U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Clean. Reliable. Nuclear.

Gas Migration in Clay-Based Materials – International Collaboration Activities as Part of the DECOVALEX Project

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International Collaboration

DECOVALEX-2019 Task Lead: Jon Harrington, British Geological Survey

DECOVALEX-2019 Research Teams (9 teams from 8 countries)

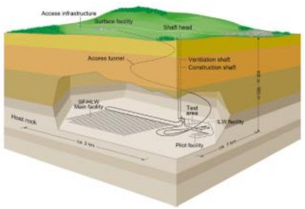
Sources of Gas

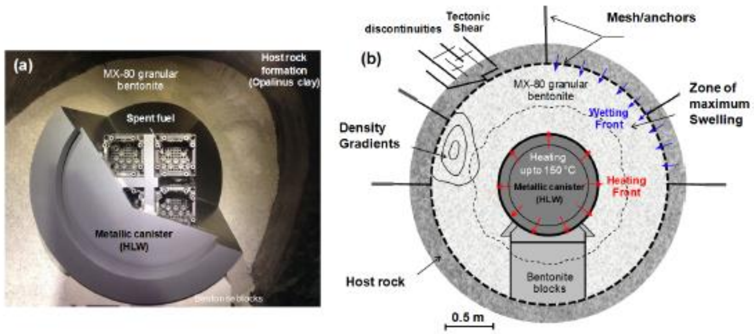
- In a repository for heat emitting radioactive waste gas will be generated through a number of processes including:
  - Corrosion of metals (H_2)
  - Radioactive decay of the waste (Rn etc)
  - Radiolysis of water (H_2)
  - Microbial activities

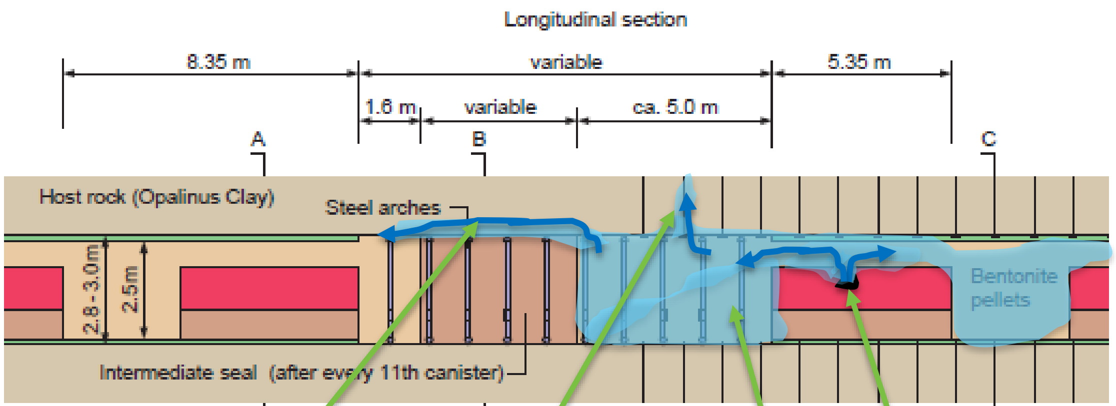
- If production exceeds diffusion capacity a discrete gas phase forms
- Gas will accumulate until its pressure becomes sufficiently large to enter the engineered barrier or host rock
- Understanding gas generation and migration is a key issue in the assessment of repository performance

Relevance to Performance

Example layout from the Swiss Concept of a Clay-based Repository (Seiphoori, 2015)







Damage to seal and EDZ?

Fracturing host rock?

Pressure build-up

Gas release

The percolation of gas through the EBS may impair the safety functions of the EBS and host rock:

- Where will produced gas go?
- Rate of gas production vs migration and release?
- Will gas migrate away along EBS or will the rock fracture?
- Permanent damage to the buffer, EDZ, seals or host rock (fracturing)?
- Could the gas de-hydrate the buffer?
- Colloid transport and erosion of buffer material (damage)?
- Microbial activities?

State of the Art with R&D Gaps and Needs

- Transport of gases in clay-based buffer materials has been the subject of several international projects (e.g. LASGIT, FORGE)
- Substantial insight has been gained in the phenomenology of gas transport processes in bentonite and low permeability host rocks
- Model-based approaches have been proposed for the analysis of gas release scenarios in the context of long-term safety assessment
- **The predictive capability of the gas transport models is still limited**, indicating that basic **mechanisms of gas transport in bentonite and low permeability host rocks are not understood in sufficient detail** to provide the ground for robust conceptual and quantitative models.

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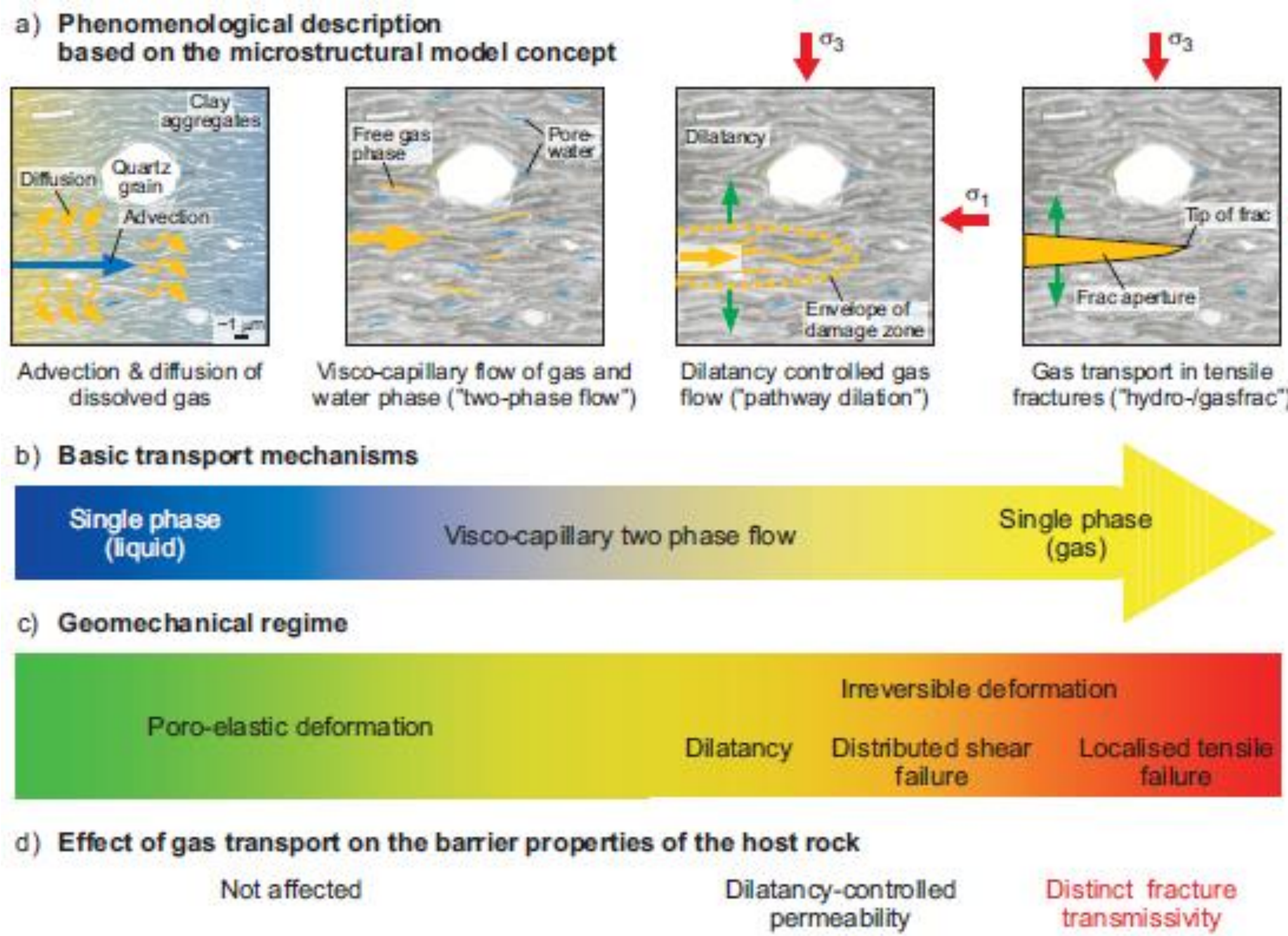
⇒ **Predictive capabilities are being developed along with participation in DECOVALEX-2019 with access to experimental data for model testing and validation**

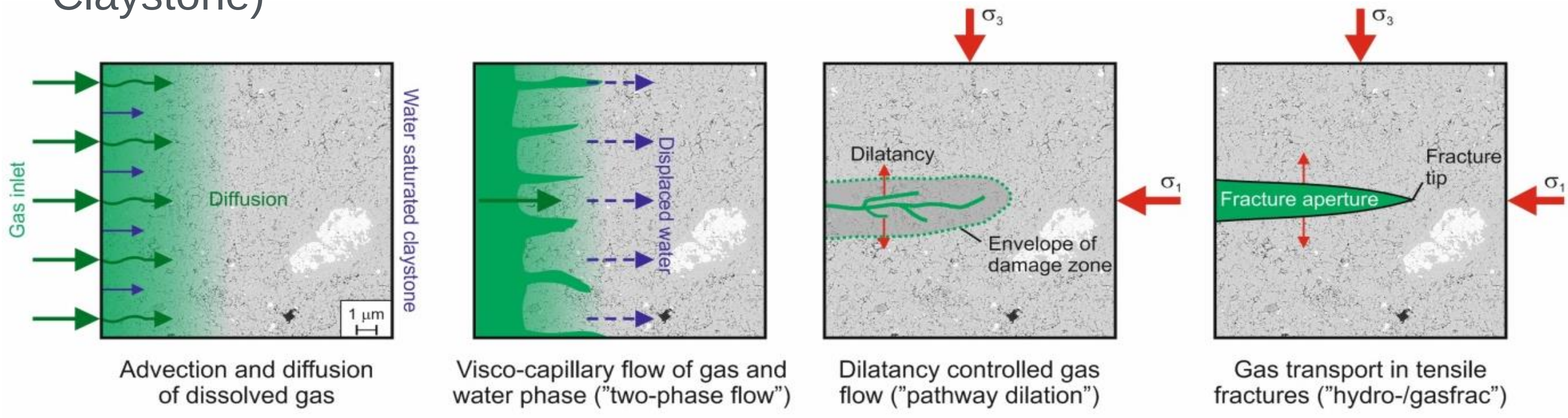
Conceptual Model of Gas Migration



(Source NAGRA NTB 08-07)

DECOVALEX-2019 Task A: modElliNg Gas INjection ExpERiments (ENGINEER)

The purpose is to better understand the processes governing the advective movement of gas in two low permeability materials (Bentonite and Claystone)



- British Geological Survey (BGS) provides laboratory data, expertise and lead this DECOVALEX-2019 task
- 9 Research Teams from 8 countries participate in analyzing and modeling the data

DECOVALEX Task A Research Teams

(i) BGR/UFZ (Germany): Federal Institute for Geosciences and Natural Resources and the Helmholtz Centre for Environmental Research.

(ii) CNSC (Canada): Canadian Nuclear Safety Commission.

(iii) KAERI (Korea): Korea Atomic Energy Research Institute

(iv) LBNL (United States of America): Lawrence Berkeley National Laboratory.

(v) NCU/TPC (Taiwan): National Central University and the Taiwan Power Company (Taipower).

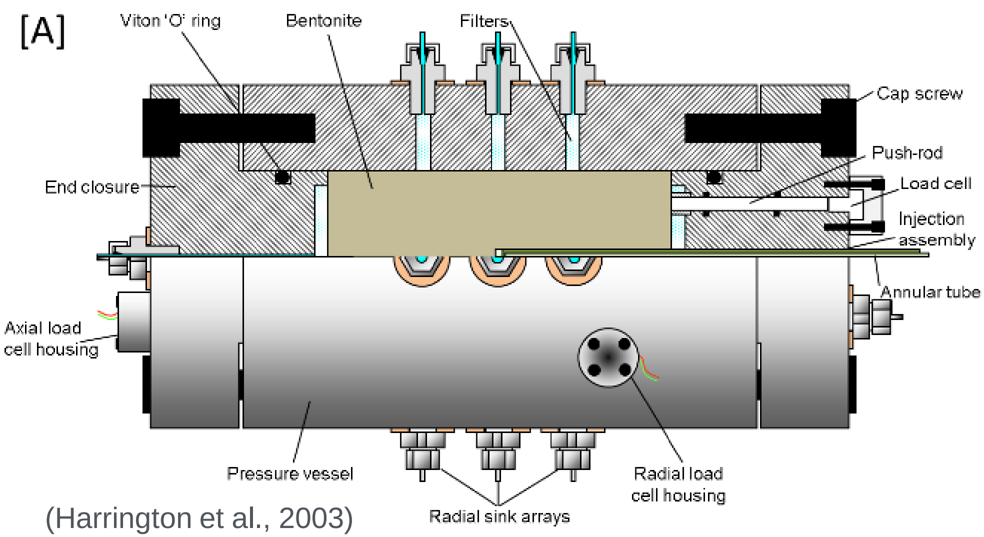
(vi) Quintessa/RWM (United Kingdom): Quintessa Ltd on behalf of Radioactive Waste Management.

(vii) SNL (United States of America): Sandia National Laboratories.

(viii) UPC/Andra (Spain/France): Universitat Politècnica de Catalunya, funded by l’Agence nationale pour la gestion des des déchets radioactifs.

Gas Flow Experimental Data on Bentonite

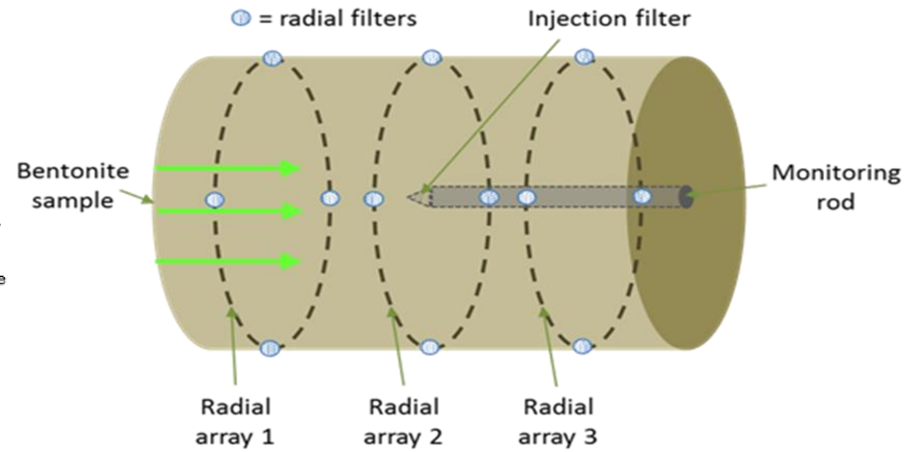
BGS Test Cell:



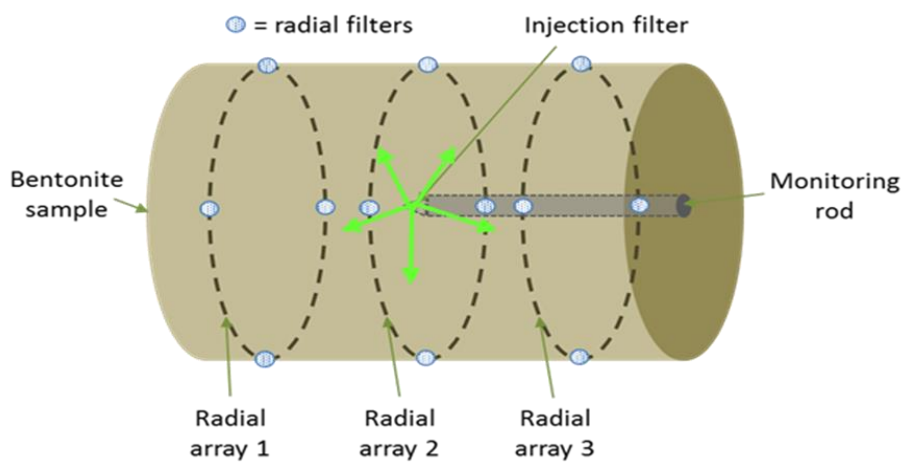
(Harrington et al., 2003)

- MX80 bentonite confined into the cell
- Saturate the sample with water to develop swelling stress
- Inject hydrogen gas
- Monitor pressure, gas outflow, and stress during 4 month

Stage 1A: 1D Gas Flow Test



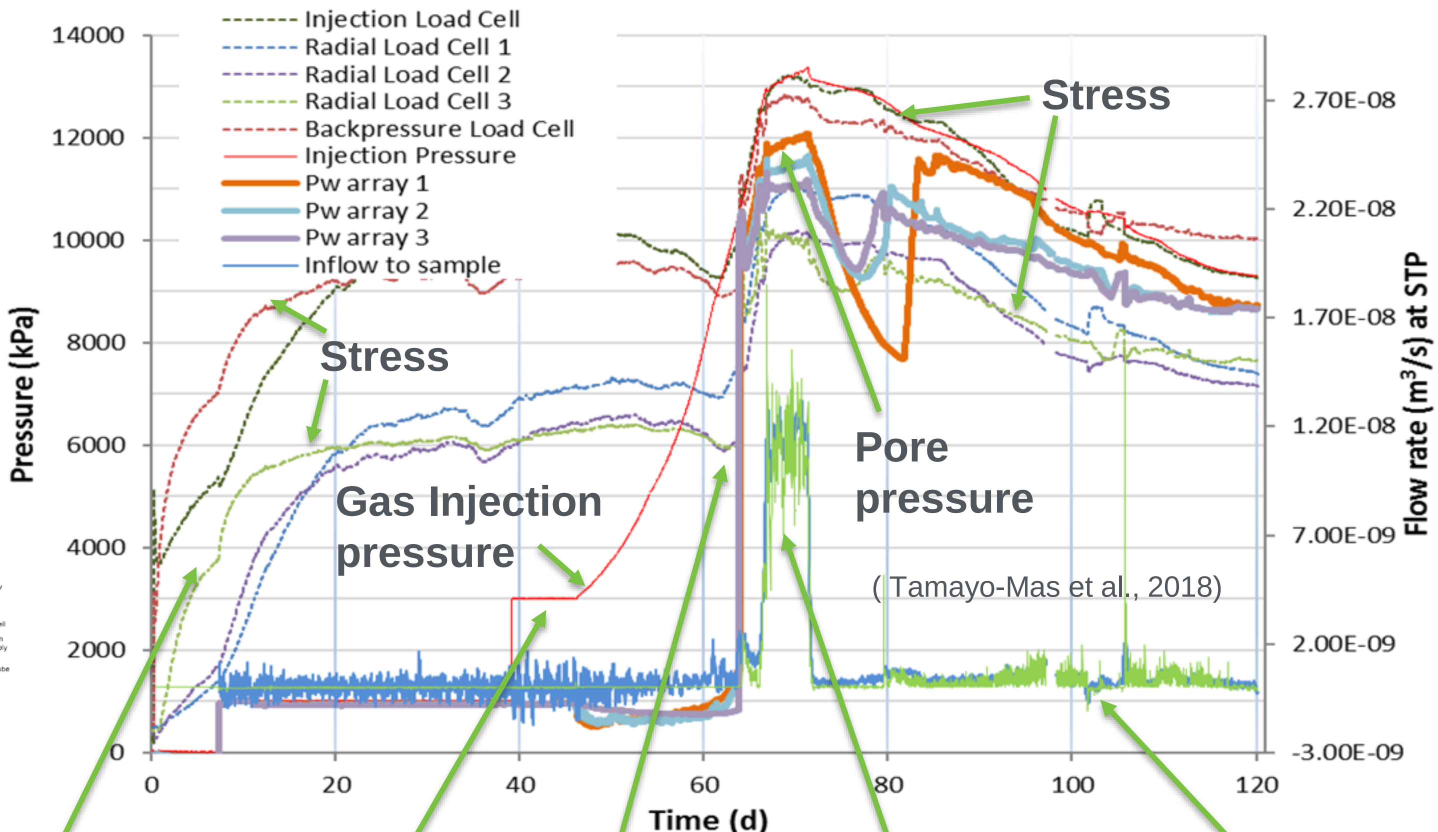
Stage 2A: Radial Gas Flow Test

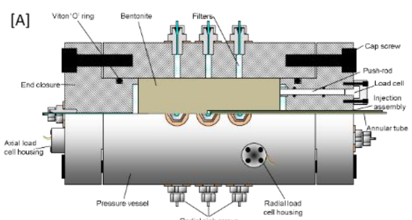


(Tamayo-Mas et al., 2018)

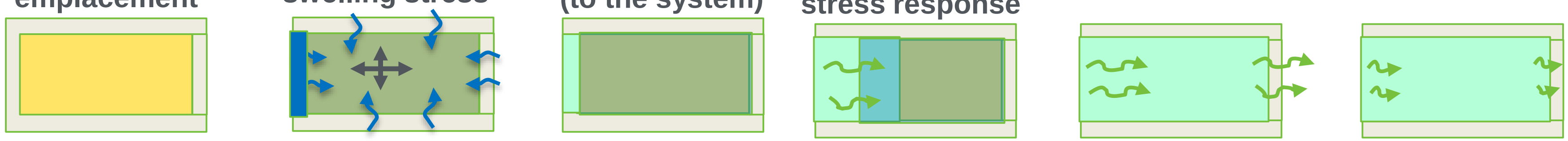
Stage 1A Tests Data (1D flow, stress, pressure)

Complex hydraulic and mechanical responses during 120 days test





1) Bentonite emplacement **2) Saturate and swelling stress** **3) Inject gas (to the system)** **4) Pressure and stress response** **5) Gas outburst** **6) Slow seepage**

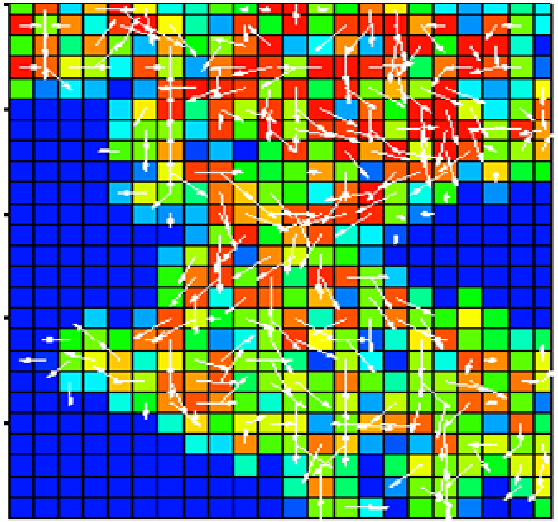


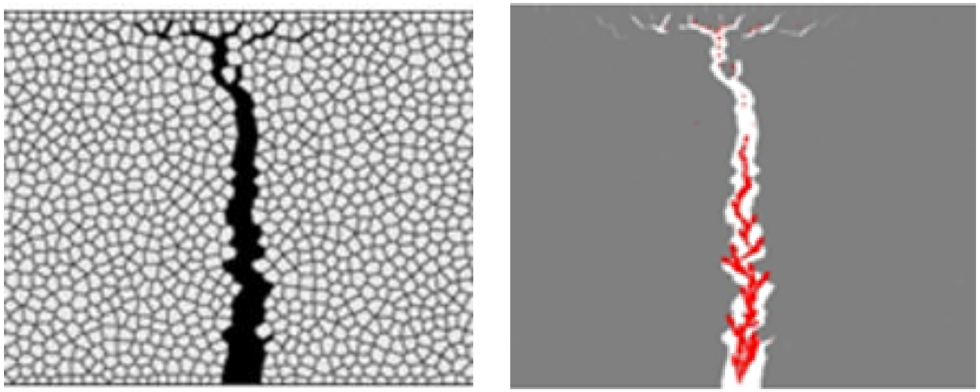
LBNL Modeling Approach

Two different TOUGH-based coupled flow and mechanical modeling approaches:

1) **LBNL-C**: Continuum model approach using TOUGH-FLAC

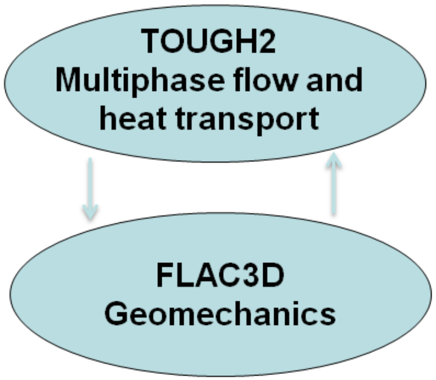
2) **LBNL-D:** Discrete fracture model approach using TOUGH-RBSN

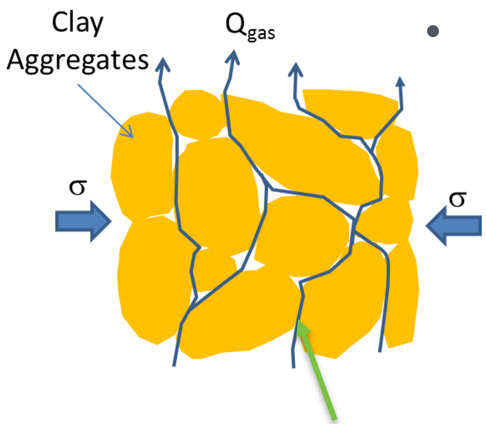




(TOUGH-FLAC and TOUGH-RBSN described in Rutqvist, 2017; Kim et al., 2017)

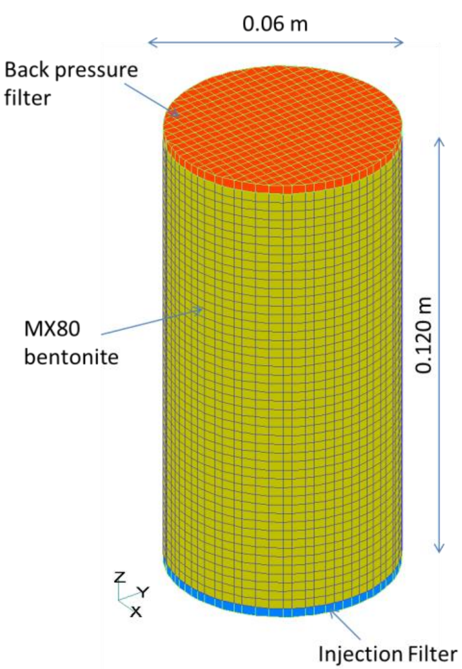
LBNL-Continuum Using TOUGH-FLAC

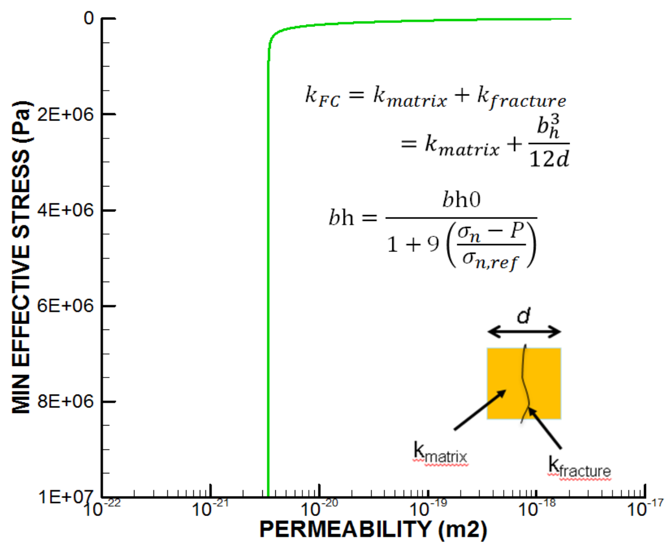


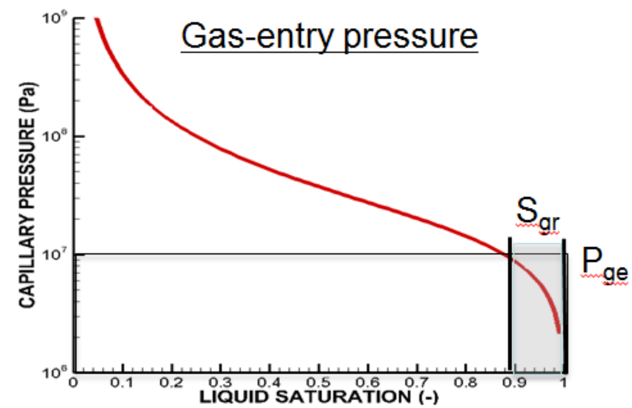


Dilatant gas flow through aggregate boundaries

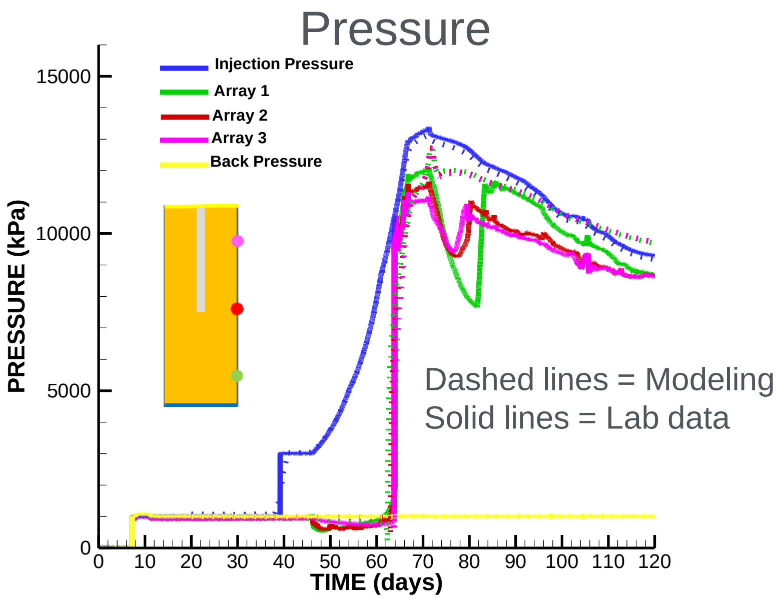
- Material conceptual model:
  - Multiphase flow
  - Poro-elasticity
  - Linear moisture swelling/shrinkage
  - Stress dependent gas permeability
  - Gas entry pressure

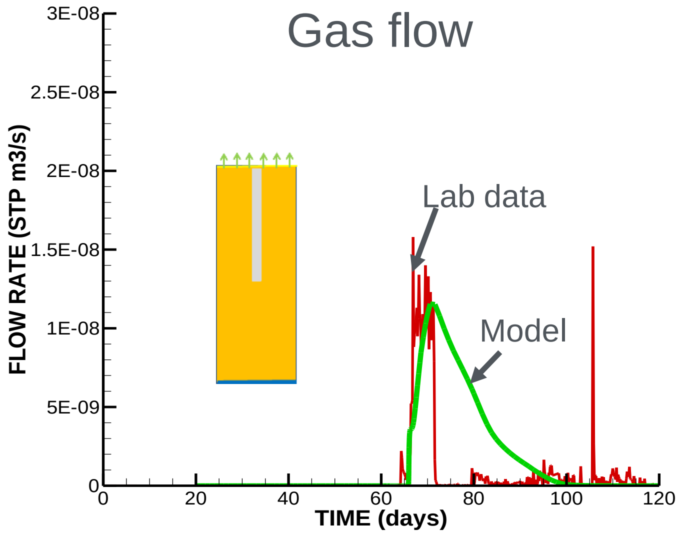




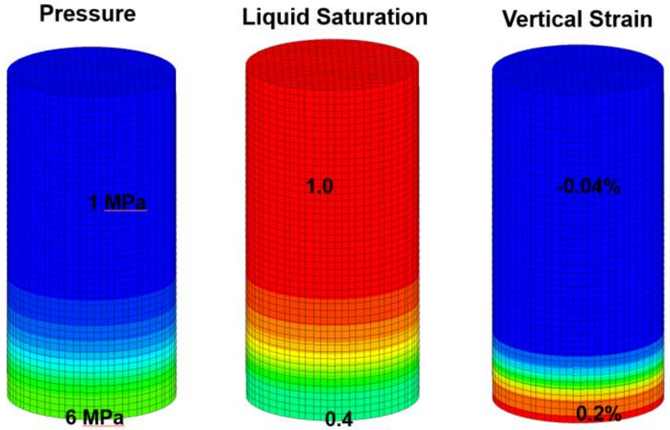


LBNL-Continuum Best Matched Case



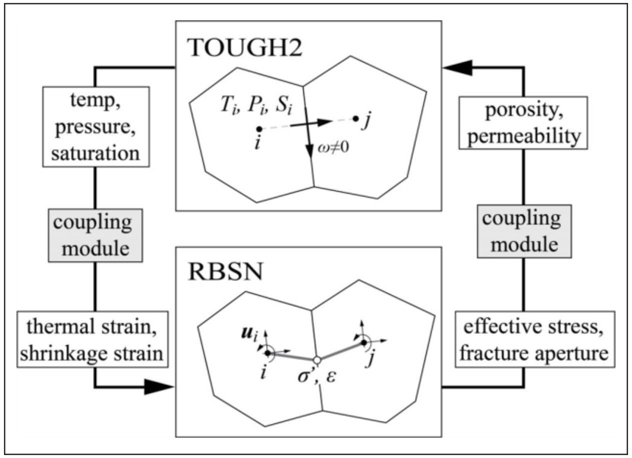


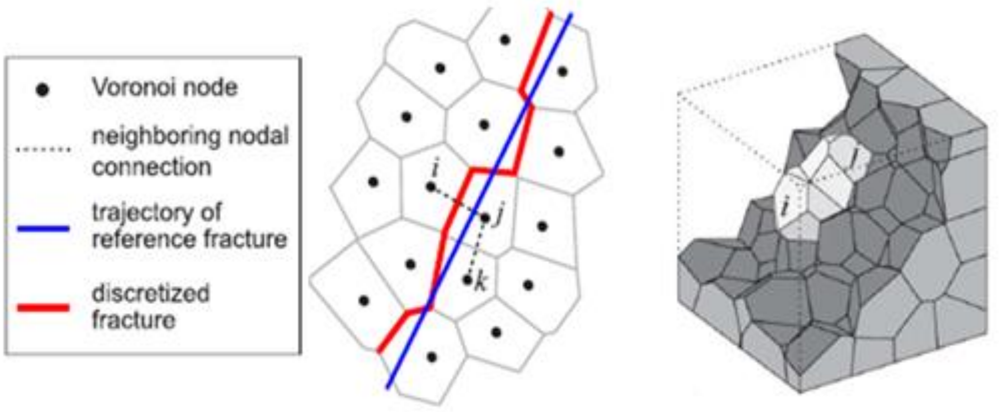
Before Gas Breakthrough



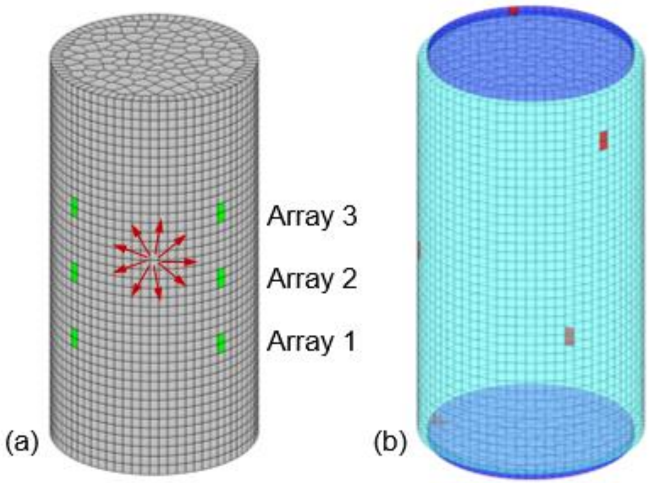
- Abrupt gas entry (gas entry pressure)
- Peak flow rate depends on stress-k function
- Moisture shrinkage necessary to match data
- Flow and stress after peak?
- Hydro-mechanical model quite simplified with several calibration parameters

LBNL-Discrete Fracture Model (TOUGH-RBSN)





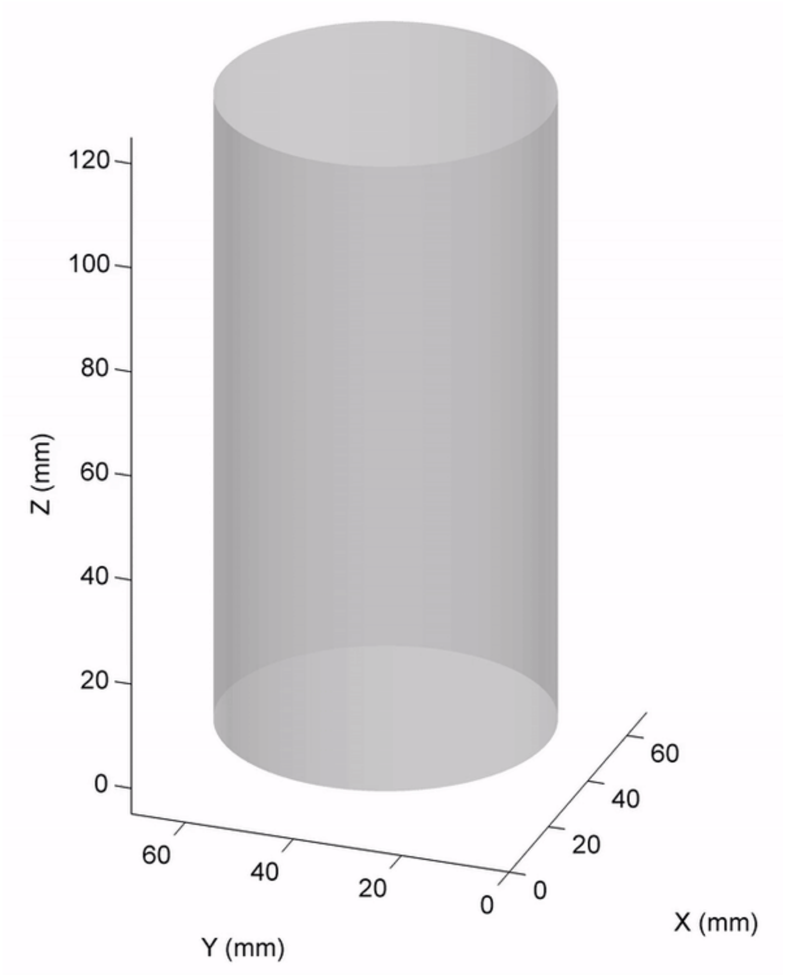
Model Grid Stage 2A

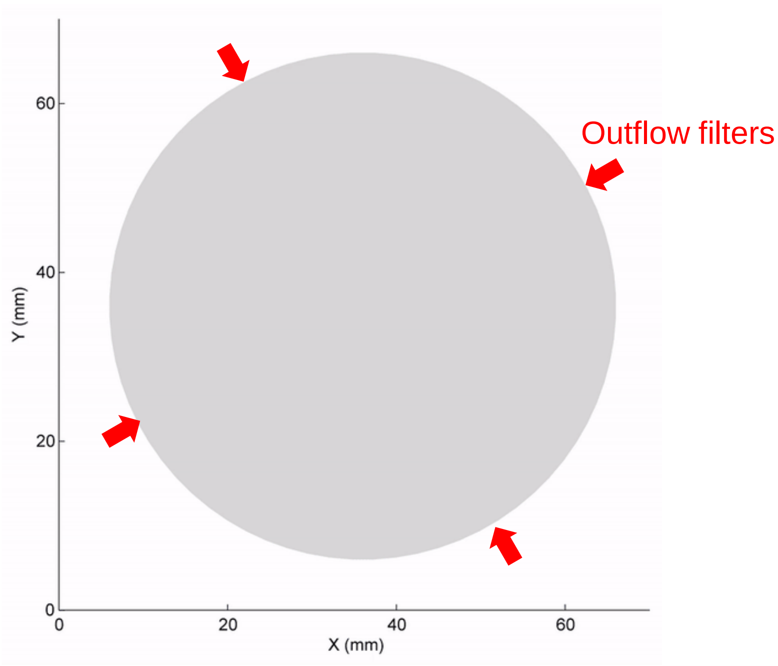


- Discrete (lattice) representation of elasticity and individual fractures
- A fracture is represented by the breakage of the springs (1D lattice elements) linking adjacent Voronoi cells
- Mohr-Coulomb criterion for fracturing
- Fracture damage degrading spring coefficients
- Fracture permeability depend on aperture
- Moisture shrinkage of matrix blocks

LBNL-Discrete Fracture Model (TOUGH-RBSN)

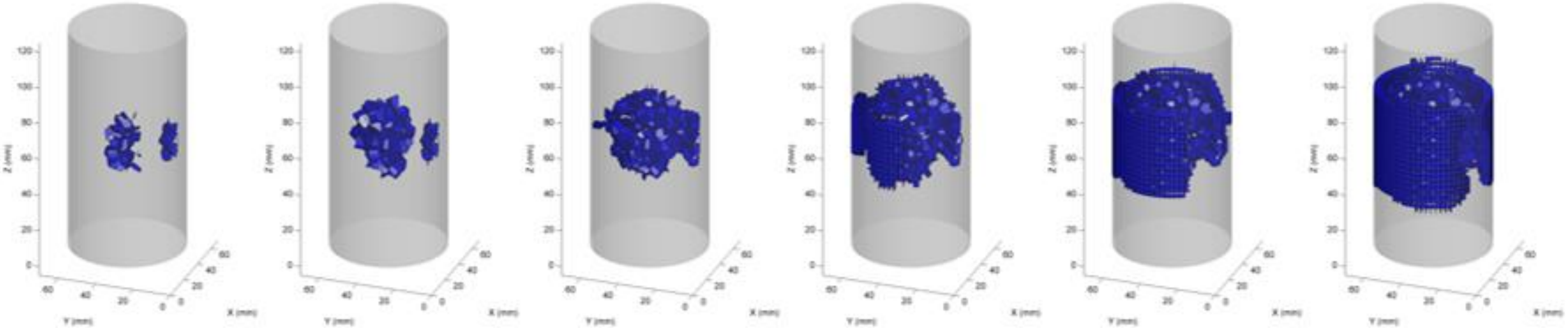
Movie of fracture (dilatant flow path) evolution:

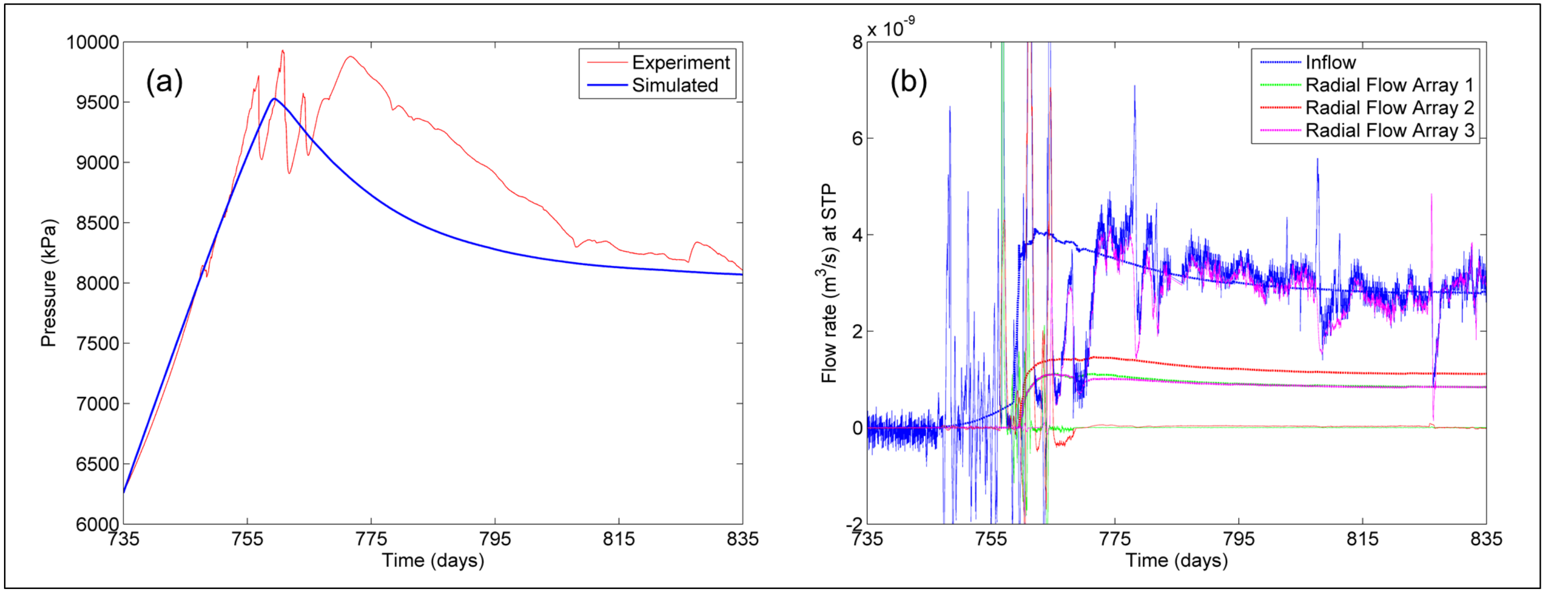




(Kim et al., 2018, TOUGH Symposium)

LBNL-Discrete Fracture Model (TOUGH-RBSN)



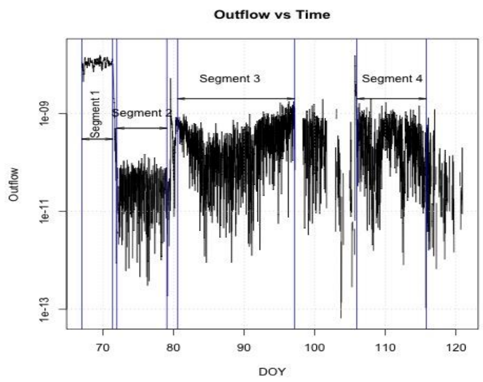


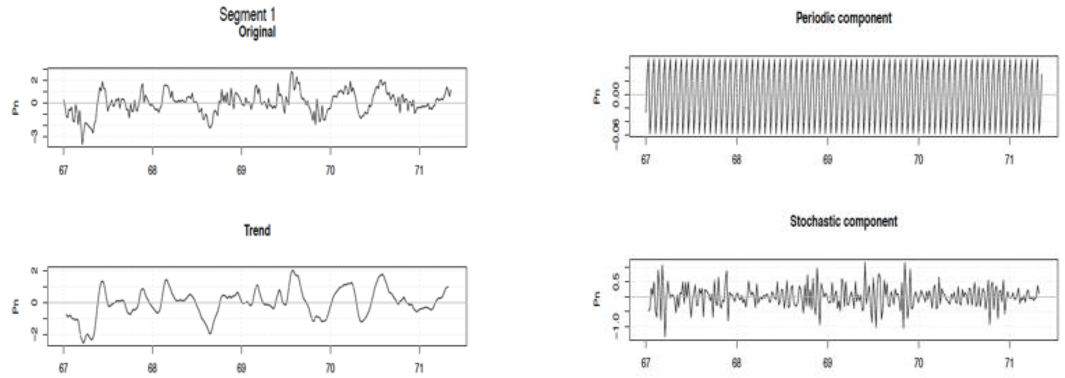
- Outflow more homogeneous (all 3 arrays) in the model

(Kim et al., 2018, TOUGH Symposium)

Other Fundamental Studies

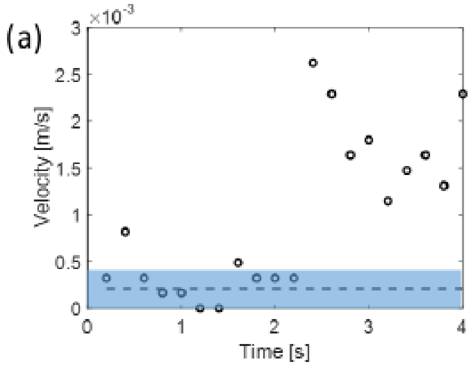
Chaotic Non-linear Dynamics (Yifeng Wang, SNL, Boris Faybishenko, LBNL)

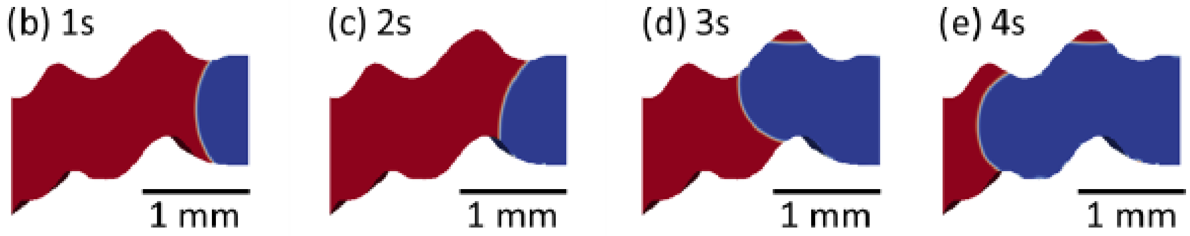




⇒ The system is deterministically chaotic…

Pore-Scale Modeling: Two-Phase Flow in a Rough Channel (Hang Deng, LBNL)





The gas migration is controlled by the interplay between the surface tension, inertial, viscous and buoyancy forces.

Modelling Approaches of DECOVALEX Teams

STAGE 1A

- **Two-phase flow continuum models**
  1. UPC/Andra-H: rigid medium
  2. LBNL-C-E: elasticity
  3. CNSC-E: elasticity
  4. CNSC-D: damage
  5. KAERI-D: damage
  6. BGR/UFZ-P: elastoplasticity
  7. CNSC-P: elastoplasticity
  8. NCU/TPC-E: elasticity
- **Enriched model with preferential pathways**
  9. Quintessa/RWM-Cap: capillary model
  10. UPC/Andra-HM-E1: elasticity
  11. UPC/Andra-HM-E2: elasticity
  12. UPC/Andra-HM-P: elastoplasticity
- **Discrete approaches**
  13. LBNL-D: discrete fracture network
- **Other**
  14. SNL: chaotic model (conceptual)

STAGE 2A

- **Two-phase flow continuum models**
  1. CNSC-D: damage
  2. KAERI-D: damage
  3. BGR/UFZ-P: elastoplasticity
  4. CNSC-P: elastoplasticity
  5. NCU/TPC-E: elasticity
- **Enriched model with preferential pathways**
  6. Quintessa/RWM-Cap: capillary model
  7. UPC/Andra-HM-E1: elasticity
  8. UPC/Andra-HM-E2: elasticity
  9. UPC/Andra-HM-P: elastoplasticity
- **Discrete approaches**
  10. LBNL-D: discrete fracture network
- **Single-phase flow model (empirical model)**
  11. Quintessa/RWM-E1
  12. Quintessa/RWM-E2
- **Other**
  13. SNL: chaotic model (conceptual)

(Tamayo-Mas et al., 2018)

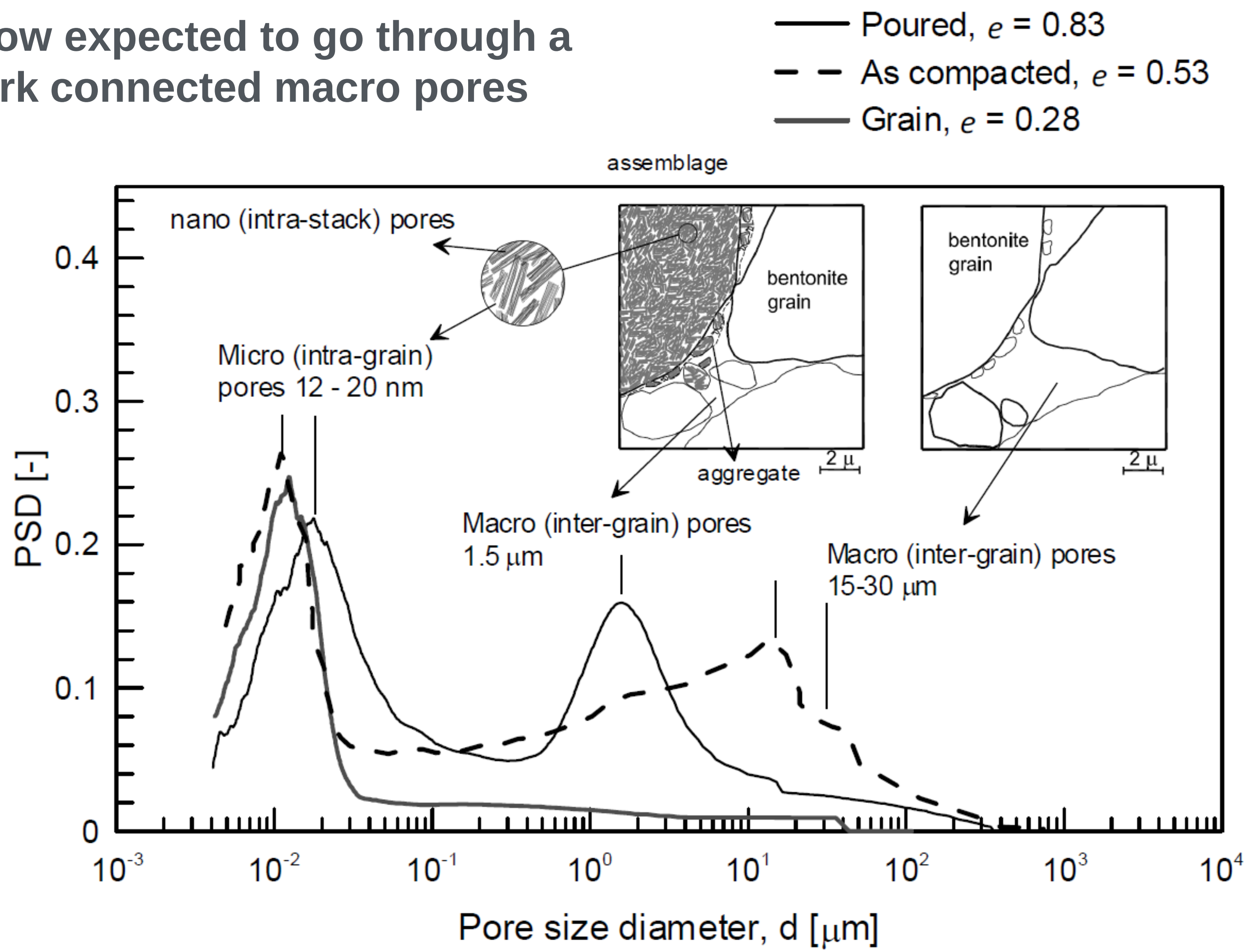
Evaluation of Different Models

Model	STAGE 1A												STAGE 2A											
	Radial stress				Axial stress				Pore pressure				Radial stress				Axial stress				Bulk flow			
	Initial	Break.	Peak	Decay	Initial	Break.	Peak	Decay	Initial	Break.	Peak	Decay	Initial	Break.	Peak	Decay	Initial	Break.	Peak	Decay	Initial	Break.	Peak	Decay
BGR/UFZ-P																								
CNSC-D																								
CNSC-P													Not provided											
KAERI-D																								
LBNL-C-E													Not implemented											
LBNL-D																								
NCU/TPC-E																								
Quintessa/RWM-Cap																								
Quintessa/RWM-Emp	Not provided																							
UPC/Andra-H													Not implemented											
UPC/Andra-HM-P																								

- **Some models match the data better (green), but do they really model the underlying micro-to-macro scale mechanisms correctly?**
- **Can they be up-scaled and applied at the field scale?**

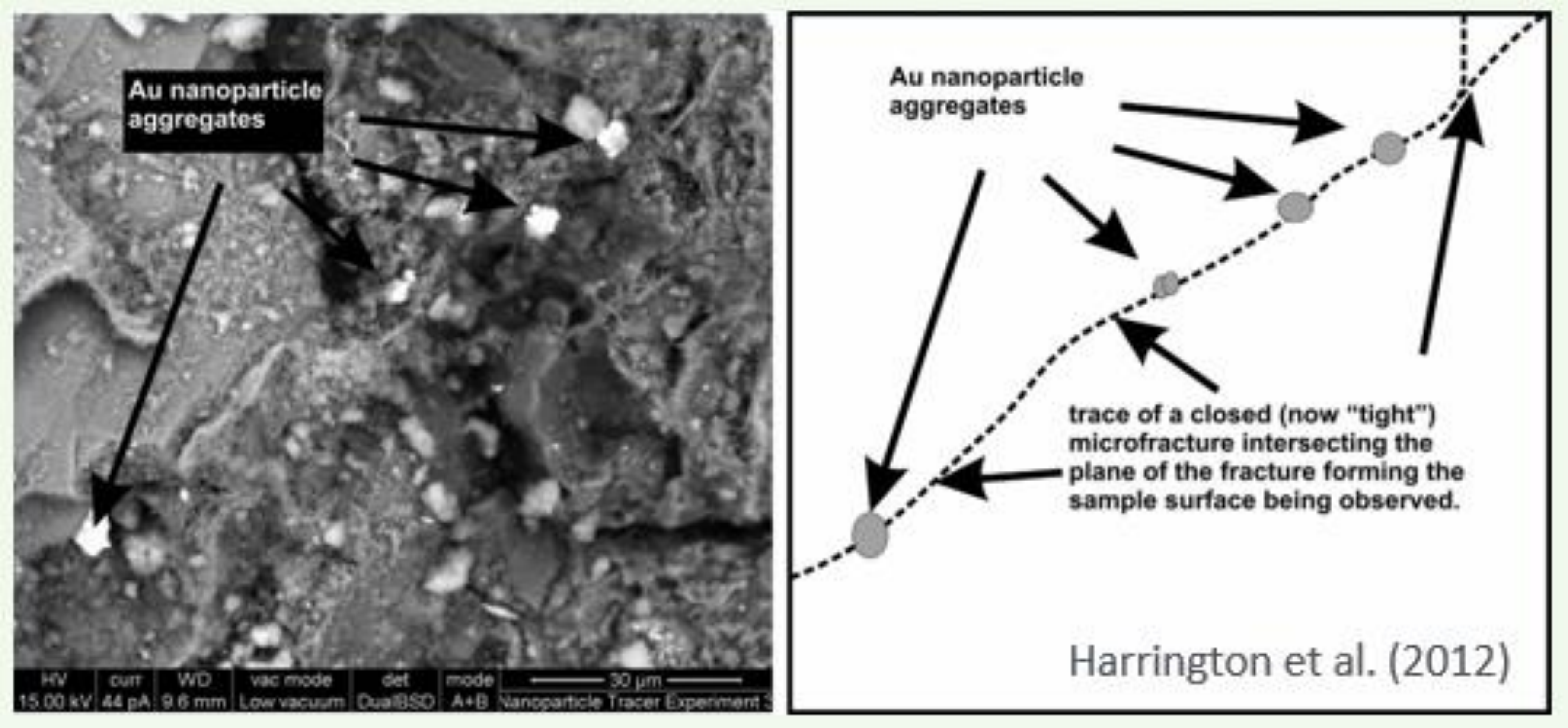
Dual Structure of Bentonite

Gas flow expected to go through a network connected macro pores



(Seiphooir 2015: Pore structure from Mercury Intrusion Porosimetry (MIP) analysis Scanning Electron Microscopy (SEM) observations)

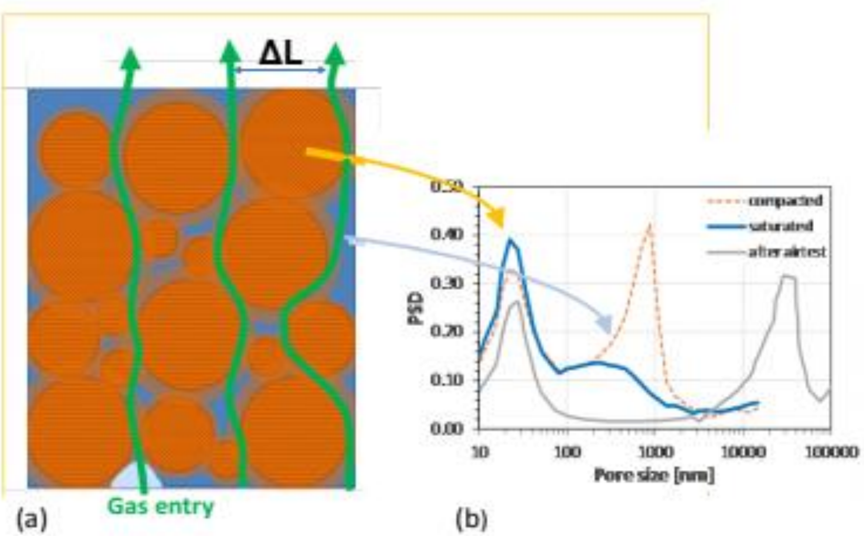
Dilatant Flow Observations



- Gas injection test (with nanoparticles) designed to demonstrate the presence of pressure-induced dilatant pathways in Boom Clay

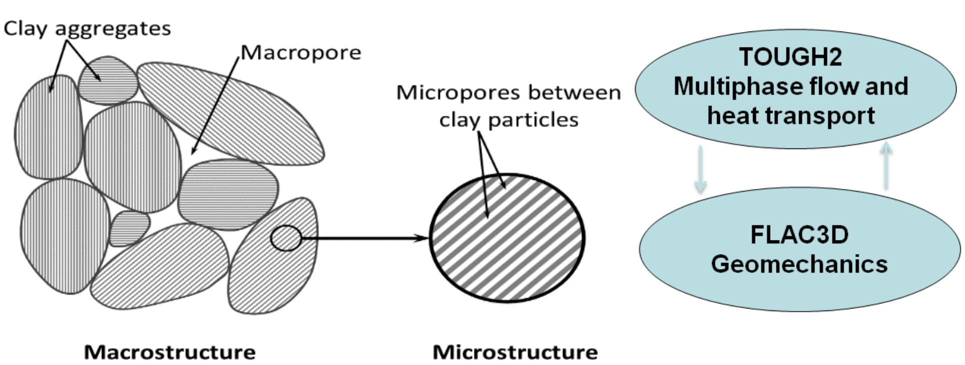
Avenue for Future Model Developments?

NAGRA-INTERA employs dual-continuum models to consider structural changes during free gas migration



Senger et al., (2018)
TOUGH 2018 symposium

LBNL's TOUGH-FLAC simulator with Barcelona Expansive Model (BExM) considers the two structural levels and could be applied to study gas migration



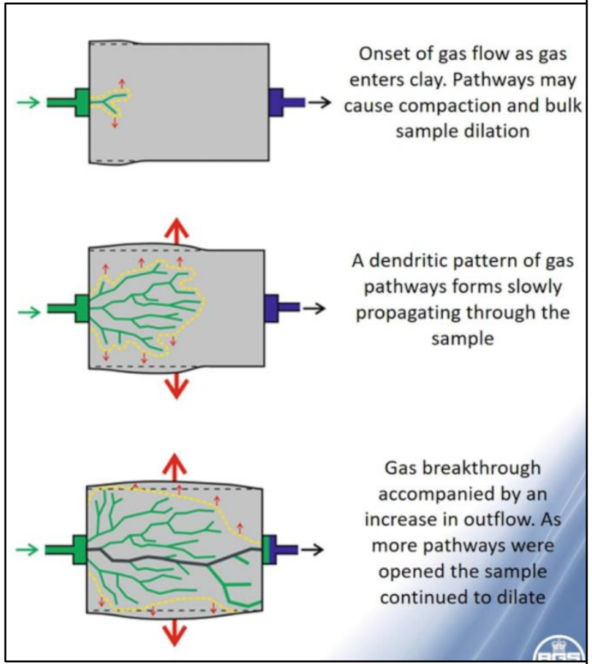
LBNL's TOUGH-RBSN discrete fracture model can be further developed to consider long-term sealing and healing of dilated flow paths

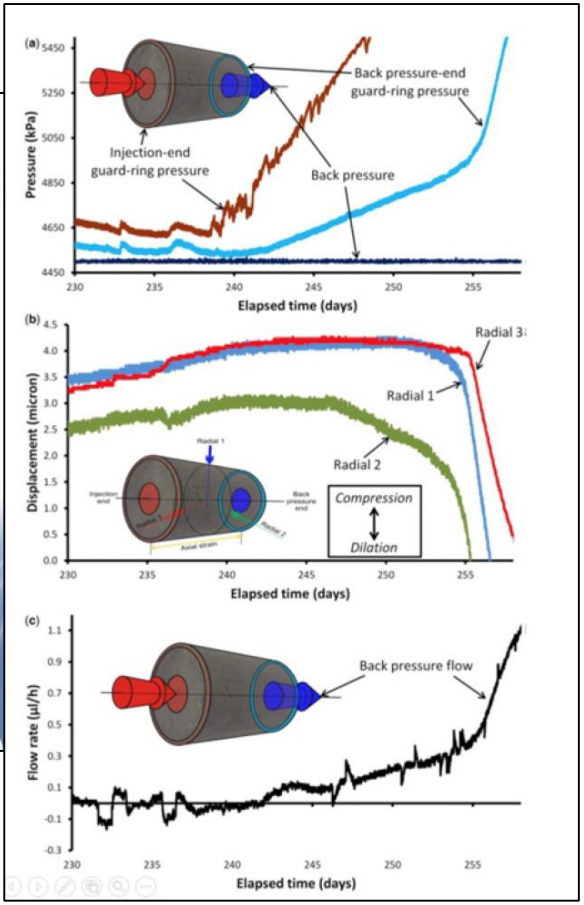
Any model needs to be validated against laboratory and (if possible) field data, and needs to be demonstrated for application at the large scale….

Planned Mont Terri Project Experiment

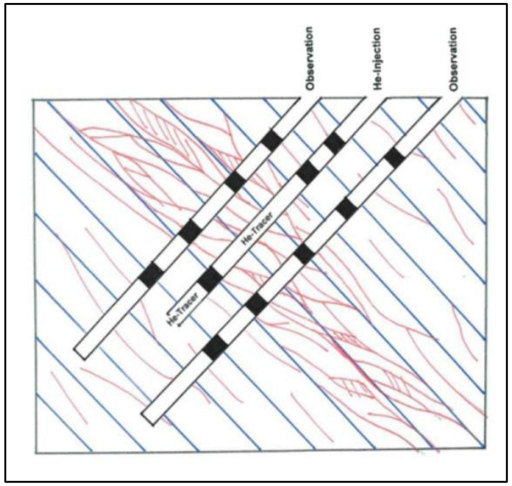
GT Experiment: Evaluation of gas transport models and of the behavior of clay rocks under gas pressure

Lab Studies 2018 to 2020

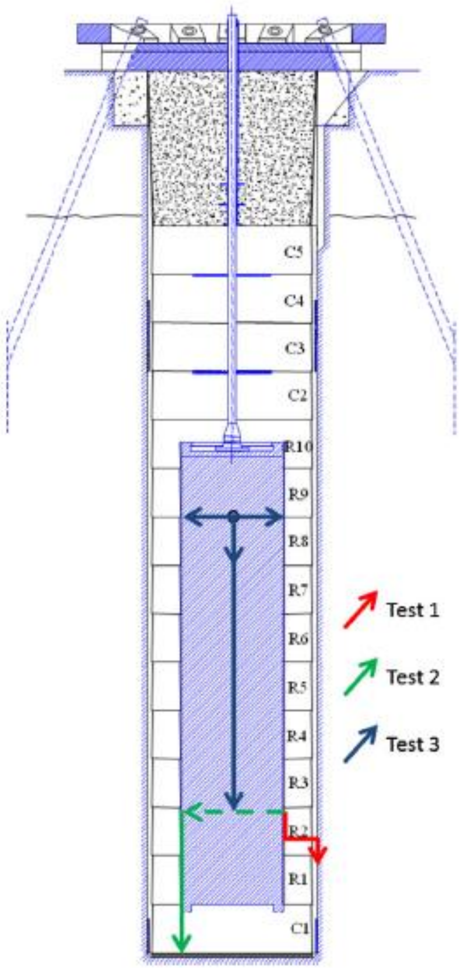


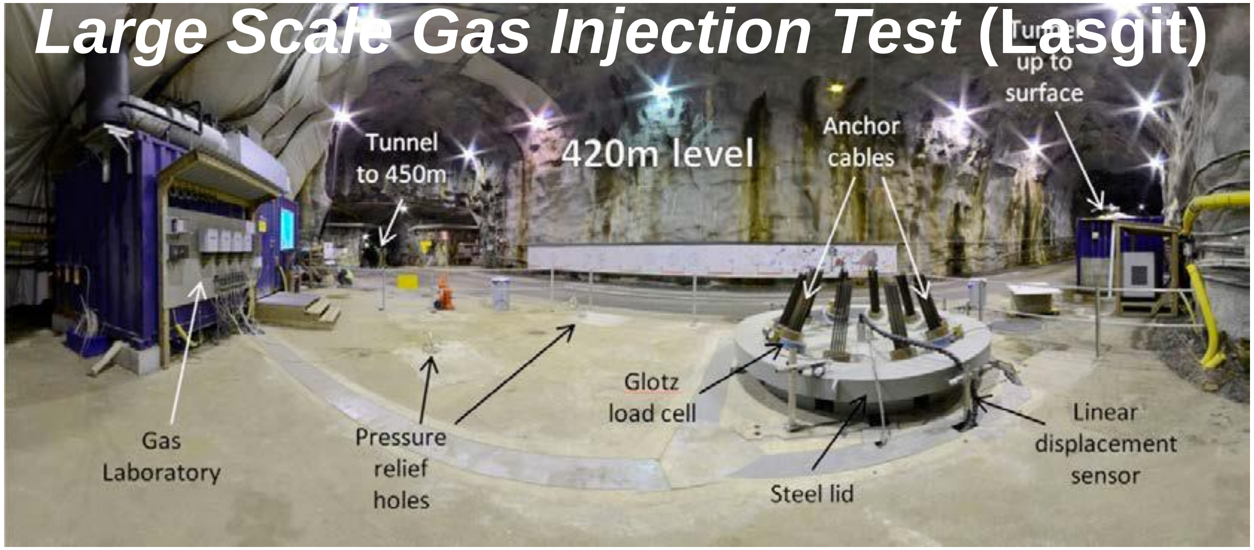


Field Studies 2019 to 2021



Potential DECOVALEX-2023 Task (Lasgit field-scale test)





- The installation phase, including the deposition of canister and buffer, was finalized in 2005.
- Preliminary hydraulic and gas injection tests in 2008.
- Natural and artificial hydration of the bentonite buffer.
- A unique data set for model validation at a relevant field scale

(SKB, 2017, TR-17-10)

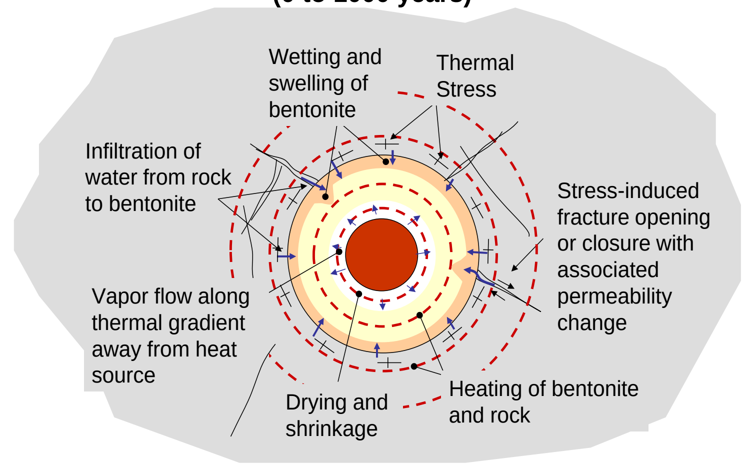
Input to GDSA from Near-Field Coupled Processes Model

- The analysis for coupling to the PA model might be focused on the **near field of an emplacement tunnel or a few emplacement tunnels in different parts of a repository** and for different FEPs such as nominal case or **cases of extensive gas generation.**

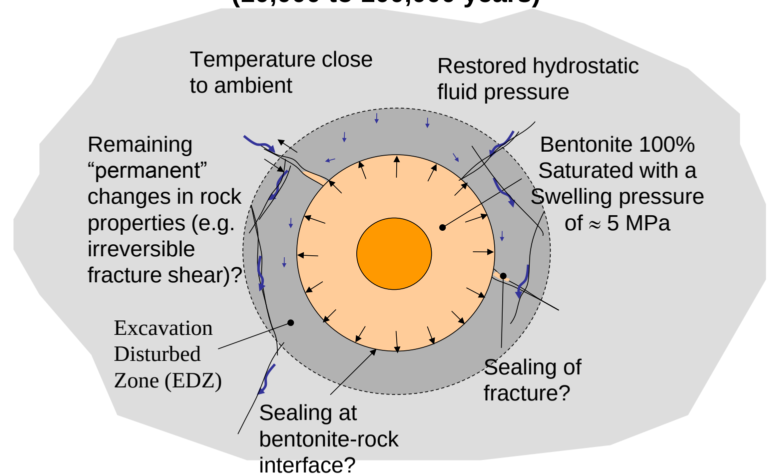
- The **inputs r**equired are the geometry, heat source, THM properties of buffer and host rock, initial THM conditions (such as in situ stress).

- The **output** to the PA model would be the changes in flow properties (e.g. permeability and porosity) in the EBS and near-field including the buffer and DRZ and also to inform PA related to local flow created by coupled THM processes.

SHORT TERM THM PROCESSES (0 to 1000 years)



LONG TERM IMPACT? (10,000 to 100,000 years)



Summary and Recommendations

- The study of gas flow migration in clay-based material has been to topic of several international studies, increasingly over the last 5-10 years
- Still the basic mechanisms of gas transport in bentonite and low permeability host rocks are not understood in sufficient detail, and therefore the predictive capacities are limited
- Further work should strive to better represent the correct underlying physics, such as dual structure behavior, in models that should still be efficient to be applied at a repository tunnel scale
- International projects, such as the DECOVALEX project, provide avenues for faster capability developments through exchanges of ideas and collaborations, and through access to experimental data

References

Harrington, J.F., Milodowski, A.E., Graham, C.C., Rushton, J.C., and Cuss, R.J. (2012) Evidence for gas-induced pathways in clay using a nanoparticle injection technique. Mineralogical Magazine. December 2012, Vol. 76(8), pp.3327-3336. DOI: 10.1180/minmag.2012.076.8.45.

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Questions?

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