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# IEAGHG Technical Report 2020-03

# IEAGHG 'Faults and their Significance for Large-Scale $CO_2$ Storage' Workshop

23rd August, 2019

An IEAGHG meeting, hosted by the University of Calgary

UNIVERSITY OF CALGARY

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Front & Back Cover Images: Network meeting at University of Calgary in progress (Image courtesy of University of Calgary); View of the Containment and Monitoring Institute (CaMI) field research station, (Image Courtesy of CMC ).

# Contents



*The Containment and Monitoring Institute (CaMI) field research station (Image Courtesy of CMC).*

# Summary

The success of $CO_2$ Capture and Storage (CCS) technology depends on the safe, secure and long-term storage of $CO_2$ at large-scale (mega tonnes per site). Upward migration and leakage of injected $CO_2$ along faults is a key risk. The aim of the workshop was to gain a greater understanding on how faults could influence long-term storage of $CO_2$. The workshop built on oil and gas industry experiences, as well as the research community, to gain a clear perspective on fault properties that are important to $CO_2$ storage. The 1-day event provided an opportunity to review laboratory experiments, field studies, and modelling results, to gain insights on the importance of faults for $CO_2$ storage. Current practices to evaluate fault seal as well as critical technical gaps were discussed.

The workshop gave an opportunity to review current research on $CO_2$ controlled release experiments and what could be learned from them, plus the contribution from simulations. The 1-day event documented critical issues for $CO_2$ storage related to faults, the experience of current experimental work, and identify remaining gaps in knowledge.

IEAGHG would like to thank the sponsors University of Calgary, CMC Research Institutes and Canada First Research Excellence Fund, for their contributions to this event.

# Session Overviews

## Session 1: Overview of Faults and a Perspective on their Importance for $CO_2$ Storage

**'Faults – the business perspective'**
**Owain Tucker, Shell**

What is a fault? Is it a complexity, a problem, or an asset? Faults can cause concern amongst geologically literate stakeholders creating uncertainty. Potential issues that could arise need to be assessed and risk management plans needed to be developed to manage risks associated with storage systems. For a candidate storage site we need to know what faults are there (and do they juxtapose, do they cross the deal, do they block flow, are they critically stressed?) and we need to understand how much flow can occur along a fault, where the fault goes, how much $CO_2$ or brine could move on a storage timescale (given storage volume and conditions), how will it be seen and will its presence be picked up by monitoring. We must look at how it is monitored, whether it poses a risk and how can this be fixed if the risk is significant.

Capacity and sustained injectivity is about managing the commercial risk. Faults can lead to issues with permitting and handover. If faults are suspected of being conduits, or if they are suspected of becoming a leakage route, then capacity may be limited. Conformance monitoring may be required and handover may be delayed; all causing increased costs. Handover of liability often requires that the operator can show that containment risk is understood and will not increase over time. Stakeholder concerns must also be considered (a change in stress fields could cause induced seismicity etc.), which in turn could affect the licence to operate, reduce injection rates, change injection patterns and pressure fields, thereby leading to increased monitoring effort. We need to be able to assess what may happen in the geological setting. Faults need to be understood and uncertainty managed, whilst thinking through the consequences; if it does flow, what do we do?

### Fault Architecture and Terminology
### Malcolm Lamb, Macquarie North America Ltd.

Caused by stress, strain and pressure, comparing faults to fractures is a question of scale. Strain can lead to brittle or ductile deformation and pressure acts in all directions equally against the confining stress, resulting in effective stress. This means we can affect the failure criterion of a rock and pressure can be changed by activities such as injection. There are sealing faults and non-sealing faults; seals are dynamic and dependant on the fluid pressure in the system, and a sealing fault can become a non-sealing fault if enough fluid pressure is introduced. The main type of faults are normal faults, reverse faults, transverse faults and thrust faults. All faults are classed as 'leaky' faults, and it was proposed in the discussion that this term be stricken from our lexicon as it comes with negative connotations; the word transmissive should be used instead.

### 'An Industry Perspective on Fault Related Fluid Flow'
### Doug Connelly, NOC

The petroleum industry's problem is that faults occur in nearly all reservoirs and can affect business in several ways, including trap adequacy and size (is there an economic accumulation), field segmentation (is there one large accumulation or several small ones), field production (can water injection pressure support be expected across faults) and reservoirs in low porosity, brittle rocks (with the complication of potential for along fault flow). Predictions should therefore capture uncertainty. Practical, probabilistic predictions that adequately estimate the most likely and probable extreme outcomes is typically the objective of industry. Understanding the geological setting, including fault and fault setting characteristics to indicate how the reservoirs and seals will behave, is crucial. Obviously, this is more complicated with multiple reservoirs and it's important to identify where across-fault interactions may occur.

All fault flow behaviour can be classified by a simple conduit-barrier system approach. Accurate fault mapping is the most important need for cross-fault seal and permeability prediction, followed closely by understanding fault rock development where flow units are juxtaposed. When making interpretations, fault timing, deformation processes and rock types must be considered. Most faults in sand or shale reservoirs are dominated by permeability reduction, and faults in carbonates and other low porosity, brittle, fractured rocks could have significant permeability increases.

## Discussion

It's important to know the geometry and fault characteristics, as faults can sometimes channel flow and low permeability can result in fluids moving to a higher permeability area. A stratigraphic model is therefore equally as important as knowing the fault geometry and leads to fault prediction.

A lot of the concern in $CO_2$ storage scenarios is related to vertical connectivity, and how much the horizontal knowledge can be applied to the vertical structure to lessen uncertainty. It was noted that the brittle connectivity is very important and the fact that with injection there is a possibility of fault reactivation. The assumption in $CO_2$ storage is that faults leak vertically. Pressure can be managed to avoid the situations that could lead to fault reactivation. Faults can be conduits and migration pathways, but can also act as seals, and it's important to note it's not always easy to identify which is which. It's therefore crucial to ensure due diligence is upheld in the background work and site characterisation. With bigger volumes, the bigger the pressure increase is, which could lead to induced seismicity. Learning from other industries, such as those in hydraulic fracturing, would be beneficial.

## Session 2: Lessons Learned from Field and Experimental Work

**'Fault Zones & Fluid Flow: What we know from natural analogues'**
**Gareth Johnson, Strathclyde University**

Faults are uncertain, poorly exposed, they are heterogeneous, complex, can be poorly characterised and vary in space and time. They can still be modelled, but the uncertainty must be considered and they hold implications for monitoring, modelling and risk assessment. Of the 76 investigated $CO_2$ reservoirs worldwide (as of 2017) in this study, most (66) do not leak. Where they do leak (6 reservoirs), they do so via faults. At faults with associated $CO_2$ seeps, the flow tends to be expressed at hot spots, which can be along the fault zone, highly localised and with different types of emissions. Seepage also changes with time and occurs at a range of rates.

Most faults will leak and seal depending on the location in the fault zone. Fault architecture controls bulk permeability, pathways along or across the fault are often discrete. Heterogeneity can be modelled and characterised, but the range of uncertainty needs to be captured. MMV plans should incorporate the understanding of seep rates, styles and locations (of the leakage) and fault heterogeneity (containment potential). An important role for field experiments injecting $CO_2$ into the fault zone is to test MMV plans.

**'CSIRO In-Situ Laboratory Project – A Controlled $CO_2$ Release Experiment in a Shallow Fault Zone, SW Hub (Western Australia)'**
**Allison Hortle, CSIRO**

Fault zones are notoriously difficult to characterise and understand. This experiment is testing the hypothesis as to whether $CO_2$ entering a fault zone will travel vertically up the zone. The In-Situ laboratory concept looks at a controlled release that's mimicking migration and accumulation from a deeper reservoir.

In practise, the results indicated injection into a low permeability reservoir with a competent seal, i.e. as if the fault zone wasn't there, when it was thought that injection was directly into a high permeability interval with a semi-permeable seal at the edge of a fault zone. This disparity could be due to a combination of wellbore damage, mud invasion and/or reservoir compartmentalisation due to sealing faults. No vertical $CO_2$ migration was detected beyond the injection interval.
The site is now ready for future experiments. These could look at injection deeper into the fault, aquifer injection, pressure and reactivity, surface detection technologies, upwell casing leakage, and more.

## Updates on 3 Field Experiments i.e. $CO_2$ Fault Release Experiments

**'CO2CRC Otway Shallow Fault Experiment: Phase 2'**
**Andrew Feitz, Geoscience Australia**

Most fault models are based on oil and gas experience. Models are able to predict flow across a fault (but not up it). They can't handle strike-slip faults and therefore cannot accurately predict $CO_2$ migration. The CO2CRC Otway experiment targets shallow injection at a fault bend to better understand migration behaviour within faults with the intention of helping to design better near surface monitoring strategies. This particular fault is a strike-slip fault, which is almost vertical near the surface. The experiment has helped to provide a new conceptual understanding of the near surface geology; confirming general high porosity / permeability in the rock, that it's most likely a weak rock / weak fault scenario and that the best injection target appears to be below the lower permeability interval at approximately 40m.

Initial modelling shows that it's not easy for $CO_2$ to migrate up a fault. Next steps will be to refine modelling with measured permeability, porosity, mineralogy and rock strength data. Future work may also include a Phase 3 injection experiment (if the site is suitable), planned to inject over 10 tonnes of $CO_2$ over one month to test plume tracking technologies.

**'$CO_2$ leakage experiments at the Sotacarbo Fault Lab in south-west Sardinia, Italy'**
**Alberto Pettinau, Sotacarbo**

The purpose of this fault lab is to investigate $CO_2$ migration phenomena into faults, to help the development of advanced monitoring systems and to look at rock behaviour and micro seismicity. There is a vertical monitoring well, one deviated injection well, six piezometers, one seismic sensor and 50 geochemical monitoring probes at the €2 million site to help investigate $CO_2$ and faults. The facility is in close proximity to a local village where it will facilitate particular attention to social issues associated with the topic. The site characterisation, conceptual studies, field acquisition and design have all been completed. As of August 2019, the drilling of the wells was underway and experiments are due to begin in late-2020, with significant progress on the project between 2019 into 2020.

**'Imaging the long-term loss of faulted host rock or caprock integrity' at the Mont Terri Lab**
**Alba Zappone, ETH**

The Mont Terri Laboratory is located on a SW-NE trending anticline which is a flat-ramp-flat structure thrust towards the NW, with the fault (reverse) being analogous to a minor fault that would hardly be detectible on surface seismic surveys. Despite being a small fault, it does display the characteristics of a 'regular' fault. The original fault slip experiment (2015) showed that the discharge of excess pressure in the fault induced micro- to millimetre scale crack and slip events, an increase in permeability, some micro-seismicity and a loss of fault sealing, demonstrating heterogeneity of the effective stress spatio-temporal variations in the fault zone. More insights are needed into the fault in different dimensions. Consequently the second (current) experiment is designed to explore what is happening perpendicular and parallel to the fault and to investigate the self-sealing of faults. This second experiment is larger than the first, using geophysical techniques such as seismic, DSS, DAS and pressure sensors and will carry out long-term post-activation monitoring to study the eventual sealing.

## Discussion

### A Comparison of Field Experiments – Commonality of Objectives, Approach, Measurements

It was noted that the experiments presented here are all shallow. Rocks behave differently at different depths; CCS projects will be dealing with much deeper depths. This suite of shallow experiments of course is good for testing the instruments and techniques, but once the data from such experiments is released, it is generally publicly available. Such datasets may not be relevant or applicable, but could worry the public if there were higher rates of leakage. The key issue here is how to answer the public's questions and how to manage the messaging. Technology such as simulations could be good for public acceptance and engagement, as they show that it is hard for the $CO_2$ to get to the surface. Emphasising that monitoring is a key contributor for such experiments, and will lead to improvement in all the techniques in use, should convey a positive impression. Messaging has to explain the relevance of shallow experiments, how controlled release results relate to an improved understanding of leakage and migration; and the relevance to the understanding of these processes at much greater depths.

## Session 3: Geomechanics, Modelling and Comparison Research

**'Modelling Fault Activation, Seismicity and Leakage in Geologic $CO_2$ Sequestration'**
**Jonny Rutqvist, LBNL**

The geomechanics of $CO_2$ storage in deep sedimentary formations can mean that injection may induce stress, strain and / or deformation, bringing unwanted mechanical changes. Potential consequential fault reactivation will affect safety, security and public acceptance, meaning it's important to model fault reactivation. Potential consequences of fault activation include seismic wave, ground vibration and effects on the community.

Heterogenous (immature) faults tend to show localised pressurisation and lower magnitude events, whereas mature (homogenous) faults pressurise and rupture over a larger area leading to larger magnitude events – this is important. The LBNL work concluded that fault orientation, stress field and rock properties are all important. Seismicity seems more likely for brittle faults with continuous permeability, where heterogenous faults tend to give multiple unfelt events and would impede upward $CO_2$ leakage. Large scale pressure increases with invisible faults is a valid concern.

**'Non-isothermal Injectivity Considerations for Effective Geological Storage of $CO_2$ at the Aquistore Site, Saskatchewan'**
**Dr. Alireza Rangriz Shokri, University of Alberta**

$CO_2$ injection began in 2015 at the Aquistore site, with more consistent injection nearing the end of 2015, and extensive monitoring programmes around the injection and observation wells. Thermal monitoring showed rapid heating and cooling of the wellbore associated with injection and a negative relationship between the $CO_2$ injectivity and downhole temperatures. The work here has included MMV programmes, geological model and fluid flow simulations, spinner logs, mechanical earth models, studies on thermal conductivity, THM experimental testing and non-isothermic runs near the wellbore.

There was localised thermal fracturing and permeability enhancement, and a flexure was found (using 3D seismic data to identify potential faults) in the Pre-Cambrian basement formation which is affecting the evolution of the $CO_2$ plume. However, this is no fault. There is complex phenomena near the wellbore region due to the cold injection; more work is needed in this area to look at more geochemical effects, transport mechanisms and geomechanical effects.

## Discussion

The LBNL work uses a scenario of 100 Mt of $CO_2$, hence why the pressure increase was estimated at 7 MPa when lots of $CO_2$ projects worldwide predict that their bottom-hole pressures would be increasing by approximately 1 MPa. In Salah was actually over 10 MPa and Snøvhit had a high pressure condition in a confined reservoir which is why injection was redirected into another formation. If there is a large area where a fault is critically stressed, there is a possibility of a seismic event. It was noted that this was an extreme case and hydraulic fracturing along the fault will depend on the situation. Higher, more brittle, older, shale-rich rocks will differ in their fracture properties.

If risk assessments based on Monte Carlo simulations using large models are run then data needs to be simplified, perhaps by coming up with some sort of criteria to indicate how much differentiation and changes can be used in the assessments.

The applicability of regional models taken up to an even larger scale (for example 100 Mt) was discussed. There are lots of uncertainties and although there is confidence in locating and characterising faults, reactivation needs to be avoided. Seismicity is obviously a risk which should be avoided; but when the amount of leakage is the primary concern, the extent of leakage and related fault reactivation needs to be known. This is a case of the caprock versus reservoir geomechanics; in non-cemented, low cohesion sediments. The caprock could form a slip surface during a slip event therefore there wouldn't be much change in permeability structure. No two faults are the same; not only is it important to consider the fault setting but also the fault history.

Different histories will lead to different permeability structures and so it's important that modellers improve the detail and complexity in the geology, such as including the mechanical rock properties and history of the setting, rock and fault. There is a lot of information in the literature and petroleum industry on this approach. More collaboration would be useful. It was noted that the Shell-led DETECT project is trying to tackle this issue by looking at the surfaces of fault deformations, to try and reflect true fault geometries to be able to put into the models and simulations for improved accuracy.

## Session 4: Summary and Wrap-Up

### A Panel Session on the Workshop Outputs

The aim of this final session was to establish critical issues related to faults for large-scale $CO_2$ storage sites. It also aimed to compile experience on setting up different $CO_2$ fault release experiments and establish the degree of commonality, and to draw on the understanding gained from other sectors, and to identify gaps in the knowledge base.

**Key Messages & Conclusions**

- Faults are one of the pathways that $CO_2$ leakage could occur along (the seal being another).
- The risk imposed by faults is the key question.
- The petroleum industry has significant experience in how to assess and estimate the sealing capacity of fault systems, especially in the geological timescales. These same concepts could also be developed for a $CO_2$ injection timescale.
- Experience shows that cross-permeability is important, as is up-dip permeability. There is lots of experience and data on the lateral sealing of faults and the interaction of fault systems in 3D and fluid migration.
- Technology exists for deriving fault gouge permeability based on the stratigraphy and basin history, along with experimental data.
- The difference between $CO_2$ storage and the petroleum industry with regards to faults needs to be considered, as does $CO_2$ storage in areas where there is no oil and gas industry (and the implications of this on faults and potential leakage), noting that $CO_2$ injection operations are governed by location and engineering, whereas with hydrocarbon extraction there is no control over their location.

- Incorporating uncertainty is very important, as is modelling the uncertainty estimation.
- Current data is subject to bias towards fluids that are already trapped versus non-trapped and where to drill for success.
- There is an exposure bias in faults, for example they are easily identifiable in road cuttings and outcrops, meaning we don't have great predictability, as yet, of fault architecture in the subsurface.
- We need to look for low-hanging fruit.
- There are lots of models but little experimental data for $CO_2$ migration through faults. However, there are many experiments regarding the release of $CO_2$ which are currently being planned or conducted and the Workshop attendees will look forward to the results. Current experimental programmes are focussing on faults at shallower depths, so the relevance to conditions at much deeper depths needs to also be considered.
- The comparison between experiments' real benefits between different geologies, fault histories etc. is important and comparable measurement techniques are needed. These criteria need to be emphasised in the messaging of these results.
- There should be a focus on detection technologies.
- The incorporation of a more detailed geological context needs to be developed.
- There was a suggestion that because collaboration is so important, an organisation such as IEAGHG could work to help coordinate comparisons between future fault experiments.
- This workshop expressed the view that models may be predicting pressures that are higher than anticipated in reality.
- Work in the subject area has demonstrated the capabilities to model and couple multi-physics. Opportunities exist for taking these models to the next stage by incorporating complexity (the distribution of mechanical and hydraulic properties).
- It's important to look into how much will stay in the formation or migrate (and stay) in the next formation.
- A key question to consider is the ranges of $CO_2$ and brine that could reach the surface, or other formations, under different storage conditions.

## Gaps / Future Work

There are a number of gaps in the current knowledge base that should be looked into further, including:

- Predicting faults in the basement rocks (and trying to avoid storage in the more complex areas if possible).
- To do more on the calibration models.
- To look more into the heterogeneity of faults and fractures and the characterisation of such systems.
- As industry and experience is more focused on areas around sand and shale stratigraphies and normal faulting, it's important to look at getting more empirical data on other stratigraphic systems (such as carbonates and the geomechanics of coal in storage strata) and faulting methods (reverse, transverse etc.).

# Steering Committee

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