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Geological storage of CO_2 in saline aquifers

by

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The LRET Research Collegium
Southampton, 11 July – 2 September 2011

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Introduction

Capture and storage of CO_2 provide a way to avoid emitting CO_2 into the atmosphere by capturing CO_2 from major stationary sources, transporting it usually by pipeline, and storing it.

Various CO_2 storage options are considered at present, namely geological, ocean and mineral storage. Among these **geological storage** has achieved most attention and development, reaching a stage at which large deployments are foreseeable.

(Source: Schiermeier, 2006)

Introduction

Content:

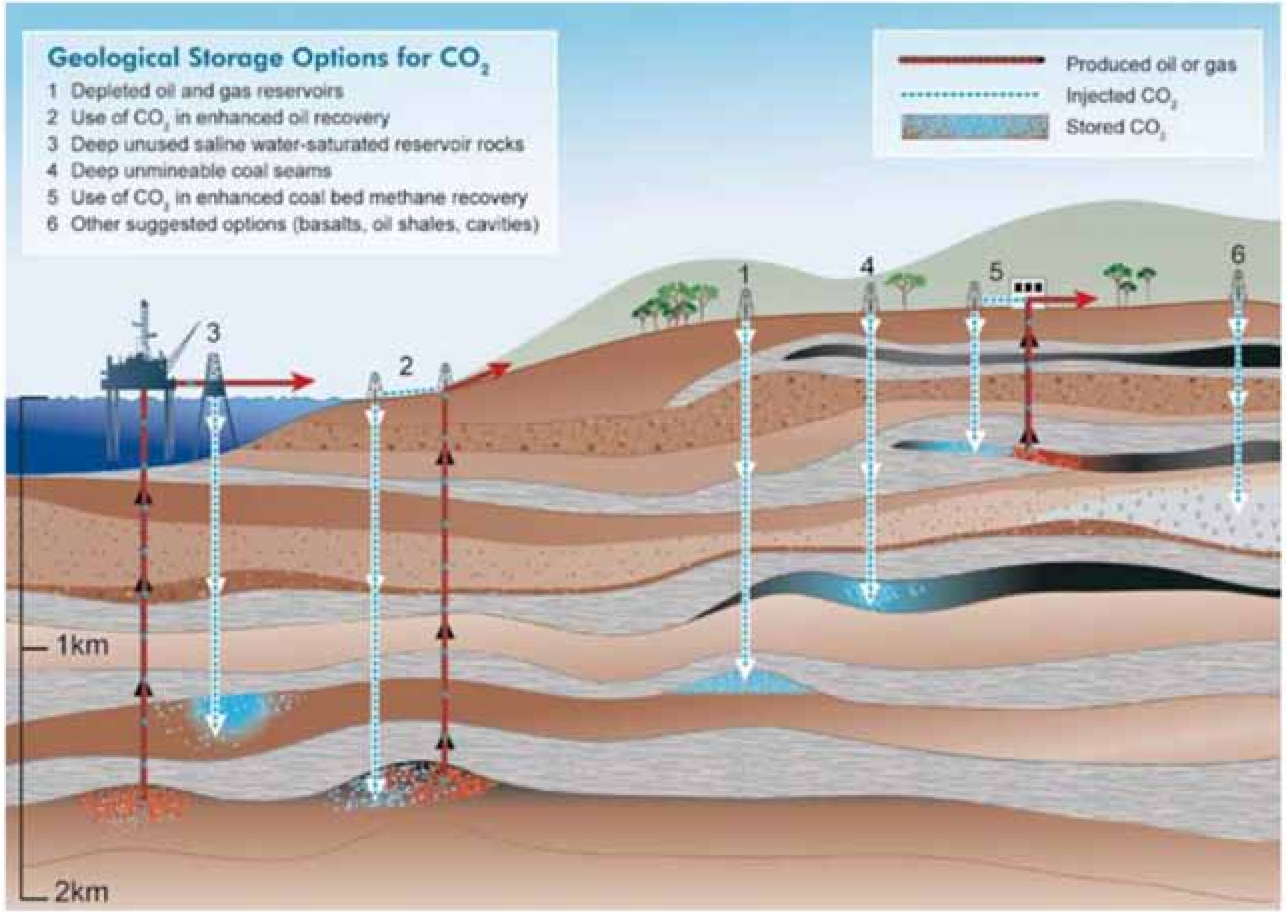
- Storage mechanisms and security
- Storage formations and capacity
- Characterization and performance prediction
- Monitoring and verification
- Risk management
- Legal issues
- Summary and conclusions

The main source of information:

IPCC, 2005: **IPCC Special Report on Carbon Dioxide Capture and Storage**. Prepared by Working Group III of the Intergovernmental Panel on Climate Change [Metz, B., O. Davidson, H. C. de Coninck, M. Loos, and L. A. Meyer (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 442 pp.

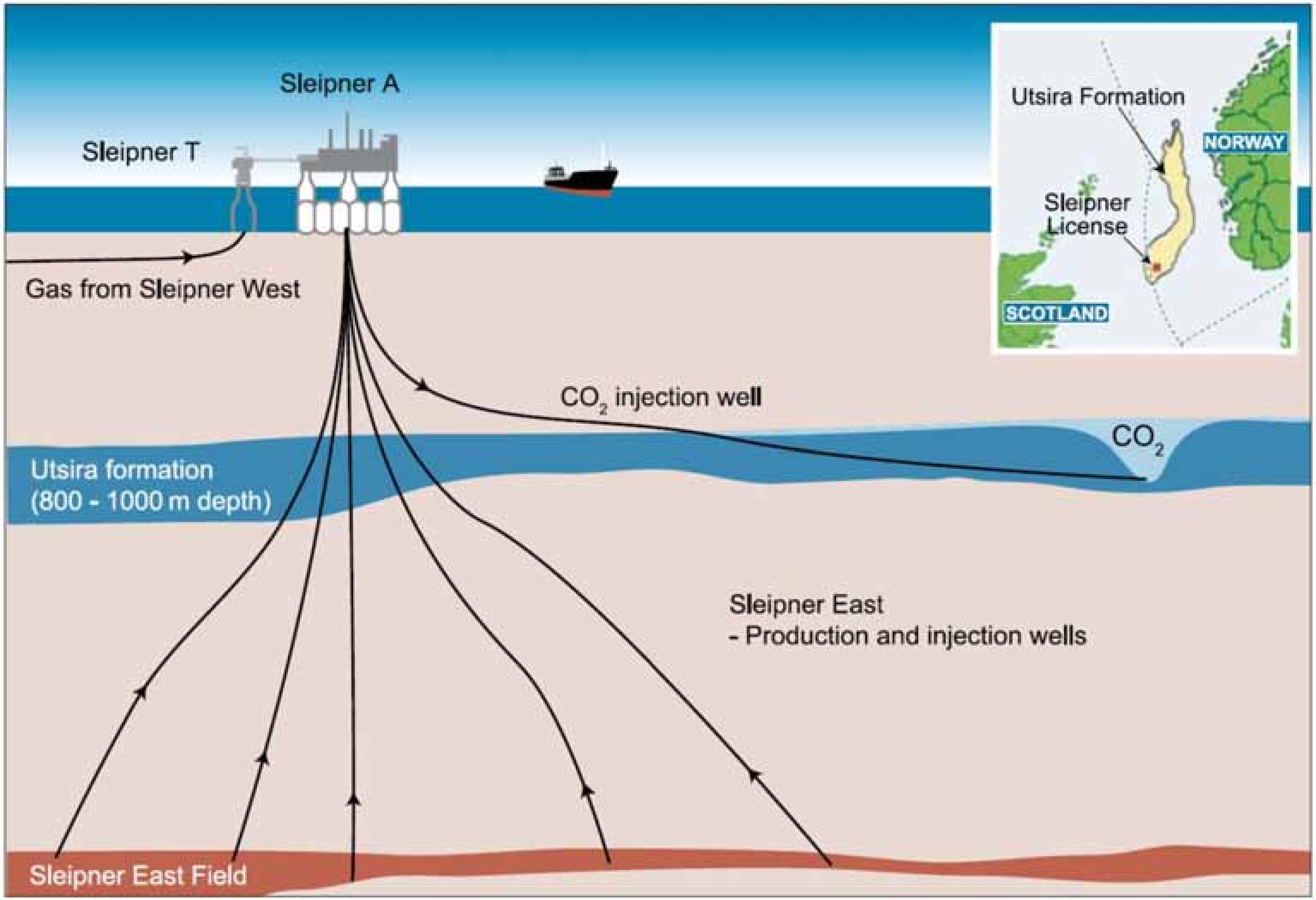
Introduction

Options for geological storage (Source: Cook, 1999)

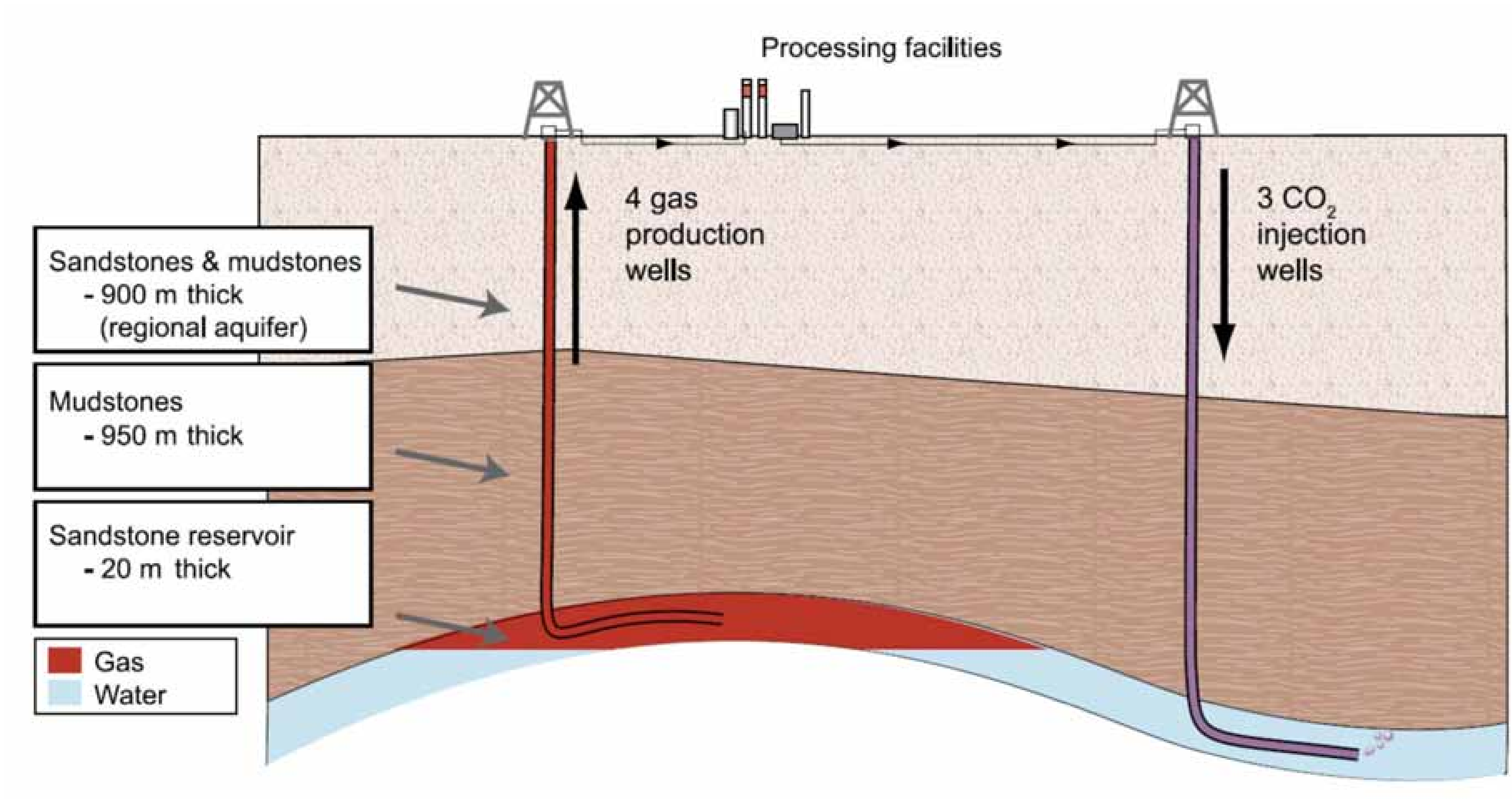


Numerous CO_2 storage projects already exist and are planned in Algeria, Canada, China, Japan, Netherlands, Norway, UK, USA, etc.

Sleipner Project, Norway (Source: IPPC, 2005)



In Shalah Gas project (Source: IPPC, 2005)



- **Main CO2 Storage Pilot/Demo**

  Starting operation

  – **Shenhua 100,000 t/a CCS demonstration, Inner Mongolia**

- **Features:**

  Technologies: CO2 chemical source capture + saline aquifer storage

  Injection scale: 10,000-100,000 tons per year

  Injection life: for Phase I, 3 years

  Target Layer: Deep saline aquifers

  Expected Depth: 1000-2500 m

  Number of wells: 1 injection well, 2 monitoring well

  Implementation Period: On-site injection started in 2010

  CO2 Source: Captured from coal liquefaction plant

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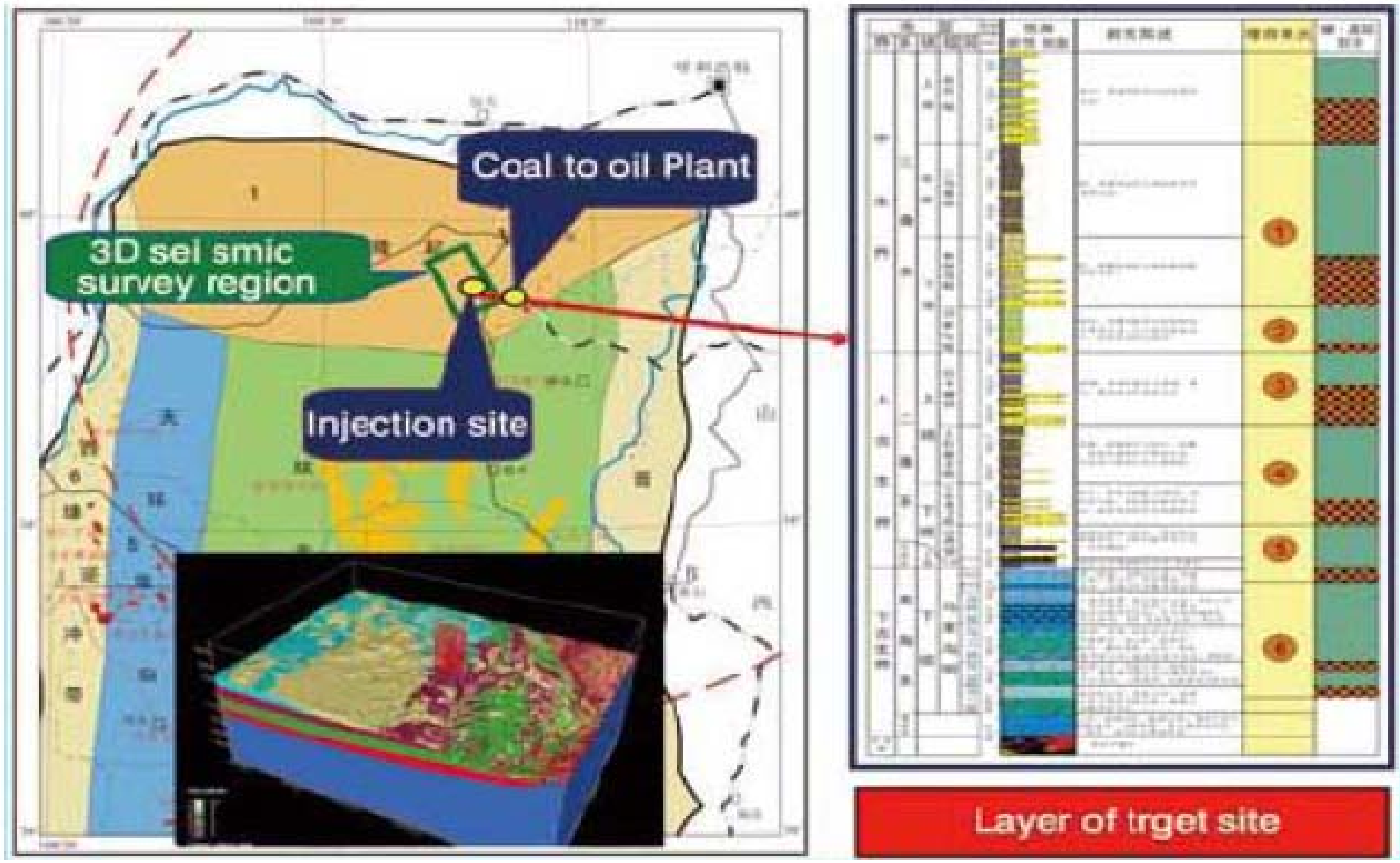
Shenhua 100,000 t/a CCS demonstration site and site analysis



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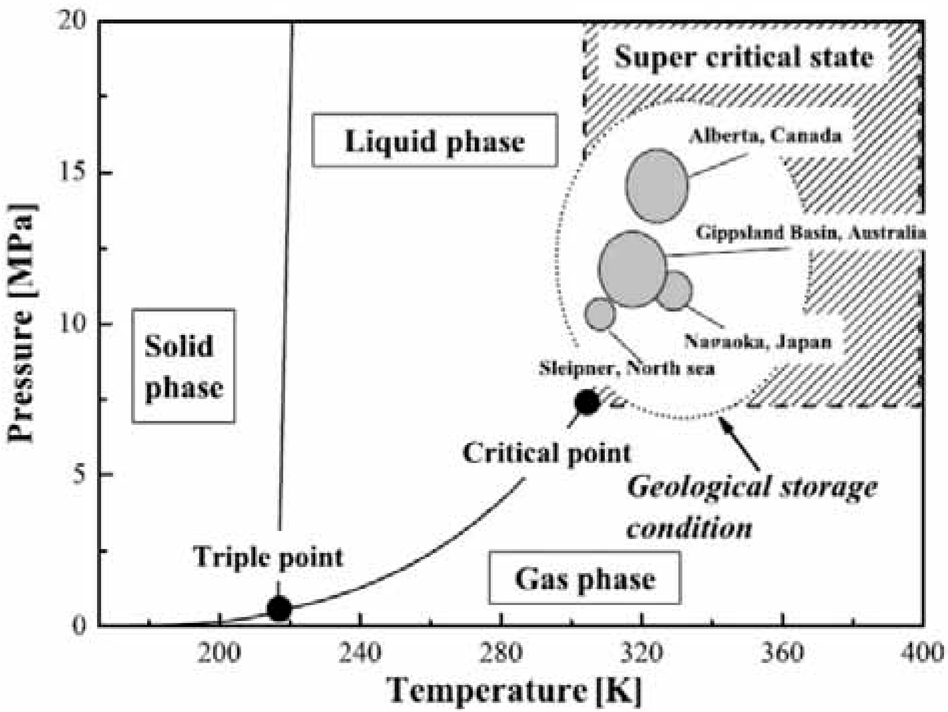
Storage mechanisms and security

Injection of CO_2 into deep geological formations is achieved by pumping it down into a well.

It is typically in super-critical state.



Source: Sasaki et al. (2008)

Storage mechanisms and security

Injection of CO_2 into deep geological formations is achieved by pumping fluids down into a well.

Transport mechanisms in the subsurface:

- **Advection** in response to pressure gradients due to injection or to natural pressure gradients
- **Buoyancy** due to density difference between CO_2 and formation fluid
- Molecular **diffusion**
- **Dispersion** and fingering due to formation heterogeneities and mobility contrast between CO_2 and formation fluid
- **Dissolution** into formation fluid
- **Mineralisation**
- Pore space trapping (**residual trapping**)
- **Adsorption** of CO_2 onto organic material

Storage mechanisms and security

Experimental investigation of CO_2 migration in porous media

Courtesy of Profs Pei-Xue Jang and Ruina Xu, Tsinghua University, Beijing

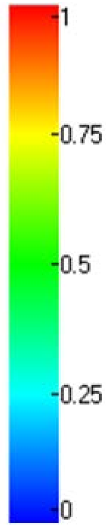
Parameter of Core

Berea Stone

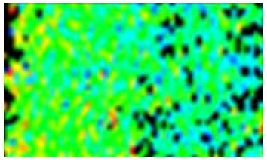
- **Diameter: 24.73mm**
- **Length: 50mm**
- **Porosity: 22.1%**
- **Permeability: 650mD**

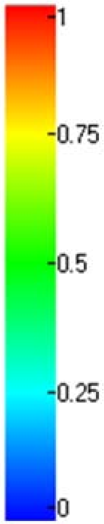
NMR images

Courtesy of Profs Pei-Xue Jang and Ruina Xu, Tsinghua University, Beijing

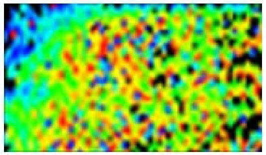


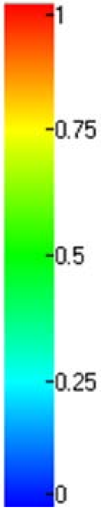
Saturated Water



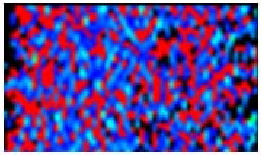


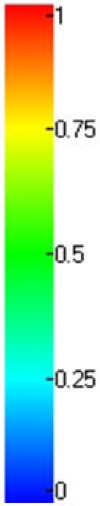
Irreducible Water





CO_2:H_2O=1:1



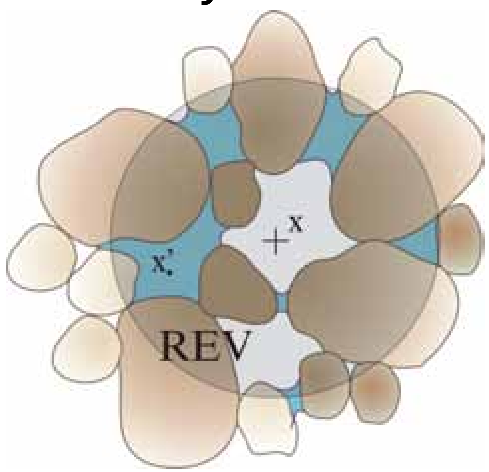


CO_2:H_2O=1:3

Storage mechanisms and security

Simulation models can be used to predict migration of CO_2.

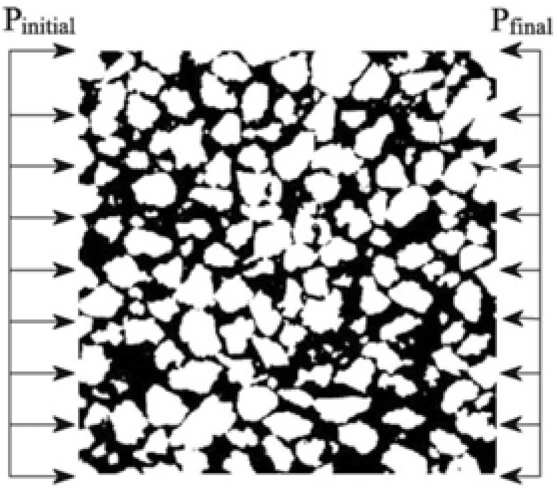
Pore scale – usually research



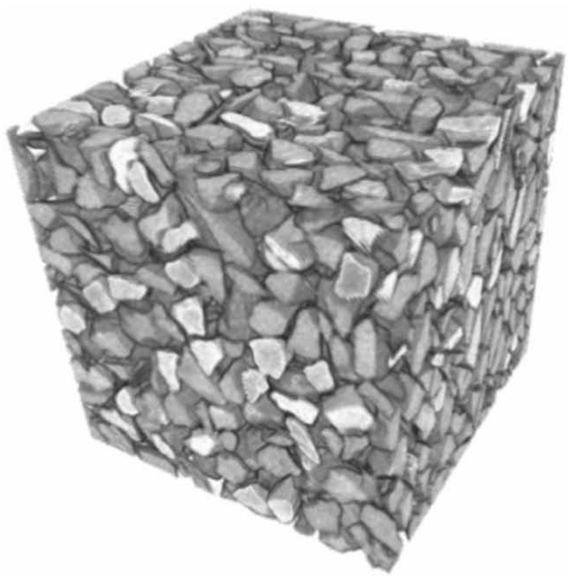
Aquifer (reservoir) scale – real world engineering problems or research Available commercial simulators: ECLIPSE, TOUGH, NUFT, MOFAT etc.

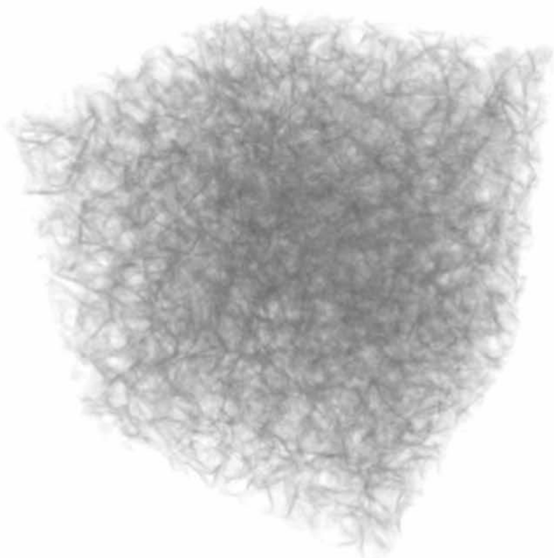
Storage mechanisms and security

Input data for pore scale models:
- Pore geometry
- Initial and boundary conditions



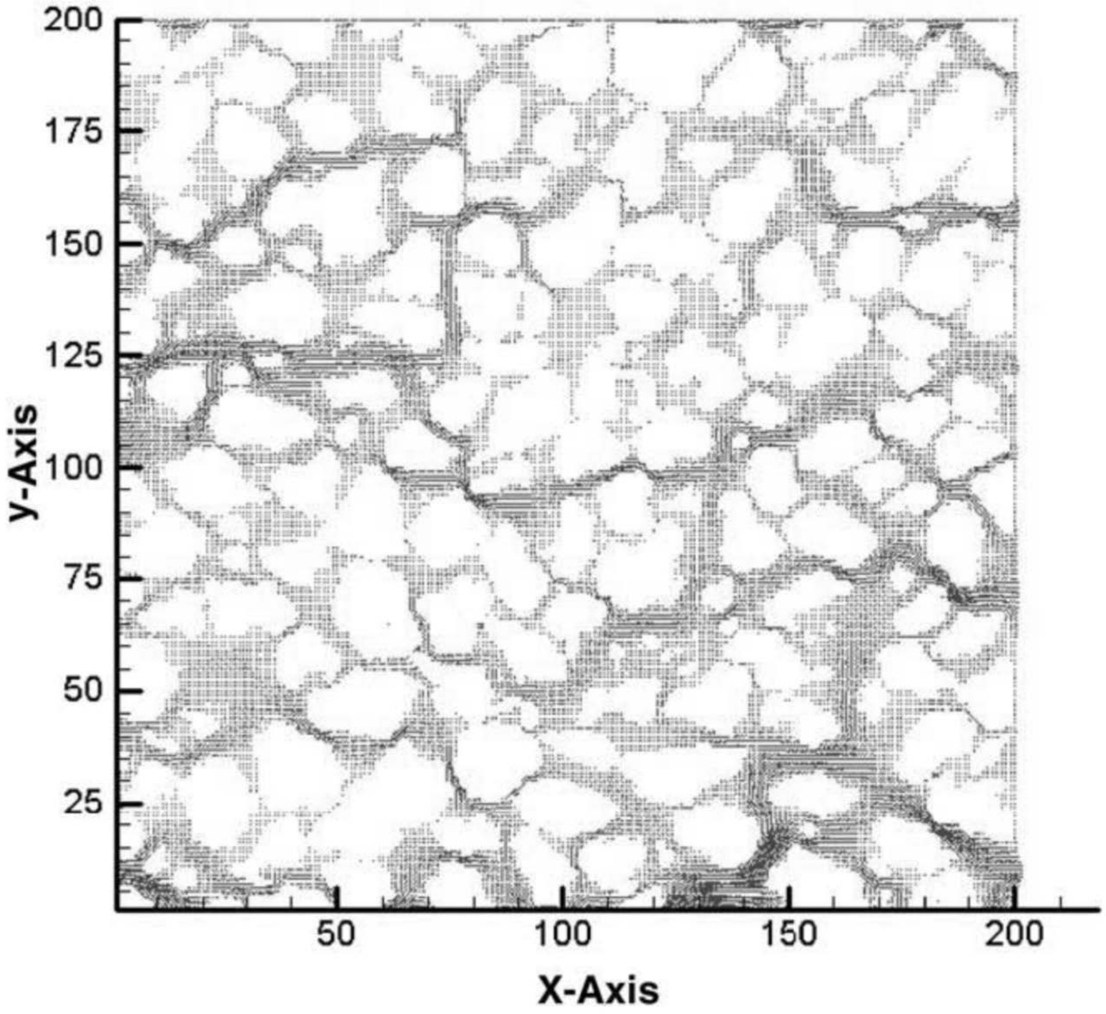
(Source: Tashman et al. 2003)





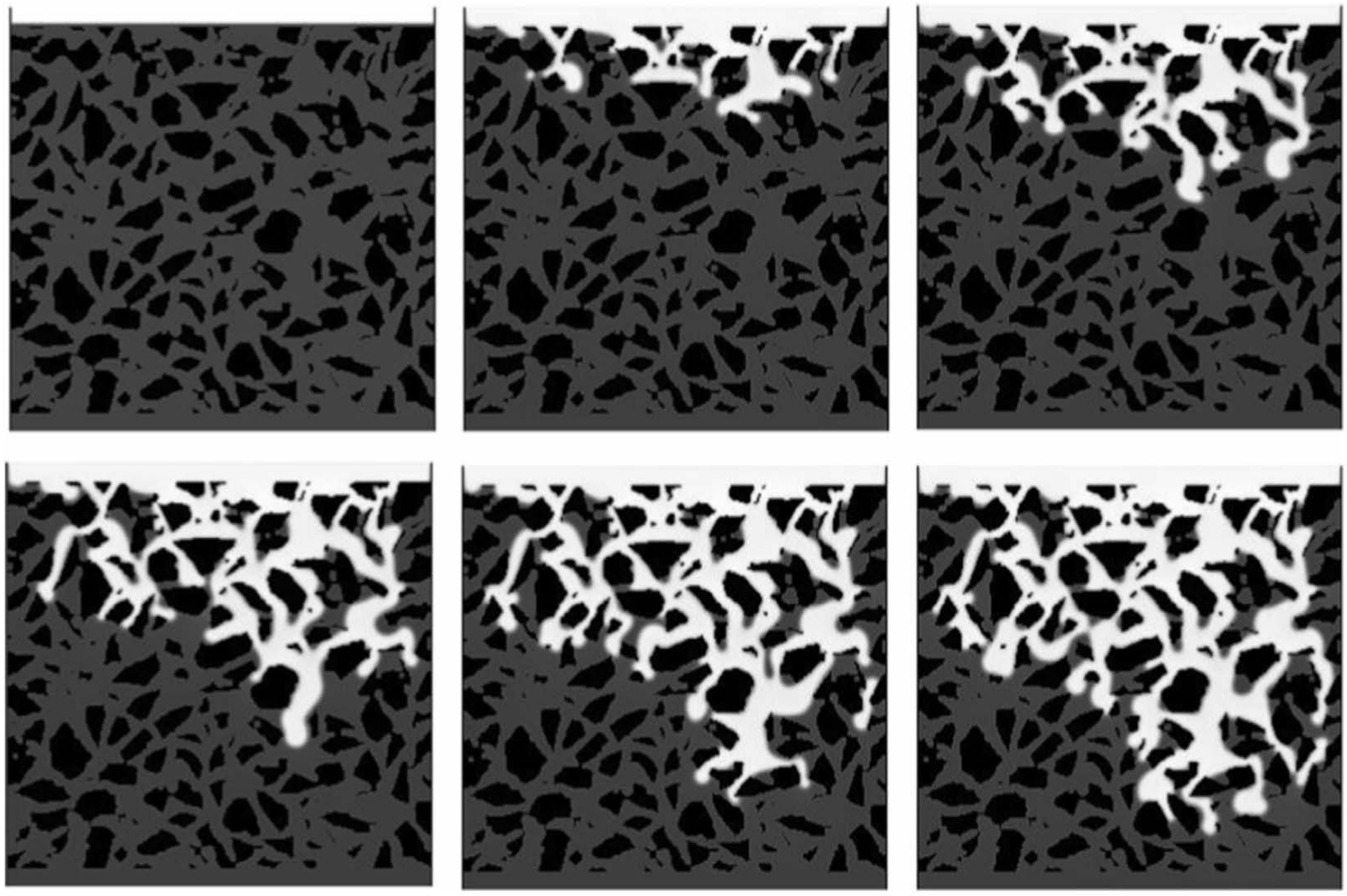
(Source: Lin et al. 2010)

Simulation of fluid flow in Ottawa sand



(Source: Tashman et al. 2003)

Simulation of two-phase flow in a packed bed of sand particles.

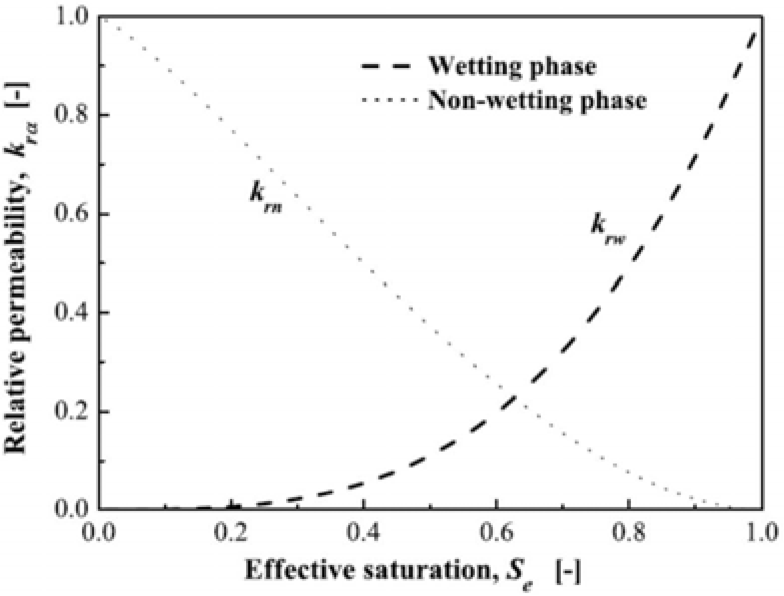


(Source: Lin et al. 2010)

Storage mechanisms and security

Input data for aquifer scale models

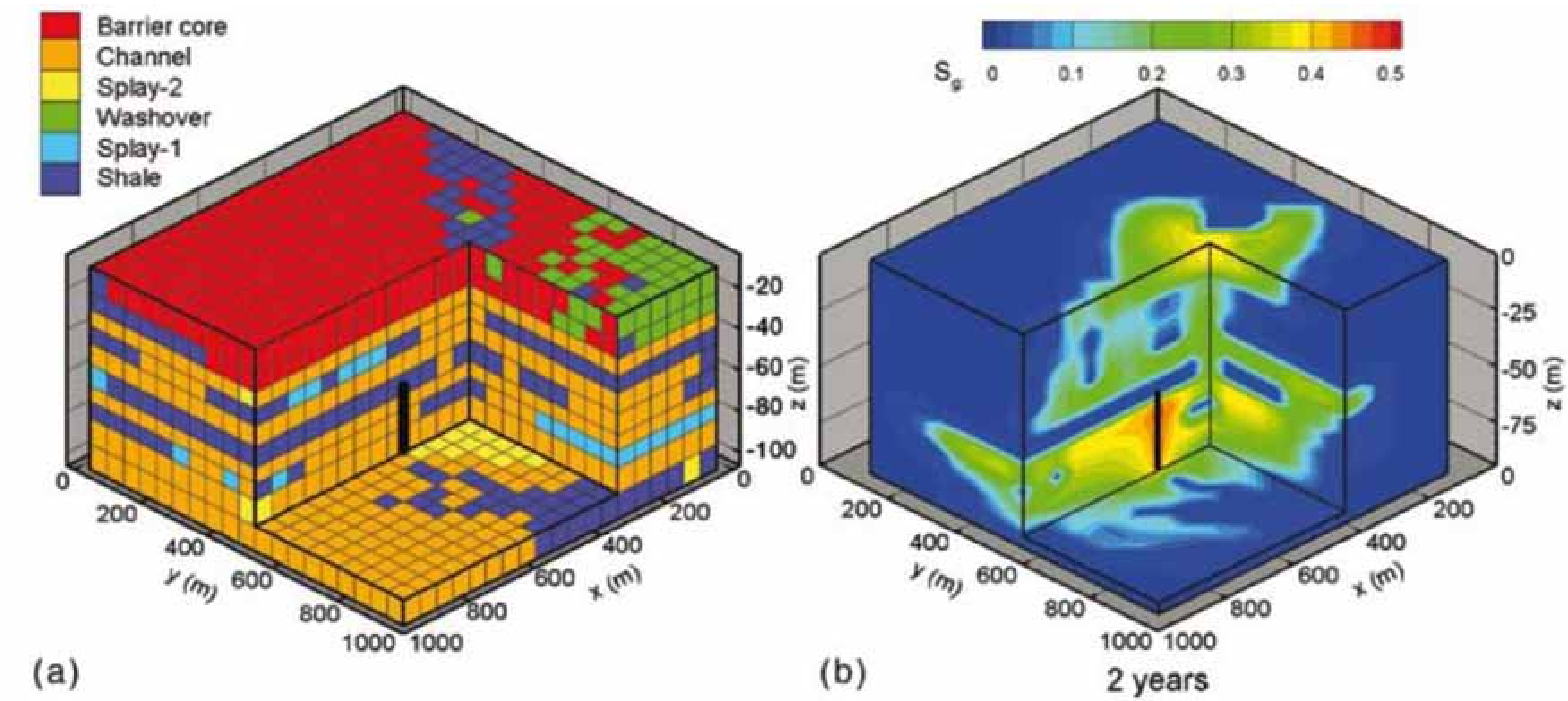
- Saturated permeability for each phase
- Relative permeability curves
- Porosity
- Simulation domain
- Initial and boundary conditions



(Source: Sasaki et al. 2008)

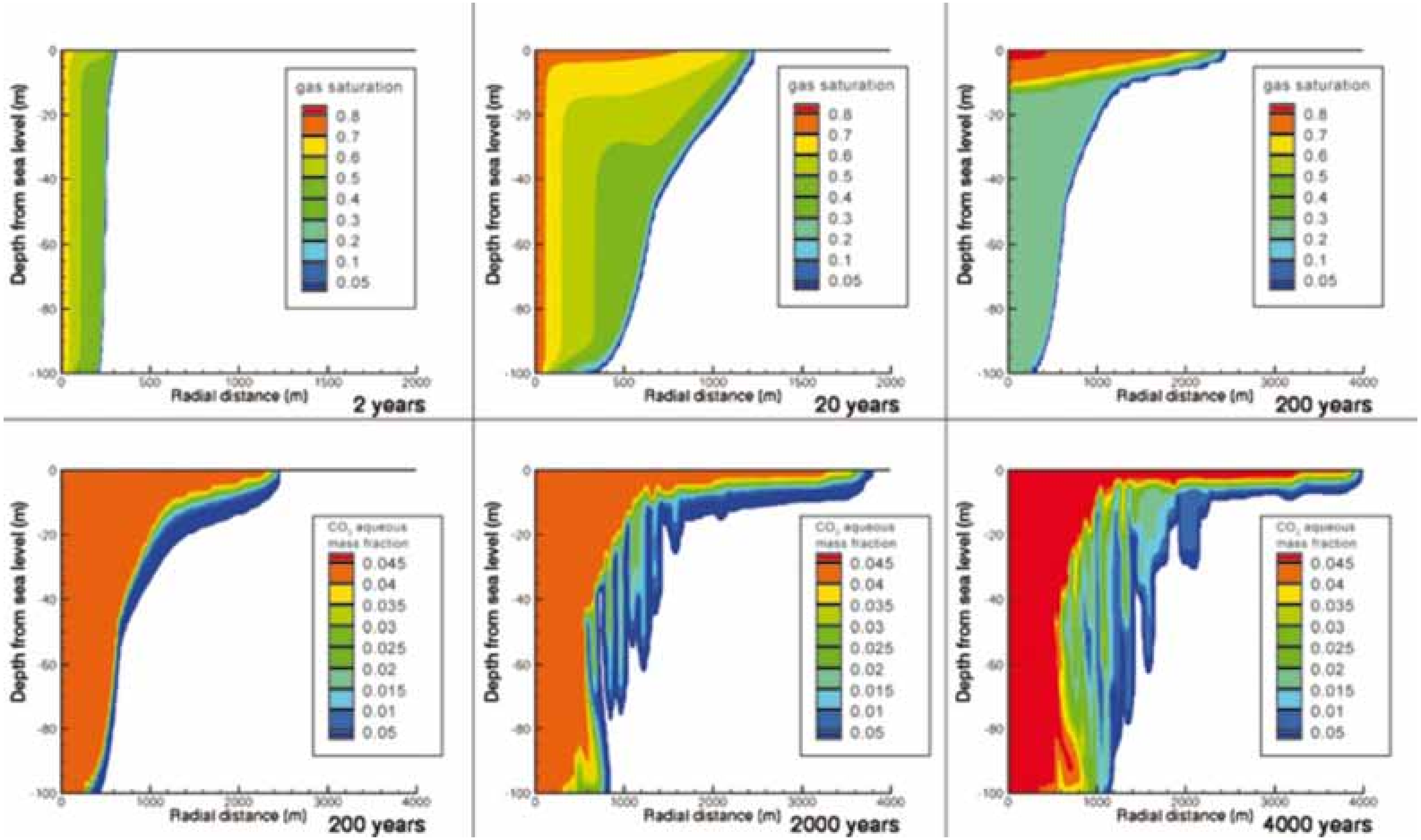
Storage mechanisms and security

Distribution of CO_2 after two years of injection simulated using TOUGH code



(Source: Doughty and Pruess, 2004)

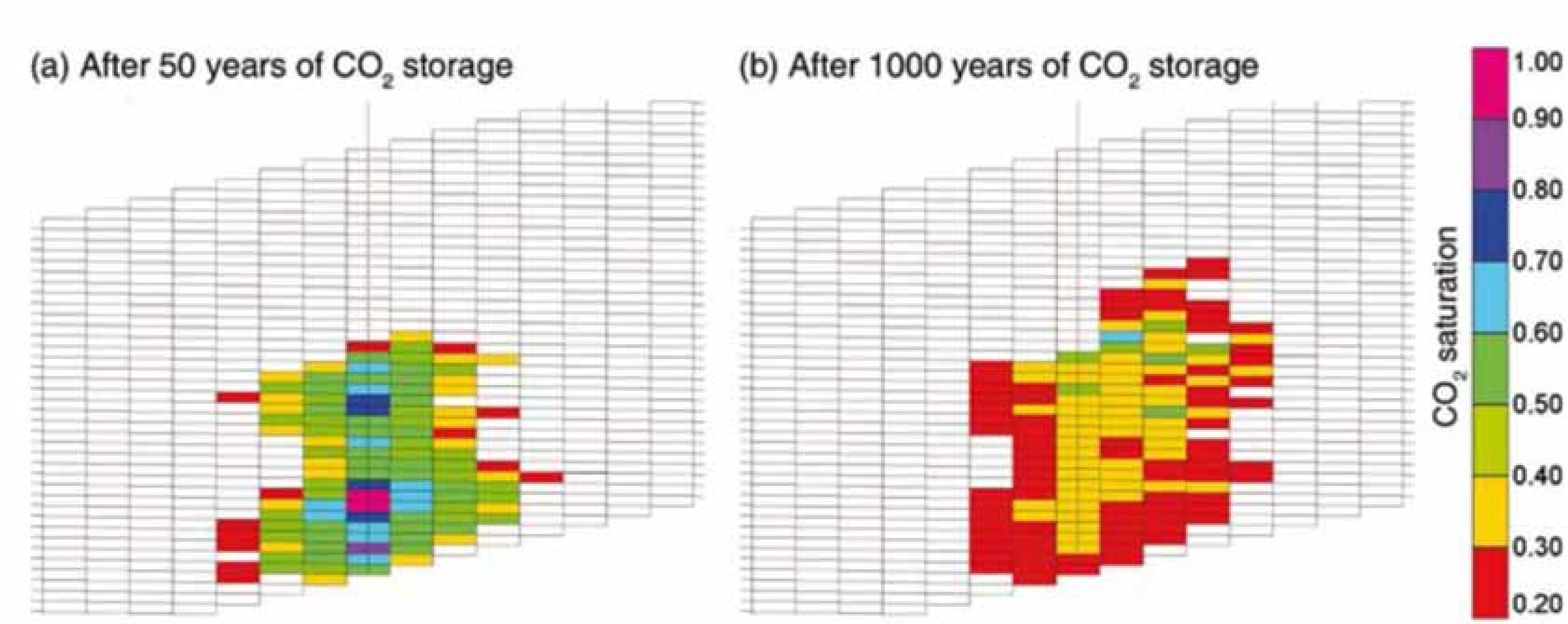
2D radial model of CO_2 injection into homogeneous 100m thick formation



(Source: Ennis-King and Paterson, 2003)

Storage mechanisms and security

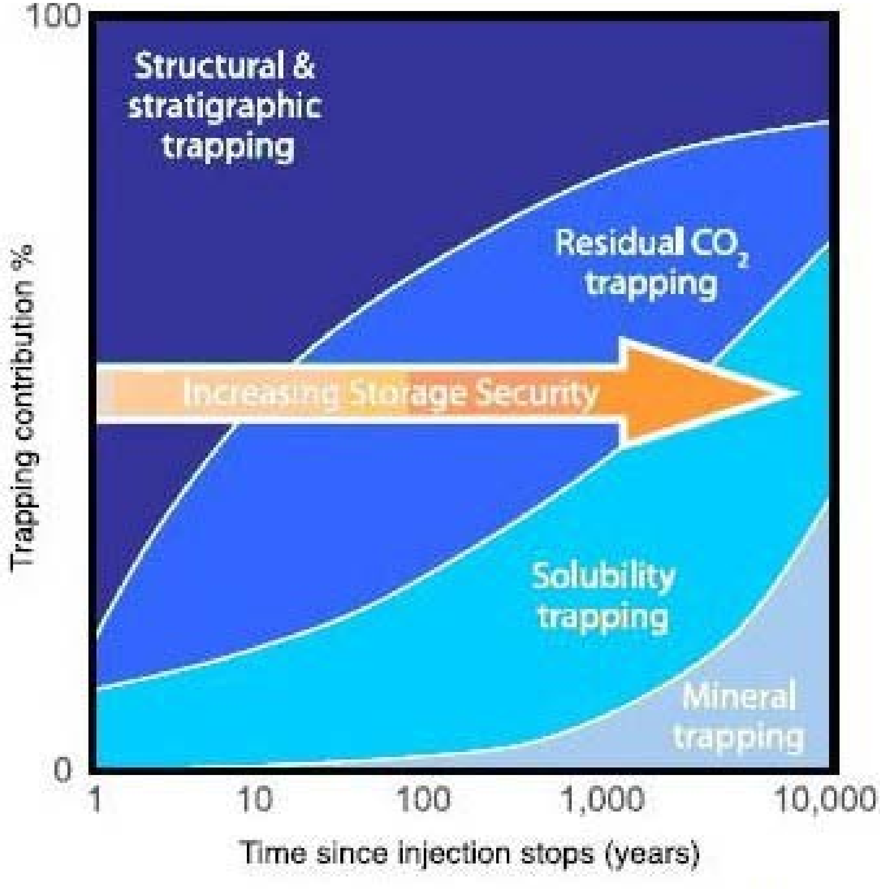
Simulation of 50 years of CO_2 into the base of a saline formation



(Source: Kumar, 2005)

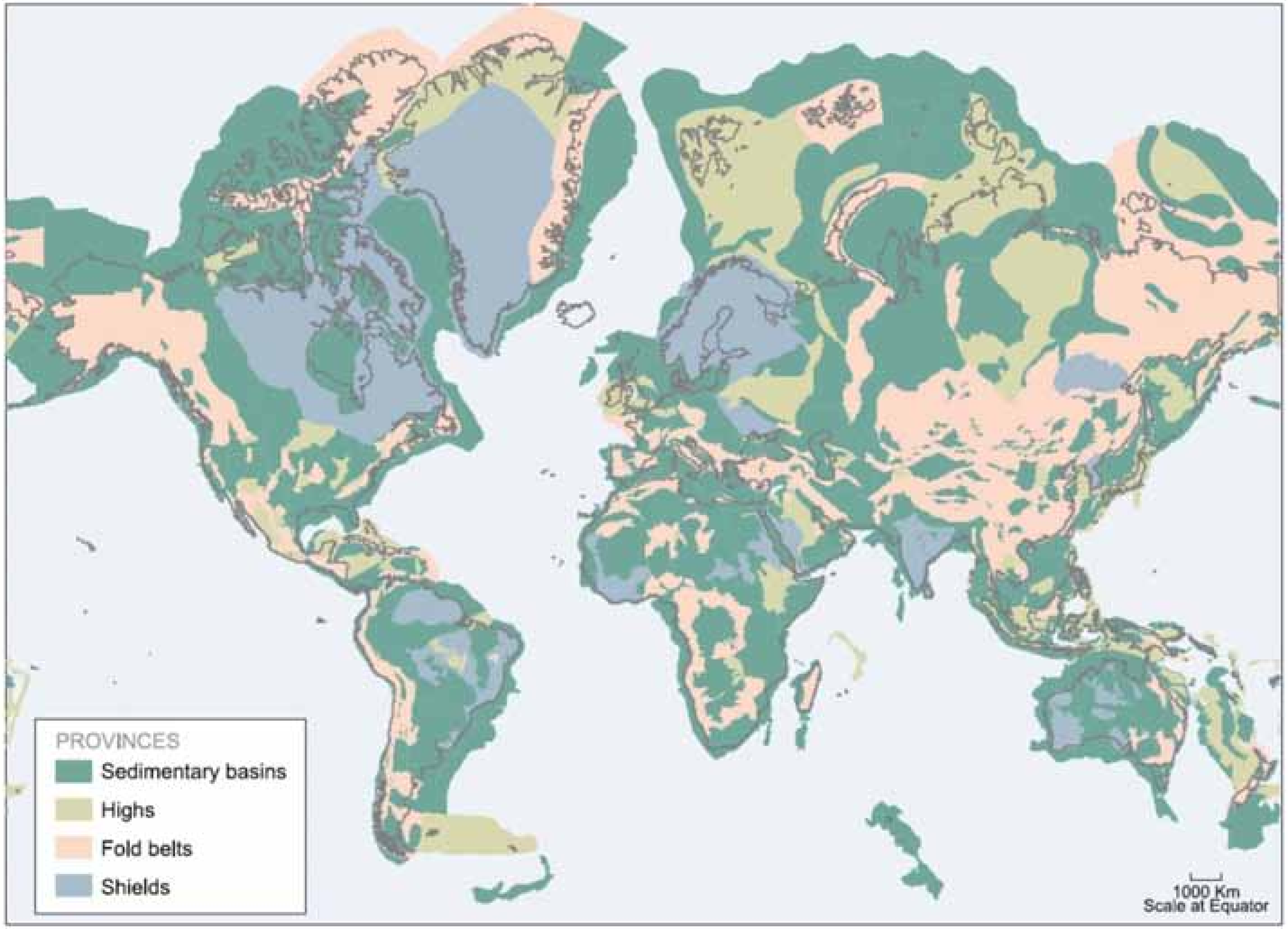
Storage mechanisms and security

CO_2 storage mechanisms in geological formations



(Source: IPCC, 2005)

Storage formations



Potential CO_2 storage sites (Source: IPCC, 2005)

Storage formations

Storage sites should have

- Adequate **capacity** and **injectivity**
- Satisfactory **sealing** caprock or confining unit
- Sufficiently **stable** geological environment to avoid compromising integrity of the storage site

Criteria for site selection

- Basin characteristics (tectonic activity, sediment type, geothermal and hydrodynamic regimes);
- Basin resources (hydrocarbons, coal, salt),
- Industry maturity and infrastructure
- Societal issues (level of development, economy, environmental concerns, public education and attitudes)

Storage formations

Efficiency of CO_2 storage in geological media = amount of CO_2 stored per unit volume. Important parameters are:

• CO_2 **density** (for efficiency and safety)
Increases with depth while CO_2 is in gaseous phase, but levels off when it is supercritical or liquid.
Decreases with temperature, so ‘cold’ sedimentary basins are favoulable – CO_2 attains higher density at shallower depth (Bachu, 2003)

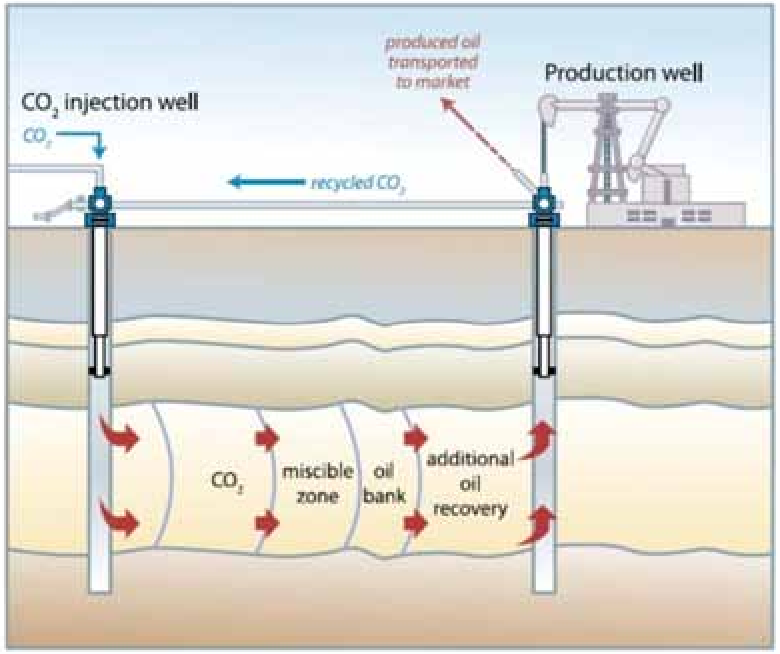
• Formation **porosity** and thickness (for storage capacity)

• Formation **permeability** (for injectivity)

Storage formations

Possible sites

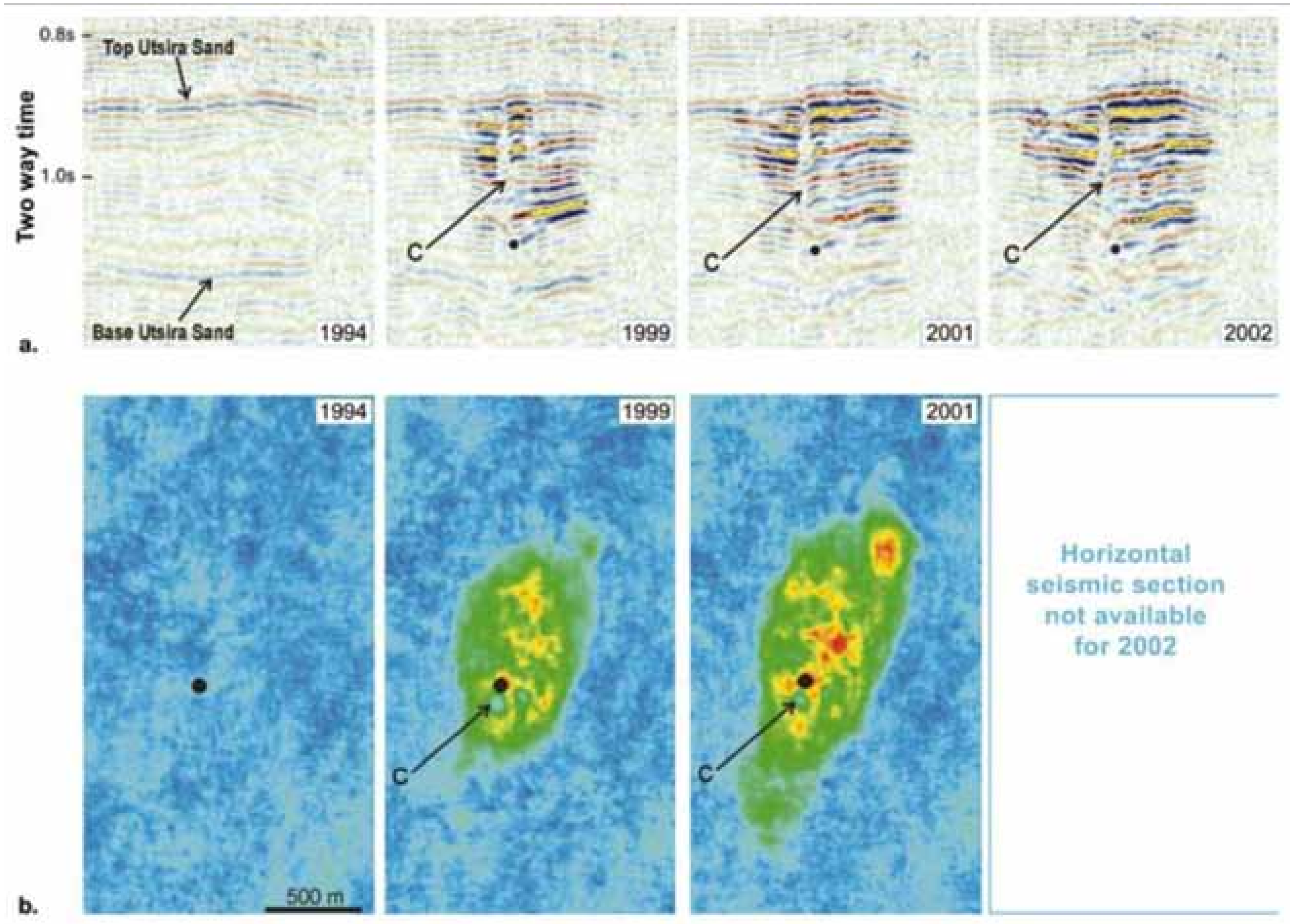
- **Oil & gas**:
  - Abandoned oil and gas fields
  - Enhanced oil recovery
  - Enhanced gas recovery



(Source: IPCC, 2005)

Storage formations

- **Saline** formations



(Source: IPCC, 2005)

Storage formations

- **Coal seams**. CO_2 trapping not well understood. Screening criteria:
    - adequate permeability,
    - geometry (a few thick seams),
    - simple structure (minimal faulting and folding),
    - homogeneous, laterally continuous and vertically isolated seams,
    - adequate depth,
    - suitable gas saturation,
    - ability to dewater the formation
    - coal rank

- Other geological media
    - Basalts
    - Oil or gas rich shale
    - Salt caverns
    - Abandoned mines

Storage formations

Capacity of storage sites is evaluated, depending on the trapping mechanism, as:

- **Volumetric** trapping: product of available volume and CO_2 density at *in situ* temperature
- **Solubility** trapping: amount of CO_2 that can be dissolved in formation fluid
- **Adsorption** trapping: product of coal volume and its capacity for adsorbing CO_2
- **Mineral** trapping: based on available minerals for carbonate precipitation and the amount of CO_2 that will be used in these reactions

Scale of evaluation:

- Global capacity – simplifying assumptions
- Country-, region- or basin- specific estimate

Storage formations

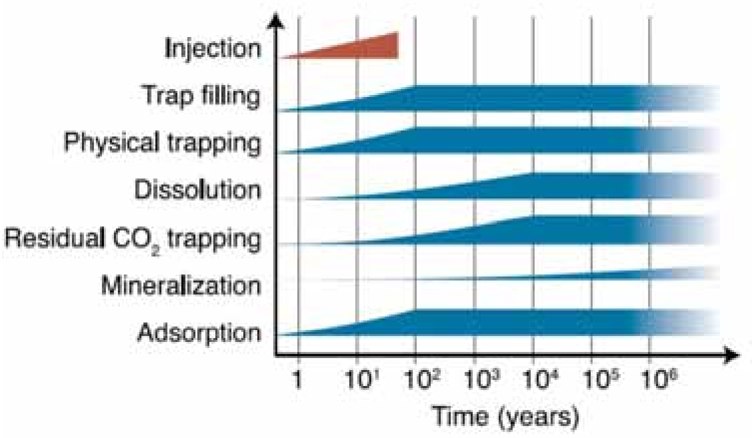
Global storage capacity (Source: IPCC, 2005)

Reservoir type	Lower estimate $GtCO_2$	Upper estimate $GtCO_2$
Oil & gas fields	**675**	**900**
Unminable coal seams	**3-15**	**200**
Deep saline formations	**1000**	Uncertain, possibly **10,000**

Storage formations

Evaluation of storage in deep saline formations is a challenge for the following reasons:

- **Multiple mechanisms** for storage
- Mechanisms operate both simultaneously and on different **time scales**
- Relations between various mechanisms are very **complex**, evolve with time and are highly dependent on local conditions
- There is no single consistent and broadly available **methodology**
- Limited **data**



(Source: IPCC, 2005)

Storage formations

Matching of CO_2 sources and geological storage sites.

Examples of regional studies:

- **Canada** (Bachu, 2003)
  - -Oil & gas several $GtCO_2$,
  - - Deep saline formations 100 to 1000 times more
  - - Most emitters have potential storage sites close
- **Australia**
  - -Total capacity 740 $GtCO_2$ (= 1600 years);
  - - Realistic capacity 100-115 Mt CO_2/year
  - - 'Cost curve' capacity 20 – 180 Mt CO_2/year

Storage formations

Criteria for selection and matching of sites

- Volume, purity and rate of the **CO_2 stream**;
- **Suitability** of the storage sites including the seal;
- **Proximity** of the source and storage sites;
- **Infrastructure** for the capture and delivery of CO_2;
- Existence of a **large number** of storage sites to allow diversification;
- Known or undiscovered energy, mineral or groundwater **resources** that might be compromised;
- Existing wells and **infrastructure**;
- **Injection strategies** and (for EOR and ECBM) also production strategies which affect the number of wells and their spacing;
- **Terrain** and right of way;
- Location of **population** centres;
- Local **expertise**;
- Overall **costs** and economics.

Identified sites

Data required for site characterisation

- **Seismic** profiles;
- **Structure contour maps** of reservoirs, seals and aquifers;
- Detailed maps of the structural **boundaries**;
- Maps of the predicted **CO_2 pathways** from the point of injection;
- Documentation and maps of **faults**;
- **Facies** maps
- Core and drill cuttings **samples**;
- **Well logs** (geological, geophysical and engineering logs);
- **Fluid** analyses and tests from downhole sampling;
- Oil and gas **production data** (if a hydrocarbon field);
- Reservoir and seal **permeability**;
- ...

Identified sites

Data required for site characterisation continued:

- ...
- **Petrophysical** data: porosity, mineralogy, seal capacity, pressure, temperature, salinity, rock strength;
- **In situ stress** analysis to determine the maximum sustainable pore fluid pressure during injection (for reservoir, seal, faults)
- **Hydrodynamic** analysis to identify the magnitude and direction of water flow, hydraulic interconnectivity of formations and pressure

decrease associated with hydrocarbon production;

- **Seismological** data, geomorphological data and tectonic investigations to indicate neotectonic activity

Identified sites

Factors affecting site integrity:

- **Stratigraphic** (capacity of a seal rock to hold back fluids)
- **Geomechanical** (to prevent reservoir or seal rock deformation)
- **Geochemical** (change of pore water pH affects CO2 solubility – more acid – less soluble; chemical reactions with minerals in the rock, borehole cements and seals may cause mineral dissolution, hence breakdown of the rock matrix or mineral precipitation, hence plugging of the pore system)
- **Athropogenic** (active or abandoned wells and mine shafts can provide short circuits)

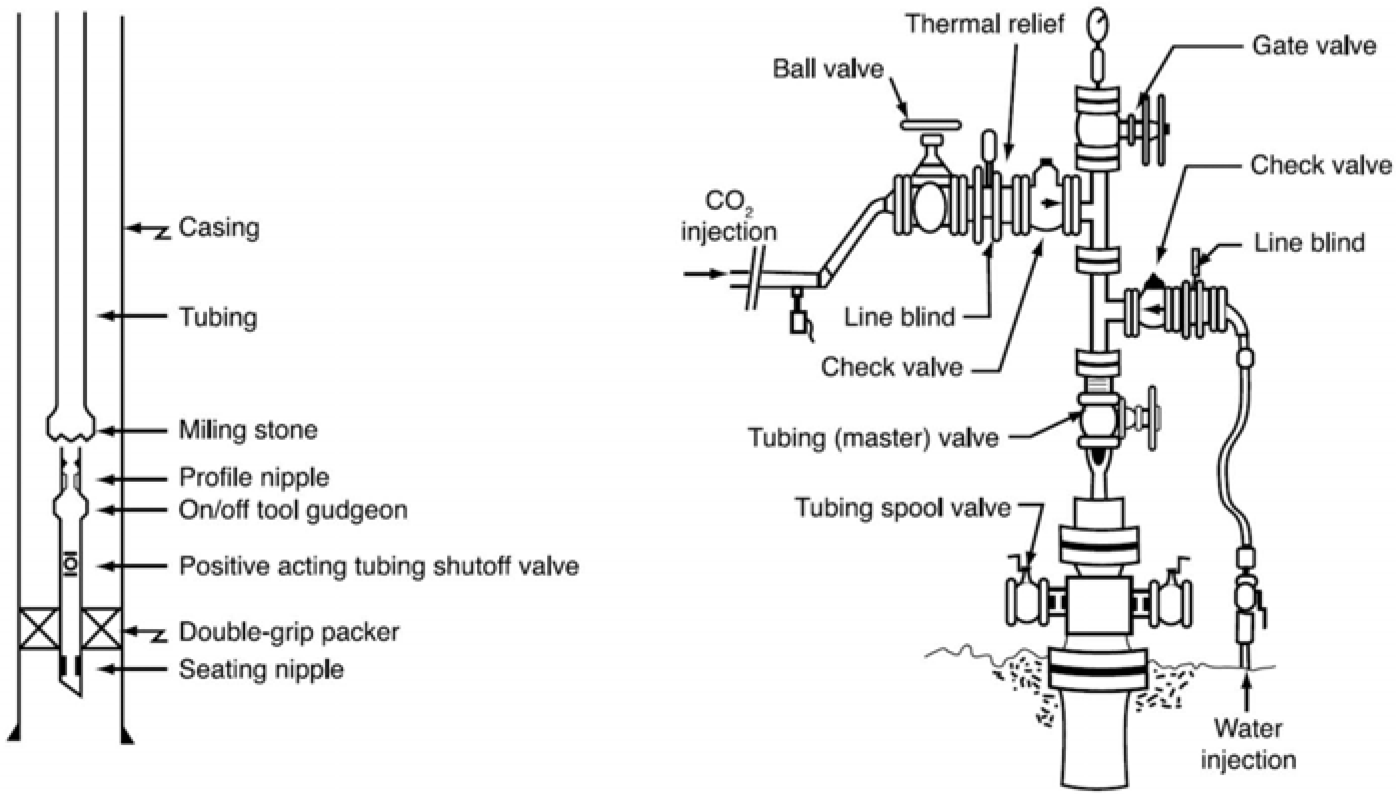
Identified sites

Performance prediction and optimisation rely heavily on simulation models.

A **code intercomparison study** was conducted (Pruess et al. 2004) to evaluate the capabilities and accuracy of numerical simulators. The test problems addressed CO2 storage in saline formations and oil &gas reservoirs. Comparison is overall encouraging but there are areas with only fair agreement or even discrepancies. The disagreements were mainly due to the description of fluid properties.

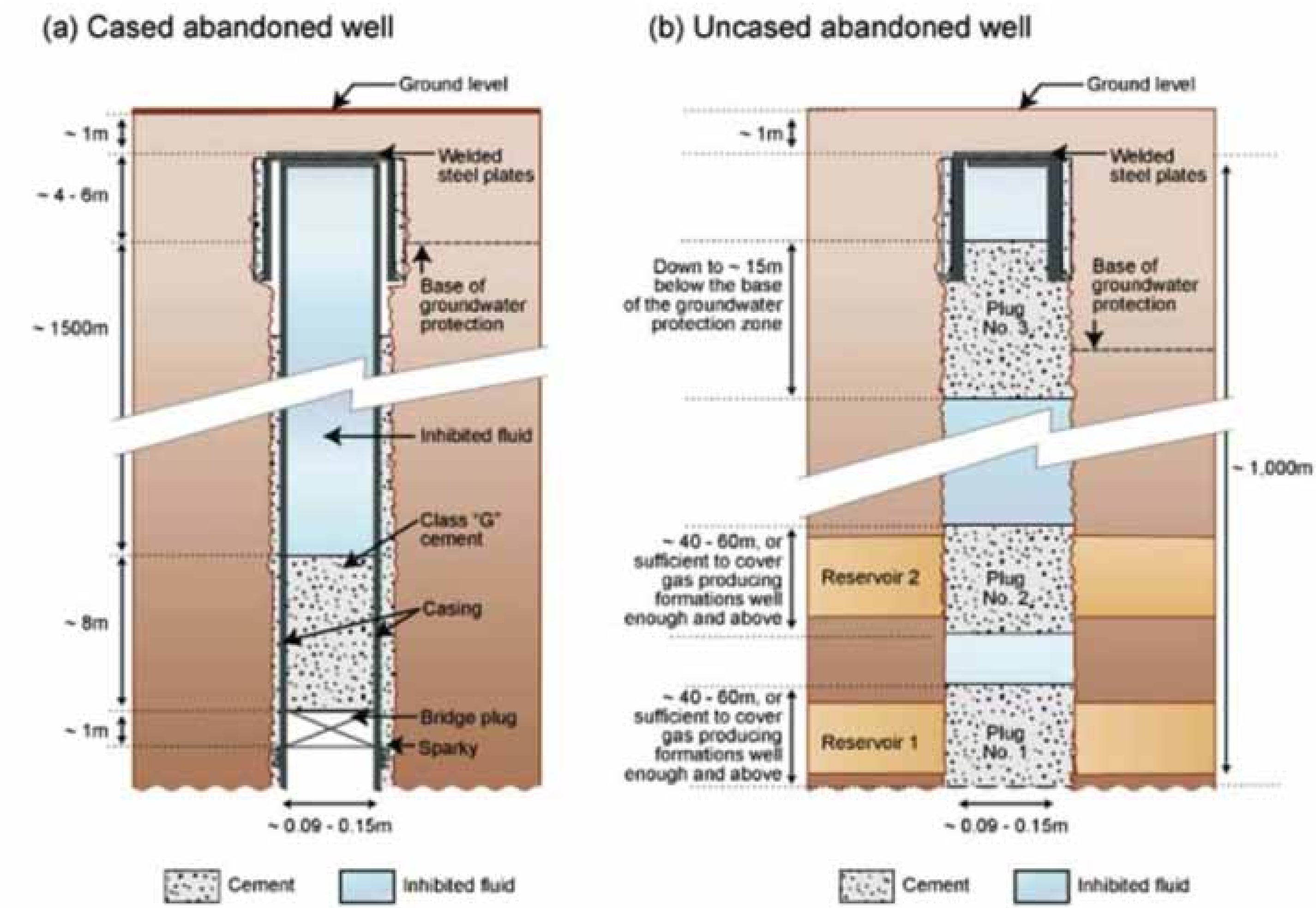
The main source of uncertainty in field applications is in the **data interpretation** and **sparse data sets**.

CO$_2$ injection well is very similar to gas injection well in an oil field or natural gas storage project. Number of wells depends on a number of factors.



(Source: IPCC, 2005)

Well abandonment (Source: IPCC, 2005)



Well technology

Injectivity of CO_2 is significantly greater than brine injectivity. However, it can be less than predicted and it may decline with time

Injection pressure must be higher than formation pressure. Safe injection pressure is site-specific. It is determined based on the measurements of *in situ* formation stresses and pore fluid pressure.

Relationship for the maximum safe injection pressure (Van der Meer, 1996):

- **1.35** x hydrostatic pressure for depth down to 1000m
- **2.4** x hydrostatic pressure for depths 1-5km.

The maximum pressure gradients for natural gas stored in an aquifer are different in different countries.

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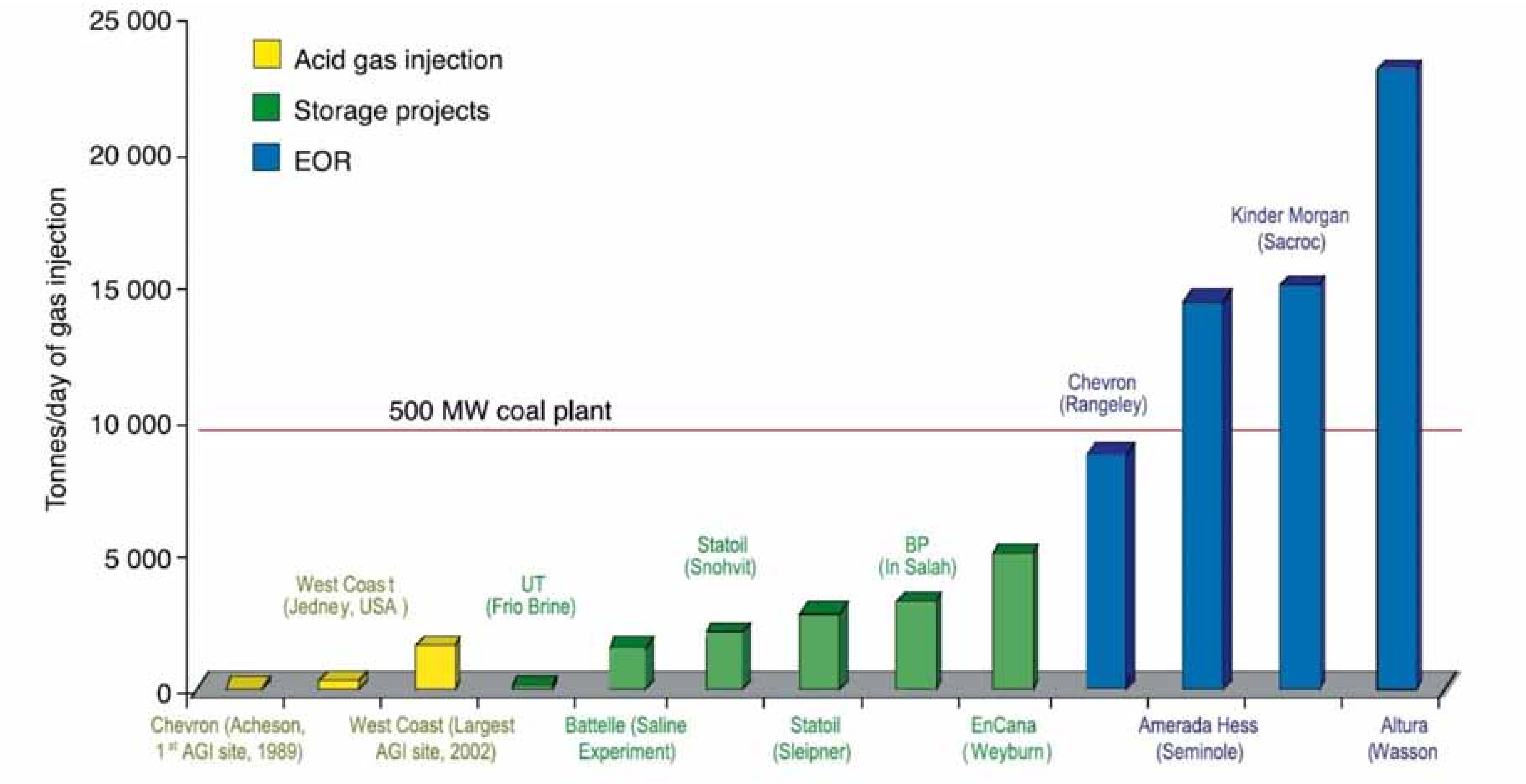
Injection rates for selected CO_2 storage projects

(Source: IPCC, 2005)



Monitoring

Monitoring is used to:

- Ensure **effective injection** and well control
- Verify the **quantity** of injected CO_2
- **Optimise** the efficiency of the storage project
- Demonstrate that CO_2 remains **contained** in the intended formation
- **Detect leakage** and provide an early warning

The following needs to be monitored:

- Injection rates and pressures
- **Subsurface distribution of CO_2**
- Well integrity
- Local environmental effects

Monitoring

Technique	Measured quantity
Tracers	Travel time Partitioning of CO_2 into brine or oil Identification sources of CO_2
Water composition	CO_2, HCO_3^-, CO_3^{2-} Major ions Trace elements Salinity
Pressure	Subsurface pressure Formation pressure Annulus pressure Groundwater aquifer pressure
Well logs	Brine salinity Sonic velocity CO2 saturation
Time-lapse 3D seismic imaging	P and S wave velocity Reflection horizons Seismic amplitude attenuation
Vertical seismic profiling and crosswell seismic imaging	P and S wave velocity Reflection horizons Seismic amplitude attenuation

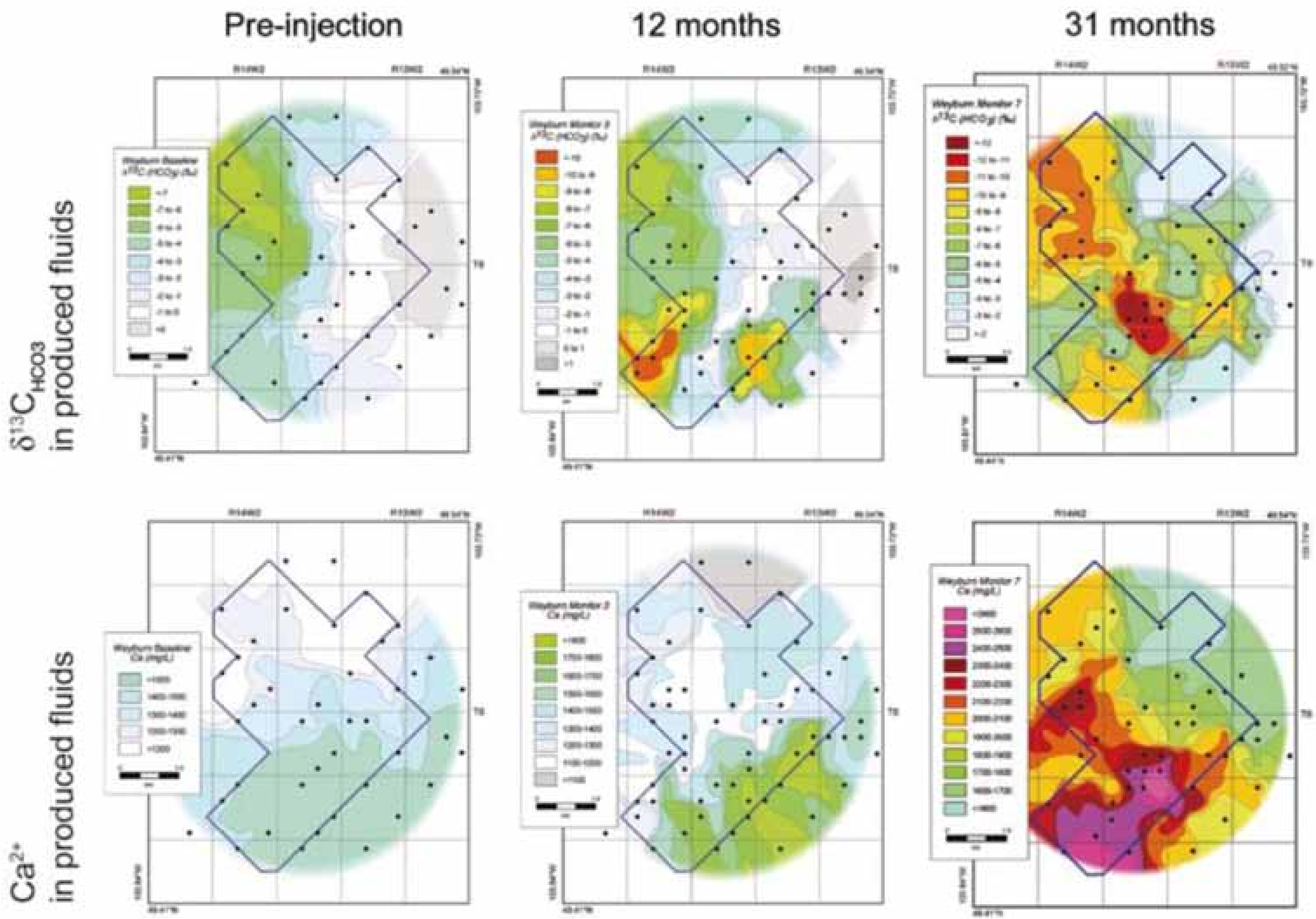
(Source: IPCC, 2005)

Monitoring

Technique	Measured quantity
Passive seismic monitoring	Location, magnitude and source characteristics of seismic events
Electrical and electromagnetic techniques	Formation conductivity Electromagnetic induction
Time-lapse gravity measurements	Density changes caused by fluid displacement
Land surface deformation	Tilt Vertical and horizontal displacement using interferometry and GPS
Visible and infrared imaging from satellite or planes	Hyperspectral imaging of land surface
CO_2 land surface flux monitoring using flux chambers or eddy covariance	CO_2 fluxes between the land surface and atmosphere
Soil gas sampling	Soil gas composition Isotopic analysis of CO_2

(Source: IPCC, 2005)

Monitoring



Produced water chemistry at Weyburn (Source: Perkins et al., 2005)

Risk management

The environmental impacts arise from release of stored CO_2 into the atmosphere. They into two broad categories:

• **Global** – uncertainty in the effectiveness of storage

• **Local** – health, safety and environmental hazards arising from:

- Direct effect of the elevated CO_2 concentrations
- Effects of dissolved CO_2 on groundwater chemistry
- Effect arising from the displacement of fluids by the injected CO_2

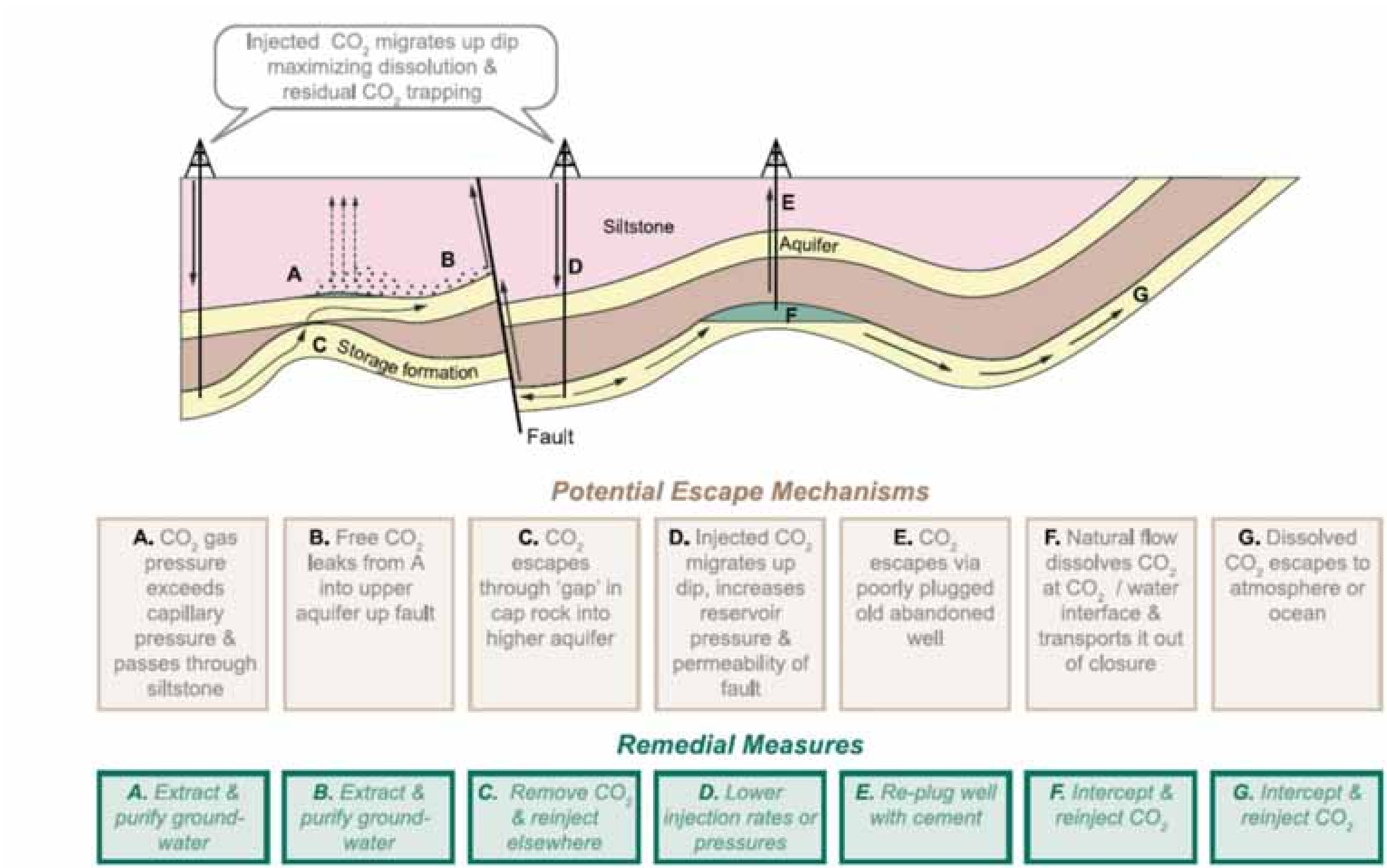
Pathways for release of CO_2 from geological storage sites:

• Through the **pore system** in low-permeability caprocks

• Through **openings** in the caprock or **fractures** and **faults**

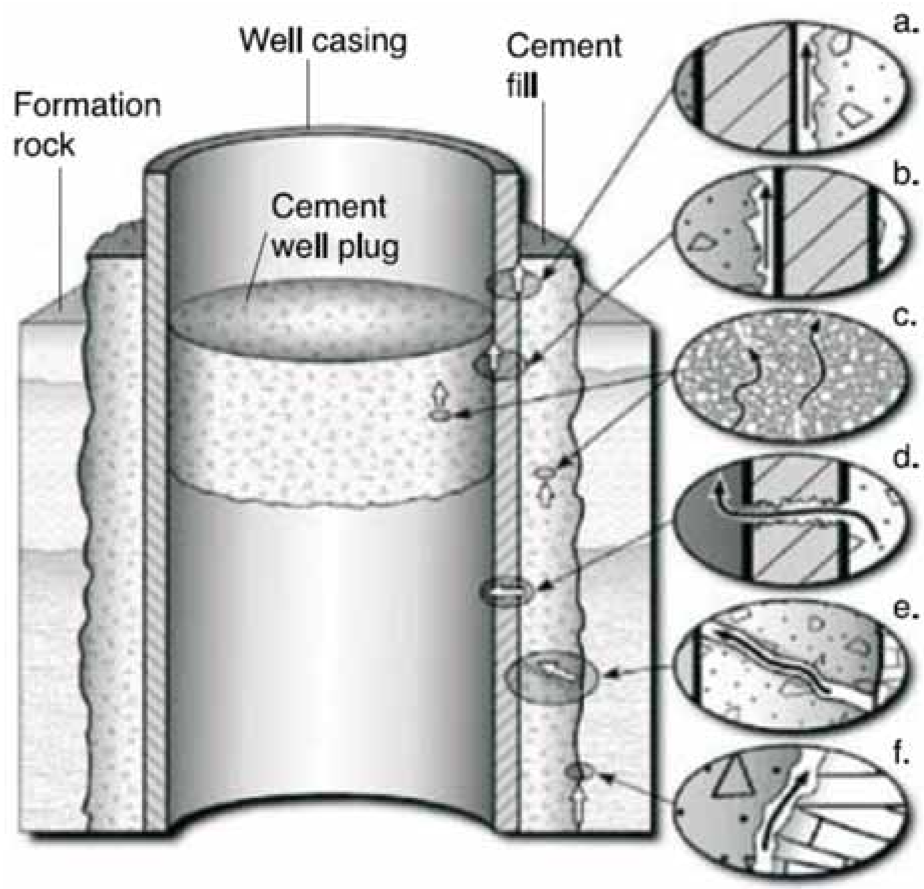
• Through **man-made** structures

Risk management



Potential escape routes for CO_2 injected into saline formations
(Source: IPPC, 2005)

Risk management



Possible leakage pathways in an abandoned well

(Source: Gasda et al., 2004)

Risk management

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Probability of release from geological storage sites:

• No systematic study exists, but rough evaluations can be made based on:

- data on natural systems
- data on engineered systems such as natural gas storage
- fundamental processes
- numerical modelling and
- data from current storage projects

• For large-scale operational CO_2 project, assuming that they are well selected, designed, operated and monitored, the available evidence suggests that

- **99%** of CO_2 is **very likely** to remain retained over first **100 years**
- **99%** of CO_2 is **likely** to remain retained over first **1000 years**

Risk management

Possible local and regional **hazards**:

- Human health and safety
- Groundwater quality from CO_2 leakage and brine displacement
- Terrestrial and marine ecosystems
- Induced seismicity

Risk assessment is an integral element of risk-management activities. Methodologies are diverse, usually based on **scenarios** that describe possible future states of the storage facility and events that result in leakage of CO_2 or other risks, which are **simulated** using numerical models.

If leakage occurs a range of **remediation** measures exist.

Legal issues

International laws

Relevant treaties: global and regional environmental treaties, notably those on **climate change** and the law of the sea and **marine environment**.

Key issues in applying marine treaties to CO2 storage

- Is storage **'dumping'** or not?
- Does CO_2 classify as waste arising from **normal operations**, or discharge or emission from them (and hence can benefit from treaty exemption)?
- Is CO_2 **'industrial waste', 'hazardous waste'** or does the process of storage constitute **'pollution'** or it is none of these?
- Does the method of CO_2 reaching the storage site involve **pipelines**, **vessels** or **offshore structures**?

National regulations and standards

In North America, Europe, Japan and Australia there is a **lack of regulations** specifically relevant for CO_2 storage.

EU CO2 storage has to conform with relevant EU Directives such as those on waste, landfill, water, environmental impact assessment and strategic environmental assessment. These directives do not specifically mention CO_2 capture and storage.

Canada deep-well injection of fluids in the subsurface, including disposal of liquid wastes, is legal and regulated. Jurisdiction is provincial.

USA the Safe Drinking Water Act regulates most underground injection activities.

Australia Only South Australia has legislation regulating the underground injection of gases such as CO_2 for EOR and for storage. Stringent environmental impact assessments are required for all activities that could compromise the quality of surface water or groundwater.

Cost

Major cost elements:

- **Capital** costs: drilling wells, infrastructure, project managemenr
- **Operating** costs: manpower, maintenance, fuel

Monitoring costs are usually reported separately

Some cost estimates for **saline formations**:

- Australia onshore med **0.5** US$/t$CO_2$ (0.2 – 5.1) US$/t$CO_2$
  offshore med **3.4** US$/t$CO_2$ (0.5 – 30.1) US$/t$CO_2$
- USA onshore med **0.5** US$/t$CO_2$ (0.4 – 4.5) US$/t$CO_2$
- Europe onshore med **2.8** US$/t$CO_2$ (1.9 – 6.2) US$/t$CO_2$
  offshore (4.7 – 12.0) US$/t$CO_2$

Overall – significant storage at cost in the range **0.5-8 US$/t$CO_2$**

Conclusions

- While there are uncertainties, the global **capacity** to store CO_2 deep underground is **large**
- CO_2 migration and trapping in geological formations are reasonably **well understood**
- **Technologies** for CO_2 injection, monitoring and risk assessment **exist**, although more work is needed to improve technologies and reduce uncertainties
- There appear to be **no** insurmountable technical **barriers** to an increased uptake of geological storage as an effective mitigation option