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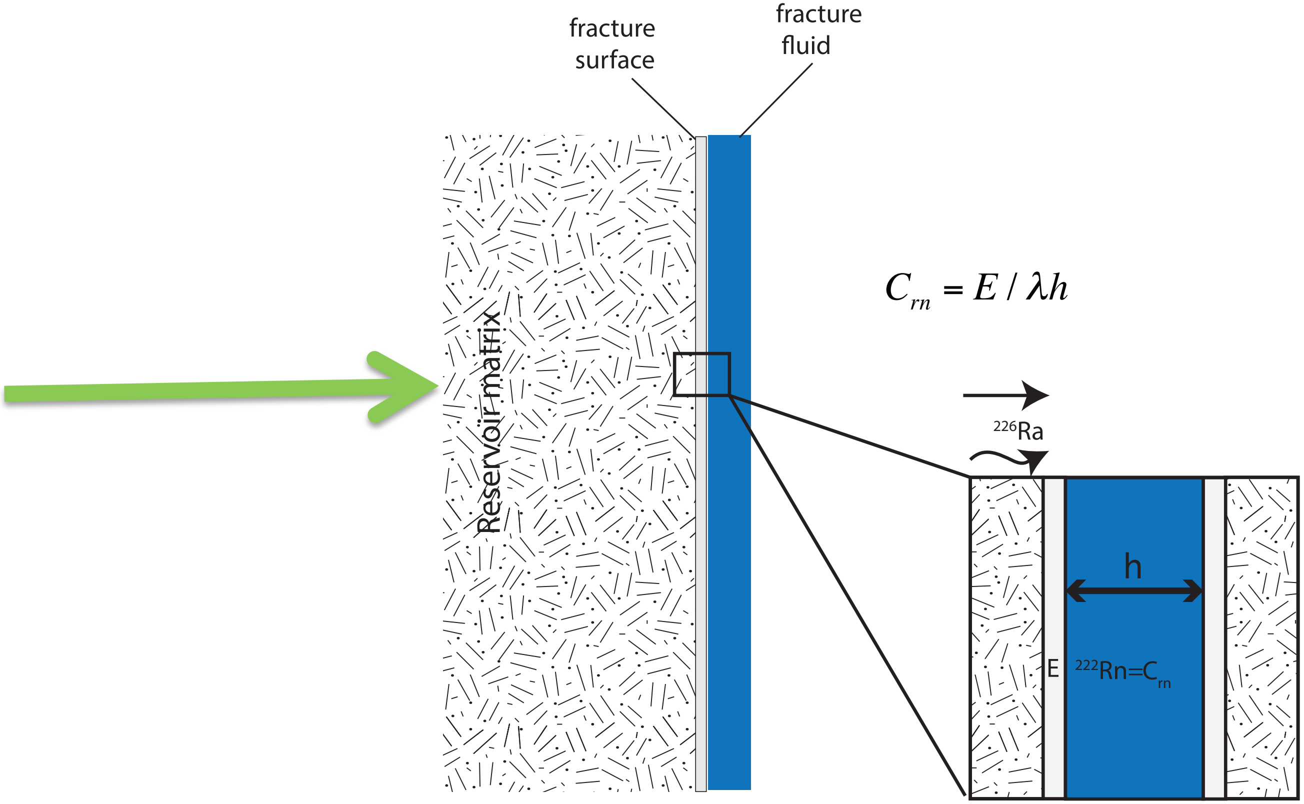

Radioisotope Tracers to Define Fracture Attributes for EGS

Project Officer: Elisabet Metcalf
Total Project Funding: $1.013M
November 2017

Principal Investigator: Shaun T. Brown
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EGS Tools

Relevance/Impact of Research

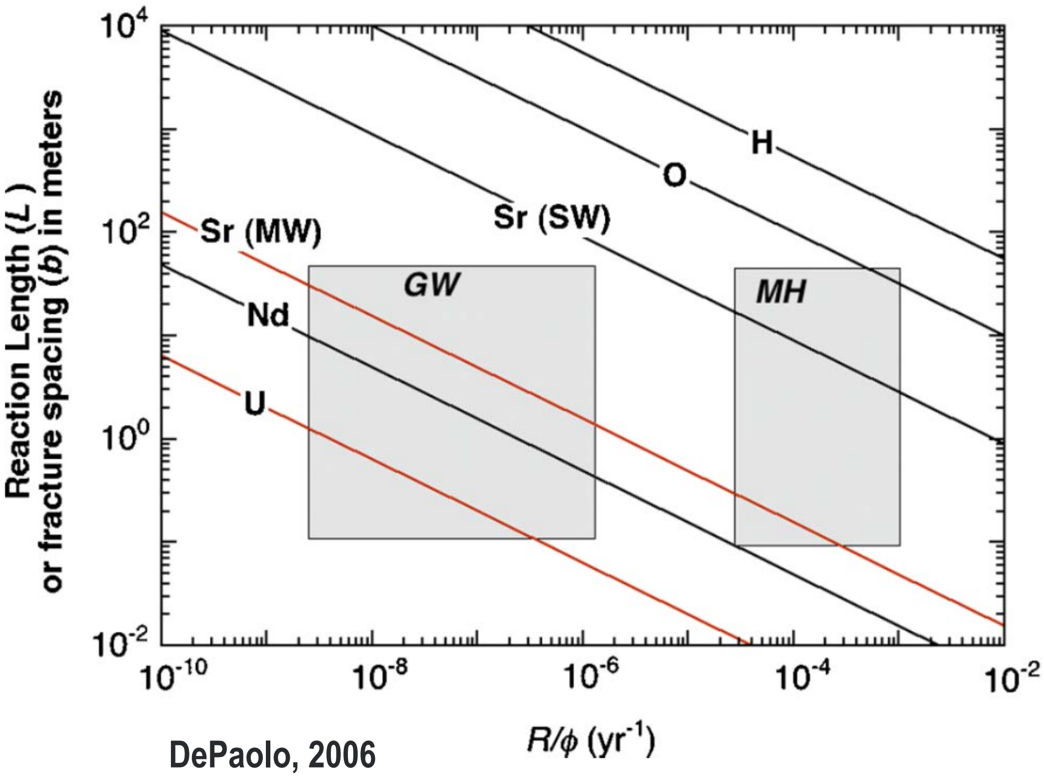
Characterization goal:

- Complete 3D reservoir, stress and fracture models constrained by all observations

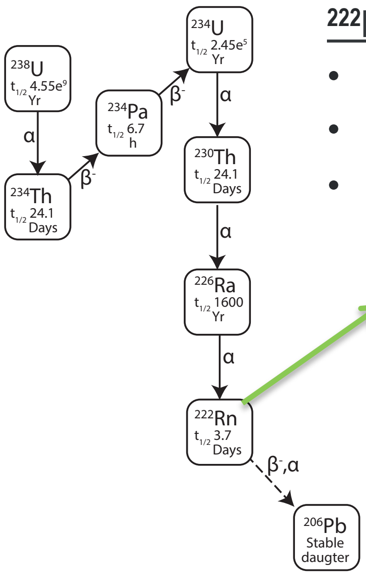
Contribution:

- Isotopic tracers that will constrain the surface area and aperture of hydraulically conductive fractures
  - Focus on short lived radioisotopes such as ^{222}Rn
  - Compliment with $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ that probe fracture spacing

Challenge: The distribution of fractures and their properties (e.g. surface area, aperture, spacing and reactivity) are poorly quantified in both natural enhanced geothermal systems.



DePaolo, 2006



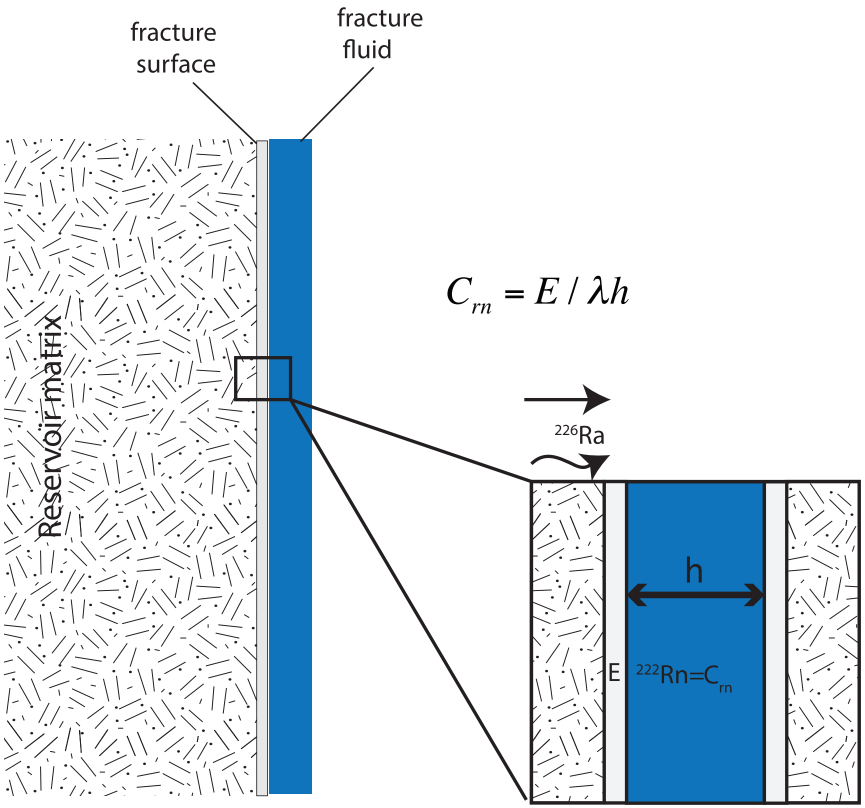
^{222}Rn:

- $t_{1/2}$=3.7 days
- Noble gas
- Nominally low sorption/ partitioning to solid phases

Proposed Solution: Utilize isotopes with differing reactive length scales to quantify surface properties.

Relevance/Impact of Research

Challenge: Prior work using ^{222}Rn to calculate fracture aperture was not widely successful.



We hypothesize a mechanistic understanding of the emanation factor (*E*) at fracture surfaces will make ^{222}Rn a powerful tracer of fracture surface properties.

Proposed Solution: Careful lab experiments coupled with reactive transport modeling.

Technical Approach Summary

1) ✓ Construct simplified analytical and numerical models to approximate uranium series isotope behavior in geothermal water-rock systems

2) Use preliminary model results to design hydrothermal experiments ✓

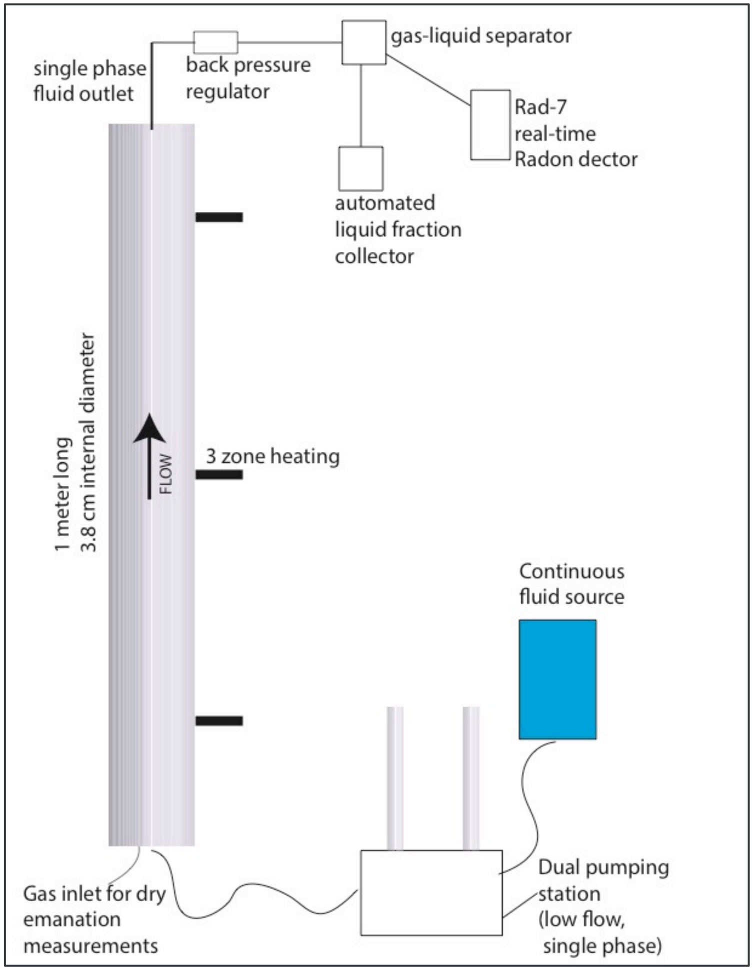
3) Characterize the physical, chemical and isotopic properties of the starting rock material ✓

4) Conduct reactive transport experiments

5) ✓ Compare experimental and model results, revise hypotheses as necessary

6) Validate at multiple field scales/locations

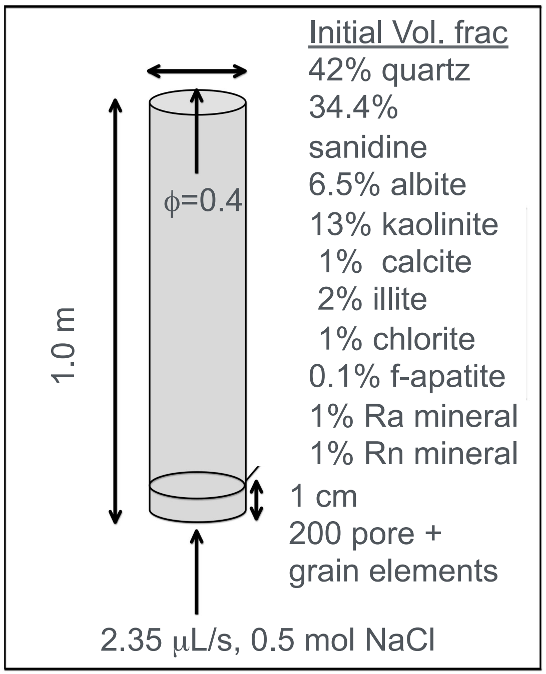
Technical Approach Summary: Reactor Design



Key features:

- Precise control of T, P and fluid velocity
- Continuous and automated influent
- Continuous and automated ^{222}Rn
- Fraction collection of fluid samples
- Ability to adapt for temperature gradient non-H_2O fluids (e.g. CO_2) in the future

Technical Approach Summary: Modeling Design

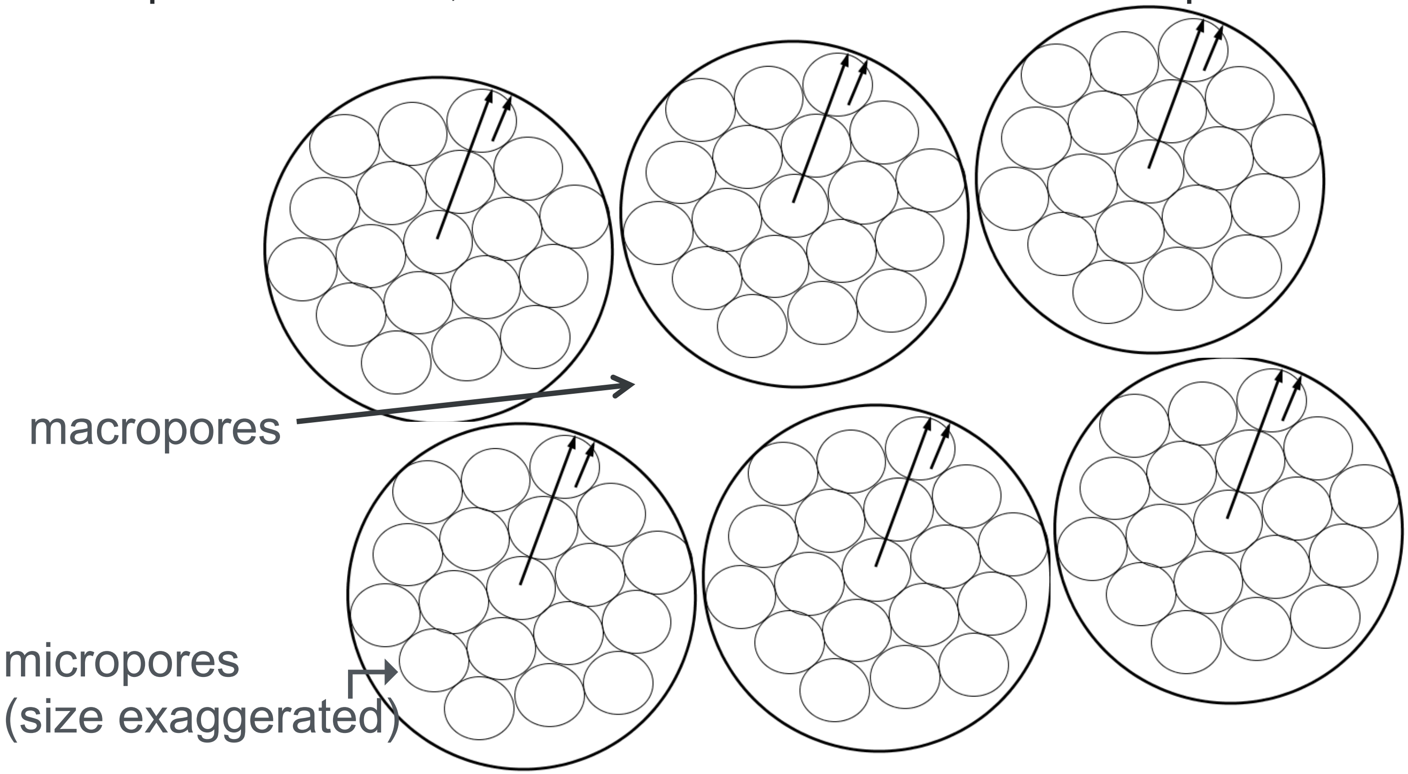


1. Dual Porosity 1-D 1 meter column
2. Pore space: $k=10^{-11}$ m^2, 40% of total volume
3. Grains: $k=10^{-22}$ m^2, 1% internal porosity
4. Diffusive (dominant) and advective transport between grains and pores
5. 3% “direct” emanation of ^{222}Rn from grains: R = 6.54e-18 mol/s. 6ppm Uranium in bulk rock
6. ^{222}Rn emanation from minerals: 1e-23 mol/s
7. ^{226}Ra+2(aq) -> ^{222}Rn(aq): R = 1.372 e-11 mol/L/s
8. ^{222}Rn(aq) decay: Decay constant = 2.095e-6 1/s
9. Desert Peak Tuff chemistry (will change to Bishop Tuff once characterization is complete)

Scientific/Technical Approach

Pore-Scale Dual-Continuum Model For Porous Grains:

- To capture diffusion, local reactive surface area and equilibria



At each spatial location, there are two coexisting continua: grains and pores.
For a dual-continuum, under transient conditions the distance from internal micropores to external macropores should be ~ 1/6 the radius (Zimmerman et al., 1993).

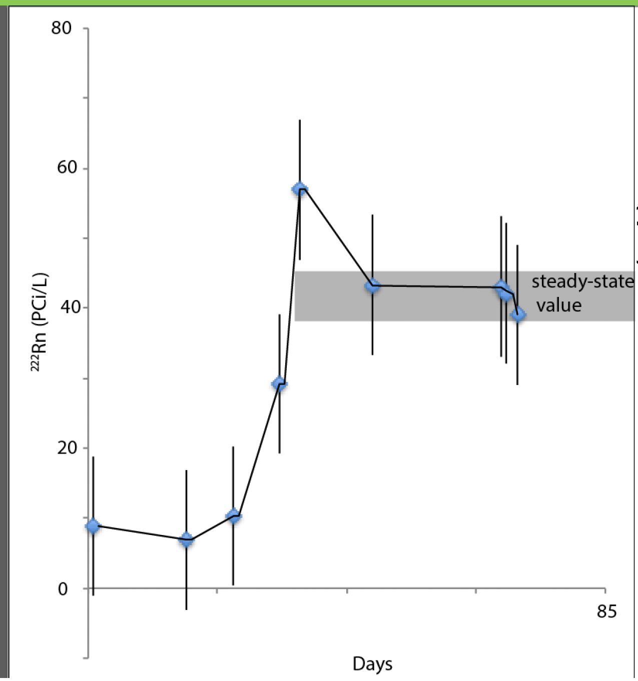
Thus 2 reactive surfaces areas: External grains and internal pores

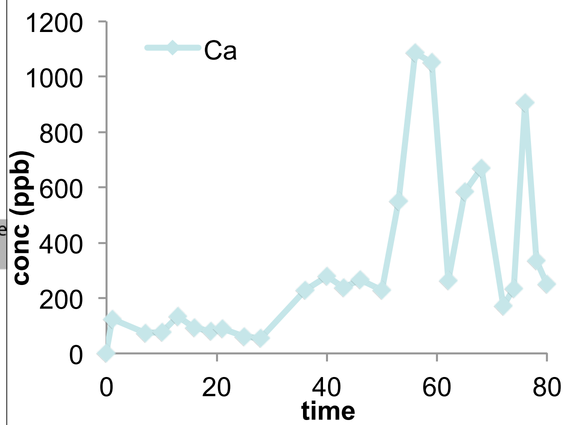
Technical Accomplishments and Progress

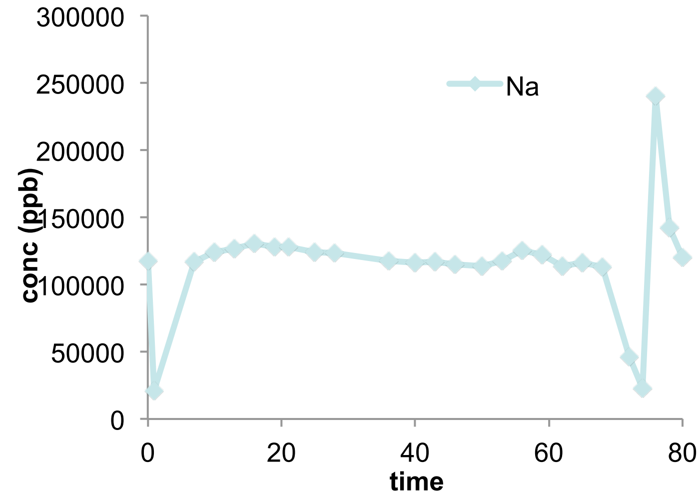
- Accomplishments/Progress to date.
  - Reactive transport experiments completed
  - Field validation study completed (low T)
  - Data collection completed
  - Stanford and GRC papers presented
  - technical target/goals.
  - Identify the most important technical challenge(s) faced during this reporting period and their impacts on the accomplishments and progress.
- Challenges
  - Relatively low ^{222}Rn concentrations in our lab scale experiments
  - Some minor technical challenges with experiments requiring revision of design

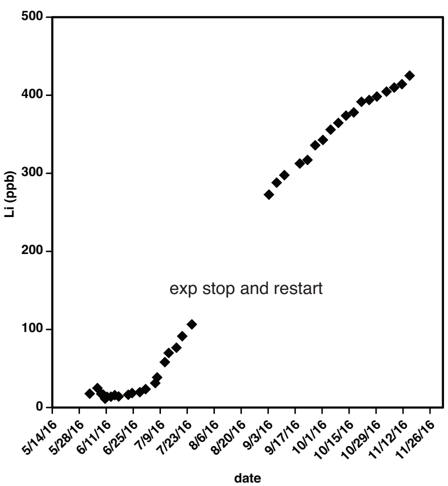
Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Field Scale Analog Experiment (High T)	Field Scale Analog Experiment (Low T)	8/2016
Column Experiments	Column Experiments	5/2017

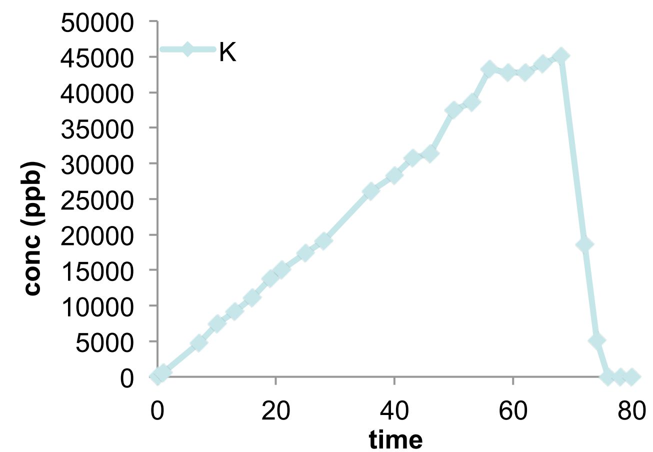
Technical Accomplishments and Progress







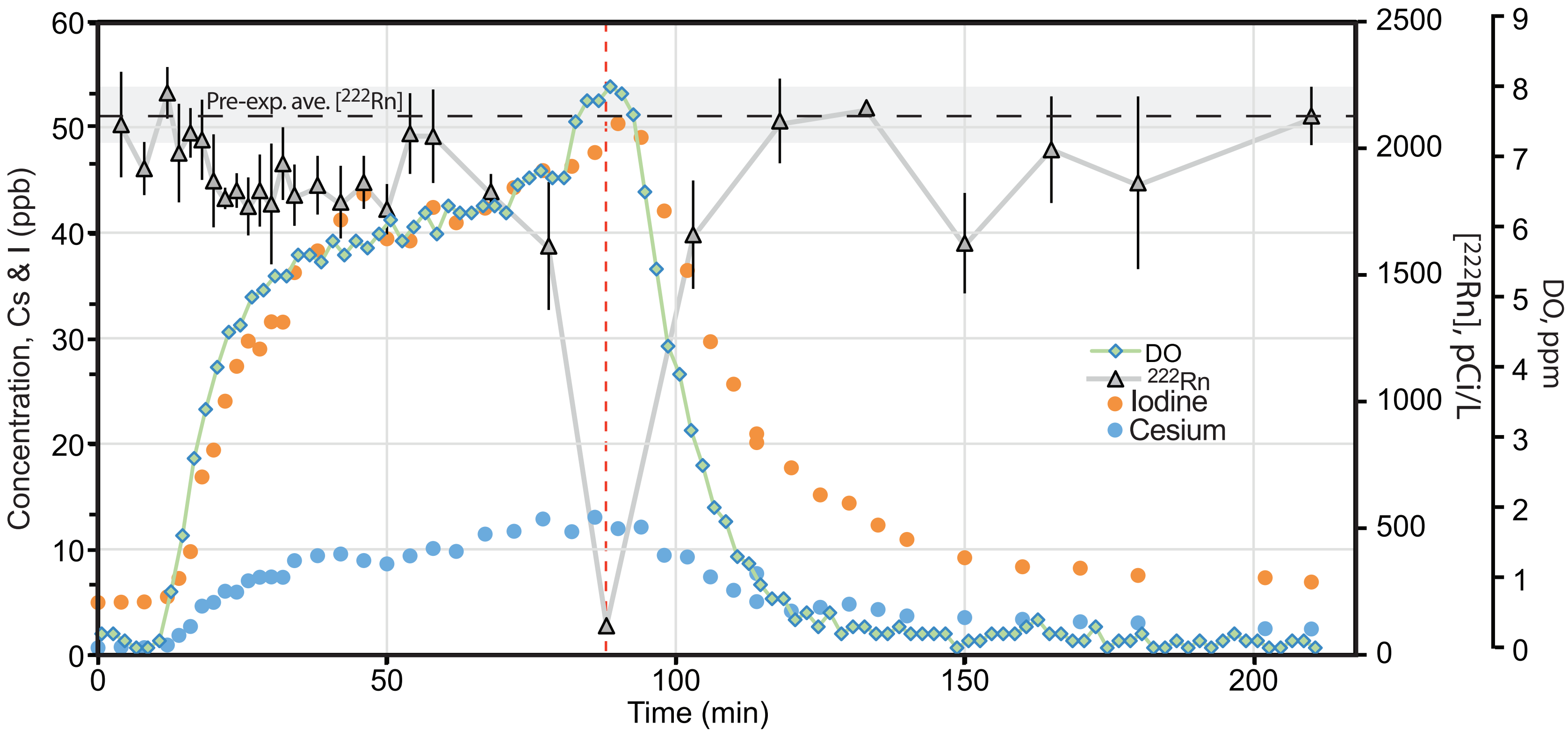




- Example data from Rn reactive transport experiments
- Once the experiments reach steady-state the activity is ~40 PCi/L.
- This value has a propigated uncertainty of ~10 PCi/L or 25%.
- This is an upper bound on the uncertainty we expect at the field scale.

Representative cation concentrations

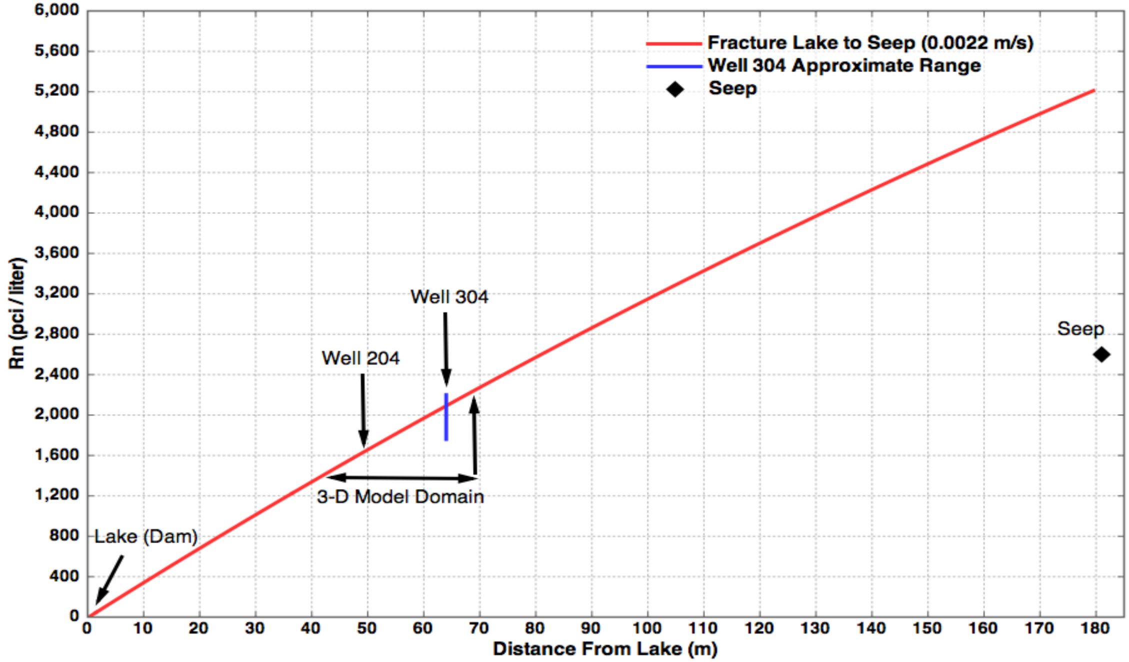
Technical Accomplishments and Progress



- Altona pump test
- 650 liters of zero radon water injected at ~6 l/m with recirculation thereafter.
- Cs and I added as tracers to injectate.
- Oxygen from the injection solution is an unintended conservative tracer

Results of Lake to Seep Calibration

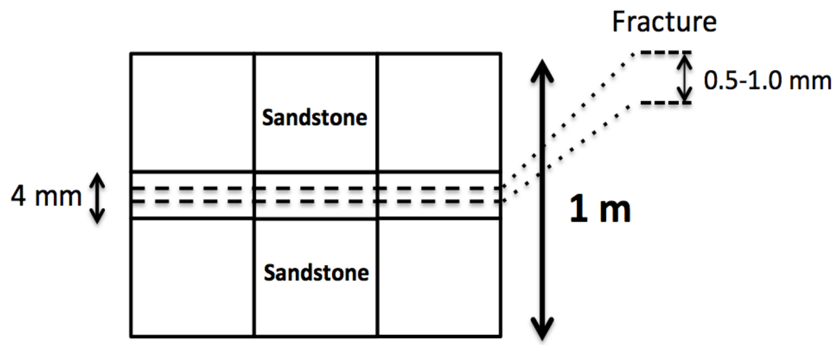
- Assume lake water with 0 pci/liter ^{222}Rn
- Fracture aperture of 0.5 mm and a hydraulic gradient of 0.0037
- Intrinsic ^{222}Rn flux of 1 x 10^{-14} mol/kg H_2O/s/mol U-238 gives ^{222}Rn activity of about 2100 pci/liter at well 304
- Does not predict seep composition, indicating seep may not be directly related
- Note difference of ~ 500 pci/liter between Well 204 (injection) and 304 (pumping) over a distance of only 14 m **(not observed in 2017 direct measurements)**
- **Now relaxing the lake boundary condition and directly quantifying ^{222}Rn from the fracture**



Reactive Transport Model Setup & Parameter Sets

- Discrete fracture models (2D & 3D) used to evaluate Rn-222 activities and dissolved O_2 concentrations, during groundwater flow and injection/pumping
- Reactive-transport simulations include Rn-222 generation, decay, advection, and diffusion
- Simulator: TOUGHREACT V3.3-OMP (based o Sonnenthal et al. 2014; Xu et al. 2011)
- 2-D lake-seep model used to calibrate Rn-222 fluxes using aperture, flow rate, and hydraulic gradient from Hawkins et al. (2016)
- Apertures and permeabilities (anisotropic) varied in 3-D site model to capture the observe O_2(aq) arrival time (pumping/injection)
- Radon fluxes varied based initially on estimated uranium abundance of 4 ppm

Schematic diagram showing fracture zone and bounding rock matrix grid blocks



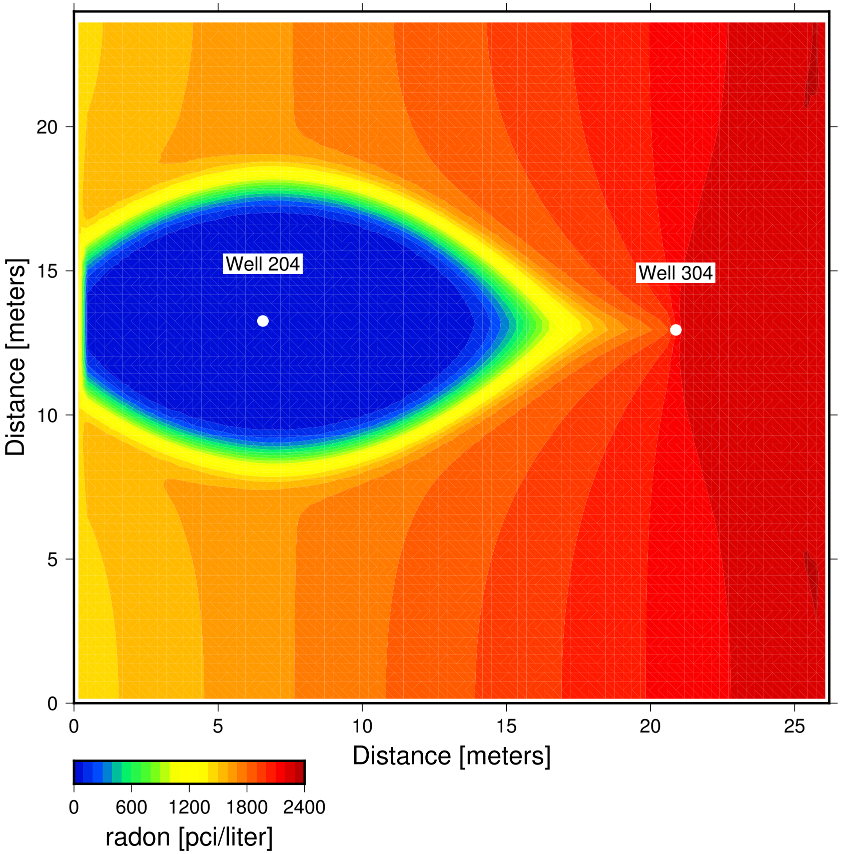
Hydrological and Transport Parameters for Lake-Seep (L-S) and 3-D Site Model

Parameter	Fracture (L-S)	Sandstone (L-S)	Fracture Case 1	Sandstone Case 1	Fracture Case 2	Sandstone Case 2
ϕ	0.125	0.01	0.115	0.01	0.15	0.01
k_x (m^2)	9.34×10^{-9}	10^{-16}	6.24×10^{-9}	10^{-15}	2.0×10^{-8}	10^{-15}
k_y (m^2)	9.34×10^{-9}	10^{-16}	3.12×10^{-9}	10^{-15}	1.0×10^{-8}	10^{-15}
k_z (m^2)	10^{-16}	10^{-16}	10^{-15}	10^{-15}	10^{-15}	10^{-15}
Aperture (mm)	0.50	-	0.46	-	0.6	-
τ	1.0	1.0	1.0	1.0	1.0	1.0
Rn flux/mol U (mol/kg H_2O/s)	10^{-14}	10^{-14}	10^{-14}	10^{-14}	3×10^{-14}	3×10^{-14}

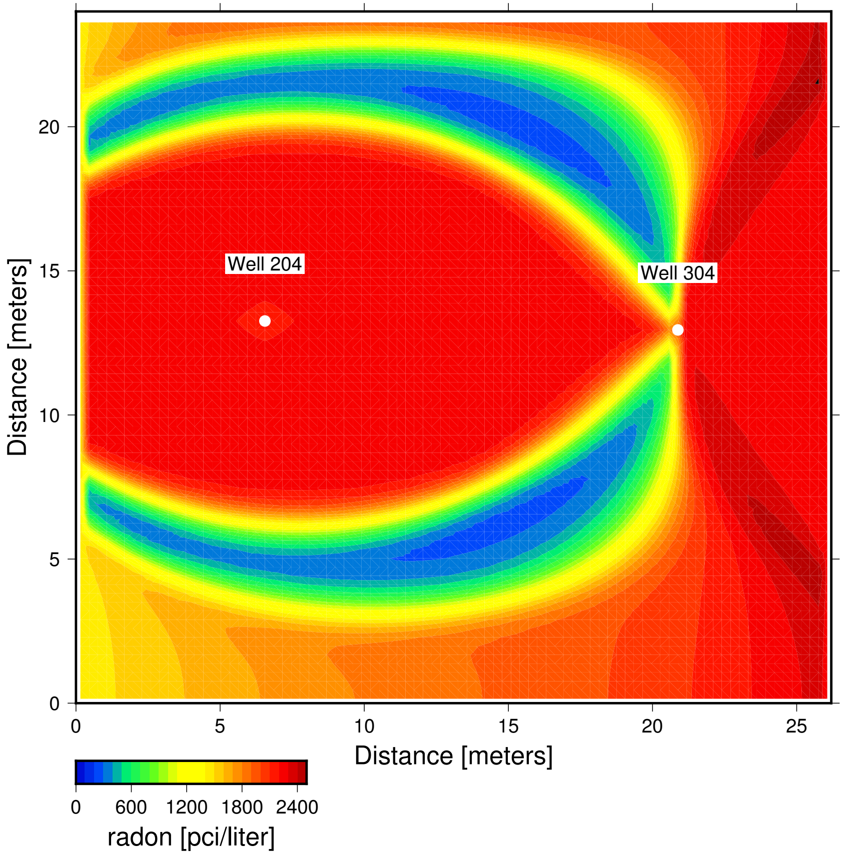
Modeled 3-D Injection/Pumping Rn-222 Activities

- Fracture plane Rn-222 activity contours
- Pumping results in mixing much higher activity downstream Rn-222 groundwater with ~10 pci/liter tank water

10 minutes tank water injection



120 minutes: Groundwater injection after 81 minutes of tank water injection



5.7 liters/minute injection; 6.8 liters/minute pumping

Comparison to Measured O_2 (aq) and Rn-222

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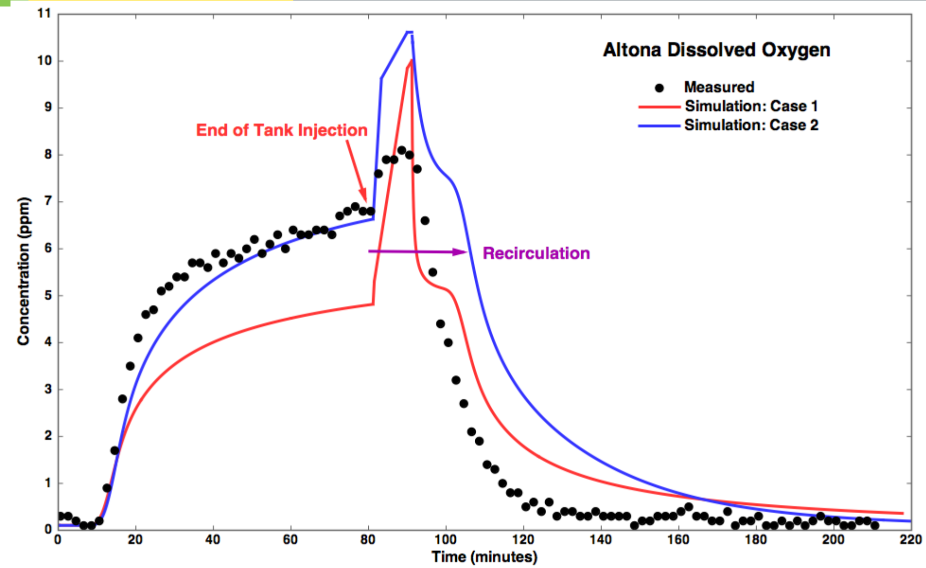
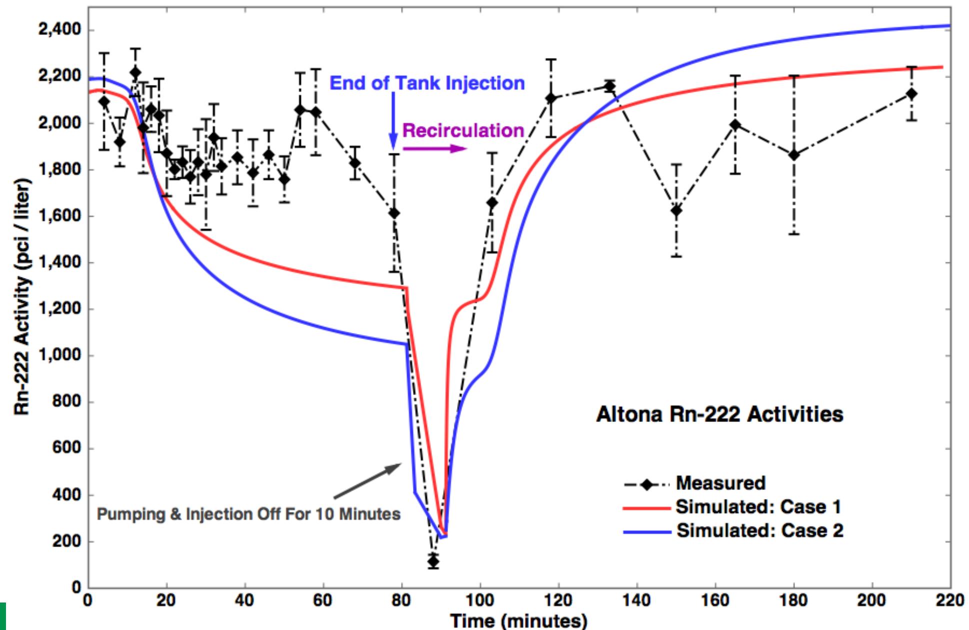
- Dissolved O_2 matches best with larger aperture (0.6 mm: Case 2) and equilibrated with atmosphere at groundwater temperature (10.5 °C), and no redox effects over a few hours
- Rn-222 activities match better with smaller aperture (or higher Rn flux)
- Peak in O_2 concentration and sharp drop in Rn-222 potentially explained by shut-off of injection/pumping with solely downstream flow for ~10 minutes, probably a result of changing to recirculated water
- High measured Rn-222 activities during pumping could be a result of other factors such as gas evolution from matrix during pumping or better connection to connected fractures with high Rn-222 without dilution of O_2 (aq)
- **Now we are reevaluating the interpretation of the O2 data compared to the other tracers**





Research Collaboration and Technology Transfer

- Academic engagement:
  - Collaboration with Cornell on the Altona field site
  - Academic partners UC Berkeley and U. Delaware involved in project
  - Supported current secondary science educator (MS student) on summer research experience
- Private Sector Engagement:
  - In the next 6-12 months as publications are released we plan to engage industry contacts
  - Additional opportunities to engage outside of geothermal

Future Directions

- Immediate future work:
  - Revise models for experiments and field scale tests, submit publications
  - Adapt work and begin validation efforts as part of Collab/Sigma V.
  - Apply model to Long Valley/Mammoth geothermal system Explain key activities for the rest of FY2018 and to project completion.
- Long range future work:
  - Validate temperature dependence of ^{222}Rn emanation
    - Develop ^{222}Rn as a monitoring tool (TMT suggestion)
    - Incorporate other surface area tracers for cross validation (e.g. lithium)

Milestone or Go/No-Go	Status & Expected Completion Date
Publications submissions (peer review)	12/1/2017
All data to geothermal database	2/1/2018
Final report	4/1/2018

Mandatory Summary Slide

- ^{222}Rn concentration in geothermal fluids are primarily controlled by reservoir surface area and geochemical properties of the reservoir rock
- Models of ^{222}Rn emanation can be related to fracture surface area
- Secondary effects such as temperature and fracture surface alteration still need to be addressed in a more quantitative fashion