Resolving the effects of production-induced overburden dilation using simultaneous TV-regularized time-lapse FWI

Application to field seismic data

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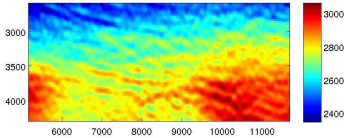
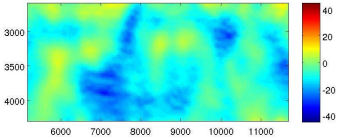


Stanford Exploration Project

May 19, 2015



Motivation: improved reservoir monitoring

- Current methods: conversion of time shifts $\Rightarrow$ impedance changes
- More automated tomographic methods exist
- Goal: design a robust 4D FWI less sensitive to repeatability issues

Full-waveform inversion

Find a model $\mathbf{m}$ that minimizes misfit between the true $\mathbf{d}$ and predicted $\mathbf{u}(\mathbf{m})$ data (Lailly, 1983; Tarantola, 1984)

$$\text{Misfit} \;=\; \|\mathbf{W}_d\,[\mathbf{d}-\mathbf{u}(\mathbf{m})]\,\|^2 \;\rightarrow\; \min, \tag{1}$$

with optional model regularization

$$\beta\|\mathbf{R}\mathbf{W}_m\left[\mathbf{m}-\mathbf{m}^{\text{prior}}\right]\|^2, \tag{2}$$

where $\mathbf{m}$ is a subsurface velocity model, $\mathbf{W}_d$ and $\mathbf{W}_m$ are data residual and model weighting operators, $\mathbf{R}$ is a model regularization operator, and $\mathbf{m}^{\text{prior}}$ is a model prior.

Existing model-space 4D FWI methods

- *Parallel Difference* FWI

$$\mathbf{m}_{\mathrm{INIT}} \rightarrow \text{BASE FWI} \Rightarrow \mathbf{m}_b \rightarrow \Delta\mathbf{m} = \mathbf{m}_m - \mathbf{m}_b$$

$$\mathbf{m}_{\mathrm{INIT}} \rightarrow \text{MON FWI} \Rightarrow \mathbf{m}_m \rightarrow \Delta\mathbf{m} = \mathbf{m}_m - \mathbf{m}_b$$

- *Sequential Difference* FWI

$$\mathbf{m}_{\mathrm{INIT}} \rightarrow \text{BASE FWI} \Rightarrow \mathbf{m}_b \rightarrow \text{MON FWI} \Rightarrow \mathbf{m}_m$$

$$\text{BASE FWI} \Rightarrow \mathbf{m}_b \rightarrow \Delta\mathbf{m} \leftarrow \text{MON FWI} \Rightarrow \mathbf{m}_m$$

Joint 4D FWI: simultaneous inversion and cross-updating

- NEW: *Simultaneous FWI* of baseline and monitor with *difference regularization*:

$$\text{Baseline Misfit} + \text{Monitor Misfit} + \tag{3}$$

$$\alpha \|\mathbf{R}\mathbf{W}_m \left[\mathbf{m}_2 - \mathbf{m}_1\right]\|_2^2. \tag{4}$$

- NEW: *Cross-updating* Approximation to the Simultaneous FWI:

$$\begin{tikzcd}
\mathbf{m}_{\mathrm{INIT}} \arrow[r] & \text{BASE FWI} \Rightarrow \mathbf{m}_b \arrow[r] & \text{MON FWI} \Rightarrow \mathbf{m}_m \arrow[dl] \\
\mathbf{m}_m \Leftarrow \text{MON FWI} \arrow[dr] & \mathbf{m}_b \arrow[l] & \Leftarrow \text{BASE FWI} \arrow[dl] \\
& \Delta\mathbf{m} &
\end{tikzcd}$$

Total-variation difference regularization

- NEW: *Simultaneous FWI* of baseline and monitor with the *total-variation difference regularization*:

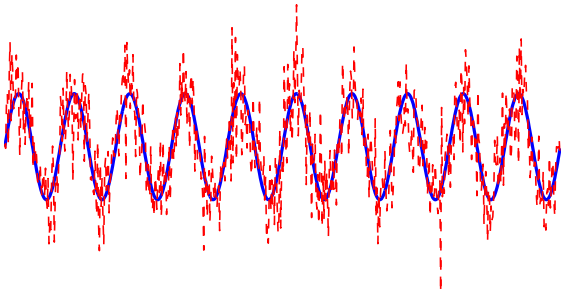
$$\text{Baseline Misfit} + \text{Monitor Misfit} + \tag{5}$$

$$\alpha \| |\nabla \mathbf{W}_m \left[\mathbf{m}_2 - \mathbf{m}_1 \right] | \|_1 . \tag{6}$$

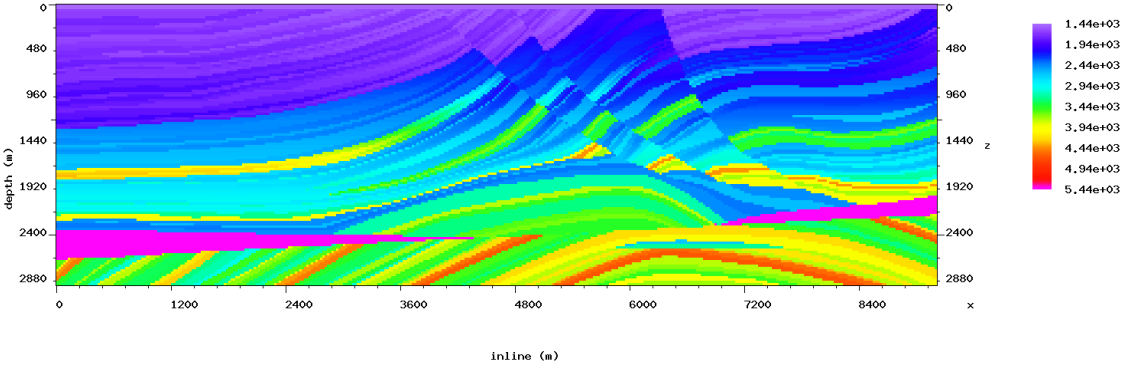
- The Total-variation (TV) seminorm (6) provides **edge-preserving** regularization that promotes model **"blockiness"** and helps to reduce spurious oscillations ("**ROF**" model of Rudin, Osher, and Fatemi, 1992).

Test: total-variation difference regularization

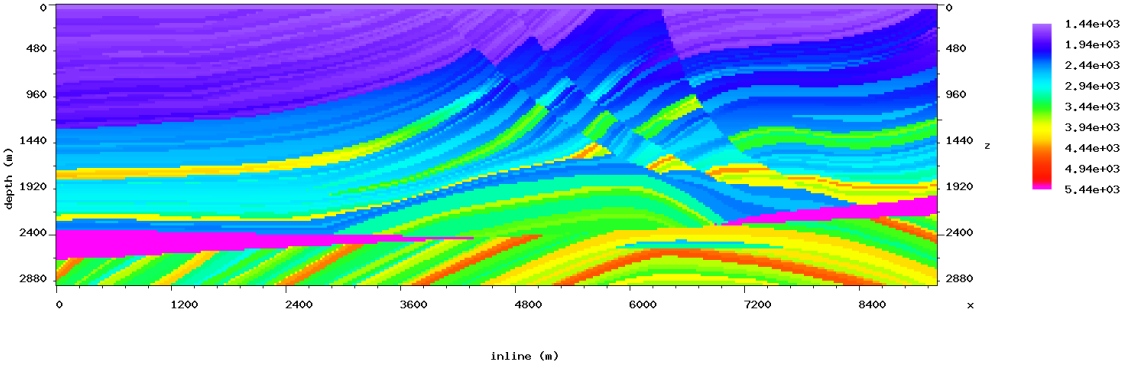
7 dB = 2.2 SNR synthetic



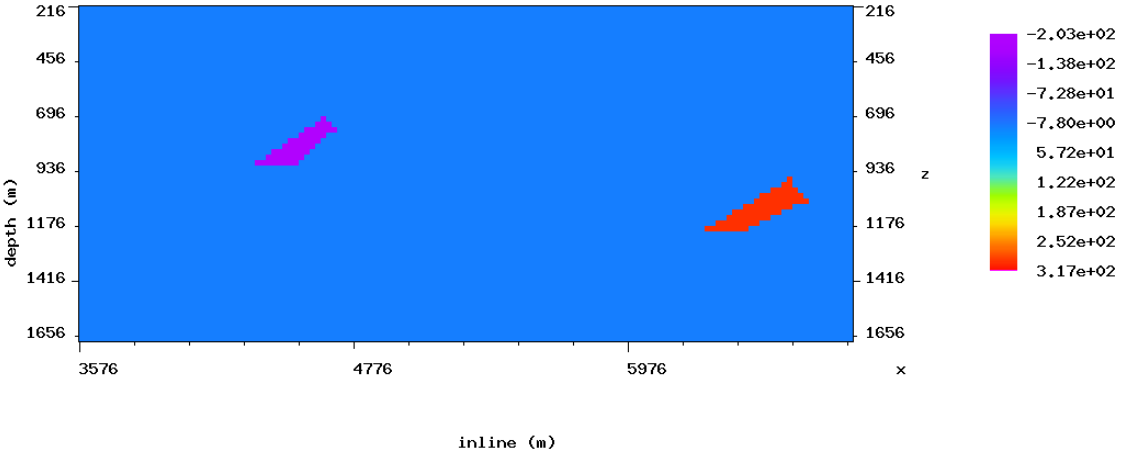
“Marmousi” model: true baseline



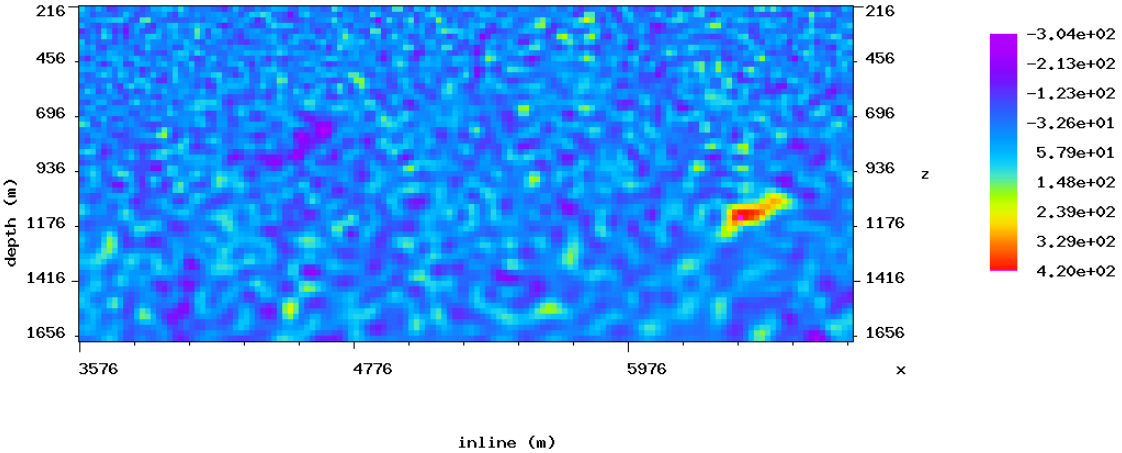
Modified "Marmousi": true monitor



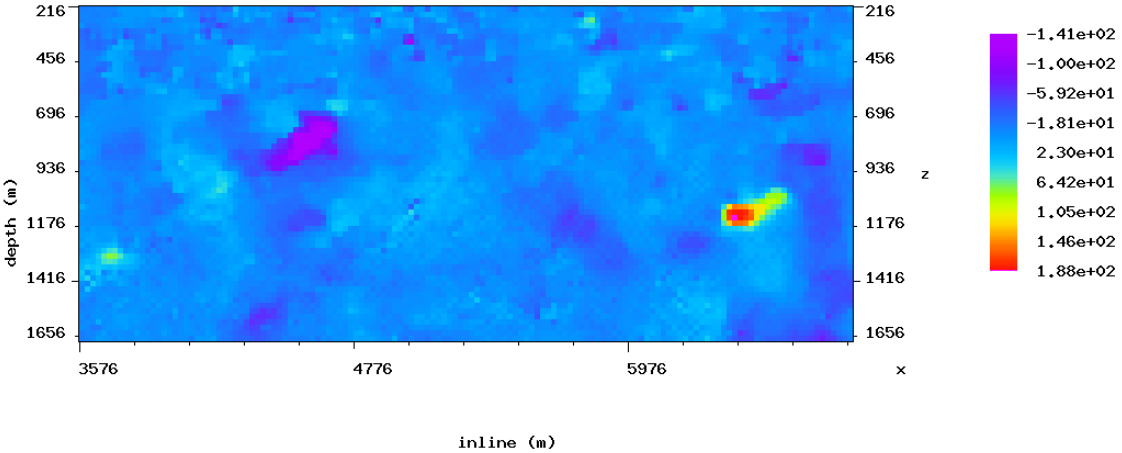
True difference



Cross-updating

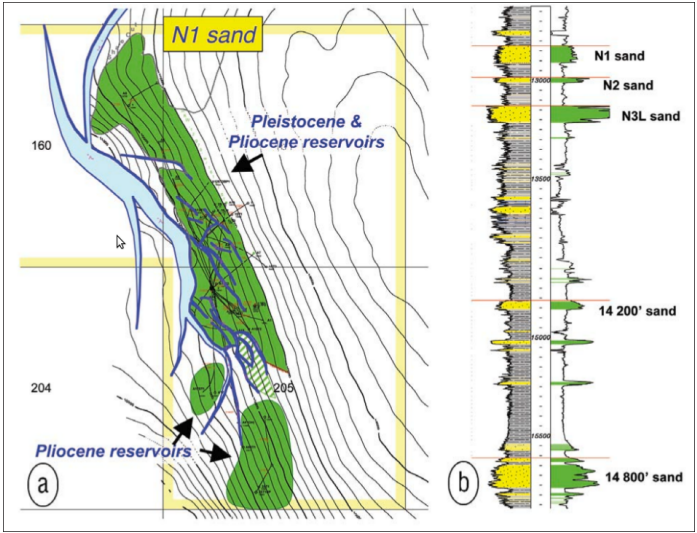


Total-variation difference regularization

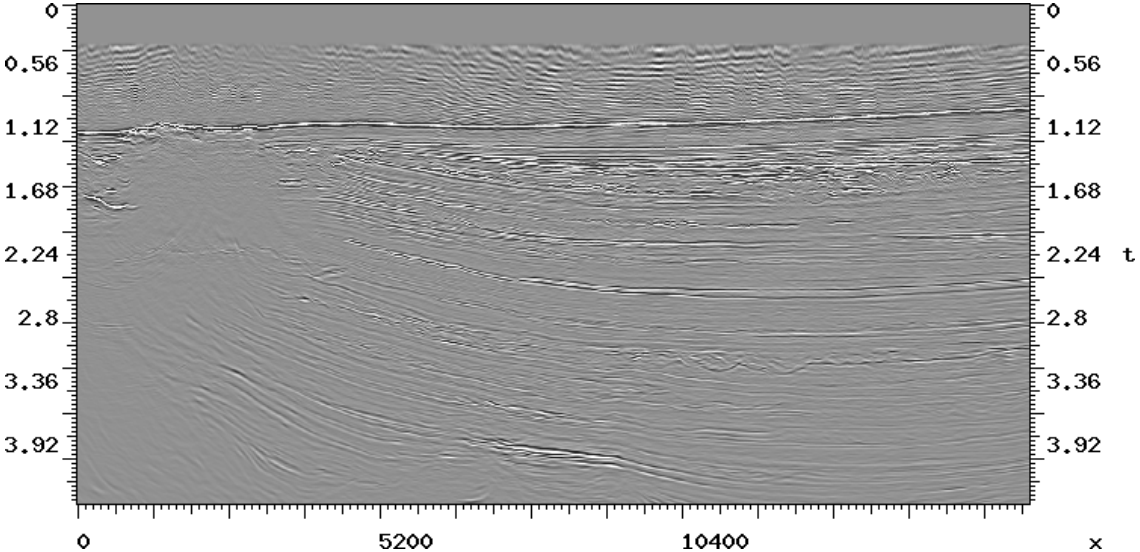


GoM Genesis field data: estimating production-induced overburden dilation

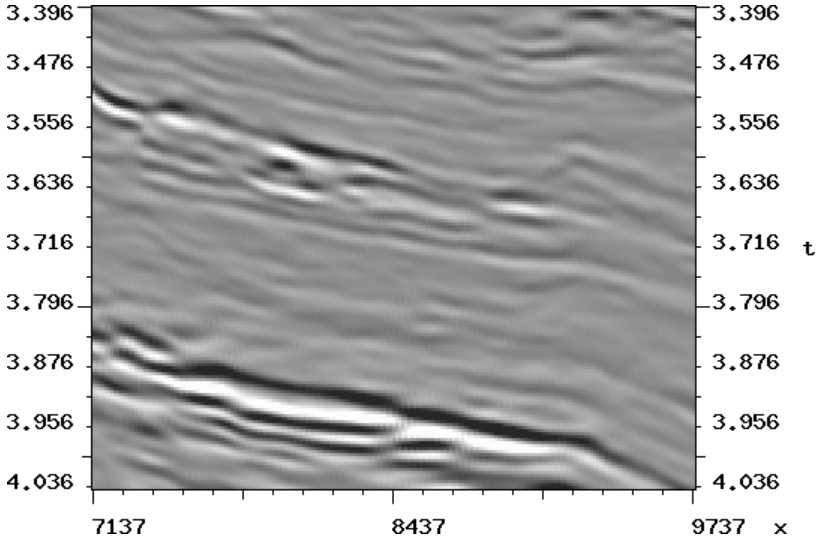
Genesis target (Magesan et al., 2008)



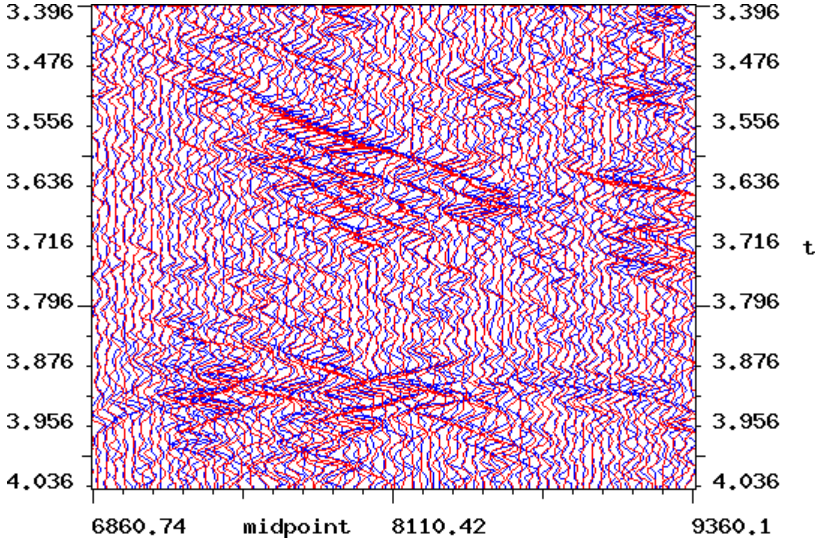
Baseline time migration image by Chevron



Monitor-Baseline image difference by Chevron



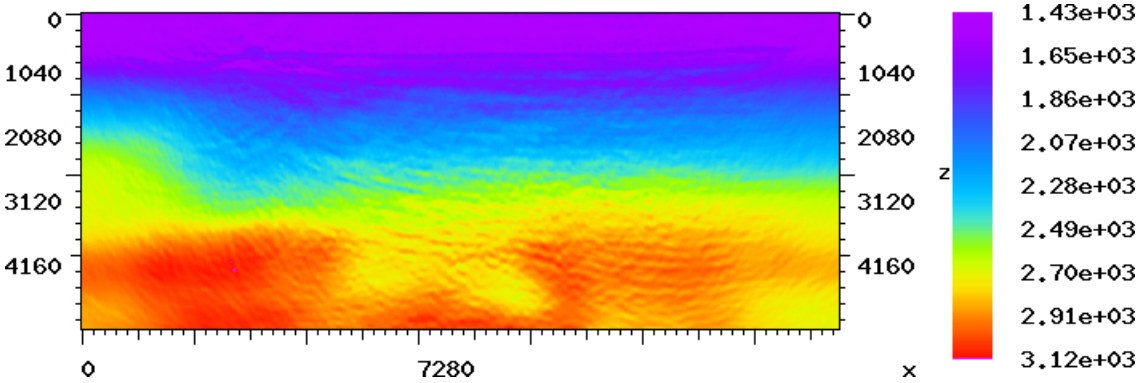
Kinematic differences (time shifts) in 1074m common-offset gathers



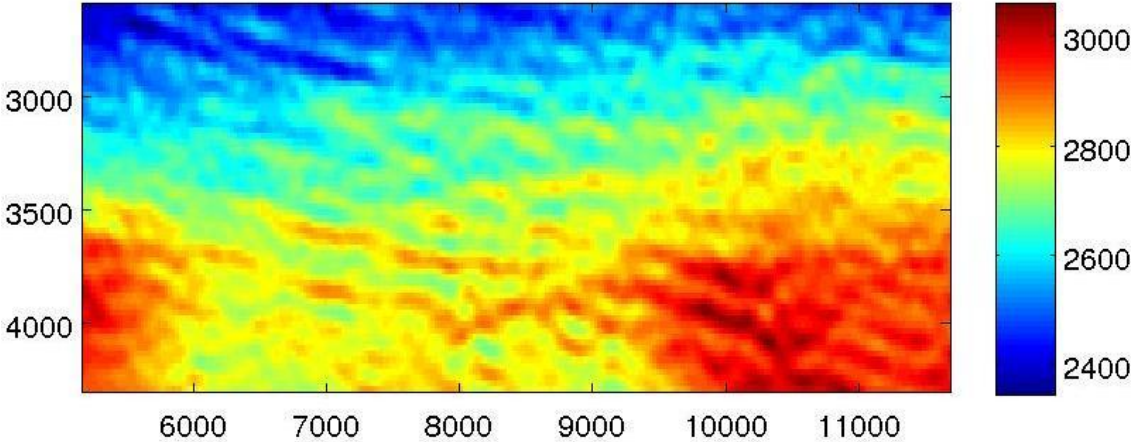
Genesis 2D FWI

- Frequency-domain inversion, 3-30Hz
- Shot gathers interpolated from the provided sparse CDP gathers
- Phase-only inversion as prior processing made amplitude information unreliable
- Baseline: 1264 shots with up to 175 receivers each
- Monitor: 1264 shots with up to 175 receivers each (a platform gap exists)
- Maximum 10 iterations per frequency

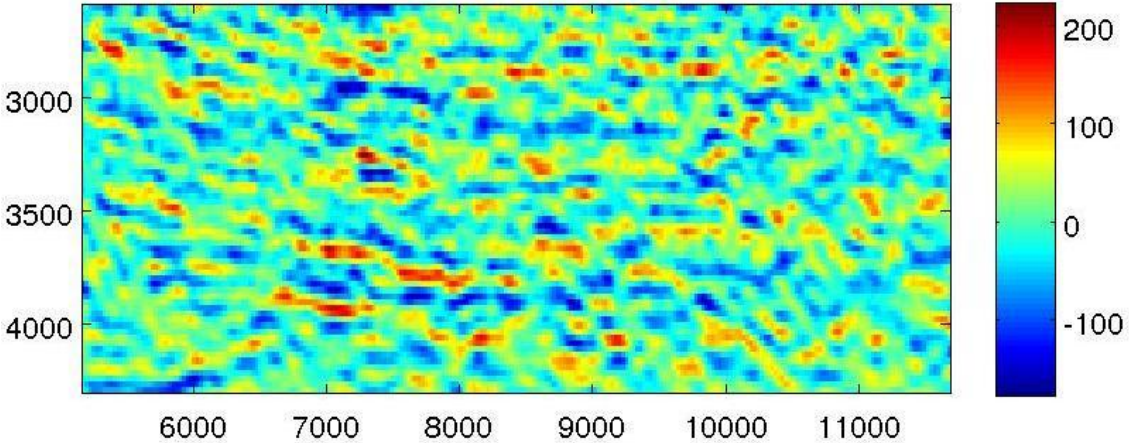
Baseline inversion, 3-30Hz



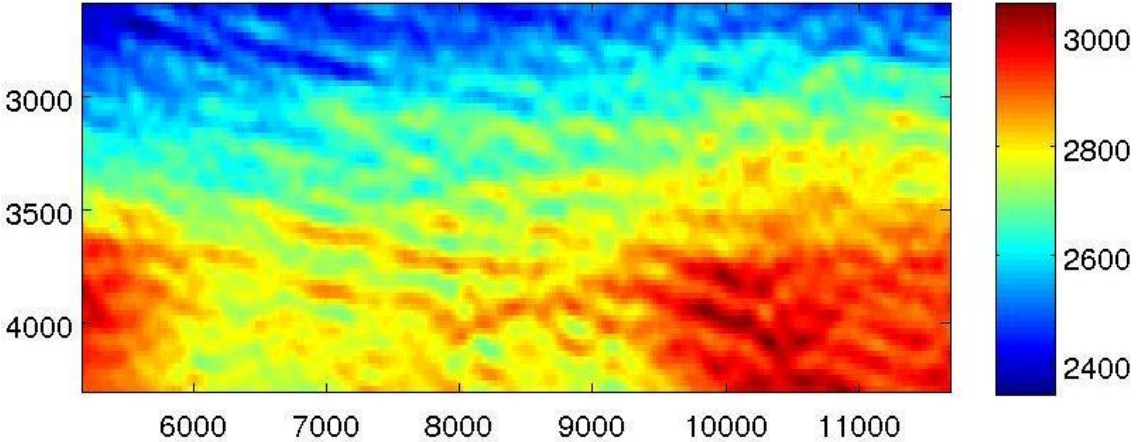
Baseline target



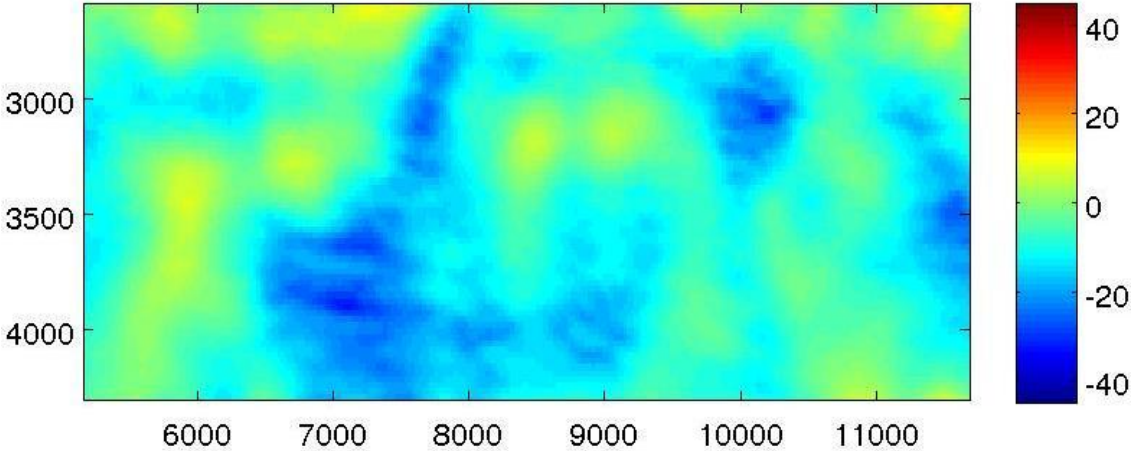
Parallel Difference



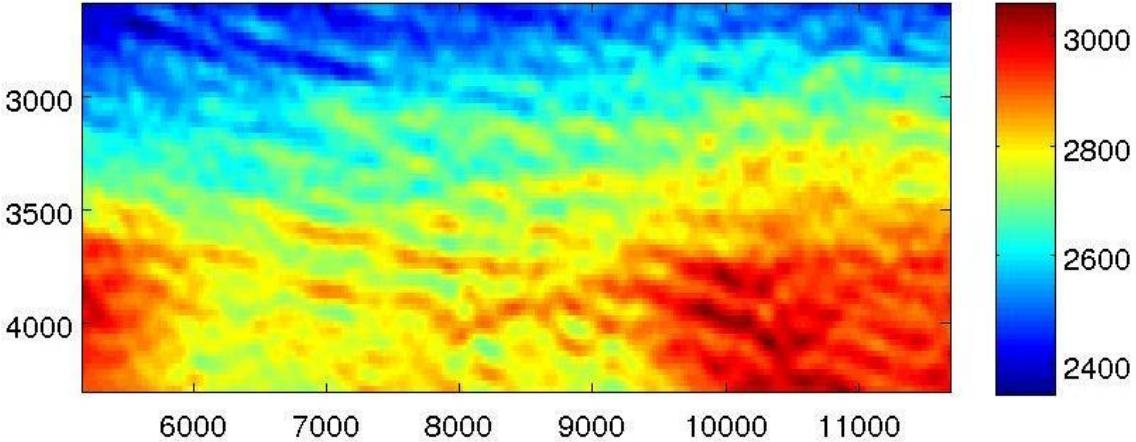
Baseline target



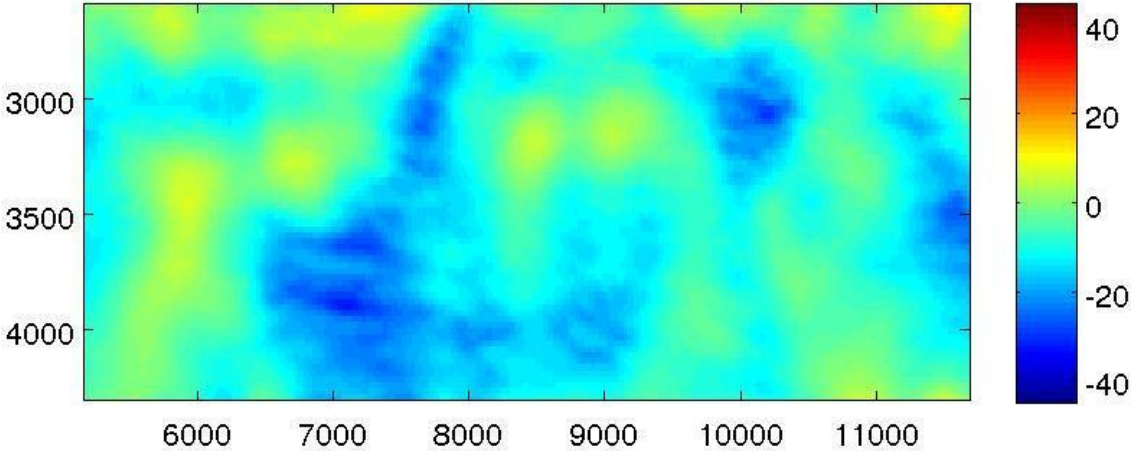
Model difference, strong TV regularization



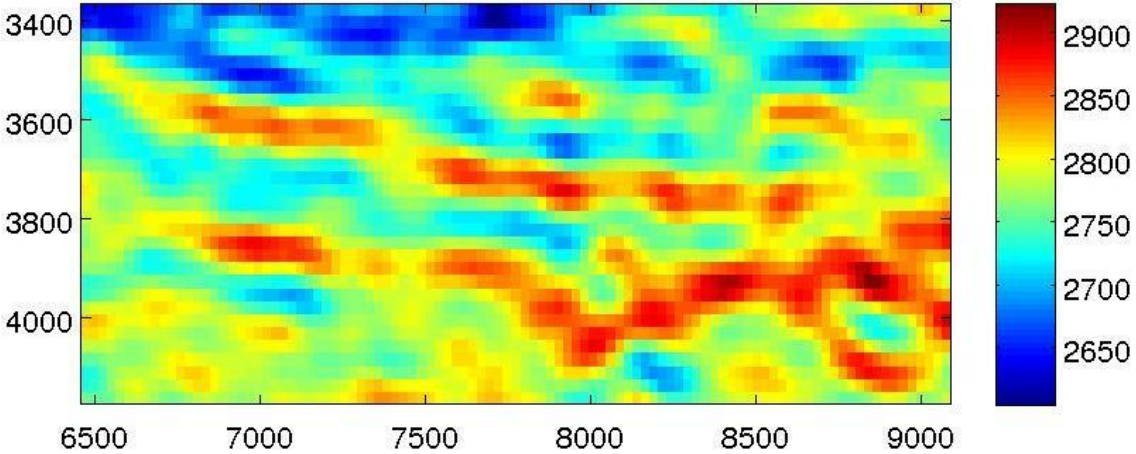
Baseline target



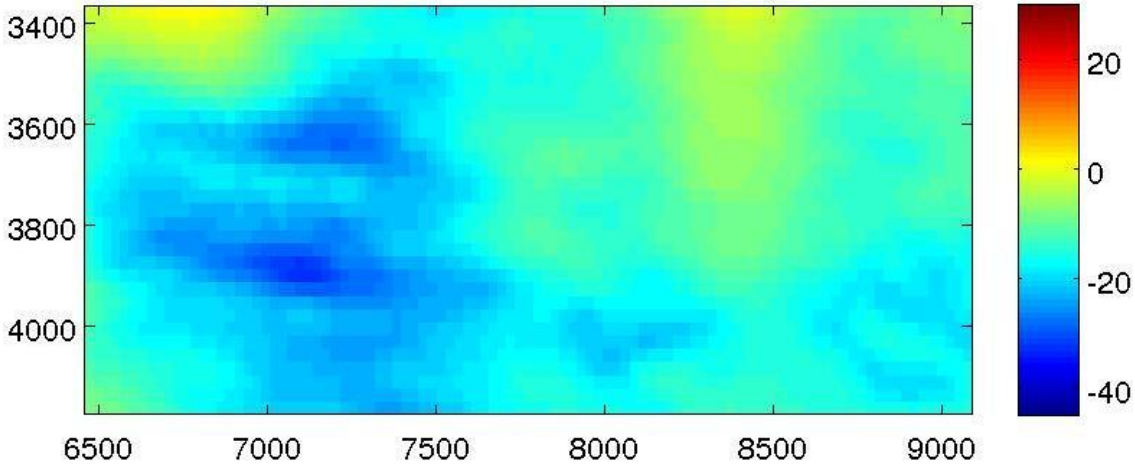
Model difference, strong TV regularization



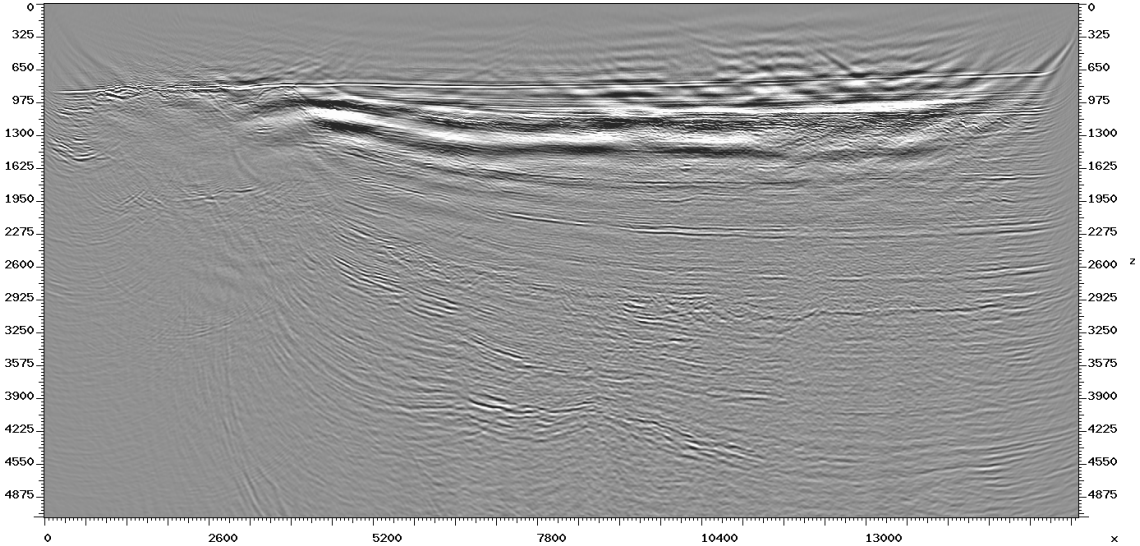
Zoomed-in baseline target



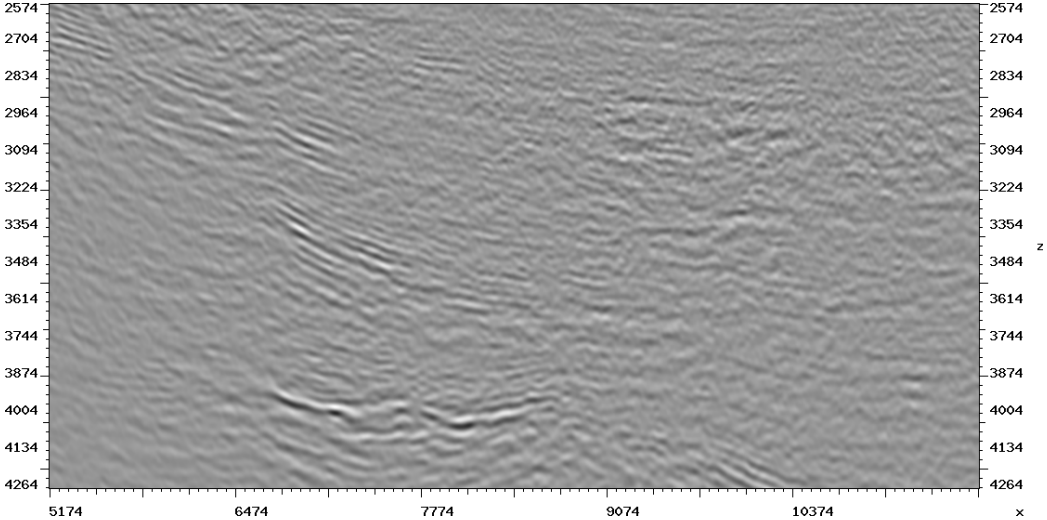
Zoomed-in model difference, strong TV regularization



Migrated baseline image



Migrated image difference (target area)



Velocity difference

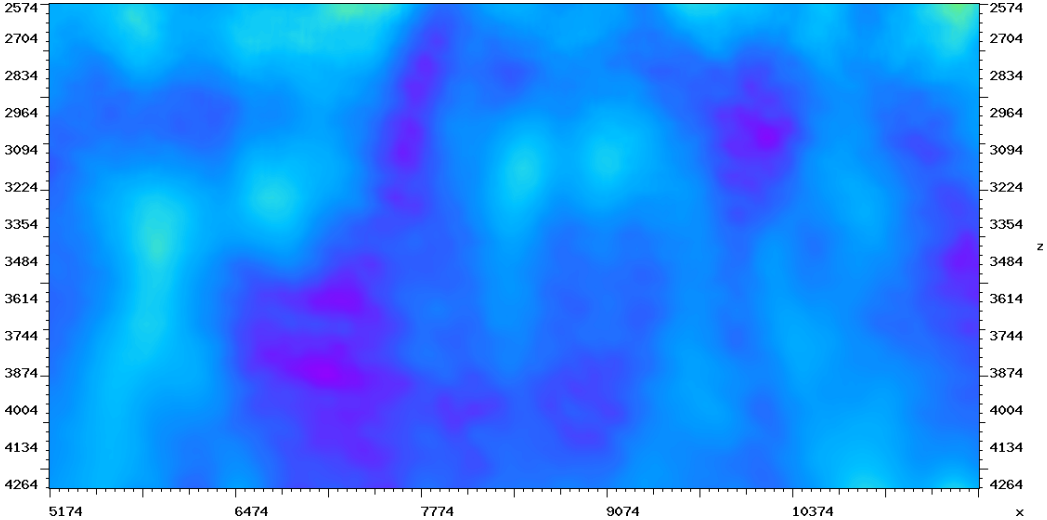
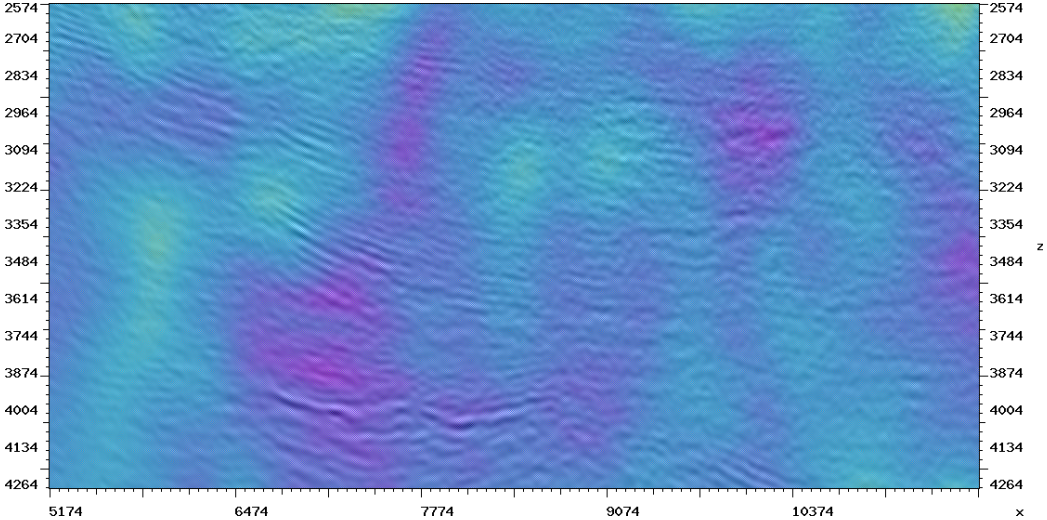
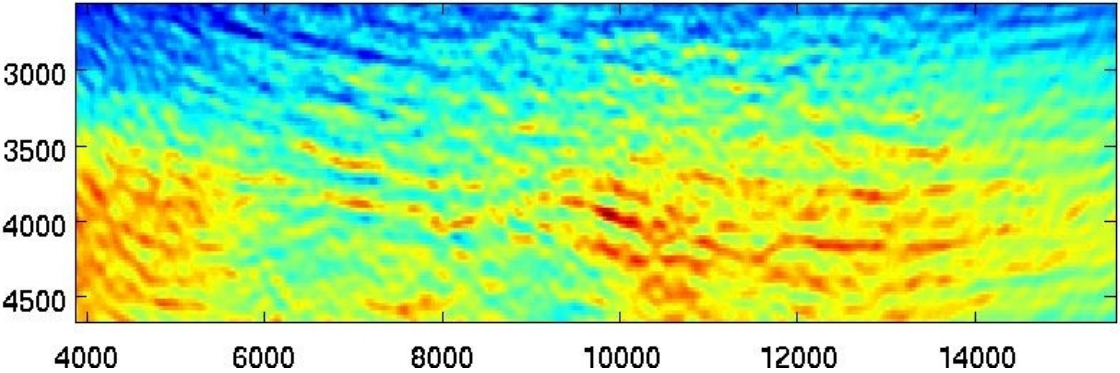


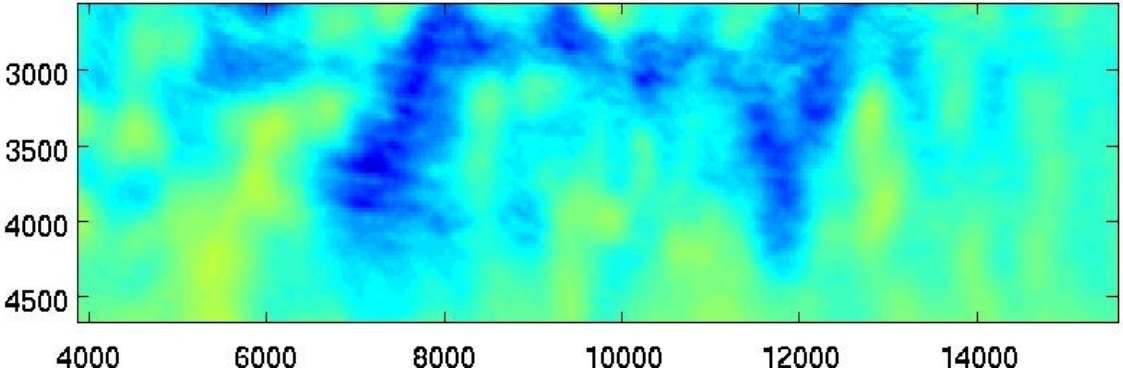
Image vs velocity difference



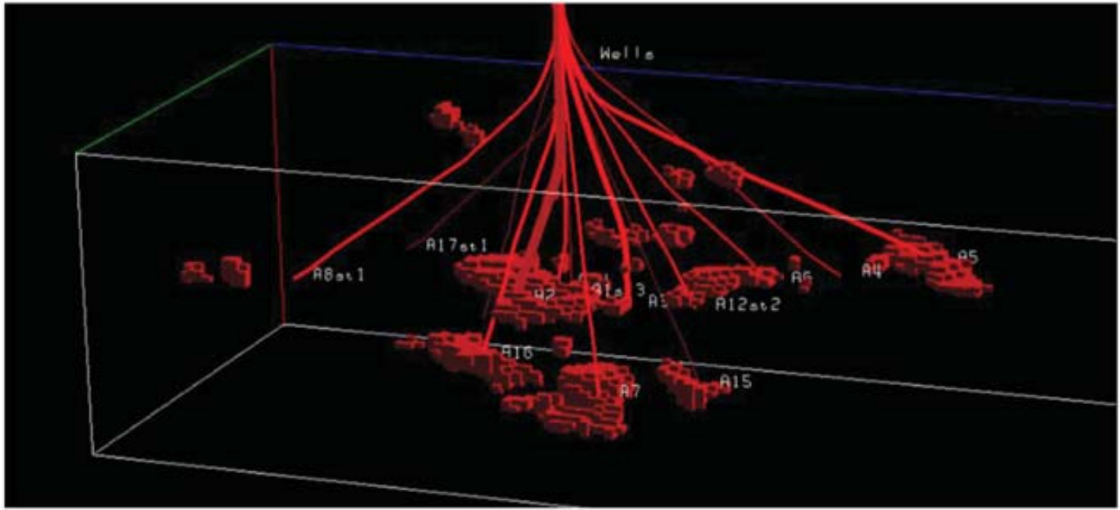
Overburden dilation appears even in non-masked inversion...



Overburden dilation appears even in non-masked inversion...



Genesis production wells (Rickett et al., 20007)



Conclusions and perspectives

- TV-regularized simultaneous time-lapse FWI can resolve velocity changes induced by overburden dilation
- Peaks of inverted velocity difference match the largest observed time strains
- Resolving fine features of compacting reservoirs may require multi-scale inversion (Maharramov and Biondi, SEP155, pp 187-192)
- 3D time-lapse FWI experiments (including analysis of sensitivity to cycle-skipping) are underway

Acknowledgements

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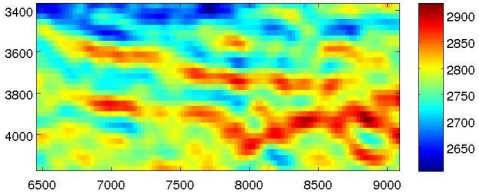
Q&A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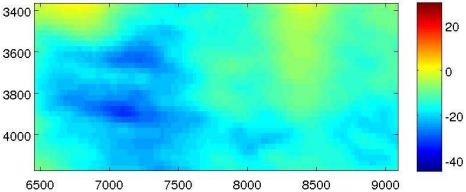
Q&A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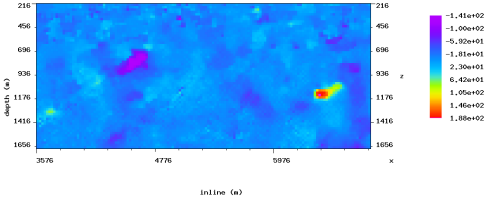
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inline (m)
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2.30e+01
6.42e+01
1.05e+02
1.46e+02
1.88e+02

Appendices – discussion slides

Multi-model (4D) FWI

Model decomposition into "blocky" and "wiggly" components = cartoon+texture decomposition (Meyer, 2001):

$$\min_{\mathbf{m},\mathbf{m}_b} \|\mathbf{F}(\mathbf{m}) - \mathbf{d}\|_2^2 \; + \; \alpha \||\nabla \mathbf{m}_b|\|_1 + \beta \|\mathbf{R}\mathbf{m}_w\|_2^2, \mathbf{m} \; = \; \mathbf{m}_b + \mathbf{m}_w, \quad (7)$$

where

$$\mathbf{R} \; = \; \mathbf{I} \text{ or } \mathbf{\Delta}.$$

R-factor analysis

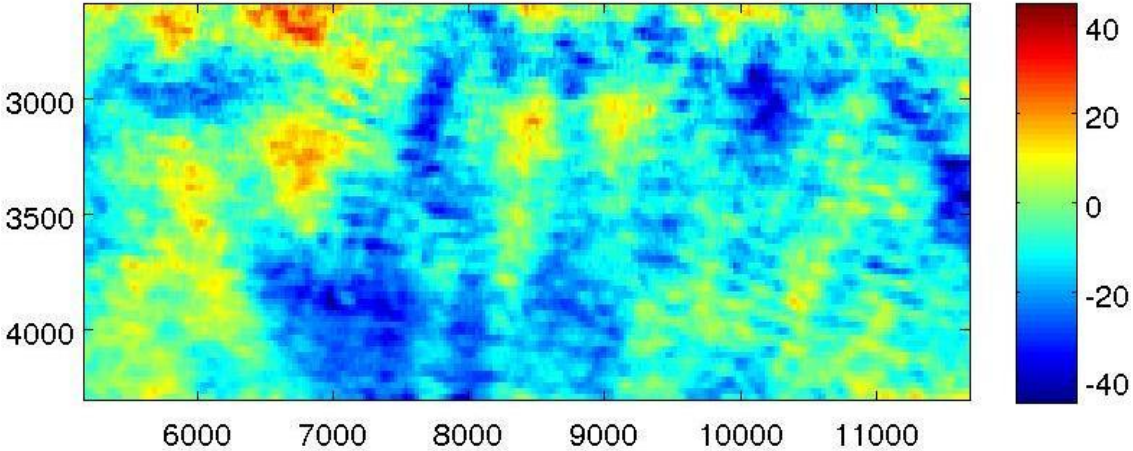
$$\frac{d\tau}{dt} \approx \frac{\Delta t}{t} = \frac{\Delta z}{z} - \frac{\Delta v}{v}, \tag{8}$$

$$\frac{\Delta v}{v} = -R\frac{\Delta z}{z}, \tag{9}$$

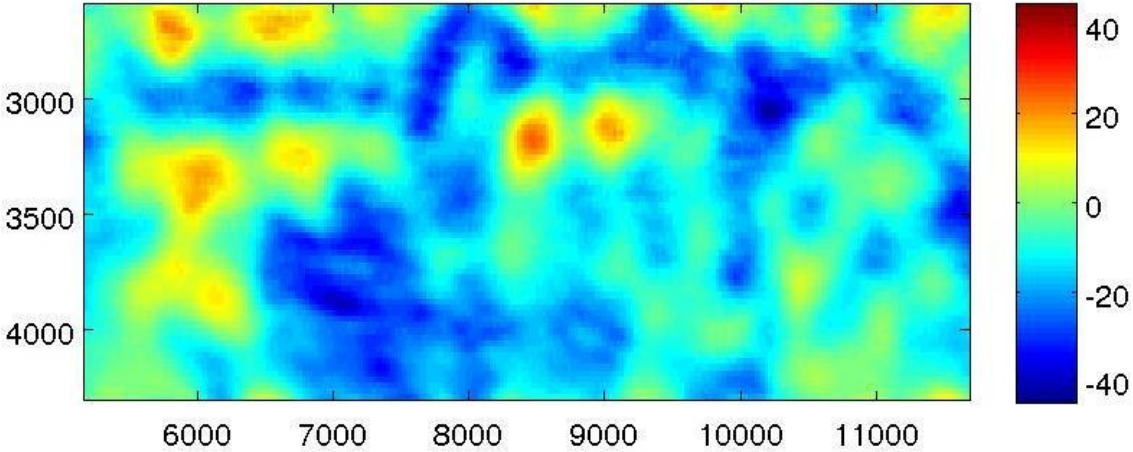
$$\frac{\Delta v}{v} = -\frac{R}{R+1}\frac{\Delta t}{t} \approx -\frac{\Delta t}{t} \approx -\frac{d\tau}{dt}. \tag{10}$$

$$\Delta v \approx -.02 \times 2,800 \text{ m/s} = -56 \text{ m/s}. \tag{11}$$

Model difference, small TV regularization



Model difference, medium TV regularization



Model difference, strong TV regularization