In Salah High-Resolution Heterogeneous Simulations of CO₂ Storage*

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Abstract

The In Salah CO₂ storage site, Algeria, is part of an industrial-scale capture and storage project within the In Salah Gas Joint Venture. CO₂ from several fields within the development is removed from the production stream and injected into a saline aquifer 1900 m below the surface and several kilometers away from one of the gas reservoirs - the Carboniferous sandstone at Krechba.

CO₂, injected into three horizontal wells down-dip from the natural gas field at Krechba, has been actively monitored since the injection start-up in 2004. Satellite surveys (InSAR) showing subtle surface deformation and analysis of well data (gas geochemistry and tracer analysis) give indications of the spatial distribution of the injected CO₂. The 20 meter thick reservoir/aquifer unit is pervasively fractured with the predominant joint set (NW-SE) in close alignment with the present-day stress field. The reservoir/aquifer is also segmented by a number of strike-slip faults (E-W) related to a regional mid-to-late Carboniferous basin inversion. The heterogeneous nature of the storage formation is a key influence on the distribution of stored CO₂ in the subsurface.

We use a non-deterministic stochastic modeling approach assuming capillary limit conditions to simulate the CO₂ migration process. The field-scale model involves 410 million cells with dimensions of 10x10x2 meters. The high-resolution model captures the reservoir heterogeneity with respect to both fault and fracture distributions and uses invasion percolation algorithms to assess the distribution of CO₂ within the storage unit. The simulation results are consistent with the observed CO₂ distribution after 5 years of injection and indicate that the current distribution of CO₂ is principally related to the fracture network. Initial results for predictive simulations of
the post-injection period (decadal distributions) are sensitive to, and principally constrained by, the fault distribution and the multi-phase flow behavior. The simulations results highlight the key role that high-resolution heterogeneous field-scale models can play in developing a comprehensive, cost-effective and fit-for-purpose storage monitoring program. We now aim to model the pressurization of the reservoir near the injection wells to further understand the initial CO$_2$ distribution and investigate the capillary limit conditions of the inversion percolation model.

**Selected References**


**Website**

In Salah
High Resolution Heterogeneous Simulations of CO2 Storage

Andrew Cavanagh
The Permedia Research Group
In Salah
High Resolution Heterogeneous Simulations...

Mona Lisa: 120,000 pixels
In Salah
High Resolution Heterogeneous Simulations...

Mona Lisa: 120,000 pixels

Mona Lisa: 120 pixels
In Salah
High Resolution Heterogeneous Simulations...

- Megatonne CO₂ Storage Sites
- In Salah Overview
- Modeling Strategy
  - Flow domains
  - Capillary numbers
- Field Scale Model
- Simulations
  - Pilot
  - Faulted
  - Faulted and Fractured
- Comparison with Observations

Mona Lisa, Leonardo da Vinci, c. 1519
Megatonne Storage Sites

In Salah: 20x18 km

Injection depth
Sleipner: 1000 m
Weyburn: 1400 m
In Salah: 1900 m

Weyburn-Midale: 50x40 km

3 Mt

Sleipner: 300x400 km

13 Mt

22 Mt
In Salah Stratigraphy

- Water table, 450-300 m (msl)
- Cretaceous Superieur... siltstones and limestones 0 m
- Pan Saharan Aquifer... sandstones with mudstones 170 m
- Regional Hercynian U/C, top of Visean, overlain by thin anhydrite 940 m
- C20-7... fractured mudstones with strong gamma ray response (Visean, Carb) 1590 m
- C20-3... fractured mudstones (Visean, Carb) 1790 m
- C20-2... fractured mudstone with open fracture sets, unstable (Visean, Carb) 1820 m
- C20-1... fractured mudstone thin dolomites and siltstones (Visean, Carb) 1860 m
- C10-3... fractured siltstones and sandstones (Tournasian, Carb) 1885 m
- C10-2... fractured sandstone (Tournasian, Carb) 1900 m
- D70... dolomitic sandstone with thin silt and mudstones (Fammenian, Dev) 1920 m

Ages
- U Cretaceous 100 - 65 Ma
- Sakamarian 288 - 283 Ma
- Visean 342 - 327 Ma
- Tournasian 354 - 342 Ma
- Fammenian 364 - 354 Ma
In Salah Reservoir
Sandstone: massive, rippled, fracture-influenced, matrix-dominated
Facies: tidal deltaic, deposited in a broad palaeovalley
Porosity: ~15% (13-20)
Permeability: ~10 md (0.1 - 300)

Faults
Fault throw less than 20 meters
No faults cut the reservoir communication
E-W faults easiest to map, N-S faults, NE-SW faults
Prolific and sparse fault models

Fractures
2-sigma plane orientation NW-SE, density: 2-3/meter, aperture: 0.1-1 mm, length: 6-25 m
Fractures conform to recent stress field

Wells, KB-501, -502, -503
Injection rate: 0.2 Mt/yr/well... 30 Mmscf/day... 8 litres/well/second
Horizontal: 1.3 - 1.5 km
Azimuth: perpendicular to stress field
Observations: logged, cored and monitored

Storage Site Observations
3D seismic baseline, downhole geophysics, 4D seismic monitoring,
InSAR: Interferometry Satellite Airborne Radar, geochemical tracers...
## Flow Domains and Dimensionless Numbers

<table>
<thead>
<tr>
<th>Flow Domain</th>
<th>Flux rate; occurrence</th>
<th>Dimensionless number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbulent flow</td>
<td>Very high; near-well, unusual</td>
<td>Re &gt; 10</td>
</tr>
<tr>
<td>Darcy flow</td>
<td>High-to-moderate; near-well</td>
<td>Re &lt; 10, Ca &gt; 0.0001</td>
</tr>
<tr>
<td>Invasion percolation</td>
<td>Low; reservoir and basin-scale</td>
<td>Ca &lt; 0.0001, Kn &lt; 1</td>
</tr>
<tr>
<td>Knudsen flow</td>
<td>Extremely low; unconventional</td>
<td>Kn &gt; 1</td>
</tr>
</tbody>
</table>

Key: Re, Reynolds No.; Ca, Capillary No.; Kn, Knudsen No.
Capillary Number Calculations

\[ Ca = \frac{\mu q}{\gamma} \]

- \( \mu \), viscosity \([\text{Pa}\cdot\text{s}]\)
- \( q \), flux \([\text{m/s}]\)
- \( \gamma \), interfacial tension \([\text{N/m}]\)

Capillary flow \( \sim \times 10^{-4} \) \([1:10,000]\)

(Henri Bouassé, *Capillarity and Wetting Phenomena*, 1924)

- In Salah injection, \( Ca \sim \times 10^{-6} \) \((8 \text{ litres/well/second})\)
- In Salah migration, \( Ca \sim \times 10^{-7} \) \((1.3 \text{ km/2 years})\)
Field Scale Model, Invasion Percolation

104 million cells, 17.5x25 km, 20x20x2 m
Field Scale Model, Invasion Percolation

104 million cells, 17.5x25 km, 20x20x2 m
Simulations...

Migration beneath the Caprock

Stochastic analysis of probable migration paths (N=120)
Simulations...

Southern Area

Stochastic analysis for KB-501 (N=55)
Simulations...

Northern Area

Stochastic analysis for KB-502 & KB-503 (N=55)
Simulations...

Migration with Faults

Prolific fault scenario (BP seismic mapping team)
Simulations...

Migration with Faults

5-10-15-20 meter column height (frequency analysis, N=60)
Simulations...

Migration with Faults

5-10-15-20 meter column height (frequency analysis, N=60)
Simulations...

Migration with Faults

5-10-15-20 meter column height (frequency analysis, N=60)
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Migration with Faults

5-10-15-20 meter column height (frequency analysis, N=60)
Simulations...

Migration with Faults

5-10-15-20 meter column height (frequency analysis, N=60)
Simulations...

Comparison of field-scale migration with and without faults
Fracture Model

Northern area contour map  Log-normal fracture distribution  Contour map after fabric added
Simulations...

Migration with Fractures

Reservoir with fabric added
Simulations...

Migration with Fractures

Before

After
Comparison to Observations

Northern Area early filling sequence
Comparison to Observations

Ringrose et al. (EAGE, 2008)

Northern Area early filling sequence
Simulations...

Northern Area early filling sequence (N=20)
Simulations...

Northern Area early filling sequence (N=20)
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Northern Area early filling sequence (N=20)
Simulations...

Northern Area early filling sequence (N=20)
Comparison to Observations

Ringrose et al. (EAGE, 2009)

Match to expected CO2 distribution
Conclusion

Topography  
Faults  
Fractures  
Fractured and Faulted
Conclusion: why model at low resolution?
Conclusion: why model at low resolution...

...when heterogeneity matters?
Conclusion: why model at low resolution...

...when heterogeneity matters?
References


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Fault Leakage
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Invasion Percolation
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Curvature Analysis
- McGill University Seismic Research Group
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