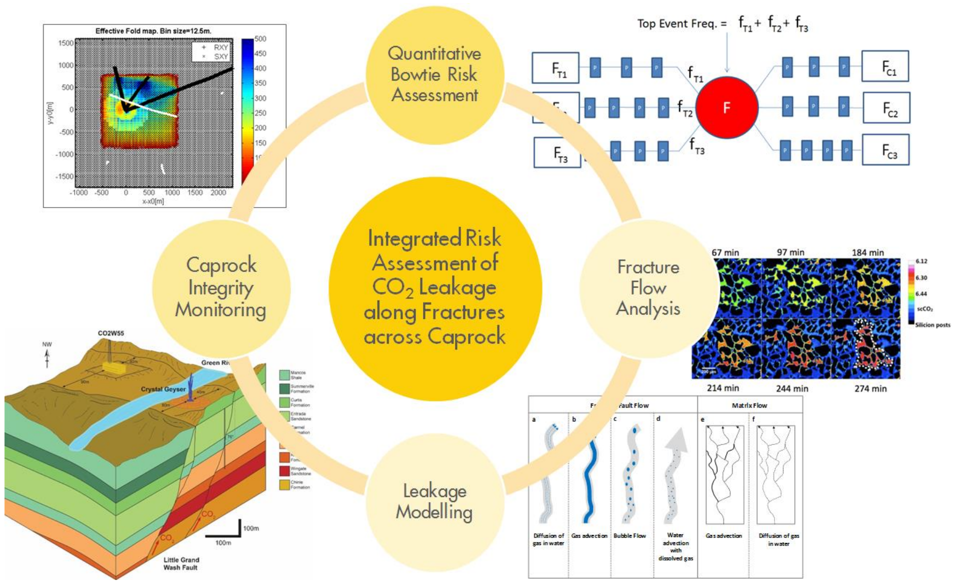
DETECT Project – first results and insights after two years



Objectives

Shell-led consortium aims to generate CCS industry leading guidance for managing geological CO_2 storage risks allowing stakeholders to:

1) Perform effective caprock and seal integrity risk assessment
2) Select realistic and efficient leakage rate modelling approaches
3) Understand realistic leakage rates and related implications
4) Select cost effective and innovative containment monitoring technologies
5) Communicate clearly and logically assessed caprock risks

Collaboration partners

Shell Global Solutions International B.V. (Marcella Dean, WP1 project lead and WP4 lead, Jeroen Snippe, WP3 lead), Heriot-Watt University (Andreas Busch, WP2 lead), RWTH Aachen University (Reinhard Fink, Hannes Claes), Risktec Solutions B.V. (Sheryl Hurst, WP5 lead).

The project has been funded through the ERANET Cofund ACT (Project no. 271497), the European Commission, the Research Council of Norway, the Rijksdienst voor Ondernemend Nederland, the Bundesministerium für Wirtschaft und Energie, and the Department for Business, Energy & Industrial Strategy, UK.

Overview of project status after two years

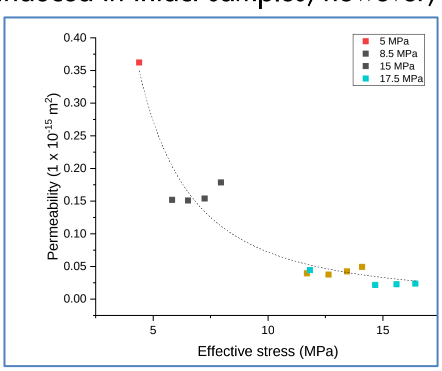
The project has made excellent progress in 2019 and is well on track to achieve all goals outlined in the proposal. WP2 teams completed three types of experimental setups to measure pressure, mineralisation and clay swelling effects which influence CO_2 flow through faults and fracture networks. The insights gained from these experiments are important for determining constitutive relationships required by the meso-scale and large-scale modelling efforts in WP3. Significant advancements have been made by the modellers at small-, meso-, and large-scales, incorporating findings from laboratory experiments and field observations. First large-scale modelling results on Green River show good agreement with actual measured leakage rates. Further initial work package results are described in more detail in the sections below.

The project findings will be incorporated in a risk-assessment toolbox for CO_2 storage operators. Users will be able to assess and communicate risks related to leakage across fractures/faults in the caprock using qualitative bowties and quantitative risk assessment modelling, including:

- Parent bowties to outline all potential containment risks related to a CO_2 storage site. This will give an operator a starting point for their site-specific risk assessment.
- Child bowties including all factors that can influence flow through fractures/faults in a caprock. This gives an operator the ability to test their site-specific caprock fracture/fault leakage risks in a qualitative sense.
- Quantitative risk assessment tool which is based on large-scale integrated geomechanical, geochemical, and fluid dynamic modelling done for North Sea CO_2 storage scenarios. This will give the user the opportunity to test parameter sensitivities for similar scenarios. The tool will be designed to allow expansion with site-specific models provided by an operator.

Technical highlights, associated impacts, challenges and next steps

WP2.1 Fracture flow (Heriot-Watt University): Set up a fully automated permeameter that can handle a wide range of permeabilities needed to record fracture flow (up to 80°C, 20MPa Pp, 50MPa Pc). Measured permeability of caprock samples (Figure 1, left) and investigated micron-scale surface topography using digital optical scanning techniques to characterise the discrete roughness in natural and 3D printed synthetic samples (Figure 1, right). As a result, improved our understanding of fracture roughness which is a primary control parameter for flow under high effective stress conditions. Preparing rock samples with natural fractures is very challenging and as an alternative, fractures can be induced in intact samples, however, we are uncertain how representative these fractures are.



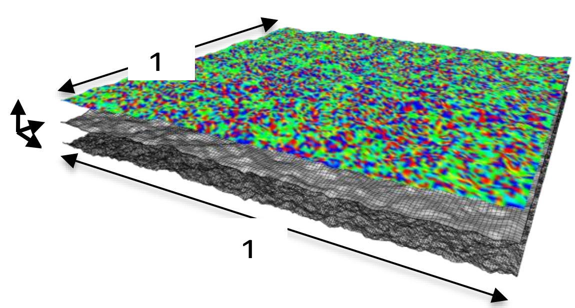


Figure 1: Left) Experimental results using Carmel Formation sample with a natural fracture (Nathanial Forbes Inskip, HWU). Right) Fracture roughness characterisation at micron-scale using natural and synthetic fracture surfaces (Tom Philips, HWU).

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WP2.2 Mineralisation (RWTH Aachen University): Delivered experimental system (Figure 2, left) with capillaries to simulate mineral precipitation at different temperature, pressure and flow ranges. Investigated challenges of 1st nucleation and determined that nucleation rates of mixed alum (K^+ and Cr^+) are significantly higher. Observed that $KClO_4$ achieves much better reproducibility (Figure 2, right) than alum and no crystal seeding is necessary. As a result, continued further experiments with $KClO_4$ at a wide range of conditions.

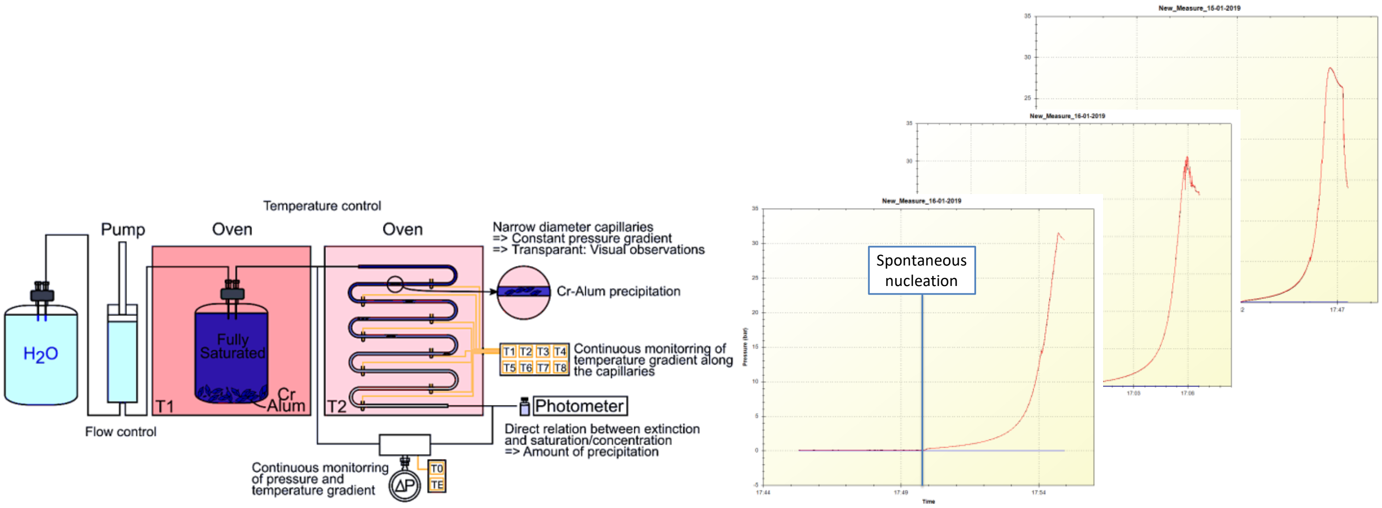

Figure 2: Left) Experimental system for measuring mineral precipitation under controlled temperature and pressure conditions. Right) $KlCO_4$ exhibits good reproducibility without seeding (Hannes Claes, RWTH Aachen).

WP2.3 Clay swelling (RWTH Aachen University): Progressed understanding of the role of clay swelling in CO_2 flow through fractures/faults in caprocks with laboratory experiments. Constructed an experimental set-up that allows measuring of CO_2 swelling stress at controlled relative humidity and developed a method for moisturising samples by gas flow through the sample at in-situ conditions. CO_2 clay swelling as a function of relative humidity can now be measured for the first time and further experiments are ongoing. Moisturising samples is a very slow process, requiring long experimental times.

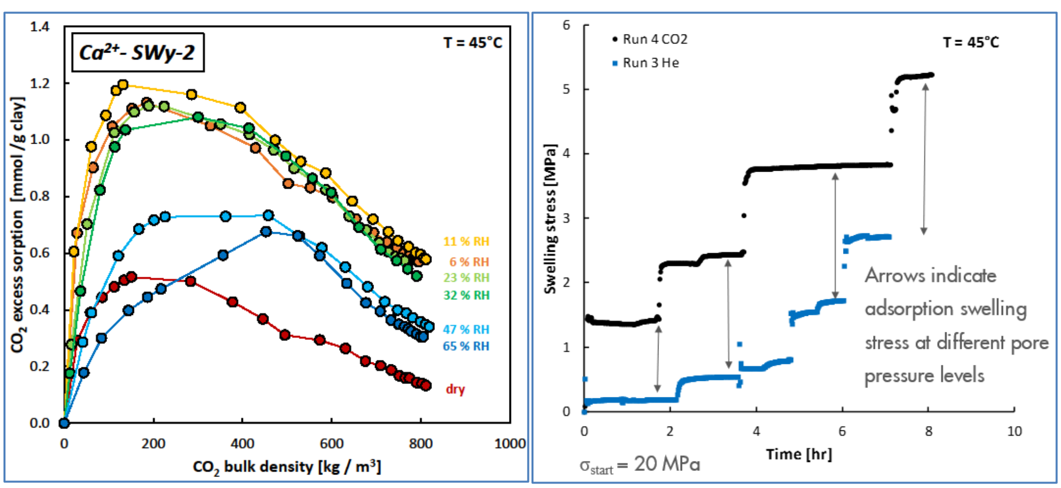

Figure 3: Left) CO_2 excess sorption vs. CO_2 bulk density. Right) Swelling induced by CO_2 adsorption calculated using control experiments with He (no adsorption) at the same P-T conditions (Reinhard Fink, RWTH Aachen).

Accelerating CCS Technologies

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WP3.1 Fracture characterisation (Shell, Heriot-Watt University): 2D Mont Terri fracture network was extracted (Figure 4, left) and full fault structure was digitised in MOVE (Figure 4, right). The Green River shallow fault zone fracture network was set up as input to meso-scale modelling.

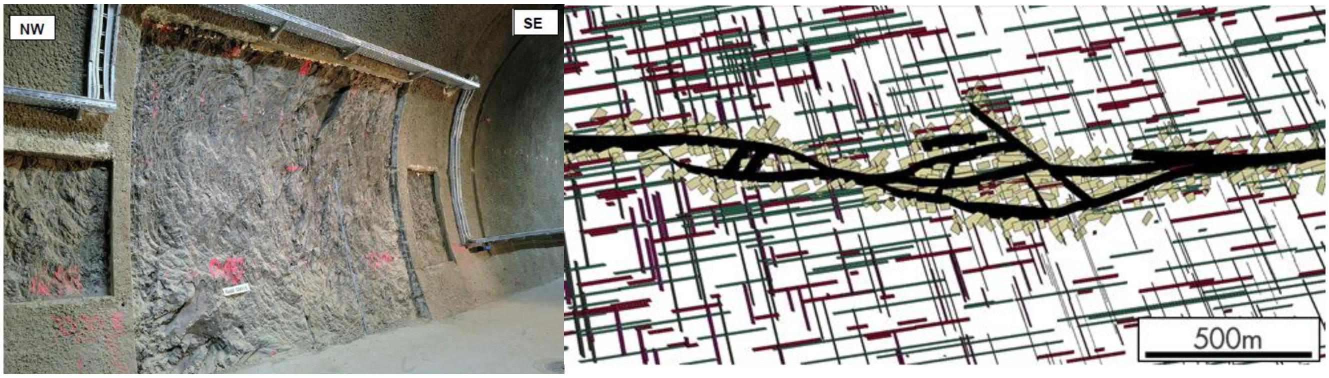

Figure 4: Left) Mont Terri fracture network exposed in tunnel. Right) Digitised fracture network as input to meso-scale modelling (Kevin Bisdom, Shell).

W3.2 Fine-scale flow modelling (Shell, Heriot-Watt University): Selected, implemented and validated normal as well as frictional contact algorithms. As a result, determined initial stress vs. permeability curves for rough fractures. Developed a numerical code for explicit modelling of the fracture opening, closing and slip which was used to investigate stress dependency and was verified with analytical methods. Implemented Stokes solver to calculate permeability in complicated deformed geometries (Figure 5, left). Performed fine-scale reactive transport modelling to model fracture permeability. Tested prediction of single fracture permeability from simulations against prediction from cubic law and mean fracture aperture which showed up to 3 orders of magnitude difference. Mineral reactions are dominated by carbonate dissolution and precipitation (Figure 5, right). Progress of mineral reactions are controlled by multiple factors including fluid mixing, matrix dissolution, matrix diffusion and CO_2-degassing. Propagation of mineral reactions in fracture wall depend on balance of surface reaction rate and diffusion (transport) control.

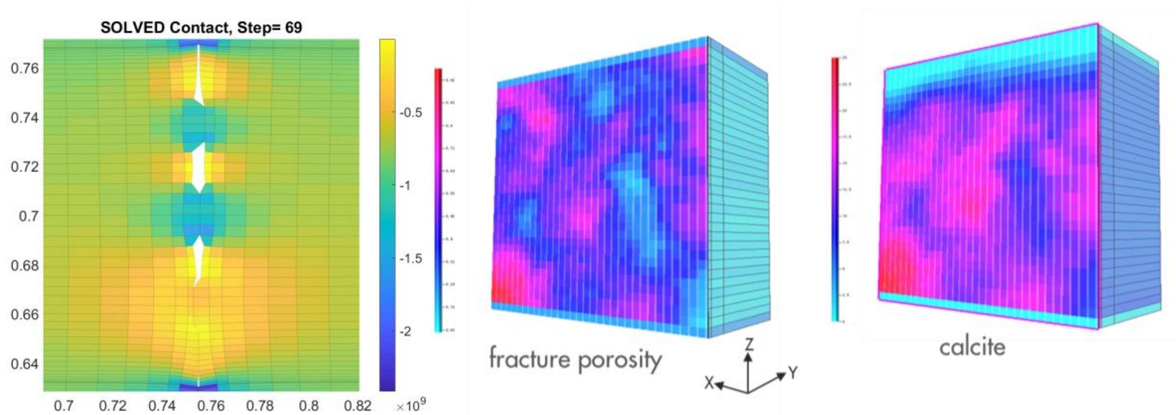

Figure 5: Left) Fine-scale flow-mechanical model (σ_{xx}) to obtain stress-permeability relationships. The colours indicate contact pressure in Pascal. As contact forms, compressive contact pressure is created (Amanzhol Kubeyev, HWU). Right) Fine-scale reactive transport modelling showing that mineral reactions are controlled by calcite dissolution and precipitation (Niko Kampman, Shell).

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Further, numerical modelling of brine and CO_2 flow was done to derive brine-CO_2 relative permeability relationships in rough single fractures. Observed strong phase interference between the brine and CO_2 at intermediate saturations that reduces the effective permeability. Showed effects of capillarity limit the ability of CO_2 to invade portions of the fracture surface. Identified systematic relationships between the relative permeability behaviour, fracture roughness, fracture closure and capillary number. Seen significant reduction in the effective permeability of the fractures to two phase flow which results in reduced leakage rates through tight rough fractures (Figure 6).

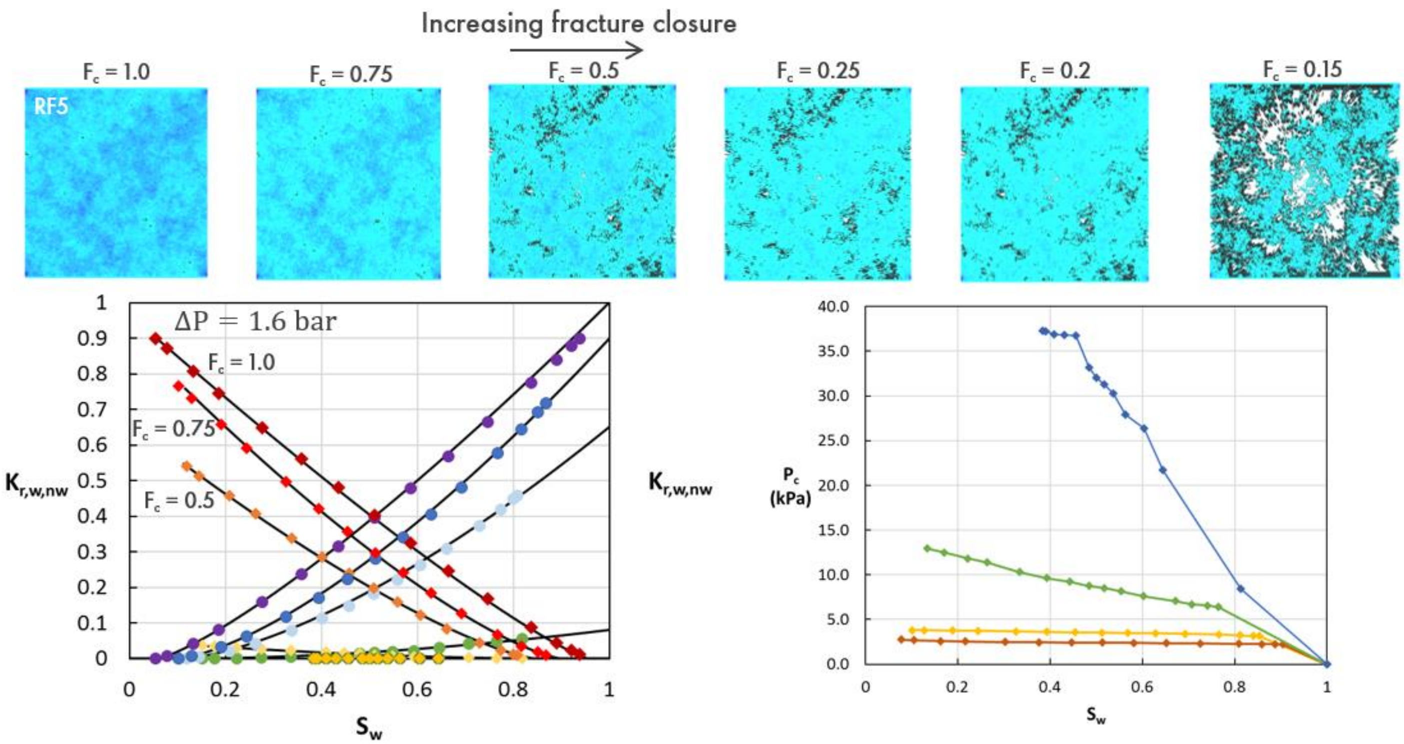

Figure 6: Top) Rough Fracture Model 5 (RF5) and increasing fracture closure (F_c = relative aperture compared to original) as inputs to investigate the impact of fracture closure on relative permeability. Bottom left) Relative permeability curves showing relative permeability vs. water saturation (S_w), where $K_{r,w,nw}$ indicates CO_2 phase and $K_{r,w,n}$ water phase. Bottom right) capillary pressure (P_c) vs. water saturation (S_w) showing increasing capillary pressure with increasing fracture closure (Niko Kampman, Shell). Red curve: F_c=1, yellow curve: F_c=0.75, green curve: F_c=0.5, blue curve: F_c=0.15.

W3.3 Meso-scale flow modelling: (Heriot-Watt University). Developed a simplified contact-mechanics algorithm that allows the computation of fracture apertures of a stressed fracture network. Incorporated algorithm into a computational package to perform upscaling of permeability of fracture network. Extended the previously developed discrete fracture network (DFN) model to include flow in the matrix. Validated the effective permeability models against results obtained using commercial packages that consider more advanced contact mechanics. Preliminary results show that the approximations of the present algorithm provide accurate results while keeping the computations fast and efficient. Implemented the computational tools to upscale the permeability of a fracture network digitized from the Mont Terri site (Figure 7).

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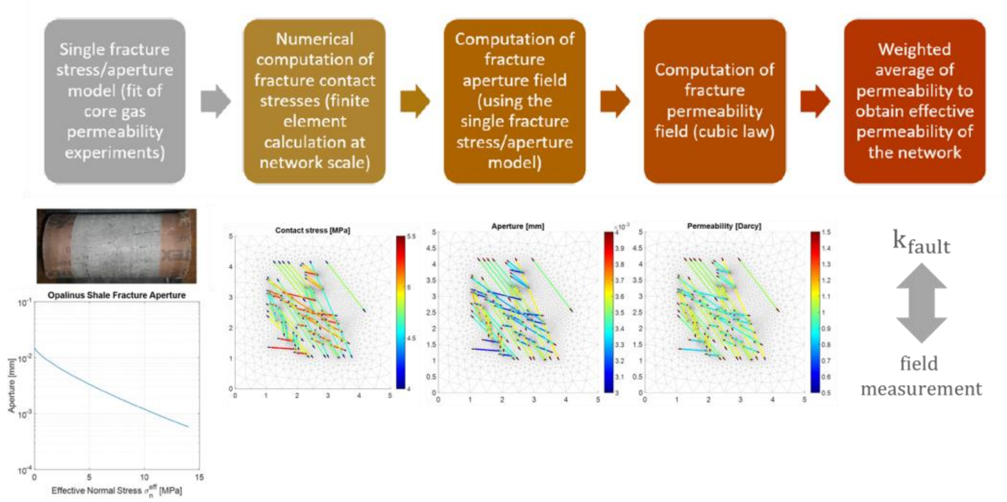

Figure 7: Permeability upscaling workflow implemented using Mont Terri underground rock laboratory data (Rafael March, Florian Doster, HWU).

W3.4 Large-scale flow modelling (Shell): The large-scale model, underpinned by experimental data and detailed fracture flow modelling conducted at Heriot Watt University, reproduces the observed leakage rates and patterns at the Green River natural analogue. Green river is a leaky fault/fracture system and therefore would not be used for CO_2 storage, however it serves as an excellent test case (natural field lab). The successful modelling indicates that we understand the main control processes and their parameter ranges, and will be able to forecast, within a credible uncertainty range, leakage probability and potential leakage rates (if any) for CO_2 storage site candidates. The quality of the large-scale modelling depends critically on the delivery of experimental and detailed modelling results, so timely delivery of these results is essential. Challenges have occurred, but have been overcome through initial integrated planning, flexibility to update the plan where needed, and in general a very collaborative spirit and a common understanding of the ultimate project goals.

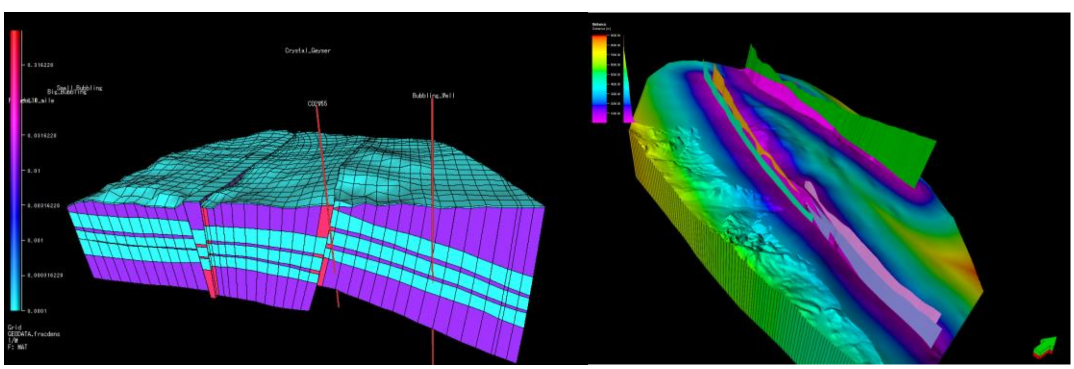

Figure 8: Green River model geometry used for large-scale geologic leakage modelling: XY grid resolution 500m x 500m in MoReS, 50m x 50m Petrel model, vertical grid currently 1 cell per formation.

WP4 Containment monitoring for caprock integrity (Shell): Completed feasibility studies. Technologies suitable for caprock integrity monitoring are continuous downhole pressure and temperature monitoring, time-lapse Neutron and

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Thermal Neutron Capture (TNC), as well as continuous fiber optics Distributed Temperature Sensing (DTS) and Distributed Acoustic Sensing (DAS). The most promising geophysical tools include continuous microseismic (downhole, geophones and DAS), time-lapse DAS Vertical Seismic Profiling (VSP), high-resolution surface seismic, and seabed geodesy. Based on expert reviews, additional modelling for lower leakage rates will be performed. The results will be combined into a monitoring technology ranking matrix (technology feasibility vs. leakage rates) which will be linked to the quantitative risk assessment tool in collaboration with WP5.

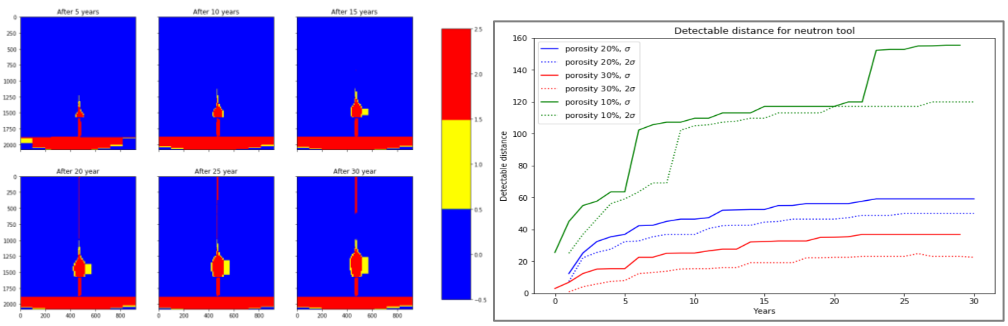

Figure 9: Left) The detectable area for the neutron tool after 5,10,15, 20, 25, and 30 years, assuming 20% porosity and 40mD permeability in the primary and secondary reservoir and a high leakage rate. The plot shows (x, z) slices of the 3-D model at the leakage location. Blue means < tool accuracy (σ), yellow > σ < 2σ, red > 2σ. Detectable distances modeled for the neutron tool assuming a range of porosities, expected accuracy (σ, 2σ), and varying distances from monitoring well to the fault.

WP5 Qualitative and quantitative risk assessment (Risktec): Facilitated three bowtie/integration workshops to ensure alignment of final outputs within the bowtie risk assessment framework. Made significant progress towards final WP5 deliverables: A customisable qualitative parent bowtie to generate a starting point for site-specific bowtie analysis. A customisable qualitative child bowtie (Figure 10) to illustrate site-specific conditions for caprock leak via fault/fracture network. This will allow CO_2 storage operators to identify which barriers increase/decrease or have no effect on rate of leak through fault/fracture network. The quantitative risk assessment tool will generate flow rate vs. probability as a prediction based on data stored from the North Sea cases modelled. The quantitative tool output will be graphs of leakage flow rate with error bars and traffic lights (low to high potential risk of leakage). We will link monitoring feasibility studies output (monitoring technology ranking matrix) with the quantitative risk assessment tool output (low to high leakage rates). The results will be used as a communication tool – the child bowtie will enable messaging of the key findings of DETECT. Finally, workflow description and user guides for both qualitative and quantitative risk assessment approaches will be generated to enable site-specific adaptation of our workflow.

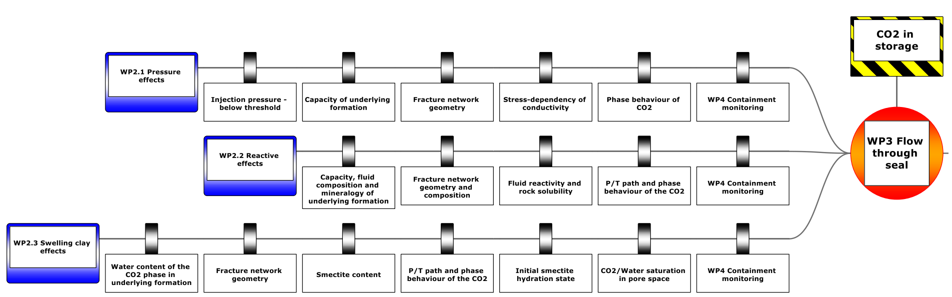

Figure 10: Draft child bowtie with barriers that can influence flow across fractures in caprocks.

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