DETECT

Determining the risk of CO_2 leakage along fractures of the primary caprock using an integrated monitoring and hydro-mechanical-chemical approach

D E T E C T

INTEGRATED GEOLOGICAL CO_2 LEAKAGE RISK ASSESSMENT

DETECT Project – Results and impact after 2 years

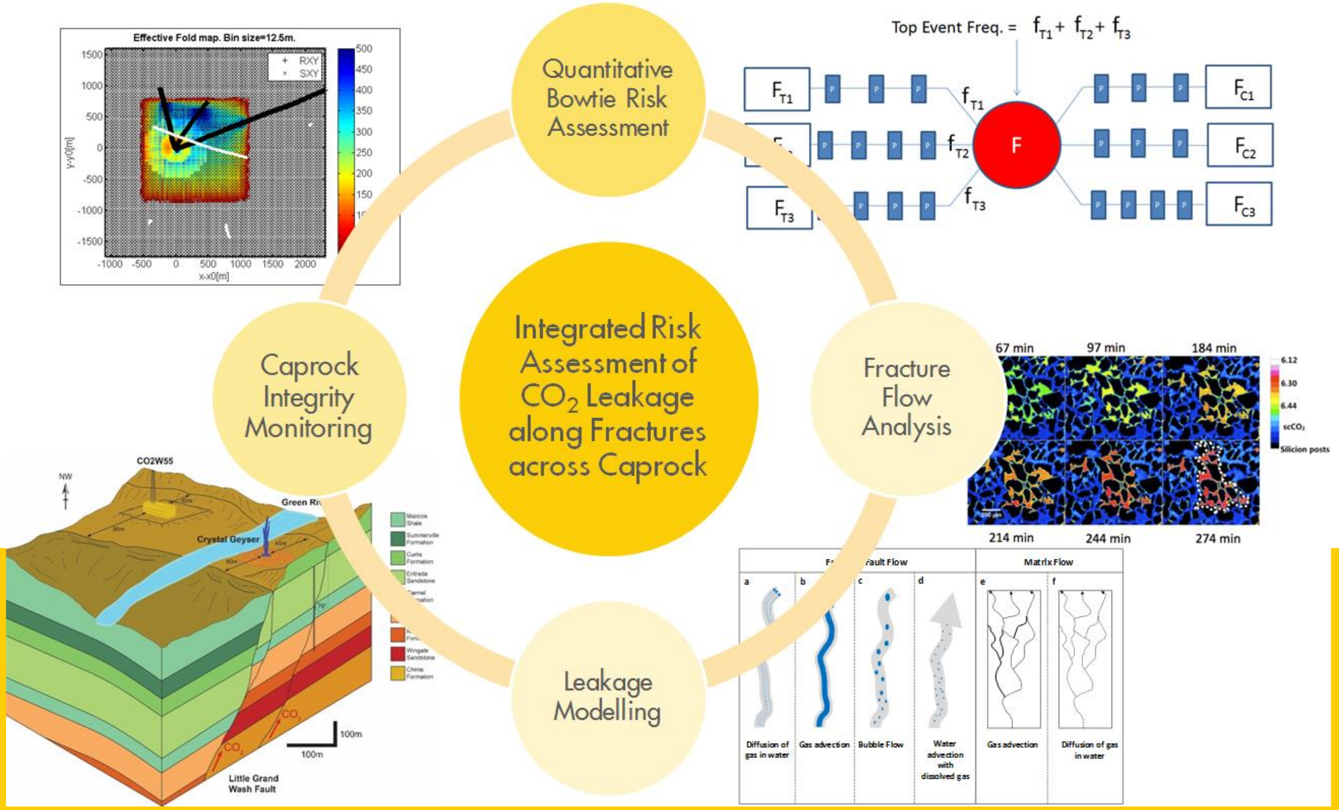
4th ACT Knowledge Sharing Workshop
6th & 7th November 2019, Athens

Shell Global Solutions International B.V.: Marcella Dean, Project Manager & 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

Accelerating CCS Technologies

The project has been subsidized 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.

DETECT Project



Overview
Project Management

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DETECT – Integrated geological CO_2 leakage risk assessment

Determining the risk of CO_2 leakage along fractures of the primary caprock using an integrated monitoring and hydro-mechanical-chemical approach

D E T E C T
INTEGRATED GEOLOGICAL CO_2 LEAKAGE RISK ASSESSMENT

Objectives

- Shell-led consortium will generate CCS industry leading guidance for managing geological CO_2 storage risks allowing stakeholders to:
  - RISK ASSESSMENT Perform effective caprock and seal integrity risk assessment
  - INTEGRATED MODELLING Select realistic and efficient leakage rate modelling approaches
  - LEAKAGE RATES Understand realistic leakage rates and related implications
  - MONITORING Select cost effective and innovative containment monitoring technologies
  - COMMUNICATION Communicate clearly and logically assessed caprock risks

Collaboration

- WP1 Project Management
  - Shell
- WP2 Fracture Characterisation
  - Heriot-Watt University
  - RWTH Aachen University
- WP3 Hydro-mechanical and hydro-chemical modelling
  - Shell
  - Heriot-Watt University
- WP4 Containment Monitoring
  - Shell
- WP5: Risk Assessment
  - Risktec Solutions

HERIOT WATT UNIVERSITY

EMR Energy & Mineral Resources Group
RWTHAACHEN

TÜVRheinland®
Risktec

Accelerating CCS Technologies

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Project Status

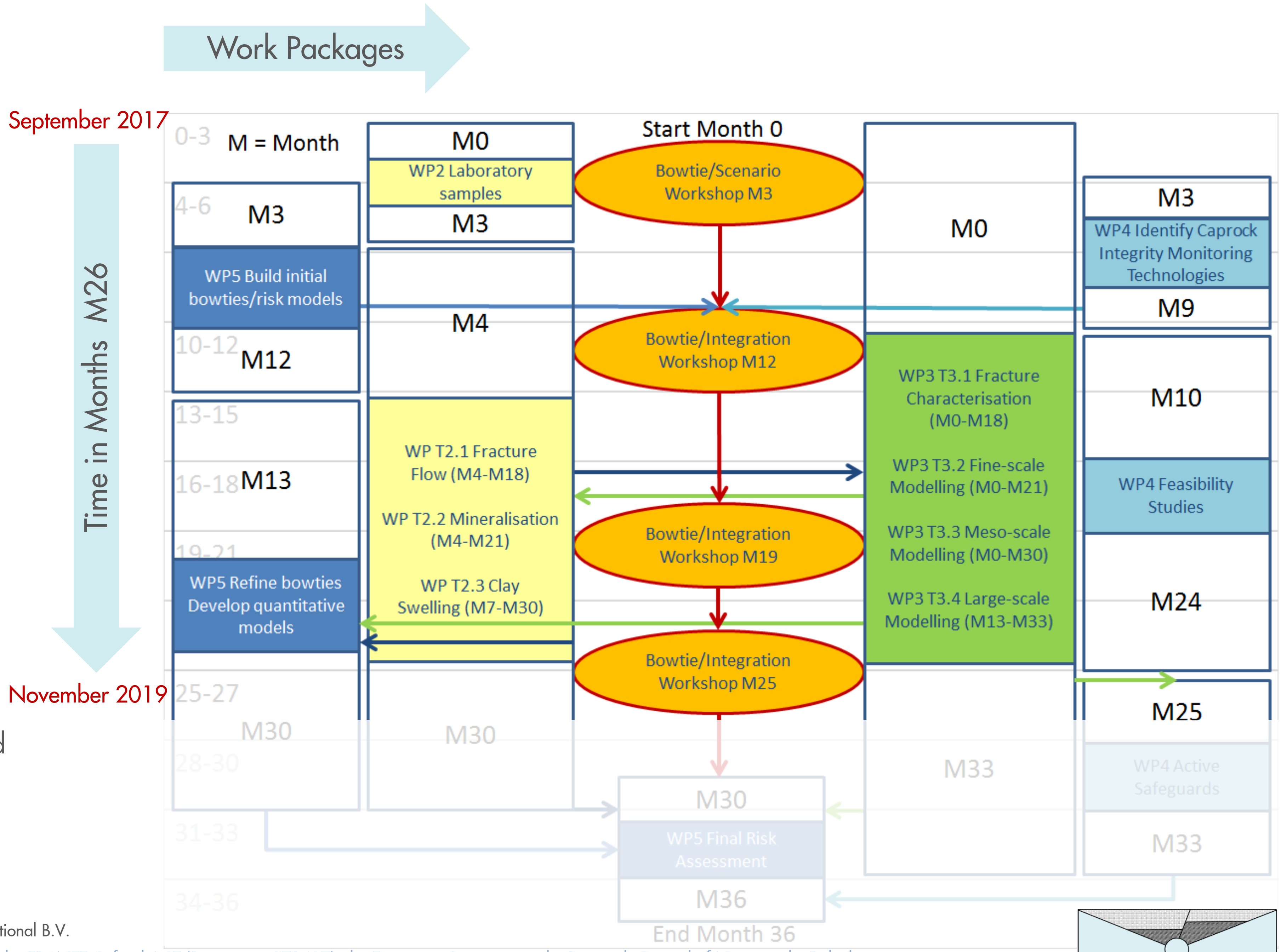
Status

On Track with Deliverables

- No major delays or issues

Excellent Collaboration

- Regular virtual meetings and email contact among all partners:
  - WP3 biweekly progress meeting Shell with HW
  - WP3 and WP5 every three weeks progress meeting
- Regular F2F meetings:
  - Shell visits to partners
  - 5 meetings/workshops as planned (one additional integration workshop)



Accelerating CCS Technologies

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WP1 Project Management – Deliverables

Deliverables

- D1.1. Dissemination plan (completed second edition)
- All Traffic Light Reports to RVO submitted on time, no major issues
- D1.2. Second annual meeting report completed
- Year 2 summary report for ACT website

ID	Task Name	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2
	Project Events												
E1.1.	Kick-off Meeting	1											
E1.2.	Bowtie/Integration Workshop 1				10								
E1.3.	Bowtie/Integration Workshop 2							19					
E1.4.	Bowtie/Integration Workshop 3										28		
E1.5.	Close-out and dissemination Meeting												36
WP1	Project Management												
T1.1.	Establish project office	0											
T1.2.	Dissemination plan		6				18				30		
D1.1.	Generate dissemination plan		6				18				30		
T1.3.	Arrange and report on all project meetings				12				24				36
D1.1.	Generate progress and final reports				12				24				36
T1.4.	Oversee project activities												
T1.5.	Manage project risks												

Workshops/meetings

- September 14th, 2017: Kick-off meeting September 14th, 2017 at Shell Technology Centre Amsterdam
- November 14th, 2017: 1st bowtie/Integration workshop in at Risktec in Manchester
- April 17-18, 2018: 2nd bowtie/Integration workshop and first SAB meeting at Heriot-Watt University in Edinburgh
- January 21-22, 2019: Integration workshop in Aachen
- April 26, 2019: SAB review meeting at Shell Technology Centre Amsterdam
- September 23-24, 2019: 3rd bowtie/integration workshop at Heriot-Watt University in Edinburgh

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WP1 Project Management - Dissemination

Industry conferences/external workshops (15)

- Andreas Busch, Stephanie Zihms (HW), poster at EGU meeting (April 12th, 2018, Vienna)
- Florian Doster (HW) talk at PROTECT workshop (April 2018, Geilo, Norway)
- Hannes Claes (RWTH Aachen University) talk at 6th International Geologica Belgica Meeting, September 2018
- Marcella Dean (Shell) posters/talks at GHGT-14; at Curtin University and CSIRO; at Shell Geophysics Conference, Q4 2018
- Niko Kampman and Kevin Bisdom (Shell) presented DETECT posters at EAGE CO2 Storage Workshop in Utrecht, 21-23 November 2018. Opening Versus Self-Sealing Behaviour of Single Fractures; Quantifying the Risk of CO2 Leakage Along Fractures Using an Integrated Experimental, Multiscale Modelling and Monitoring Approach in Mudstone Caprocks During CO2 Migration.
- Marcella Dean & Jeroen Snippe (Shell) presented to Shell RST team, May 2019
- Owain Tucker, Kevin Bisdom (Shell), poster at IEAGHG Fault workshop Canada, August 2019
- Amanzhol Kubeyev (Heriot-Watt University), ARMA conference paper: Geomechanics Numerical Code for Modelling Contact in Fractures using VEM, May 2019
- Jeroen Snippe (Shell), 2nd Pre-Act Stakeholder Meeting, Brussels.10th October 2019; CSIRO virtual workshop, October 2019
- Florian Doster (HWU), talk at FRISK kick-off meeting, October 2019
- Marcella Dean (Shell), Northern Lights MMV R&D virtual meeting with Equinor and Total; Shell-Equinor virtual workshop on DETECT year 2 results, October 2019

Publications/press release (3)

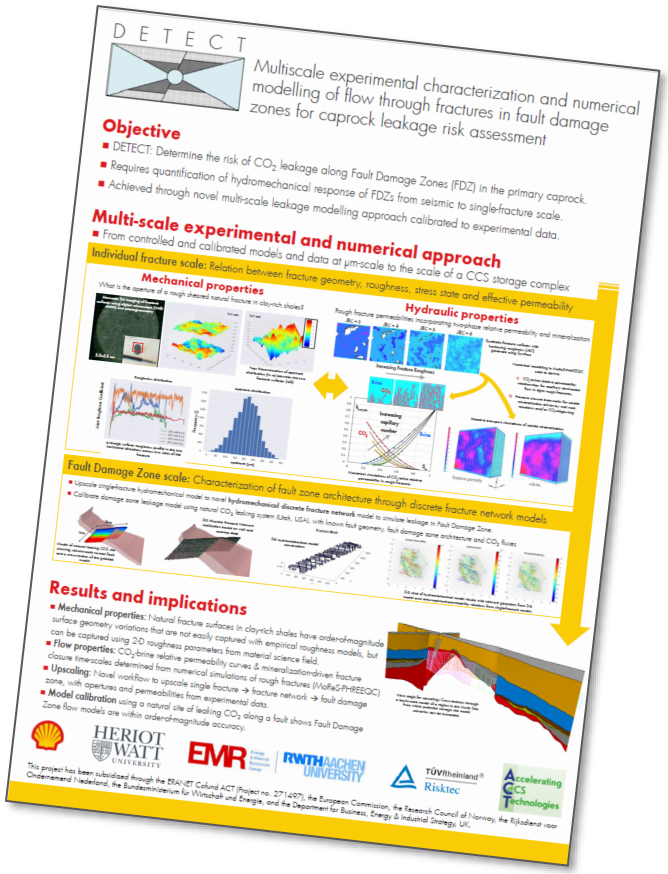
- Press release on DETECT by HWU in January 2018
- Busch, A., Kampman, N. (2018). Migration and Leakage of CO_2 From Deep Geological Storage Sites. In: Geological Carbon Storage: Subsurface Seals and Caprock Integrity, pp.283-303.
- Busch, A., Hangx, S., Wentinck, H. M., Marshall, J. (accepted), Swelling clay minerals and containment risk assessment for the storage seal of the Peterhead CCS project, International Journal of Greenhouse Gas Control.

ACT knowledge sharing workshops (3)

- Marcella Dean (Shell) 2017 ACT knowledge sharing workshop (October 24, 2017, Bucharest), 2018 ACT knowledge sharing workshop (November 13, 2018, RVE Niederaussem), 2019 ACT knowledge sharing workshop (November 6-7, 2019, Athens)

Online presence

- DETECT page on Research Gate website: ResearchGate 705 reads, 71 followers
- DETECT website via HWU website: https://geoenergy.hw.ac.uk/research/detect/



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DETECT

INTEGRATED GEOLOGICAL CO_2 LEAKAGE RISK ASSESSMENT

WP2 – Fracture flow, mineralisation, clay swelling

Heriot Watt University: Nathaniel Forbes Inskip (WP2.1), Tom Phillips (WP2.1), Onos Esegbue (WP2.1), Yihuai Zhang (WP2.1), Andreas Busch (WP2 lead)

RWTH Aachen University: Reinhard Fink (WP2.3), Hannes Claes (WP2.2)

Accelerating CCS Technologies

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WP2 – Fracture flow, mineralisation, clay swelling

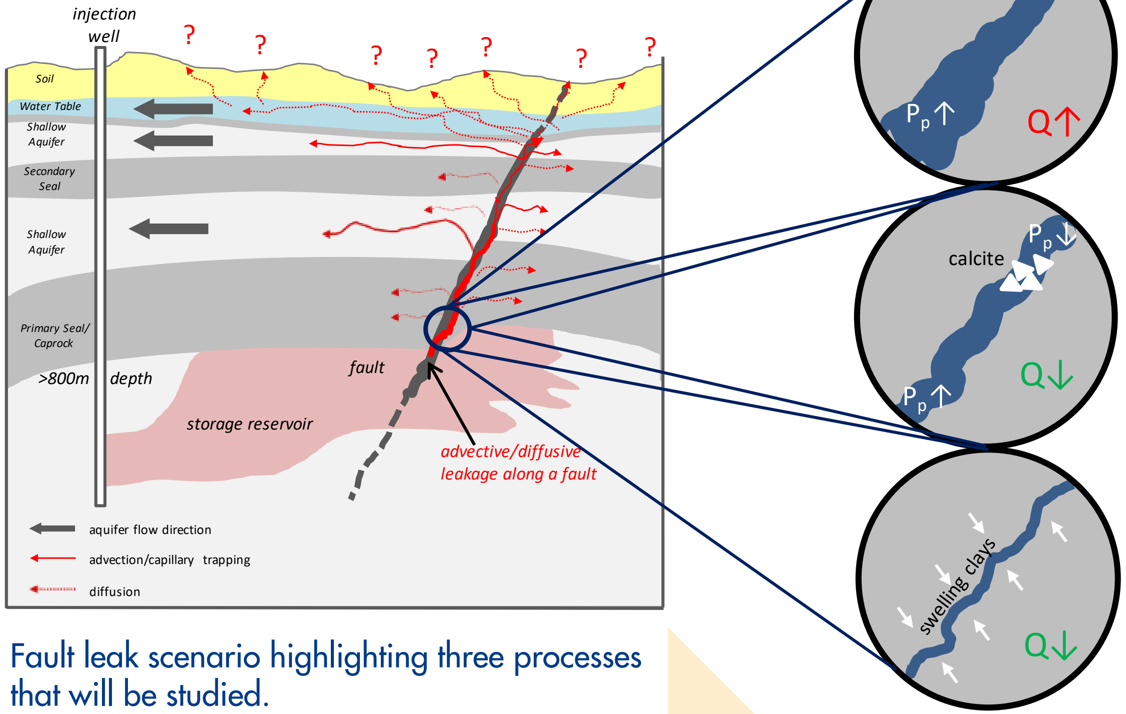
WP2 will test sensitivities of leakage rates along fracture networks or fault damage zones to fluid pressure, chemistry, mineral reaction rates, saturation changes and effective stress changes to generate the necessary input parameter for leakage modelling in WP3.

Objectives

- Identify and analyse factors controlling fracture flow as a function of pore pressure, confining stress, mineralogy or strength parameters
- Significantly improve fundamental understanding of the impact of CO_2 induced expansion of swelling clays in fractures
- Determine effects of CO_2-induced water-rock interactions on transport through fractures

Collaboration

- Heriot-Watt University, RWTH Aachen University, Shell IRD, Utrecht University



Fault leak scenario highlighting three processes that will be studied.

WP2.T1. Fracture Flow: stress-permeability relations

WP2.T2. Mineralisation: mineralisation in fractures

WP2.T3. Clay Swelling: clay swelling affecting fracture apertures

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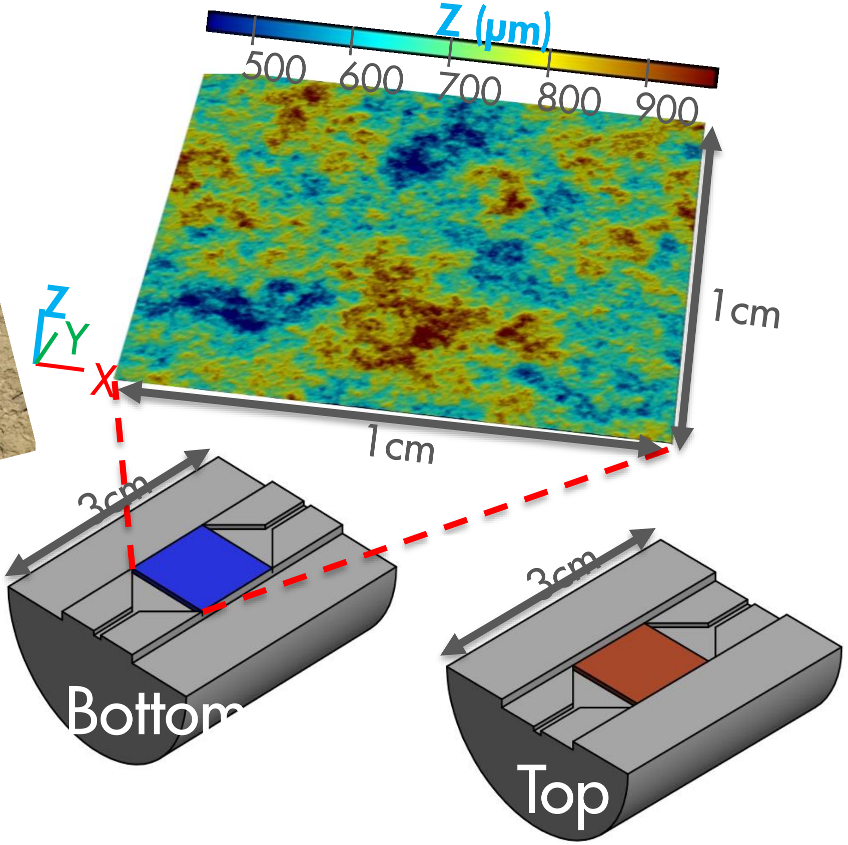
Nathaniel Forbes Inskip, Tom Phillips, HWU

WP2.1 – Fracture flow

Samples prepared for isotopic fracture flow experiments and surface topography studies

- Carmel shale from Utah core drilled by Shell in 2012
- Tight carbonates from Brazil (field trip July/2018)
- Opalinus shale from Mont Terri, sent to UU in March/2019
- Mercia mudrock samples from field trip in Feb/2019
- Generated artificial samples with 3D printing



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Nathaniel Forbes Inskip, Tom Phillips, HWU

WP2.1 – Fracture flow

Experimental setup

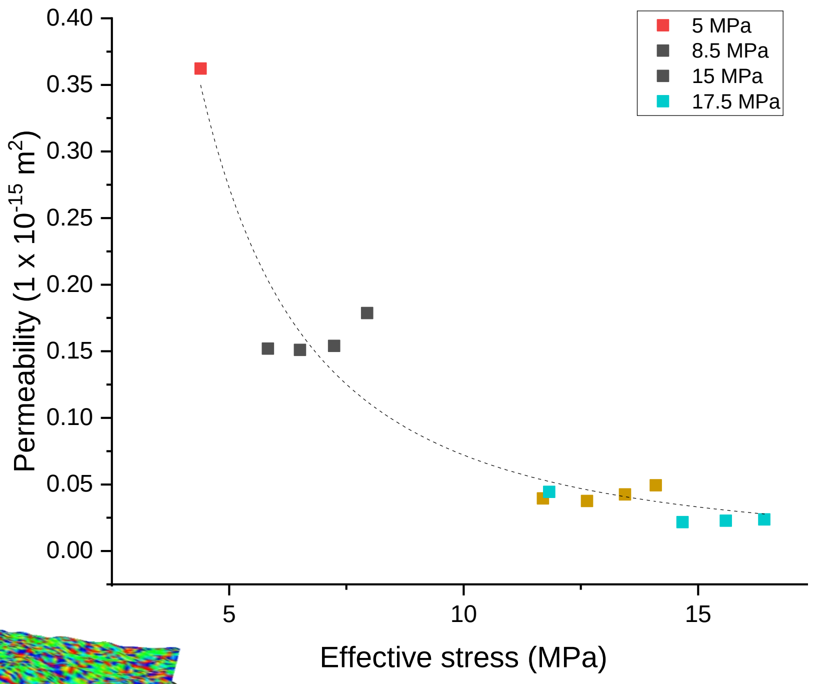
- Fully automated permeameter that can handle wide range of permeabilities needed to record fracture flow
- Temperatures up to 80 C, Pp up to 20 MPa, Pc up to 50 MPa

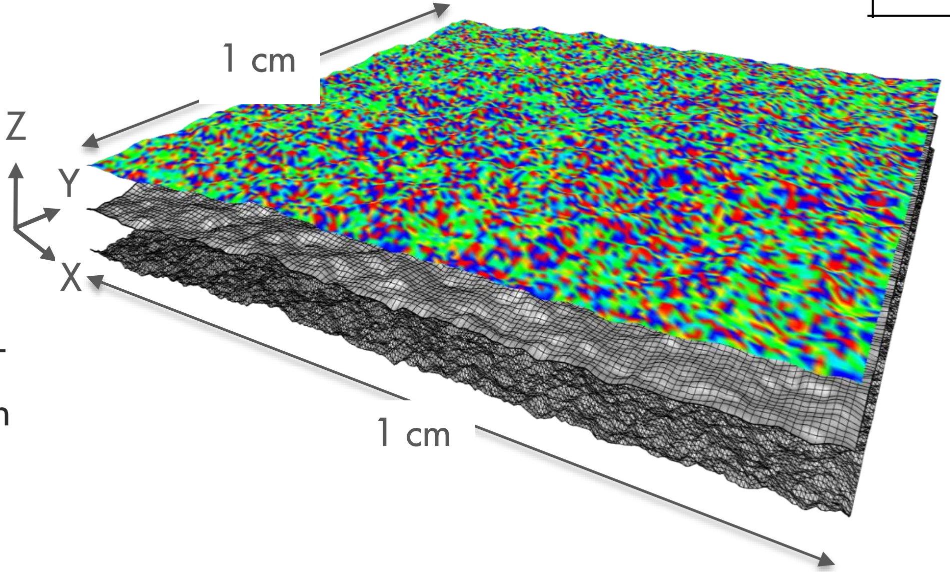
Results

- Measured the permeability of caprock samples– key input to modelling effort
- Investigated micron-scale surface topography using digital optical scanning techniques to characterise the discrete roughness in natural and 3D printed synthetic samples
- Improved understanding of fracture roughness – a primary control parameter for flow under high effective stress conditions

Right: Experimental results using Carmel Formation sample with a natural fracture.

Below: Fracture roughness characterisation at micron-scale using natural and synthetic fracture surfaces.





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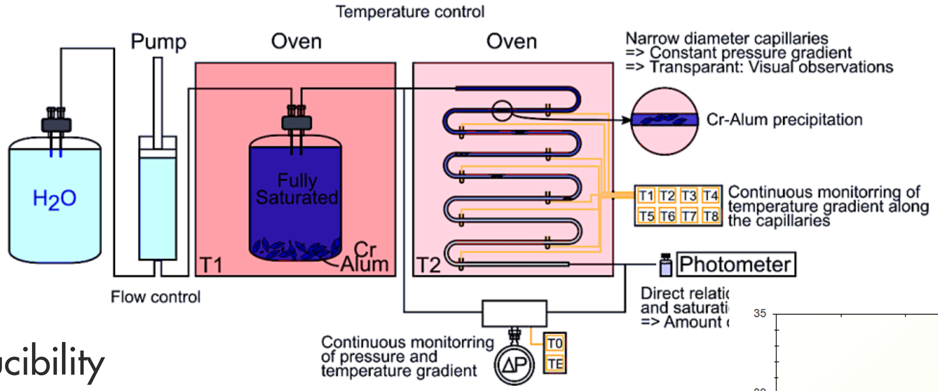
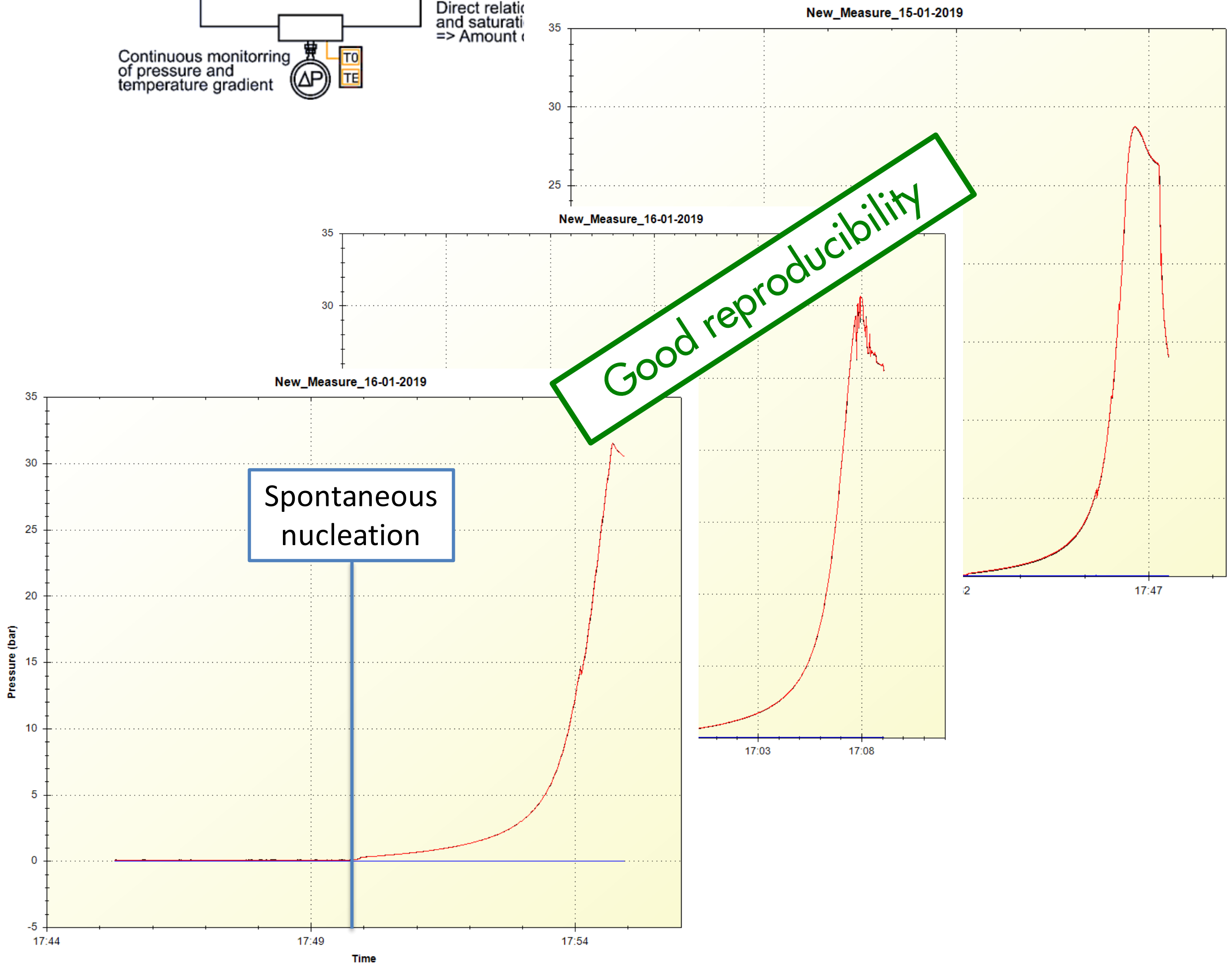
Hannes Claes, RWTH Aachen

WP 2.2 – Mineralisation



Experimental setup and results

- Investigated challenges of 1st nucleation
- Variation in the induction period hampers reproducibility
- Nucleation rates of mixed alum (K^+ and Cr^{3+}) are significantly higher
- Crystal Seeding to control location and initiation of crystal growth



Results

- $KClO_4$ exhibits good reproducibility
- 2 reservoirs, oven 1: 55°C, oven 2: 50°C
- 1 mL/min, no seeding
- First contact followed by heterogeneous nucleation
- Further measurements ongoing with variation in flow rate, temperatures → saturation, capillary diameters, capillary material

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W2.3 – Clay swelling

Experimental setup

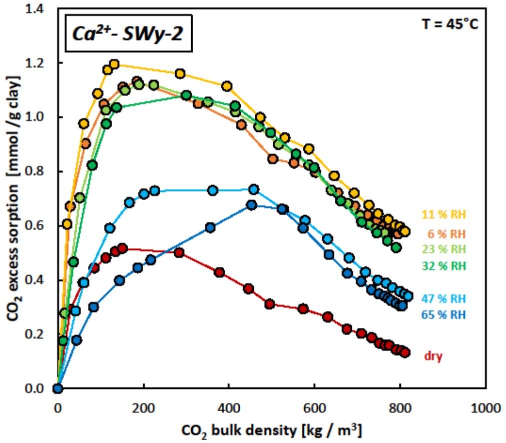
- Constructed 1-D flow through compaction vessel
- Long-term experiment on in-situ compacted and water-saturated Na-smectite
- Constructed a set-up that allows measuring of CO2 swelling stress at controlled relative humidity

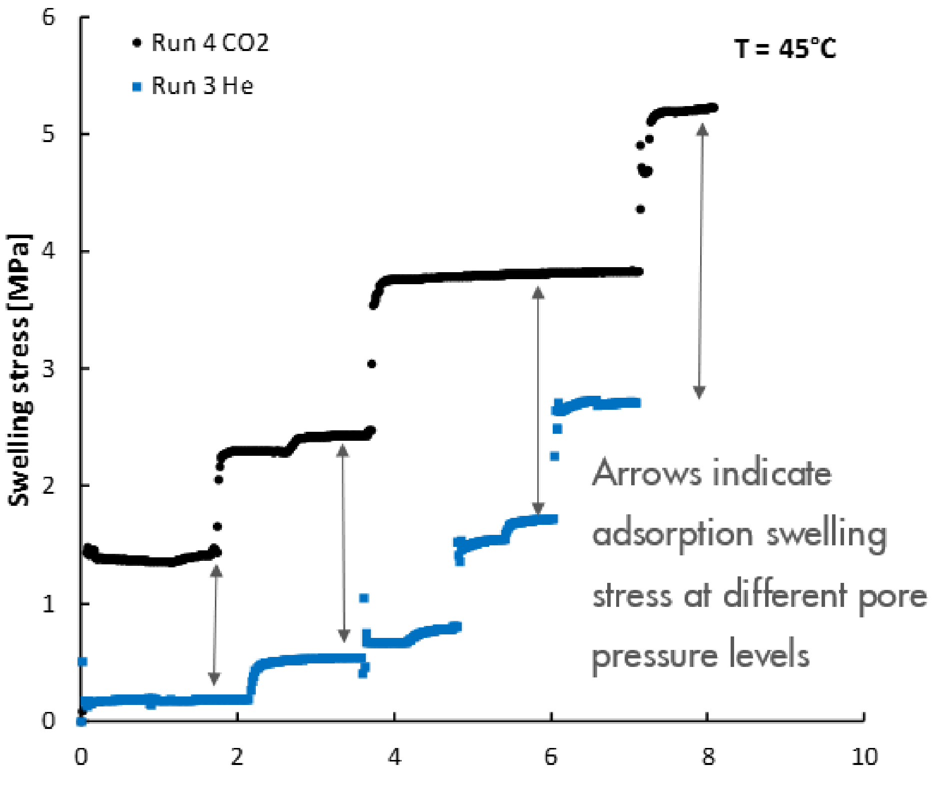
Results

- Studied effect of CO_2-induced clay swelling on fracture flow
- Measured > 20 high-pressure CO_2 sorption isotherms
- Determined effect of interlayer cations (Na^+ vs Ca^{2+}) and water content
- Flow of dissolved CO2 through water saturated Na-smectite does not result in swelling or significant permeability change

Implications

- Clay swelling for a fully saturated system is not a relevant mechanism for CO2 storage





σ_{start} = 20 MPa

Above: Swelling induced by CO_2 adsorption calculated using control experiments with He (no adsorption) at the same P-T conditions.

Left: CO_2 excess sorption vs. CO_2 bulk density.

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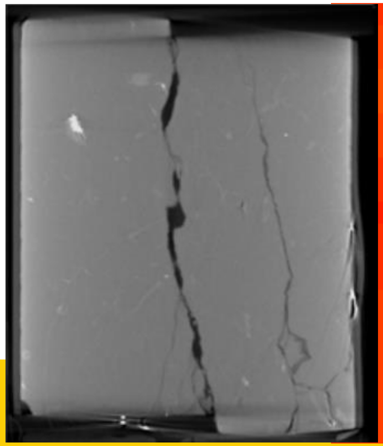
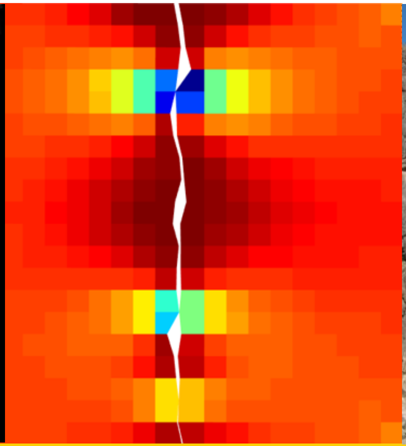
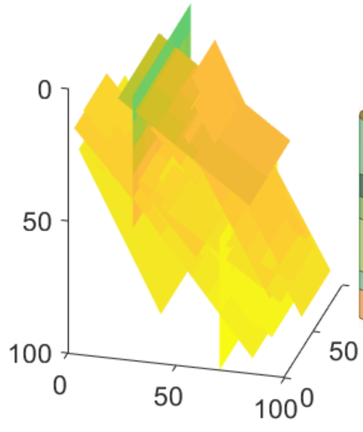
D E T E C T

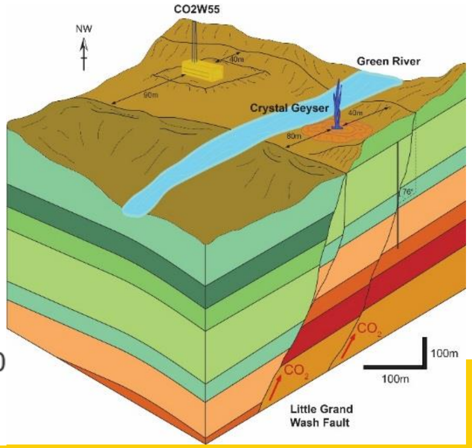
INTEGRATED GEOLOGICAL CO_2
LEAKAGE RISK ASSESSMENT

WP3 – Fracture characterisation and modelling









Shell Global Solutions International B.V.: Jeroen Snippe (WP3 Lead; WP3.4), Niko Kampman (WP 3.2,WP 3.4), Kevin Bisdom (WP 3.2, WP 3.3), Karin de Borst (WP 3.2, WP 3.3)

Heriot Watt University: Andreas Busch (WP 3.1), Nathaniel Forbes Inskip (WP 3.1), Tom Phillips (WP 3.1), Florian Doster (WP 3.2, WP 3.3), Rafael Castaneda Neto (WP 3.2, WP3.3), Amanzhol Kubeyev (WP 3.2)

Accelerating CCS Technologies

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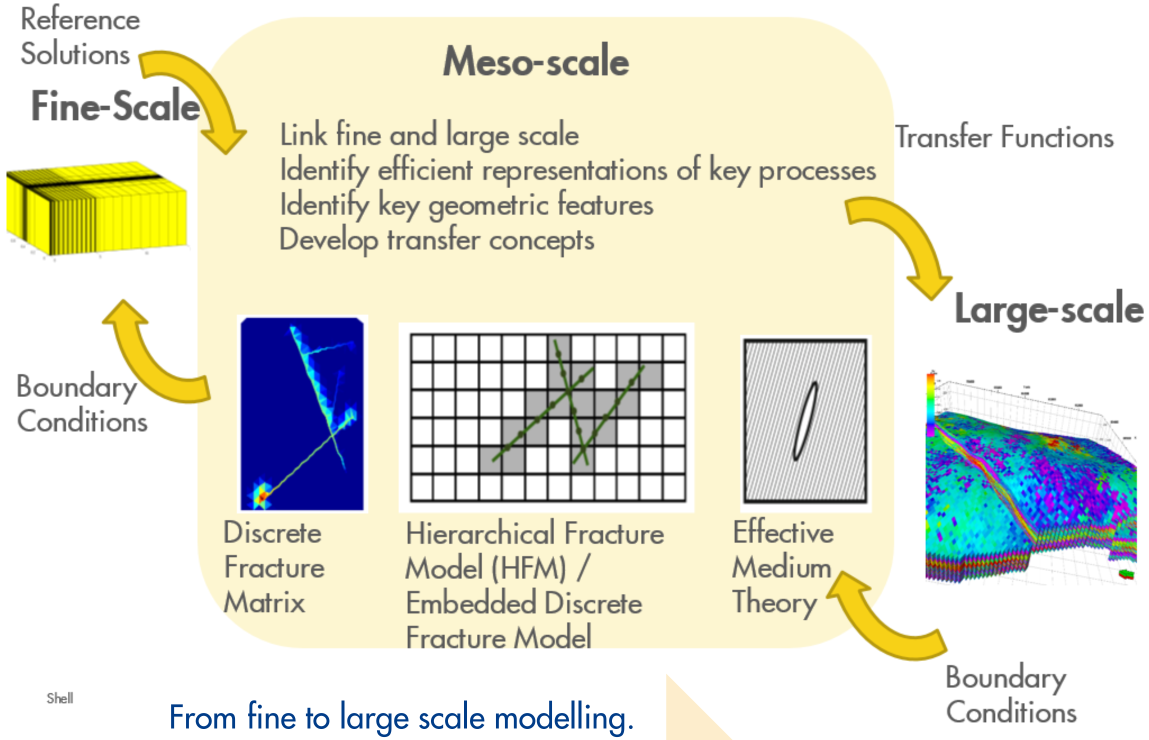
WP3 Lead: Jeroen Snippe, Shell

WP3 – Fracture characterisation and modelling

WP3 will characterise 2D/3D fracture network pattern for flow modelling. It will also perform innovative hydro-mechanical-chemical CO_2 and brine leakage modelling at fine-scale, meso-scale and large-scale. Results inform WP4 and WP5.

Objectives

1. Develop and apply a predictive modelling workflow for realistic CO_2 and brine leakage rates along realistic fault/fracture damage zones through the primary caprock and continuing into shallower formations
2. Incorporating effects on fracture aperture of mineral dissolution/precipitation and clay swelling



From fine to large scale modelling.

Collaboration

- Shell IRD, Heriot-Watt University

WP3.1. 2D/3D fracture network pattern characterisation for flow modelling	WP3.2. Fine-scale modelling of flow in a single facture and connected matrix	WP3.3. Meso-scale modelling and upscaling of flow in fault damage zones	WP3.4. Large-scale fault zone leak path modelling of storage complexes

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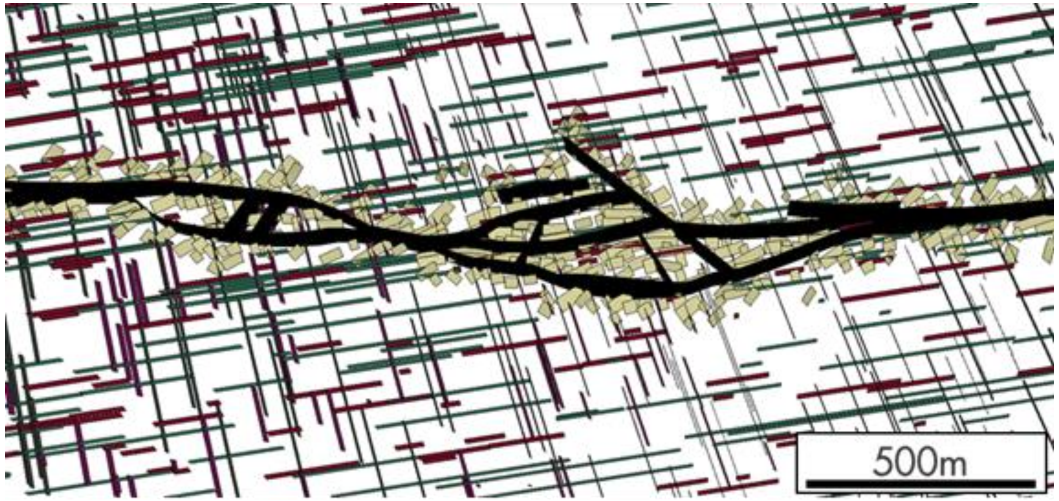
Nathaniel Forbes Inskip, HWU, Kevin Bisdom, Shell

WP3.1 – Fracture network characterisation

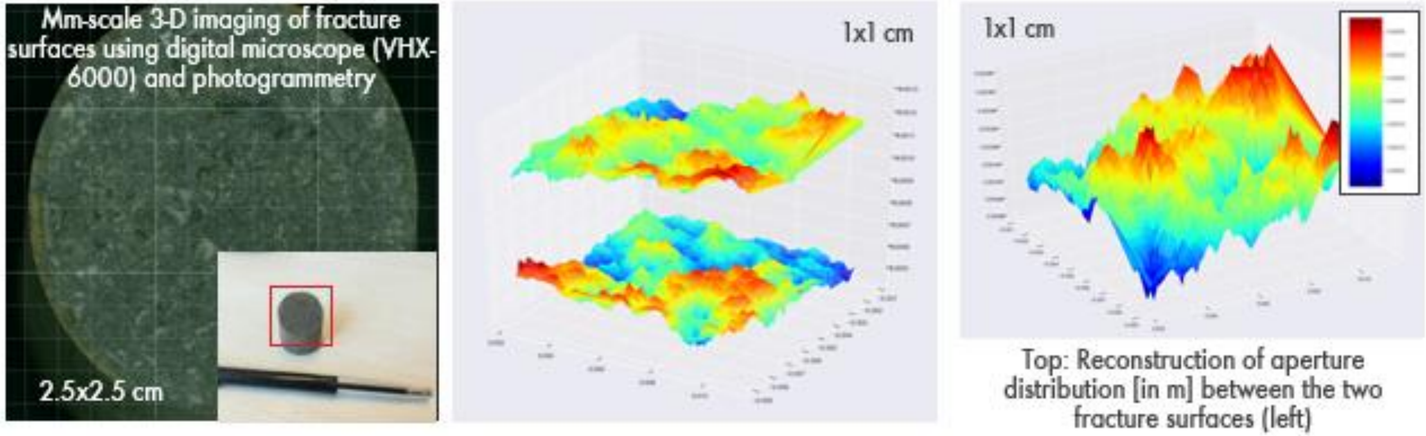
Results

- 2D Mont Terri fracture network extracted and used in WP3.3
- Digitised the full MT fault structure in MOVE
- 2D Green River shallow fault zone fracture network set up as input into WP3.3
- Green River core samples selected and are currently being tested
- Opalinus shale core tested at Utrecht University



Meso-scale fracture network as input for large-scale modelling.

Mont Terri: exposed fracture network.



Top: Reconstruction of aperture distribution [in m] between the two fracture surfaces (left)

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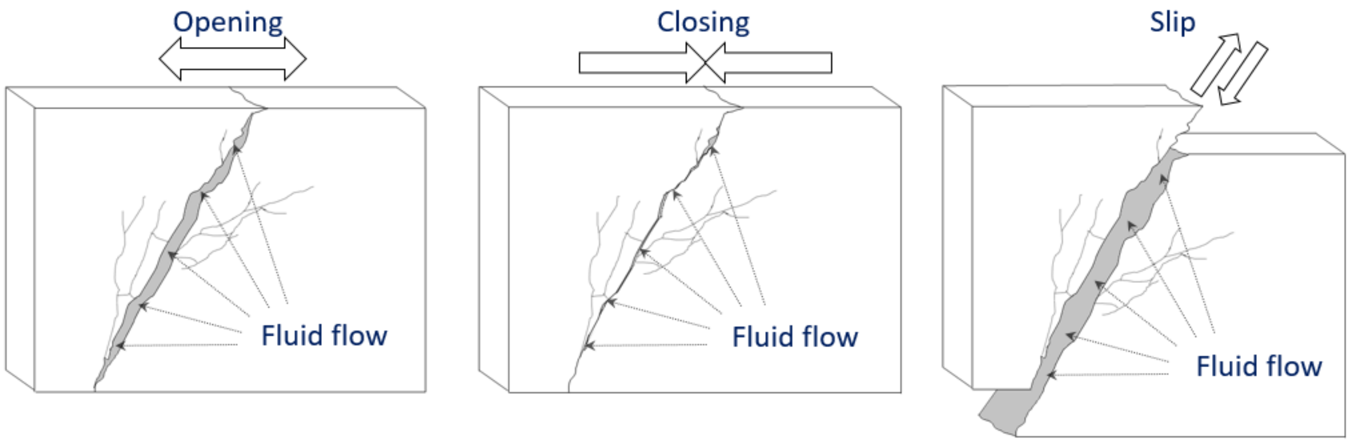
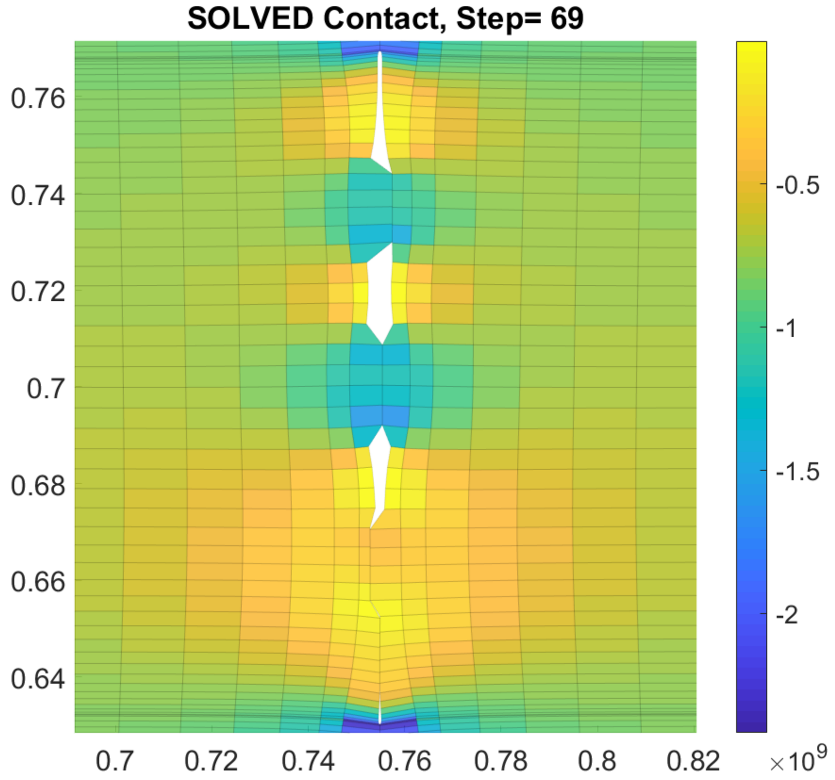
WP3.2 – Fine scale flow-mechanical modelling

Results

- Selected, implemented and validated Normal Contact Algorithm
- Implemented and validated Frictional Contact Algorithm
- Implemented Contact Area Refinement by Hanging Nodes in VEM
- Initial Stress vs Permeability Curves for Rough Fracture (Trapezium, Sinusoidal and Rough)
- Developed a numerical code for explicit modelling of the fracture opening, closing and slip
- Used this code and analytical methods to investigate stress dependency
- Implemented a Stokes solver to calculate permeability in complicated deformed geometries
- Obtained numerical stress-permeability relationships for several fracture parametrisations





Fine-scale fracture flow-mechanical modelling to obtain stress-permeability relationships.

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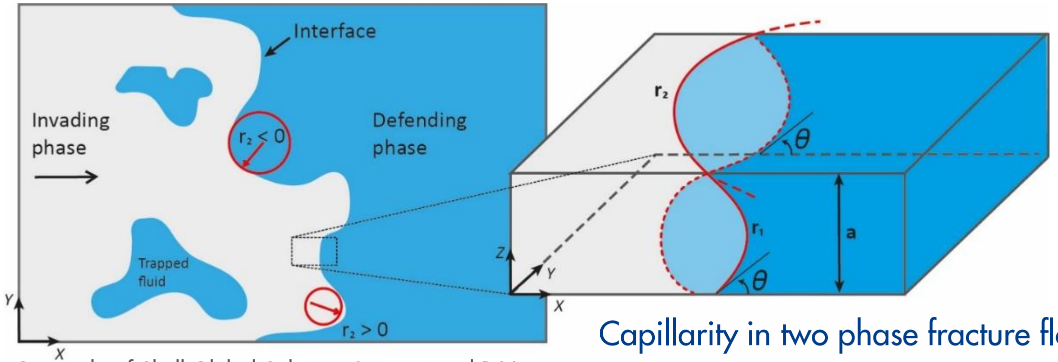
Niko Kampman, Shell

WP3.2 – Fine-scale modelling: relative permeability simulations

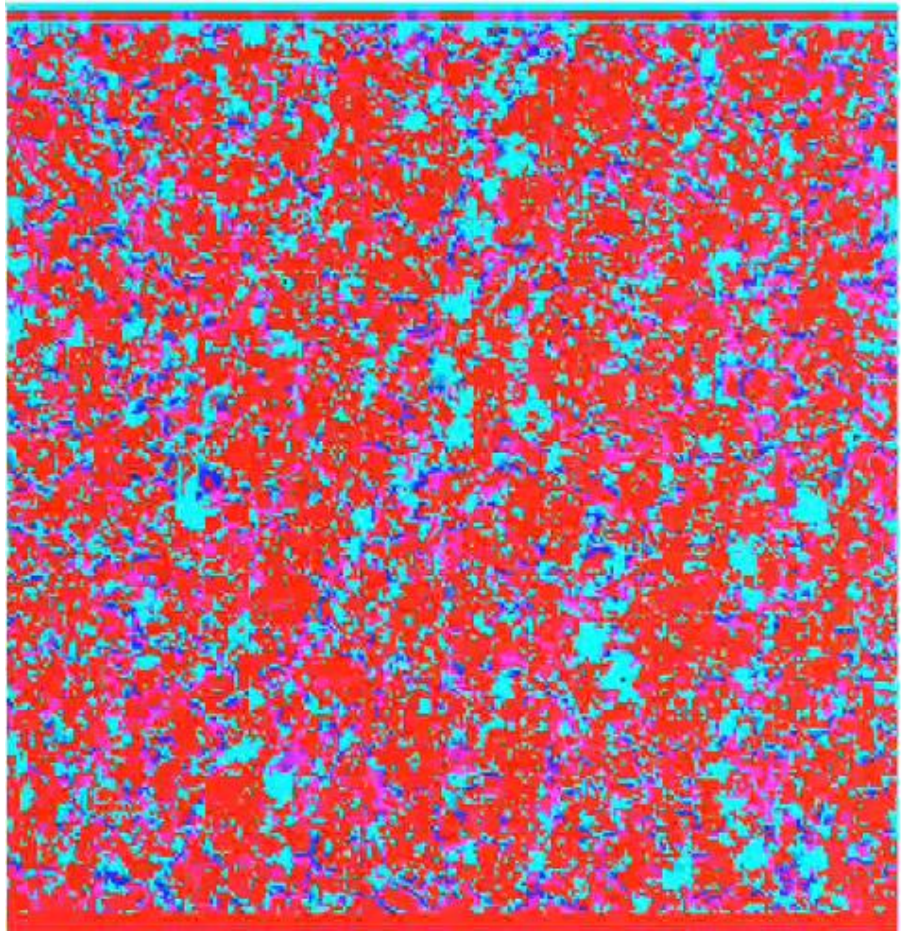
Results

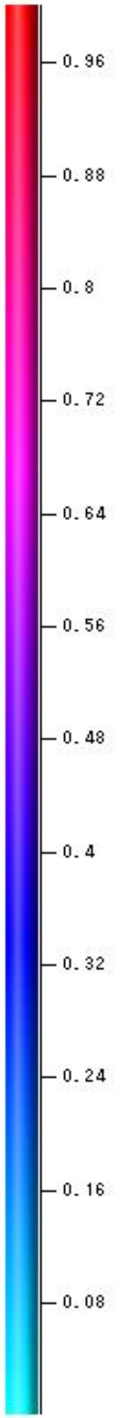
- Numerical modelling of brine and CO_2 flow was done to derive brine-CO_2 relative permeability relationships in rough single fractures:
- Observed strong phase interference between the brine and CO_2 at intermediate saturations that reduces the effective permeability
- Showed effects of capillarity limit the ability of the non-wetting 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 reducing leakage rates through tight rough fractures



Capillarity in two phase fracture flow.

High roughness CO_2 saturation JRC = 13.8





Scale: CO_2 saturation

Accelerating CCS Technologies

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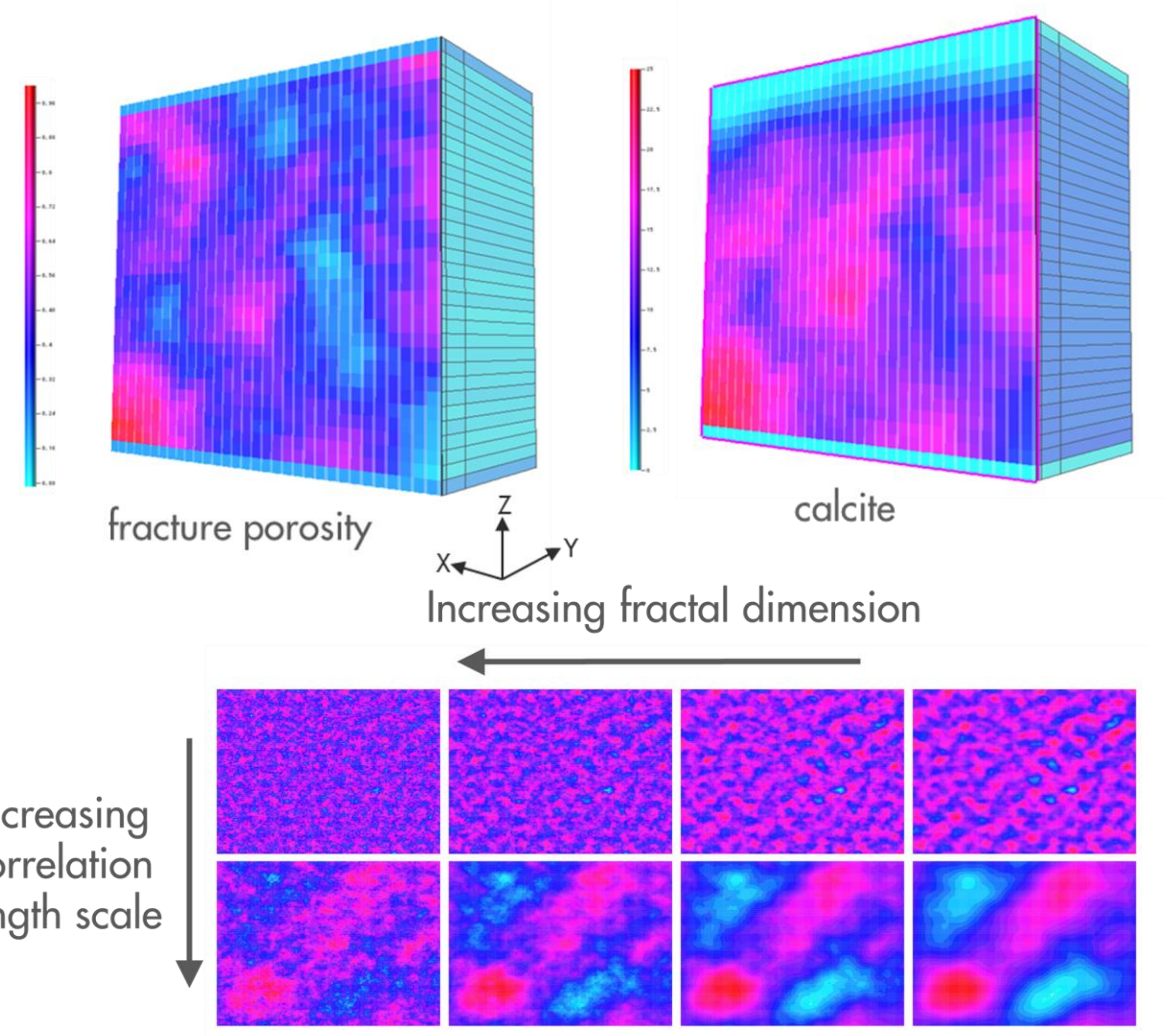
Niko Kampman, Shell

WP3.2 – Fine-scale Reactive Transport Modelling (RTM)

Results

- Built MoReS-PHREEQC 2.5D & 3D RTM with code to model fracture permeability, account for local aperture and fracture tortuosity, track reaction front propagation in fracture walls with mixed diffusion & surface reaction control, …
- Tested prediction of single fracture permeability from simulation against prediction from cubic law and mean fracture aperture (up to 3 orders magnitude difference)
- Mineral reactions dominated by carbonate dissolution and precipitation
- Progress of mineral reactions 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



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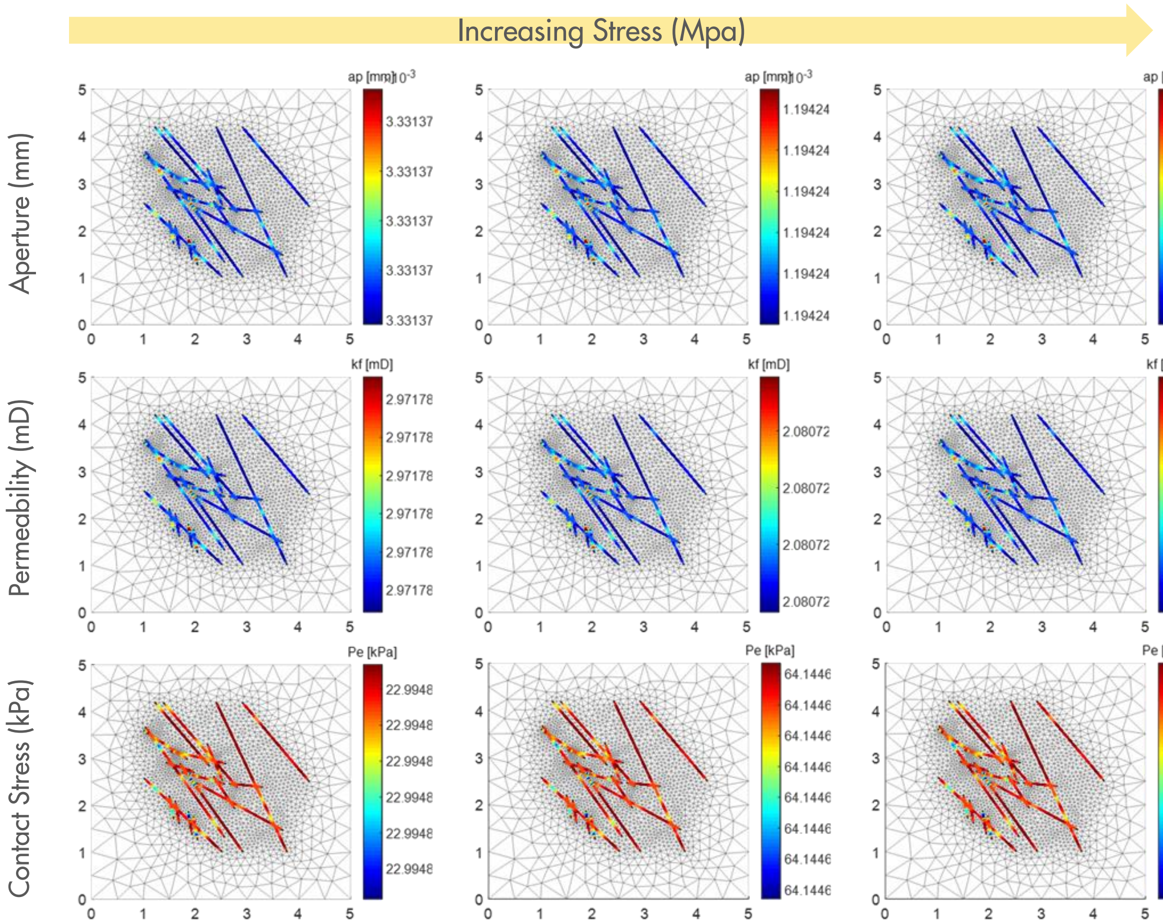
WP3.3 - mesoscale flow-mechanical modelling

Results (method development and application to Mt. Terri)

- Development of 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
- Successful application of the computational tools to upscale the permeability of a fracture network digitised from the Mt. Terri site



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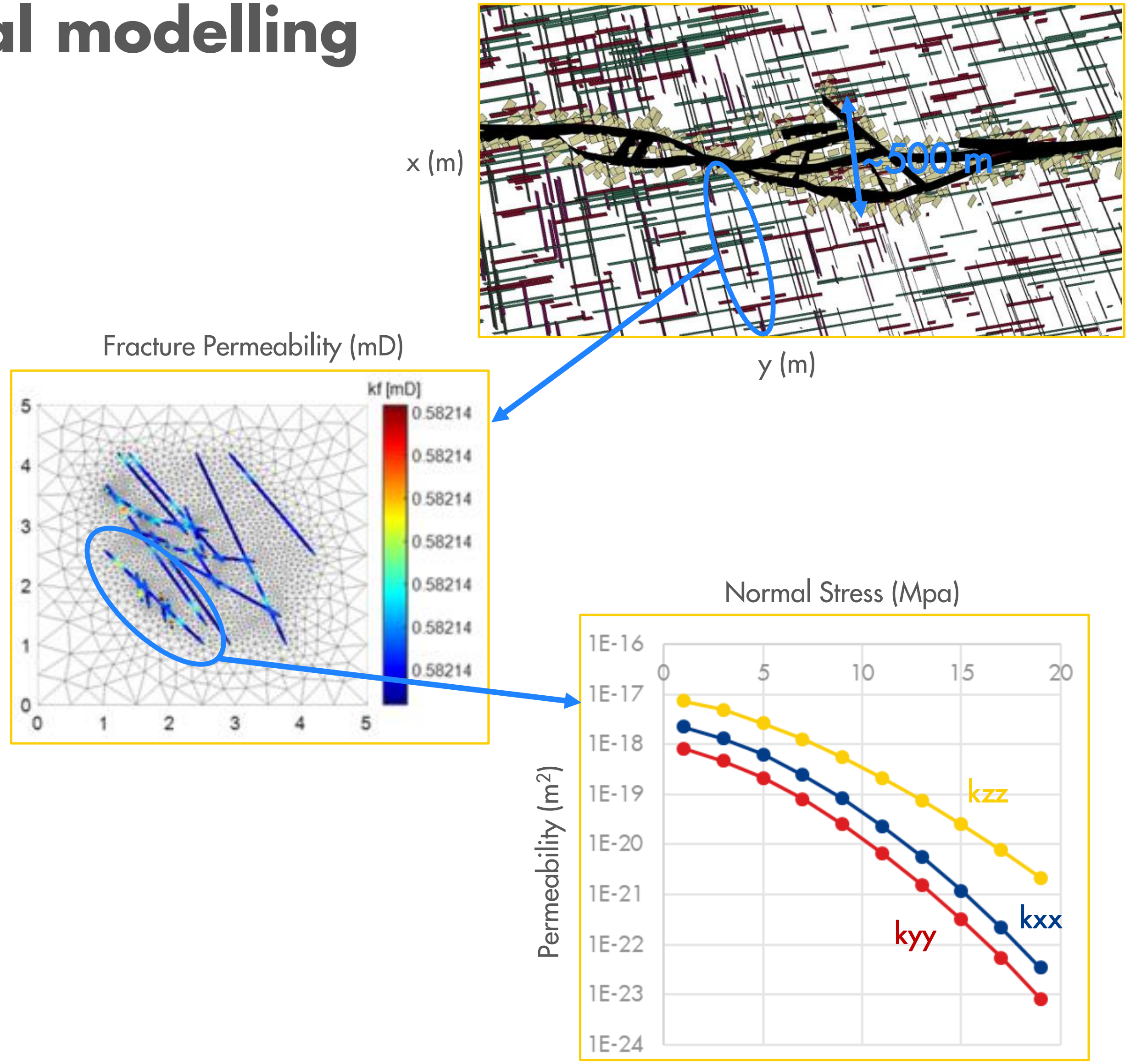
WP3.3 - mesoscale flow-mechanical modelling

Results (Green River)

- For the fracture networks that were investigated, we have observed an increase between 1 and 2 orders of magnitude relative to the background caprock permeability
- In-situ fracture apertures are typically very small which could make capillary pressure effects relevant
- Capillary pressure could potentially prevent CO_2 leakage through fracture networks

Outlook

- Develop tools for upscaling of relative permeability curves of the fracture network. These curves will improve the accuracy of the leakage rate estimates provided by the large scale modelling.
- Develop tools for upscaling of capillary pressure of the fracture network
- Develop tools for upscaling of mineral dissolution/precipitation in the fracture network



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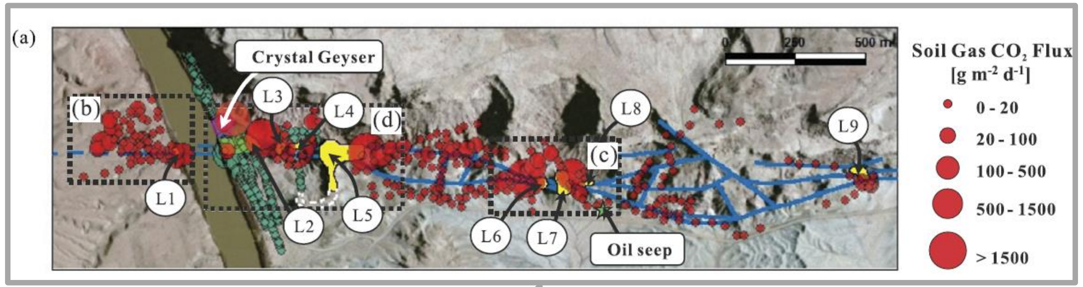
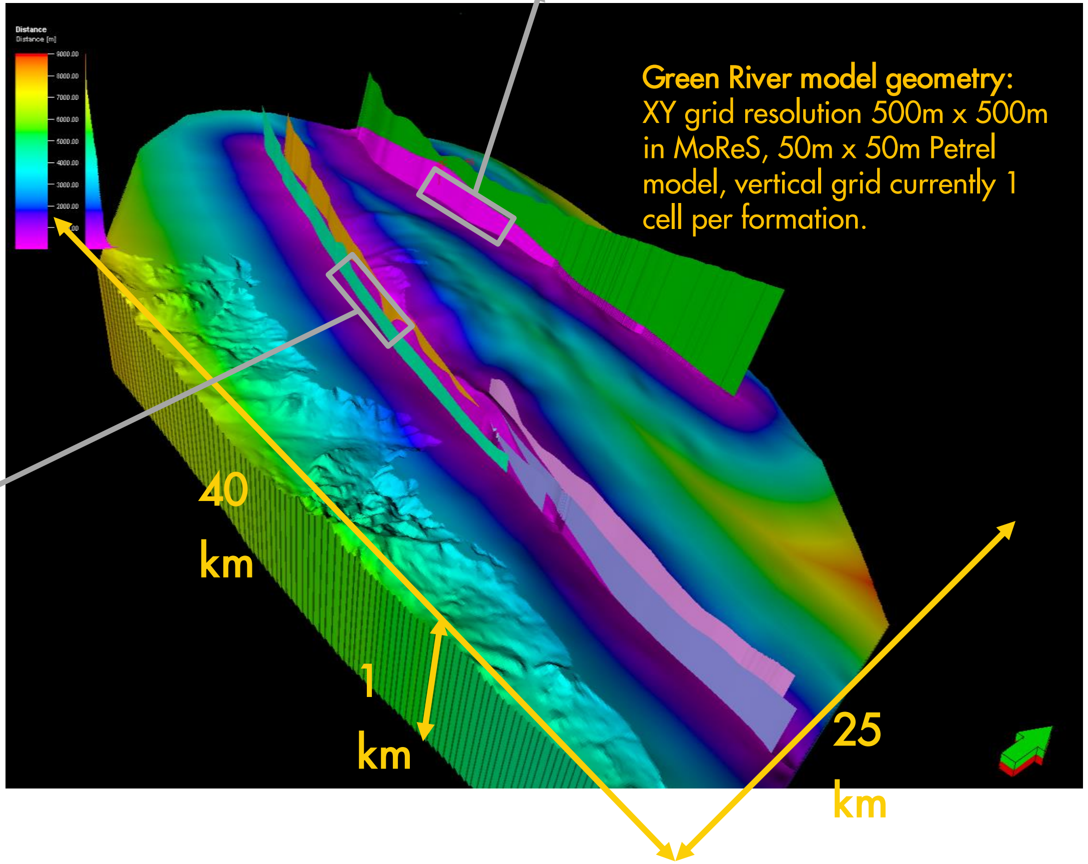
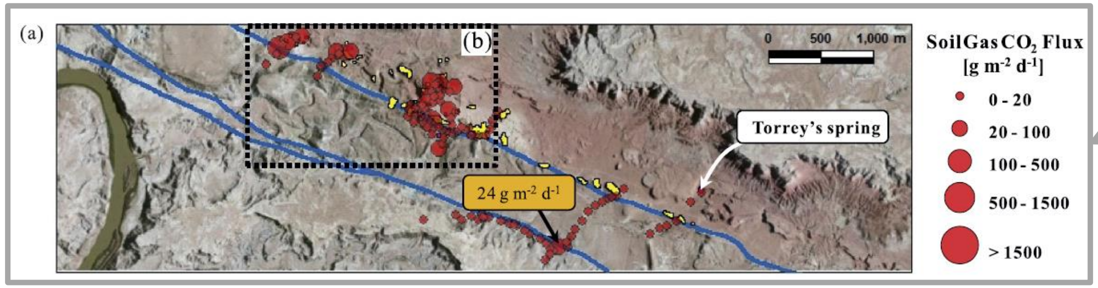
WP3.4 - large scale modelling



Application to Green River natural site

- 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).
- Site has been extensively characterised
- Extensive CO_2 surface flux measurements by Jung et al. (Earth and Planetary Science Letters, 2014)





Accelerating CCS Technologies

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WP3.4 - large scale modelling

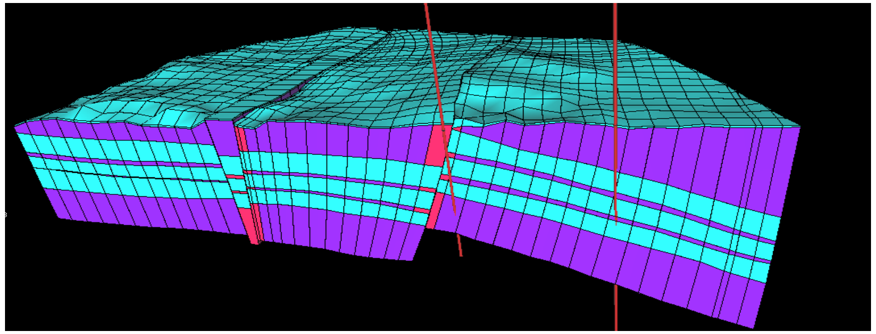
Results (preliminary)

- 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.
- 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.

Outlook

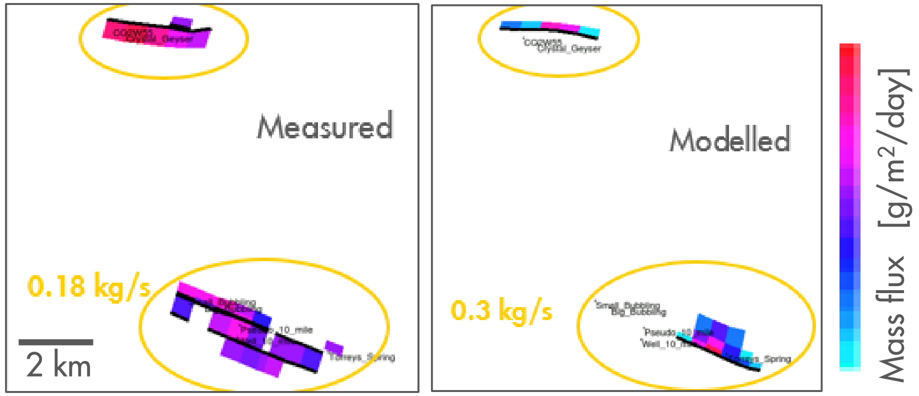
- Enhancements to the large-scale model (e.g. model resolution, uncertainty analysis). Not expected to change the main conclusions but will improve the reliability and understanding about impact of input parameters.
- Once this is completed, the modelling workflow will be applied to North Sea CO_2 storage site candidates in the Moray Firth area 100 km offshore Scotland, to quantify and de-risk the probability of leakage.

Green River CO_2 migration model



Green River model response (preliminary)

Credible match already achieved using base setting for a priori input parameters, based on fracture flow experimental data and high-resolution models. A quantitative match can be obtained by varying the input parameters within their uncertainty ranges



Observed CO_2 flux map   Simulated CO_2 flux map

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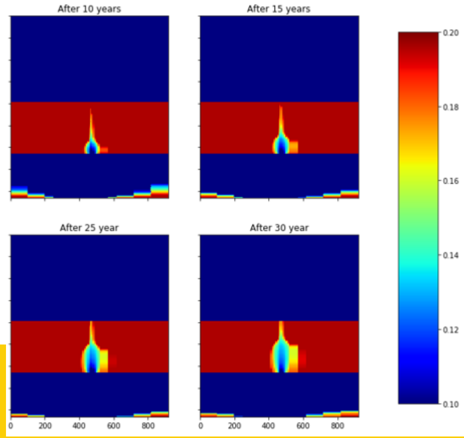
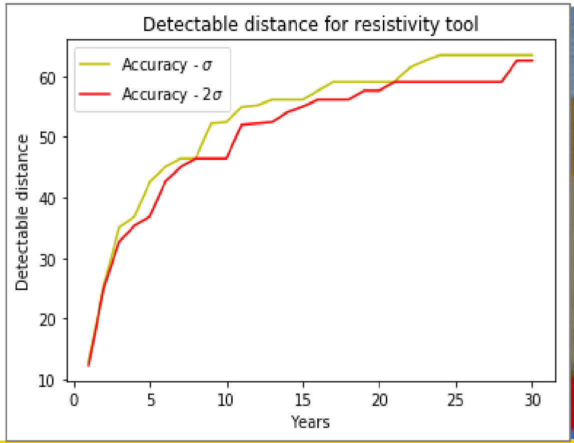
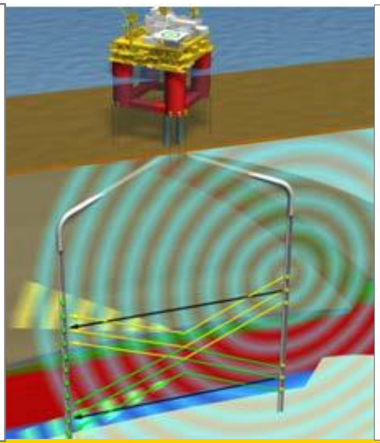
DETECT

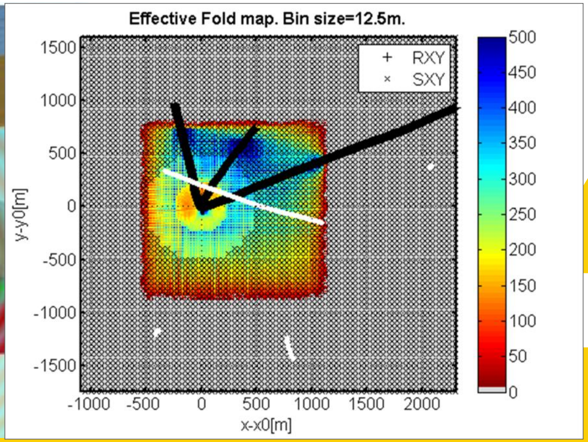
INTEGRATED GEOLOGICAL CO_2 LEAKAGE RISK ASSESSMENT

WP4 – Containment monitoring for caprock Integrity









Shell Global Solutions International B.V.: Marcella Dean (WP4 Lead), Yuan Qiu (In-well Sensing Technology), Daria Spivakovska (In-well Sensing Technology), Samantha Grandi (Areal Surveillance Technology)

Accelerating CCS Technologies

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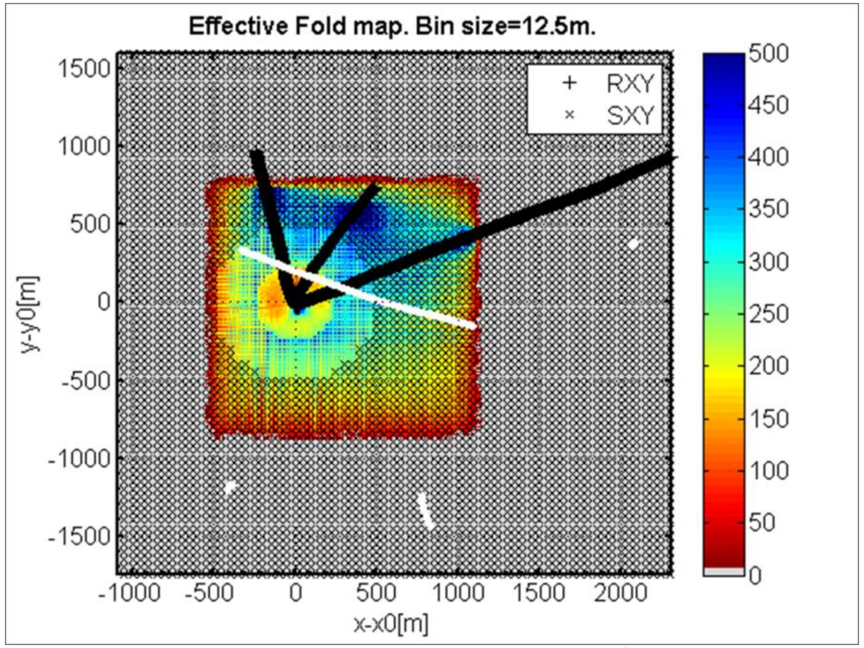
WP4 – Containment monitoring for caprock integrity

WP4 will select cost-efficient and effective caprock monitoring technologies which will be incorporated as active safeguards in bowties and quantitative risk assessment models (WP5).

- **Objectives**

1. Identify which containment monitoring technologies can act as effective and efficient barriers to the risks posed by CO_2 leakage along fractures of the caprock
2. Give a comprehensive overview of selected containment monitoring technologies with their respective detection threshold ranges for a number of investigated leakage path scenarios

- **Collaboration**
  - Shell Global Solutions, Risktec Solutions



Goldeneye DAS VSP feasibility study.

- WP4.T1 Overview of relevant containment monitoring technologies
- WP4.T2 Identify monitoring technologies suitable to detect leakage across caprock
- WP4.T3 Perform feasibility studies for selected monitoring technologies
- WP4.T4 Identify detection thresholds based on results from T3 and other WPs
- WP4.T5 Incorporate results as active safeguards in bowtie with WP5

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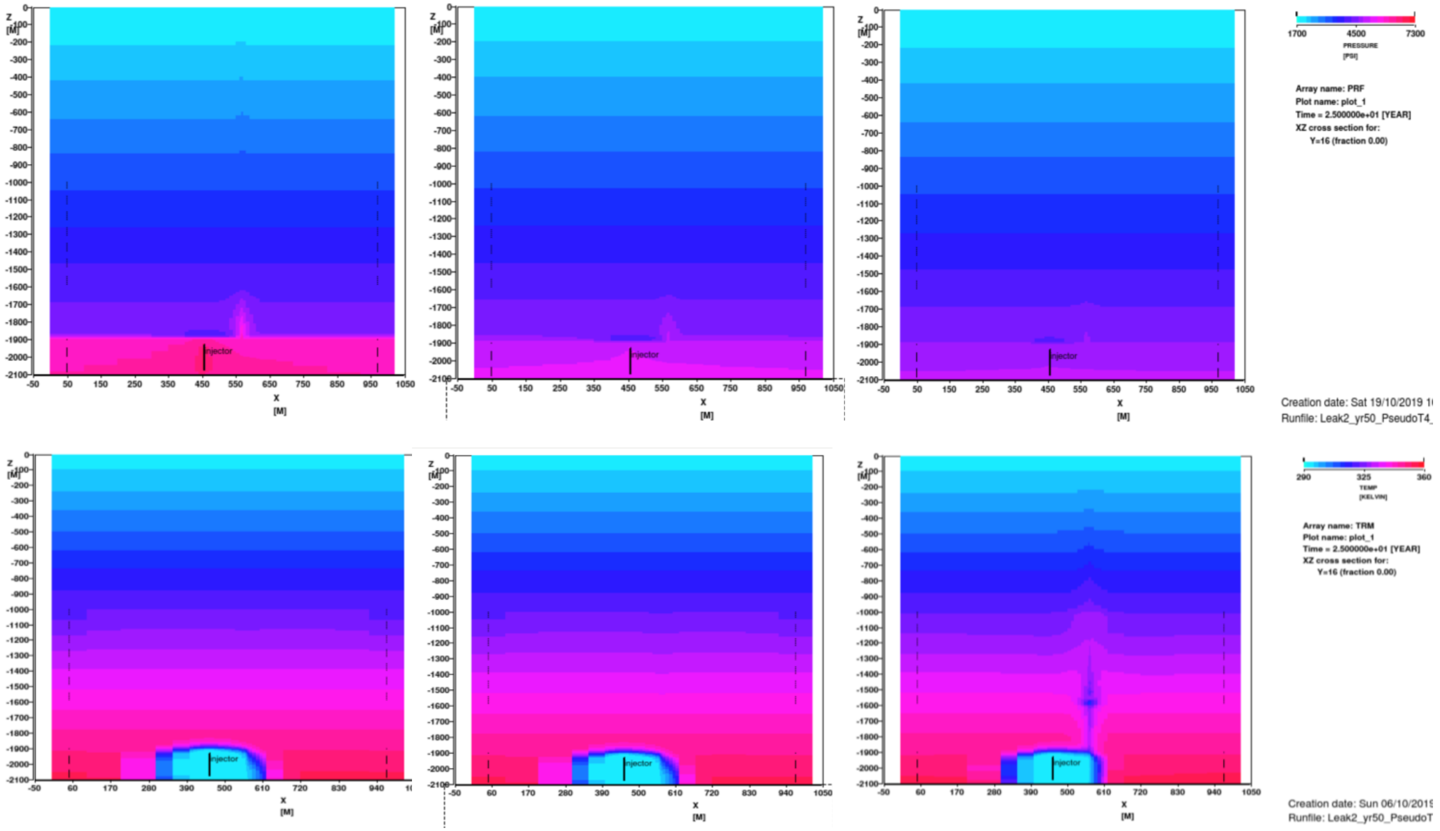
WP4 – In-well monitoring

Results

- Using a pseudo-thermal leakage model we modelled the effects of changing permeabilities, distance to leak and leakage rates
- Temperature and pressure monitoring for geologic leakage detection is expected to perform well. The performance depends on permeability, saturation and distance to fault/fracture system
- Neutron and Thermal Neutron Capture (TNC) are recommended low-cost tools for leakage detection
- Fiber optics Distributed Temperature Sensing (DTS) (installed behind casing) is considered one of the best options for monitoring leakage within the vicinity of the instrumented well

Modelled temperature and pressure responses



Top: Cross section of the modelled pressure response for low (left), mid (middle) and high (right) matrix cases, with the same base case leak. The low matrix permeability has high pressure build up in the primary reservoir, and visible pressure increment along the faulty leakage plane (Left). After 25 million tons of CO_2 injection.

Bottom: Cross section of the modelled temperature response for low (left), mid (middle) and high (right) leak cases, with the same base case matrix properties. After 25 million tons of CO_2 injection.

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Samantha Grandi, Shell

Geophysical monitoring

Results

- Assuming shallow marine storage locations (~100m water depth). Amber means a more detailed site-specific feasibility study is needed
- Microseismic monitoring with fiber optic cables (or geophones in a monitoring well) is recommended
- Surface seismic methods: only high-resolution seismic methods like P-cable are considered feasible as traditional seismic methods lack resolution or are too costly
- Seabed geodesy with pressure monitoring transponders (PMTs) is a good option to monitor seafloor displacement directly (as an indication of fault reactivation)

	Technology	Can detect CO2 migrating along a fault/fracture	Can detect fault reactivation & induced fracture opening	Doable? Practical?	Maturity
Borehole	Continuous downhole DAS micro-seismic (and strain fronts)	No*	Yes	F.O. cables cemented behind casing (preferred) in multiple, deviated wells	medium
	4D DAS VSP reflections	Pending feasibility	Pending feasibility	Low cost	medium
	4D DAS VSP refractions	Pending feasibility	Pending feasibility	Ultra low cost. May be only for shallow monitoring	low
	Time-lapse DAS cross-well seismic	Pending feasibility	Pending feasibility	Two wells, intervention in source well	low
	Time-lapse borehole acoustic reflection survey or deep sonic imaging	Pending feasibility	Pending feasibility	Repeated wireline intervention if not with DAS	none
Surface	Time-lapse seismic with streamers (NAZ)	Unlikely	No	Insufficient repeatability and azimuth	high
	Time-lapse seismic with OBNs or OBCs (PRM)	Pending feasibility	Pending feasibility	Costly	high
	High-resolution 4D seismic	Unlikely	Pending feasibility	Low cost. Water multiples may obscure imaging. Shallow monitoring (1000 m depth)	medium
	(micro) Seismicity monitoring with broadband seismometers	No*	Pending feasibility	Costly, not a dense array, insufficient detectability	high
	Passive seismic with PRM or OBNs	Unlikely	Unlikely	Costly	medium
	Continuous seabed geodesy with PMTs	No	Pending feasibility	Low cost but for this application array must be large and dense enough	medium
	Time-lapse seabed AUV surveys (SBP)	Pending feasibility	Pending feasibility	Low cost. Shallow monitoring (150 m depth)	low

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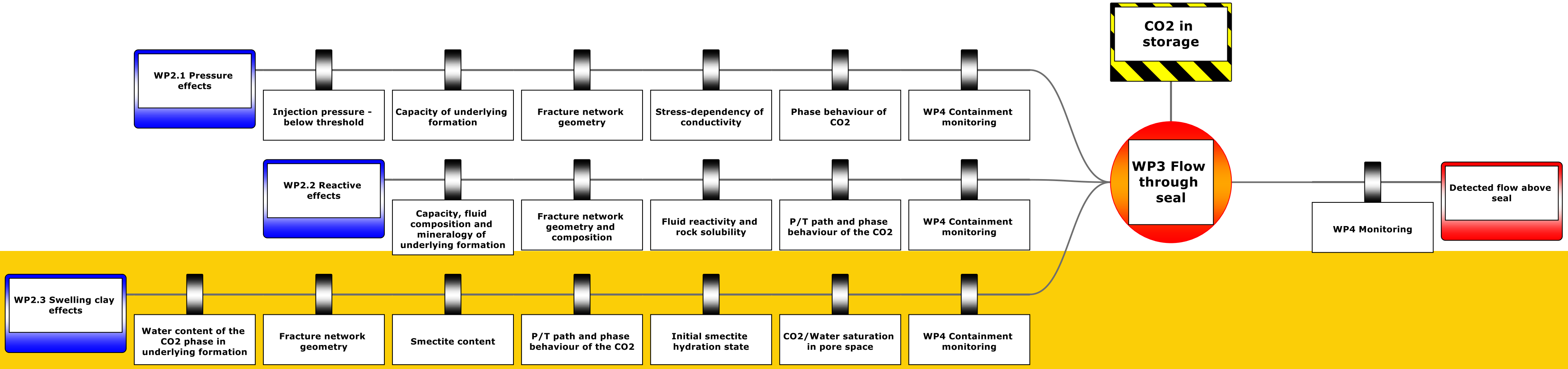
WP5 – Qualitative and quantitative risk assessment



Risktec Solutions B.V.: Sheryl Hurst (WP5 Lead)

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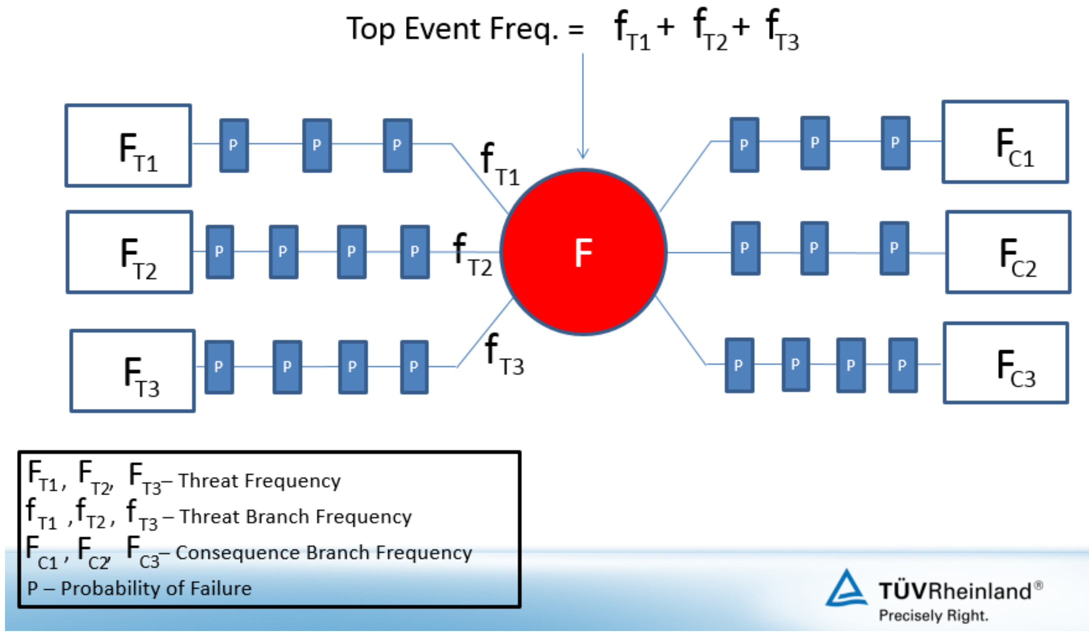
WP5 – Qualitative and quantitative risk assessment

WP5 will integrate learnings from DETECT into qualitative bowties and quantitative model to serve as an industry guideline for risk assessment of CO_2 leakage across fractures in the caprock.

- **Objectives**

1. To develop bowtie diagrams depicting the natural pathways for CO_2 release from subsurface storage and the measures in place to prevent/mitigate the risk
2. To develop a quantitative risk assessment model aligned to the bowtie, using output from the other WPs to determine prevention/mitigation measure effectiveness
3. To calculate relative risks of CO_2 leaking through caprock, enabling the model to be used for comparison purposes

- **Collaboration**
  - Risktec (TÜV Rheinland Group), Shell IRD



An example of a semi-quantitative risk analysis model.

WP5.T1. Identify suitable quantitative bowties risk analysis models	WP5.T2. Bowtie risk assessment for different leakage scenarios	WP5.T3. Quantitative risk analysis for different leakage scenarios

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WP5 – Qualitative bowtie risk assessment

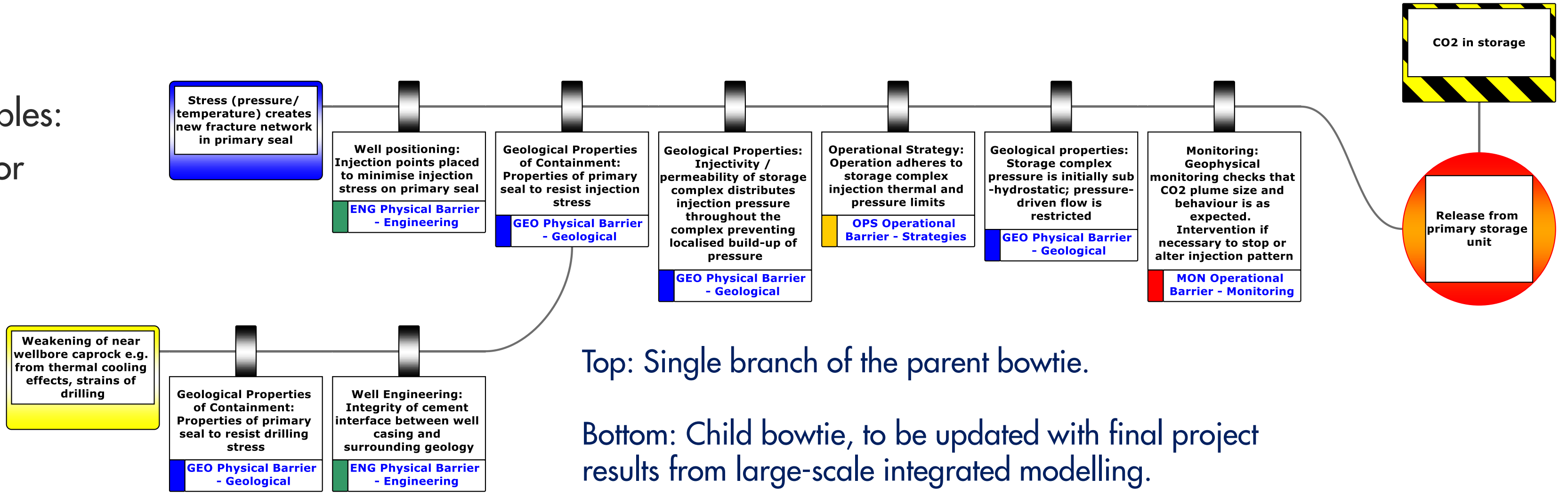
Results

Made significant progress towards final deliverables:

- Qualitative parent bowtie – sets the context for DETECT leak paths
- Qualitative child bowtie – which barriers increase/decrease or have no effect on rate of leak through fault/fracture network

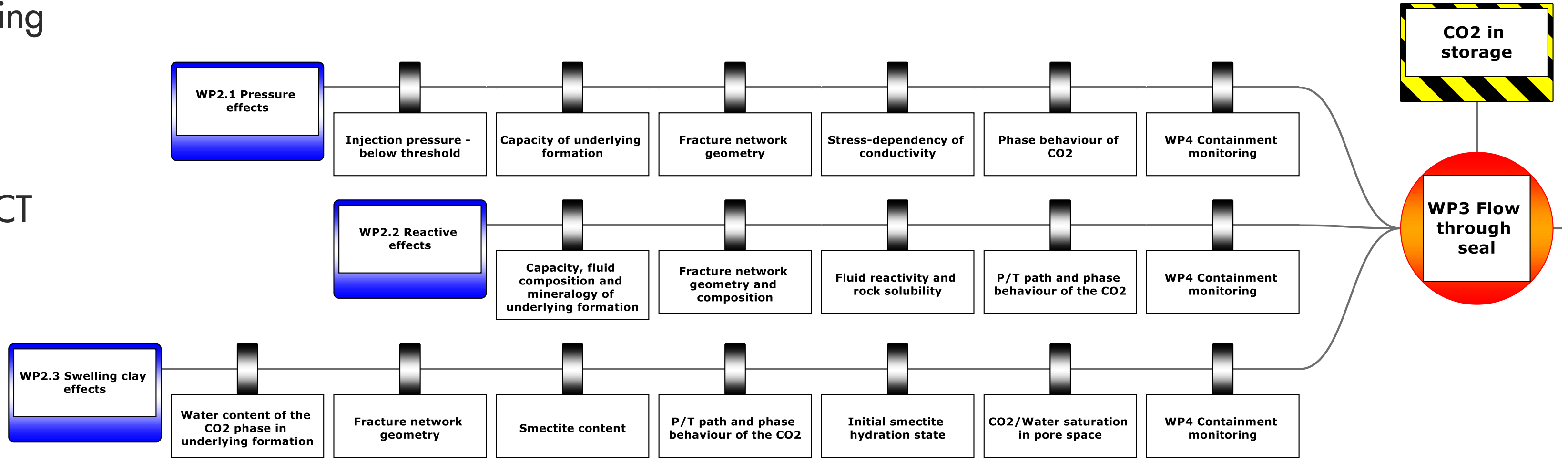
Outlook

- Parent bowtie – customisable to generate starting point bowtie for site-specific bowtie analysis
- Communication tool – the child bowtie will enable messaging of the key findings of DETECT
- User guide for qualitative parent bowtie and child bowtie – allows users to follow the same analysis process



Top: Single branch of the parent bowtie.

Bottom: Child bowtie, to be updated with final project results from large-scale integrated modelling.



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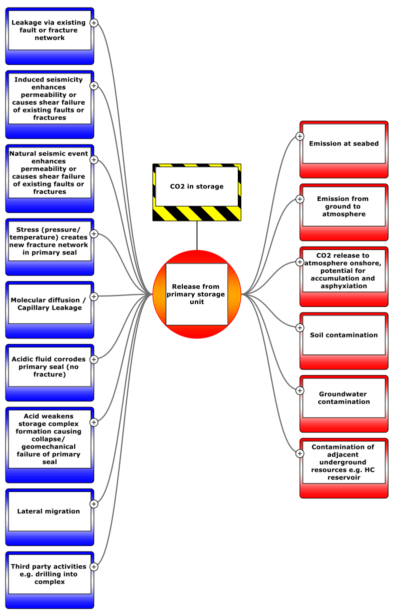
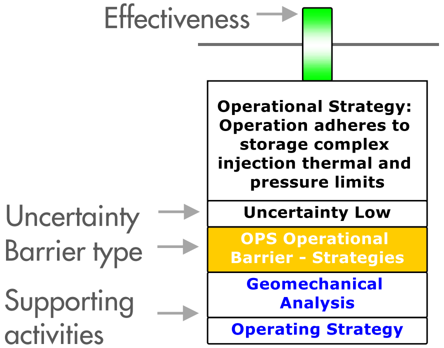
WP5 – Qualitative bowtie risk assessment

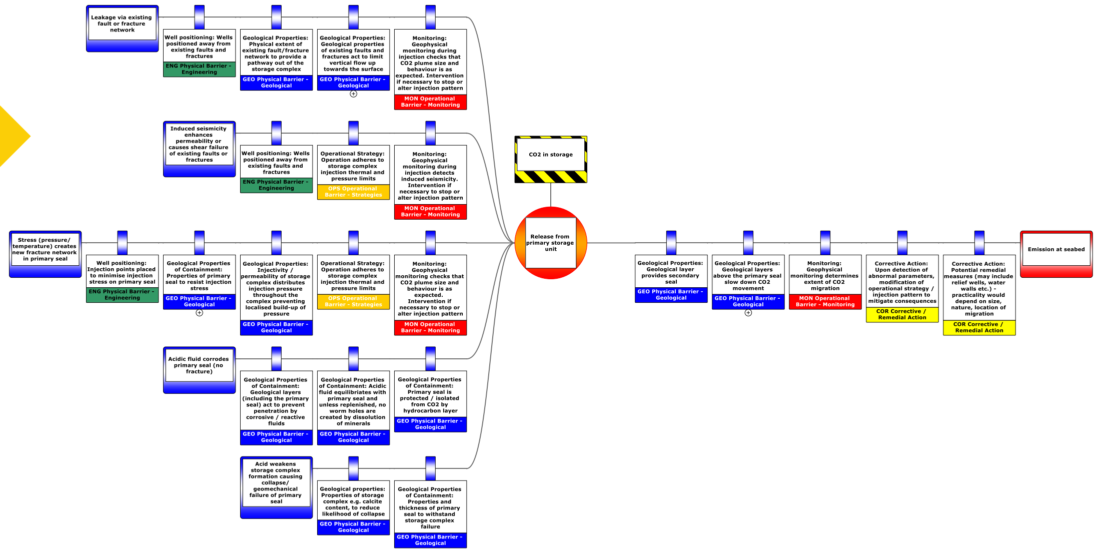
Customisable parent bowtie

- Customisable parent bowtie – starting point for site-specific bowtie analysis



- Presence/relevance of threat / consequence / barrier?
- Barrier effectiveness – good / fair / poor?
- Effectiveness uncertainty – low / medium / high?





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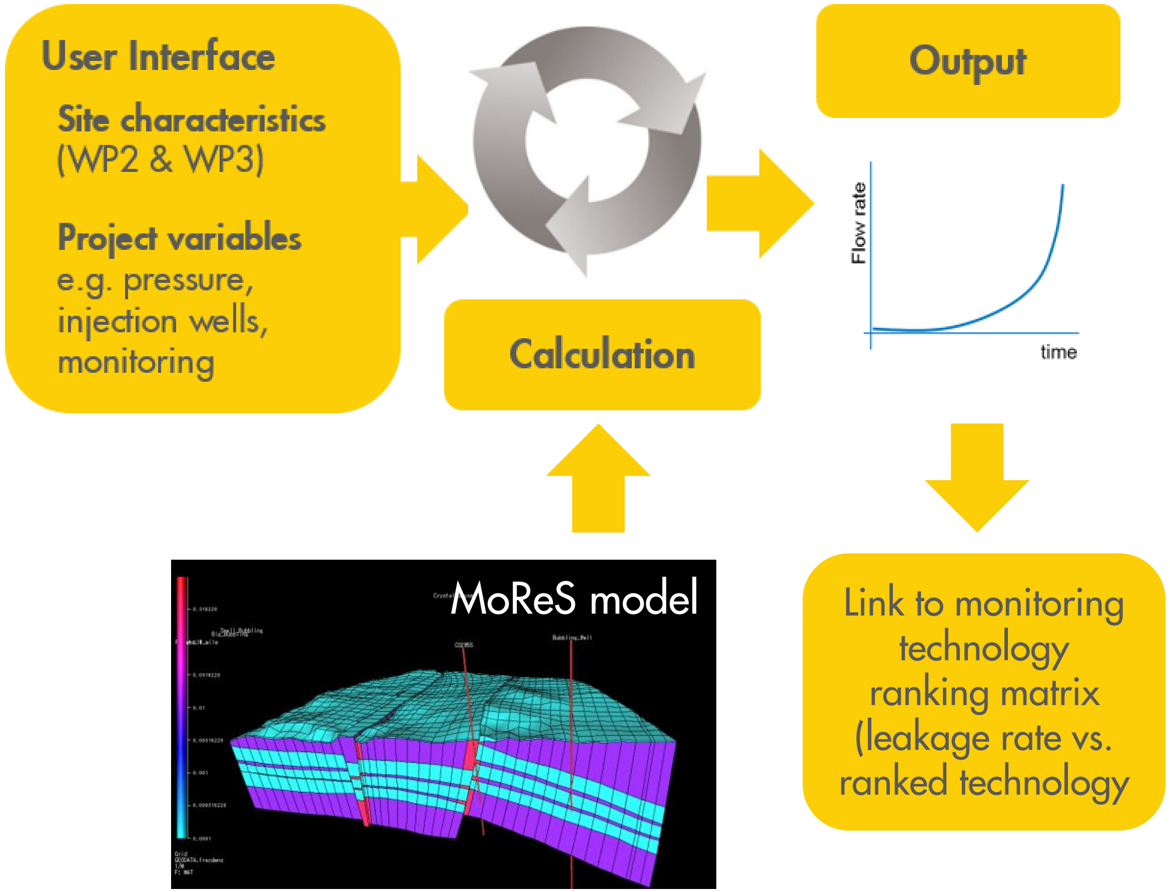
WP5 – Quantitative risk assessment

Results and Outlook

At the third bowtie/integration workshop this September, we clarified the final form of the quantitative tool:

- Quantitative tool to generate flow rate vs. probability as a prediction based on data store from North Sea cases modelled
- Quantitative tool output will be graphs of leakage flow rate with error bars, but also e.g. traffic light (low to high potential risk of leakage)
- Link monitoring feasibility studies output (monitoring technology ranking matrix) with quantitative risk assessment tool output (low to high leakage rates)
- Document process so users can 1) test parameter sensitivities for similar North Sea cases and 2) follow process to develop their own site-specific quantitative tool



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