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Estimates of Deep Permeability

Project Officer: Eric Hass

Total Project Funding: $475K over two years

May 14, 2015

Principal Investigator : B. Mack Kennedy, Eric Sonnenthal (Co-PI)

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Track 2 HRC Tracers/Zonal Isolation/Geochemistry

Relevance/Impact of Research

- **Project Objectives and Purpose**
  - Establish a more quantitative understanding of helium isotopic variations as they pertain to geothermal resource potential, with a focus on amagmatic extensional regimes
  - Develop a technique for estimating subsurface permeability from surface measured helium isotopic compositions,
  - Advance our understanding of deep crustal permeability and how it relates to present day surface strain and geologic structure, and
  - Establish ^{39}Ar and ^{81}Kr as viable tools for determining residence ages of geothermal fluids and providing additional constraints on helium isotopes and THC models applied to geothermal systems.
- **Project Impact on Geothermal Development/Deployment.**
  - If successful, the project will lower the risk associated with exploration for conventional but deep geothermal systems by providing better characterization of subsurface permeability prior to drilling.
- **Innovative Aspects**
  - Incorporation of noble gas isotopes into THC models (TOUGHREACT V3-OMP)
  - Develop reliable technique for estimating rates of fluid flow feeding geothermal systems

Scientific/Technical Approach

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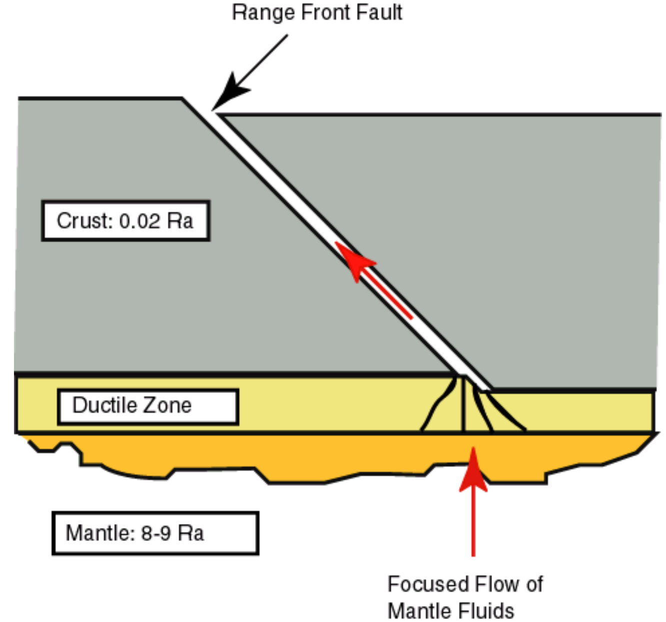
- **Technical Approach:** focus is on $^{3}He/^{4}He$ anomalies relative to regional trend across Northern B&R.
  1. Are the anomalies associated with crustal scale structural features that may provide enhance permeability?
  2. Develop reactive transport models (THC) combined with noble gases to estimate fluid flow rates into and through geothermal reservoirs, based on surface measured $^{3}He/^{4}He$ ratios
  3. Apply THC-noble gas model to the Desert Peak and McGinniss Hills geothermal systems
  4. Use fluid residence ages determined from unconventional isotopes ($^{81,85}Kr$ and ^{39}Ar) to add additional constraints to THC model.

- **Analytical Methods:**
  1. THC Model: TOUGHREACT V3-OMP – modified database to incorporate noble gas isotopes
  2. Atom Trap Trace Analysis (ATTA), ANL: ^{81}Kr, ^{85}Kr, ^{39}Ar
  3. Low Level Counting Facility, Univ. of Bern: ^{39}Ar

Background: He Isotopes Provide Indirect Measure of Permeability

Helium Isotope Primer:

- $R/Ra = (^3He/^4He)_{sample}/(^3He/^4He)_{air}$
- $(R/Ra)_{mantle}$ = 8-30 (“primordial” ^3He + radiogenic ^4He)
- $(R/Ra)_{crust}$ = 0.02 (radiogenic ^4He + minor contribution from $^6Li(n,\alpha)^3He$)
- Helium in geothermal fluid samples dominated by mantle and crustal contributions
- High diffusivity in crustal minerals – helium closure temperatures <100 C
- $[^4He]$ in minerals = f(U,Th, Closure Temp)
- At T > 100C: $[^4He]$mineral ~ steady state
- ^4He addition rate to crustal fluids ~ $P(^4He)$



Steady state 1-d advection upward flow scaled to crustal thickness:

$$q = \frac{H_{crust} * \rho_s * P(He)}{\rho_f * [^4He]_{f,mantle}} \left[\frac{(R/Ra)_{meas} - (R/Ra)_{crust}}{(R/Ra)_{mant} - (R/Ra)_{meas}} \right]$$

q = fluid upflow rate in fault zone

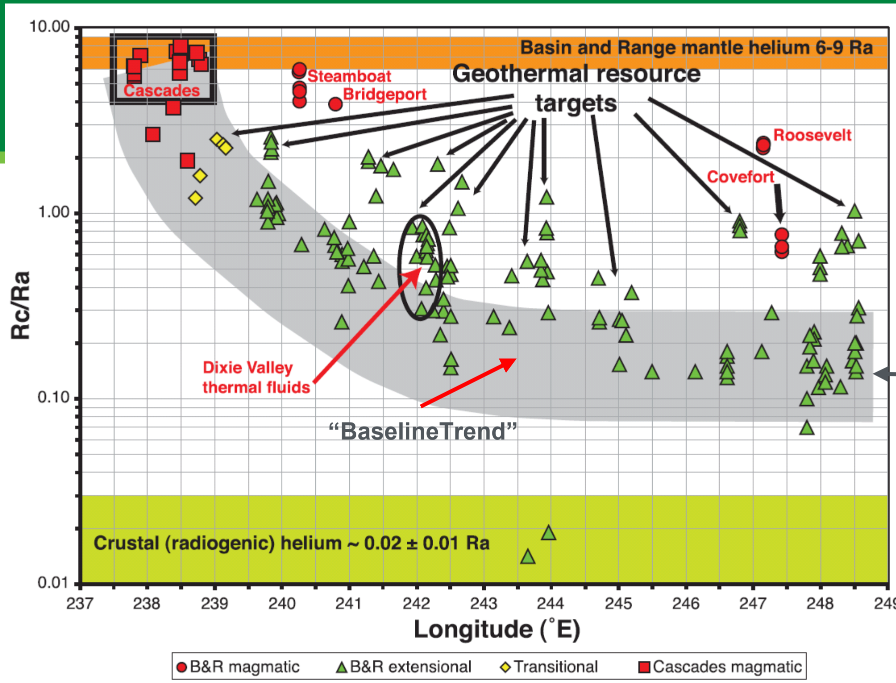
Hcrust = thickness of brittle + ductile crust

ρs, ρf = density of solid and fluid

P(He) = present day 4He production rate from U+Th in fault zone minerals

(R/Ra) = helium isotopic composition

[4He]f,mantle = original 4He concentration in the upwelling mantle fluid



Surface He isotopic compositions across the northern Basin and Range

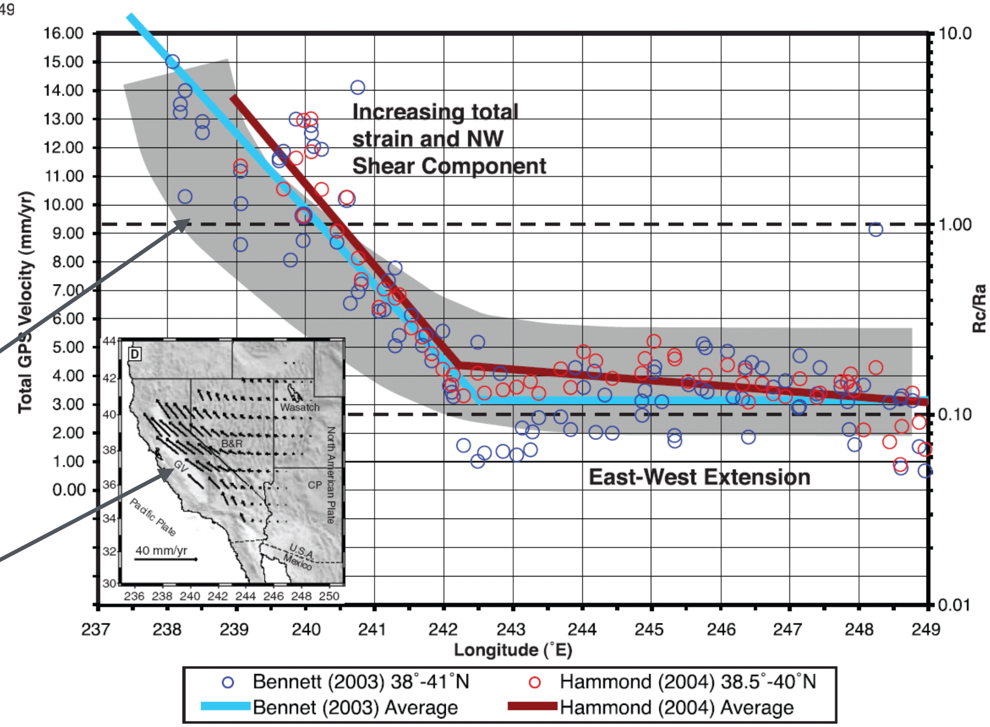
(1) East-West baseline trend (gray zone) suggests increase in average permeability from East-to-West

(2) Anomalous values wrt Baseline Trend signal higher permeability and high geothermal potential (e.g.Dixie Valley)

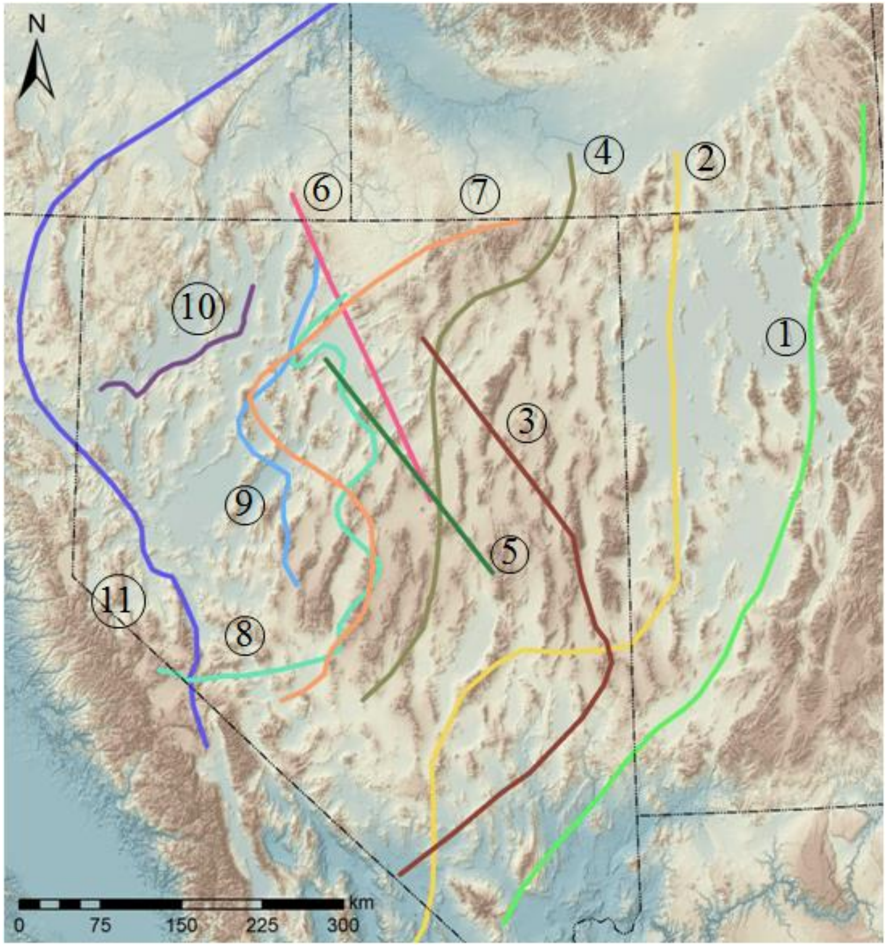
"BaselineTrend" He isotopic composition and strain rate and direction

(1) Baseline He Trend coincides with East-to-West increase in strain rate and direction – as strain rate increase the contribution from NW-SE shear increases – added shear coupled with increased strain rate drives increase in permeability indicated by He isotopes

(2) Increase in shear component reflects tectonic influence from Pacific Plate



Helium Isotope Anomalies and Crustal Scale Discontinuities



Mapped extents of identified discontinuities

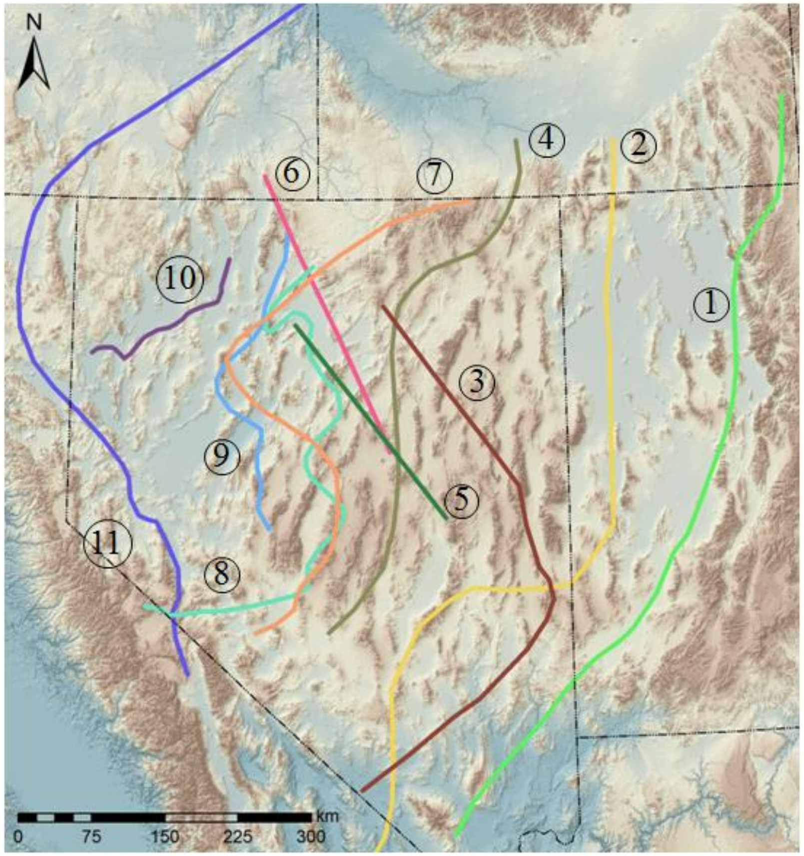
Focused on 11 Crustal Discontinuities

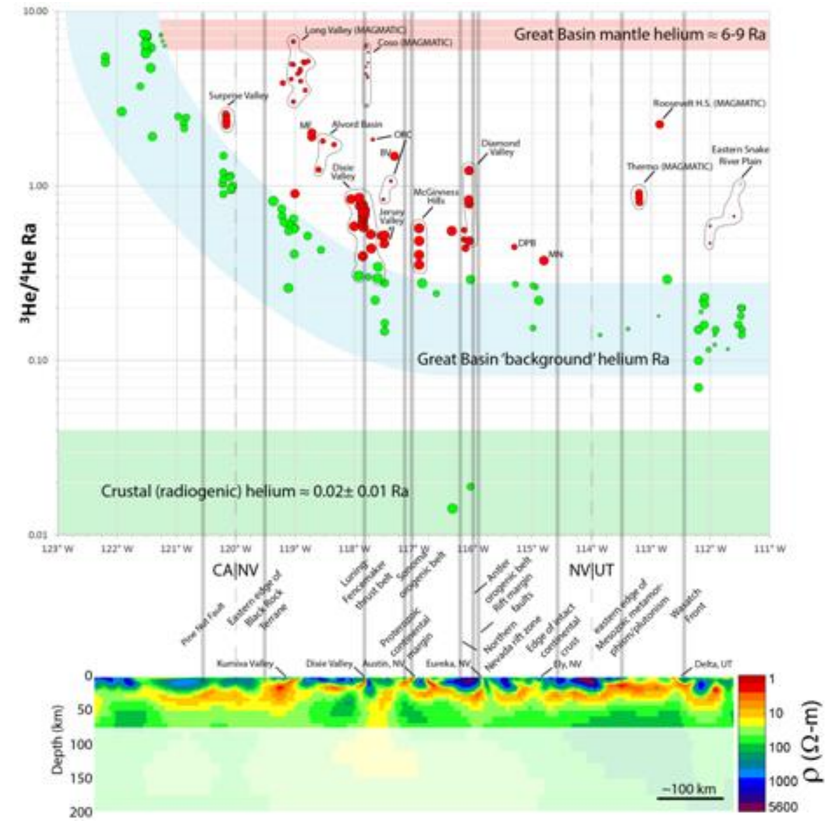
1. Wasatch Front (Cenozoic extension)
2. Mesozoic Plutonism/metamorphism and Cenozoic extension – eastern extent
3. Intact Proterozoic Crust – eastern extent
4. Antler Orogeny (Devonian-Mississippian ?)
5. Rift Margin Faults (Eocene magmatism/mineralization)
6. NNR/Mineralization (Miocene rifting)
7. Continental Margin
8. Sonoma Orogeny (Permian-Triassic)
9. Luning-Fencemaker Thrust Belt (Jurassic-Cretaceous)
10. Black Rock Terrane Boundary (Jurassic Thrust)
11. Pine Nut Fault (Western edge of B&R and Walker Lane extension)

Goal: Test for correlation between the occurrence of "anomalous" He isotope compositions and reactivated crustal discontinuities

Accomplishments, Results and Progress

Helium Isotope Anomalies and Crustal Scale Discontinuities



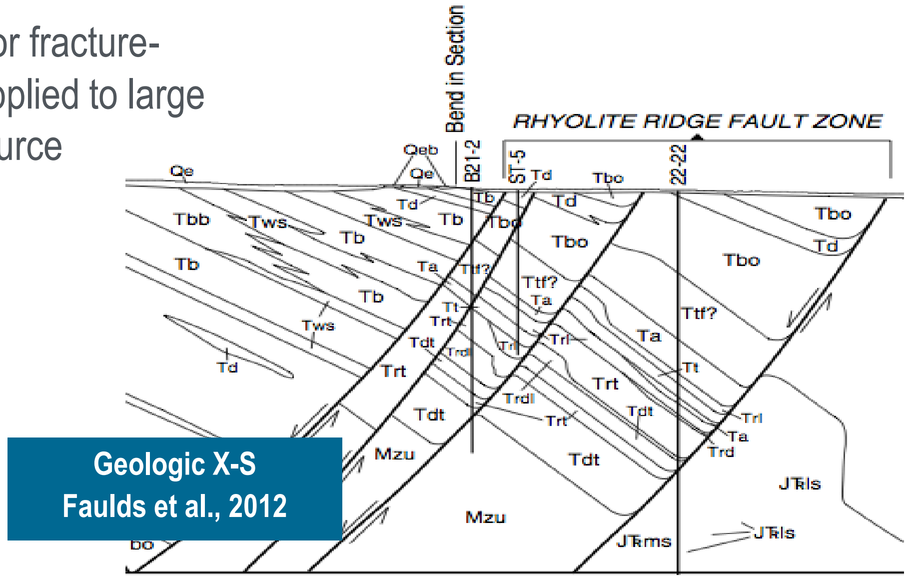


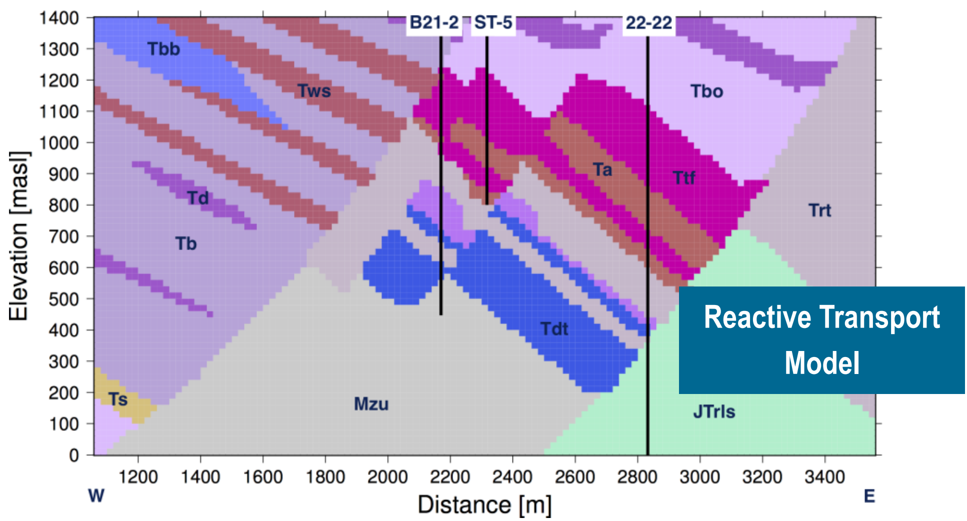
* Symbolize size ∝ distance from *(Wannamaker 2011)* MT line

Original Planned Milestone/ Technical Accomplishment	Actual Milestone/Technical Accomplishment	Date Completed
Not part of original Planned Milestones	Evaluate He anomalies wrt crustal discontinuities/Good correlation between He isotopes and reactivated discontinuities and deep high conductivity zones (MT)	9/2014 – GRC best paper award

NEW ADVANCEMENT: Multiple continuum model for fracture-matrix flow, reactive transport, noble gases and heat applied to large geothermal reservoirs to constrain flow pathways, resource evaluation

- **Model Developed for TOUGHREACT V3-OMP**
  - ^{3}He, ^{4}He, Ar and Xe water solubility data added to thermodynamic database
  - Model considers
    - Addition of radiogenic ^{4}He to the fluid flow system from host crustal lithologies
    - Noble gas partitioning between solid-liquid-vapor phases
    - Transport by advection-diffusion for gas and liquid phases
    - Diffusive fractionation of gas phases during transport
- **Geologic Cross Sections**
  - 2-D geologic cross section models from field/well data constructed for Desert Peak and McGinness Hills geothermal fields
  - Numerical mesh developed for TOUGHREACT V3-OMP, including fracture and matrix geologic and geochemical properties





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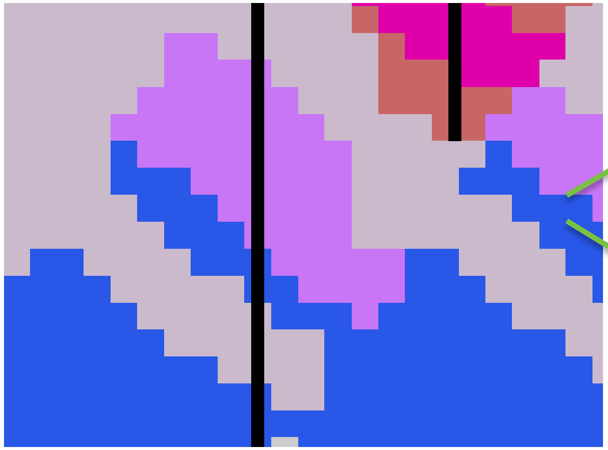
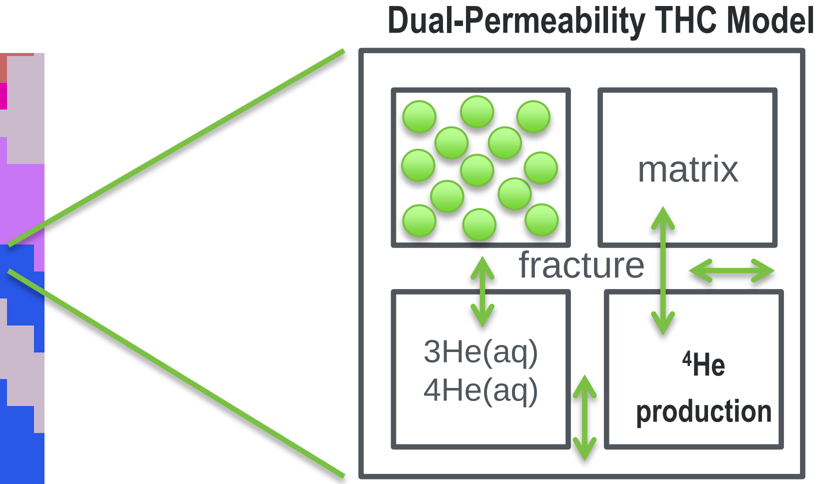
$^3He/^4He$ Model of Desert Peak

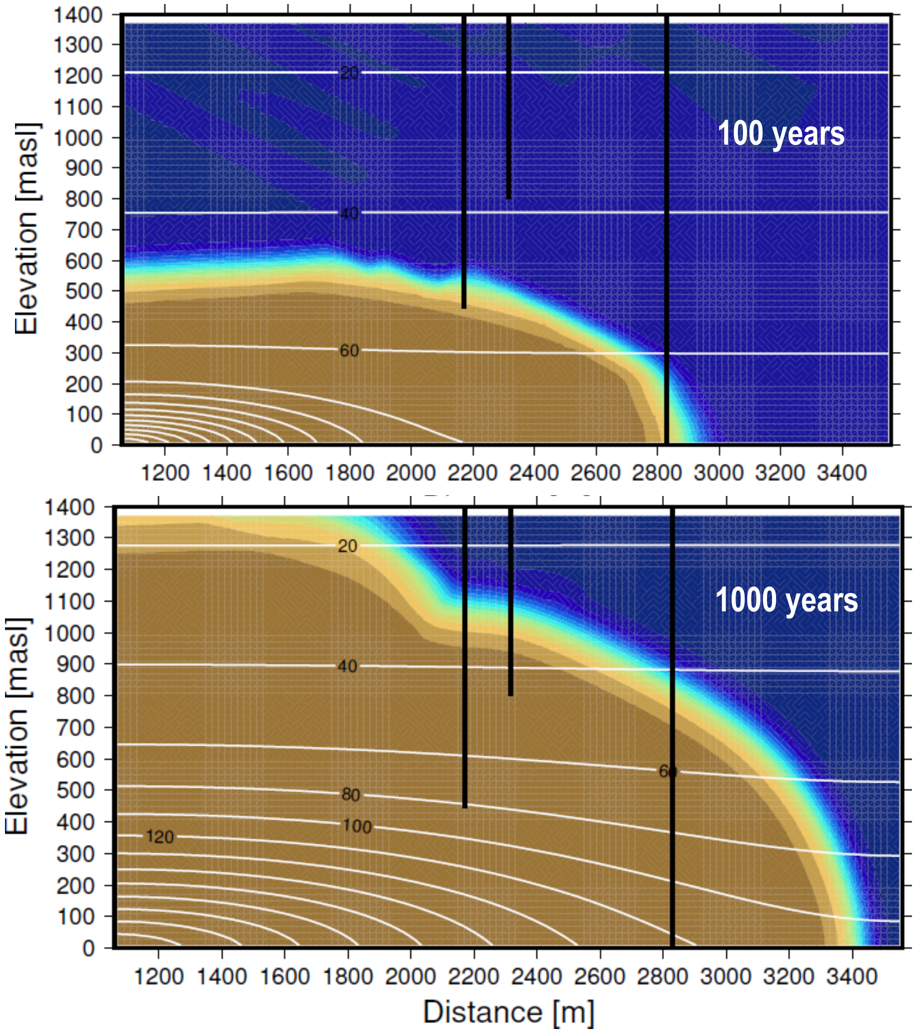
- Dual Permeability (fracture-matrix) 2-D cross-section
- Main rock types: Chlorapagus basalts & andesites, diatomite, rhyolite (main reservoir unit), Jurassic metavolcanics, Jurassic limestones
- Aqueous diffusive and advective transport of $^3He(aq)$ and $^4He(aq)$
- Steady state: radiogenic ^4He flux from minerals to fluid = 7.256×10^{-17} mol/m^{2}s
- Initial formation water starts as meteoric water value
- Magmatic/geothermal fluid initially injected at lithostatic pressure in fractures with He R/Ra = 7.5, and He(aq) ~ 6×10^{-6} mol/kg H_2O





THC Modeling

- **Sensitivity Studies: Desert Peak 2-D Model**
  - Deep addition of mantle derived He (~7.5 Ra)
  - Mantle helium diluted by mixing with shallow crustal radiogenic 4He-rich fluids along faults and rock units of different permeability
  - Each rock unit and through going fault assigned a permeability consistent with lithologic properties



White line contours: Temperature (^{o}C)
Color contours: R/Ra (Brown = 8 Ra; Blue = 0.02 Ra

Initial Sensitivity Study: Observations

- Clearly unrealistic in terms of R/Ra – reflects high ratio at injection point
- Subtle structure in R/Ra contours reflect impact of variable permeability of the various lithologies and through going faults
- Important challenge: Identify appropriate boundary conditions, specifically the flux and composition of mantle helium at the model injection point
- Test different fault permeability structures

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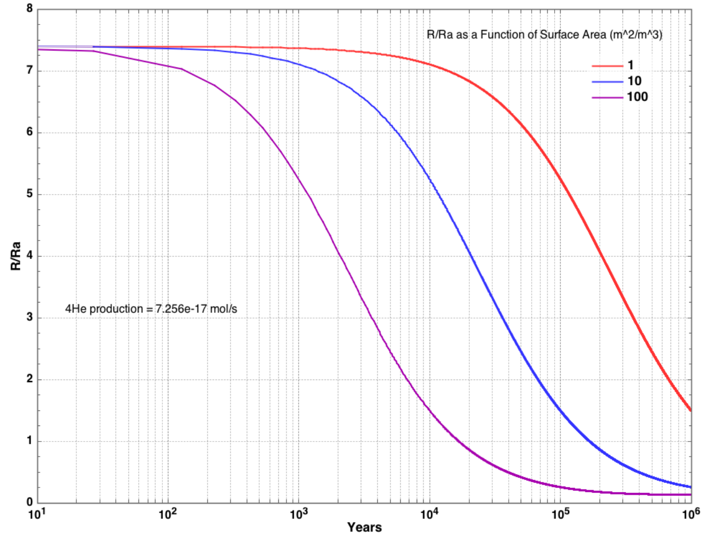
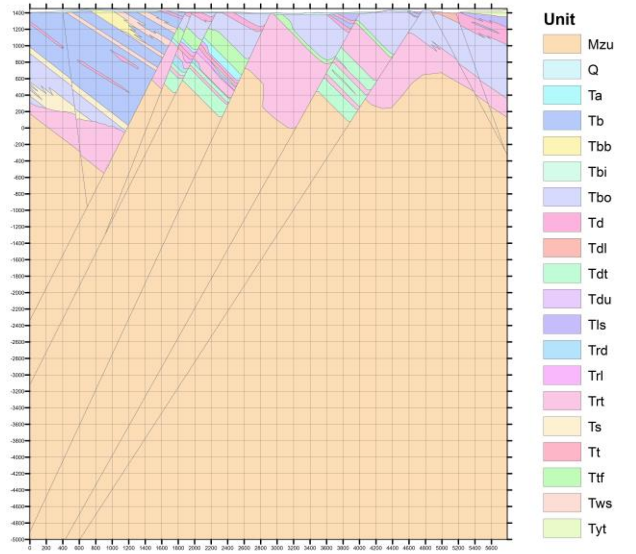
THC Modeling

- **Evaluation of radiogenic ^{4}He addition over time**
  - Addition of radiogenic ^{4}He is much slower than upward flux of mantle ^{3}He
  - Sensitivity studies performed on surface area effects
  - More sensitivity studies on initial U and Th content of rocks and ^{4}He production, particularly in deep Mesozoic carbonates and metamorphics



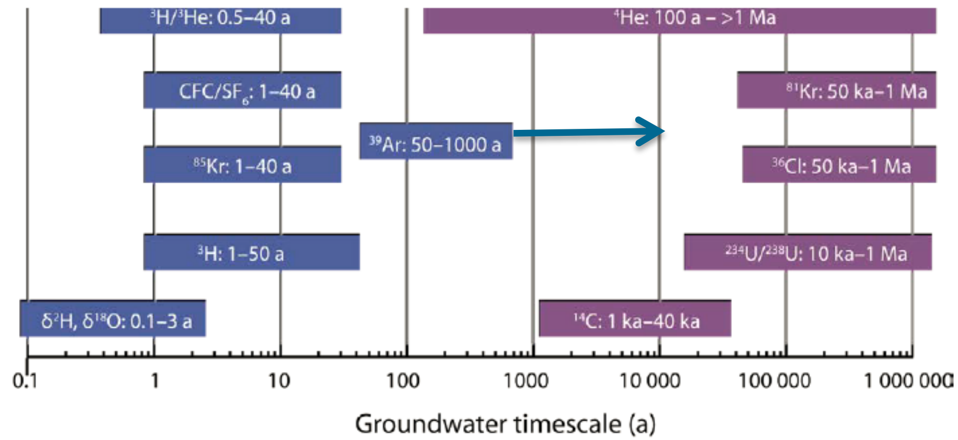
- **Deep fault structure simulations**
  - Transport and mixing of mantle ^{3}He along deeply propagating faults depends on fault structure
  - Current near-surface geologic models do not show faults dipping steeply enough to intersect deep mantle fluids
  - Testing of different fault geometries necessary to evaluate ^{3}He/^{4}He at reservoir-depths of a few km
  - Revised cross-section of Desert Peak developed with steeply dipping faults to 5 km depth

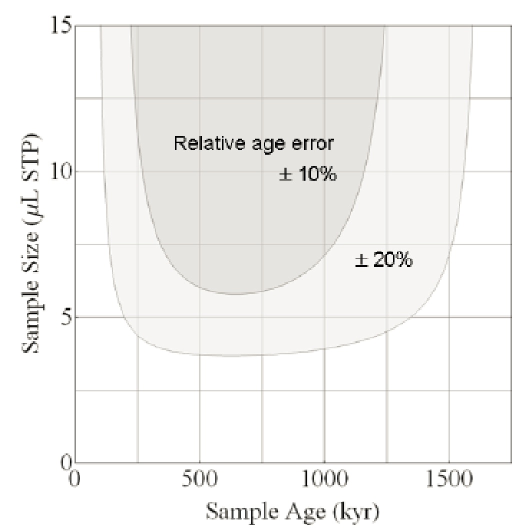


Fluid Residence Ages

Background Information

- Use rare noble gas isotopes to estimate groundwater residence ages
- Noble gases advantageous being chemically inert
- Three isotopes of interest
  - ^{39}Ar ($t_{1/2}$ = 269 days)
  - ^{85}Kr ($t_{1/2}$ = 10.8 years)
  - ^{81}Kr ($t_{1/2}$ = 229,000 years)
- Source and atmospheric abundance
  - Atmospheric ^{39}Ar: cosmogenic ($^{39}Ar/Ar = 8 \times 10^{-16}$)
  - Crustal 39Ar: $^{39}K(n,p)$
  - Atmospheric ^{85}Kr: nuclear reactor ($^{85}Kr/Kr \sim 2 \times 10^{-11}$)
  - Atmospheric ^{81}Kr: cosmogenic ($^{81}Kr/Kr = 5.2 \times 10^{-13}$)
- Very low abundance precludes analysis by conventional mass spectrometry
- Two analytical techniques available
  - Low level counting facilities (University of Bern)
  - Atom Trap Trace Analysis – ATTA (ANL)





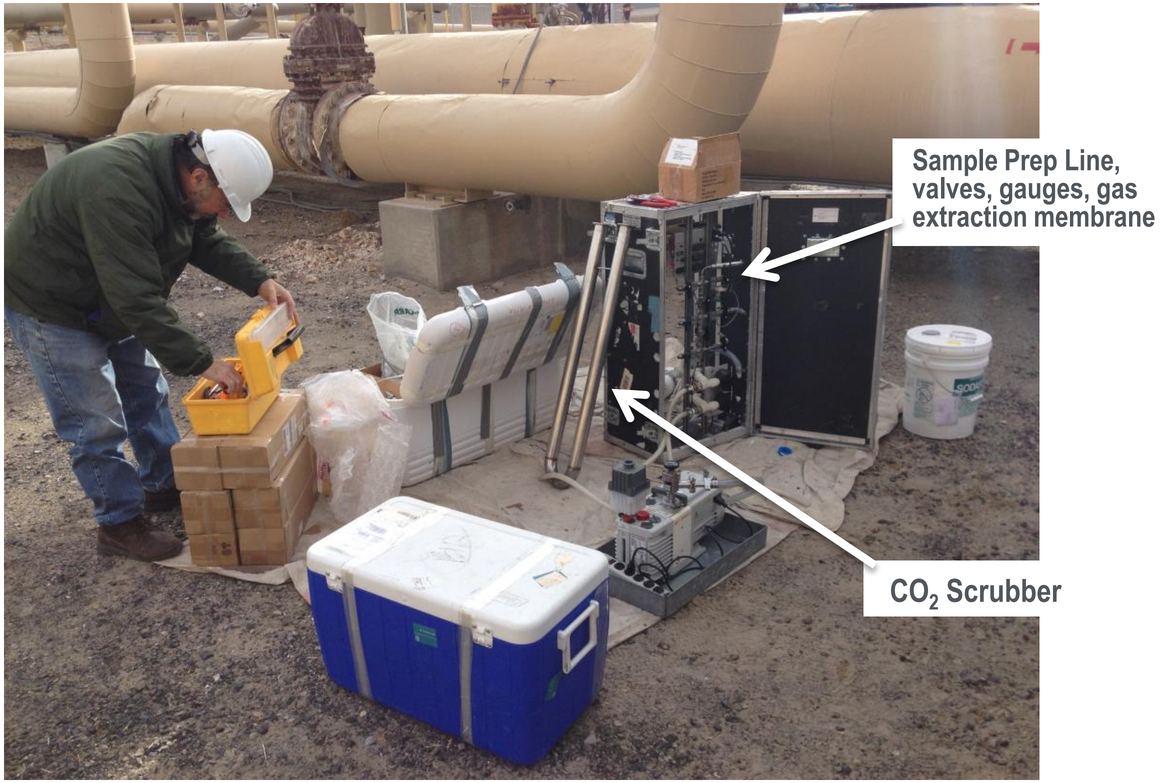
ATTA ^{81}Kr analytical precision

Lu, Z-T et al., 2014, Earth Science Reviews, v138

Accomplishments, Results and Progress

Fluid Residence Ages

- **Completed two sampling trips**
  - Desert Peak: 86-21 (10/2014)
  - Desert Peak: Vapor Port (12/2014)
  - McGinness Hills: Post heat exchanger (12/2014)
- **Sample requirements**
  - Low abundance requires large sample size
  - ~200 liters of production fluid processed
  - Fluid must be cooled to <50 °C
  - CO2 must be scrubbed to insure adequate sample
- **Challenges**
  - No atmospheric contamination
  - Large sample size and long sampling time
  - First generation sample prep line
  - Many connections
  - Hard to maintain vacuum tight system
- **Solutions**
  - New sample prep line
  - Smaller more compact
  - Fewer connections, valves, etc
  - Improved design with added pressure gauges in critical locations
  - New system field tested



Desert Peak Sampling 12/2014

Milestones

Milestone or Go/No-Go	Status & Expected Completion Date
Develop thermal-hydrologic-chemical (THC) model incorporating ^{39}Ar, ^{81}Kr, and $^{3}He/^{4}He$	Completed (Q1, 2014)
Develop 2-D Desert Peak THC model incorporating noble gases that captures deep fluid circulation and flow-focusing in faults to shallow springs (Wanner et al., Geothermics, v51, 2014).	Completed (improvements ongoing) (Q2, 2014). Third sampling trip planned for Q3, 2015.
Perform sensitivity studies using Desert Peak 2-D model	Completed (Q3, 2014)
Collect samples for ^{39}Ar, ^{36}Cl and ^{81}Kr from power plants operating in the identified study area to determine fluid residence ages	Expected completion Q3, 2104; Initial sampling completed (Q1, 2015)
Finalize geologic and reactive transport models for Desert Peak and initiate and finalize geologic and reactive transport models for McGuinness Hills	Completed (Q1 and Q2, 2015)
Evaluate additional geothermal sites for incorporation into the deep permeability study	On going in collaboration with Ormat Technologies. Tuscarora identified as a possible site.
Collect and analyze samples for rare isotopes at the newly identified sites, if applicable	Expected completion date: Q3, 2015. More realistic date: Q4, 2015
Complete and publish final report	Expected completion: Q4, 2015

Future Directions

- **Task 1**: He anomalies associated with crustal scale features: Completed, paper submitted to Geothermics
- **Task 2**: Develop reactive transport models (THC) combined with noble gases to estimate fluid flow rates into and through geothermal reservoirs, based on surface measured $^{3}He/^{4}He$ ratios: Adaptation to TOUGHREACT V3-OMP Completed, model tested with sensitivity tests
- **Task 3**: Apply THC-noble gas model to the Desert Peak and McGinness Hills geothermal systems:
  - Address boundary conditions related to composition and flux of fluid injected at the base of the 2-D geologic model
  - Run increasingly more complex model scenarios (permeability structure, fluid injection rates, etc) to probe for more realistic results and ultimately to match compositions observed in production wells and surface features (if present)
  - Identify non-geothermal wells for sampling to better constrain the shallow fluid compositions for input into the 2-D geologic models
- **Task 4**: Use fluid residence ages determined from unconventional isotopes ($^{81,85}Kr$ and ^{39}Ar) to add additional constraints to THC model.
  - Third sampling trip April, 2015: Re-visit Desert Peak and McGinness Hills – sample same ports as 12/2014 field work
  - Sample additional non-geothermal wells for rare and conventional noble gases

Mandatory Summary Slide

- Found a strong to good correlation between He isotopes and reactivated structural discontinuities and deep high conductivity zones (MT) confirming relationship between He isotopes and integrated permeability and the importance of mantle underplating in driving He isotope compositions in surface features
- The use of a multiple continuum model for fracture-matrix flow, advective and diffusive transport of noble gas isotopes, reactive transport, and heat in a large-scale geothermal system provides a new advance in constraining fluid flow pathways and resource evaluation.
- Sensitivity tests of 2-D model indicate the more complex and realistic model runs will enable better constraints on fluid flow rates
- Connecting measured $^{3}He/^{4}He$ ratios with model derived flow rates is attainable
- Issues preventing collection of optimum samples for residence age measurements identified and solved.