Paleostress and Slip Recovery from Complex Faults Geometry Using Mechanical Interactions: Application to Fracture Prediction*

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Abstract

Methods for stress inversion, using measure striation and/or throw, are mainly based on the following assumptions:

- the stress field is uniform within the rock mass embedding the faults (assuming no perturbed stress field), and
- the shear traction has the same direction and sense as the resolved far field stress onto the fault plane.

However, it has been shown that slip direction are highly affected by:

- anisotropy in fault compliance caused by irregular tipline geometry,
- anisotropy in fault friction (surface corrugations),
- heterogeneity in host rock stiffness and
- perturbation of the local stress field mainly due to mechanical interactions of adjacent faults.

Therefore, mechanical interactions due to complex faults geometry in heterogeneous media have to be taken into account while doing stress inversion.

We investigate this approach using Poly3D, a 3D Boundary Element Method (3D-BEM) using linear elasticity in heterogeneous, isotropic whole- of half-space. Given some measures of the fault throw and/or dip-slip (plus constraints such as slikenline directions if any), as well as the faults geometry, we recover for paleostress orientation and magnitudes as well as for the unknown slip distribution onto the faults.

Having the paleostress as well as the slip distribution onto the faults, it is then possible to compute anywhere within the 3D elastic field, the strain, stress and displacement. Particularly, the stress field can be used to predict fractures and subseismic faults. We show examples from different field areas, such as complex faulted reservoirs.

PaleoStress and slip recovery on complex faults geometry using mechanical interactions: Application to fractures prediction

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Outline

- Subsurface fracture modeling (geomechanics)
- PaleoStress/strain estimation for modeling fractures
- Case study: Oseberg Syd field (Northern North sea)
- Conclusions

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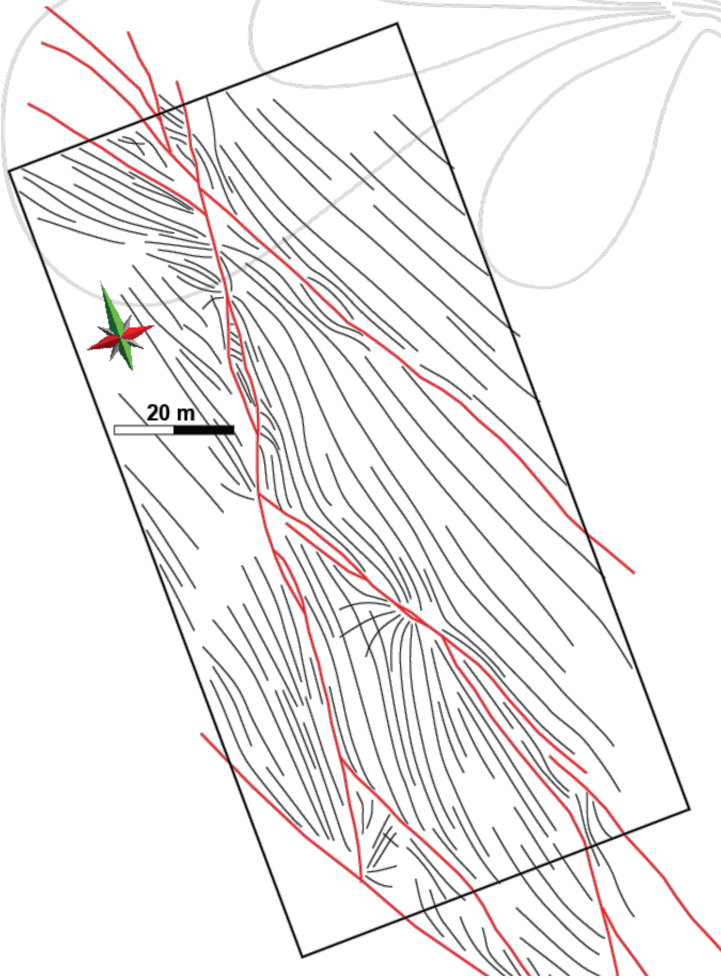
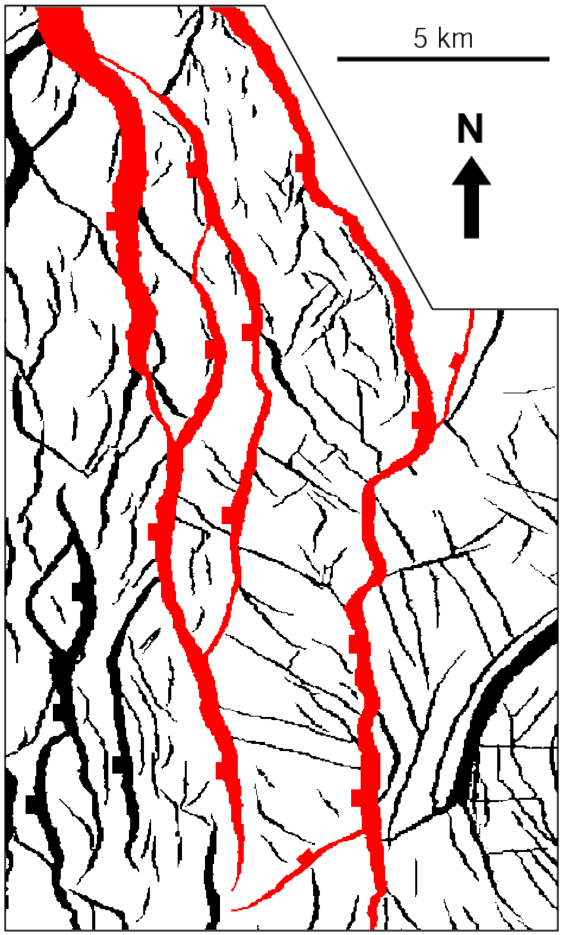
Importance of perturbed stress field
Fractures affected by nearby faults

Location, density, and orientation of joints can be affected by slip on nearby faults.

Curved joint networks in carbonates at Nash Point, England

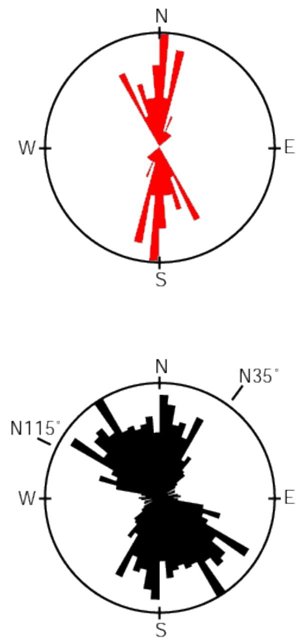


Importance of perturbed stress field
Faults affected by nearby major faults



(after Maerten et al., 2006)

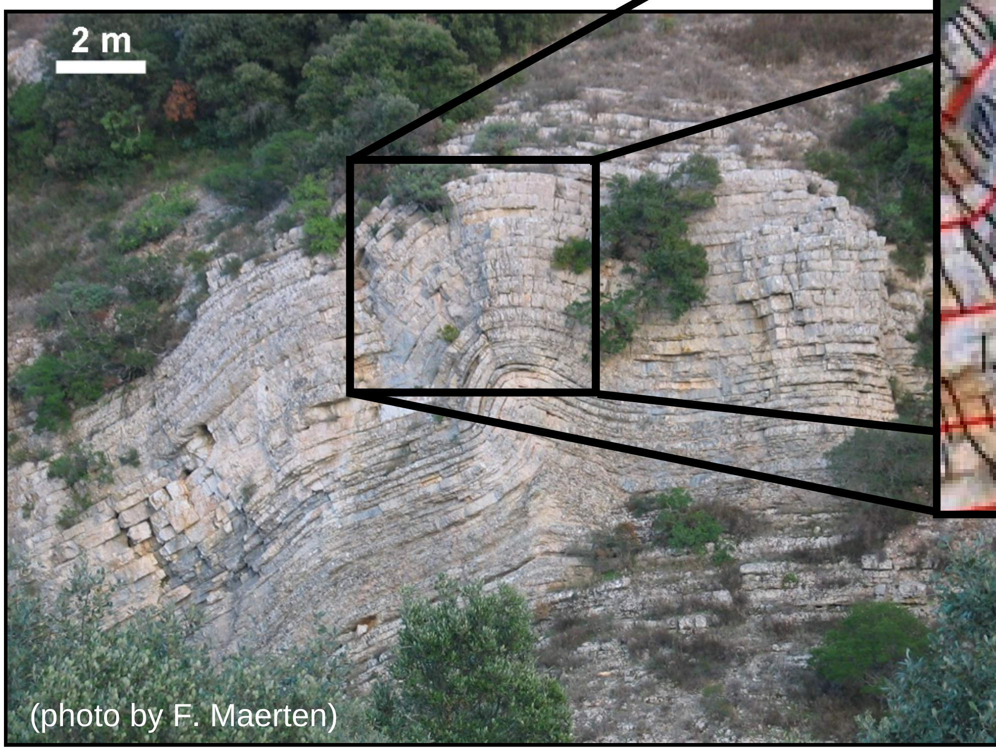
Location, density, and orientation of faults can be affected by slip on nearby major faults.



Influence of major faults on secondary fault network, North Sea.

Importance of perturbed stress field
Joints and faults affected by folding

Location, density, and orientation of both joints and faults can be affected by folding.



Fold in carbonates near Montpellier, France

Influence of folding on joint patterns.

Summary and basic principle for modeling

Fracture characteristics (kind, orientation, location) at the time of their development depend on:

1 **The objects that perturb the stresses** *(faults, folds, fractures, salt domes, cavities, etc.)*

Main unknown !

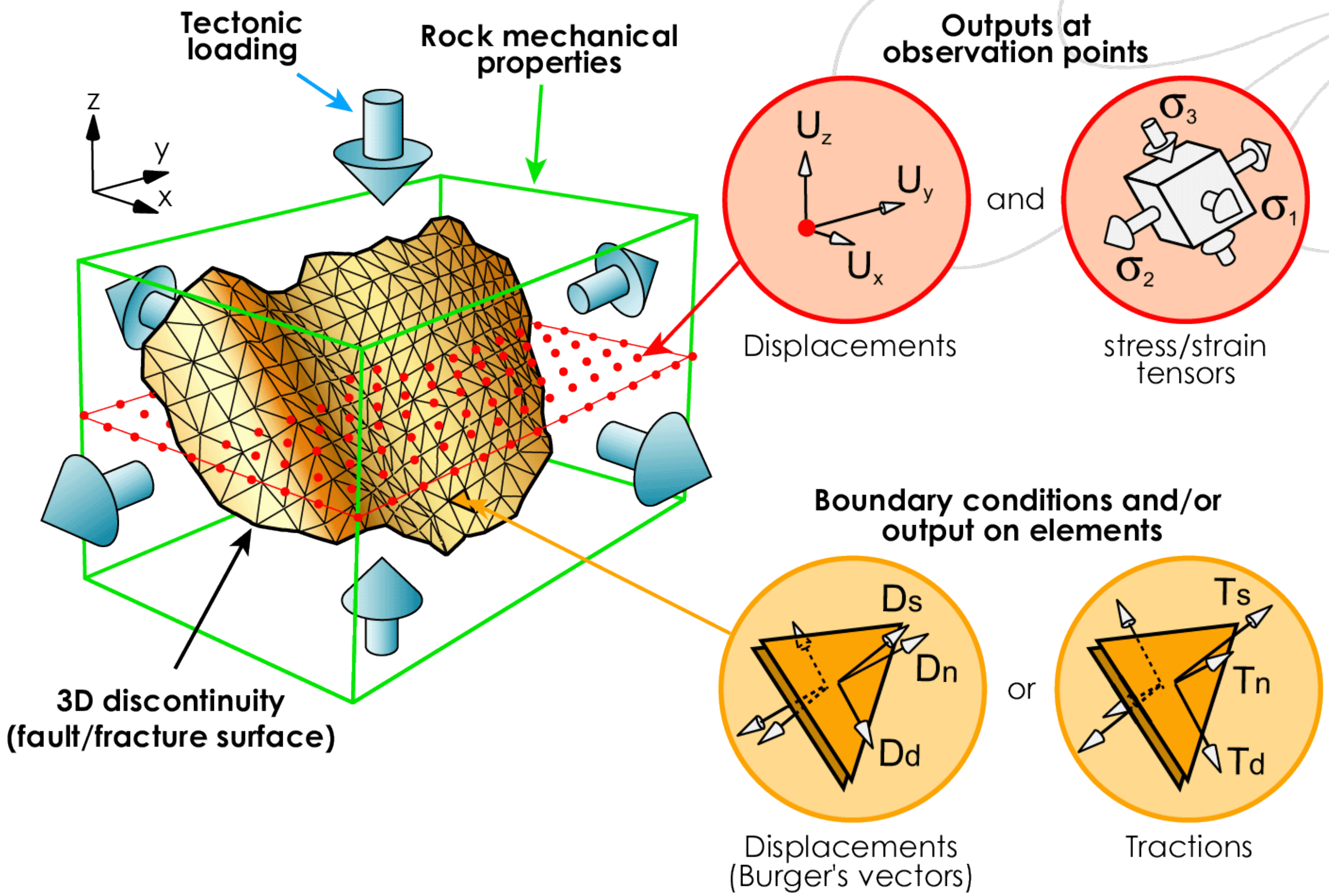
2 **The tectonic loading** *(regional or local stress regime)*

3 **The rock type** *(behavior and physical properties)*

Thus, on the local state of stress at a given time !

The goal is to estimate the
local state of stress based on these 3 points
using
geomechanical modeling (Poly3D)

Background: Poly3D key elements



AAPG Denver, 2009

Poly3D *vs* standard dislocation methods

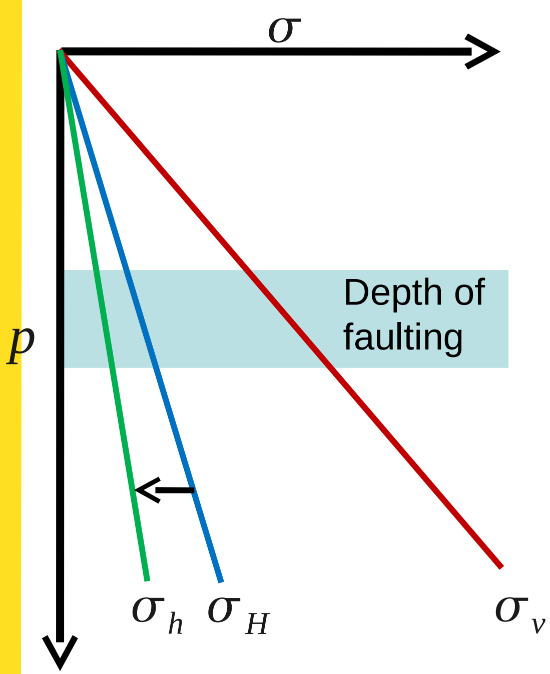
- Poly3D uses triangular elements (complex geometries)
- Heterogeneous material + frictional faults
- Can model interacting branching and overlapping faults
- Takes into account far field stresses or strains
- Can be used for fault interpretation QC
- Can be used for fracture modeling

- Other methods use rectangular elements (perturb the solution, Maerten et al., 2005)
- They are limited to model simple fault geometries (non-branching and non-overlapping)
- Complete slip on fault must be known
- No physical equilibrium when adding far field stress

How to estimate the far field stress/strain?

Existing methods:

By hand



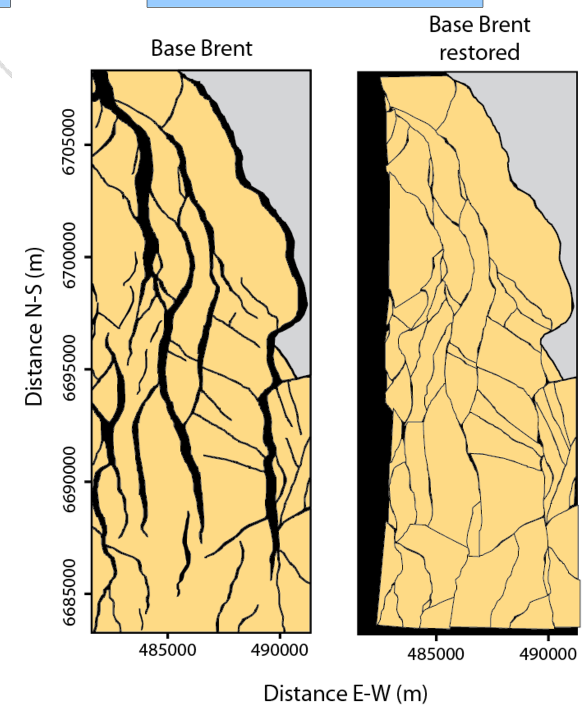
No info about the orientation

Angelier, Etchecopar...

Reconstructing of the paleostress based on measurements of the directions and sense of slip along outcropping fault surface.

Need measurements of slickenlines

Restoration

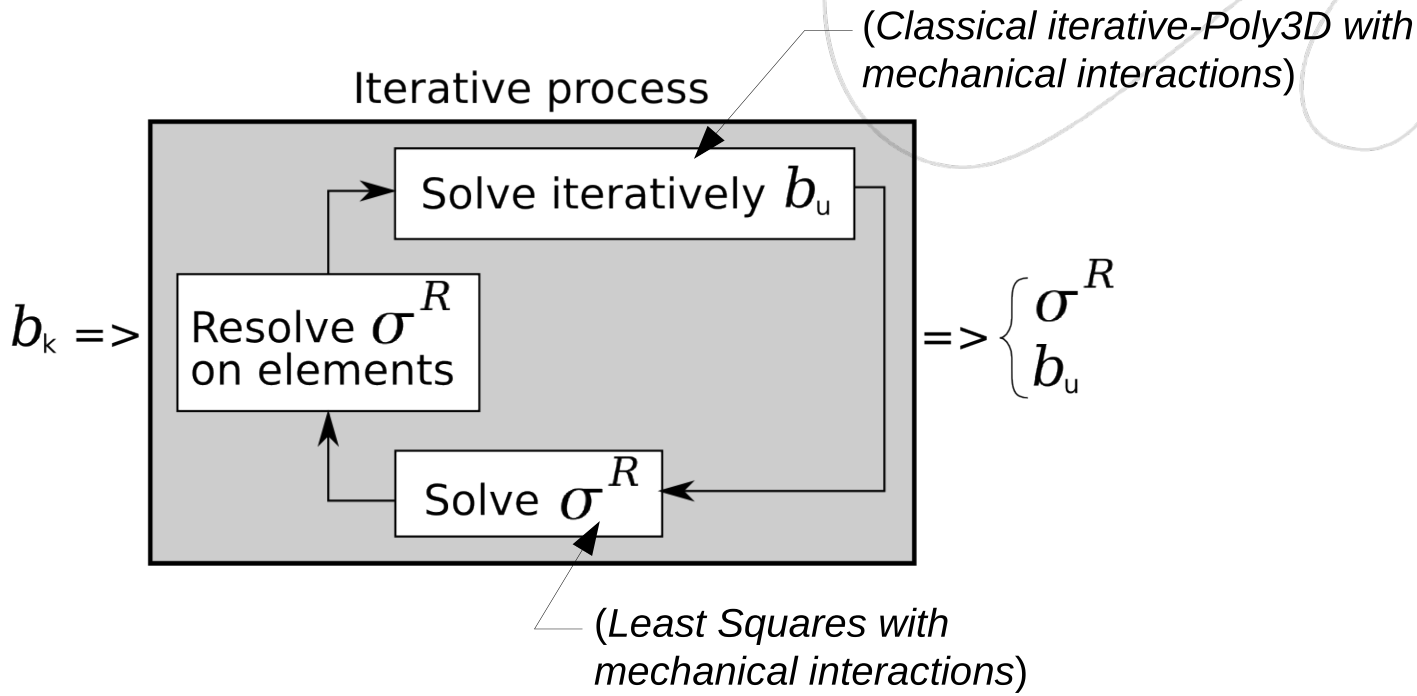


Access to strain only, time consuming

Paleostress/strain estimation: Theory

- Based on Poly3D kernel functions (mechanical interactions)
- Use measured slip magnitudes onto the faults (e.g. throw)
- Use slickenline measurements if necessary to better constrain the inversion
- Use a dual iterative coupled systems where shared variables are exchanged during each iteration
- Recover for both paleostress and unknown displacements on faults or part of the faults
- Inversion can be constrained with inequality on displacement and/or stress/strain magnitude and orientation

Paleostress/strain estimation: Algorithm



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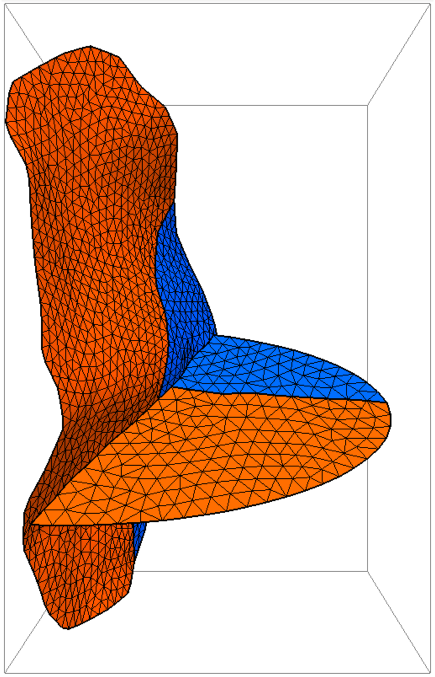
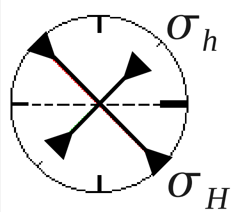
Paleostress/strain estimation: Validation



Forward modeling configuration



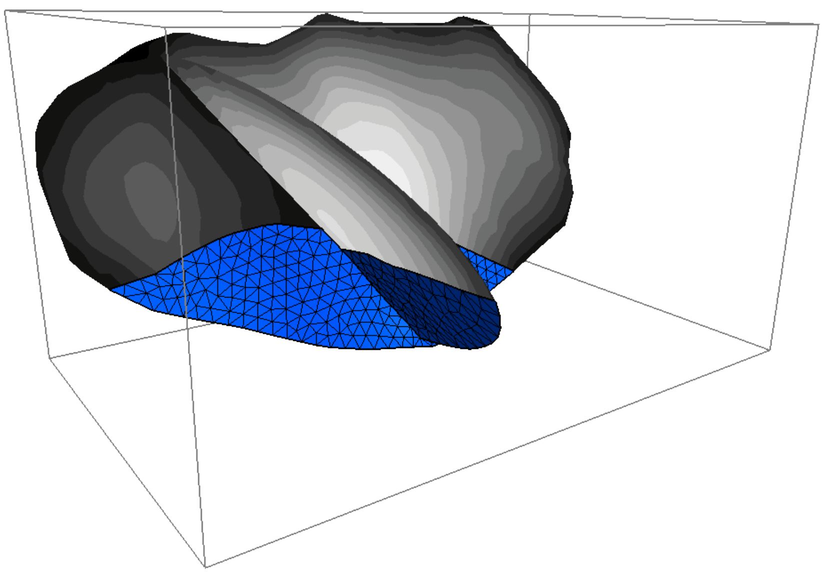
Imposed far field stress

$\sigma_v = 1$

$\sigma_H = 3 \quad N135E$

$\sigma_h = 2 \quad N45E$

Faults are free to slip



Imposed computed dip-slip onto the upper part of the faults

Paleostress/strain estimation: Validation

Result:

Imposed (forward model)

$$\sigma_v = 1$$
$$\sigma_H = 3 \quad N135E$$
$$\sigma_h = 2 \quad N45E$$

Recovered (paleostress)

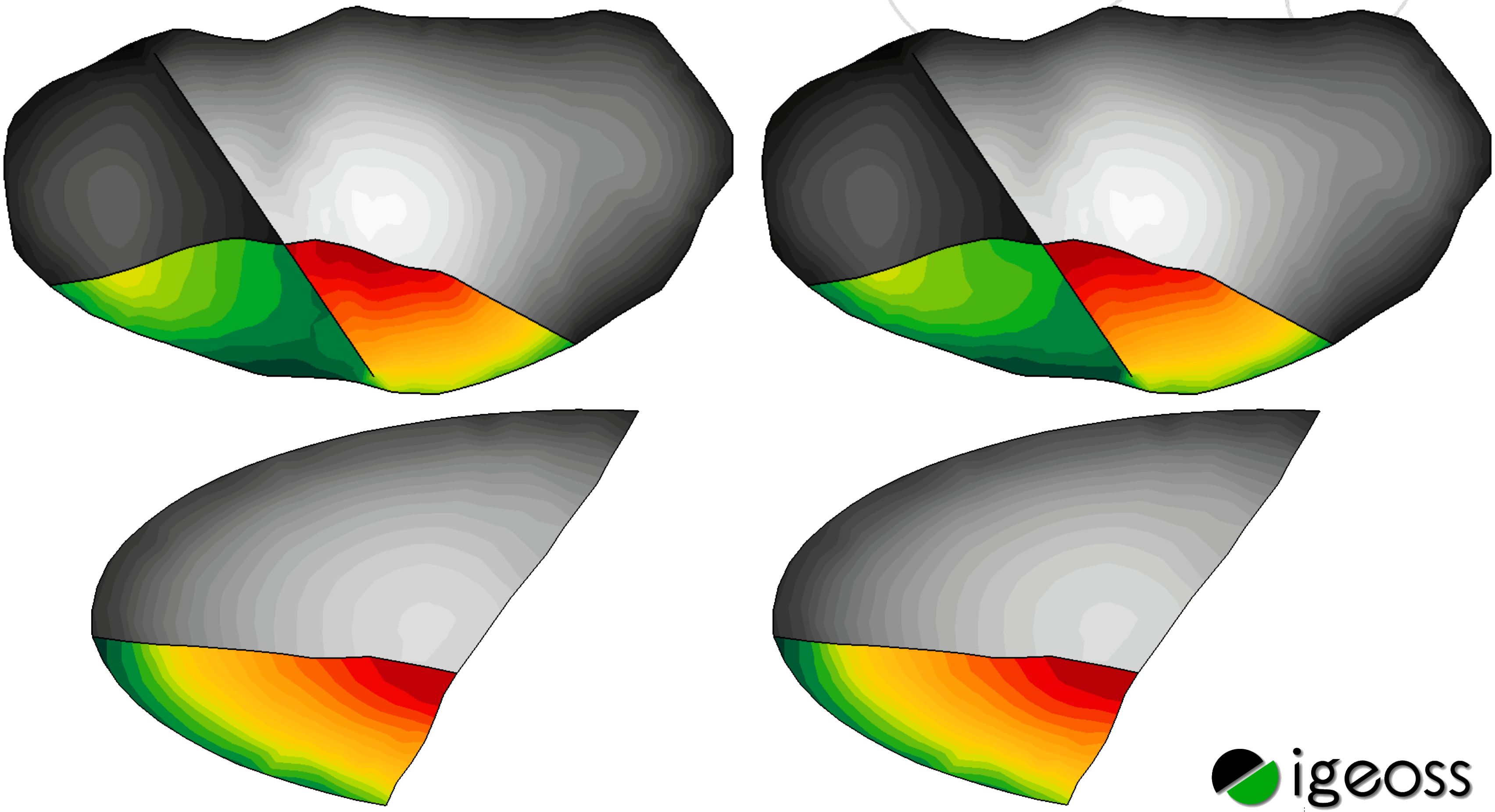
$$\sigma_v = 1$$
$$\sigma_H = 2.99758 \quad N134.96E$$
$$\sigma_h = 2.00079 \quad N44.969E$$

Paleostress/strain estimation: Validation

Dip-slip recovered (colored parts)

Forward (as it should be)

Recovered



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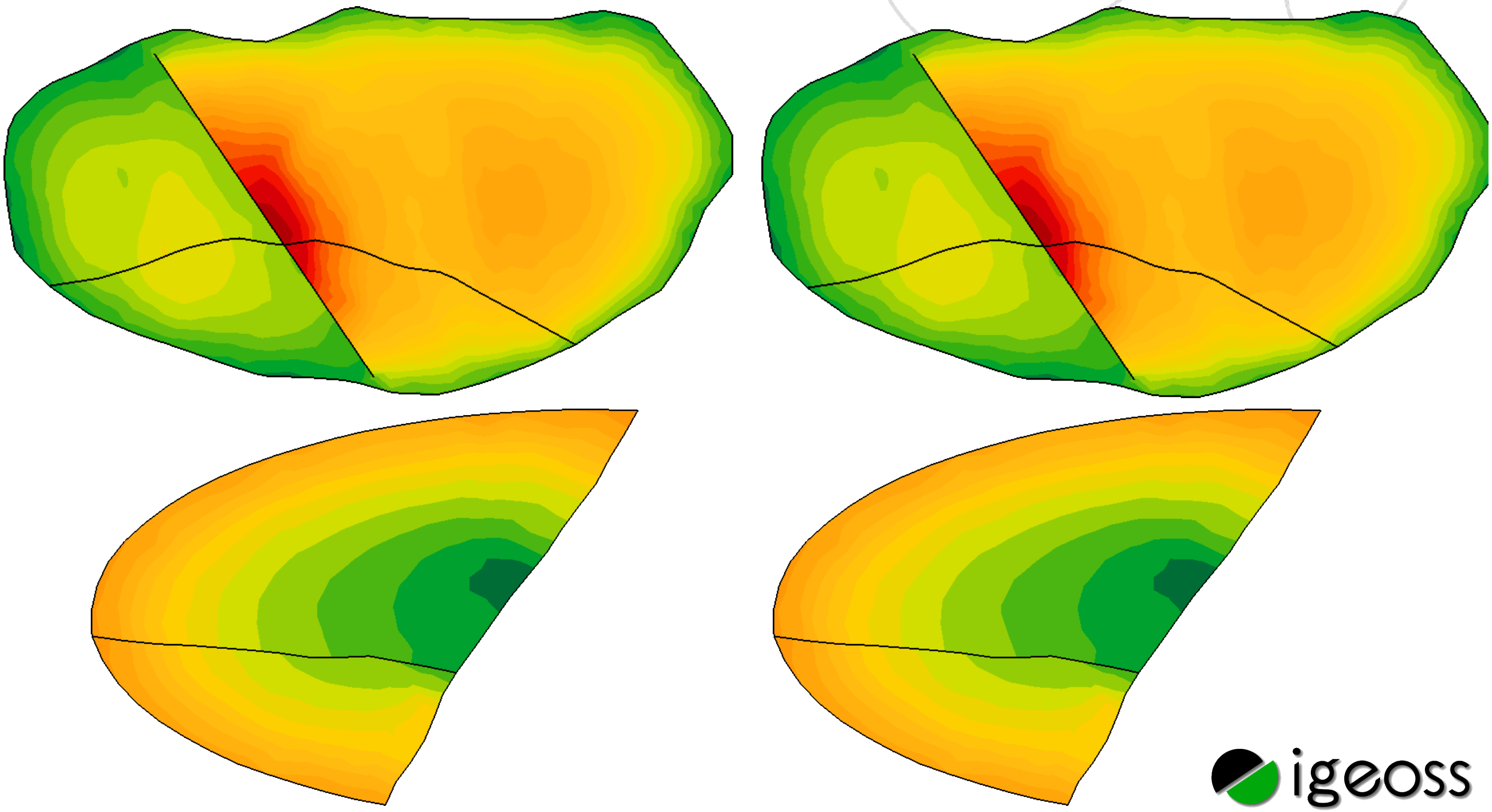
Paleostress/strain estimation: Validation

Strike-slip recovered (everywhere)

Forward (as it should be) | Recovered

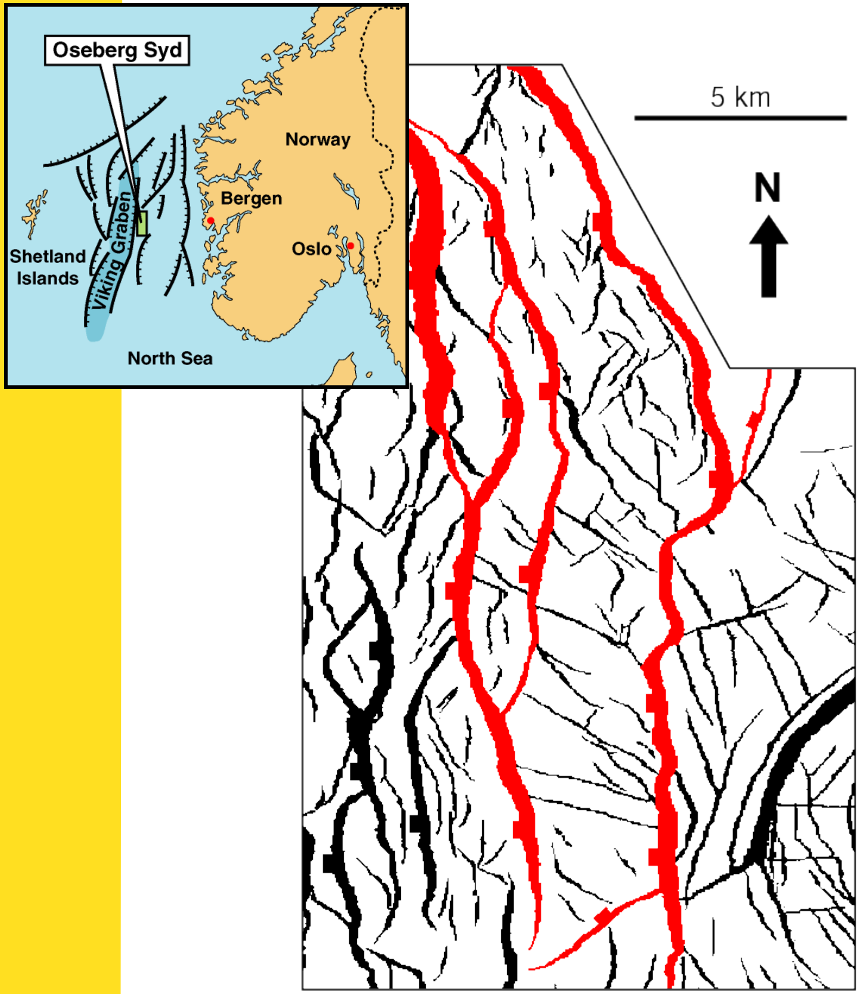


Advantages and limitations

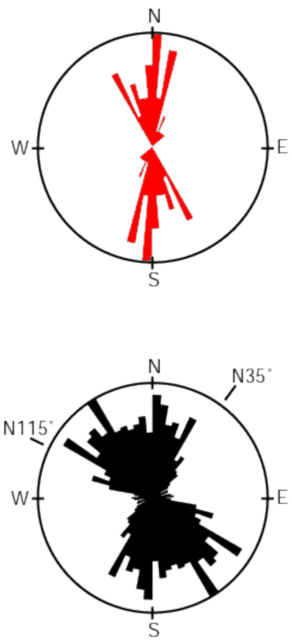
- Takes into account fault interactions
- Use complex fault geometry
- Use displacement magnitude and slickenline information
- Recover for the unknown displacement on faults (e.g. strike-slip)
- Recover for both magnitude and orientation of the paleostress/strain

- Single phase
- Use linear elasticity: magnitudes of paleostress can be very high

Case study:
Oseberg Syd (Northern North Sea)
(Maerten et al., 2006)

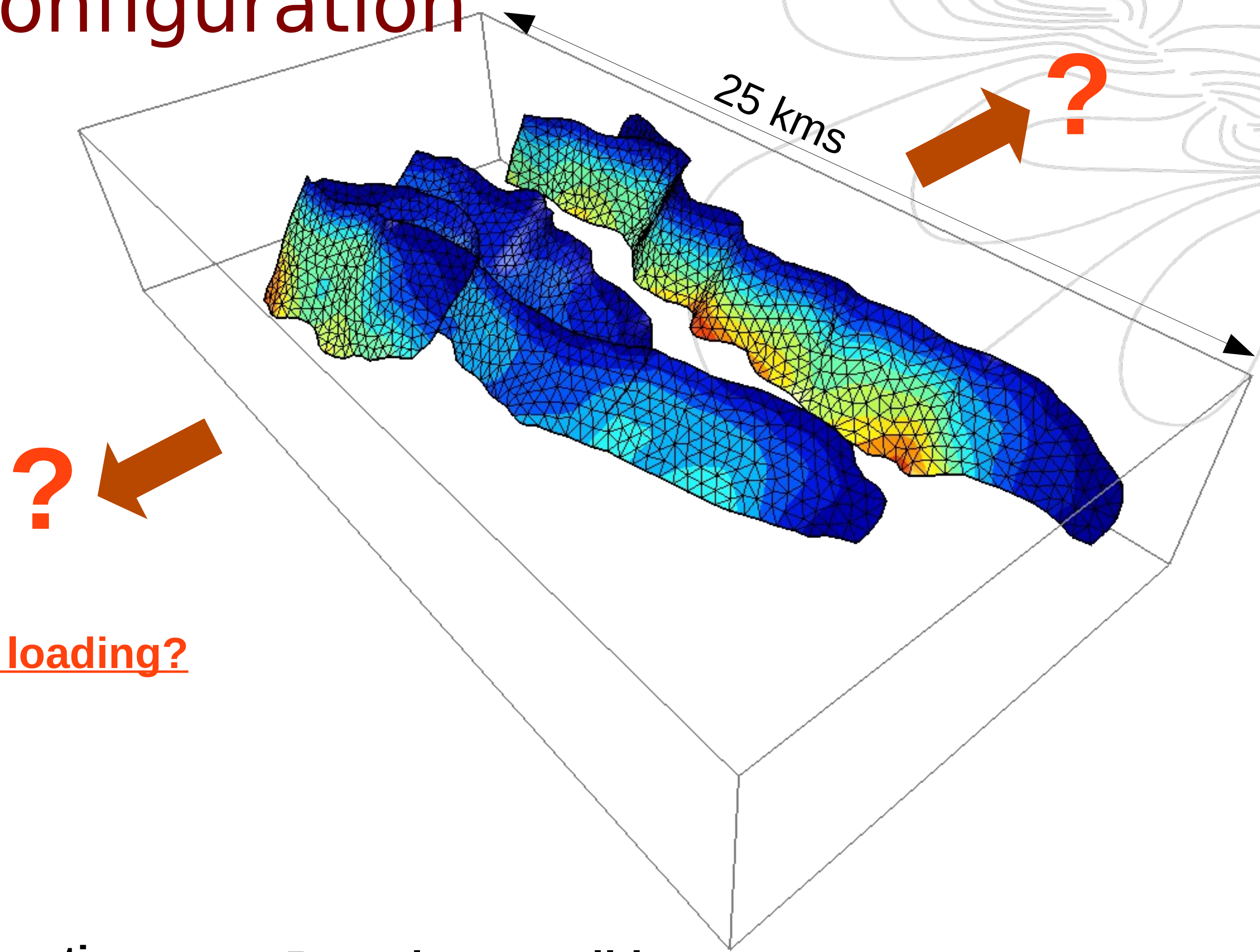


Highly deformed reservoir with numerous normal faults that appear to be sealing faults



Goal:
model undetected faults using the perturbed stress field with Poly3D

Model configuration



Tectonic loading?

$\varepsilon_H = ?$

$\varepsilon_h = ?$

$\varepsilon_v = ?$

Rock properties:

E = 45 GPa

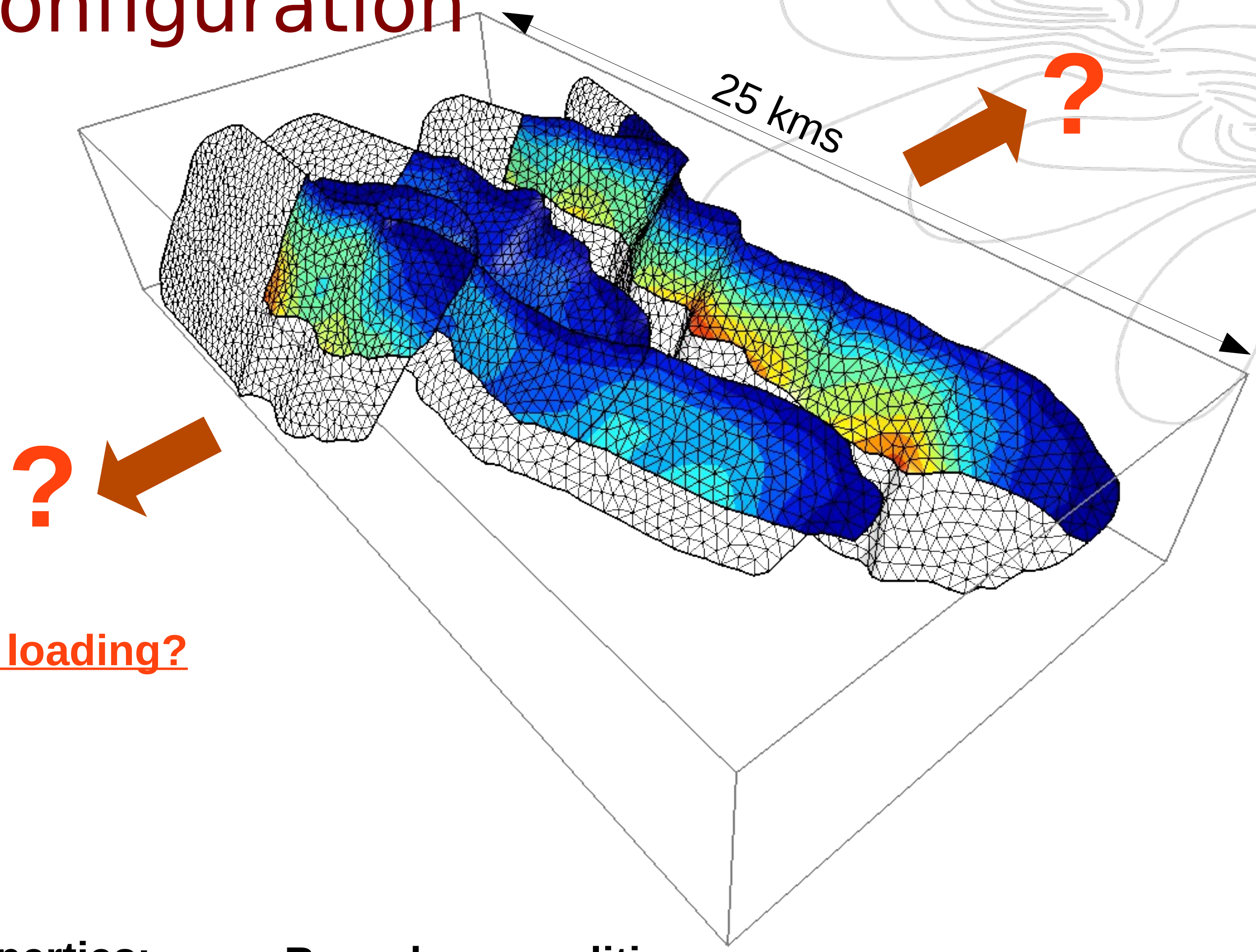
ν = 0.21

Boundary conditions:

Imposed dip-slip: $0 < D_x \leq 1300\mathrm{m}$ (colored parts)

Faults free to slip

Model configuration



Tectonic loading?

$\varepsilon_H = ?$

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Rock properties:

E = 45 GPa

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Boundary conditions:

Imposed dip-slip: $0 < D_x \leq 1300\mathrm{m}$ (colored parts)

Faults free to slip

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Paleostrain and slip recovery

Paleostrain recovery

Recovered (2mn)

ε_H = N11W (-0.14)

ε_h = N79E (-0.25)

ε_v = (0.1)

Recovered (from restoration)

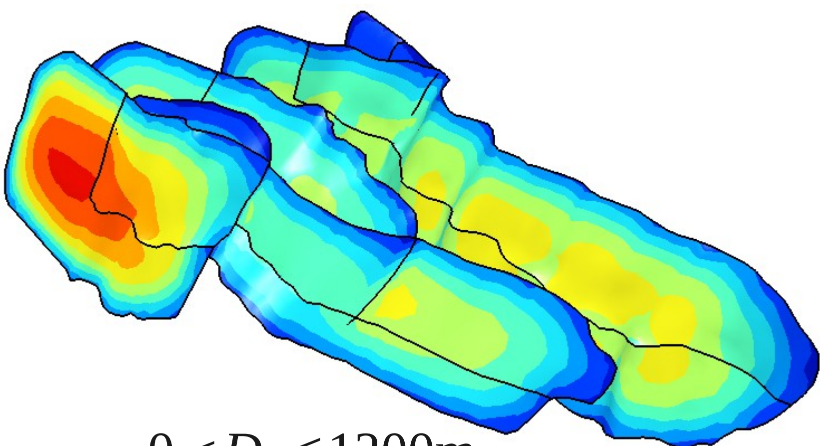
ε_H = N10W (-0.04)

ε_h = N80E (-0.13)

ε_v = (0.17)

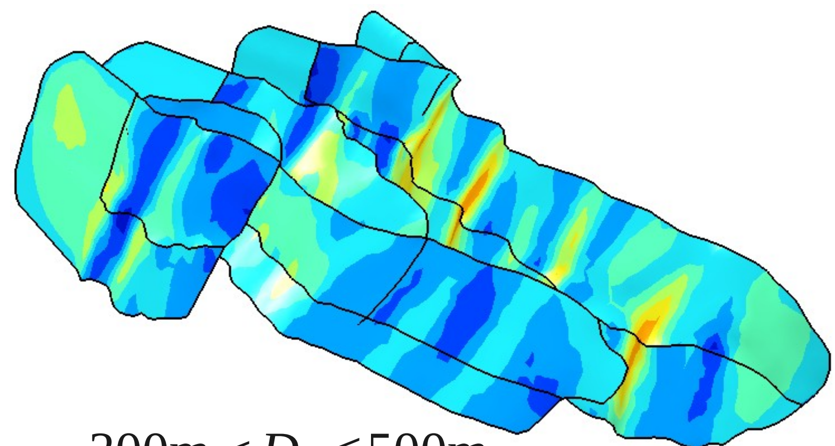
(Maerten et al., 2006)

Dip-slip recovery



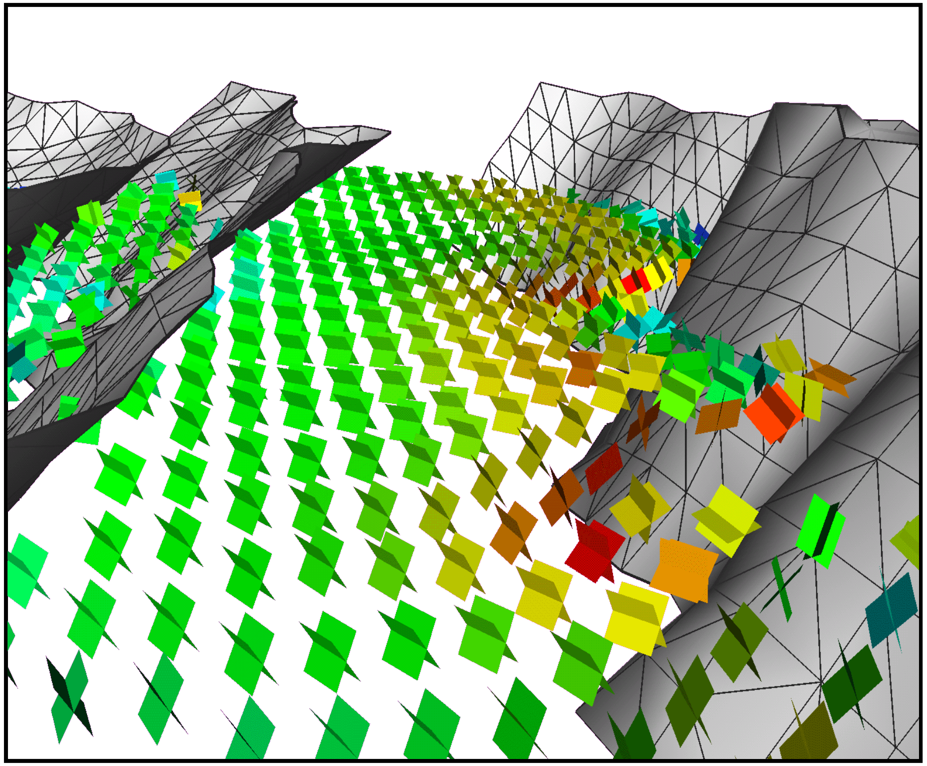
$$0 < D_x \leq 1200\text{m}$$

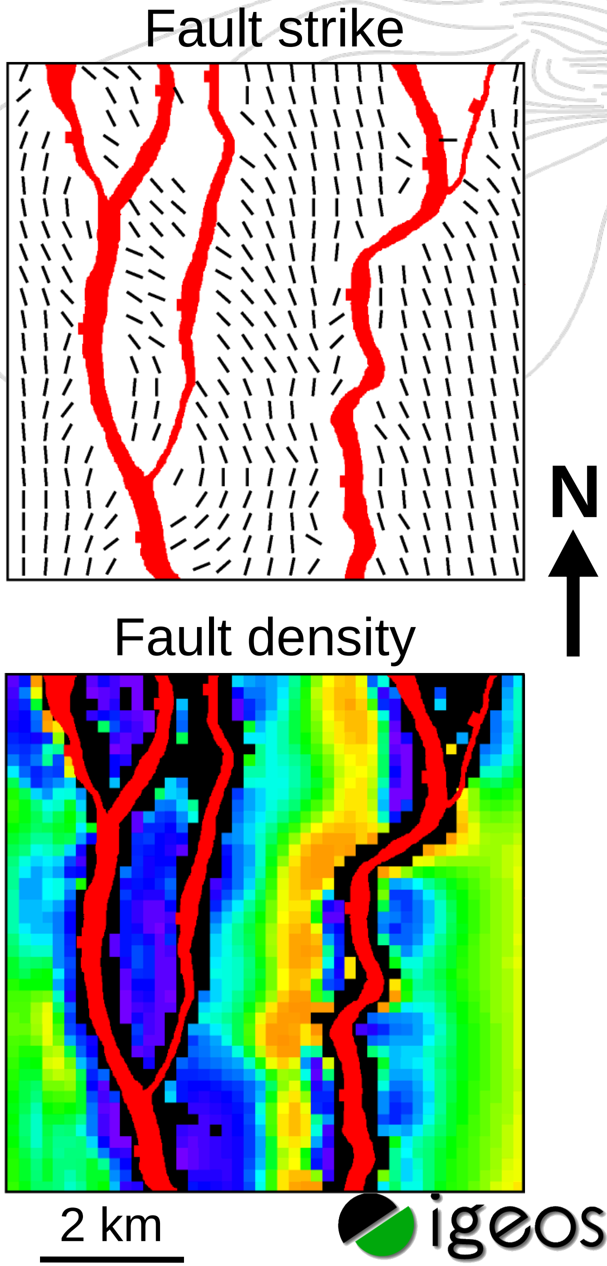
Strike-slip recovery



$$-300\text{m} < D_y \leq 500\text{m}$$

Subseismic fault and fracture modeling



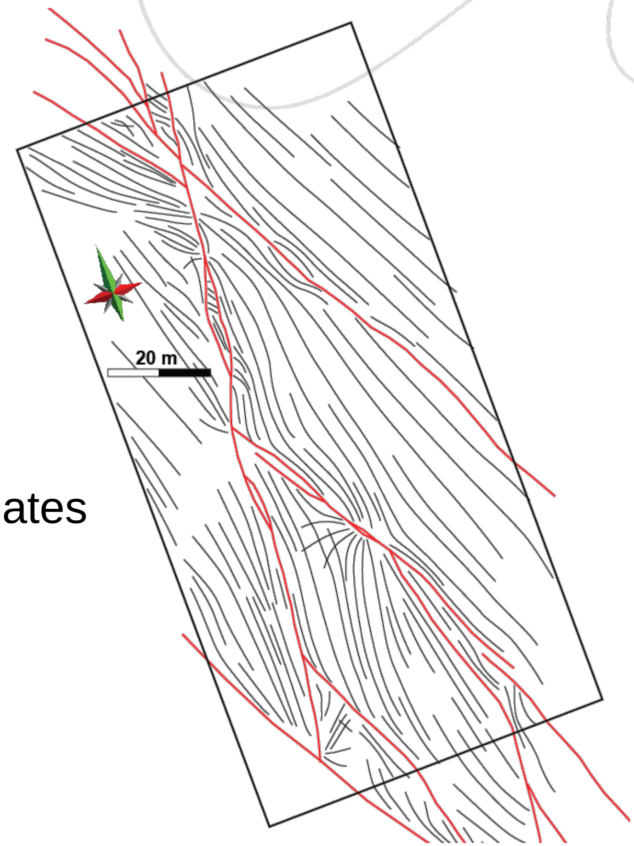


Conclusions

- Geomechanically based inversion
- Recover for both paleostress/strain and unknown displacements onto the faults
- Fast and simple method
- Can give a good estimate of the paleostress/strain (single phase)

Future work

- Will take into account measured fracture orientation from field observations, wellbore, seismic data,etc. to better constrain the inversion.



Curved joint networks in carbonates
at Nash Point, England

Thanks for your attention

Available for research at: www.igeoss.com

References cited:

Maerten, L., Gillespie, P., Daniel, J.-M., 2006, 3-D geomechanical modeling for constraint of subseismic fault simulation, AAPG bulletin, v.90

Maerten, F., Resor, P. G., Pollard, D. D., Maerten, L., 2005, Inverting for Slip on Three-Dimensional Fault Surfaces using Angular Dislocations, BSSA, v.95

Publications (in prep.):

Theory: with O. Kaven and D. Pollard

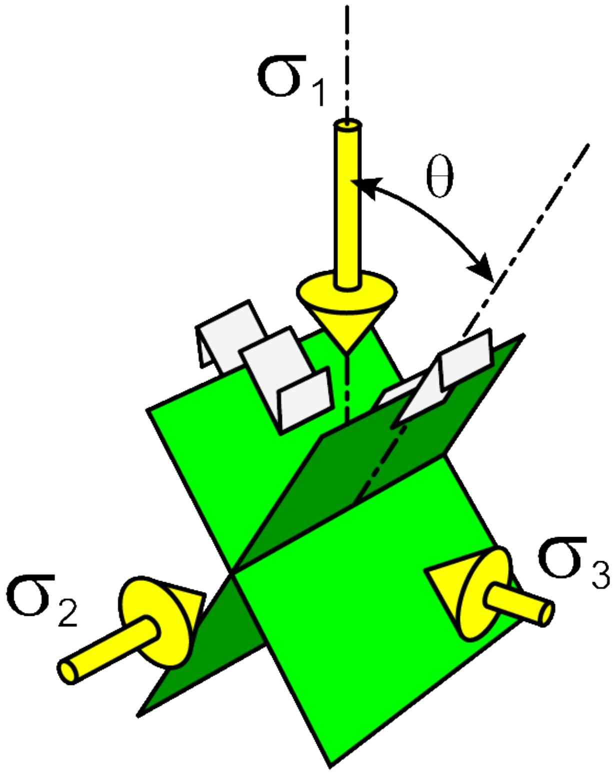
Application: with P. Lovely, E. Flodin, C. Guzofski and D. Pollard

Input: known b_k
Output: unknown b_u and σ^R
while not converge **do**
  S1: Solve for b_u using Poly3D and the resolved σ^R as BC and b_k
  S2: Solve for the unknown σ^R using b_u and b_k
  Resolve σ^R on each triangular elements as initial BC
end

Failure criterion for faults

Direction and density of potential faults

Coulomb shear failure criterion



$$\tan 2\theta = \mp \frac{1}{\mu}$$

$$Sc = \frac{\sigma_1 - \sigma_3}{2}\sqrt{(1+\mu^2)} - \mu\,\frac{\sigma_1 + \sigma_3}{2}$$

Sc represents the amount of shear stress on the two planes optimally oriented for failure.

References

Maerten, L., P. Gillespie, and J. M. Daniel, 2006, 3-D geomechanical modeling for constraint of subseismic fault simulation, AAPG Bulletin, v. 90, p. 1337-1358.

Maerten, F., P G. Resor, D. D. Pollard, and L. Maerten, 2005, Inverting for slip on three-dimensional fault surfaces using angular dislocations, BSSA, v. 95.