# GÉOMÉCANIQUE APPLIQUÉE À LA CARACTÉRISATION DE RÉSERVOIRS DANS DES FORMATIONS GÉOLOGIQUES À STRUCTURE COMPLEXE : ILLUSTRATION PAR LE STOCKAGE GÉOLOGIQUE DU $CO_2$

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IFP Energies nouvelles

# OUTLINE

- About geomechanical coupling
  - Coupling fluid flow and geomechanics
  - Coupling approaches
  - The case of continuous models: illustration on SAGD process

- The case of non-continuous models, overview of faults and geomechanical modeling
  - Workflow to model fault in reservoir context
  - Some methods from basin modeling context
  - An example of fault modeling in a reservoir context: application to $CO_2$ storage

- Conclusions and perspectives

# COUPLING FLUID FLOW AND GEOMECHANICS

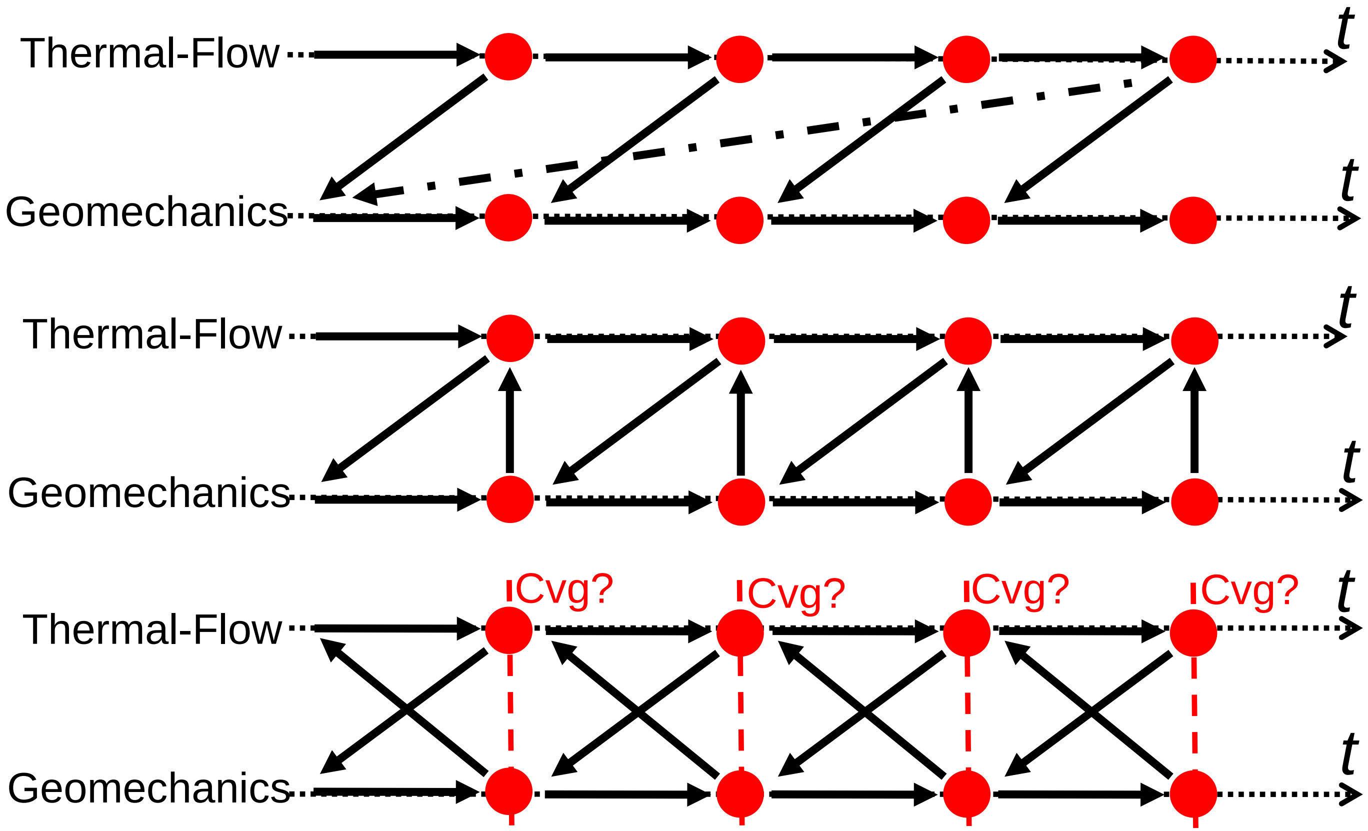
- Historical reservoir approach
  - No stress equilibrium
  - Simplified geomechanics integrated in dynamic fluid flow simulator
    - Pressure-temperature-vertical stress / porous volume dependency
    - Pressure-temperature / permeability dependency

- Real coupling objectives
  - Well stability
  - Faults reactivation/sliding
  - Caprock integrity/overpressures
  - Subsidency
  - Effect of geomechanics on fluid flow
  - Fracturing and fracture opening/closing

# COUPLING APPROACHES

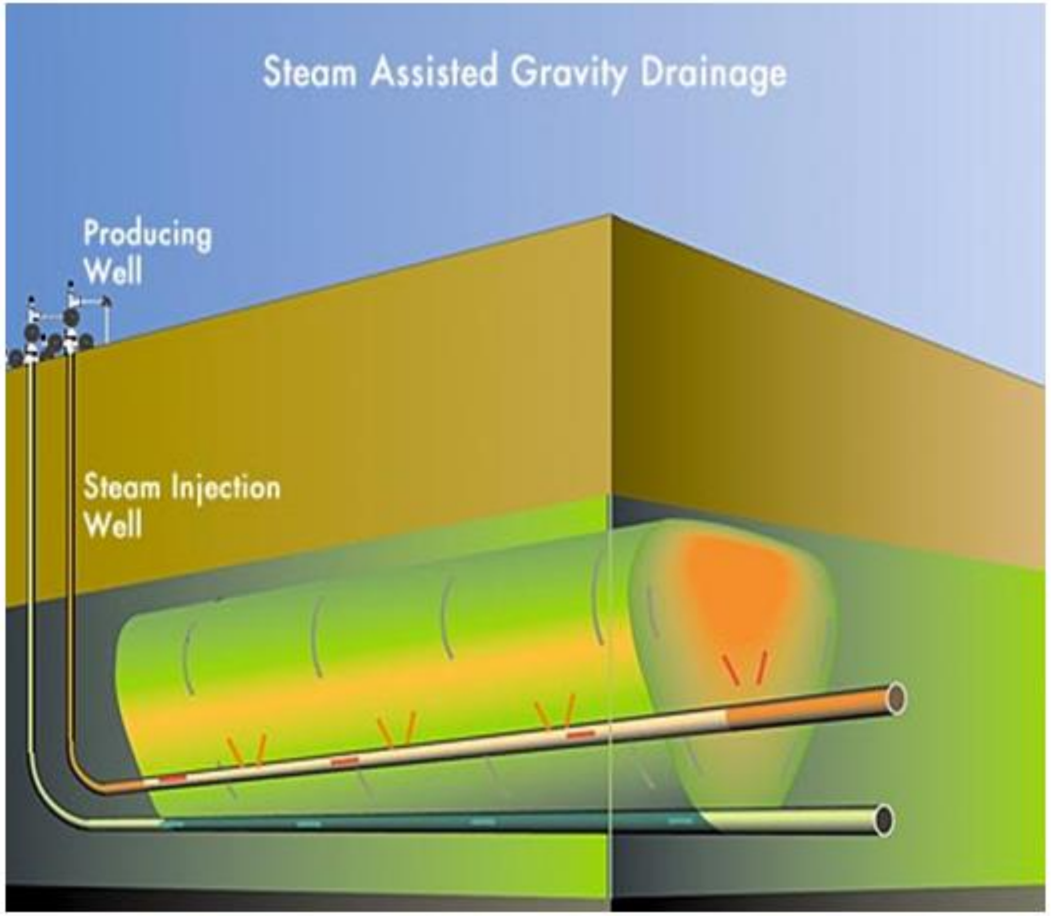
## Algorithms

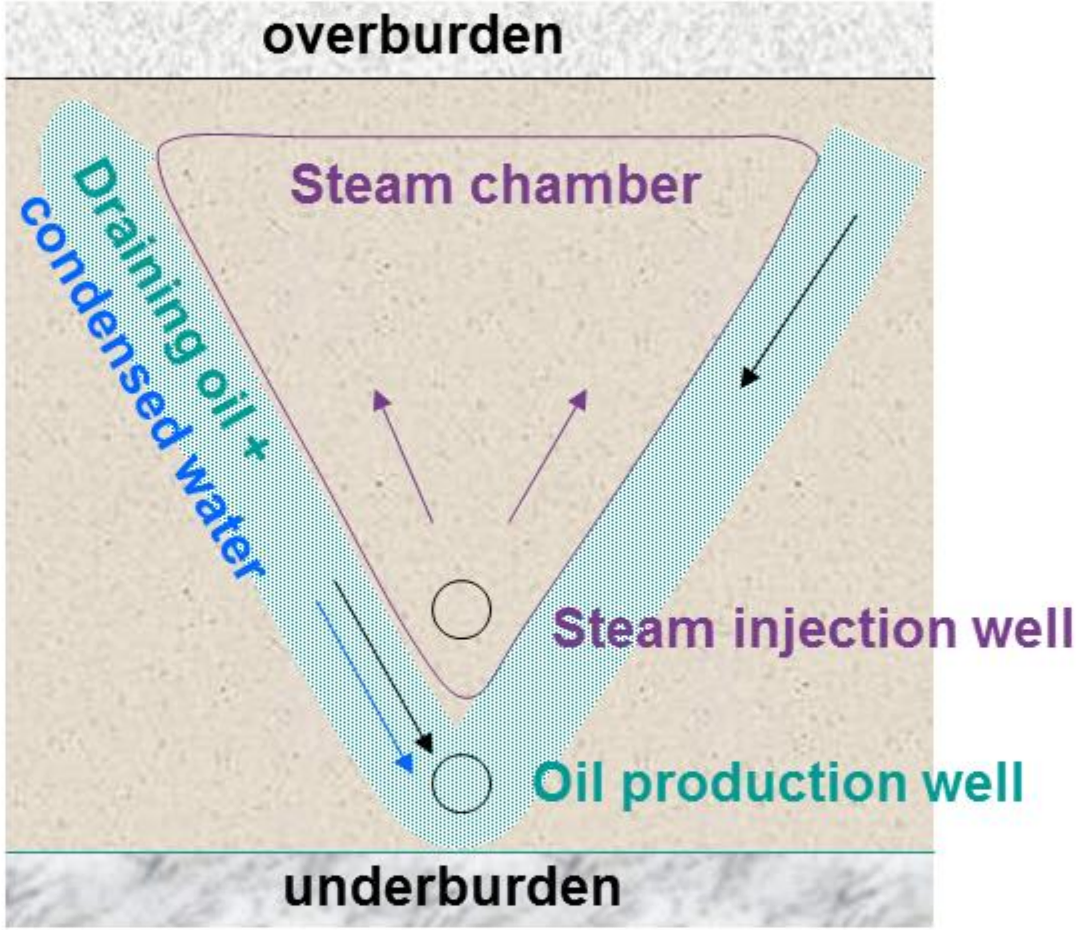
- One way
- Sequential explicit
- Sequential iterative




Zandi et al. 2011

# SAGD PROCESS: PRINCIPLE

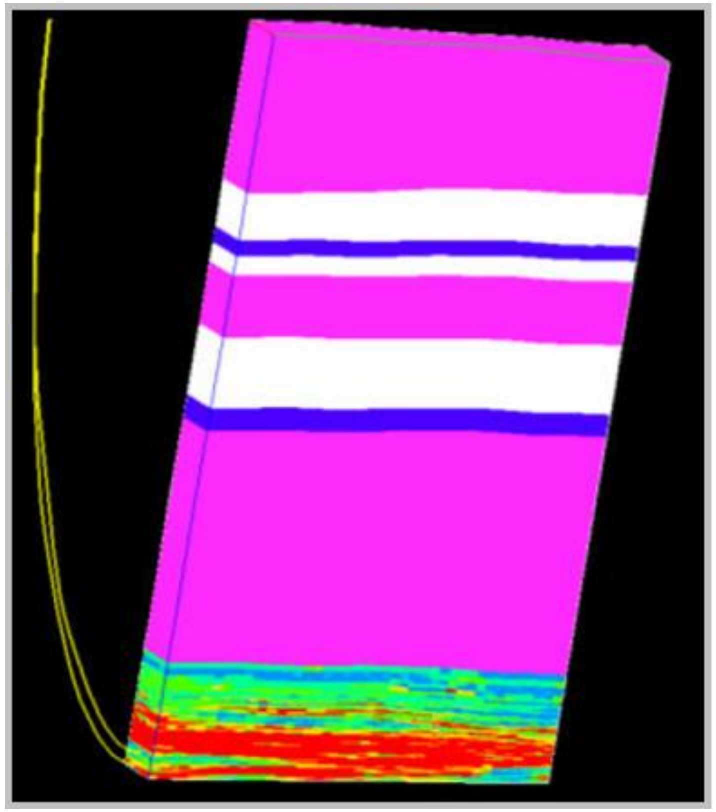



- Involve thermal multiphase flow (here considering a dead oil model) eventually in an heterogeneous media
- Significant geomechanical effects

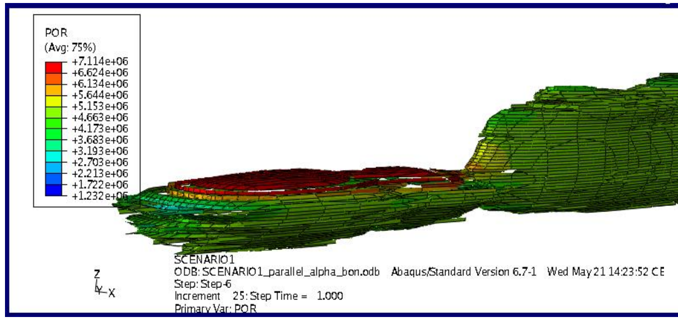
# AN EXAMPLE OF EXPLICIT COUPLING

*Key phenomena: fracturing, fracture opening/closing, dilatancy*

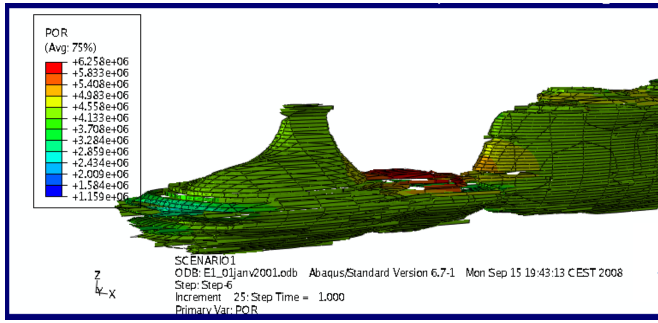


Lerat et al. 2010

Steam chamber (100°C) after 6 months of production




One way – clay = barrier




Sequential – Clay fracture

Sequential coupling with similar geometry in the reservoir area has a strong influence on steam chamber shape

**EXAMPLE WITH:**

**Sequential iterative coupling**

**+**

**Separate grids for Reservoir and Geomechanics (here, AMR reservoir grid)**

**+**

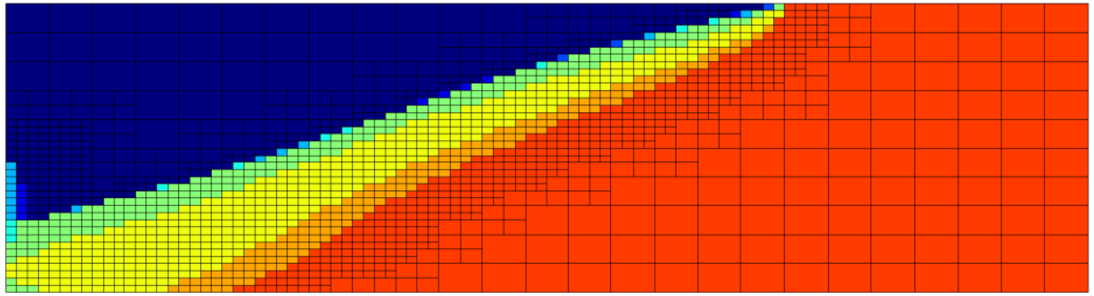
**Diffuse Approximation Method**

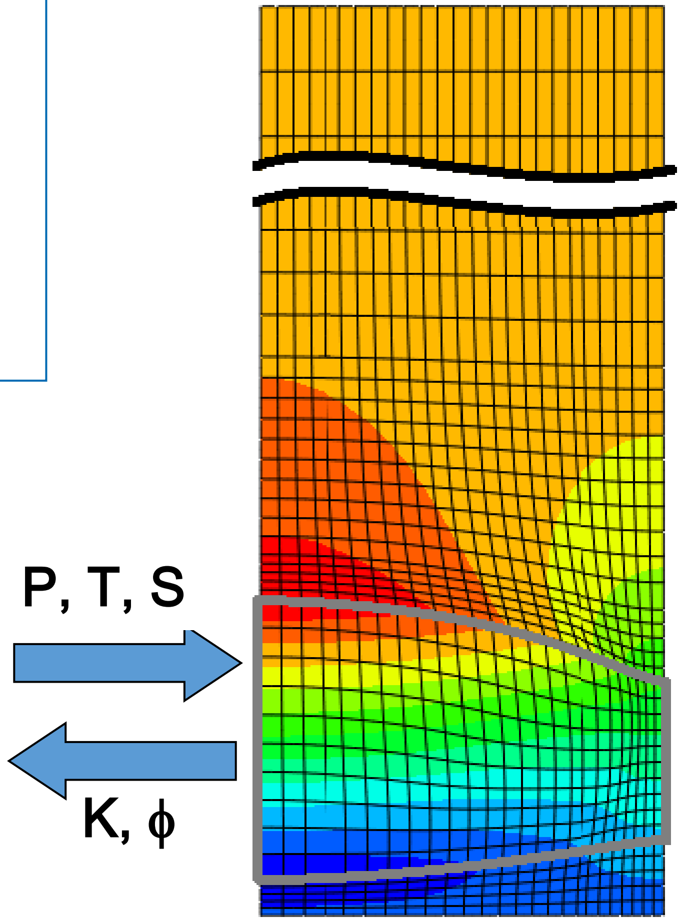
**Geomechanical Model**

Vertical displacement on deformed grid

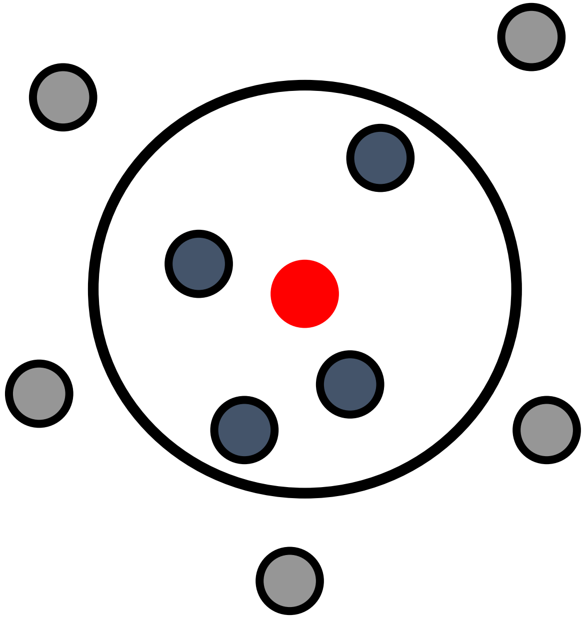
**Reservoir AMR-model**

Oil Saturation



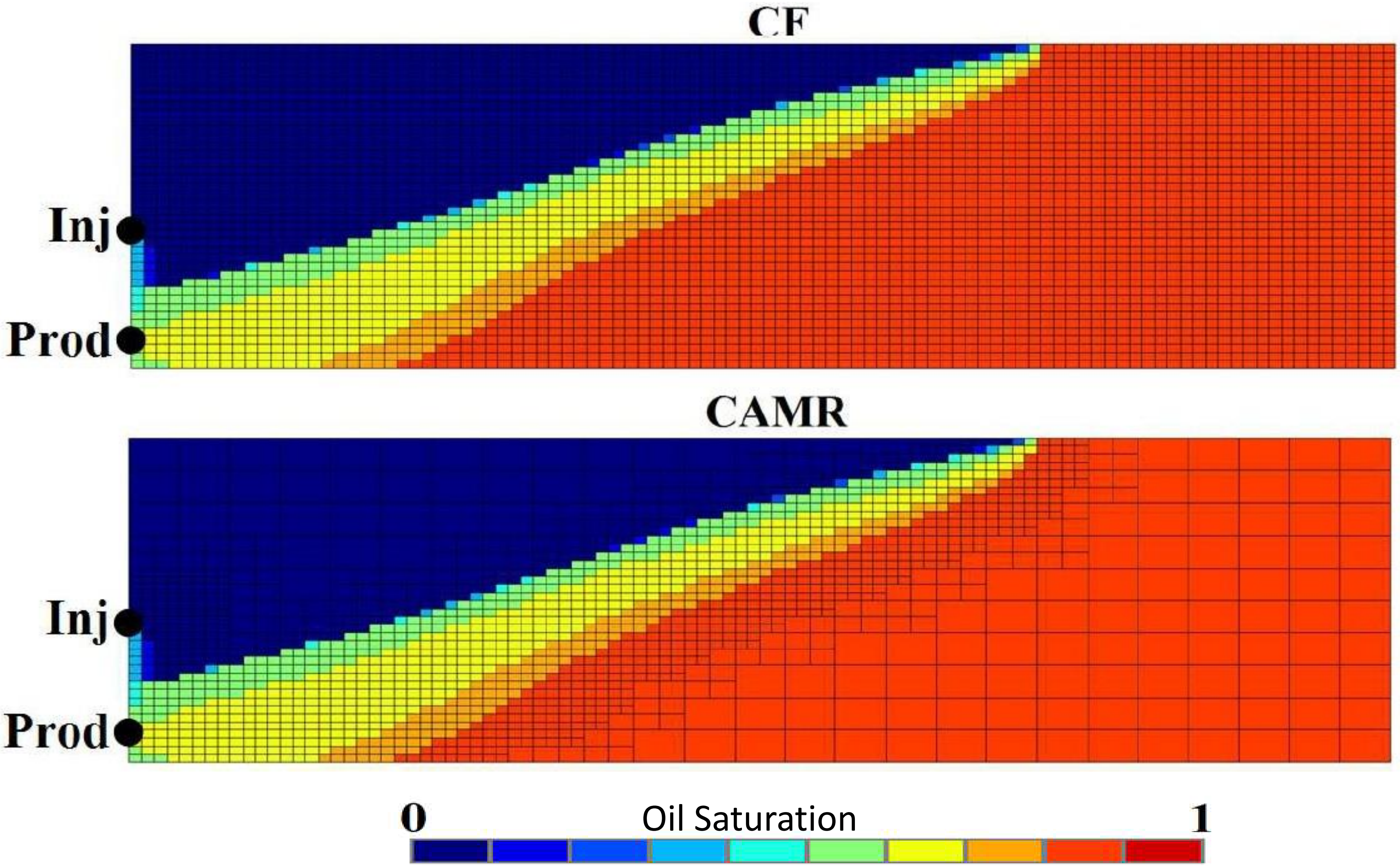



Diffuse approximation method



Guy et al. 2012

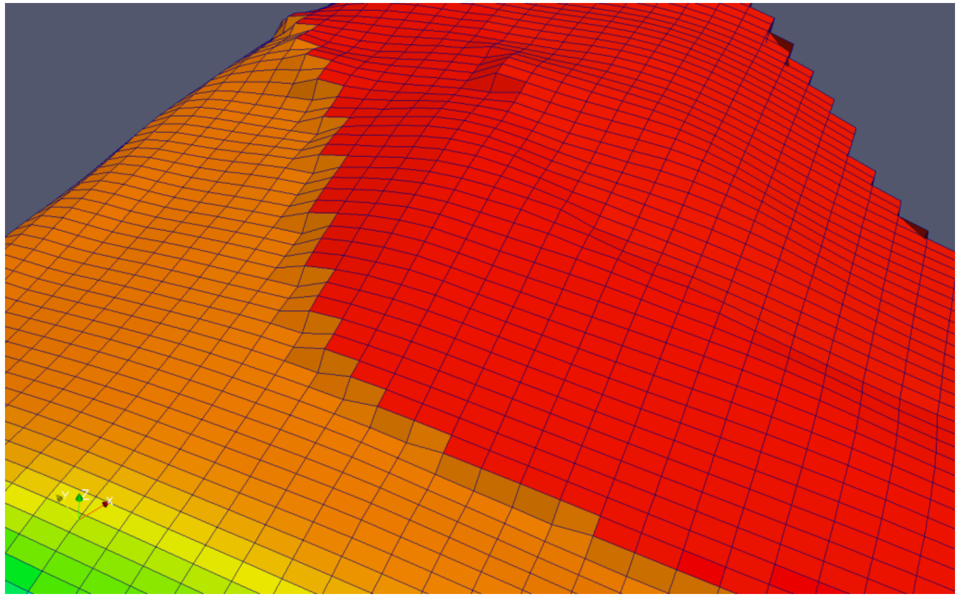
# STEAM CHAMBER GROWTH WITH AND WITHOUT AMR



# HANDLING FAULT MODELING

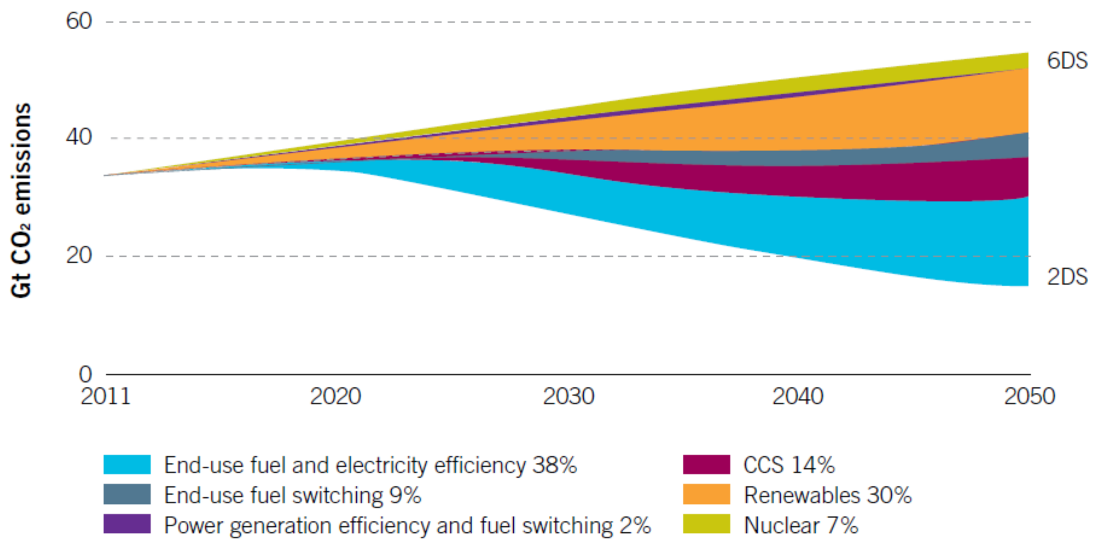
- Major issues
  - Meshing
    - In reservoir, stair stepping with CPG grid are not suited for geomechanical computation
    - …
  - Defining properties
    - Permeability/conductivity along and across the fault
    - Mechanical properties
    - The fault material is mostly unknown

      → A solution for flow related properties in basin context

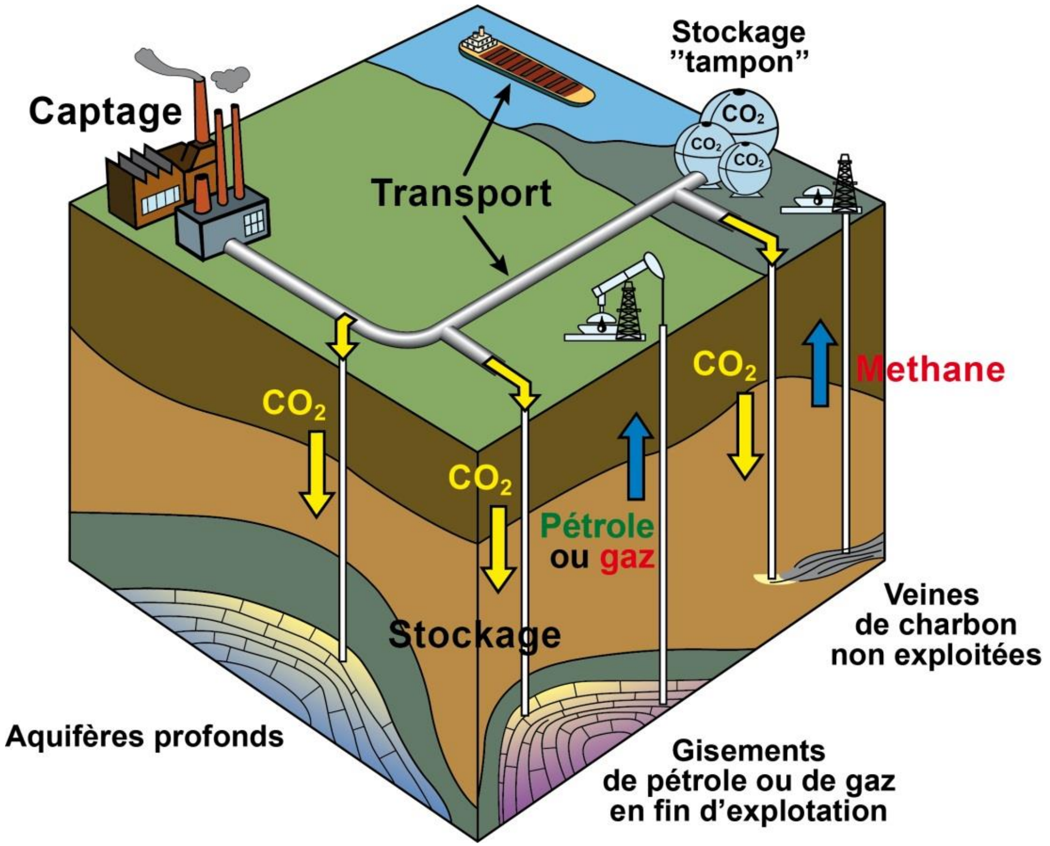


# CARBON CAPTURE AND STORAGE

- One of the key options to reconcile the rising demand for fossil fuels with the need for reducing greenhouse gas emissions in the transition to a low-carbon economy
  - ➢ Fight against the climate change by decarbonising the energy mix



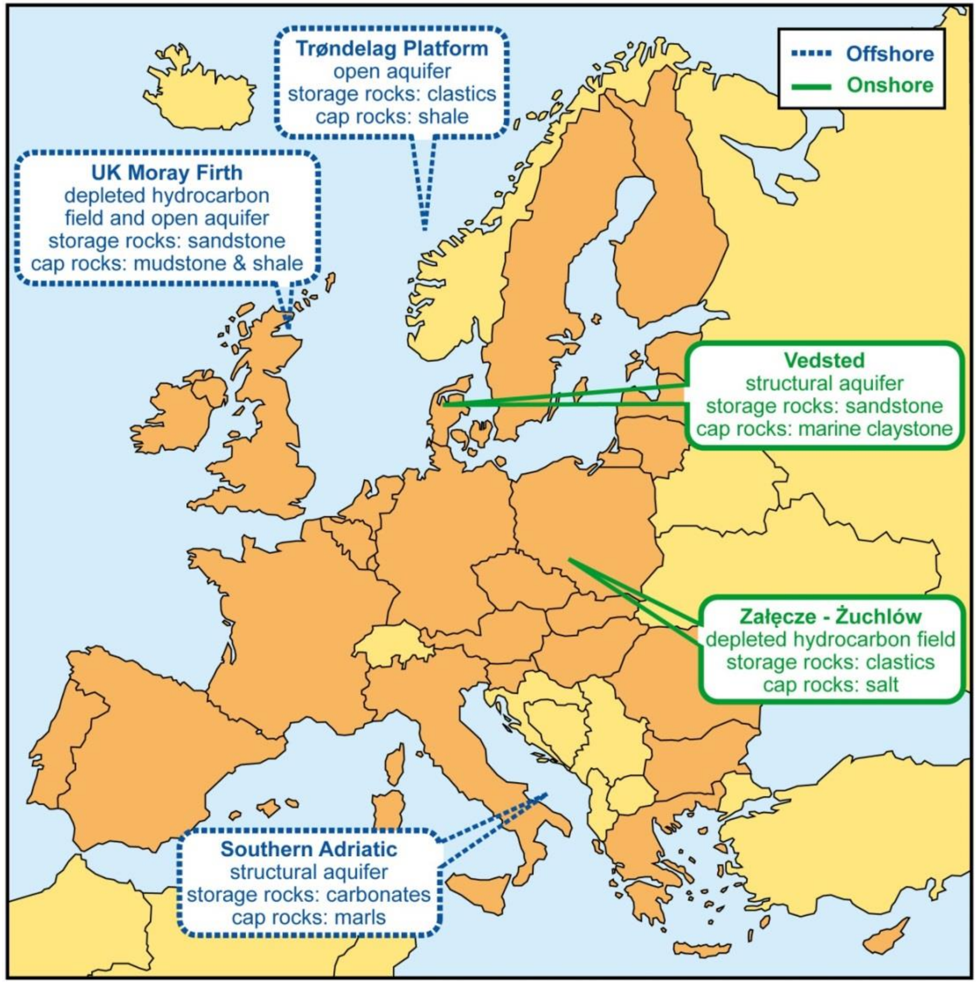

**Source:** IEA, 2014. *Energy Technology Perspectives 2014.*



# SITECHAR - CHARACTERIZATION OF EUROPEAN $CO_2$ STORAGE

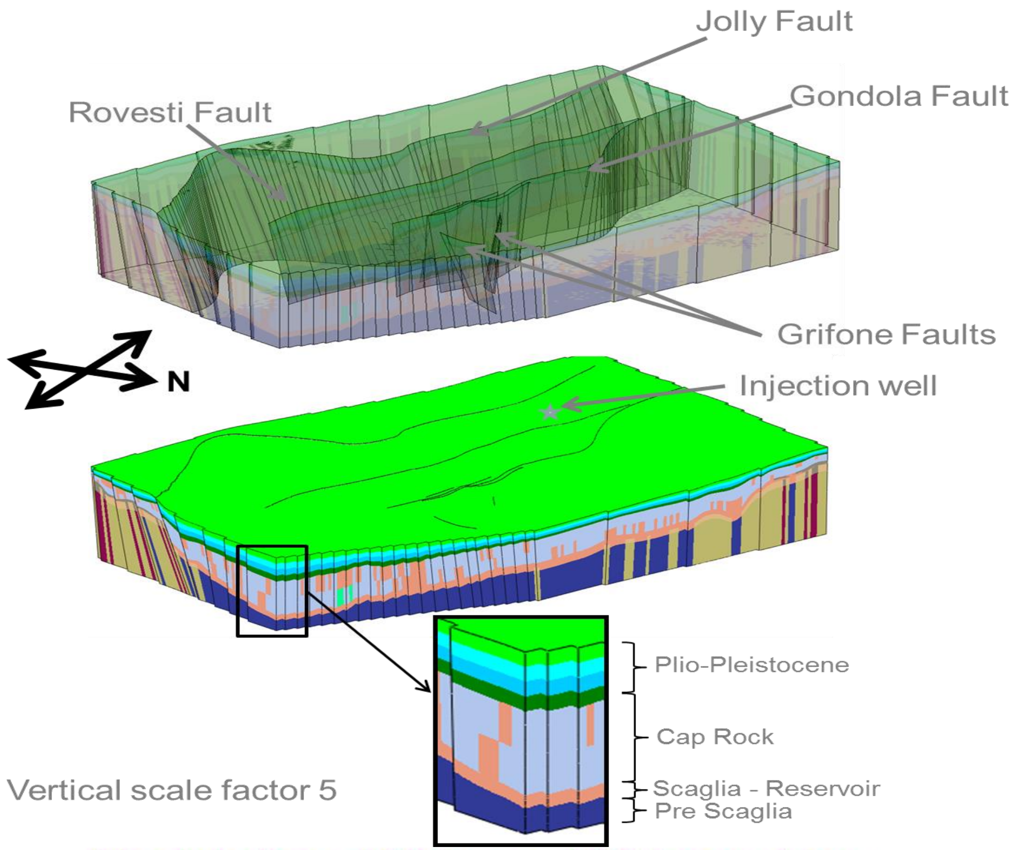
Provide the key steps required to make on-time effective large-scale implementation of $CO_2$ storage in Europe

- Demonstrate the level of geological characterization and the assessment of long-term storage complex behaviour in accordance with the regulatory requirements (EC Storage Directive)
- Develop a methodology for the preparation of storage permit applications, accounting for all the technical and economic data, as well as the social dimension
- Raise public awareness and enable informed opinion formation

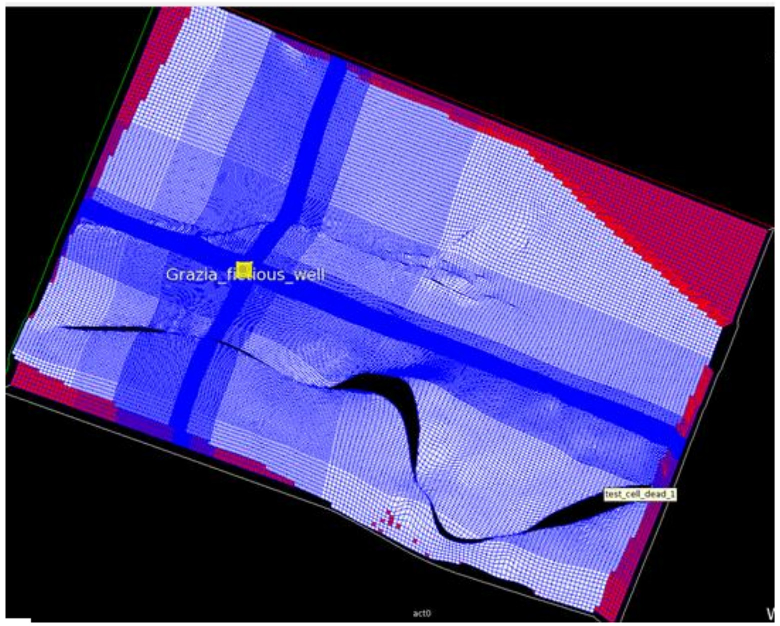



Delprat-Jannaud et al. 2015

# MODELING OF FAULT IN RESERVOIR CONTEXT




Model size: 150 km x 100 km x 4 km



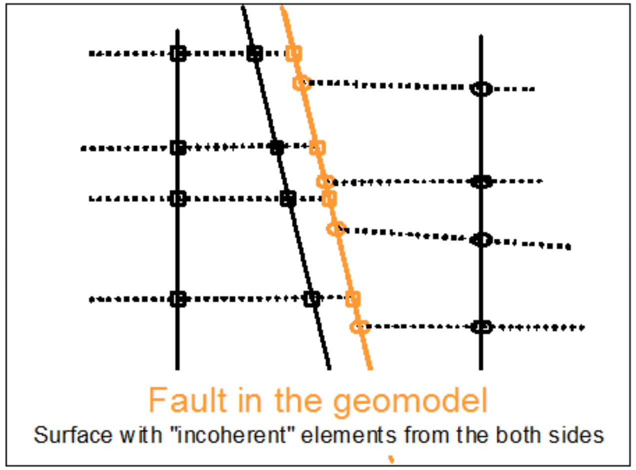
Top view of the reservoir simulator grid

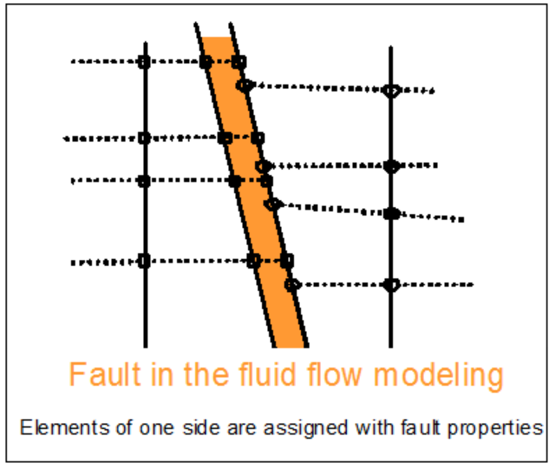
- One-way coupling
- CPG Reservoir grid built to be compatible with geomechanics
- Geomechanical model meshed up to the surface
- Fault modeled by porous cohesive elements in Abaqus

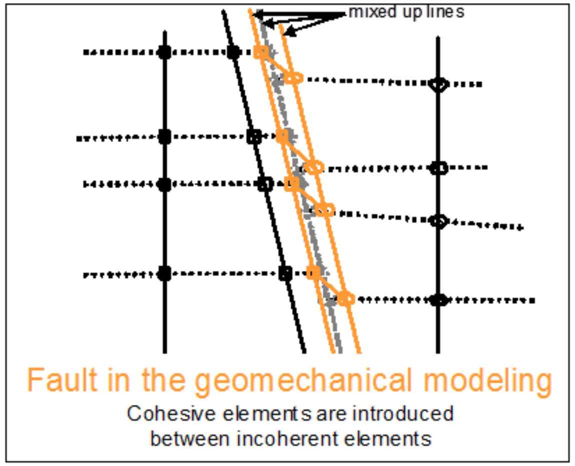
 

## Cohesive elements for geomechanical computations

### Compatible fault representations



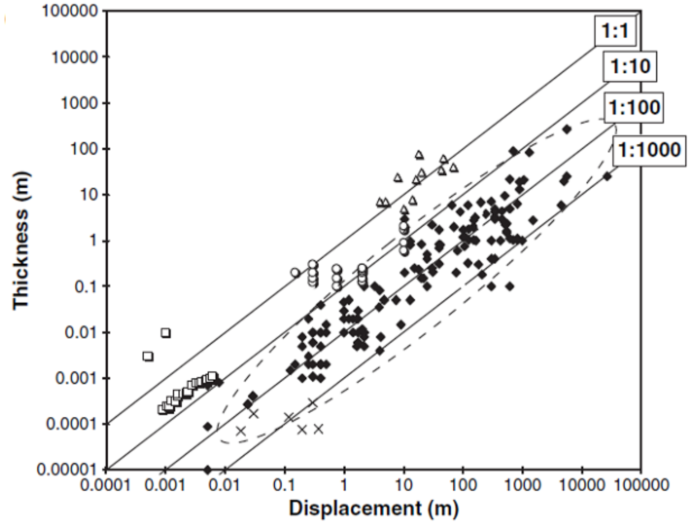




Baroni et al. 2015

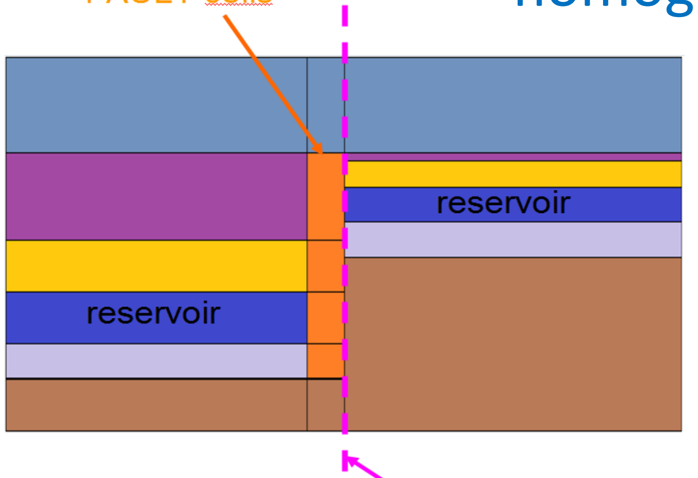
Faults are complex elements and require various representations to make compatible the geometries required by the geomechanical and the fluid flow modelling

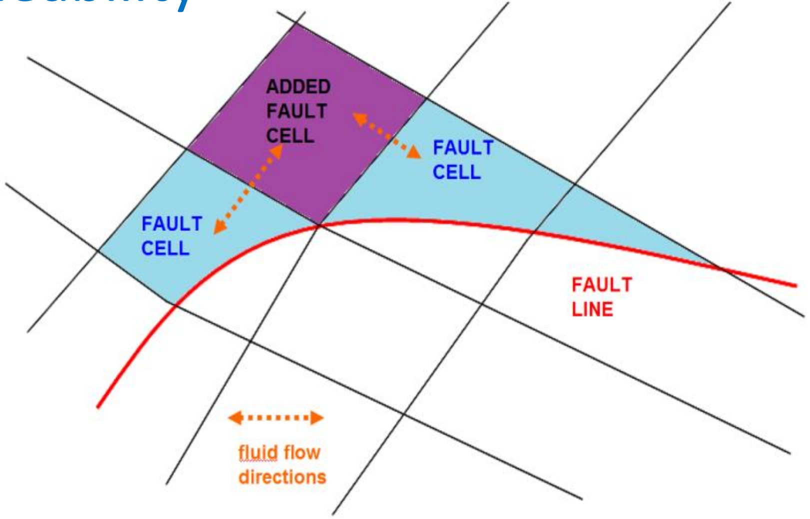
**Fault thickness** is deduced from displacement between both sides considering correlations

Wybberley et al. 2008




**Fault geometry in the reservoir** should allow flow along and across the fault with an homogeneous permeability



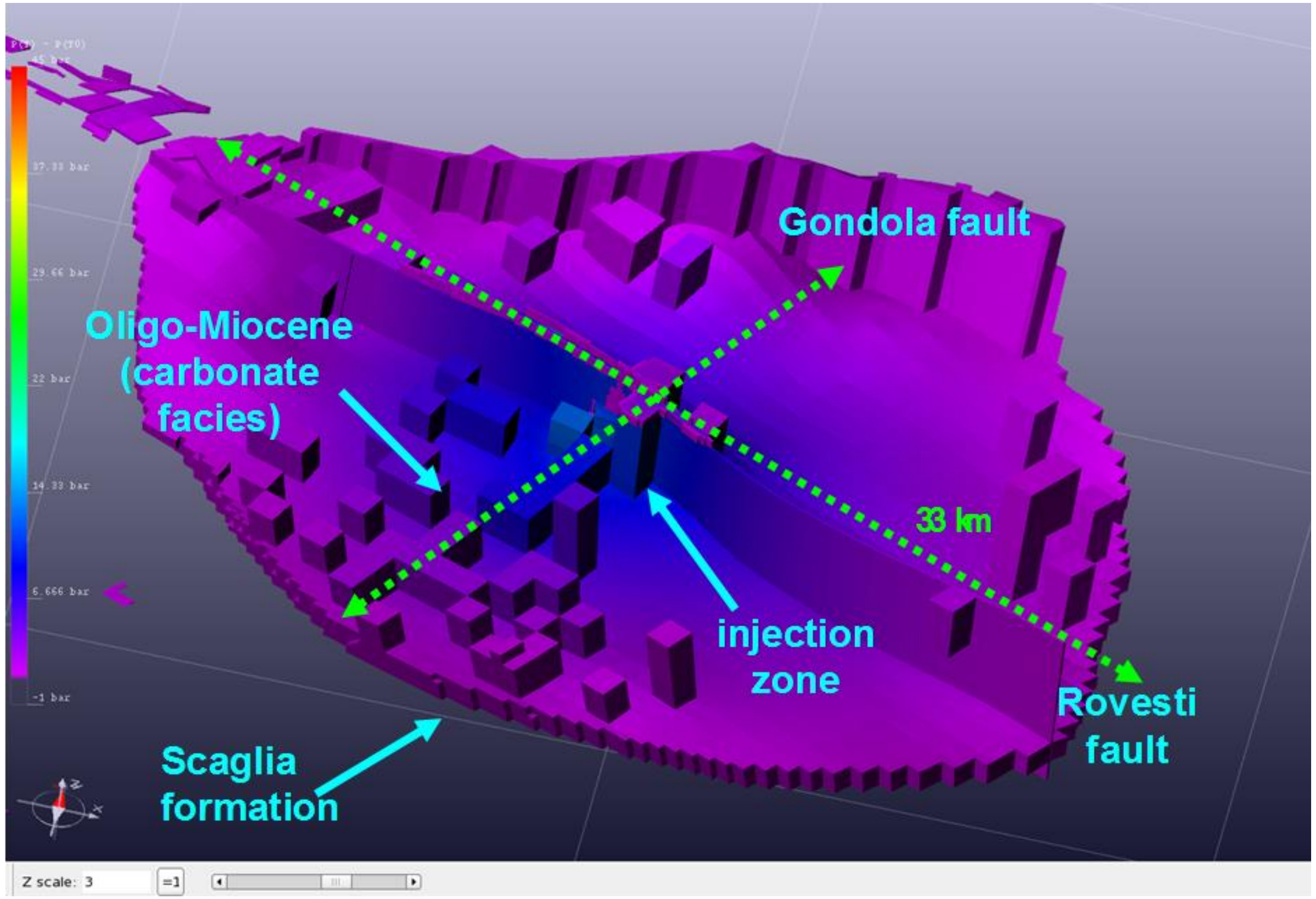



# MODELING OF $CO_2$ INJECTION

The modeling is done over 30 years.
$CO_2$ is injected into Grazia reservoir during 10 y, with an injection rate of 1 Mtonne/year

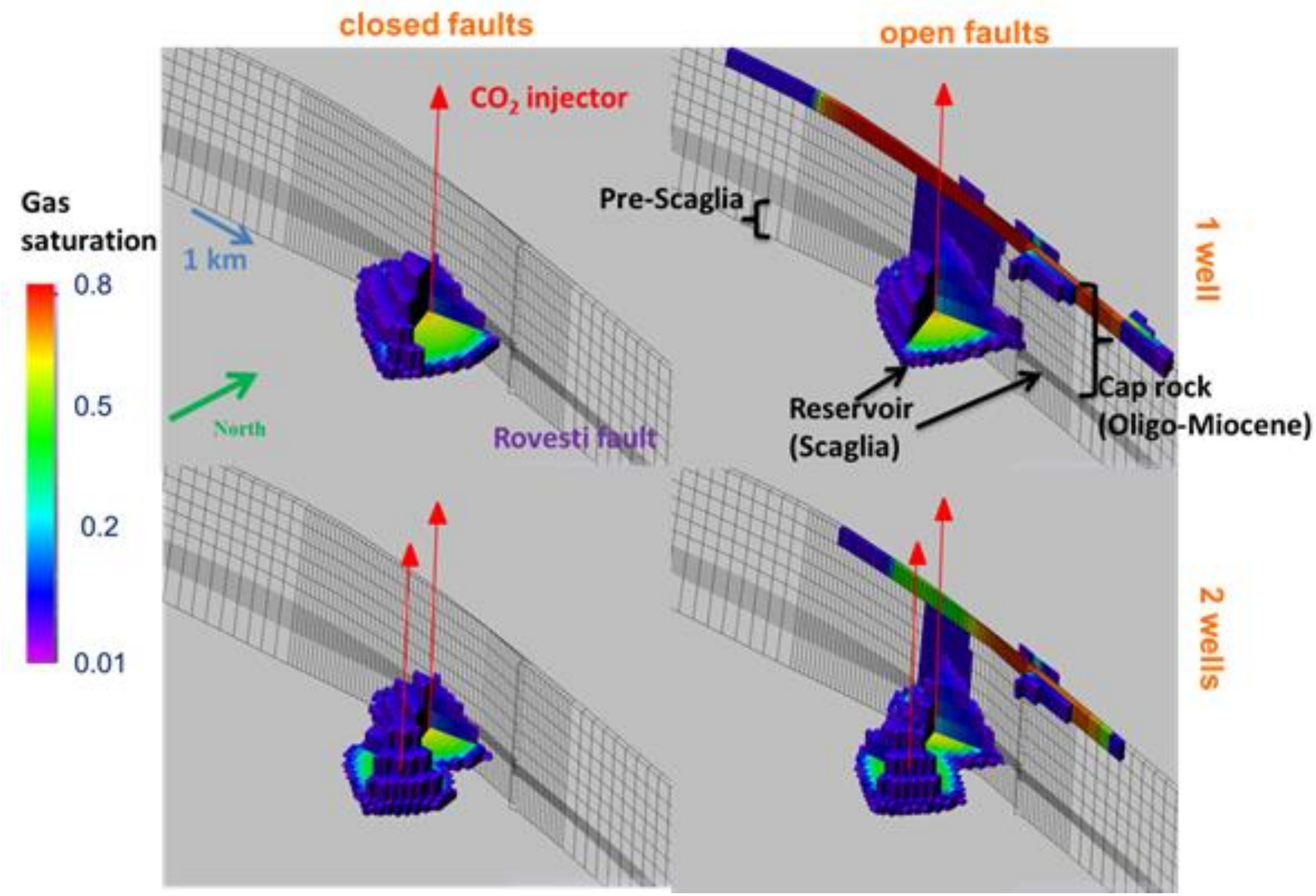
Four regional stress states (=initial state) are considered
SS0, SS45, SS135 & NF



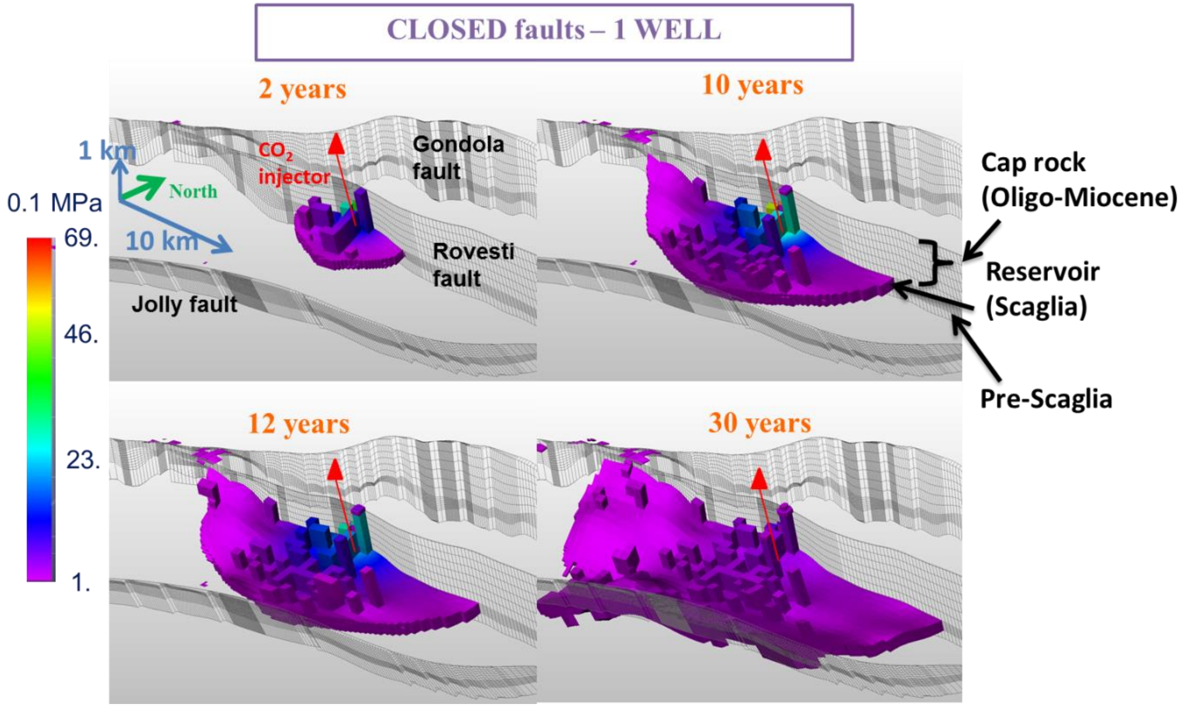

Baroni et al. 2013

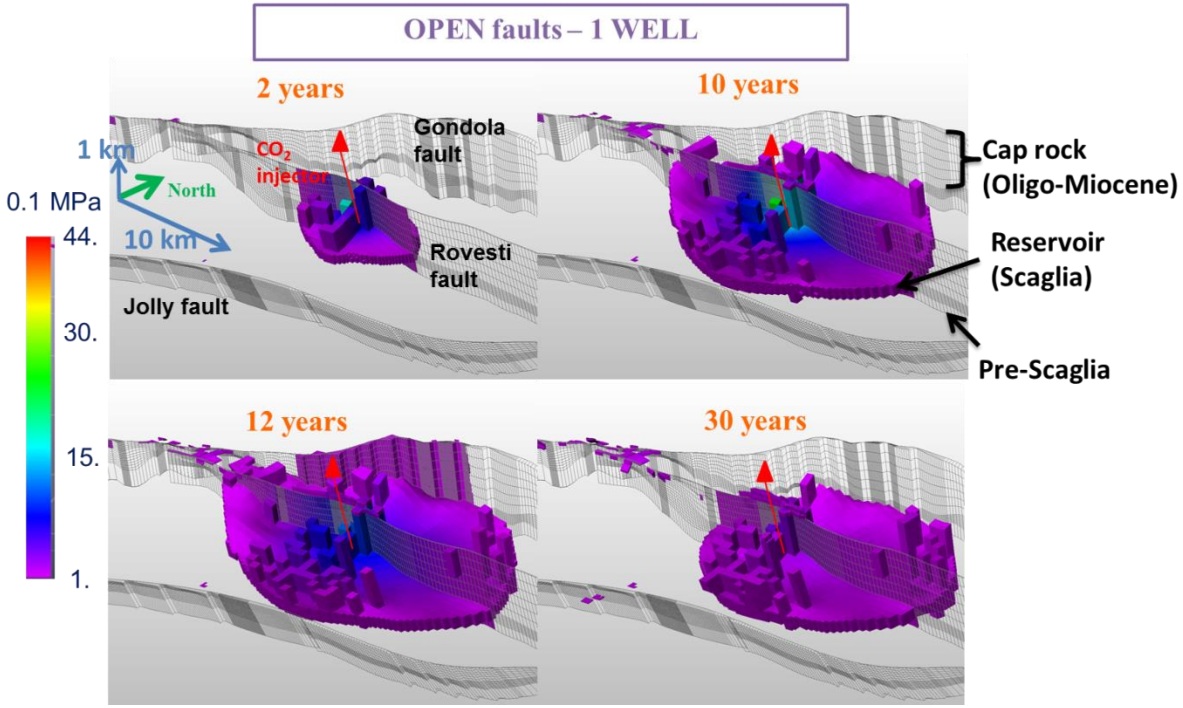
3D overpressure (bar) at 12 years
(OAb – OPEN FAULT scenario)

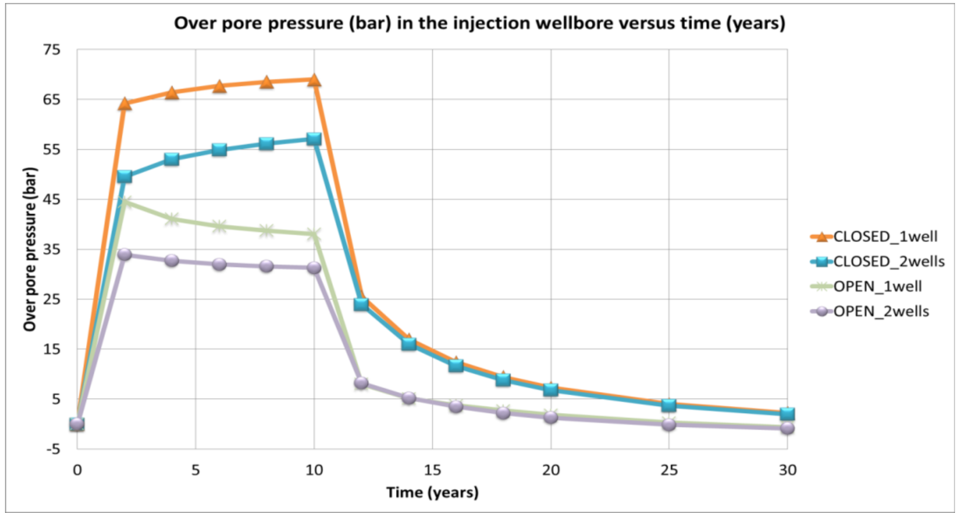
# GAS SATURATION IN TWO SCENARIO



# PORE PRESSURES

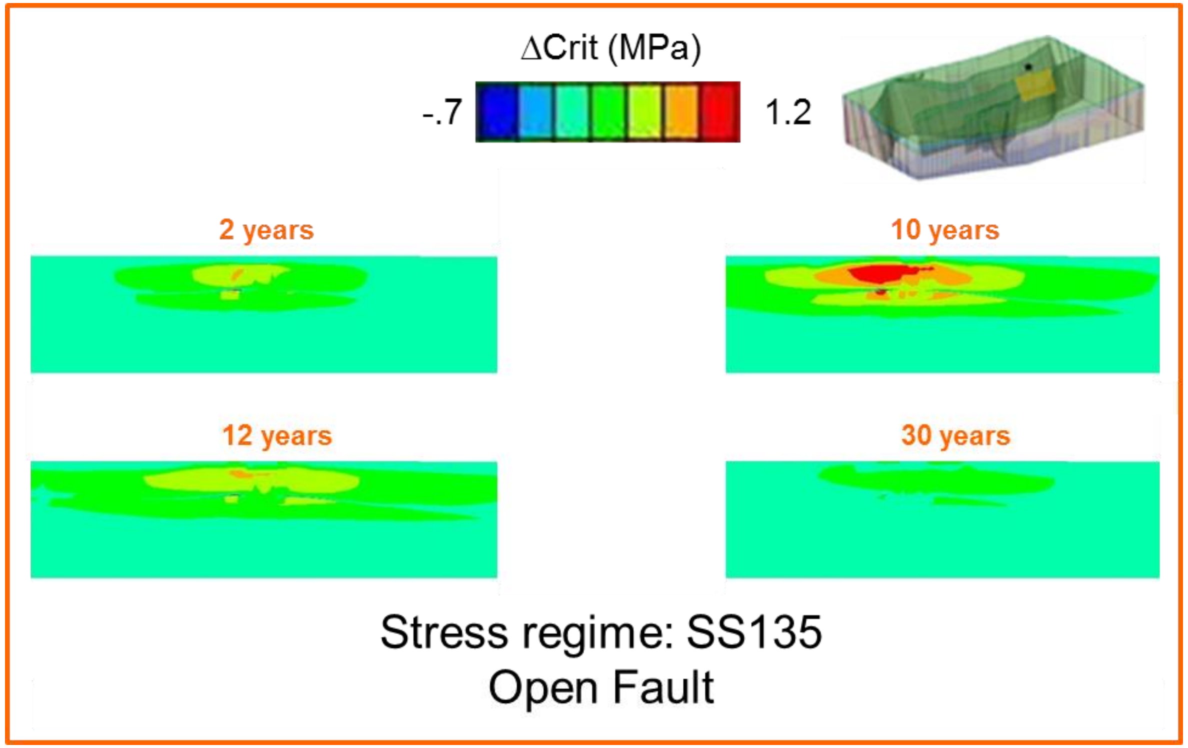


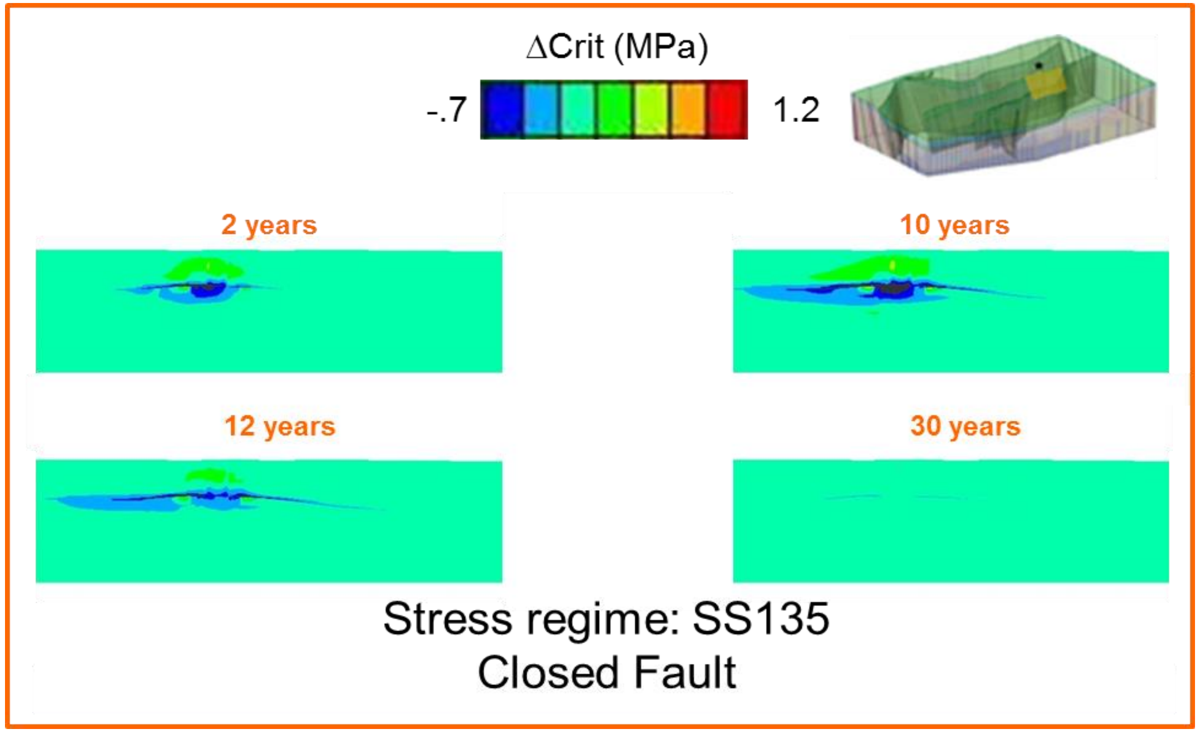



# MODIFICATION OF THE STRESS STATE IN THE FAULT

Post-processing allows the estimation of the fault reactivation through comparing the final stress state with the Mohr-Coulomb criteria for instance.
Computation, results show $\Delta Crit = Crit_{END} - Crit_{INI}$ : if $\Delta Crit > 0$, the area get closer to the criteria.




ΔCrit parameter on Rovesti
If ΔCrit>0, the area get closer to the criteria.

# MODIFICATION OF THE STRESS STATE IN THE FAULT

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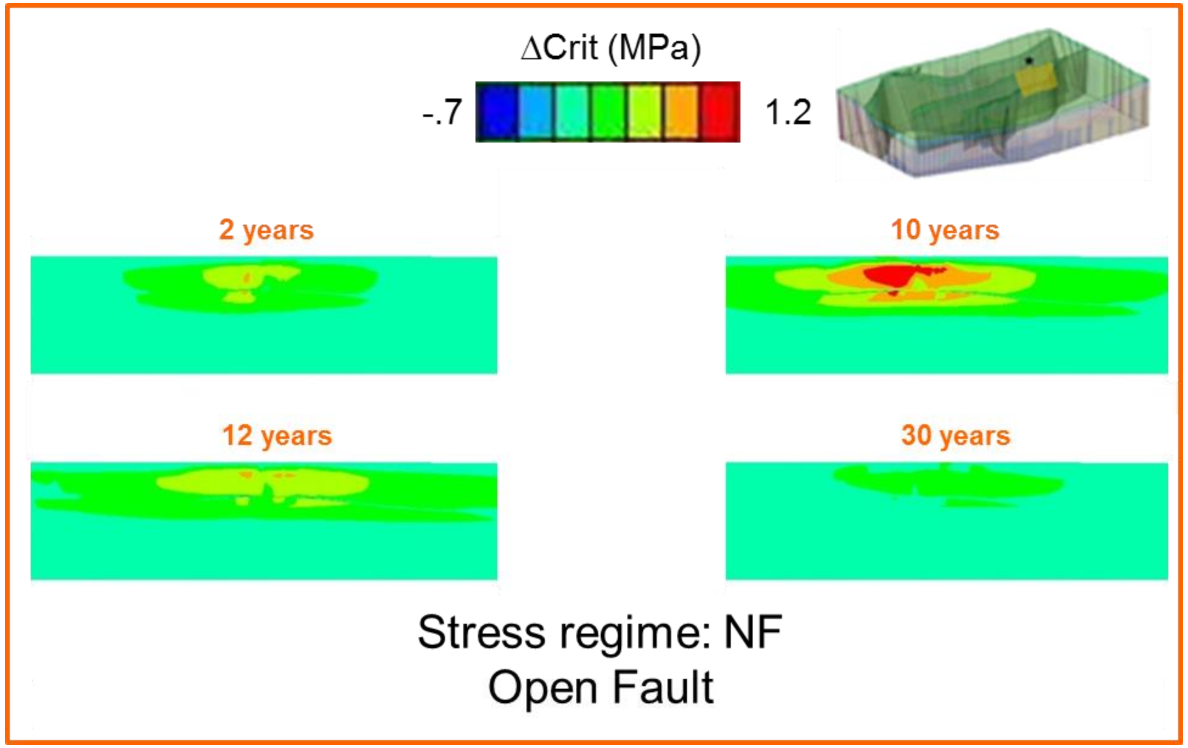
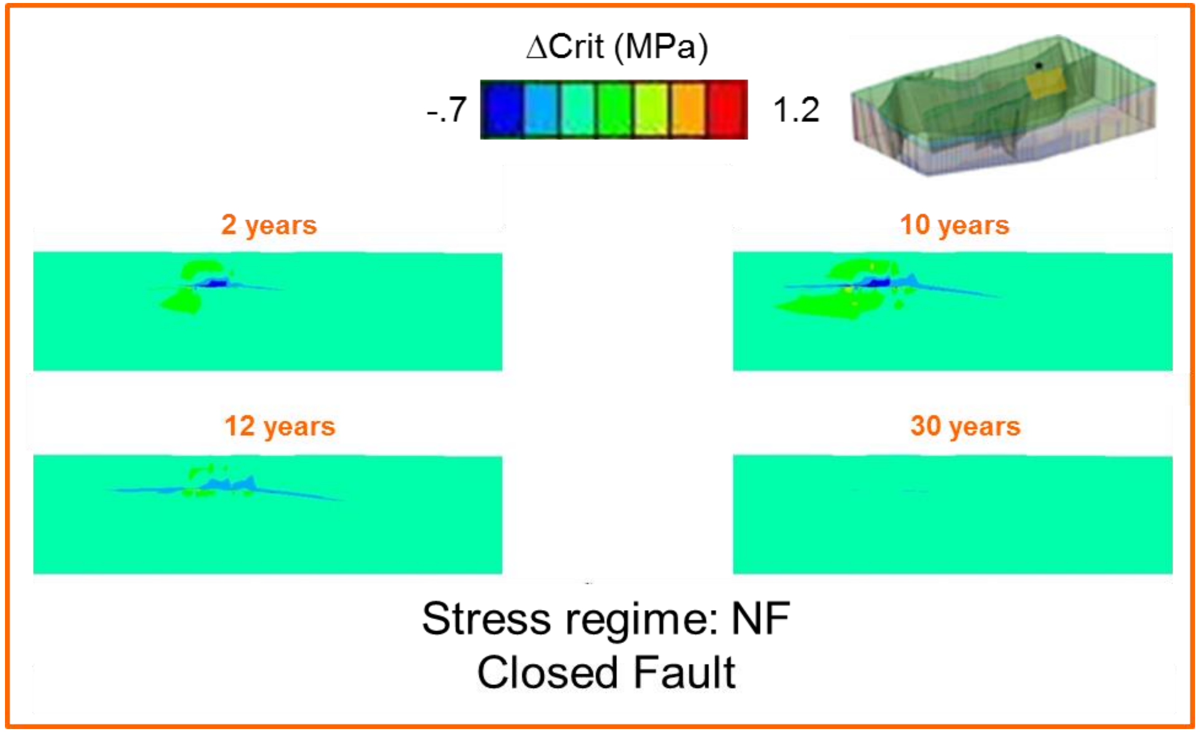



$\Delta$Crit parameter on Rovesti
If $\Delta$Crit>0, the area get closer to the criteria.

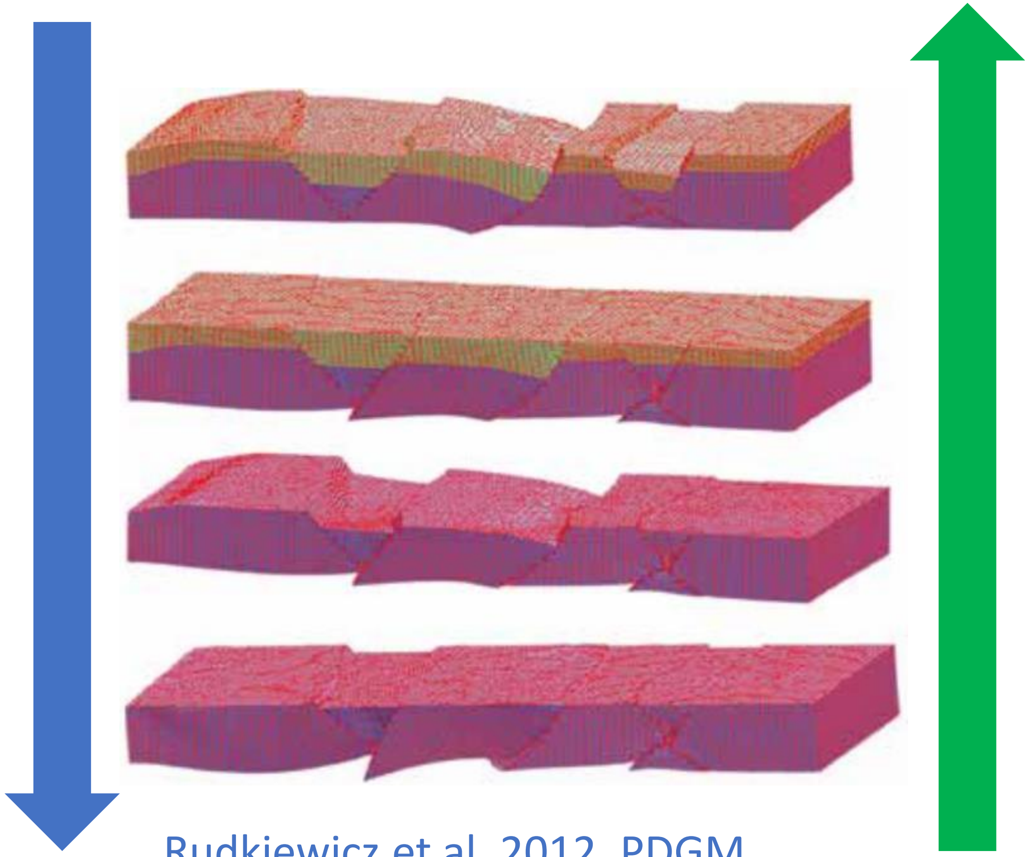
# FAULT PROPERTIES IN BASIN MODELING

- **Aim of basin modeling**

  → Get a better understanding of actual basin state through the modeling of basin history to estimate overpressures and trap location

- **Through the simulation of**
  - *Heat transfer and fluid flow*
  - *Simplified geomechanics (presently)*
  - *With sedimentation and erosion*

- **On an evolving geometry considering**
  - *Finite strain*
  - *Flow along and across faults*

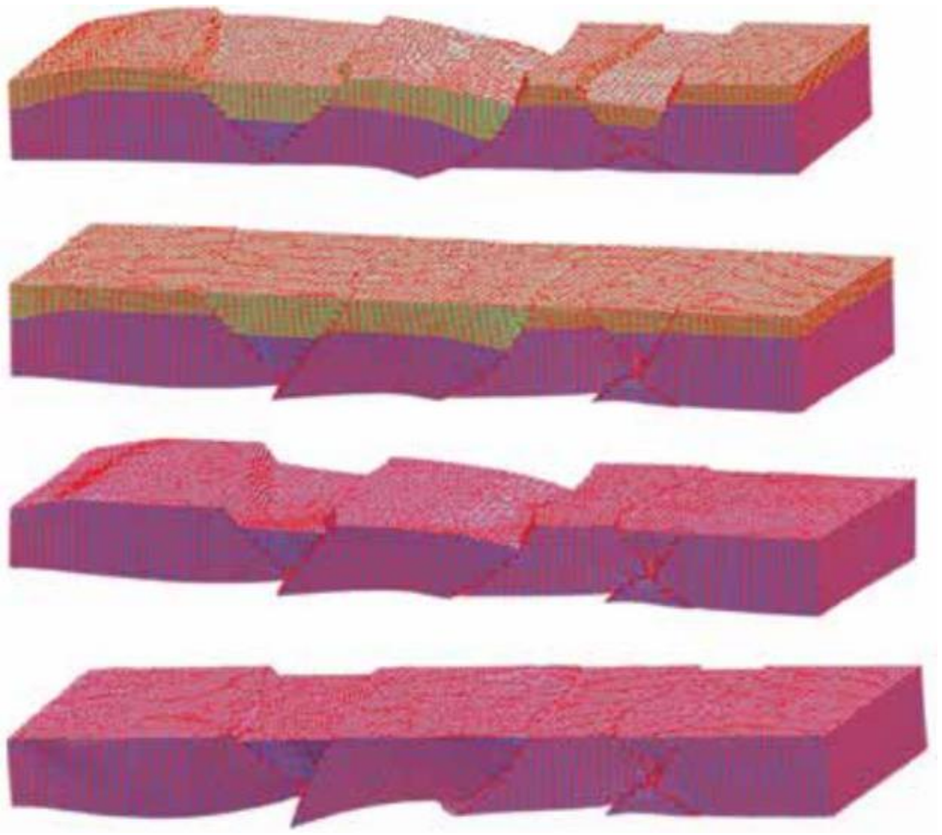


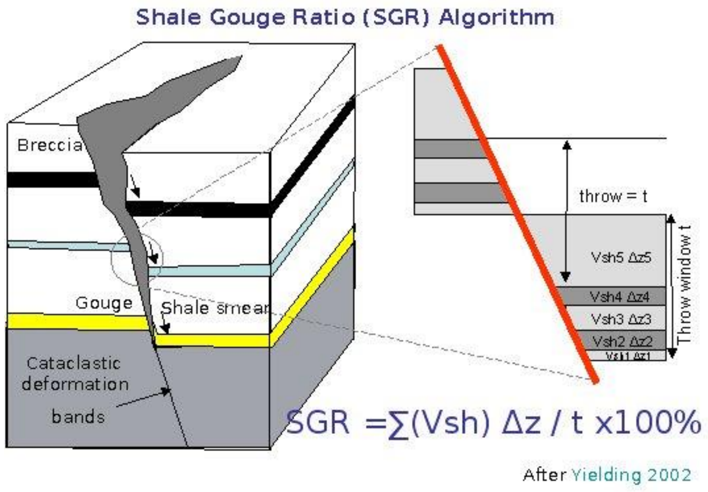
Rudkiewicz et al. 2012, PDGM

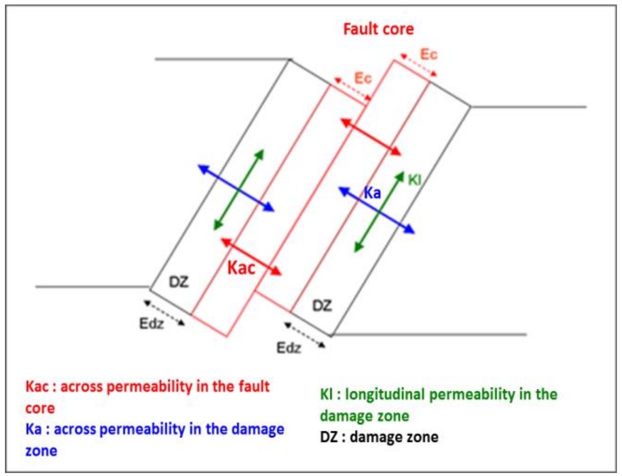
**Phase 1: restoration**
Considering geometric criterion (*Kronos/Kine3D*)
**Phase 2: Forward simulation**
Considering all the embedded physics (*ArcTem*)

# FAULT PROPERTIES DEFINITION IN BASIN MODELING



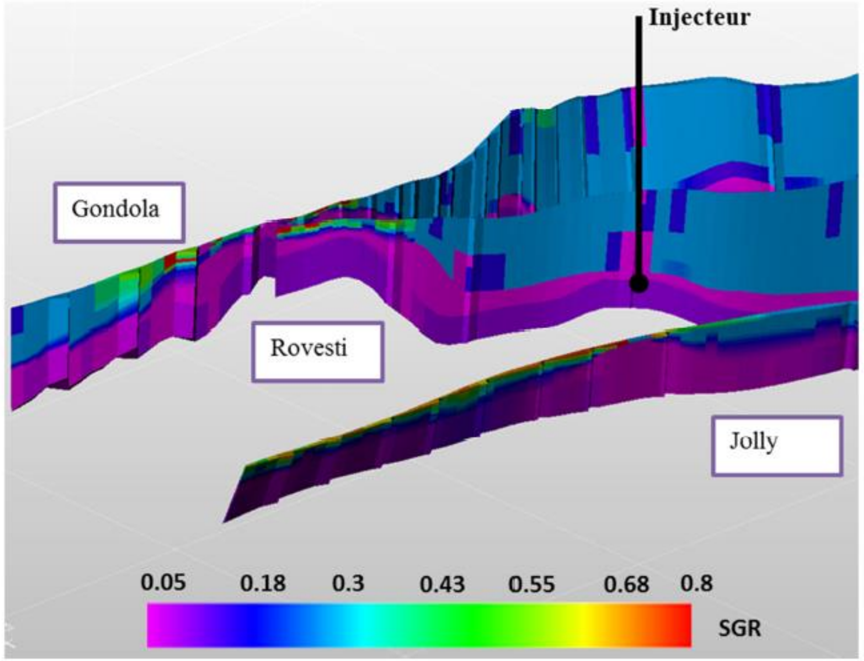


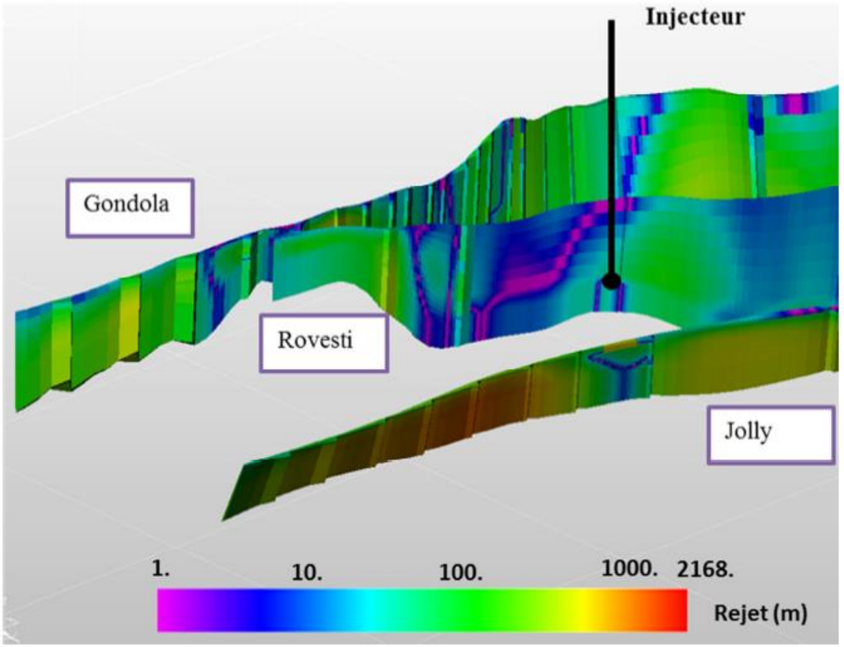

Faille et al. 2014

- **Kinematics is used to compute Shale Gouge Ratio**
- **Shale Gouge Ratio is used to compute fault properties**
- **Fault properties are used for simulations**

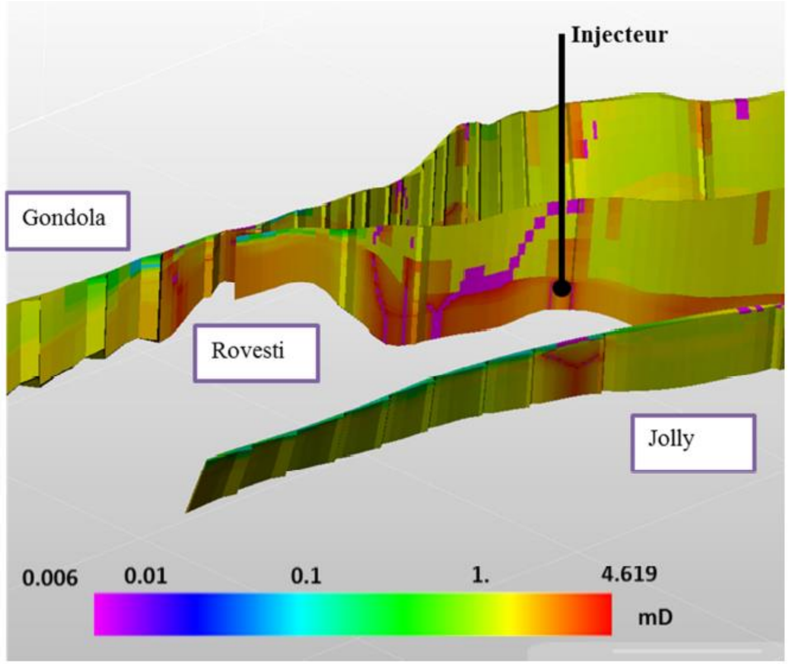
# ENHANCE FAULT PROPERTIES DEFINITION WITH WORKFLOW FROM BASIN MODELING




Shale Gouge Ratio




Reject

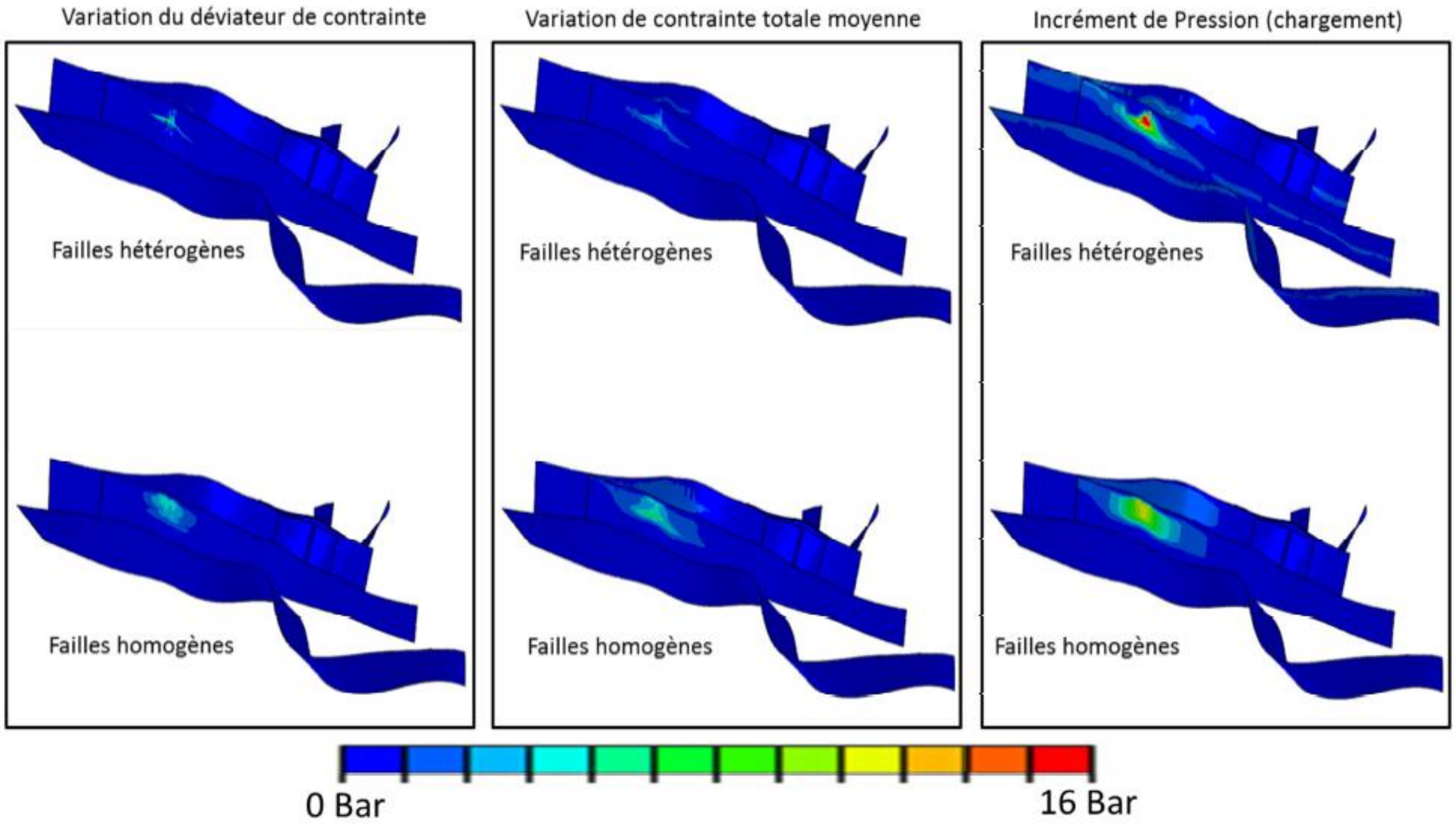



Along permeability

The workflow allows to a heterogeneous description of fault permeability which is more realistic

# ENHANCE FAULT PROPERTIES DEFINITION WITH WORKFLOW FROM BASIN MODELING

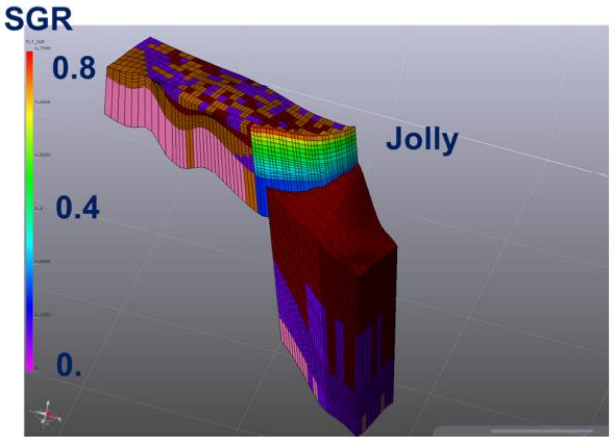



The effect of fault heterogeneity on stress modification is very significant

## Use the SGR based workflow to define mechanical properties of faults

Compute the mechanical fault properties considering fault SGR and Reject

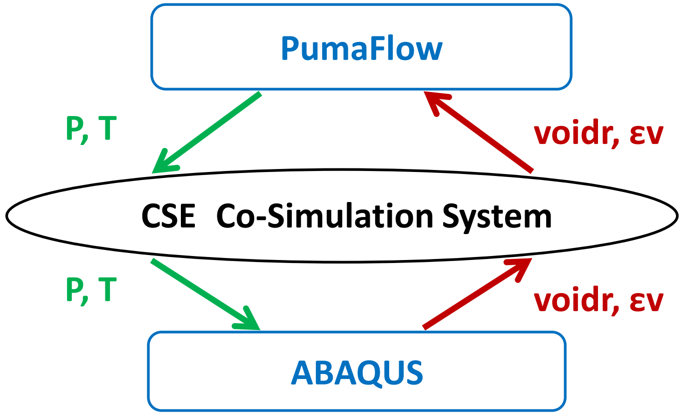
OBJECTIVE: improve the relevancy of fault stability analysis




## Enhance coupling between Pumaflow and ABAQUS with the Co simulation System (CSS)

Coupling PumaFlow and Abaqus using the CSS, a C++ based coupling tool

OBJECTIVE: significant usability enhancement and computation time decrease



## CONCLUSIONS

- Reservoir modeling, tools are available to
  - Take into account the effect of geomechanics on fluid flow in a continuous context
  - Evaluate the risk of fault reactivation

- Future work
  - Improve the workflow usability in the context of faults
  - Build a workflow to automatically define fault geomechanical properties
  - Enhance coupling geomechanical coupling usability and performance with CSS

- Ongoing work (not mentioned here)
  - Workflow to compare to both seismic and well data

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