Used Fuel Disposition Campaign

DRZ modeling and Testing

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UFD WG Meeting in Las Vegas

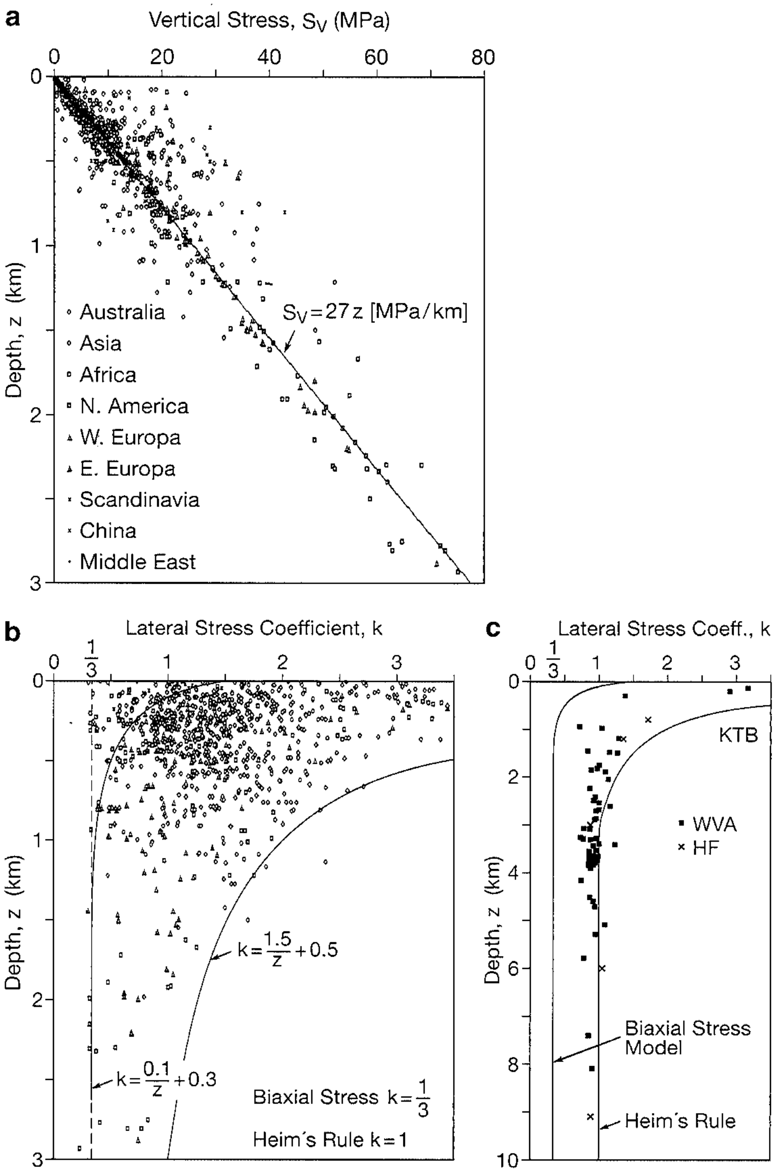
Deep Borehole Discussion

June 8, 2016

OUTLINE

- Stress and Permeability at Depth
- Spalling, borehole break-out and Disturbed zone
- Initial TH modeling of thermal pressurization and upflow through Disturbed Zone
- Proposed THM modeling
- Disturbed Zone modeling
- Disturbed Zone laboratory experiments

Stress and Permeability at Depth



Zang and Stephansson (2010) Referring to Hoek and Brown and others.

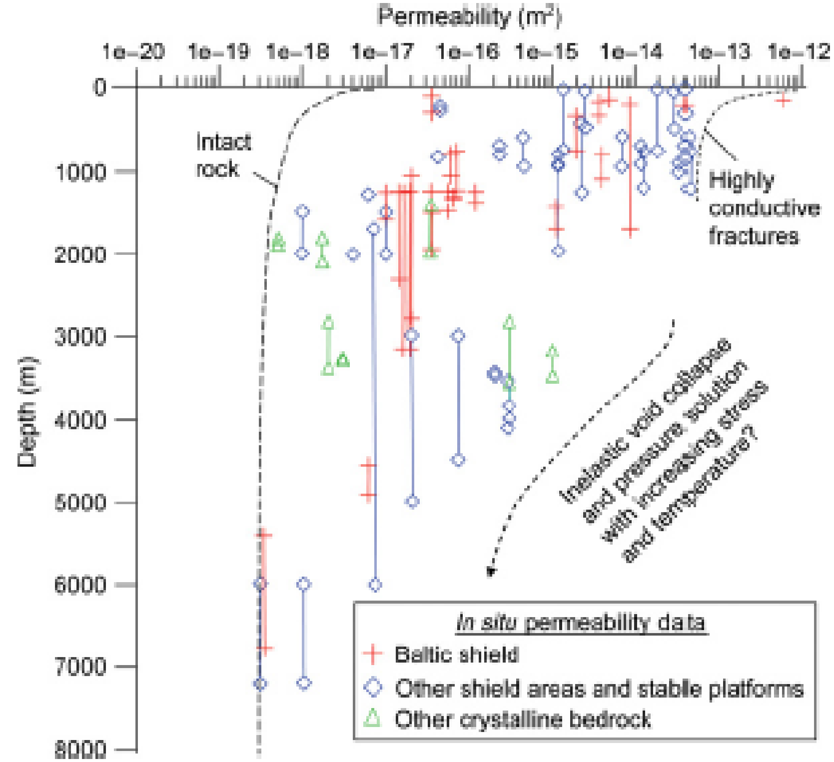


Fig. 22. Compilation of permeability measurements in boreholes in crystalline bedrock (from Juhlin *et al.* 1998) with added schematic of upper and lower limits of permeability related to mechanical and chemo-mechanical behavior.

Rutqvist (2015)

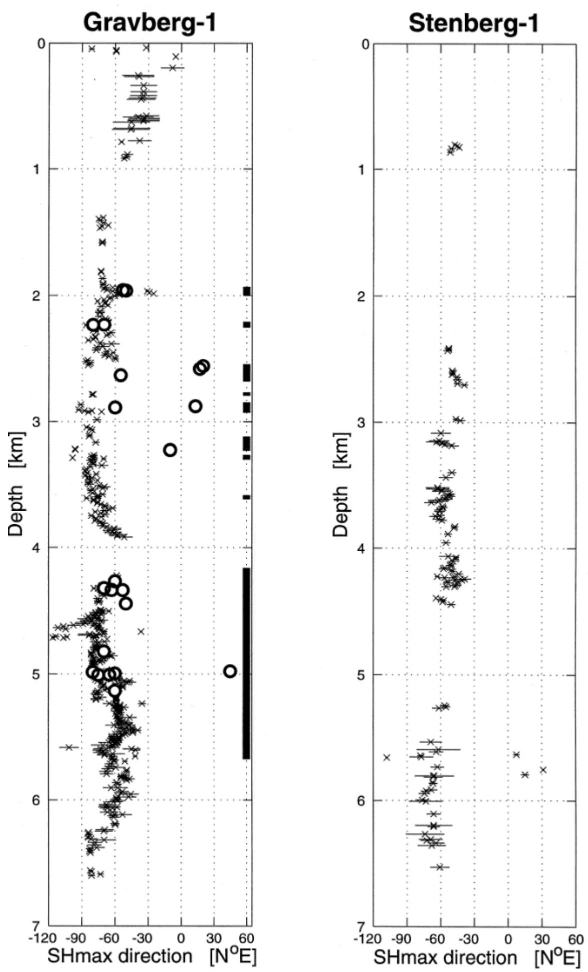
- Stress state at 3 km about 80 MPa (at 5 km would be extrapolated to 100 MPa)
- Stress concentration around hole > ~ 200 MPa…
- Could encounter permeable fractures even at 5 km depth
- Durham and Bonnier (1994) experiment showed offset fracture could be open to flow at 160 MPa

Borehole Break-out and Disturbed Zone

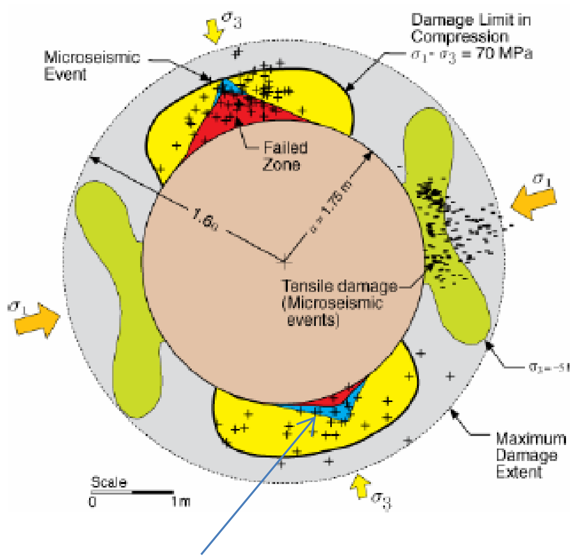
Should consider potential scale-dependency and time dependent effects:

In situ compressive strength (spalling around tunnels) about 50% of laboratory compressive strength at Manitoba URL and Äspö HRL (e.g. Derek Martin and others):

Borehole break-out data to 6.5 km (Siljan, Sweden):



Damage phenomena at the Mine-by tunnel, URL, Canada (Martin, 2005).



In Situ measurements at URL shows 6 orders of magnitude increase in permeability in the spalled zone

Time dependent strength degradation (Rutqvist et al. 2009):

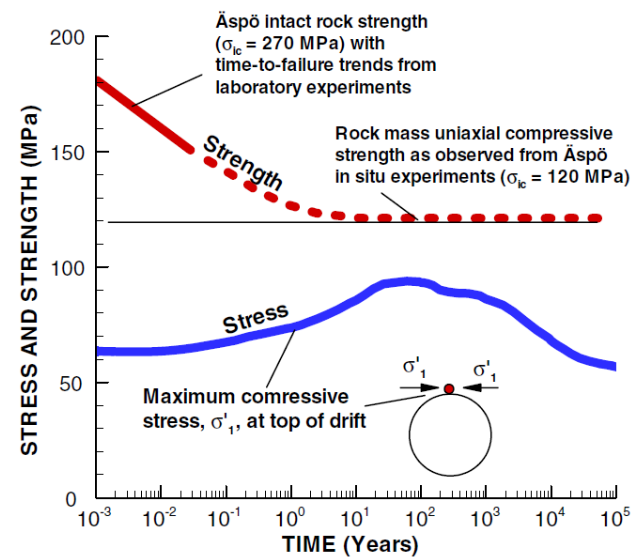
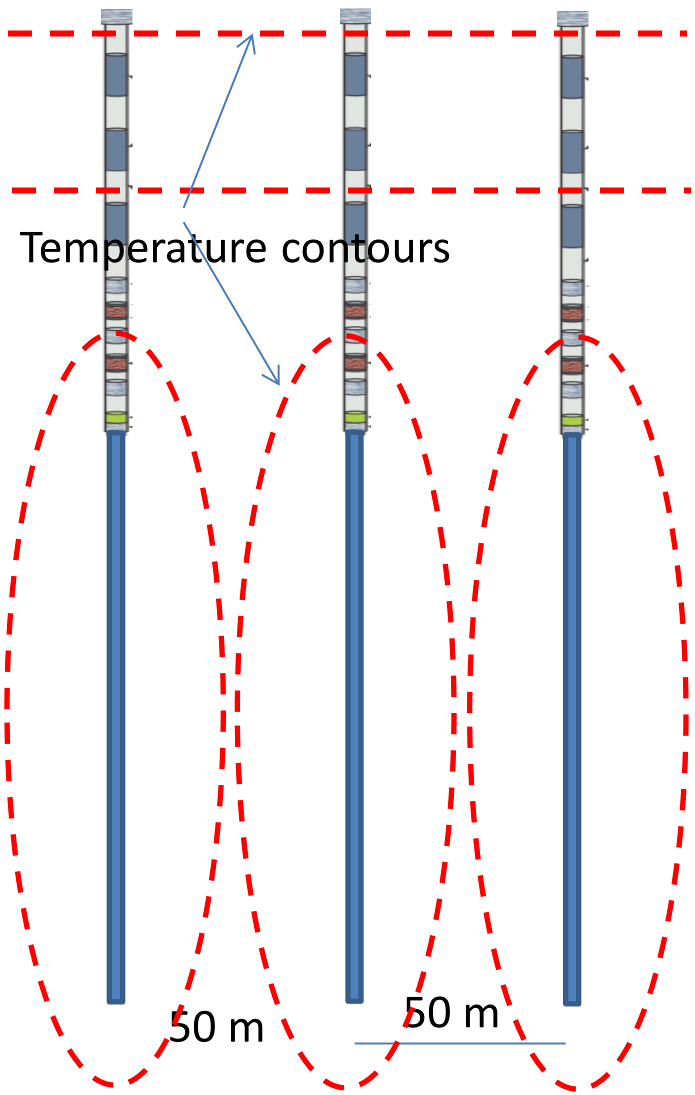


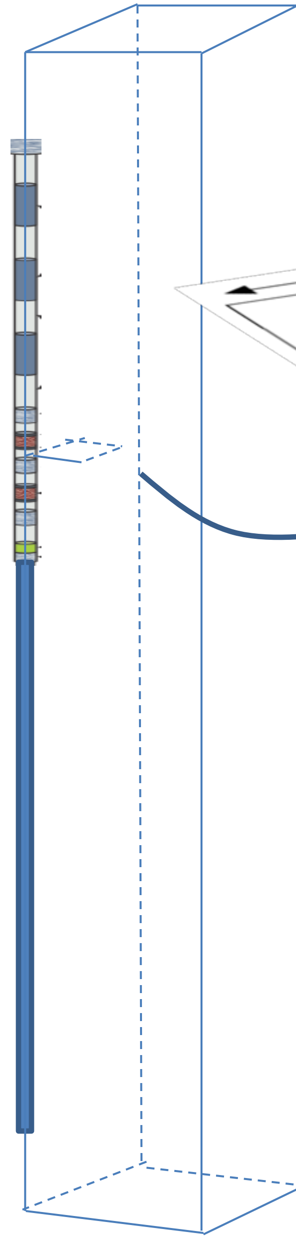
Fig. 8 Schematic of time-dependent strength degradation and the evolution of maximum principal stress at the top of the emplacement drift in this simulation problem. The short-term strength was assumed to be 270 MPa; it has already dropped to 180 MPa at 10^{-3} years (8 h)

The evolution of the disturbed zone through different stages of disposal development (borehole break-out) is a key issue

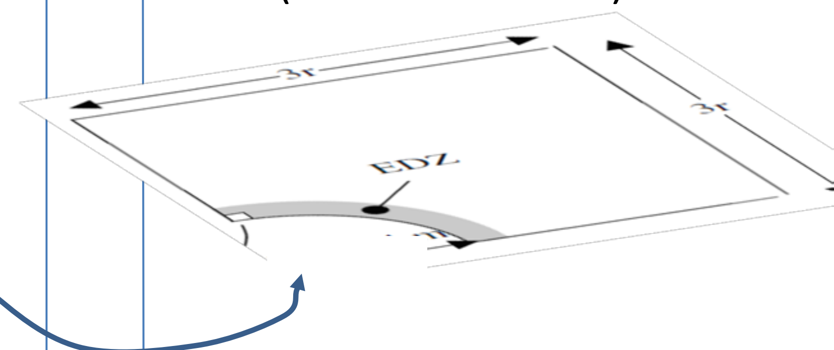
Proposed THM and Disturbed Zone Modeling

Quarter symmetric 3D to calculate temperature, pressure, stress evolution





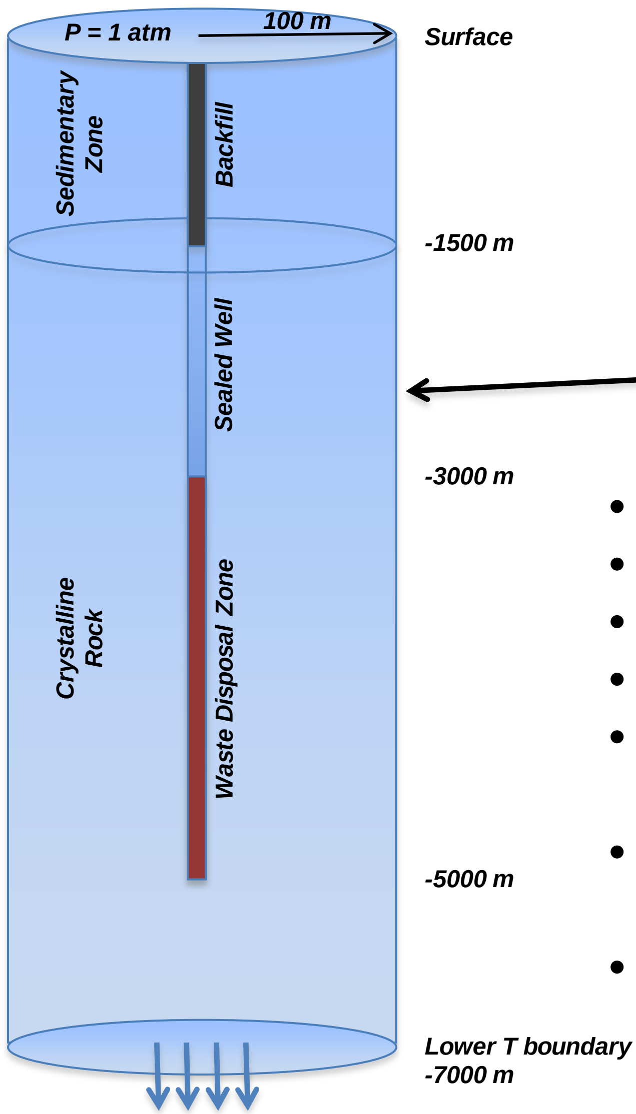
Near field model (2D cross-section)

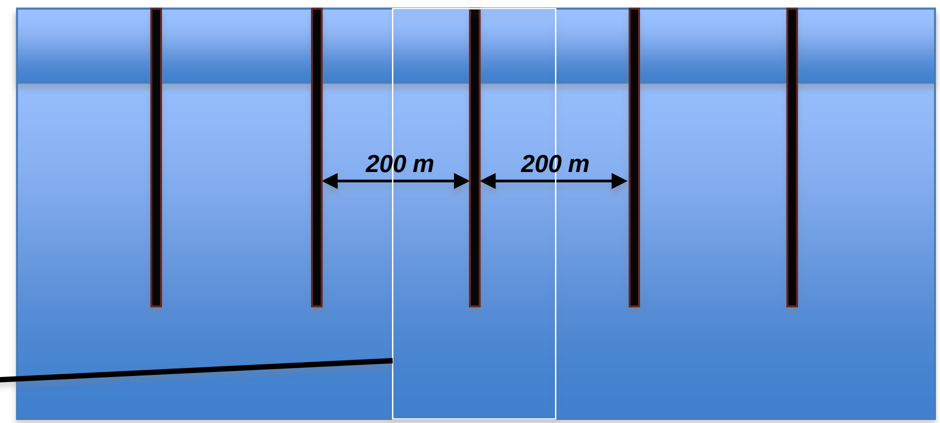


Will be important to consider all steps,

1) Drilling (with mud-weight poro-elastic)
2) Emplacement of casing
3) Emplacement of canisters
4) Removal of part of casing
5) Emplacement of cement and bentonite sections
6) Heating and thermal pressurization
7) Swelling of bentonite
8) Return to ambient conditions

TH Modeling of Thermal Pressurization and Upflow through DRZ

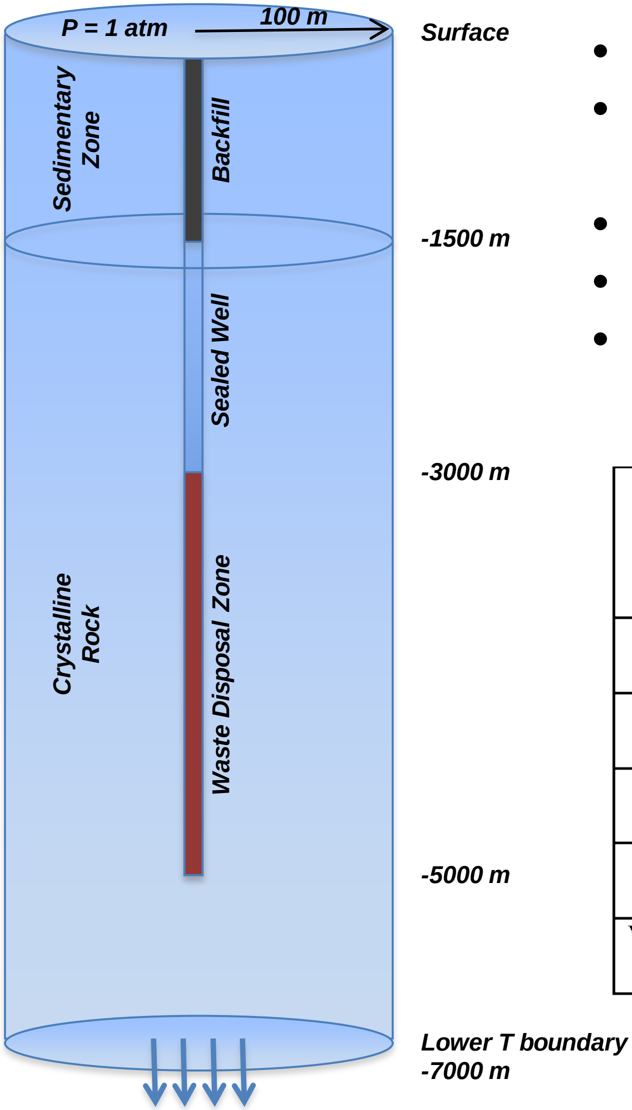




- *Modeling a field of wellbores, not an isolated well*
- *Radially-symmetric 2D grid (20,505 elements)*
- *Variable refinement near boundaries/borehole*
- *r = 100 m (i.e. 200 m borehole spacing)*
- *Disturbed rock zone along borehole*

- *Monitoring points along midpoint of WDZ, zone boundaries, surface*
- *Monitoring flow in disturbed rock zone at several depths*

TH Modeling of Thermal Pressurization and Upflow through DRZ

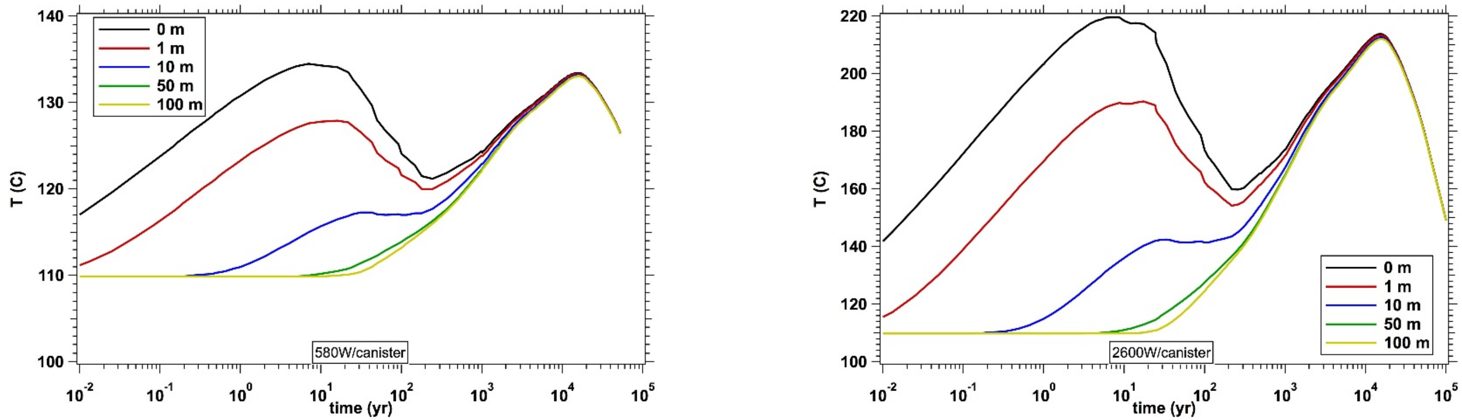


- *580W and 2600W waste canisters*
- *Variable permeability in disturbed rock and sealed-well zones*
- *Hydrostatic P profile, linear T profile*
- *TOUGH2/EOS4 (saturated, non-isothermal)*
- ***Next:** TOUGH+RealGasBrine (saturated, variable brine concentration, non-isothermal)*

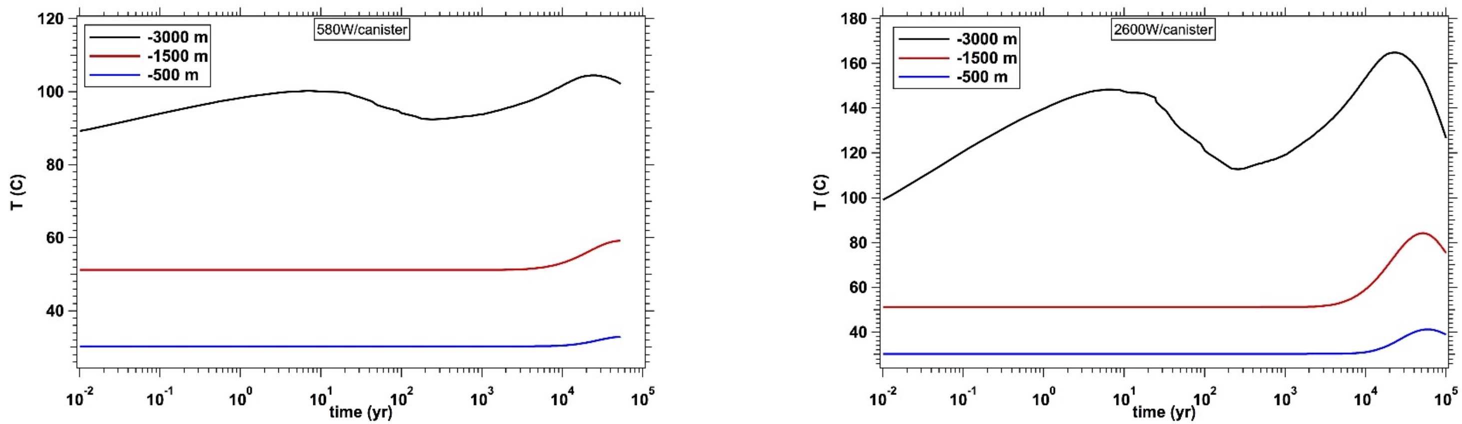
From: Brady et al. (SAND2009-4401)	k (mD)	ϕ	ρ (kg/m^3)	Spec. Heat (J/kg/K)	Thermal Cond. (W/mK)
Sedimentary Rock	10/1.0	0.30	2750.0	1000.0	3.3
Crystalline Bedrock	0.0001	0.01	2750.0	790.0	3.0
Damaged Bedrock	0.2 (2.0,20.0)	0.01	2750.0	790.0	3.0
Sealed Borehole	0.1 (1.0)	0.35	2750.0	760.0	0.8
Waste/Sealed Well Casing	0.00001	0.0001	2750.0	760.0	46.0

TH Modeling of Thermal Pressurization and Upflow through DRZ

Temperature changes at z = - 4000 m, r = 0 – 100 m (midpoint of WDZ)



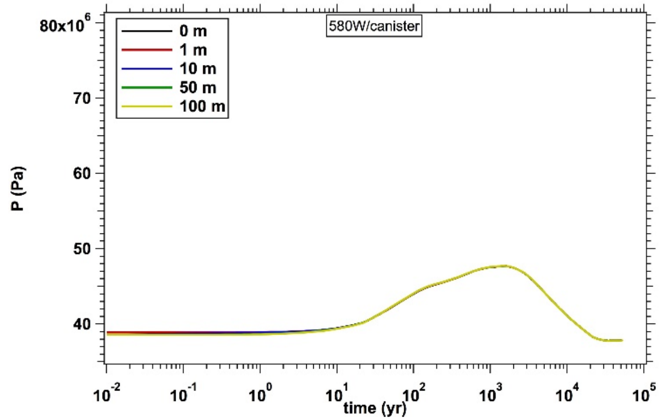
Temperature changes at r = 0 m, z = -3000, -1500, -500 m depths

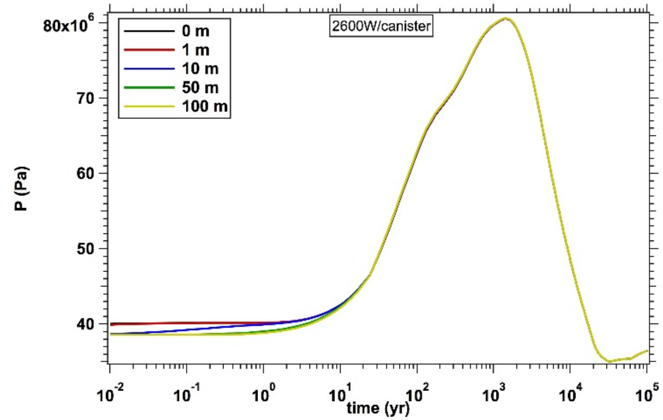


- *Thermal interaction between multiple wellbores results in second temperature peak before decline*
- *Some previous studies have examined only isolated wellbores*

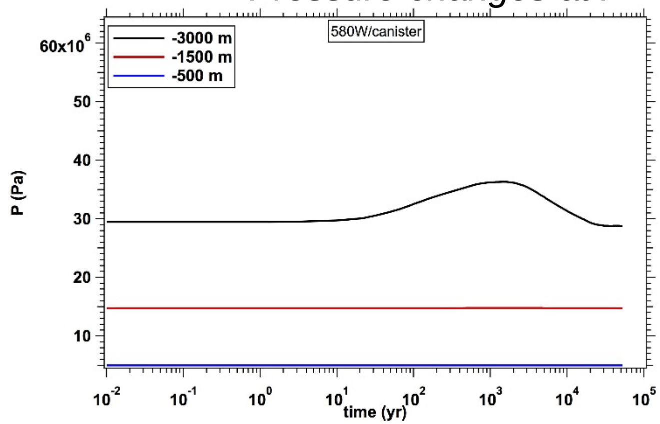
TH Modeling of Thermal Pressurization and Upflow through DRZ

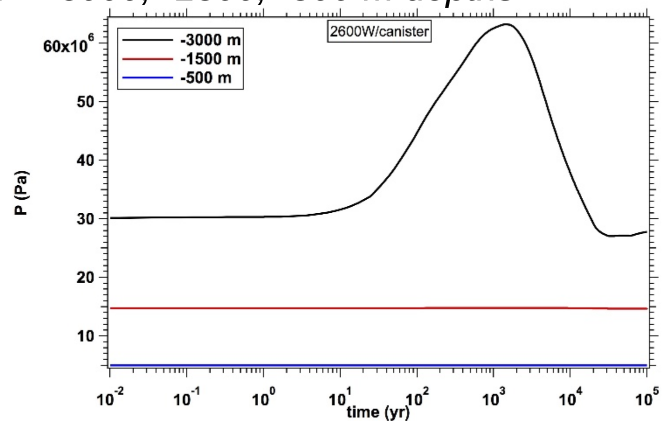
Pressure changes at z = - 4000 m, r = 0 – 100 m (midpoint of WDZ)





Pressure changes at r = 0 m, z = -3000, -1500, -500 m depths

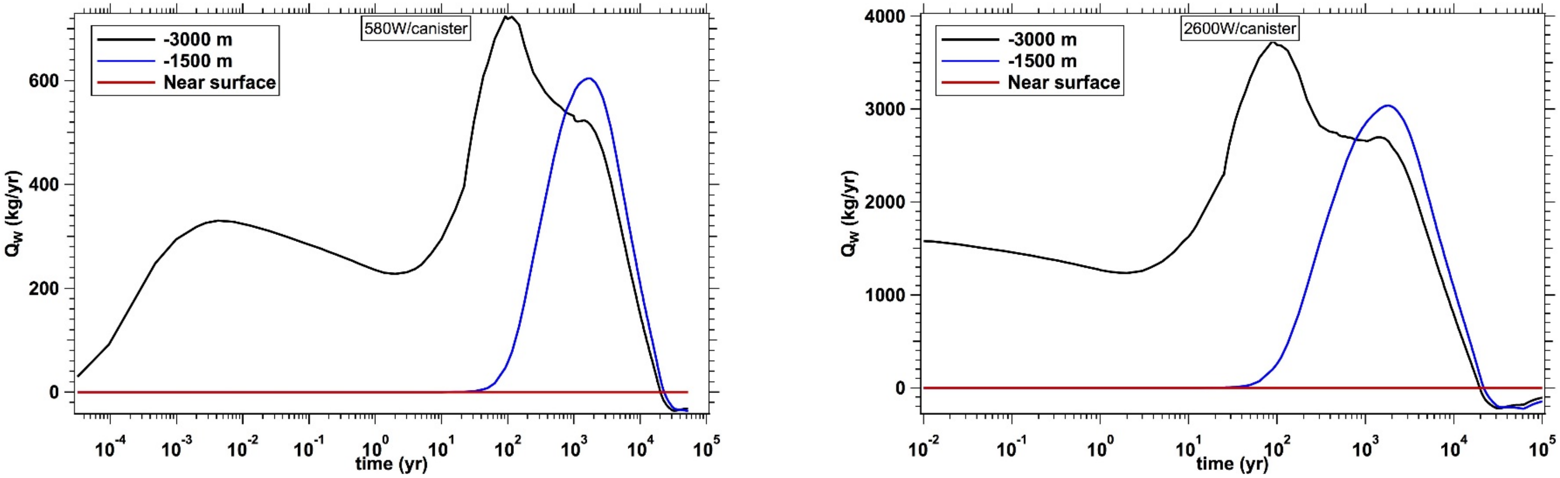




- *Interaction between multiple wellbores results in higher peak pressures*
- *Pressure increases at late times, during second temperature surge*

TH Modeling of Thermal Pressurization and Upflow through DRZ

Water flow in disturbed rock zone, z = 0 – -3000 m

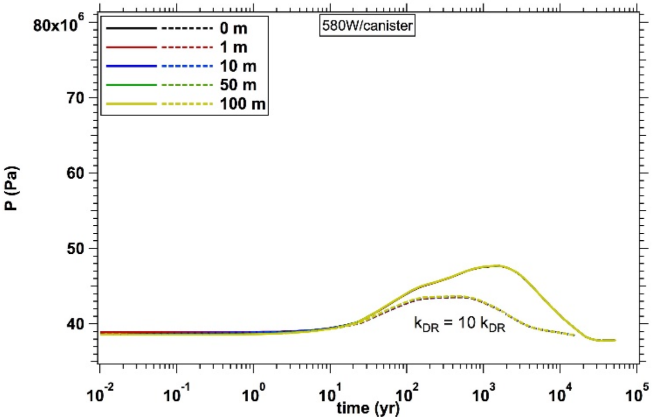


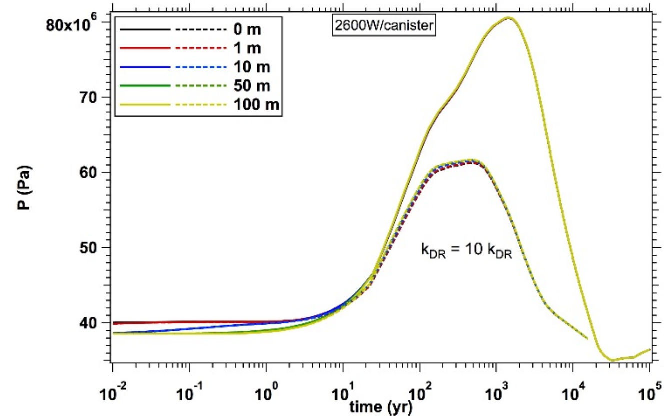
- *Temperature and pressure interaction between wellbores results in larger peak upward flows than seen for isolated wellbores*
  - *Higher peak pressures driving upward flow*
  - *Lack of open boundaries for heat and mass flow*

- *Sensitivity: vary k of disturbed rock zone by 10X, vary permeability of sealed wellbore by 10X-100X*

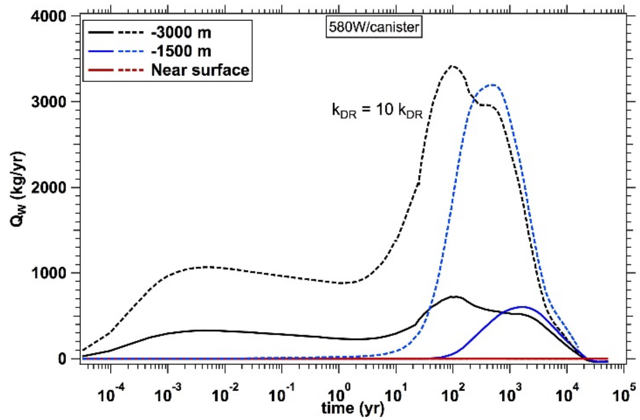
TH Modeling of Thermal Pressurization and Upflow through DRZ

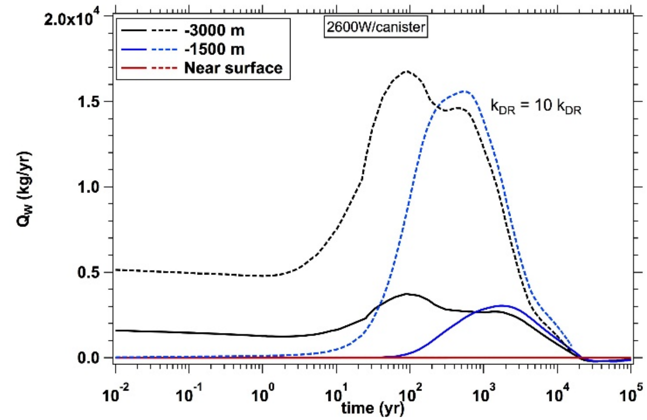
Pressure changes at z = - 4000 m, r = 0 – 100 m (midpoint of WDZ) after 10X increase in k





Water flow in disturbed rock zone, z = 0 – -3000 m after 10X increase in k





- *Decreased peak pressure, greater peak upward flow*
- *Conversely, increase in sealed-well permeability (10X or 100X) shows no significant increase in upward flow*

Planned Disturbed Zone Modeling

1) Simple stress-permeability model (mean and deviatoric stress vs permeability) with in situ calibrated parameters at the Manitoba URL Canada (tight granite)
2) Anisotropic damage model with anisotropic crack propagation under tensile and shear stress (Hao Xu, postdoc)
3) Discrete fracture propagation model (TOUGH-RBSN) 2D cross-section model (Kunhwi Kim, postdoc)

1) Stress-permeability

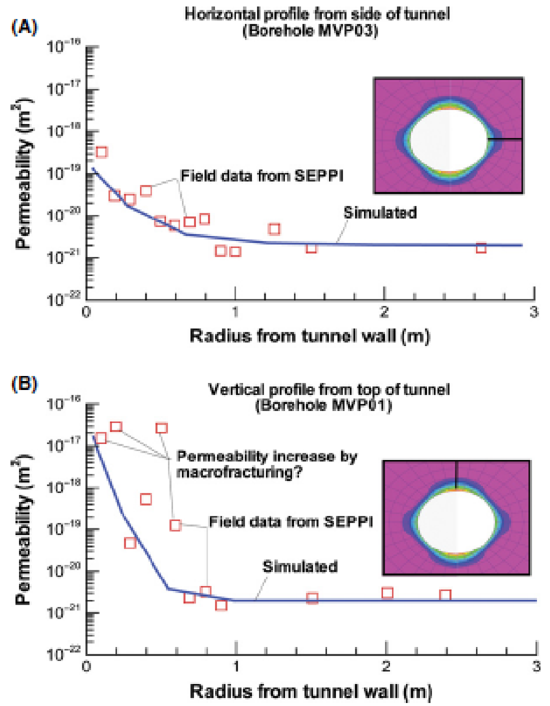
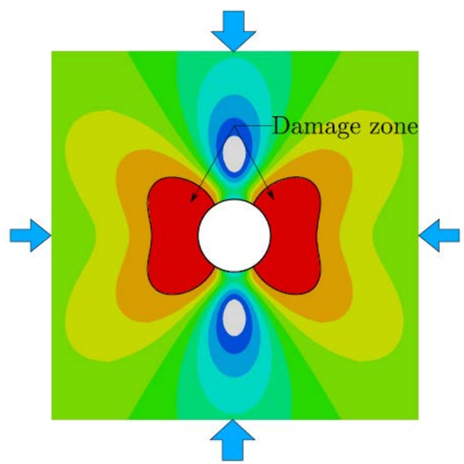
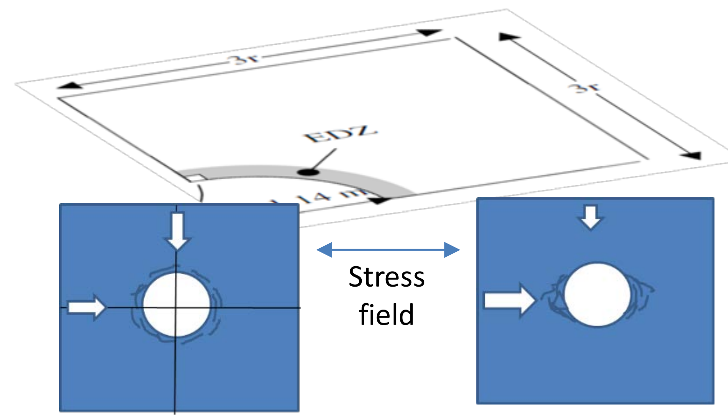


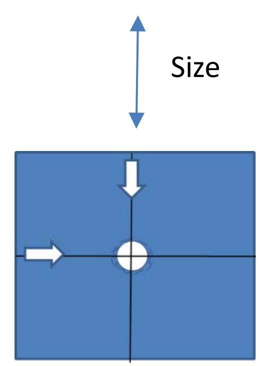
Fig. 9. Calculated and measured permeability changes around the TSX tunnel (Rutqvist *et al.* 2009b). Permeability versus radius along (A) a horizontal profile from the side of the tunnel and (B) a vertical profile from the top of the tunnel.

2) Anisotropic damage



3) Discrete fracture model





Discrete fracture modeling of borehole break-out:

Effects of stress field on break-out geometry?

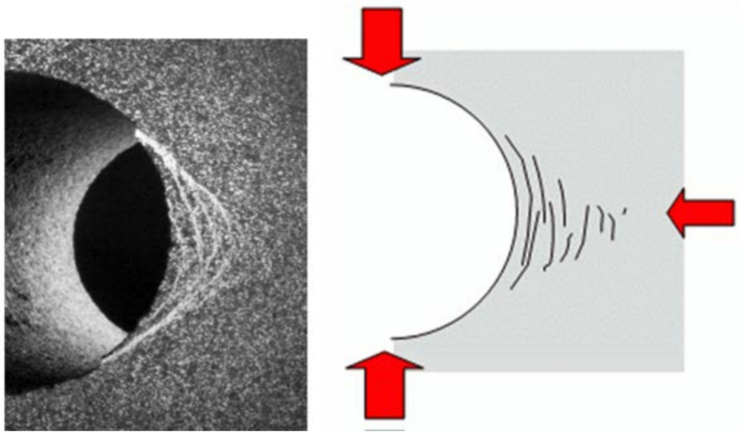
Effects of hole size?

Planned Laboratory Study of the Impact of Excavation-Induced Fractures Around a Deep Borehole

Tim Kneafsey and Seiji Nakagawa, LBNL

Objectives

In a deep borehole, presence of tectonic forces can lead to anisotropic and high stress levels, which causes damage (typically in the form of borehole breakout) near the borehole surface. This can potentially lead to upward flow pathways along the borehole, within otherwise sealed and low-permeability repository environment.



Planned Disturbed Zone Experiments

Approach

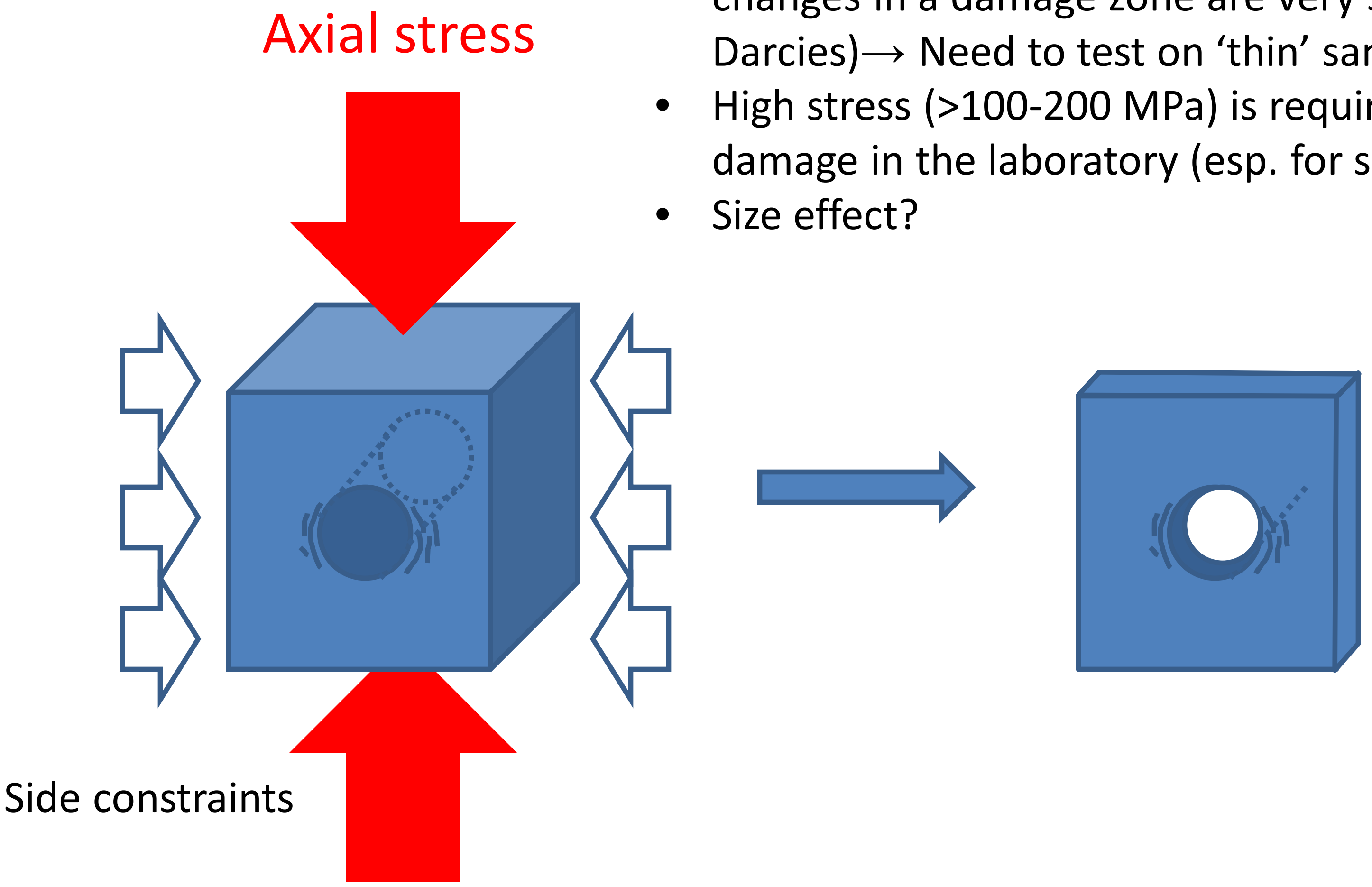
1. In the laboratory, borehole breakout will be induced around an analogue borehole within an intact crystalline rock block, by applying anisotropic stress under confined uniaxial compression
2. Damage zone structure (extent of the fractures, fracture density, connectivity) and properties (strength and integrity of the damage zone, anisotropic permeability) will be examined/assessed
3. Short and long-term changes in the permeability of the damage zone and the rock and seal plug (Bentonite, Cement) interface will be examined.
   - Short term changes: stress [e.g., Bentonite swelling pressure] and clogging (cement and Bentonite)-induced changes in the permeability
   - Long term changes: chemically induced rock dissolution and mineral precipitation (will not be conducted in the first year)
4. 'To remove or not to remove?': Removal/cleaning of the high-permeability zone may be necessary
5. Geophysical characterization of the mechanical/hydrological properties of the damage zone. Use of borehole guided waves? (Rayleigh type)

Planned Disturbed Zone Experiments

Approach

Challenges:

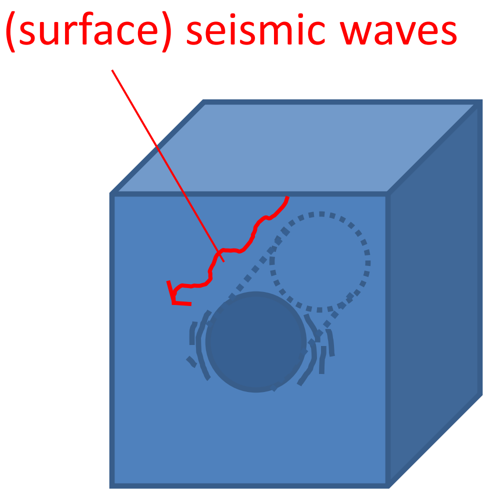
- Expected initial permeability of rock and permeability changes in a damage zone are very small (~micro Darcies)⟶ Need to test on ‘thin’ samples
- High stress (>100-200 MPa) is required to induce the damage in the laboratory (esp. for small samples)
- Size effect?

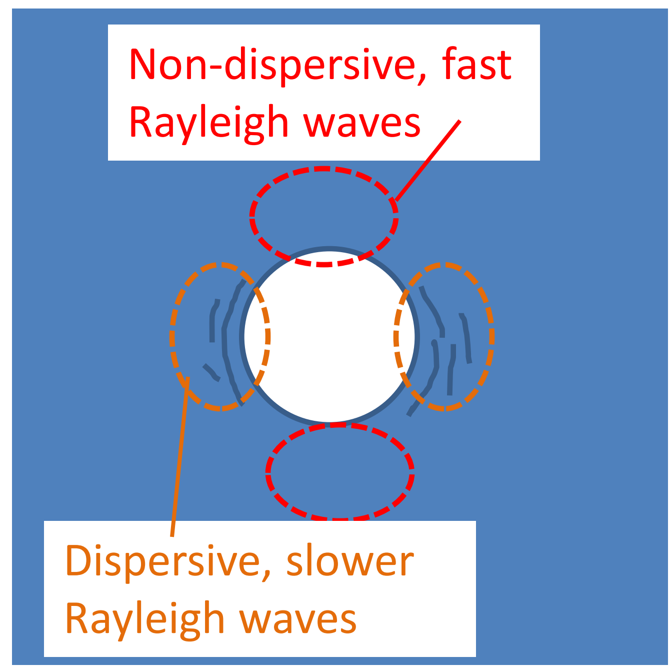


Planned Disturbed Zone Experiments

Geophysics

Damage zone properties should vary along the depth and the length of the borehole. While the borehole wall is still accessible, seismic measurements can be conducted to assess the degree of damage (and possibly permeability) from the wave propagation velocity. The depth of the damage could also be assessed from the dispersion (wave-length [or frequency] dependent changes in the wave velocity) -> Can lead do decision on damage treatment (rock removal)

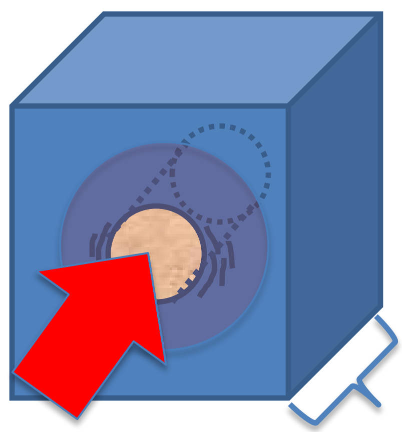




Planned Disturbed Zone Experiments

Hydrogeology

The damage zone is likely to have anisotropic permeability (possibly stress-dependent) providing an enhanced vertical pathway. The magnitude of that enhancement is not known. We propose to measure the permeability enhancement under constant stress and constant chemistry conditions. Changes in chemistry (time dependent), pressures, and permeant (water, hydrogen) can be addressed in the future.



transient quantification of
ΔP vs. flow

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