Carbon Capture & Storage (CCS)

Themes from EAGE2023

I summarized over 30 abstracts from the EAGE 2023 Conference & Exhibition related to various aspects of CCS. Five broad themes are addressed with hyperlinks provided to each relevant abstract. Familiarity with the academic and industry literature related to CCS, as well as the research methods and scientific conventions used in these fields, would be beneficial when reading the following.

- CO_2 Storage Methods: Various methods exist for storing CO_2 in subsurface geological formations such as depleted hydrocarbon reservoirs, saline aquifers, and shale formations.
- Geomechanical Considerations and Subsurface Characterization: Geomechanical aspects such as pressure-induced leakage, induced seismicity, and fault-induced CO_2 migration must all be understood. Subsurface characterization and modeling before CO_2 injection are critical to mitigate risks associated with these phenomena.
- Measurement and Monitoring Technologies: The application of ultra-high resolution (UHR) towed streamer seismic and distributed acoustic sensing (DAS) in measuring seismic data for CCS applications is growing. These technologies help in high-resolution imaging of the CO_2 plume and can potentially monitor the CO_2 plume dynamics.
- Site Screening and Selection: Several abstracts presented methodologies for CCS site screening and selection, with emphasis upon data-intensive processes, machine learning-based interpretation, and comprehensive geological evaluations. Basin-scale considerations, reservoir properties, subsurface characterization, and uncertainty management are all relevant to the site selection process.
- Long-term CO_2 Sequestration and Monitorability: The transition from structural and stratigraphic trapping to dissolution trapping over geological timescales is highlighted. It also highlights the importance of 4D (time-lapse) seismic monitoring for detecting changes due to CO_2 injection.

CCS Abstracts at EAGE 2023: Setting the Scene

I reviewed over 30 related abstracts from the 84th EAGE Conference & Exhibition, held in Vienna during June 2023, and summarize several key themes below. Hyperlinks to the relevant PDF abstracts hosted at the https://www.earthdoc.org database are provided on the assumption that readers have appropriate access.

Broadly speaking, CO_2 injected into the subsurface can be trapped via three mechanisms: Structural trapping, residual trapping/capillary trapping, and mineral trapping. Correspondingly, four considerations are relevant to the selection of CCS injection sites and the long-term monitoring of the project integrity:

- **Capacity**: The storage ‘container’ volume, and static reservoir and CO_2 properties.
- **Containment**: Description of the overburden and seal integrity, including all geomechanical considerations.
- **Injectivity**: Architecture of the storage reservoir, permeability, pressure regime, and dynamic performance.
- **Monitorability**: Ability to monitor CO_2 plume movement, detect leakage, establish model conformance, etc.

When evaluating these considerations, geoscientists and reservoir engineers must consider the properties of relevant fluids, how pressure and temperature evolve within the reservoir, and how the fluid phases evolve or chemically interact with the reservoir rocks. Therefore, the life cycle of identifying and operating CCS sites must consider everything between the geological basin scale to the poroelastic scale of investigation.

Most CCS abstracts at EAGE 2023 addressed CO_2 storage in either depleted hydrocarbon reservoirs or saline aquifers. Nevertheless, it was noted that due to their wide availability, advantageous mineralogy, and pore structure, shale formations have also become an alternative for CO_2 storage. Because of the high reactivity of CO_2 to shales, the mineralogical alteration (contingent upon mineralogy) after CO_2/brine/shale interaction will play a crucial role in determining the sealing properties of shales at the geological time scale. Furthermore, the formation of carbonic acid can also create an excellent possibility for mineral trapping. It is worth noting here that supercritical CO_2 can typically only be injected into shales (primarily associated with EOR in unconventional shale developments) when the formation is extensively fractured.

Beyond geochemical processes, relevant geomechanical considerations include pressure-induced leakage and the possibility of induced seismicity. Faults and associated fracture sets can act as hydraulic pathways for unintended CO_2 migration, ill-defined stress states can lead to numerous operational difficulties, and induced seismicity may be a risk as CO_2 is injected into saline aquifers. Accurate *subsurface characterization* prior to CO_2 injection is critical, and several abstracts involved forms of quantitative seismic inversion and subsurface property prediction.

As subsurface pressure regimes may be unknown prior to CO_2 injection, it was noted that where appropriate microseismic measurements are available, seismicity can reveal the location and extent of faults and fractures and can be used to invert for the state of stress. Where appropriate 3D seismic data are available, efforts should be made to establish realistic 3-D reservoir geometries so that the incremental stress fields can be accurately modelled. Structural analyses of the stability of complex geometry faults and fractures are typically performed under static conditions. Dynamic changes in fluid pressure from injection can be effectively modelled using numerical reservoir simulators and simulation workflows should be implemented to account for this', such as by linking, in real-time, dynamic reservoir simulation with structural modelling tools, to reduce uncertainty and risks related to the stability of sub-surface structures. Geomechanic models may also address such considerations.

Regards the *measurement* of seismic data for CCS applications, the two emerging themes are greater application of UHR (ultra-high resolution) towed streamer seismic (achieved by bespoke survey designs with traditional towed streamer vessels and using UHR towed streamer technology) and investigations into the applicability of DAS (distributed acoustic sensing with borehole fiber operatic systems). A combination of dense multisensor streamer spreads and wide-tow multi-source shooting has been successfully applied to several CCS projects in the North Sea, and these principles now being achieved with P-Cable UHR acquisition to deliver 1m spatial sampling and sub-10m near offsets are applicable to both CCS and offshore windfarm development (refer to **Figure 1**).

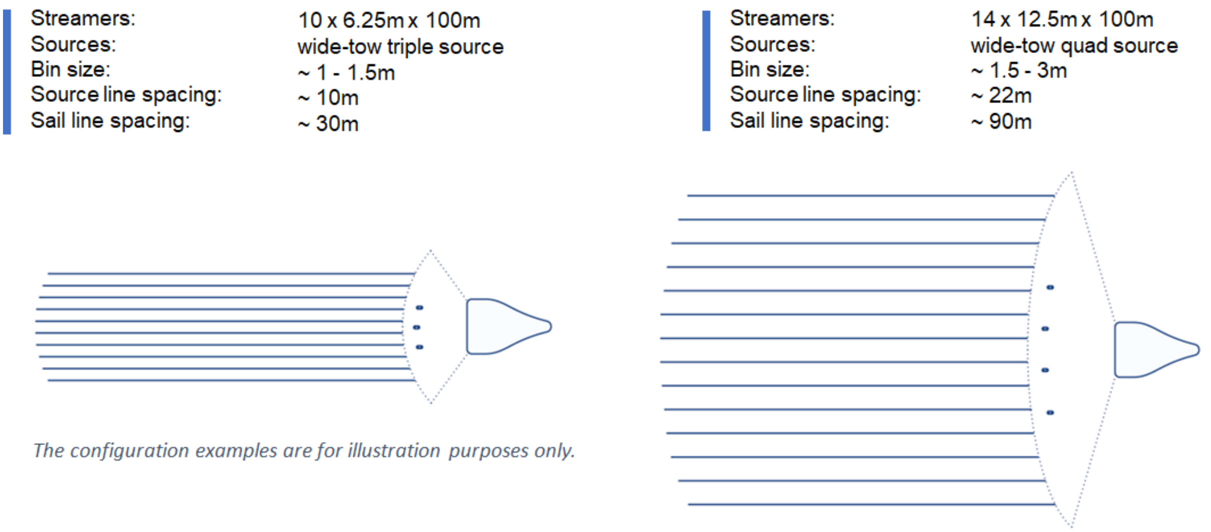

Figure 1. Example of flexible P-Cable configurations. Courtesy of Martin Widmaier, PGS.

It was also shown that 3D UHR data can image the CO_2 plume with high resolution in the shallow overburden (100-300 ms two-way time) and with superior data quality to previously acquired 2D XHR (extremely high resolution) site survey tests.

Questions were raised about the repeatability of DAS measurements due to sensitivity of the DAS fiber optics, whilst highly complex illumination patterns of up-going reflections can challenge 3D imaging. However, 3D imaging that incorporates down-going multiple reflections can increase the imaging aperture and the potential for using DAS-VSP for CO_2 plume monitoring. At a fundamental level, synthetic modelling of DAS data is still evolving, and one abstract compares three DAS formulae analytically and numerically.

In the sections below, I summarize CCS site screening and selection strategies with increasing subsurface detail, starting with basin-scale considerations, and concluding with the specific mechanics of how reservoir properties are characterized and predicted at the pore scale. I also mention advances in how CO_2 plumes may be detected during time-lapse (4D) seismic monitoring, and advances in seismic imaging and subsurface model building.

Site Screening and Selection

Basin Scale and Fundamental Analysis

A "Double Funnel" CCS screening workflow consisting of "data sweep" and a "data target" phases identified the Heidrun and Marulk fields in the Norwegian Sea as suitable areas for CCS. 490,000 pages and 440,000 images, covering a total of 361 wells, were used to rank candidate CCS sites from five basins in Norway, consolidating 50 years of exploration, development, and production. Following this data sweep phase, additional analysis through the data target was then recommended using related wells, seismic and interpretation data.

An example workflow from the Gulf of Mexico pursued a preliminary screening of the oil and gas sands, filtered out reservoirs with less desirable geological attributes and ensured that the candidate sands or reservoirs are of good quality, i.e., allowing for sufficient storage, good injectivity, and ensuring that CO_2 would remain in the supercritical phase. Criteria considered in the static evaluation section of the workflow included storage capacity and proxies for reservoir injectivity, gravity-to-viscous ratio (number), well risk and geologic risk. The dynamic evaluation section included the estimation of maximum injection rate, dynamic storage capacity, formation pressure build-up, and the predicted number of injection wells.

Traditional basin analysis can be adapted to provide an improved assessment of the temperature and pressure distribution as well as conceptual fluid flow patterns for screening the potential for subsurface CO_2 storage on a country or basin scale. Regions of favorable pressure and temperature conditions for super-critical carbon dioxide injection can be identified, and pressure potential driven regional flow patterns can be used to understand the risk of plume migration related to faults or phase separation. The results can be used to quantify the risk of identified storage containers and to map the chance of success for long term storage of carbon dioxide on a regional scale.

Site screening may also be augmented by modelling efforts to determine which 3D sedimentological and stratigraphic heterogeneity types at which temporal and spatial scales and in which configurations are most important for successful long-term CO_2 storage in a particular basin.

Many basic site-selection approaches do not consider uncertainty and intervention in/among criteria. Advanced site-selection approaches can be developed based on either Multi-Criteria Decision-Making (MCDM) analysis or Pinch analysis (PA). The MCDM-based frameworks are employed to study the effect of multiple conflicting criteria on the site-selection procedure. PA-based frameworks developed based on Pinch analysis can decrease the risks in the CCS deployment by considering the uncertainty in the availability time of storage sites.

Embracing Detailed Subsurface Characterization

An argument was made that the focus for future oil and has exploitation should be on 'advantaged' hydrocarbons. These are those hydrocarbon assets that are both economically robust and have a low carbon intensity associated with their exploitation. Secondly, large-scale CCS is required in both depleted fields and deep saline aquifers. Identifying 'advantaged' hydrocarbons and screening for CO_2 storage requires a superior understanding of subsurface characterization.

Several abstracts described bespoke seismic reprocessing efforts and traditional play-based interpretation studies to pursue CCS site screening.

After reprocessing 3D seismic data from the Central North Sea to have improved resolution for overburden (i.e., containment) analysis, synthesized maps of reservoir thickness, net to gross and depositional facies were produced to indicate areas of high, medium and low risk. Carbon storage reservoir potential maps were then combined with seal potential maps built from thickness and facies maps of the corresponding seal pair to establish overall carbon storage potential maps.

An increasingly common element of CCS site selection studies is the application of machine learning-based interpretation of stratigraphic surfaces and fault planes. Aside from augmenting geological interpretation, automatically extracted information can also be used to compare and QC seismic images which have undergone different parameterization during processing workflows.

Continuing the theme of incorporating subsurface uncertainty mentioned earlier, one abstract combined the assisted interpretation of faults, seismic horizons, the machine learning based predictions of porosity and permeability from well logs, and the interpretation of lithology in available wells. Multiple realizations of rock property information, P10-P50-P90 total porosity predictions, and effective porosity estimates, created multiple rock property and velocity models, thereby addressing key uncertainties influencing container volumetrics, and specific questions regarding the potential injection, migration, and storage of CO_2 in each storage location.

Another abstract integrated machine learning-assisted petrophysical data conditioning, rock physics modeling, seismic horizon and fault plane interpretation, and the generation of chronostratigraphic risk maps. The seismic AVO seismic sensitivity to various injection scenarios and their effect on the rock frame can be modelled, and the impact of CO2 injection on the rock frame can be understood and predicted through potential assessment of any pore-scale cementation (refer to **Figure 2**).

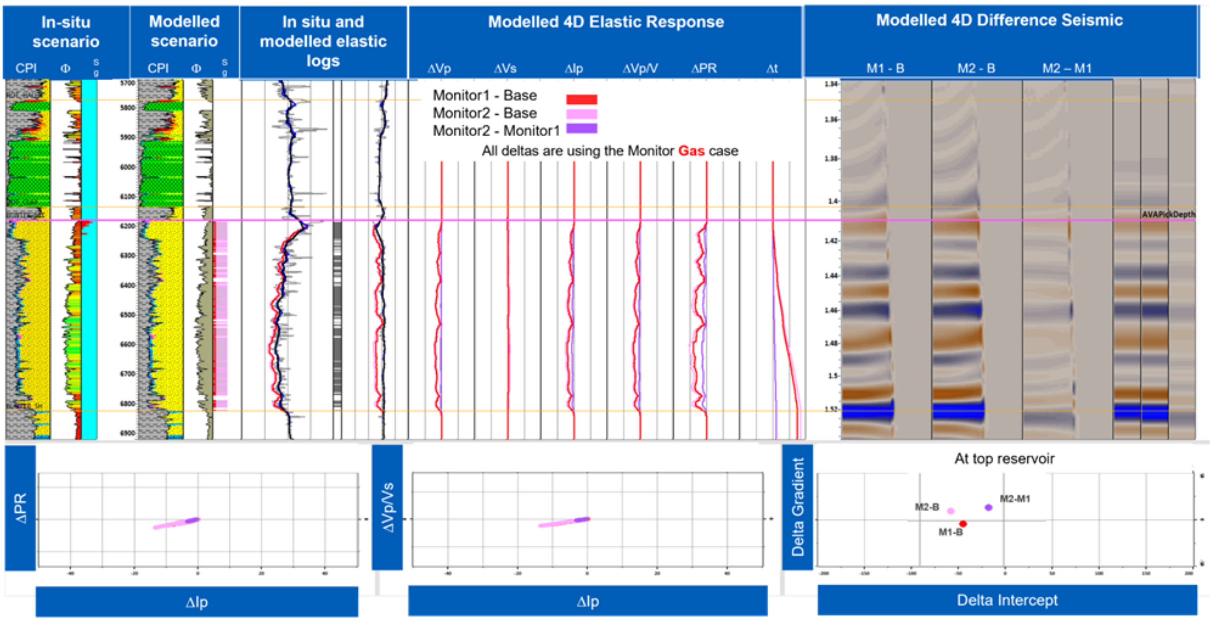

Figure 2. Illustration of the result of models for a well located in a UK CCS licensed area and the associated 4D difference panels. A homogenous fluid substitution with gas saturation of 10% and 50% is shown for the first and second monitor surveys (M1 and M2), respectively, and CO_2 gas density of 1.539 g/cm^3. Some seismic differences are observed in both the seismic gathers and the cross-plots of Delta Ip (acoustic impedance) versus Delta PR (Poisson Ratio). From Reiser and Ruiz (2023).

It may also be possible to build seismic facies maps through sub-waveform analysis of seismic events (their "waveform genomes"), and thereby automatically compute a horizons/faults/attributes database. It is claimed that unconformities, stratigraphic traps, seals, and reservoir units can be identified in the stratigraphic domain, and fault polygon properties are used to identify the structural domain.

Accommodating Specific Reservoir Properties into Site Screening

The density of useful data for CCS site screening associated with saline aquifers is typically much lower than for depleted oil and gas fields. Furthermore, local hydraulic conditions can present unique challenges to CO_2 storage.

Overpressure in saline aquifers after injection can reach significant distances, and in the case of closed systems, pressure build-up will limit the storage capacity and challenge the caprock integrity. Water can be pumped out of aquifers through water production wells to relieve the pressure and provide additional storage volumes, but CO_2

breakthrough into water producers is a setback to aquifer pumping. When favorable conditions of low mobility ratio, buoyancy viscous equilibrium, and large well spacing exist; the breakthrough time can be postponed to more than 60 years and the storage efficiency can reach up to 13%. However, results have shown that in most cases less than 3% of CO^2 will be stored as it will breakthrough into the water producers within the first 20 years of the project life due to the formation of a "gravity tongue" at the top of the aquifer.

CO_2 sequestration over geological timescales should consider the transition from structural and stratigraphic trapping to dissolution trapping that is believed to occur over time. Most CO_2 trap portfolio studies focus on positive-buoyancy traps, usually four-way closures. Salinity is a fundamental control on the solubility of CO_2, affecting how fast solution trapping happens. The density inversion from positively to negatively buoyant relative to reservoir water leg that accompanies CO_2 dissolution means that synclinal traps are also required as part of a long-term dynamic trapping system. Therefore, regional structural mapping plus constraints on hydraulic head gradients should be included in regional geological criteria for CO_2 sequestration site portfolio development.

The specific fluid state, saturation, and evolution of injected CO_2 may also be considered during screening studies.

Temperatures greater than 31.1°C and pressures greater than 7.38 MPa allow CO_2 to be stored in a supercritical state, and thereby have gas-like viscosity, but with the density of a liquid. One site screening methodology was based upon these criteria to identify and constrain candidate geological fairways over a geographic area. Each fairway was then assessed and ranked via a risk index, which considers reservoir, seal and operational factors that may impact the viability of CO_2 storage.

Mineralogy and diagenetic effects are also relevant.

Based on the clay content and mercury injection capillary entry pressure data from faulted *hydrocarbon reservoir* sandstones and intraformational seals in the North Sea, it was found that capillary entry pressures for CO_2 in water-wet rocks increase with increasing clay content up to a clay content of about 35-50%, both for host rocks and fault rocks. Above this value, the retention capacity of clay-rich rocks does not increase further.

Injection of large volumes (million tons scale) of supercritical CO_2 into the geological formations causes evaporation of formation water near wellbores and precipitation of salt crystals inside the porous medium. CO_2-induced salt precipitation can therefore substantially threaten sequestration in *saline aquifers*.

4D (Time-Lapse) Seismic Monitorability

At a fundamental level, injecting CO_2 into an *oil* reservoir appears much more visible on high quality towed streamer seismic data as compared to CO_2 injection into a *gas* reservoir. Another study from offshore Malaysia of clastic gas reservoirs also suggested a relatively low seismic response if the CO_2 migrates within the reservoir. However, leakage or unanticipated CO_2 movement *outside* the predefined container is likely to be observable.

Regards saturation and pressure effects, modelling of several reservoirs from their current in situ pressure to the pressure at start of CO_2 injection was pursued for saturation at the start of injection and for final saturations at the end of each planned CO_2 injection phase. A 4D seismic detection threshold was linked to the sand thickness, porosity, reservoir stiffness and level of CO_2 saturation at the time of surveying.

Time-lapse FWI combining reflections and diving waves have the potential to improve CO_2 thin layer detection for multi-tiered CO_2 plumes. Detection of thin CO_2 layers at their true depth is not possible with reflections only, yielding a depth increasing error for the depth of the CO_2 layers.

Summary

Overall, the diversity and complexity of subsurface processes necessary to plan for CCS projects are emphasized. Site screening projects will progress from the basin scale to the pore scale, and will be customized to each site-specific CO_2 trapping mechanism, geomechanical, mineralogical, hydraulic, and porolelastic behavior in response to injection, long-term CO_2 dissolution, plume migration, and how such effects are likely to be expressed during seismic subsurface characterization and monitoring.

Further Reading

- rockAvo | Experience Realtime Exploration Analysis and Rock Property Perturbation (webinar, 15 minutes): Roberto Ruiz demonstrates rapid screening for analogs, and scenario testing of lithology, fluids and porosity.
- CO2 Site Characterization | Appraise Capacity, Ensure Containment (webinar, 32 minutes): Noémie Pernin outlines a risking workflow for the efficient characterization of viable carbon storage sites (CCS).