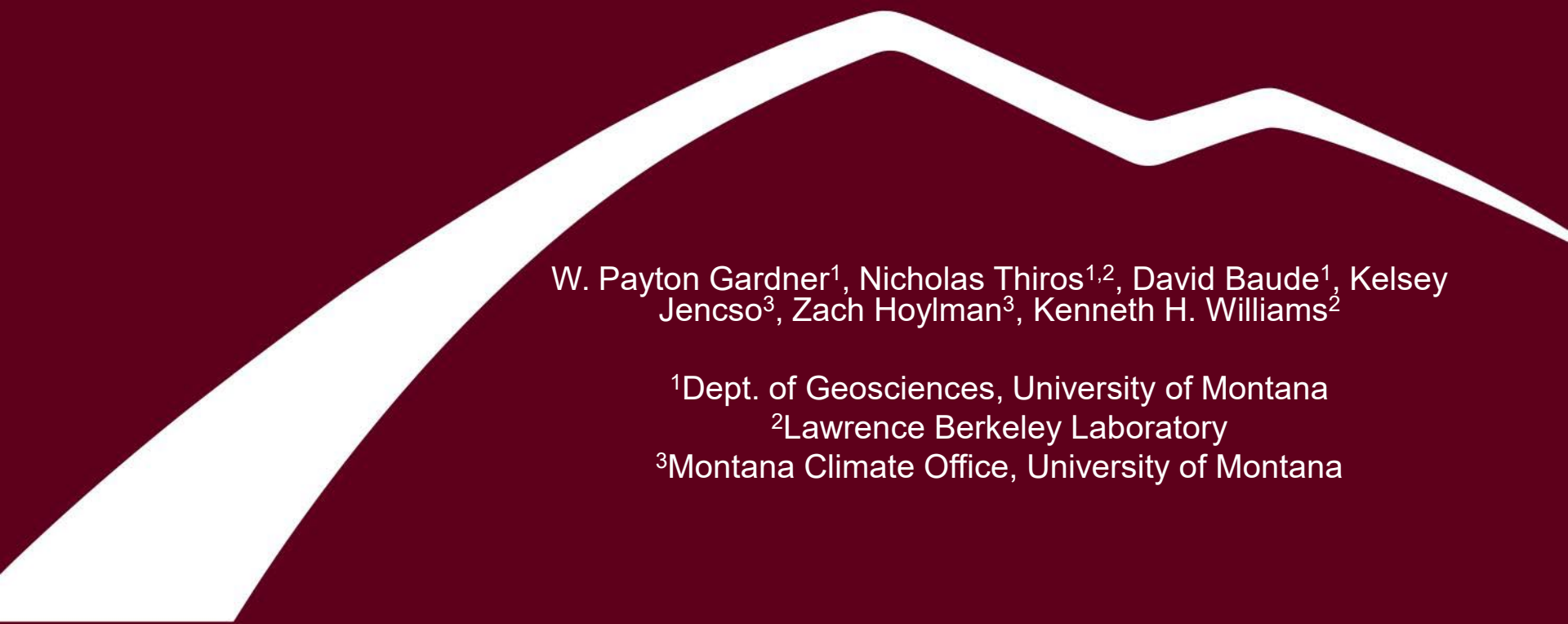


Comparative Observations of Mountain Aquifer System Dynamics in western Montana and Colorado



W. Payton Gardner¹, Nicholas Thiros^{1,2}, David Baude¹, Kelsey Jencso³, Zach Hoylman³, Kenneth H. Williams²

¹Dept. of Geosciences, University of Montana

²Lawrence Berkeley Laboratory

³Montana Climate Office, University of Montana

Acknowledgments

Students:

Isabellah VonTrapp, Jenna Rolle, Kimberly Bolhuis, Rob Livesay

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U.S. DEPARTMENT OF
ENERGY

Office of Science



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Environmental
System Science



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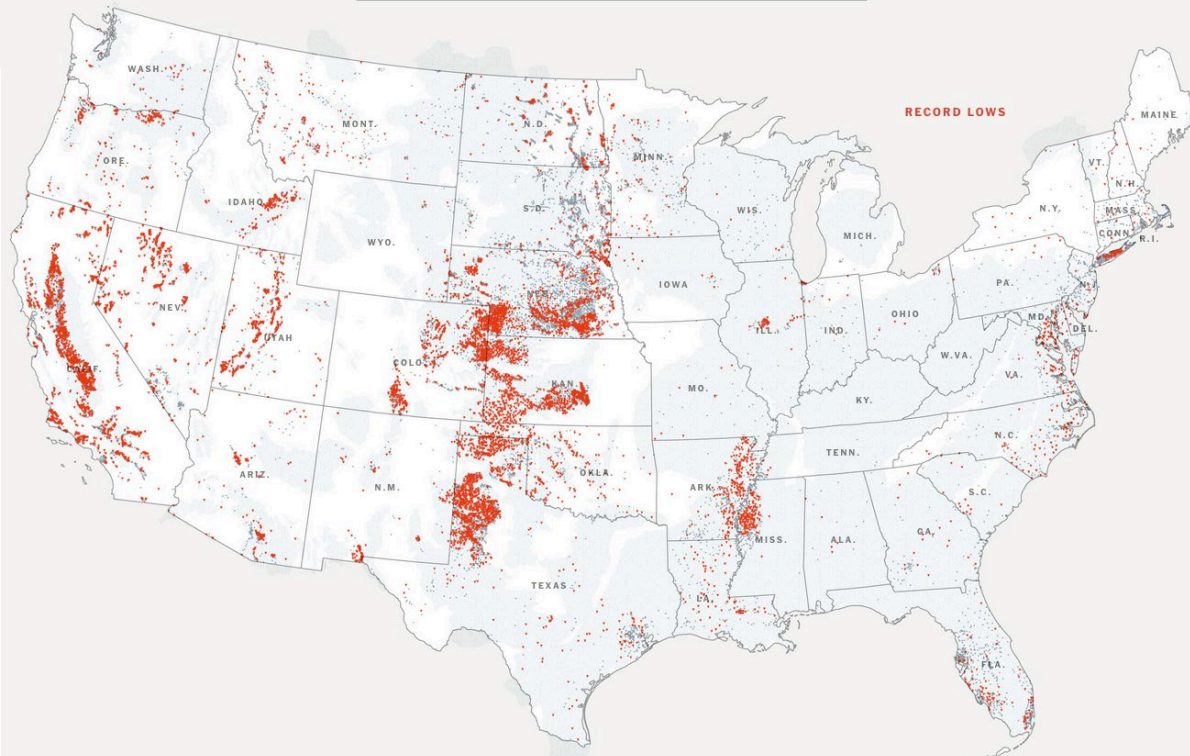
UNCHARTED WATERS

America Is Using Up Its Groundwater Like There's No Tomorrow

Overuse is draining and damaging aquifers nationwide, a New York Times data investigation revealed.

In the past decade, four of every 10 sites hit all-time lows. And last year was the worst yet.

 Record low annual water levels, past decade

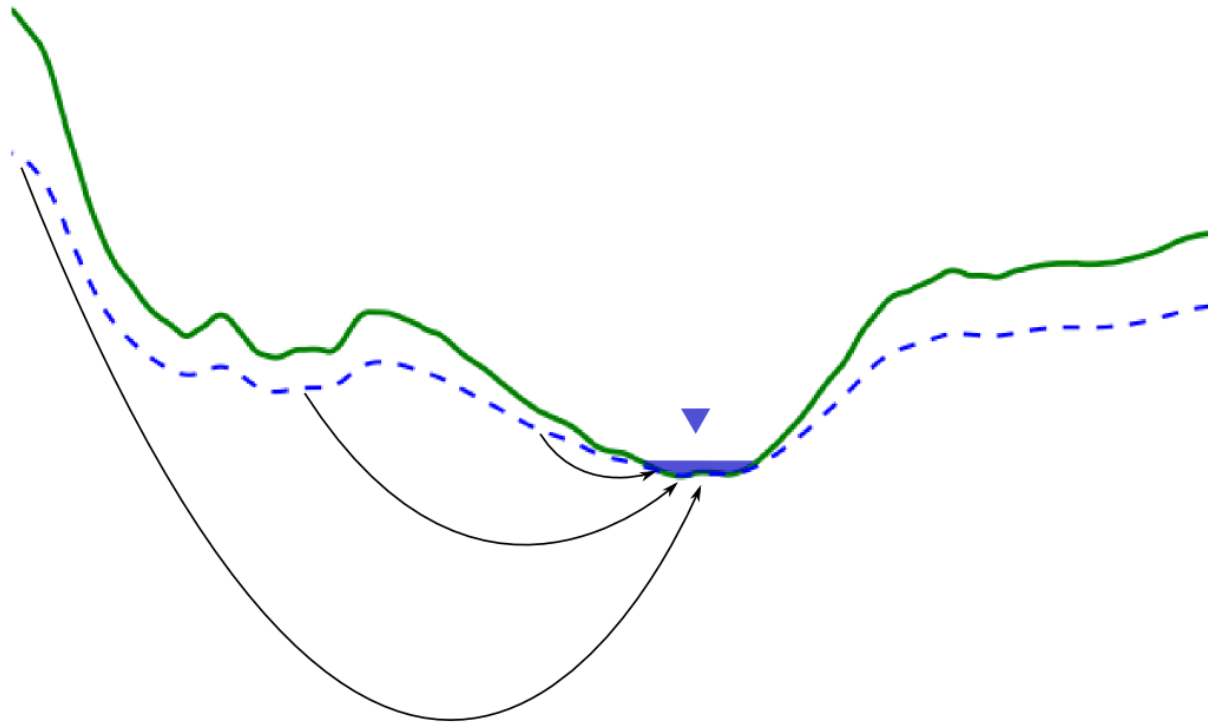


By [Mira Rojanasakul](#), [Christopher Flavelle](#), [Blacki Miglozzi](#) and [Eli Murray](#)

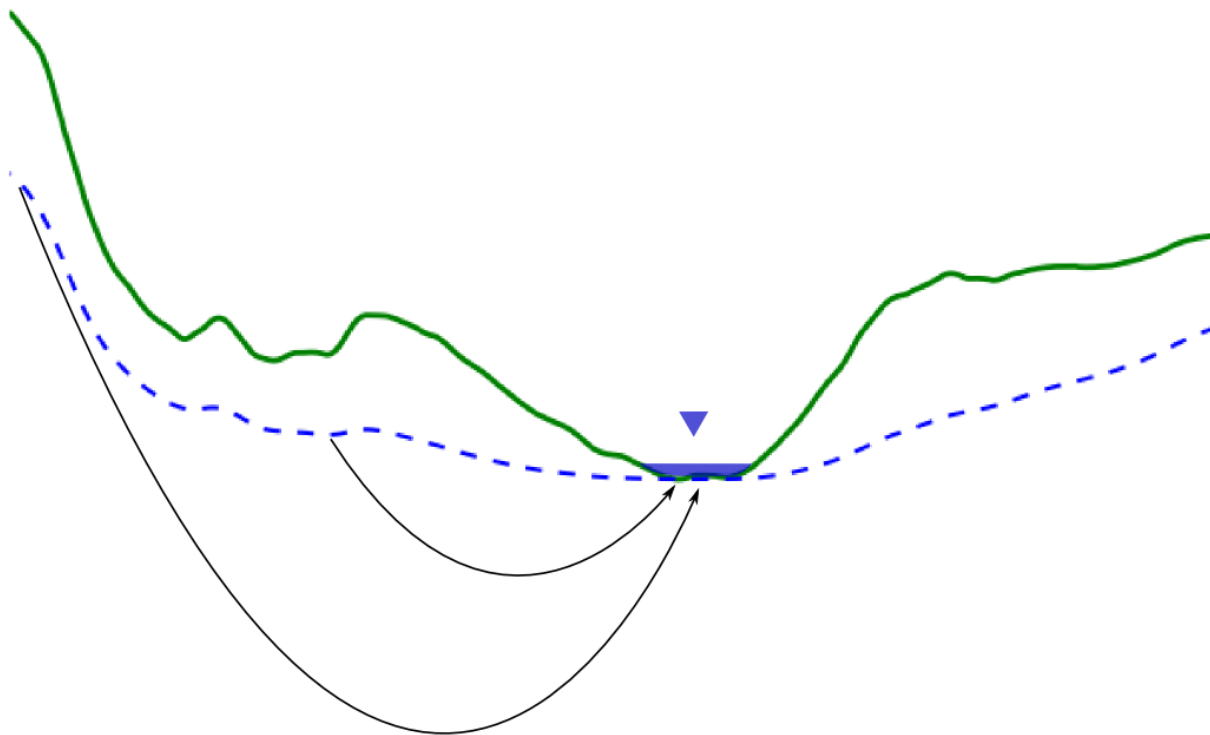
The first article in a series on the causes and consequences of disappearing water.

Aug. 28, 2023

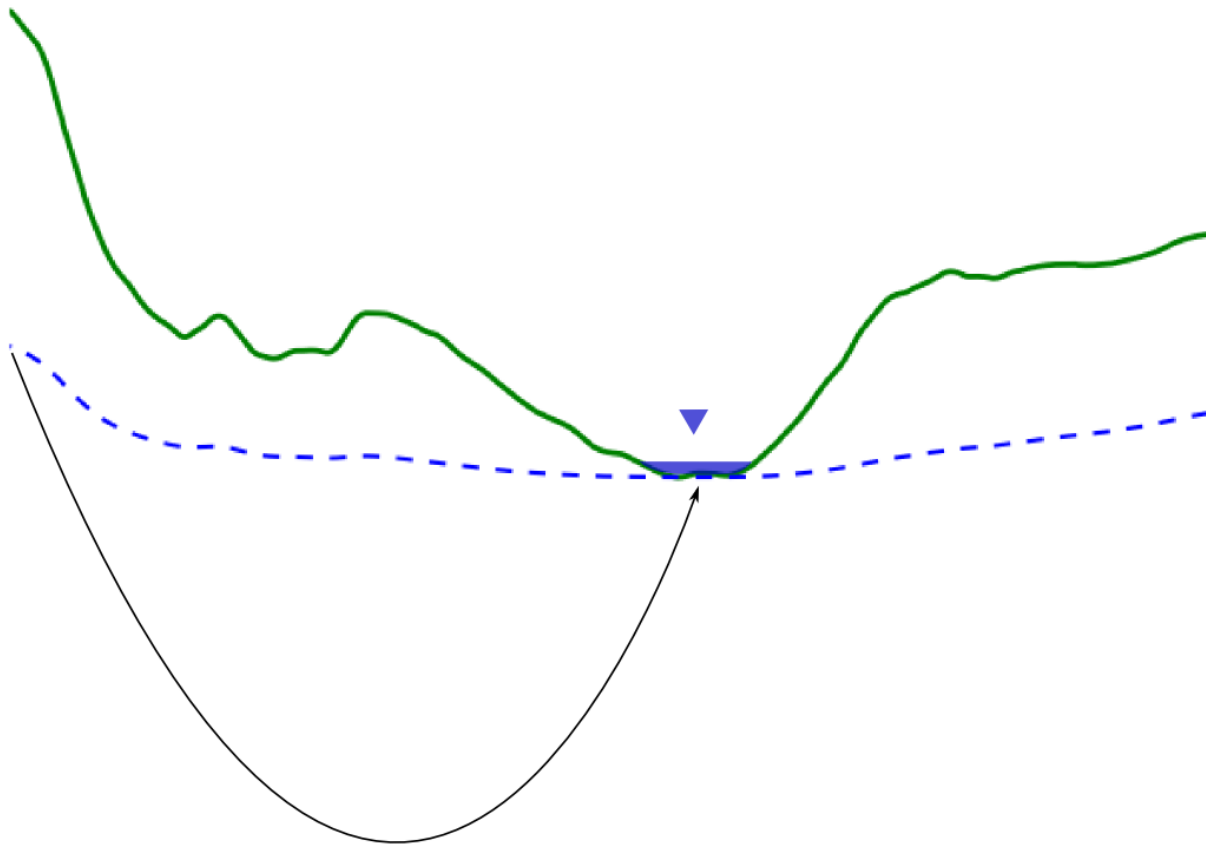
Why do we care?



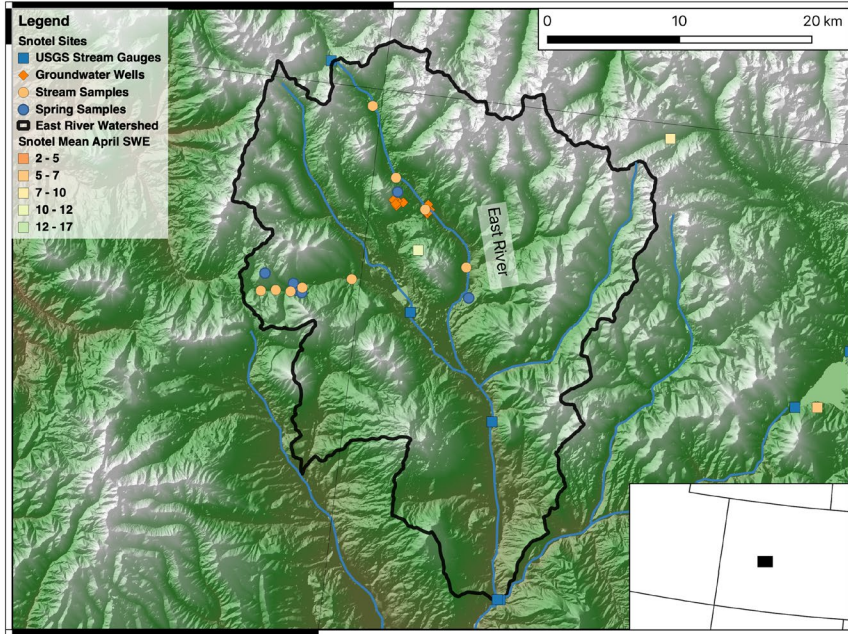
The Drought Continues...



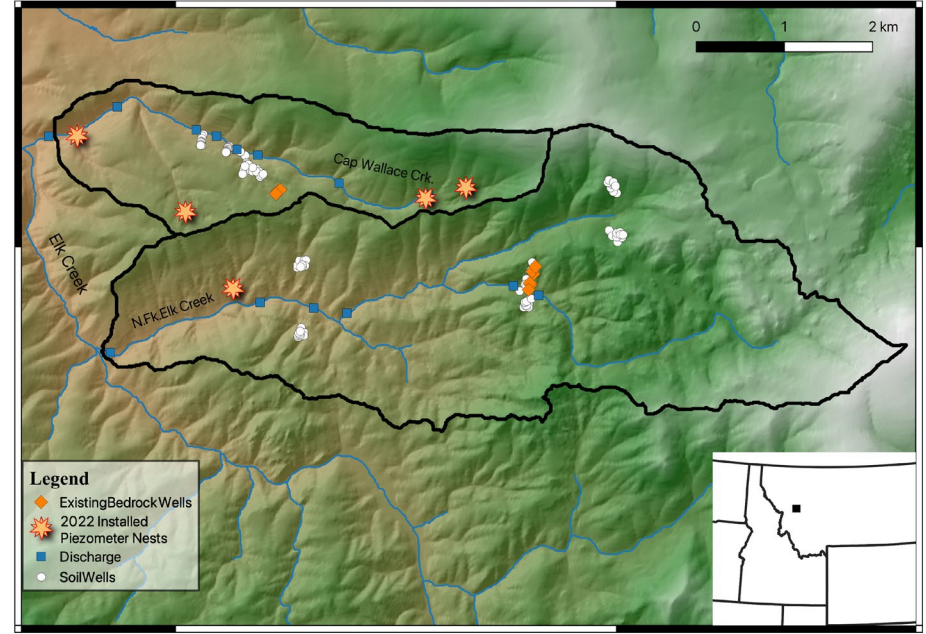
And Continues



Field Locations Discussed Today

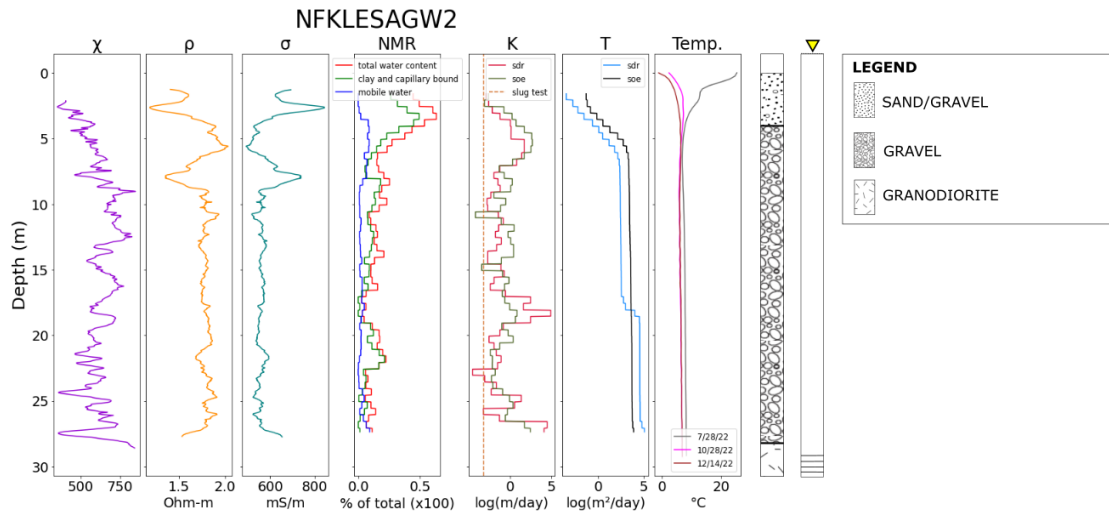
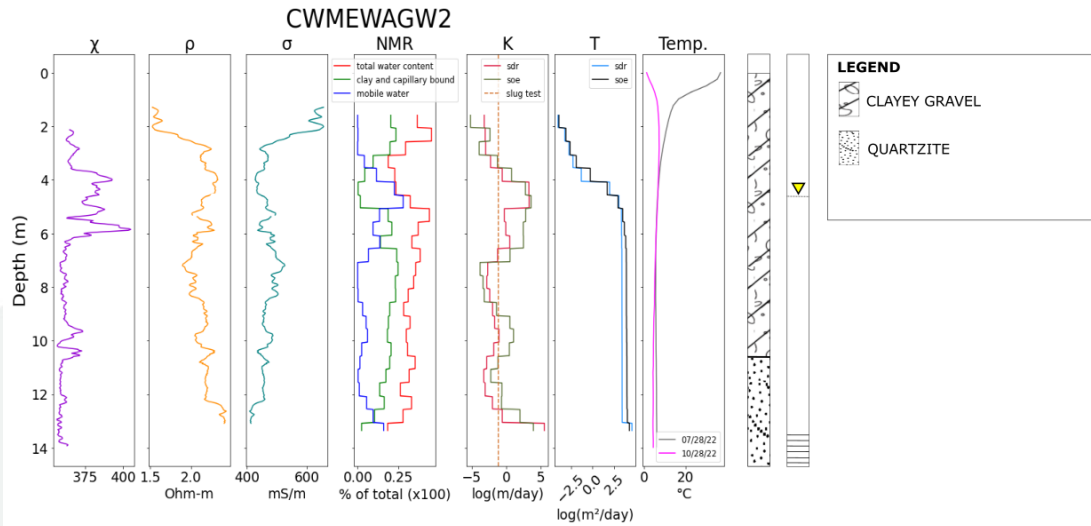


- East River near Crested Butte CO
- Site underlain by the Cretaceous Mancos Shale
- Alpine to montane

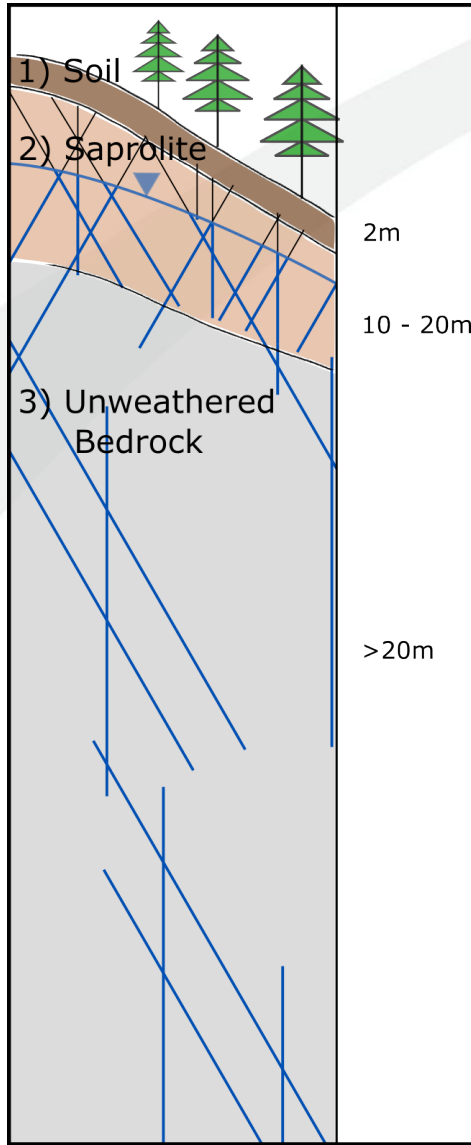


- Lubrecht site near Missoula
- Cap Wallace underlain by the pre-Cambrian Garnet Range (silt stone) and Bonner (quartzite)
- N Fk. Elk Creek underlain by the Cretaceous granite.
- Sub-alpine to montane

Typical Borehole logs



Typical Subsurface Architecture



- Typical structure from drilling logs in Montana and Colorado
- Weathering grades from soil to fractured bedrock
- Approximately three layers
 - Soil
 - Saprolite
 - Bedrock

Active Bedrock Groundwater Systems

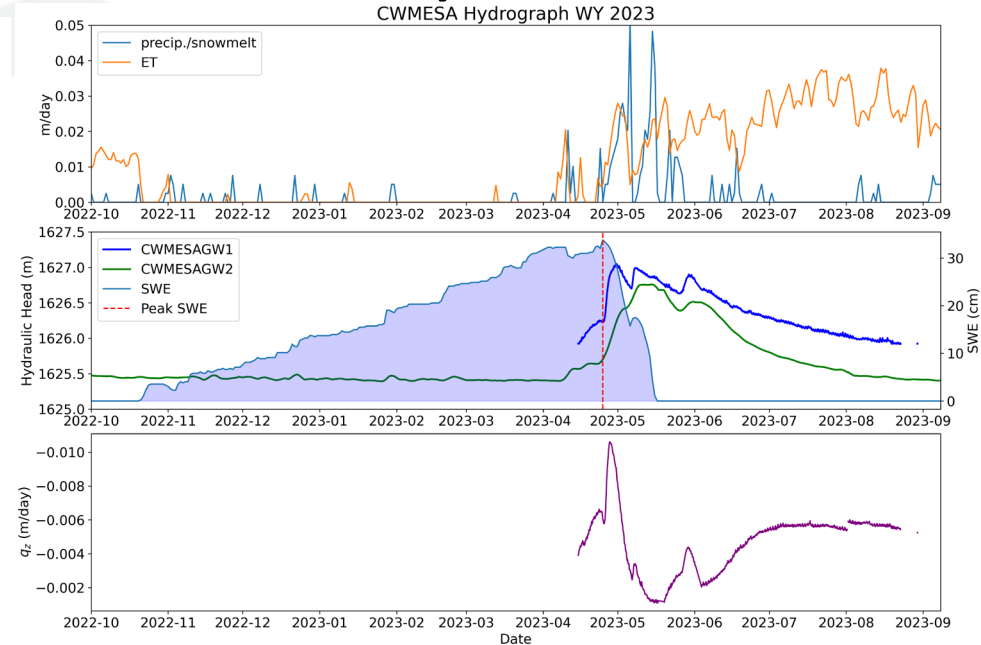
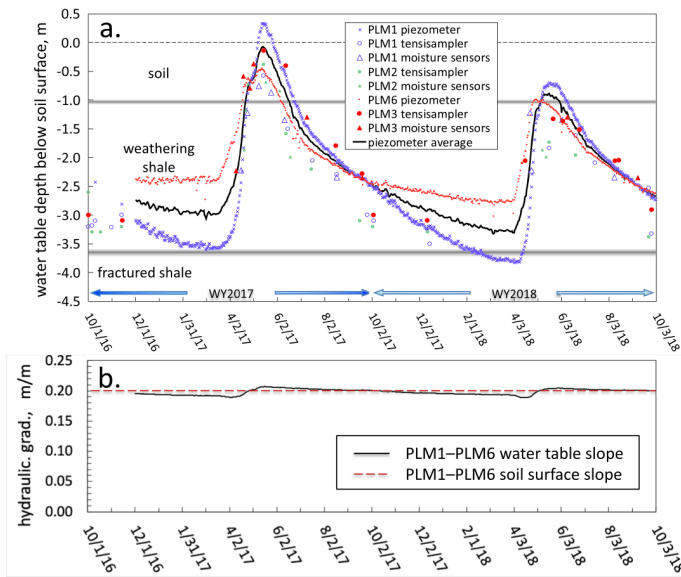


Figure 7. Time trends in the water table along the hillslope transect during WY2017 and WY2018. (a) Depths to the water table determined with piezometers, and estimated with tensiometers and moisture sensors. The heavy black line is the average of PLM1 and PLM6 piezometers, used in transmissivity feedback calculations. (b) Comparison between the water table slope and the average soil surface slope (0.200 m m^{-1}) along the transect.

- Bedrock Groundwater Responds Rapidly to Snowmelt
- Single Recharge Event in the Spring
- Decline for the rest of the year, even in the heavy monsoon period in Colorado.

Water Resources Research

RESEARCH ARTICLE
10.1029/2019WR025093

Key Points:

- Hillslope groundwater flow depth and water mass balance are reconciled using transmissivity feedback
- Solute concentrations are diminished during low snowpack years because of limited transmissive fluxes along the soil and weathering zones
- Subsurface concentration-discharge relations were developed to explain time-dependent hillslope exports of solutes to surface waters

Depth- and Time-Resolved Distributions of Snowmelt-Driven Hillslope Subsurface Flow and Transport and Their Contributions to Surface Waters

Tetsu K. Tokunaga¹, Jiamin Wan¹, Kenneth H. Williams¹, Wendy Brown², Amanda Henderson², Yongman Kim¹, Anh Phuong Tran^{1,3}, Mark E. Conrad¹, Markus Bill⁴, Rosemary W.H. Carroll⁴, Wenming Dong⁵, Zexuan Xu¹, Adi Lavy⁶, Ben Gilbert⁷, Sergio Romero^{1,3}, John N. Christensen¹, Boris Faybishenko¹, Bhavna Arora¹, Erica R. Siirila-Woodburn¹, Roelof Versteeg⁸, Jonathan H. Raberg¹, John E. Peterson¹, and Susan S. Hubbard¹

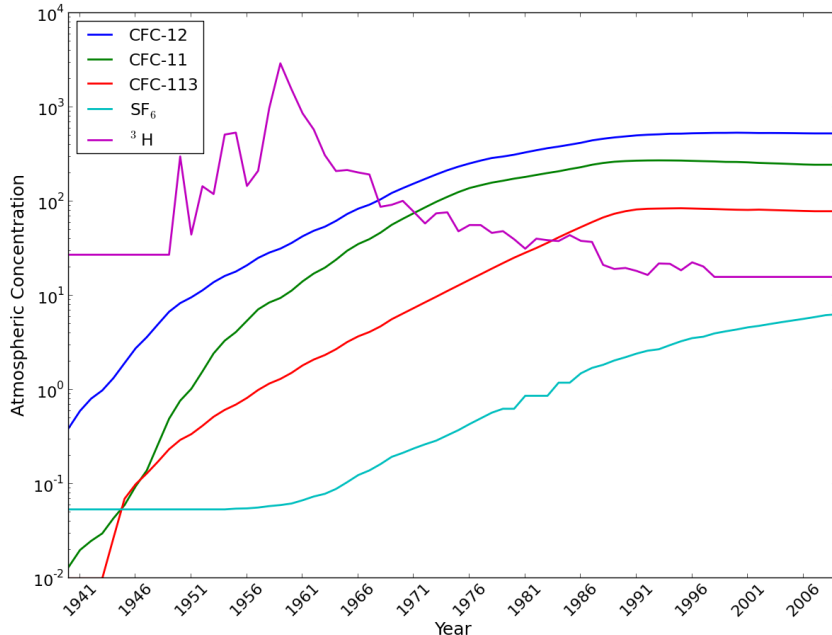
¹Earth and Environmental Sciences Area, Lawrence Berkeley National Laboratory, Berkeley, California, USA, ²Rocky Mountain Biological Laboratory, Crested Butte, Colorado, USA, ³Water Research Institute, Hamoi, Vietnam, ⁴Division of Hydrological Sciences, Desert Research Institute, Reno, Nevada, USA, ⁵Department of Earth and Planetary Science, University of California, Berkeley, California, USA, ⁶Subsurface Insights, Hanover, New Hampshire, USA

Supporting Information:
• Supporting Information S1

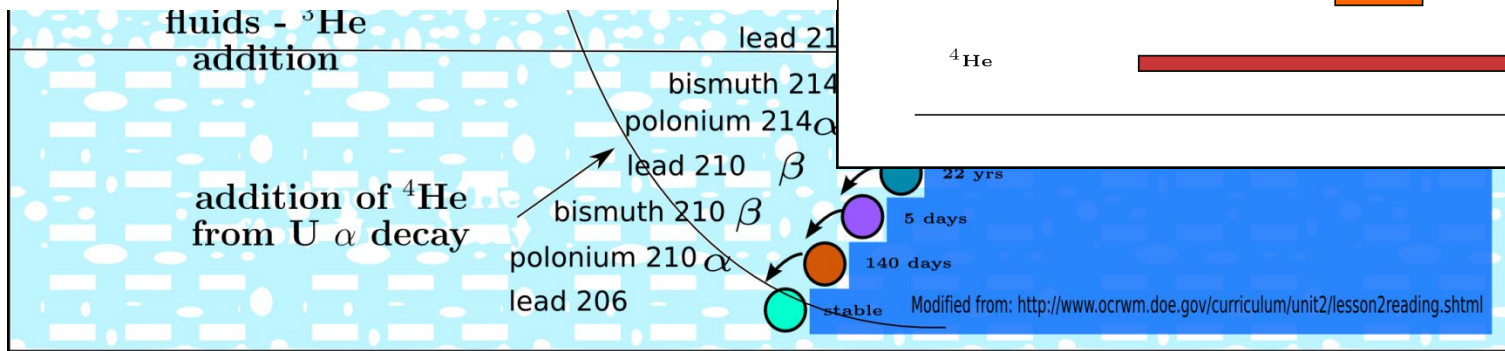
Looking into the Black Box. What is age and

Provenance of Mountain Air if We Can

Cosmic Ray
Bombardment,
Anthropogenic →



Tracer	Approximate Age Dating Range Log Years Before Present							
	1	2	3	4	5	6	7	8
^{222}Rn	█							
$^3\text{H}/^3\text{He}$	█	█						
^{85}Kr	█	█						
CFC's	█	█						
^{32}Si			█	█				
^{39}Ar			█	█				
^{14}C				█	█			
^{36}Cl						█	█	
^{81}Kr						█	█	
^4He								█

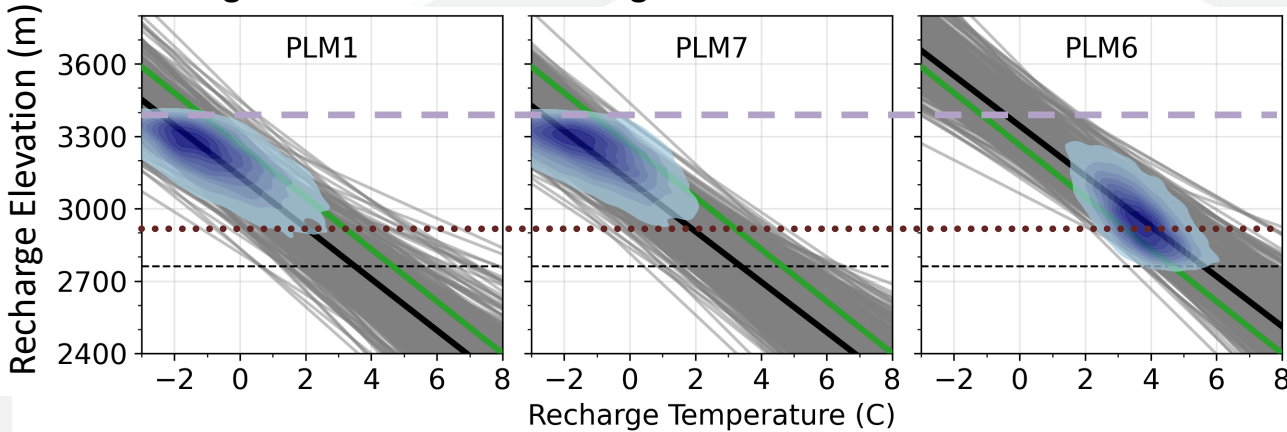
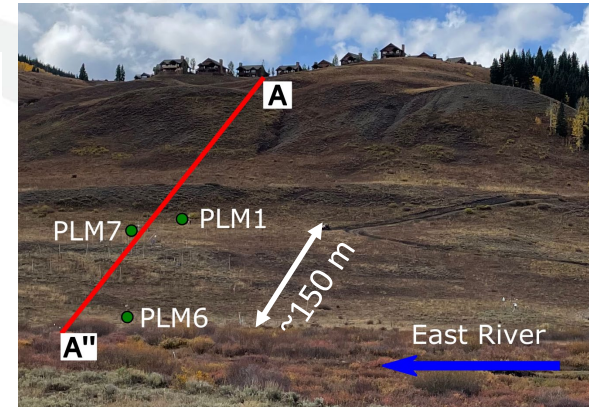


Noble Gas Recharge Conditions are Variable Along the Hillslope

Mid-slope
Cold Temperatures
High Elevations

Mid-slope
Cold Temperatures
High Elevations

Toe-slope
Warm Temperatures
Low Elevations



Mid-slope
Cold
Temperatures
High Elevations

Toe-slope
Warm
Temperatures
Low Elevations

Mid-slope
Cold
Temperatures
High Elevations

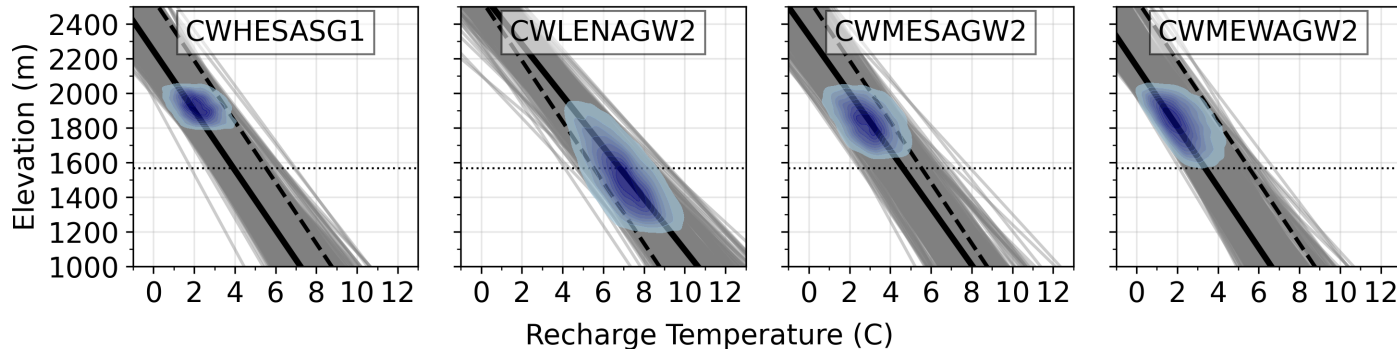
Mid-slope
Cold
Temperatures
High Elevations

-- Prior Model

— Max a Posteriori

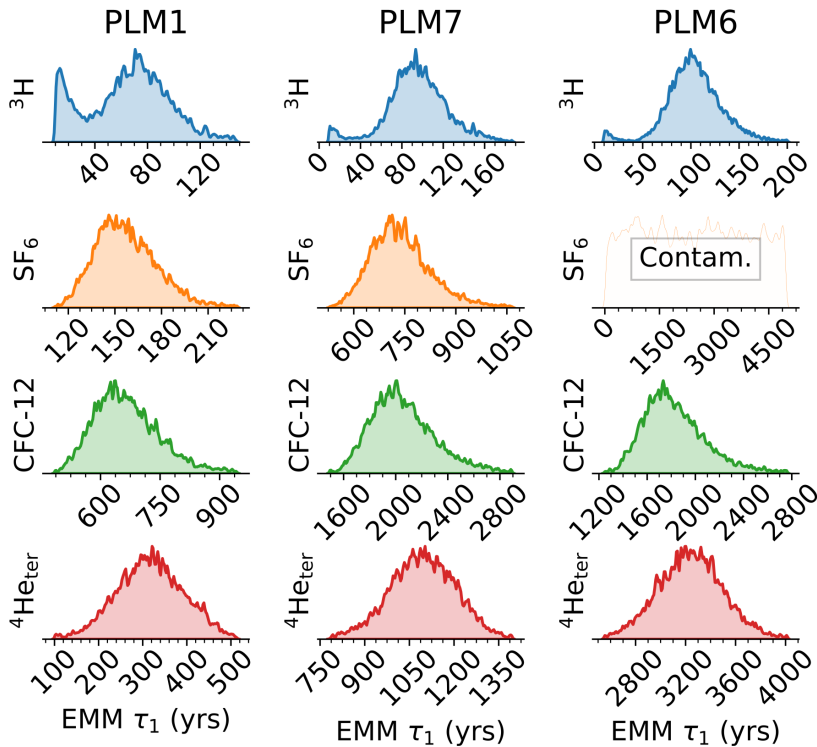
— Posterior Uncertainty

■ Posterior Distribution

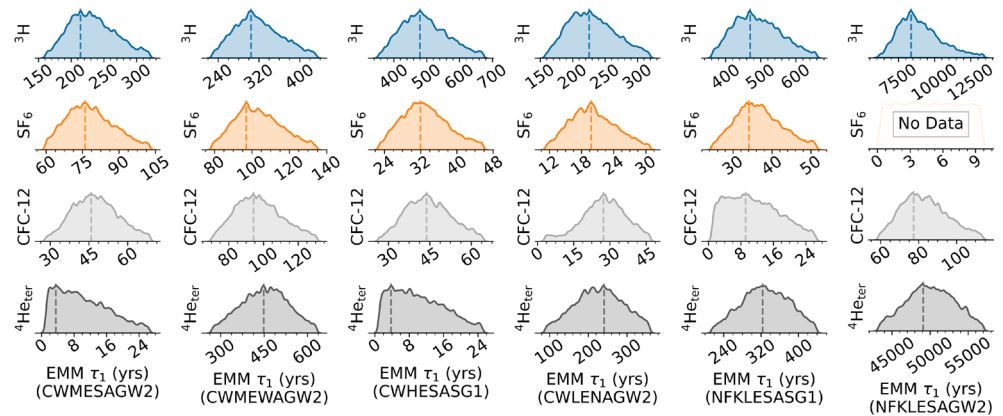


Groundwater Ages

Crested Butte

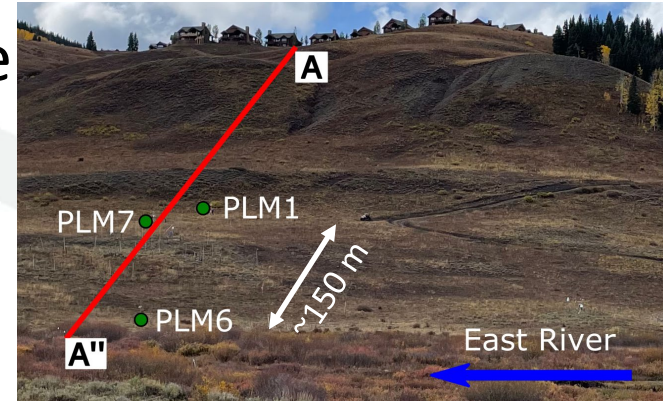
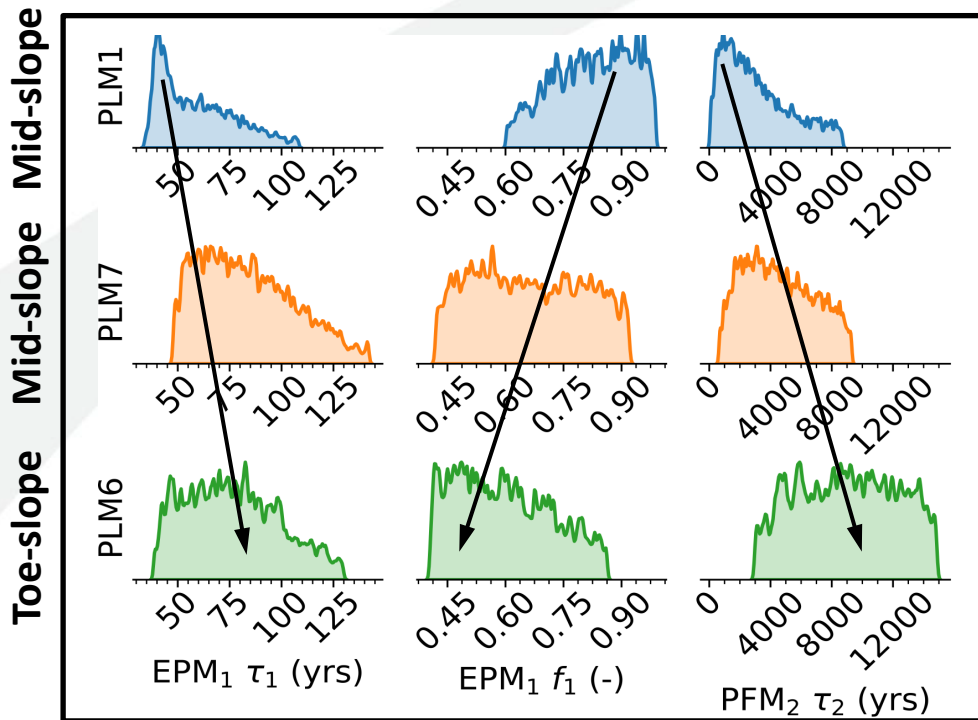


Lubrecht



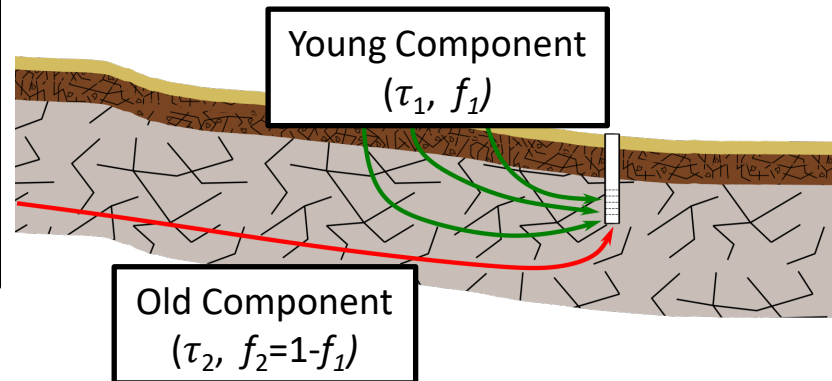
- Definitely a significant old water component
- Groundwater Ages between 10's to 1000's of years
- In general, increase downslope, but trend is more complicated when not a single hillslope.
- Mixing of ages is apparent.

Mean Ages Increase Moving Downslope



Binary Mixing Model

Exponential Piston-Flow : Piston-Flow



Moving
Downslope...

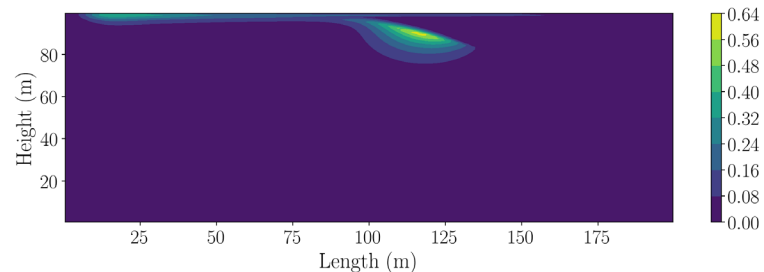
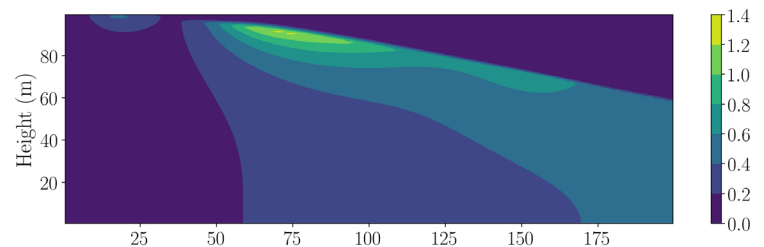
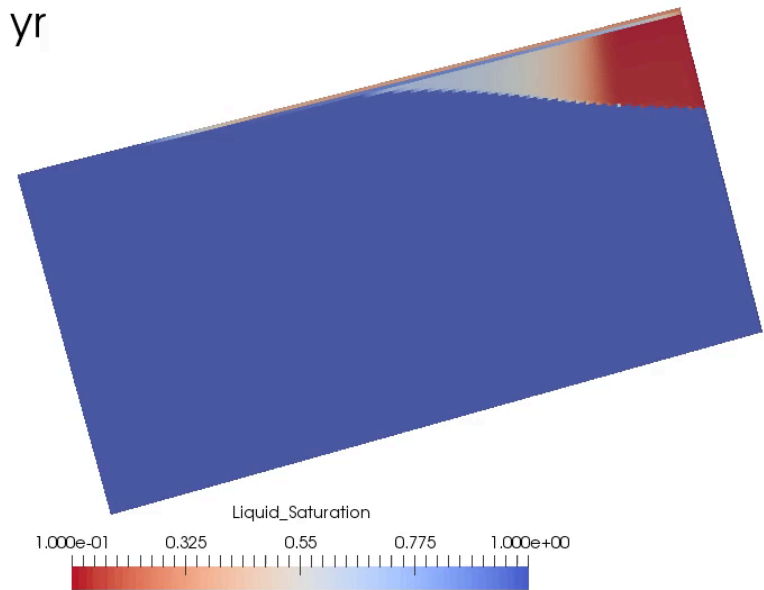
Young
Comp.
Mean Age
Increases

Young
Comp.
Fraction
Decreases

Old Comp.
Mean Age
Increases

Conclusions

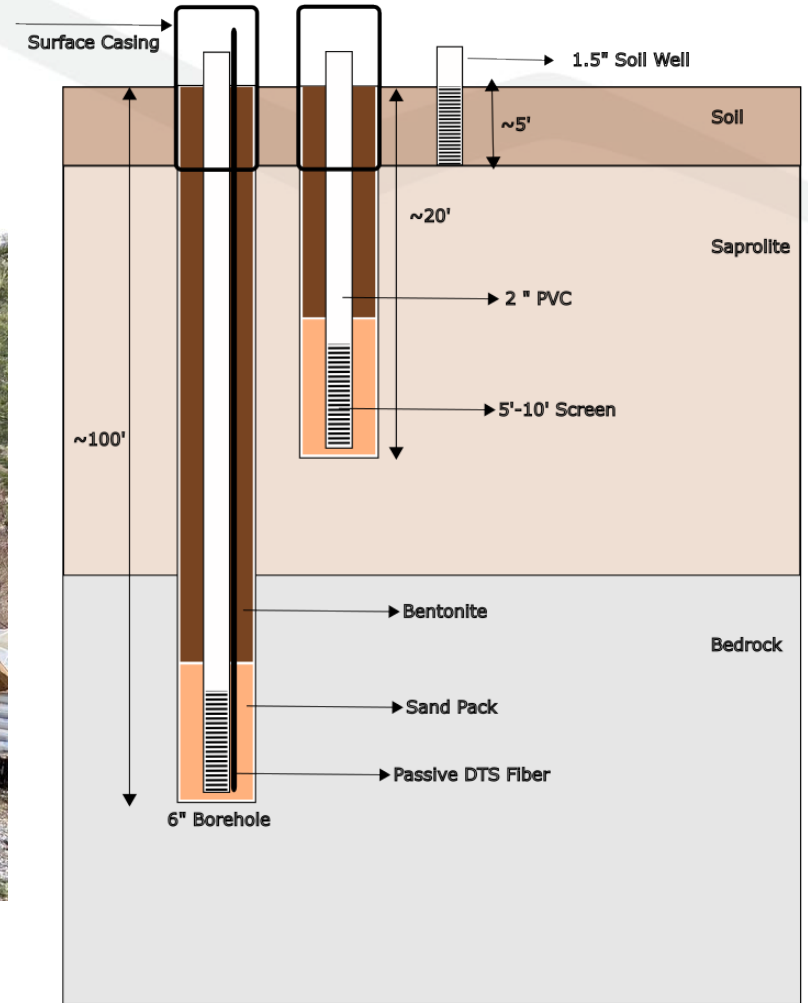
- Mountain blocks host active aquifer systems
- Water table fluctuates between deep bedrock through saprolite into soil
 - Seasonally
 - Depends on landscape position
- Recharge location on hillslopes is generally high on the hillslope, $\sim 2/3$ of total ridge elevation
- Bedrock groundwater has long residence times
 - Residence time >100 years indicated by multiple tracers
 - Mixing of younger and older reservoirs and matrix diffusion can explain our long residence times
 - Fraction of older water increases the farther downslope we go
- Better constraints on residence time will help us understand the volume and depth of active groundwater circulation



Thanks!



Lubrecht Drilling



Recharge Conditions Inferred from Dissolved Noble Gases

Measured Dissolved Noble Gases

Ne, Ar, Kr, Xe

$f(\text{Temperature, Elevation, Excess-air})$

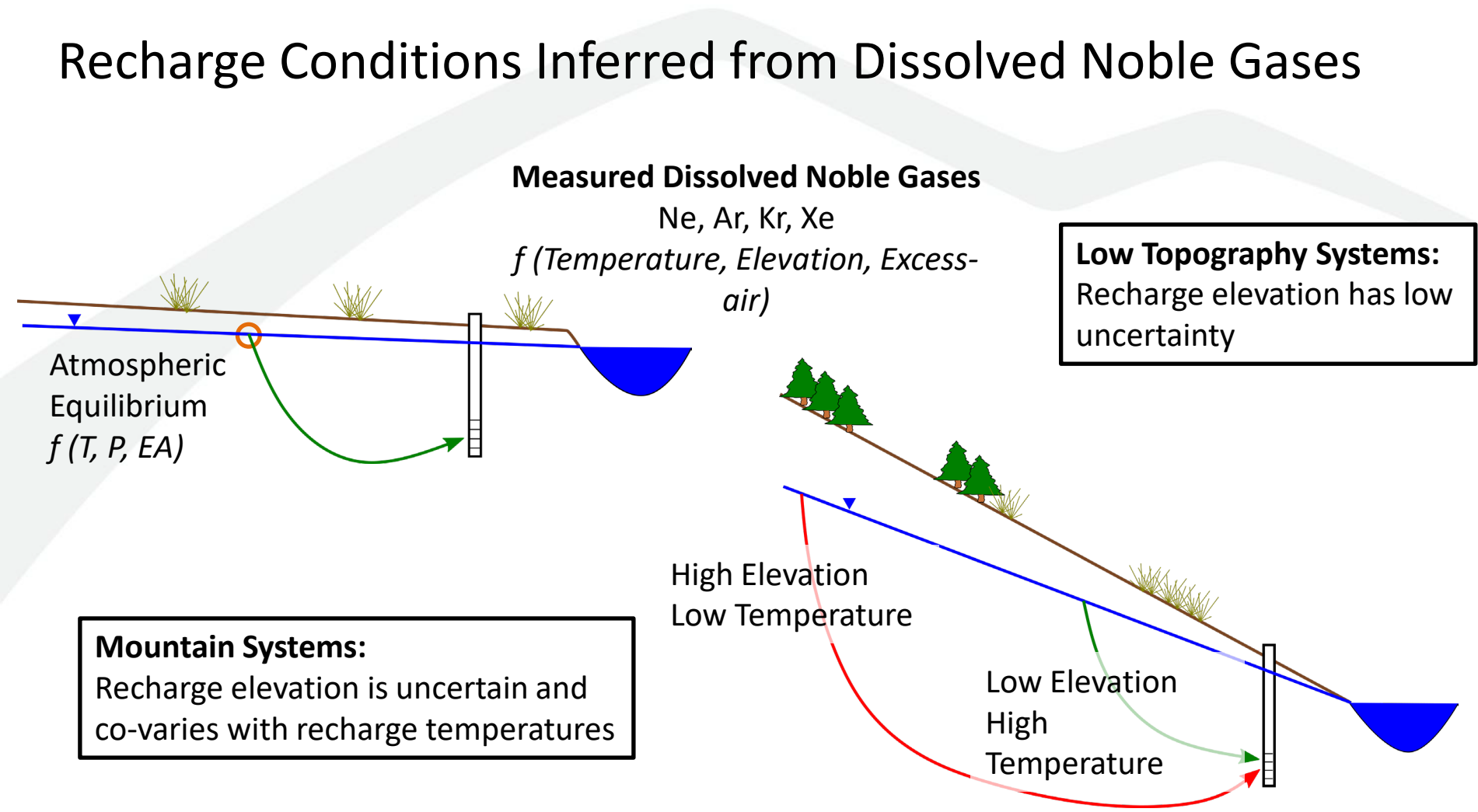
Atmospheric
Equilibrium
 $f(T, P, EA)$

Low Topography Systems:
Recharge elevation has low
uncertainty

Mountain Systems:
Recharge elevation is uncertain and
co-varies with recharge temperatures

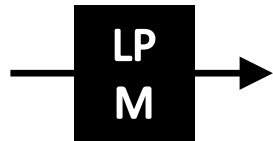
High Elevation
Low Temperature

Low Elevation
High
Temperature



Inferred Groundwater Ages Depend on the Uncertain Groundwater Recharge Conditions

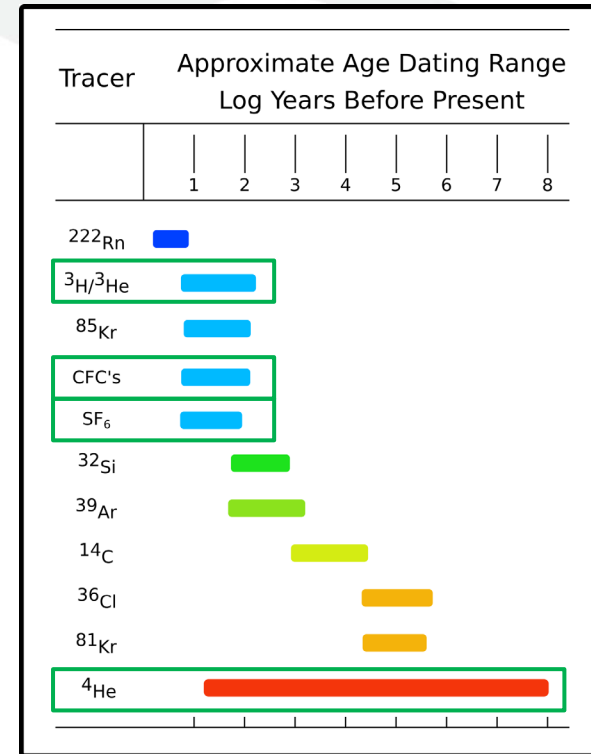
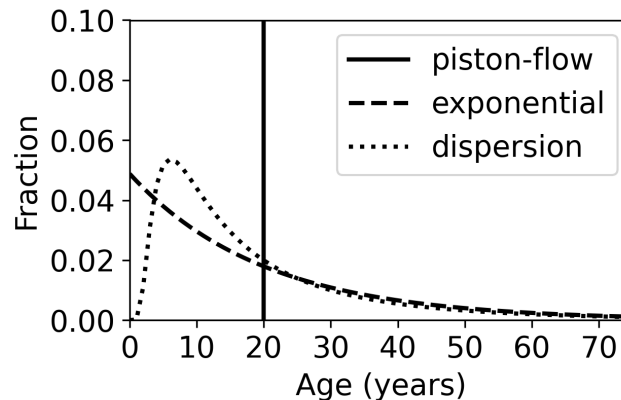
Environmental Tracer Observations
 ^3H , CFC-12, SF_6 , ^4He



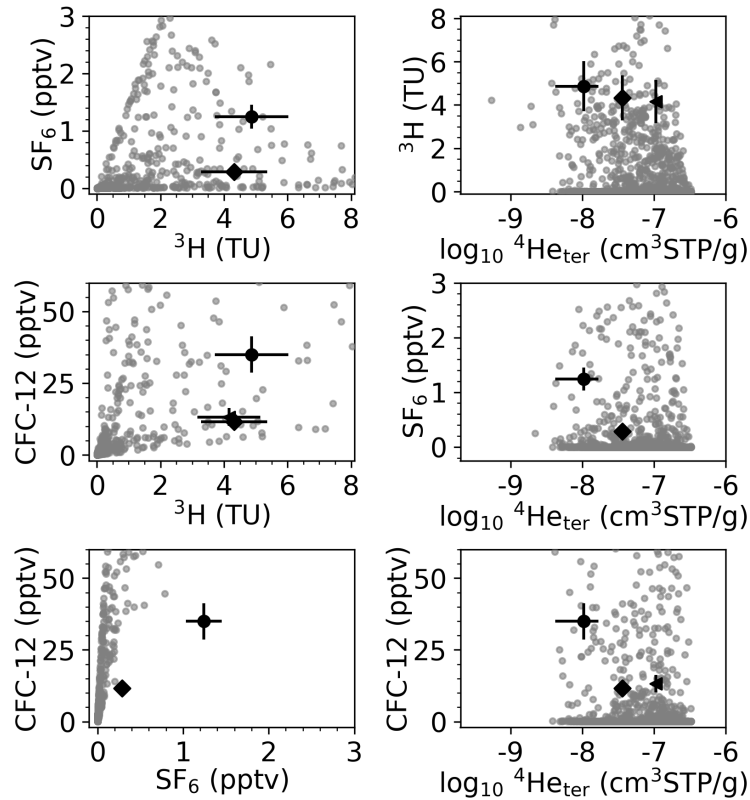
Bedrock Groundwater Mean Age

Function of:

- Recharge temperatures
- Recharge pressures
- Excess air conditions



Potential Processes Controlling Long Residence Time Fraction



Left: **EPM-EPM RTD** bi-variate tracer-tracer concentration plots generated using 15000 Monte Carlo samples of τ_1 , f_1 , η_1 , τ_2 , and η_2 .

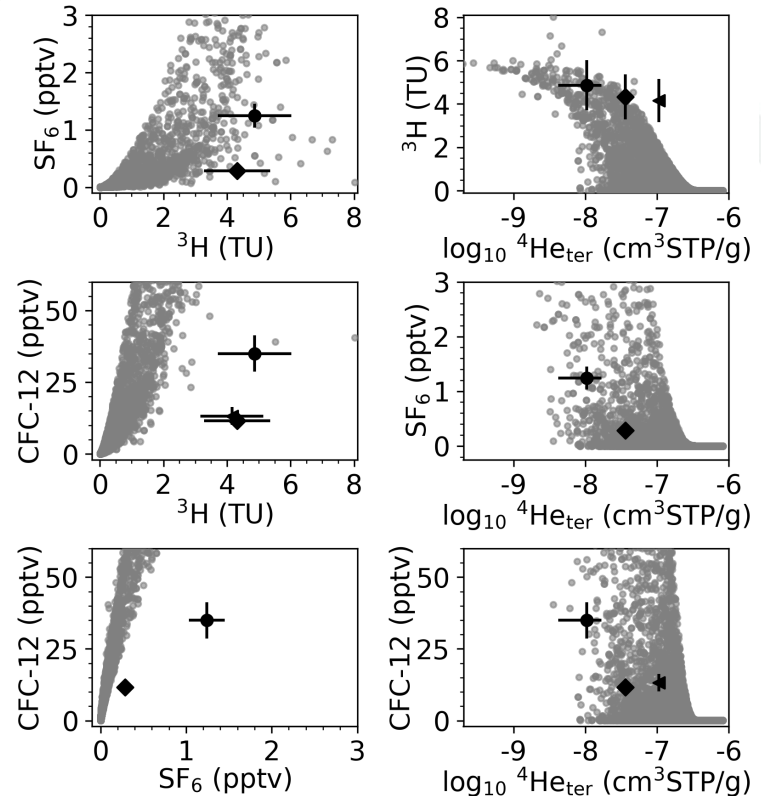


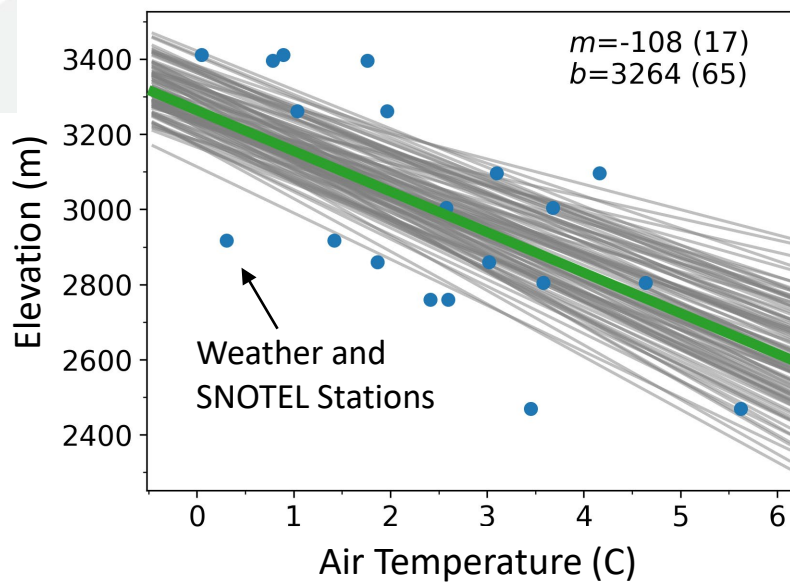
Figure 13: **Fracture Diffusion RTD** bi-variate tracer-tracer concentration plots generated using 10000 Monte Carlo samples of τ_{adv} , D , \bar{b} , and ϕ_{im} .

Inference of Dissolved Noble Gas Recharge Parameter Uncertainties with Markov-chain Monte Carlo

Goals

Infer noble gas recharge parameters using:

- (1) Temperature-elevation lapse rates
- (2) MCMC uncertainty analysis



Noble Gas Recharge Parameter Uncertainties

