Anisotropic permeabilities evolution of reservoir rocks under pressure: New experimental and numerical approaches

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Context of our study:

Reservoir permeability drop due to compaction during the production

- Primary recuperation → Pore Pressure $P_p$ decreases
- Effective stress increases
  \[ \sigma_{eff} = \frac{2\sigma_h + \sigma_v}{3} - P_p \]
- Effective vertical stress increases (dependent of the distance to the borehole)
- Horizontal permeability dependency of the production

Motivations:
Relation between the evolution of the stress field anisotropy and the transport properties anisotropy?
Effects of the stress path on reservoir compressibility? → Reservoir simulation
EXPERIMENTAL SET-UP

Triaxial cell specially designed to directional permeabilities measurements

P_max = 69 MPa
T_max = 130°C
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Special Core sleeve equipment

**Tridirectional Permeabilities:**

**Axial permeability measurements:** $k_{az,FL}$ & $k_{az,ML}$
- Classical between inlet and outlet of the sample
- Pore pressure sampling at the mid-length of the sample

**Radial permeability measurements:** $k_{rx}$ & $k_{ry}$
- 2 pairs of injector/receptor at the contact of lateral sample surface.
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Special Core sleeve equipment

**Tridirectional Permeabilities:**

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**Complementary measurements:**

**Sample strains:**
- Axial displacement of the upper piston: external LVDT
- Radial strains: Cantilever fixed on the core sleeve

**Porosity Evolution:**
- $\Delta V_p$ recorded by ISCO Pump during each confining pressure increase.
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Modified Darcy law:
Geometric Factor Calculation using Finite Elements Method

Modified Darcy law: \[ \frac{Q}{A_a} = -G \frac{k_r \Delta P}{\mu D} \]

True radial flow
Equivalent Darcy flow

\[ Q_n = A_n \frac{k_n \Delta P_n}{\mu D} \]
\[ Q_a = A_a \frac{k_a \Delta P_a}{\mu D} \]

Effective cross-section Area
Injector Area

Considering an isotropic permeability case:

Geometric factor \[ G = \frac{A_a}{A_n} = \frac{\Delta P_n}{\Delta P_a} \]

FEM simulation \[ G = 0.18 \]

Bai & al. SPE#78188 (2002)
EXPERIMENTAL RESULTS
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Tested Samples

**Fontainebleau Sandstones:**

Porosity: 5.4 to 8%  Permeability: 2.5 to 30mD

→ Hydrostatic loading

**Bentheimer Sandstones:**

Porosity: 24%  Permeability: 3000 mD

→ Hydrostatic and Deviatoric loading at low confining pressure

**Estaillades Limestones:**

Porosity: 27%  Permeability: 150mD

→ Hydrostatic and Deviatoric loading at low confining pressure
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Experimental results: Low permeability sandstone (Fontainebleau)

HYDROSTATIC LOADING

SAMPLE 1: $\phi = 5.4\%$

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Experimental measurements validation on Fontainebleau sandstones

Confrontation of measured $k-\phi$ and a model of diagenetic compression of Quartz aggregates

Grain Pore Throat Model*

$$k \propto \left( \phi^{1-u} - \phi_r^{1-u} \right)^4$$

$\phi_r$: Residual Porosity; $U$: Geometrical Exponent

defined as $S \propto \phi^U$

Verified for 3 Fontainebleau Samples (low porosity and low permeability)

* Chauveteau G. (2002) SPE#73736
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Experimental results: High permeability sandstone (Bentheimer)

**HYDROSTATIC LOADING**

- $k_{0az,FL} = 1840 \text{ mD}$
- $k_{0az,ML} = 2900 \text{ mD}$
- $k_{0ry} = 2825 \text{ mD}$
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**« UNIAXIAL » LOADING**

Brittle failure: \( \sigma_a = 53.5 \text{ MPa} \)

Effective Elastic moduli calculated in the range of axial stress [20:40] MPa:

\[
E = 10.3 \text{ GPa} \\
\nu = 0.2
\]

Rupture influence on 3D permeabilities

<table>
<thead>
<tr>
<th>Axial</th>
<th>( k_{az,FL \text{ before failure}} = 1185 \text{ mD} )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( k_{az,FL \text{ after failure}} = 1560 \text{ mD} )</td>
</tr>
<tr>
<td>Radial</td>
<td>( k_{rx \text{ before failure}} = 2139 \text{ mD} )</td>
</tr>
<tr>
<td></td>
<td>( k_{rx \text{ after failure}} = 631 \text{ mD} )</td>
</tr>
</tbody>
</table>

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Experimental results: intermediate permeability limestone (Estaillades)

Porosity evolution - hydrostatic loading

Homogeneous Pore Collapse

$P^* = 30$ MPa

Permeability evolution - hydrostatic loading

$k_{0az,FL} = 152$ mD
$k_{0az,ML} = 162$ mD
$k_{0ry} = 70$ mD

$k_{0az,FL} = 20$ mD
$k_{0az,ML} = 20$ mD
$k_{0ry} = 13$ mD
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Experimental results: Intermediate permeability limestone (Estaillades)

High Resolution Micro-Scanner Slides (3 μm resolution)

BEFORE LOADING

AFTER LOADING
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Experimental results: Intermediate permeability limestone (Estaillades)
CONCLUSIONS #1

• Simultaneous radial and axial permeability measurements are feasible.
• Classical axial permeability measurements may be affected by end effects.
• The pressure dependency of permeabilities is well captured.

ON GOING EXPERIMENTAL WORK:

- Investigation of the influence of strains localization on flow properties (In-situ Observations)
- Focus on stress paths more representative of reservoir conditions.
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PORE SCALE MECHANISMS MODELISATION
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Modelisation of pore-scale mechanisms

Equivalent Pore Network extraction*:

- Pores: Equivalent Volume spheres
- Throats: Cylindrical channels

Output data:
- Throats dimension: $L_T$, $r_T$ & AR
- Equivalent pores volumes: $\phi$
- Network connectivity

* Youssef et al. (2007) SCA
## Transport properties simulation

- **Individual channel conductance:**
  \[
g = \frac{\pi r^4}{8 L}
\]

### Problem formulation:

- In the throat between pores i and j:
  \[
  q_{ij} = g_{ij} (P_i - P_j)
  \]

- In the Pores:
  \[
  \sum_{i \to j} q_{ij} = 0
  \]

- Matrix formulation:
  \[
  G \cdot \bar{P} = \bar{S}
  \]

- → Resolution of network effective hydraulic conductivity

## Network compaction implementation

### Spherical Pores:

- \[
  r_p \approx r_{p,0} \left(1 - \gamma_p (p - p_0)\right)^* \\
  \gamma_p = \frac{(1 + \nu)}{2E}^{**}
  \]

### Cylindrical Pore Throats:

- \[
  r_T \approx r_{T,0} \left(1 - \gamma_T (p - p_0)\right)^* \\
  \gamma_T = \frac{(1 + \nu^2)}{E}^{**}
  \]

\(l_T\) pressure dependency neglected

\[
G_T(P) \rightarrow G(P) \rightarrow k(P)
\]

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Modelisation of pore-scale mechanisms: Bentheimer Sandstone Example

Extracted equivalent pore network
Volume = 500x500x500 x 6 µm

\[ \phi_{\text{exp}} = 24.5\% \quad \leftrightarrow \quad \phi_{\mu CT} = 24.4\% \]
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Modelisation of pore-scale mechanisms: Bentheimer Sandstone Example

Extracted equivalent pore network
Volume = 500x500x500 \times 6 \mu m

\[
\begin{align*}
  k_{\text{exp}} &= 3000 mD \\
  k_{\mu CT} &= 847 mD \\
  A_{k, \mu CT} &< 10\%
\end{align*}
\]

Discrepancy lies to the definition of \( r_T \)
(minimum local pore throat radius)

\[
g_h = \frac{\pi r_T^4}{8 L}
\]
CONCLUSIONS #2: MICRO-TOMOGRAPHY CONTRIBUTION

• Simple pressure dependency model can be applied on the equivalent pore network.

ON GOING NUMERICAL WORK:

- Alternative description of throats dimensions
- Investigation of the anisotropic distribution of the channels
- FEM simulation of the coupled effects of deforming matrix and fluid flows (TRUE GEOMETRY OF THE POROSITY)
THANKS FOR YOUR ATTENTION
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New Experimental Set-up:
Triaxial cell specially designed to directional permeabilities measurements

\[ P_{\text{max}} = 69 \text{ MPa} \]
Max Using Temperature = 130°
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Experimental results: Low permeability sandstone (Fontainebleau)

Sample 2: $\phi = 8\%$

Directional permeability evolution SAMPLE 2

Preliminary Experimental Conclusions:
- Radial and axial permeabilities values differences due to G calculation
- Intermediate axial permeability measurements looks more consistent than classical measurements