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 Overview

Final Project Webinar
December 1st, 2020

Shell Global Solutions International B.V.: Marcella Dean (PL, WP4 lead), Jeroen Snippe (WP3 lead), Niko Kampman, Kevin Bisdom, Karin de Borst, Kees Hindriks

Heriot Watt University: Andreas Busch (WP2 Lead), Sebastian Geiger, Florian Doster, Nathaniel Forbes Inskip, Tom Phillips, Rafael Castaneda Neto, Yihuai Zhang, Amanzhol Kubeyev, Onos Esegbue, Roberto E. Rizzo

RWTH Aachen University: Reinhard Fink, Hannes Claes, Bernhard Krooss

Risktec Solutions B.V.: Sheryl Hurst (WP5 Lead), Andy Lidstone, Frank Hart, Paul van Rossum, James Bradbury, Connor Bloodworth

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.

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An introduction to the DETECT project & WP4

D E T E C T

INTEGRATED GEOLOGICAL CO_2
LEAKAGE RISK ASSESSMENT

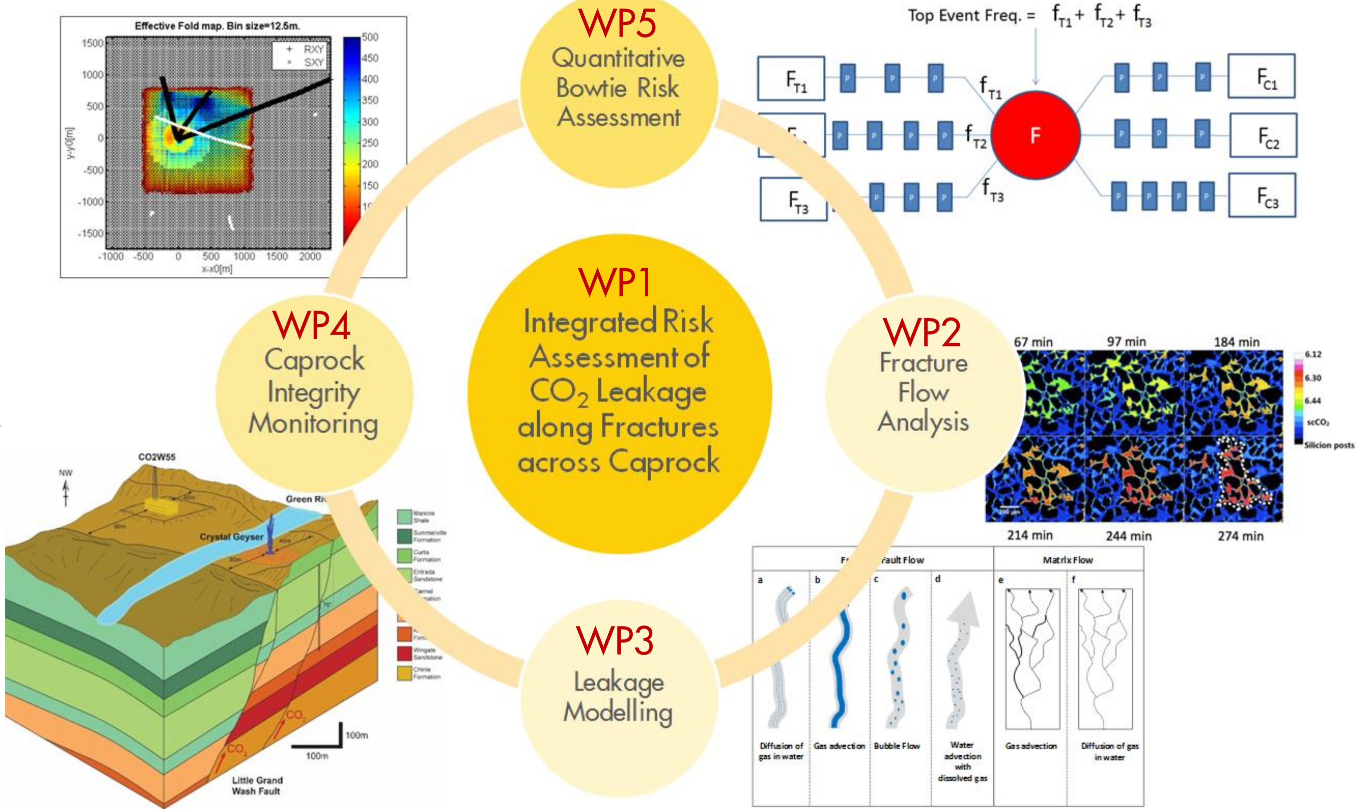
Introduction to project

- Motivation, objectives, approach, partners
- Introduction to DETECT workflow
- Dissemination and publication to date

Introduction to work packages

- WP2 - Fracture flow, mineralisation, clay swelling
  - Presentation by Andreas Busch (HW University), WP2 lead
- WP3 – Fracture characterisation and modelling
  - Presentations by Niko Kampman (Shell), Florian Doster (HW University), Jeroen Snippe (Shell), WP3 lead
- WP4 – Containment monitoring for caprock Integrity
  - This presentation, Marcella Dean (Shell), WP1 & WP4 lead
- WP5 – Qualitative and quantitative risk assessment
  - Presentation by Sheryl Hurst (Risktec)

Overview and results WP4



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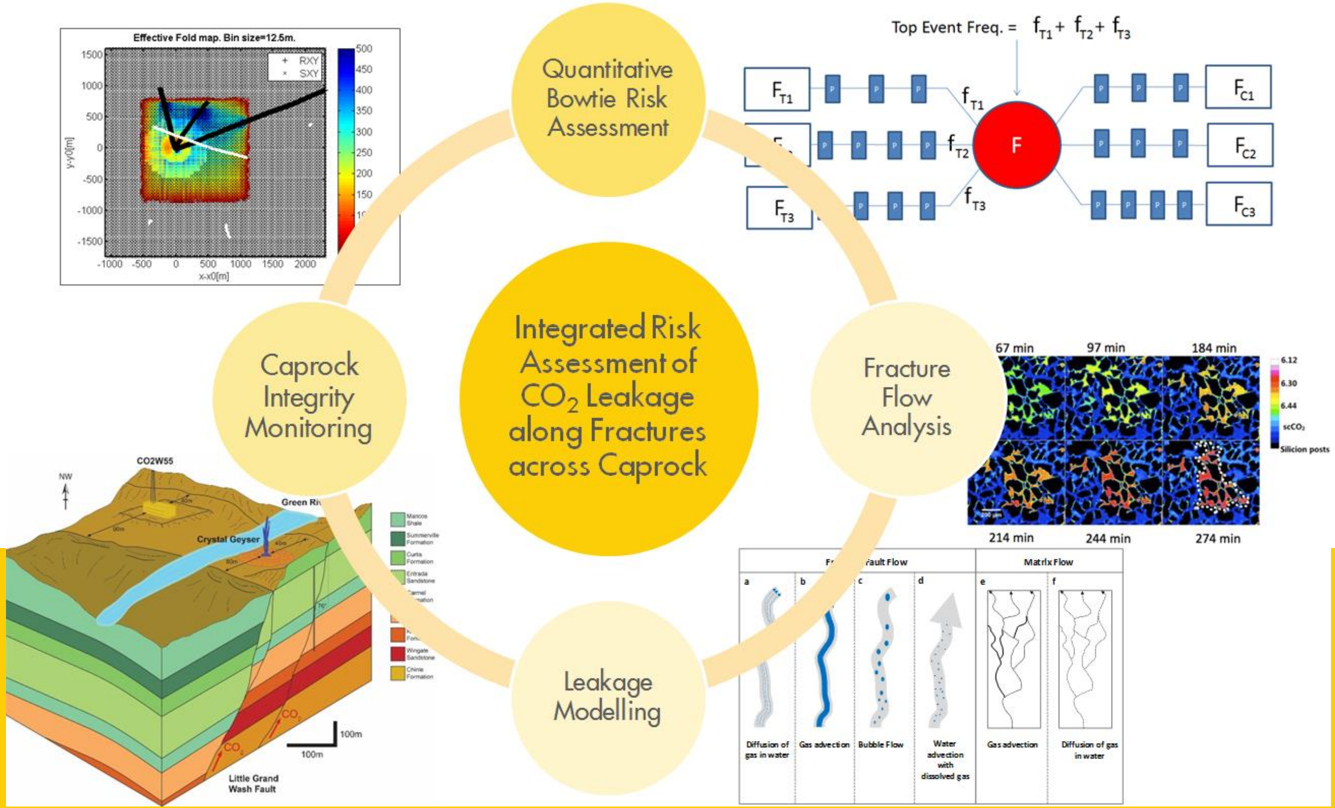
DETECT Project



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

Motivation

A focused effort to increase understanding of geologic leakage risks along fractures in caprocks. This is particularly relevant for large-scale deployment of CCS which may increase exposure to containment risks.

Objectives

The goal of DETECT is to develop tools to assess geological leakage risks related to fault and fractures in caprocks.

Approach

Modeling workflows developed and suitable monitoring technologies identified are integrated as barriers within the bowtie risk framework, allowing holistic assessment of geological leakage risks across caprocks.

Collaboration

Small consortium with relevant expertise and proven track record to deliver our objectives.

HERIOT WATT UNIVERSITY

EMR Energy & Mineral Resources Group RWTH AACHEN

TÜVRheinland® Risktec

Accelerating CCS Technologies

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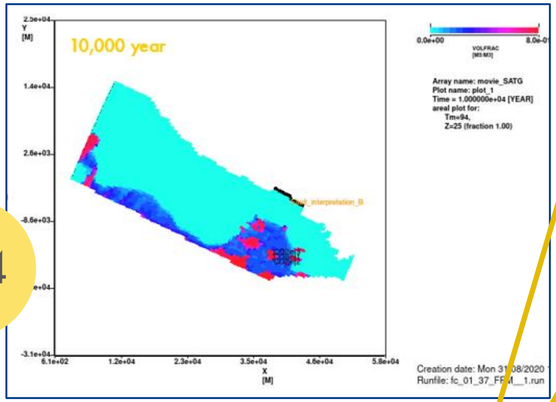
DETECT workflow

The goal of DETECT is to assess geological leakage risks related to fault and fractures in caprocks.



WP4

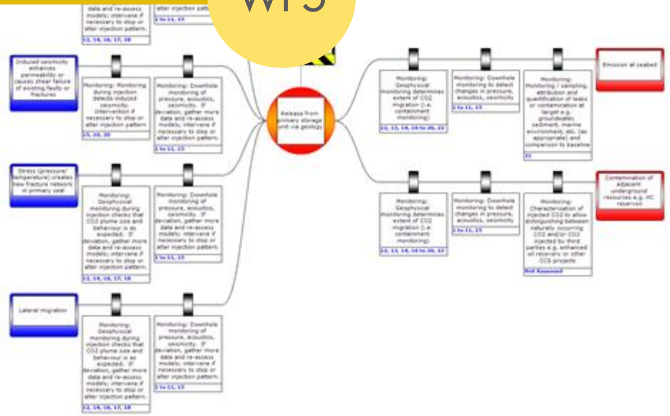
Identify active monitoring barriers relevant for site and expected leakage rates

Modelling results inform effectiveness of passive barriers (in seals and secondary storage units)

Geological Leakage Risk Assessment

Incorporate all modelling and monitoring barriers in a qualitative bowtie risk assessment framework with associated quantitative scenario modelling tool

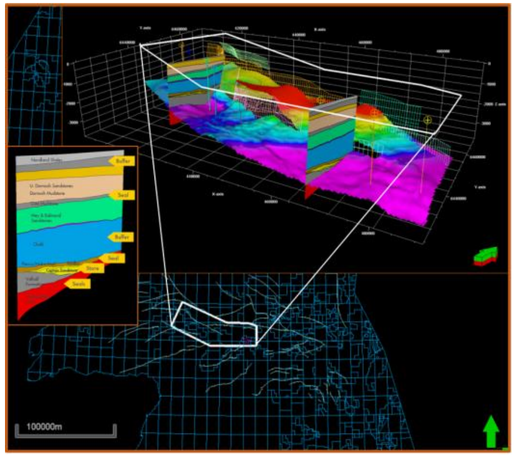
WP5



WP3

Probabilistic dynamic simulation using uncertainty ranges on all (parametrized) controls

Estimation of leakage rate distribution and likelihood at each caprock in CO_2 storage complex



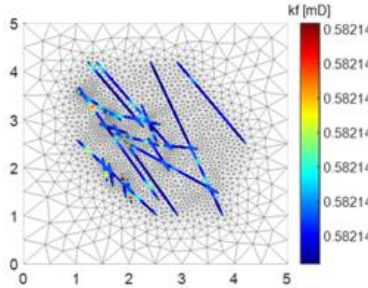
Hydromechanical coupling using lab-derived stress-permeability relations and analytical stress-state model

Effective fracture + matrix vertical permeability, RLP, CPR for each cell in seal derived from numerical up-scaling

Simulate flow in fracture networks in caprocks

Scaling relations based on meso/fine-scale modelling & analogues

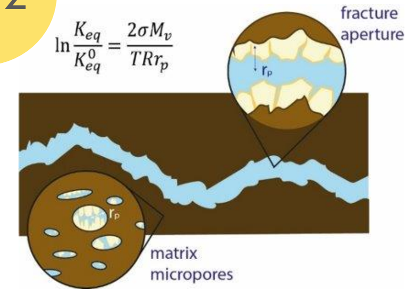
Characterise background stresses and log-derived rock transport and geomechanical properties



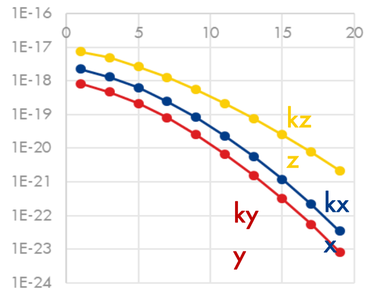
WP2

Experimentation and numerical modeling to characterise single fracture processes

$$\ln \frac{K_{eq}}{K_{eq}^0} = \frac{2\sigma M_v}{TRr_p}$$



Quantifying the impact of small-scale physics on CO_2-brine flow at fine-scale



Characterise fault-fracture networks using analogue derived scaling relations: fault throw-length-frequency

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DETECT – Dissemination and publications

Online presence

- DETECT page on Research Gate website: ResearchGate 942 reads, 83 followers
- DETECT website via HWU website: https://geoenergy.hw.ac.uk/research/detect/

Industry conferences/external workshops (>20)

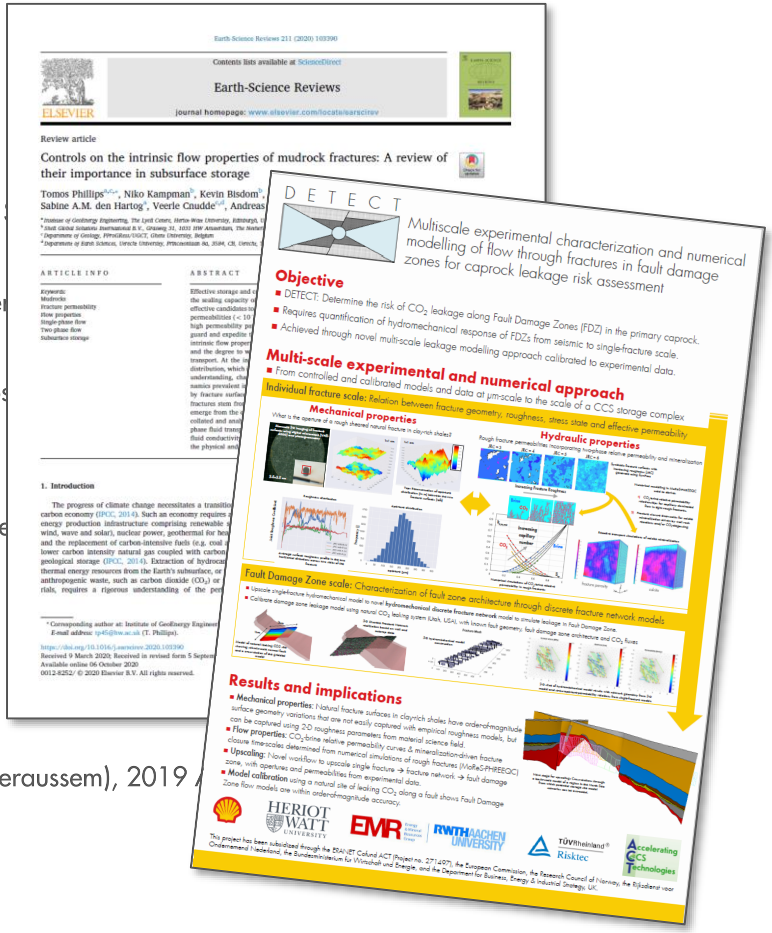
- 2018: EGU meeting, PROTECT workshop, Geologica Belgica Meeting, GHGT-14, Curtin University, CSIRO, Shell Geophysical Conference, EAGE CO_2 Storage Workshop 2 posters
- 2019: IEAGHG Fault workshop, Shell Reservoir Surveillance Team presentation, Pre-ACT Stakeholder Meeting Brussels, CSIRO virtual workshop, FRISK kick-off meeting, Northern Lights MMV, Shell/Equinor DETECT workshop
- 2020: Shell internal review technical review workshop, DETECT final webinar, GET2020, GHGT-15 abstract accepted, Interpore, SPE CCUS

Publications (7)

- Kubeyev, A. (2019). ARMA conference paper: Geomechanics Numerical Code for Modelling Contact in Fractures using VEM.
- Fink, R., Bertier, P., Krooss, B., & Weniger, P. (2019). Hydration State and Interlayer Cation Type (Ca2+, Na+) Control CO2 Sorption Behaviour of Workshop (Vol. 2019, No. 1, pp. 1-5). European Association of Geoscientists & Engineers.
- Philips, T. et al. (2020). Controls on the intrinsic flow properties of mudrock fractures: A review of their importance in subsurface storage. Earth-Scie
- Busch, A. et al. (2020). Swelling clay minerals and containment risk assessment for the storage seal of the Peterhead CCS project. IJGGC, 2020.
- K. Bisdom, P.A. Swaby (2020). Green River Fault and Fracture Structural Model. Conceptual model for hydromechanical leakage modelling and ups Unrestricted Shell report SR.20.00919, Shell Global Solutions International B.V., Amsterdam

Book Chapter (in print):

- Busch, A. (Heriot-Watt University) published a book chapter (pp.283-303) in Geological Carbon Storage, Migration and Leakage of CO2 From Dee Caprock Integrity, November 2018
- March, R.; Maier, C.; Doster, F.; Geiger, S. (2021). A unified Framework for Flow Simulation in Fracture Reservoirs
- In Lie, K.-A. and Møyner, O. (2021). Advanced Modelling with the MATLAB Reservoir Simulation Toolbox (MRST), Cambridge University Press



ACT knowledge sharing workshops (3)

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

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DETECT
INTEGRATED GEOLOGICAL CO_2 LEAKAGE RISK ASSESSMENT

WP2 – Fracture flow, mineralisation, clay swelling

2

Heriot-Watt University: Andreas Busch (WP2 lead), Nathaniel Forbes Inskip, Tom Phillips, Yihuai Zhang, Amanzhol Kubeyev, Onos Esegbue, Roberto E. Rizzo

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

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WP2 – Fracture flow, mineralisation, clay swelling

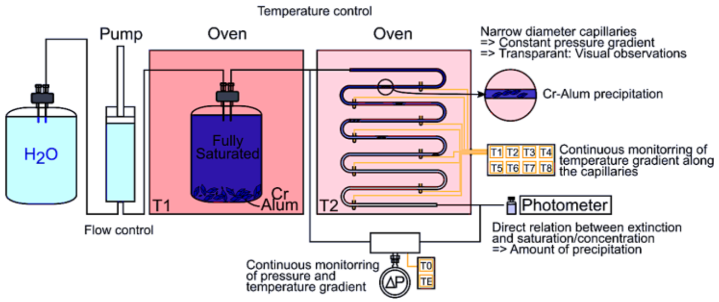
WP2 tested sensitivities of leakage rates along fracture networks or fault damage zones to fluid pressure, chemistry, mineral reaction rates, saturation changes and effective stress changes to generate the necessary input parameter for leakage modelling in WP3.

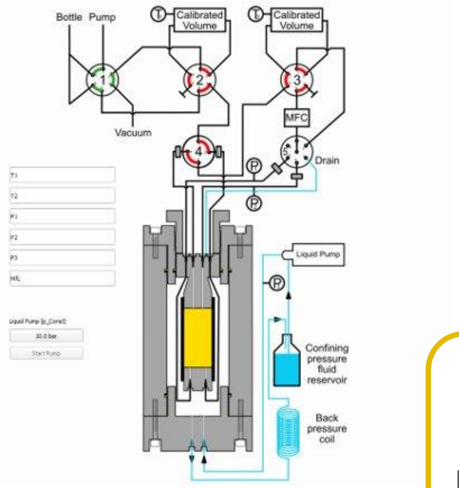
Objectives

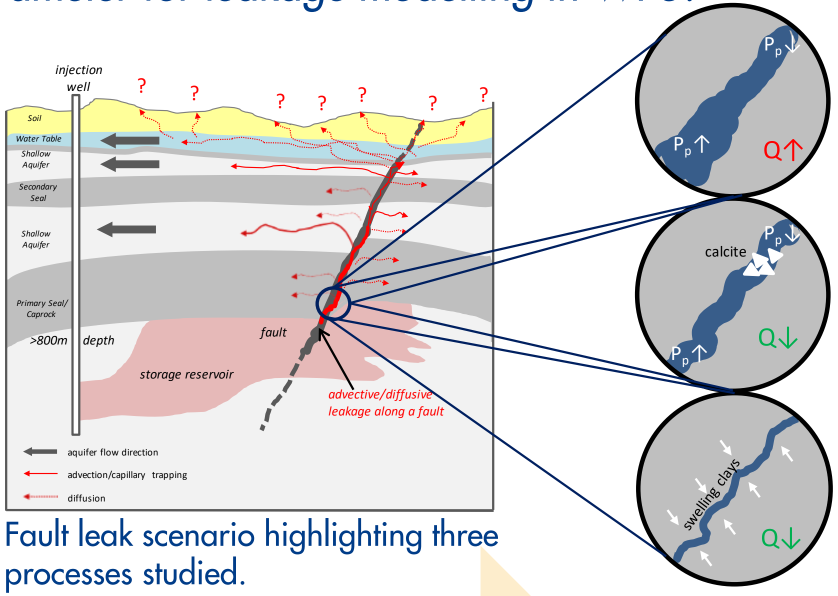
- **Pressure:** Identify and analyse factors controlling fracture flow as a function of pore pressure, confining stress, mineralogy or strength parameters
- **Clay swelling:** Significantly improve fundamental understanding of the impact of CO_2 induced expansion of swelling clays in fractures
- **Mineralisation:** 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 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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DETECT

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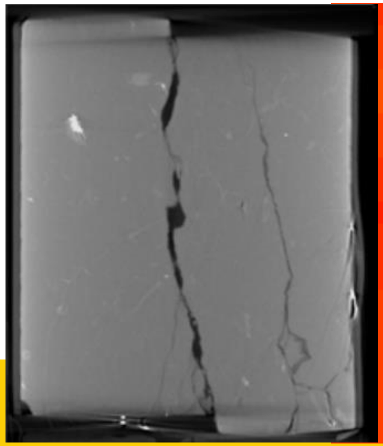
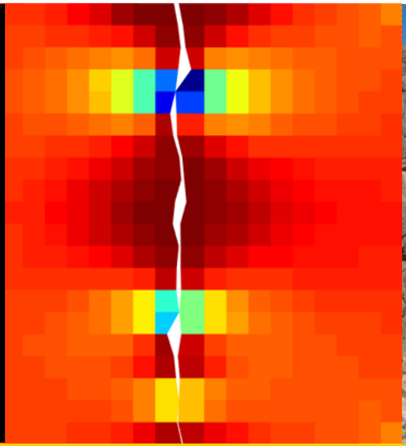
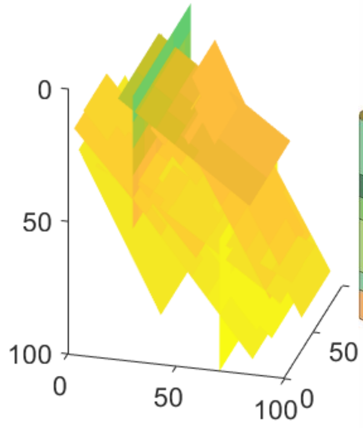
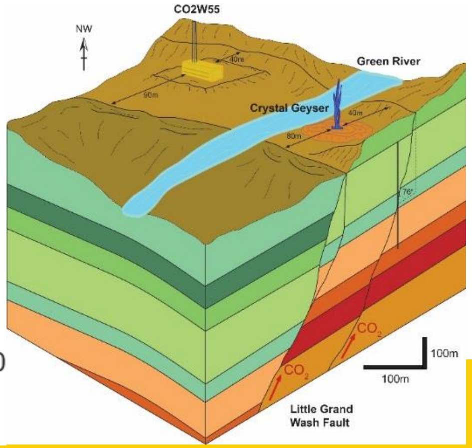
WP3 – Fracture characterisation and modelling









Shell Global Solutions International B.V.: Jeroen Snippe (WP3 Lead), Niko Kampman, Kevin Bisdom, Karin de Borst, Kees Hindriks

Heriot Watt University: Andreas Busch, Nathaniel Forbes Inskip, Tom Phillips, Florian Doster, Rafael Castaneda Neto, Amanzhol Kubeyev

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WP3 – Fracture characterisation and modelling

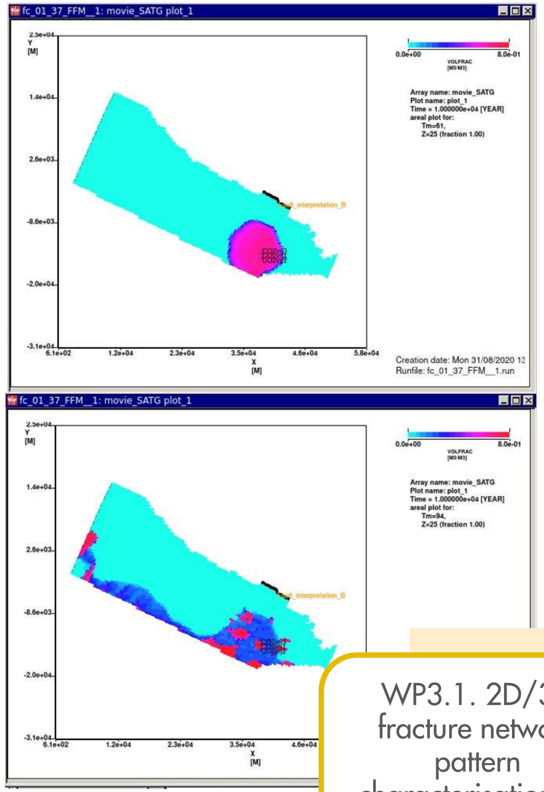
WP3 characterised 2D/3D fracture network pattern for flow modelling. Developed innovative hydro-mechanical-chemical CO_2 and brine leakage modelling at fine-scale, meso-scale and large-scale.

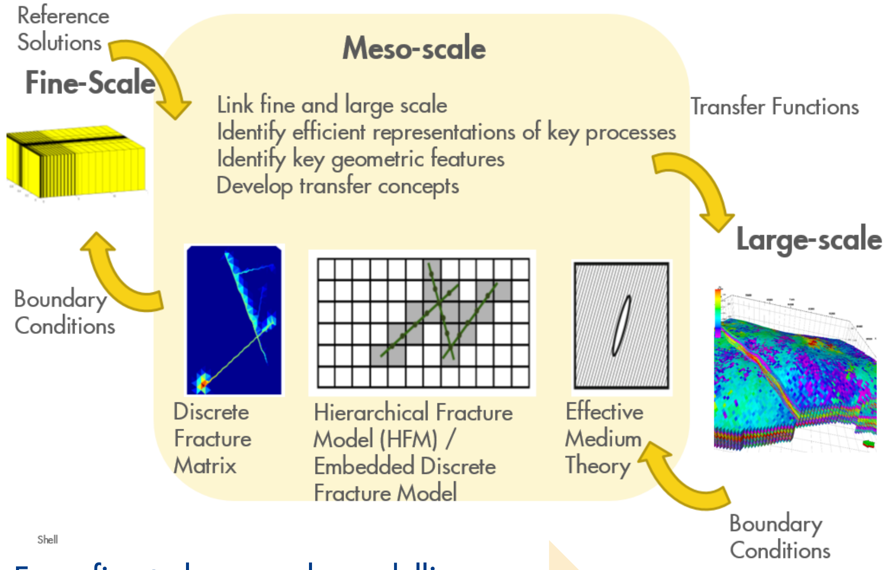
Objectives

- **Modelling:** 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
- **Characterisation:** Incorporating effects on fracture aperture of mineral dissolution/precipitation and clay swelling

Collaboration

Shell IRD, Heriot-Watt University





From fine to large scale modelling.

- 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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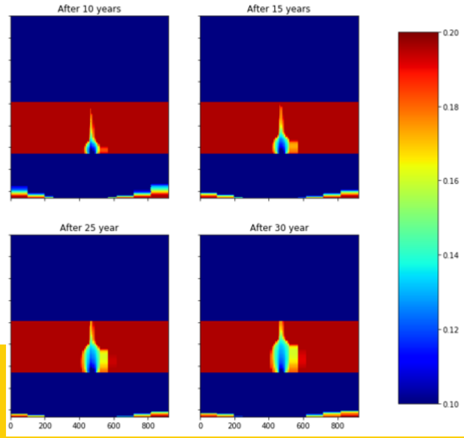
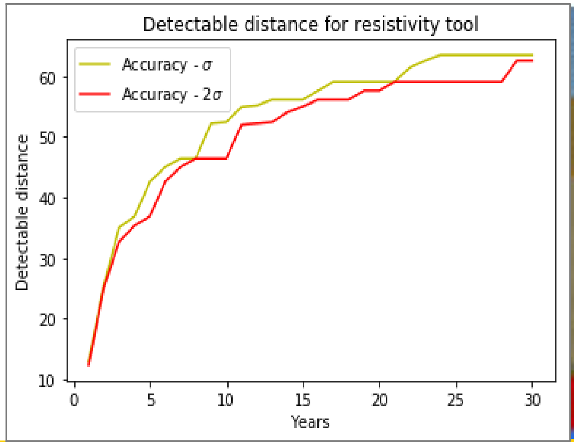
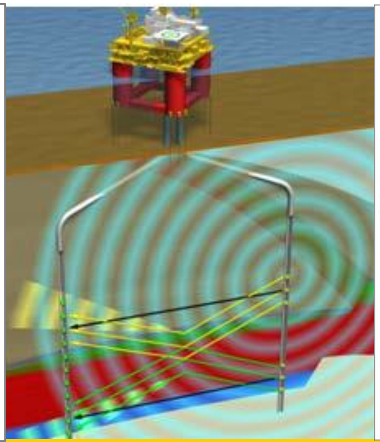
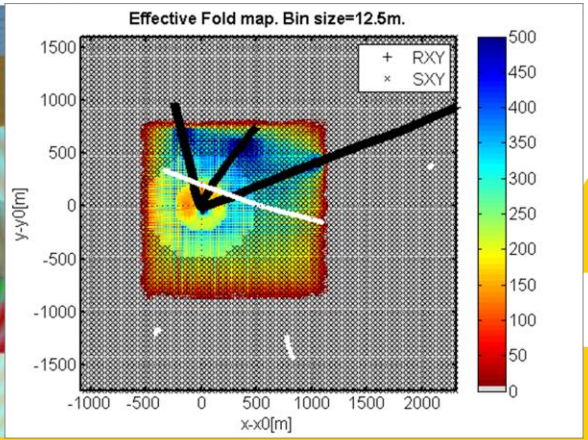
WP4 – Containment monitoring for caprock Integrity









Shell Global Solutions International B.V.: Marcella Dean (WP4 Lead), Yuan Qiu, Daria Spivakovska, Samantha Grandi

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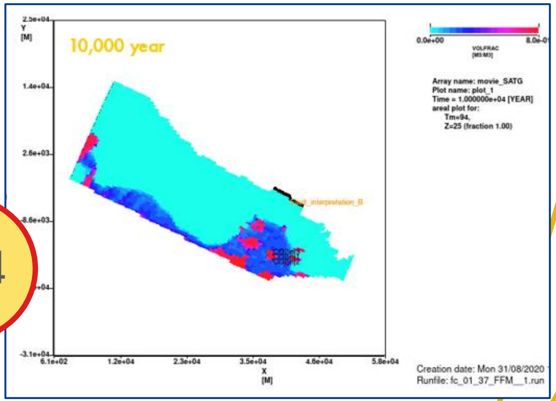
DETECT workflow

The goal of DETECT is to assess geological leakage risks related to fault and fractures in caprocks



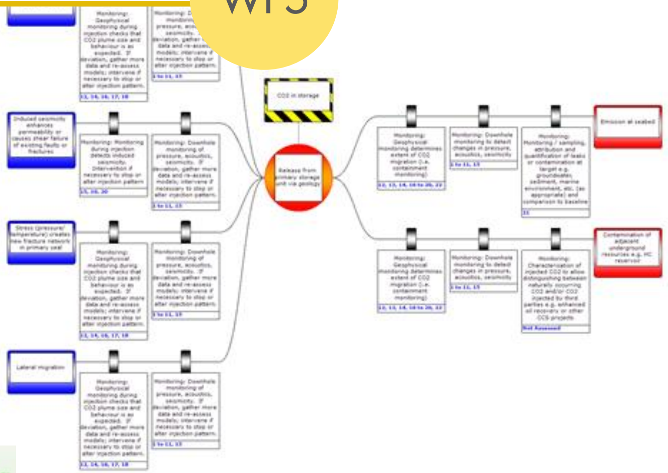
WP4

Identify active monitoring barriers relevant for site and expected leakage rates

Geological Leakage Risk Assessment

Incorporate all modelling and monitoring barriers in a qualitative bowtie risk assessment framework with associated quantitative scenario modelling tool

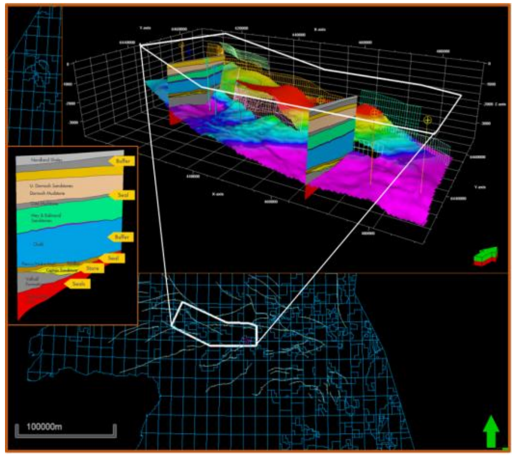
WP5



Modelling results inform effectiveness of passive barriers (in seals and secondary storage units)

Probabilistic dynamic simulation using uncertainty ranges on all (parametrized) controls

Estimation of leakage rate distribution and likelihood at each caprock in CO_2 storage complex



WP3

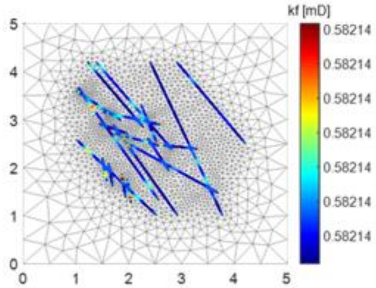
Hydromechanical coupling using lab-derived stress-permeability relations and analytical stress-state model

Effective fracture + matrix vertical permeability, RLP, CPR for each cell in seal derived from numerical up-scaling

Simulate flow in fracture networks in caprocks

Scaling relations based on meso/fine-scale modelling & analogues

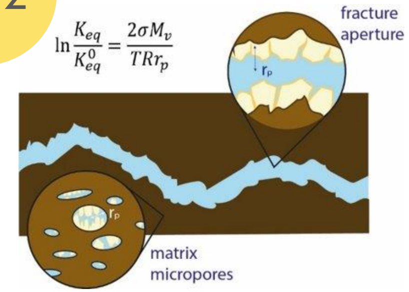
Characterise background stresses and log-derived rock transport and geomechanical properties



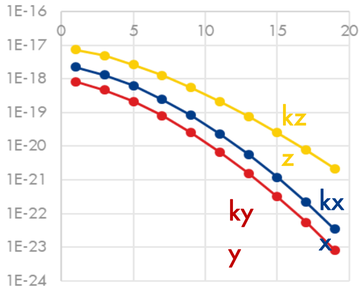
WP2

Experimentation and numerical modeling to characterise single fracture processes

$$\ln \frac{K_{eq}}{K_{eq}^0} = \frac{2\sigma M_v}{TRr_p}$$



Quantifying the impact of small-scale physics on CO_2-brine flow at fine-scale



Characterise fault-fracture networks using analogue derived scaling relations: fault throw-length-frequency

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WP4 – Containment monitoring for caprock integrity

WP4 selected cost-efficient and effective caprock monitoring technologies which were incorporated as active safeguards in the bowtie risk framework (WP5).

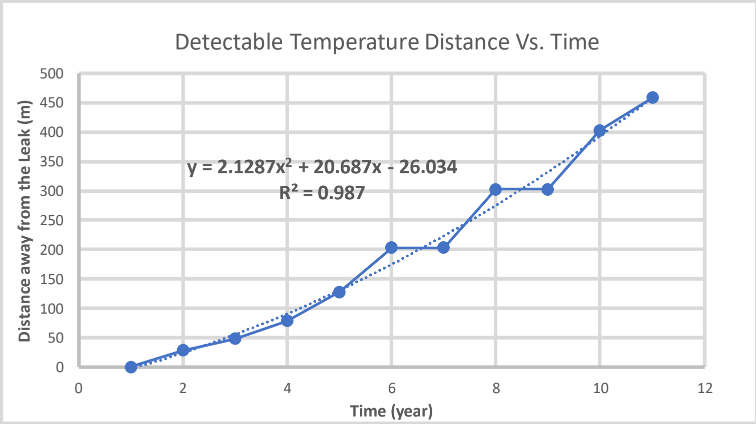
Objectives

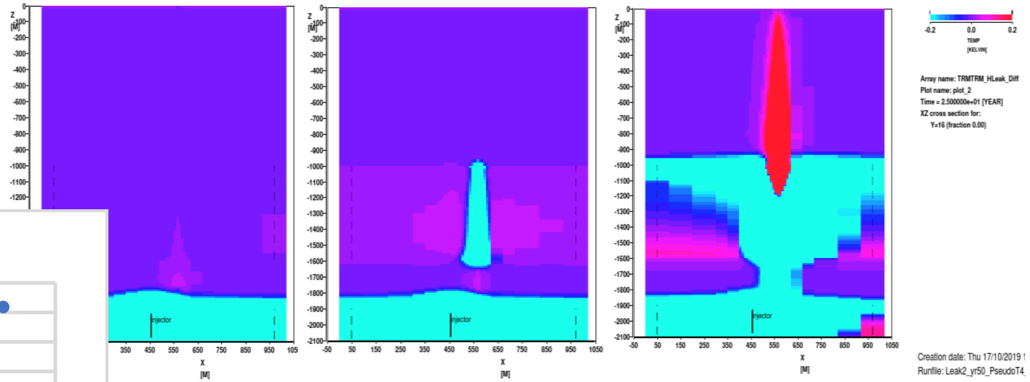
- **Feasibility studies:** Identify which containment monitoring technologies can act as effective and efficient barriers to the risks posed by CO_2 leakage along fractures of the caprock
- **Active barriers:** Assess effectiveness of individual containment monitoring technologies and integrate as active barriers in containment bowtie

Collaboration

Shell Global Solutions, Risktec Solutions

The detectable temperature travel distance using cut-off of 0.1°C for the high leakage case.





Cross section of expected temperature changes for the low, mid and high leakage scenarios (from left to right) with the same base case matrix properties.

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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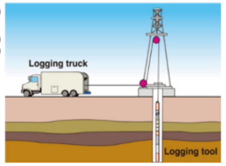
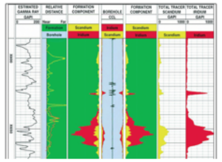
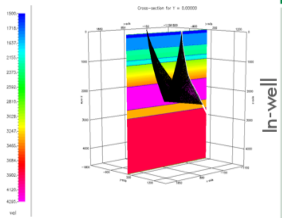
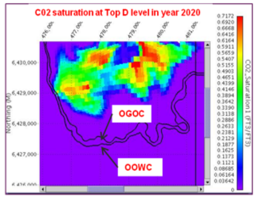
Results: Containment monitoring options for a North Sea site

1. Continuous downhole pressure and temperature monitoring
2. Time-lapse logging technologies (Neutron and Thermal Neutron Capture)
3. Distributed Acoustic, Temperature and Pressure Sensing
4. Time-lapse DAS VSP, DAS cross-well
5. Continuous microseismic monitoring

In-well Monitoring Technologies – Logging and Fiber Optic Methods

	Measurement Method	Evaluation method	Challenges/Opportunities
Time-lapse wireline logging 	• Saturation monitoring • Sonic logging • Noise logging • Temperature logging	• Change in log response due to change of CO_2 concentration • Acoustic signal from fault reactivation • Temperature change due to leaking	• The well should be located near the leakage path • The logging requires well interventions • The measurements are not continuous
Radioactive tracers 	• Radioactive tracers • Gamma logging	• Gamma ray response in overburden due to CO_2 leakage	• The well should be located • The measurements are not continuous • Tracer application for CO_2 is challenging in practice • HSE exposure and high cost
Fibre Optics Sensing 	• Distributed Acoustic Sensing • Distributed Temperature Sensing • Distributed Pressure Sensing	• Acoustic signal from fault reactivation • Change in temperature and pressure due to CO_2 leakage	• The well should be located near the leakage path • The accuracy of temperature and pressure measurements is not high

Geophysical Monitoring Technologies

	Measurement Method	Evaluation method	Challenges/Opportunities
In-well 	• 2D and 3D VSP* (geophones and DAS) • Microseismic (geophones and DAS) • Cross-well EM (source and sensor in well, i.e. casing); EM in cased holes; surface source EM	• Identify time-lapse signals due to pressure, saturation, and temperature changes • Record microseismicity • Changes in EM response due to saturation changes	• Geophones cannot easily be deployed in injection wells • DAS has directional limitation • Need sufficient sensors to locate microseismic sources • EM methods have limited resolution, but a linear response to saturation changes
Surface 	• 2D and 3D surface seismic (streamers, OBN, OBC, P-cable, PRM) • Microseismic (surface passive acoustic sensors) • Seabed geodesy	• Identify time-lapse signals due to pressure, saturation, and temperature changes • Record microseismicity • Detect seabed movements with pressure and sonar methods	• Most costly, but highest spatial resolution • Non-linear response to saturation changes • Limited sensitivity to detect microseismic events at depth • Requires sufficient spatial and temporal coverage (cost – benefit analysis required)

In-well Pressure and Temperature Monitoring

	Measurement Method	Evaluation method	Challenges/Opportunities
Pressure	• PDG (Permanent Downhole Gauges) or DPS (Distributed Pressure Sensors) shall be able to pick up the pressure signal within certain distance away from the faults and/or fractures leak path.	• Unexpected pressure changes due to containment loss • Site-specific expected CO_2 leakage flow rate and distance between monitoring well locations to likely leakage paths must be evaluated	• In-well monitoring for pressure is restricted to the well locations for installation, i.e., limited the areal coverage for potential leakage along faults and fractures • The pressure increasing caused by CO_2 leakage is typically much higher than the accuracy (~0.002% FS, i.e., ~2Psi) of pressure gauges
Temperature	• The temperature cooling caused by CO_2 leakage can be detected	• Unexpected temperature changes due to containment loss • The temperature signal is local and restricted to the immediate vicinity of the leakage pathway	• In-well monitoring for temperature is restricted to the well locations for installation, i.e., limited the areal coverage for potential leakage along faults and fractures

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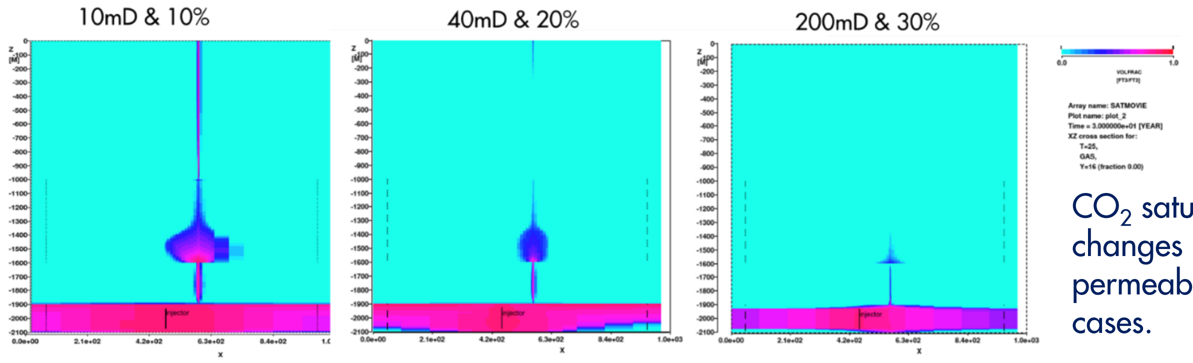
Yuan Qiu, Daria Spivakovska Shell

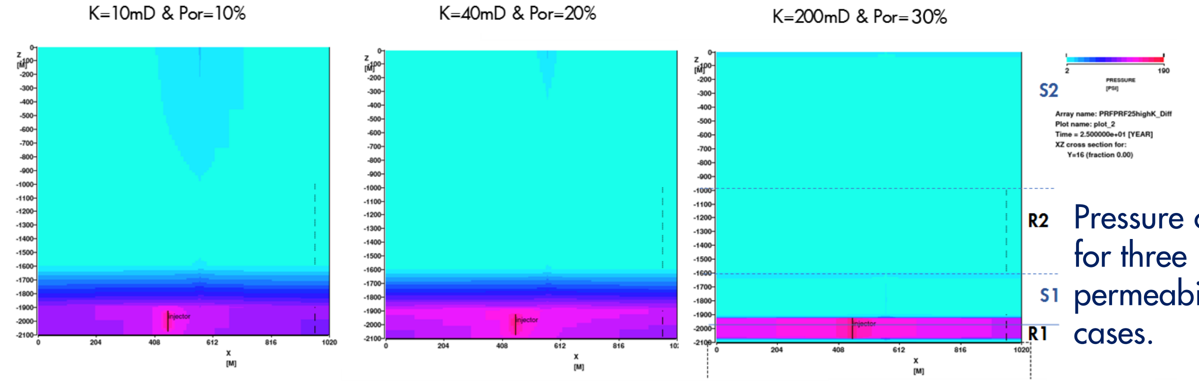
In-well monitoring assessment

Example of 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

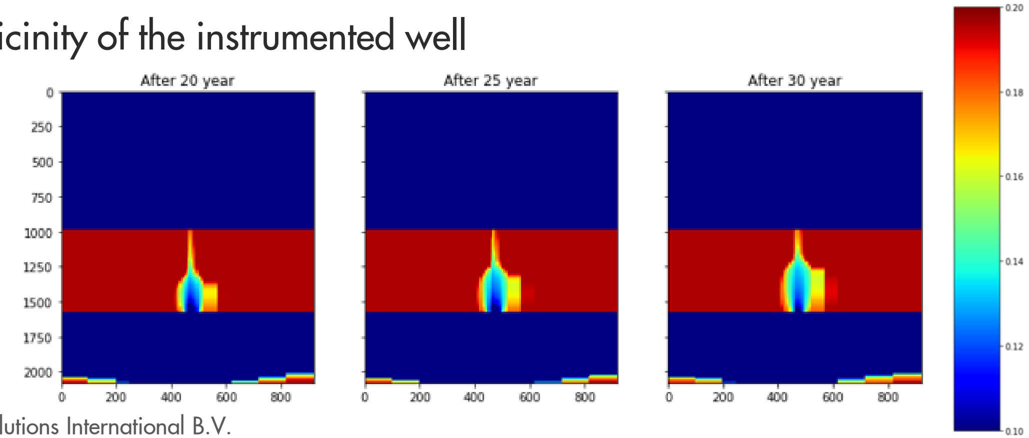


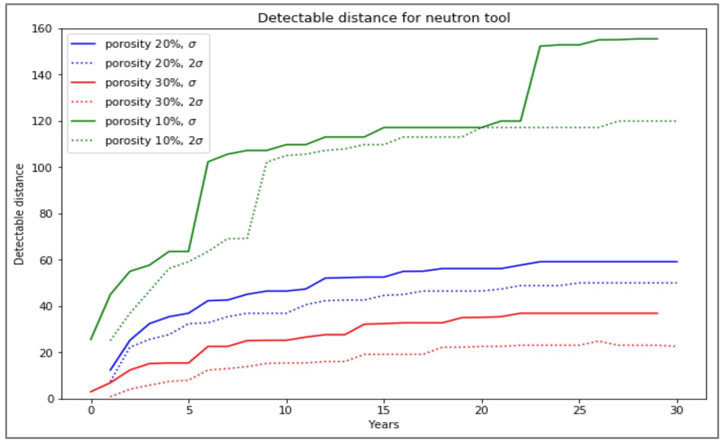
CO_2 saturation changes for three permeability cases.



Pressure changes for three permeability cases.

Modelled neutron tool response after 20, 25, 30 years (left).





Detectable distance for neutron tool.

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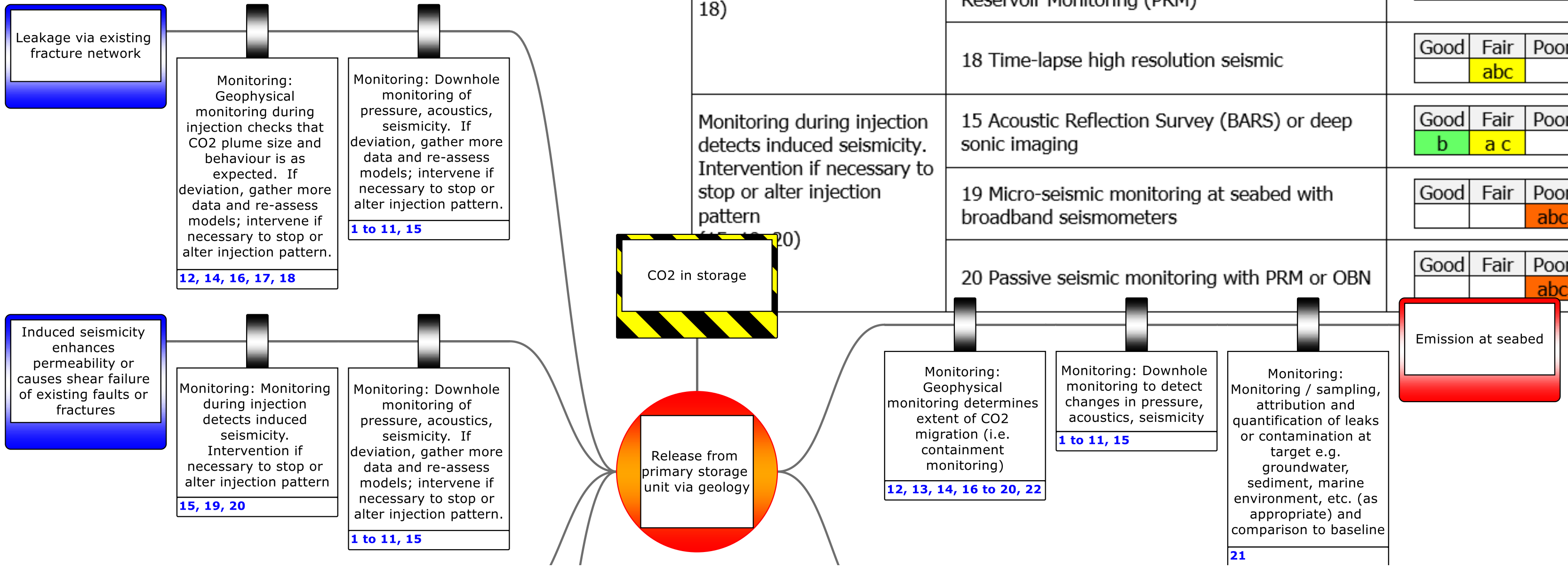
Assessed effectiveness of active containment monitoring barriers in the bowtie

- The expected performance of different monitoring technology options was assessed for low, medium and high leakage rates
- Effectiveness of active barriers was assessed for primary seal, secondary storage and secondary seal

Bowtie : Release from primary storage unit via geology		High flux (1363 kg/day*m²):			Medium flux (7.9 kg/day*m²):			Low flux (0.2 kg/day*m²):		
Monitoring barrier on bowtie	**Potential Monitoring Technology**	a – Primary Seal : b – Secondary Storage : c – Secondary Seal								
Release from primary storage unit via geology – prevention measures (left side of bowtie)										
		Good	Fair	Poor	Good	Fair	Poor	Good	Fair	Poor
Geophysical monitoring during injection checks that CO_2 plume size and behaviour is as expected. If deviation, gather more data and re-assess models; intervene if necessary to stop or alter injection pattern. (12, 14, 16, 17, 18)	12 Time-lapse DAS VSP reflection survey	b	a c			abc				abc
	14 Time-lapse cross-well seismic	b	a c			abc				abc
	16 Time-lapse surface seismic with streamers (narrow azimuth)		abc				abc			abc
	17 Time-lapse Ocean Bottom Nodes (OBN) or Ocean Bottom Cables (OBC) or Permanent Reservoir Monitoring (PRM)		abc			abc				abc
	18 Time-lapse high resolution seismic		abc			abc				abc
Monitoring during injection detects induced seismicity. Intervention if necessary to stop or alter injection pattern ([illegible] 20)	15 Acoustic Reflection Survey (BARS) or deep sonic imaging	b	a c			abc				abc
	19 Micro-seismic monitoring at seabed with broadband seismometers			abc			abc			abc
	20 Passive seismic monitoring with PRM or OBN			abc			abc			abc



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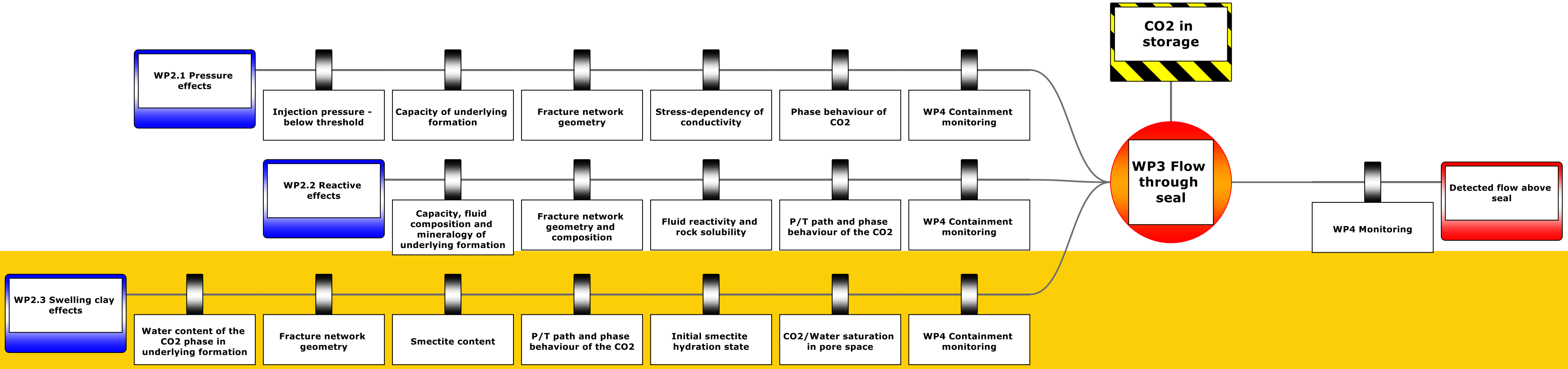
WP5 – Qualitative and quantitative risk assessment



5

Risktec Solutions B.V.: Sheryl Hurst (WP5 Lead), Andy Lidstone, Frank Hart, Paul van Rossum, James Bradbury, Connor Bloodworth

Accelerating CCS Technologies

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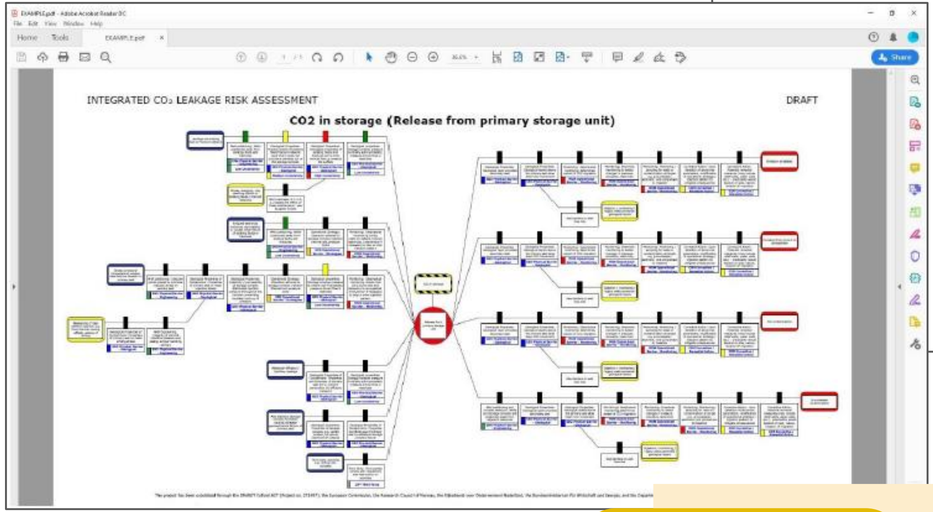
WP5 – Qualitative and quantitative risk assessment

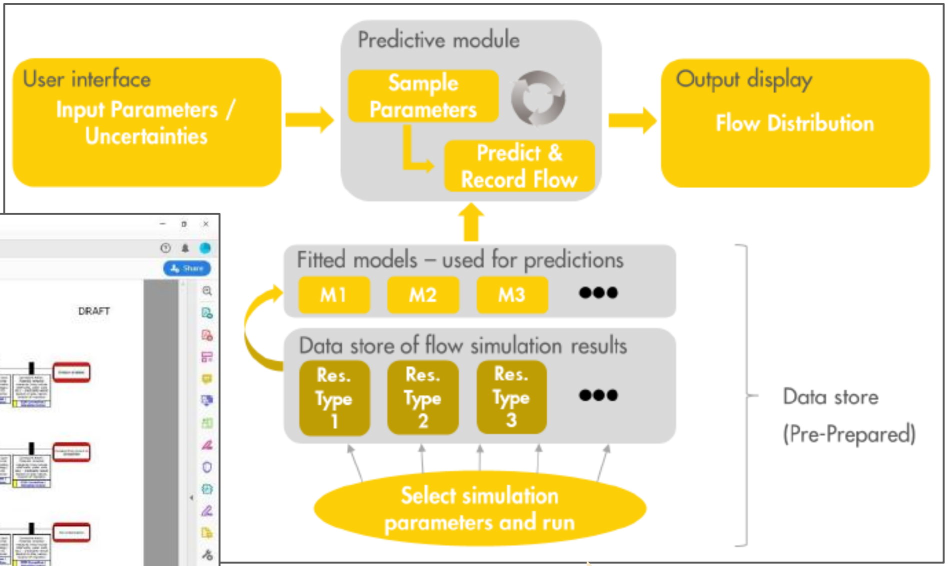
WP5 integrated learnings from DETECT into qualitative bowties and quantitative model to serve as an industry guideline for risk assessment of CO_2 leakage across fractures in the caprock.

Objectives

- **Qualitative risk assessment:** 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
- **Quantitative risk assessment:** To develop a quantitative risk assessment model aligned to the bowtie, using output from the other WPs to determine prevention/mitigation measure effectiveness



Qualitative bowtie tool.



Quantitative model structure.

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

Collaboration

Risktec (TÜV Rheinland Group), Shell IRD

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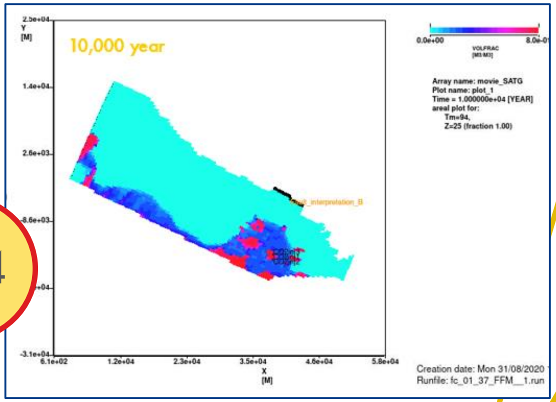
DETECT workflow

The goal of DETECT is to assess geological leakage risks related to fault and fractures in caprocks

WP4

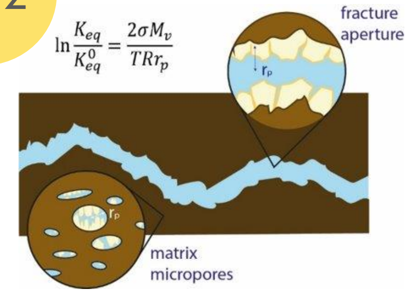
Identify active monitoring barriers relevant for site and expected leakage rates



Hydromechanical coupling using lab-derived stress-permeability relations and analytical stress-state model

Experimentation and numerical modeling to characterise single fracture processes

WP2



Effective fracture + matrix vertical permeability, RLP, CPR for each cell in seal derived from numerical up-scaling

Geological Leakage Risk Assessment

Incorporate all modelling and monitoring barriers in a qualitative bowtie risk assessment framework with associated quantitative scenario modelling tool

WP5

Modelling results inform effectiveness of passive barriers (in seals and secondary storage units)

Probabilistic dynamic simulation using uncertainty ranges on all (parametrized) controls

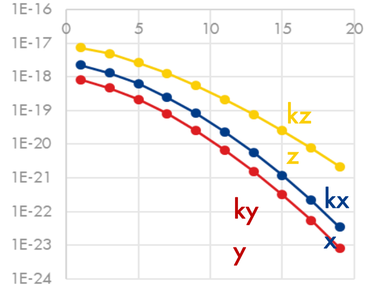
Estimation of leakage rate distribution and likelihood at each caprock in CO_2 storage complex

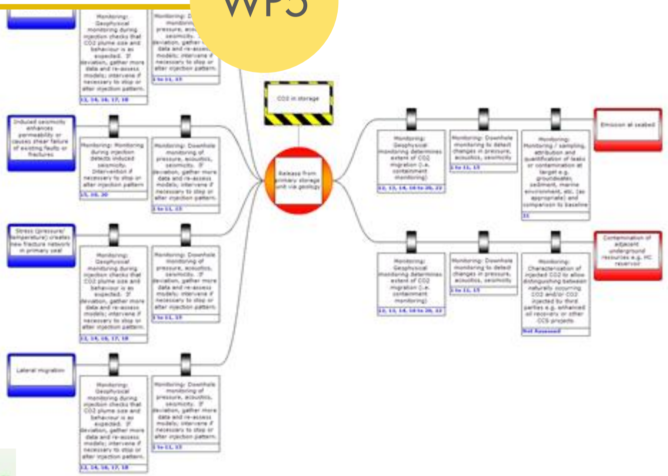
WP3

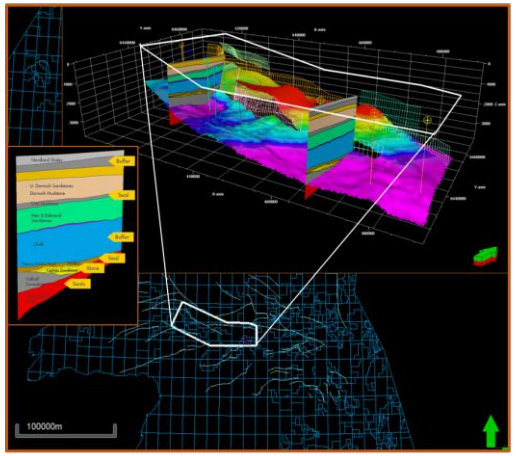
Simulate flow in fracture networks in caprocks

Scaling relations based on meso/fine-scale modelling & analogues

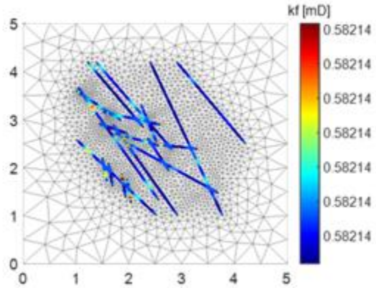
Quantifying the impact of small-scale physics on CO_2-brine flow at fine-scale







Characterise background stresses and log-derived rock transport and geomechanical properties



Characterise fault-fracture networks using analogue derived scaling relations: fault throw-length-frequency

Accelerating CCS Technologies

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