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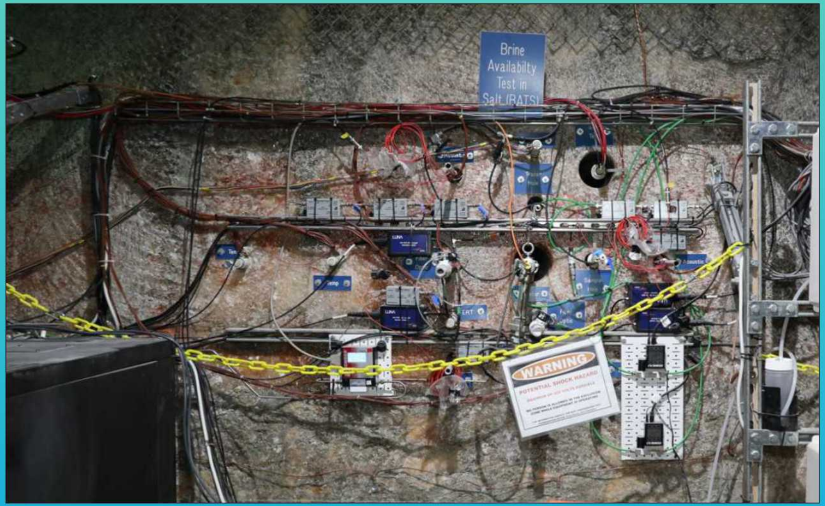
Spent Fuel and Waste Science and Technology (SFWST)

SAND2020-5391PE



Design and Implementation of the Brine Availability Test in Salt (BATS) Heater Test at the Waste Isolation Pilot Plant (WIPP)

SFWD Telecommuting Seminar

May 2020

Kristopher L. Kuhlman
Sandia National Laboratories

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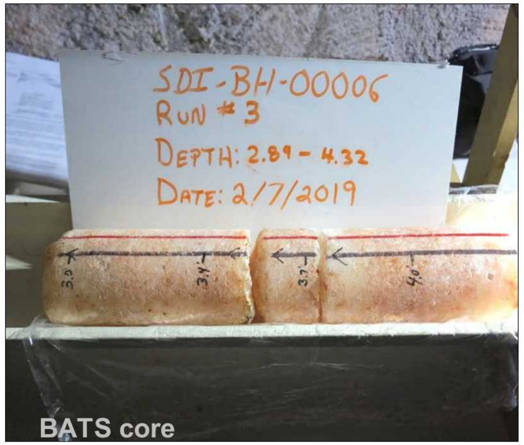
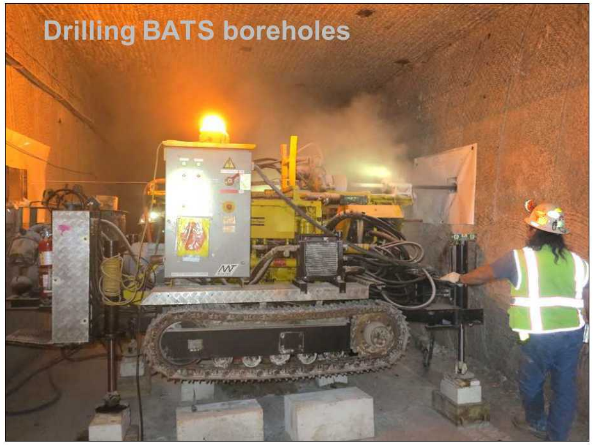
What Are We Doing?

Brine Availability Test in Salt at WIPP (BATS)

Monitoring brine from heated salt using geophysical methods and in-drift analysis or sampling.





Brine Availability Test in Salt (BATS) Team

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BATS is funded by DOE Office of Nuclear Energy (DOE-NE)

WIPP is run by DOE Office of Environmental Management (DOE-EM)

Sandia National Laboratories

Los Alamos NATIONAL LABORATORY EST. 1943

WASTE ISOLATION PILOT PLANT WIPP NWP • DOE • LANL • CTAC • SNL

BERKELEY LAB

Motivation and Background

Why are we doing this?

Motivation

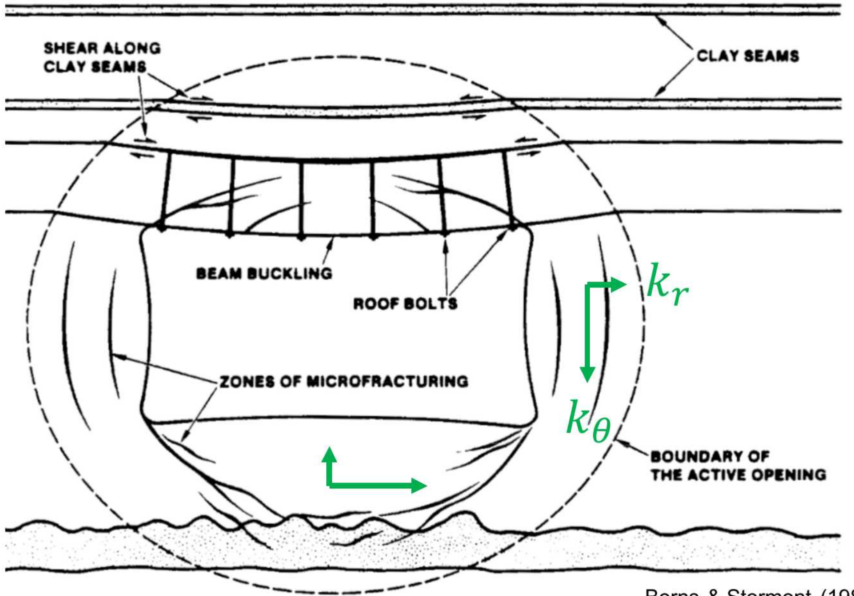
Alpine miner at WIPP

Salt long-term ($10^4 - 10^6$ yrs.) benefits at km-scale

- Low porosity ($\phi \leq 0.1$ vol-%) and permeability ($k \leq 10^{-22}$ m^2)
- High thermal conductivity ($\sim$5 W/(m $\cdot$ K))
- No flowing groundwater (≤ 5 wt-% water)
- Rooms, damage, and fractures will creep closed ($10^0 - 10^2$ yrs.)

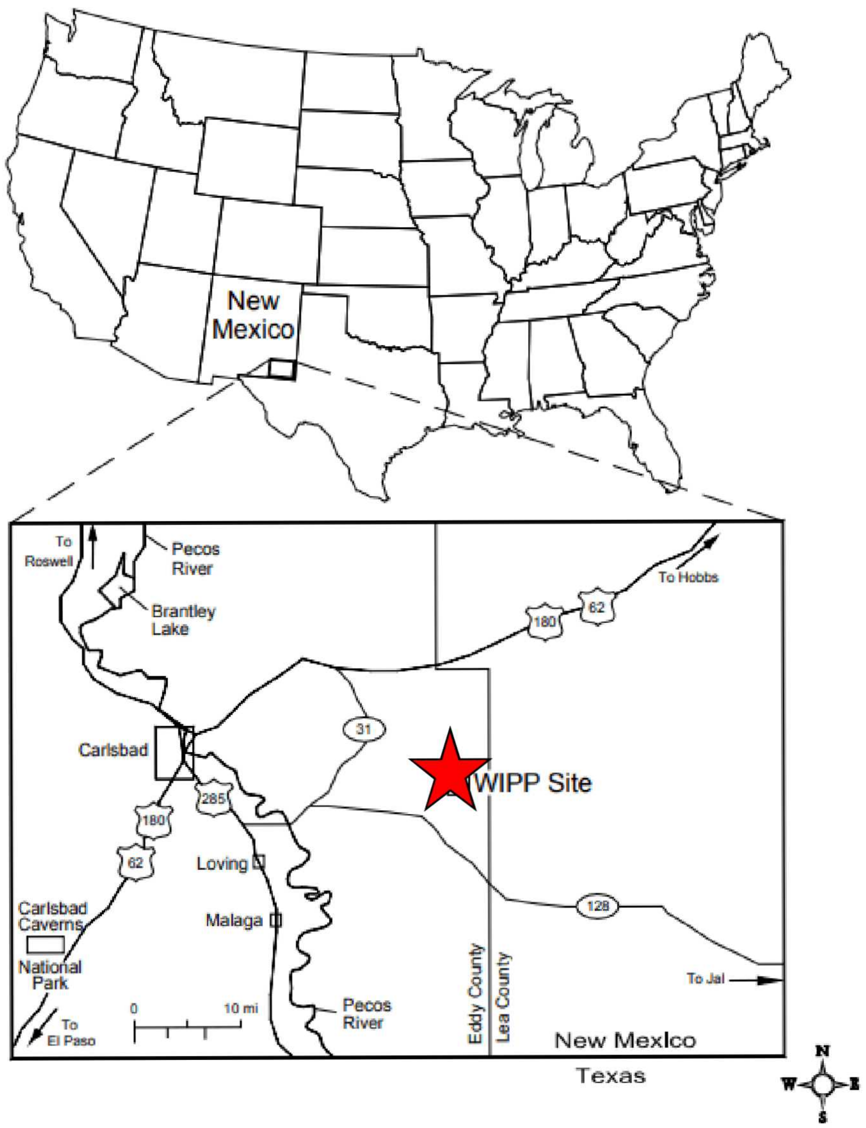
Near-field (cm – 10 m) short-term (hr. – month) complexities

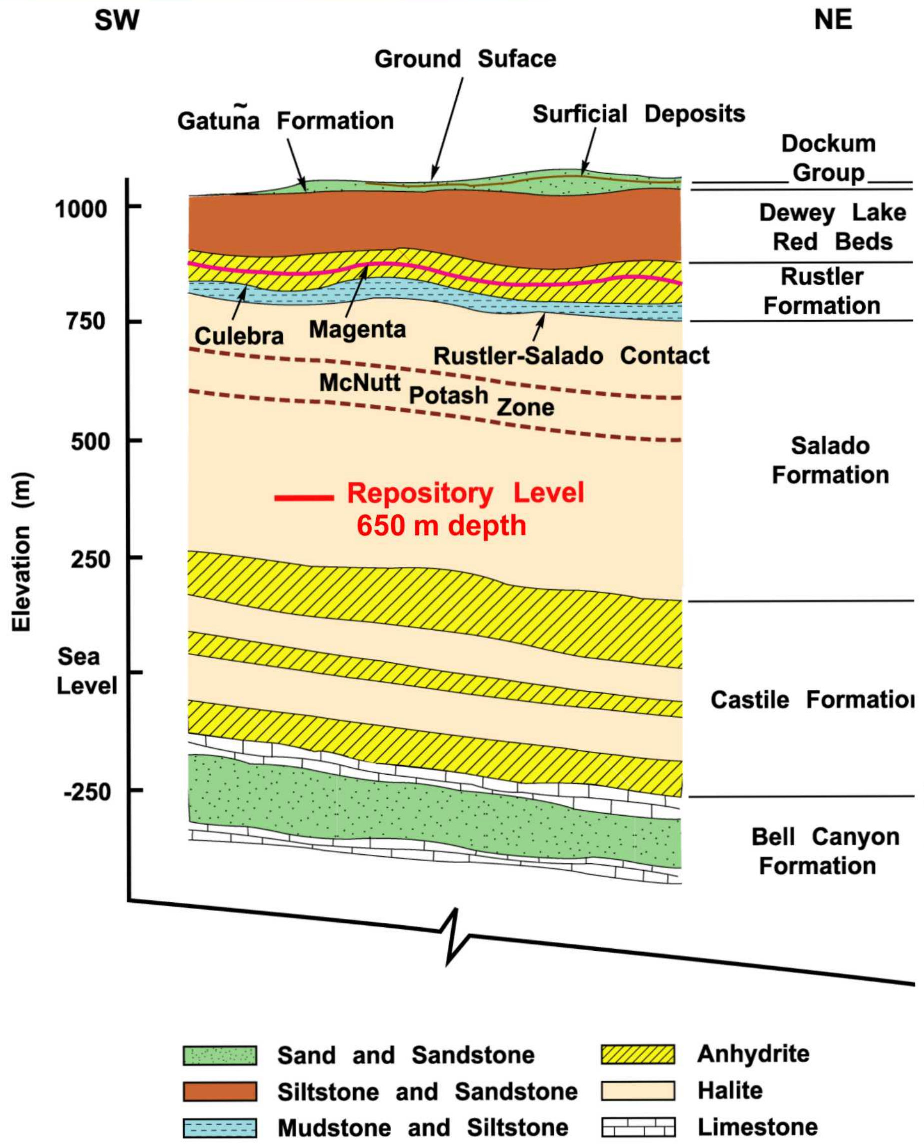
- Brine and salt are corrosive
- Evaporites are very soluble in water
- Salt creep requires drift maintenance
- Excavation Damaged Zone (EDZ):
  - Is main source of ϕ and k near drift
  - May be highly anisotropic ($k_r \ll k_\theta$)
  - Has steep gradients in properties and system state
  - Evolves with stress and temperature

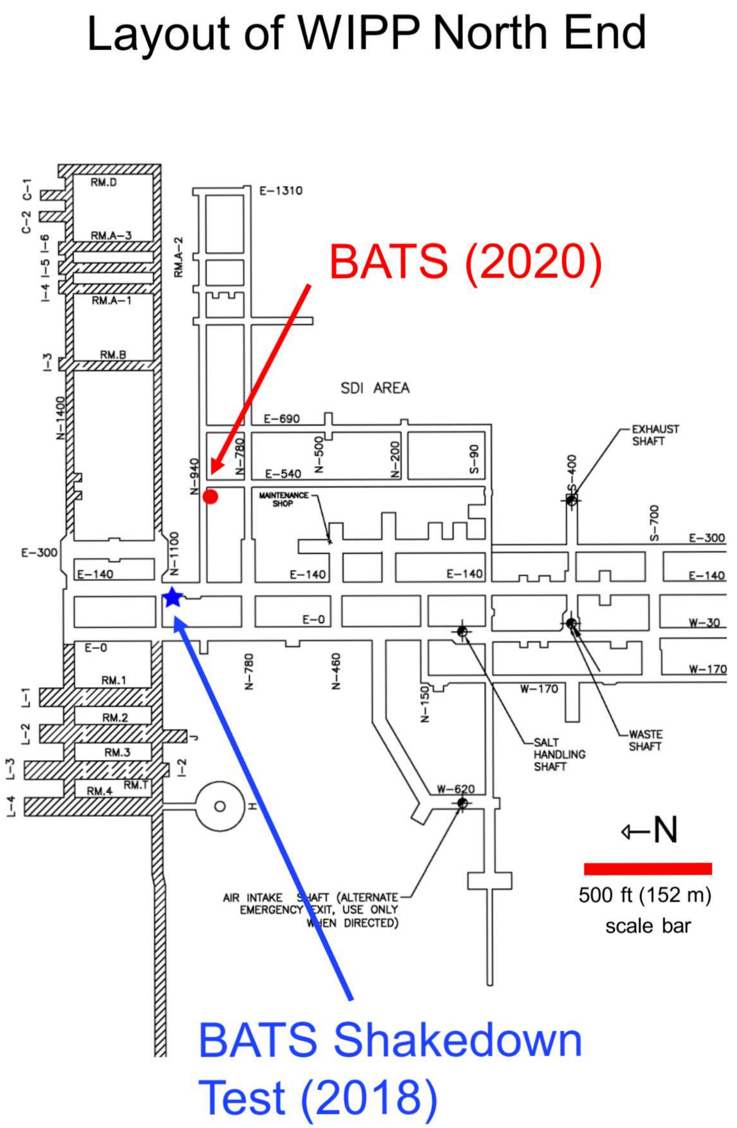


Borns & Stormont (1988)

Waste Isolation Pilot Plant (WIPP) Context







Brine in Bedded Salt

- Water types in bedded salt
  1. Disseminated clay (< 5 vol-% total; ~ 25 vol-% brine)
  2. Intragranular brine (fluid inclusions; $1 - 2$ vol-%)
  3. Hydrous minerals (e.g., polyhalite, bischofite, epsomite)
  4. Intergranular brine (between salt crystals; $<< 1$ vol-%)

- These water types:
  - respond differently to heat & pressure
  - have varying chemical composition
  - differ in stable water isotope makeup

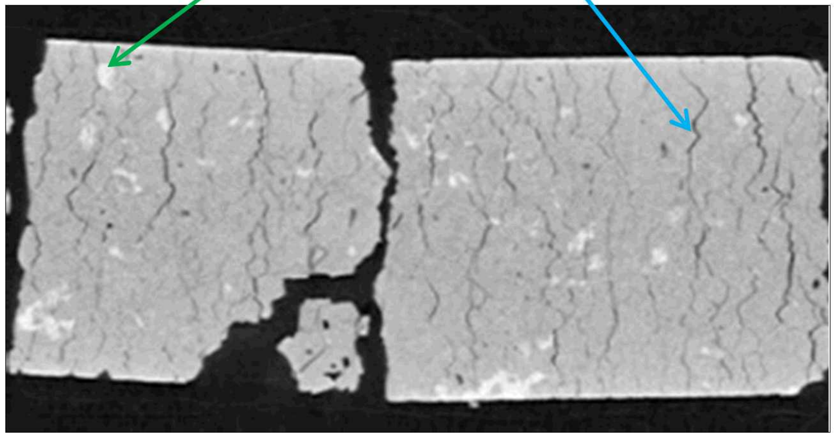
WIPP fluid inclusions, 2 mm scale bar (Caporuscio et al., 2013)

- EDZ increases intergranular $\phi \rightarrow$ primary flow path

How do water types contribute to *Brine Availability?*

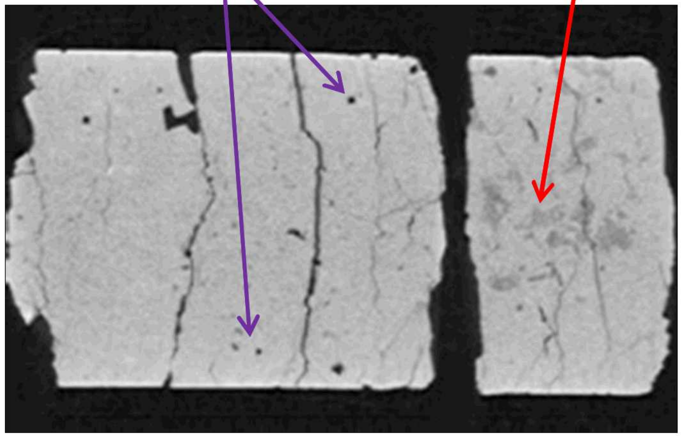
Polyhalite

Intergranular Fractures



Fluid Inclusions

Clay



10.1 cm diameter core CT data (Betters et al., 2020)

Why is Brine Important in a Repository?

Brine Availability: *Brine distribution in salt & how it flows to excavations*

- Initial conditions to post-closure safety assessment
  - Brine migration and re-distribution
  - Evolution of disturbed rock zone (DRZ) porosity and permeability
- Brine causes corrosion of waste package / waste form
- Brine is primary radionuclide transport vector
- Liquid back-pressure can resist drift creep closure


WIPP Room B heated brine migration

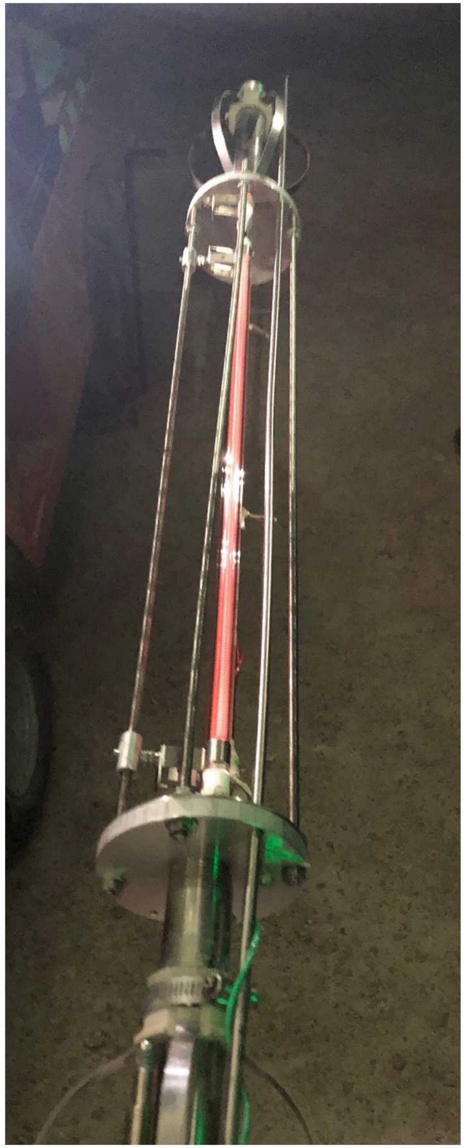

WIPP Room J canister tests


WIPP Room Q brine inflow

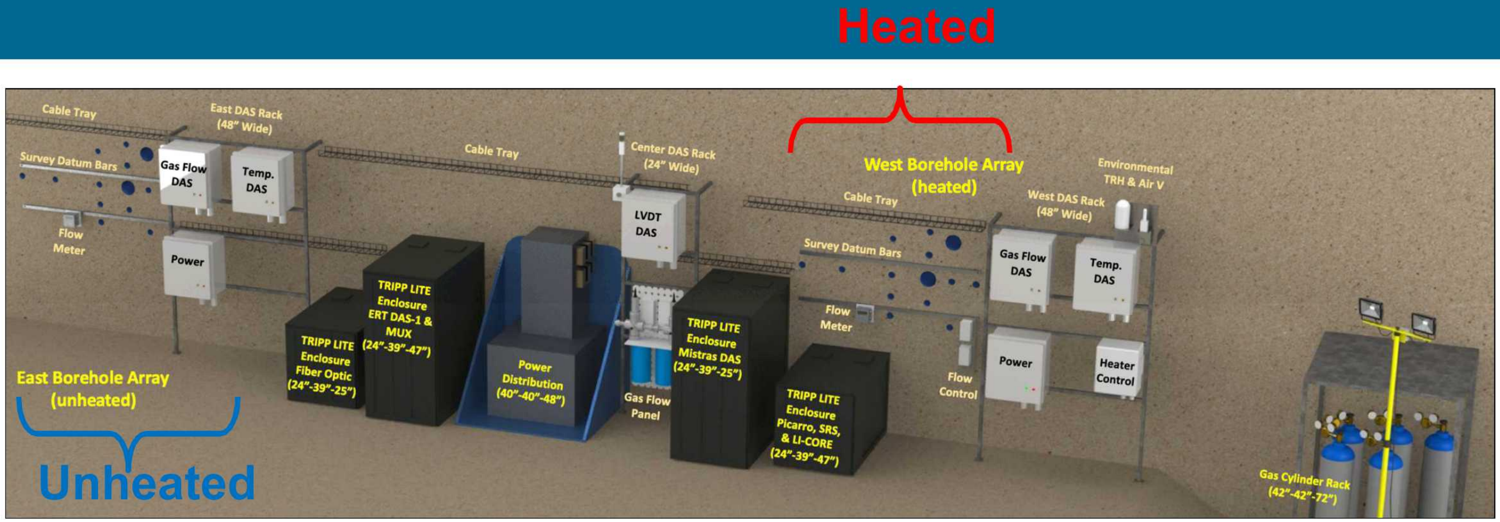

WIPP brine permeability testing

Why Perform a Heated Test?

- Impact heat-generating radioactive waste would have on salt
- How do water types respond to heat
  - Brine & salt thermal expansion
  - Thermal gradient drives fluid inclusions
  - Dry-out of hydrous minerals
- Mechanical response to heating
  - Creep accelerated at higher T
  - Rapid ΔT (up or down) cause damage

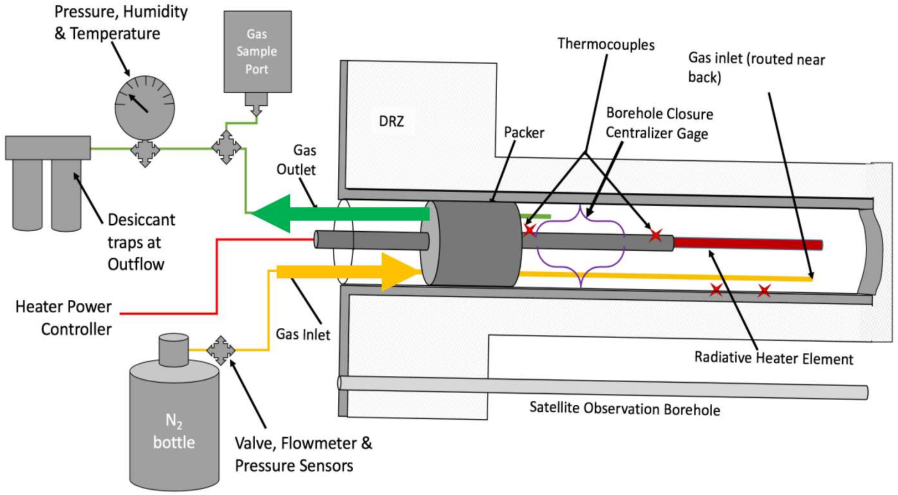


What Data are We Collecting?

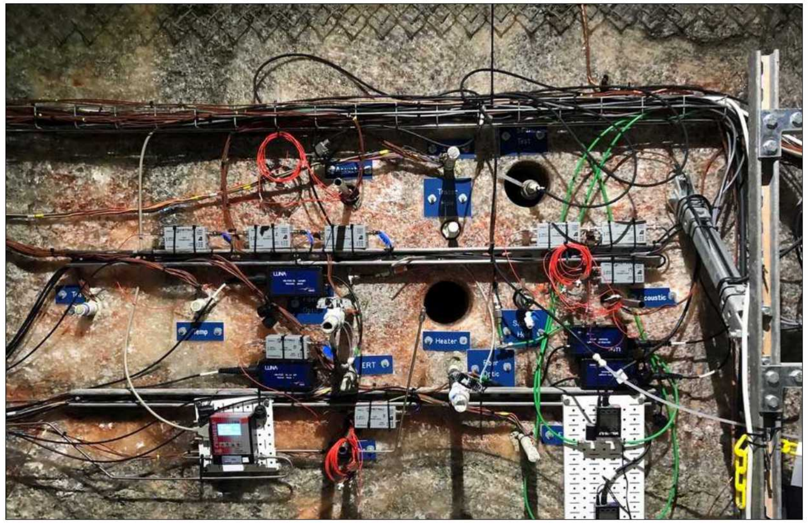


- Two Arrays: Heated / Unheated
- Behind packer
  - Circulate dry N_2
  - Quartz lamp heater (750 W)
  - Borehole closure gage
- Samples / Analyses
  - Gas stream (natural / applied tracers and isotopic makeup)
  - Liquid brine (natural chemistry and natural / applied tracers)
  - Cores (X-ray CT and fluorescence at NETL)
- Cement Seals
  - Sorel cement + Salt concrete: 3-axis strain & temperature
- Geophysics
  - 3 × Electrical resistivity tomography (ERT)
  - 3 × Acoustic emissions (AE)
  - 2 × Fiber optic distributed strain / temperature sensing

Cross-section central borehole



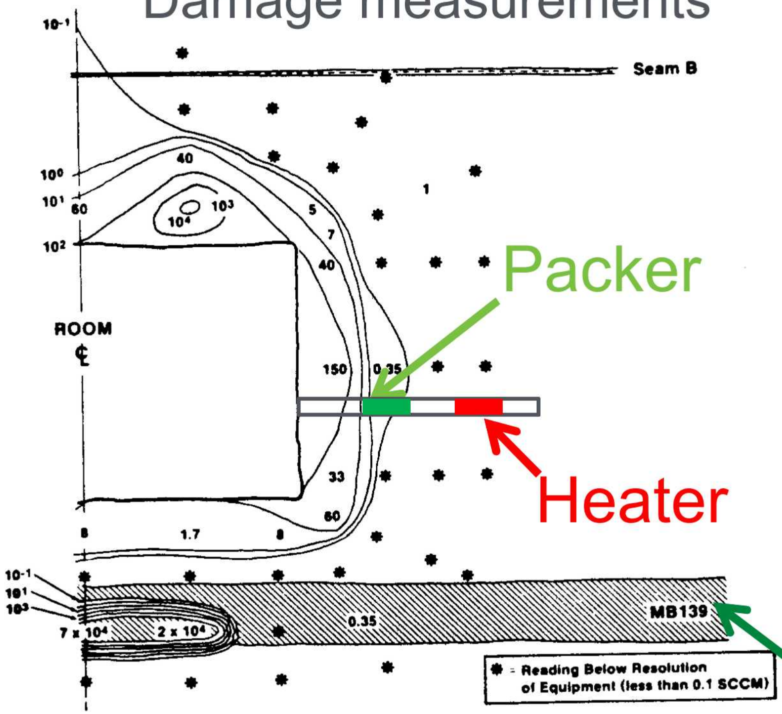
Why are These Data Useful?



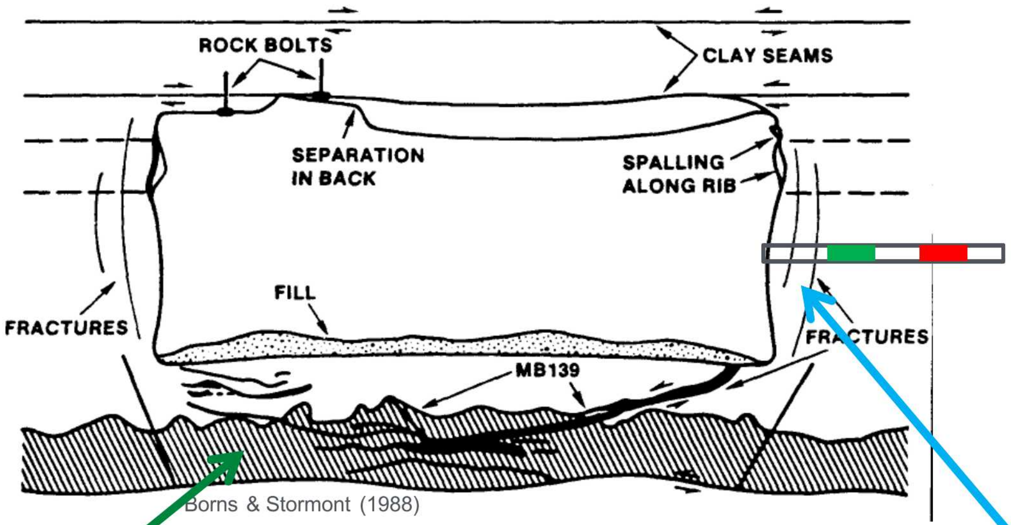
- Brine composition samples / H_2O isotope data
  - Observe change in brine sources with temperature
- Geophysics
  - Evolution of **saturation** / **porosity** / **permeability**
- Temperature distribution
  - More brine at high T (inclusions + hydrous minerals)
  - Thermal expansion brine driving force
  - Salt dry-out near borehole (above boiling)
- Gas permeability and borehole closure
  - Thermal-hydrological-mechanical (THM) evolution of salt
- Tracer migration through salt
  - Monitor brine movement through salt damage zone

Why use Horizontal Boreholes with Packers?

Damage measurements



Disturbed Rock Zone (DRZ)



BATS borehole

Near-drift vertical fractures

Anhydrite layer below floor

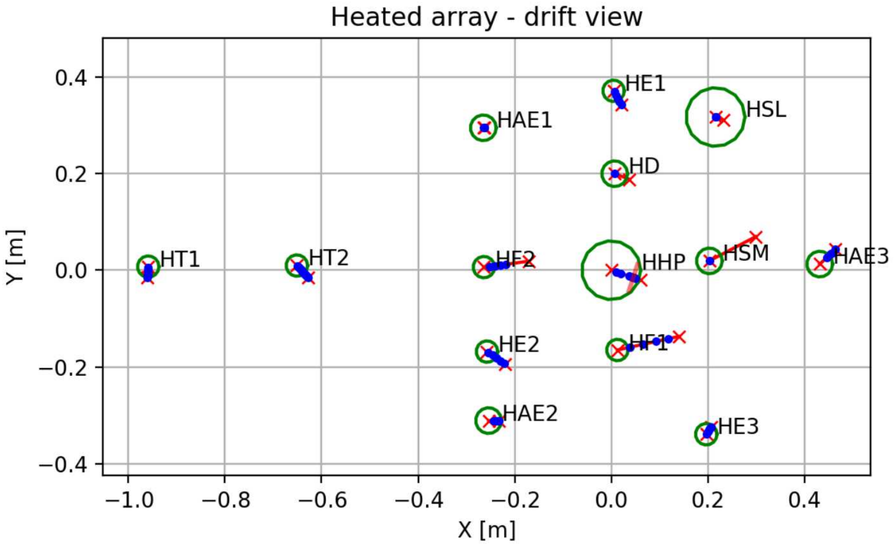
We want to characterize DRZ, avoiding most damaged areas

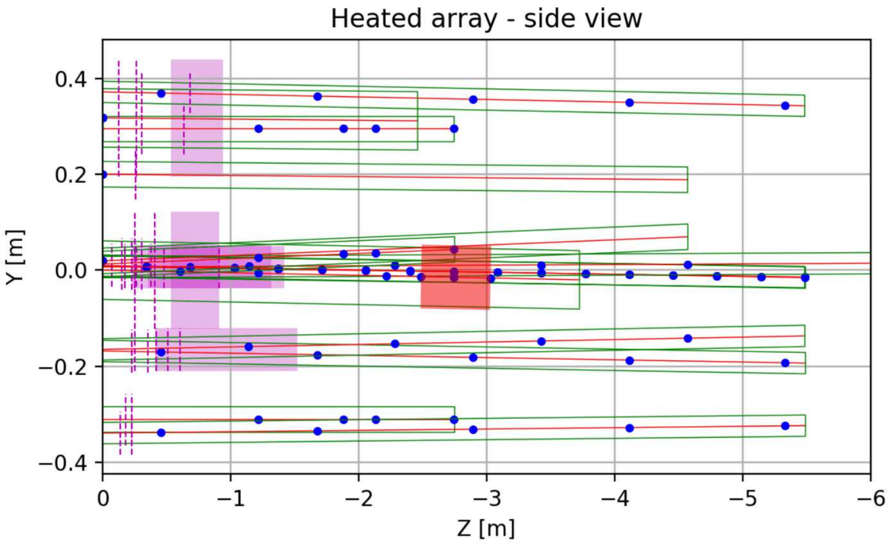
- *Horizontal borehole* avoids clay & anhydrite layers (e.g., MB139) in floor
- *Inflatable packer* isolates heater from near-drift vertical fracutres

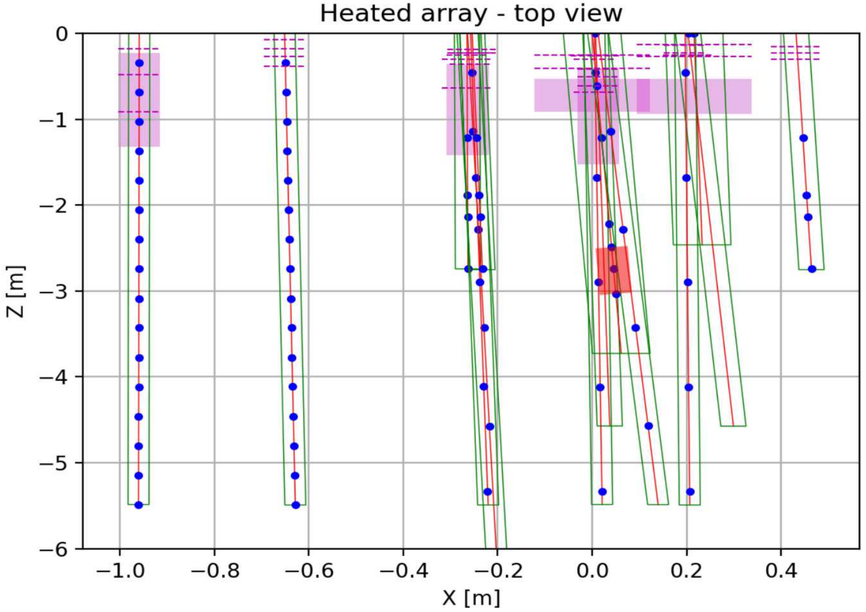
Test Description

What types of data are we collecting?

BATS Boreholes As-Built



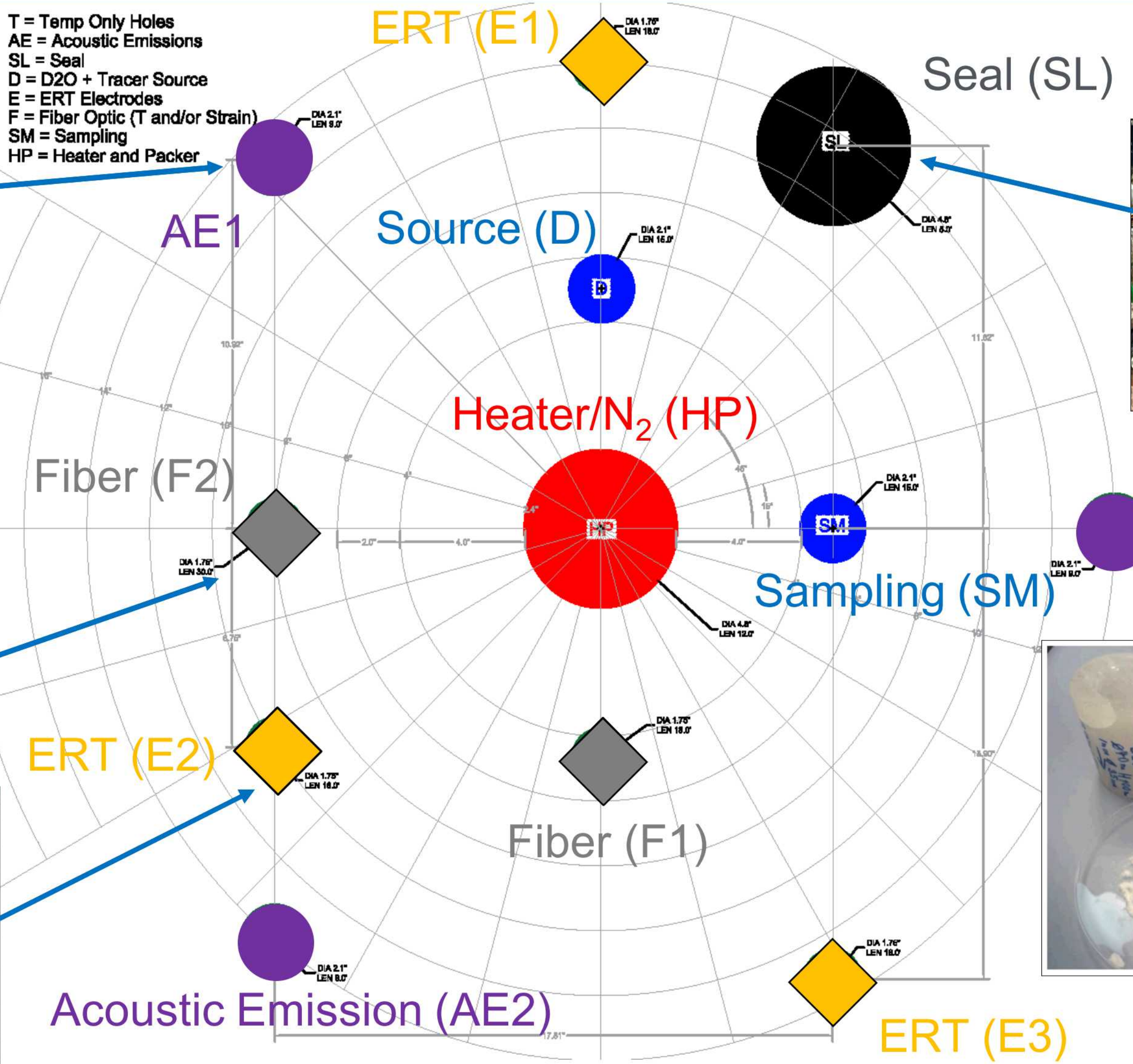




- Heated array as-built
- Drilled Feb-Apr 2019
- Side/ top view shows
  - Thermocouples (blue dots)
  - Heated interval (red box)
  - Fractures/damaged zone (purple)

Discrete fractures in BATS near-drift EDZ

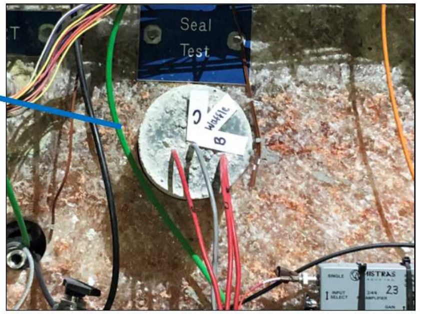
BATS Borehole Arrays



Diamonds = grouted

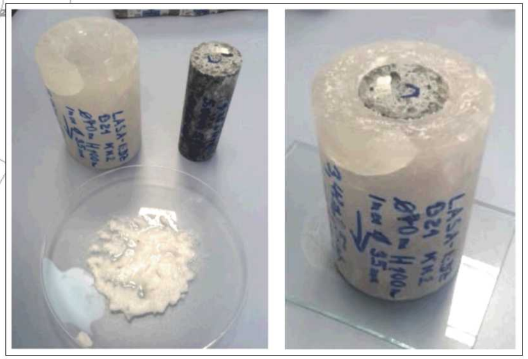
Circles = not grouted/packer

Lab-made seal installed in borehole subsequently sealed behind packer



Field (BATS)

Lab (GRS)



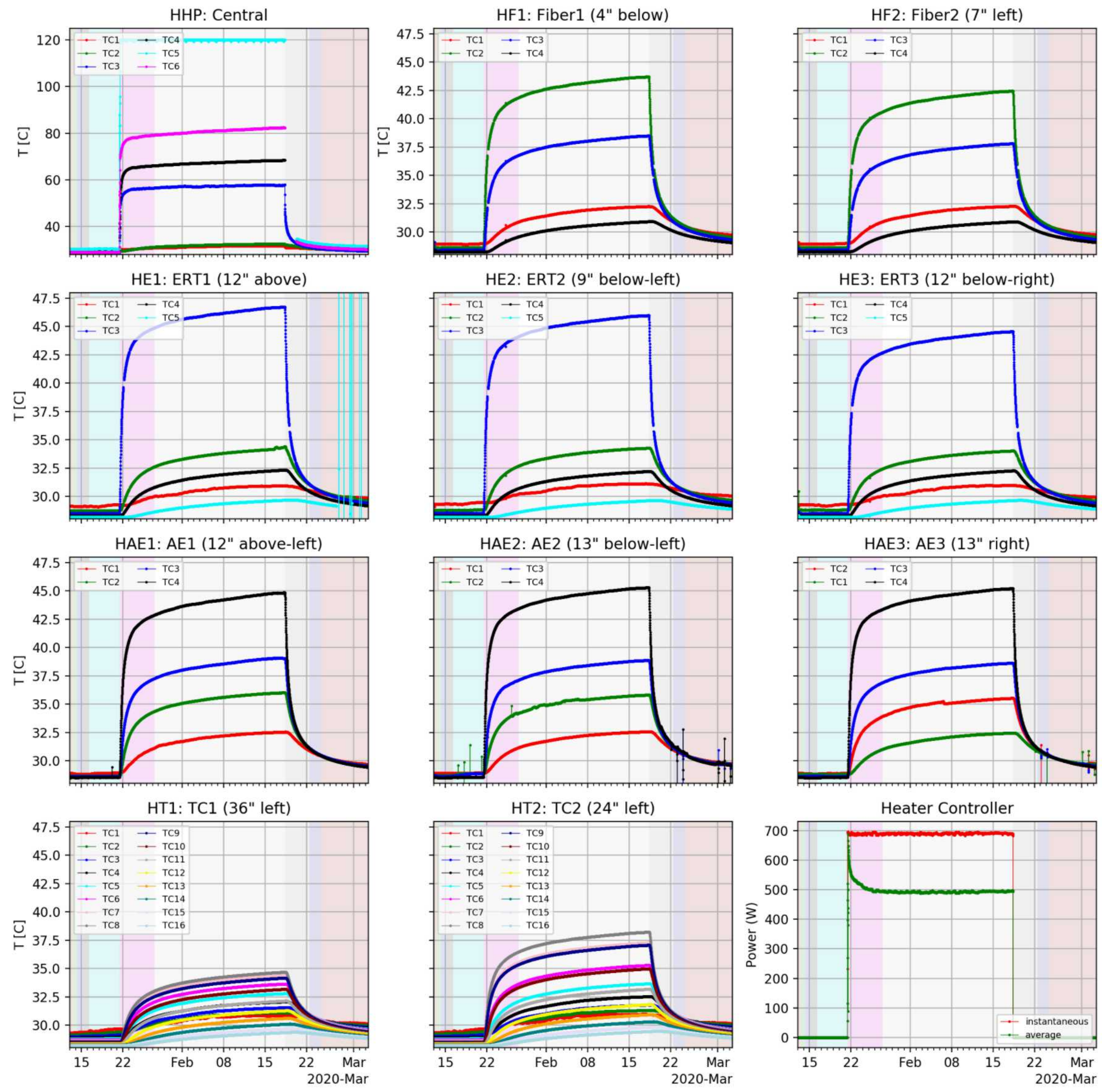
Czaikowski et al. (2016)

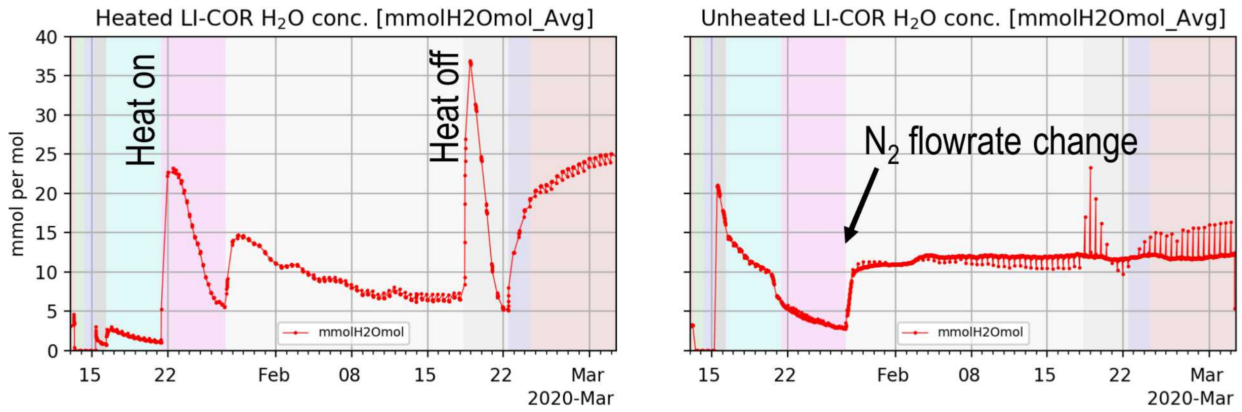
Fiber optic DSS/DST

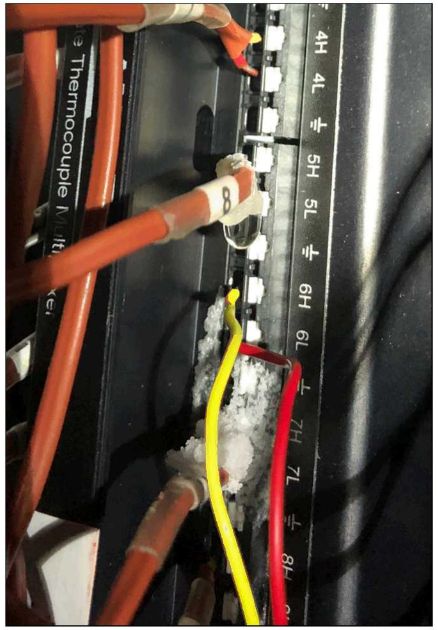
ERT controller

(Borehole layout drawing by WIPP TCO)

Temperature Data (Heating phase 1)







Lesson: Brine can seep through thermocouple wires!

Brine Inflow (strong THM coupling)

Gas flowrate + humidity

Brine inflow to boreholes

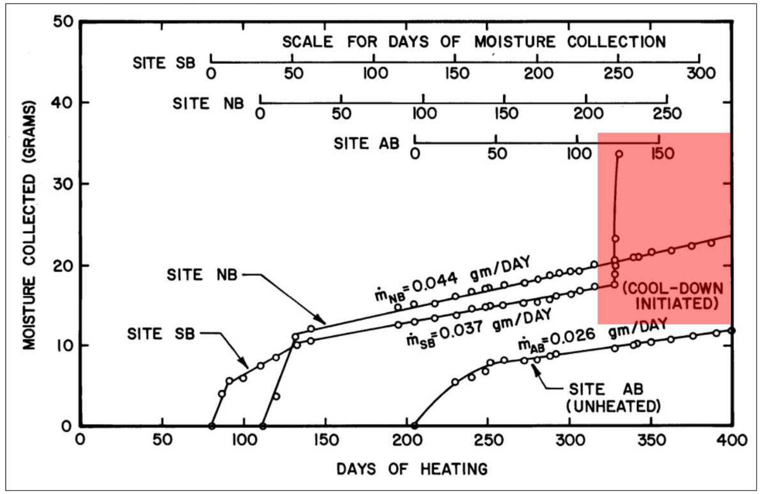
- Highest inflow rate initially
- Exponential decay with time

Brine inflow *jumps* at $\pm\Delta T$

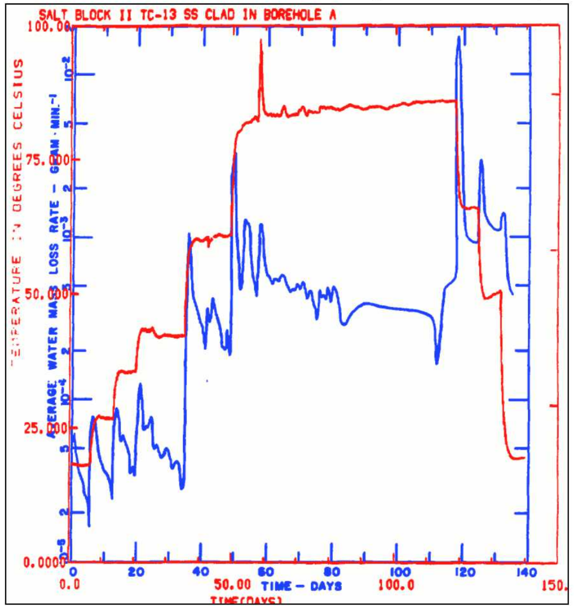
Permeability in DRZ from fractures

- Fractures are stress-sensitive
- Thermal expansion changes stress
- Permeability changes with temperature
- ➜ Thermal pressurization
- ➜ Release of brine at cooling

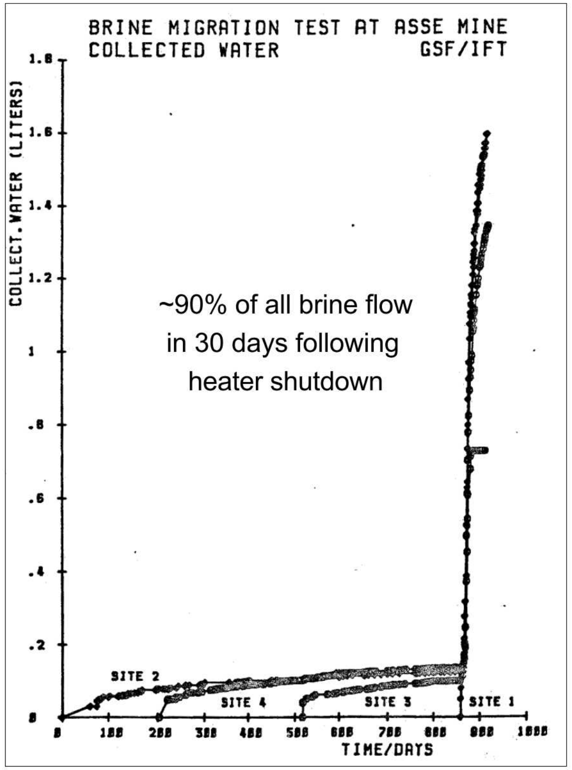
Avery Island (Krause, 1983)



1-m bedded salt lab test (Hohlfelder, 1979)

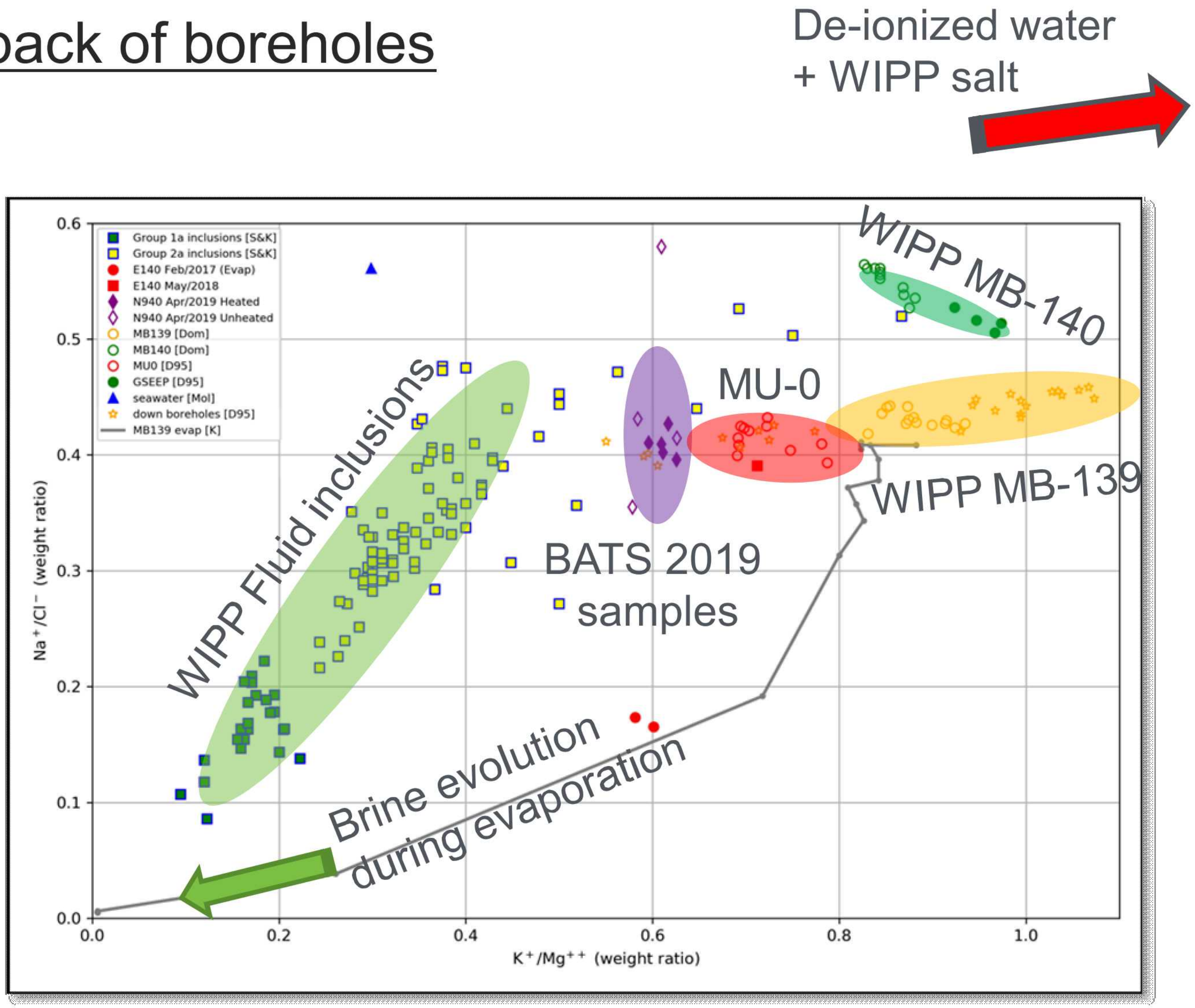


Asse (Rothfuchs et al., 1988)



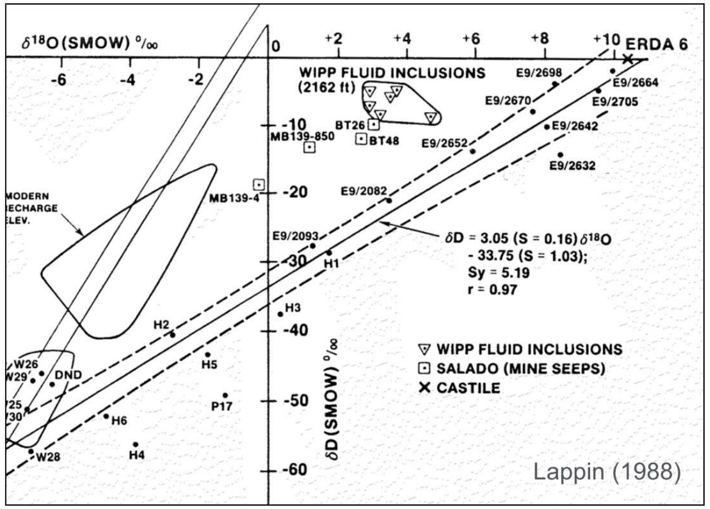
Brine Composition

- <u>Liquid brine samples vacuumed from back of boreholes</u>
- Distinguish sources of water in salt?
  - Not all brine is same composition
  - Different formations at WIPP
  - “Natural” brine vs. dissolved salt
- Add / monitor liquid tracers
  - Perrhenate ($NaReO_4$)
  - Blue fluorescent dye
  - Isotopically distinct H_2O
- <u>Data will inform:</u>
  - Contribution of 3 brine types (brine)
  - Advection / diffusion / reaction (tracers)

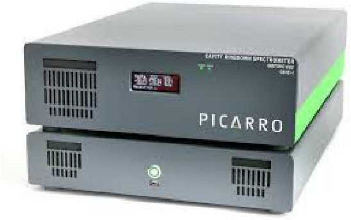


Gas Stream Water Isotope Composition

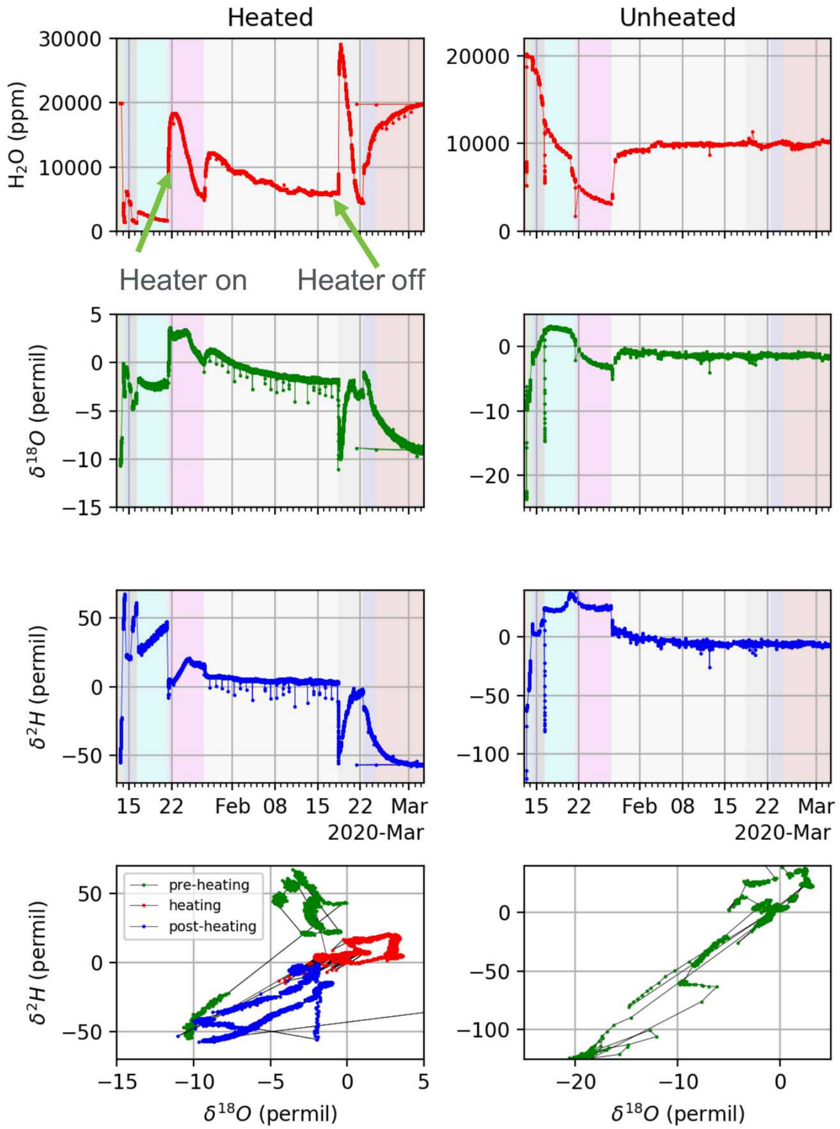
- <u>Continuously analyze gas stream</u>
- Isotopic makeup of humidity stream
  - Info on brine source (fluid inclusions vs. clays)
  - When is there a puddle in back of borehole?
- <u>Data will inform:</u>
  - Isotopic identification of 3 brine types
  - Advection / diffusion / reaction (water as a tracer)



Lappin (1988)

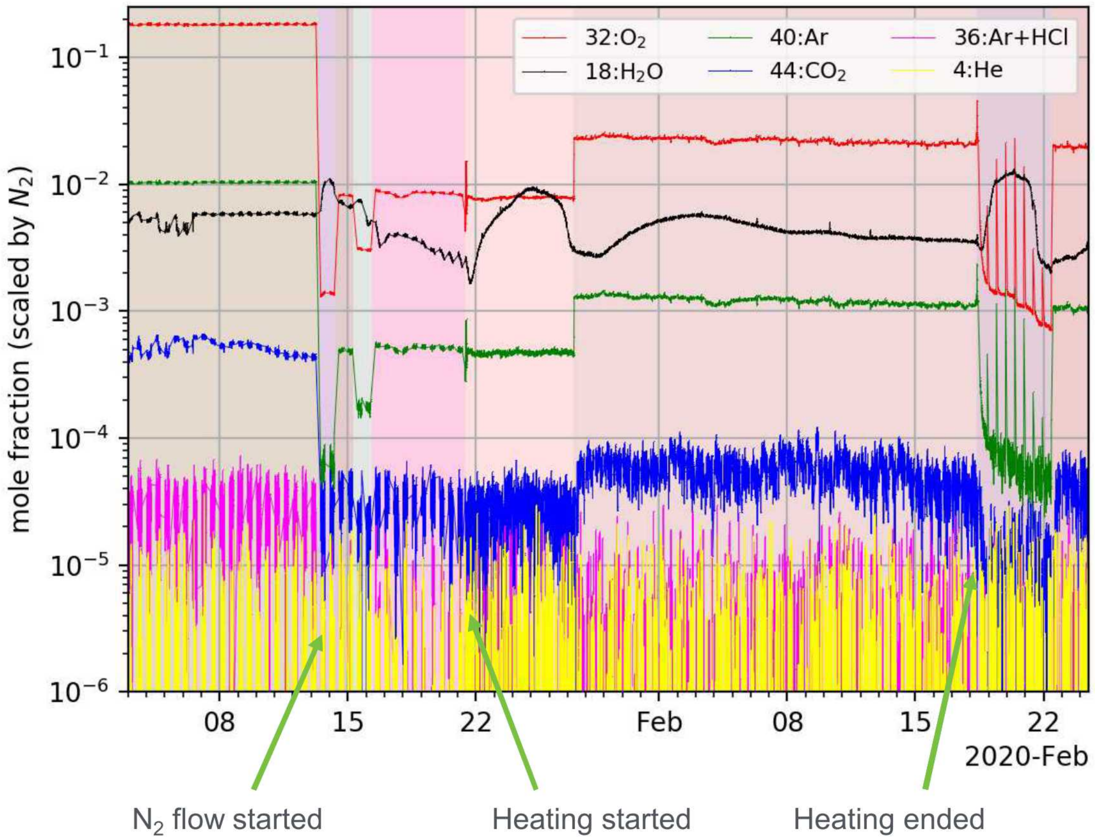


Picarro cavity ringdown Spectrometer (CRDS)



Gas Stream Composition

- <u>Continuously analyze gas stream</u>
- Gases may come from
  - Dissolved in brine
    - Less soluble in lower pressure, hotter brine
  - Sorbed to salt (CO_2)
  - Geogenic gases within salt (e.g., He & Ar)
  - Added gas tracers (Ne, Kr & SF_6)
- <u>Data will inform:</u>
  - Gases produced from heating salt
  - Leakiness of packer system
  - Advection / diffusion /reaction (tracer)



SRS quadrupole mass spectrometer (QMS) gas analyzer

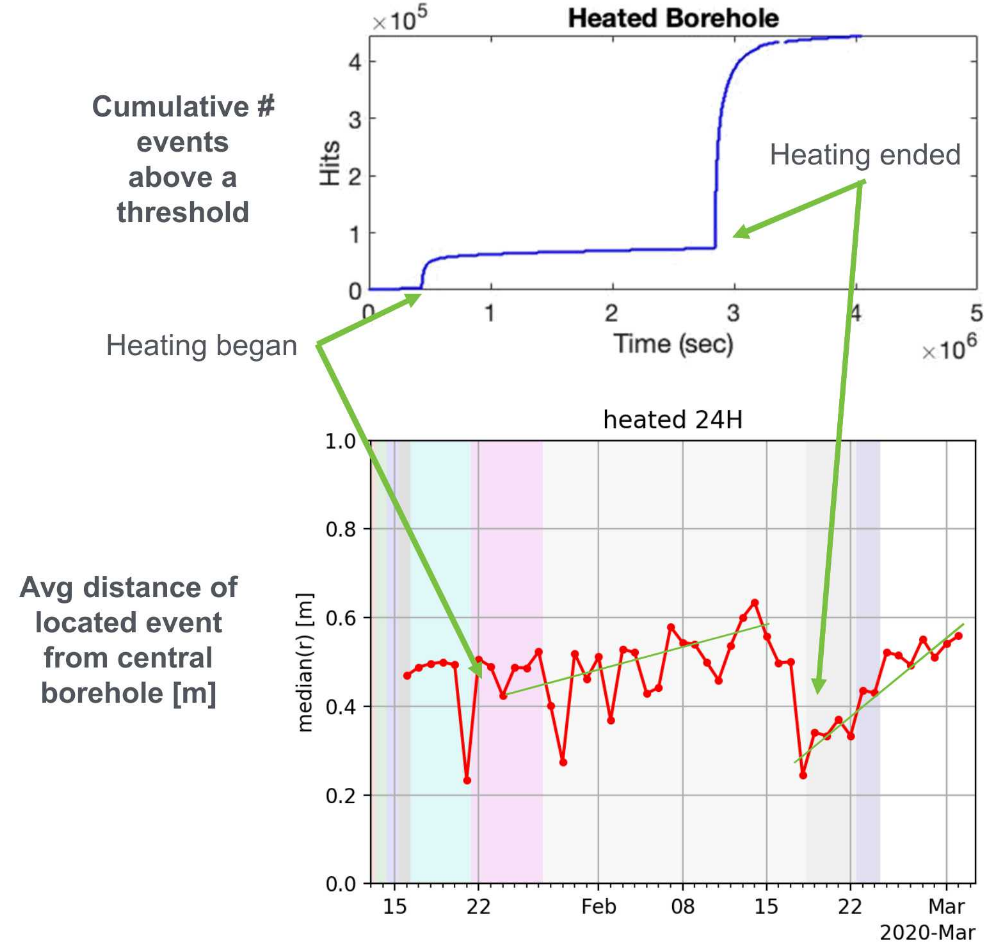
Acoustic Emissions (AE)

<u>Listen to salt with piezoelectric transducers</u>

Passive AE

- Salt cracking during heat up & cool-down
- Triangulate AE sources around heated borehole
- AE correlated with permeability increases

- Active AE
  - “Ping” sensors while listening
  - Lower velocity in damaged rock
  - Difficult to hear in ambient noise
- <u>Data will inform:</u>
  - Where & when damage occurs
  - Estimate damage extent
  - Monitor damage evolution

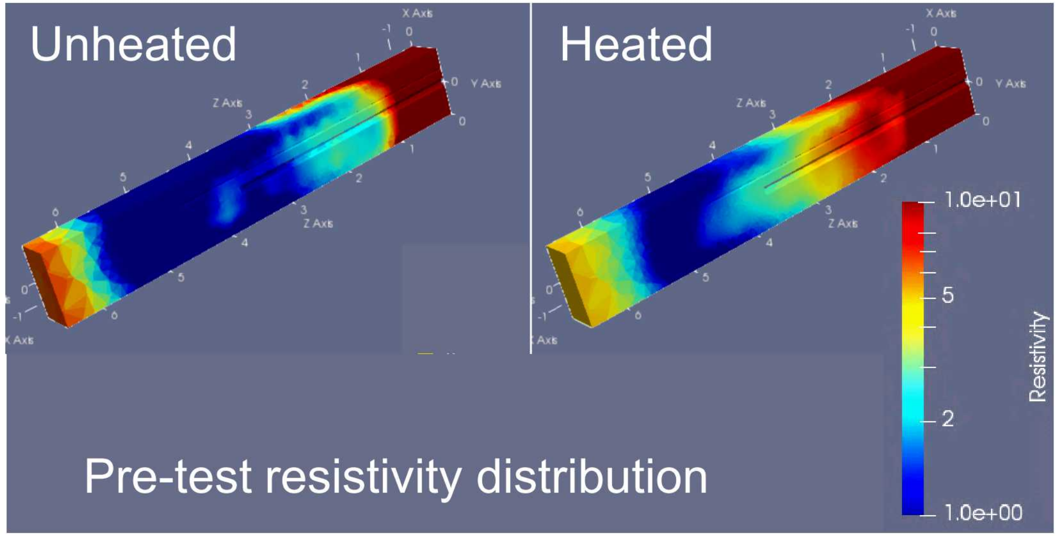


Decentralizers and piezoelectric transducers

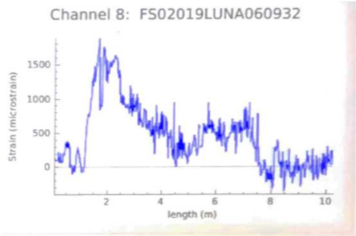
Electrical Resistivity Tomography (ERT) and Fiber Optics

ERT: Measure voltage from applied current at every electrode pair

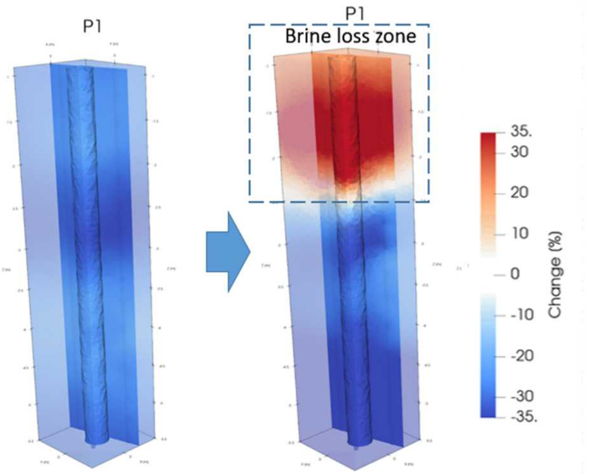
- Multiple AC frequencies (1-10 Hz)
- Electrodes grouted into boreholes
- Data will inform evolution of brine content (i.e., dry-out)



- Fiber-optic distributed sensing
  - Scattering in grouted fiber-optics
  - Measure temperature and strain
    - Sub-mm resolution in space
    - 1 Hz resolution in time
  - Fiber is delicate!

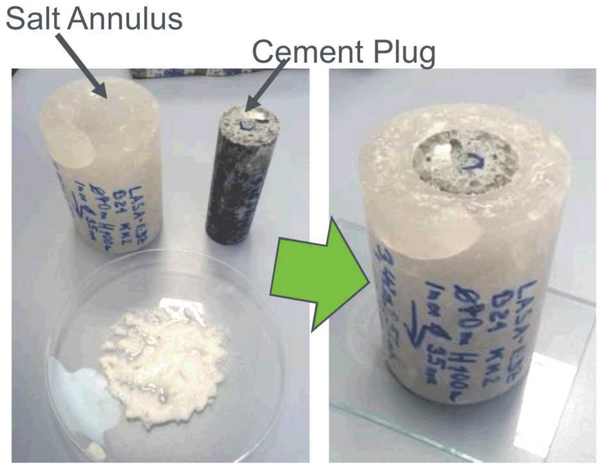


Change in resistivity from heating

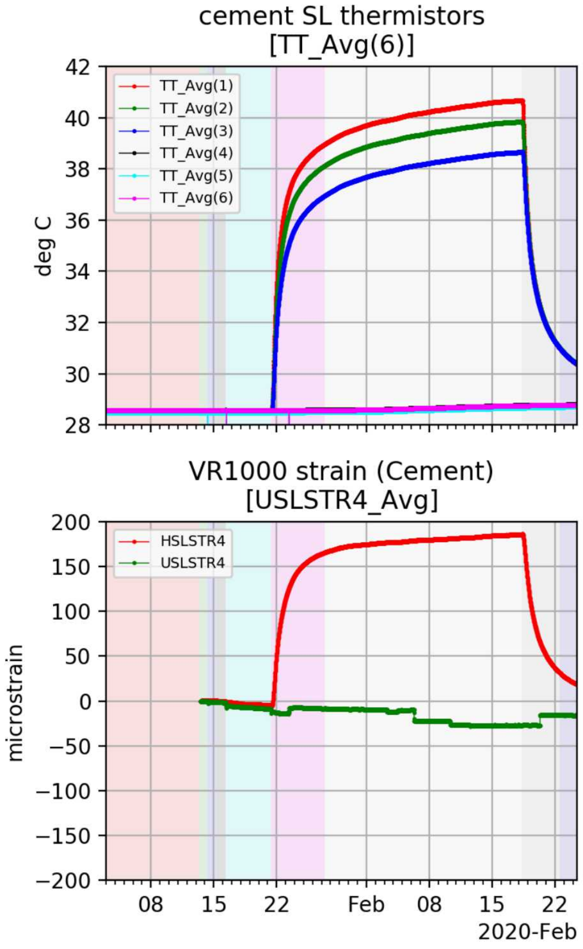


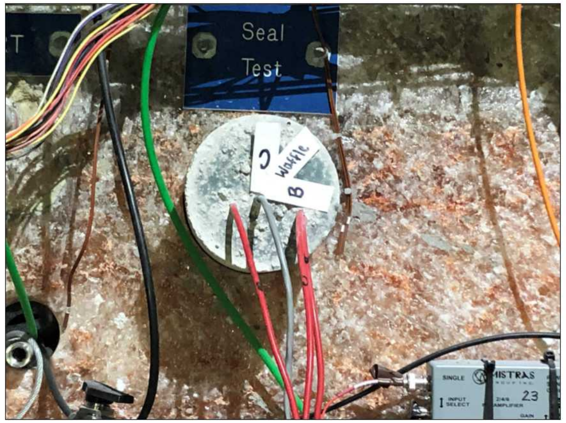
Cementitious Seals

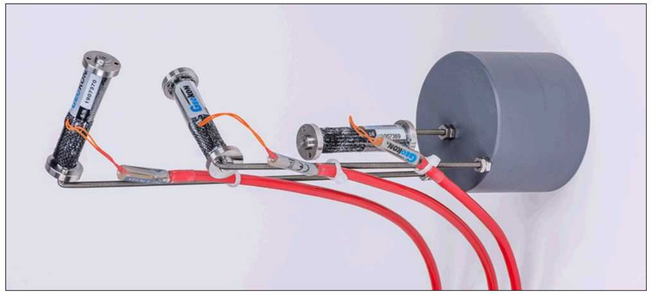
- Emplace pre-fabricated cement plug
  - Snug fit into satellite borehole
  - Monitor seal evolution as borehole closes
  - Strain gages inside plugs
  - Upscale Lab Seals Tests
- Compare:
  - Sorel cement (MgO) and salt concrete plugs
  - Heated and unheated conditions
- Observe salt / brine / cement interactions



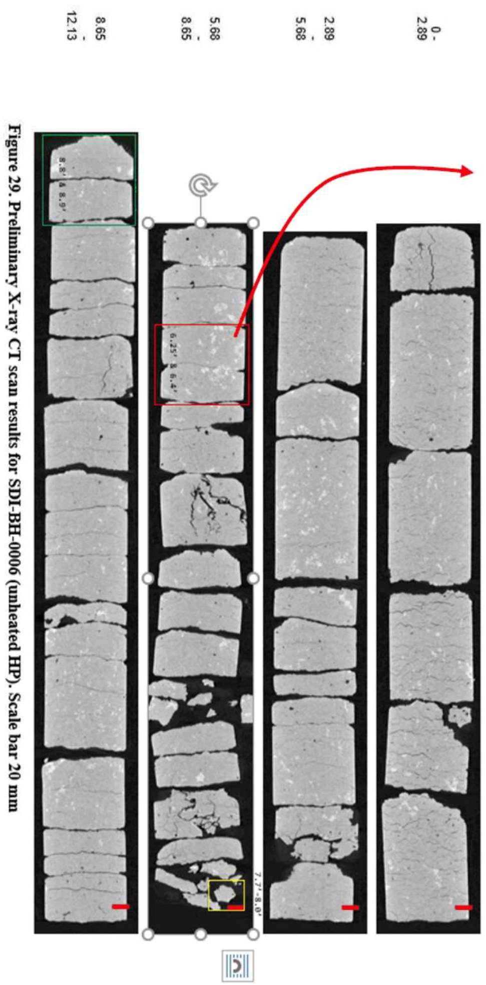
Czaikowski & Wieczorek (2016)



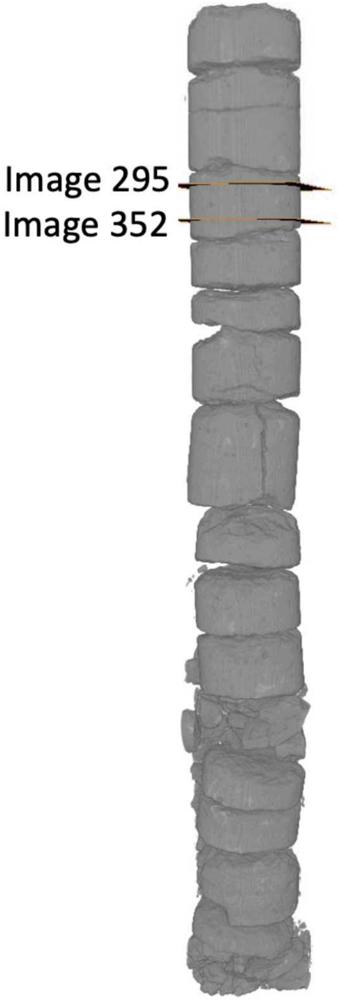




X-Ray CT Data

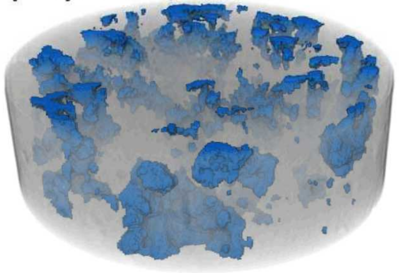


Medical CT, 0077H

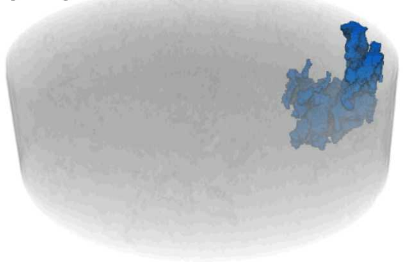


ilastik, simple segmentation
Pergeos, visualization and vol. fractions

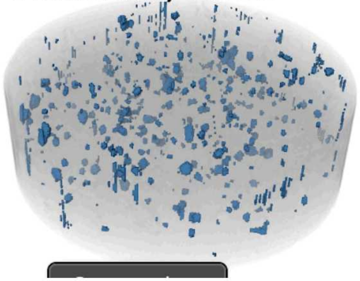
polyhalite, 8.58%

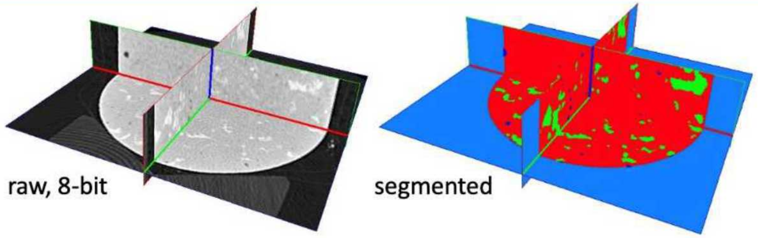


polyhalite, z-connected

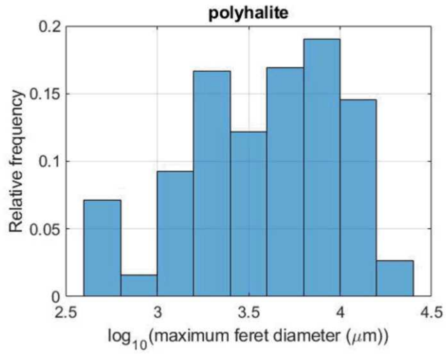


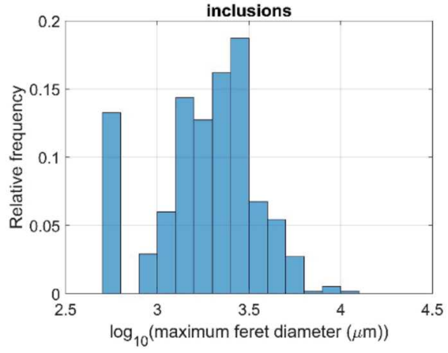
inclusions, 0.58%





Volume fractions (no breaks in core)
inclusions, 0.58% (dark blue)
halite, 90.83% (red)
polyhalite, 8.58% (green)



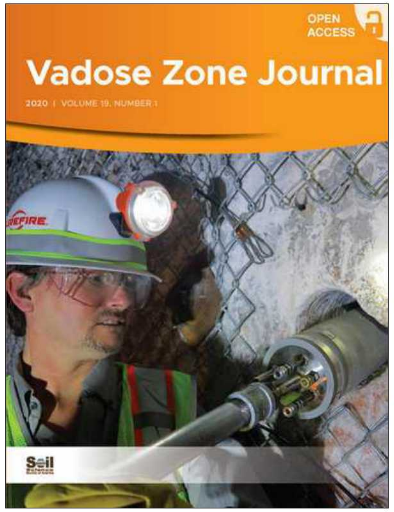


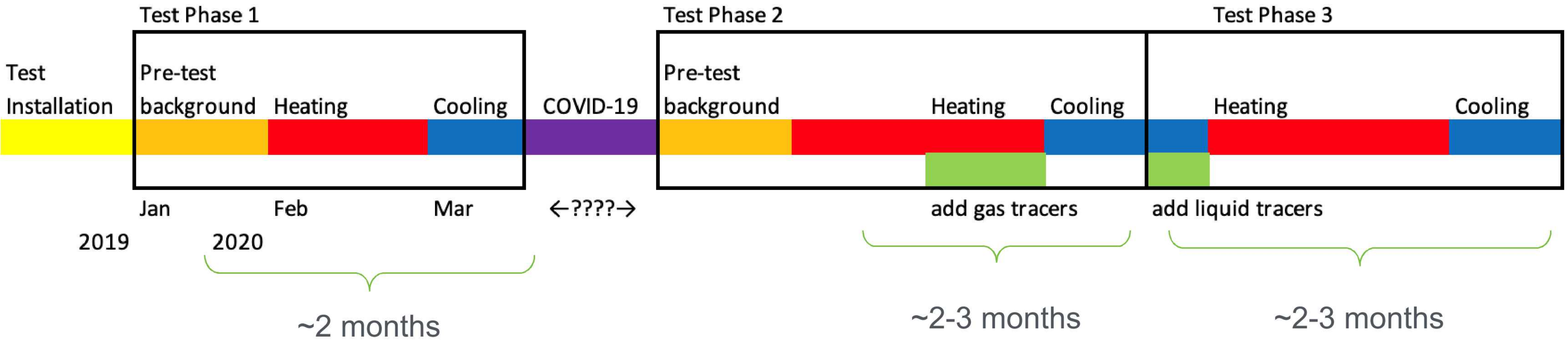
Looking to the Future

What is next?

Test Status

- Boreholes drilled (Feb-Apr 2019)
- Installed instrumentation (May-Aug 2019)
- Plumbed and wired experiment (Aug-Oct 2019)
- Currently in COVID-related shutdown
- First BATS publication: Vadose Zone Journal (Apr 2020)
  - "Temperature response and brine availability to heated boreholes in bedded salt"





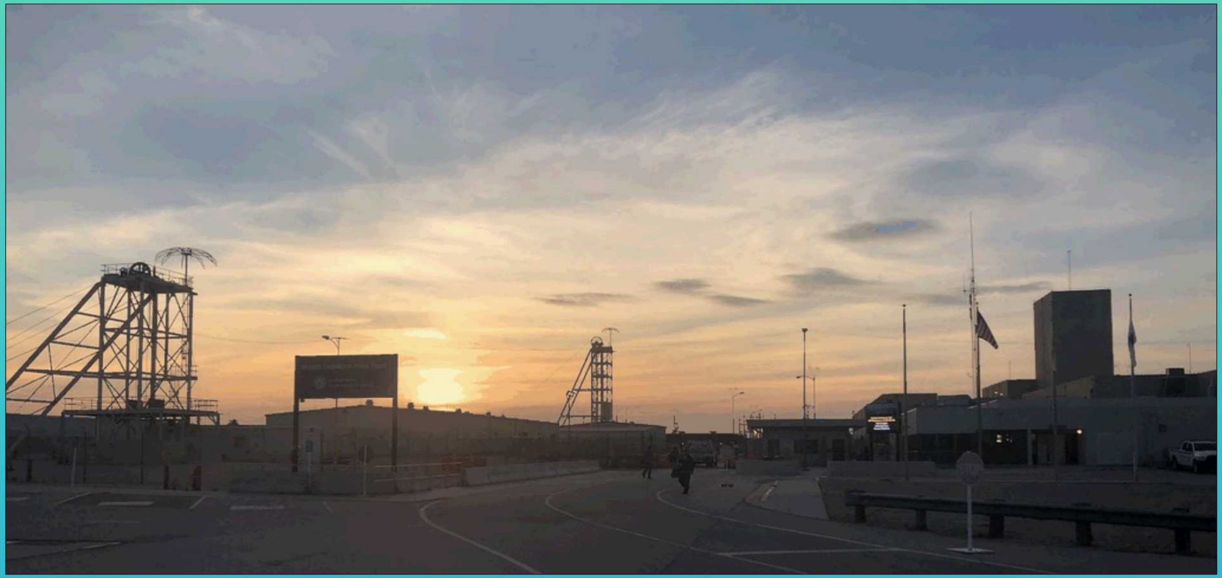
DECOVALEX 2023 BATS Collaboration

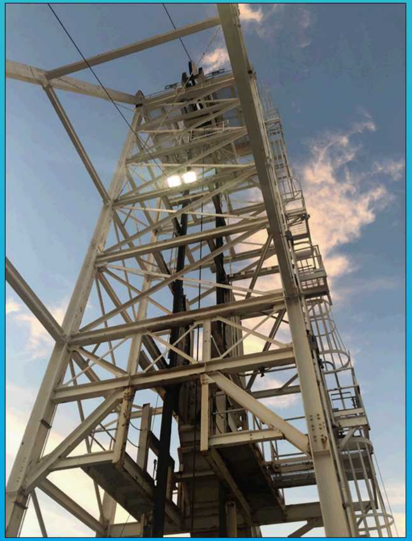
- ***DE**velopment of **CO**upled models and their **VAL**idation against **EX**periments*
- Current DECOVALEX phase 2020-2023 (decovalex.org)
  - Began in 1992, previous phase was 2015-2019
- BATS Task is 1 of 7 (Task E)
  - Uncertainty quantification & model sensitivity, while building complexity
  - Thermal / hydro ➜ Thermal Hydro Mechanical (THM) ➜ THM + Chemistry
- Participating teams:
  - US (Sandia, Los Alamos, Lawrence Berkeley national labs),
  - Germany (GRS, BGR),
  - Netherlands (COVRA),
  - UK (Quintessa/RWM)

Summary / Looking Forward

- Design and Implementation of field experiment at WIPP
  - Some unexpected problems (electronics + brine = bad)
  - More brine in places than expected (brine in thermocouple wires)
  - Less brine in other places than expected (small liquid samples ~few mL)
- COVID-19 shutdown
  - Won't restart test until consistent access is assured
  - Time to reconsider data acquisition / repair instruments
- Looking forward to next tests
  - More tests in existing boreholes (tracer tests, permeability $f(T)$)
  - Next set of boreholes in a different map unit
- International collaborations increase project impact

Thank you!





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Acronyms and Initialisms

AE	acoustic emissions
BATS	brine availability test in salt
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe
COVRA	Centrale Organisatie Voor Radioactief Afval
CT	computed tomography
DECOVALEX	DEvelopment of COupled models and their VALidation against Experiments
DOE	Department of Energy
DOE-EM	DOE Office of Environmental Management (energy.gov/em)
DOE-NE	DOE Office of Nuclear Energy (energy.gov/ne)
DRZ	disturbed rock zone
DSS, DTS	distributed strain, temperature sensing
EDZ, EdZ	Excavation Damaged Zone, Excavation disturbed Zone
ERT	electrical resistivity tomography
GRS	Gesellschaft für Anlagen- und Reaktorsicherheit
LANL	Los Alamos National Laboratory
LBL	Lawrence Berkeley National Laboratory
NETL	National Energy Technology Laboratory
RWM	Radioactive Waste Management
SFWST	Spent Fuel and Waste Science & Technology (DOE-NE program)
SNL	Sandia National Laboratories
TCO	WIPP Test Coordination Office (LANL)
TH^2MC	thermal, two-phase hydrological, mechanical, and chemical (also TH^1, TH^2M, TH^2C)
WIPP	Waste Isolation Pilot Plant (DOE-EM site, wipp.energy.gov)