CO_2 injection: EOR and Sequestration

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Part 1: CO_2 EOR applications and sequestration

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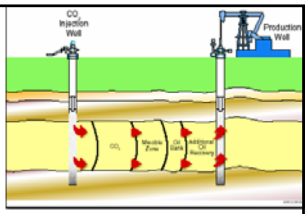
Introduction



CO_2 – excellent EOR agent (technologically and ecologically)

CO_2 injection involves different phenomena which have to be correctly represented in numerical simulation

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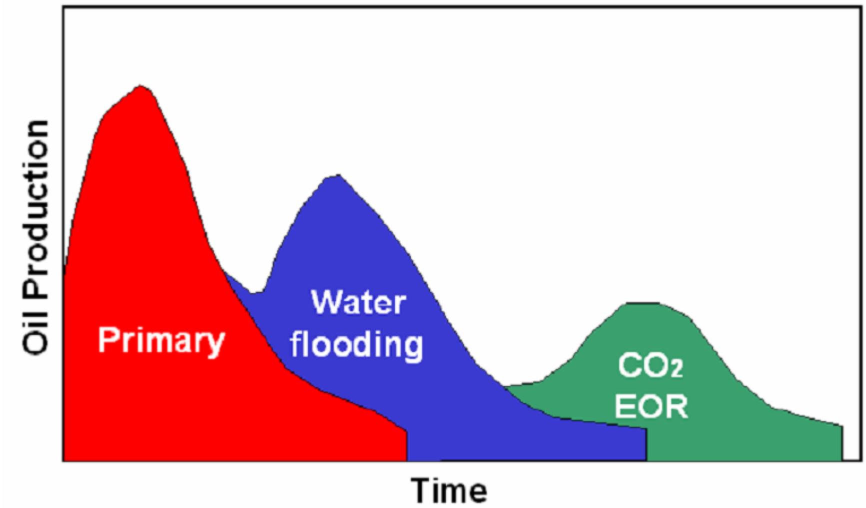
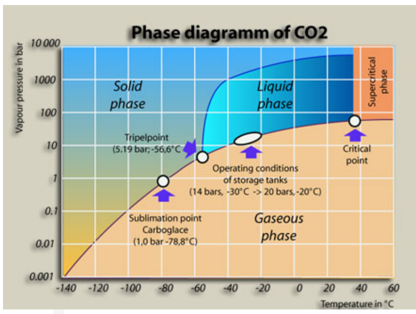
Expected Sequence of Oil Recovery Methods



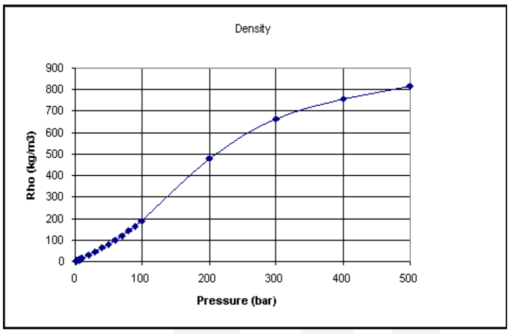
Carbon dioxide flooding

- **is carried out by injecting large quantities of CO_2 (30% or more of the hydrocarbon PV) into the reservoir.**
- **If CO_2 is not first-contact miscible with the crude oil, the CO_2 extracts the light-to-intermidiate components from the oil, and, if the pressure is high enough, develops miscibility to displace the crude oil from the reservoir.**
- **Immiscible displacements are less effective, but they recover oil better than waterflooding.**



CO_2 for EOR

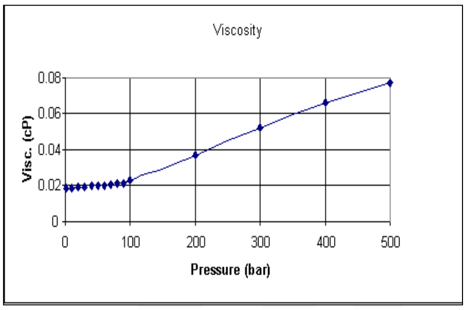
- At 1 bar, CO_2 exhibits a "gas like" density while at reservoir pressure CO_2 density is "liquid like"
- At reservoir conditions CO_2 density is much higher than methane or nitrogen density and can vary in the range of 400 - 700 kg/m3



Density of CO_2 at 100° C

CO_2 for EOR

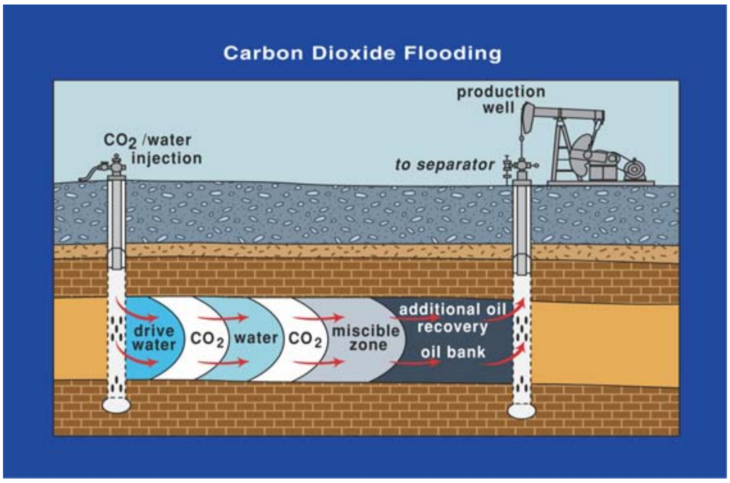
- CO_2 injection is an efficient oil recovery method, if required volumes of non-expensive CO_2 can be available for injection
- The gravity override of oil by CO_2 is not fast developing
- The displacement becomes more efficient, if CO_2-oil mobility ratio can be controlled



Viscosity of CO_2 at 100° C

CO_2 Flood Demonstration

for onshore field with dense well spacing



Source: Carr, Nissen & Qi, 2005

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CO_2 injection

- Has proven to be an efficient improved oil recovery method.
- Need sufficient volume of in-expensive CO_2.
- Miscible displacement of light oil at reservoir pressures above 200 bars.
- An option is to combine CO_2 storage with IOR.

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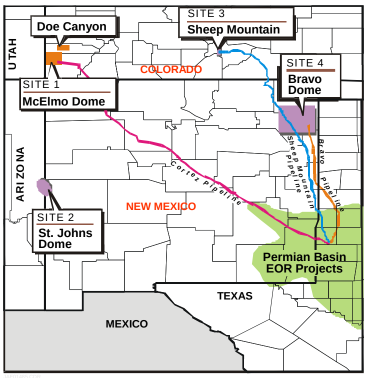
Brief History of CO_2 Flooding

- 1960s - First successful field test (Mead Strawn, Texas)
- 1970s - First full-scale floods
- 1980s - Development of natural CO_2 sources in Colorado and New Mexico
  - Number of new projects (some outside Permian Basin and U.S.)
  - Significant effort on laboratory and pilot studies
- 1990s - Implementation of new projects with heavy dependence on EOS simulation
  - Creation of Altura (Shell/Amoco), dominant force in Permian Basin and CO_2 utilization

U.S. natural CO_2 reservoirs



LOCATION OF NATURAL CO_2 FIELDS IN THE SOUTHWESTERN U.S.

	Original CO_2 in Place		1998 CO_2 Production		Reservoir Lithology	Depth (m)
	10^6 t	Tcf	10^6 t/yr	MMcfd		
McElmo Dome, CO	1,600	30	15.9	820	Carbonate	2,300
St. Johns, AZ	830	16	0	0	Sandstone	500
Bravo Dome, NM	260	5	7.2	375	Sandstone	700
Sheep Mtn., CO	100	2	2.9	150	Sandstone	1,500

1 Sm^3 = 35,31 f^3

Advanced Resources International, Inc.

U.S. CO_2 flood experience and screening criteria

Gravity º API	Viscosity cp	So	Oil composition	Formation type	Net pay	Permeability	Depth m
>22 <u>36</u>	<10 <u>1.5</u>	>20 <u>55</u>	High % of C_5-C_{12}	Sandstone and carbonates	Not critical	Not critical	>800

<u>Underlined values represent the approximate mean or average for current field projects</u>

Ref. Joseph J.Taber *et all* SPE 35385, 1996

Depth vs. Oil Gravity Screening Criteria for *Miscible CO_2 flooding*

Oil gravity, º API (g/cm³)	**Depth,** m
> 40º (0,825)	>800
32-40º (0,865-0,825)	>850
28-32º (0,887-0,865)	>1000
22-28º (0,922-0,887)	>1200

Reservoir temperature is assumed from depth

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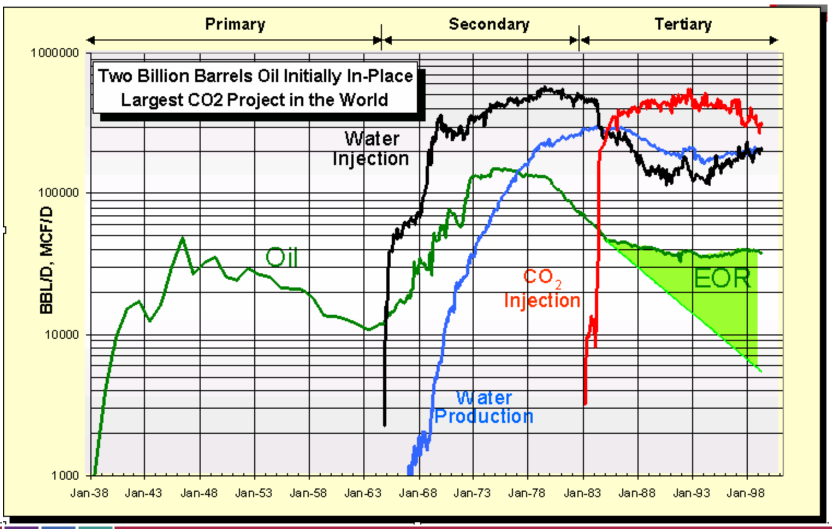
Denver Unit Production/Injection History



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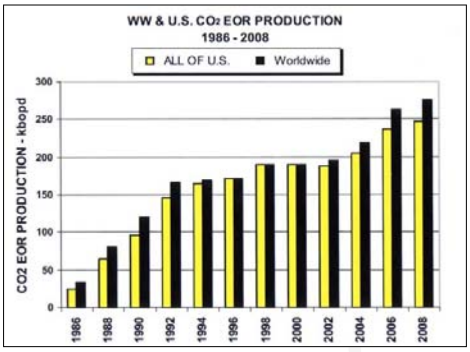
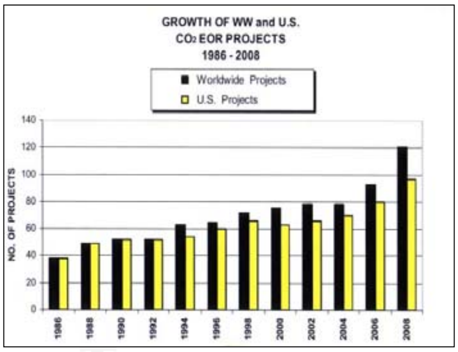
Production growth based on CO_2 EOR





	Number of projects	Production, bopd	EOR production, bopd
In the world	125	373.500	285,100
USA	105	323,100	249,700
Canada	8	43,000	28,000

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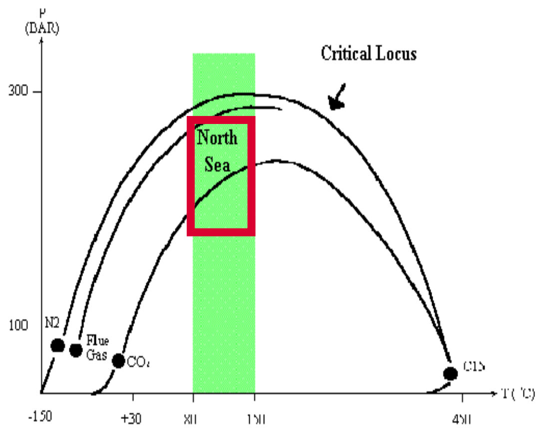
Critical conditions for gas injection: CO_2, N_2, flue gas

- ✓ In many North Sea reservoirs with pressures above 200-220 bars CO_2 injection will be at developed miscibility or miscible conditions
- ✓ To achieve miscible conditions for nitrogen or flue gas injection, reservoir pressures should be above 260-290 bars



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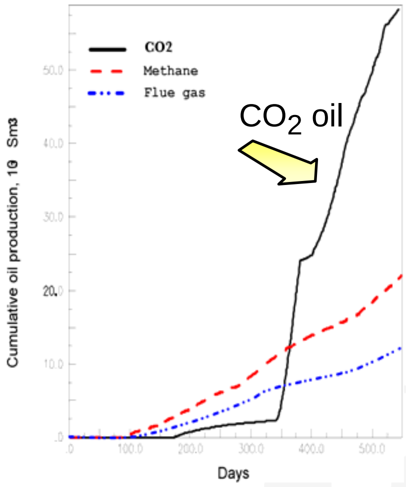
Immiscible CO_2, methane and flue gas injection



Troll paleo oil zone

Low So recovery

Residual oil saturation can be significantly reduced by CO_2 injection

The volume of vaporized and mobilized oil under CO2 injection is 3-5 times larger in comparison with methane and flue gas injection

Skauge, A.; Surguchev, L.: "Gas Injection in Paleo Oil Zones", SPE 62996, 2000.

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Low oil saturation CO_2 injection projects

Field	Operator	Oil saturation	Thickness	Status
Denver Unit	Altura	From high to low	about 30 m	Ongoing
Seminole Unit	Amerada Hess	About 32%	about 60 m	Phase 1: 500 acres / 25 wells
South Creek	Mobil	-		CO2 injection in naturally flooded area

The process is efficient due to compositional effects such as vaporization and swelling.

Residual oil saturation can be significantly reduced by CO_2 injection.

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Environmental aspects of CO_2 injection

- ✓ Reduced emissions
- ✓ Long residence time for CO_2 underground
- ✓ Large volume of CO_2 remains dissolved in residual oil and water in the reservoir
- ✓ CO_2 reacts with carbonate rock
- ✓ Disposal of CO_2 in situ

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CO_2 for enhanced oil recovery in Norwegian fields

- Studies for the Norwegian continental shelf indicate
  - Large potential
  - Uncertain economics
- Evaluations for several oil fields (examples)
  - Ekofisk
  - Gullfaks
  - Brage
  - Grane
  - Oseberg East
  - Draugen
  - Heidrun
  - Volve
- 20 field candidates

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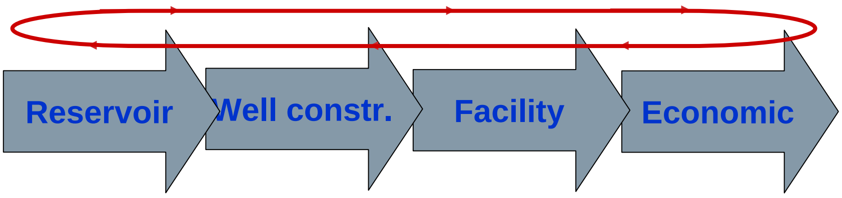
CO_2 Full Circle Analysis



- PVT - MMP
- Initial concept screening
- Upscaling
- Concept optimisation
- Reserves
- Input to design

- Corrosion
- Ability to reuse existing wells and completions
- Costing to prepare for EOR
- HSE issues

- Corrosion
- Ability to reuse existing facility set-up
- Separation
- Transport
- HSE issues

- NPV
- Future incentives
- Sensitivities

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Gullfaks field CO_2 potential study

A Study of IOR by CO_2 Injection in the Gullfaks field, Offshore Norway (Statoil, SPE 89338)

- Miscible CO_2-WAG study
- Significant IOR potential
- Supply of CO_2 too costly to make the project economic

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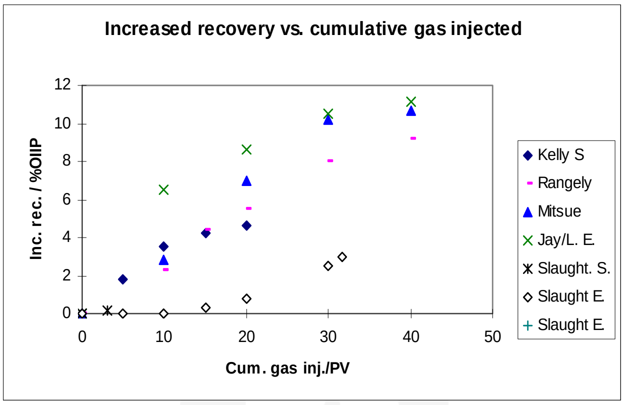
Increased recovery vs. cumulative gas injected



Tapering: efficient tool for breakthrough control
Increasing Water-Gas injection ratio with time

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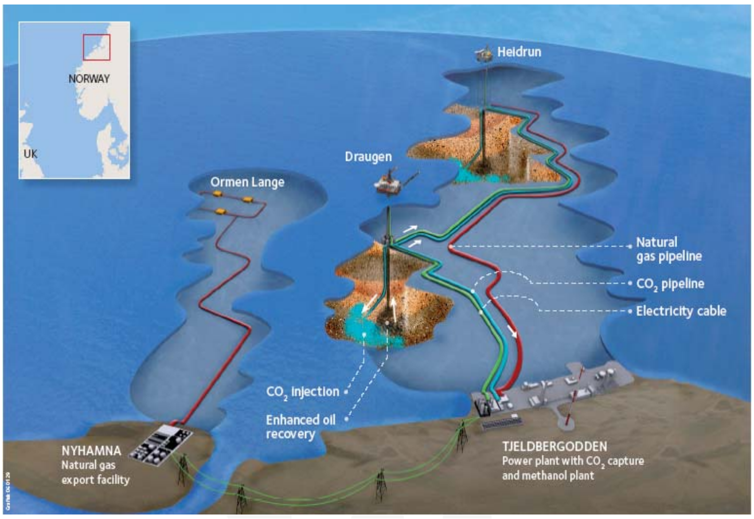
CO_2 value chain in Halten area
including Draugen CO_2 flood



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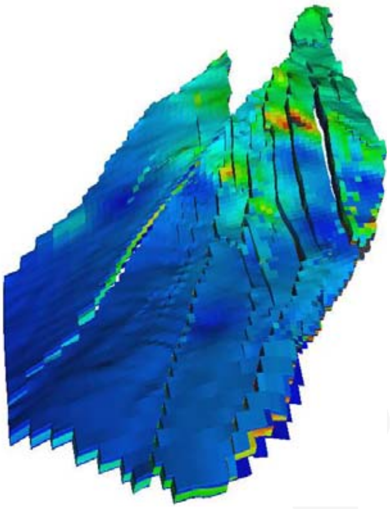
Heidrun - Upper Tilje



Complications to CO_2-WAG

- Limiting gas capacity
- High recovery with water injection
- CO_2-WAG planned on late stage of field development

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Value Chain: CO_2 Offshore Project Cost

Power Plant	**24%**
CO_2 Capture Facilities	**19%**
CO_2 Pipeline	**10%**
Platform Modifications & Wells	**47%**

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CO_2 value chain

- Challenges
  - Access to large volumes of cheap CO_2
    - CO_2 capture from large power plant(s)
    - Pipeline transport to field(s)
  - High cost of upgrading processing facilities and wells
  - Incremental oil recovery (% of oil volume initially in place)
    - 2-18 % in US field examples
    - 3-7 % in water flooded reservoirs on the NCS (indicated by studies)
  - Excess CO_2 may be stored in stable geological formation(s)
  - Uncertainty in oil price affects viability

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CO_2 value chain

- Pan-European plan needed?
  - CO_2 capture at European power plants and industrial plants
  - CO_2 infrastructure (pipelines) to the relevant oil fields
  - Long term geological storage in gas/oil fields and aquifers
- EOR potential in Norway
  - Optimistic estimate: 300 mill. Sm3
- EOR value can only cover a fraction of the total cost associated with CO_2 capture, transport and storage
- Large scale CO_2 storage (from Europe) is possible using depleted oil/gas fields and aquifers

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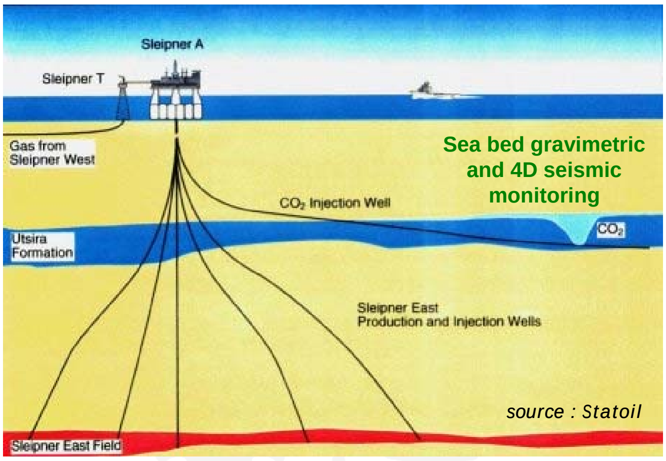
Sleipner CO_2 sequestration project offshore

- The Sleipner project in the North Sea in Norway is the world's first commercial-scale CO_2 capture and storage project (started 1996)
- 1 million tonnes are stored yearly in the Utsira formation 800 m below the sea bed
- The project triggered by the Norwegian offshore CO_2 tax

Sleipner - CO_2 injection into the Utsira formation



In order to achieve sequestration of 50 Gtons per year by 2050 every 2 weeks new Sleipner project should be starting

World's Top Five CO_2 Emitters

Country	2005		2015		2030	
	Gt	*rank*	*Gt*	*rank*	*Gt*	*rank*
USA	**5.8**	**1**	**6.4**	**2**	**6.9**	**2**
China	**5.1**	**2**	**8.6**	**1**	**11.4**	**1**
Russia	**1.5**	**3**	**1.8**	**4**	**2**	**4**
Japan	**1.2**	**4**	**1.3**	**5**	**1.2**	**5**
India	**1.1**	**5**	**1.8**	**3**	**3.3**	**3**

Source: IEA 2007 report

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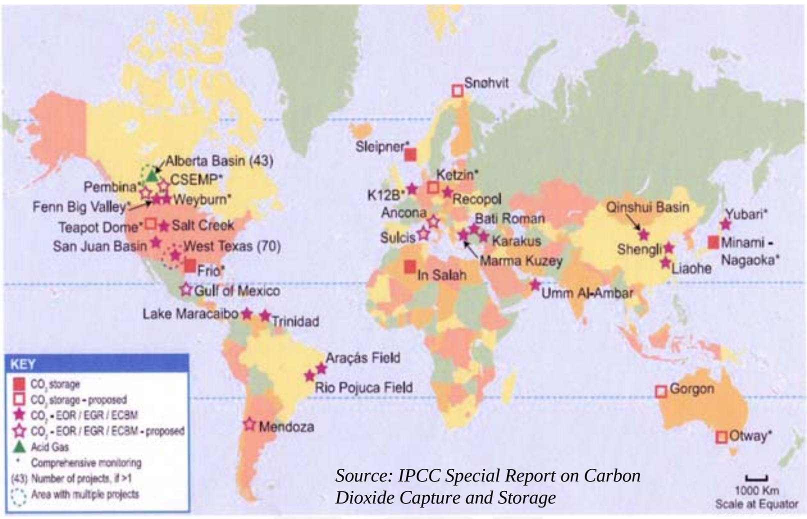
CO_2 injection projects in the world



Source: IPCC Special Report on Carbon Dioxide Capture and Storage

CO_2 EOR outside US: Canada, Turkey, Trinidad, Malaysia, China, other
Planning: Australia; Croatia, Norway, Mexico

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IRIS' CO_2 Storage R&D Activities

- **CO_2 GeoNet - Joint Research Activities**
  - JRAP 15 - Enhanced Oil Recovery From Depleted Oil Reservoirs Through CO_2 Storage
  - JRAP 16 - Geological Models, Heterogeneity Catalogue and Scale-relations
- **CO_2 GeoNet - Vattenfal CO_2 Sequestration Project**
- **CO_2 Field Lab**
  - Investigate monitoring techniques, tools and methodologies for CO_2 storage in two shallow aquifers in Norway
  - Research Partners – BGS, BRGM, IFE, IRIS, NGI, NGU, NIVA, SINTEF (project manager), UiB, UiO
  - Participating companies – PGS, Schlumberger
- **Joint CO_2 Project in Czech Republic**
  - Identify the potential of CO_2 storage in Czech Republic in
    - Depleted oil reservoirs, and
    - Aquifers
  - Investigate the use of CO_2 for custom-tailored EOR techniques to improve oil recovery from mature assets
  - Partner - Czech Geological Survey

Part 2: Modelling CO_2 flow in the reservoir

CO_2 injection

Favourable effects for oil displacement and extraction by CO_2

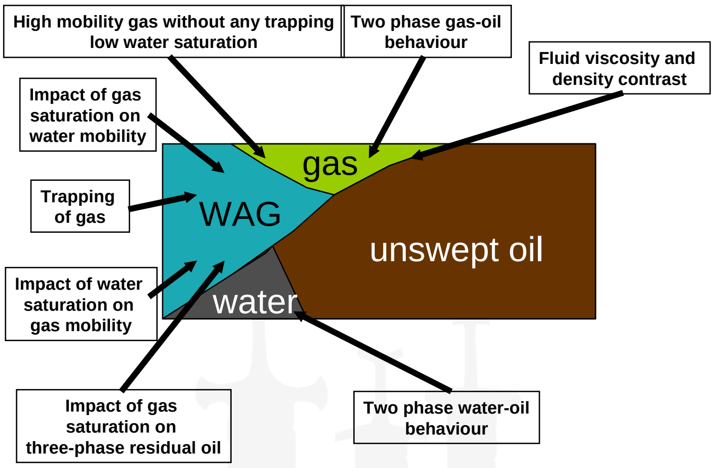
- Potential of CO_2 to evaporate hydrocarbon components into the CO_2 rich mobile phase.
- Oil viscosity reduction with dissolution of CO_2.
- Oil swelling with dissolution of CO_2, when oil formation volume factor can increase by a factor of 1.4 – 1.7.
- Interfacial tension on the oil-water contact is reduced in the presence of CO_2 in the phases.
- In the reservoirs containing carbonates the rock permeability will increase due to chemical reactions with CO_2. Permeability of sandstones may be increased by 5-15%, carbonates and dolomites by 6-75%.
- CO_2 is soluble in oil and water. Its solubility in water is higher than solubility of methane or nitrogen. At reservoir conditions CO_2 solubility in oil can be 4-8 times higher than in water.
- CO_2 dissolution in water may slightly increase its viscosity.
- Permeability increase in carbonate rocks.

Full field simulation approach for miscible gas injection

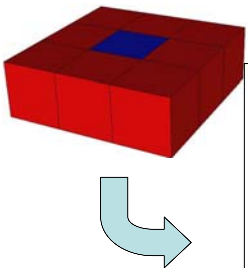
- **MMP slim tube experiment**
- **Calibration of fluid description by history matching slim tube experiment – pseudo components, EOS**
- **Fine grid 2D or 3D sector model compositional simulation**
- **Calibration of black oil coarse grid sector of the full field model against similar fine grid compositional simulations**
  - **If calibration is successful, full field black oil simulation of miscible gas injection process**
  - **If calibration is unsuccessful, further compositional simulations on a larger field scale**

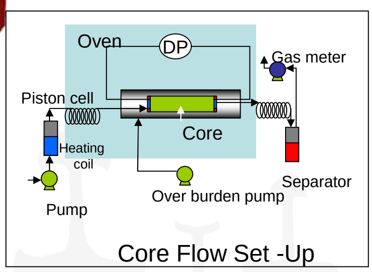
Oil & Gas

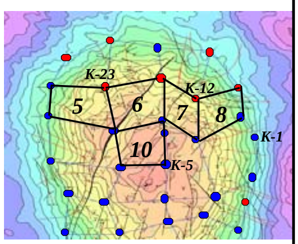
Processes important for immiscible WAG injection



Time line



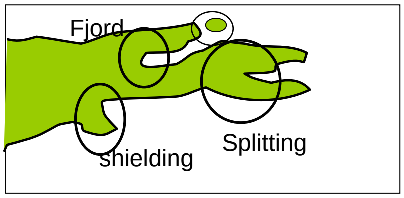


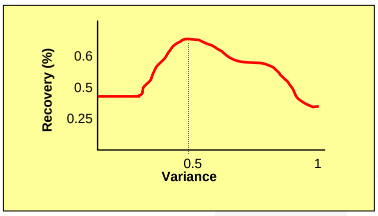


Gradually building complexity to build confidence in our simulation tools and create consistent model

Fingering mechanism and modeling

Hele-Shaw cell experiments show the onset of **viscous instability** and subsequent **fingering** under sharp mobility contrast for both **miscible and immiscible** conditions.





Breakthrough recovery as a function of heterogeneity level, for Peclet = 500, gravity number Ra=1, viscosity ratio=2. Optimal recovery is optimal for intermediate values. Modified plot from **Camhi**

An **unfavorable-mobility ratio** and **heterogeneity of porous media** affect significantly **viscous instability**, which in turn affect the displacement efficiency of MCM processes, sweep efficiency, and breakthrough time.

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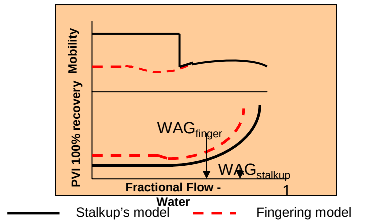
Multiphase flow at CO_2 flooding

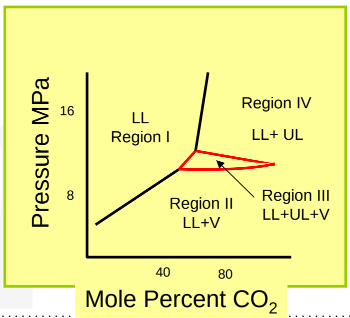
Research of three-phase (gas-liquid-water) flow at CO_2 flooding with viscous fingering effects did not account so far for **mass transfer effects**.

CO_2 viscous fingering through a water phase has been scarcely studied so far.
Most of the studies have been focused on density fingering and CO_2/water phase behavior for CO_2 sequestration.

Multi-hydrocarbons-phases modeling
Vapor CO_2 enriched phase (V)
Liquid CO_2 rich phase (UL)



The model without viscous fingering predicts a constant mobility contrast and PVI for 100 % recovery for WAG ratios below the equal velocity. Modified plot from ***Juanes & Blunt.***



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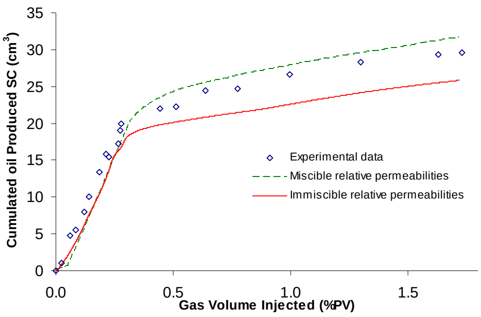
4-phases and miscibility

- Experiments with pre-generated 3rd HC phase
- Different viscosity oils used; amount of 3rd phase varied
- While 3rd HC phase is miscible with oil, CO_2 is not
- Commercial tools can not handle three HC phases flow



To account for different concentration of 3rd phase single set of *IFT dependent relative perms* may be used.

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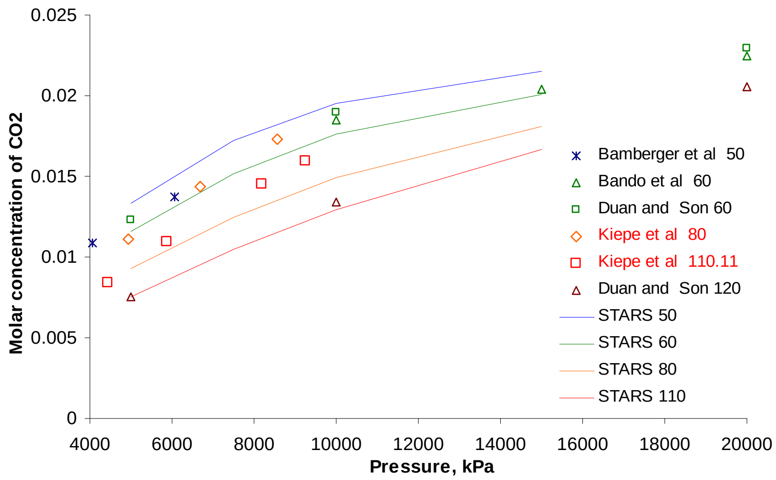
CO_2 solubility in water



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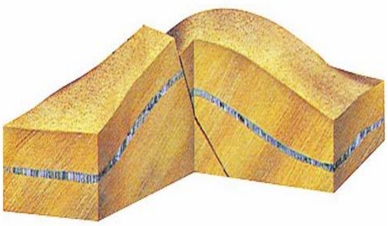
Fractured carbonate reservoirs

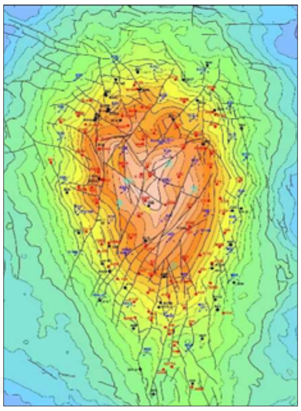
- Necessary to simulate a dual porosity system on matrix block scale and field scale.
- Diffusion and gravity segregation are important for the transportation of CO_2 between the fractures and the matrix.
- At HP light oil reservoir conditions the CO_2 can often be in a supercritical state, and behave as a liquid
  - The diffusion process will be a liquid-liquid diffusion
  - The segregation process will not be controlled by any capillary forces, i.e. the important elements will be the density difference between the fluid in the fractures and the fluid in the matrix, the viscous resistance to vertical flow, and the capillary continuity.

CO_2 in fractured carbonate

Ekofisk field



+1% incremental RF ~ 80 MMBOE



Carbonate rock dissolution modelling

- Rock dissolution reaction is introduced:
  $CaCO_3(s) + CO_2 + H_2O \rightarrow Ca(HCO_3)_2$
- Carmen-Kozemy formula to get permeability from porosity dependence

Effective porosity and permeability increase observed in the core flood experiments. Rock is dissolved through the core, injection rate constantly increases.

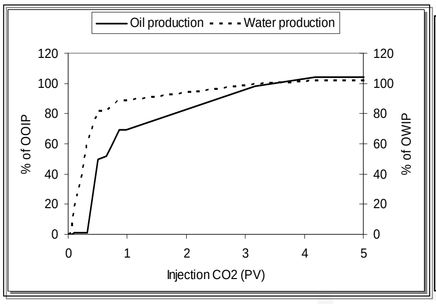
CO_2 study example, Ekofisk Summary experiments

STO and brine

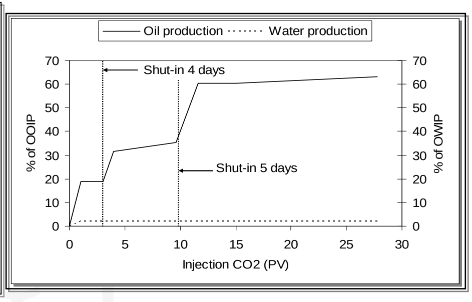
No	Type of flood	Rock	Conditions	Start conditions for CO_2-flood	$S_{or}(CO_2)$
1	Viscous displacement	Berea sandstone	30°C, 340 bar	100% oil saturated	0.01
2	Viscous displacement	Liege chalk	90°C, 340 bar	S_{orw}	0.00
3	Diffusion dominated (simulating fracture)	Liege chalk	90°C, 340 bar	S_{orw}	0.10

CO_2 laboratory study
Ekofisk analogue core production

Viscous displacement (Liege)

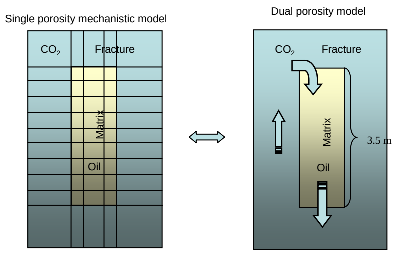


Diffusion dominated (Liege)



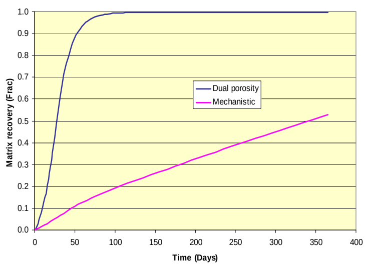
Lower and slower production than in viscous displacement

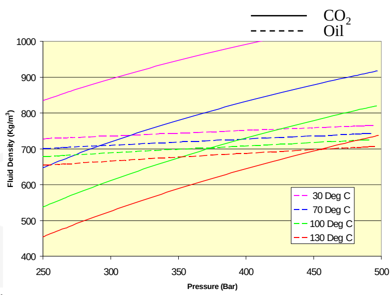
Segregation/Convection modeling



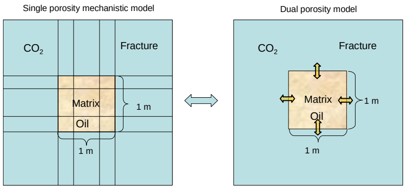
Gravity segregation challenges

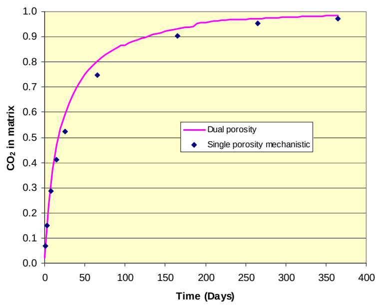
- Supercritical CO_2 perceived as liquid (by model)
- Normal gravity drainage formulations do not apply
- Alternative gravity segregation model does not match with mechanistic simulations
- CO_2/oil density contrast changes importantly with temperature and pressure



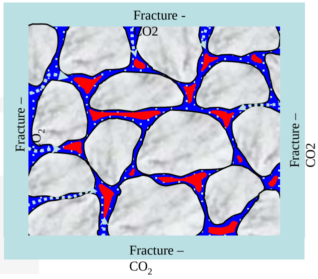


Diffusion modeling





- Diffusion appears to be correctly modeled in dual porosity
- Diffusion parameters are "rough numbers"
- Concerns
  - What is the effect of temperature and pressure?
  - What is the impact of high water saturation?

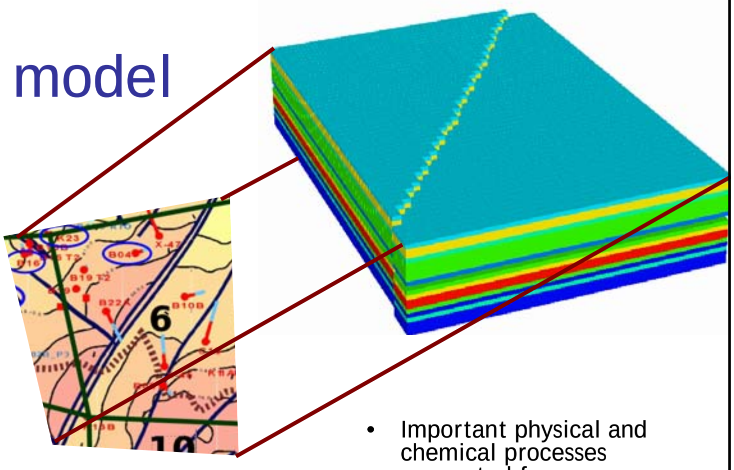


Ekofisk summary, fractured chalk field

- Large EOR potential from CO_2 flooding
- Gravity segregation is important
- Process controlled by diffusion between the fractures and the matrix
- CO_2 WAG can be a good option
- An option is to inject CO_2 dissolved in the injection water (carbonated water)
- The potential rock weakening must be evaluated/controlled

Sector model

- **Representative for field geological setting**
- **Simplified, but reflecting key reservoir characteristics**
- **Enabling accurate compositional and numerical calculations**



- Important physical and chemical processes accounted for
- Process efficiency evaluation
- Suitable for many different sensitivity simulations

IRIS

Critical parameters - process simulation

Parameters for sensitivity evaluation:

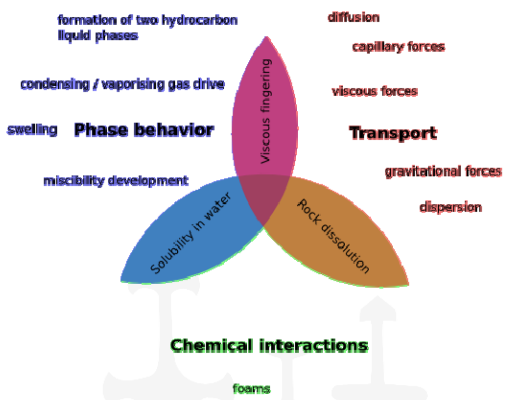
- Continuous vs. WAG injection
- Injection rate
- WAG ratio (f.e. 3:1, 1:1, 1:3), tapering
- Re-injection of produced gas consisting of CO_2, N_1, CH_4 to C_4H_{10}
- CO_2 dissolution in water
- Grid resolution sensitivity
- Endpoints (Sorw, Sorg) and hysteresis if immiscible
- Well economic cut-off (min oil rate Sm^3/d, limiting GOR, …)

IRIS

Leading recovery mechanisms CO_2-flooding

- Swelling oil (10-100%)
  - Greatest for lighter oils
- Reduction of oil viscosity
  - Greatest for high viscosity oils
  - Reduction of mobility ratio
- Mass transfer by mixing of CO_2 and oil
  - CO_2 condenses into oil phase and light/medium oil components vaporize
- Recovery mechanisms depend on conditions (T, P) and oil characteristics

Natural phenomena



Net CO_2 cost in the North Sea

According to Kinder-Morgan-ELCAM (CENS) study:

	$ per Tonne
• Delivered price for CO_2:	$35
• Less SAVINGS:	
– Taxes - Oil and Gas Industry	$14.5
– Other direct tax benifits	$4.4
– Prices paid by E&P Companies	$12.0
Total SAVINGS	$31.0
<u>NET Cost - CO_2 for IOR</u>	$4.0

30+ million tons per year CO_2 emission reduction
Industrial CO_2 - coal/gas fired power stations in Europe