Carbon Sequestration in Sedimentary Basins

Physical Processes in C Sequestration...

Maurice Dusseault
Department of Earth and Environmental Sciences
University of Waterloo
C Sequestration

- As $CO_2$ (risks...)
  - An enhanced oil or gas recovery agent
  - Displacing formation water in deep aquifers
  - Dissolved in the aqueous phase
  - Storage in caverns (salt or rock caverns...)

- As solid C (minimal risk)
  - Injection of petcoke, coal wastes, etc
  - Biosolids injection and biodegradation to C

- As a mineral precipitate (minimal risk)
  - We will not consider this option much
Where to put the CO$_2$?
Geological Sequestration of C
Shake!!

Northridge earthquake 24/01/2004
Earthquakes and CO$_2$

- Can earthquakes cause release of CO$_2$?
- Sealing and non-sealing faults
- Inherent risk (Manitoba vs Haida Gwaii)
- Induced seismicity,
- Did the Northridge Earthquake break the seal on any of the local CH$_4$ storage reservoirs?
Ontario Quakes...

Southern Ontario Earthquake Monitoring Network
http://www.gp.uwo.ca/
National Earthquake Hazards Program
http://www.seismoscan.gc.ca/links_e.php
Earthquakes and CO$_2$

- We can choose our siting
- We can control our injection pressures and temperatures to stay within certain limits, based on oilfield experience
- We can monitor using deformation or seismic measurements in addition to $p$, $T$, Q...
- Inherent risks are very low, and...
- Manageable through monitoring...
Comments on CO$_2$ Separation

- Costly... 60% of sequestration costs
- Membranes (not quite there yet)
- Forced adsorption (amine solutions, etc.)
- High reactivity calcium oxide
- Cryogenic (low T methods)
- These would increase the cost of power in current configurations by ~30%
- Modification of combustion process?
- New sequestration method?
### CO₂ Purity, Various Sources

<table>
<thead>
<tr>
<th>Source</th>
<th>CO₂ Content</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ammonia</td>
<td>100%</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>10-100%</td>
</tr>
<tr>
<td>Ethylene oxide</td>
<td>100%</td>
</tr>
<tr>
<td>Gas processing</td>
<td>100%</td>
</tr>
<tr>
<td>Cement</td>
<td>15-30% (CaCO₃...)</td>
</tr>
<tr>
<td>Iron and steel</td>
<td>15%</td>
</tr>
<tr>
<td>Ethylene</td>
<td>10-15%</td>
</tr>
<tr>
<td>Refineries</td>
<td>3-13%</td>
</tr>
<tr>
<td>Power</td>
<td>3-15% (13/87 flue gas)</td>
</tr>
</tbody>
</table>
Coal power with CO₂ separation 1982, Lubbock, Texas. The plant was based on an oil price of 30$/barrel and was discontinued when the oil prices were sinking in the late 1980’s. Only the (now mothballed) MEA separation plant is shown. The power plant itself is still running and is located to the right of the picture.
CO₂-capture Pilot Plant at Kaarstoe - Norway: Capture from exhaust gas by use of membrane/amine technology
Separation Options...

- Absorption: fluid dissolves or permeates into a liquid or solid.
- Adsorption: attachment of fluid to a surface (solid or liquid).
- Cryogenic (low-temperature distillation): separation based on the difference in boiling points of $N_2$, $CO_2$...
- Membranes: separation based on different physical & chemical interactions with membrane (molecular weight, molecular diameter, solubility...).
Separation of $\text{CO}_2$ from $\text{CH}_4$...
Carbon Sequestration Options

- Store $CO_2$ as SC fluid in depleted reservoirs, suitable traps
- Dissolve $CO_2$ into deep fluid reservoirs
- Use $CO_2$ in Enhanced Recovery to displace oil or gas from strata
- Deep slurry injection of biosolids, coal, or any other solid organic waste
- Place $CO_2$ in a dissolved salt cavern (the NaCl brine is industrial feedstock)
- Mineral reaction with peridotite...
Peridotite Absorbs $CO_2$...
Peridotite-Rich Ophiolites...
**CO₂ Adsorption...**

- Minerals change to carbonates
- Drill holes 4-8 km deep, inject hot water saturated with CO₂ at high pressures
- Reaction is exothermic - \( T \uparrow \) - accelerates
- No risk of “escape”...
Is it Realistic?

- Far less than sequestering $\text{CO}_2$ in reservoirs...
- Reactions are very slow, rock permeability is low, volumes needed are huge, etc.
- More costly by a factor of at least 10
- Limited areas in the world with large peridotite volumes (none in Canada)
- Nevertheless... research continues, as it must...
**CO₂ Behavior...**

- Extremely complex (p, T, chemistry...)
- Oil swelling with CO₂ adsorption
- Interfacial tension issues (changes as a function of p, T, oil chemistry...)
- Diffusion rates into H₂O, oil...
- Phase relationships in mixtures of gases, liquids (e.g. SC-CO₂ + oil + H₂O), ...
- Changes in rock wettability...
- Formation of hydrate phases...
**CCS – CO₂ Capture & Seques.**

- CO₂ is captured from some source
- Or, flue gas is used, (partly enriched?)
- It is injected into the ground, into suitable porous and permeable media
- The CO₂ stays there indefinitely

**Typical Issues:**
- Capacity and rate
- Value-added process?
- Economics
- Long-term fate
  - ... ...
Value-Added Options?

- No value-added
  - Direct storage, no other “resource” is accessed or extracted
  - This is only feasible in an incentive regime that favors sequestration or places an explicit value on C (e.g. tax or credit)

- Value-added sequestration
  - C or CO₂ used to access resources, is a byproduct of an valuable process, ...
  - Sequestration is a +ve but secondary factor
HC Enhanced Recovery with \( \text{CO}_2 \)

- Enhanced Oil Recovery - EOR
- Enhanced Natural Gas Recovery - EGR
- Enh. Coalbed Methane Recovery - ECBM

In each of these cases...

- HC exists in a fluid or accessible form...
- Conventional methods of production leave significant % behind
- \( \text{CO}_2 \) can improve the recovery factor
- \( \text{CO}_2 \) largely left behind - i.e.: sequestered
- Biosolids injection (\( \text{CH}_4 \) generated...)
Geological Sequestration of Carbon

- CO₂ capture

- Coal Mine

- Coalbed Methane Reservoir

- Gas Reservoir

- Oil Reservoir

- Saline Aquifer

- +C-rich coal waste injection

Alberta Research Council
Exploring Some Possibilities...

- Oil reservoirs suitable for \( \text{CO}_2 \) found at depths from 400 to 6000 metres
  - Shallower - risks of escape too high
  - Deeper - no oil, very expensive, etc.

- Now, we have to understand several factors:
  - How does \( \text{CO}_2 \) behave?
  - Technical options for oil recovery?
  - Does \( \text{CO}_2 \) injection fit in with these?
We must understand the behavior of CO$_2$ and the site conditions!
$CO_2$ Behavior...
Pure CO$_2$ Behavior

- **Gaseous state storage...**
  - Low density, low viscosity, under low p, T

- **Liquid state storage...**
  - High density, low $\mu$, high p, low T <35°C
  - Not compatible with real reservoirs

- **Supercritical state, > 35°C, > 7.2 MPa**
  - (> 95°F, > 1035 psi, approximately)
  - High $\rho$, low $\mu$,
  - Fully miscible with water and oil

- **Hydrate formation - low T, high p, +H$_2$O**
Depth and CO$_2$ State - I...

- T increases w. depth ~20-25°C/km
- In most areas, T > 35°C below ~800 m
- In cold conditions, pure CO$_2$ will be in a liquid state
- In the presence of water and high p, a CO$_2$-H$_2$O clathrate (hydrate) forms

Typical range of T with depth: T$_{SC}$ ~35°C

Practical conditions for CO$_2$ placement
Depth and CO₂ State - II...

- Most reservoirs to Z = 3 km: hydrostatic pressures ~10 kPa/m
- Pure CO₂ is SC below ~750 m, if T > 35°C
- In general, CO₂ is a supercritical fluid at Z > 800 m (~2620')
- Otherwise, it is a gas or a liquid, depending on p & T
CO$_2$ Behavior...
Depth and Density of $CO_2$...

Assuming a geothermal gradient of 25°C/km from 15°C at the surface, and hydrostatic pressure.
So... to achieve volume-efficient storage in porous media, almost everyone believes in SuperCritical $CO_2$ placement – SC-$CO_2$
Geomechanics Issues??

- Restricting the discussion to sandstone reservoirs and shale seals...
- And, to supercritical phase injection...
- Long-term risks of escape are the issue
- Seals are generally shale
- Stresses and pressures are important
- Slow CO$_2$ dissolution in water
- Changes in seal stresses (HF!)
- And other issues...
CO₂ Capture & Storage

Statoil
Critical SC-CO$_2$ Properties

- The viscosity of SC-CO$_2$ is on the order of 1/20$^{th}$ that of water
- Storage density of SC-CO$_2$ will likely be in the range 0.6-0.9 g/cm$^3$
- SC-CO$_2$ is miscible with H$_2$O and oil
  - Water will mix with the CO$_2$
  - Capillary barriers may be affected
- And, carbonic acid is formed..
- And, shale conditions may be altered...
Viscosity of SC-CO$_2$

Viscosity of water (H$_2$O) @ STP is 1.0 MPa·s
Thrust Faults and Mountains

**Canada**

- **NWT** (Northwest Territories)
- **Nunavut**
- **Canadian Shield**
- **Alberta**
- **Syncline**
- **BC** (British Columbia)
- **Athabasca Basin**
- **(Precambrian)**
- **Edmonton**
- **Williston Basin**
- **The Western Canadian Sedimentary Basin**

**Geology**

Alberta is the “classic” compressional (thrust fault) regime.
Compressional Basin Section

Thrust faults

Massive heavy oil deposits

Salt solution and collapse features

Alberta Syncline

Edmonton

SW

NE

Rockies

Regional Cretaceous unconformity

Cretaceous sands, shales

Jurassic and older carbonates, sandstones, shales

Devonian reefs

Prairie Evaporites (halite)

Precambrian rocks

Geological Sequestration of C

Schematic cross-section through Edmonton, Alberta

not to scale
**X-Section: Stress, Structure**

**Mountains → Golden Colorado → Banff Alberta → Distant plains**

- **Golden Colorado → Eastern Colorado → Calgary Alberta**

**Near mountains:**
- Very high $\sigma_{HMAX}$
- For great depth, $\sigma_v = \sigma_3$
- Thrusts, folds...
- Fractured strata
- Low to modest $p_o$

**Distant from mountains:**
- Moderate to high $\sigma_{HMAX}$
- For some depth, $\sigma_v = \sigma_3$
- Flat-lying, no faults
- Strata are relatively intact
- Low pressures

Generally very high pore pressures are not found in thrust regimes and their forebasins, as rocks are somewhat fractured, pressures dissipate.
Technologies for CO$_2$ use

- In shallow reservoirs, CO$_2$ as an inert gas to aid gravity drainage
- Displace CH$_4$ from coal seams
  - Deeper seams could be depressurized so $p_{\text{inj}} < p_{\text{sc}}$ for CO$_2$
- CO$_2$ could be used to “chase” gas from low permeability reservoirs (solubility in water may help considerably)
- Miscible CO$_2$ flooding (Weyburn, SK...)

Geological Sequestration of C
CO₂, then a Water Slug, etc.
Miscibility of Oil and \( \text{CO}_2 \)

- **68 bar – 1000 psi**: Immiscible \( \text{CO}_2 

- **102 bar – 1500 psi**: Miscibility begins to develop

- **170 bar – 2500 psi**: \( \text{CO}_2 \) has developed miscibility

**Geological Sequestration of C**

Final stage: Higher HC forms continuous phase - \( \text{CO}_2 \) immiscible

Higher hydrocarbons (dark spots) begins to condense
Miscibility...

- Natural gas or N₂ and CO₂ mixtures are fully miscible; they form a single fluid phase.
- CO₂ (liquid or supercritical) and water are immiscible (but CO₂ can dissolve readily in water!)
- CO₂ and oil are miscible or immiscible depending on oil composition and thermodynamic conditions (p, T).
- CO₂ and Coal: very complex; surface adsorption also plays a role.
Miscible Conditions

Recovery methods in this category include both hydrocarbon and non-hydrocarbon miscible flooding. These methods involve the injection of gases (carbon dioxide, nitrogen, flue gases, etc.) that either are or become miscible (mixable) with oil under reservoir conditions. This reaction lowers the resistance of oil to flow through a reservoir, making it more easily produced, either by water drive or injected gas pressure.
Cyclic $\text{CO}_2$ (also in THEOR)

**CYCLIC CARBON DIOXIDE STIMULATION**

Carbon dioxide is introduced into an oil reservoir during injection. The injection well is then shut off for a "soak period" during which the carbon dioxide swells the oil and reduces its viscosity. The well is then opened and the carbon dioxide provides a solution gas drive, allowing the oil and fluids resulting from the soak period to be produced. This process is repeated.

Schematic portrays one well during the 3 phases of this process. Flow pattern is stylized for clarity.
**CO₂ - EOR**

- **CO₂ Injection**
- **Recycled CO₂**
- **Production Well**
- **Reservoir**

Other permeable and non-permeable strata

Cap-rock or seal

Δp

Geological Sequestration of C

OIL

Production
CBM

- Inject CO$_2$ to displace the CH$_4$
- Coal has a high adsorptivity for CO$_2$
- And high porosity (capacity)
Viscosity of SC-CO$_2$

Viscosity of water (H$_2$O) @ STP is 1.0 MPa·s
Is SC-CO$_2$ Viscosity Important?

- The rate we can inject into a porous permeable reservoir depends on it...
- Low viscosity = much easier to do
- However! Low viscosity leads to the problem of viscous fingering...
- The low viscosity phase does not displace the high viscosity phase uniformly
- Similar to trying to waterflood heavy (viscous) oil...
Viscous Fingering...

- Oil - viscosity is 35 MPa·s
- Water is displacing the oil, viscosity ~ 1 MPa·s
- Unstable fingering develops
- Of course, these two phases are immiscible
Potential for CO$_2$ in EOR

- World-wide, perhaps $100 \times 10^9$ m$^3$ oil could be recovered with CO$_2$-EOR in a supercritical or liquid state.
- To recover 1 m$^3$ of oil, likely we will have to inject from 0.5 to 2 m$^3$ of SC-CO$_2$, $\rho \sim 0.80$, into the reservoir permanently.
- Mass sequestered =
  \[ 100 \times 10^9 \text{ m}^3 \times 0.80 \text{ t/m}^3 \times 0.5 = 40 \text{ Gt} \]
- Other assumptions, other figures...
Miscibility of Oil and CO₂

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Immiscible CO₂

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Miscibility begins to develop

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Geological Sequestration of C

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- In each of these cases...
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  - Conventional methods of production leave significant % behind
  - CO$_2$ can improve the recovery factor
  - CO$_2$ largely left behind - i.e.: sequestered
Physical Properties...

- Porosity - $\phi$ - controls storage volume available:

- $\phi$ = fractional void space of the rock

$$\phi = \text{fractional void space of the rock}$$

$V$ of solid mineral

$V$ of solid mineral

$\phi$ - Void space (fluids)

Geological Sequestration of C

$1 - \phi$
Physical Properties...

- Permeability is the ability to transmit fluid (gas or liquid or SC-fluid)

- L = 40 – 100 mm
- In the field, “L” = 100 – 2000 m
Fluids - Oil, H₂O, Gas, CO₂ ...

- Viscosity = \( f(T...) \), Salinity (of H₂O)
- Solubility behavior (diffusivity, mixing, h, contact area...)
- Density = \( f(p, T...) \), i.e.: p-V-T behavior (EOS) (API gravity, Compressibility...)
- Miscibility-pressure relationships in CO₂
- Surface tensions
- Asphaltene\%, Other oil characteristics
- And so on...
$CO_2$ Solubility in Water

This is at 1.0 atmosphere pressure. Increasing T means lower solubility.
$\text{CO}_2$ Dissolution in H$_2$O

Geological Sequestration of C
T Effects on \( \text{CO}_2 \) Solubility

- \( \text{CO}_2 \) solubility decreases with \( T \) until about \( 100^\circ \text{C} \)
- At higher \( T \), solubility starts to increase with \( T \)
$N_2$ Solubility in Water

$N_2$ is less than $1/10^{th}$ the solubility of $CO_2$ at atmospheric pressure.
Gas Solubility in Water

- In water, N$_2$ and CH$_4$ are about 1/10$^{th}$ the solubility of CO$_2$
- (Oxygen is slightly more soluble than CH$_4$ but we don’t worry about it)
- Hence, water will absorb and hold a lot more CO$_2$, stripping it from flue gas
- We have also to look at the issue of pressure ($\approx$ depth $\times$ 10 kPa/m)
p-T Solubility of CO₂ in H₂O

Above 1050 psi, CO₂ approaches supercriticality

http://www.kgs.ku.edu/PRS/publication/2003/ofr2003-33/P_1-05.html
CO$_2$...

Higher $p$: Larger amount of CO$_2$ in solution

$\text{h} = 298.15 \, \text{mol/ kg} \times \text{bar}$

C. Ophardt, c. 2003
Pressure Solubility, $\text{CO}_2$ in $\text{H}_2\text{O}$

- As $p$ goes up, more gas in solution
- Henry’s Law for ideal gases: $V(\text{gas})_{\text{STP}}$ in solution = $h \times p \times V(\text{water})$
- Henry’s constant $h \sim 0.832 \text{ m}^3/\text{m}^3/\text{atm}$, but only for dilute solutions well below $p_c$ - the critical pressure
- Once $p_c$ is approached, the system departs from linearity, and then $\text{CO}_2$ becomes fully miscible with $\text{H}_2\text{O}$
Effects of p on CO₂ Solubility

- At constant T and constant salinity, the solubility of CO₂ increases directly with pressure.
- However, this pressure solubility effect decreases with increasing p.
- So, at lower pressures the solubility increases more rapidly than at higher pressures.
CO₂ Solubility in Brine

The effect of dissolved NaCl
Salinity & CO₂ Solubility in H₂O

- Addition of any salt (usually NaCl of course), leads to a decrease in the solubility of CO₂ in water.
- There are effects of the nature of the salt (NaCl is worse than divalent salts such as CaCl₂).
- So, saturated brine is not as good as fresh water for CO₂ dissolution!
- In presence of reactive minerals......?
...and, the Effect of pH!
How Much $CO_2$ in $H_2O$?

- Depends on $p$ in the aquifer (partial pressure of $CO_2$)
- Depends on the $T$ of the reservoir
- Depends on the pH of the water
- Depends whether it is carbonate or not
- Depends on the salinity of the $H_2O$
- Depends on other solutes
- So, to calculate the capacity...
Reservoir Conditions

- Pressure (in the fluids)
- Temperature
- Stress (solid rock matrix)
- pH
- Current bubble point pressure of liquids
- Gas-to-oil ratio *in situ*
- Saturations: $S_o$, $S_w$, $S_g$
- Production history, well test data...
Can Oil or Gas Flow in Shales?

Typical pore size in shale: 0.1-0.5 μm

\[ \Delta p = \gamma / 2r \]

\[ \gamma = \text{interfacial tension} \]
\[ r = \text{radius of curvature} \]

\[ \Delta p = p_o - p_w \]

Darcy flow requires huge \( \Delta p \)

Conclusion: oil or gas cannot flow through intact shale!
Can Water Flow Easily in Shale?

Conclusion: oil or gas cannot flow through intact shale!

Much of the water in shales is not free to move easily:
- Adsorbed on the clay fragments
- Hydrated onto cations
- Pore throats are “blocked” by adsorbed water

Geological Sequestration of C

Bound water

Hydrated cations

Cations

Bound water

H₂O molecules

Free water, partly on ions
Fluid Generation & Fracturing

Flow in shales must be through fractures!

- Flow in shales must be through fractures!
- Semi-solid organics, $p_o < \sigma_h < \sigma_v$
- Fractures develop and grow
- Fluids are expelled through the fracture network, $p_o$ declines

Shale

Kerogen

Micro-fissure

High $T$, $p$, $\sigma$

Fluid flow

Generation of hydrocarbon fluids

Oil and gas
Reservoir “Valving”, Shearing

**Stresses along A-A’**

Hydraulic fracture when $p_o > \sigma_h$

Fault slips when $\tau > (\sigma_n - p_o) \cdot \tan \phi'$, i.e. when $\tau > \sigma'_n \cdot \tan \phi'$

Fluid migration is a function of stress as well as pressure!

- H$_2$O density = 1.05-1.2
- SC-CO$_2$ cap, low density
- $\Delta \rho$ effect
- $\sigma'_n = \sigma_n - p_o$
Density Effect

- Because of the lower density, there will always be a buoyancy force, promoting upward flow wherever possible.
- In cases where the lateral stresses are low, a tall column of SC-CO$_2$ can lead to a higher p at the top of the column.
- Will less dense phases be generated as CO$_2$ dissolves into water containing CH$_4$, H$_2$S, surrounding rocks?
Effects of Increasing $p_o$

Fluid migration is a function of stress as well as pressure!
What Will Governments Require?

- New Class VI wells (US-EPA), will need...
- Geomechanical analysis of injection ops.
- Analyze & report induced seismicity potential as the result of injection ops.
- Integrated modeling & monitoring prog.
  - Compositional modeling recommended...
  - Monitoring methods to be negotiated...
- p measurements in overlying formation
- CO₂ plume geophysical monitoring
Reservoir Simulation

- A reservoir model is put together (see elsewhere for how this is done)
- The physics are incorporated as well as we can
  - pVT laws, dissolution kinetics, multiphase fluid flow, hydrate formation...
  - Supercritical conditions and properties
  - Contaminating gases and phase behavior...
- Calibration, if possible, then predictions
- Prediction confirmation by monitoring...
CO₂ Distribution with Time
Dissolved CO$_2$ Distribution
Leakage Mechanisms

- Flow through intact pore structure in shale or anhydrite cap rocks is slow
- The main concerns appear to be...
  - Flow along an anthropogenic path, old or new wells, perhaps improperly sealed
  - Flow through natural fracture systems
  - Flow along a faulted structure
  - Degradation of capillary barriers to SC-CO$_2$
  - Other concerns?
Shrinkage of Shale?

A small amount of shrinkage will reduce $\sigma_h$.

Hydraulic fracture when $p_o > \sigma_h$.

SC-CO$_2$ cap, low density.

$H_2O$ density = 1.05-1.2.

Geological Sequestration of C

$\Delta\rho$ effect.

stresses along A-A'.

depth $p_o$ $\sigma_h$.
Interfacial Tensions

- In the immiscible state, the CO₂ that remains undissolved has a surface tension with water \( f(p, T, \text{salinity...}) \)
- With \( SC-CO₂ \), no surface tension (mutually miscible)
- Similarly with light oils
- The situation with heavy oils is more complicated because of asphaltenes...
- However, this means that capillarity as a flow barrier almost disappears!
Fractures and Capillarity...

SC-CO₂

Capillary barrier?

2-10 μm

Geological Sequestration of C
Capillary Barrier Integrity

- CH₄ - H₂O have limited miscibility and a capillary barrier forms
- Such barriers are stable over geological time (shales - silts)
- SC-CO₂ - H₂O are mutually miscible
- Under what conditions can a capillary barrier be assured indefinitely?
- Is a shale cap rock that trapped CH₄ for 30 MMyr OK for CO₂ to 1000 yr?
CO₂ Behavior...

- Extremely complex...
- Oil swelling with CO₂ adsorption
- Interfacial tension issues (changes as a function of p, T, oil chemistry...)
- Diffusion rates into H₂O, oil...
- Phase relationships in mixtures of gases, liquids (e.g. SC-CO₂ + oil + H₂O), ...
- Changes in rock wettabiliy...
- Formation of hydrate phases...
Cooling-Induced Fractures

Water displacement front

Geological Sequestration of C
Surface Deformation ($CO_2$ injection)

Algeria – at the BP In Salah project

$CO_2$ injectors: KB-502 and KB-501

Surface heaves can be explained by $\Delta p$ & $\Delta\sigma$ : there are also changes in reservoir properties – $k$, $\phi$, $\sigma$. 
Geomechanics and 4D seismic signal

Time-shifts in Valhall

Change in reflector depth

\[ \frac{\Delta T}{T} = \frac{\Delta Z}{Z} + \frac{\Delta V}{V} \]

Also, see slide notes...
In principle, if gas can be uniformly injected, it is best to have as much length as the compressors can handle. Should we cool the gas before injection into the reservoir? High T reduces CO$_2$ solubility… Careful analysis is always needed…
Banjarpanji-1 Location Area

14 Aug 2005
Banjarpanji-1 Location Area

7 Aug 2007
1,500 balls dropped, March 2007: Effect?
None...
Usahakan di Relief Well ini tidak ada aliran lumpur

Tembok pabrik rotan
jebol 22 Juli 2006
Km aliran lumpur dari gorong2

29 Juli 2006