



**Methodology for selection and qualification of sites and  
project development for geological storage of CO<sub>2</sub>**

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# CGS Europe

CO<sub>2</sub> Capture and Storage – Response to Climate Change  
Regional workshop for the Baltic Sea Region and C&E European Countries

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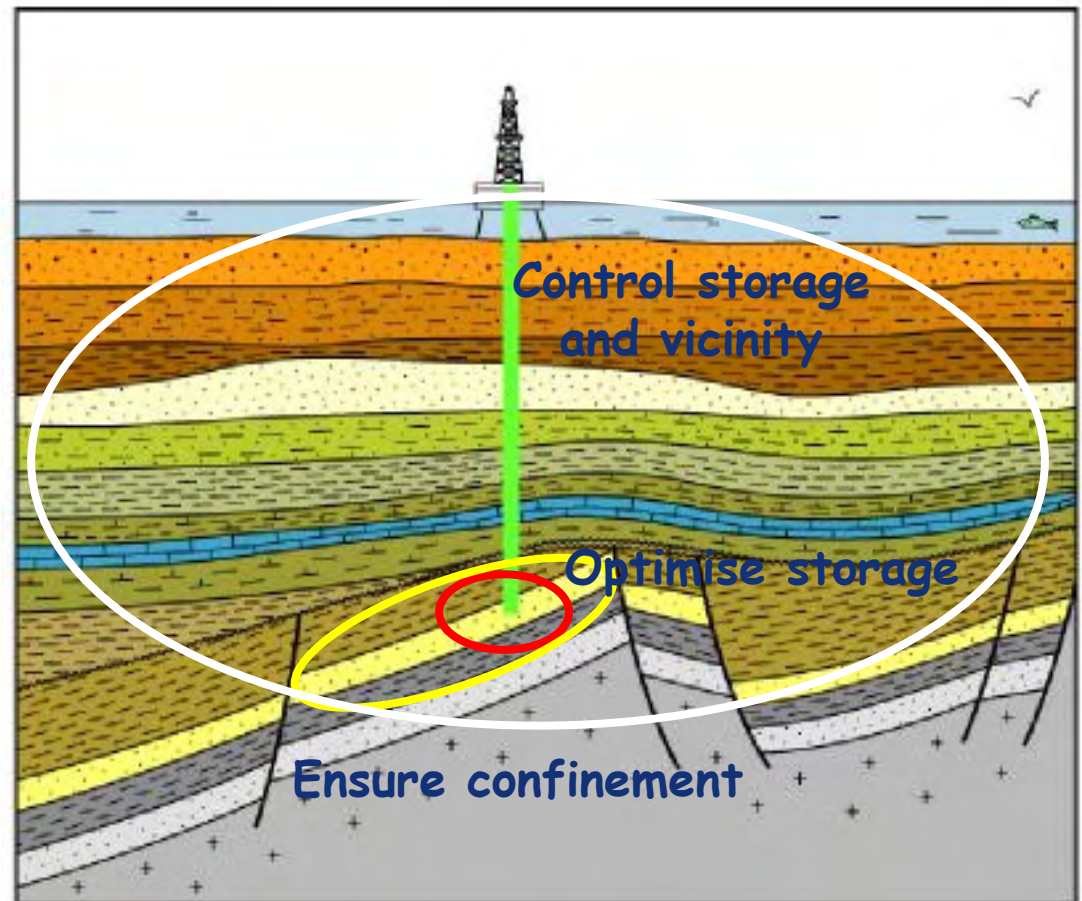
# Agenda

- Introduction
- Site selection and characterization
  - Basic criteria
  - Geological parameters
  - Storage assessment
  - Modelling
  - Geochemical parameters
  - Ranking criteria
  - Conflicts of interests
- Risk assessment
  - Safety criteria
  - Legislation, regulations and guidelines
- Monitoring plan
  - Legislation, safety and operation



# What is to be done when a potential operator or government decides to find and develop a storage site

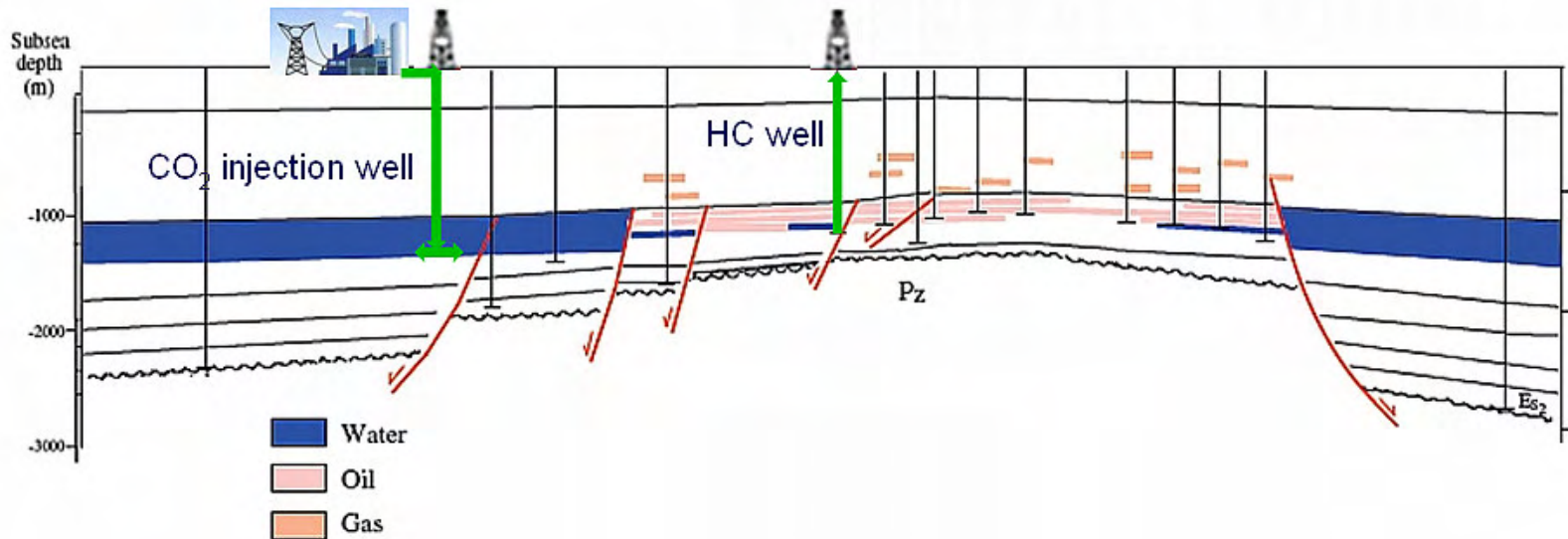
- Site selection
- Characterisation
- Predictive models
- Risk assessment and remediation
- Monitoring (plan)



# Basic site selection criteria

## Sufficient depth and storage capacity

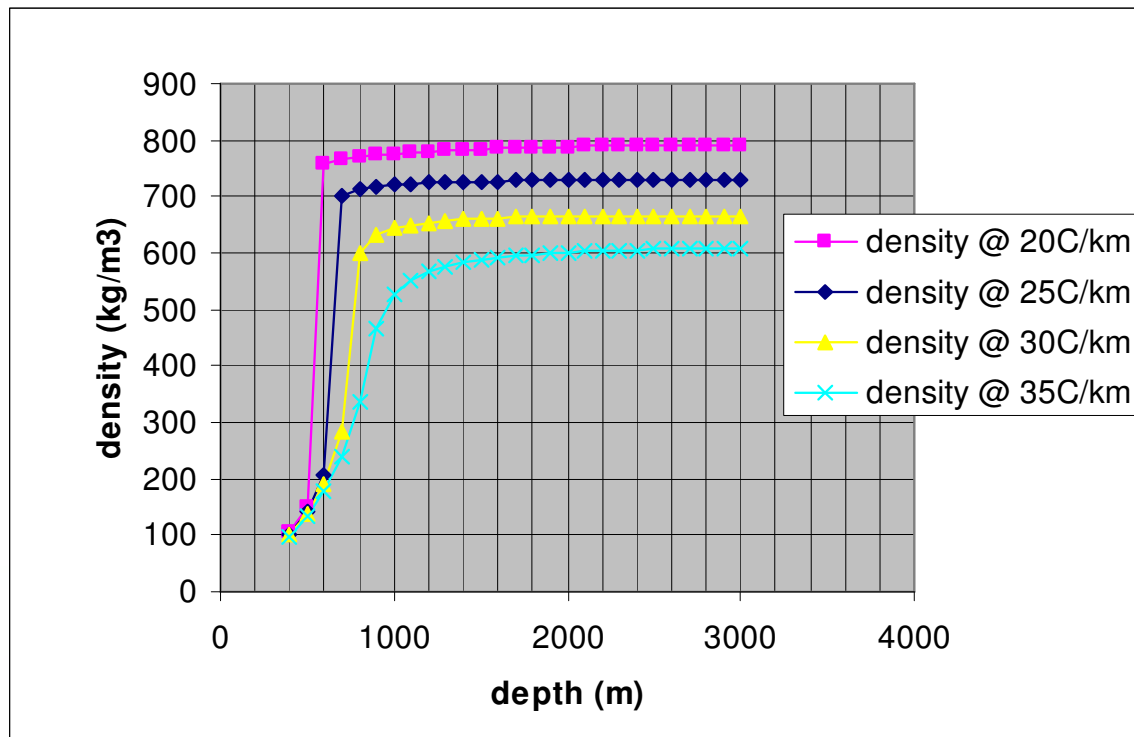
- Below 800 m
- Above 2500-3000 m
- Trap type / areal extent / thickness / complexity
- Storage capacity



# Basic site selection criteria

Sufficient depth and storage capacity

- supercritical CO<sub>2</sub> below 800 m

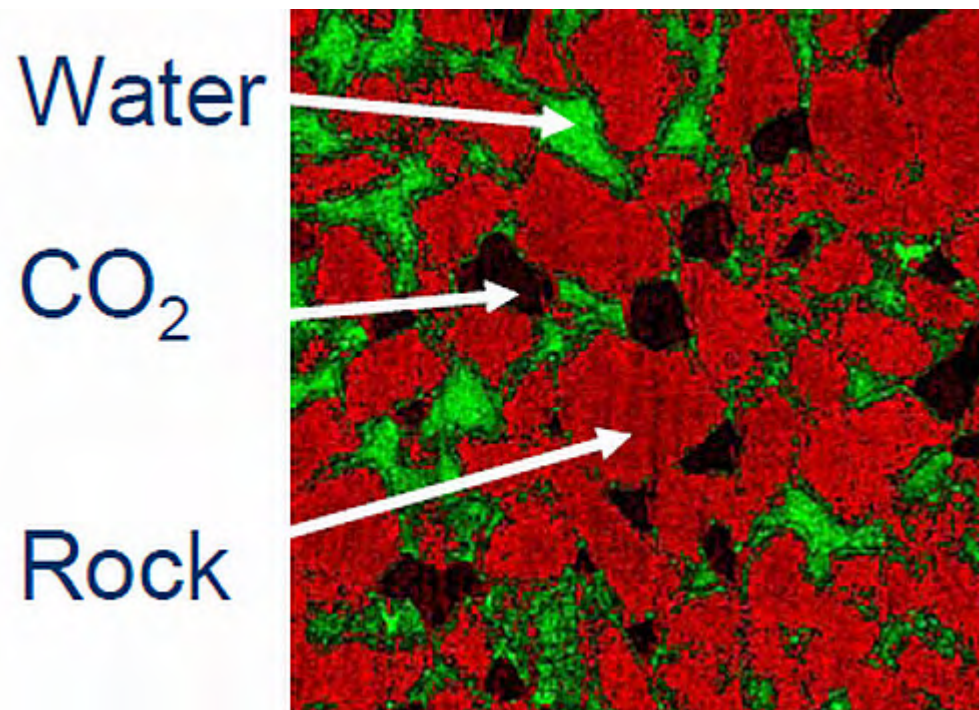




# Basic site selection criteria

## Porosity

- may deteriorate below 2500-3000 m



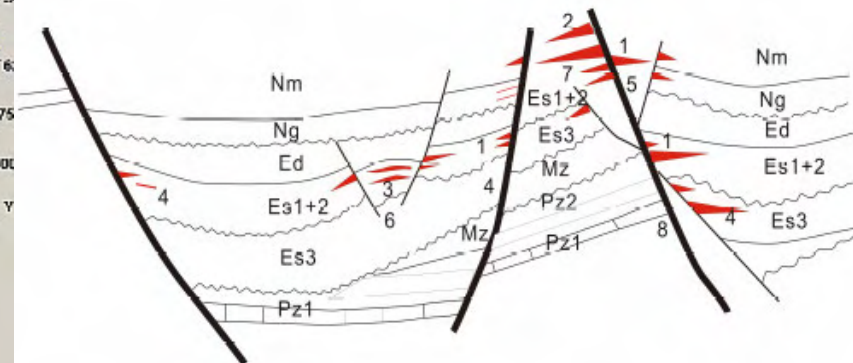
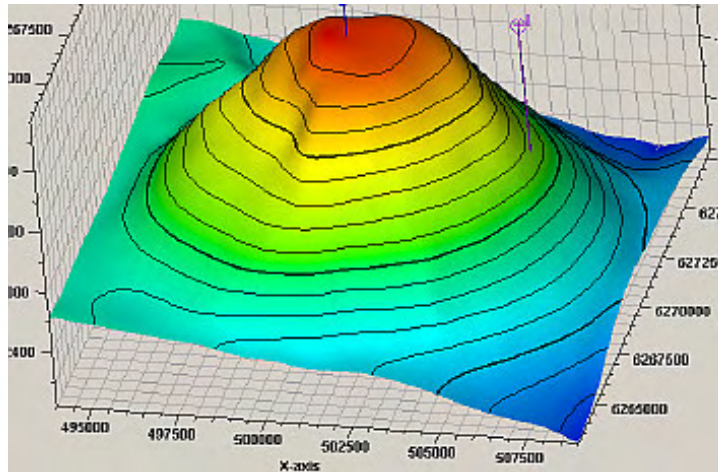
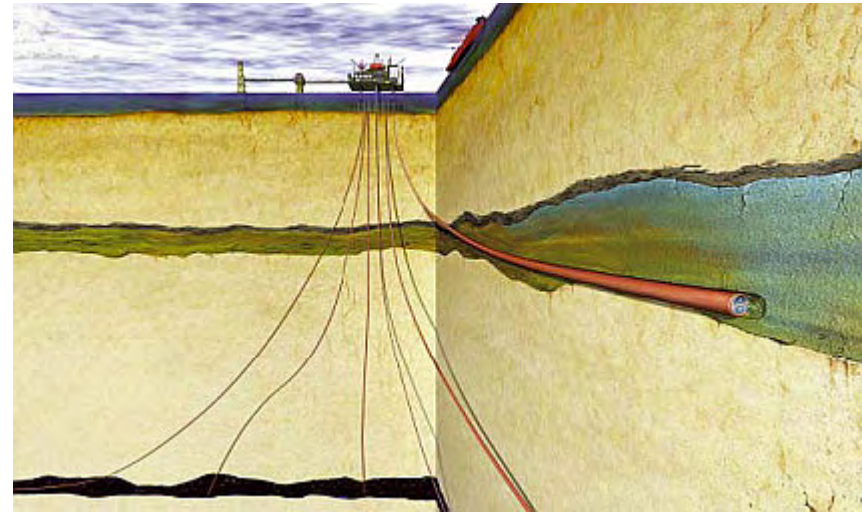
# Geological parameters

- **Trapping mechanisms**
  - Reservoir trap type and size
  - Seal = cap rock
  - Tectonic activity - faults, fractures
- **Reservoir properties**
  - Permeability and porosity
  - Storage capacity (calculations/modelling)
  - Injectivity
  - Mineralogy and geochemistry
    - Types of minerals
    - Interaction of CO<sub>2</sub> with rocks and pore fluids
    - Geochemical simulations

# Trapping mechanisms

## Trap type

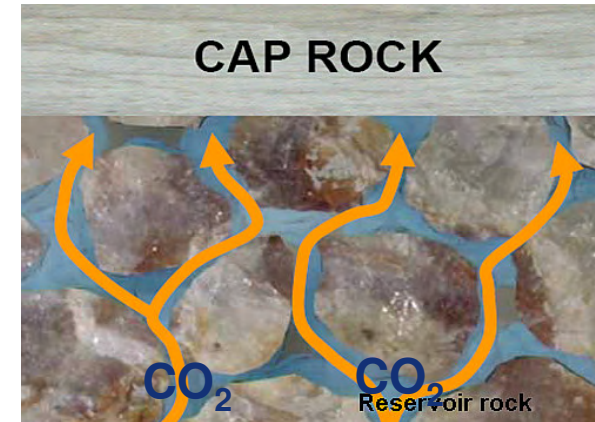
- Areal extent
- Thickness
- Complexity (compartmentalised)





# Buoyancy and trapping

- Seal (cap rock) lithology and permeability
- CO<sub>2</sub> does not mix with water but it dissolves in water
- Faulting, tectonic activity, fracture pressure



# Porosity and permeability

## CO<sub>2</sub> Injection at Sleipner

- 38% porosity and 1000-8000 mD permeability (Ringrose 2009)

## CO<sub>2</sub> Injection at Snøhvit

- permeability c. 350 mD (Ringrose 2009)

## The Ketzin CO<sub>2</sub> Storage Project

- Porosity 23%, Permeability 500-1000 mD (Bernstone 2009)

## The Altmark CO<sub>2</sub> Storage Pilot

- Porosity 4-28%, Permeability 30 mD (Bernstone 2009)

## The Vedsted CO<sub>2</sub> Storage Demo

- Porosity 30%, Permeability 2000 mD (Bernstone 2009)

## The Birkholz/Neutrebbin CO<sub>2</sub> Storage Demo

- Porosity 14-18%, Permeability 450-600 mD (Bernstone 2009)

## In-Salah Gas Project

- Porosity 13-17 %, Permeability 13 mD (Rutqvist et al., 2009)

As a rule of thumb > 200 mD



# Storage capacity calculations

## Methodological resources

### ➤ CSLF Task Force on CO<sub>2</sub> Storage Capacity Estimation

➤ Joule II, GESTCO, Castor, GeoCapacity, COACH and US DOE

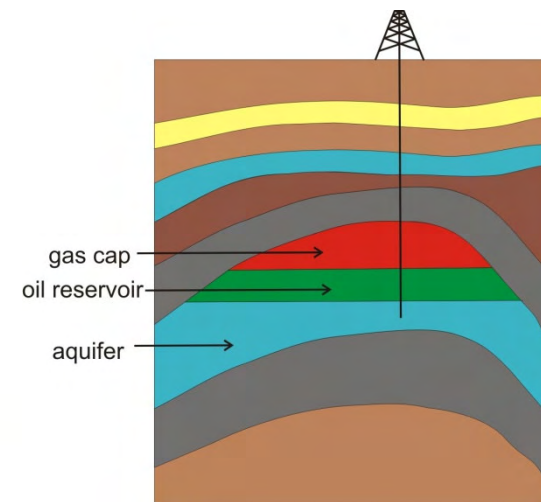
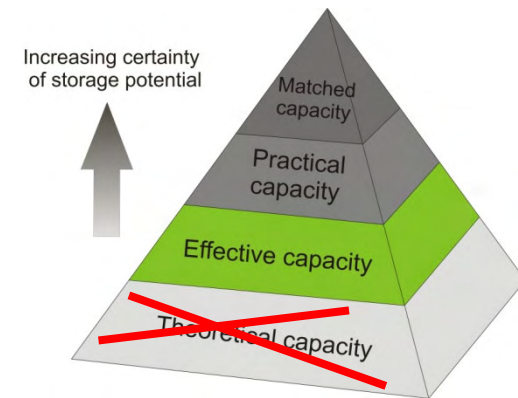
- ❖ Aquifers
- ❖ Hydrocarbon fields
- ❖ Coal beds

Example: Aquifers capacity estimates

$$M_{CO_2} = \rho_{CO_2} \times U_{Rp} \times B \times S_{eff} \Leftrightarrow$$

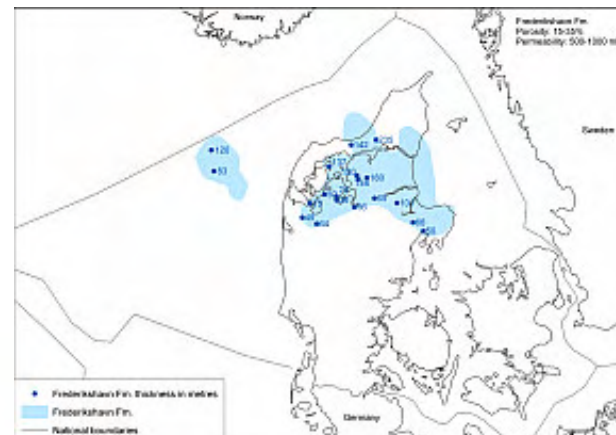
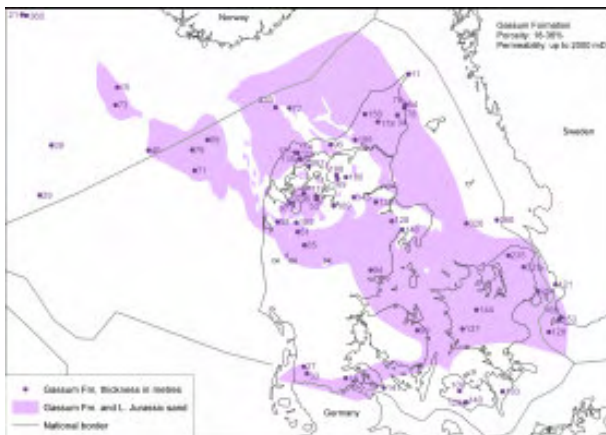
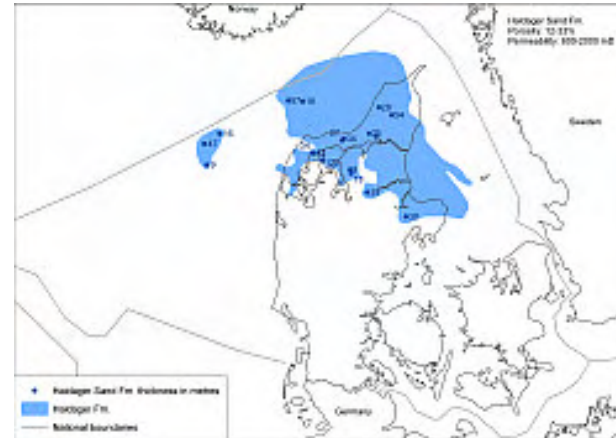
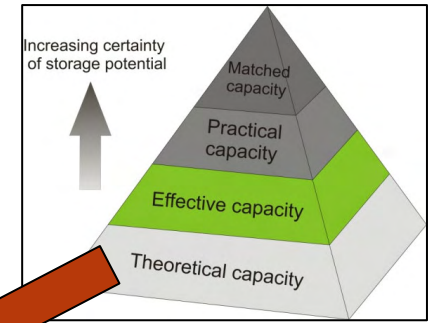
CO<sub>2</sub> storage capacity =

(CO<sub>2</sub> density) × (displaceable volume)



# Theoretical reservoirs within the depth interval 800-2500 m

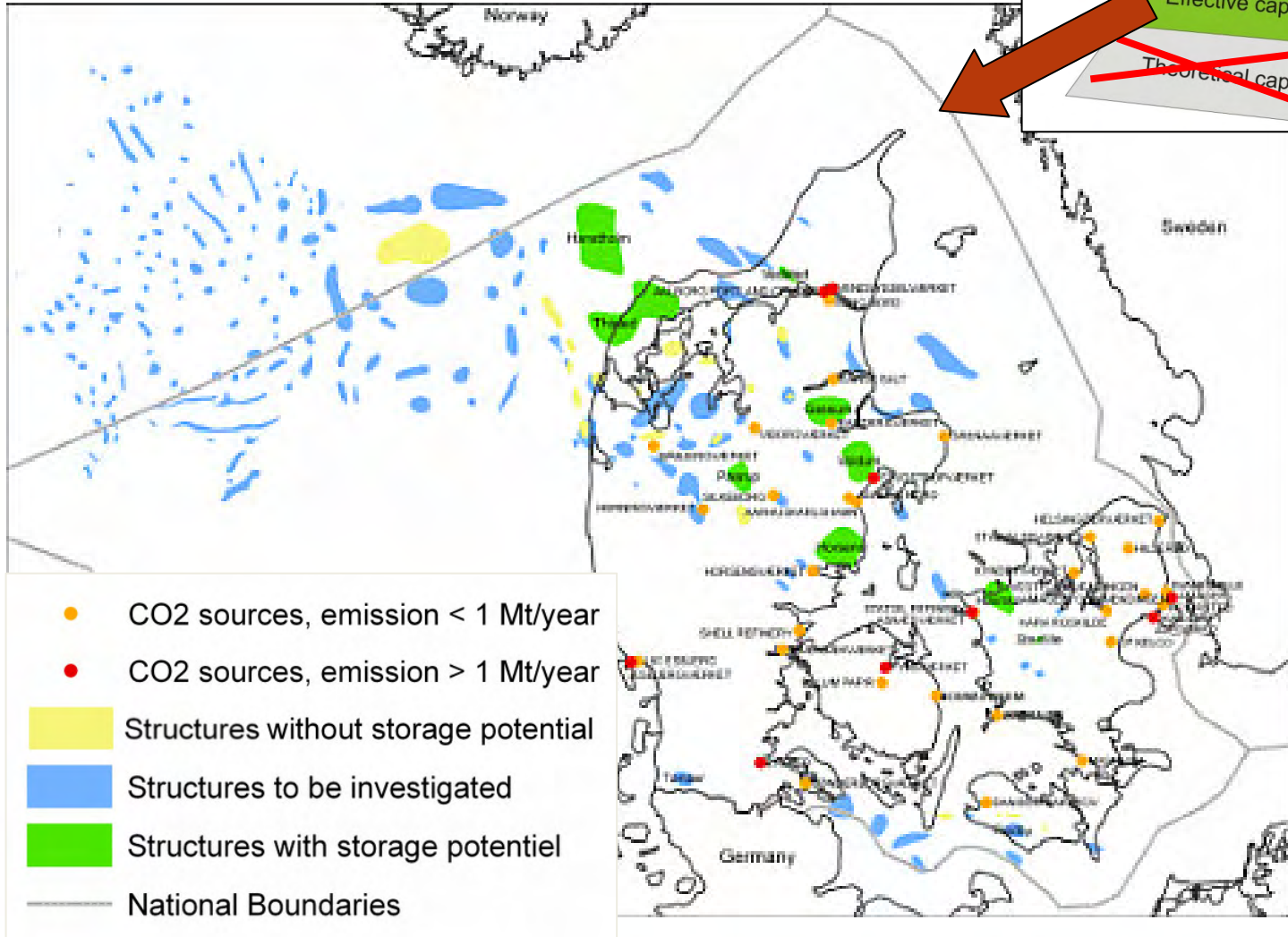
Hole porevolume



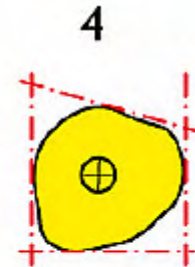
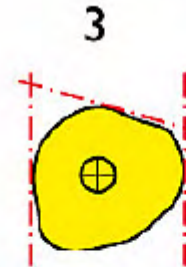
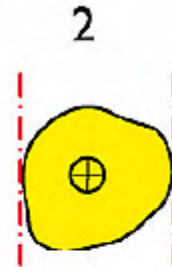
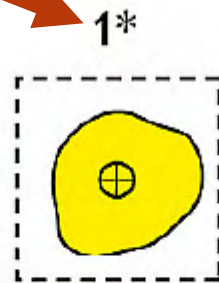
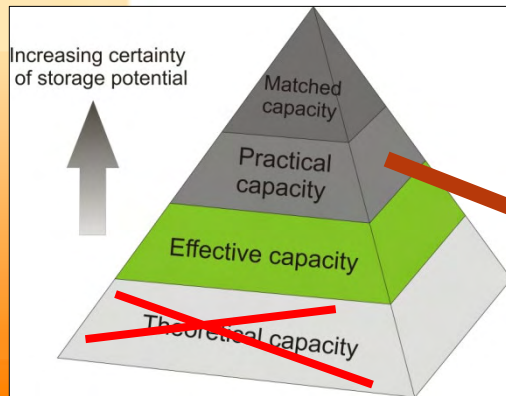


# Identify reservoir potentials

## Geological limits



# Storage coefficient $S_{eff}$ for open and semi-closed aquifers



High quality reservoir

40 %

20 %

10 %

3-5 %

Low quality reservoir

20 %

10 %

5 %

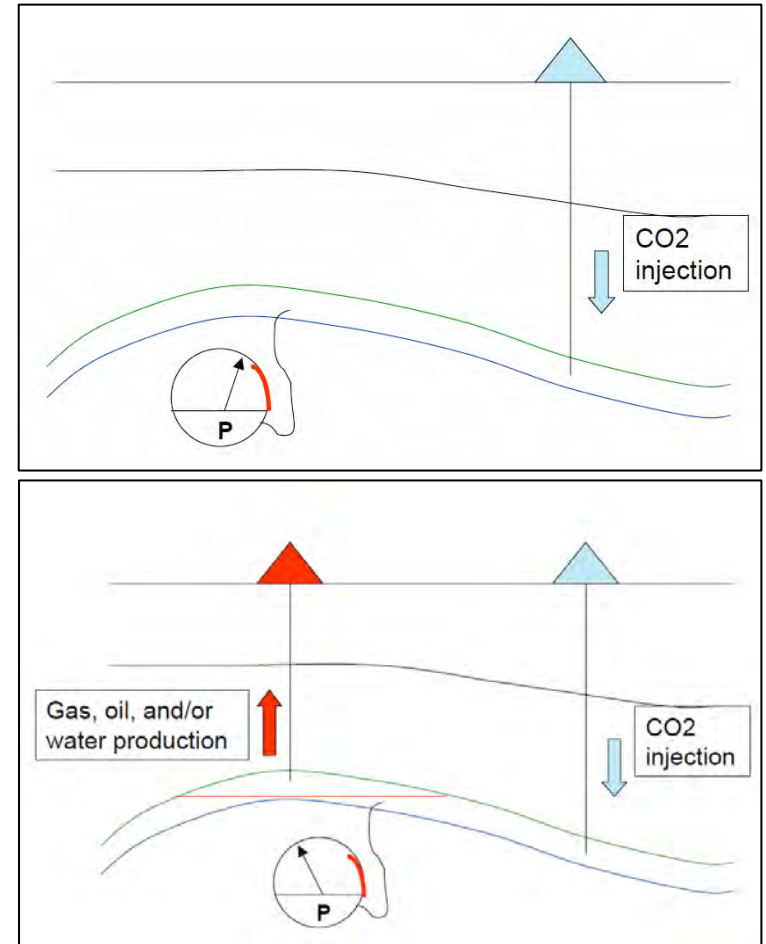
<3 %

\*Volume of bulk reservoir shall be 5-10 times the volume of the reservoir

--- Fault

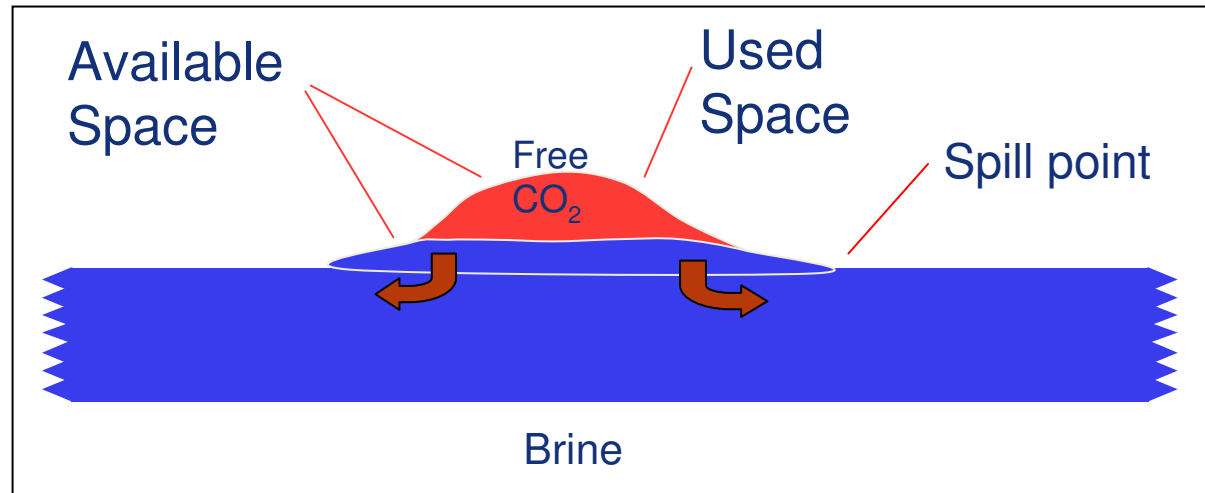
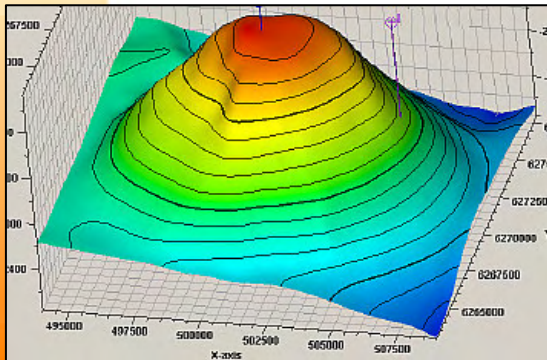
# CCS and EOR

- CCS: Aquifer volume needs to be large to keep pressures reasonable
- EOR: Production keeps pressures reasonable



Storage space is generated by displacing existing fluids and distributing **pressure** increase in surrounding aquifer system

# Model for open aquifers

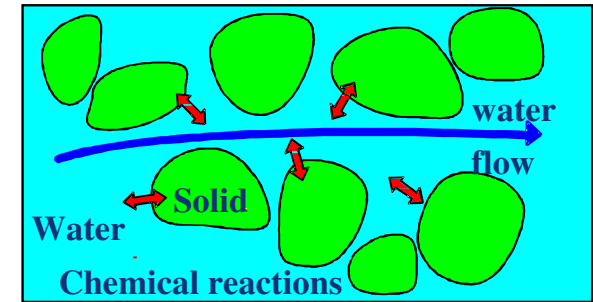


Storage space is generated by displacing existing fluids and distributing **pressure** increase in surrounding aquifer system



# Geochemical parameters

- **CO<sub>2</sub>-water-rock interactions can affect:**
  - CO<sub>2</sub> storage capacity
  - Sealing efficiency
  - Design of the injection/storage operations
  - Safety and stability of storage
- **Highly complex interactions, that can occur in the reservoir, in the cap rock as well as in fractures and well cements**
- **Beneficial or detrimental**
- **Short-term and long term effects**
- **Site specific **modelling** essential to address processes**





# Modelling

Brussels, 23.1.2008  
COM(2008) 18 final  
2008/0015 (COD)

Proposal for a

**DIRECTIVE OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL**  
**on the geological storage of carbon dioxide and amending Council Directives 85/337/EEC, 96/61/EC, Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC and Regulation (EC) No 1013/2006**

## ANNEX I

### CRITERIA FOR THE CHARACTERISATION AND ASSESSMENT OF STORAGE SITES REFERRED TO IN ARTICLE 4

**CRITERIA FOR THE CHARACTERISATION AND ASSESSMENT OF STORAGE SITES REFERRED TO IN ARTICLE 4**

The characterisation and assessment of storage sites referred to in Article 4 shall be carried out in four steps according to the following criteria. Deviation from one or more of these criteria may be possible, provided that the overall assessment to enable the Commission pursuant to Article 4 is not affected.

**Step 1: Data collection**

Sufficient data shall be accumulated to construct a **static and dynamic three-dimensional (3-D) model** for the storage site and storage complex, including the reservoir, and the surrounding area including the hydraulically connected areas. This data shall cover at least the following intrinsic complex characteristics:

- (a) Reservoir geology and geophysics;
- (b) Hydrogeology (in particular structure and porosity of ground water);
- (c) Reservoir engineering (including volumetric calculations of pore volume for CO<sub>2</sub> injection and ultimate storage capacity, pressure and temperature conditions, pressure volume relations as a function of formation integrity, cumulative injection rate and time);
- (d) Geomechanics (deformation rates, mineralisation rates);
- (e) Geostatic stress (pressure, fracture pressure);
- (f) Seismicity (assessment of potential for induced earthquakes);
- (g) Presence and condition of natural and man-made pathways which could provide leakage pathways.

The following characteristics of the complex vicinity shall be documented:

- (a) Domain surrounding the storage complex that may be affected by the storage of CO<sub>2</sub> in the storage site;
- (b) Population distribution in the region overlying the storage site;
- (c) Proximity to suitable natural resources (including in particular Natura 2000 areas pursuant to Directives 79/409/EEC and 92/43/EEC, protected groundwater and hydrocarbon);
- (d) Possible interactions with other activities (e.g. agriculture, production and storage of hydrocarbon, agricultural use of aquifers);
- (e) Proximity to the potential CO<sub>2</sub> source(s) (including estimation of the total potential mass of CO<sub>2</sub> economically available for storage).

**Characterisation of the candidate storage complex including the reservoir and the hydraulically connected areas shall be built using computer reservoir simulation. The static geological and hydrological shall characterise the complex in terms of:**

- (a) Geometrical structure of the physical trap;
  - (b) Geomechanical and geostatic properties of the reservoir;
  - (c) Presence of any faults or fractures and fault fracture sealing;
  - (d) Overburden (reservoir, with pressure and permeability variations);
  - (e) Areal and vertical extent of the storage formation;
  - (f) Pore space volume (including permeability characteristics);
  - (g) Any other relevant characteristics;
- The uncertainty associated with each of the parameters used to build the model shall be assessed by developing a range of scenarios for such parameters and calculating the associated confidence limits. Any uncertainty associated with the model itself shall also be assessed.

**Step 2: Security and secondary characterisation**

Security characterisation shall be based on **dynamic modelling**, comprising a variety of long-term simulations of CO<sub>2</sub> injection into the storage site using the **three-dimensional static geological model** in the completed storage complex, simulated constructed under the following factors shall be considered:

- (a) Injection rates and CO<sub>2</sub> properties;
- (b) The efficacy of capture processes (i.e. the way reactions of the injected CO<sub>2</sub> with in situ minerals feedback in the model);
- (c) Reactive processes (i.e. the way reactions of the injected CO<sub>2</sub> with in situ minerals feedback in the model);
- (d) The reservoir simulation used conditions shall be constrained in order to validate certain parameters;
- (e) Short and long-term simulations (to establish CO<sub>2</sub> fate and behaviour over decades and millennia including the solution velocity of CO<sub>2</sub> in water);
- (f) **Dynamic simulation** shall provide insight to:
- (g) Pressure volume behaviour vs. time of the storage formation;

- (h) CO<sub>2</sub> trapping mechanisms and rates (including spill points and lateral and vertical seals);
- (i) Secondary containment systems in the overall storage complex;
- (j) Storage capacity and pressure gradients in the storage site;
- (k) The risk of breaching the storage formation(s) and caprock;
- (l) The risk of CO<sub>2</sub> entry into the caprock (e.g. due to transience of capillary seal permeability of the caprock or due to caprock degradation);
- (m) The risk of leakage through abandoned or inadequately sealed wells;
- (n) The rate of migration in open-celled reservoirs;
- (o) Fracture sealing rates;
- (p) Changes in geochemistry (fluid chemistry and subsequent reactions (e.g. pH change, mineral formation) and inclusion of reactive modelling to assess above);
- (q) Displacement of formation fluids;

Multiple simulations shall be undertaken to identify the sensitivity of the assessment to key parameters. The simulations shall be based on storage conditions in the **static geological model**, which shall be used to assess the sensitivity of the **dynamic model** to key parameters. The risk assessment shall be based on the **dynamic model**.

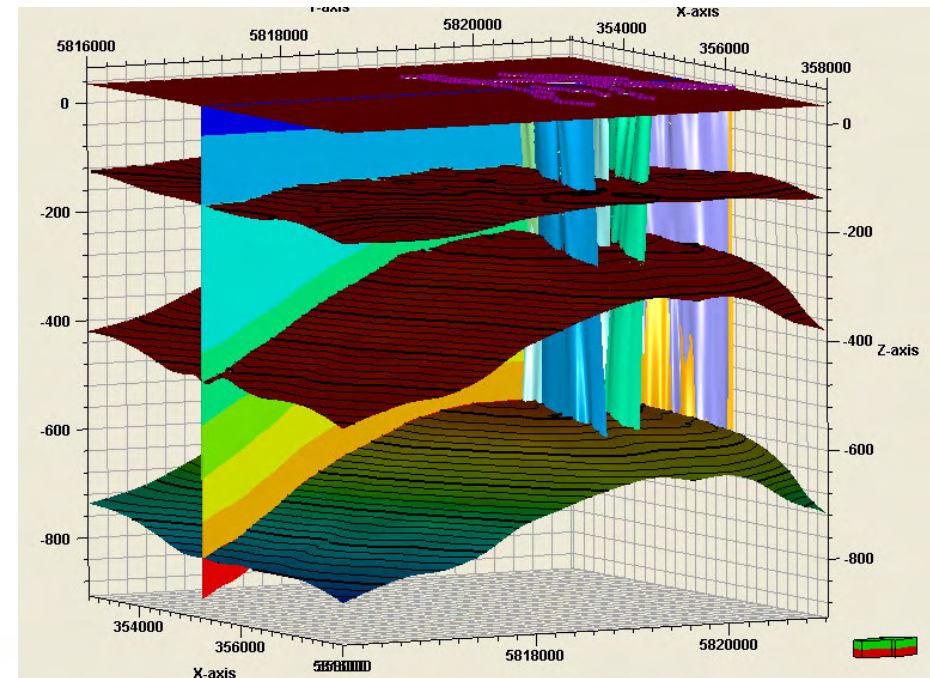
**Step 3: Risk assessment**

Planned characterisation shall be undertaken to identify the sensitivity of the assessment to key parameters. The simulations shall be based on storage conditions in the **static geological model**, which shall be used to assess the sensitivity of the **dynamic model**.

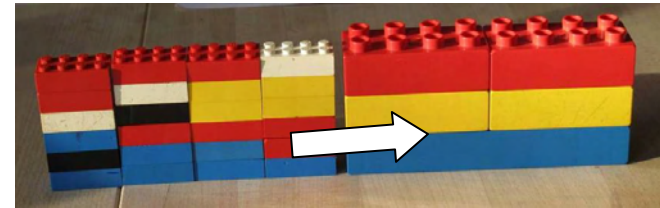
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# What is new for CO<sub>2</sub> site modelling compared to oil/gas

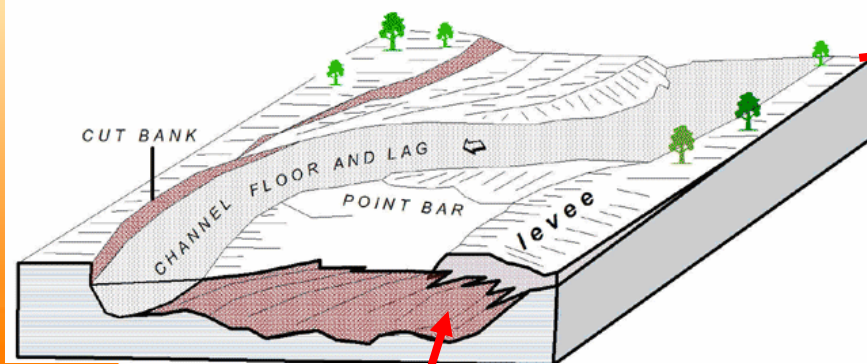
- Few data to start with in saline aquifers
- Longer time perspective for predictions
- Pressure rise from injection in aquifers
- Mobility and gravity
- Trapping mechanisms
- Geochemical reactions and geomechanics
- Continue in symbiosis with monitoring activities



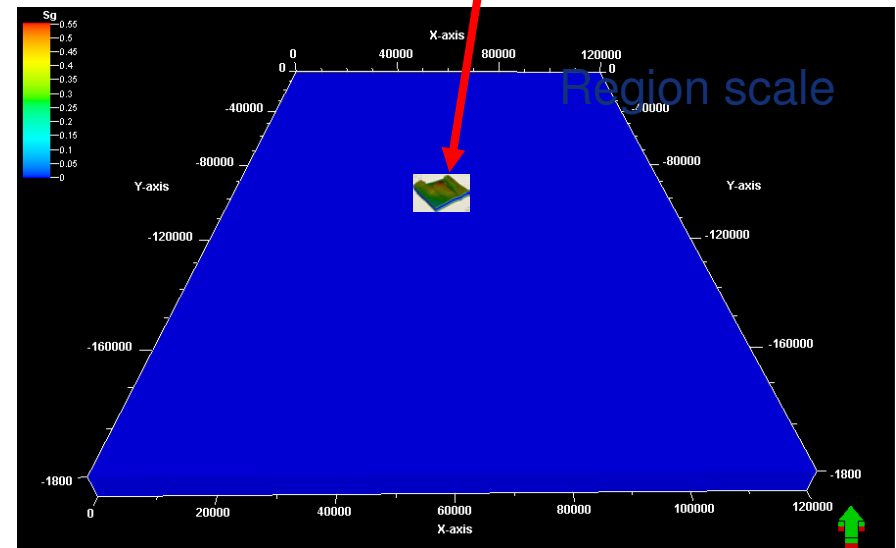
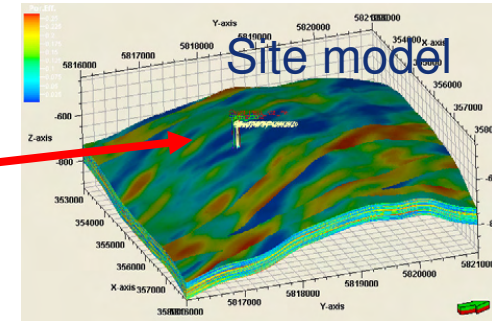
# Building a model



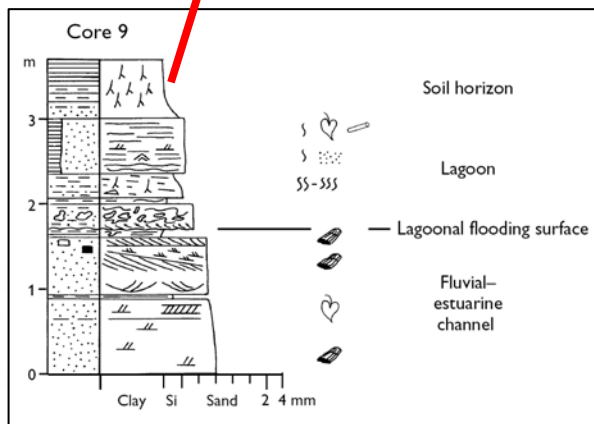
10 m – 100 scale



Meter scale



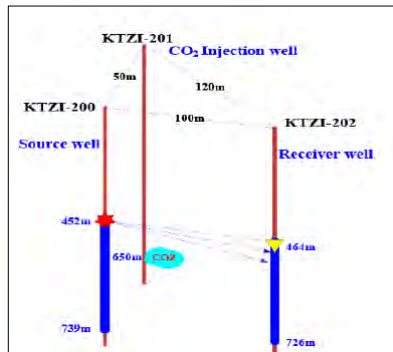
120x190 km region model



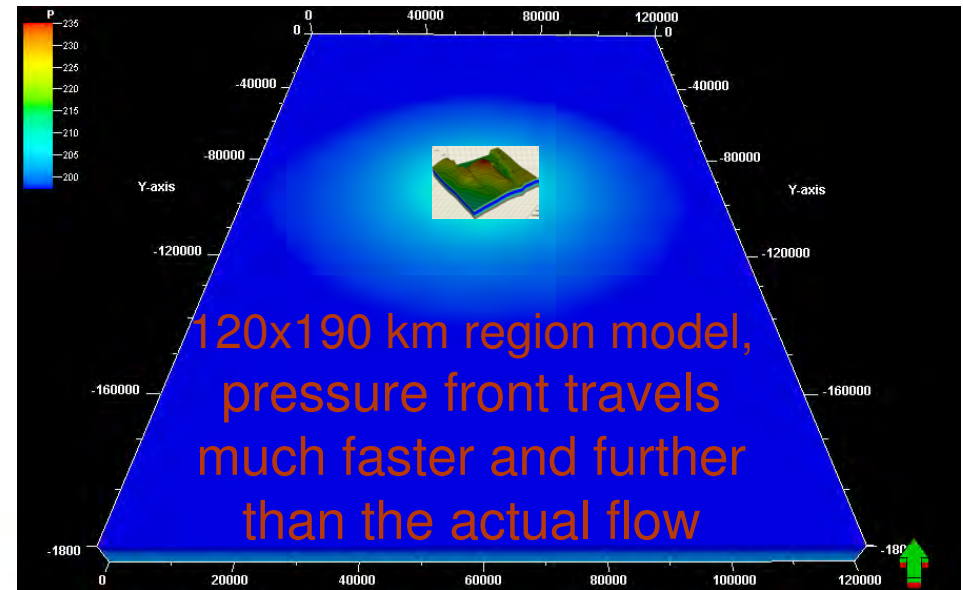
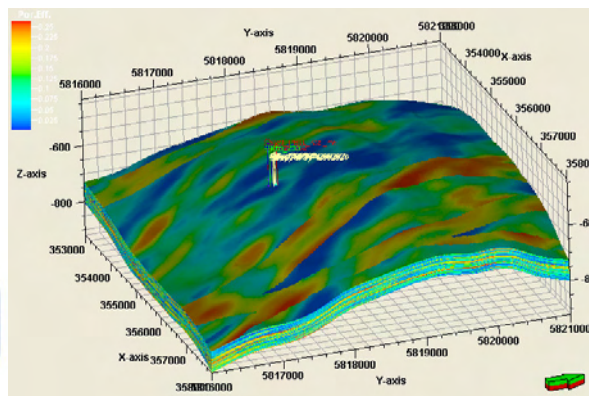


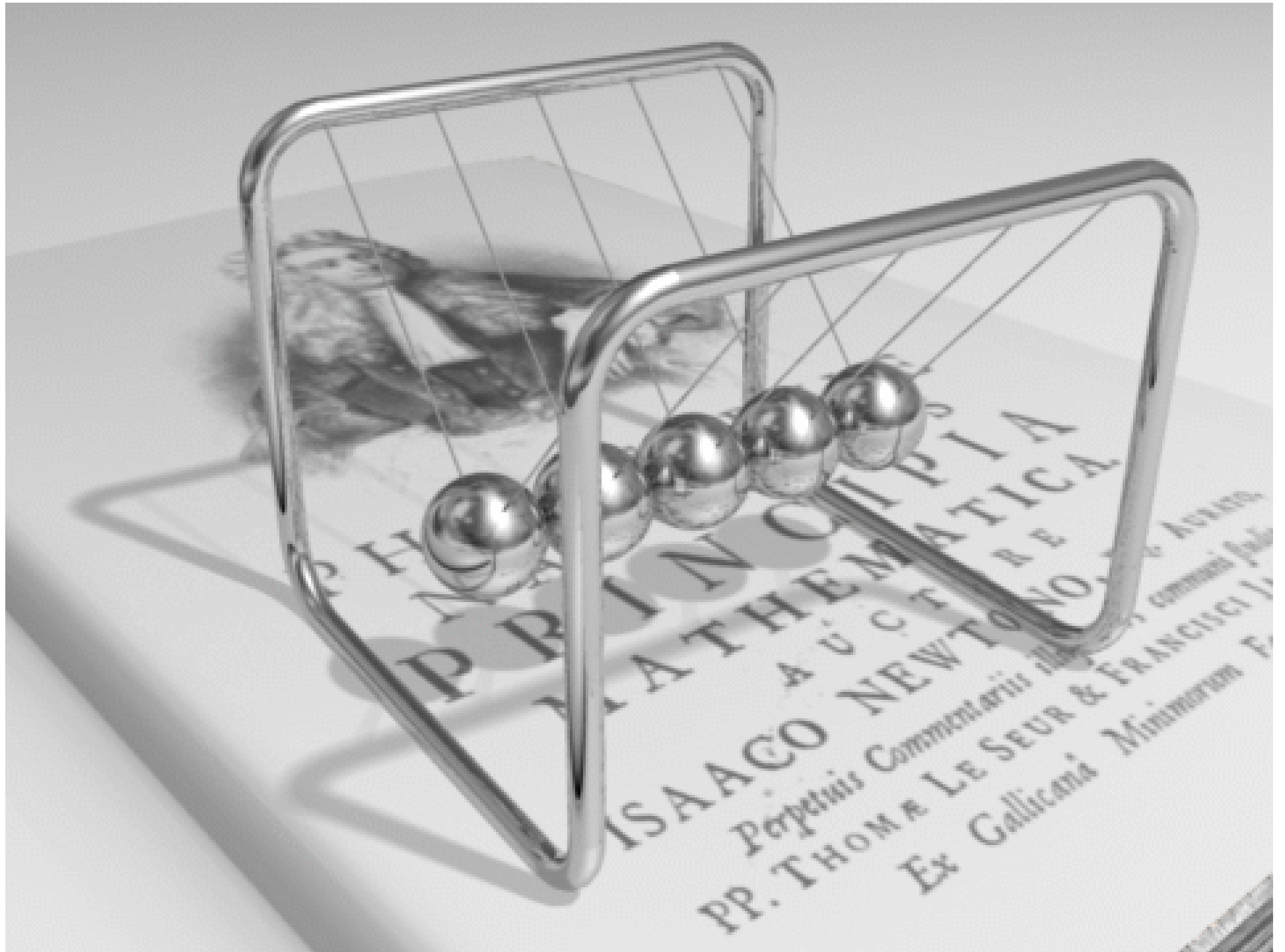
# Large-scale interaction

- Site model looks OK “at a distance”, but what have we missed?
- Test of storage site



➤ Improvement of the geological model based on data from monitoring





# Ranking criteria

## Sufficient depth and storage capacity

- Below 800 m
- Above 2500-3000 m
- Trap type / areal extent / thickness
- Storage capacity

## Sufficient injectivity to be economically viable

- Permeability
- Reservoir lithology
- Heterogeneity of reservoir

## Conflicts of interests

- Other use of area or the underground
  - Recreation, geothermal energy, etc.

# Conflict of interests?

## Explore geothermal heat production with CCS

- When storing large amounts of CO<sub>2</sub> in deep saline aquifers, the fluid pressure of the storage system may increase to levels where production of salt water is desirable (Gorgon42 project in Western Australia)
- With temperatures ranging from 45°C to 90°C, production of water may be used for geothermal heat production
- In short, water production may result in increased storage capacity and benefits for local residents



# Conflict of interests?

- What does it do to house prices
- Not in my backyard (NIMBY)
- Ground water is at risk



# Risk assessment

- Risk assessment and safety criteria are essential all along the lifecycle of storage to ensure that:
  - Health, Safety & Environmental impacts are negligible
  - Impacts to **underground resources** are negligible
- **Regulations** (International, EU level, state, local) set the framework,
- States will define the level of detail of safety requirements (**laws, licences, ..**)
- **Guidelines** already exist or will be available soon
- Economy



## What needs to be characterized considering CO<sub>2</sub> storage

- Trapping mechanisms
  - Reservoirs, trap type
  - Seal = cap rock
  - Depth
- Reservoir properties
  - Permeability and porosity
  - Storage capacity (calculations/modelling)
  - Injectivity
  - Mineralogy and geochemistry
- Stress regime and tectonic activity
  - Faults, fractures

## What needs to be characterized considering CO<sub>2</sub> storage risks

- Trapping mechanisms
  - Reservoirs, trap type
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  - Storage capacity (calculations/modelling)
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  - Mineralogy and geochemistry
- Stress regime and tectonic activity
  - Faults, fractures
- ❖ Economic limitations
- ❖ Hazards
  - ❖ On shore
  - ❖ Off shore
- ❖ Regulatory limitations
- ❖ Public opinion and acceptance



# Monitoring

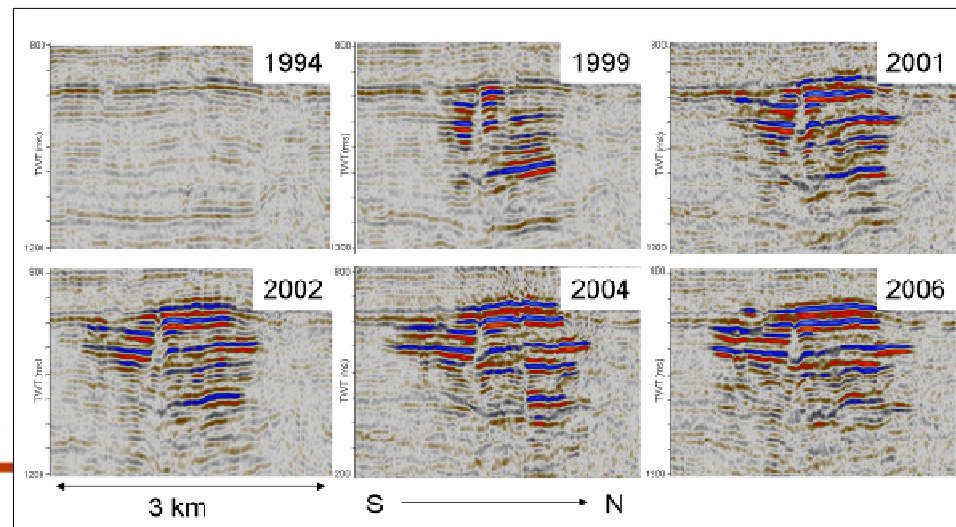
## Most important legislation in the EU around monitoring

- Main focus: safety and environment
- EU directive on storage (2009)
- OSPAR guidelines (2008)

## Safety

## Distribution of CO<sub>2</sub>

## Optimizing storage or EOR production





Thank you for your  
attention



