Sedimentary basin modeling
Petroleum system modeling

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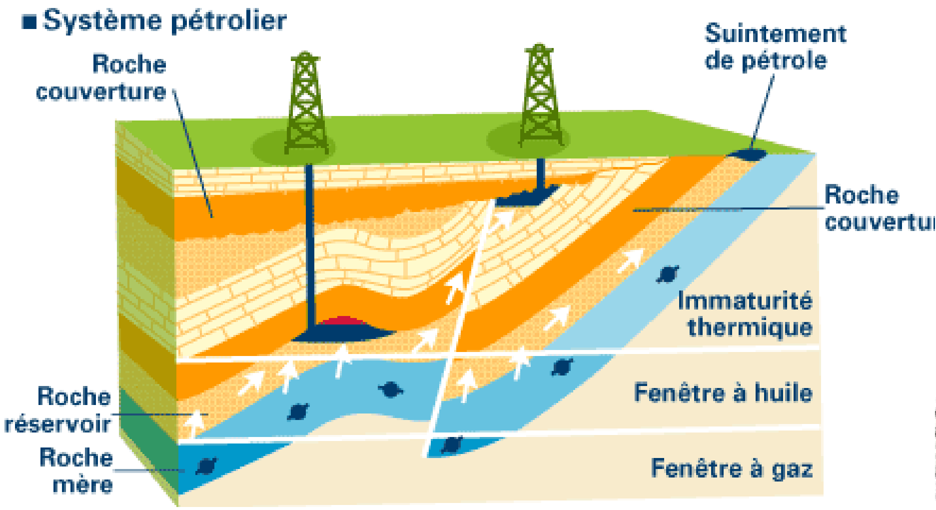
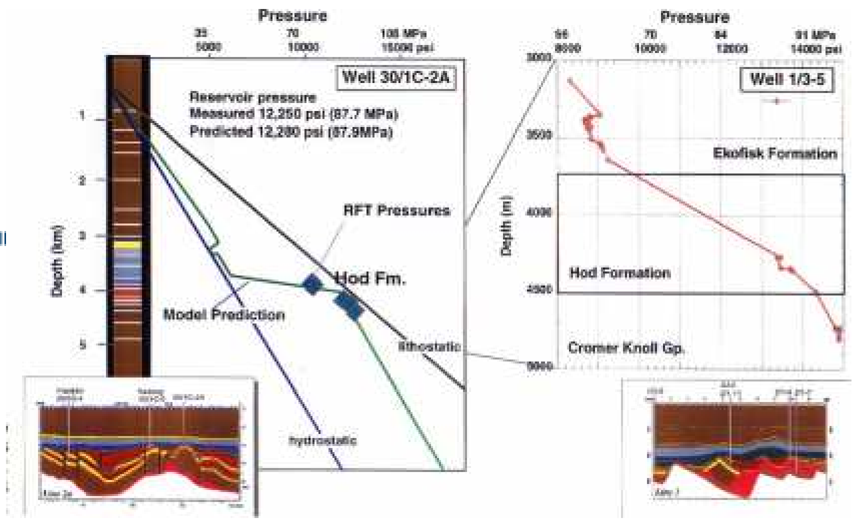
Sedimentary basin modeling

- Model the basin formation (sediments and fluids that fill in) to help answer the following questions :
  - Does a prospective structure contains hydrocarbons ?
  - If yes, what is the volume and the quality of the trapped hydrocarbons?
  - Is there a risk of encountering abnormal pressures ?





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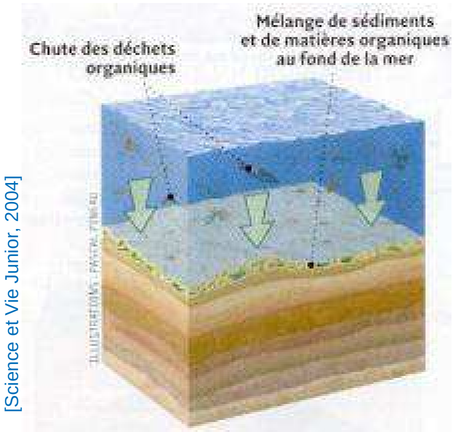
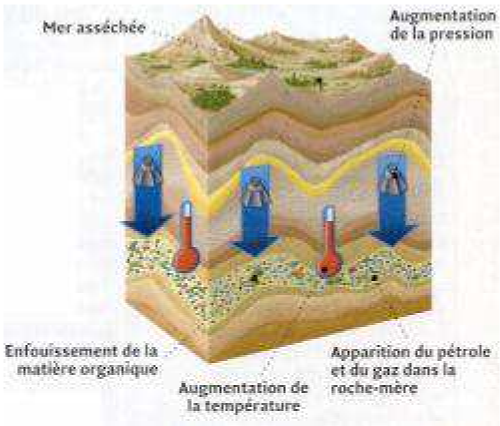
Sedimentary basin history

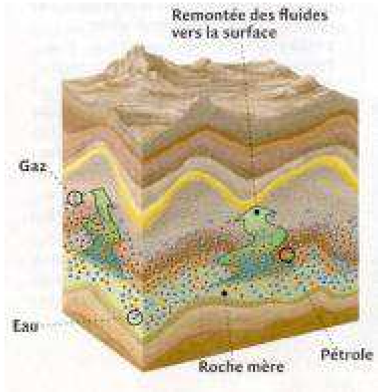
[Science et Vie Junior, 2004]



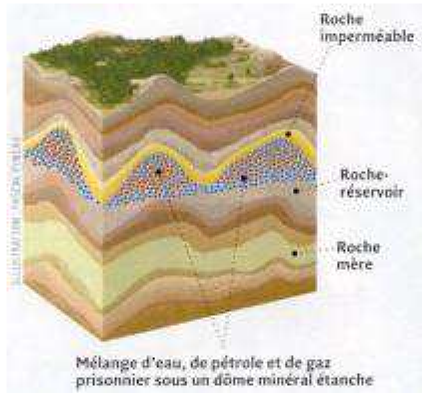
Deposition (/erosion) of sediments and organic matter



Burial - Compaction - Temperature increase



Kerogen maturation, HC generation and expulsion - migration



HC trapping and accumulation in reservoirs

- Geological time scale (10 to 400 Ma)
- Space scale : 100 km extension, 10km depth
- Sedimentary layers

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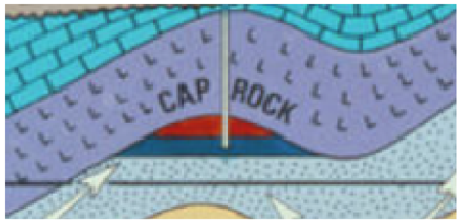
Sedimentary basin history

- Fluid transfer
  - Highly heterogeneous porous media
    - Permeability : Up to six orders of magnitude
  - Overpressure:
    - Ability for the fluids to flow / ability for the rock to compact
    - Transient state
  - Oil trapping
    - Multi-phase flow
    - Discontinuous entry capillary pressure : oil accumulates under capillary barriers
- Heat transfer
  - Slightly heterogeneous
  - Conduction dominant

Sand, a few mm

Shale, a few 1/10mm



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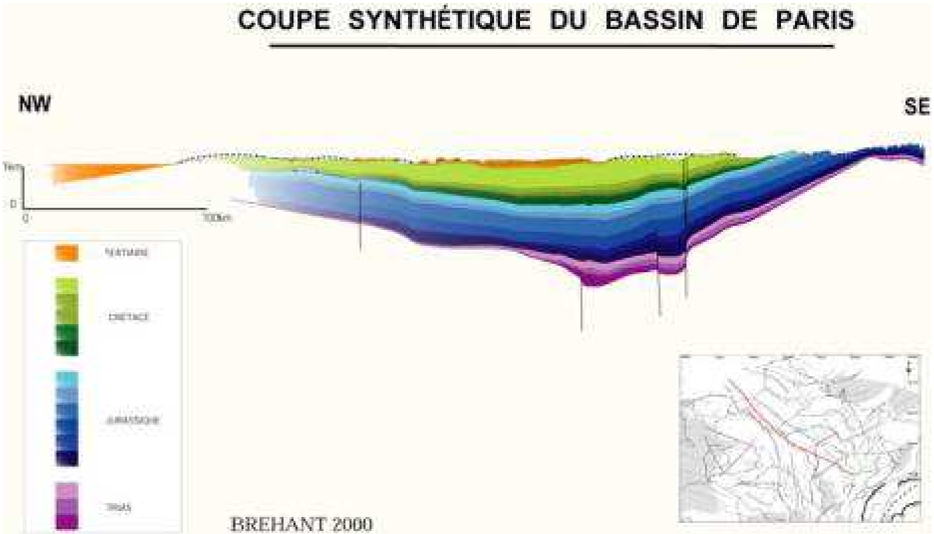
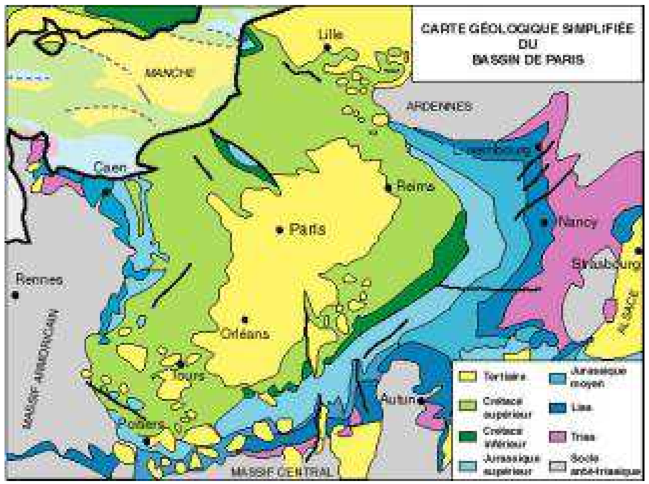
Simple geological context





- Pile of sedimentary layers

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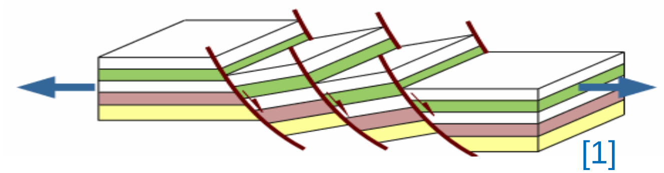
Structurally complex basin

- Extensive settings



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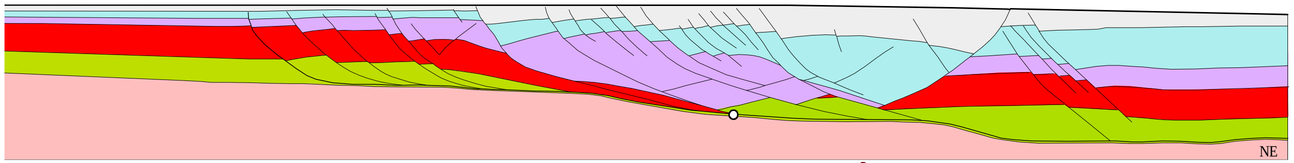
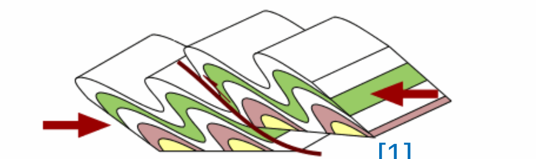


- Compressive settings



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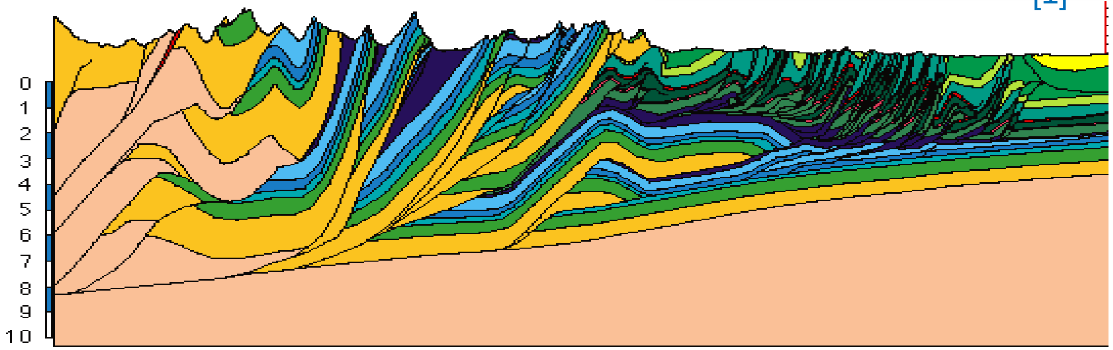

[1] http://www2.ggl.ulaval.ca/personnel/bourque/intro.pt/planete_terre.html

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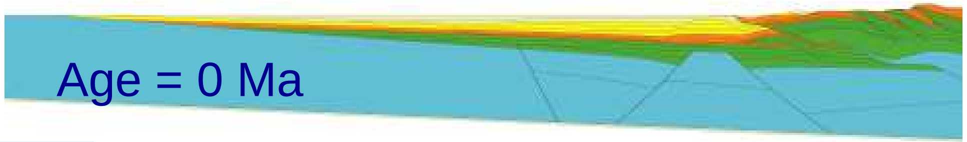
Simulation workflow

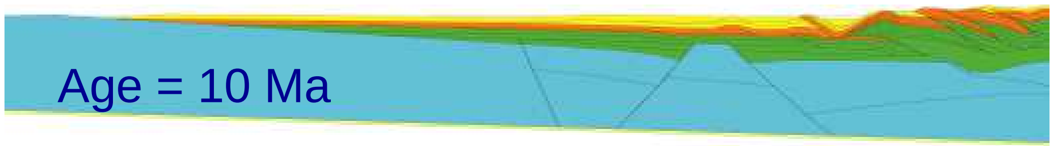
- **Data**

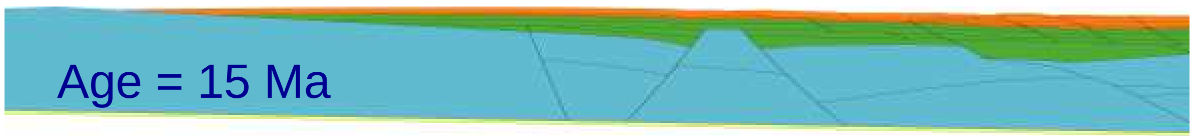
Present day geometry
Lithology distribution



Structural Restoration
Past architecture of the basin

Bassin simulation
-Porosity
-Pressure
-Hc





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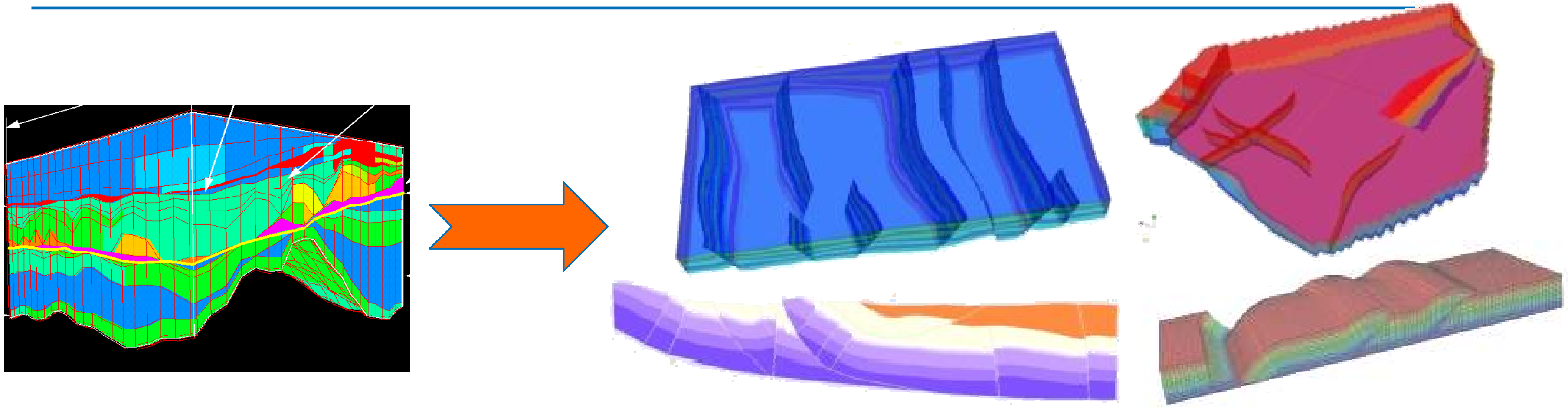
3D basin simulation : from simple to complex context



- Pile of layers
  - Vertical deformation
- Conformal structured mesh
  - Degeneracies
  - LGR

- Basin cut by faults
- Any kind of deformations
  - Extension and/or compression
  - Sliding along fault surfaces

- Past Geometries given by the restoration process
- Heat and fluid transfer

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3D basin simulation : from simple to complex context

- ArcTem Simulator
- Main characteristics and potential improvements
  - Mesh
  - Heat transfer and fluid flow
    - “standard” model and FV discretization
  - Faults
    - Interface fault model
    - Different discretization

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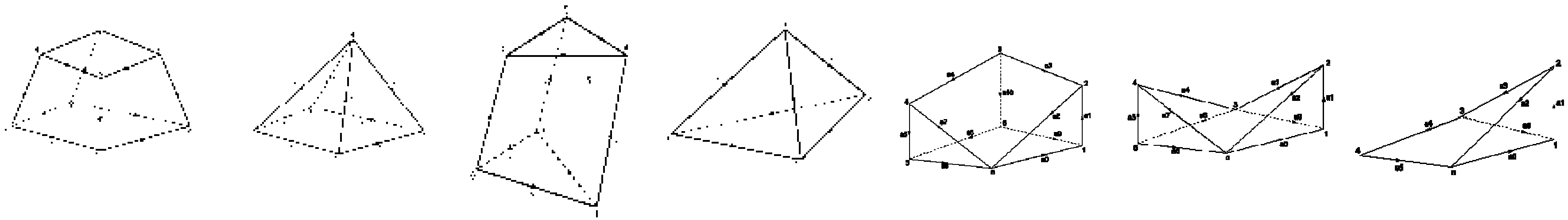
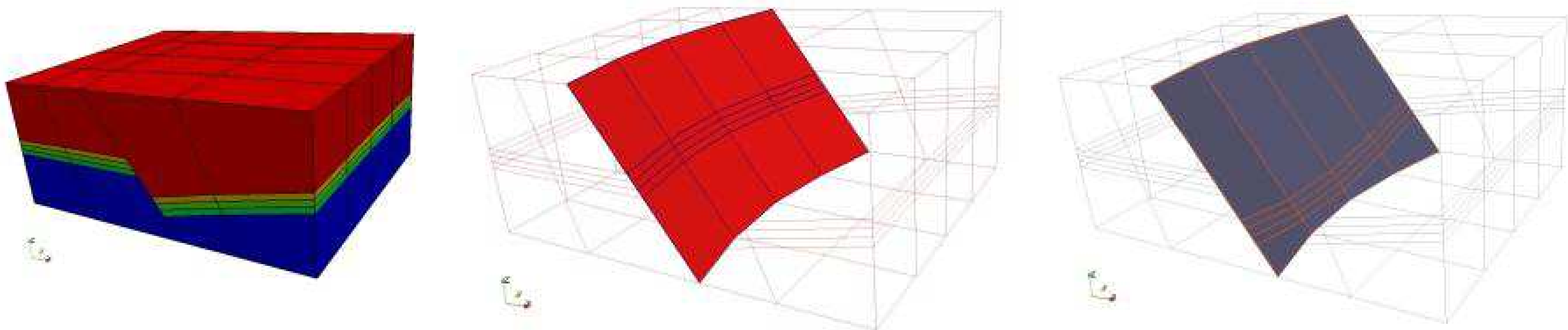
4D Mesh (space, time)

- At a given time
  - Mesh that conforms to the stratigraphic layers
  - Non structured



  - Non matching
    - A fault is represented as two sliding surfaces : two sets of faces, that are eventually in contact



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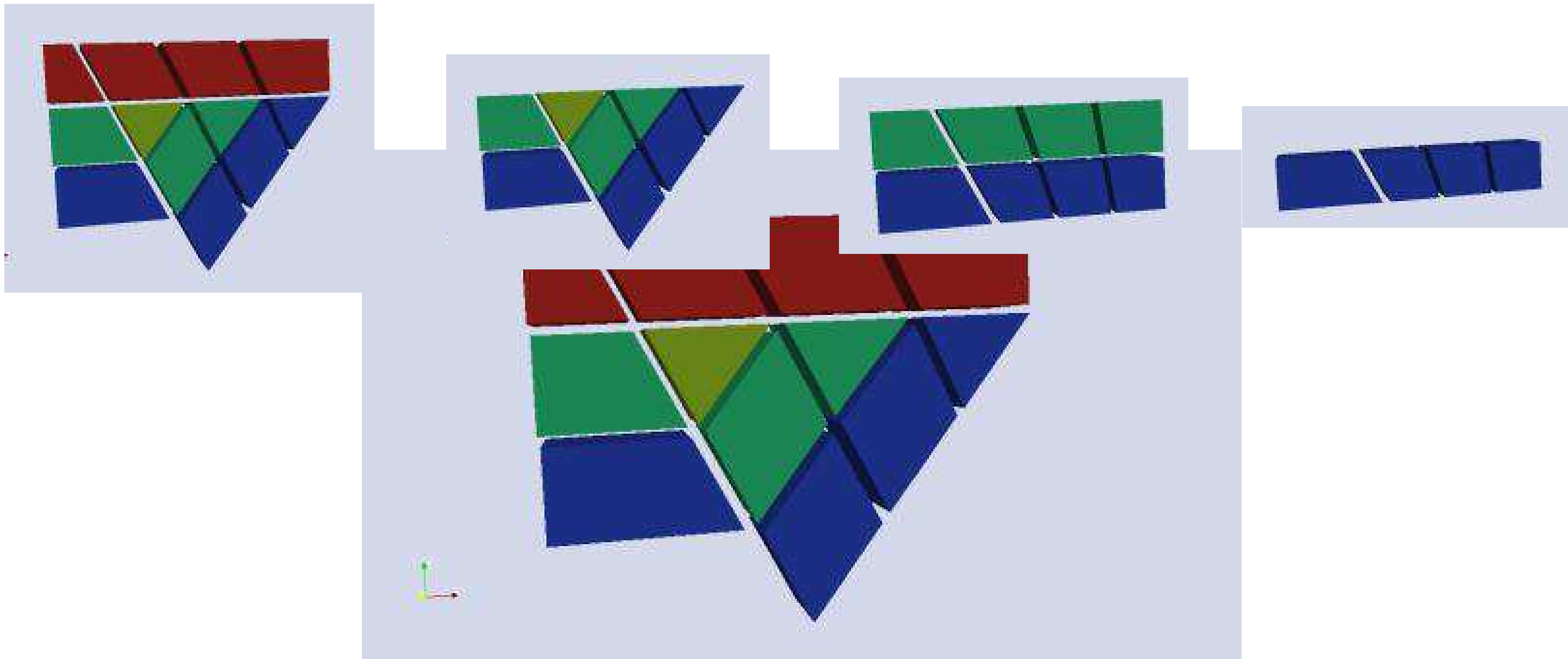
4D Mesh (space, time)

- Mesh that follows rock deformation
  - Able to follow :
    - Sedimentation, erosion, deformation, sliding along fault surfaces
  - Geological phenomena correspond to incremental modifications of the grid
  - A toy example (not geological …)



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Two phase fluid flow / Heat transfer

- Single-phase flow : simple rock compaction / Fluid flow
  - Compaction is the main driving phenomenon for fluid flow
    - Mass conservation
    - Darcy's law
    - Vertical mechanical equilibrium
    - Elastoplastic rheology

$$\frac{\partial}{\partial t}(\phi\rho_w) + div(\rho_w \mathbf{v}_w) = q_w$$

$$\phi(\mathbf{v}_w - \mathbf{v}_s) = -m_w \mathbf{K}(\nabla P_w - \rho_w \mathbf{g})$$

$$\frac{\partial}{\partial z}\sigma_v = (\rho_w\phi + \rho_s(1-\phi))g$$

$$\phi = \mathcal{F}_\phi(\sigma_v - P)$$

- Heat transfer
  - Accumulation, conduction, convection

$$\frac{\partial}{\partial t}(\rho_s c_s(1-\phi) + c_w\rho_w\phi)T + div(\rho_s c_s(1-\phi)T\mathbf{v}_s + \rho_w c_w T\mathbf{v}_w)$$
$$+ div(-\lambda_b\nabla T) = q_T$$

- Two-phase flow
  - Hydrocarbon generation
  - Oil migration and trapping under cap-rocks

$$\frac{\partial}{\partial t}(\phi\rho_\alpha S_\alpha) + div(\rho_\alpha \mathbf{v}_\alpha) = q_\alpha$$

$$\phi S_\alpha(\mathbf{v}_\alpha - \mathbf{v}_s) = -m_\alpha(S_\alpha)\mathbf{K}(\nabla P_\alpha - \rho_\alpha \mathbf{g})$$

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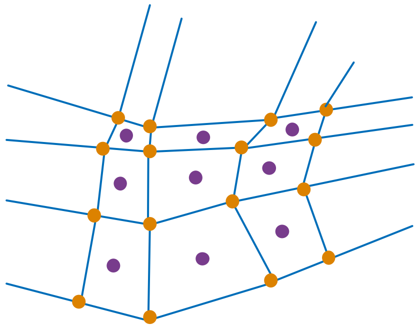
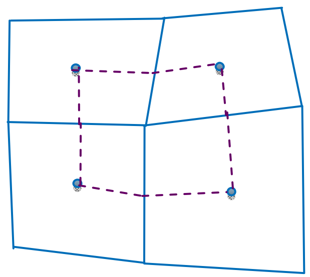
Cell centered Finite Volume discretization



- Discrete unknowns
  - Pressure, porosity, temperature, saturation in each cell
  - Overburden at each node
- Cell centered FV scheme for diffusive terms
- Upstream weighting for the saturation
- Main issue
  - "DivKgrad" scheme for very distorted grids
    - Flow $div(-\lambda\nabla T)$
    - Heat transfer $div(-\mathbf{K}\nabla P)$
    - O-scheme / TPFA *[Aavatsmark et al]*

$$F_\delta = \sum_{\mathcal{L}\in\mathcal{S}_\delta} T_{\delta,\mathcal{L}} u_{\mathcal{L}}$$



- Implicit time discretization
  - Fully or sequential implicit for the pressure/saturation

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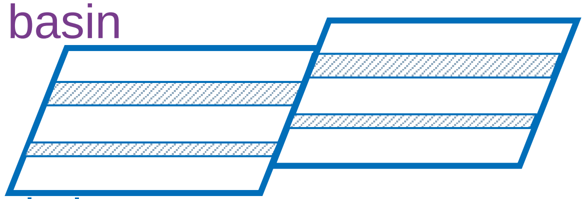
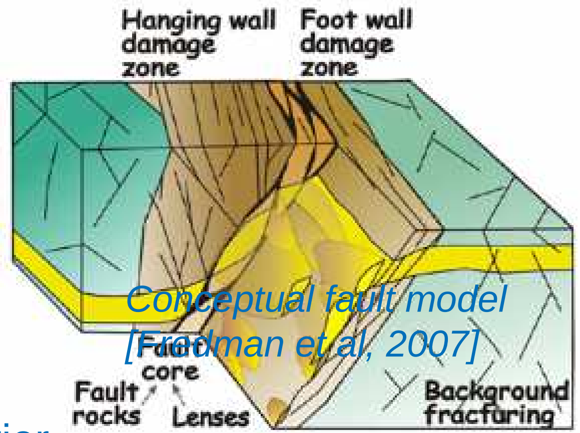
Faults

- Structure
  - A fault is a fracture that becomes a slip surface across which there is significant relative displacement at basin scale
  - A volumetric zone of complex architecture
    - Core zone (highly deformed) that can be filled with shale
    - Damage zone (fractured rock)
    - Thickness (10m)<< basin scales (10 to 100 km)
    - Large vertical extension (kms)
- Impact on fluid flow
  - Juxtaposition of distinct stratigraphic layers
  - Properties
    - Conduit to fluid flow
    - Barrier to fluid flow
    - Damage zone as a conduit and core zone as a barrier
  - Pressure prediction and hc migration





Conceptual fault model [Fredman et al, 2007]

Conceptual fault model [Fredman et al, 2007]

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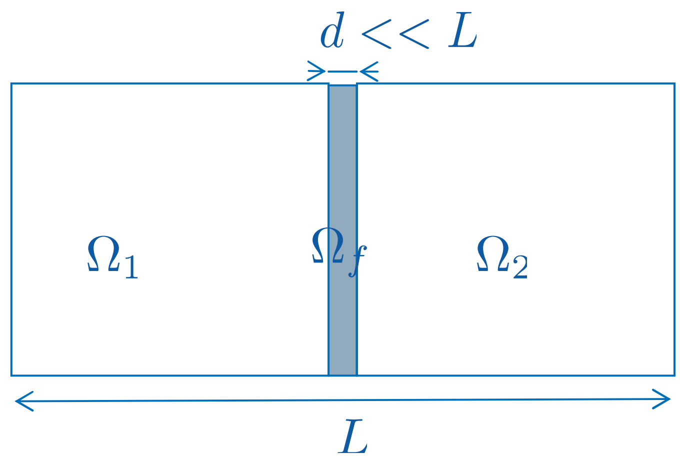
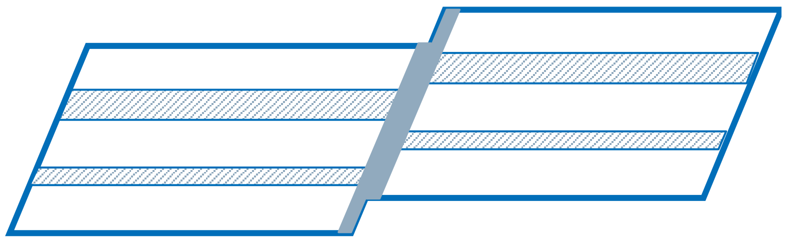
Faults

- Strong similarities with flow through fractured porous media
  - Fracture domain which is very thin with respect to the domain extension, but has potentially a major influence
  - Thickness that varies over space and time
  - Flow governed by Darcy's law
- But some differences
  - At geological time scales : slip along the fault surface
    - Large displacement
    - Very heterogeneous fault zone
  - Less dense network



$$-div(\mathbf{K}\nabla P) = f$$



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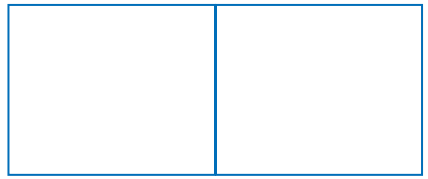
Interface fault model

- Discrete fracture models
  - Geometrically, fracture thickness is not represented in the domain
    - A fracture is only represented as an interface



  - "Discrete" approach
    - 2D [Granet et al 1998], 3D [Karimi-Fard et al, 2004],… [Al-Hinai et al, 2013]…
    - "Virtual" volumetric mesh : extrusion in the normal direction
  - "Continuous" approach
    - [Alboin et al, 1999], [Martin et al, 2005] , [Flauraud et al, 2003], [Angot et al, 2005]…
    - Continuous Interface model derived assuming that d<<L
    - Fracture width becomes a parameter of the model
- Two-interface fault model
  - Continuous approach
    - Model and TPFA/ MPFA Finite Volume discretization
  - Discrete approach
    - Hybrid Finite Volume discretization
- Basin simulation
    - Some results for single-phase flow and Hc migration

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Interface fault model

- A double interface fault model
  - Extension of the reduced fracture model
  - Single phase Darcy flow (viscosity = 1)
  - Additional unknowns $P_{f,I},\ P_{f,II}$
  - Normal and tangential permeability in the fault

$$-\frac{\partial}{\partial y}(\tilde{K}_{f,y}\frac{\partial}{\partial y}P_{f,I}) = u_I - u_{I,II}$$

$$-div(K\nabla P_1) = f \qquad\qquad I \qquad II \qquad\qquad -div(K\nabla P_2) = f$$

$$-\frac{\partial}{\partial y}(\tilde{K}_{f,y}\frac{\partial}{\partial y}P_{f,II}) = u_{I,II} - u_{II}$$

$$\tilde{K}_{f,y} = K_{f,y} * d$$

$$\tilde{K}_{f,x} = \frac{K_{f,x}}{d}$$

$$u_I = 2\tilde{K}_{f,x}(P_1 - P_{f,I}) \qquad u_{I,II} = \tilde{K}_{f,x}(P_{f,I} - P_{f,II})$$

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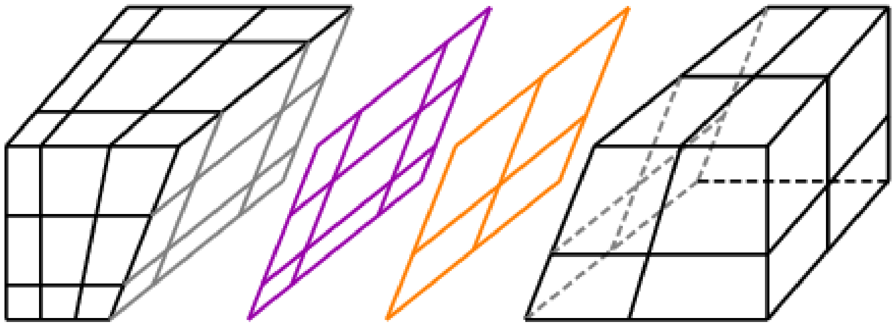
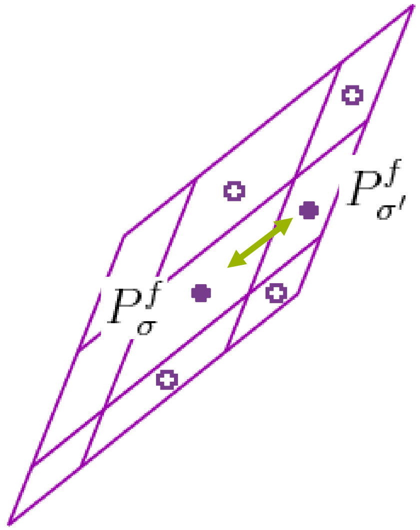
Two-interface fault model : continuous approach

- TPFA/O-scheme discretization (X.Tunc Phd/ T.Gallouët)
  - "Natural" grids for the interfaces
    - Compatible with the geometrical definition of the fault



  - Cell centered scheme
    - One unknown in each cell and in each fault edge
    - Adaptation of TPFA, O-Scheme (or other MPFA…)
  - Mass balance in each cell and in each fault edge
  - Flux approximations
    - Along fault flux
      - 2D VF approximation
      - If non planar fault surface, one normal per edge



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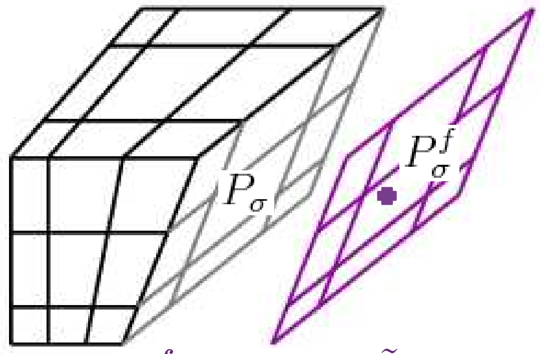
TPFA/O-scheme discretization

- Fault-matrix flux
  - Given by the fault model
  - Combined with a standard approximation on the matrix side : Two-points, O-scheme, ..., to eliminate P_σ

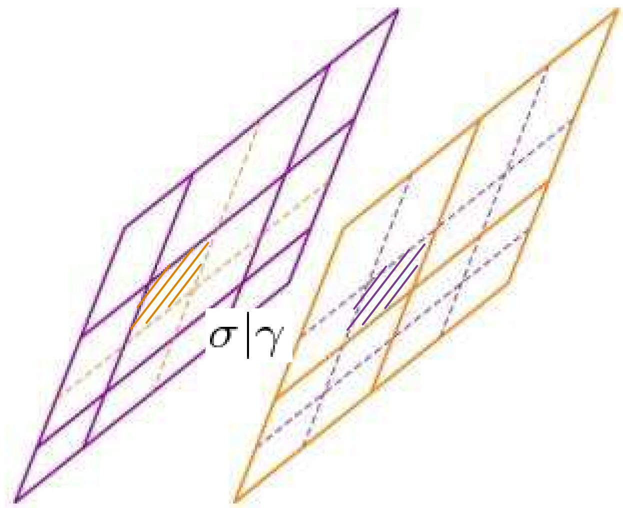


$$F_\sigma^{f,m} = |\sigma| 2\tilde{K}_{f,x,\sigma}(P_\sigma - P_\sigma^f)$$

- Fault-fault flux
  - Computed on sub-faces
  - Given by the fault model

$$F_\sigma^{f,f} = |\sigma|\gamma| \tilde{K}_{f,n,\sigma}(P_{\sigma|\gamma}^f - P_{\gamma|\sigma}^f)$$

  - $P_{\sigma|\gamma}^f$ obtained by piece-wise constant or piece-wise linear approximation compatible with flux along the fault approximation



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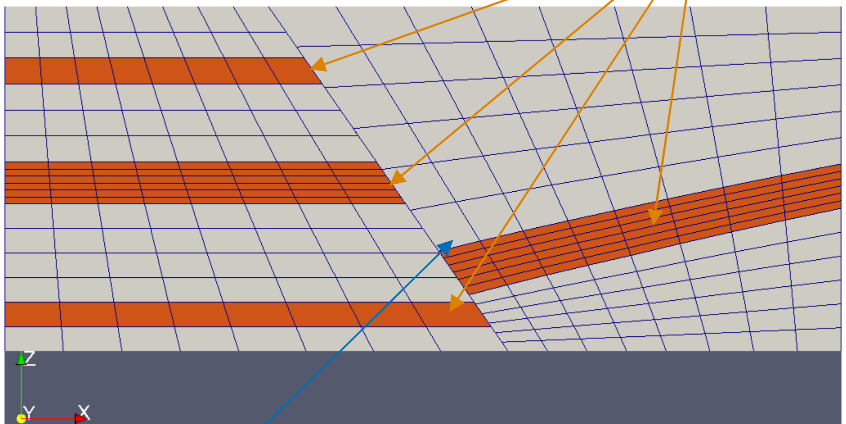
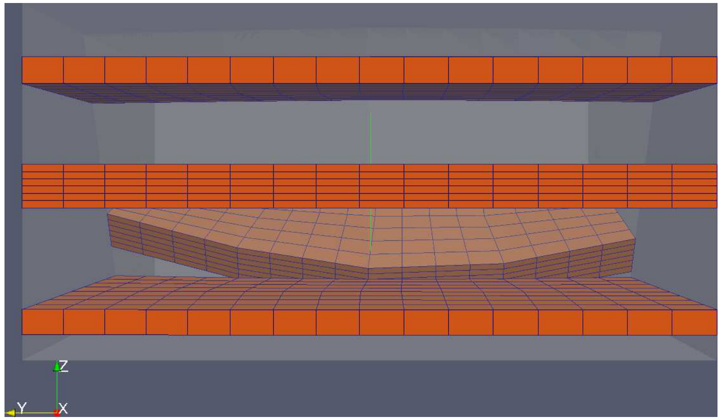
Some results on a static geometry

- Single phase flow

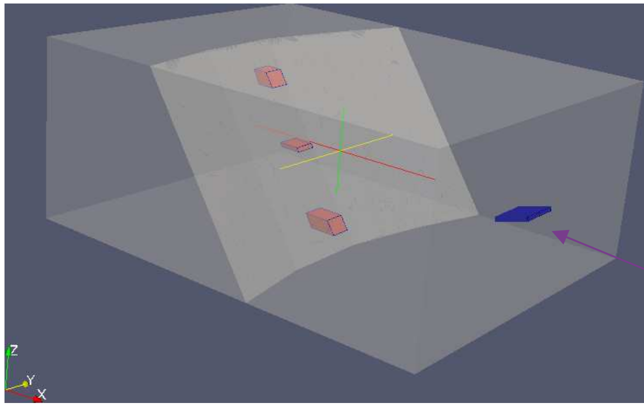
Permeable layers

Open boundary





Fault zone
• more permeable (*100)
• small width (5m / 6km)



Slightly compressible single-phase flow

Injection

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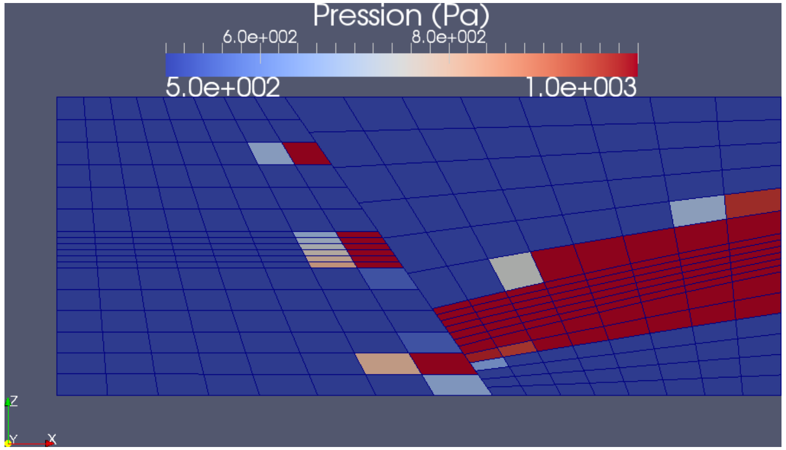
Some results on a static geometry

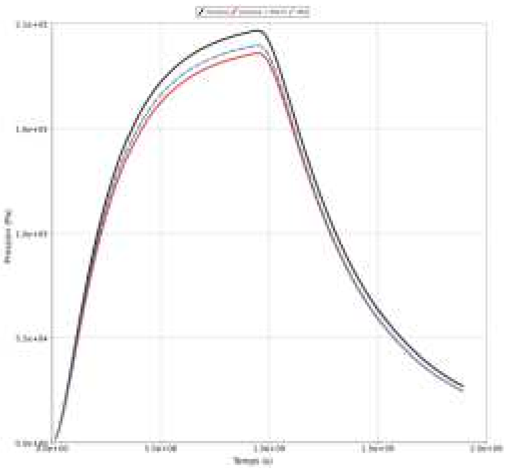
OverPressure field at first time step



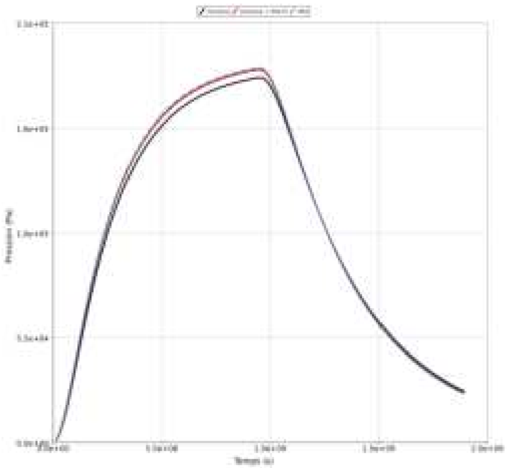
- The model captures the connectivity induced by the fault zone
- TPFA versus O scheme
  - TPFA for fault-fault fluxes tends to smooth the pressure profile along the fault
  - If too high fault permeability, lack of stability for the O scheme

OverPressure evolution over time

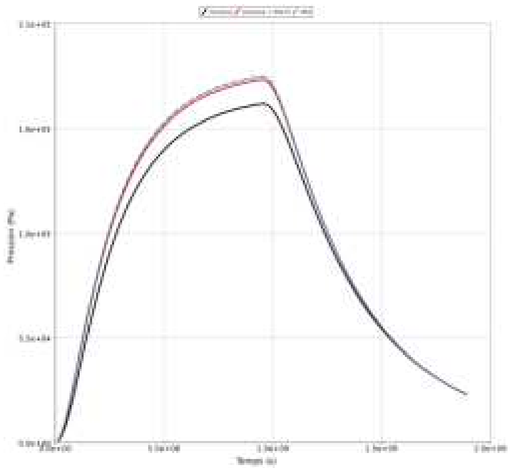
OScheme / OScheme + TPFA FF / TPFA



Bottom cell



Medium cell



Top cell

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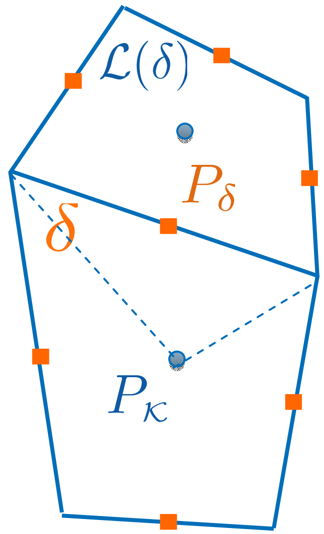
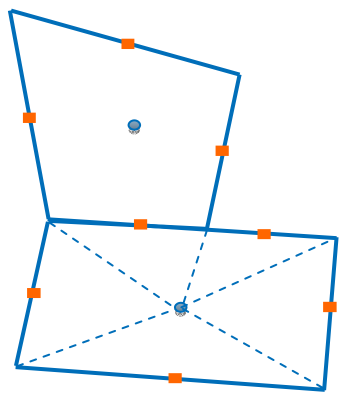
Hybrid Finite Volume scheme

- Introduced to overcome the lack of stability of MPFA *[Eymard et al,2007]*
  - Cell and Face unknowns
  - Discrete equations
    - Flux per cell and face $$F_{\mathcal{K},\delta} = \sum_{\delta' \in \mathcal{E}_K} T_{\delta,\delta'}(P_\mathcal{K} - P_{\delta'})$$
    - Balance over each cell $$\sum_{\delta \in \mathcal{E}_\mathcal{K}} F_{\mathcal{K},\delta} = |\kappa| q_\mathcal{K} = f_\mathcal{K}$$
    - Flux continuity on each face $$F_{\mathcal{K}(\delta),\delta} + F_{\mathcal{L}(\delta),\delta} = 0$$



  - Flux expression : built to ensure coercivity
    - Discrete gradient in each cone $$\nabla_{\mathcal{K},\delta} u = \nabla_\mathcal{K} u + \alpha_\mathcal{K} R_{\mathcal{K},\delta}(u) \vec{n}_{\mathcal{K},\delta}$$
  - Handles non-matching grids : sub-faces unknowns
  - Generalized Hybrid scheme *[Droniou et al, 2010]*
    - Equivalent to Mimetic Finite Difference



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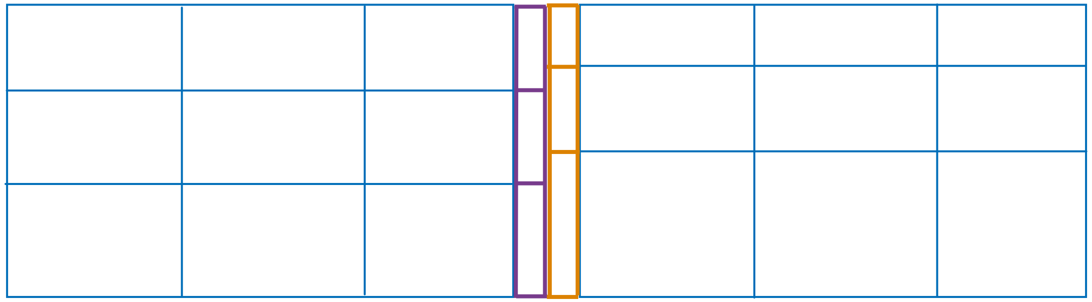
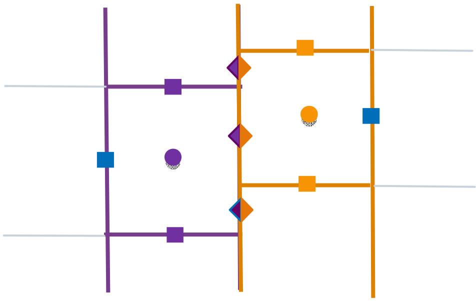
Double Interface Model : virtual fault mesh

- Virtual volumetric mesh of the fault zone (A. Fumagalli Postdoc/ J. Jaffré/ J. Roberts)
  - Extrusion of each (n-1)D fault surface in the normal direction
  - Two layer mesh



  - Discretization with HFV
  - Non matching grids : additional discrete unknowns on the fault/fault interface



- Fault-fault flux defined on sub-faces
- For any face or sub-face of the virtual cell

$$F_{\sigma,\delta} = \sum_{\delta' \in \mathcal{E}_\sigma} T_{\delta,\delta'}(P_\sigma^f - P_{\delta'}^f)$$

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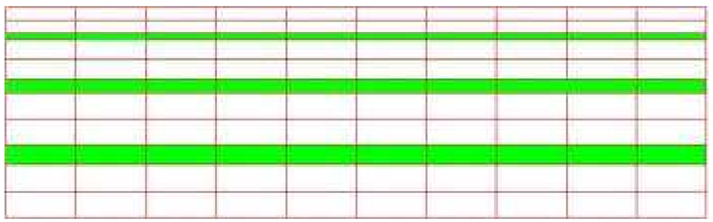
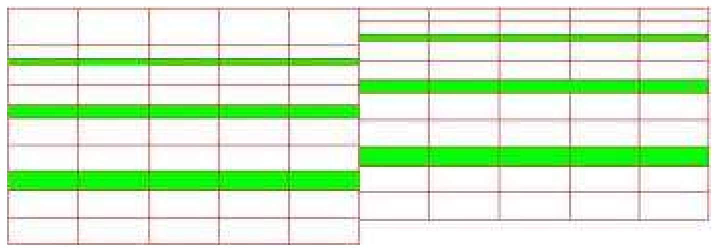
Some results on a toy problem

- Vertical fault, sliding blocks
- Alternatively shale and sand layers

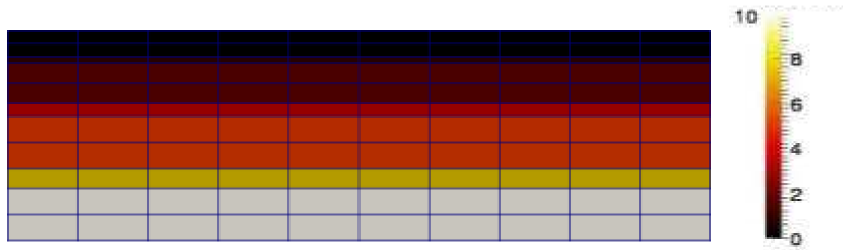
Initial geometry



Final geometry



- Slightly compressible fluid
  - Shale K=1.e-4 mD
  - Sand K=1mD
- Initial pressure field



- Influence of fault zone properties

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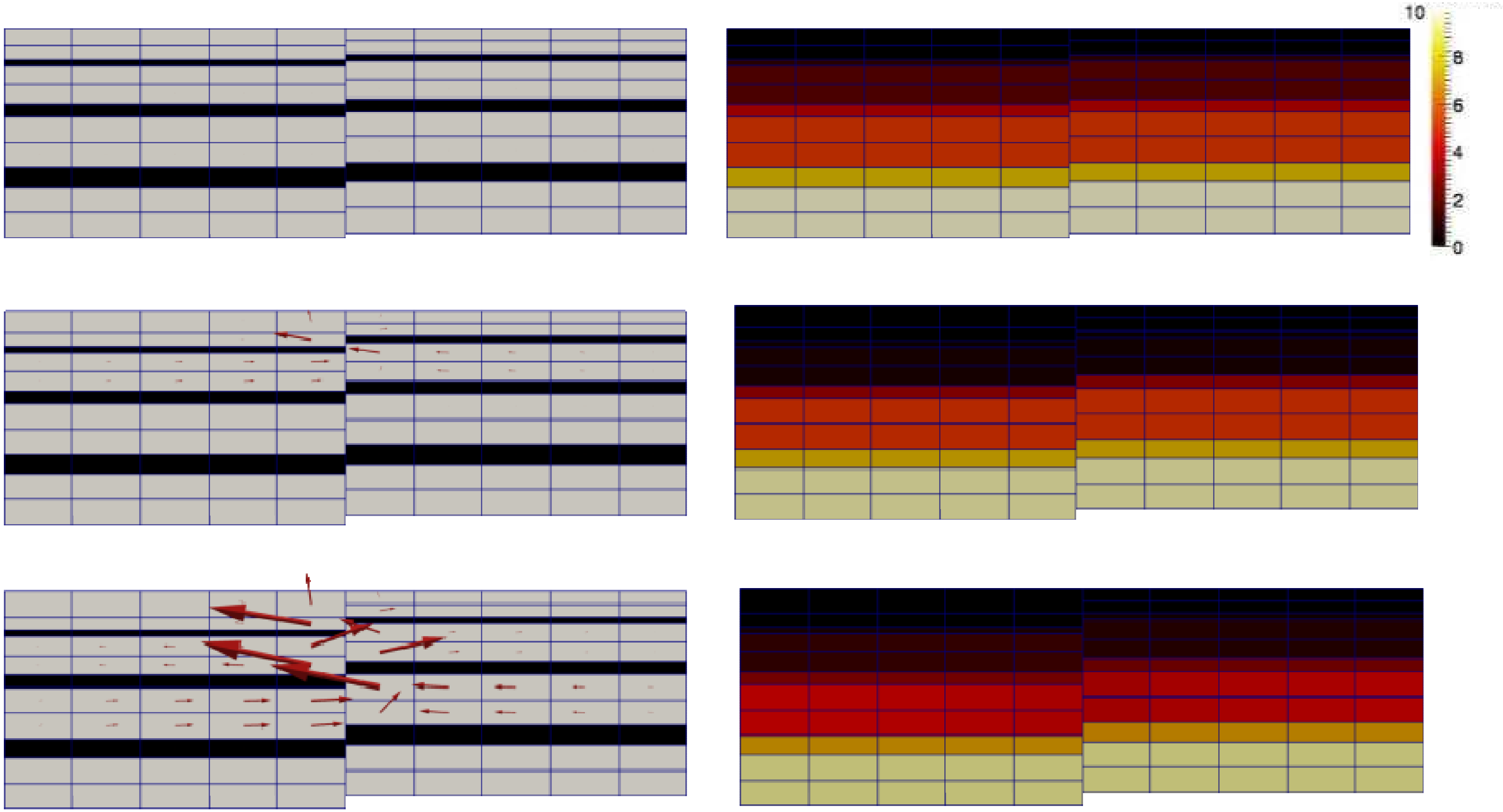
Juxtaposition fault

- Fault face permeability is identical to that of its neighboring matrix cell

t=22

t=24

t=26



Velocity field

Pressure field

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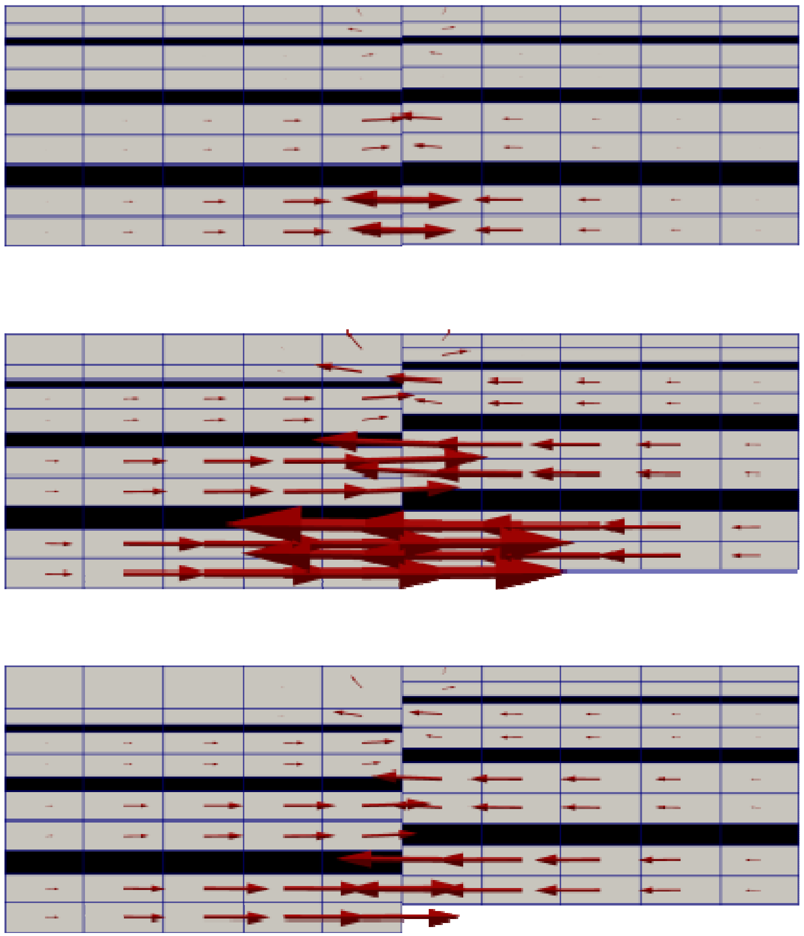
Fault as a chanel

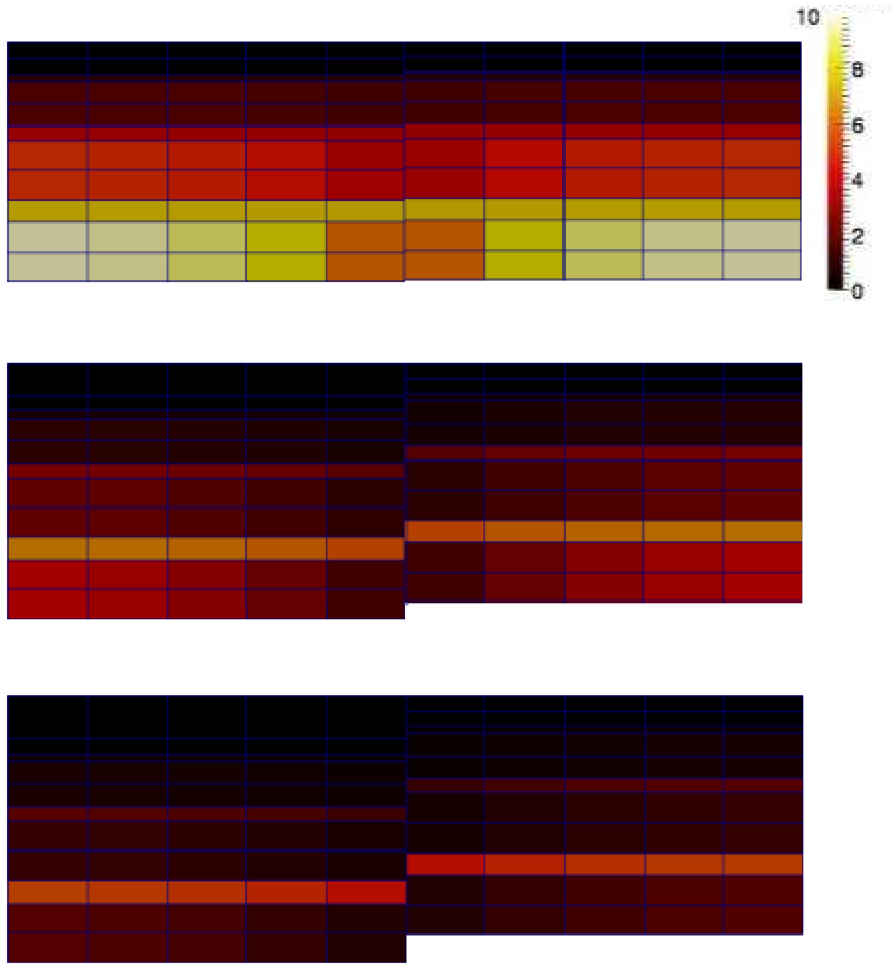
- Fault face permeability is 100mD

t=22

t=30

t=36





Velocity field

Arrow size is reduced by a factor 5

Pressure field

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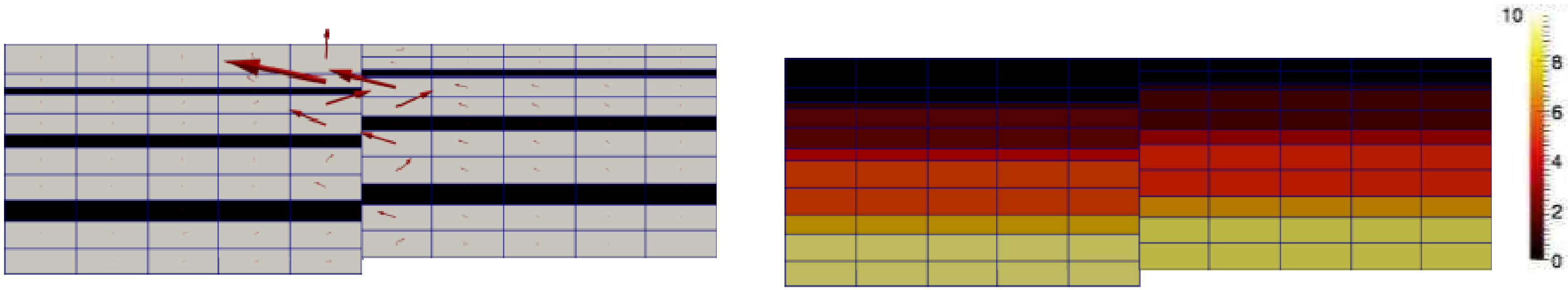
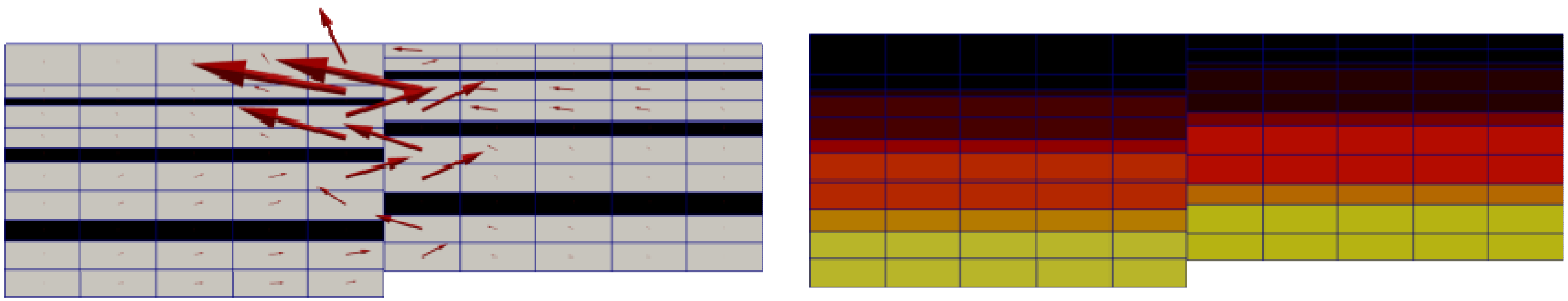
Fault as a moderate barrier

- Fault face permeability is 0.01 mD

t=31



t=36



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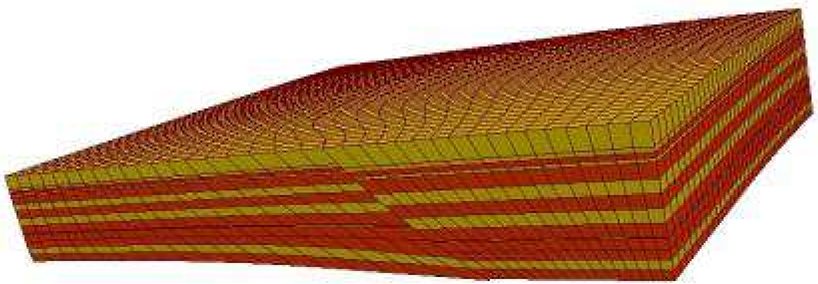
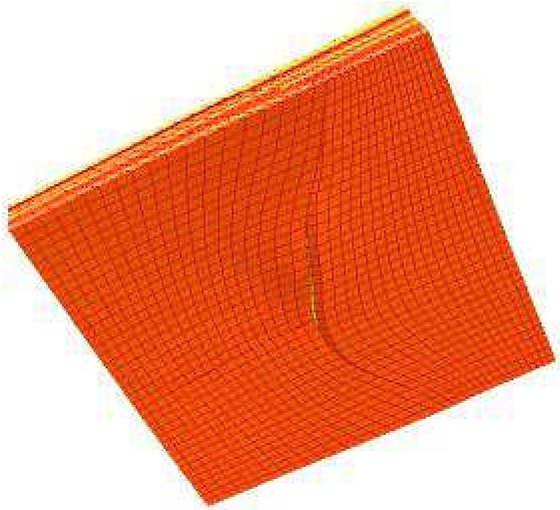
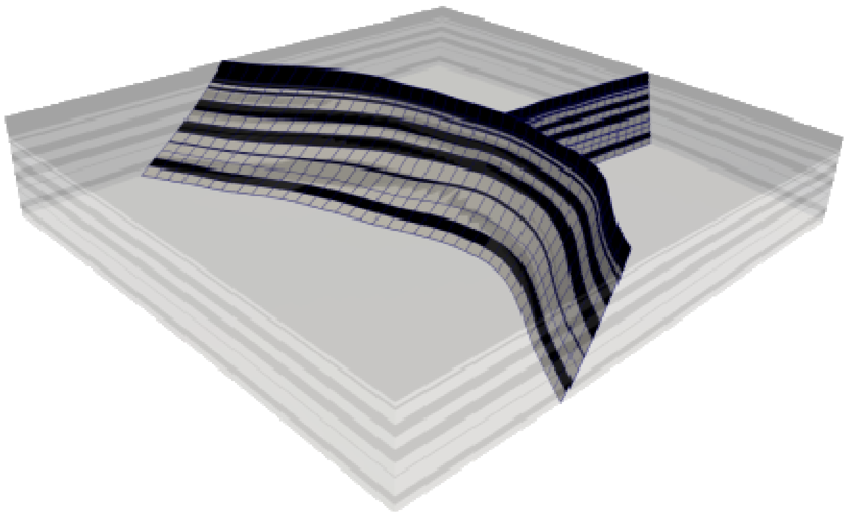
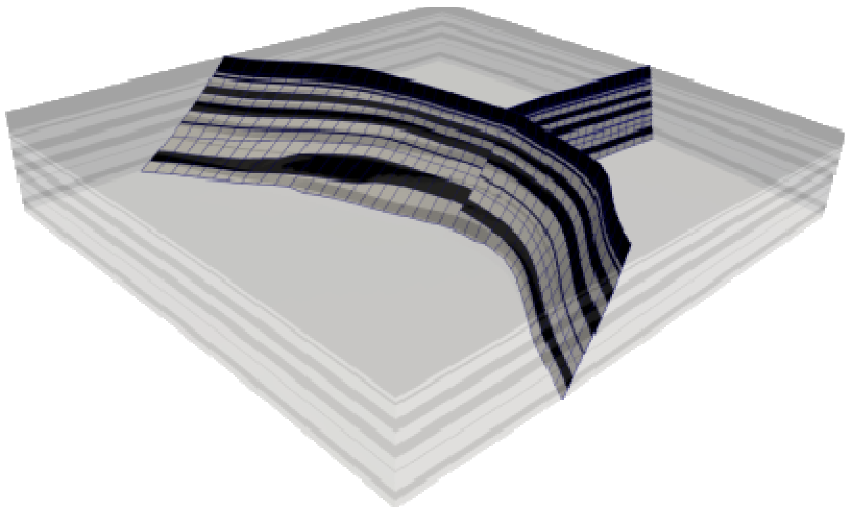
Some results for a realistic test case

- 3D domain, 2 intersecting faults









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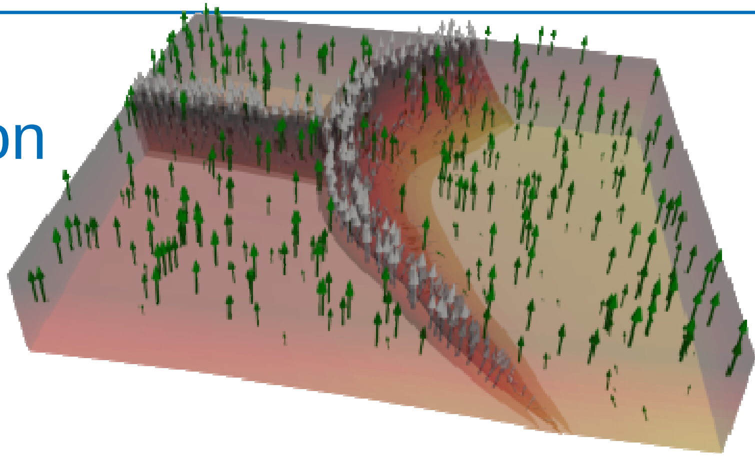
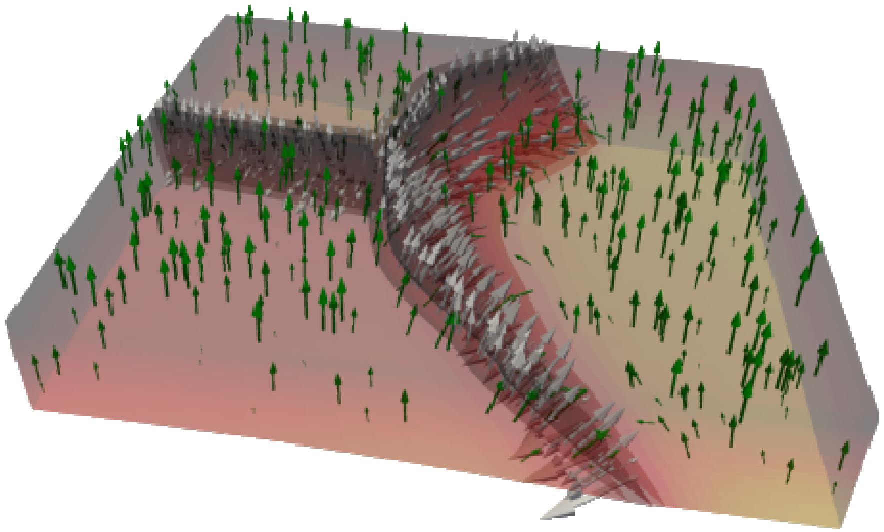
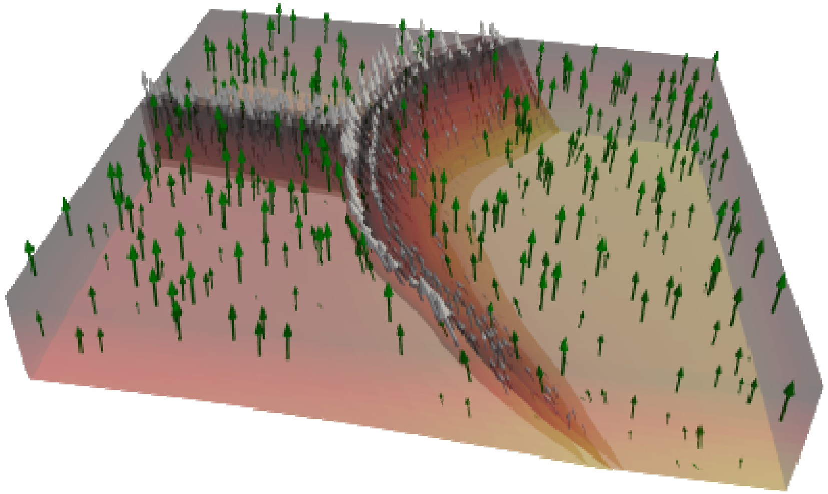
Homogenous domain K=0.01mD

Initial condition





Fault as a chanel K=1mD



Fault as a barrier K=1.e-4mD

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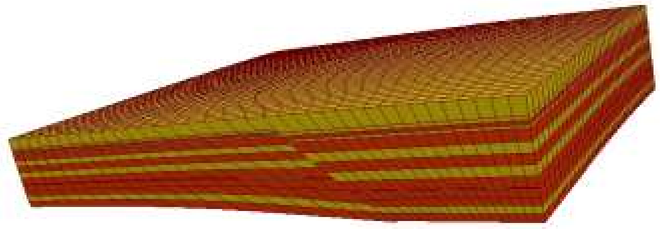
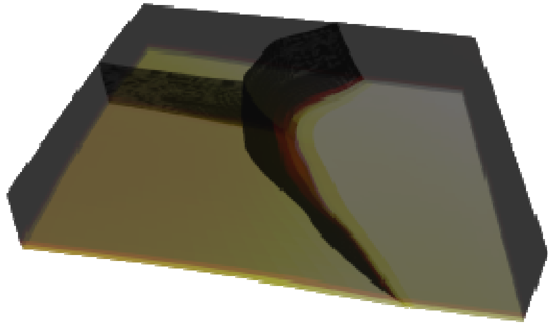
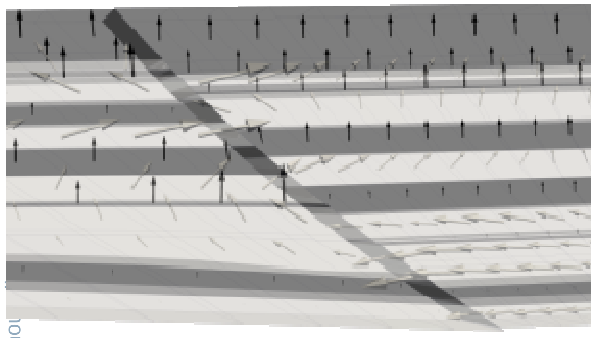
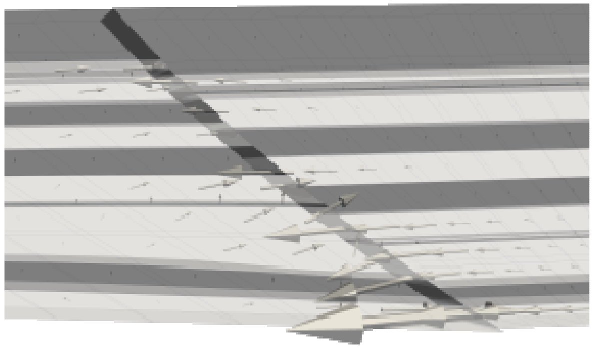
Heterogeneous domain 1mD/ 0.01mD

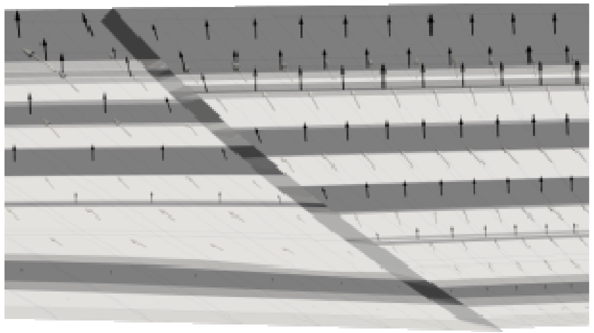




Velocity field







Juxtaposion fault

Fault as a chanel 100mD

Fault as a barrier 1.e-4mD

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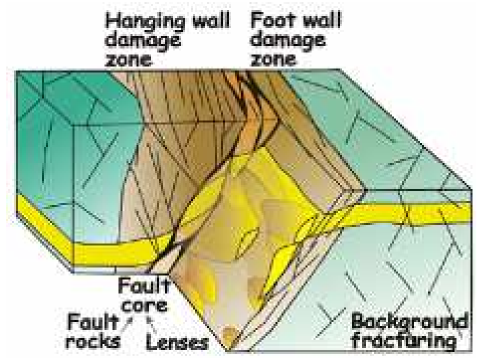
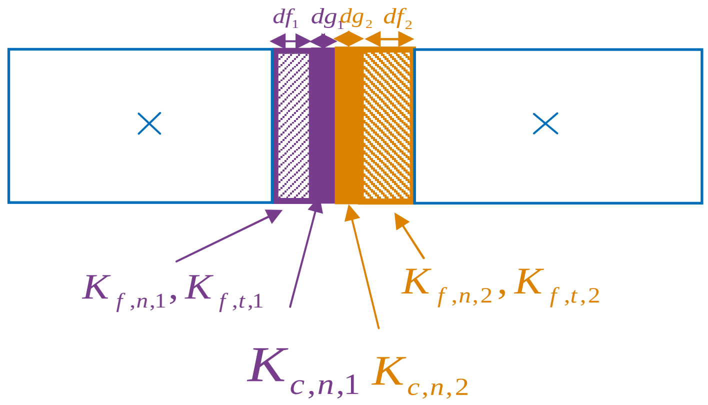
Basin simulation

- Single phase fluid flow coupled with compaction
  - Two-points or O-scheme in the matrix
  - Two-points for the fault model
- Sliding surfaces
  - Common-refinement of the two fault surfaces
    - Computed at each time step
    - After projection on an average surface (gap/overlap)
- Fault representation
  - Damage and core zone
    - Core zone can act as a barrier
    - Fault-fault fluxes
  - Fault properties can change over time
- Extension to two-phase flow
  - Simpler model for capillary pressure





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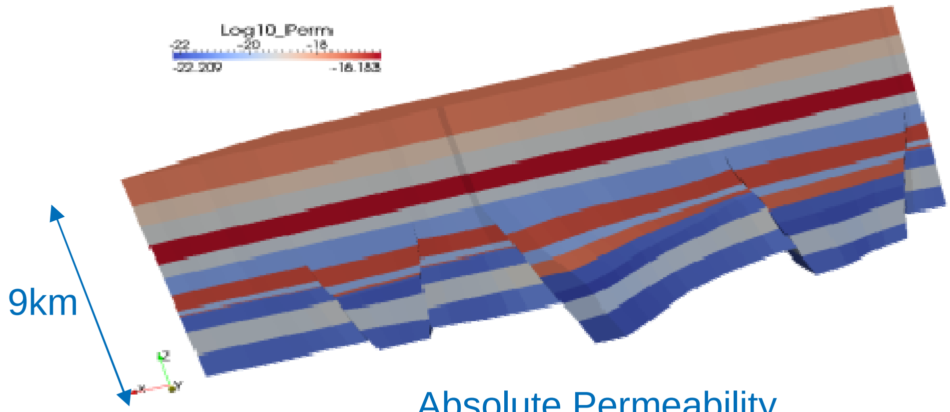
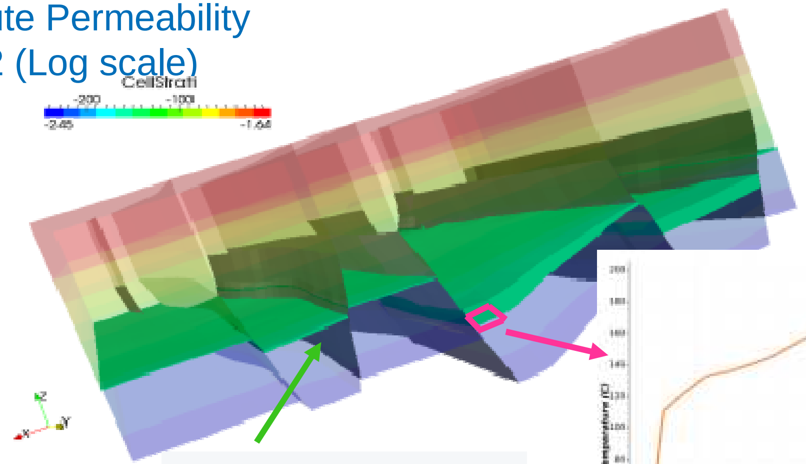
Two-phase flow in a semi-synthetic basin



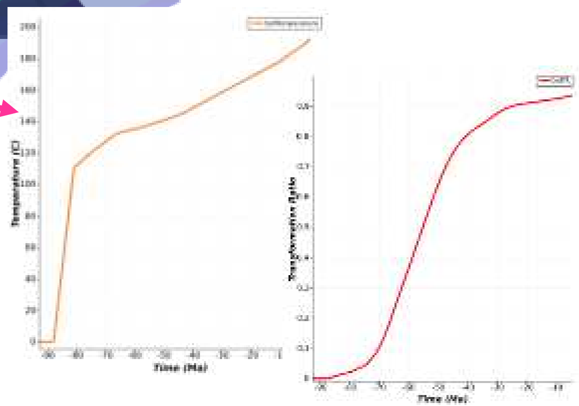
Absolute Permeability
m2 (Log scale)



Source Rock

- Temperature
- HC generation
- Two-phase flow

Temperature and
maturity evolution



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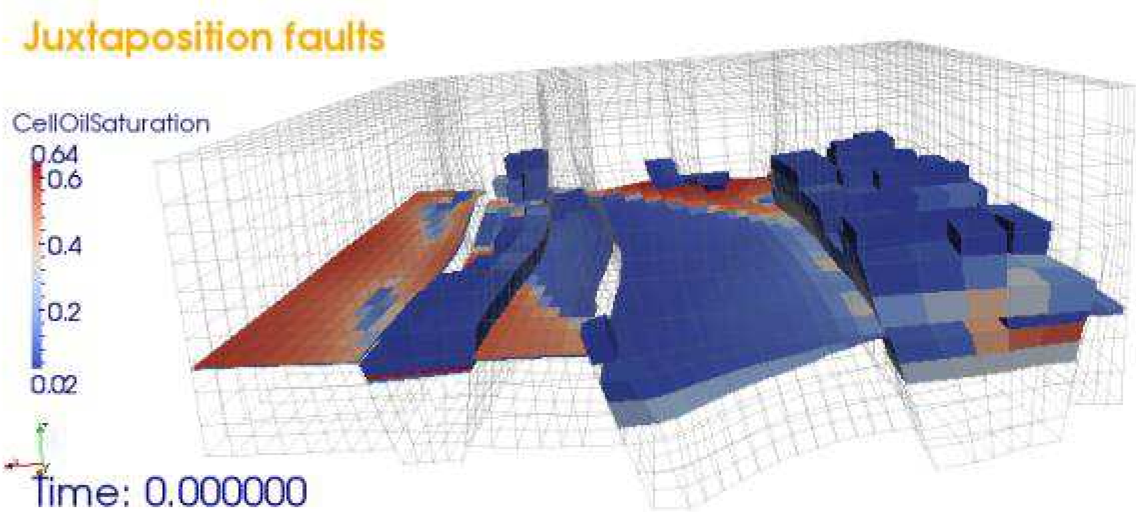
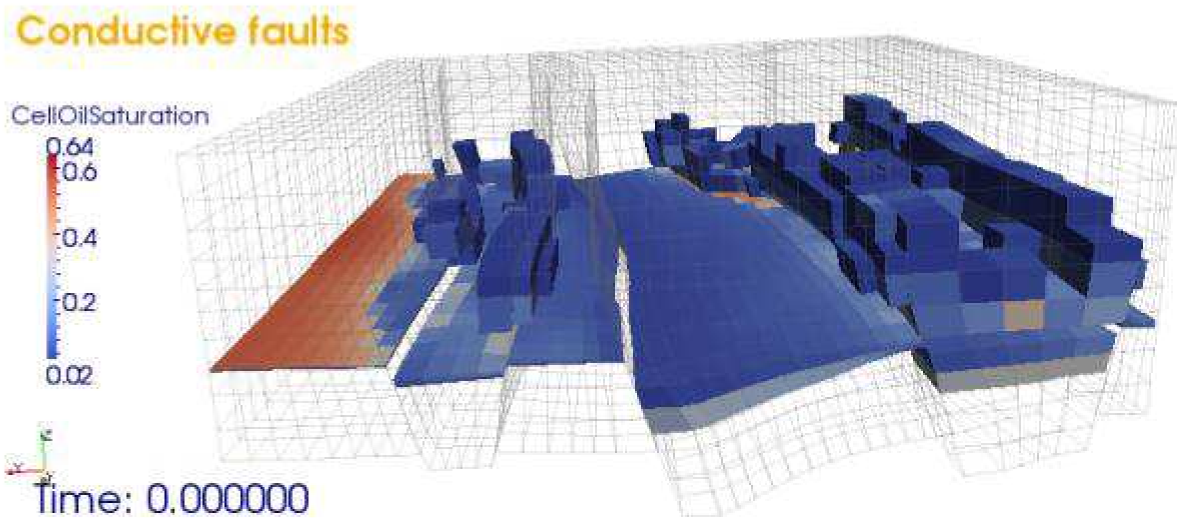
Two-phase flow



Fault faces properties are the same as the neighboring cells



Uniform permeability fault faces
No capillary pressure

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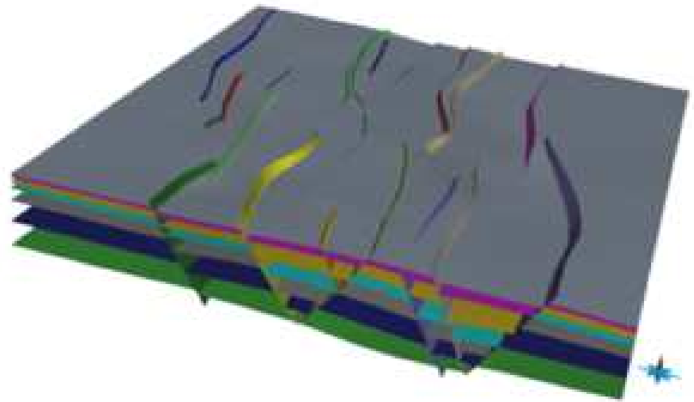
Conclusions - Perspectives

- Basin modeling in complex geological context
- 3D moving mesh
  - Fully unstructured, poor quality
  - Non-matching and sliding across faults
  - Mesh generation remains an issue for complex real basins
- Fault zones
  - A two-interface fault model
  - Single-phase flow
    - Continuous approach : MPFA/TPFA FV
    - Virtual mesh approach : HFV
  - Two-phase flow
    - O-scheme/TPFA + upstream weighting
    - More robust MPFA scheme
    - HFV
- 3D compaction
  - a more mechanics-based approach



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