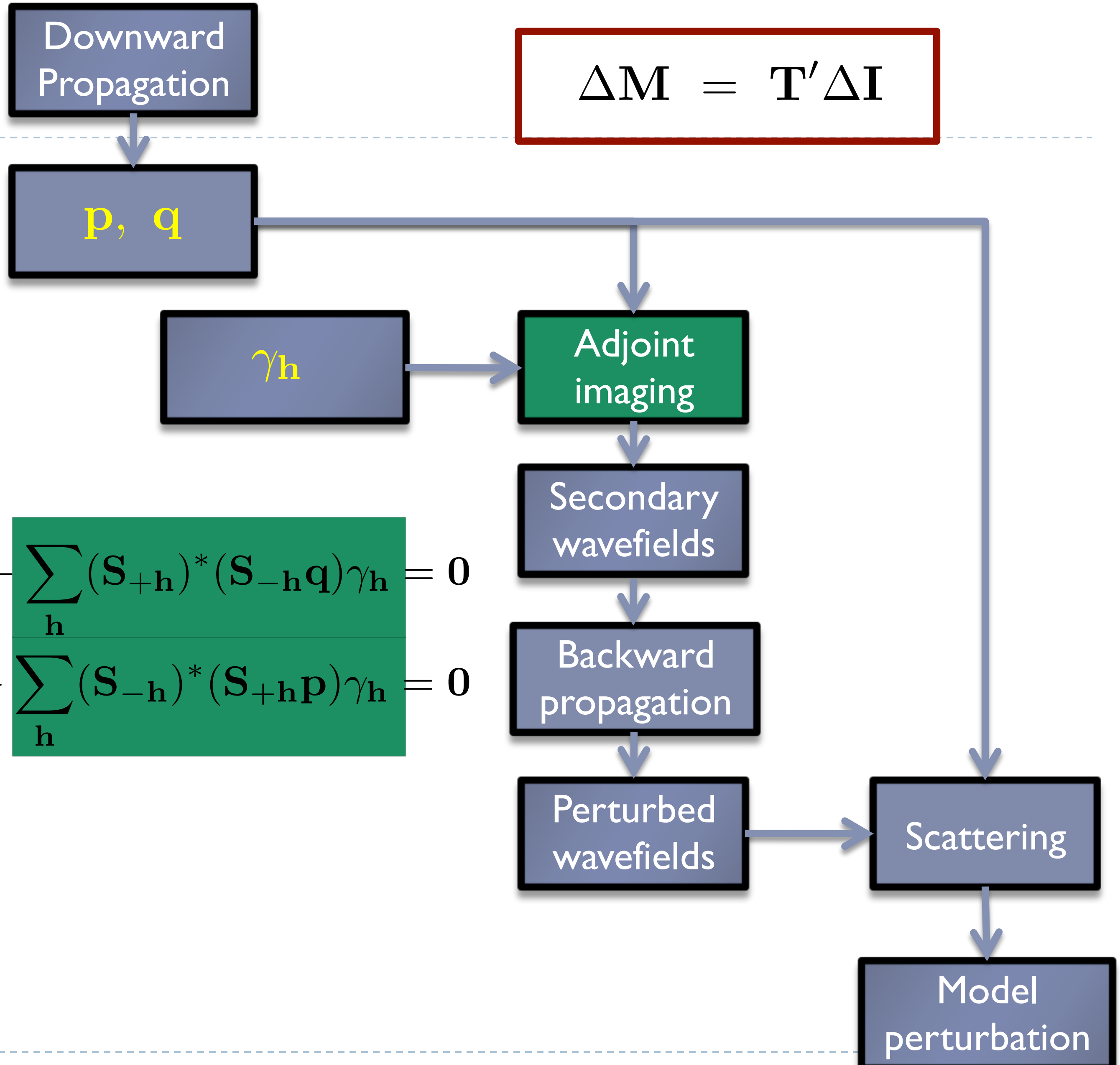
$$\Delta \mathbf{M} = \mathbf{T}'\Delta \mathbf{I}$$

$$\frac{\partial \mathcal{L}}{\partial I_{\mathbf{h}}} = -\gamma_{\mathbf{h}} + \mathbf{h}^2 I_{\mathbf{h}} = 0, \quad \forall\ \mathbf{h}$$



Theory

$$\Delta \mathbf{M} = \mathbf{T}'\Delta \mathbf{I}$$

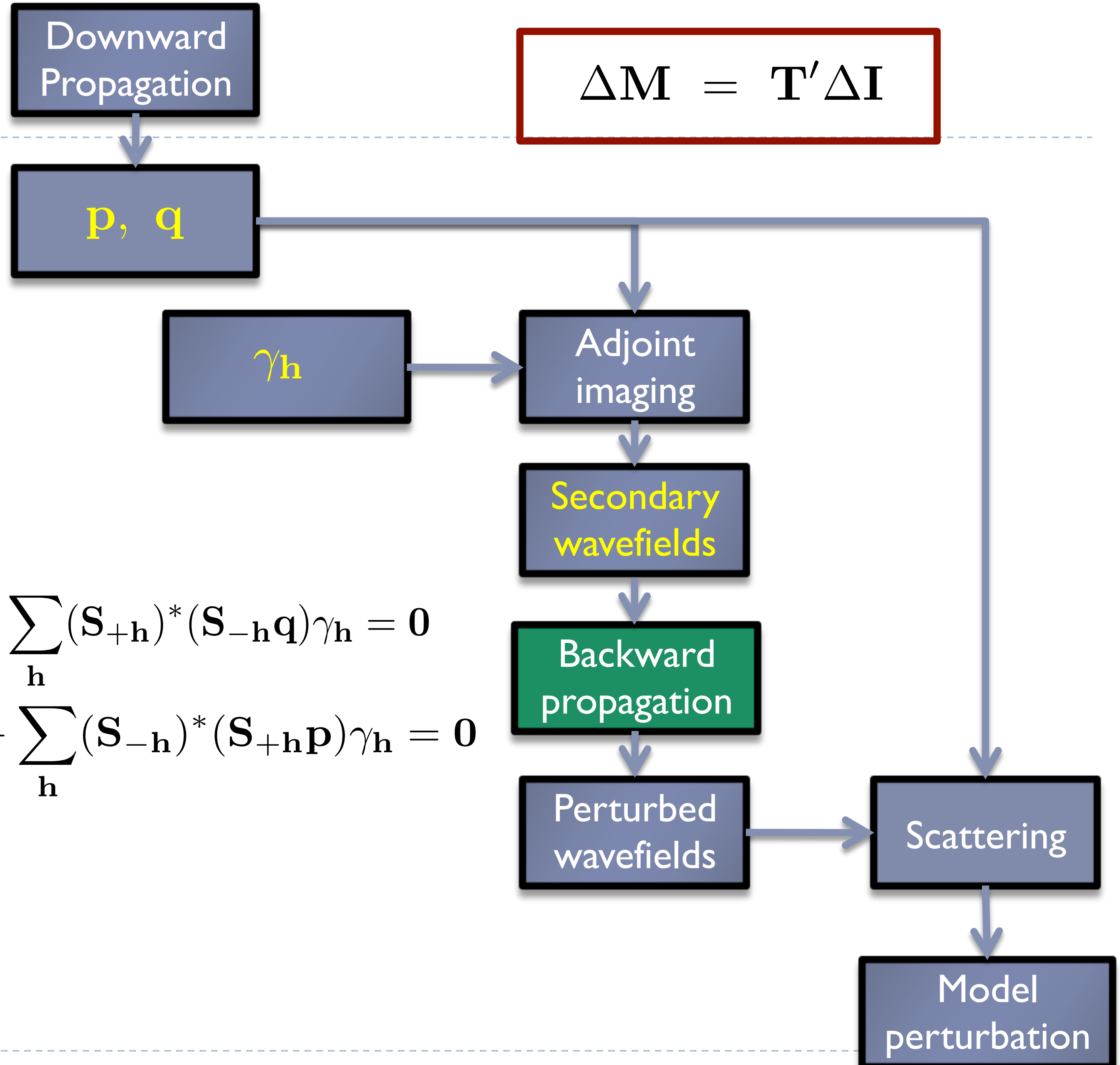


$$\frac{\partial \mathcal{L}}{\partial \mathbf{p}} = -\mathbf{L}^*(s_n,\eta)\lambda + \sum_{\mathbf{h}} (\mathbf{S}_{+\mathbf{h}})^*(\mathbf{S}_{-\mathbf{h}}\mathbf{q})\gamma_{\mathbf{h}} = \mathbf{0}$$

$$\frac{\partial \mathcal{L}}{\partial \mathbf{q}} = -\mathbf{L}(s_n,\eta)\mu + \sum_{\mathbf{h}} (\mathbf{S}_{-\mathbf{h}})^*(\mathbf{S}_{+\mathbf{h}}\mathbf{p})\gamma_{\mathbf{h}} = \mathbf{0}$$

Theory

$$\Delta \mathbf{M} = \mathbf{T}'\Delta \mathbf{I}$$



$$\frac{\partial \mathcal{L}}{\partial \mathbf{p}} = -\mathbf{L}^*(s_n,\eta)\lambda + \sum_{\mathbf{h}} (\mathbf{S}_{+\mathbf{h}})^*(\mathbf{S}_{-\mathbf{h}}\mathbf{q})\gamma_{\mathbf{h}} = \mathbf{0}$$

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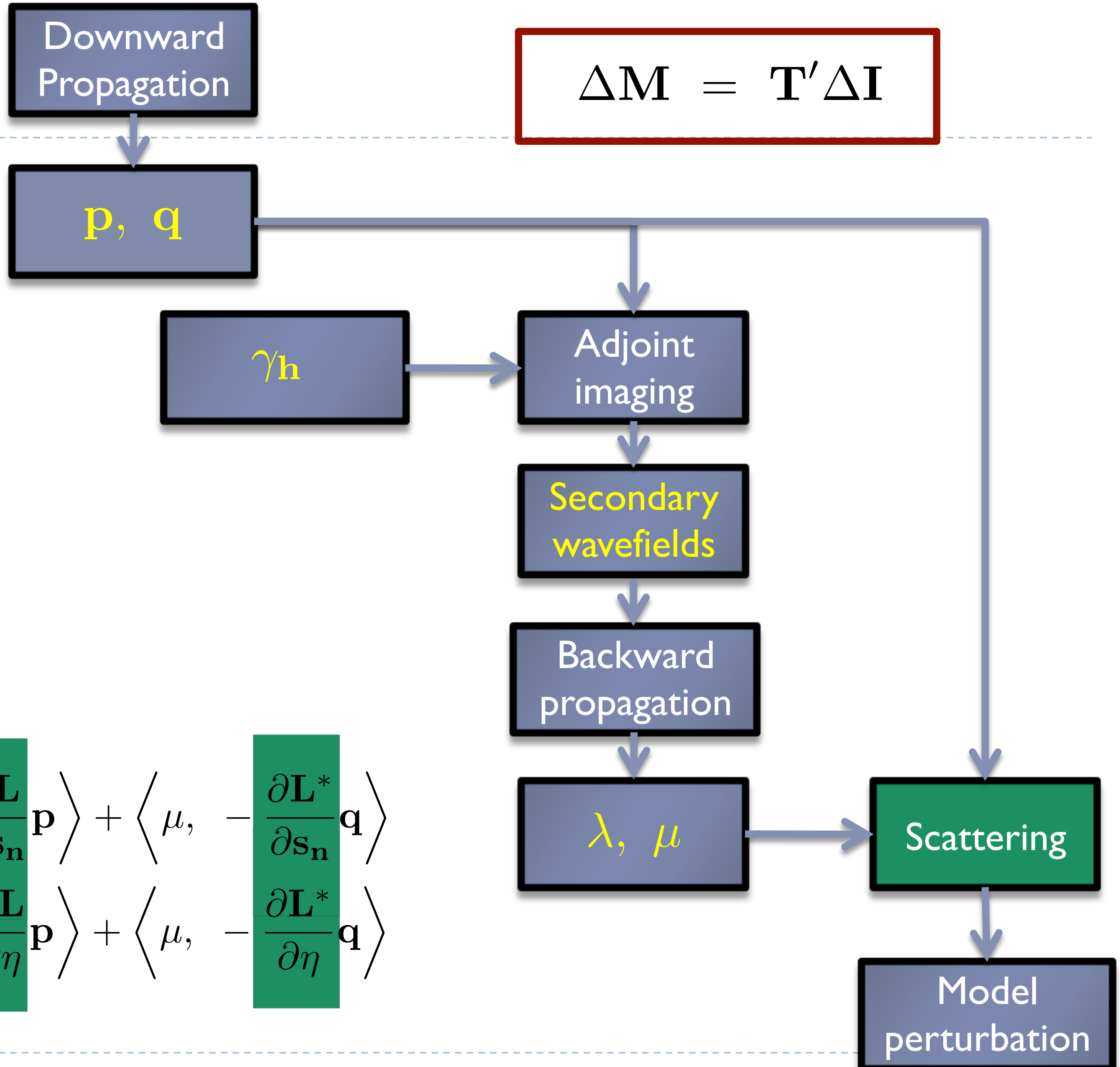
Theory

$$\Delta \mathbf{M} = \mathbf{T}'\Delta \mathbf{I}$$

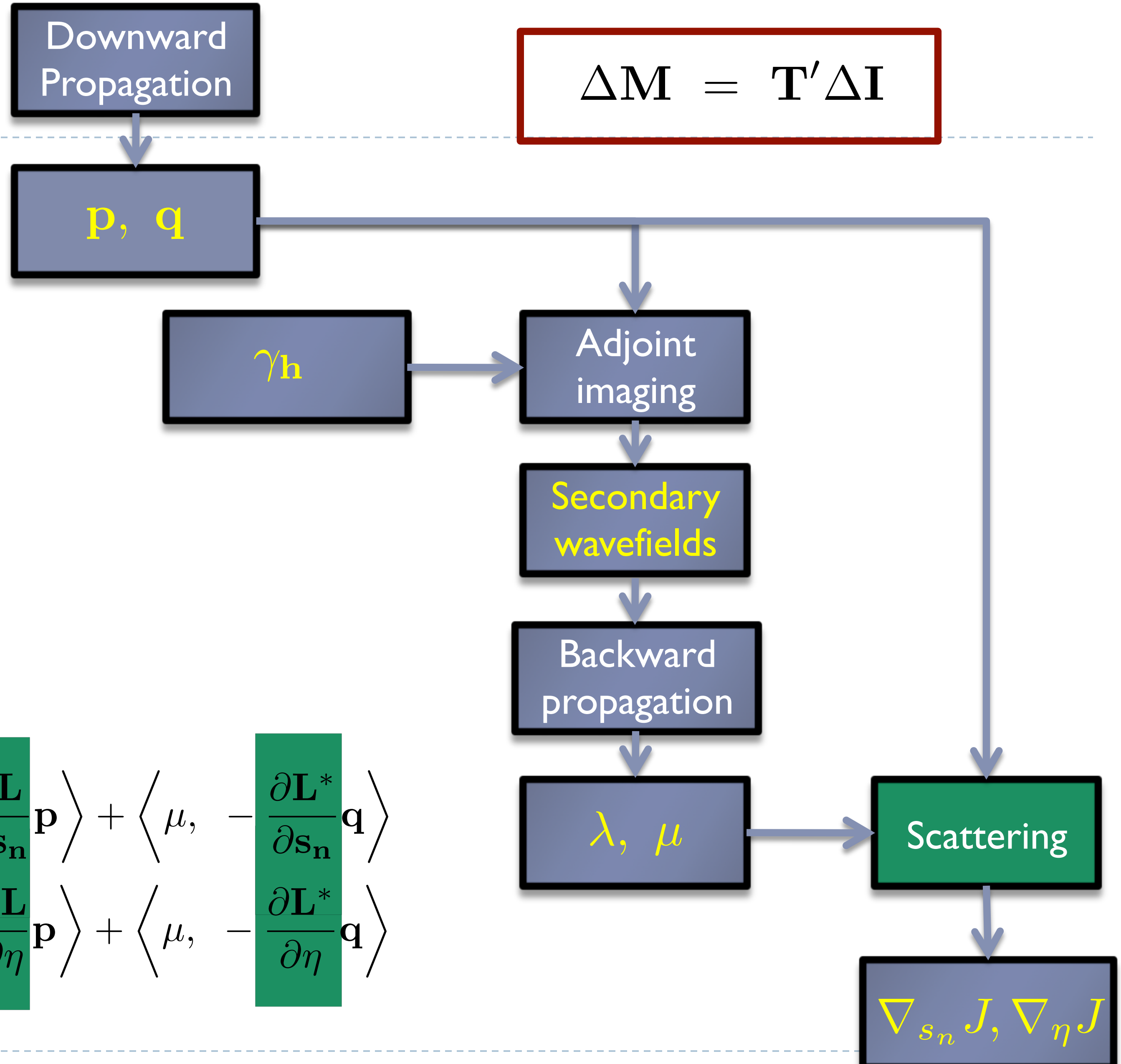


$$\nabla_{s_n} J = \left\langle \lambda, \; -\frac{\partial \mathbf{L}}{\partial \mathbf{s_n}} \mathbf{p} \right\rangle + \left\langle \mu, \; -\frac{\partial \mathbf{L}^*}{\partial \mathbf{s_n}} \mathbf{q} \right\rangle$$

$$\nabla_{\eta} J = \left\langle \lambda, \; -\frac{\partial \mathbf{L}}{\partial \eta} \mathbf{p} \right\rangle + \left\langle \mu, \; -\frac{\partial \mathbf{L}^*}{\partial \eta} \mathbf{q} \right\rangle$$

Theory

$$\Delta \mathbf{M} = \mathbf{T}' \Delta \mathbf{I}$$



$$\nabla_{s_n} J = \left\langle \lambda, \ -\frac{\partial \mathbf{L}}{\partial \mathbf{s_n}} \mathbf{p} \right\rangle + \left\langle \mu, \ -\frac{\partial \mathbf{L}^*}{\partial \mathbf{s_n}} \mathbf{q} \right\rangle$$

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Preconditioning

$$d\mathbf{m} = \mathbf{B\Sigma}\ d\mathbf{n}$$

$$\nabla_{\mathbf{n}} J = (\frac{\partial \mathbf{m}}{\partial \mathbf{n}})^* \nabla_{\mathbf{m}} J = \mathbf{\Sigma}^* \mathbf{B}^* \nabla_{\mathbf{m}} J$$

$$\mathbf{m}_{i+1} = \mathbf{m}_i + \alpha_i \mathbf{B\Sigma\Sigma}^* \mathbf{B}^* \nabla_{\mathbf{m}} J$$

$\mathbf{m} = [s_n, \eta]'$ model parameter

$\mathbf{B} = \begin{vmatrix} \mathbf{B}_s & 0 \\ 0 & \mathbf{B}_\eta \end{vmatrix}$ Spatial standard deviation matrix

$\mathbf{n} = [\tilde{s}_n, \tilde{\eta}]'$ Preconditioning parameter

$\mathbf{\Sigma} = \begin{vmatrix} \sigma_{ss} & \sigma_{s\eta} \\ \sigma_{\eta s} & \sigma_{\eta\eta} \end{vmatrix}$ X-parameter standard deviation matrix

Preconditioning

$$d\mathbf{m} = \mathbf{B}\boldsymbol{\Sigma}\ d\mathbf{n}$$

$$\nabla_{\mathbf{n}} J = \left(\frac{\partial \mathbf{m}}{\partial \mathbf{n}}\right)^* \nabla_{\mathbf{m}} J = \boldsymbol{\Sigma}^* \mathbf{B}^* \nabla_{\mathbf{m}} J$$

Semi-positive definite matrix

$$\mathbf{m}_{i+1} = \mathbf{m}_i + \alpha_i \mathbf{B}\boldsymbol{\Sigma}\boldsymbol{\Sigma}^* \mathbf{B}^* \nabla_{\mathbf{m}} J$$

$\mathbf{m} = [s_n, \eta]'$ model parameter

$\mathbf{B} = \begin{vmatrix} \mathbf{B}_s & 0 \\ 0 & \mathbf{B}_\eta \end{vmatrix}$ Spatial standard deviation matrix

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Example: VTI Marmousi

- Model grid: 300*901, 10m spacing in x and z
- Source: 180 shots * 50m
- Born modeled data with maximum offset = 6km * 10m
- Propagator: first-order two-way VTI wave-equation (Duveneck et al., 2008)
- Objective function: $J = \frac{1}{2}\langle \mathbf{D}\mathbf{I_a}, \mathbf{D}\mathbf{I_a} \rangle$

$$\mathbf{B} = \begin{vmatrix} \mathbf{B}_s & 0 \\ 0 & \mathbf{B}_\eta \end{vmatrix}$$

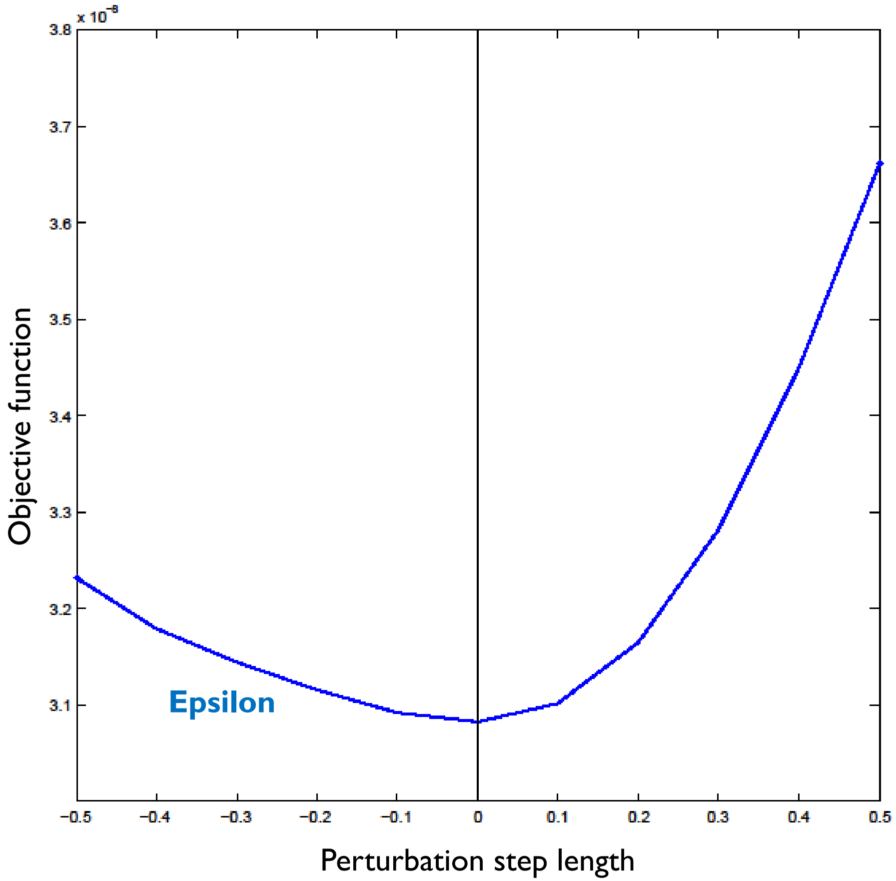
B-spline interpolator

$$\mathbf{\Sigma} = \begin{vmatrix} \sigma_{ss} & 0 \\ 0 & \sigma_{\eta\eta} \end{vmatrix}$$

Scaling without X-terms

Example: VTI Marmousi

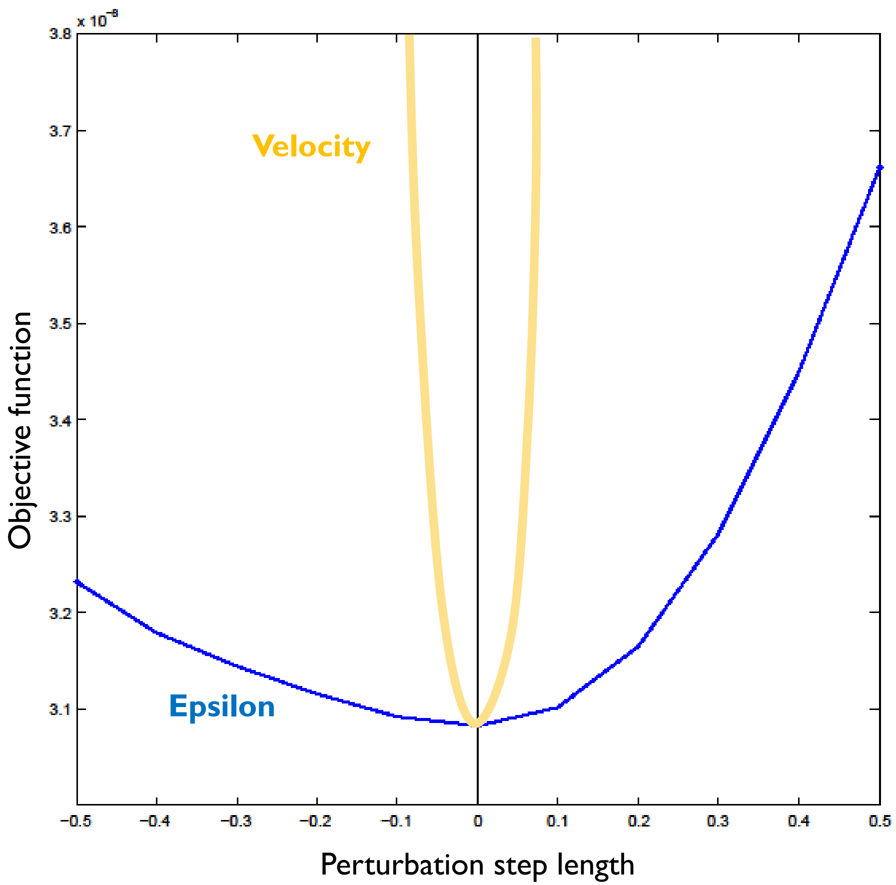
Objective function: $J = \frac{1}{2}\langle \mathbf{DI_a}, \mathbf{DI_a} \rangle$



- Objective function can very well characterize the epsilon error.

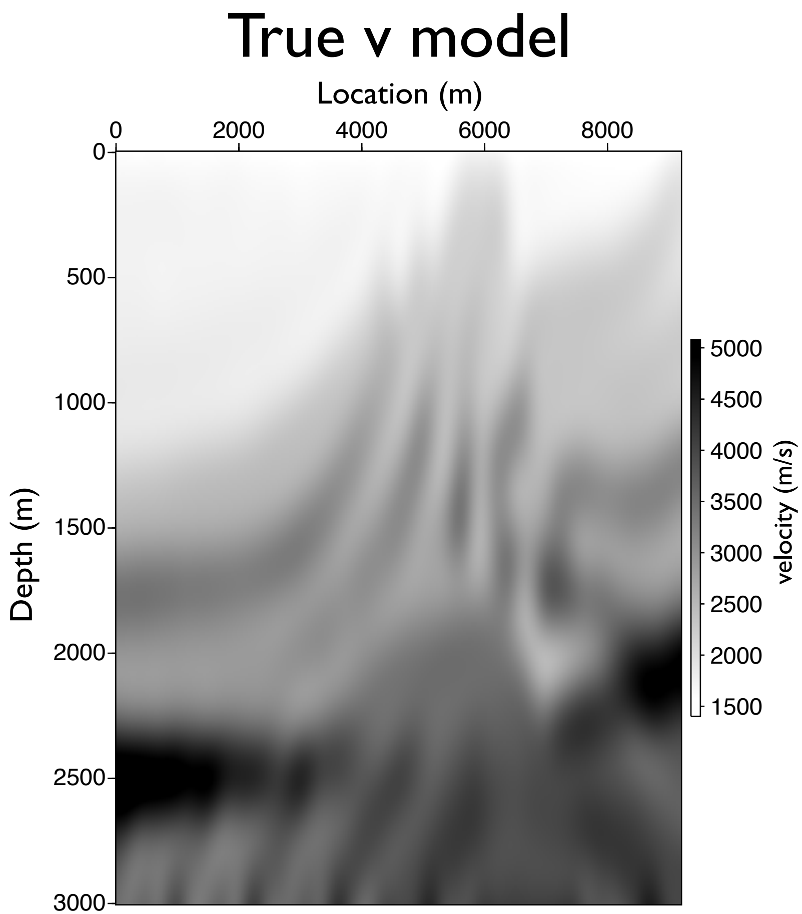
Example: VTI Marmousi

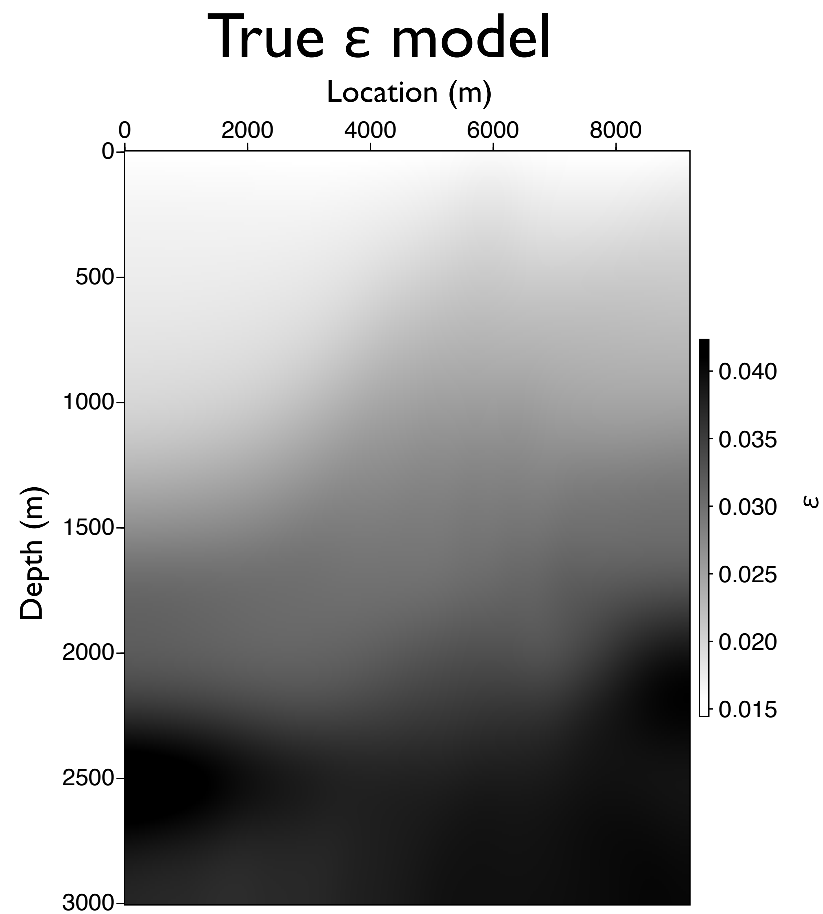
Objective function: $J = \frac{1}{2}\langle \mathbf{DI_a}, \mathbf{DI_a} \rangle$



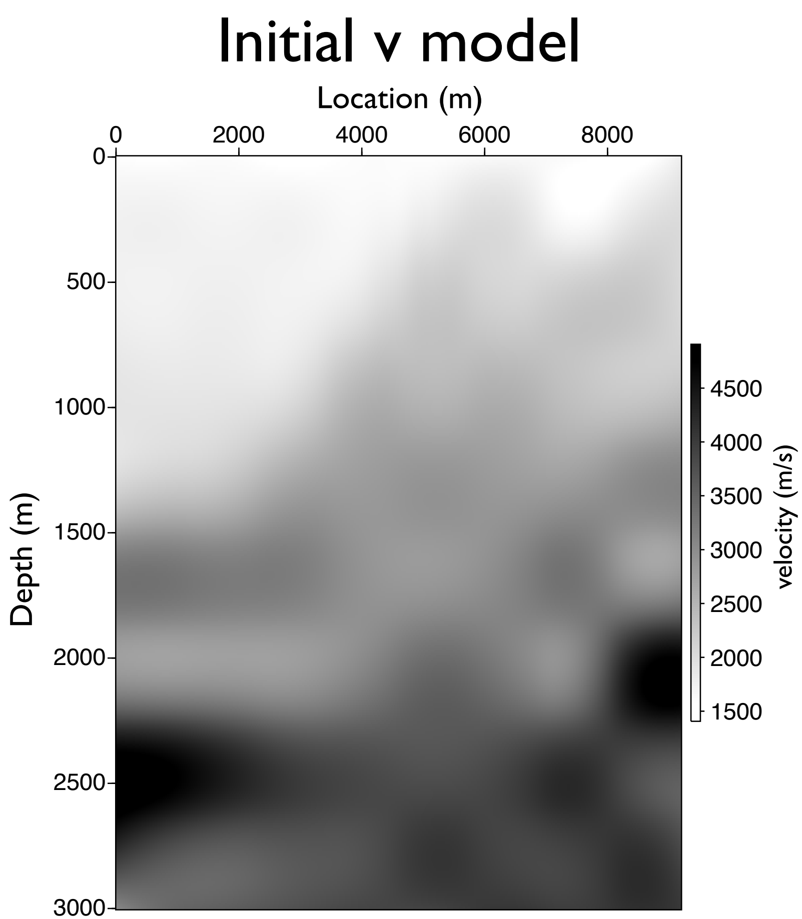
- Objective function can very well characterize the epsilon error.
- Flat bottom:
  - low resolution
  - High tolerance for the purpose of imaging

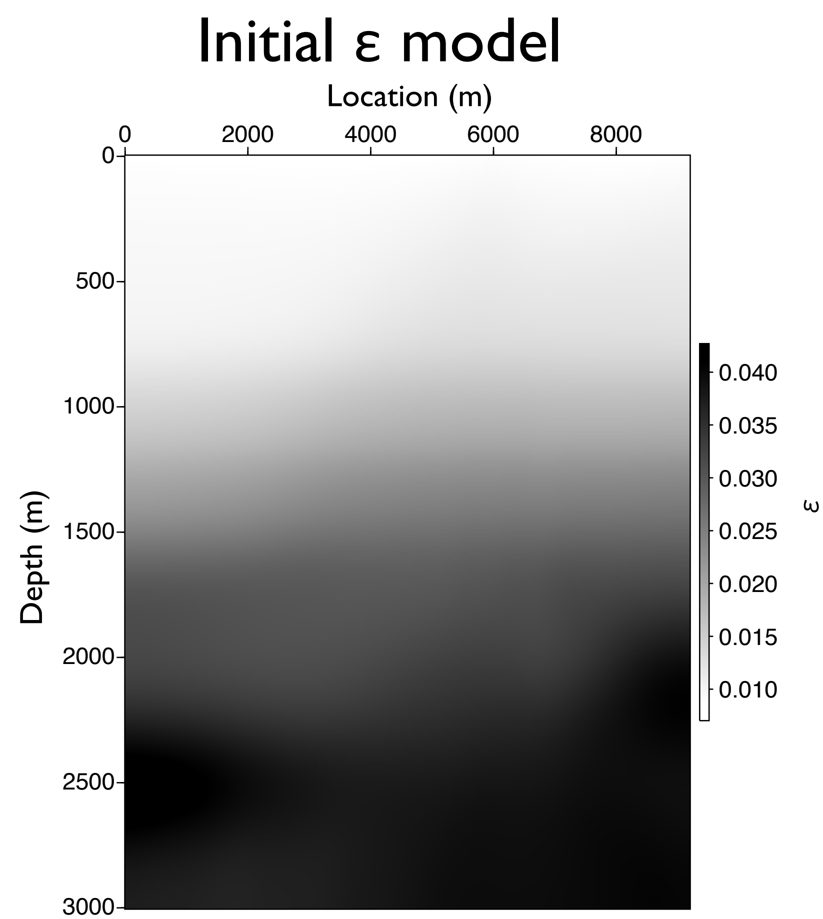
Example: VTI Marmousi





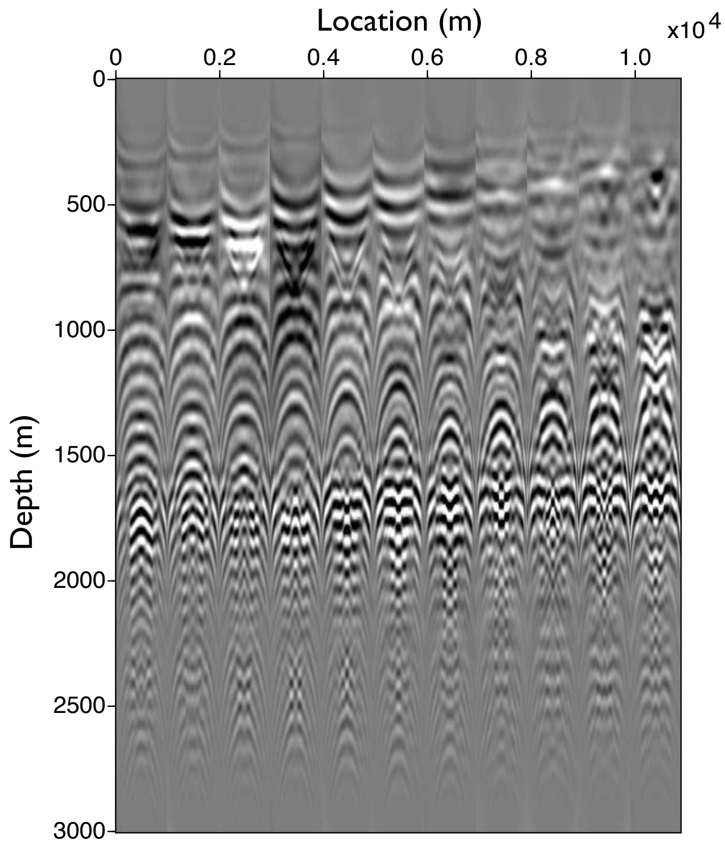
Example: VTI Marmousi



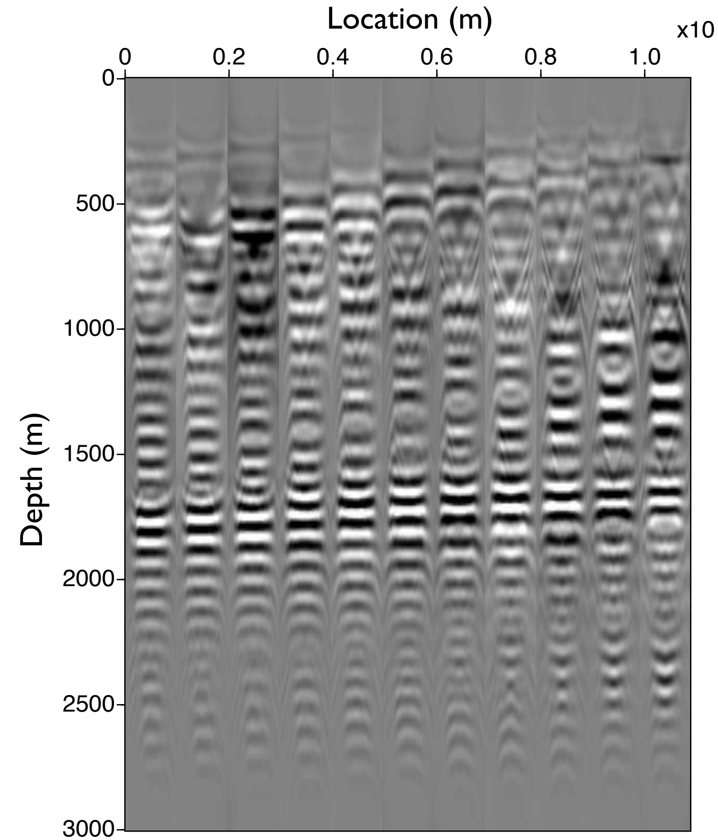


Example: VTI Marmousi

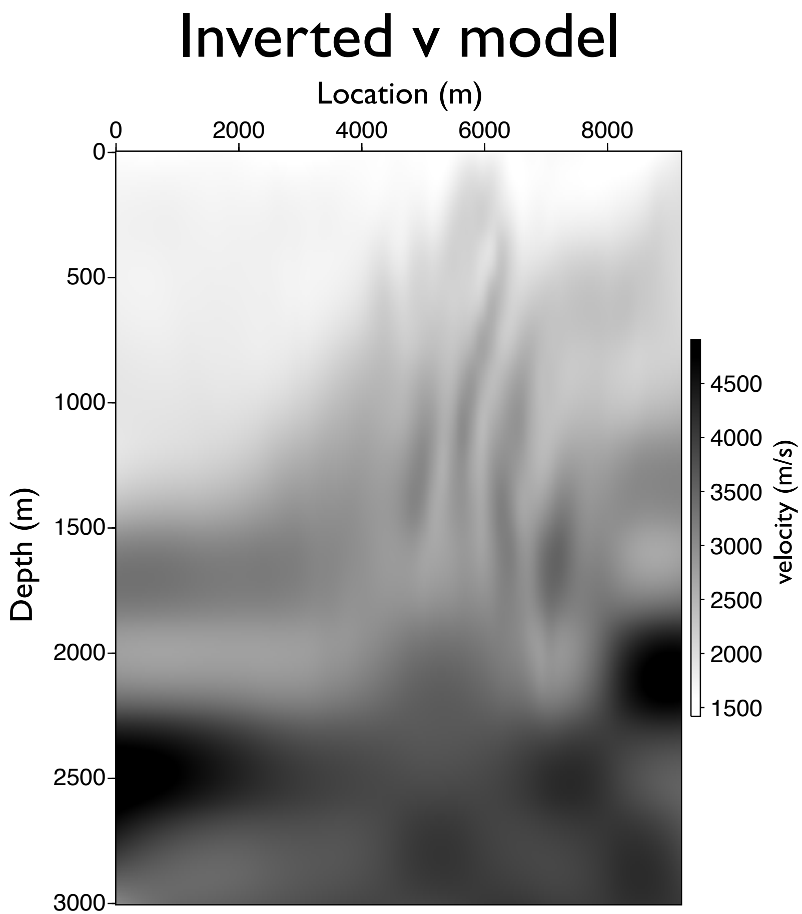
Initial angle gathers

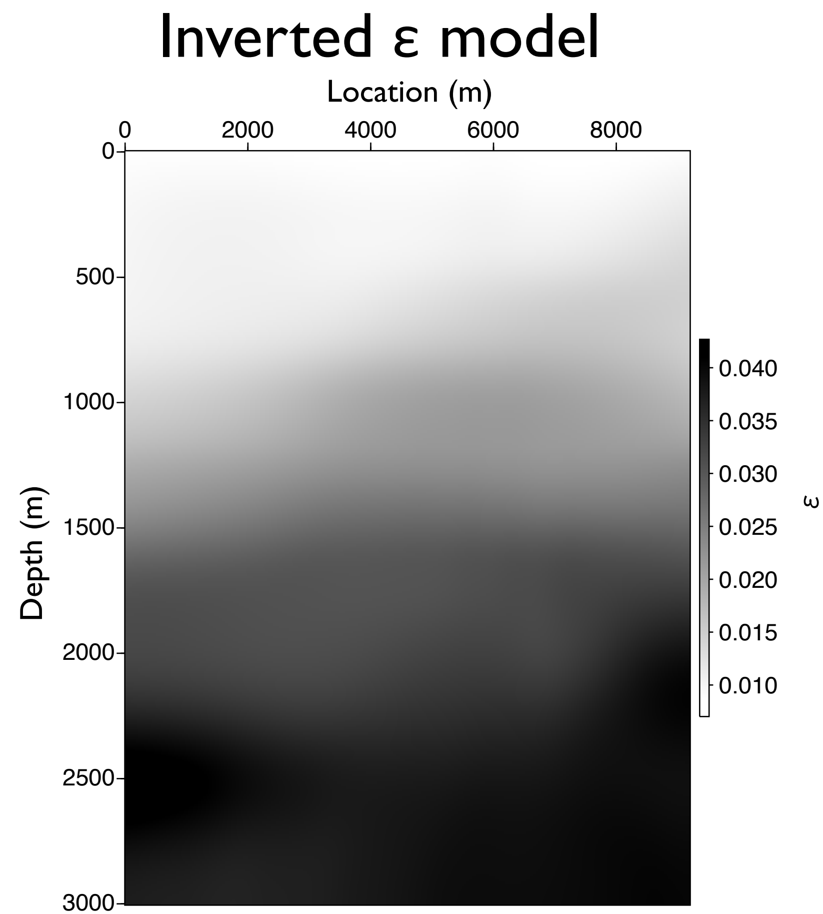


Final angle gathers



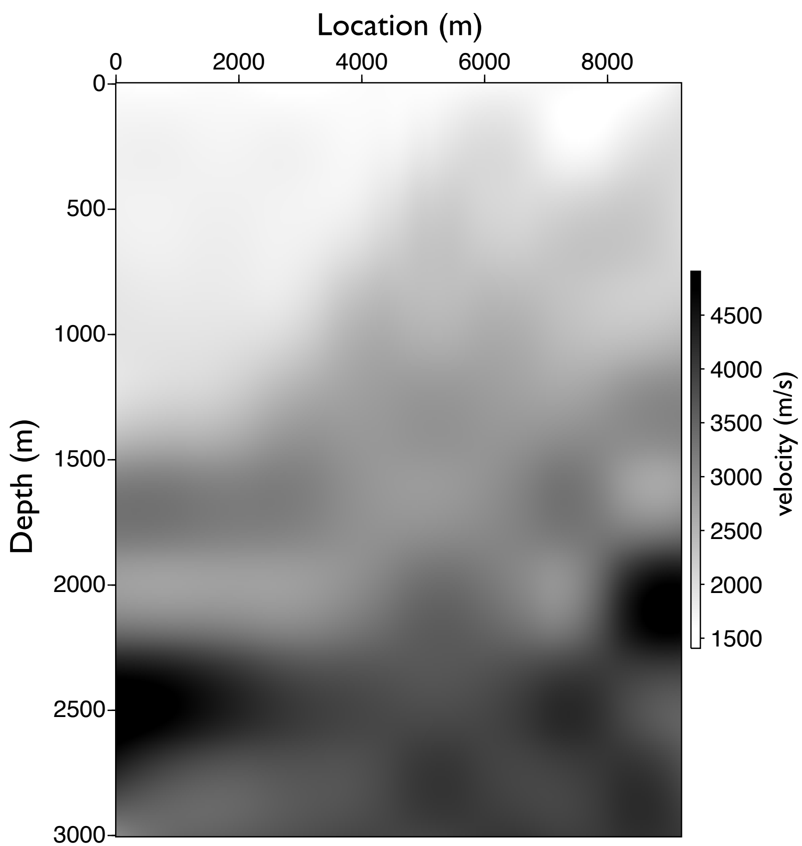
Example: VTI Marmousi



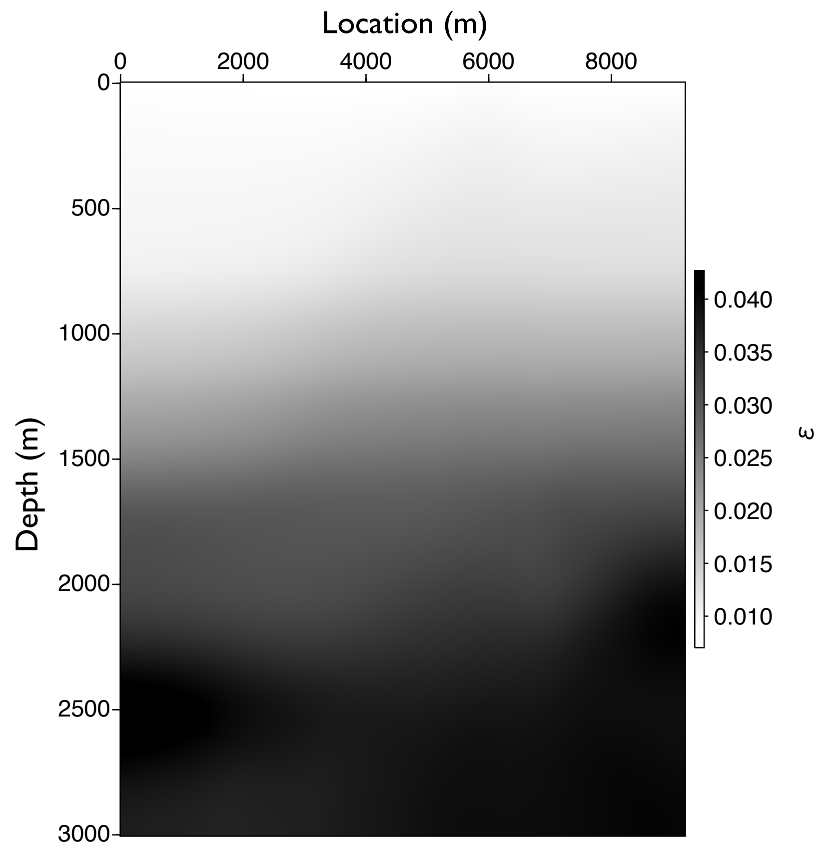


Example: VTI Marmousi

Initial v model

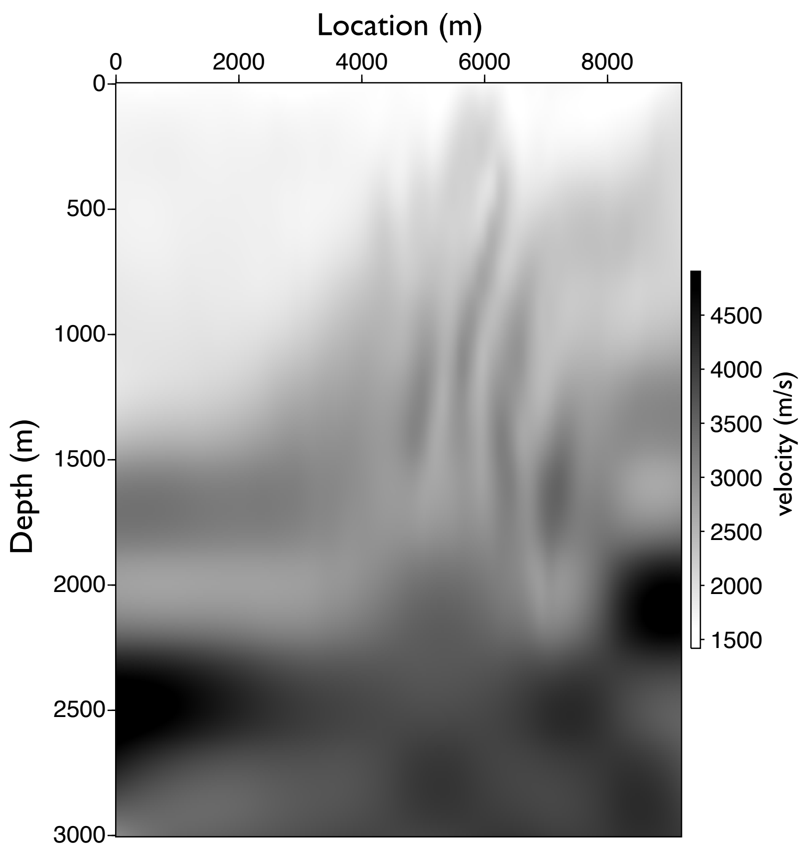


Initial ε model

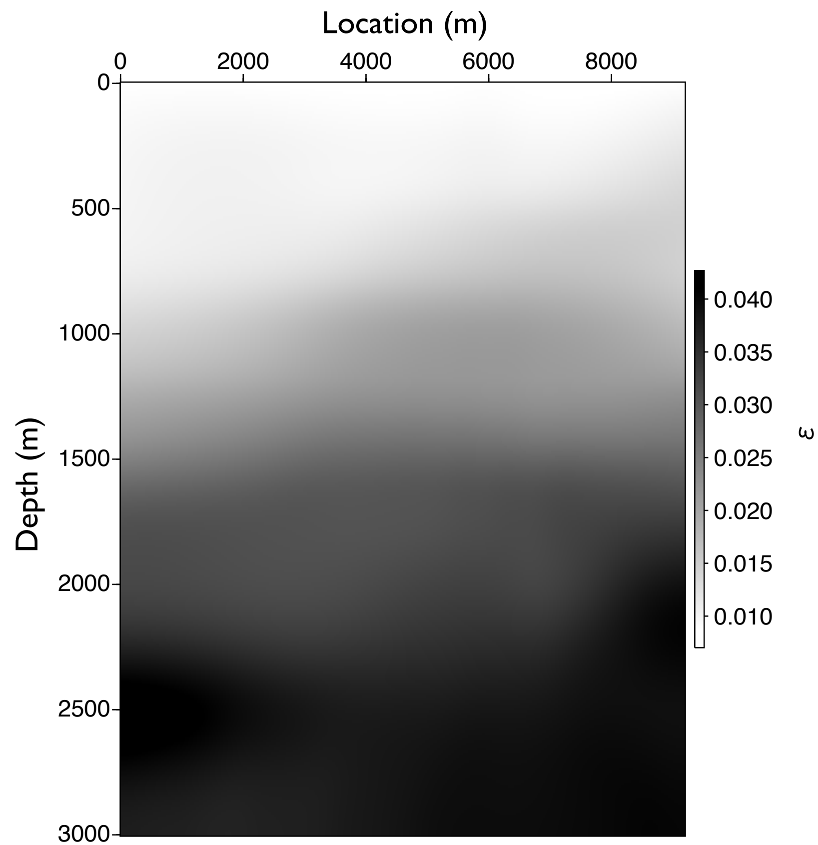


Example: VTI Marmousi

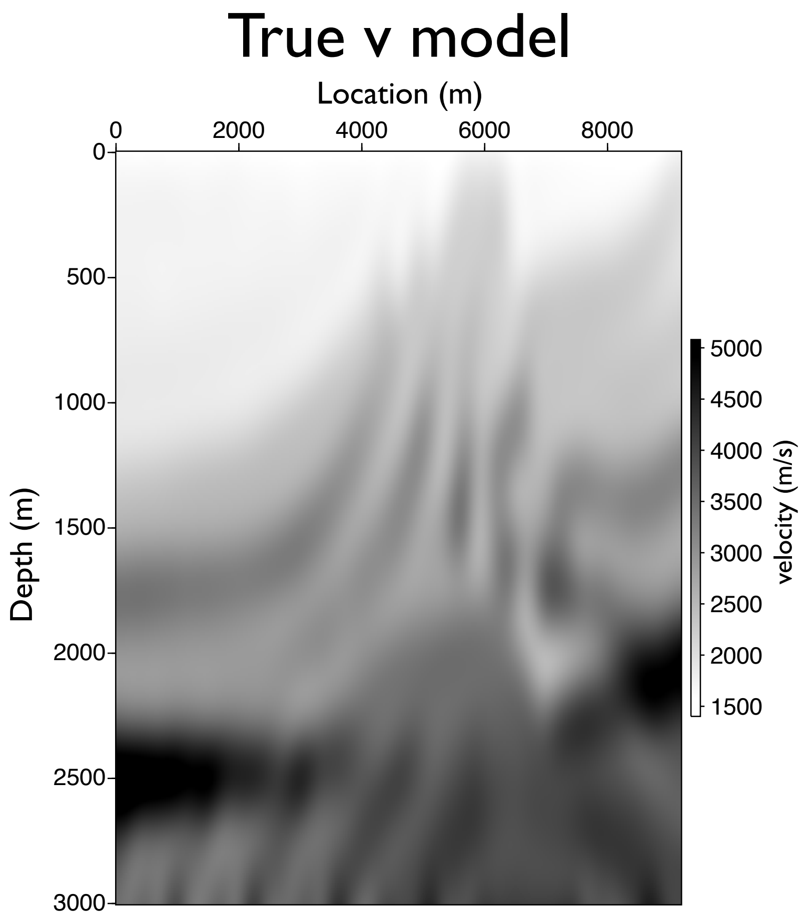
Inverted v model

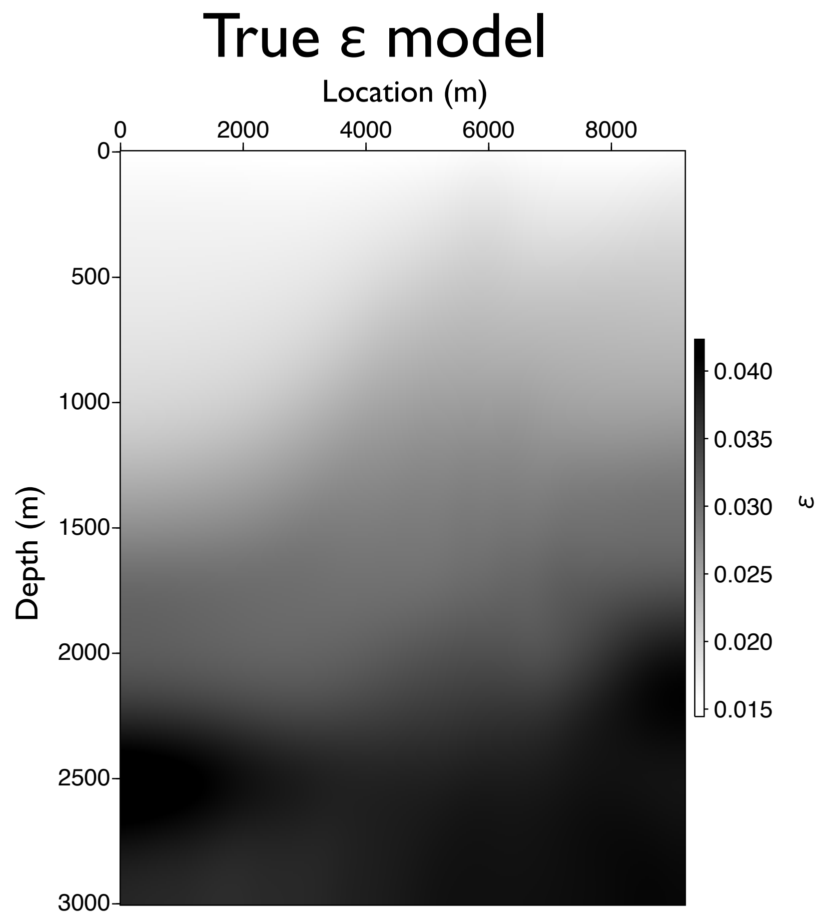


Inverted ε model



Example: VTI Marmousi





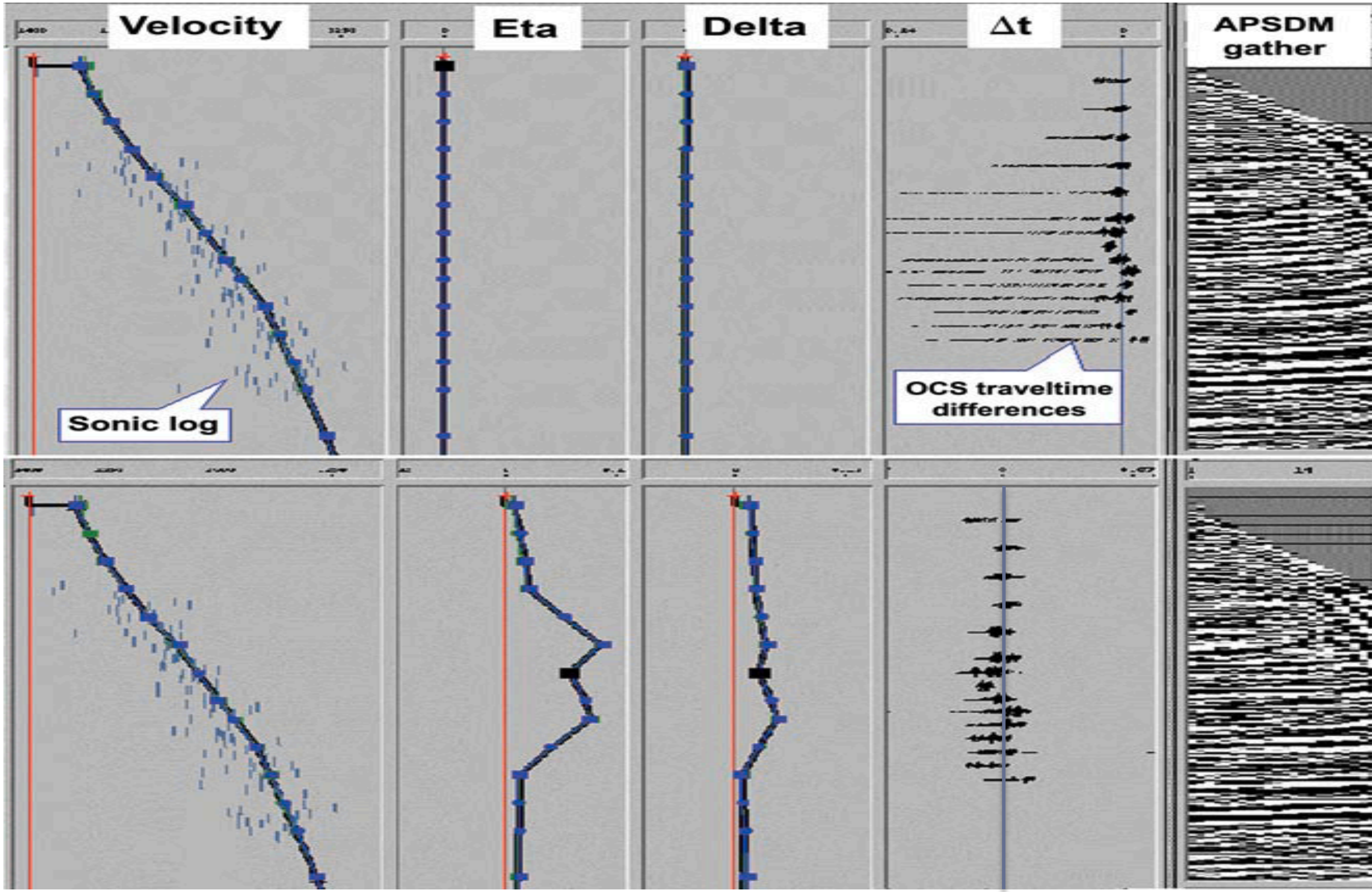
Example: VTI Marmousi

- Summary
  - Able to resolve high wavenumber velocity anomalies
  - Able to better define the anisotropic model
  - First-order two-way VTI wave-equation
    - \+ Simplicity in code
    - \+ Accuracy for high angle waves
    - – 5 fields to propagate
    - – Large I/O requirements
    - – High computational cost

Example: ExxonMobil field data

- Streamer geometry: 270 shots * 50 m
- Offset: maximum 4 km; minimum 150 m; 25 m spacing
- Initial model built using an interactive visualization method (Bear et al., 2005)

Example: ExxonMobil field data



Courtesy of Bear et al. (2005)

Example: ExxonMobil field data

- Streamer geometry: 270 shots * 50 m spacing
- Offset: maximum 4 km; minimum 150 m; 25 m spacing
- Propagator: PSPI VTI one-way wave-equation (Tang and Clapp, 2006)
- Objective function: DSO + stack power

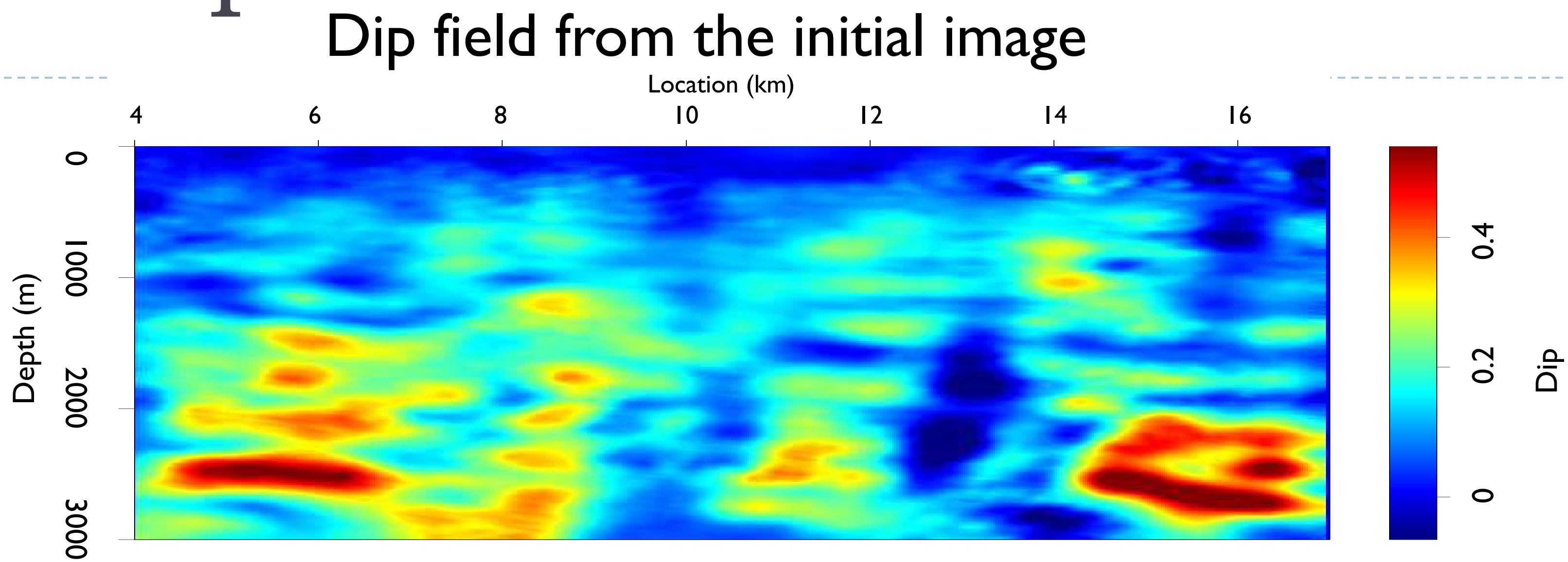
$$\mathbf{B} = \begin{vmatrix} \mathbf{B}_s & 0 \\ 0 & \mathbf{B}_\eta \end{vmatrix}$$

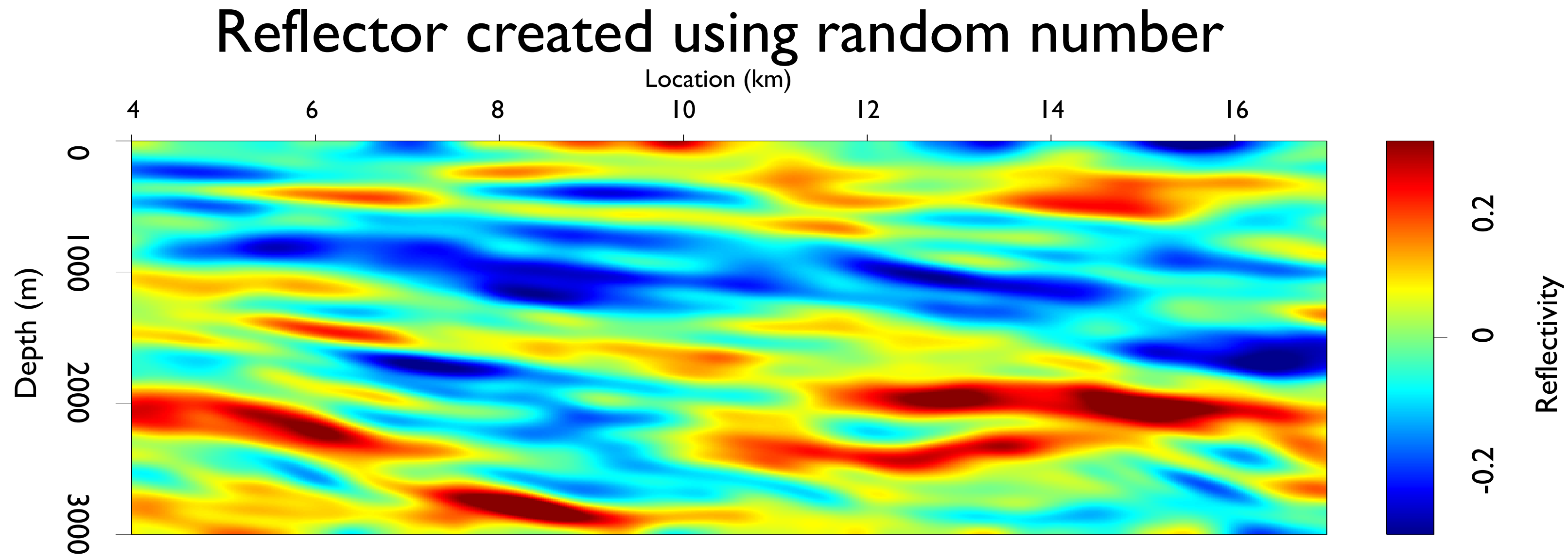
Steering operator

$$\mathbf{\Sigma} = \begin{vmatrix} \sigma_{ss} & 0 \\ 0 & \sigma_{\eta\eta} \end{vmatrix}$$

Scaling without X-terms

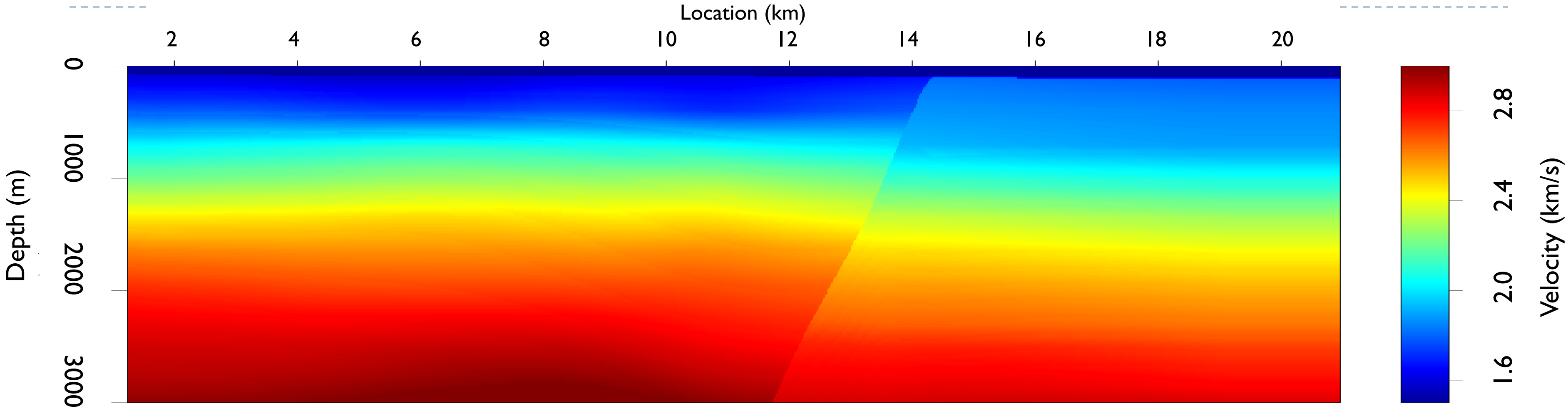
Example: ExxonMobil field data



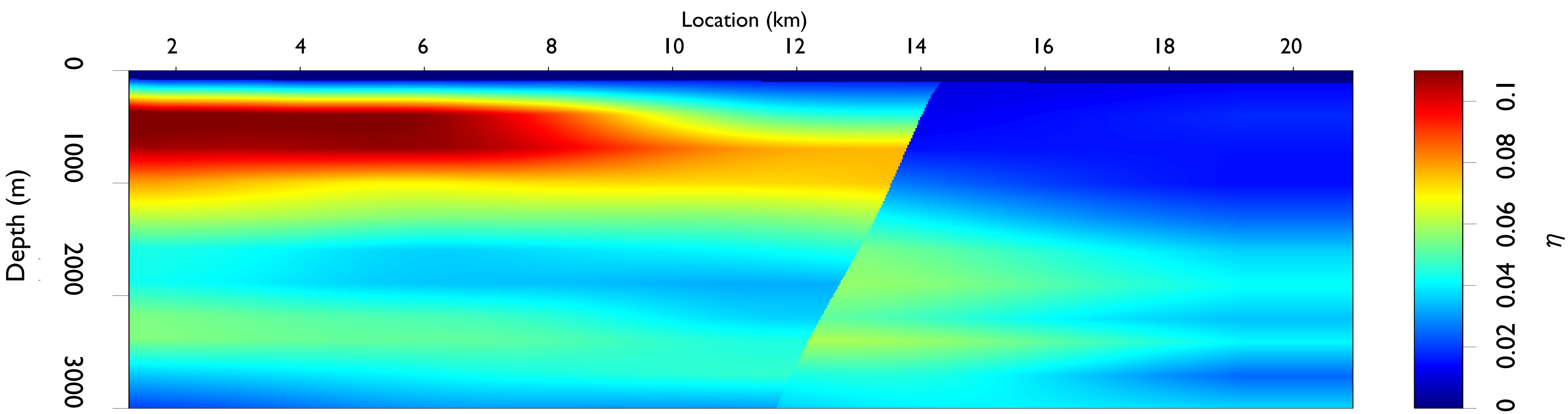


Example: ExxonMobil field data

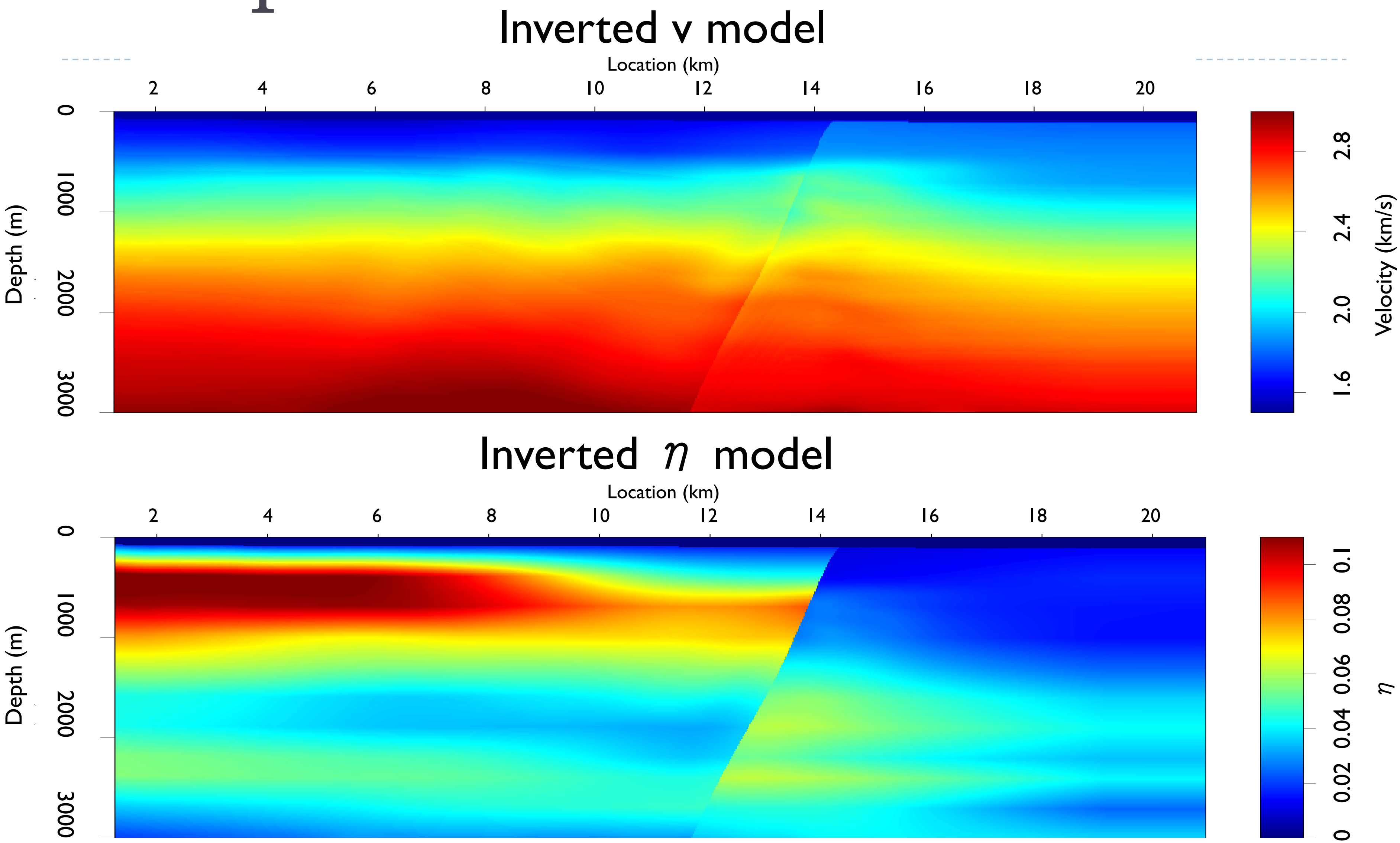
Initial v model



Initial η model

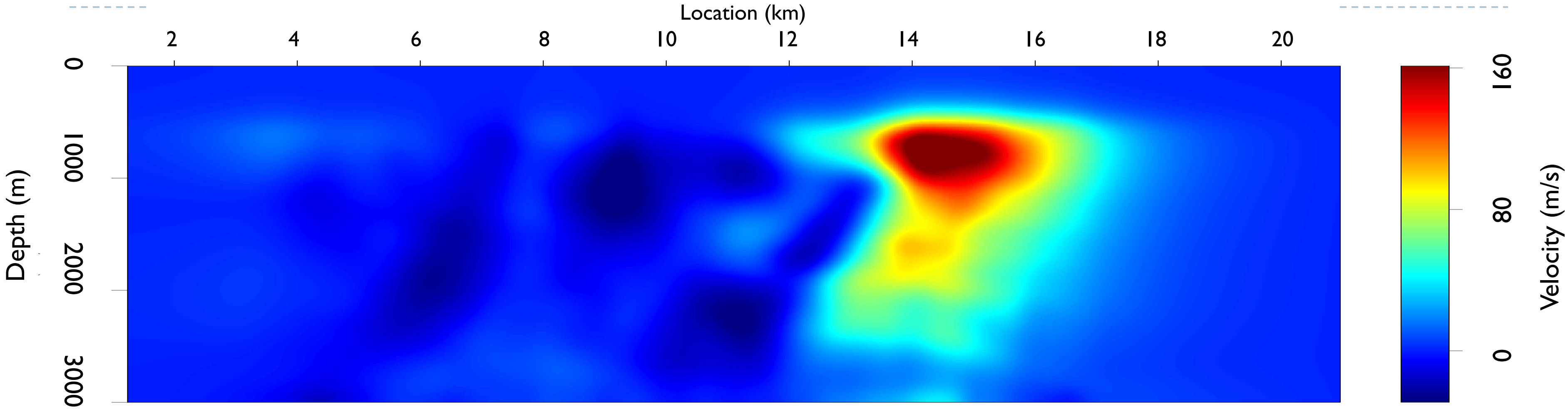


Example: ExxonMobil field data

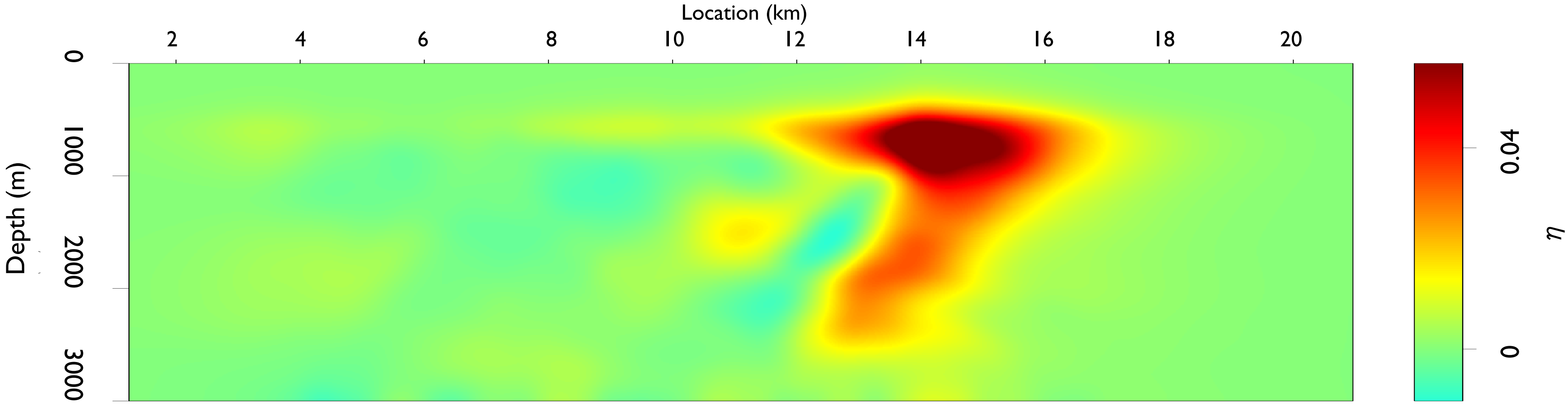


Example: ExxonMobil field data

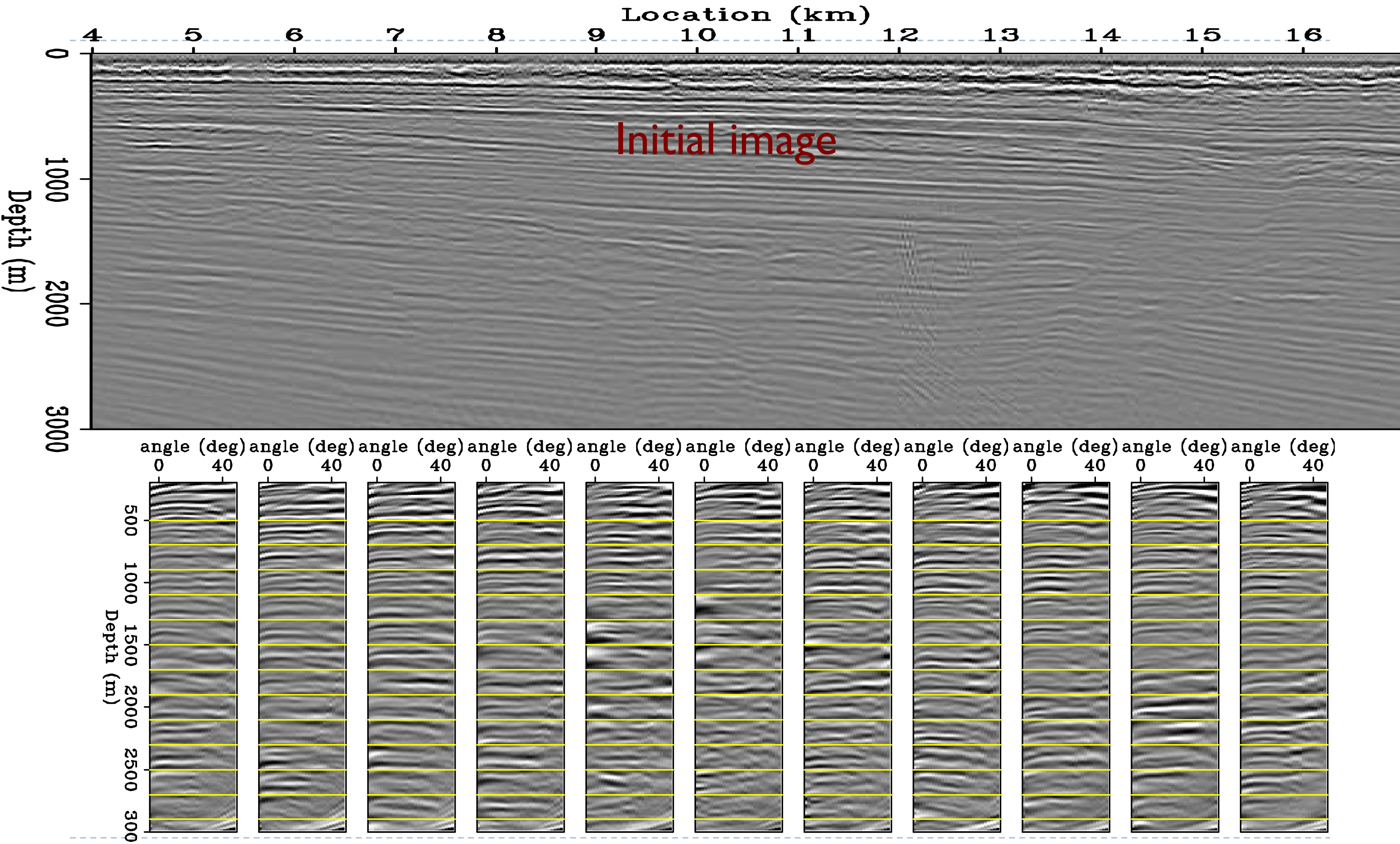
Updates in v model



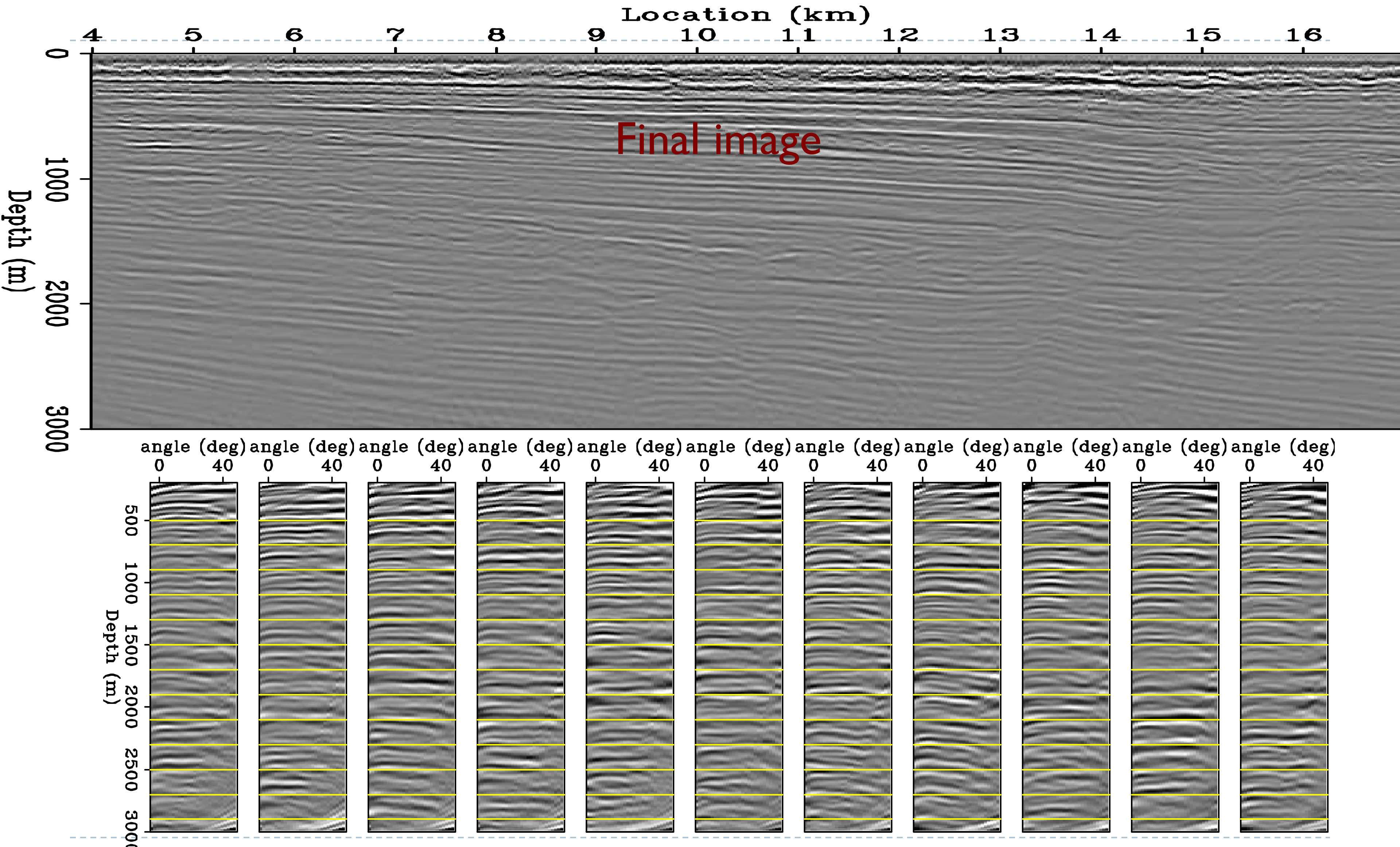
Updates in η model



Example: ExxonMobil field data



Example: ExxonMobil field data



Example: ExxonMobil field data

- Summary
  - Able to identify a shallow velocity and η anomalies
  - Improve the stacked image: higher resolution and better defined fault
  - Improve the flatness of the angle domain common image gathers
  - PSPI one-way VTI wave-equation
    - + Low (relative) computational cost
    - + Works for gently dipping reflectors
    - – Inaccurate for high angle waves

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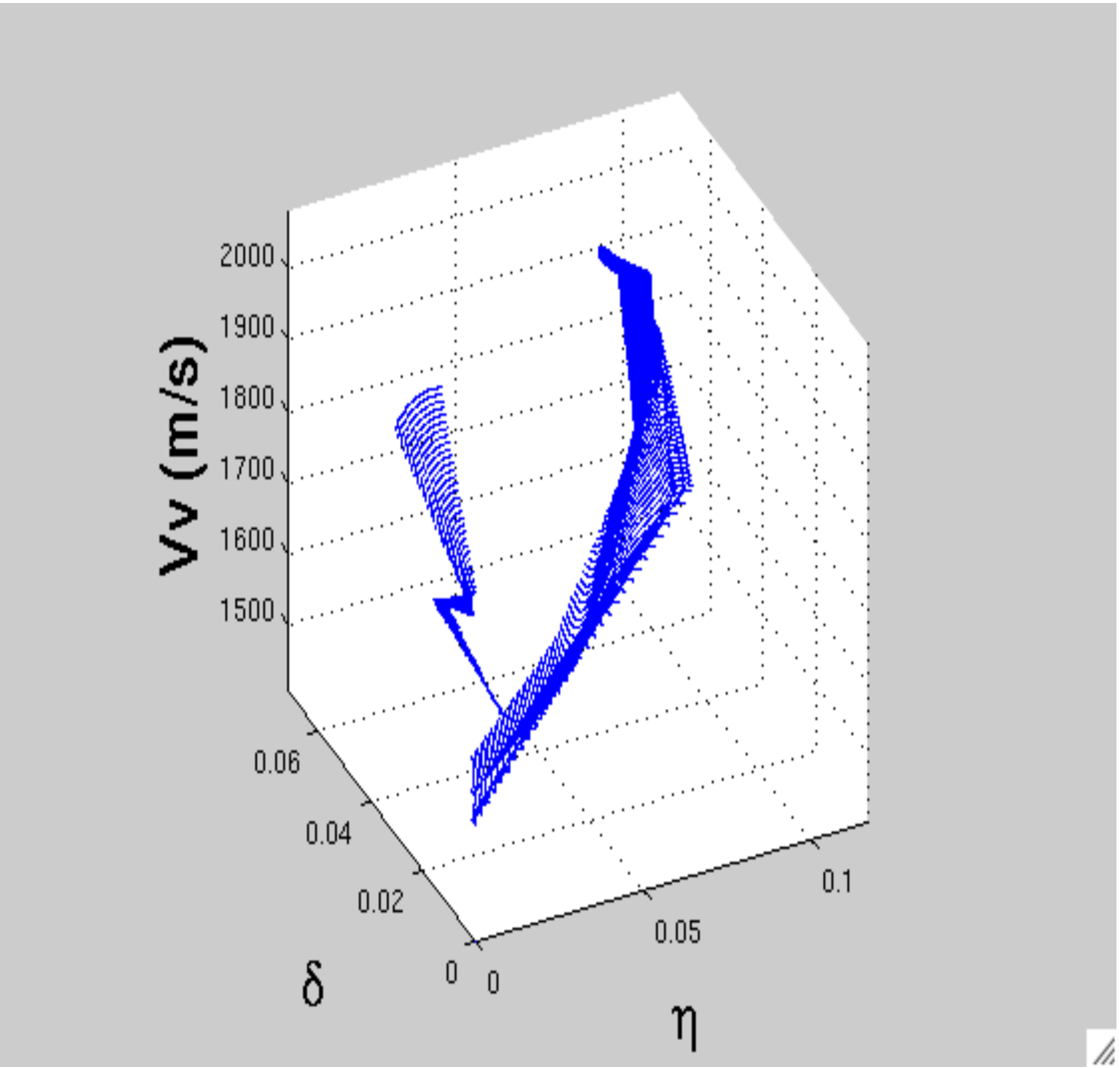
Conclusions and discussions

- Anisotropic WEMVA can improve the anisotropic earth model and produce better focused images.

- An optimal propagator is needed to achieve accuracy and efficiency at the same time.

- Ambiguity between velocity and other anisotropic parameters.

MC311 – 3D scatter of parameters



- Prior information
  - Distinct trends across the fault
  - Information need to be spread according to geology
  - Cross-parameter standard deviation matrix (Li et al., 2011)

Acknowledgement

- We thank Shell International Exploration & Production Company for the permission to publish the work.

- Thanks to ExxonMobil for the permission to publish the field data.

- Thank you all for your attention!

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