# Towards coupled flow-geomechanical data assimilation

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with contributions of Antonis Mavritsakis, Irene Platteeuw, Karlijn Beers, Denis Voskov, Phil Vardon, Ramon Hanssen

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# Agenda

- Introduction to subsidence: cause and effect
- Modeling subsidence: flow and geomechanics
- Assimilation to reconstruct subsurface processes
- Ongoing work and preliminary results
- Conclusions and Outlook

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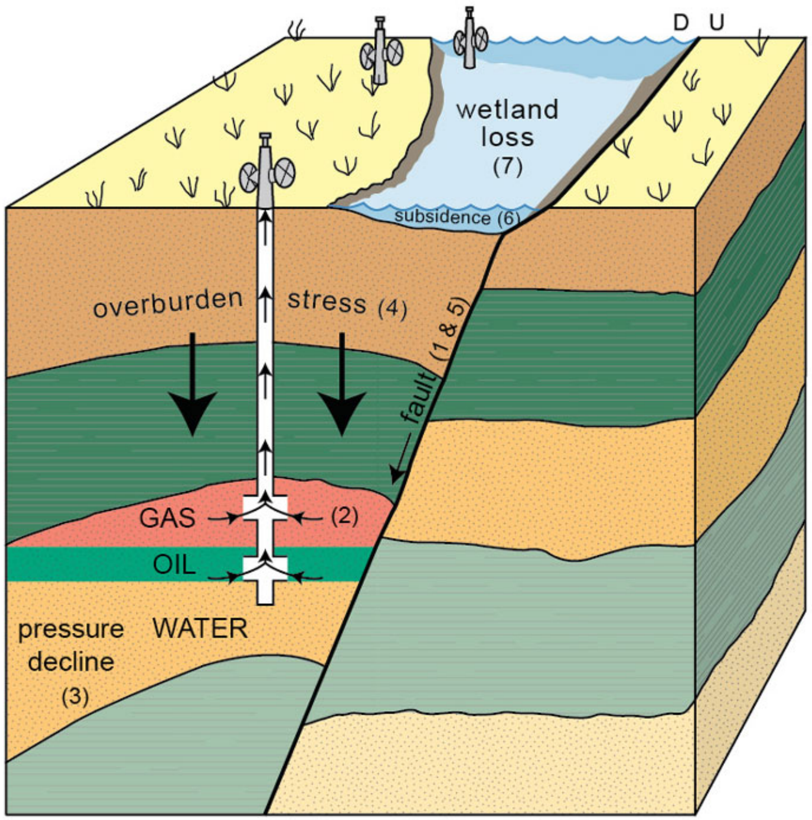
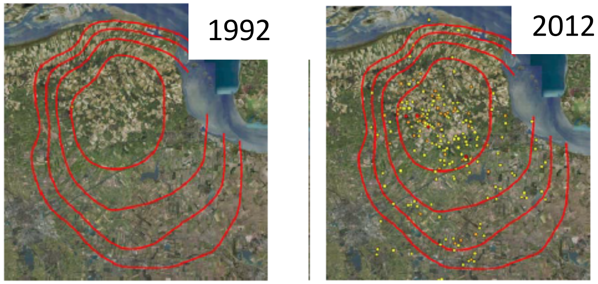
# Subsidence: cause and effect

## Examples of subsidence




1. Louisiana wetlands: fault activation
*(USGS)*

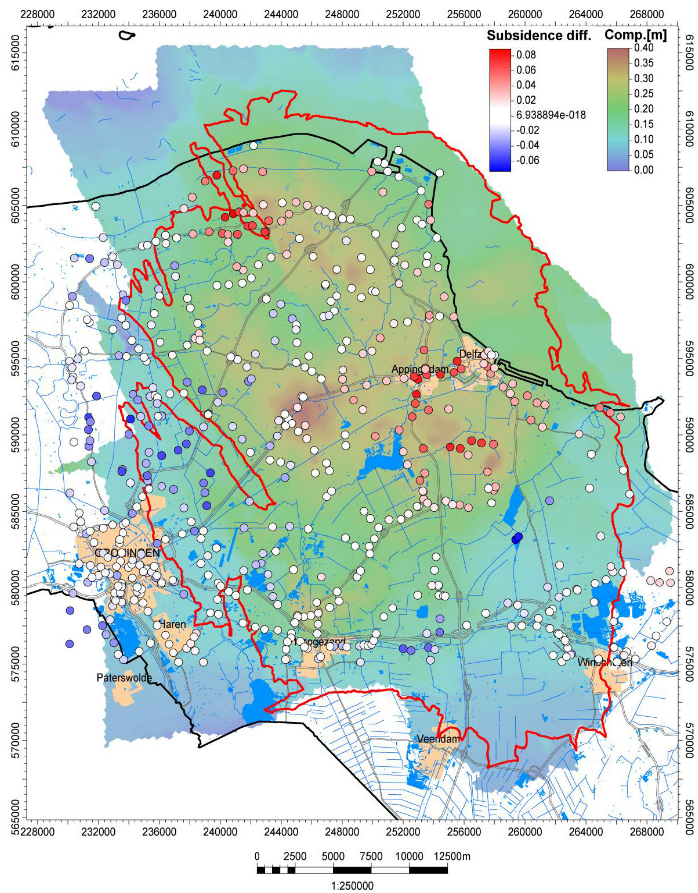



3. Groningen: seismic effects
*(NAM)*

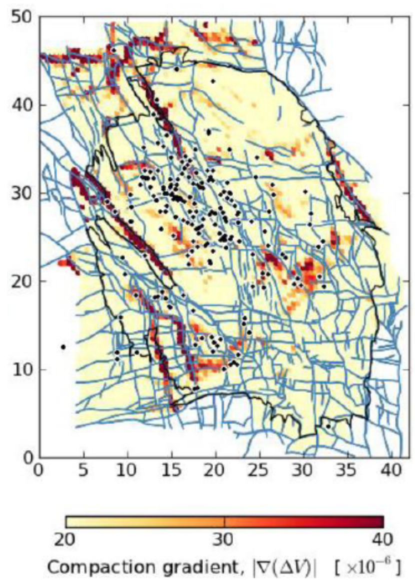
2. Venice: mixed effect of groundwater and gas extraction

# Subsidence, induced seismicity

- Subsidence to first order related to pressure drop in reservoir (e.g. Geertsma, 1963)
- Relation with induced and natural seismicity poorly understood, for example in Groningen, San Jacinto, Basel.



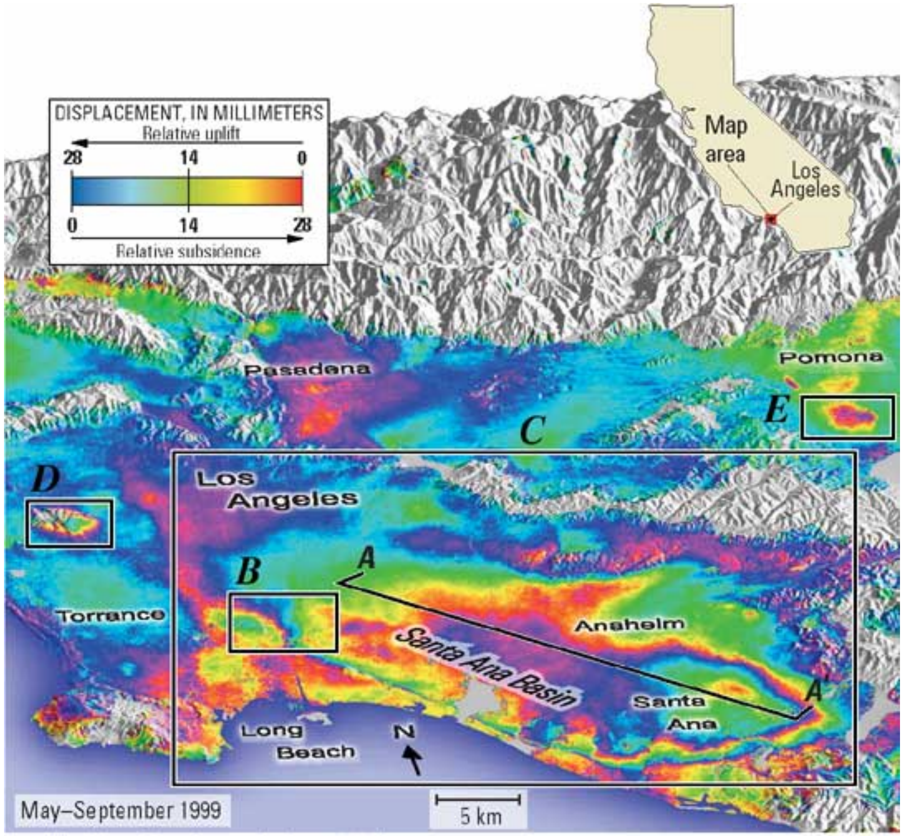

Difference between calculated and modeled subsidence indicated at benchmark locations.
*Van Thienen-Visser et al (2015)*




*Bourne et al (2014)*

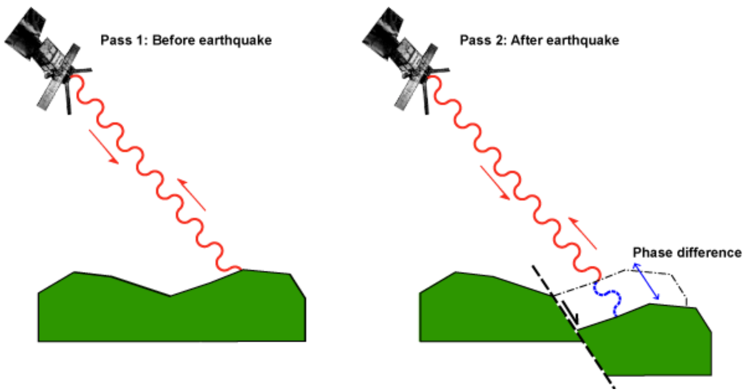
# Geodetic monitoring

- Subsidence can be observed with satellites (InSAR, GPS) as well as in situ techniques (levelling)

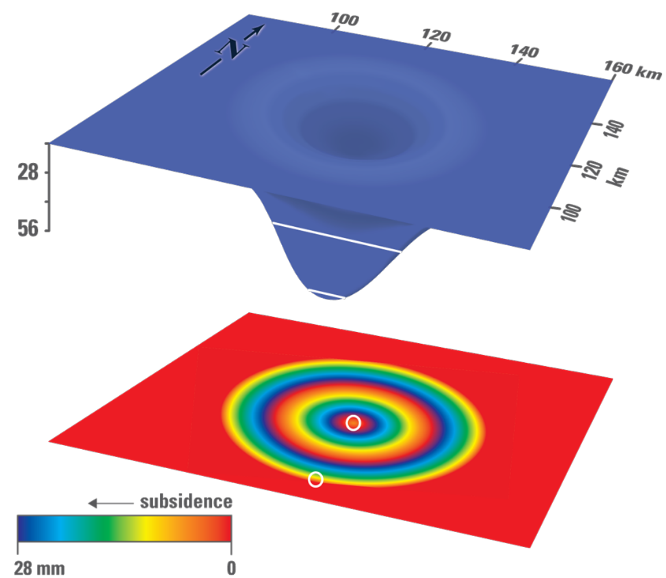



(modified from Bawden and others, 2001)

*Fact sheet USGS*




*http://comet.earth.ox.ac.uk/for_schools_radar4.html*

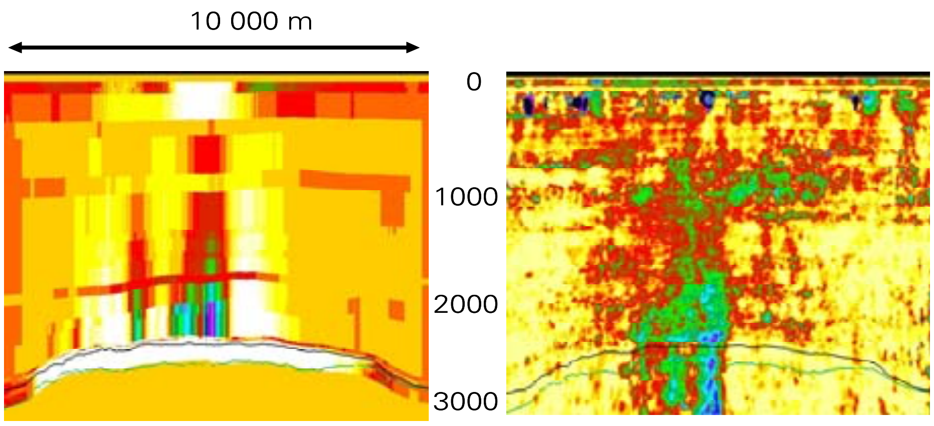



*https://ca.water.usgs.gov/land_subsidence/california-subsidence-measuring.html*

# Subsurface monitoring

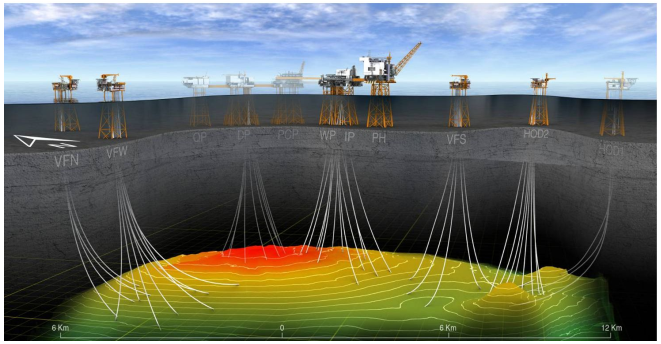
- Surface data on subsidence can be complemented by subsurface data from wells (bottom hole pressure, rates) as well as seismic

4D Seismic



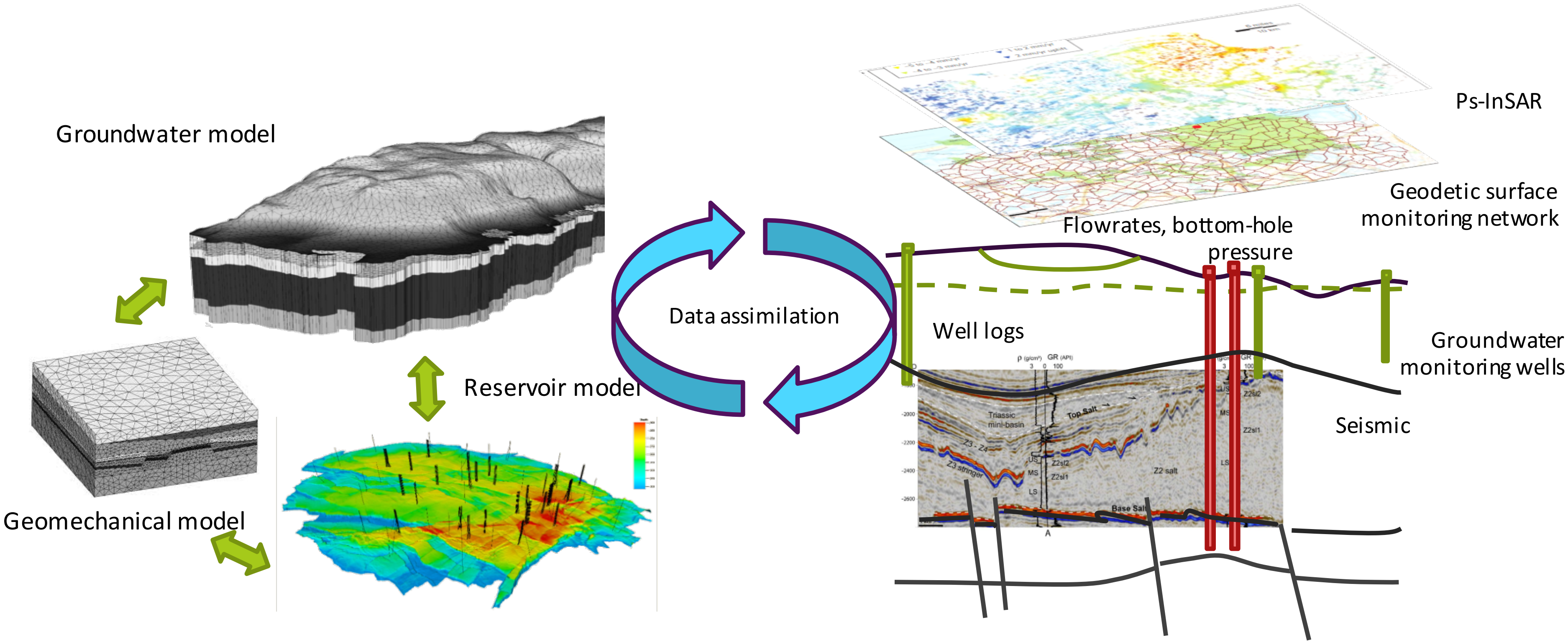

Valhall: Changes in volumetric strain 1992-2002 (left) and time shift from seismic data (right) *Barkved et al (2005)*

Production rates and pressure



Artist impression Valhall field, including wells
*http://offshoreenergytoday.com*

# Parameter estimation and data assimilation




- Integrated approach, focusing on three aspects:
  - Data: sparse subsurface, high resolution surface data
  - Model: coupled reservoir/geomechanics
  - Data assimilation method: non-linear physics

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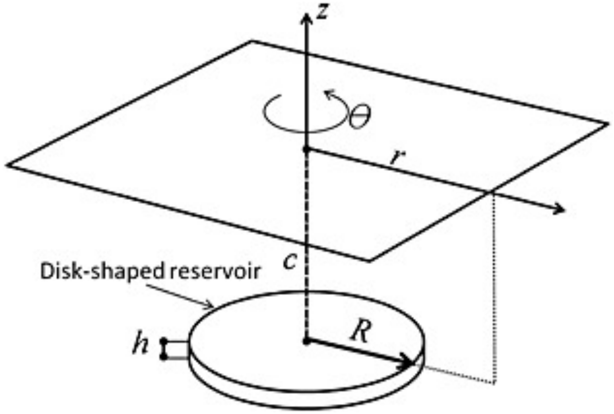
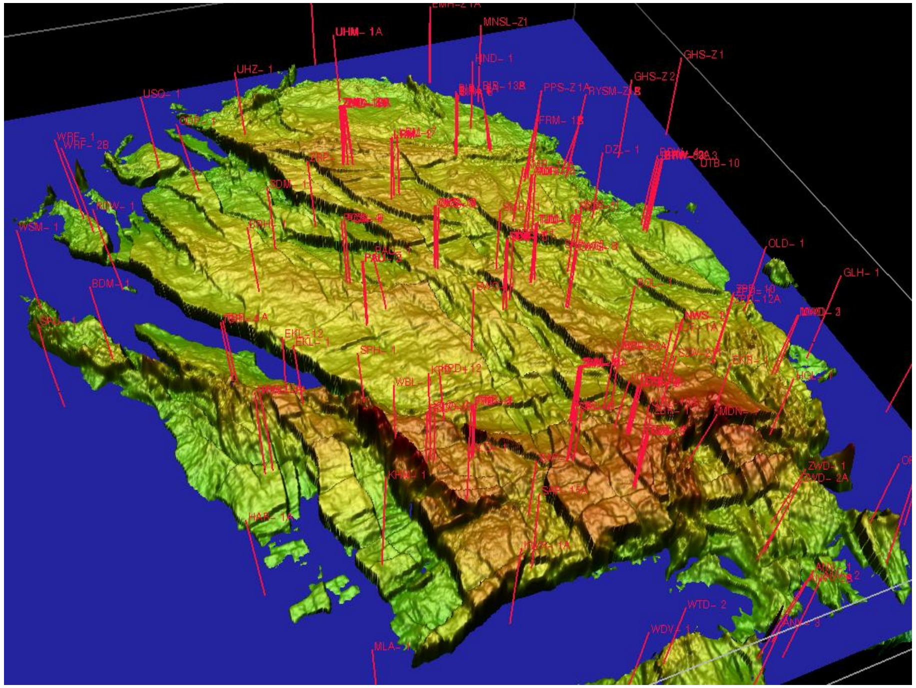
# Modelling subsidence: reservoir compaction

- Subsidence is typically modelled based on a compaction model of a disk-shaped reservoir, using Geertsma's analytical solution (1963), in combination with a time-dependent pressure distribution from a multi-layer reservoir model.




*Bau (2014), after Geertsma (1963)*

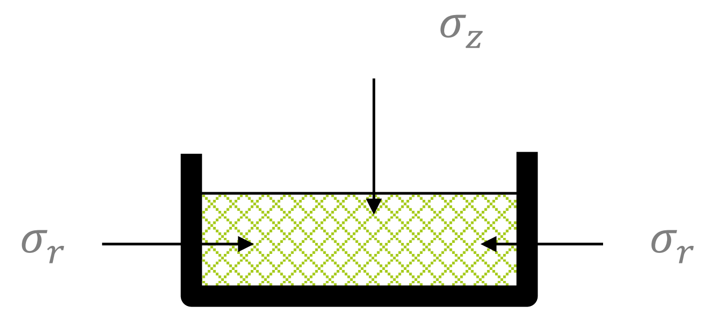


Groningen reservoir model
*Mmax workshop March 2016, http://feitenencijfers.namplatform.nl*

- Reservoir models can have various levels of complexity. Including known and less well known geological features.

# Geomechanical modelling of compaction (1)

- Geertsma's subsidence model: uniaxial compaction with effective stress resulting from pressure difference




Oedometer

$\sigma_x = \sigma_y = \sigma_r$ : radial/lateral stress

$\epsilon = \epsilon_y = \epsilon_r = 0$ : radial/lateral strain (laterally confined)

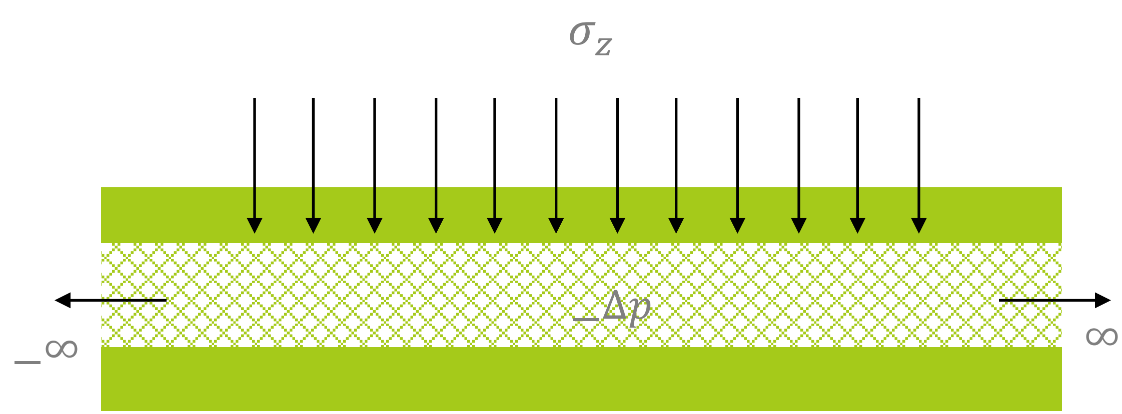
$$-\Delta p = \Delta\sigma' = \Delta\sigma_z' + 2\,\Delta\sigma_r{}'$$

$$\epsilon_z = \frac{(1-2\nu)(1+\nu)}{E(1-\nu)}\Delta\sigma_z'$$

Or

$$\epsilon_z = C_m \Delta\sigma_z'$$

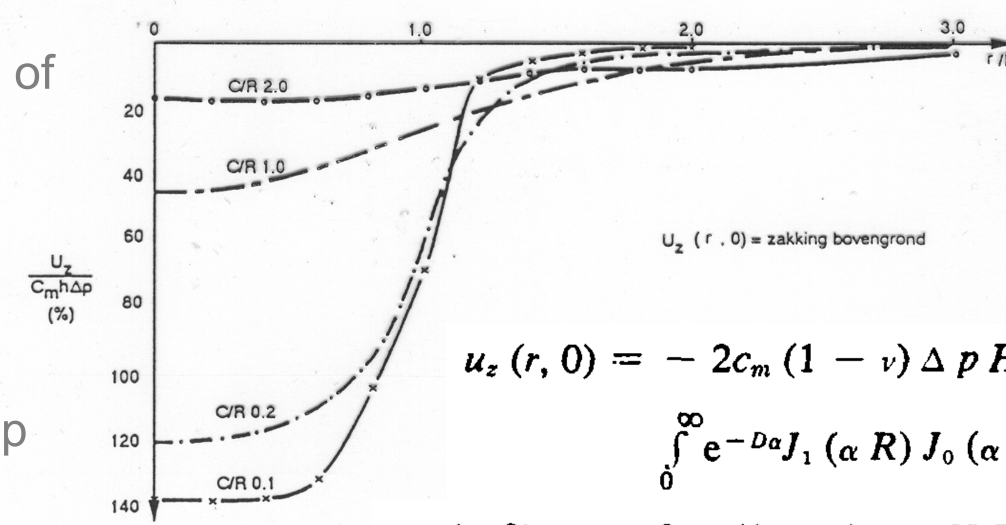
With $\Delta\sigma_z' = \Delta p$




Confined reservoir layer

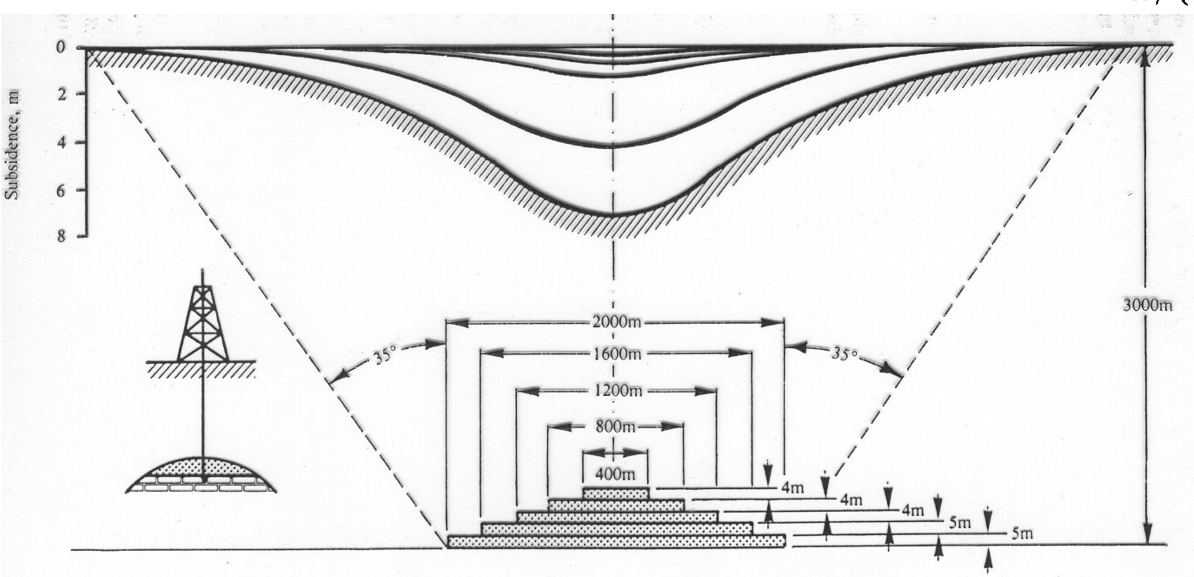
# Geomechanical modelling of compaction (2)

- Geertsma's model provides a good first-oder approximation of compaction and associated subsidence when assuming elastic behavior of the subsurface.
- How does subsidence develop over time?



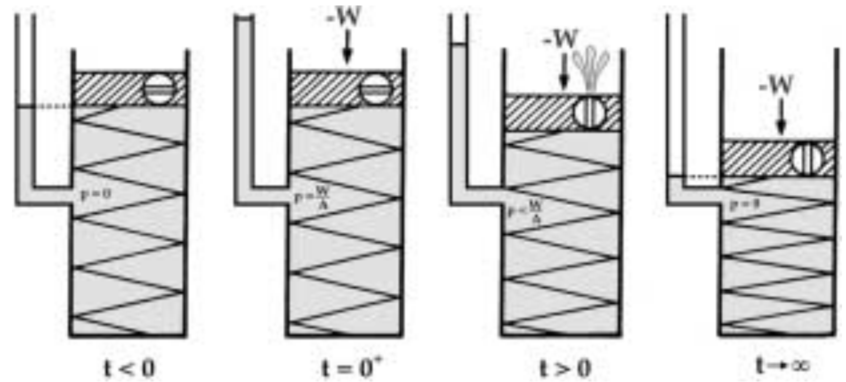

$$u_z(r,0) = -2c_m(1-\nu)\,\Delta p\,H\,R \int_0^\infty e^{-D\alpha} J_1(\alpha R)\, J_0(\alpha r)\, d\alpha$$

$$u_r(r,0) = +2c_m(1-\nu)\,\Delta p\,H\,R \int_0^\infty e^{-D\alpha} J_1(\alpha R)\, J_1(\alpha r)\, d\alpha$$

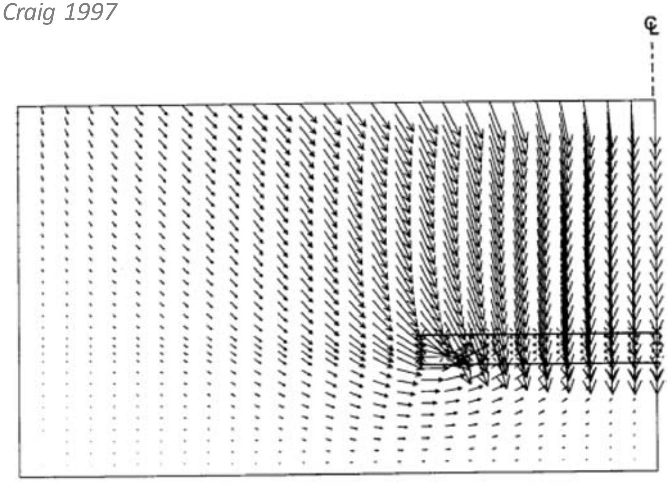


# Geomechanical modelling of compaction (3)

- Reservoir compaction can be considered as a consolidation process: axial load is initially borne by fluid, and then shifted to skeletal frame (Terzaghi)
- Compaction is not only affected by pore pressure, but also by boundary conditions, and total stress change: coupling of flow and geomechanics required




Terzaghi's uniaxially constrained soil consolidation,
*Craig 1997*



Coupled simulation of compacting disk
*Lewis & Pao, 2003*

# Generic model of coupled flow-geomechanics

**Flow** model, with governing equations:

Conversation of mass and Darcy's law, estimating pressure, saturation, flow, (possibly including energy and thermodynamic phase equilibrium)

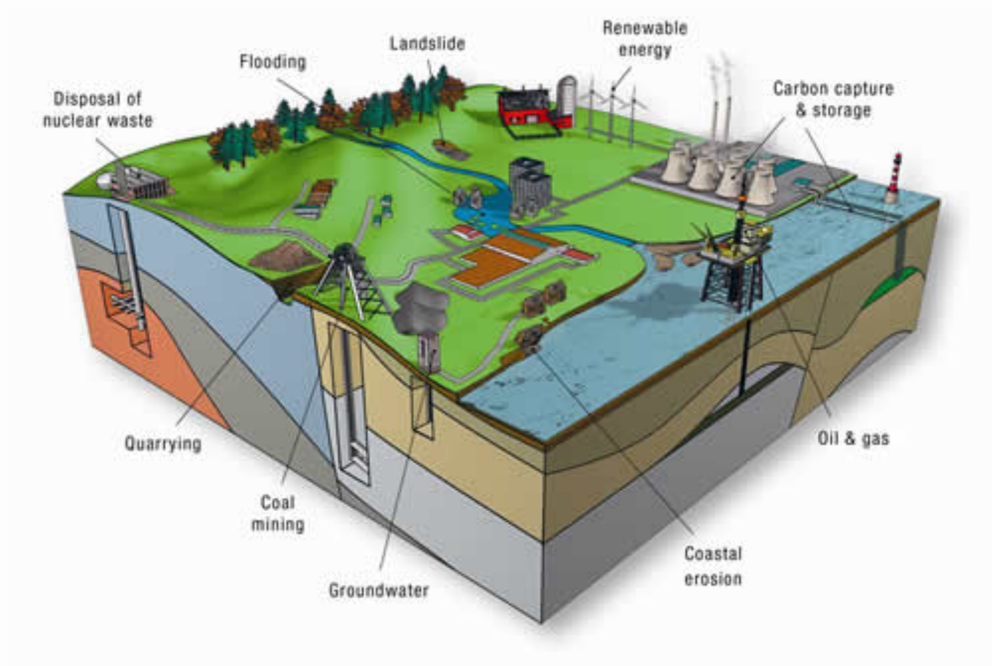
↓ $p$ ↑ $\phi$

**Mechanical** model to determine rock deformation:

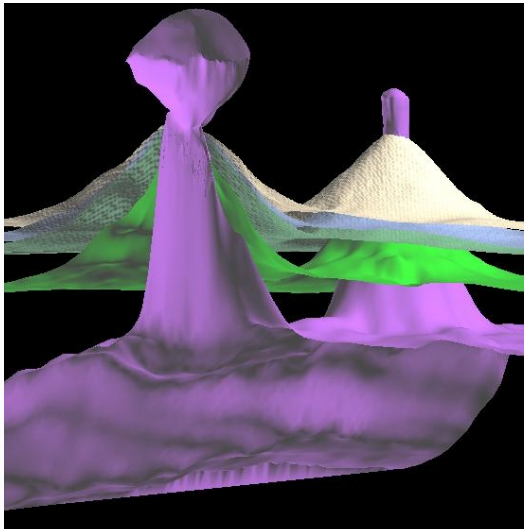
Hooke's law, estimating strain and relating porosity to pressure, strain, plastic strain, (possibly including thermal deformation)

*Based on AD-GPRS geomechanical model*

# Overburden and other geomechanical aspects

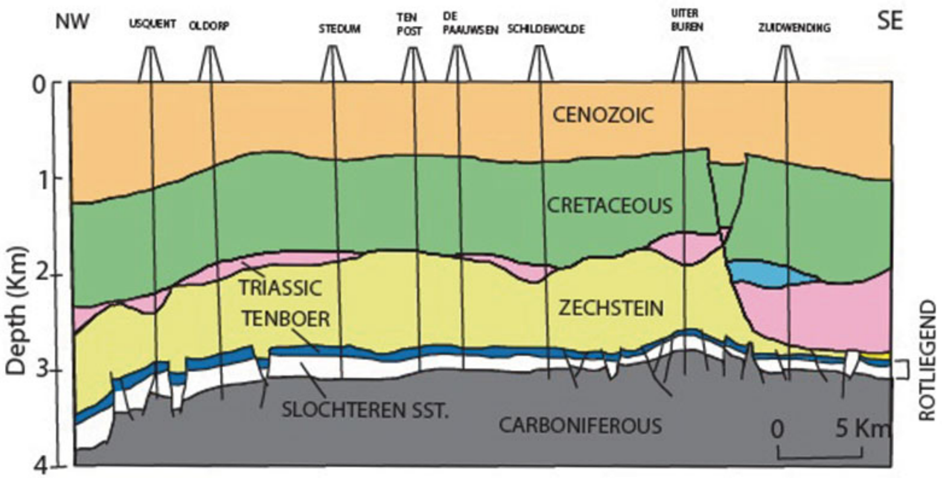



Salt creep



*Mossop, Waddenacademie, 2013*

- In reality, compaction occurs in different layers: ground water variability, ground water extraction, peat oxidation, ..
- Response of overburden may not be fully elastic. In Groningen salt creep may delay the surface response.




*Glennie, AAPG, 2013*

# Parameter uncertainty

- Fluid flow:
  - Permeability
  - Porosity
  - Saturation
  - Pressure
- Geomechanics:
  - Young's modulus
  - Poisson's ratio
- Geometry and geology
  - Overburden and reservoir layering
  - Faults and structure

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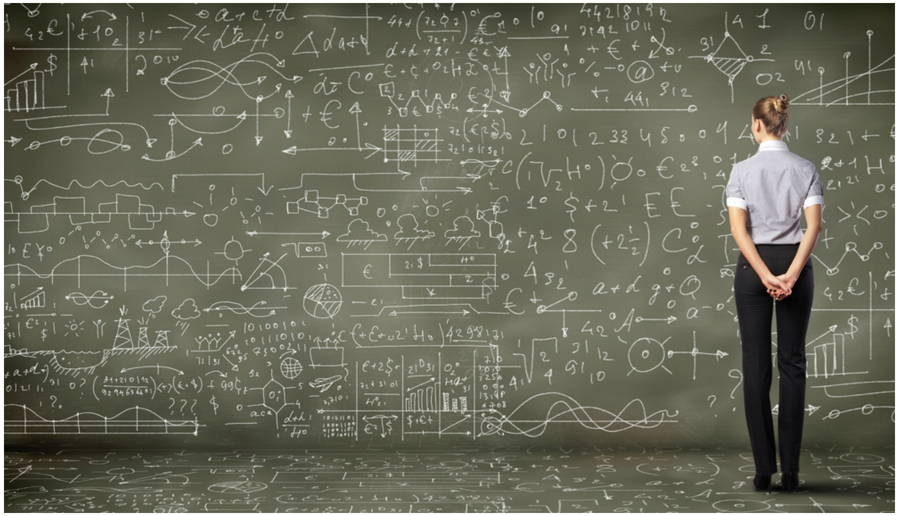
# State and parameter estimation

- Objective: estimate pressure state and corresponding subsidence based on a combination of surface observations (deformation) and subsurface observations (bottom-hole pressure, rate, seismic)
- Approach: find solution that minimizes difference between (coupled flow-geomechanical) model and observations.



# State and parameter estimation

Bayes' rule:

$$f(\psi \mid \mathbf{d}) = \frac{f(\mathbf{d} \mid \psi) f(\psi)}{f(\mathbf{d})}$$

Assume state evolution can be described by Markov process:

$$d\psi = g(\psi)dt + d\beta,$$

Minimum variance estimate:

$$\hat{\psi} = \int \psi \, f(\psi \mid \mathbf{d}) \, d\psi$$

To find this solution, several methods are being used for subsurface flow problems:

1. Ensemble Smoother (Van Leeuwen and Evensen, 1996)
2. Ensemble Kalman Filter (Evensen, 1994)
3. Ensemble Kalman Smoother (Evensen and Van Leeuwen, 2000)
4. Ensemble Square Root Filter (e.g., Zhang et al, 2010)
5. Randomized Maximum Likelihood (Oliver et al, 1996)
6. Particle Filters (review: Van Leeuwen, 2009)
7. Markov-Chain Monte Carlo (e.g., Oliver et al, 1996)

# State and parameter estimation

The practical implementation of the commonly used Ensemble (Kalman) methods have the general shape of:

$$\psi^a(\mathbf{x}, t^*) = \psi^f(\mathbf{x}, t^*) + \sum_{m=1}^{M^*} b_m \mathbf{r}(\mathbf{x}, t^*)$$

Where the term $\sum_{m=1}^{M^*} b_m \mathbf{r}(\mathbf{x}, t^*)$ involves a multiplication of the M representers or influence functions (involving the error covariances) with coefficients that effectively weight a set of model realizations with their difference from the observations . In the most commonly used EnKF:

$$\psi^a(\mathbf{x}, t^*) = \psi^f(\mathbf{x}, t^*) + \mathbf{C}_{\psi\psi}\mathbf{H}^T\left(\mathbf{H}\mathbf{C}_{\psi\psi}^f\mathbf{H}^T + \mathbf{C}_{dd}\right)^{-1}(\mathbf{d} - \mathbf{H}\psi^f(\mathbf{x}, t^*))$$

With covariances $\mathbf{C}_{\psi\psi}$ and $\mathbf{C}_{dd}$ representing uncertainty in model and data.

# State and parameter estimation

In geomechanical applications, the estimated variable $\psi^a$ is a function of a state $\mathbf{x}$, starting from an initial condition $\mathbf{x_0}$ and (geomechanical) parameters $\gamma$. Observations $\mathbf{d}$ will relate to the state (subsidence, pressure, rate), while the model $\psi^f$ will largely depend on choices of $\gamma$.

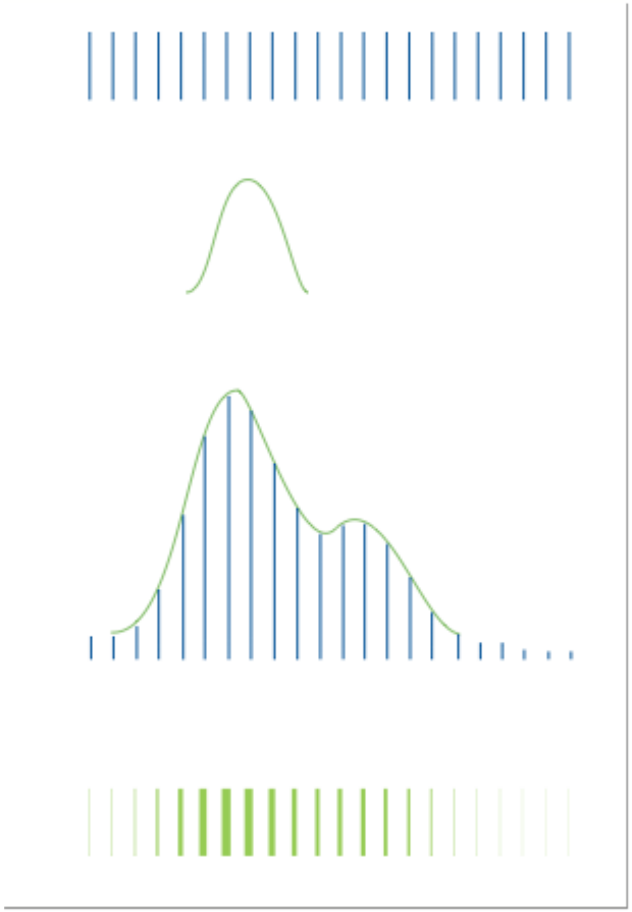
$$\psi^a(\mathbf{x}, \gamma, t^*) = \psi^f(\mathbf{x}, \gamma, t^*) + \mathbf{C}_{\psi\psi}\mathbf{H}^T \left(\mathbf{H}\mathbf{C}^f_{\psi\psi}\mathbf{H}^T + \mathbf{C}_{dd}\right)^{-1} (\mathbf{d} - \mathbf{H}\psi^f(\mathbf{x}, t^*))$$

Typically, the covariances $\mathbf{C}_{\psi\psi}$ and $\mathbf{C}_{dd}$ are based on Gaussian assumptions. For flow problems, this tends to give satisfactorily results. How about geomechanical problems?

- Strongly non-linear (consolidation, fault slip)
- Coupled models

# Particle methods

- Approximate model uncertainty with ensemble of model realisations
- Weight each particle with difference observation-model
- Can be used as a smoother or as a filter



Bayes' theory:

$$p_m(\psi \mid \mathbf{d}) = \frac{p_d(\mathbf{d} \mid \psi) p_m(\psi)}{p_d(\mathbf{d})}$$

$$p_d(\mathbf{d}) = \int p_d(\mathbf{d} \mid \psi) p_m(\psi) d\psi$$

Represent model probability density by ensemble:

$$p_m(\psi) = \frac{1}{N} \sum_{i=1}^{N} \delta(\psi - \psi_i)$$

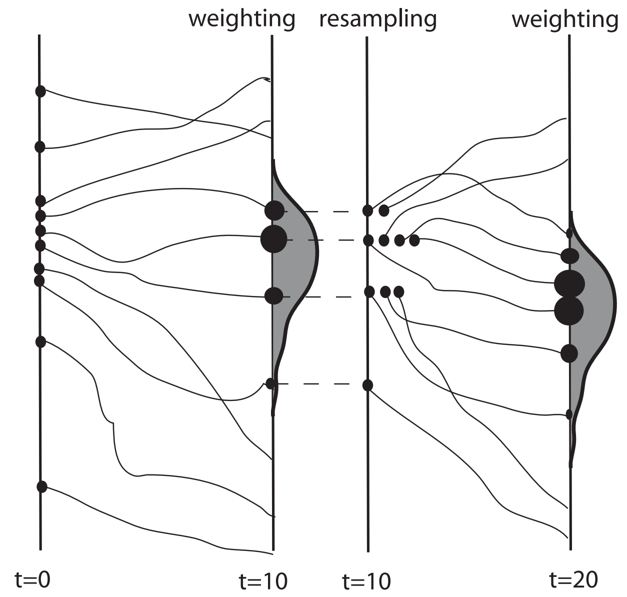
Minimum variance estimator:

$$\hat{\psi} = \int \psi p_m(\psi \mid \mathbf{d}) d\psi = \frac{\int \psi p_d(\mathbf{d} \mid \psi) p_m(\psi) d\psi}{\int p_d(\mathbf{d} \mid \psi) p_m(\psi) d\psi} = \frac{\sum_{i=1}^{N} \psi_i p_d(\mathbf{d} \mid \psi_i)}{\sum_{i=1}^{N} p_d(\mathbf{d} \mid \psi_i)}$$

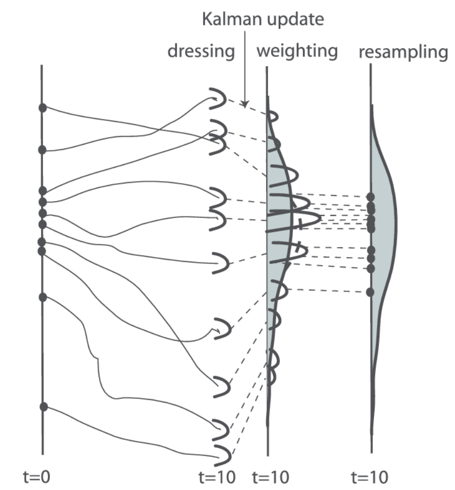
# Particle filter -sequential

*Graphs fromVan Leeuwen (2009)*

- Resample to avoid ensemble degeneracy: sequential importance resampling




- Optimize the ensemble going forward by proposal density or kernel dressing (regularised particle filter)



# Approach

- *Strain source distribution*
  - *Inversion of geodetic double difference data*
    - *Regularized Particle Filter for Darcy flow and slope stability*
- *Comparison Monte-Carlo methods and Ensemble (Kalman) methods*
- *Sensitivity fault reactivation*
  - *Sensitivity overburden lithology*

- Data interpretation
- Coupled modeling and sensitivity
- Data assimilation

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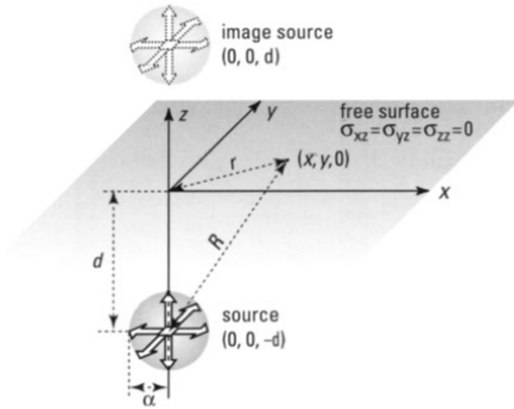
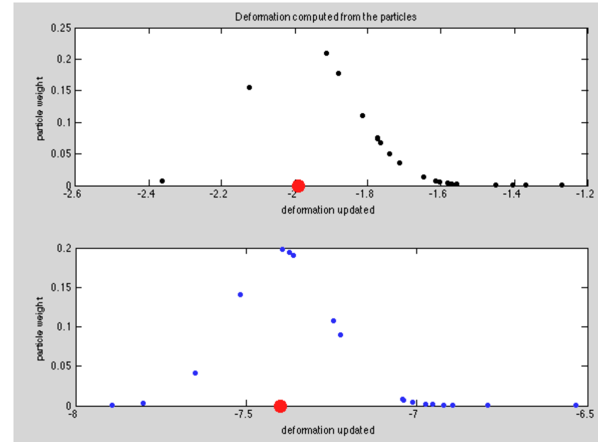
25

# Particle Filter for Groningen Subsidence (1)

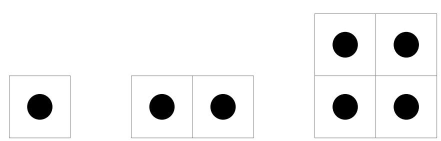
- Modeling subsidence with so-called Mogi sources, spherical sources of strain.
- Tested particle filter methodology on cases with increasing number of Mogi sources
- Importance resampling (SIR) to prevent ensemble degeneracy



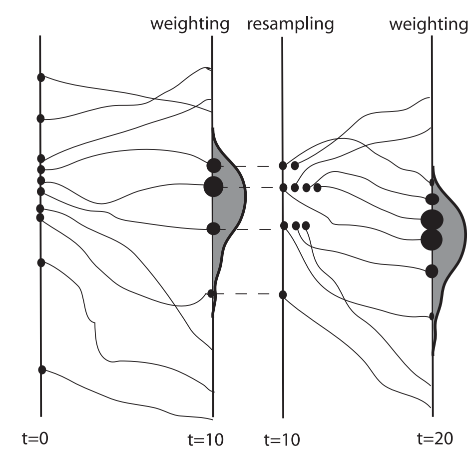

Mogi source, after Dzurisin, 2007




Particle weights



Testing with one, two and four Mogi sources

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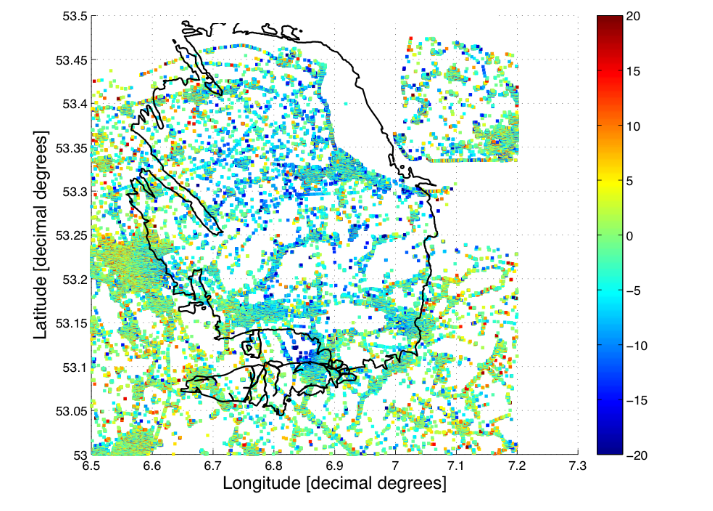
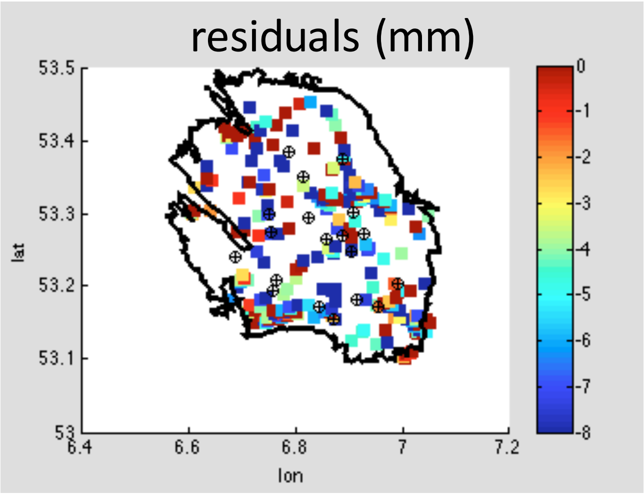
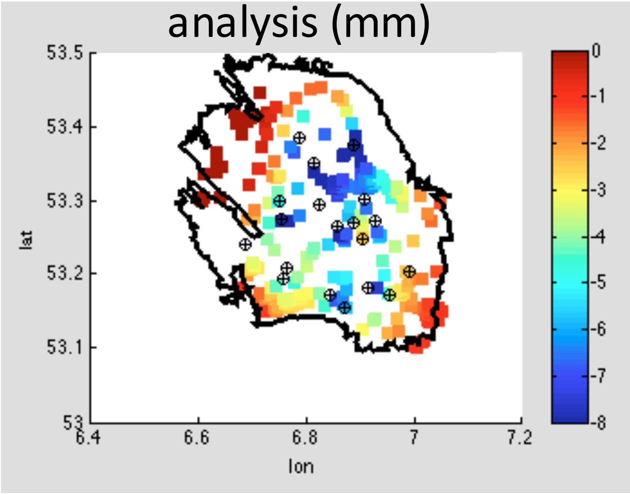
# Particle filter for Groningen Subsidence (2)

- Testing on subset of data with 19 Mogi sources
- Ensemble size N=1000
- residuals RMSE = 6.16 [mm]

InSAR data of 2009-2010 subsidence (mm)

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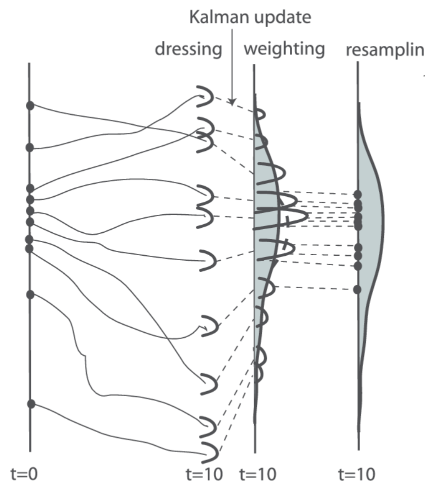
# Regularized Particle Filter for Darcy flow

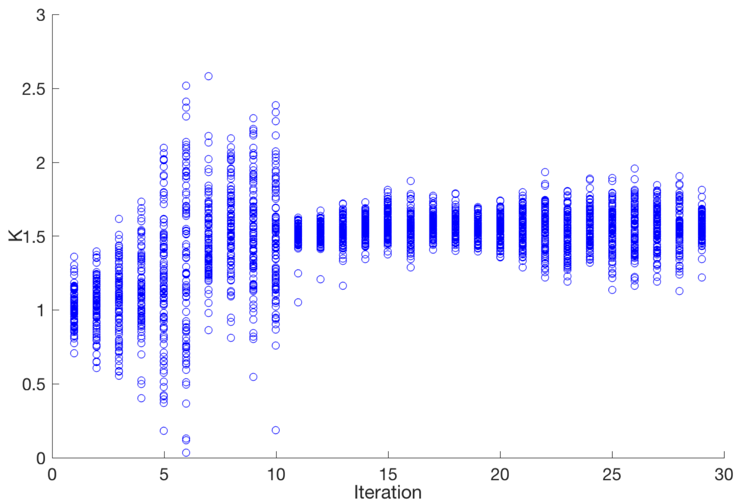
- Estimating permeability in a 1D Darcy-flow problem using a particle filter
- Resampling using the regularized particle filter (RPF)
- RPF finds good fit with analytical solution

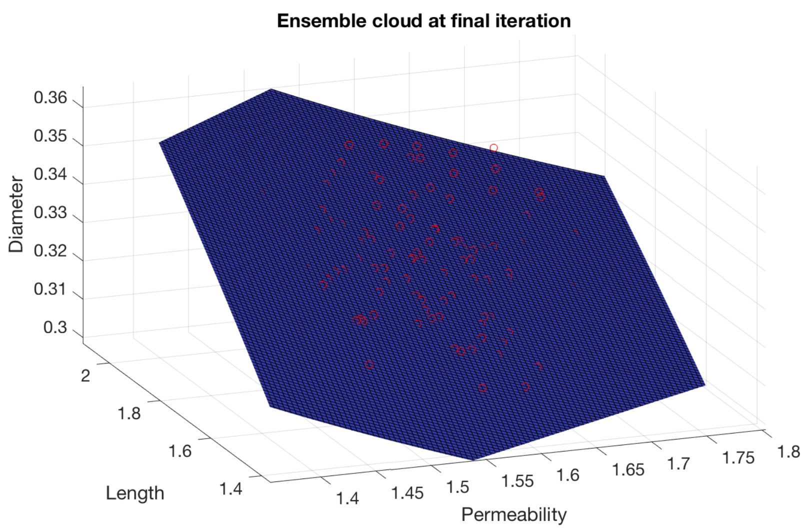
$$p(\psi|d) \approx \sum_{i=1}^{N} w_i K_h(\psi - \psi_i)$$

K: Kernel, h: Kernel width

$$K_h(\psi) = \frac{1}{h^n} K\left(\frac{\psi}{h}\right)$$

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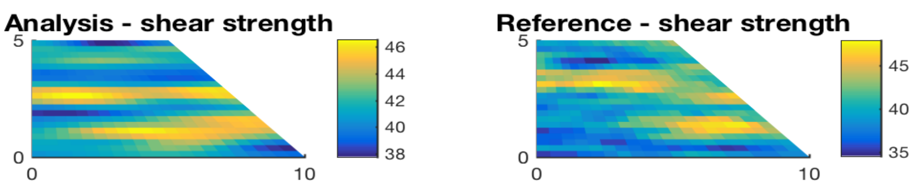
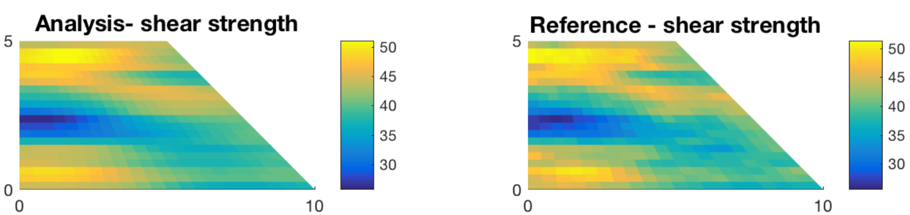
# Slope stability: MCMC vs Regularized Particle Filter

- Comparison of regularized particle filter with Markov-Chain Monte Carlo method
- MCMC gives a better fit with the data

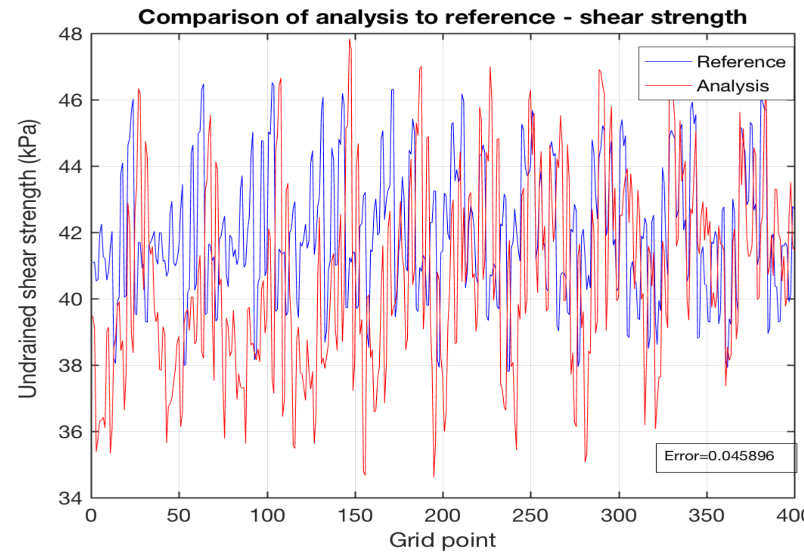
Regularized Particle Filter




Markov-Chain Monte Carlo




Regularized Particle Filter




Markov-Chain Monte Carlo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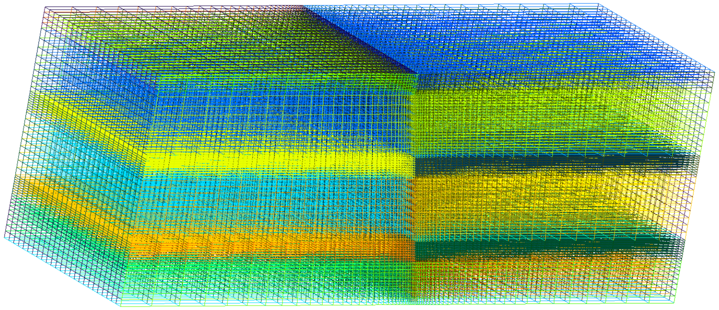
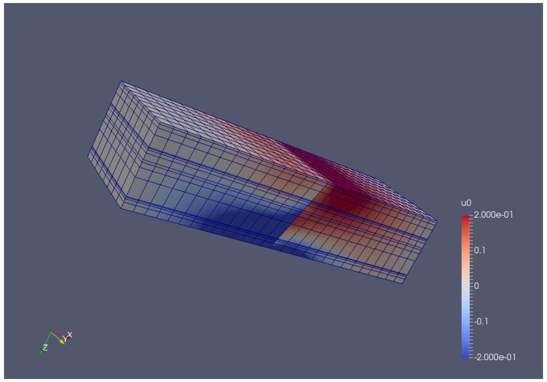
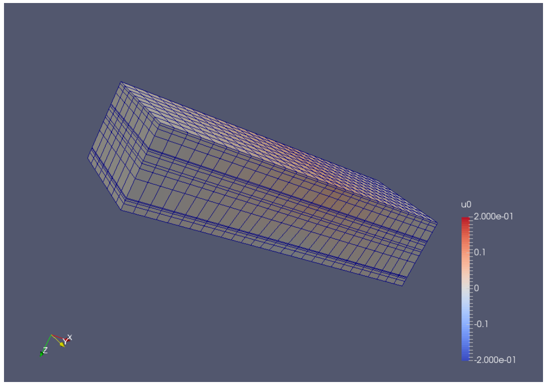
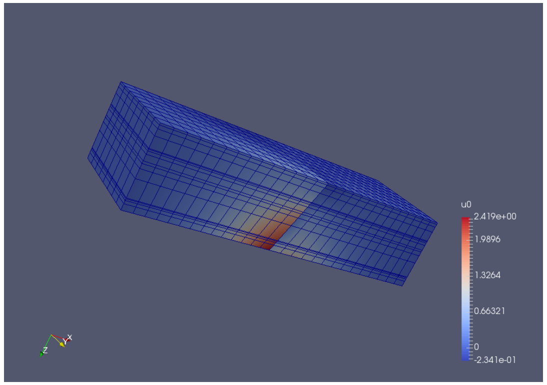
# Coupled Reservoir-Geomechanical





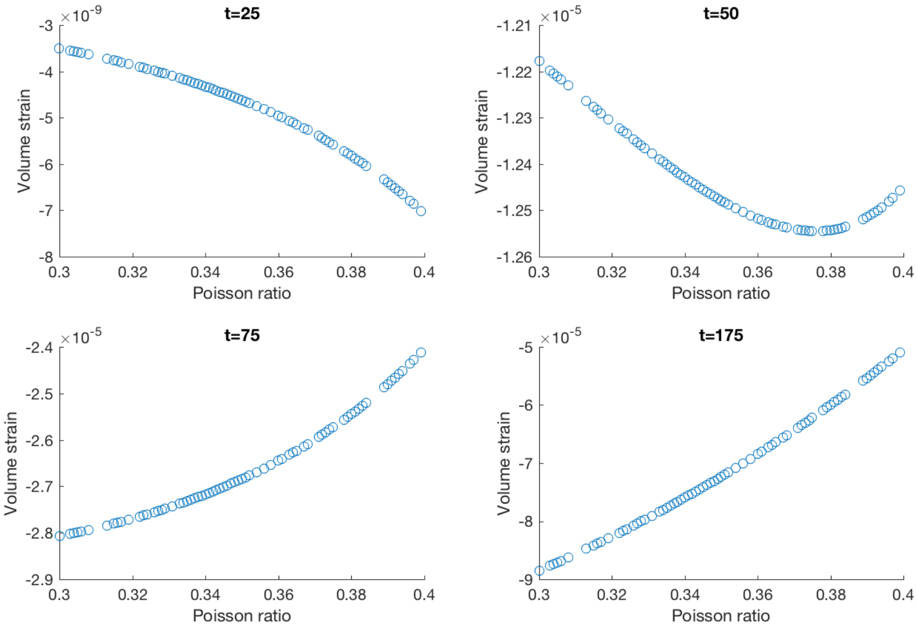



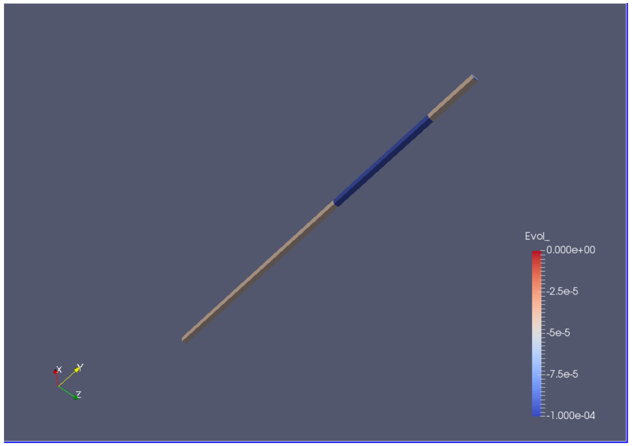



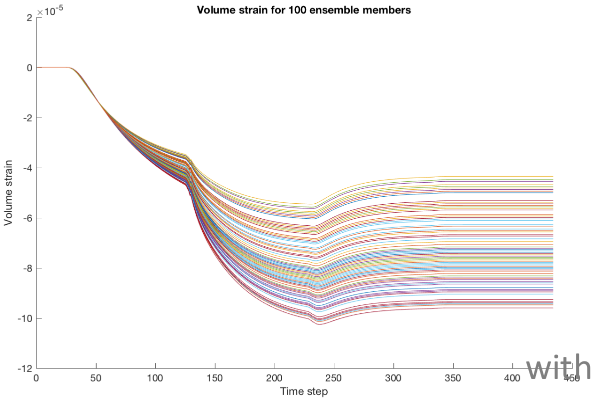

- Coupled reservoir-geomechanical model: AD-GPRS (Denis Voskov, TUD, Yifan Zhou, Timur Garipov, Stanford)
- Simplified geometry with full coupling, fully implicit methods makes model computationally efficient

# Coupled flow-geomechanical -1D Case

- Simplified, Terzaghi-like problem, 1D, 100 ensemble members
- Sensitivity studies to rock properties



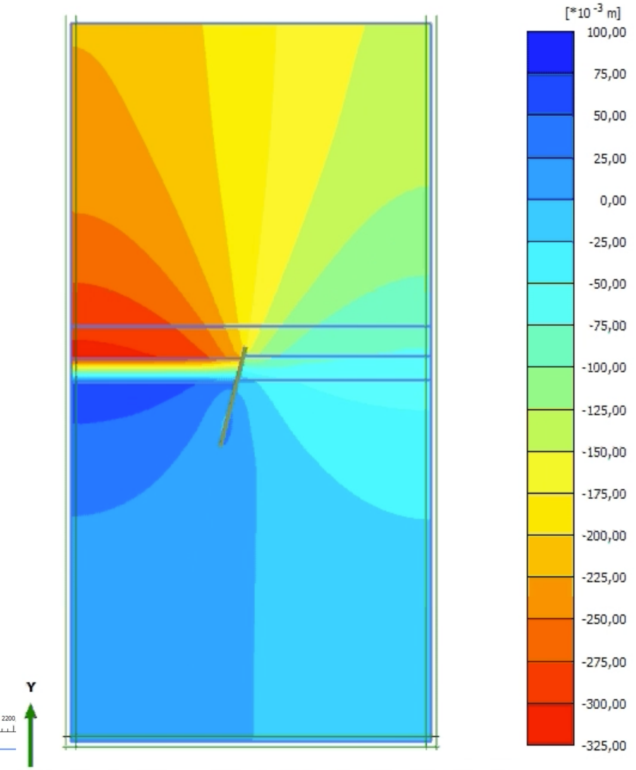



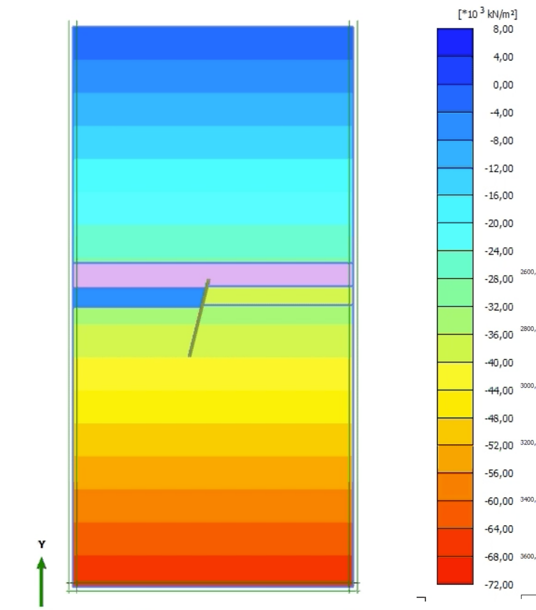

with Denis Voskov

# Fault slip

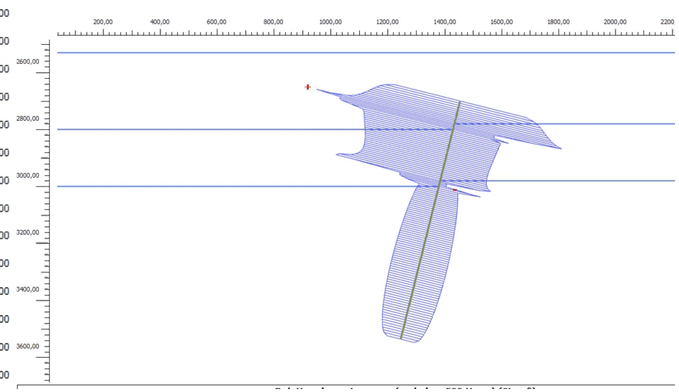
- 2D finite element model (Plaxis) simulating fault slip and associated deformation resulting from differential compaction
- Sensitivity study to fault conditions: angle, friction coefficient, Poisson's ratio, rock properties

Vertical deformation





Pore pressure



With Irene Platteeuw, Marc Hettema, Ronald Brinkgreve

# Agenda

- Introduction to subsidence: cause and effect
- Modeling subsidence: flow and geomechanics
- Assimilation to reconstruct subsurface processes
- Ongoing work and preliminary results
- Conclusions and Outlook

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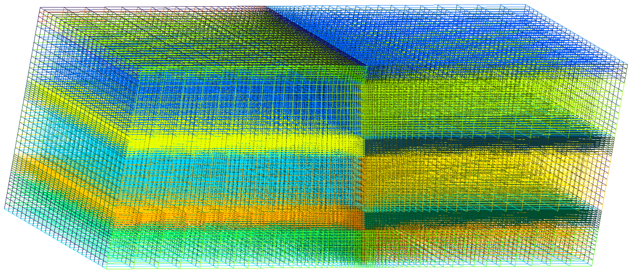
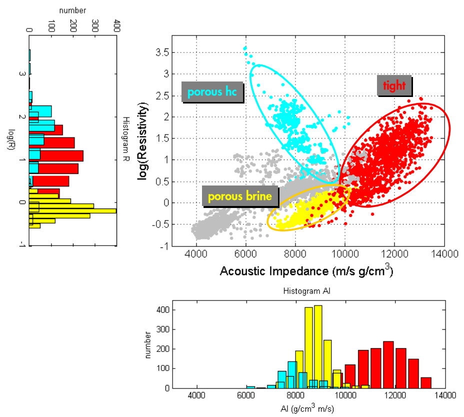
33

# Conclusions and ongoing work

- Conclusions
  - Subsidence involves processes in shallow and deep subsurface
  - Geomechanical and flow parameters can be estimated with data assimilation
  - Non-linearities and coupled models ask for Monte-Carlo based methodologies



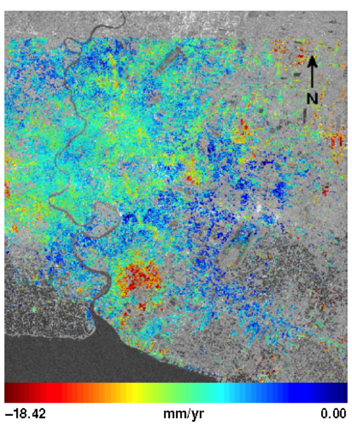



*Vossepoel et al, SEG, 2010*

- Ongoing work
  - Hybrid Monte Carlo/EnKF assimilation methods
  - Dynamic versus static forcing
  - Heterogeneities in overburden: integration of seismic and non-seismic

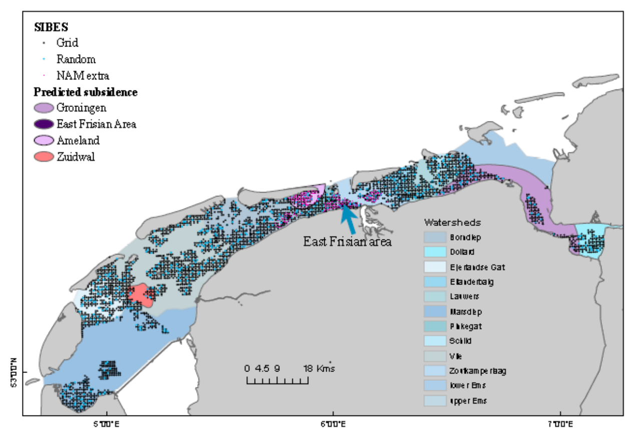
# Outlook

- Uplift due to steam injection
- Other geological settings, offshore subsidence
- Surface effects of mining, geothermal energy
- Susidence related to water extraction (Ravenna, Italy, or Thailand)
- Sea level rise and coastal subsidence (Indus and Nile delta, Wadden Sea)
- Groundwater studies and shallow subsurface




Bangkok, Thailand

Wadden Sea, Netherlands



# Q&A