WHEN TRUST MATTERS

Guidance Document 2: Characterisation of the Storage Complex, CO_2 Stream Composition, Monitoring and Corrective Measures

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Scope of GD2

Objective: Guide operators and competent authorities (CAs) on how to interpret the requirements in the CCS Directive for:

- Site selection
- Composition of the CO_2 stream
- Monitoring
- Corrective measures

EU CCS Directive
Legislative context

Directive establishes a legal framework for the environmentally safe geological storage of carbon dioxide (CO_2) to contribute to the fight against climate change

The purpose […] is permanent containment of CO_2 in such a way as to prevent and, where this is not possible, eliminate as far as possible negative effects and any risk to the environment and human health

A geological formation shall only be selected as a storage site, if under the proposed conditions of use there is no significant risk of leakage, and if no significant environmental or health risks exist

Definition & interpretation of key terms in the Directive

Term	Definition in CCS Directive	Interpretation
Storage site	A defined volume area within a geological formation used for the geological storage of CO_2 and associated surface and injection facilities	The subsurface component of the storage site is comprised of the geological stratum (or strata) into which CO_2 stream(s) are injected. This volume shall be: • contained within the storage complex; and • delineated by lateral boundaries on an area map; The surface and injection facilities considered to be part of the storage site should include all wells associated with CO_2 injection operations or monitoring, and may include associated infrastructure such as pipelines, CO_2 conditioning systems, storage tanks, offshore platforms and floating (storage and) injection units.
Storage complex	The storage site and surrounding geological domain which can have an effect on overall storage integrity and security; that is, secondary containment formations	Storage complex shall: • be contained within license area; • include the volume where a CO_2 plume may be present; and • include all legacy wells within the surrounding area that have potential to provide leakage pathways. Elevated pressure may, however, extend beyond the limits of the storage complex. Vertically, the complex will normally incorporate shallower geological formations that provide physical trapping of buoyant formation fluids, including any CO_2 plume.

Definition & interpretation of key terms in the Directive

Term	Definition in CCS Directive	Interpretation
Surrounding area	None	Surface and subsurface domain surrounding the storage complex where leakage or negative effects on the environment or human health are realistically possible. Risk assessment should be applied to determine the significance of associated risks, and this should inform the design of the monitoring of the storage complex and surrounding environment. The storage complex and surrounding area should be determined through site characterisation per Annex I and will combined normally encompass the monitoring area.
Hydraulic unit	A hydraulically connected pore space where pressure communication can be measured by technical means and which is bordered by flow barriers, such as faults, salt domes, lithological boundaries, or by the wedging out or outcropping of the formation	The hydraulic unit containing the subsurface volume for the storage site is important for determining the expected pressure build-up from the geological storage project. The hydraulic unit should be mapped and described over an areal extent where material changes in pressure as a result of the CO_2 injection activities can occur. This should also describe other known activities within the hydraulic unit that may impact pressure within the storage site.

Definition & interpretation of key terms in the Directive

Term	Definition in CCS Directive	Comments
Leakage	Any release of CO_2 from the storage complex	This refers to CO_2 in free-phase, i.e., it does not include CO_2 that has been dissolved in water, mineralized or otherwise transformed through chemical reactions. However, assessment and quantification of leakage shall include the potential for any exsolution of CO_2 outside the storage complex. Specifically, if CO_2 charged water is displaced to the water column, then it shall be counted as leakage.
CO_2 plume	The dispersing volume of CO_2 in the geological formation	This refers to CO_2 in free-phase within the geological formation where CO_2 is being injected and shall be contained. CO_2 that is fully dissolved in water, or otherwise transformed through chemical reactions is therefore not included in the CO_2 plume.
Migration	Movement of CO_2 within the storage complex	Movement of free-phase CO_2 within storage complex.
Significant risk	A combination of a probability of occurrence of damage and a magnitude of damage that cannot be disregarded without calling into question the purpose of the CCS Directive for the storage site concerned	The risk of leakage and possible negative local effects on the environment or human health should be established for each storage site based on a project specific assessment. Combinations of probability of occurrence and magnitude of damage that can represent significant risk will be discussed.

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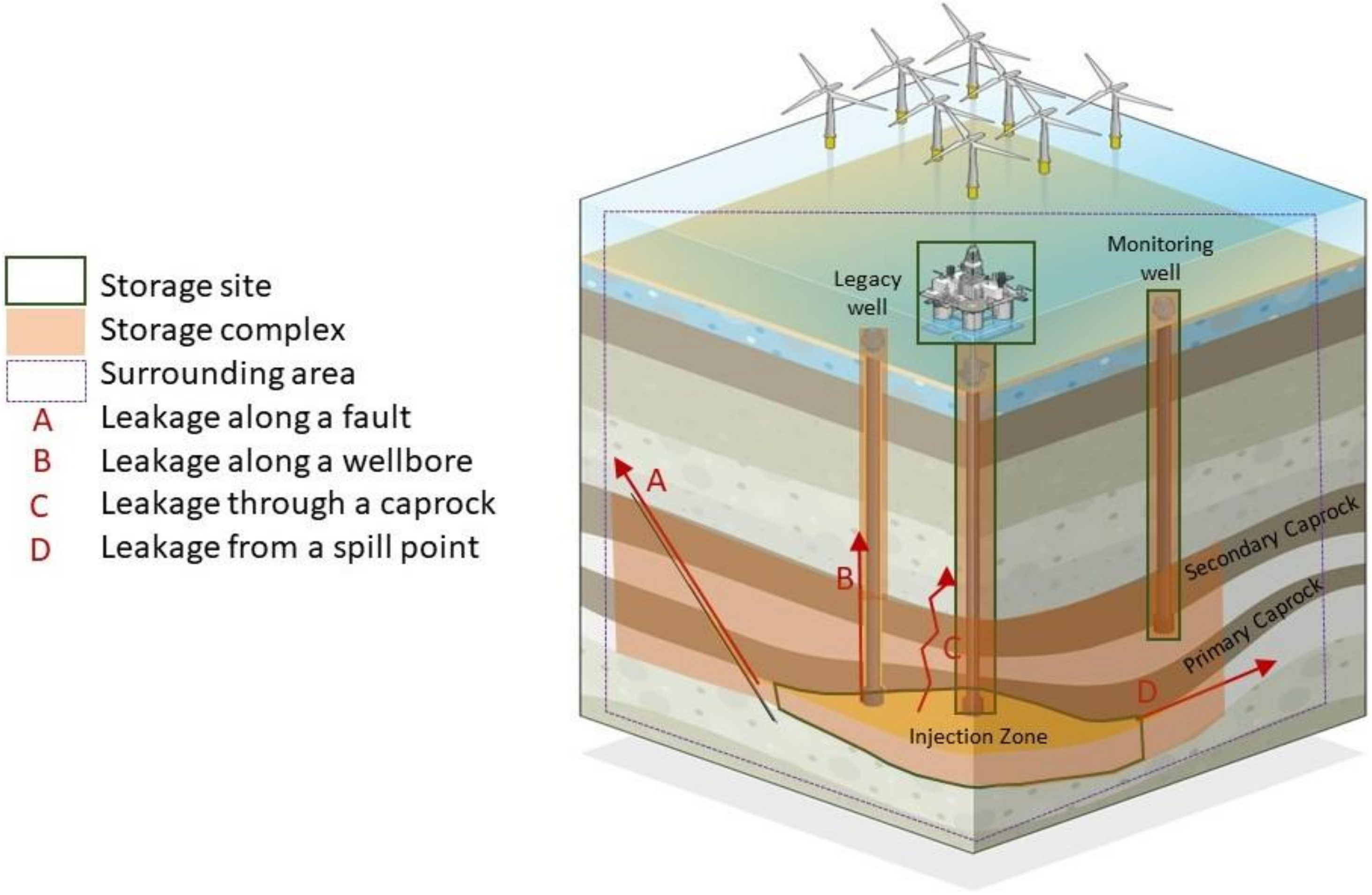
Storage site, storage complex, & surrounding area



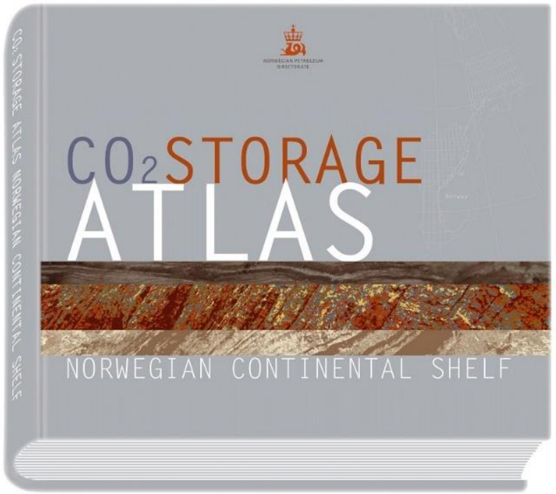
Site characterization

Evaluation of storage capacity in Member States

- The competent authority (CA) should produce/commission a storage atlas in areas potentially suitable for geological CO_2 storage within the Member State (MS) territory (under Article 4(2))
- Mainly high-level and regional capacity evaluation, site-level assessments not expected from MS
- Results should be made available digitally and searchable
- Certain areas may be excluded if they fall under protections or other restrictions
- Examples include those produced for the Norwegian and UK continental shelves

<u>Depleted field sites</u> – hydrocarbon reserves depleted or no longer economically recoverable/developable:
- Capacity estimated based on produced hydrocarbon volume, CO_2 reoccupies produced volume
- Discount/storage efficiency factor applied as CO_2 may not be able to access full reservoir volume
- A conservative factor (e.g., 50%) may be used for capacity estimates, but true values will be site-specific

<u>Aquifer sites</u> – brine-bearing formations which are often not pressure-depleted:
- Typically involves injection which increases formation pressure above the original state
- Limited by allowable pressure build-up without fracturing rock or inducing seismicity
- Capacity limited to the mass allowable before over-pressurising the aquifer, CO_2 migration generally ignored
- Hydraulic unit characteristics (e.g., open vs. closed aquifer) will limit storage efficiency and capacity



Norwegian Offshore Directorate, 2014

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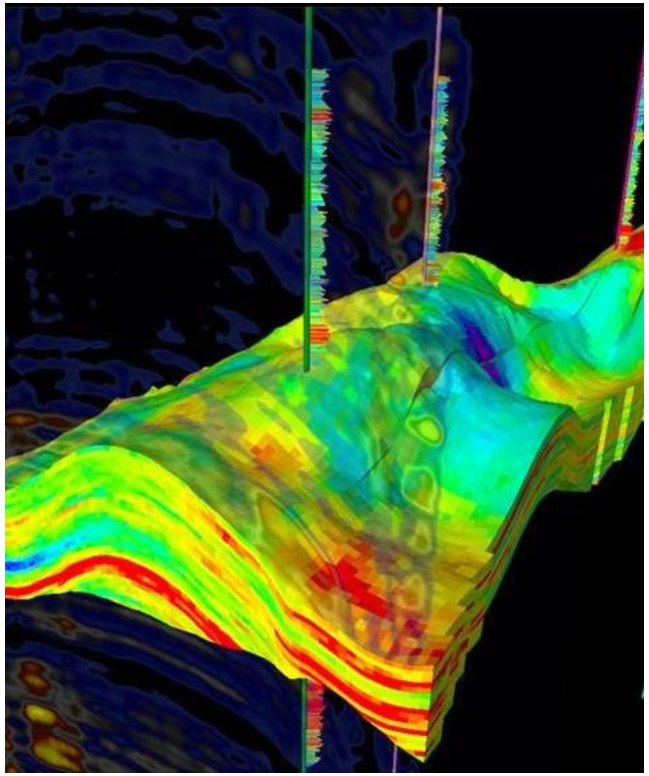
Site characterisation

Applicable under the CCS Directive
Saline aquifers
Depleted hydrocarbon fields
CO_2 mineralization
Coal seams
Other

Goals:

1. Assess the containment, capacity, injectivity, and monitorability
2. Demonstrate no significant risk to human health or environment

- Guided by risk assessments (GD1)
- Site-specific risks are identified and evaluated
- Varies by storage type, data availability, and site-specific conditions
- Characterisation of storage complex and surrounding area supports location suitability
- Steps:
  1. Data collection
  2. 3D static modelling
  3. Dynamic modelling



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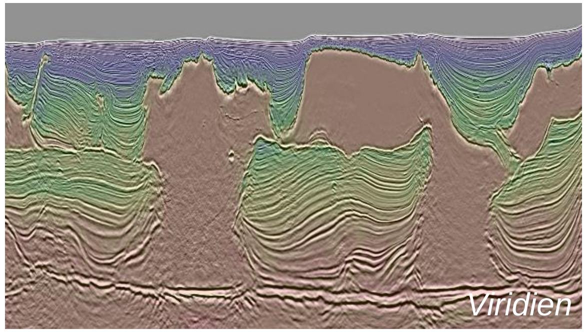
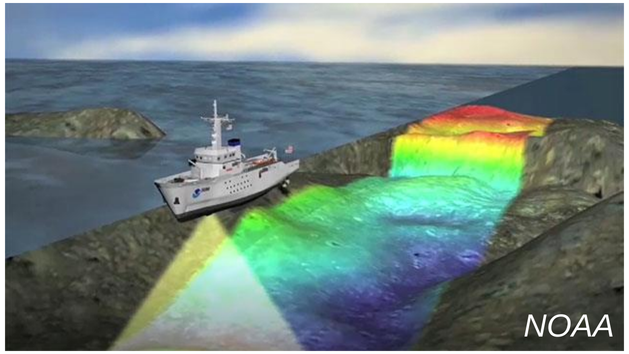
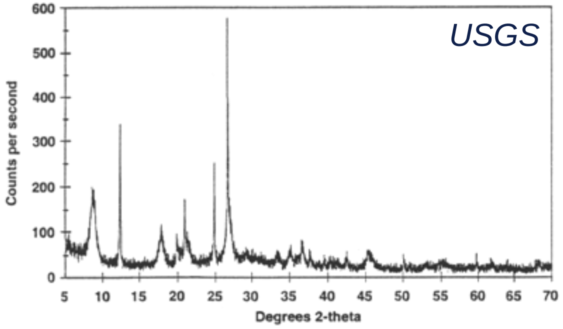
Data collection

- Data collection plans should be specific to the:
  - Type of storage site
  - Trapping mechanisms
  - Environmental and human health risks
  - Subsurface complexities
- Access to existing data from previous/ongoing activities can facilitate a reliable characterisation
- A surrounding region with similar geology can greatly support the viability of a potential storage site (i.e., analogues)



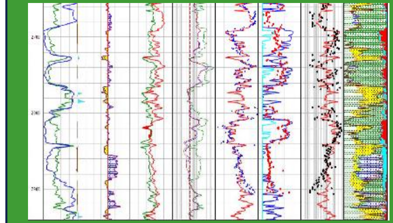




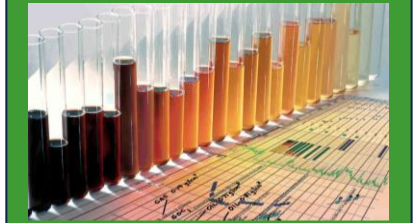
Data collection

Geology & geophysics

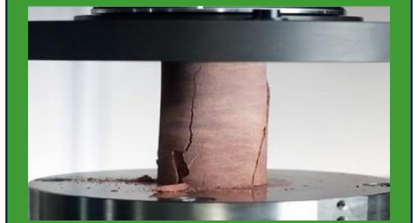
Hydrogeology



Reservoir engineering & petrophysics



Geochemistry



Geomechanics

Seismicity

Natural & man-made leakage pathways

Domains surrounding the storage complex

Population distribution

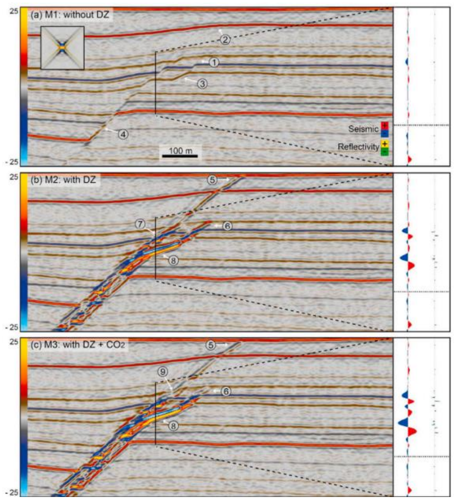
Proximity to valuable natural resources

Activities around the storage complex

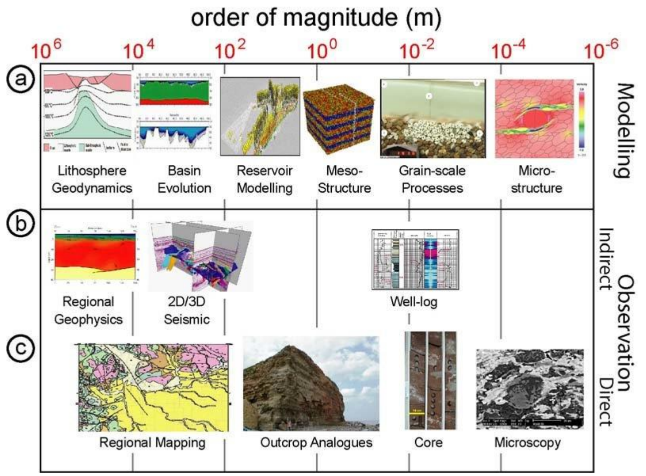
Proximity to the potential CO_2 source(s)

Modelling considerations for site characterisation

- Risk management approach is recommended
- Iterative, site-specific, and incorporate static and dynamic model updates
- Use multiple data sources for inputs
- Consider/evaluate a range of scenarios to reduce uncertainty and risk
- Investigate sensitivities for input variables
- Deterministic and probabilistic modelling may be used
- Use best practice at the time of modelling
- Consider different scales (i.e., regional vs. storage complex scales)
- Integrate models into a cohesive subsurface interpretation
- Demonstrate no significant risk to human health/environment



Faleide et al., 2022



McCaffrey et al., 2005

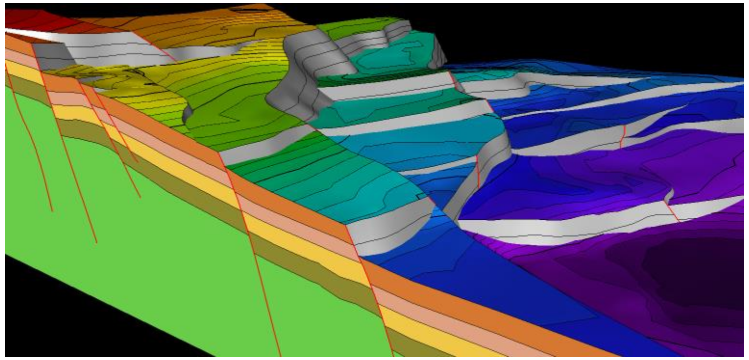
3D static geological models

- Construct 3D static geological earth models of potential storage complex with collected data:
  a) Geological structure of the physical trap
  b) Geomechanical, geochemical, and flow properties of reservoir, overburden, and surrounding formations
  c) Fracture/fault systems and presence of human-made pathways
  d) Areal/vertical extent of the storage complex
  e) Pore volume and porosity distribution
  f) Baseline fluid distribution
  g) Other relevant characteristics

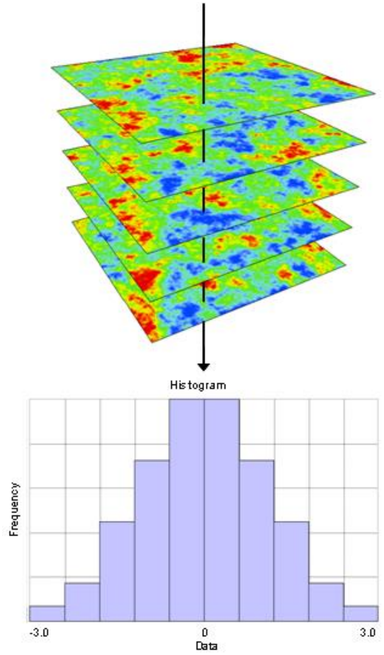
Wintershall Dea

3D static geological models

- Incorporate sufficient detail
- Assess error associated with interpretations (e.g., upscaling)
- Use and calibrate geostatistical methods for populating properties away from control points
- Use analogue data or regions to supplement or validate measured data or observations
- Can incorporate lab experiment data or observations
- Maintain/manage data, allowing for comparison during project
- Static models often provide elements of subsequent dynamic models

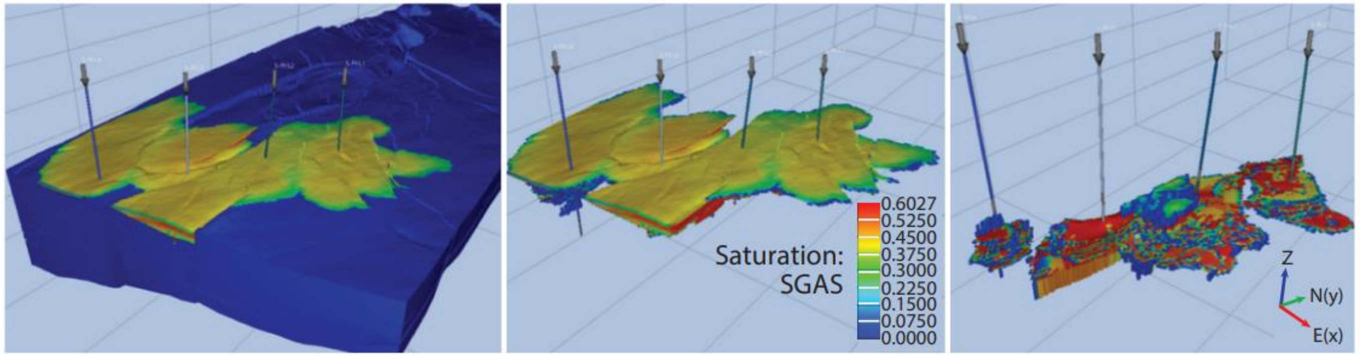


Dynamic Graphics



Esri

Dynamic models

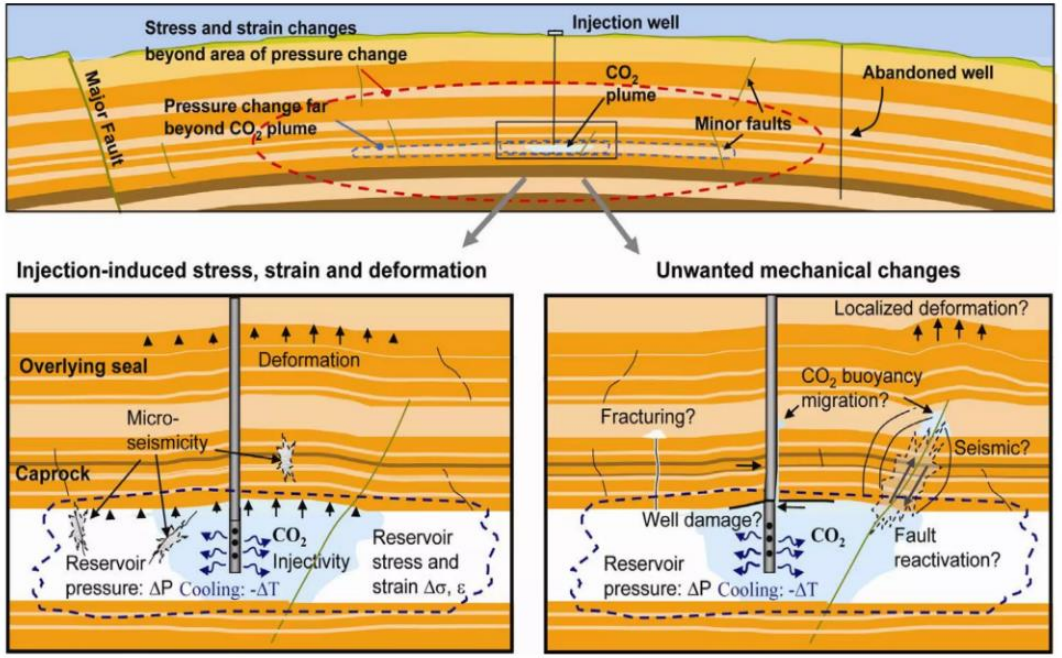


Ringrose et al., 2021

- Aids in:
  - Identifying leakage pathways
  - Defining secondary effects of CO_2 storage
  - Identifying risks to human health and the environment
  - Defining the storage complex and the monitoring area
  - Defining capacity, containment, injectivity, well placement/design, and monitorability
- Consider geologic setting, trapping mechanism(s), and heterogeneity
- History matching is recommended to calibrate CO_2 injection model results
- Sensitivity characterisation:
  - Model multiple scenarios to identify sensitivity of parameter assumptions (e.g., tornado plots)
  - Account for significant sensitivities in the risk assessment, including:
    - Parameter assumptions introducing leakage, human health, or environmental risks
    - Parameter assumptions/interpretations that impact capacity, injectivity, or monitorability

Presence & condition of leakage pathways

- Leakage pathways established from containment evaluation and linked to risk assessment, site characterisation, CO_2 composition, monitoring, and corrective actions
- Storage complex definition forms basis for identifying pathways, considers trapping mechanisms
- All scenarios posing a significant risk to human health and the environment should be considered
- Two pathway categories:
  1. Natural
  2. Human-made



Rutqvist et al., 2007

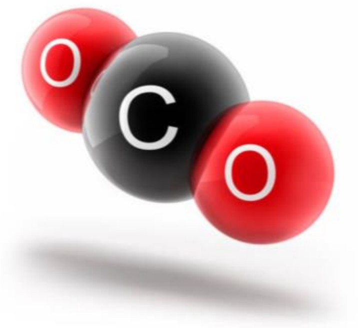
Presence & condition of leakage pathways

Natural pathways:
- Geological pathways to overlying/adjacent formations outside the storage formation or to the surface
  - Faults, seal quality variations, lack of lateral seals, geochemically altered zones, etc.
  - Mineralisation sites – CO_2 may exsolve from solution before minerals form or acidic fluid reactions with host rock minerals
  - Depleted field sites – may have additional top seal risk related to compaction resulting from production
- Risk of certain pathways will differ by trapping mechanism and geological setting, based on site characterisation and risk assessment

Human-made pathways:
- Wells within and outside the storage complex, often represent most-significant potential leakage pathways
- Evaluation should be based on available status and condition data for all wells following regulations and guidance
- Chemical/mechanical impact of CO_2/CO_2 -charged fluids and elevated pressure on long-term performance of well barriers/materials
- Need for mitigation (i.e., monitoring/intervention/remediation) depends on risk assessment for each well, risk-based approach is cost-effective (e.g., many wells)
- Barrier materials, length, position, placement, and number of barriers are key considerations regarding their performance
- 2 well barriers recommended, fewer may be acceptable (without intervention/remediation) if leakage risk is deemed insignificant or 1 barrier is as sufficient as 2
- If remediation is required, operator should demonstrate a high chance of remediation success, often costly, delays storage permit issuance
- Materials for abandonment design not prescribed in documents
- Holder of storage permit responsible for well integrity before transfer to MS or permit withdrawal, CA responsible thereafter, should be agreed on before injection
- Recommended guidance material:
  - ISO 27914:2017
  - DNV-RP-J203
  - OEUK Guidelines (2022)

CO_2 composition

CO_2 composition



- Must be consistent with the purpose of geological storage (isolate CO_2 emissions)
- Designed in consideration of the risks of leakage and contamination
- Requirements:
  1. CO_2 stream needs to consist *overwhelmingly* of carbon dioxide
  2. No waste or other matter may be added to the CO_2 stream for disposing underground
  3. The CO_2 stream may also contain:
     a) Incidental substances associated with the CO_2 emission source, capture process, or injection process
     b) Trace substances added to assist in monitoring and verification
- <u>Exception</u>: mineralisation projects which have demonstrated that CO_2 can be stored safely provided all injected CO_2 is fully dissolved in the aquifer and remain dissolved until CO_2 is mineralised via geochemical reactions with the host storage formation, ~25 parts formation water to parts CO_2 injected
- MS must keep register of CO_2 streams and ensure operators only accept verified CO_2

CO_2 composition

- *CO_2 stream: a flow of substances that results from CO_2 capture processes*
- Different CO_2 streams have associated risk considerations/implications, project-specific
- Not permitted to co-inject “waste or other matter” with the CO_2 stream (Directive 2006/12/EC)
- Co-injection of ‘other matter’ allowed if it is necessary for safety
- Additional substances may be necessary for operations/monitoring (e.g., tracers)
- Interpreted permissible if for safe/effective injection and meet CCS Directive
- Concentrations of incidental and added substances must be below harmful levels
- No specific requirements over measurement location/frequency, informed by risk
- Operators must keep record of delivered/injected CO_2 stream quantities/properties

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Monitoring

Monitoring

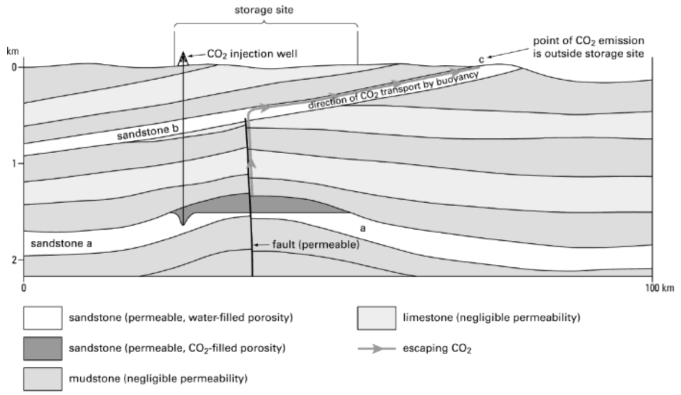
- Monitoring is required to ensure the safety of geological storage, in line with the following:
  - MS ensure operators monitor the storage site, storage complex, and surrounding area to:
    a) Compare actual and modelled behaviour of CO_2 and formation water
    b) Detect significant irregularities
    c) Detect migration of CO_2
    d) Detect leakage of CO_2
    e) Detect significant adverse effects on the surrounding environment
    f) Assess the effectiveness of any corrective measures taken
    g) Update the assessment of the safety and integrity of the storage complex
  - Operators submit monitoring plans based on a risk assessment
  - Monitoring plans updated in accordance with Annex II and every 5 years, approved by CA
- Helps demonstrate containment of injected CO_2 in the storage site
- Prevent negative effects on environment/human health

Monitoring

- Routine and non-routine inspections by CA are required, established by MS
- Includes visiting surface installations, assessing injection/monitoring, and checking records
- Routine inspections at least once a year until 3 years after closure, 5 years until transfer to CA
- Non-routine inspections shall be carried out:
  - If the CA has been notified or made aware of leakages or significant irregularities
  - If reports have shown insufficient compliance with the permit conditions
  - To investigate serious complaints related to the environment or human health
  - When the CA considers it appropriate
- CA shall prepare a report on inspection results, operators may be able to review
- Reports are publicly available in accordance with EU legislation 2 months of inspection

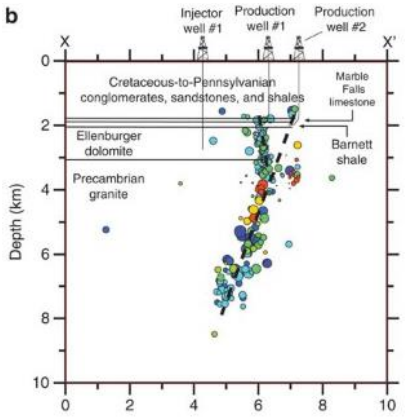
Updating monitoring plan & post-closure monitoring

- Original monitoring system and procedures may also need updating
- Plans should also be updated in the event of leakage or significant irregularities
- Changes in monitoring part of corrective measures and quantifying leakage
- Post-closure period monitoring supplements previous monitoring data
- Demonstrates permanent containment, that is:
  - a) Conformity of injected CO_2 between actual and modelled behaviour
  - b) Absence of any detectable leakage
  - c) Storage site evolving towards a situation of long-term stability
- Post-closure monitoring plan must also provide information for transfer of responsibilities to CAs
- One may expect monitoring intensity to decline over time if assessments show decreasing risk



Corrective measures

Corrective measures



Hornbach et al., 2015

- *<u>Corrective measures</u>: actions or activities taken to correct significant irregularities or close leakages, and prevent/stop the release of CO_2*
- Intended to ensure the safety and effectiveness of geological storage
- Part of the overall risk management process
- Not to be taken unless a significant irregularity is identified (e.g., leakage)
- Operators submit corrective measures plan with storage permit application
- Storage permits require that:
  - Operators of the storage site must notify the CA immediately and take corrective measures
  - Corrective measures taken based on the corrective measures plan approved by the CA
  - If operators fail to take necessary measures, the CA may do so at cost to the operators

Corrective measures

Relationship to monitoring:

- Monitoring and corrective measures closely linked, along with risk assessment
- Issues requiring corrective measures usually detected through monitoring
- Early detection of significant irregularities → early intervention
- Monitoring also used to assess effectiveness of corrective measures

Responsibilities during project phases:

- Corrective measures applicable at any stage of the project after permitting
- CA and operator interaction should be rapid/effective during implementation
- After transfer of responsibility or permit withdrawal, activities are MS responsibility

Corrective measures

Scope and format of the corrective measures plan:

- Based on site characterisation and risk assessment
- Describes potential/contingent corrective measures for each main risk
- Indicates monitoring triggers, alert thresholds, timing of deployment
- Viability/cost/number, CAs may specify minimum requirements

Documentation and reporting:

- Frequency determined by CA, at least once a year until transfer of responsibility
- Extent of reporting based on occurrence of significant irregularities, leakages, etc.
- CA ensures operators document corrective measures taken, assessed effectiveness

Corrective measures

Interpretation of corrective measures results and performance:

- Determine if leakage or significant irregularities are mitigated
- Monitoring used to assess effectiveness of corrective measures taken

Inspections:

- Routine and non-routine inspections carried out by CA
- Non-routine inspections will follow leakages or significant irregularities
- Operators bare costs incurred to perform non-routine inspections
- Monitoring and modelling reviews may be included

Corrective measures

Updates to the corrective measures plan:

- Corrective measures plans should be updated often
- No requirement on frequency or number by the CCS Directive
- Previous risks may become irrelevant or new risks might emerge
- New techniques/technology/approach might emerge or change
- Updates should be developed and consider:
  - Results from monitoring
  - Updates to the site characterisation
  - Leakage risk assessment
  - Changes to the assessed risks to environment/human health
  - New scientific knowledge and improvements in available technology

Thank you

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