The Ultimate Fate of CO$_2$
Trapping Timescales

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All errors are undoubtedly the result of my failure to follow their advice.
Trapping Processes in CO$_2$ storage

Dissolution Trapping
- onset of convection
- dissolution rate

Residual Trapping
- Horizontal Aquifer
- Sloping Aquifer

Summary
Injected CO$_2$ is buoyant!

(Ide et al. 2007)
CO₂ Trapping Processes

Residual

Dissolved

Mineralized

(Benson et al. 06)

(Riaz, Hesse et al. 06)

2.2 mm

\( \text{NaAlCO}_3\text{(OH)}_2 \)
States of CO$_2$ in Subsurface

- **Injected CO$_2$**
  - Dissolution tapping
  - Residual trapping

- **Dissolved CO$_2$**
  - Mineral trapping

- **Residual CO$_2$**

- **Mineralized CO$_2$**

- **Leaked CO$_2$**
Dissolution Trapping
Dissolved CO$_2$ Increases Brine Density

\[ \rho_{\text{mixture}} = 999 + 17.7c^* \]

\[ \rho_{\text{mixture}} = 991 + 17.8c^* \quad (R^2 = 0.947) \]

(Yang & Gu 2006)
Important Scales

Time and length scales:

1) Critical time:

\[ t_c = \frac{146\phi\mu^2 D}{(K\Delta\rho g)^2} \propto \frac{1}{K^2} \]

2) Critical wavelength:

\[ \lambda_c = \frac{2\pi\mu D}{0.07K\Delta\rho g} \propto \frac{1}{K} \]

⇒ permeability \( K \) is the important factor

high-\( K \) aquifers: \( t_c \sim 1 \text{ yr} \), and \( \lambda_c \sim 1 \text{ m} \)

(Riaz, Hesse et al. 2006)
Numerical Resolution?

Mesh size: 3cm x 4cm
grid blocks: 80,000
Onset time: 2 yrs

10m x 13m

7km x 10km x 30m

100m x 100m x 2m
grid blocks: 350,000
Onset time: 100 yrs

(Lindeberg & Bergmo 2003)
Open Aquifers

CO₂ Concentration Maps:  Evolution of Dissolution Rate:

\[ \tau = 7.3 \]
\[ \tau = 14.6 \]
\[ \tau = 22.0 \]
\[ \tau = 29.0 \]

\[ dC/d\tau \]

Ra = 4000
Closed Aquifer

\( \tau = 7 \)

\( \tau = 14 \)

\( \tau = 60 \)

\( \tau = 120 \)

\( Ra = 2000 \)

Dissolution Rate vs. time
CO₂ Dissolution at Sleipner

high permeability + large volume = efficient dissolution

\[ \phi \sim 0.3 \]
\[ K \sim 3 \text{ Darcy} \]

400 km x 50-100 km
100 - 200 m

5,000 - 50,000 years

(Chadwick et al. 2004)

(Lindeberg & Bergmo 2003)
Residual Trapping

- Residual CO₂
- CO₂-plume

Diagram showing the movement of CO₂ in a geological formation with reference to injection well, surface, saline aquifer, and outcrop/leak.
Microscopic & Macroscopic

(Benson et al. 2006)

How much is left behind? ⇒ residual saturation

(Doughty et al. 2006)

How much of the aquifer is contacted? ⇒ sweep
\[ \Delta h \Delta x \phi (1 - S_{wr}) = (Q_g(x,t) - Q_g(x + \Delta x,t)) \Delta t - \Delta h \Delta x \phi S_{gr} \]
Non-Dimensional Form

\[ \eta = h/H \quad \xi = x/L_0 \quad \tau = \frac{t}{L_0^2/(k_1 H \cos \theta)} \]

\[ \frac{\partial \eta}{\partial \tau} + \text{Pe} \sigma \frac{\partial}{\partial \xi} \left[ \frac{\eta(1-\eta)}{\eta(M-1)+1} \right] = \sigma \frac{\partial}{\partial \xi} \left[ \frac{\eta(1-\eta)}{\eta(M-1)+1} \frac{\partial \eta}{\partial \xi} \right] \]

\[ \sigma = \begin{cases} 
1; & \eta_\tau \leq 0 \\
1 - \varepsilon; & \eta_\tau > 0
\end{cases} \]

\[ \text{Pe} = \frac{L_0}{H} \tan \theta \quad \varepsilon = \frac{S_{gr}}{1 - S_{wr}} \quad M = \frac{k^*_rg}{\mu_g k^*_rw} \]
Horizontal Aquifer

\[ \frac{V}{V_0} = 0.89, \quad t < 1 \text{ yr} \]

\[ \frac{V}{V_0} = 0.72, \quad t = 17 \text{ yr} \]

\[ \frac{V}{V_0} = 0.68, \quad t = 46 \text{ yr} \]

\[ \frac{V}{V_0} = 0.59, \quad t = 522 \text{ yr} \]

\[ S_{gr} = S_{wr} = 0.2 \]

\[ L_0 = 2000 \text{ m} \]

\[ H_0 = 200 \text{ m} \]

\[ \theta = 0^\circ \]

\[ (M = 0) \]
Volume Decay Horizontal Aquifer

Volume Decay Horizontal Aquifer

\[ V \propto t^{3\beta - 1} \]

tip pos.: \[ x_{\text{tip}} \propto t^\beta \]

height: \[ h \propto t^{2\beta - 1} \]

(Bear & Ryzhik 1998)
Analytic model for large Pe

\[ \tau = 50, \varepsilon = 0, \text{Pe} = 2 \]

\[
\frac{\partial \eta}{\partial \tau} + \sigma \frac{\partial}{\partial \xi} \left[ \frac{\eta(1-\eta)}{\eta(M-1)+1} \right] = 0
\]
Evolution of Footprint

\[ \xi: \text{distance} \]
\[ \tau: \text{time} \]

- Front
- Back
Volume Decay Sloping Aquifer

Horizontal

Sloping

\[ \frac{V}{V_0} \]

- \[ \varepsilon = 0 \]
- \[ \varepsilon = 0.25 \]
- \[ \varepsilon = 0.5 \]
- \[ \varepsilon = 0.75 \]

\[ \text{diffusive time: } \theta \]

\[ \text{adveactive time: } \tau \]
Numerical Solutions

![Diagram showing numerical solutions with graphs and annotations related to geological storage.](image-url)
Residual Trapping in Alberta Basin

(Bachu et al. 2002)

(Bachu & Bennion 2007)
Summary: Dissolution Trapping

vigorous convection in high permeability aquifers

linear dissolution rate in large open aquifers

dissolution likely to be important at Sleipner

convective dissolution is numerical challenge
Summary: Residual Trapping

- power-law plume decay in horizontal aquifers
- rapid plume decay in sloping aquifers
- residual trapping likely to be important in Alberta
- thin gravity tongues are numerical challenge
课外说明

“All aquifers discussed in this presentation are fictional. Any similarity to real aquifers, intended for storage or not, is strictly a coincidence.”
References

Dissolution Trapping:

- **Riaz, Hesse, Tchelepi & Orr (2006)** Onset of convection in a gravitationally unstable diffusive boundary layer in porous media, *JFM*, *548*, pp. 87-111

Residual Trapping:

- **Hesse, Tchelepi & Orr (in prep)** Gravity Currents with residual trapping in sloping aquifers
- **Hesse, Tchelepi, Cantwell & Orr (2006)** Gravity currents in horizontal porous media: transition from early to late self-similarity, *JFM 577*, pp. 363-383
- **Hesse, Tchelepi & Orr (2006)** Scaling Analysis of the migration of CO$_2$ in saline aquifers, *SPE 102796*