Ministry of the Environment

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CMI
Accelerating Decarbonisation

CCS International Symposium

Towards Further Promotion of Social Implementation by Ministry of the Environment, Government of Japan

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Enhancing CO_2 Storage Safety and Efficiency : The Role of Advanced Modeling in CCS

Study Case :
Offshore North West Java (ONWJ)

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Today’s Topics

01

Social Implementation Challenges

The global acceptance of CCS depends on perceptions of its effectiveness, while risks diminish support.

02

Advanced Modeling for Risk Mitigation

Using geomechanical and fluid models to predict and prevent CO_2 leakage and subsidence risks.

03

Well Integrity Assessment Framework

Continuous monitoring and evaluation of well integrity to prevent CO_2 leakage during storage operations.

04

Monitoring Systems for CCS Projects

Monitoring systems are essential for ensuring the safety and effectiveness of CCS projects

05

P&A Design & Mitigation Protocols

Plugging and Abandonment (P&A) design and mitigation protocols focus on safely sealing wells after their operational life to prevent CO_2 leakage

Social Implementation Challenges

Key barriers to CCS adoption

1. **Low Public Awareness & Knowledge**
2. **Risk Perception & Negative Framing**
3. **Distrust in Effectiveness**
4. **<u>Geological Storage Concerns</u>**
5. **Responsibility & Governance Gaps**
6. **Fear of Prolonged Fossil Fuel Use**

Key Insights from Sub-seabed CO_2 Release Experiment

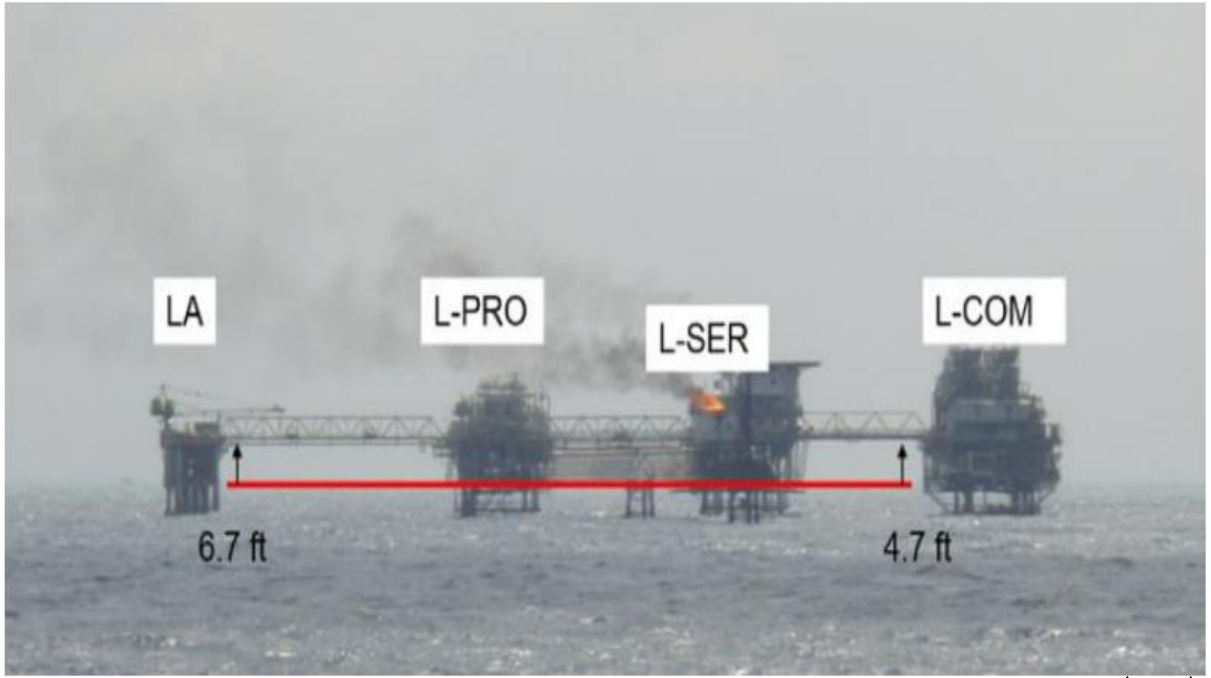
Plymouth Marine Laboratory & SAMS (2012)

1. **Minimal CO_2 Escape to Atmosphere**
   - Only **15% of the injected CO_2** bubbled out of the seabed.
   - The majority (**85%**) remained trapped in sediments, highlighting the containment potential of sub-seabed storage.

2. **Localized Environmental Impact**
   - Acidification and ecosystem changes were **confined to a 25m radius** around the release site.
   - No significant effects were observed beyond this localized area, demonstrating limited spatial impact.

3. **Rapid Recovery Post-Leak**
   - Ecosystem recovery began within **1 year** after the CO_2 release stopped.
   - Monitoring showed a return to baseline conditions, emphasizing the resilience of marine ecosystems to small-scale leaks.

Key Insights on Subsidence in Depleted Reservoirs for CCS Storage Potential



Wijaya, BR (2019)

1. **Geomechanical Risks**: Prolonged production (e.g., Parigi limestone in ONWJ) caused 3.5 m+ subsidence, leading to casing buckling, microcracks, and wellhead displacement.

2. **Porosity-Driven Compaction**: Soft, high-porosity carbonate reservoirs (e.g., Ardjuna chalk) compacted >10m, transferring stress to overburden and casing.

3. **Well Integrity Challenges**:Subsidence-induced casing deformations (buckling, shear) complicate plugging and abandonment (P&A).

4. **Mitigation Strategies**: Electromagnetic casing inspection, acoustic logging, caliper logs, cement bond logging, and bubble detection systems.

In Case ONWJ :

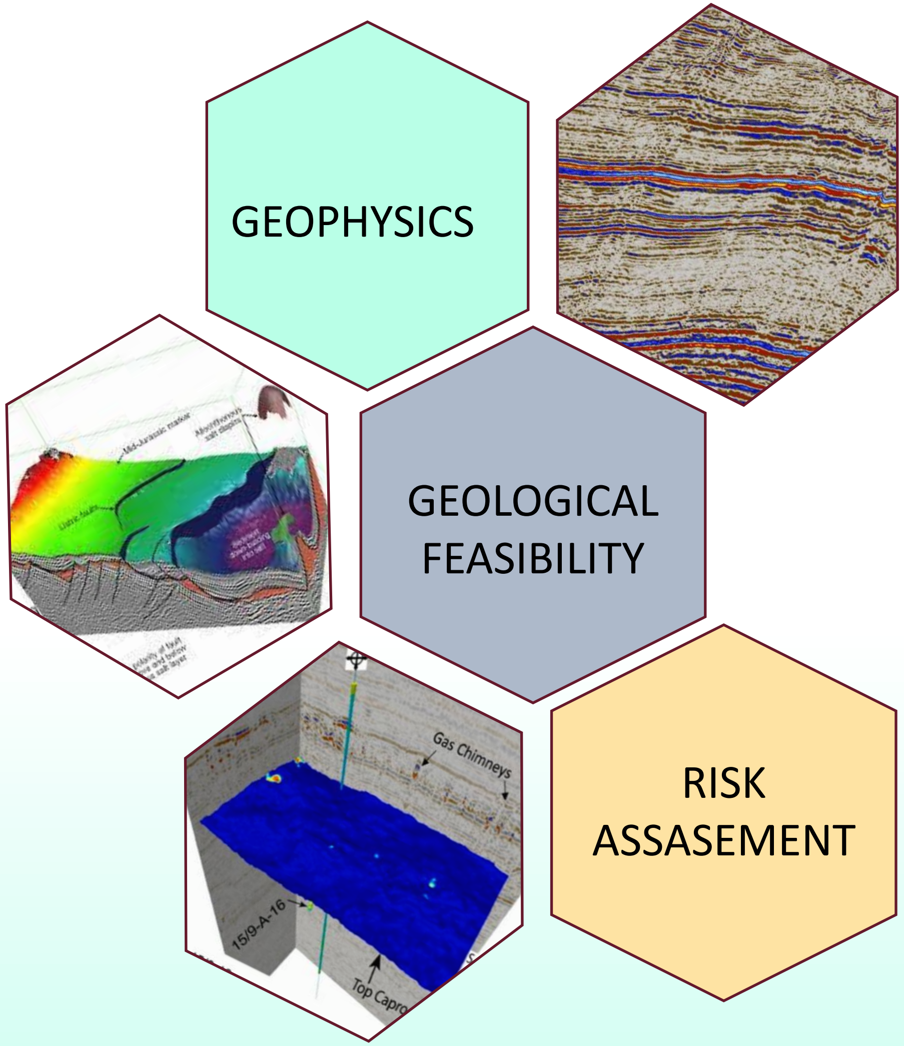
Depleted reservoirs offer CCS potential but require rigorous geomechanical assessments, real-time integrity monitoring, and adaptive abandonment designs to address subsidence legacy risks and fault reactivation. This can lead to leakage risks if utilized for CO_2 storage

Subsidence in ONWJ's depleted reservoirs (e.g., Parigi limestone) directly impacts injectivity through **porosity reduction** (>10 m compaction in the central of Arjuna field) and **casing deformations** (buckling, microcracks)

Assessment of leakage impact on CCS deployment

1. **Carbon leakage in CCS** can occur during **transportation**, **injection**, or **storage**.
2. Potential leakage pathways include:
   - **Faults and fractures** in the geological caprock.
   - **Wellbores** from previous drilling activities that may not be properly sealed.
   - **Seabed seeps**, where CO_2 escapes through weak points in the seabed.
3. **Injection Leakage.** Leakage during injection occurs at the **wellbore**, where CO_2 is injected into the storage site. Causes include: Poor cementing of the well, high injection pressures causing fractures in the surrounding rock, etc
4. **The findings reveal that even minimal leakage rates—as low as 0.1% per year**—could result in cumulative emissions of 25 gigatonnes of CO_2 ($GtCO_2$) by 2100. *Vinca, Adriano (2018)*
5. **Public perception of leakage is a critical barrier to CCS deployment**, particularly in cross-border projects. Uncertainty about which country is liable for leakage and its consequences.
6. **Site Selection and Risk Assessment.** Extensive geological assessments to identify low-risk storage sites, such as depleted oil and gas or saline aquifer fields with proven sealing integrity. **Advanced Monitoring Technologies:** Real-time pipeline monitoring systems and subsurface imaging to detect leaks early.

Advanced Modeling for Risk Mitigation



Leverage the Full Field 3D Geomechanical Model to integrate advanced complex processes, predict fault reactivation, and forecast CO_2 plume migration, ensuring safer and more efficient CCS operations.

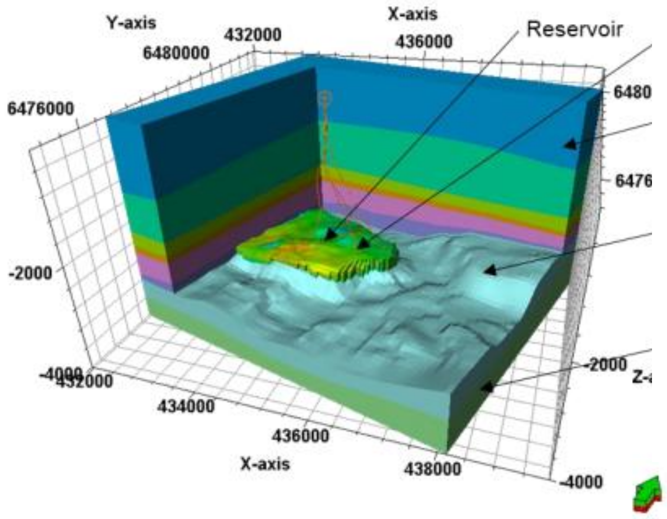
1. Coupled THMC Modeling

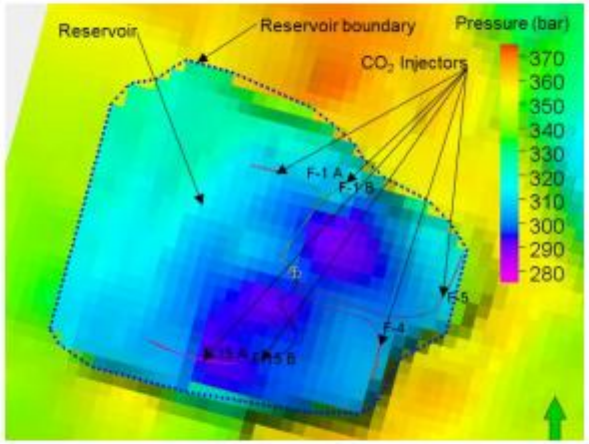
Integrate **Thermal, Hydraulic, Mechanical,** and **Chemical** processes to predict CO_2 leakage and subsidence risks (Alam et al., 2023).

2. Fault Reactivation Prediction

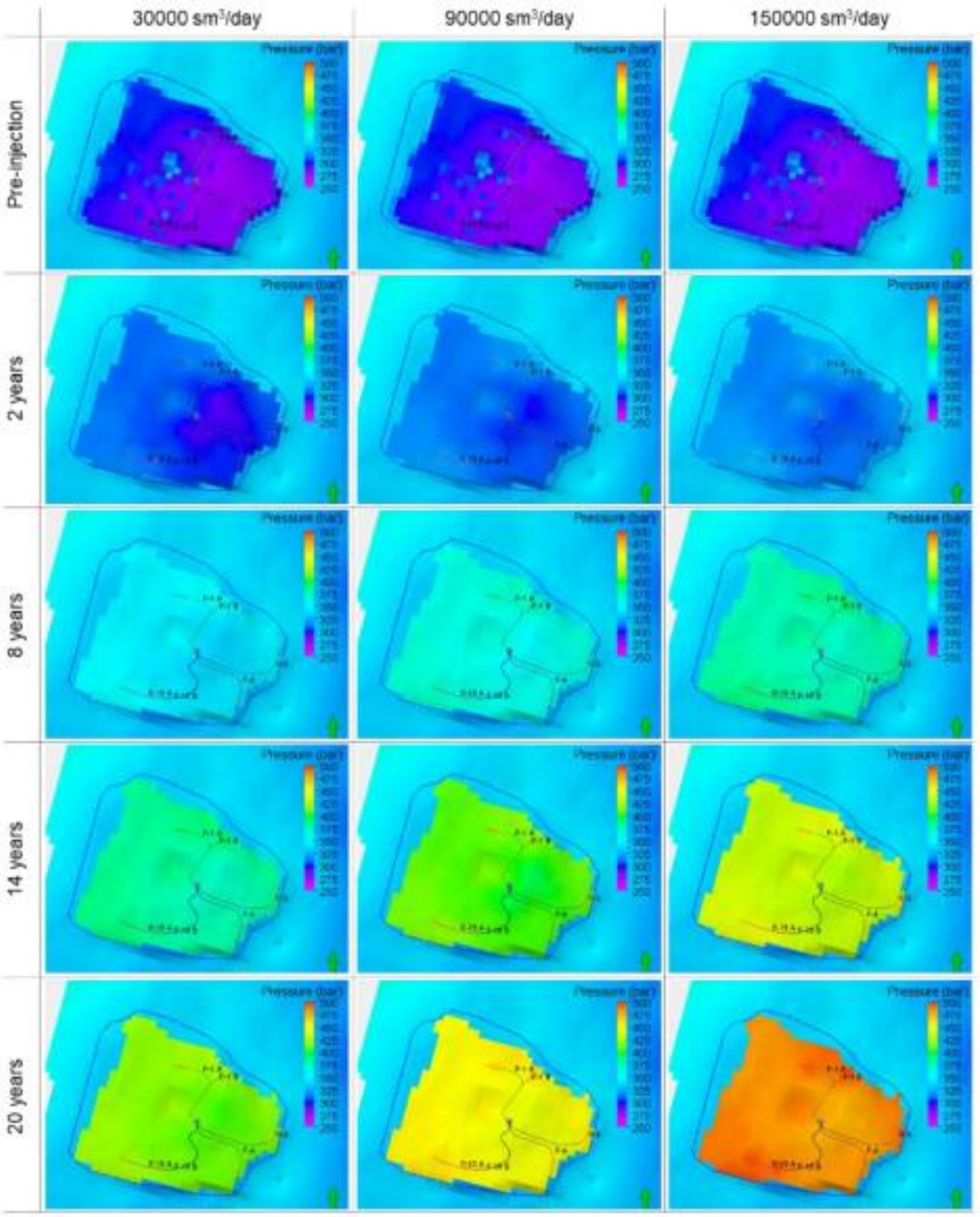
Use Mohr-Coulomb criteria and dynamic stress modeling to assess fault slip risks under injection pressures.

3. CO_2 Plume Migration Forecasting





(Alam et al., 2023).

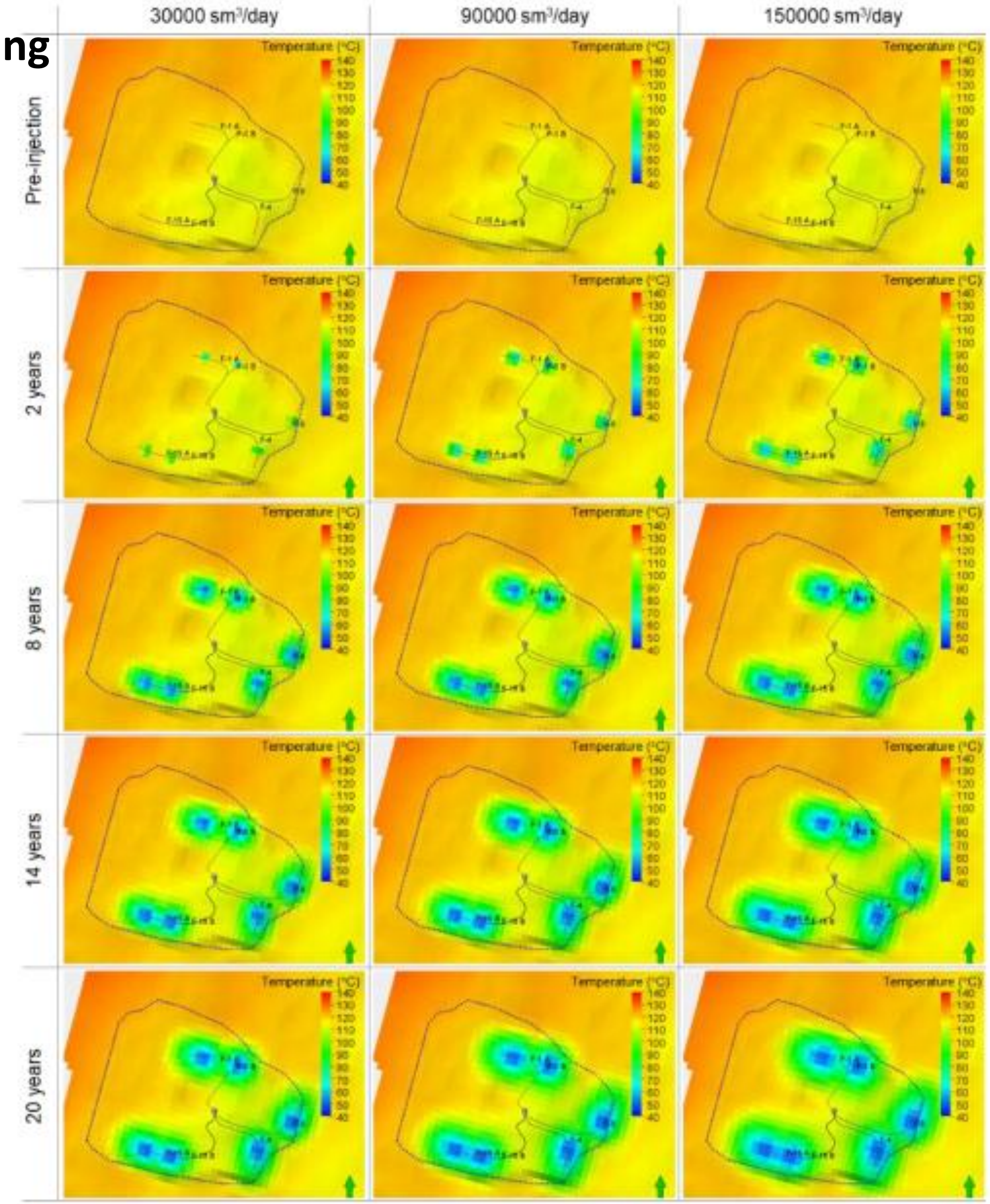


- The **Volve Field Dataset**, made publicly available by Equinor in 2018, It provides detailed real-field data covering geology, reservoir properties, production, and a geomechanical model was built based on Volve structural model which covers an area of 7.6 km by 6.9 km.

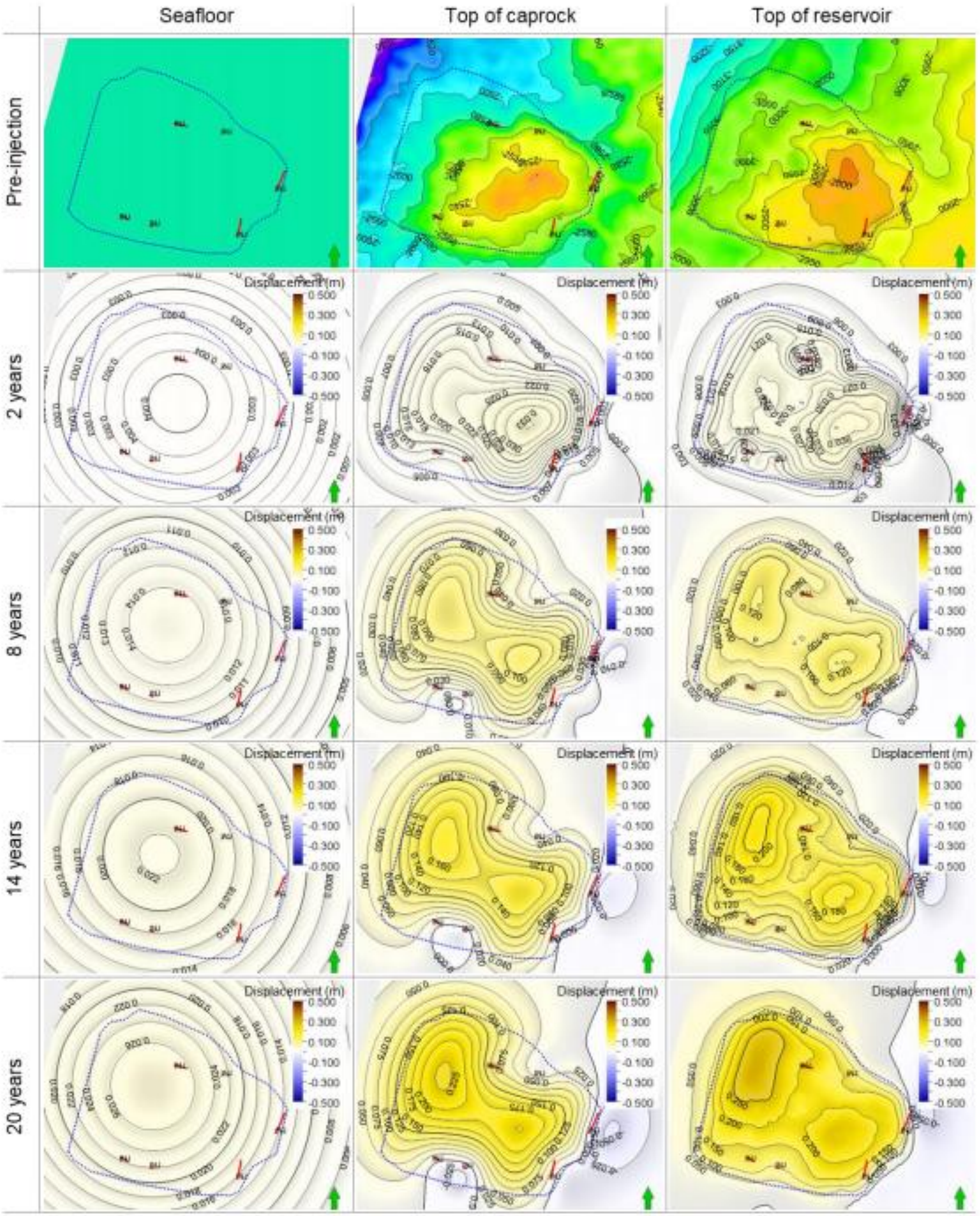
- Pressure evolution maps chart the reservoir's response over time (up to 20 years) under different CO_2 injection rates (30,000 sm³/day, 90,000 sm³/day, and 150,000 sm³/day).

- These maps show pressure propagation as CO_2 is injected, demonstrating changes in reservoir stability and potential risks like fault reactivation or overpressure zones.

Coupled THMC Modeling



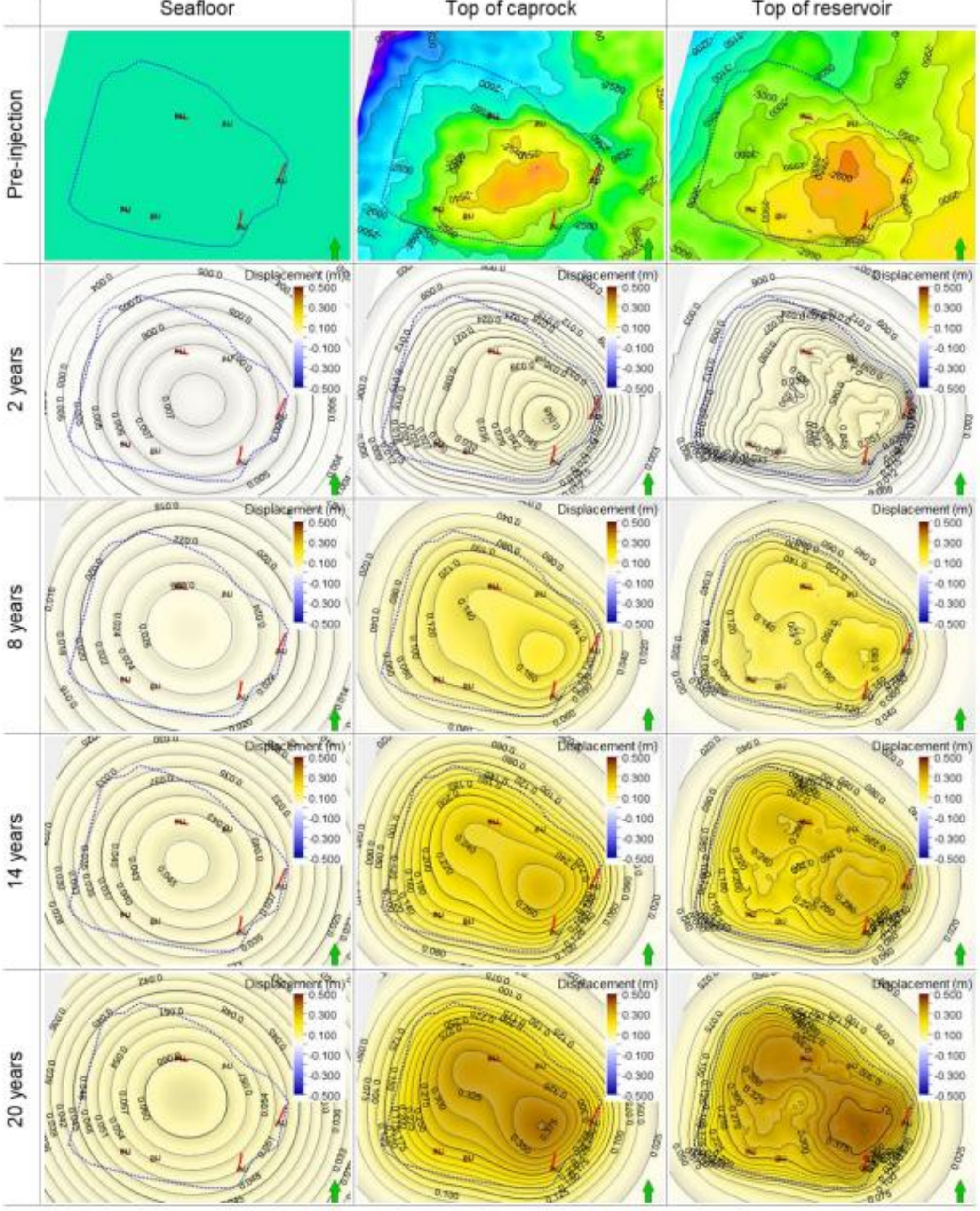
Map view of the distribution of temperature in the reservoir for three injection rates.



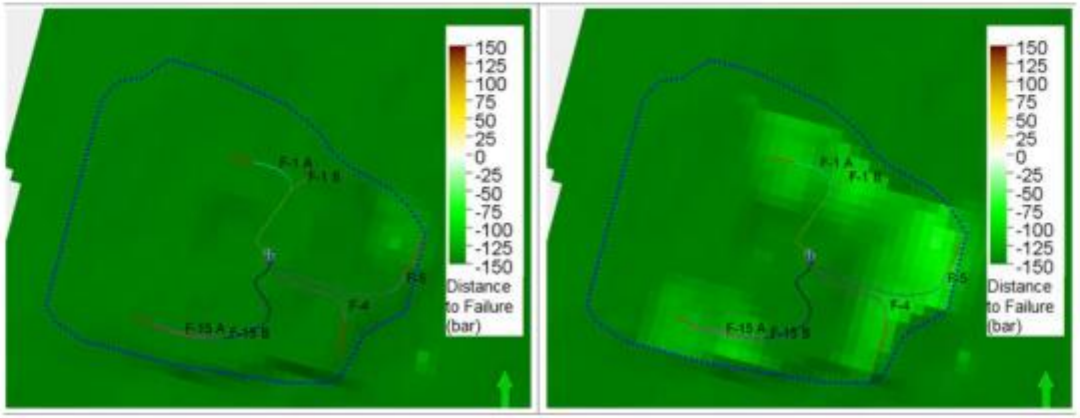
Vertical displacement with cooling.

Fault Reactivation Prediction

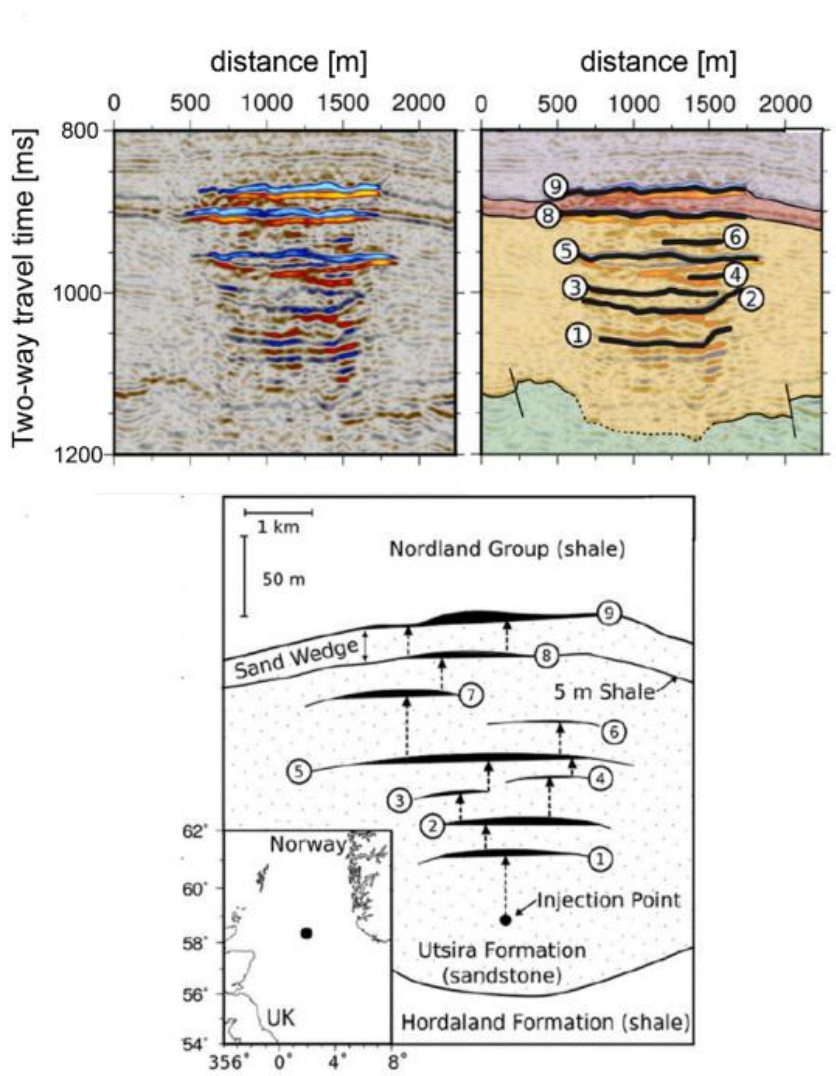
- Injection of large amount of CO_2 may cause **large displacement** of the geological formations.
- Large amount of rock displacement increases the **risk of failure** of wellbore, casing, cement, platform etc.

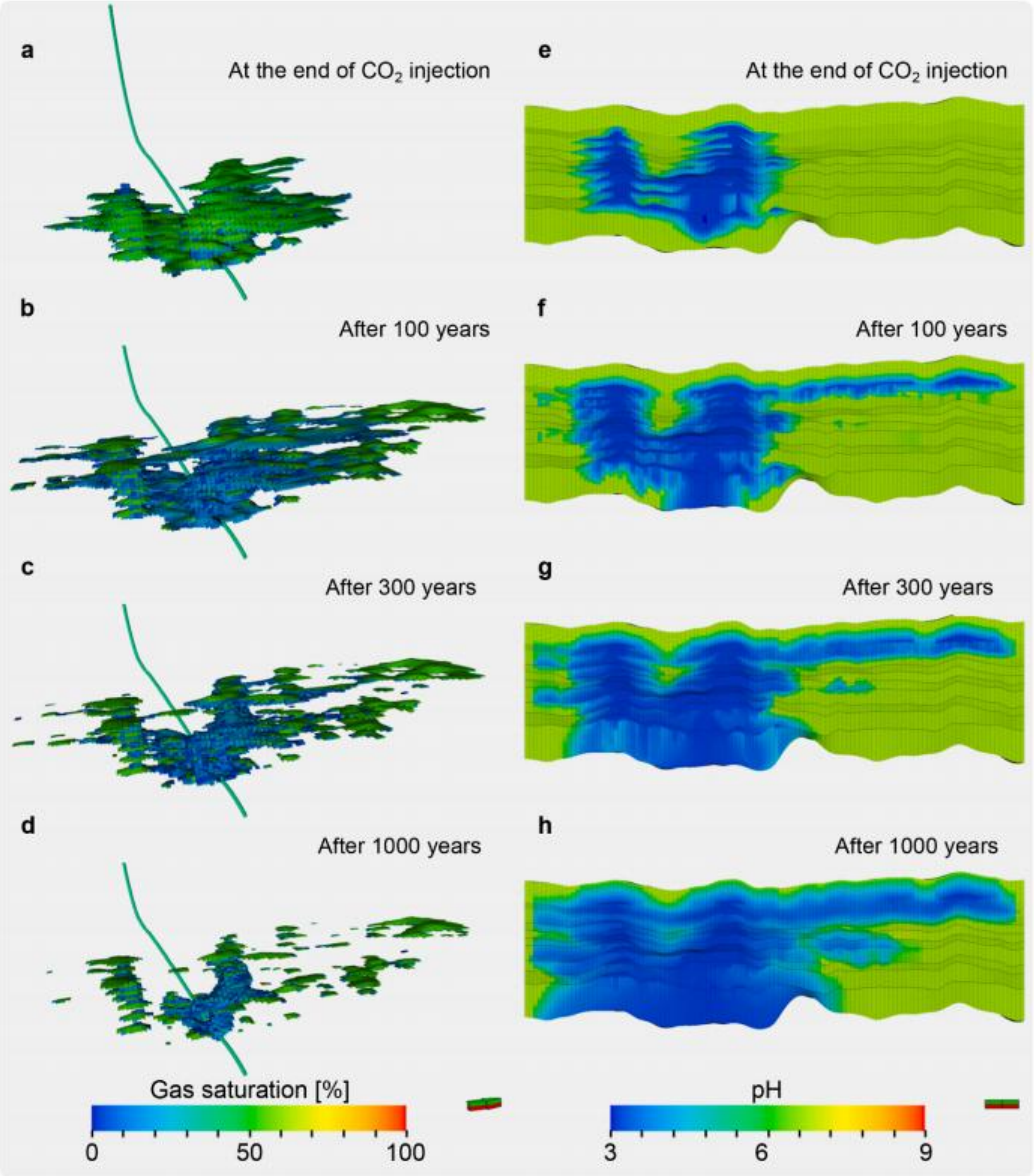


Vertical displacement without cooling. Map view of the vertical displacement at top the reservoir, the caprock and the seafloor for maximum injection rates 150000 sm3/day



Plume Migration Forecasting



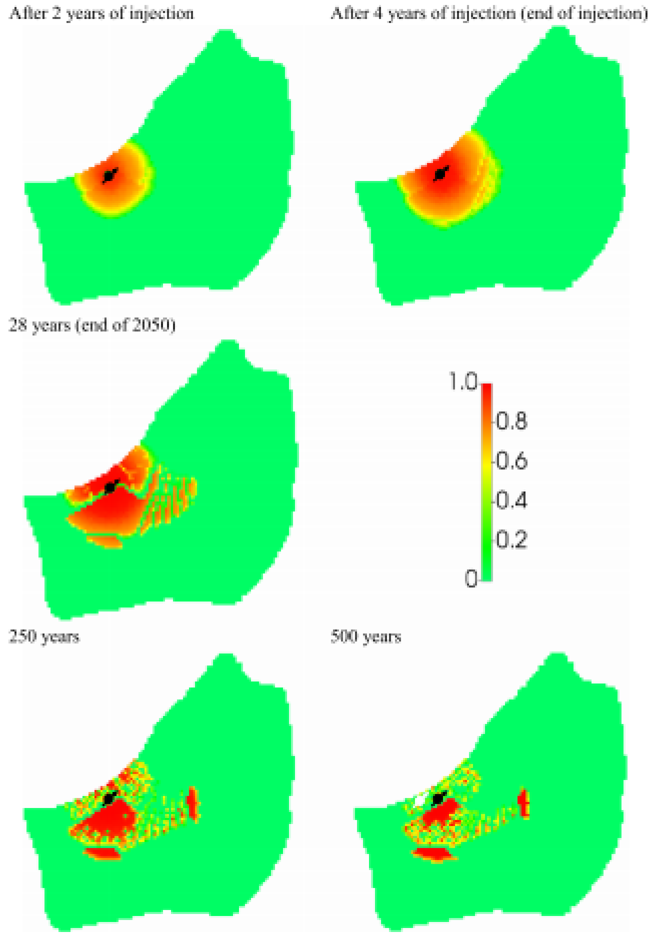


Sleipner CCS benchmark model, Akai et al (2021)

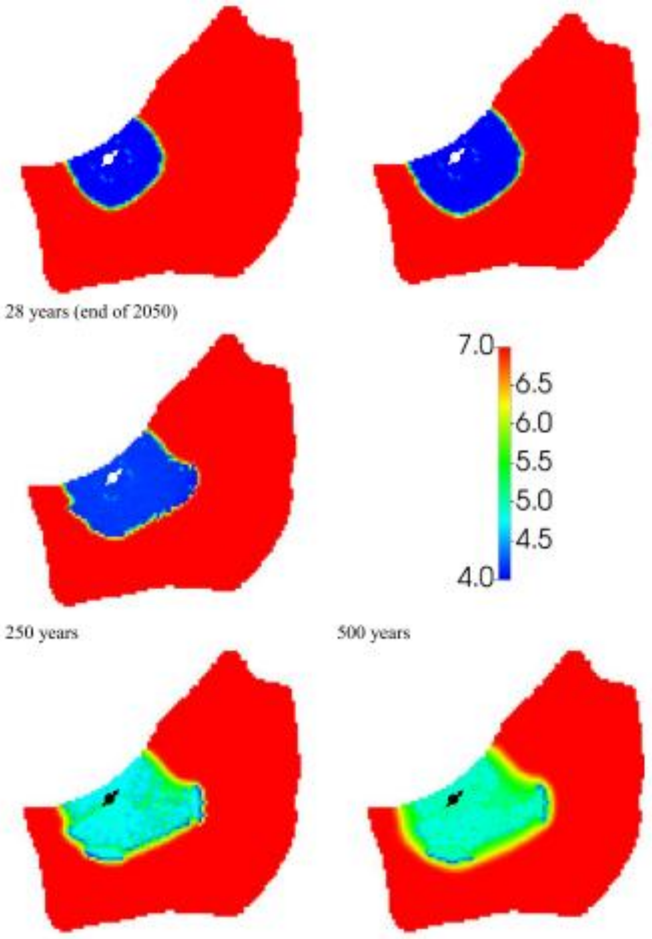
Plume Migration Forecasting

Case Offshore Pearl River Mouth Basin

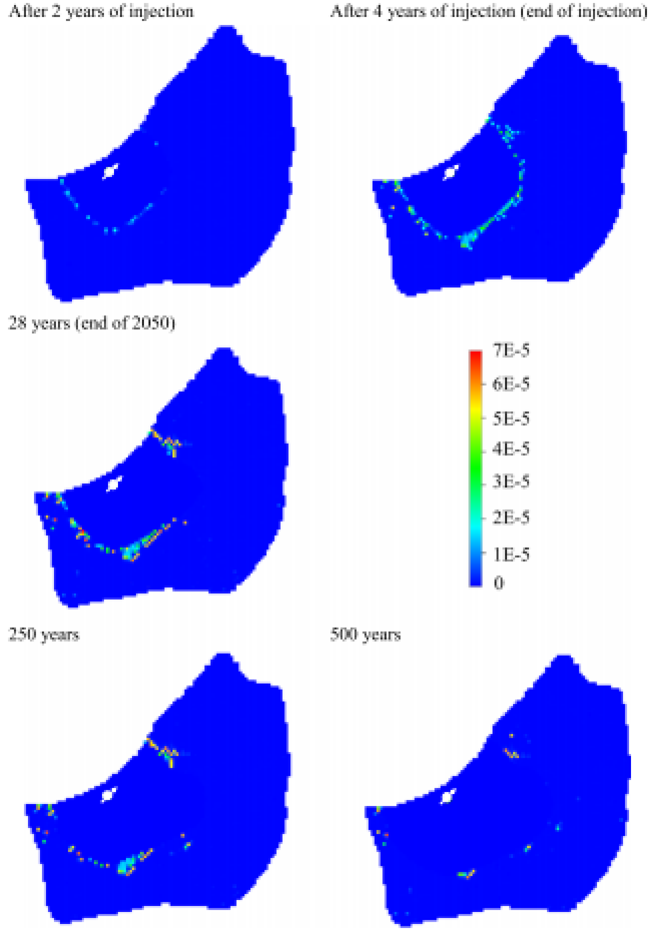
Shi & Gates (2024)



Supercritical CO_2 gas saturation in the top layer of sandstone



pH distribution at the top of the sandstone versus time

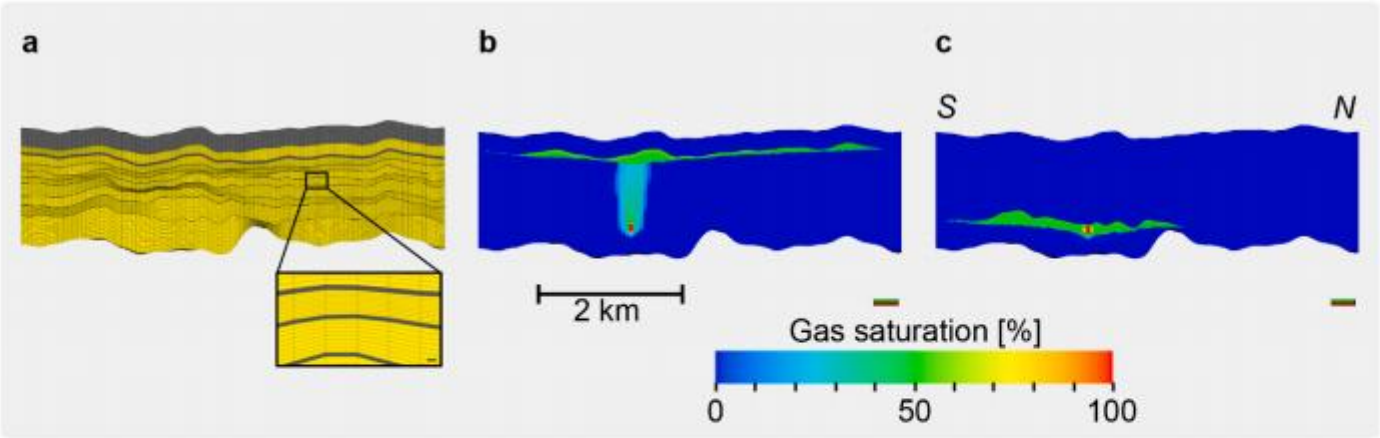


Calcite (kg/m3) mineralization at the top of the sandstone versus time.

Well Integrity Assessment Framework

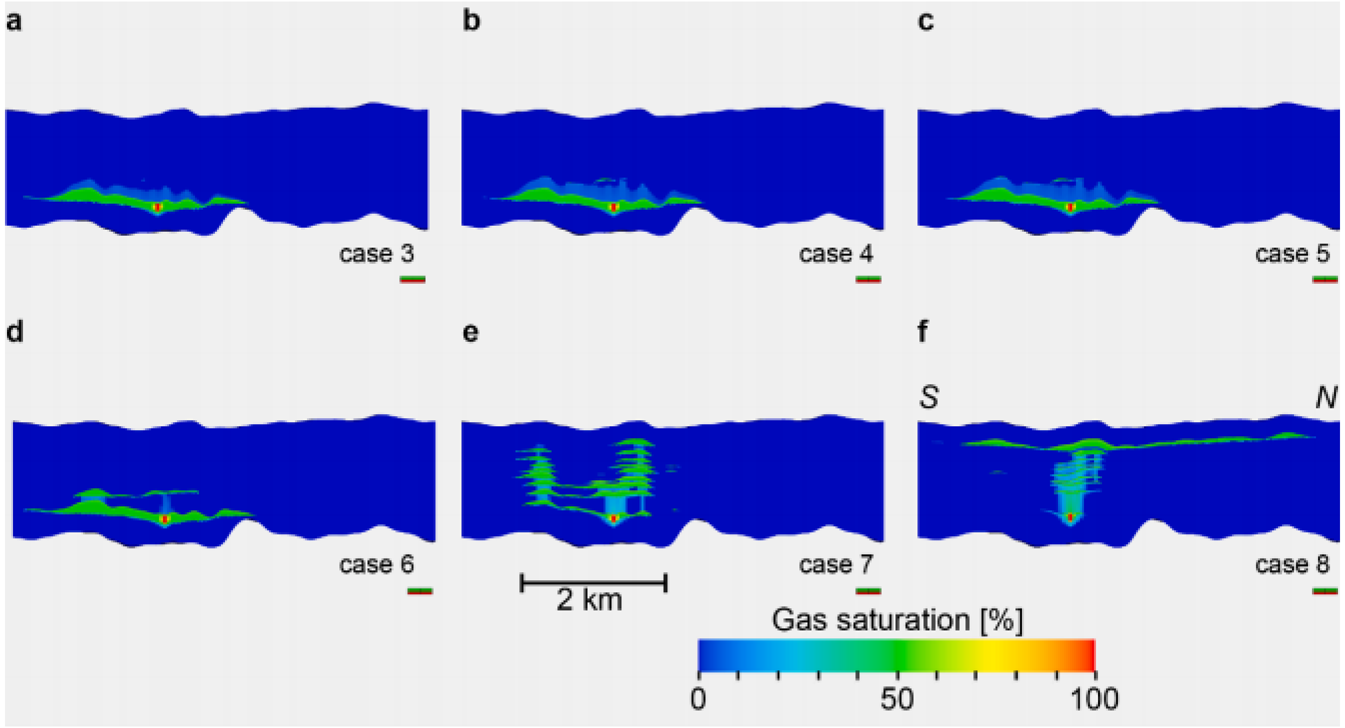
1. **Caprock Integrity**
2. **Cement Degradation**
3. **Sustained Annulus Pressure Monitoring**

Caprock Integrity



- The simulated distribution of CO_2 after 12 Mt of injection for these cases is shown. In case, the injected CO_2 moved upward from the injection point in base/bottom layer and reached caprock layer , immediately below the caprock layer.

- Thereafter, the CO_2 plume moved more than 6 km laterally within caprock layer, resulting in a broad plume distribution.



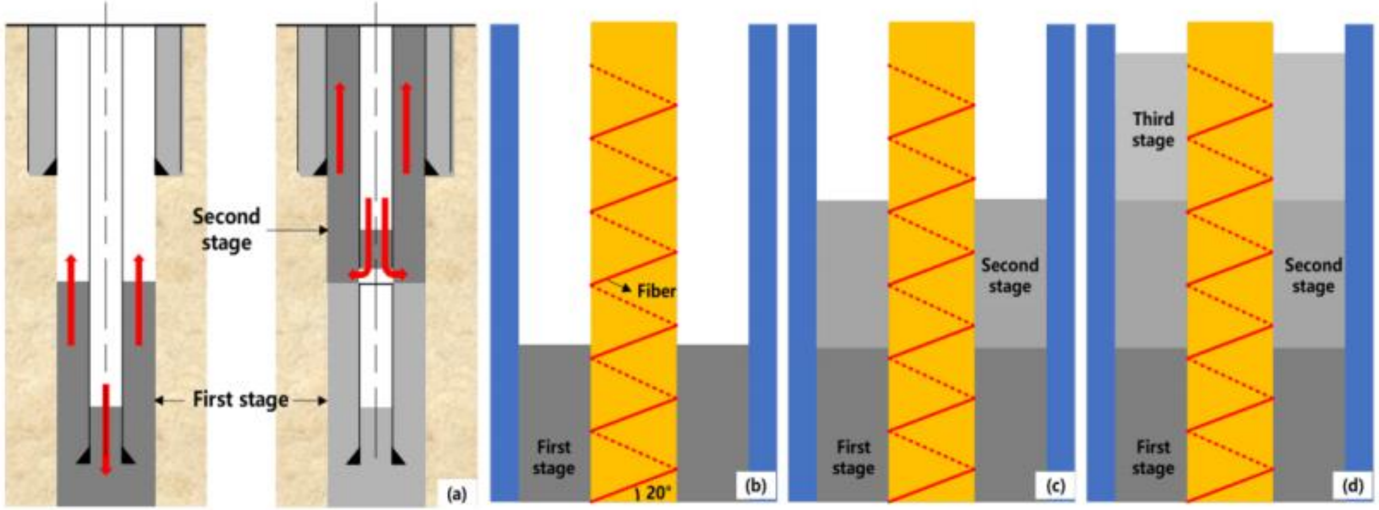
Simulated CO_2 migration after 12 Mt injection, considering different rock properties of the intraformational mudrock layers.

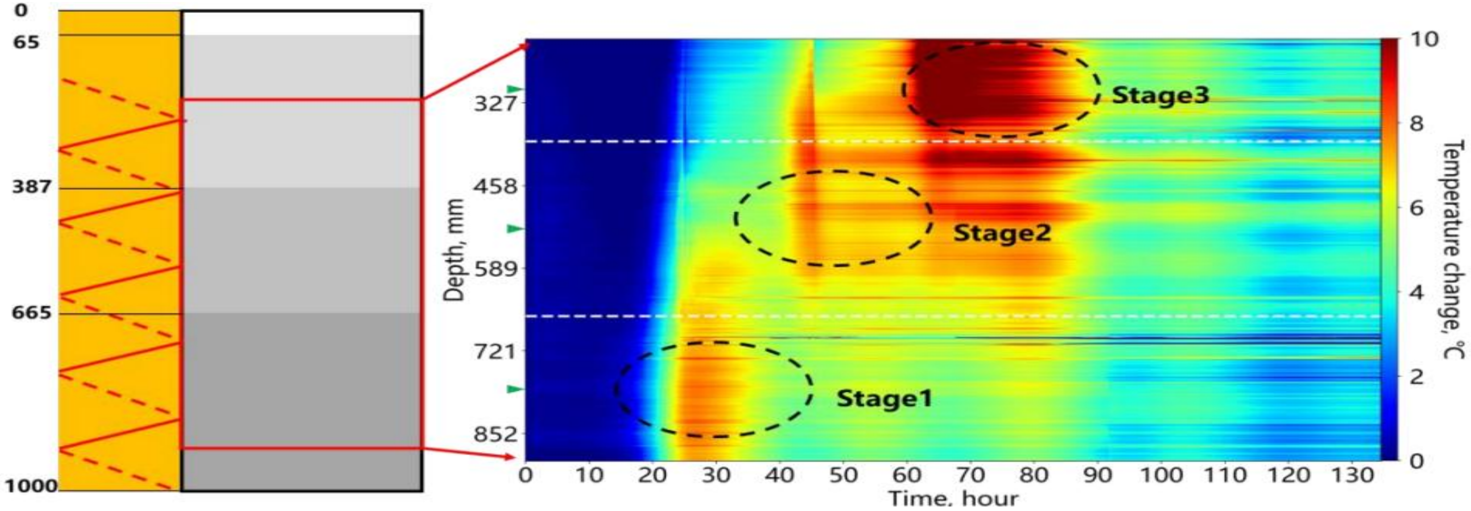
Akai et al (2021)

Cement Degradation

- Distributed fiber optic temperature (DTS)monitoring was conducted to identify annular cement/cement bond deficiencies , DTS results closely matched the thermocouple data, confirming the feasibility and accuracy of fiber optic monitoring for the cement hydration process.

- A further investigation should inspect how pressure, temperature, and chemical reaction affect the micro-annuli of casing/cement or cement/formation





Li, Zhong et al (2025)

Sustained Annulus Pressure Monitoring

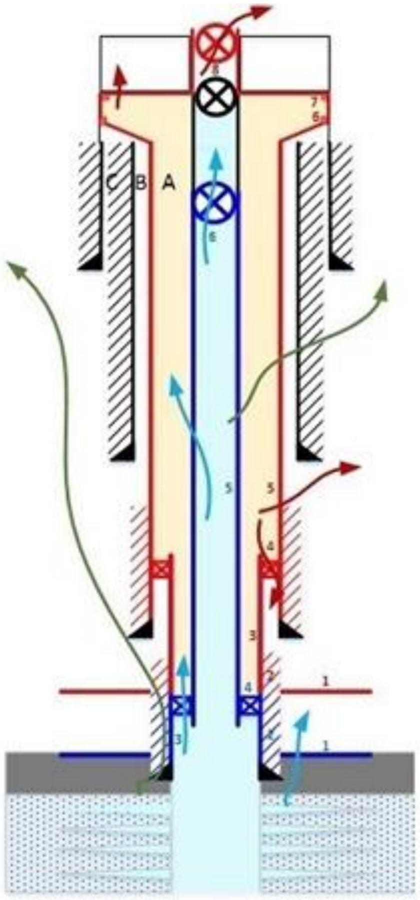


Illustration of possible leakage paths in a production/injection well, adopted from (Vrålstad et al., 2015)

- Continuous monitoring of well casing and annulus pressure to detect early signs of leakage.

- Main differences between CCS and conventional petroleum wells, the highest pressure at the end of CO_2 injection, corrosive environment , cement degradation, impurities in the CO_2 , etc

- Some of the challenges related to these aspects are potential for formation damage, efficiency of perforations, flow assurance through the well and into the reservoir, predicting phase behaviour of the CO_2 which can also be dependent on the type of reservoir (aquifer vs. depleted vs. depleted with a history of EOR).

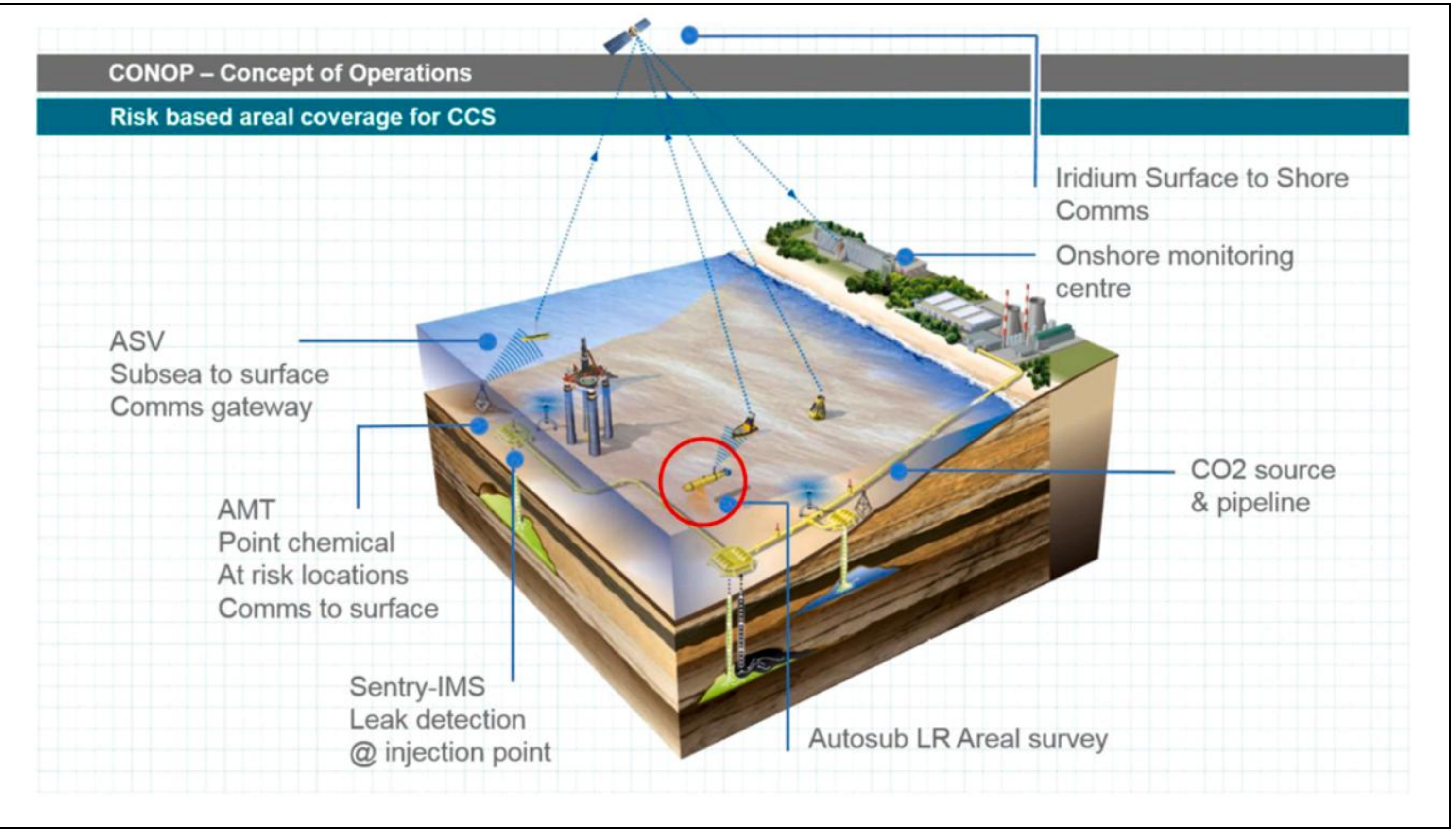
-CCS Well Design Requirements, SINTEF, 2024

Monitoring Systems for CCS Projects

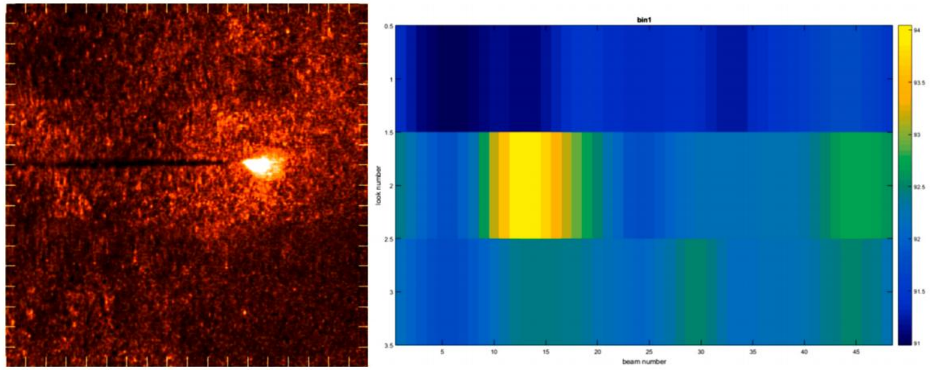
advanced monitoring technologies and workflows

1. **Integrated Monitoring Workflows**
2. **Seabed Monitoring Technologies**
3. **Microseismic Networks**

Integrated Monitoring Workflows

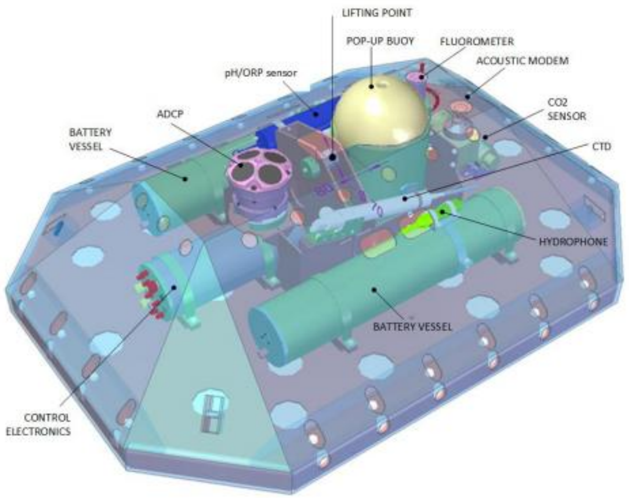


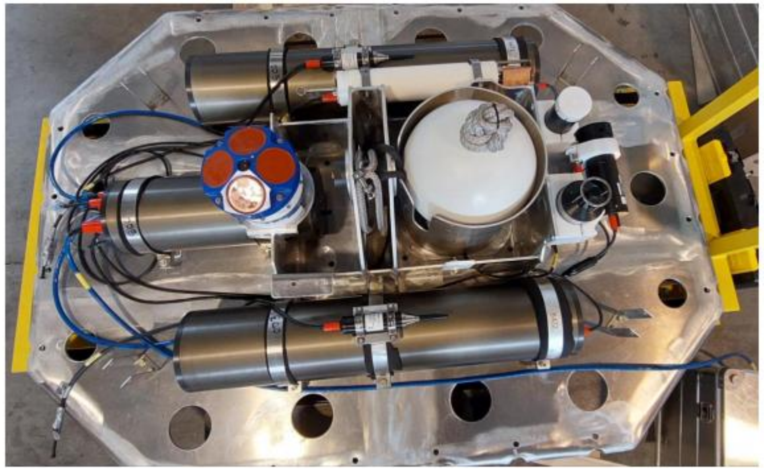
The UK Energy Technology Institute led the ETI MMV project which started in February 2014 and successfully completed by February 2018



AUV mounted solstice side scan sonar using Multipath Suppression Array Technology (MSAT) detect leak 10-50 L/min

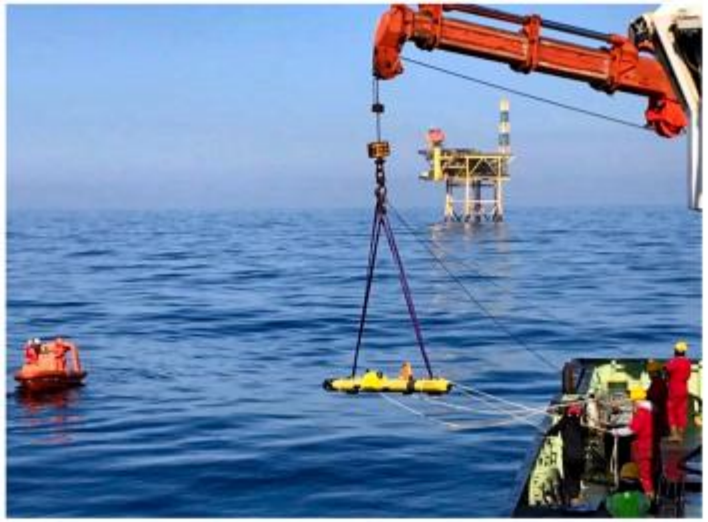
Seabed Monitoring Technologies





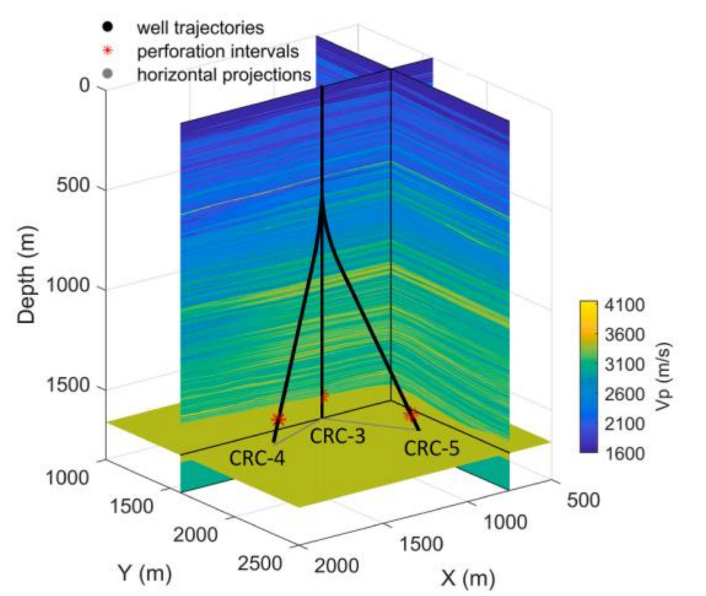
Eni S.p.A Lander instrumentation mechanical integration with : CO_2 sensor, pH/ORP sensor, CTD-O2 sensor, Fluorometer (Turbidity, Chlorophyll, CDOM), ADCP, Acoustic modem, Acoustic release, Battery pack, DACS (Data Acquisition and Control System), pop-up buoy.

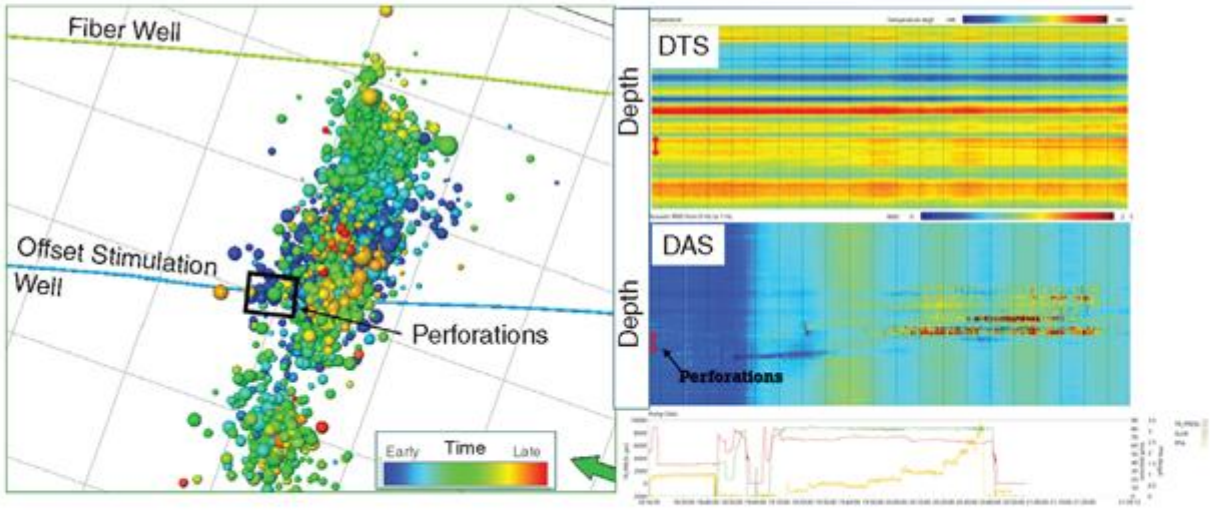
The active sonar lander prior to deployment on harbour trials



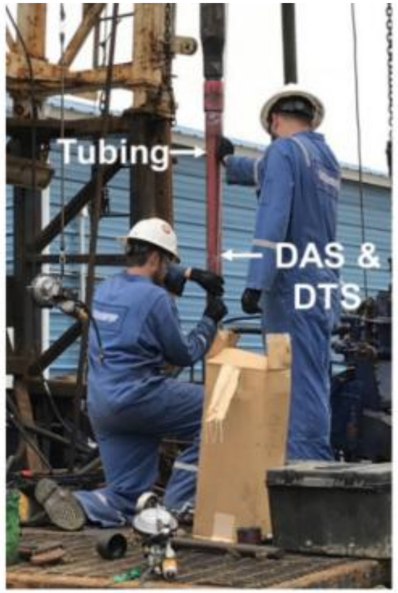
Deploying the AUV Teledyne near the platform

Microseismic Networks using DAS/Fiber optics





(a)



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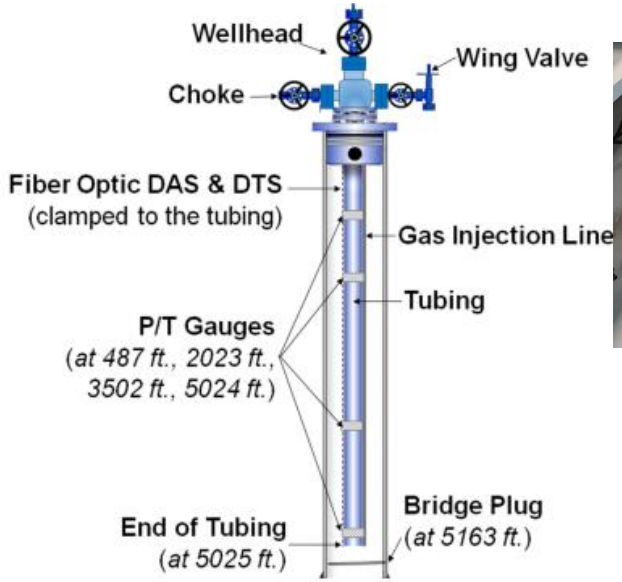
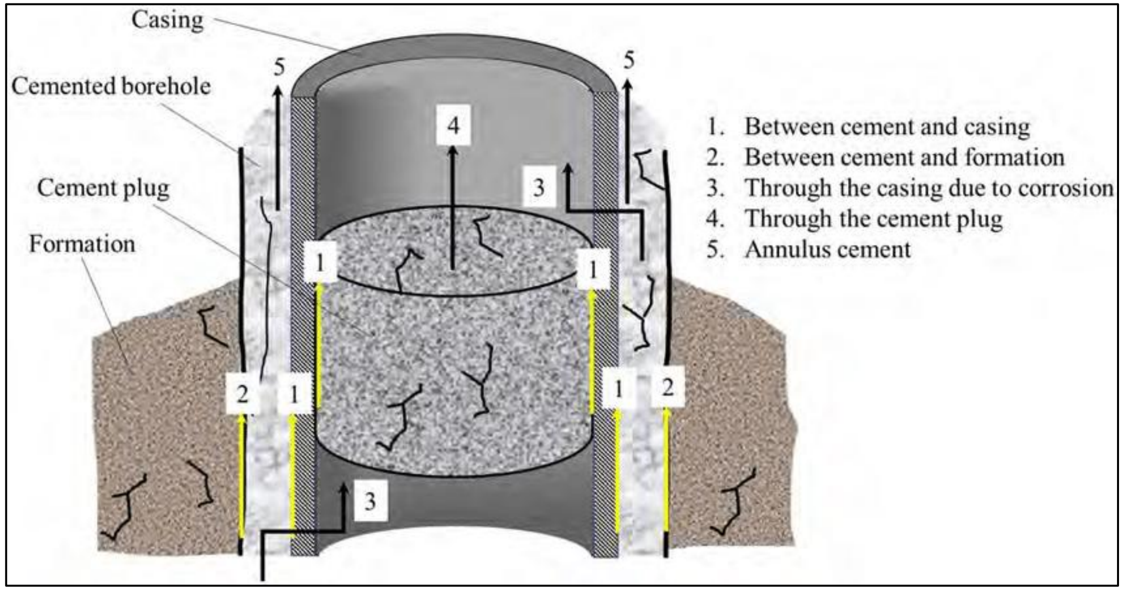


P&A Design & Mitigation Protocols

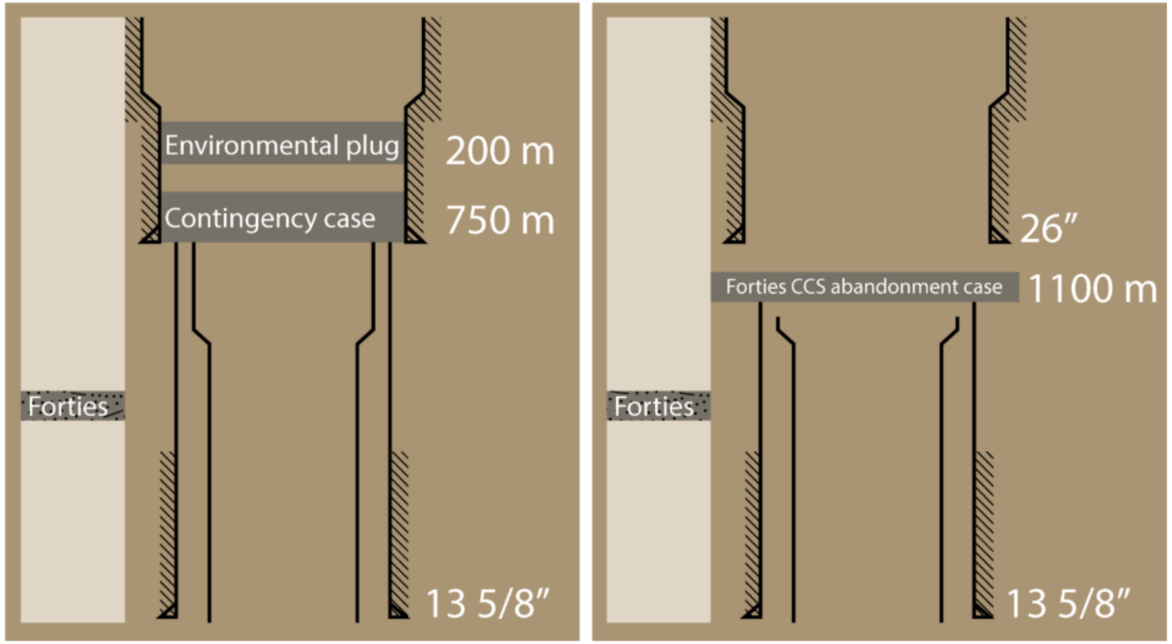
well abandonment and risk mitigation

1. **Plugging Standards**
2. **Risk Mitigation Protocols**
3. **ISO Documentation**

- Follow ISO 27914:2017 guidelines for well abandonment, including cement plug placement and verification.
- Establishing Best Practices for Well Abandonment in CCS
- Shell Abandonment Concept for Injection Wells



CO_2 leakage pathways from subsurface to atmosphere



Conventional abandonment design (left) versus CCS case abandonment design (right) for the Jaws well. Adapted from Shell.

The conventional way of abandoning this well would not have been sufficient. Shell designed and delivered the Jaws well according to the current CCS requirements, thus eliminating the risk of future CO_2 leakage pathways.

Forties sandstone that case, a plug was required approximately 500 m below the 20″ casing shoe, which means that an additional 1,000 m of casing was to pulled out of the hole in order to expose the 13-5/8″ outer casing. (GeoExpro)

Risk Mitigation Protocols

Immediately reduce injection rates to stabilize pressure.

Mechanical Isolation
, Cement Plugging

Reinforce caprock,
pH buffering,
Long-term monitoring

Leak Detection & Assessment

Well Closure Procedures

Post-Closure Mitigation

Activities in ONWJ Block

- **Pertamina Hulu Energi Offshore North West Java (PHE ONWJ)** and **POSCO International** have entered into a **Joint Study Agreement (JSA)** to evaluate potential CO_2 storage sites in the ONWJ offshore area, focusing on saline aquifers and hydrocarbon reservoirs.

- The **roadmap for Carbon Capture and Storage (CCS) development** in the ONWJ Block is currently under review by Pertamina, the licensed operator. It requires approval from **SKK Migas** if a **Plan of Development (PoD)** is proposed, integrating **Enhanced Oil Recovery (EOR)** or **Enhanced Gas Recovery (EGR)** with ongoing oil and gas exploration activities.

- **CMI** has signed a **Memorandum of Understanding (MoU)** with **Migas Utama Jabar (MUJ)** for An Inisiative on CCS concept development. MUJ holds a **10% Participating Interest** in the ONWJ Block.

CMI Activities

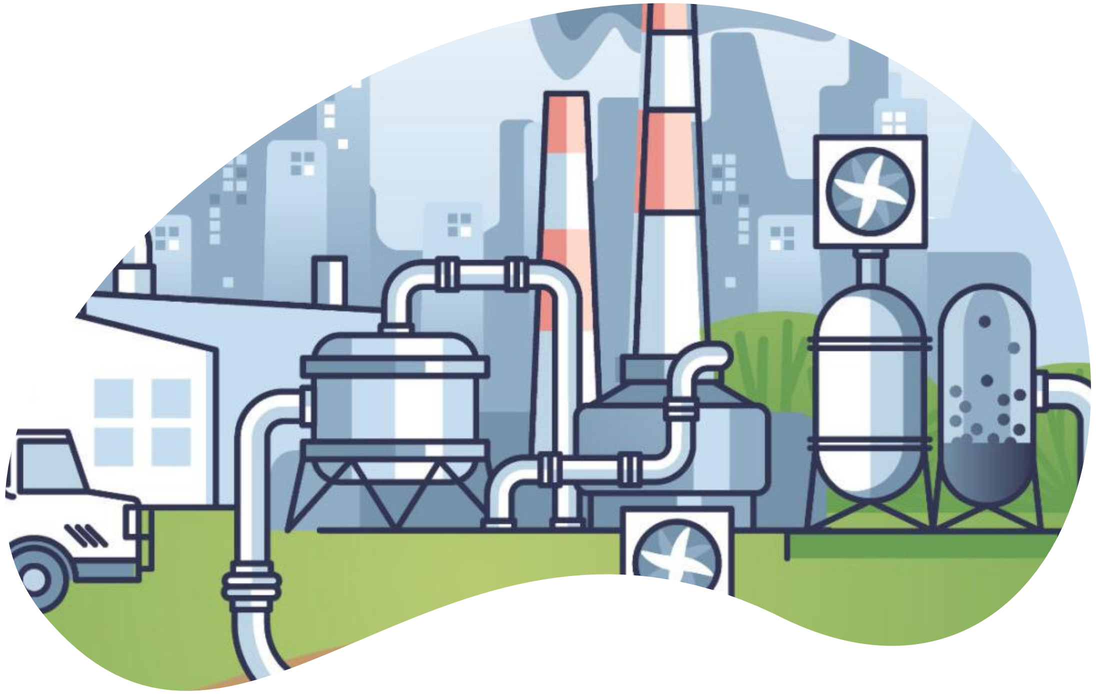
- **Screening and Ranking of Legacy Oil & Gas Wells** for **CO_2 Storage Potential** in Indonesia, with approximately **18,000 wells analyzed.**
- **Development of Distributed Acoustic Sensing (DAS) and Fiber Optic Technologies** for seismic passive and active monitoring systems. The project is conducted in collaboration with the **National Research and Innovation Agency (BRIN)**.
- **Design and Development of Electrochemical and Semiconductor Gas Sensors** for **Flare Gas-to-Power Applications.** This innovative research is carried out in partnership with the **National Research and Innovation Agency (BRIN)**.
- **Facilitation of Knowledge Sharing and Collaborative Discussions** on **Carbon Capture and Storage (CCS) implementation**, focusing on best practices and emerging technologies.

SORTED — TOTAL WELLS EXAMINE 18,230

RANK	AREA CO2 STORAGE	SITE REMARKS	SCORE	N WELLS
1	Onshore Southern Sumatera	Muara Enim, Lahat	1973.97	2,968
2	Onshore Central Sumatera	PHR	1961.22	3,485
3	Offshore Eastern Kalimantan	PHM, PKT	1476.80	2,785
4	Offshore Southern Sumatera	CNOOC	719.33	1,788
5	Offshore Western Java	ONWJ	169.64	1,083
6	Onshore Northern Sumatera	NSB, Langkat	163.29	1,362
7	Onshore Eastern Kalimantan	PHM	136.37	1,132
8	Onshore Northern West Papua	Bintuni, Wiliagar	28.88	770
9	Offshore Natuna	East & West Natuna	22.25	505
10	Onshore Central Java	Cepu, Wonocolo	19.59	389
11	Onshore Northern Kalimantan	Nunukan	11.23	330
12	Onshore Western Java	ONWJ, EP, Jatibarang	9.89	454
13	Offshore Eastern Java	WMO, Saka	4.41	290
14	Onshore Eastern Java	Blora, Cepu, Brantas	3.32	270
15	Offshore Central Kalimantan	PHM	-0.03	1
16	Offshore Central Java	Saka	-0.53	22
17	Offshore Northern Kalimantan	Bulungan, Deep Water	-0.89	38
18	Offshore N			
19	Offsho			
20	Onshore			
21	Offshore			

DAS Interrogator

Interactive Database for Screening



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