Monitoring of cyclic steam stimulation by inversion of surface tilt measurements

Methodology and results

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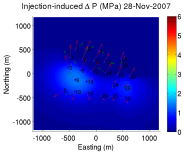
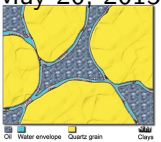
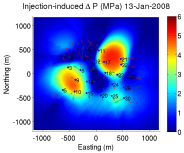
Stanford Exploration Project

May 20, 2015



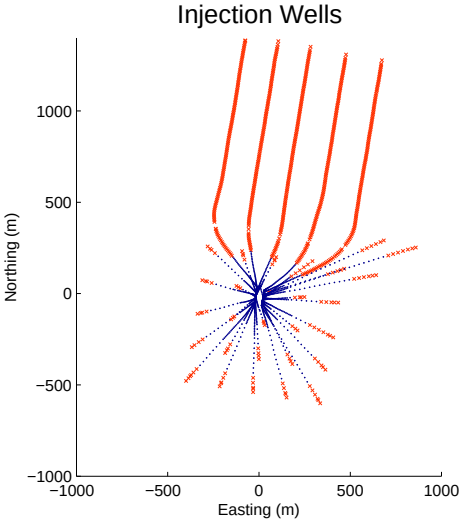




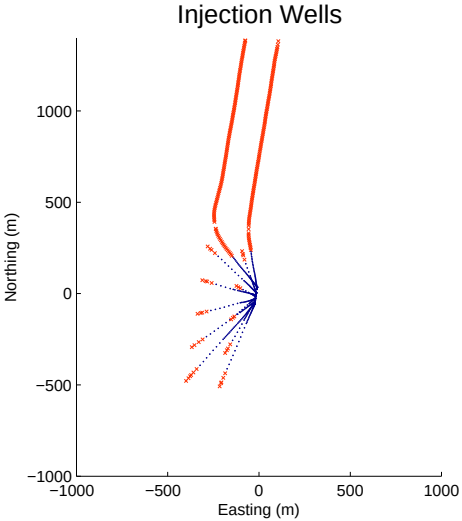
Motivation: improved reservoir monitoring

- Extraction of heavy oil from deep formations relies on Cyclic Steam Stimulation (CSS) or Steam-Assisted Gravity Drainage (SAGD).
- Effective steam injection requires understanding pressure front propagation and reservoir heterogeneity.
- Goal: design a robust computational framework for estimating pressure fronts from measurable surface deformation.

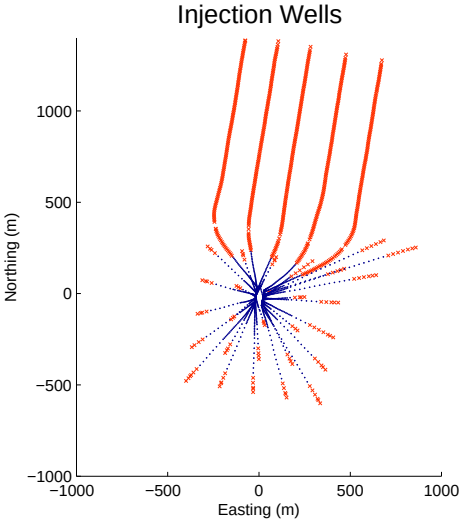
A heavy oil reservoir undergoing a 60-day steam injection



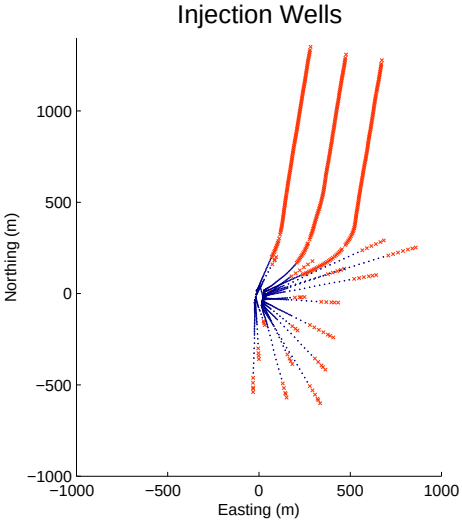
Phase 1


Injection Wells
Northing (m)
Easting (m)
1000
500
0
−500
−1000
−1000
−500
0
500
1000

Phase 1-2


Injection Wells
Northing (m)
Easting (m)
1000
500
0
−500
−1000
−1000
−500
0
500
1000

Phase 2


Injection Wells
1000
500
0
−500
−1000
Northing (m)
−1000
−500
0
500
1000
Easting (m)

Linear Poroealstic Medium Deformation

Relate deformation and pore pressure change using Biot's theory (Rice and Cleary, 1976; Segall, 1985; Segall, 2010):

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

and

$$S_\alpha \frac{\partial p}{\partial t} - \frac{\kappa}{\eta}\nabla^2 p = -\alpha\frac{\partial}{\partial t}\left(\nabla\cdot\mathbf{u}\right)), \qquad \text{(FLOW)}$$

where $\mathbf{u}$ is displacement, p is the pore pressure change, f_i is a differential body-force distribution, μ,ν,α,κ, and η are the shear modulus, Poisson's ratio, Biot coefficient, permeability, and fluid viscosity;

$$S_\alpha = \frac{3\alpha(1-2\nu)(1-\alpha B)}{2\mu B(1+\nu)}, \qquad \text{(STORAGE)}$$

where B is Skempton's coefficient.

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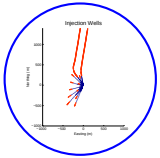
Methodology

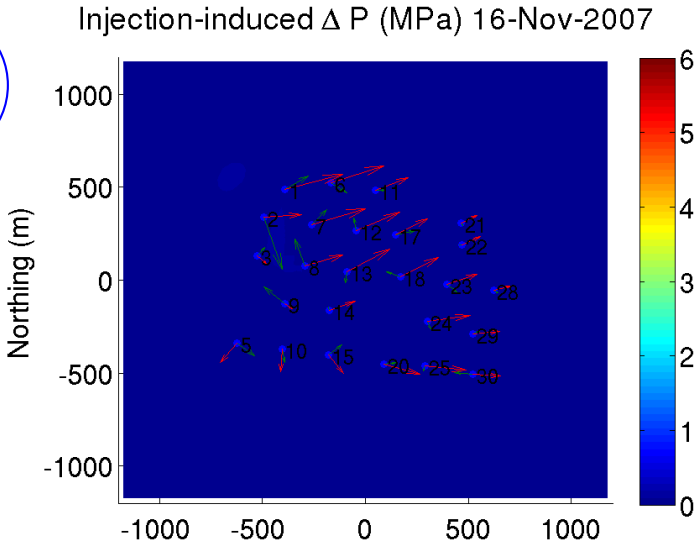
- Regard (ELAST) as a deformation modeling operator $\mathbf{A}p = \mathbf{u}$ and **decouple** it from the flow equation (FLOW) (Vasco et al., 2000; Du and Olson, 2001; Hodgson, 2007).

- Solve the regularized constrained optimization problem

$$\|\mathbf{A}p - \mathbf{u}\|_{L_2}^2 + \epsilon\|\Delta p\|_{L_2}^2 \rightarrow \min, \quad 0 \leq p \leq p_{\max}. \quad \text{(BOUNDREG)}$$

Inverted pore pressure change, $\epsilon = 10^{-3}$





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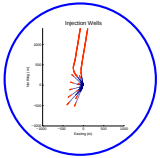

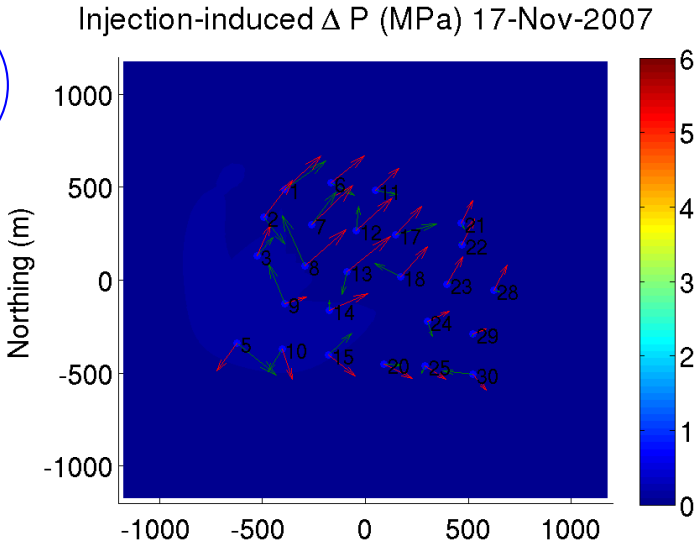

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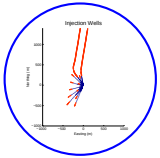

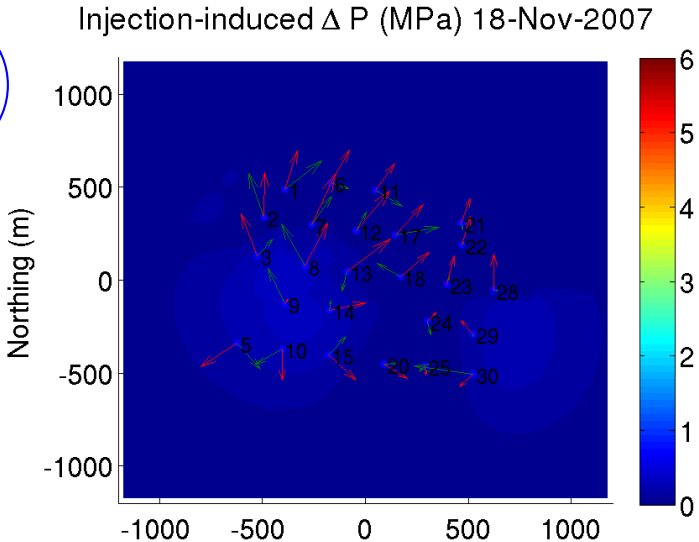

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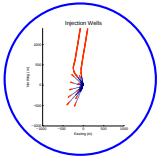

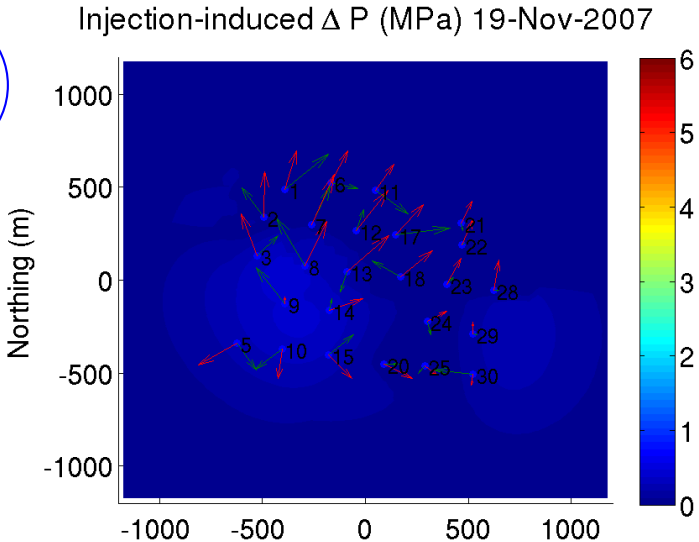

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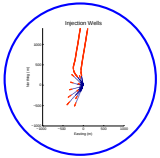

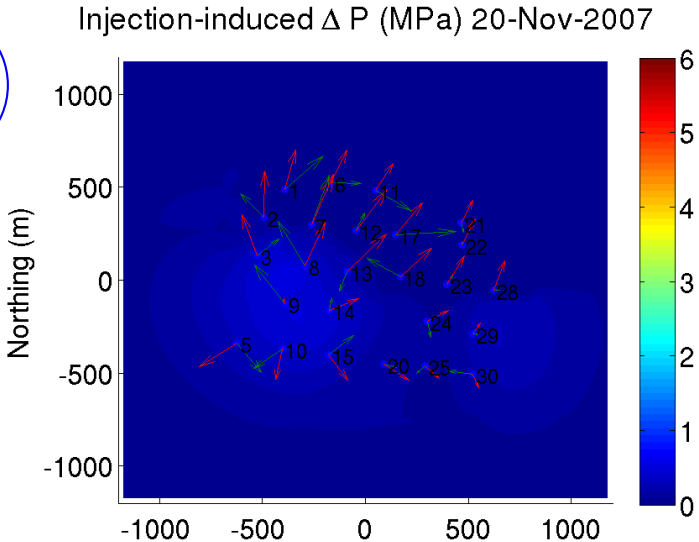

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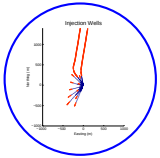

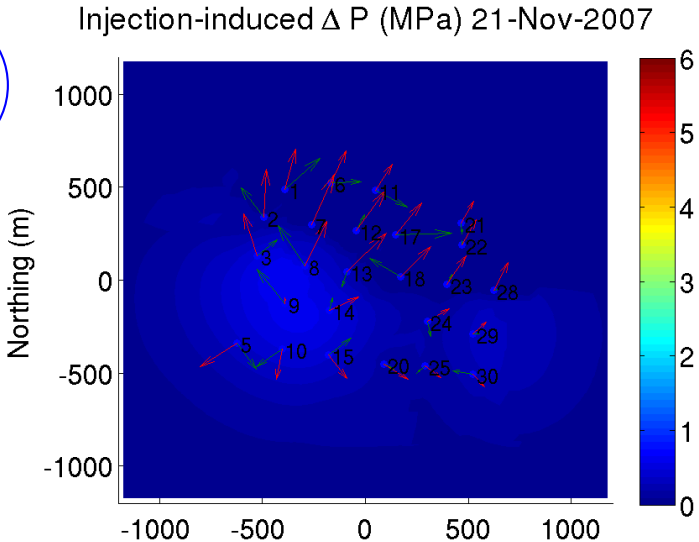

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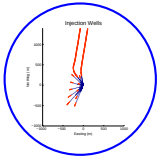

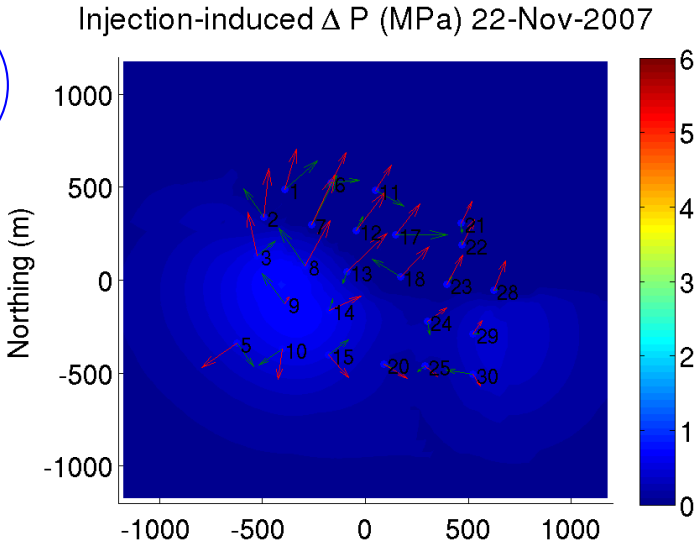

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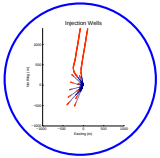

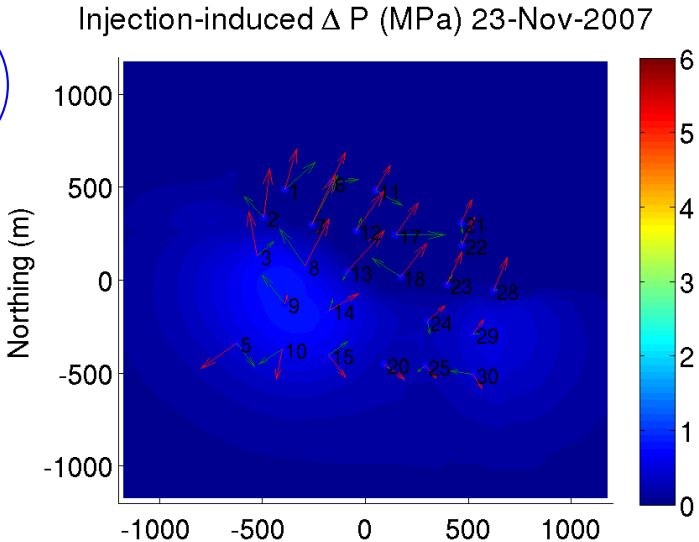

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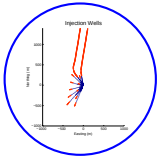

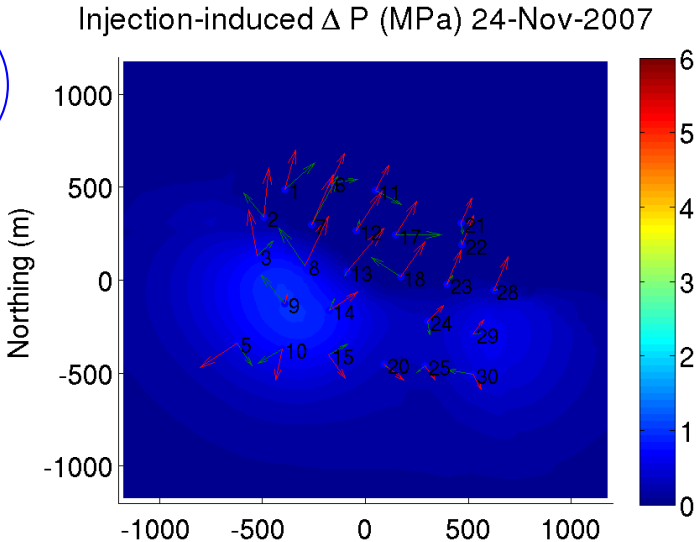

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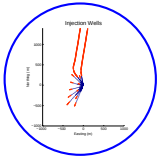

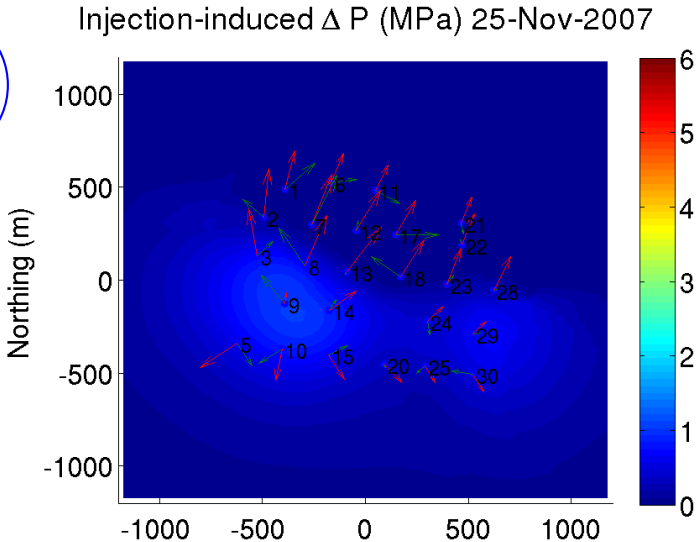

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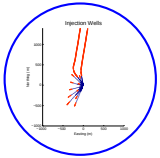

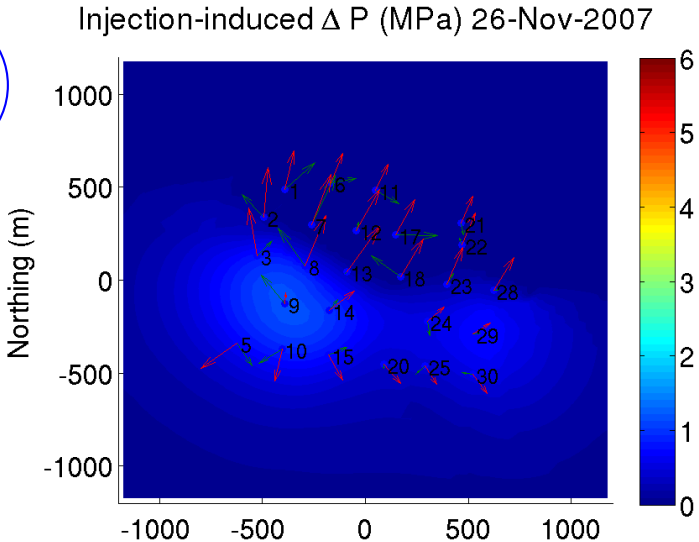

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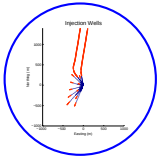

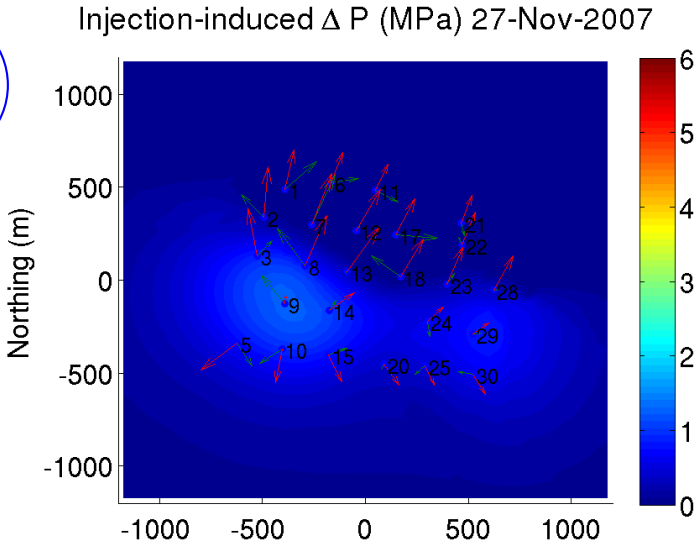

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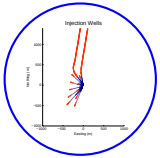

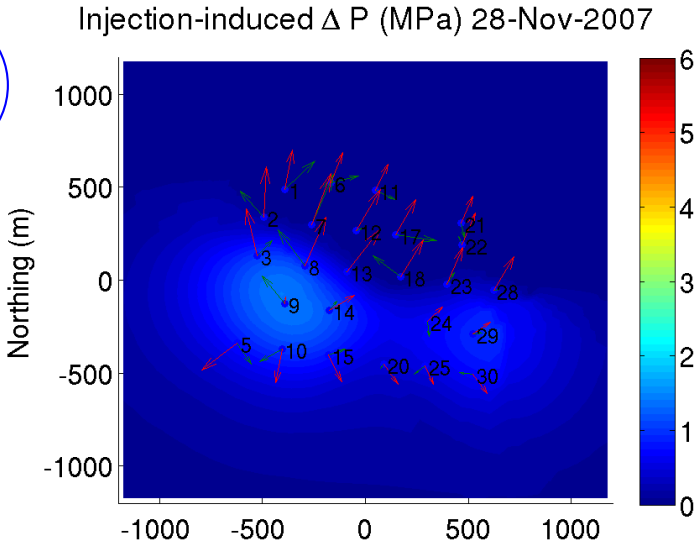

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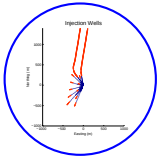

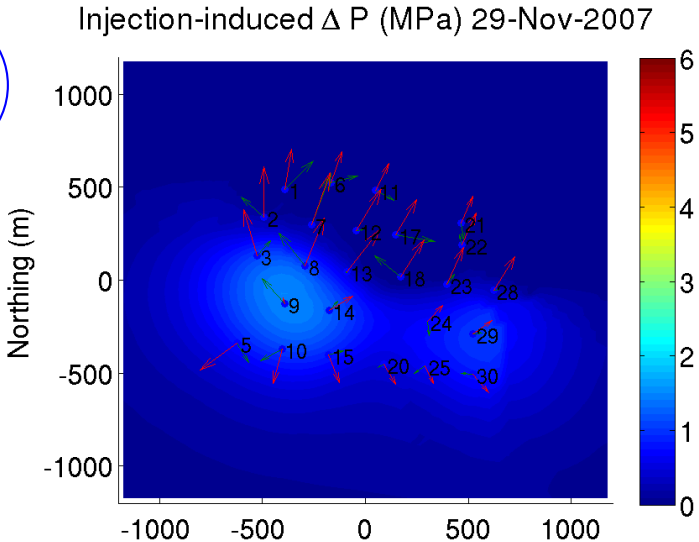

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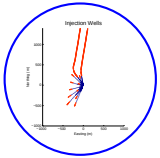

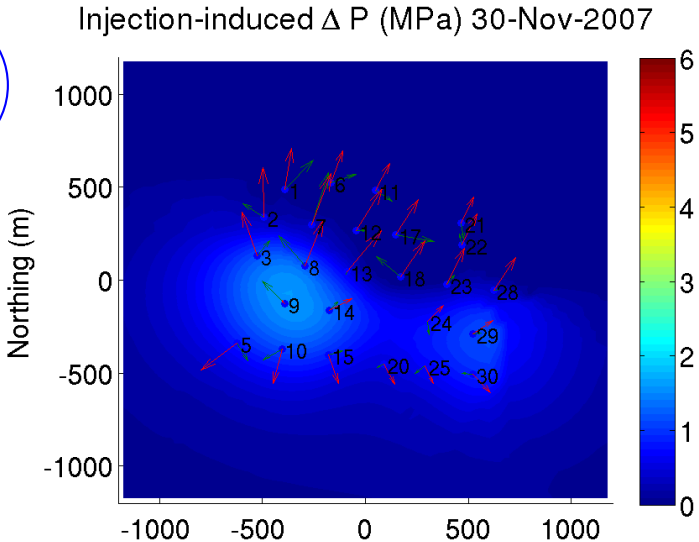

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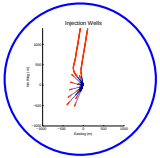

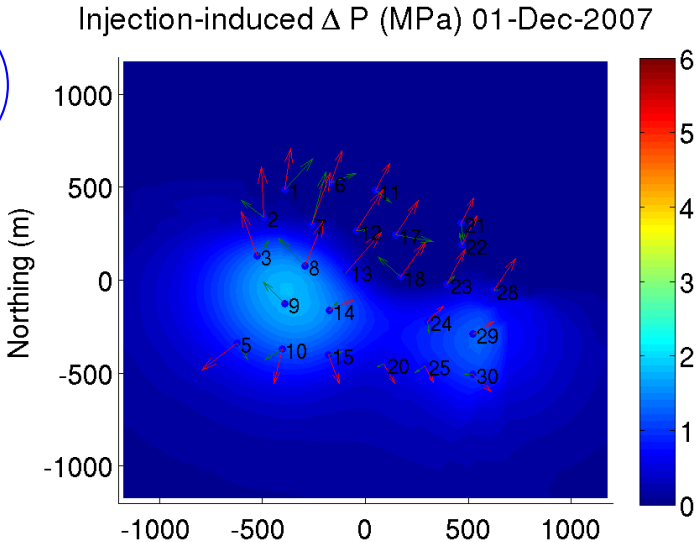

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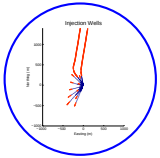

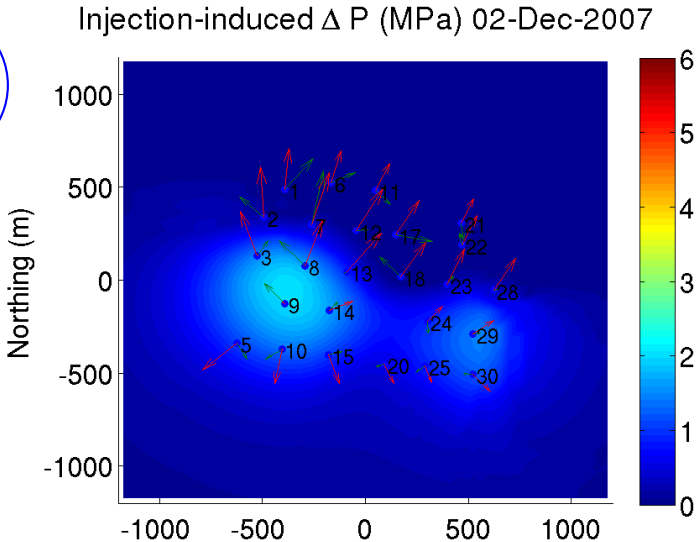

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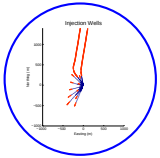

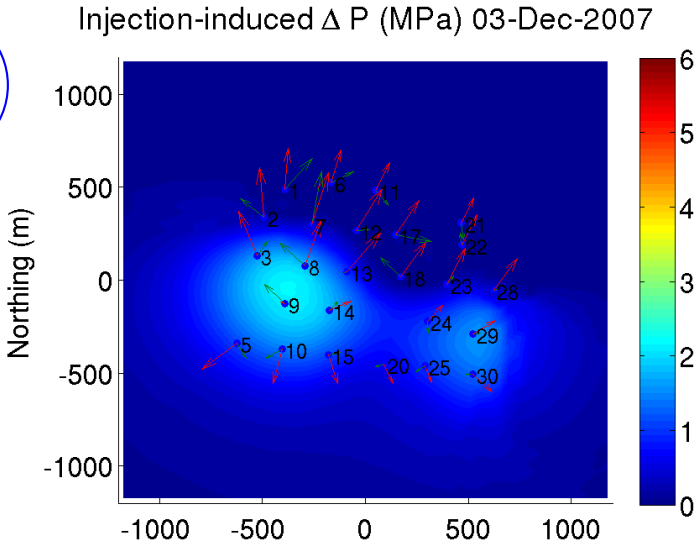

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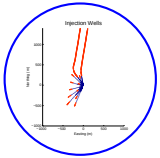

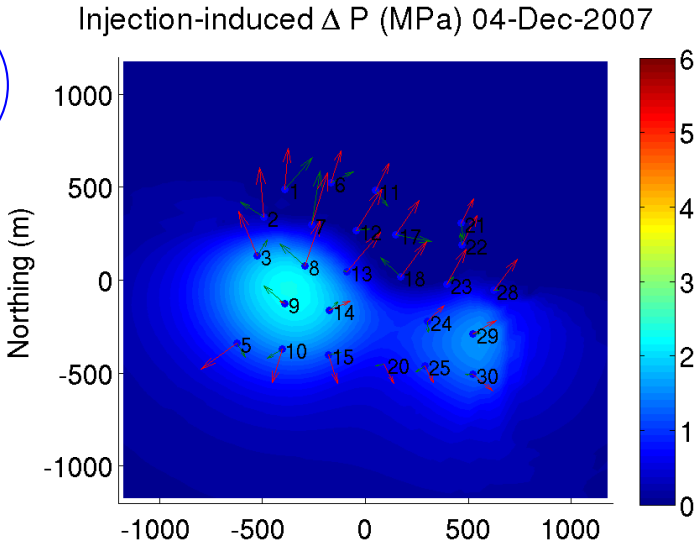

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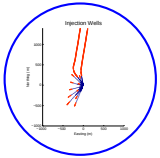

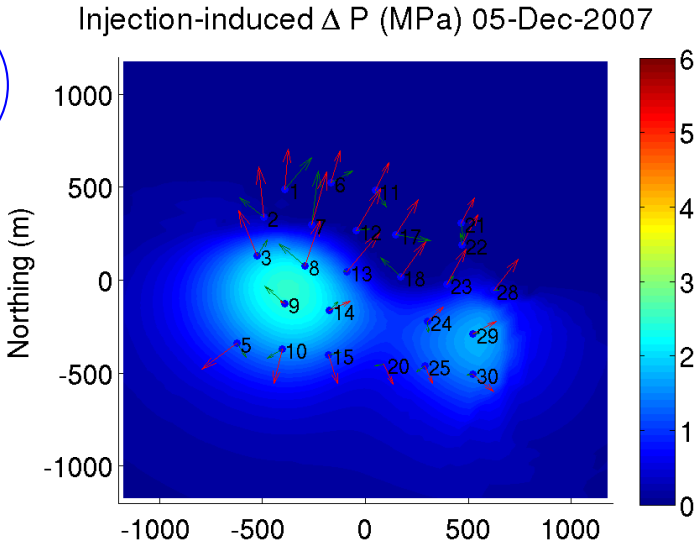

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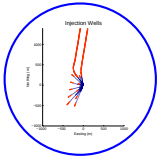

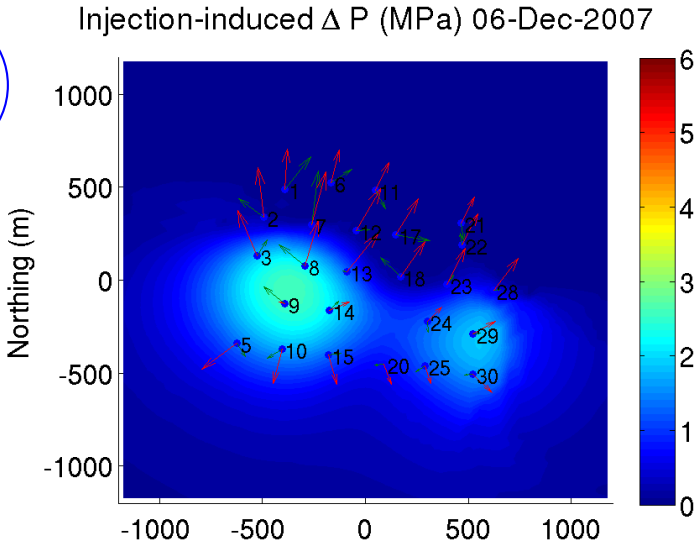

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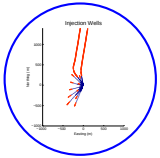
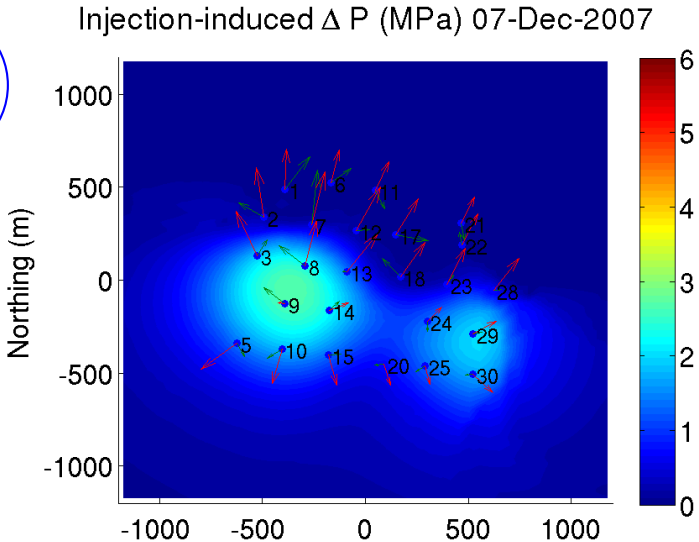
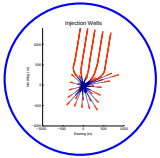
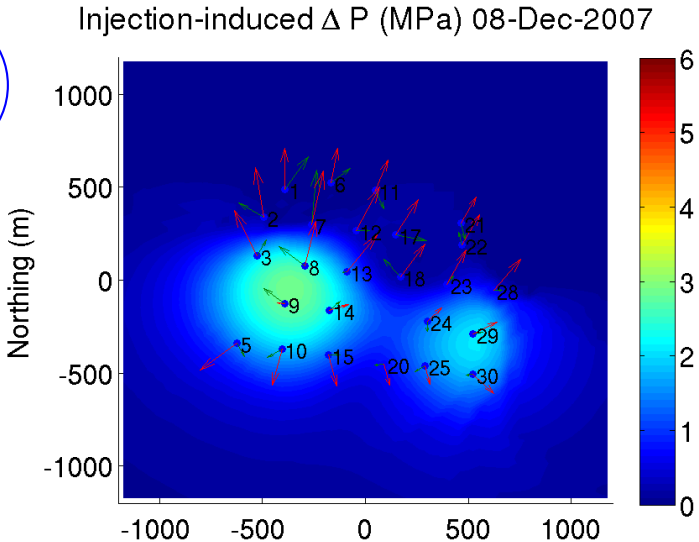


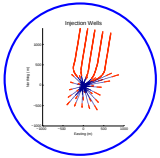


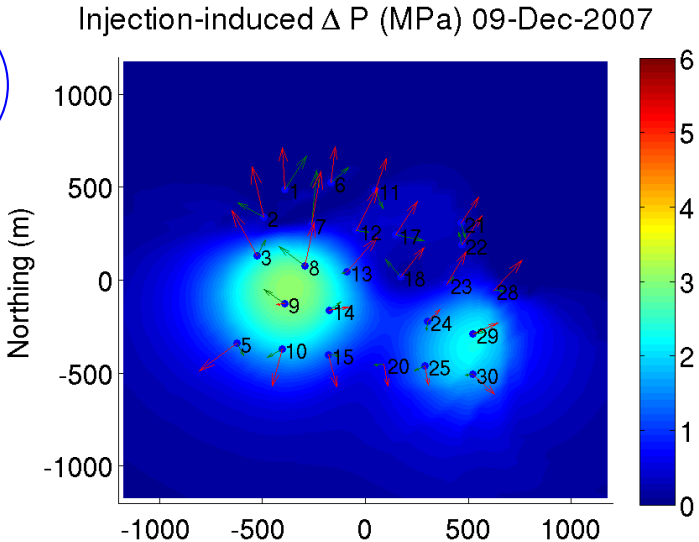
Inverted pore pressure change, $\epsilon = 10^{-3}$



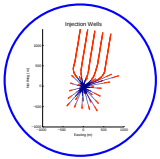


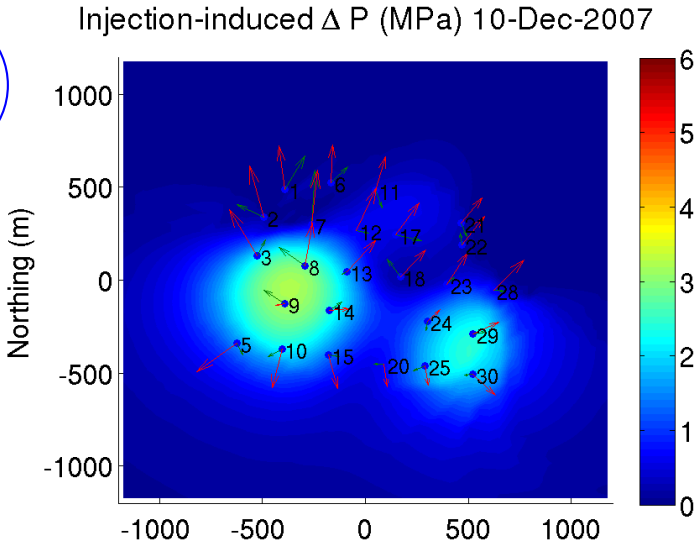
Inverted pore pressure change, $\epsilon = 10^{-3}$



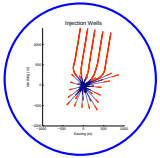


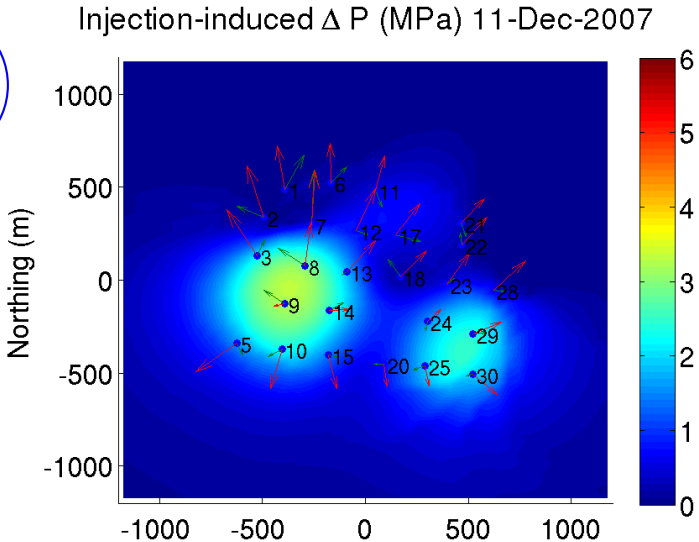
Inverted pore pressure change, $\epsilon = 10^{-3}$



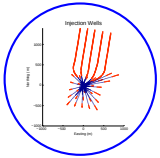


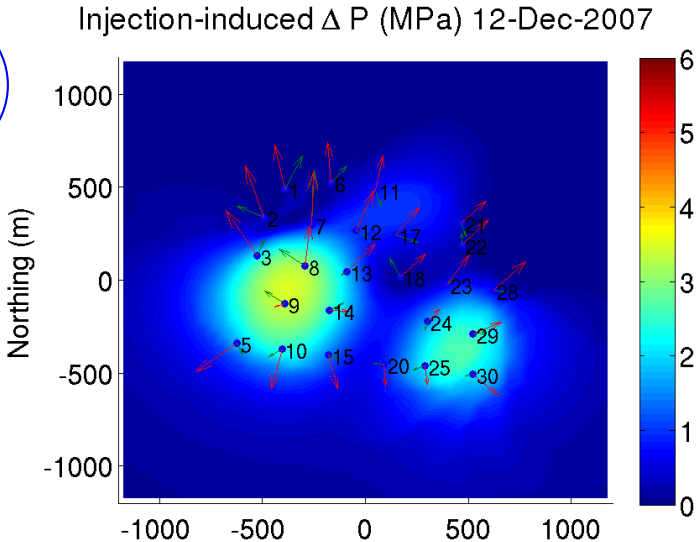
Inverted pore pressure change, $\epsilon = 10^{-3}$



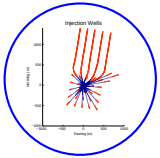


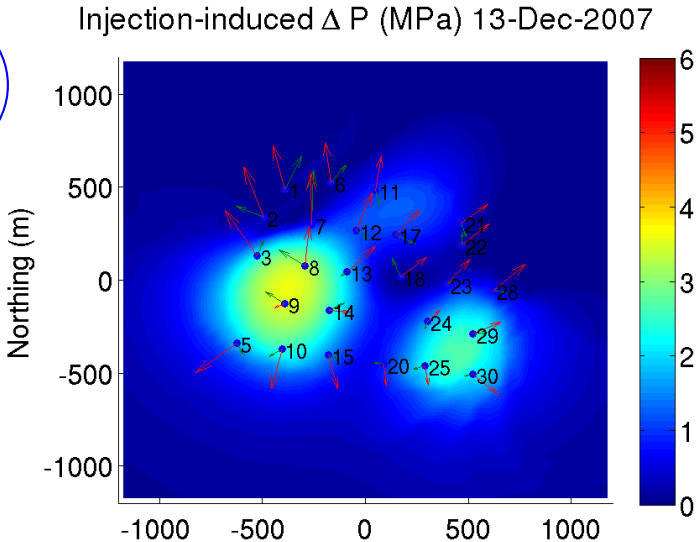
Inverted pore pressure change, $\epsilon = 10^{-3}$



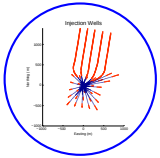


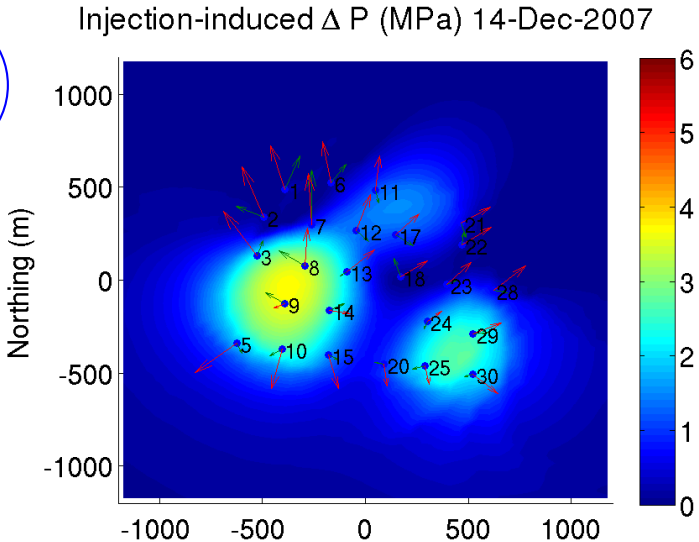
Inverted pore pressure change, $\epsilon = 10^{-3}$



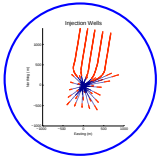


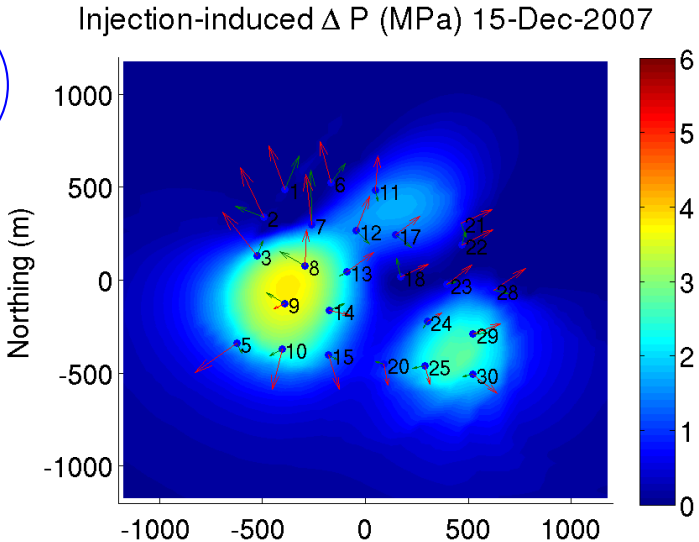
Inverted pore pressure change, $\epsilon = 10^{-3}$



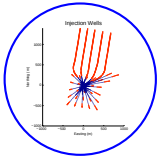


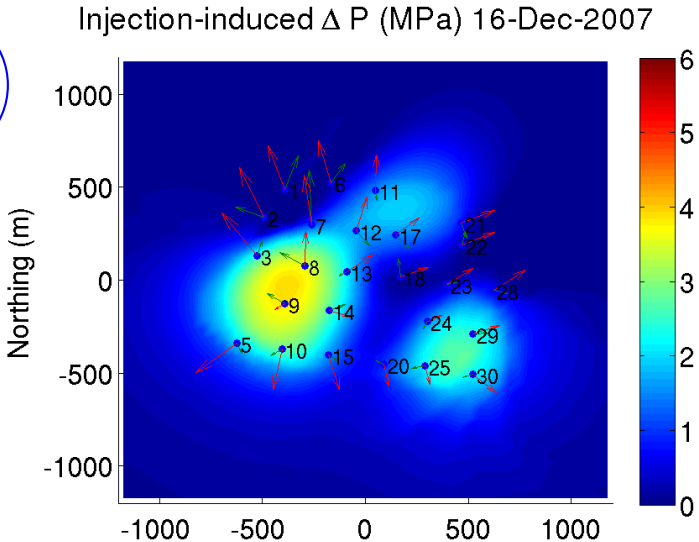
Inverted pore pressure change, $\epsilon = 10^{-3}$



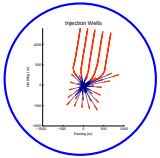


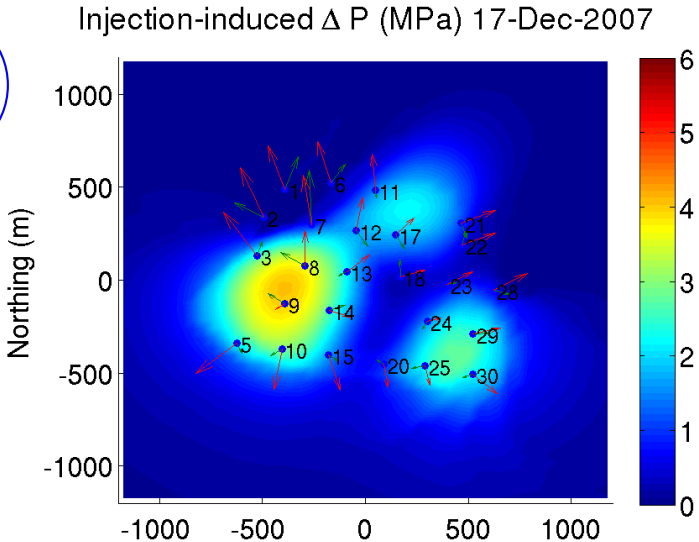
Inverted pore pressure change, $\epsilon = 10^{-3}$



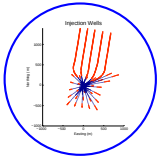


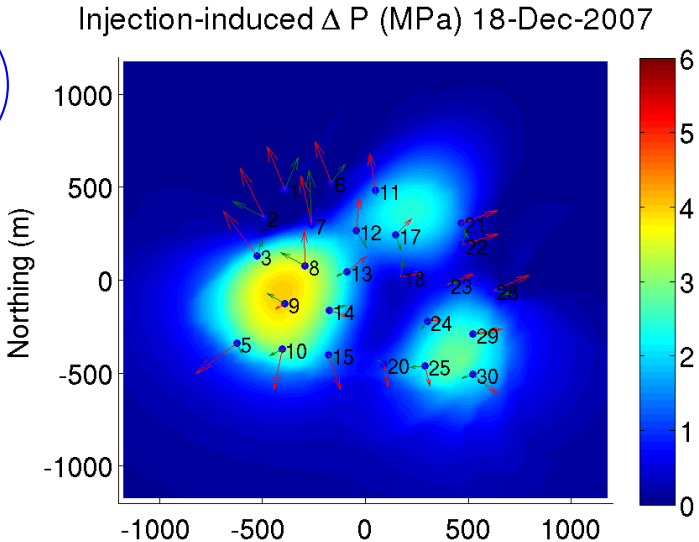
Inverted pore pressure change, $\epsilon = 10^{-3}$



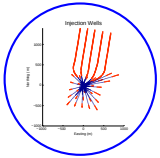


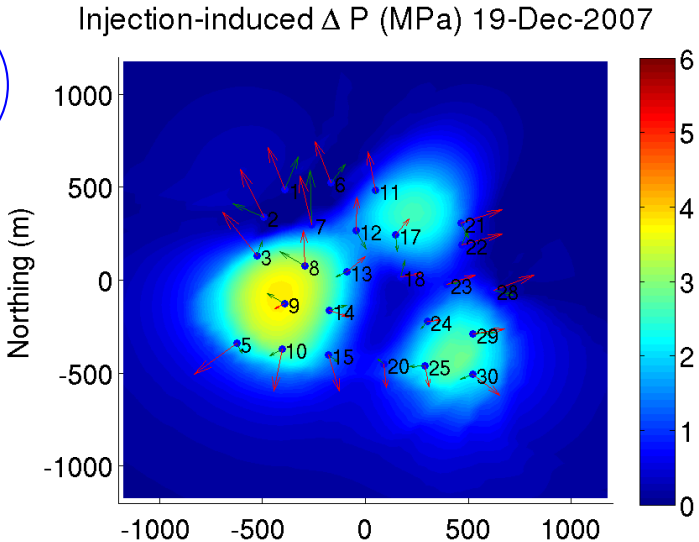
Inverted pore pressure change, $\epsilon = 10^{-3}$



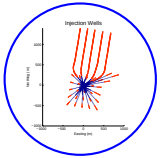


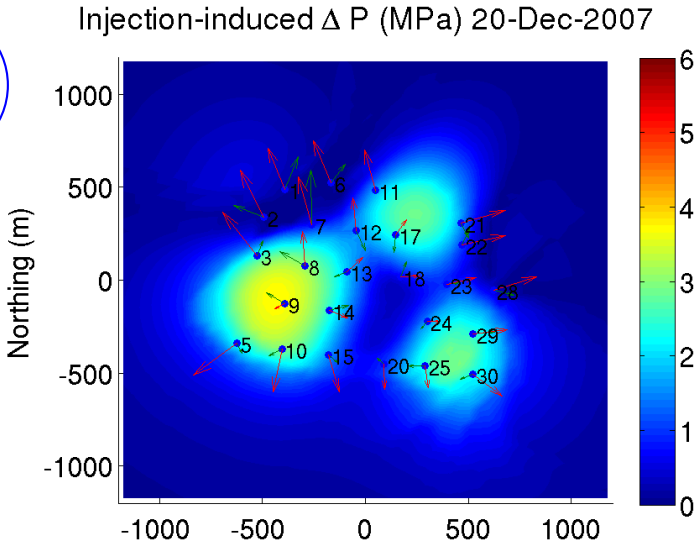
Inverted pore pressure change, $\epsilon = 10^{-3}$





Inverted pore pressure change, $\epsilon = 10^{-3}$





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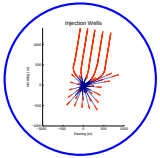
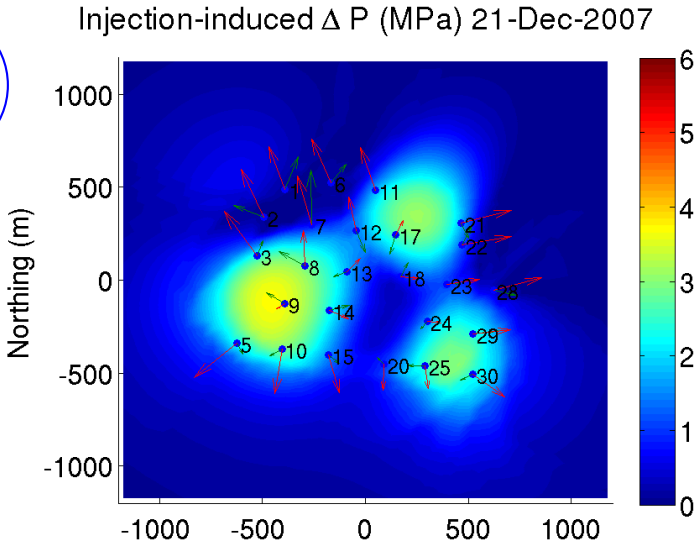
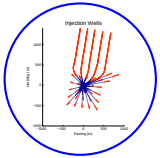
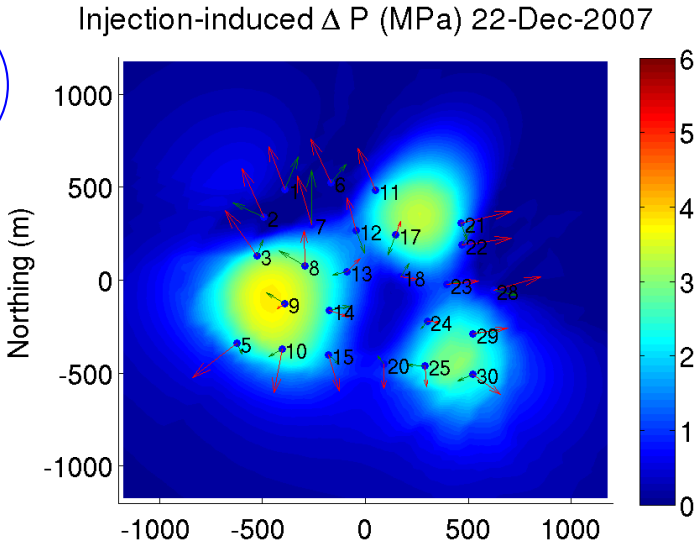


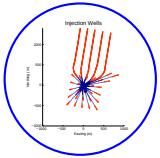


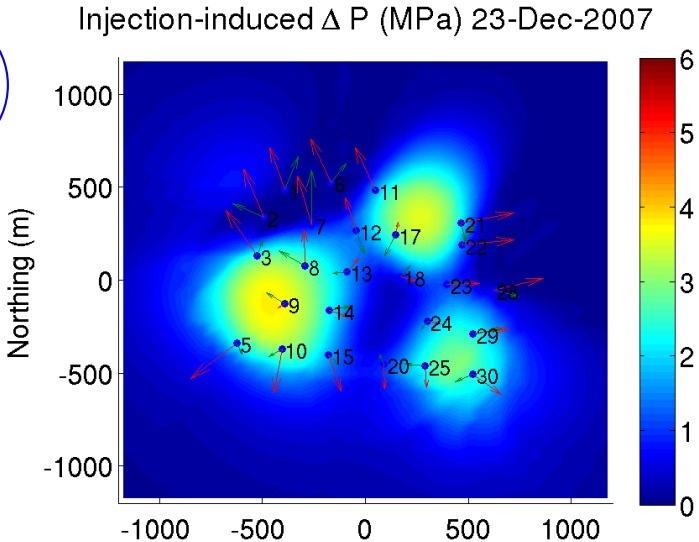
Inverted pore pressure change, $\epsilon = 10^{-3}$



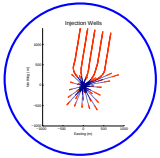


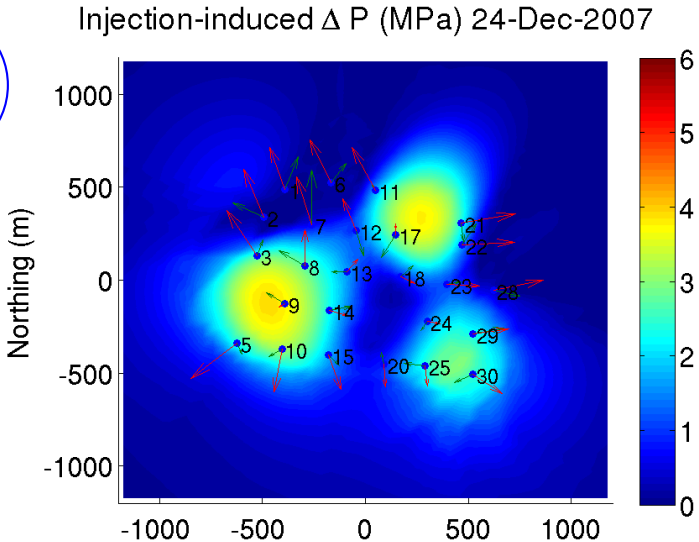
Inverted pore pressure change, $\epsilon = 10^{-3}$



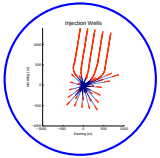


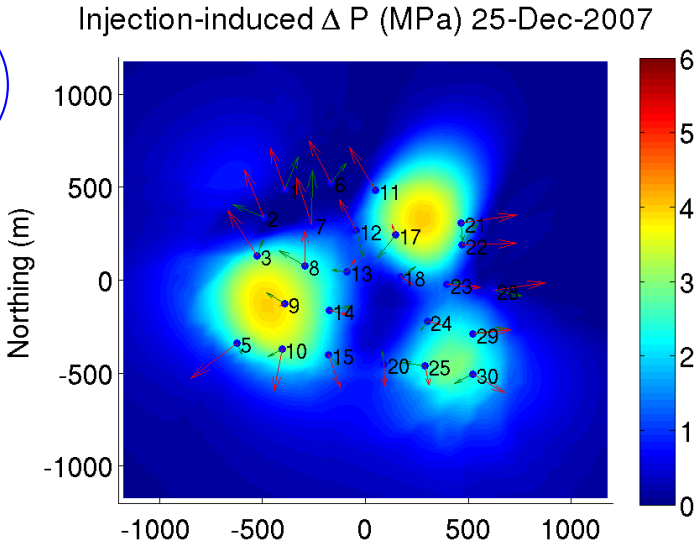
Inverted pore pressure change, $\epsilon = 10^{-3}$



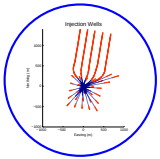


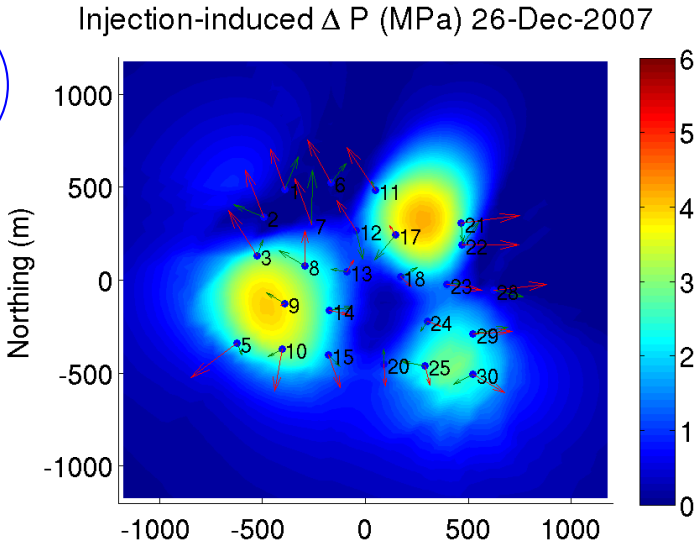
Inverted pore pressure change, $\epsilon = 10^{-3}$



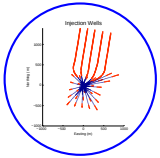


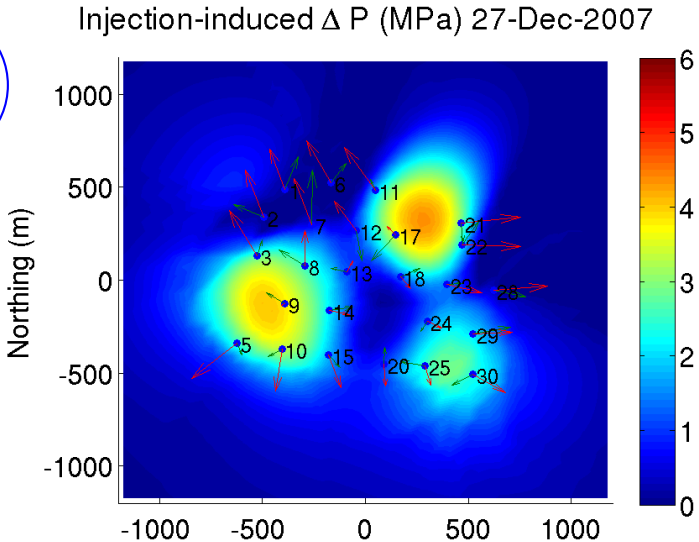
Inverted pore pressure change, $\epsilon = 10^{-3}$



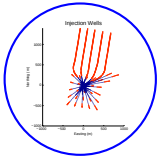


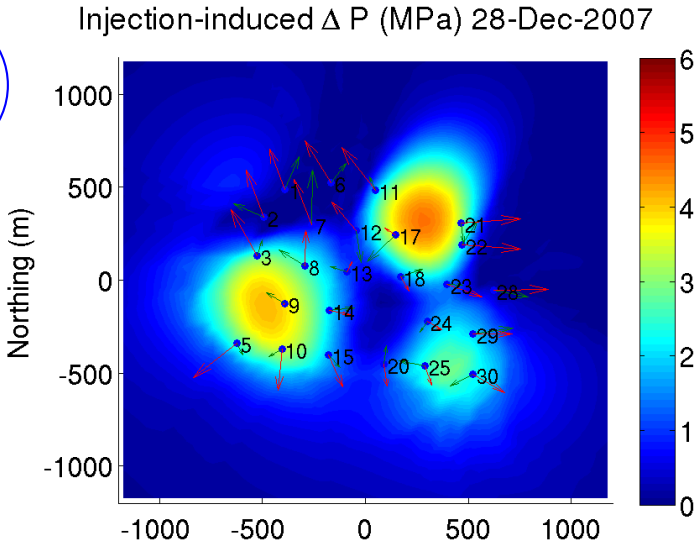
Inverted pore pressure change, $\epsilon = 10^{-3}$



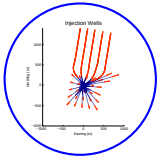


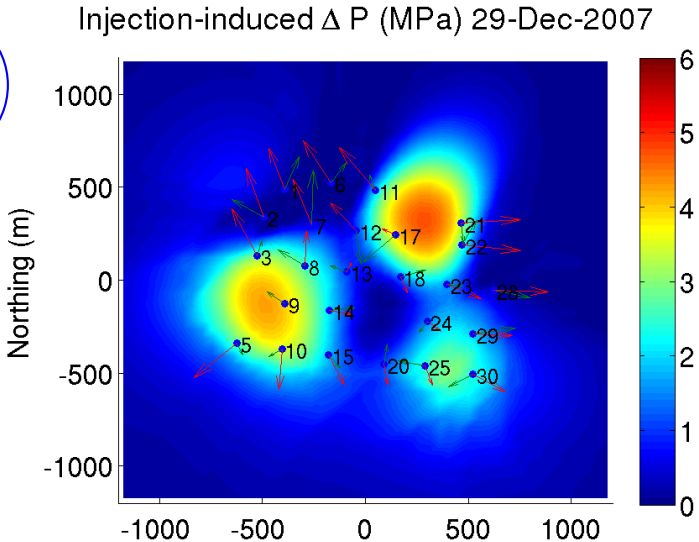
Inverted pore pressure change, $\epsilon = 10^{-3}$



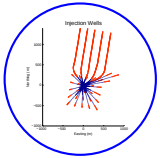


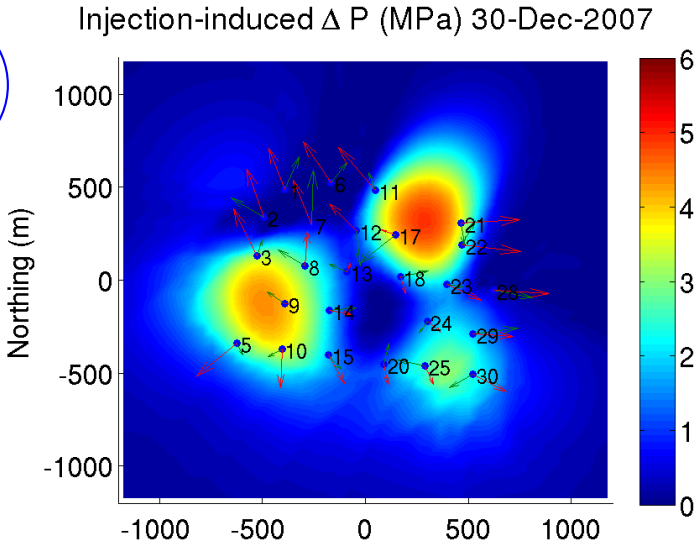
Inverted pore pressure change, $\epsilon = 10^{-3}$



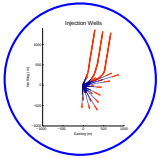


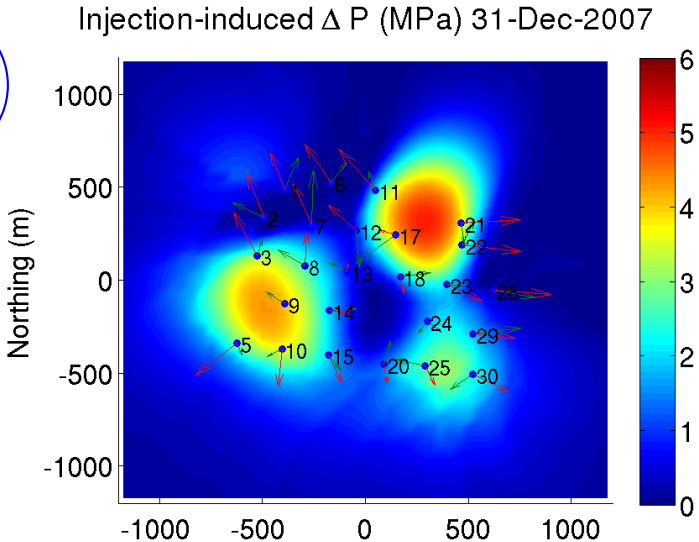
Inverted pore pressure change, $\epsilon = 10^{-3}$



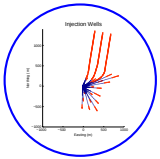


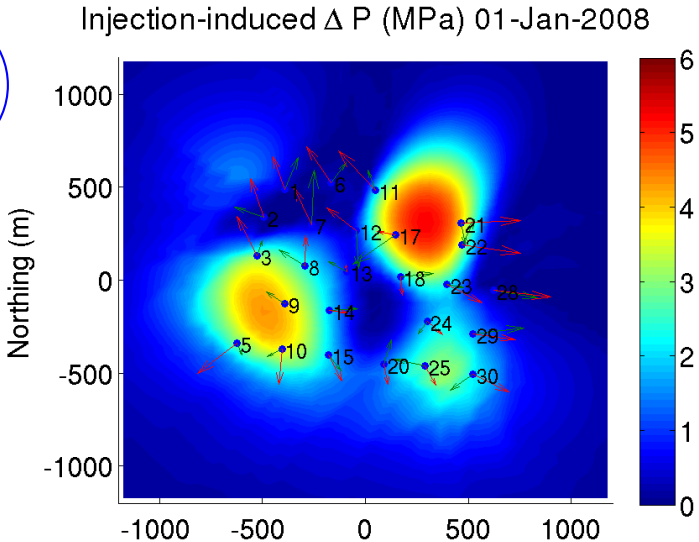
Inverted pore pressure change, $\epsilon = 10^{-3}$



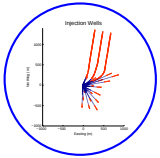


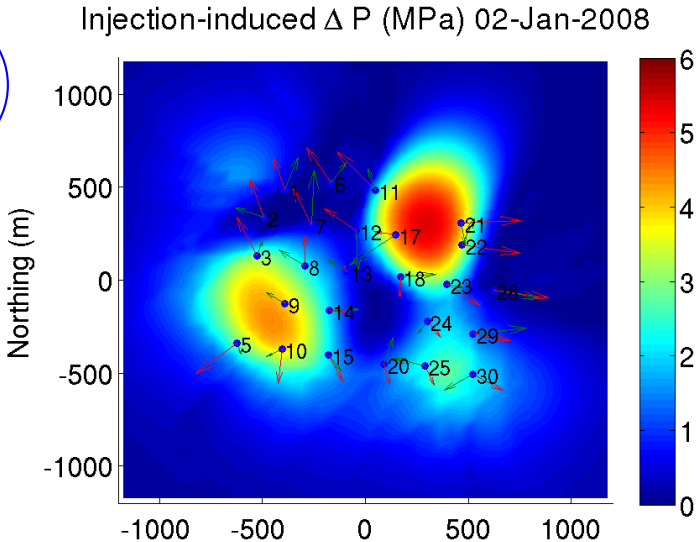
Inverted pore pressure change, $\epsilon = 10^{-3}$



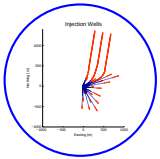


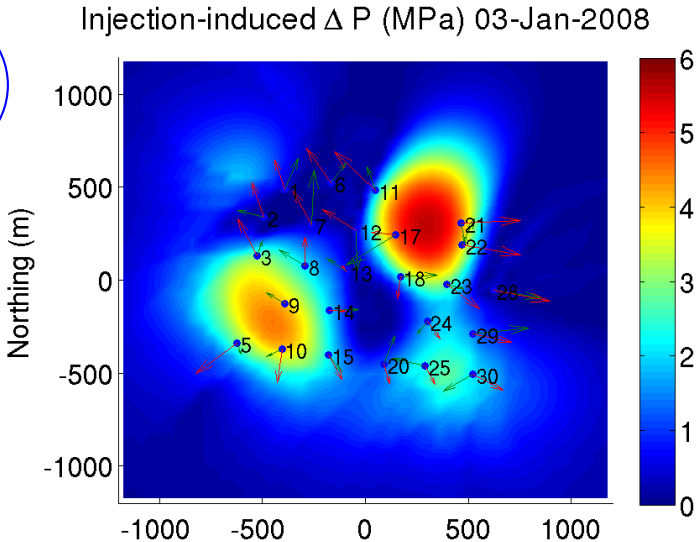
Inverted pore pressure change, $\epsilon = 10^{-3}$



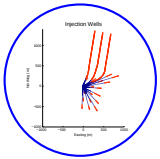


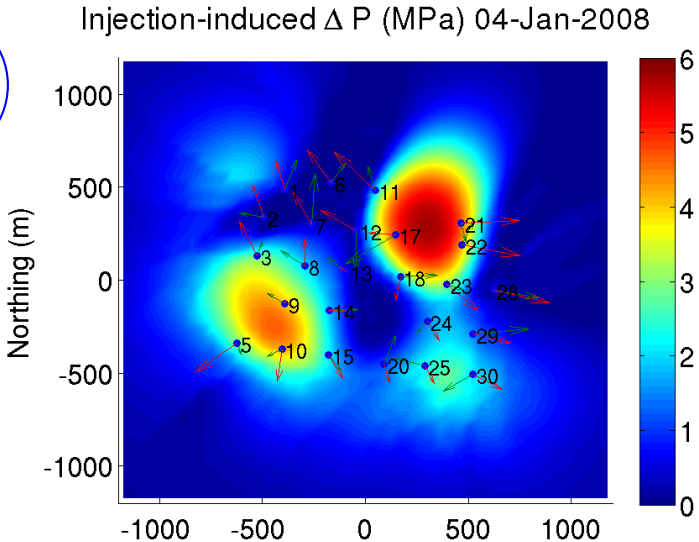
Inverted pore pressure change, $\epsilon = 10^{-3}$



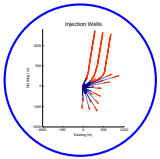


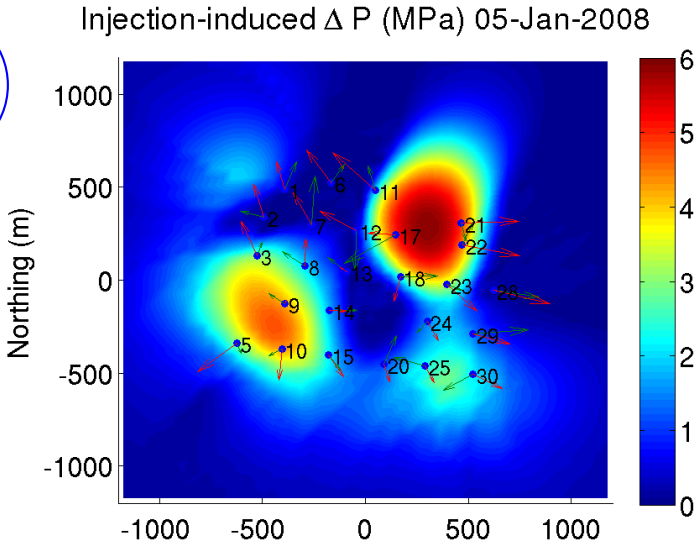
Inverted pore pressure change, $\epsilon = 10^{-3}$



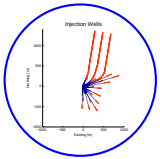


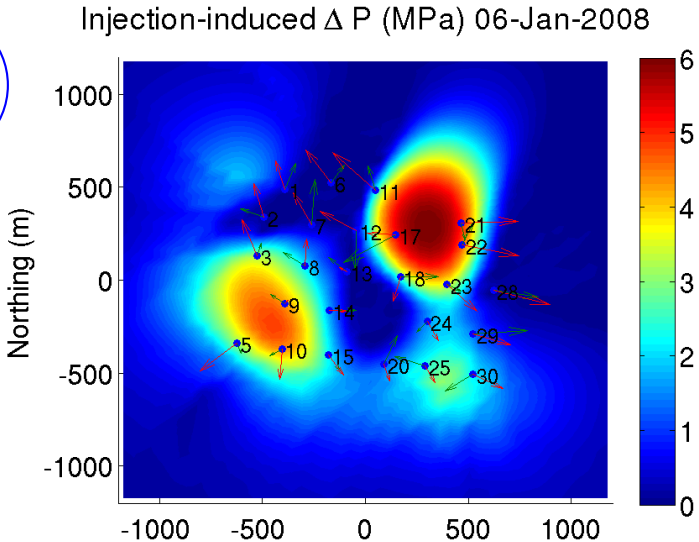
Inverted pore pressure change, $\epsilon = 10^{-3}$



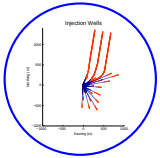


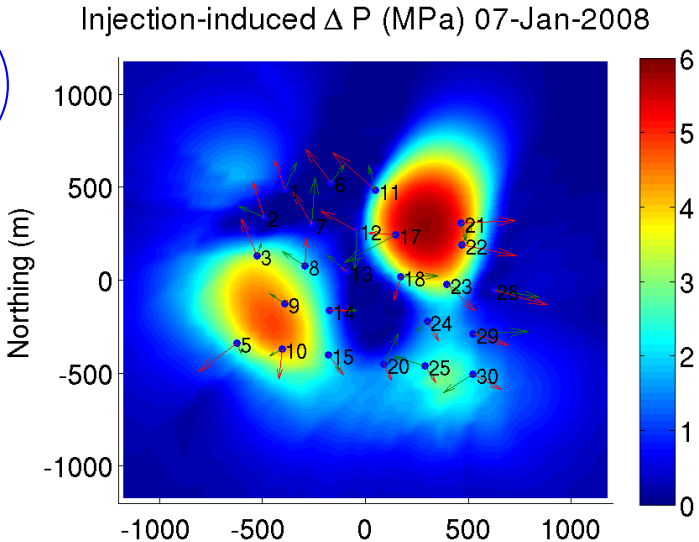
Inverted pore pressure change, $\epsilon = 10^{-3}$



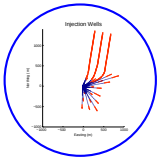


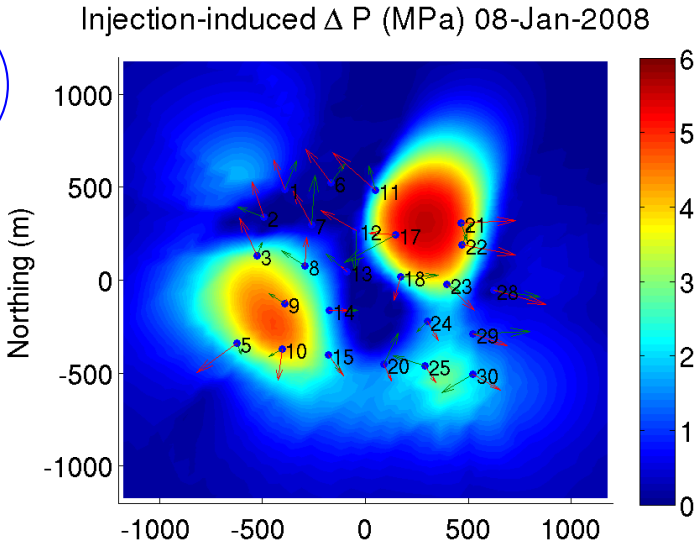
Inverted pore pressure change, $\epsilon = 10^{-3}$



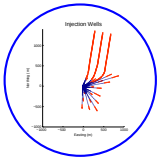


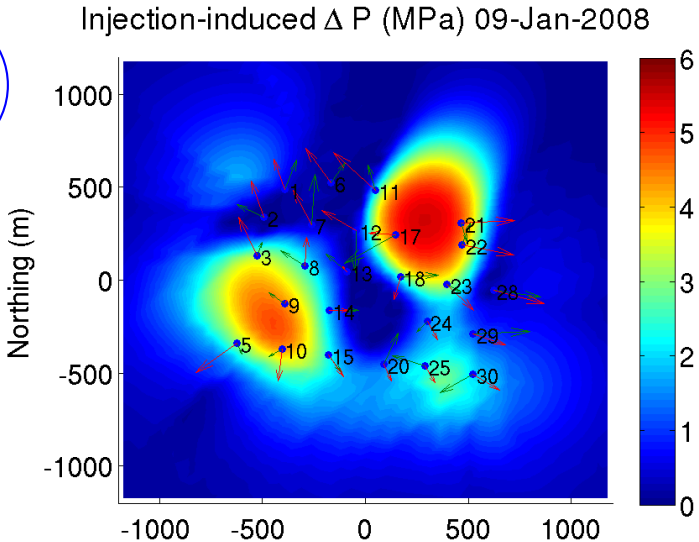
Inverted pore pressure change, $\epsilon = 10^{-3}$



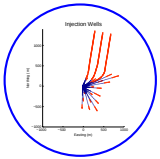


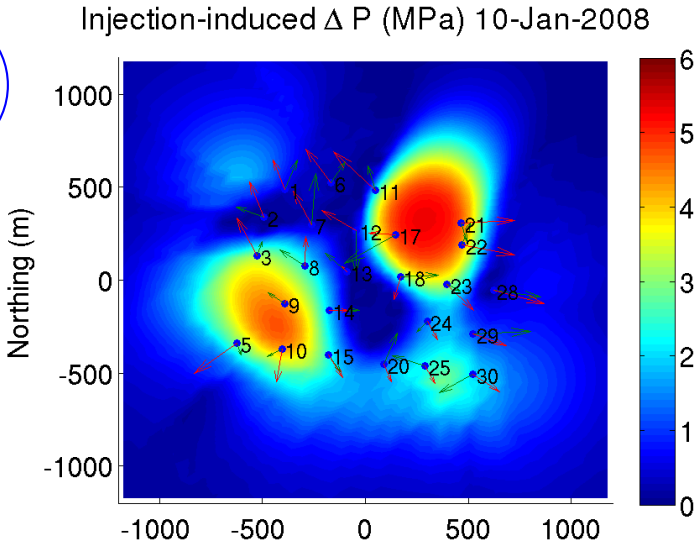
Inverted pore pressure change, $\epsilon = 10^{-3}$



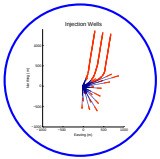


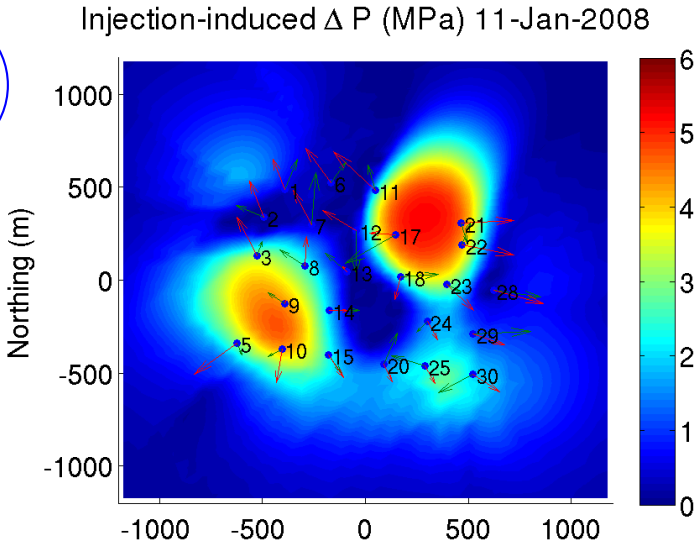
Inverted pore pressure change, $\epsilon = 10^{-3}$



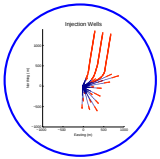


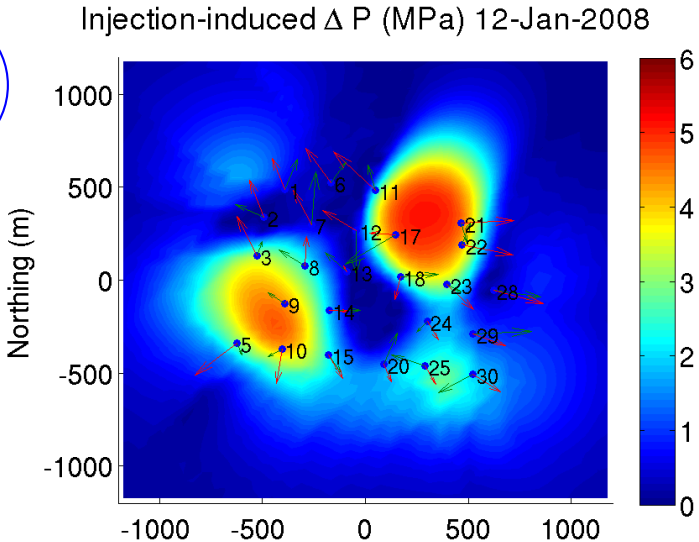
Inverted pore pressure change, $\epsilon = 10^{-3}$



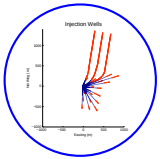


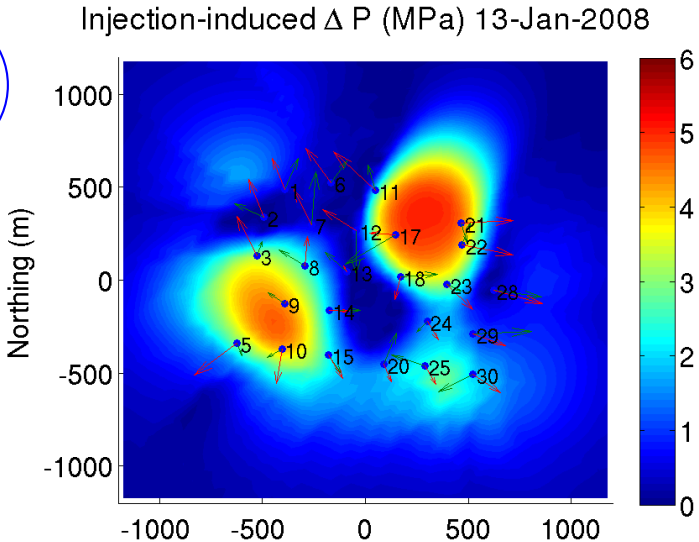
Inverted pore pressure change, $\epsilon = 10^{-3}$



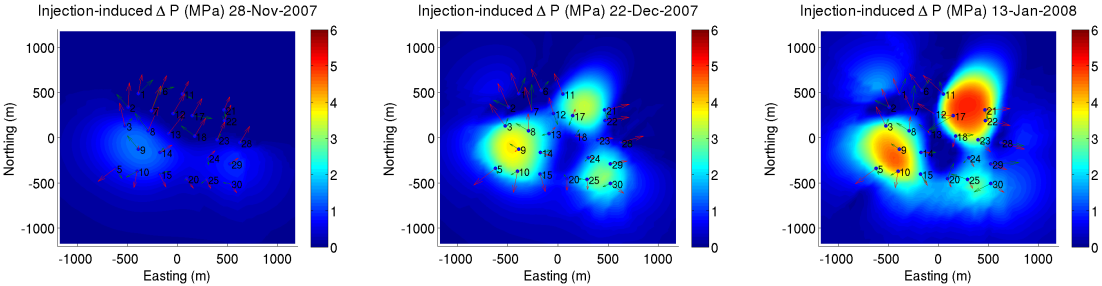


Inverted pore pressure change, $\epsilon = 10^{-3}$

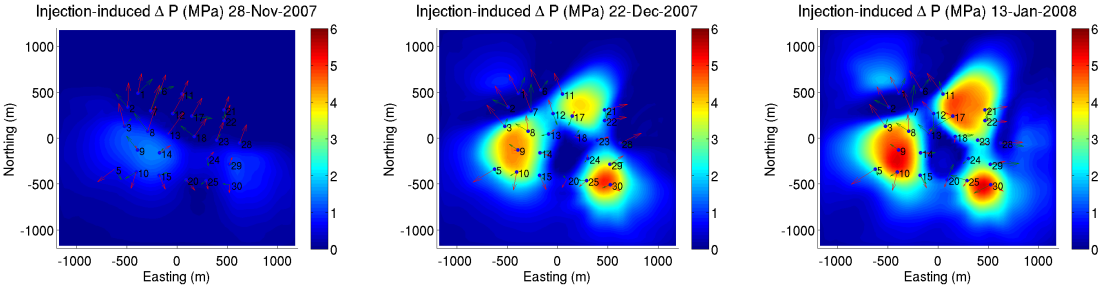




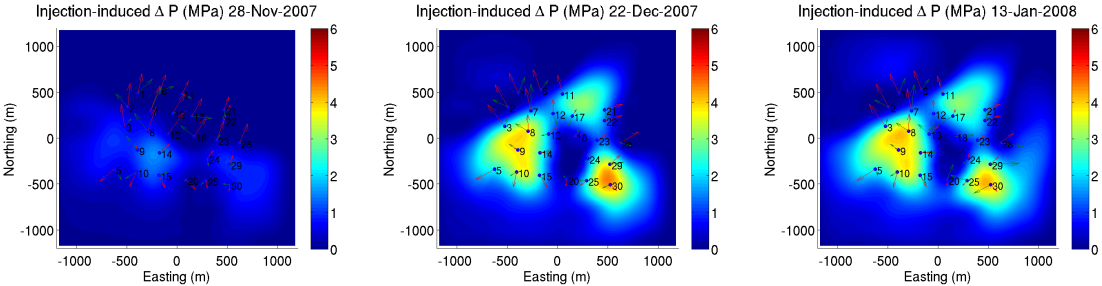
Stability with respect to regularization, $\epsilon = 10^{-3}$



Stability with respect to regularization, $\epsilon = 5 \times 10^{-3}$



Stability with respect to regularization, $\epsilon = 10^{-2}$



Resolving sharp pressure contrasts

NEW (SEP158, pp 271-278): **resolving sharp pressure contrasts**
(methodology and a synthetic example)

Boundary-preserving inversion

Achieve better resolution of subsurface heterogeneities (e.g, **permeability barriers**) by using $\boxed{\text{edge-preserving total-variation}}$ regularization:

$$\|\mathbf{A}p - \mathbf{u}\|_{L_2}^2 \; + \; \boxed{\epsilon \|\nabla \mathbf{p}\|_{L_1}} \; \rightarrow \; \min, \qquad \text{(BOUNDTVREG)}$$
$$p_1 \; \leq \; p \; \leq \; p_2.$$

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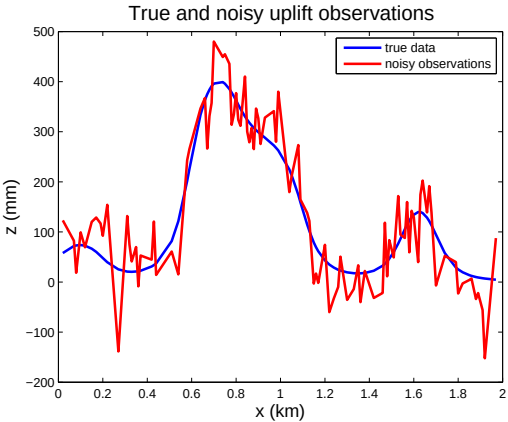
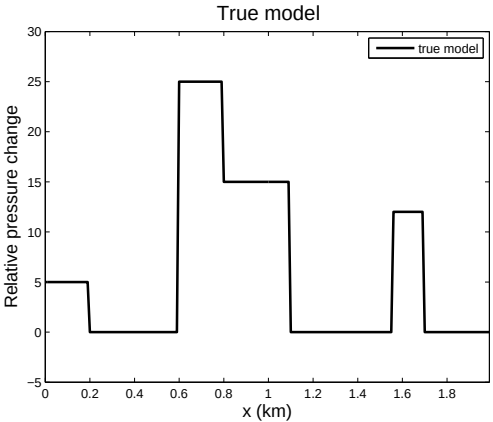
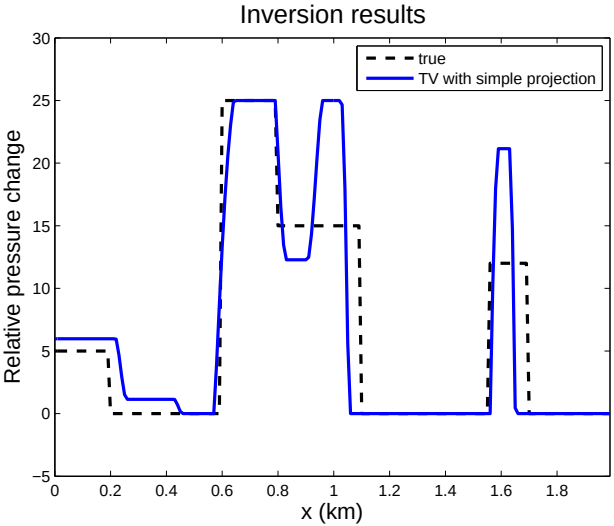
Resolving sharp pressure contrasts

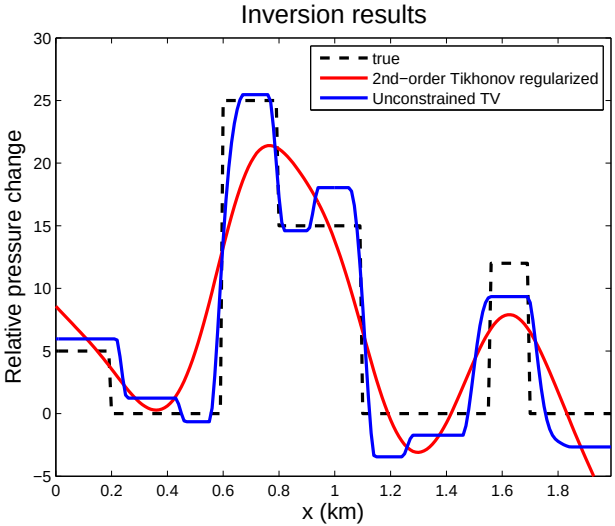




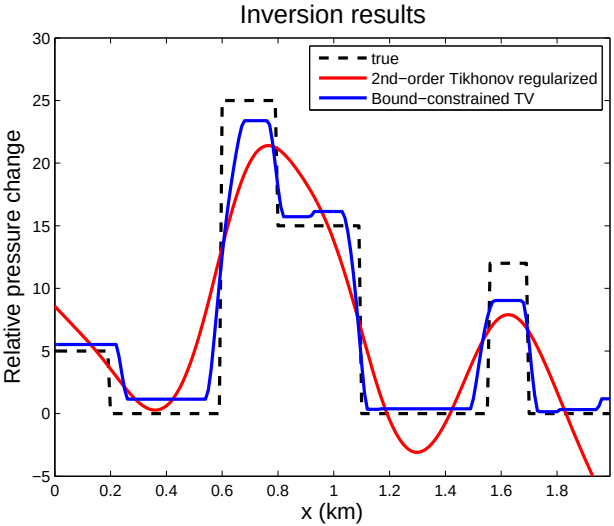
Naive constrained inversion—false contrasts



Unconstrained inversion—false contrasts and violated bounds



New constrained inversion



Conclusions and perspectives

1. Can estimate pressure front evolution from surface deformation
2. "Wormholes" (Hinkle and Batzle, 2006) and fluid-conducting faults require a different treatment
3. Not limited to directly measurable deformation; e.g., can estimate induced deformation from time-lapse (Hodgson, 2007)

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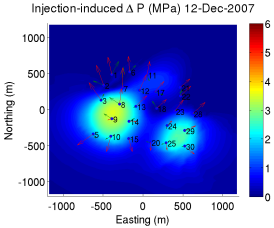
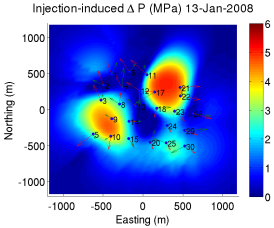
4. **SEP158 synthetic:** TV-regularization with bound constraints $\Rightarrow$ location of **sharp** pressure contrasts

Acknowledgements

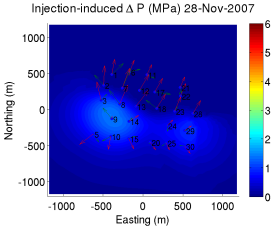
The authors thank **Biondo Biondi** and **Randi Walters** for a number of useful discussions

Q&A


Injection-induced Δ P (MPa) 12-Dec-2007
Northing (m)
Easting (m)


Injection-induced Δ P (MPa) 13-Jan-2008
Northing (m)
Easting (m)

Q&A


Injection-induced Δ P (MPa) 28-Nov-2007
Northing (m)
Easting (m)

Appendices – discussion slides

Heavy Oil Sands, from Mossop (1979)