Monitoring of Cyclic Steam Stimulation by Inversion of Surface Tilt Measurements

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Motivation: improved reservoir monitoring

- Depends on successful tracking of fluid movement and pressure.
- Steam injection is accompanied by deformation.
- For heavy oil reservoirs, surface deformation can be measured using GPS, tilt meters or InSAR.
- **Goal: design a robust framework for estimating injection-induced pressure change from surface deformation**.

Governing Equations of Poroelasticity

A closed system of equations that describes a homogeneous quasi-static linear poroelastic medium (Segall, 2010):

$$\mu\nabla^2 u_i + \frac{\mu}{1-2\nu}\frac{\partial^2 u_j}{\partial x_i \partial x_j} = \alpha\frac{\partial p}{\partial x_i} - f_i = 0,\ \ i=1,2,3 \qquad (1)$$

and

$$S_\alpha \frac{\partial p}{\partial t} - \frac{\kappa}{\eta}\nabla^2 p = -\alpha\frac{\partial}{\partial t}(\nabla\cdot\mathbf{u}). \qquad (2)$$

where u_i, $i=1,2,3$ is displacement, p is the pore pressure change, f_i is a differential body-force distribution, $\mu,\nu,\alpha,\kappa,\eta$ are the shear modulus, Poisson's ratio, Biot coefficient, permeability and fluid viscosity. The storage coefficient S_α is a known function of medium parameters (Segall, 2010).

Inverting Pressure Change from Displacements

Decoupling p and $\mathbf{u}$, and assuming p is known, we have $\mathbf{u} = \mathbf{G}p$, where $\mathbf{G}$ is the linear displacement **modeling operator**. The **mixed-determined** inverse problem of estimating p from tilt measurements can be formulated as

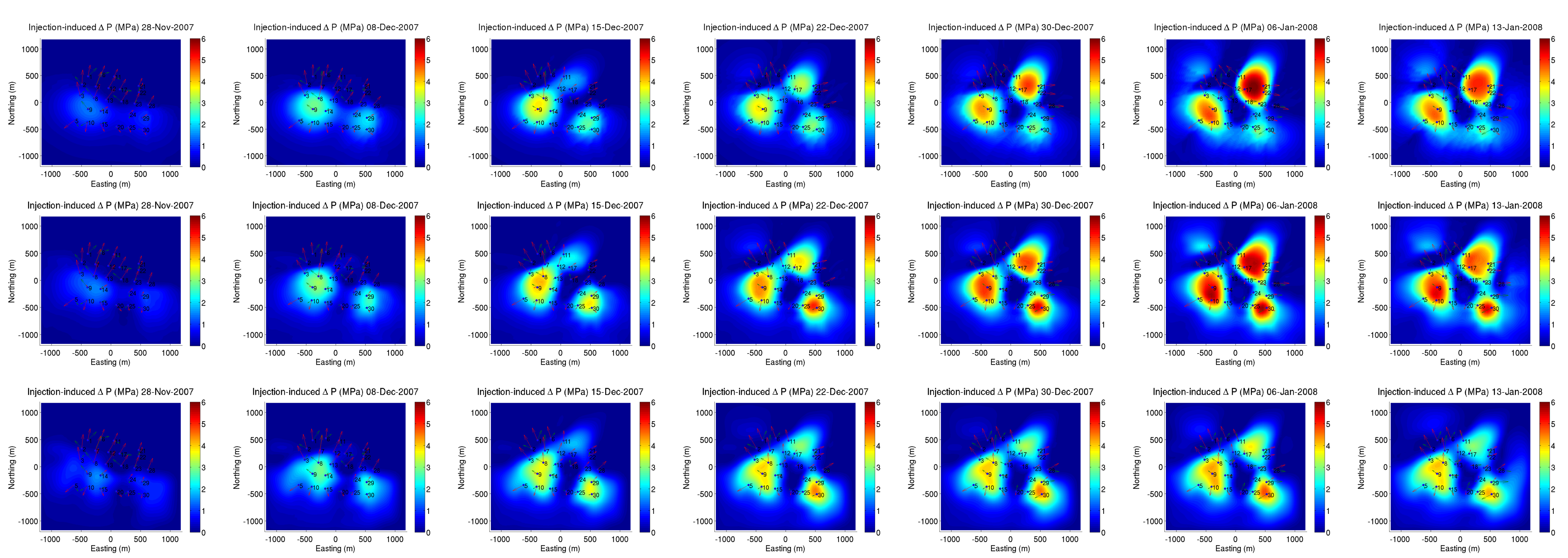
$$\|\mathbf{TG}p - \mathbf{d}\|_2^2 + \epsilon^2\|\nabla^2 p\|_2^2 \rightarrow \min, \qquad (3)$$

where $\mathbf{T}$ is the tilt modeling operator (finite difference), $\mathbf{d}$ denotes tilt measurements, and ϵ is a Tikhonov regularization parameter (Maharramov, 2014). We solve (3) for $p = \Delta P$ on a 50×50 grid, from 50 two-component continuous tilt measurements, and subject to inequality constraints

$$0 \le p \le p_{\max} = 7\ \text{MPa}. \qquad (4)$$

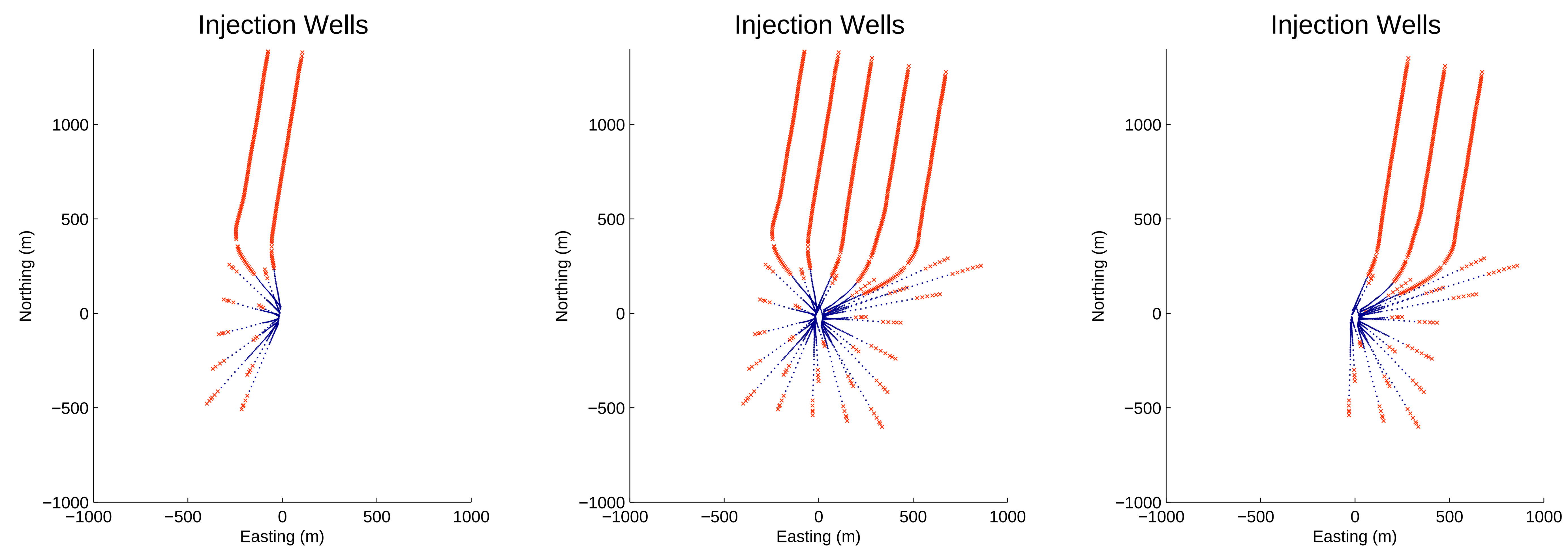
In our experiments, we assume $\mu = 1.5$ GPa, drained and undrained Poisson moduli $= .25, .45$, reservoir depth is 455 m, and thickness is 50 m.

Weekly pressure change estimates obtained using $\epsilon = 10^{-3},\ 5\times 10^{-3},\ 10^{-2}$.



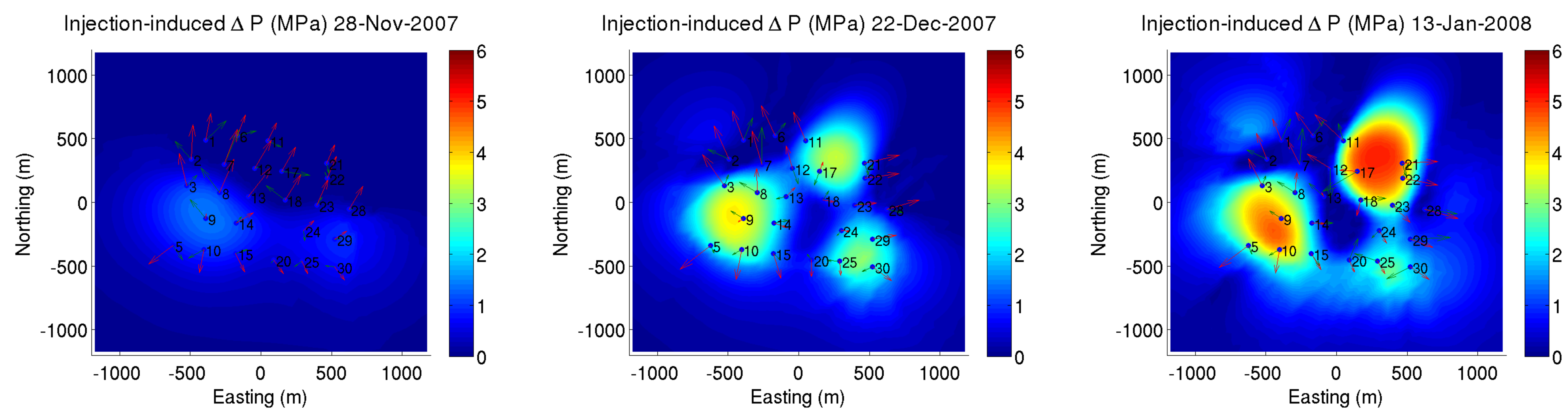
Larger ϵ produces a smoother $p = \Delta P$ but does not change the qualitative behavior of pressure fronts.

Well Trajectories and Injection Stages



(a) Injection into the Western wells in Nov-mid Dec ; (b) All wells in mid-end Dec; (c) Eastern wells in Dec-Jan.

Estimated Injection-induced Pressure Change, $\epsilon = 10^{-3}$



Estimated cumulative induced $p = \Delta P$ on Nov 28, Dec 22 and Jan 13. Maximum ΔP (reached on Jan 6) ≈ 6.1 MPa.

Summary and perspectives

- Injection-induced pressure changes can be stably estimated from surface tilt measurements, with pressure peaks following injection pattern.
- All experiments, regardless of the amount of regularization, indicate a **lower induced pressure zone** in the middle of the modeling domain.
- Obtained a **higher resolution inversion** result and better fitting of the observed tilts than in our earlier work (Maharramov, 2014).
- Quantitative inversion results are affected by parameter and data uncertainties.
- However, **qualitative evolution of pressure fronts** is stable with respect to parameter variation and amount of smoothing regularization.
- **Next**: **InSAR data could significantly improve accuracy** of the proposed algorithm due to less noise and better coverage.

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