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 contain hydrocarbons?
  - If yes, what is the volume and the quality of the trapped hydrocarbons?
  - Is there a risk of encountering abnormal pressures?
Sedimentary basin history

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, 10 km depth
- Sedimentary layers

[Science et Vie Junior, 2004]
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
Simple geological context

- Pile of sedimentary layers
Structurally complex basin

- Extensive settings

- Compressive settings

Simulation workflow

- **Data**

  - Present day geometry
  - Lithology distribution

  Bassin simulation
  - Porosity
  - Pressure
  - Hc

  Structural Restoration
  Past architecture of the basin

- **Age**
  - Age = 0 Ma
  - Age = 10 Ma
  - Age = 15 Ma
  - Age = 65 Ma
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
ArcTem Simulator

Main characteristics and potential improvements

- Mesh
- Heat transfer and fluid flow
  - “standard” model and FV discretization
- Faults
  - Interface fault model
  - Different discretization
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
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 …)
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

  \[
  \frac{\partial}{\partial t}(\phi \rho_w) + \text{div}(\rho_w \mathbf{v}_w) = q_w
  \]
  \[
  \phi(\mathbf{v}_w - \mathbf{v}_s) = -m_w \mathbf{K}(\nabla P_w - \rho_w \mathbf{g})
  \]
  \[
  \frac{\partial}{\partial z} \sigma_v = (\rho_w \phi + \rho_s (1 - \phi))g
  \]
  \[
  \phi = \mathcal{F}_\phi(\sigma_v - P)
  \]

- **Heat transfer**
  - Accumulation, conduction, convection
    \[
    \frac{\partial}{\partial t}(\rho_s c_s (1 - \phi) + c_w \rho_w \phi)T + \text{div}(\rho_s c_s (1 - \phi)T \mathbf{v}_s + \rho_w c_w T \mathbf{v}_w)
    \]
    \[
    + \text{div}(-\lambda_b \nabla T) = q_T
    \]

- **Two-phase flow**
  - Hydrocarbon generation
  - Oil migration and trapping under cap-rocks
    \[
    \frac{\partial}{\partial t}(\phi \rho_\alpha S_\alpha) + \text{div}(\rho_\alpha \mathbf{v}_\alpha) = q_\alpha
    \]
    \[
    \phi S_\alpha(\mathbf{v}_\alpha - \mathbf{v}_s) = -m_\alpha (S_\alpha) \mathbf{K}(\nabla P_\alpha - \rho_\alpha \mathbf{g})
    \]
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 \( \text{div}(\lambda \nabla T) \)
    - Heat transfer \( \text{div}(\mathbf{K} \nabla P) \)
    - 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
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]
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

\[ -\text{div}(\mathbf{K} \nabla P) = f \]
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
  - “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
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

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

\[-\text{div}(K \nabla P_1) = f\]  
\[-\text{div}(K \nabla P_2) = f\]  
\[-\frac{\partial}{\partial y} (\tilde{K}_{f,y} \frac{\partial}{\partial y} P_{f,II}) = u_{I,II} - u_{II}\]

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

\[\tilde{K}_{f,y} = K_{f,y} \times d\]  
\[\tilde{K}_{f,x} = \frac{K_{f,x}}{d}\]
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
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 \( P_{\sigma} \)

- **Fault-fault flux**
  - Computed on sub-faces
  - Given by the fault model
  
  \[
  F_{\sigma,m}^{f} = |\sigma| 2 \tilde{K}_{f,x,\sigma} (P_{\sigma} - P_{\sigma}^{f})
  \]

- \( P_{\sigma|\gamma}^{f} \) obtained by piece-wise constant or piece-wise linear approximation compatible with flux along the fault approximation
Some results on a static geometry

- Single phase flow

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

Permeable layers

Open boundary

Slightly compressible single-phase flow

Injection
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

![Graphs showing pressure evolution over time for bottom, medium, and top cells.](image)
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
      \[ F_{K,\delta} = \sum_{\delta' \in \mathcal{E}_K} T_{\delta,\delta'} (P_K - P_{\delta'}) \]
    - Balance over each cell
      \[ \sum_{\delta \in \mathcal{E}_K} F_{K,\delta} = |K|q_K = f_K \]
    - Flux continuity on each face
      \[ F_{K(\delta),\delta} + F_{\mathcal{L}(\delta),\delta} = 0 \]
  - Flux expression: built to ensure coercivity
    - Discrete gradient in each cone
      \[ \nabla_{K,\delta} u = \nabla_K u + \alpha_K R_{K,\delta}(u) \hat{n}_{K,\delta} \]
  - Handles non-matching grids: sub-faces unknowns
  - Generalized Hybrid scheme [Droniou et al., 2010]
    - Equivalent to Mimetic Finite Difference
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

\[ F_{\sigma,\delta} = \sum_{\delta' \in \mathcal{E}_{\sigma}} T_{\delta,\delta'} (P_{\sigma}^f - P_{\delta'}^f) \]
Some results on a toy problem

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

Initial geometry

![Initial geometry image]

Final geometry

![Final geometry image]

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

- Initial pressure field

- Influence of fault zone properties
Juxtaposition fault

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

- Velocity field
- Pressure field
Fault as a channel

- Fault face permeability is 100mD

Velocity field
Arrow size is reduced by a factor 5

Pressure field
Fault as a moderate barrier

- Fault face permeability is 0.01 mD
Some results for a realistic test case

- 3D domain, 2 intersecting faults
Homogenous domain $K=0.01\text{mD}$

Initial condition

Fault as a channel $K=1\text{mD}$
Fault as a barrier $K=1.e-4\text{mD}$
Heterogeneous domain 1mD/ 0.01mD

Velocity field

Juxtaposition fault
Fault as a channel 100mD
Fault as a barrier 1.e-4mD
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
Two-phase flow in a semi-synthetic basin

- Temperature
- HC generation
- Two-phase flow

Absolute Permeability m² (Log scale)

Temperature and maturity evolution

Source Rock
Two-phase flow

Fault faces properties are the same as the neighboring cells

Uniform permeability fault faces
No capillary pressure
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