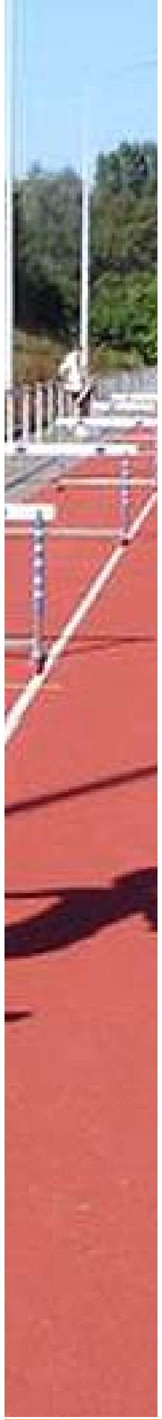

Petrad – MLR – CGS SINOPEC seminar
Chengdu, 15 – 18 September 2009

The TNO mission

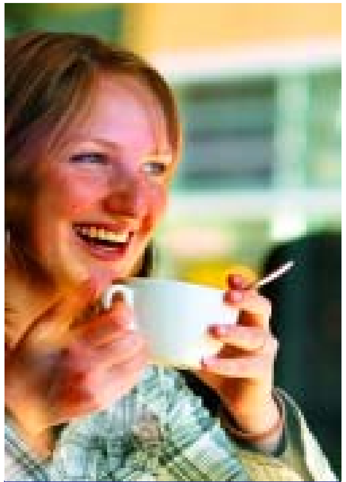
To apply scientific knowledge with the aim of strengthening the innovative power of industry and government



We do this through

- Consultancy
- Contract research
- Testing and certification
- Licences
- Performing legally required assignments

The five core areas of TNO

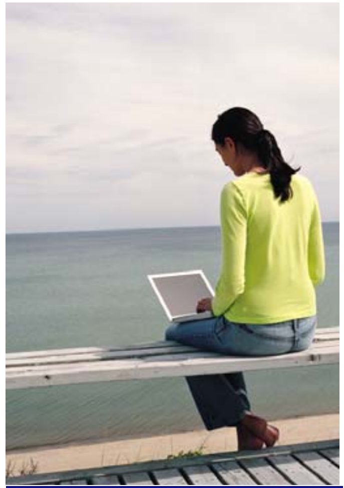


TNO Quality of Life

TNO Defence, Security and Safety

TNO Science and Industry

TNO Built Environment and Geosciences



TNO Informa-tion and Communication Technology

TNO

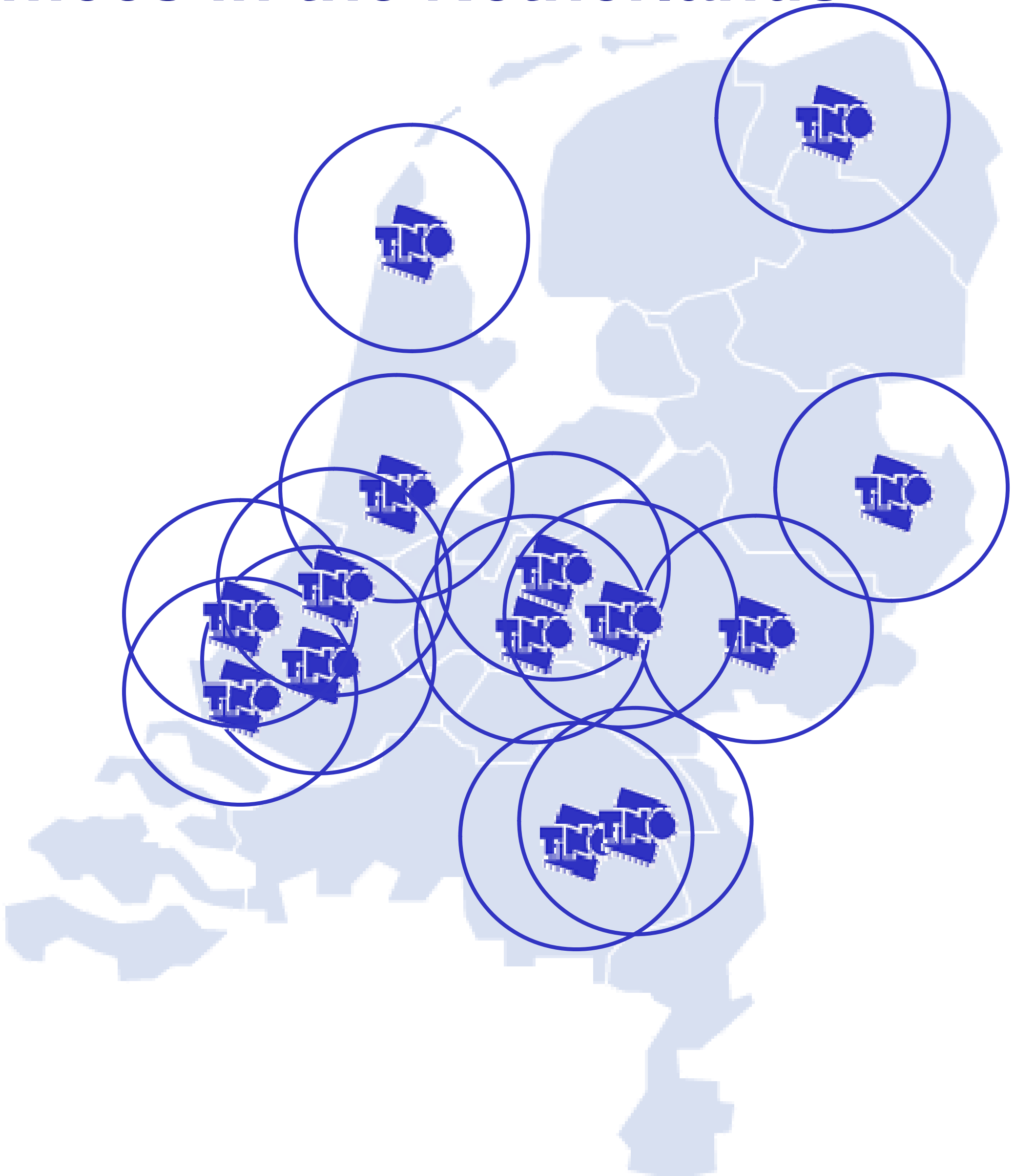
- Was founded in 1930 by act of parliament
- Helps companies with their need for specific R&D
- Is independent of private and public interests

TNO history

Milestones

- 1930 TNO Act
- 1932 TNO founded
- 1980 Radical change to the TNO structure
- 1985 Amendment of TNO Act
- 2005 Radical change to the TNO structure
- 2007 TNO is 75 years old!

TNO offices in the Netherlands



Key figures 2006

(amounts x EUR 1 m.) incl. group companies

	2006	2005	2004
Consolidated turnover	570	562	556
- base and target funding	196	196	195
- market turnover	374	366	361
Operating result	10.5	7	4
Result	13	8	5
Balance sheet total	xxx	389	381
Equity	181	181	173
Solvency	44%	47%	45%
Number of employees (effective average)	4,584	4,746	4,979

Bert van der Meer

- 40+ years of reservoir engineering (consulting).
  - Performed reservoir engineering studies all over the world.
- 20 years of work on waste gas (CO_2) disposal .
- Author of more than 50 paper on the subject.
- Involved in all major CO_2 storage projects

Waste Gas Disposal in Practice

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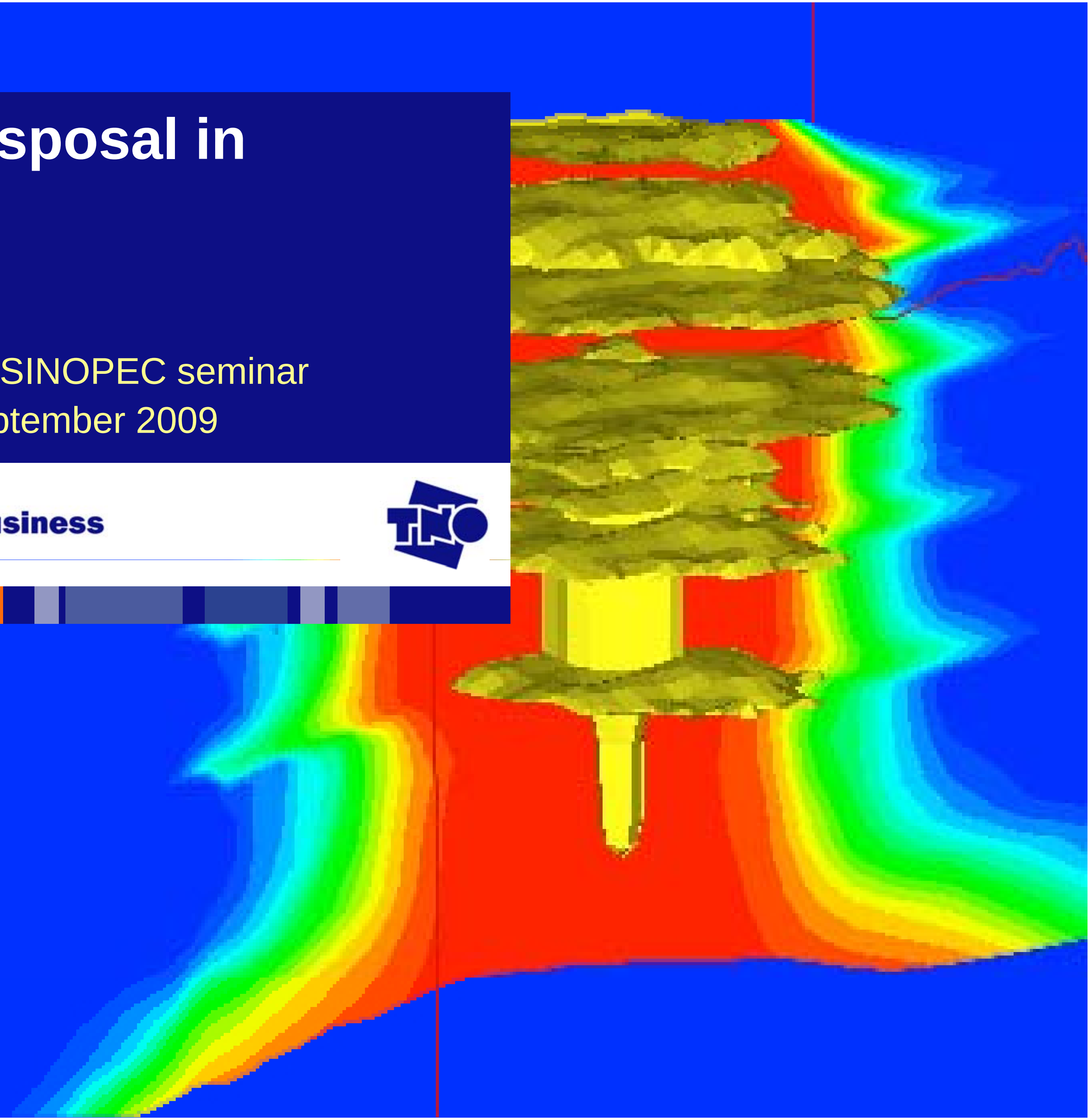
TNO | Knowledge for business



Bert van der Meer

Overview

- Introduction
- Canadian Experience
- Observations
- European Examples
  - Sleipner
  - InSalah
  - K12-B
- Conclusions

Introduction

- What is (Acid Gas) Waste Gas

Acid gas is a mixture of H_2S and CO_2 with a minor fraction of hydrocarbon gases separated from sour gas to meet pipeline and market specifications for natural gas

Introduction

- The General Dutch approach:

MIXING

We have a large number of gas field with a large spread of composition. gases are being mixed to obtain required specifications

Introduction

- **Why disposal (injection) Acid Gas?**

- More and more natural gas reservoir containing H_2S and CO_2 in the world being produced.

- H_2S and CO_2 are being stripped off from the sour gas

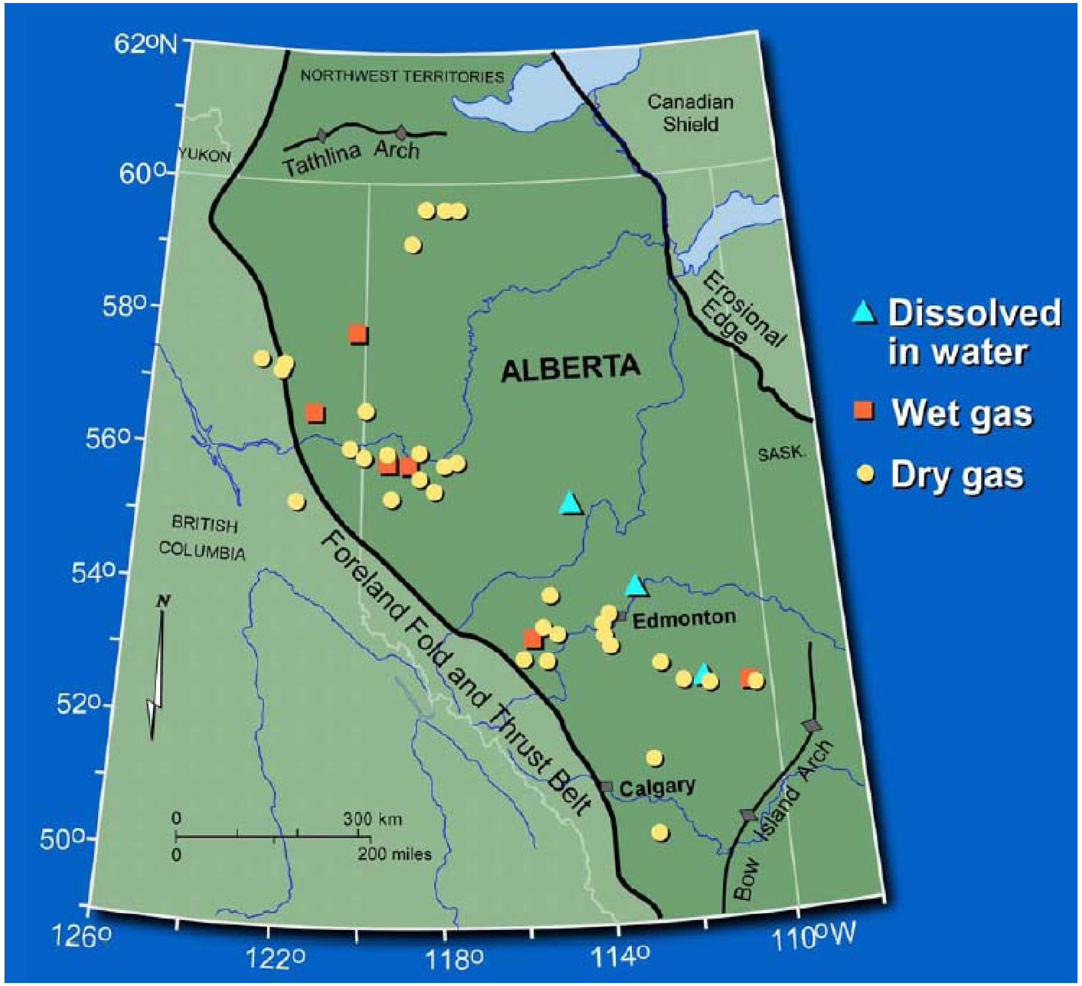
- Non or only a little bit can flared into the atmosphere (becoming more difficult)

- sulfur can be recovered at the surface at high cost, which is uneconomical; or

- The waste gas is re-injected close to the gas plant into a deep depleted hydrocarbon reservoir or a saline aquifer at less cost.

Introduction

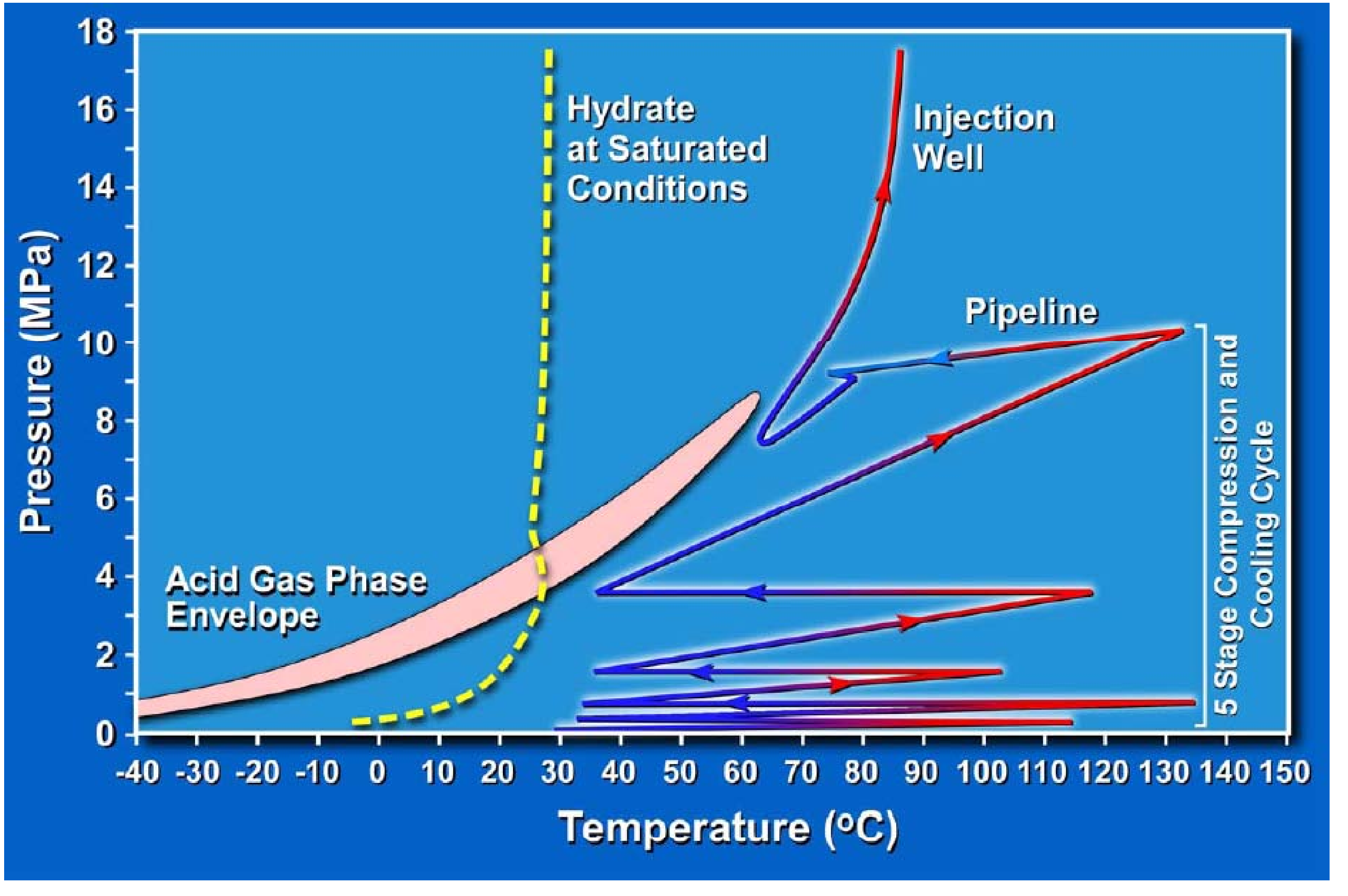
Locations of Acid Gas disposal operation Western Canada



By Bachu et al

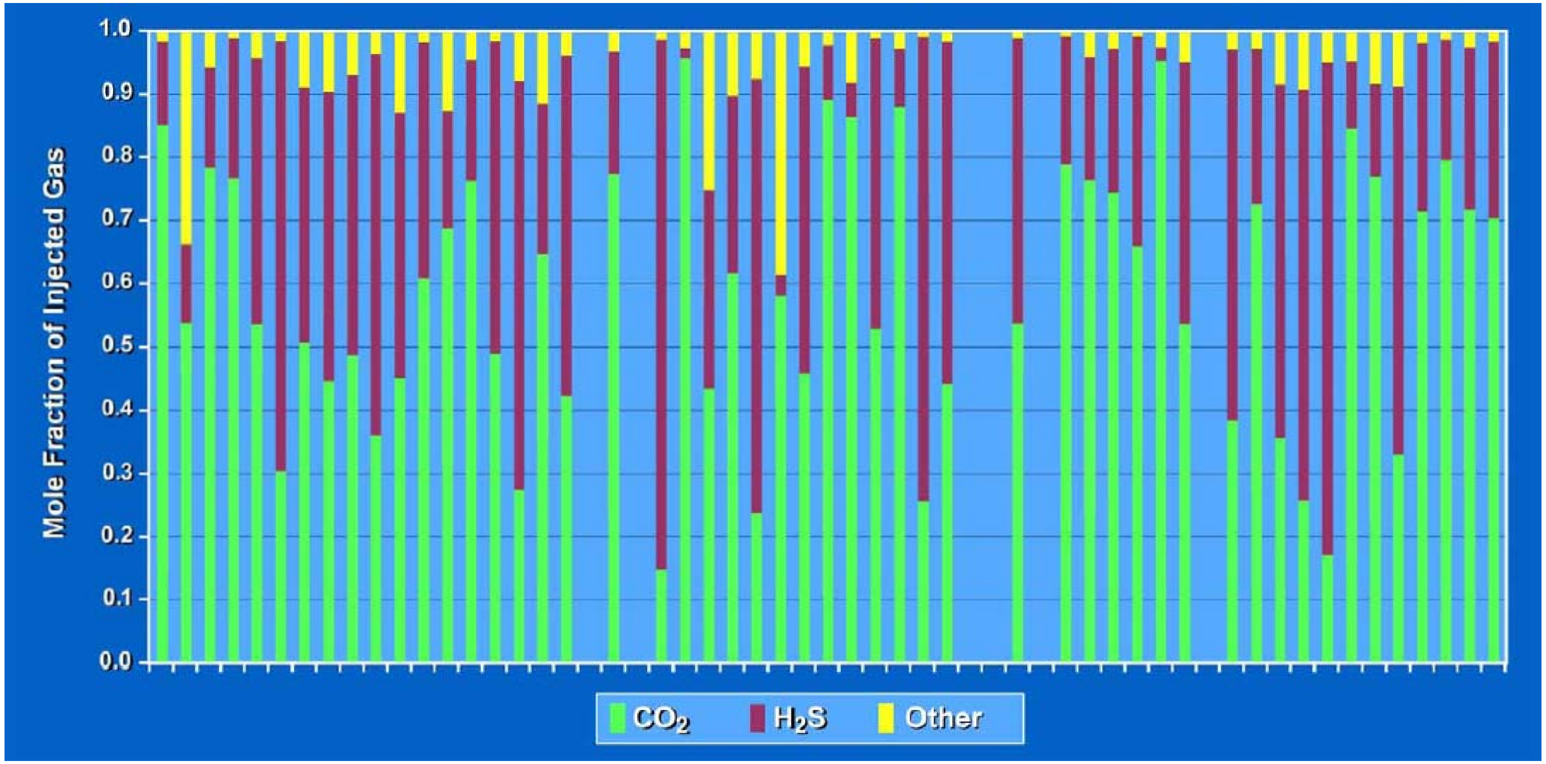
Introduction

Typical Compression Cycle



Practical Situation

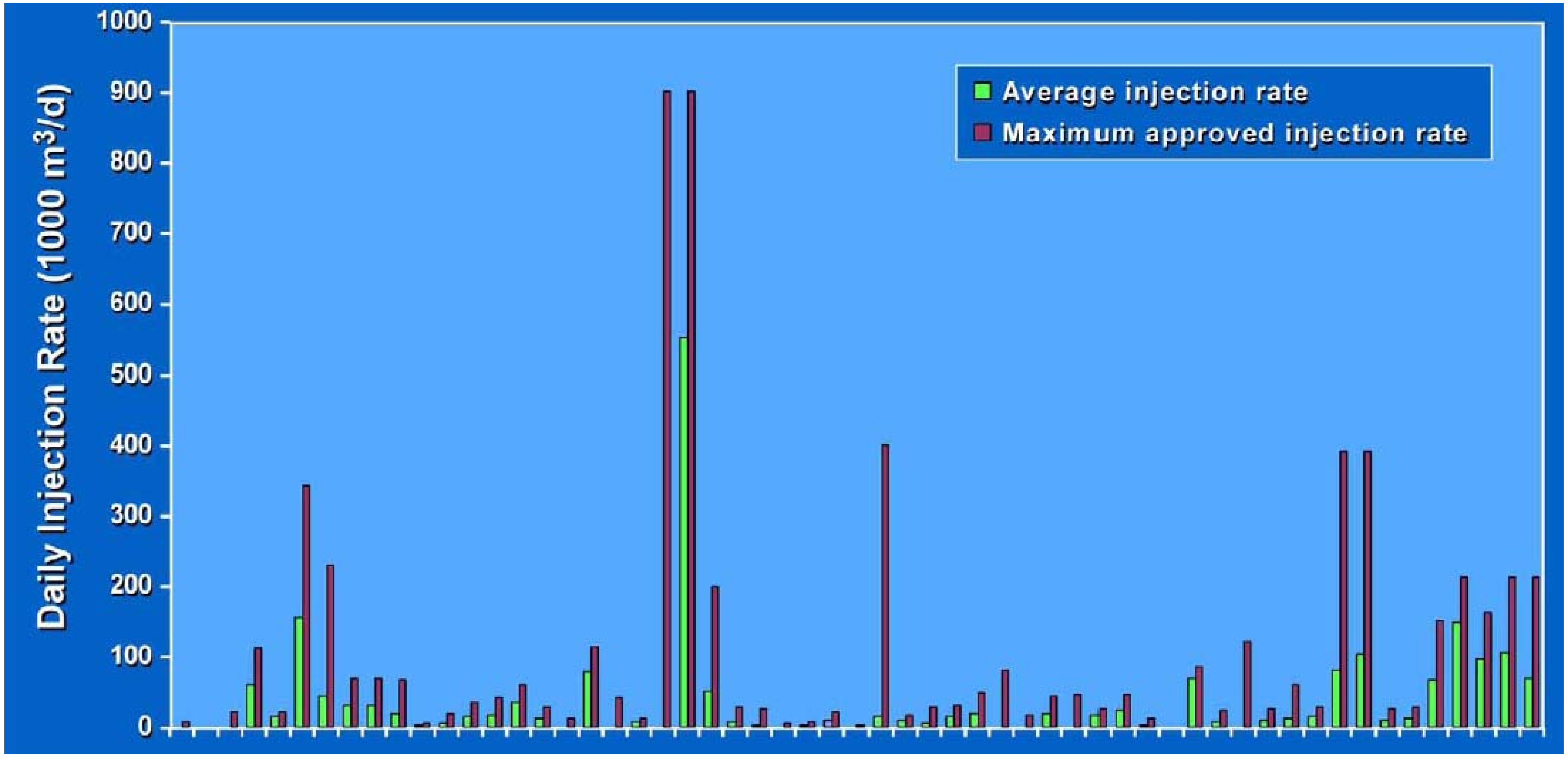
Waste Gas Composition



By Bachu et al

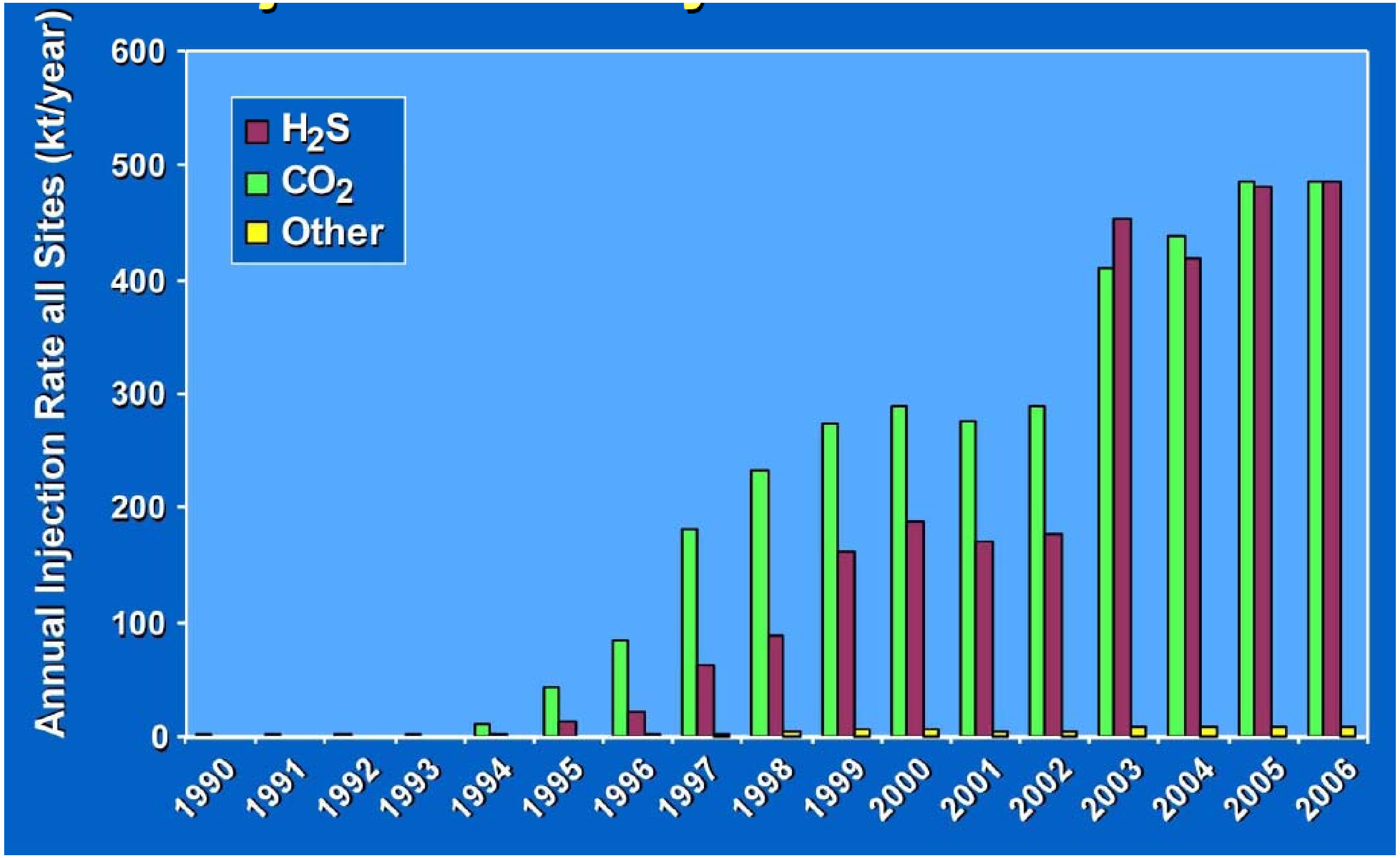
Practical Situation

Injection Rate (nearly in all cases 1 well)



Practical Situation

Average Injection Rate



Practical Situation

Operating Ranges

Characteristic	Minimum	Maximum
Licensed H_2S (mol fraction)	0.05	0.97
Actual injected H_2S (mol fraction)	0.02	0.83
Actual injected CO_2 (mol fraction)	0.14	0.95
In-situ acid gas density (kg/m^3)	204.8	728.3
In-situ acid gas viscosity (mPa·s)	0.02	0.09
Maximum well head pressure (kPa)	3,750	19,000
Maximum injection rate (10^3 m^3/day)	4.2	900
Actual average injection rate (10^3 m^3/day)	1.0	500
Maximum injection volume (10^6 m^3)	6	1,876

Practical Situation

Characteristics of Disposal Site

Characteristic	Minimum Value	Maximum Value
Average injection depth (m)	824	3432
Formation thickness (m)	4	276
Net pay (m)	3	100
Porosity (%)	4	30
Permeability (mD)	5	4,250
Formation pressure (kPa)	5,915	35,860
Formation temperature (^{o}C)	34	110
Water salinity (mg/l)	19,740	341,430
Brine density (kg/m^3)	998	1273
Brine viscosity (mPa·s)	0.36	1.32
Oil gravity (^{o}API)	16	68
Gas specific gravity	0.573	1.121

Practical Situation

- **Observations**

- Preference for storage (injection) rather than flaring or other method (sulfur recovery).

- Potential for flaring still available in case of injection facility shut down (as a concern).

- Concern for contamination of groundwater resources.

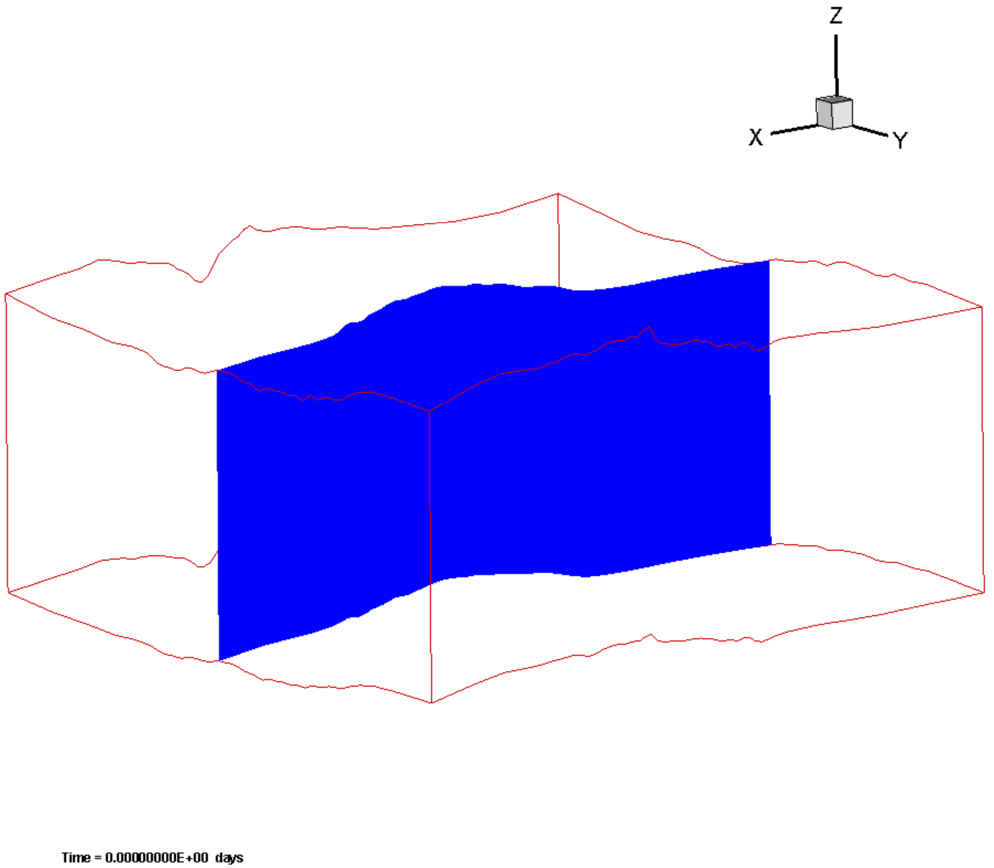
- Concern about proper monitoring

- Deep injection of acid gases is a mature technology that can be used for large-scale implementation of greenhouse gas capture and storage.

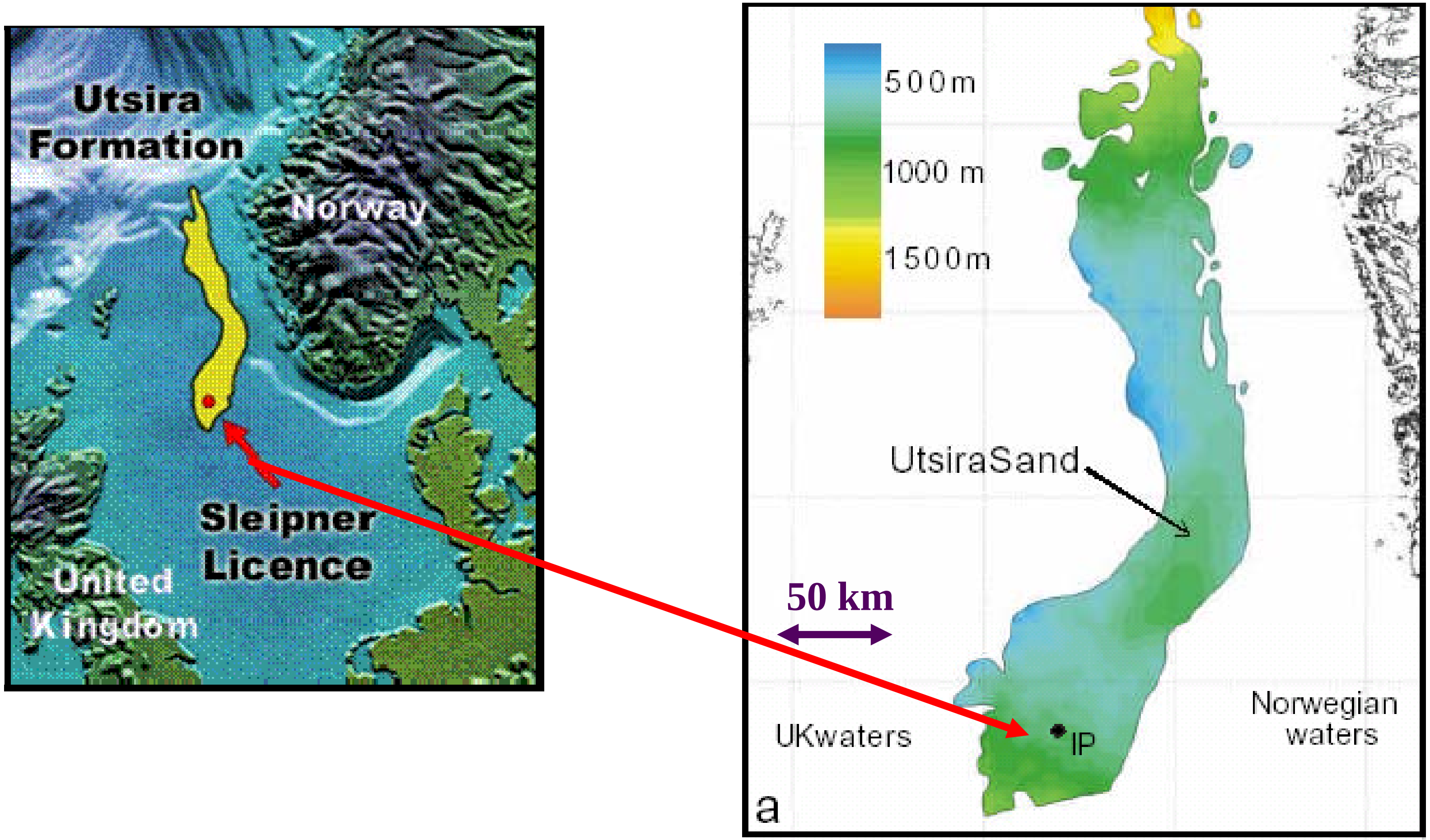
European Examples

- Sleipner
- InSalah
- K12-B

Sleipner CO_2 Storage

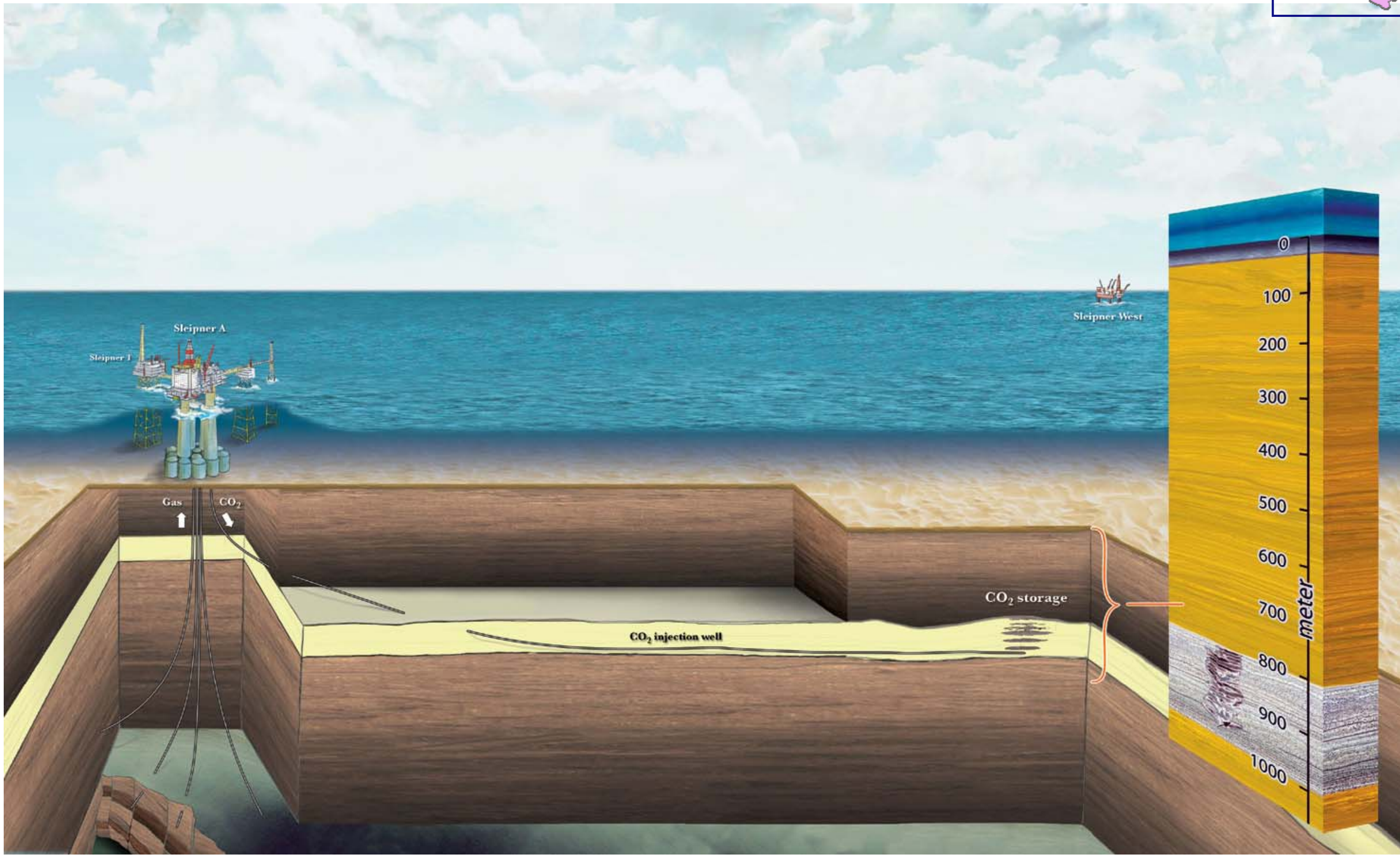


Utsira Sandstone Order of Magnitude



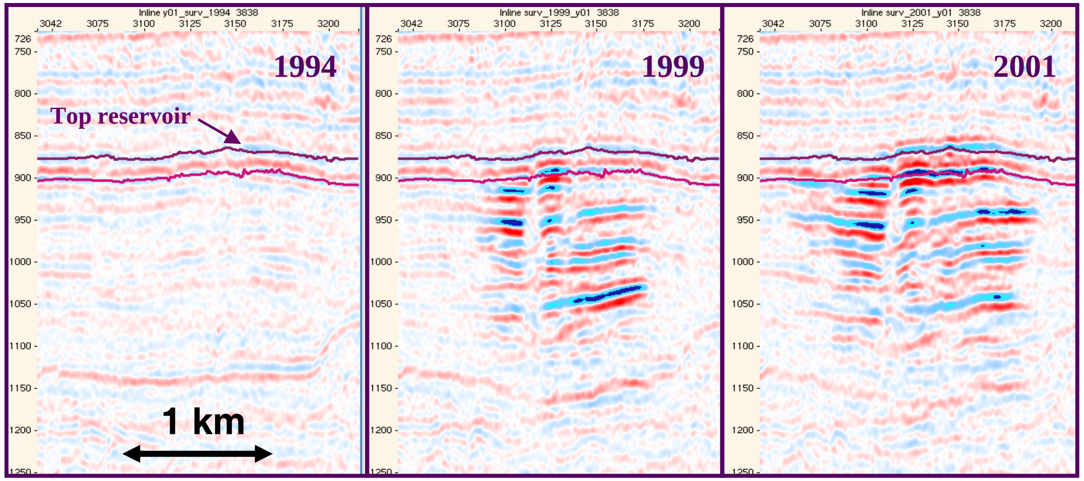
Total surface 26.000 km^2

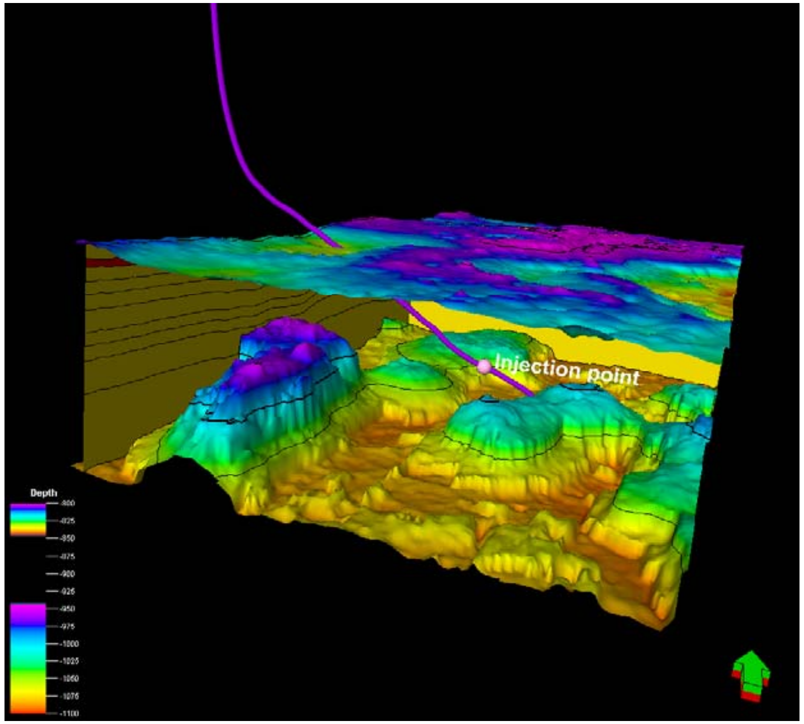
Sleipner Site

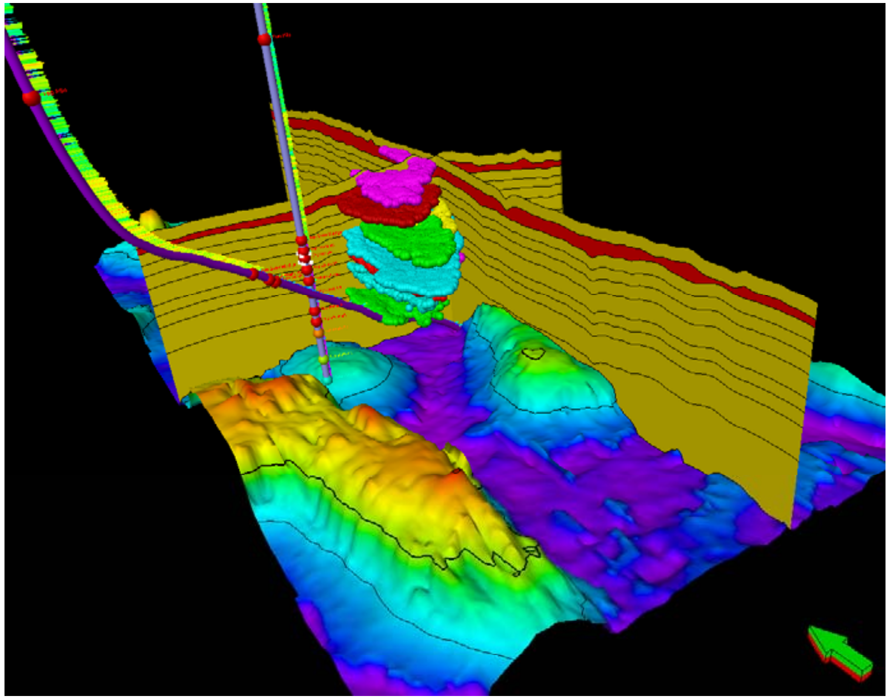


Courtesy StatoilHydro

Sleipner shows that big scale storage is possible

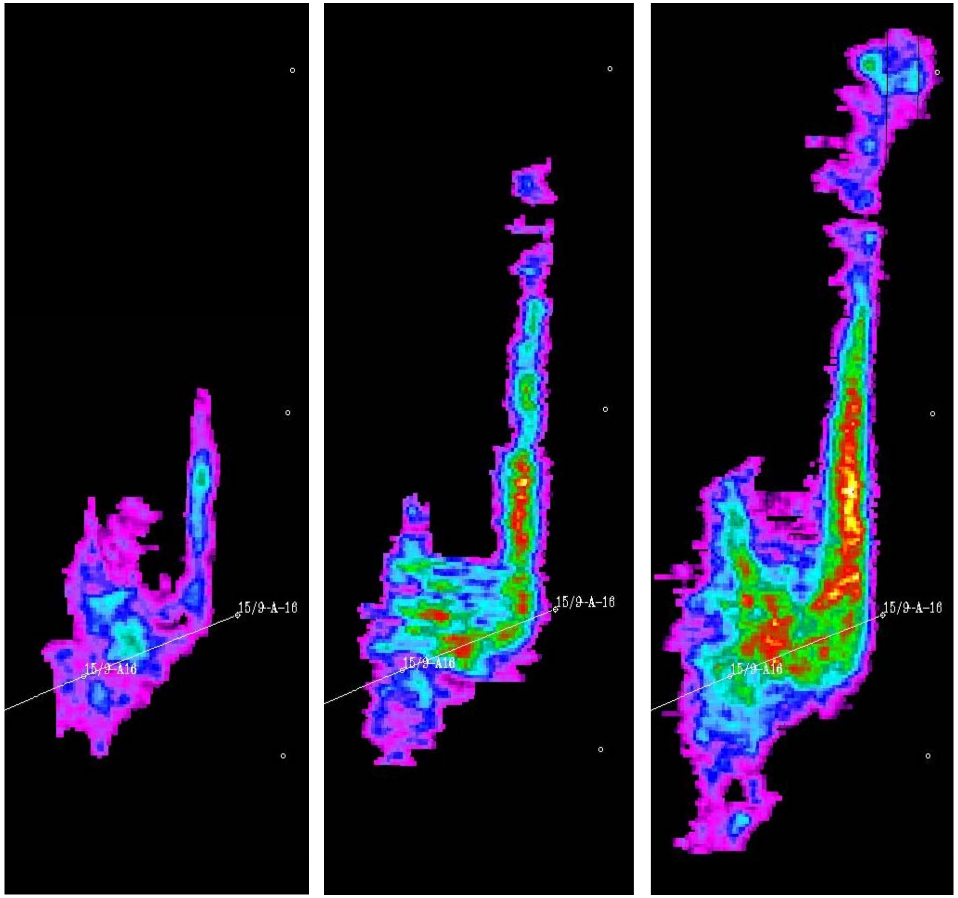






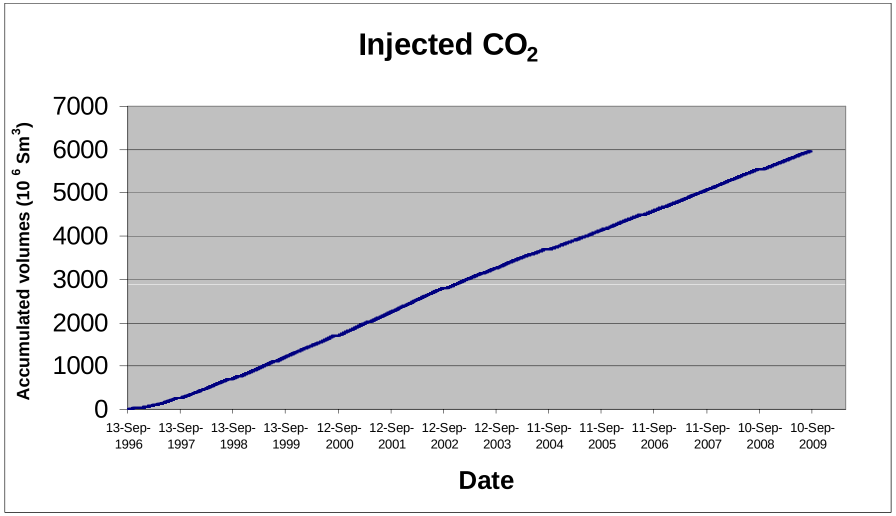
Courtesy CO2STORE Project

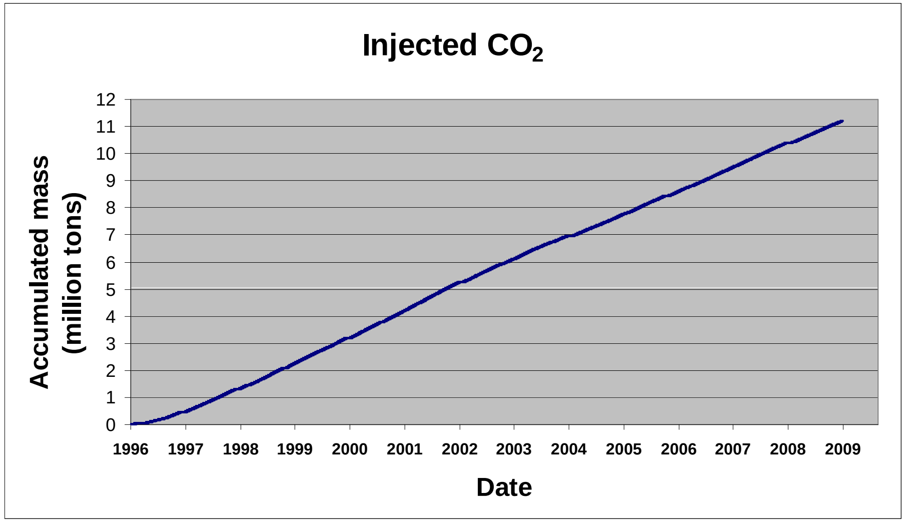
Seismic monitoring (4-D)

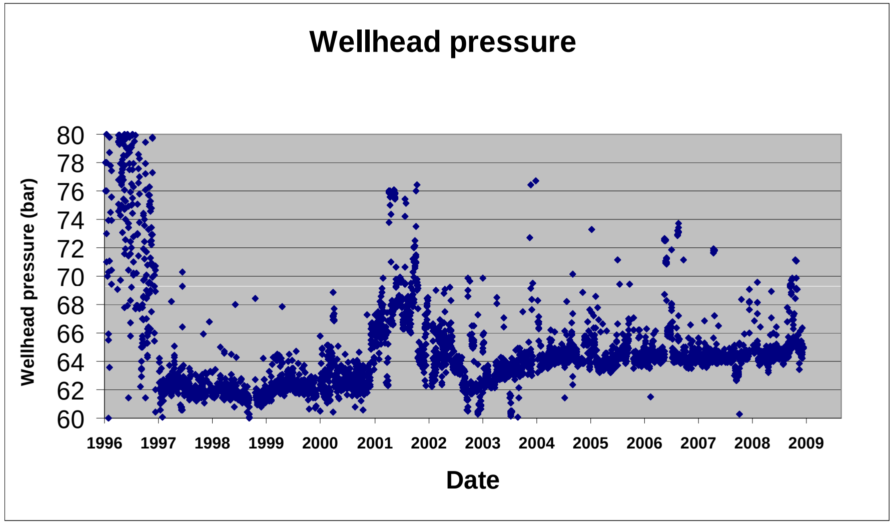


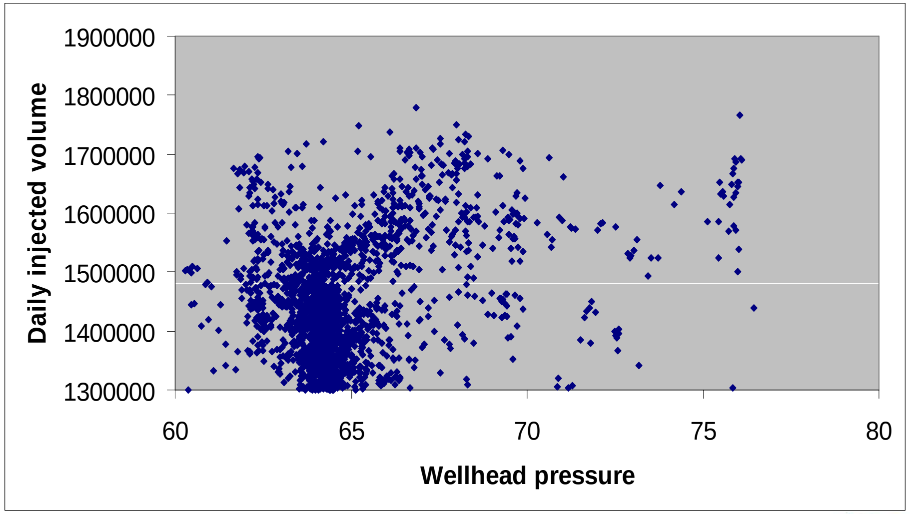
2001 2004 2006

Sleipner Data





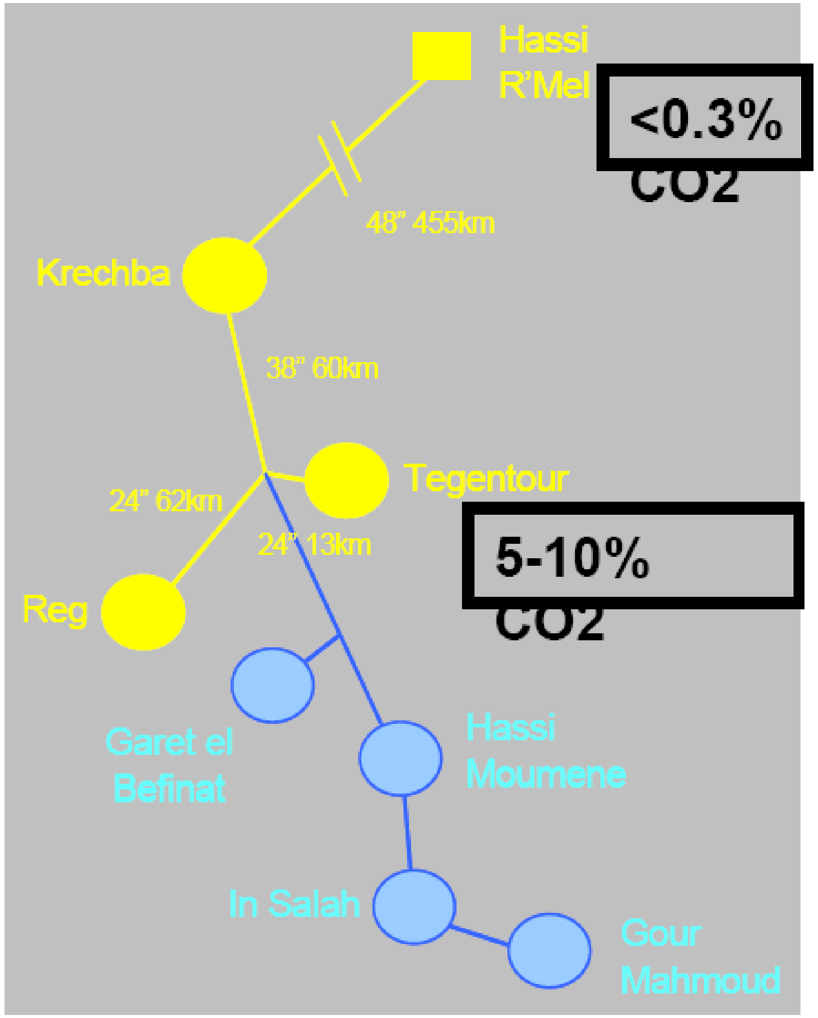




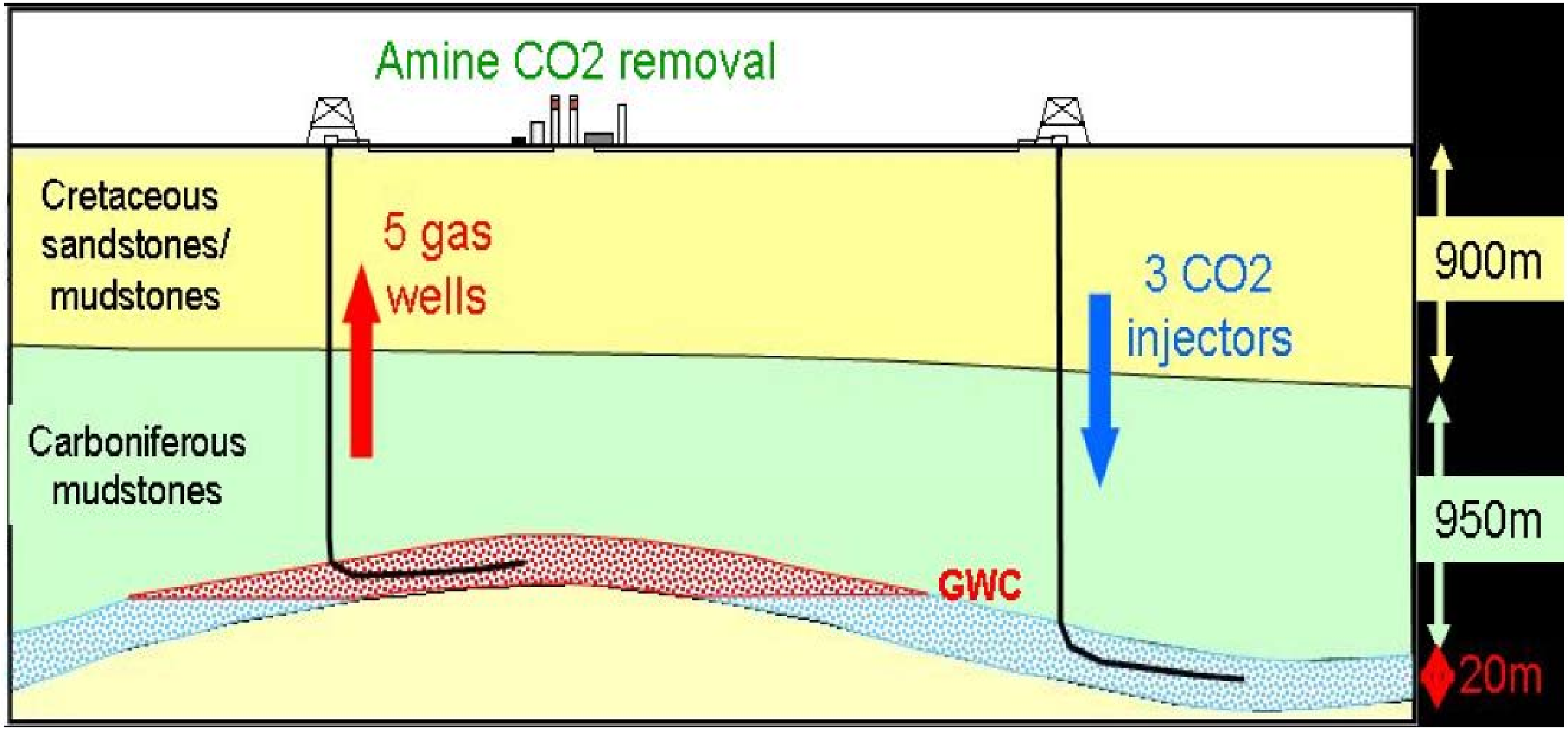
Sleipner

- No problems
- Very large structure
- Very permeable

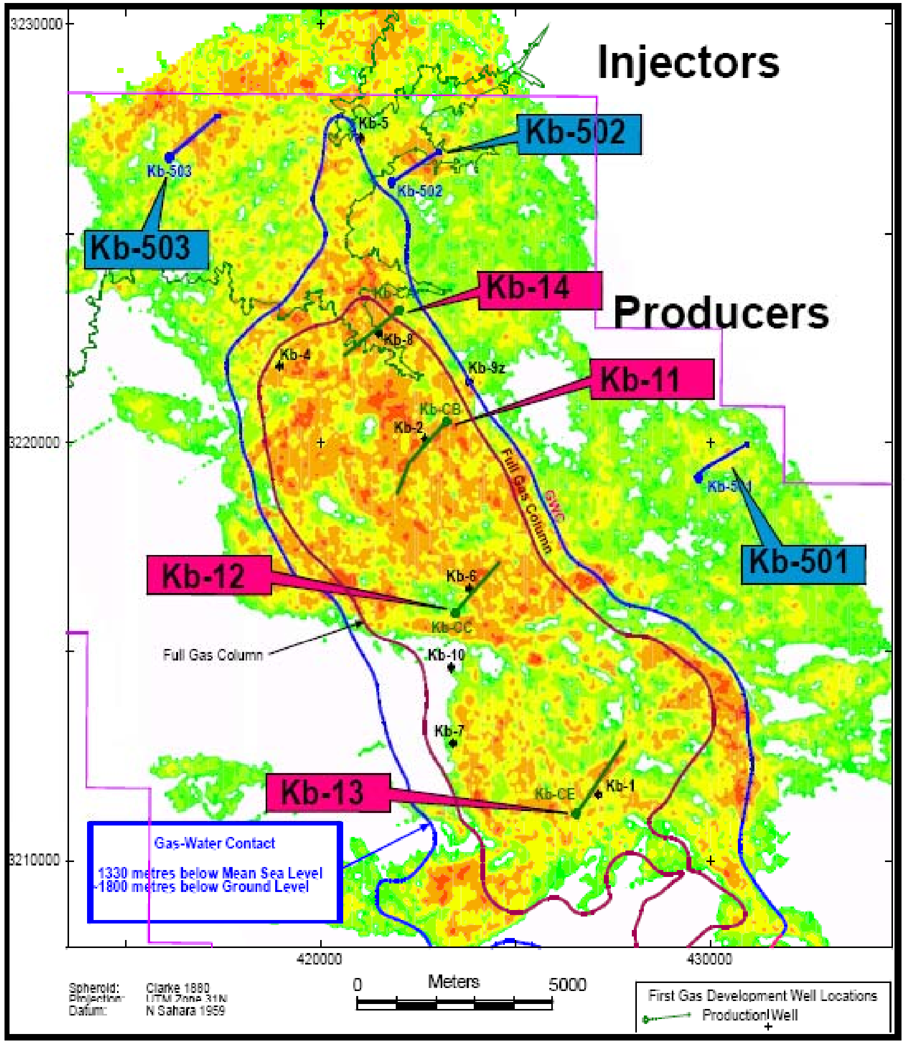
In Salah Gas Project

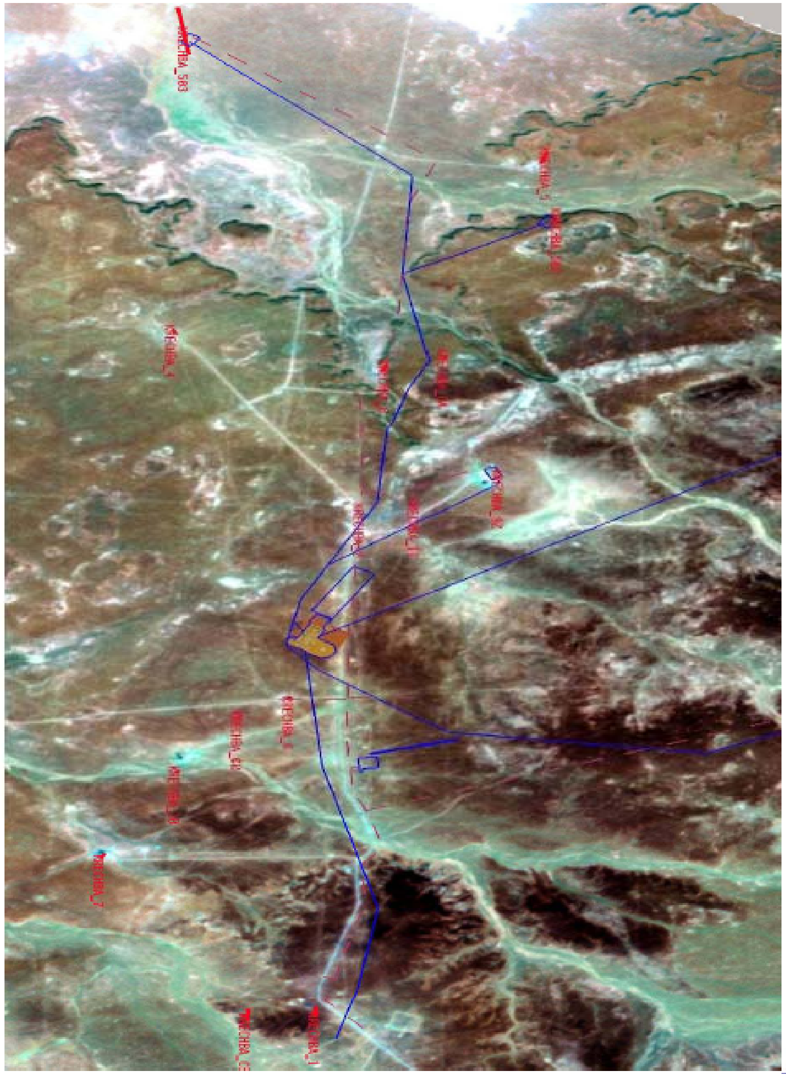


Storage Concept

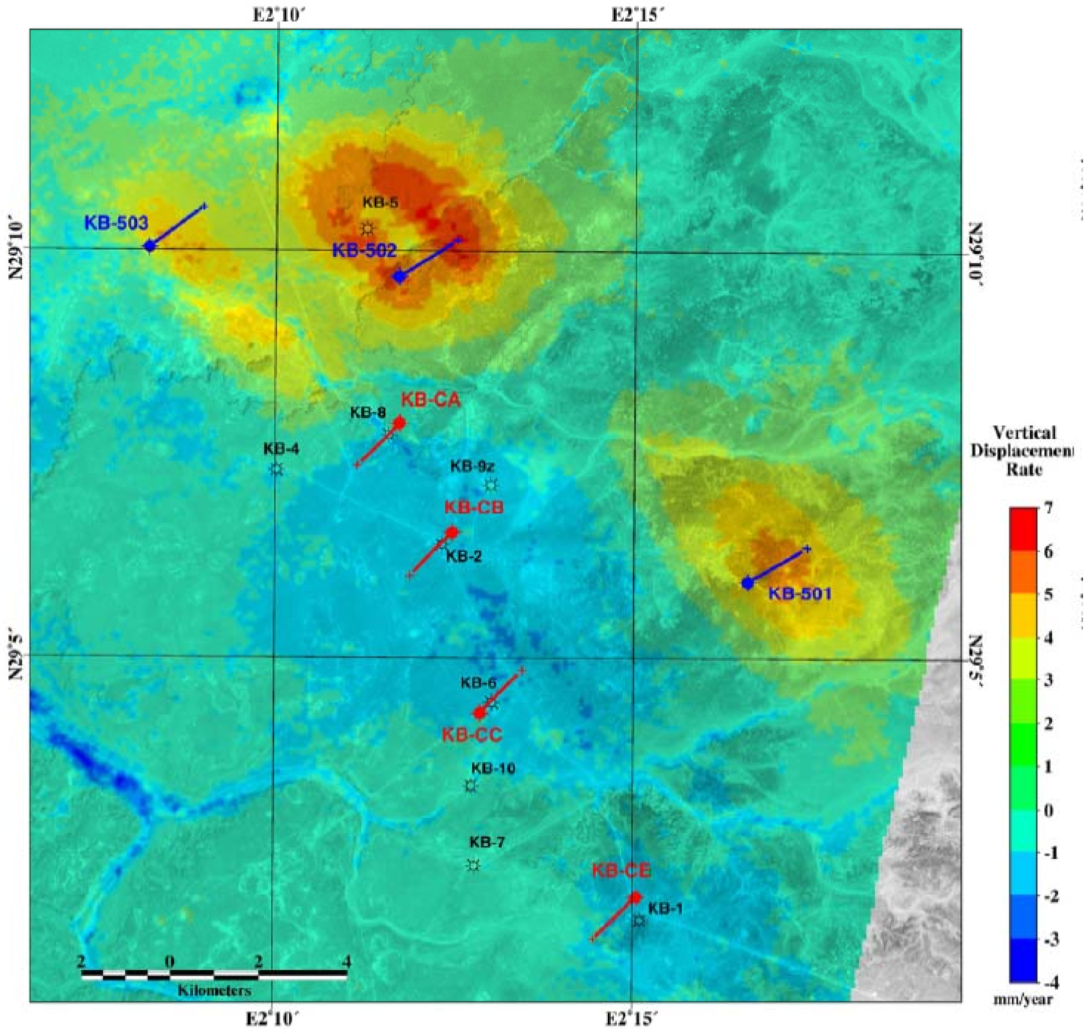


In Salah – Krechba Field





In Salah – Uplift



In Salah

- Possible problems
- Rapid uplift effects up to 2 cm
- Injectivity to low

K12-B – Storage in a Gas Field

- Early work by Shell on EGR for Dutch reservoirs (1990)
- More fundamental work by Oldenburg LBL on Californian reservoir (1996 -   )
- Papers on use of CO2 for cushion gas for gas storage
- Gas producers reluctant to pollute the gas

K12-B (not Sleipner)

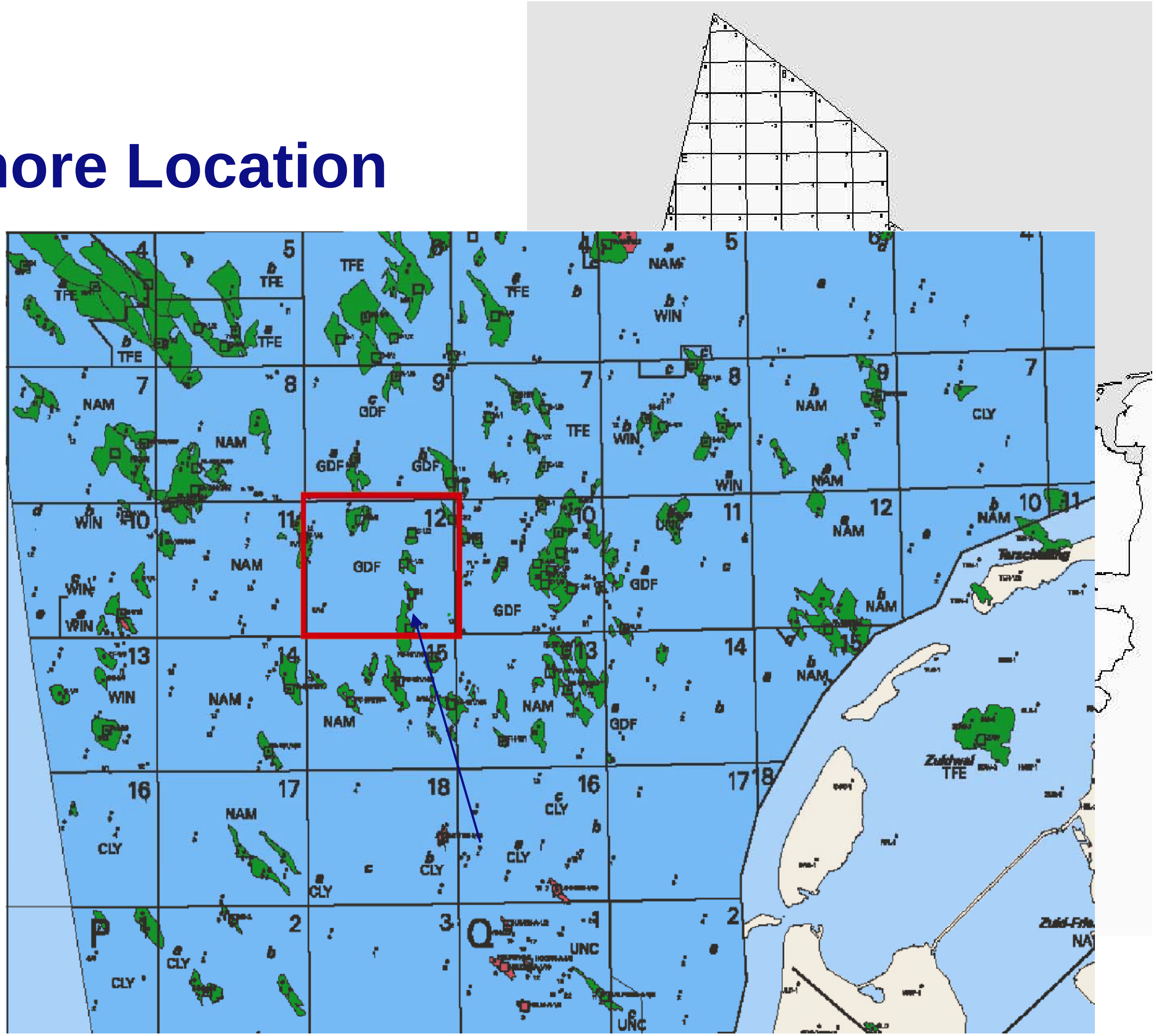
K12-B

- Gas field (nearly empty) Deep (3900m SS)
- High temperature (128 ^{0}C)
- Low pressure (40 bar)
- Low permeable (mD)
- Confined space
- Full test site

Sleipner

- Aquifer
- shallow (800 m SS)
- Temperature ~40 ^{o}C
- Hydrostatic (80 bar)
- High permeable (D)
- Extremely large
- Restricted

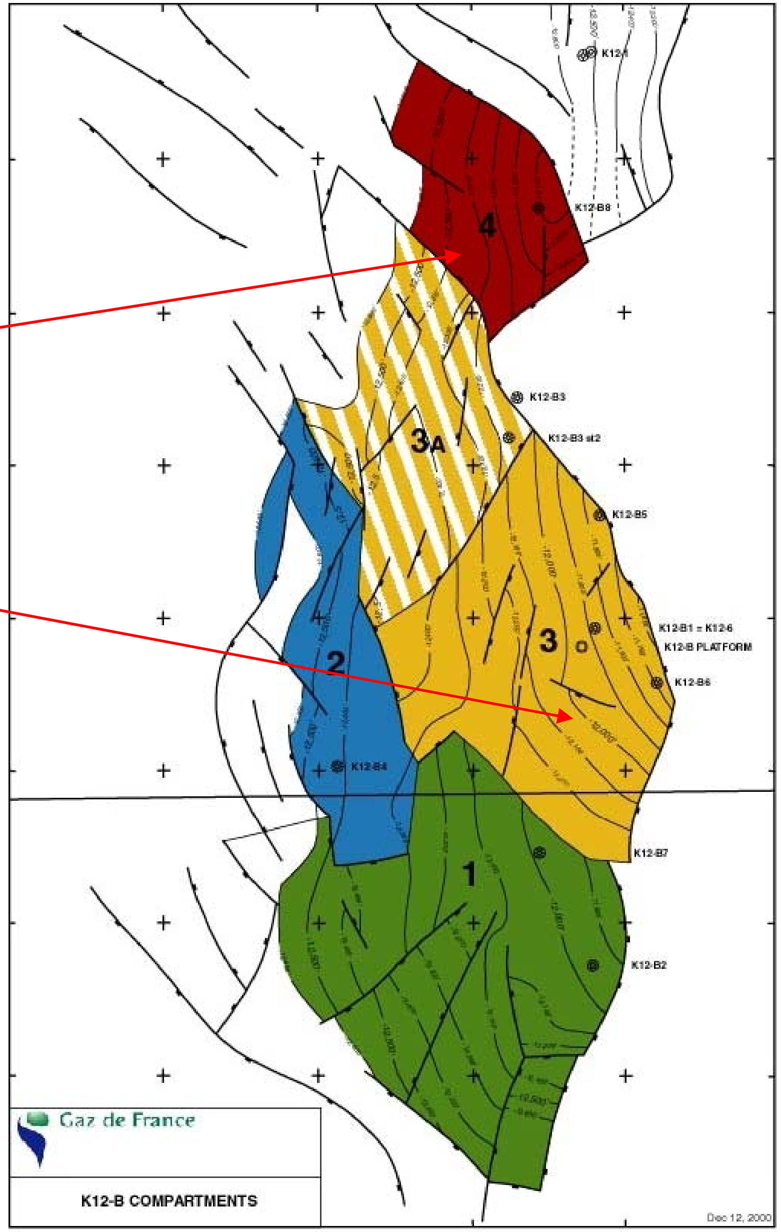
Offshore Location



Introduction –
K12-B Compartments

- Single well compartment

- CO_2 Injector and gas producer



Introduction - Feasibility Study

- Technical feasibility
- Available facilities and infrastructure
- Technical facilities for CO_2 injection

Feasibility Study

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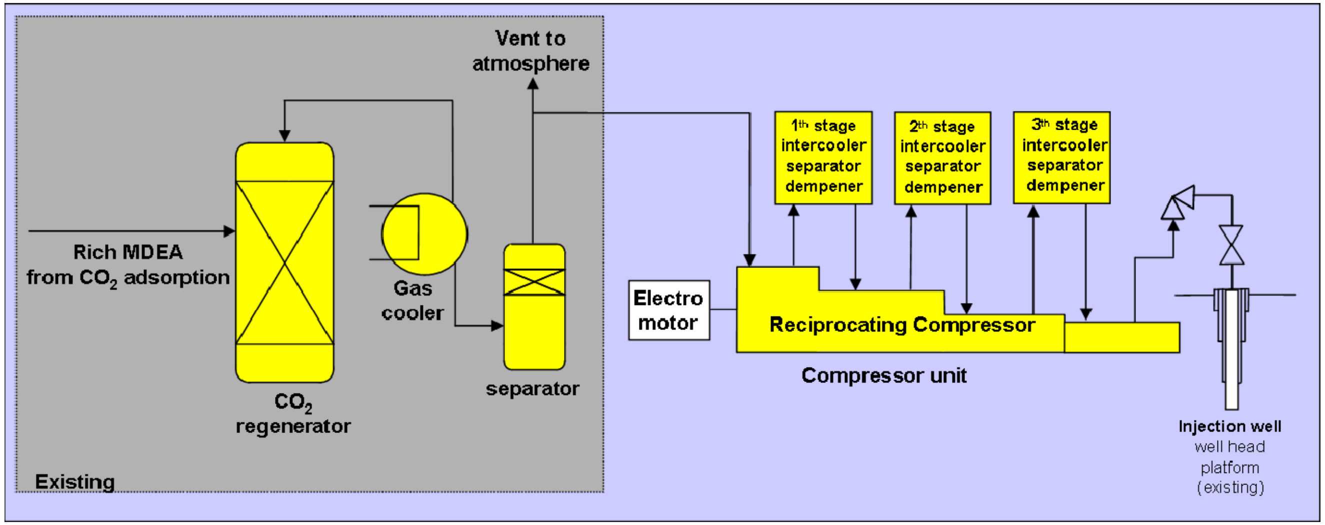


Feasibility Study

- Technical feasibility
- Available facilities and infrastructure
- Technical facilities for CO_2 injection

- Geological and field engineering aspects
- Legal and regulatory aspects
- Social aspects
- Safety and environmental aspects
- Financial and economic feasibility

Feasibility Study

- Technical feasibility
- Available facilities and infrastructure
- Technical facilities for CO_2 injection

- Geological and field engineering aspects
- Legal and regulatory aspects
- Social aspects
- Safety and environmental aspects
- Financial and economic feasibility

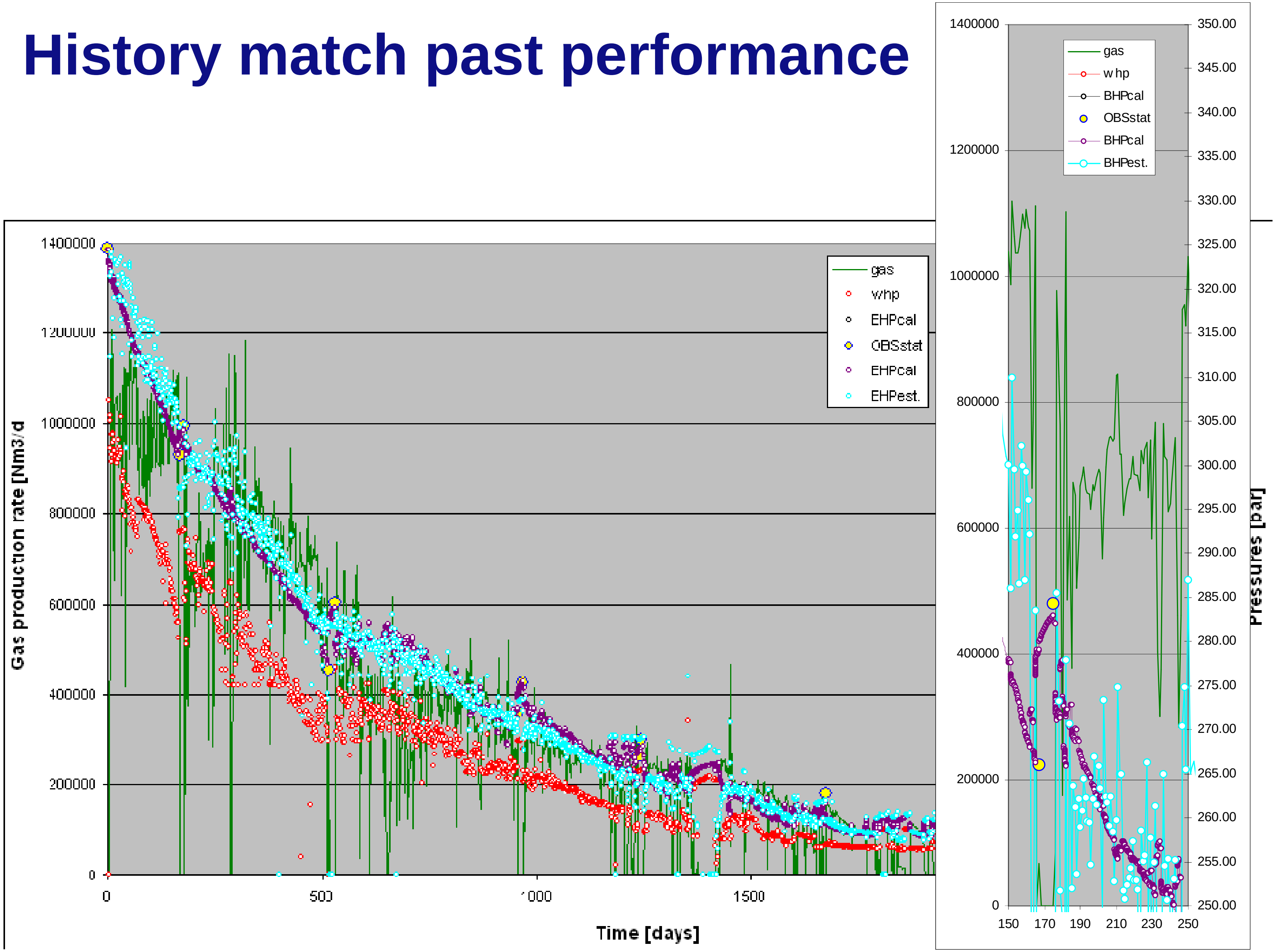
Indicative costs of a full-size unit	
CAPEX	€ 10.000,000
OPEX per year	€ 1.400,000
Other costs/revenues	unknown
Amount of stored CO_2 [Ton/y]	480,000
Costs per stored ton CO_2	€ 5,- / 10,-

Interest rate 9%; 10 years of operation.
Transport infrastructure is not included

Test Plan

- CO_2 injection Compartment 4
    - CO_2 Wellbore behavior
    - CO_2 Injectivity
- CO_2 injection and gas production Compartment 3
    - Displacement process
    - EGR possibilities
    - economics
- Safety caprock

History match past performance



TEST 1

- CO_2 injection prediction
  - Bottomhole injection pressure increase ~ 1.2 – 1.5 bar
  - Difference between THP and BHP some 19 bar

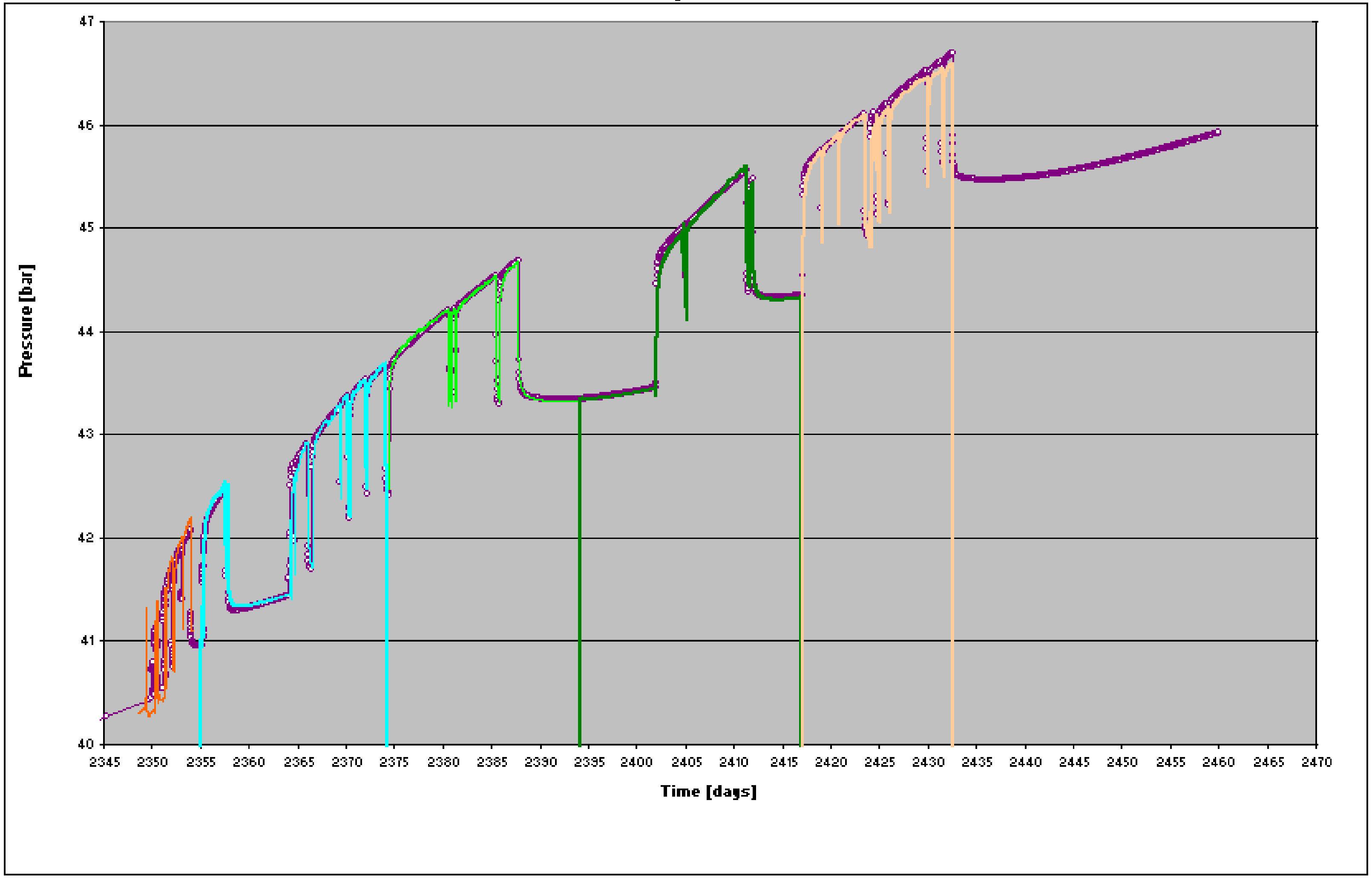
Reservoir engineering

- From history match
  - Good understanding reservoir flow behavior
  - Many questions on fluid wellbore behavior

- Need for wellbore behavior study
  - Specially for temperature sensitive CO_2

- Baseline wellbore pressure/temperature survey
  - shallow depth 15 minute stops at 20 meter interval
  - deeper stops at 1000 meter interval

TEST 1 - Injection test



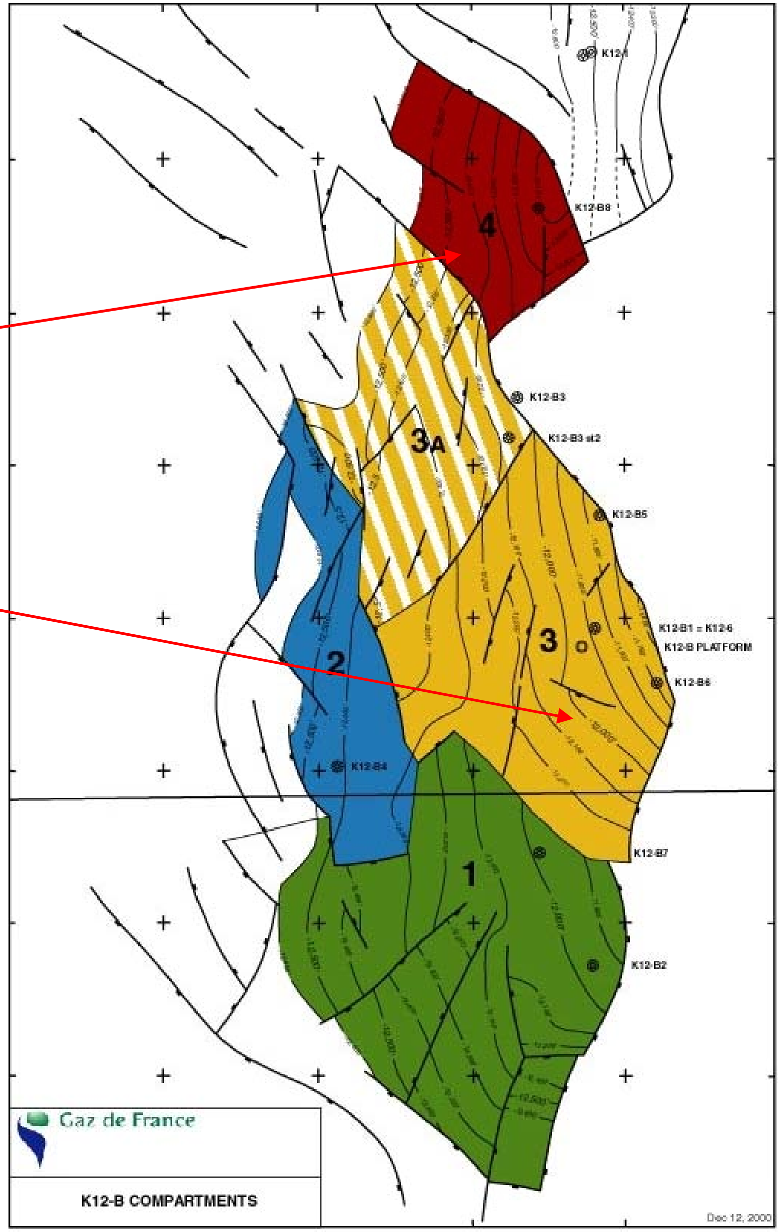
Conclusions (Test 1)

- A very good history match achieved
- Temperature of injected CO_2 at injection location close to reservoir temperature
- CO_2 gas can be injected in a nearly empty gas reservoir at a depth of 4000 m
- CO_2 injectivity high despite of relatively low permeability of the K12-B reservoir
- Testing will continue

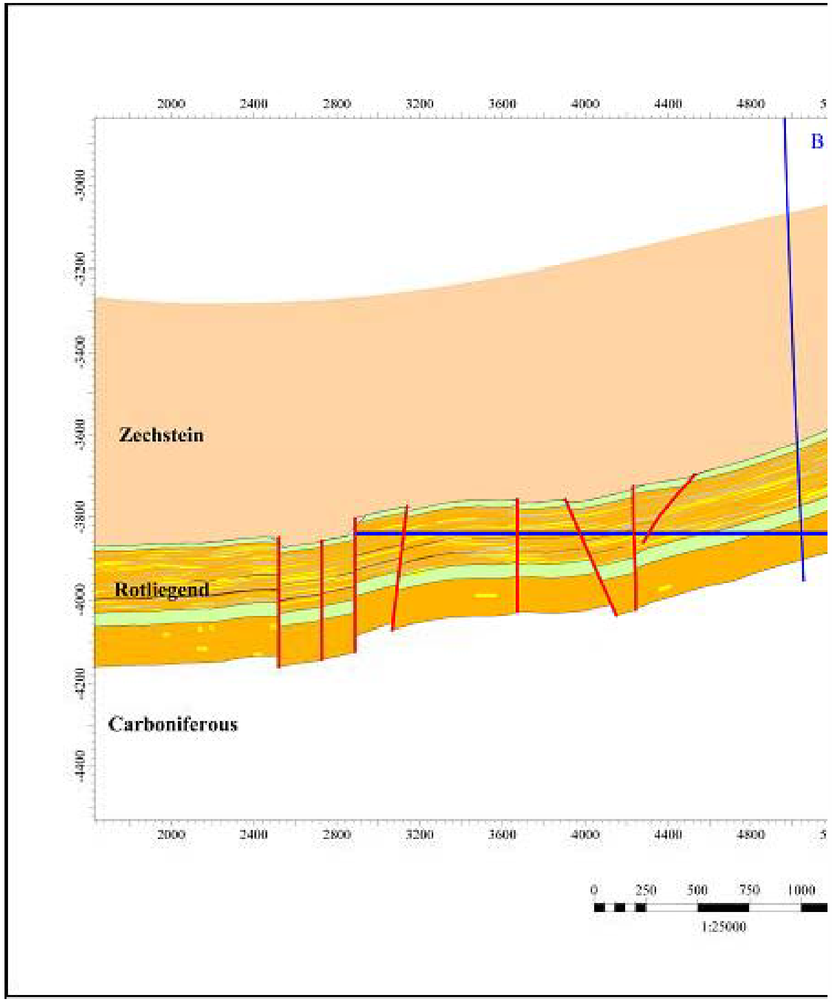
TEST 2 –
K12-B Compartments

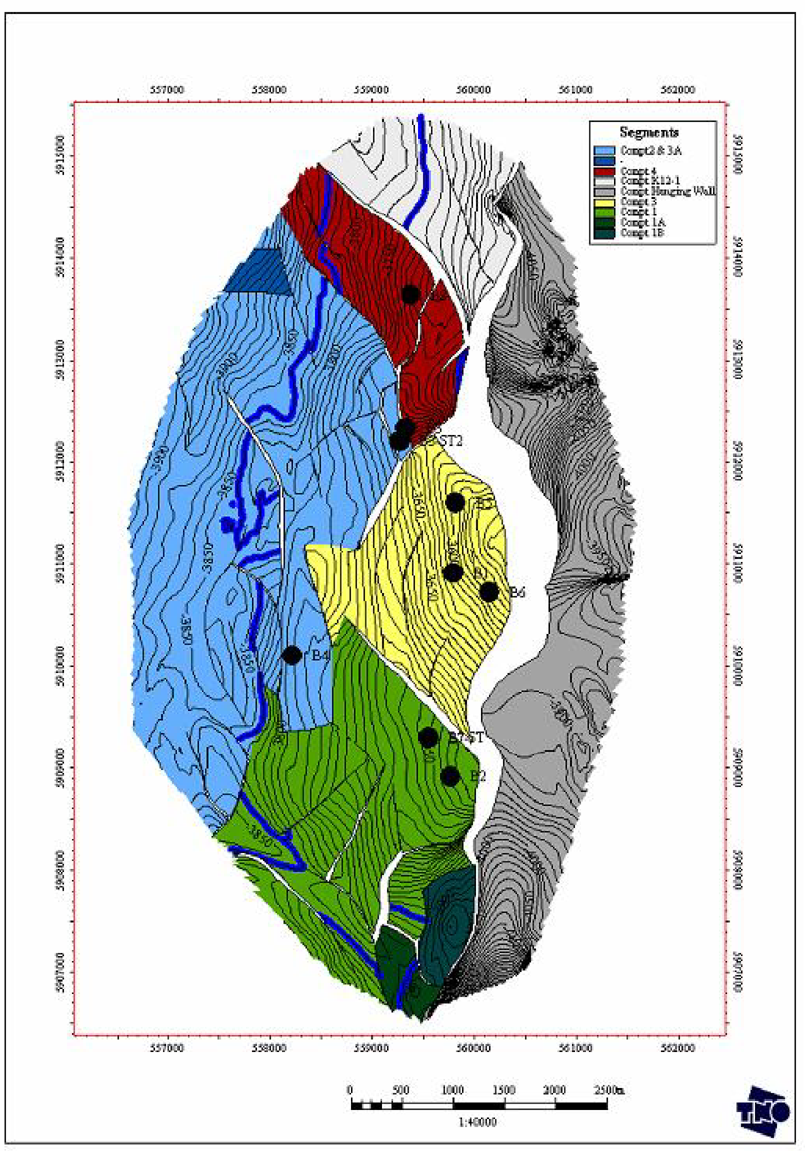
- Single well compartment

- CO_2 Injector and gas producer

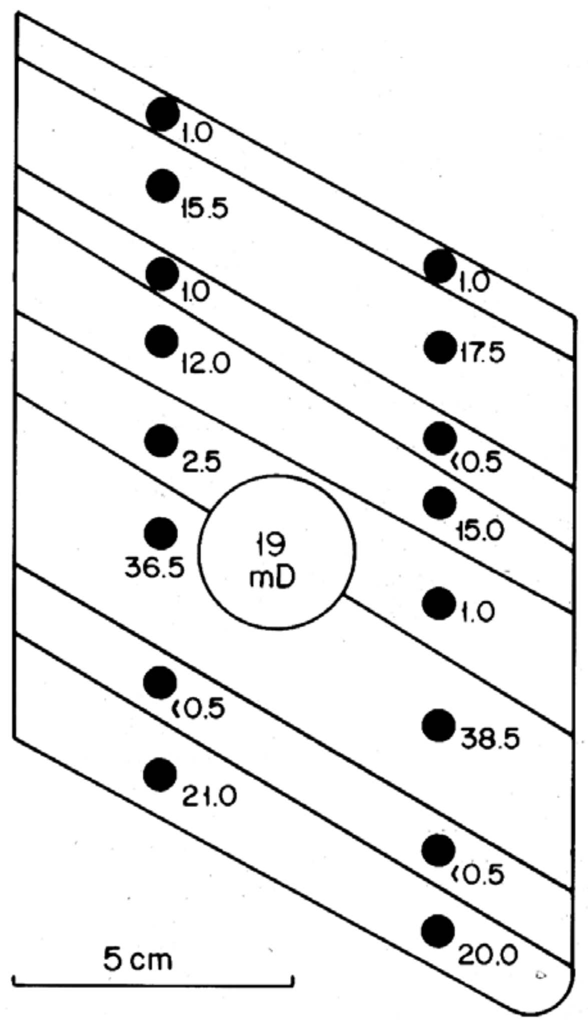


Geological Model

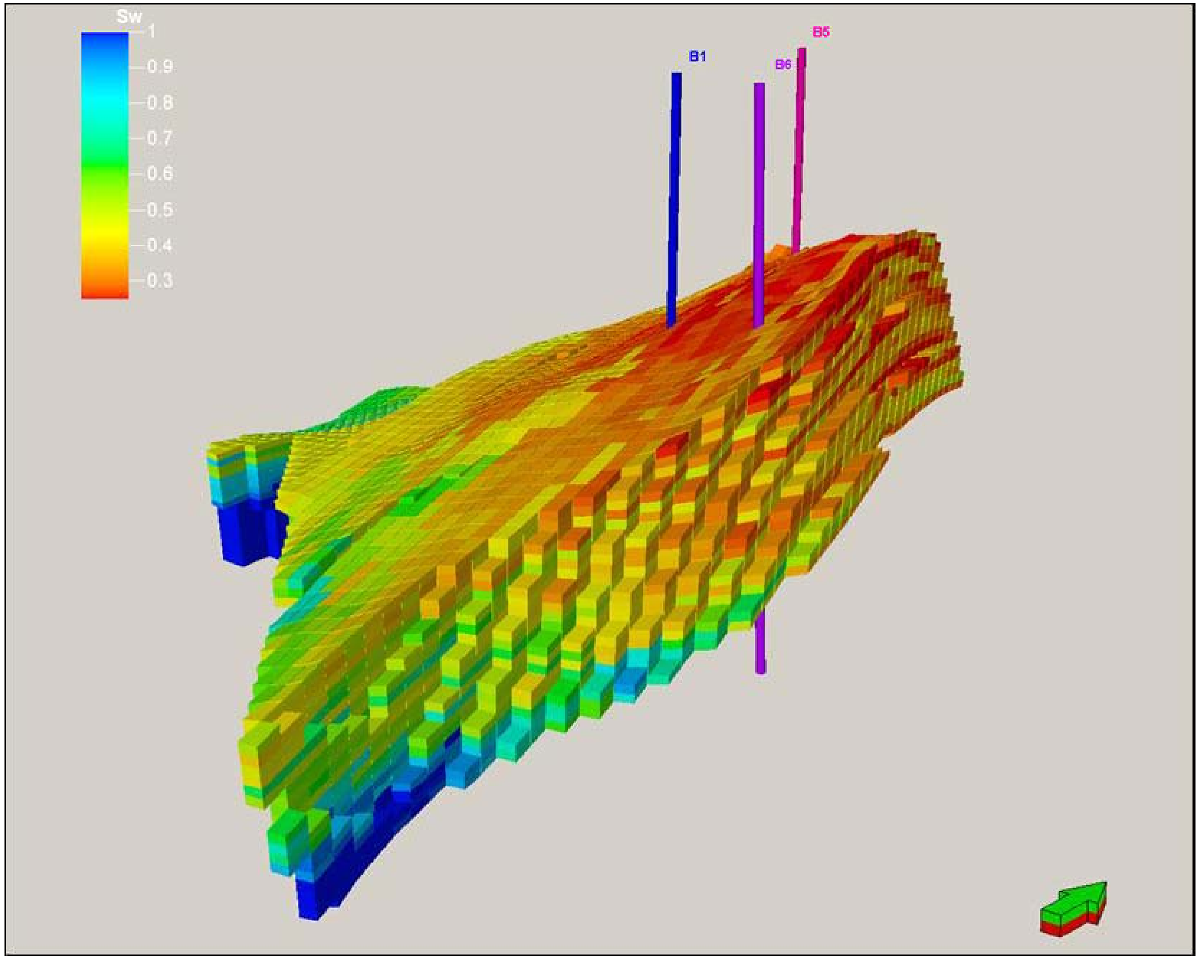




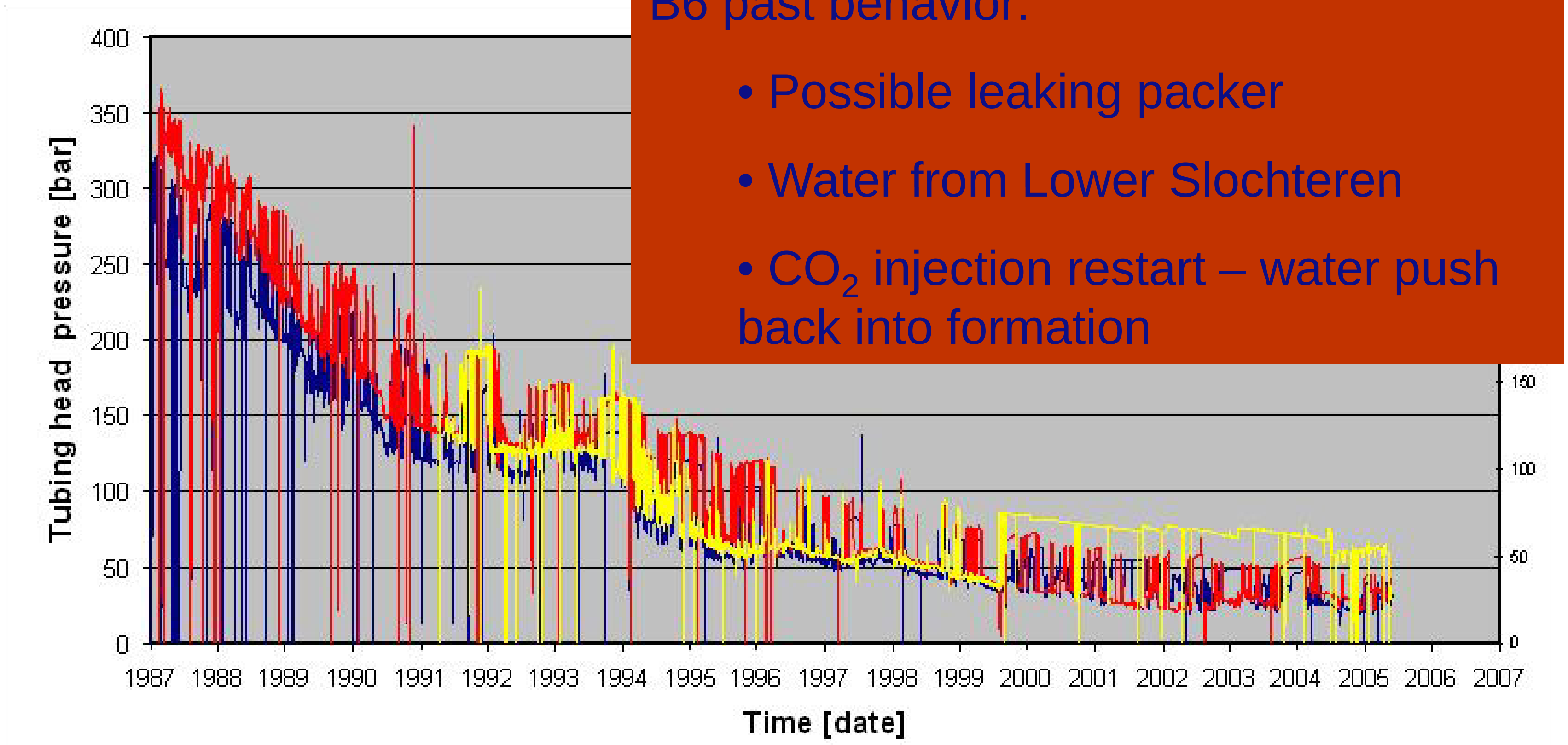
Permeability contrast in x-bed laminae



Test Results – Test 2



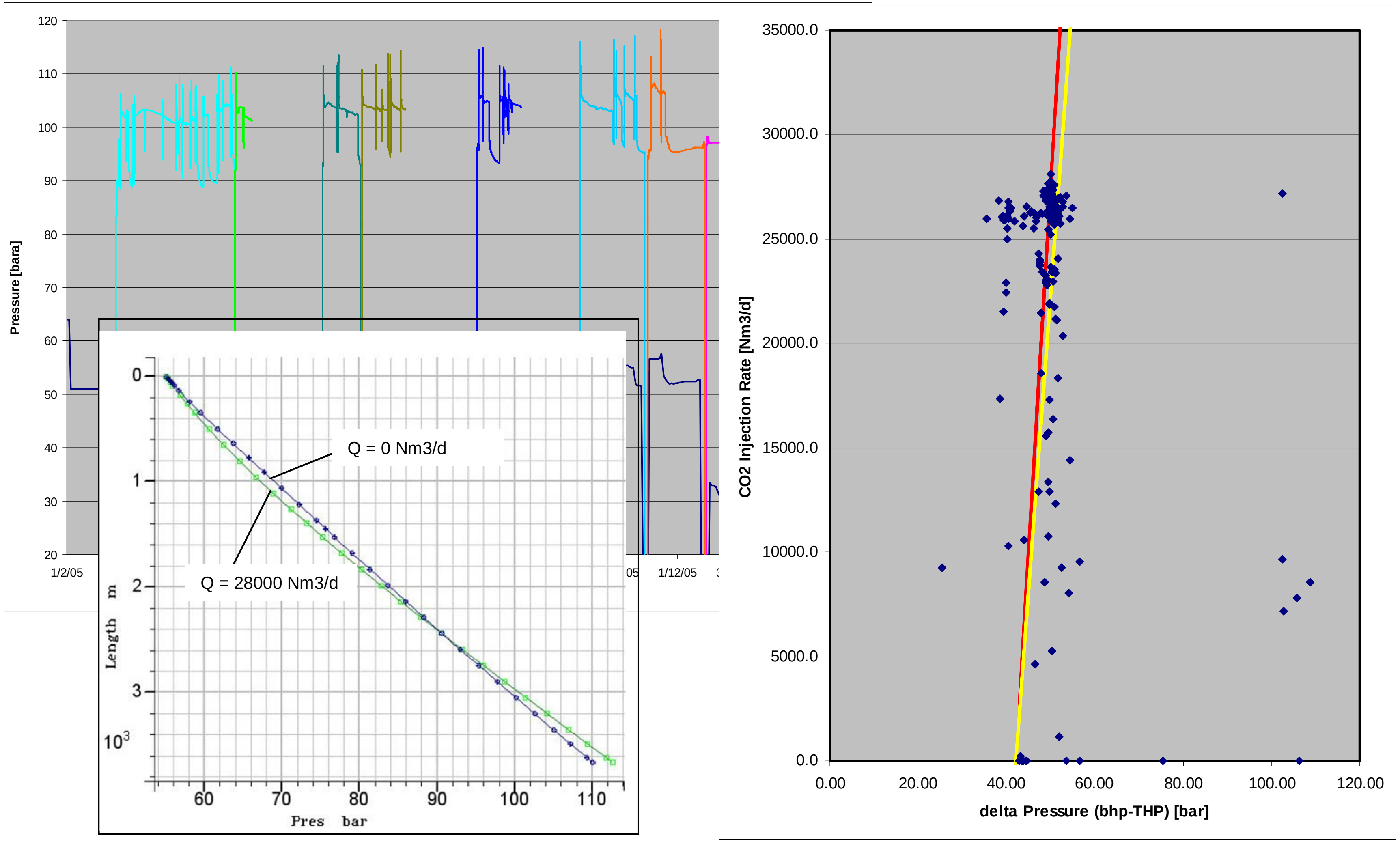
Past Performance



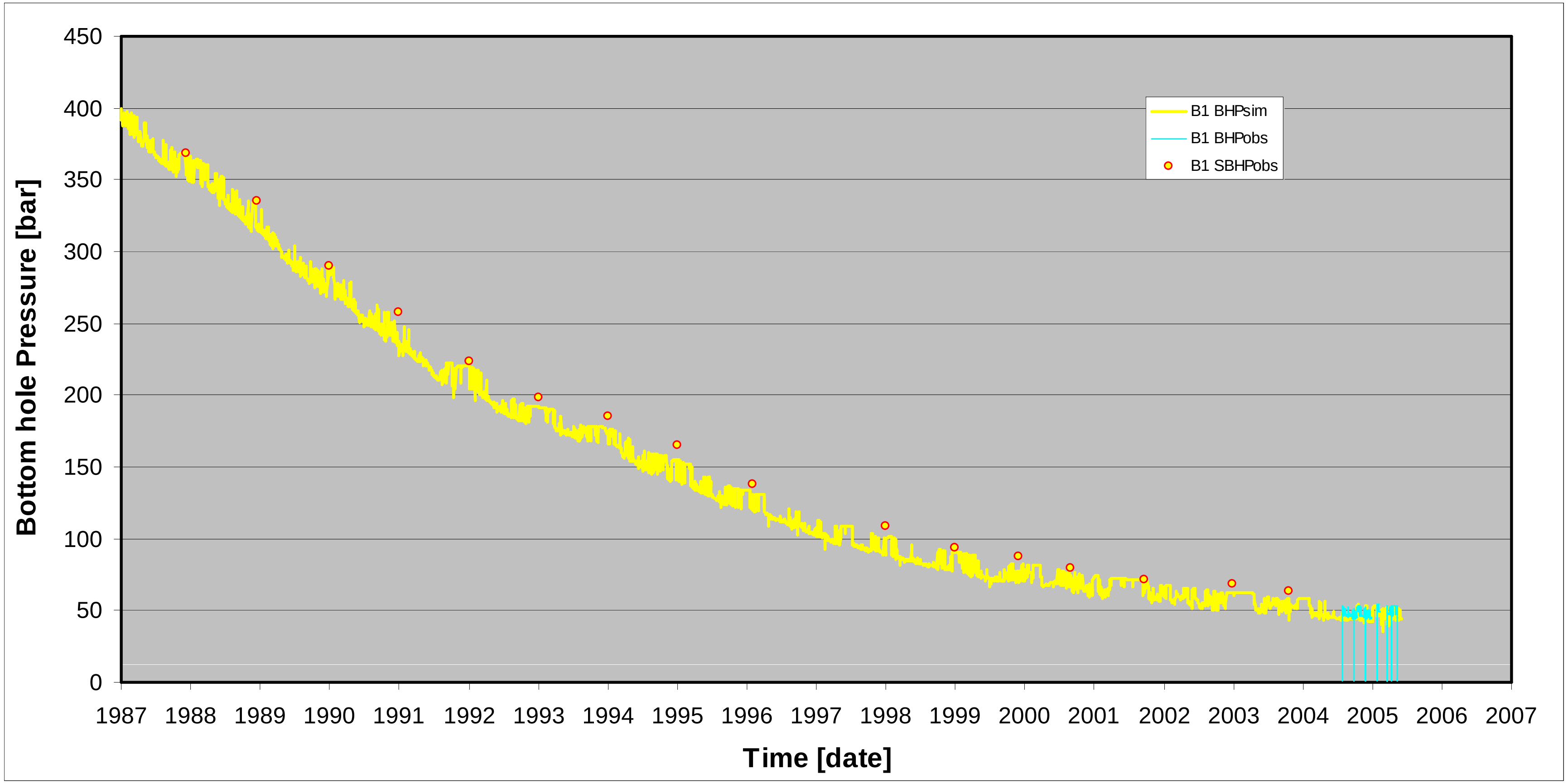
B6 past behavior:

- Possible leaking packer
- Water from Lower Slochteren
- CO_2 injection restart – water push back into formation

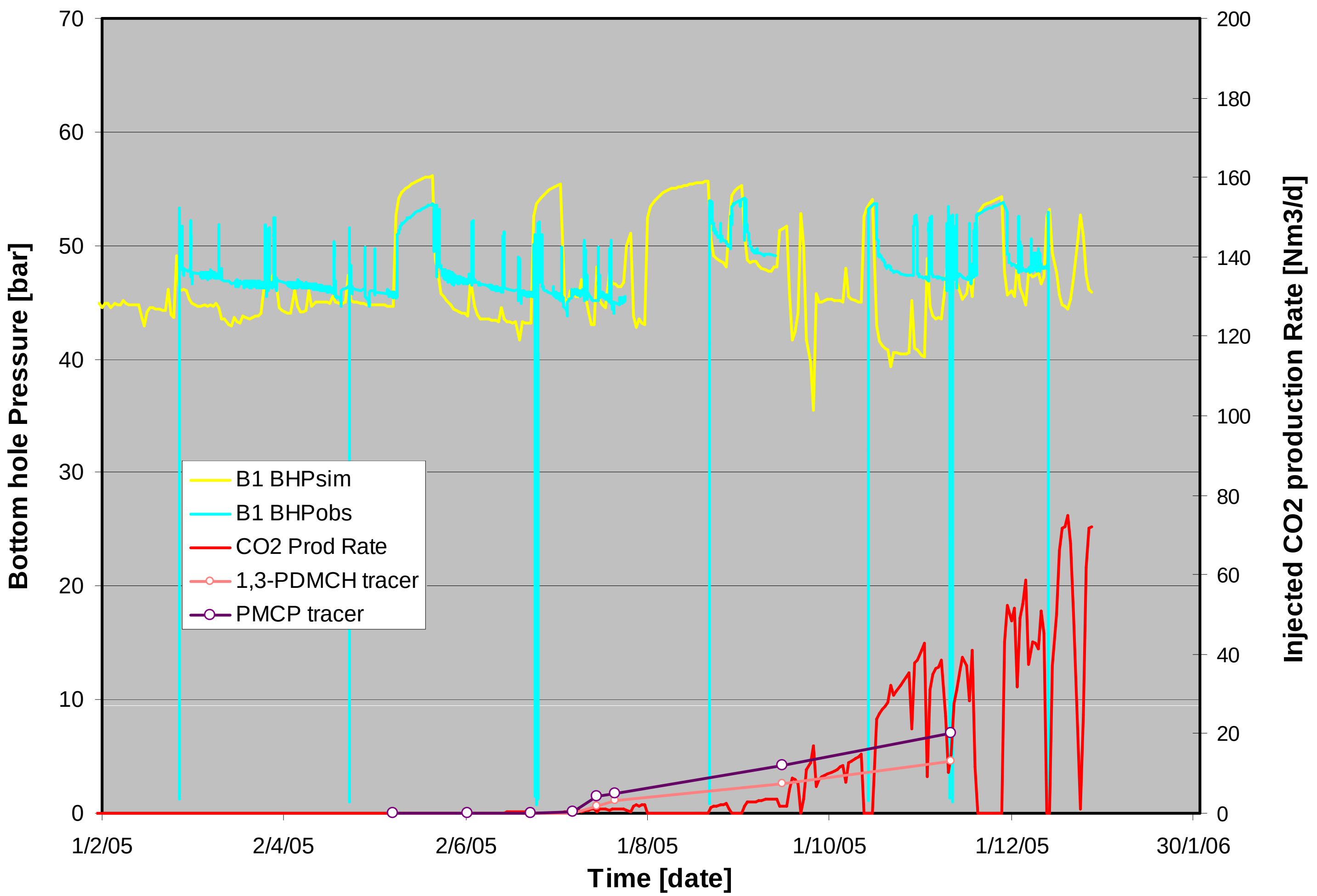
Vertical Flow Performance



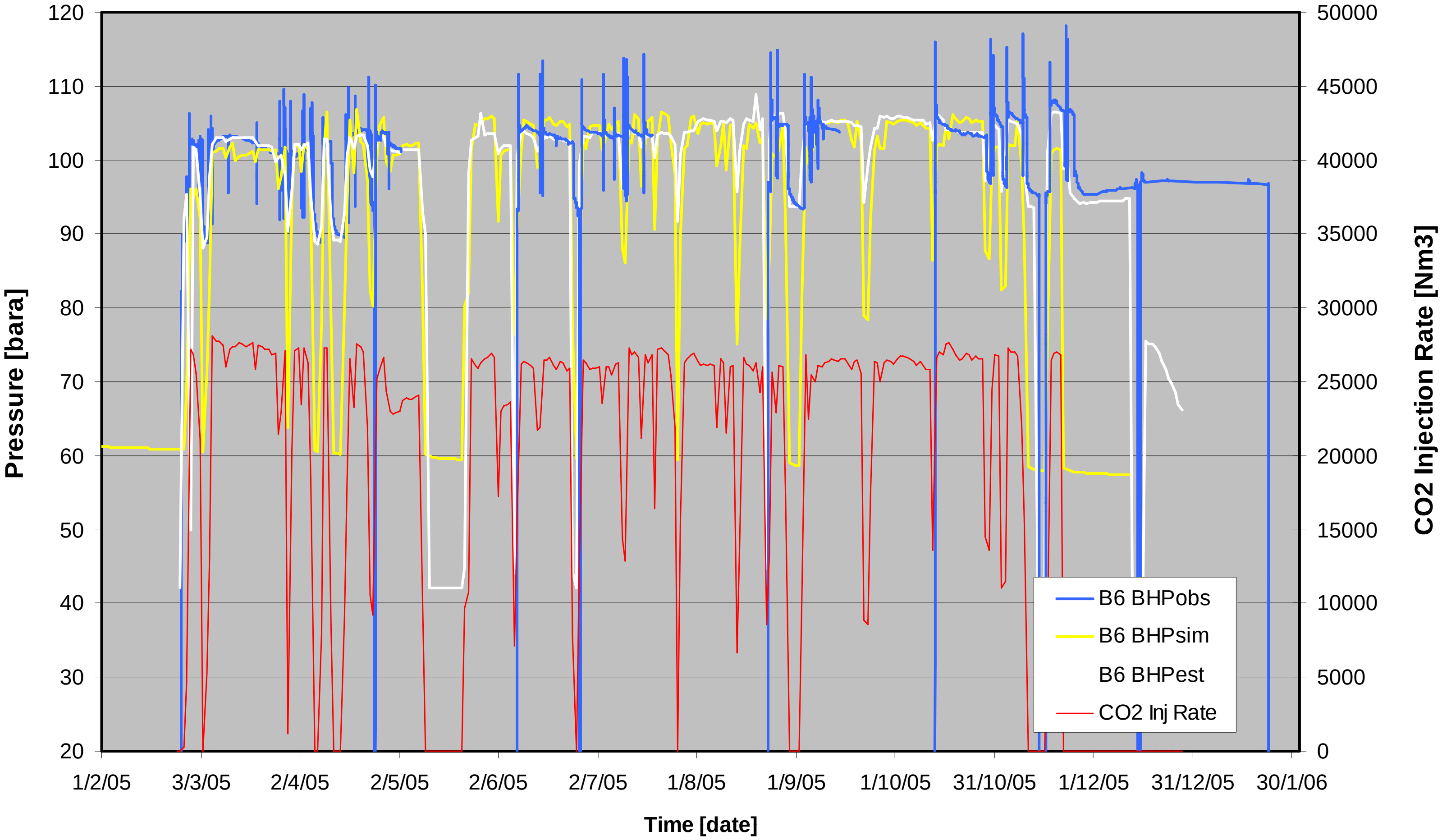
History Match – B1



Test 2 Simulation Results – B1



Test 2 Simulation Results – B6



Conclusions

- CO_2 injection first time in Netherlands and unique in respect to active gas field, depth, pressure and temperature range.
- CO_2 injection without problems and as predicted
- CO_2 breakthrough B1 modeled is slow and gradual
- Volumetric consequences of CO_2 injection undetected in 2005 test period i.e. no EGR potential yet
- Will large scale injection work?

- All in all

- Deep injection of acid gases is a mature technology that can be used for large-scale implementation of greenhouse gas capture and storage.