Large Mountain Watersheds: Using Age to Understand Their Hydrologic Response

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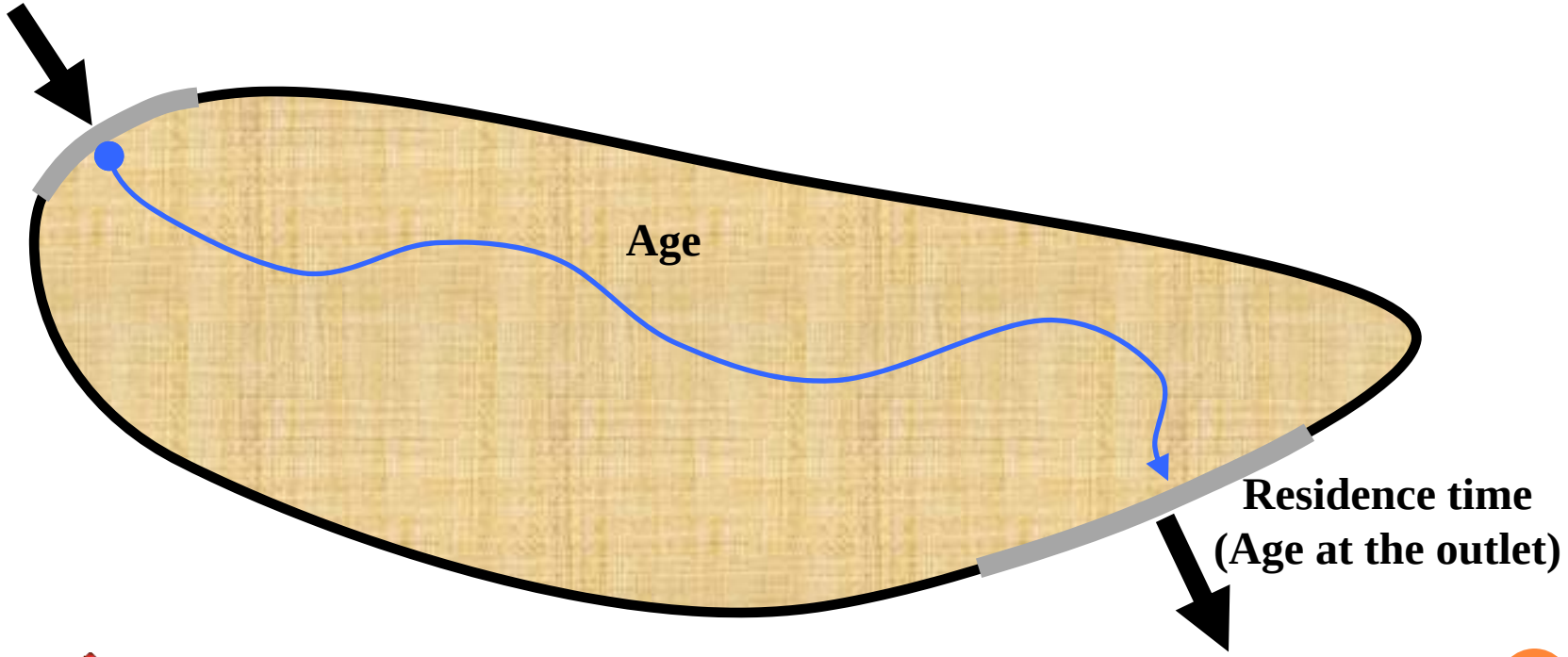
GROUNDWATER AGE

Definition:

If at some time *t* a water molecule is sampled for analysis at some location **x**, the groundwater age (τ) is defined as the time expended by this water molecule within the hydrologic system.

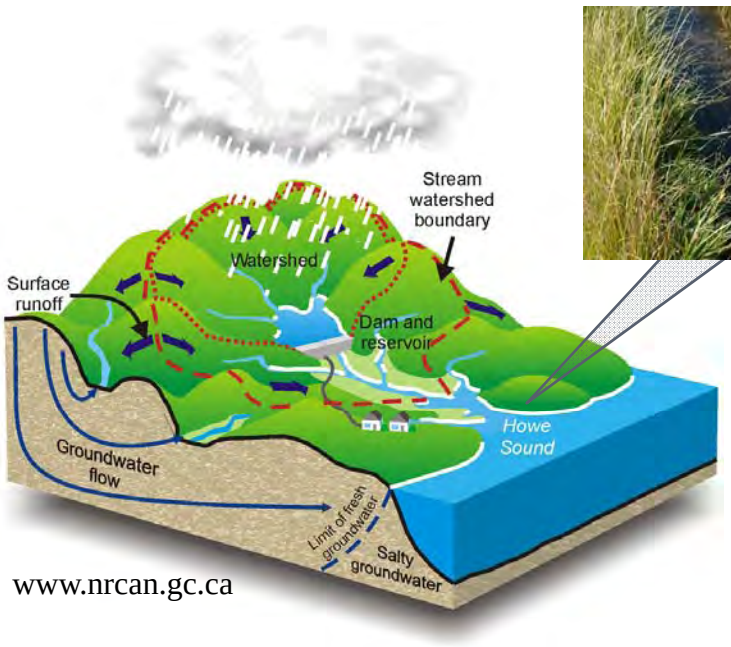
Residence time refers to the age of a water molecule when it is leaving the system



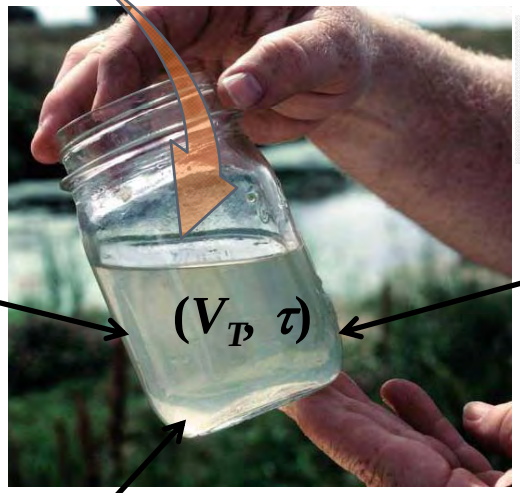
WHY DO WE CARE ABOUT AGE?

- Assessment of aquifer renewability, replenishment, and susceptibility.
- Identification of groundwater flow paths.
- Estimation of aquifer properties and groundwater velocities.
- Estimation of recharge rates.
- Model comparison.

AGE DISTRIBUTION



www.nrcan.gc.ca



(V_1, τ_1)

(V_i, τ_i)

(V_T, τ)

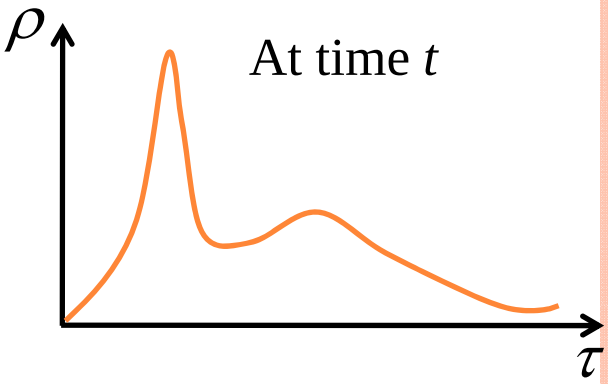
(V_2, τ_2)

Sample taken at time *t*

Measured volume and "mean" age

The sum of components of different ages τ

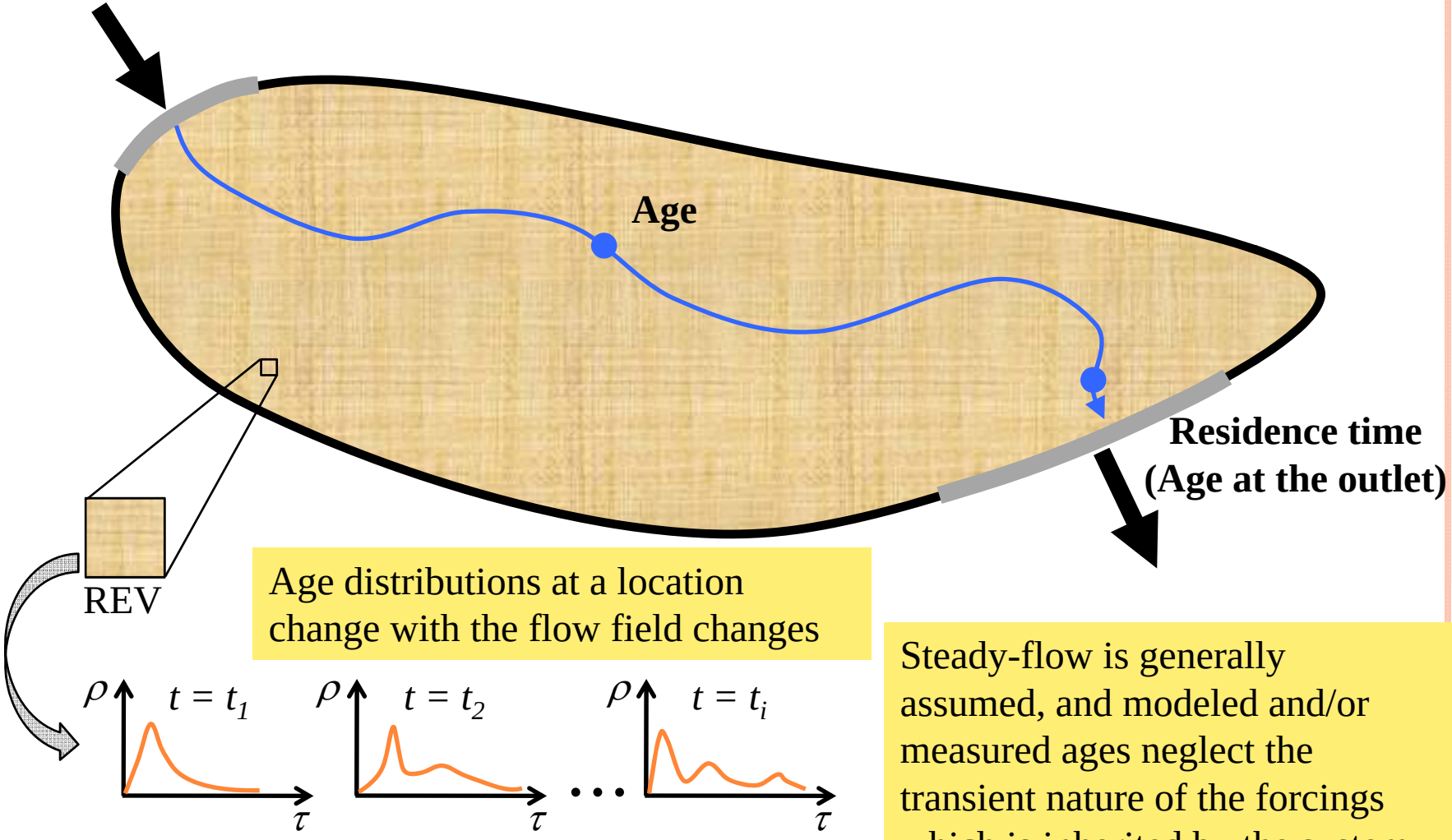
We refer to a distribution of ages ρ(τ,t)



AGE DISTRIBUTIONS

- Age distributions (ADs) encapsulate the net flow and transport characteristics of natural reservoirs.
- ADs represent the time of exposure of water to the system's biogeochemical conditions.
- This is an ubiquitous measure used in chemical engineering, atmospheric sciences, oceanography, and surface and subsurface hydrology among others. Then, any knowledge that we acquire can be transferred to other areas of research.

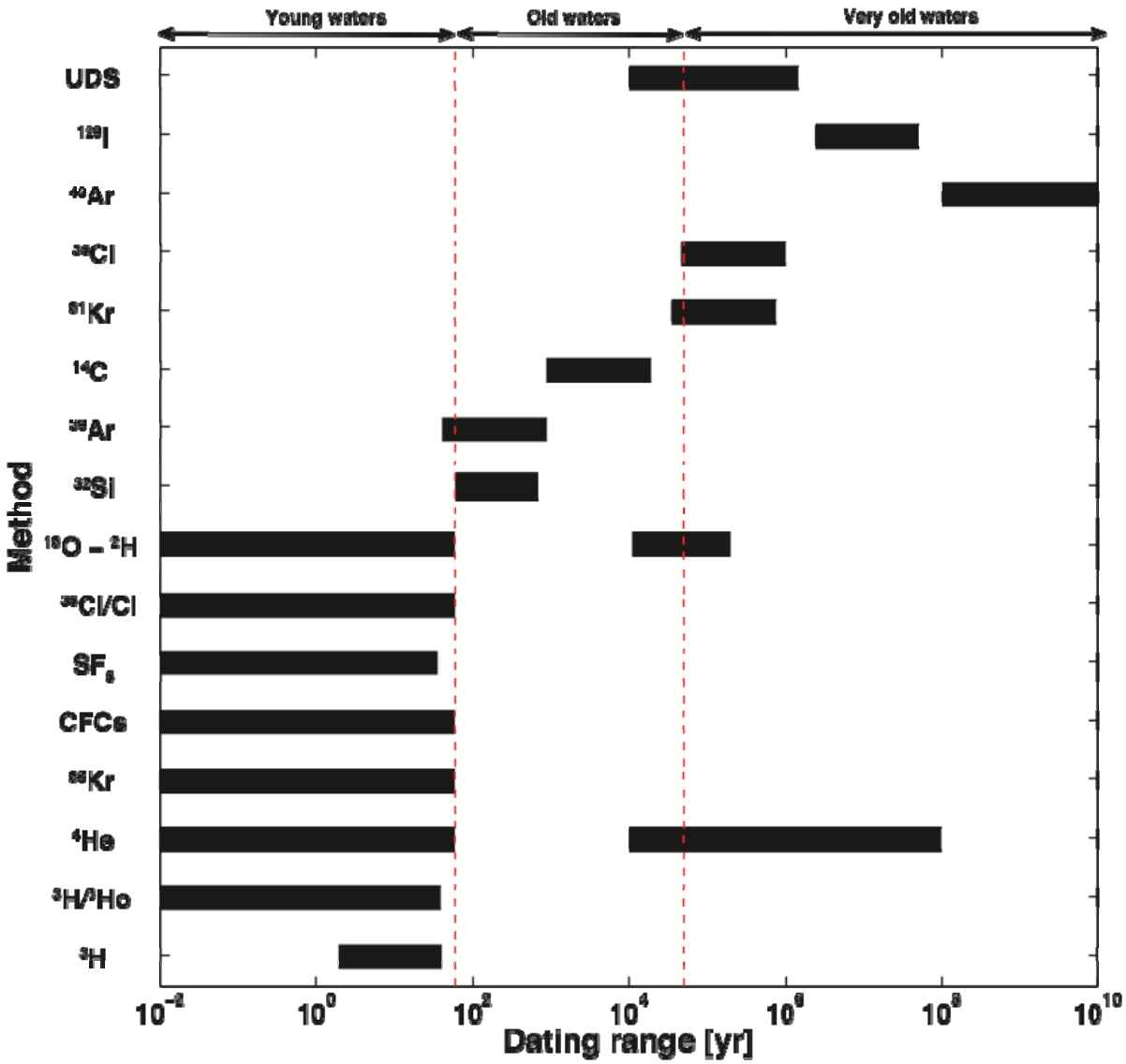
AGE DISTRIBUTIONS (AD), RESIDENCE TIME DISTRIBUTIONS (RTD), AND THE ROLE OF TRANSIENT FLOW



Age distributions at a location change with the flow field changes

Steady-flow is generally assumed, and modeled and/or measured ages neglect the transient nature of the forcings which is inherited by the system.

ENVIRONMENTAL TRACERS

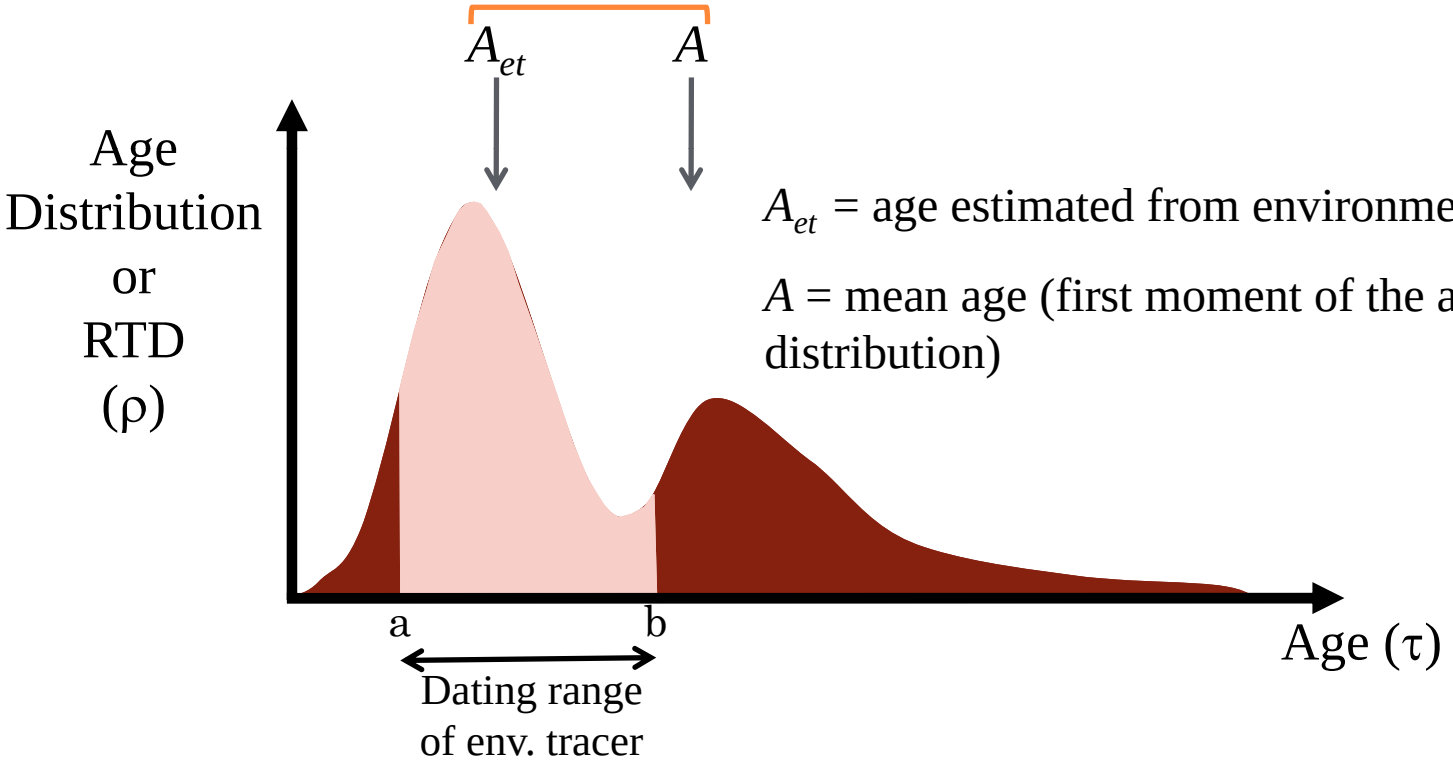


Different tracers have different dating ranges and therefore weight different subintervals of the age distributions

Mixing and flow dynamics dictate the difference between measured ages and the mean of the age distribution

WHAT IS THE ENVIRONMENTAL TRACER TELLING US?

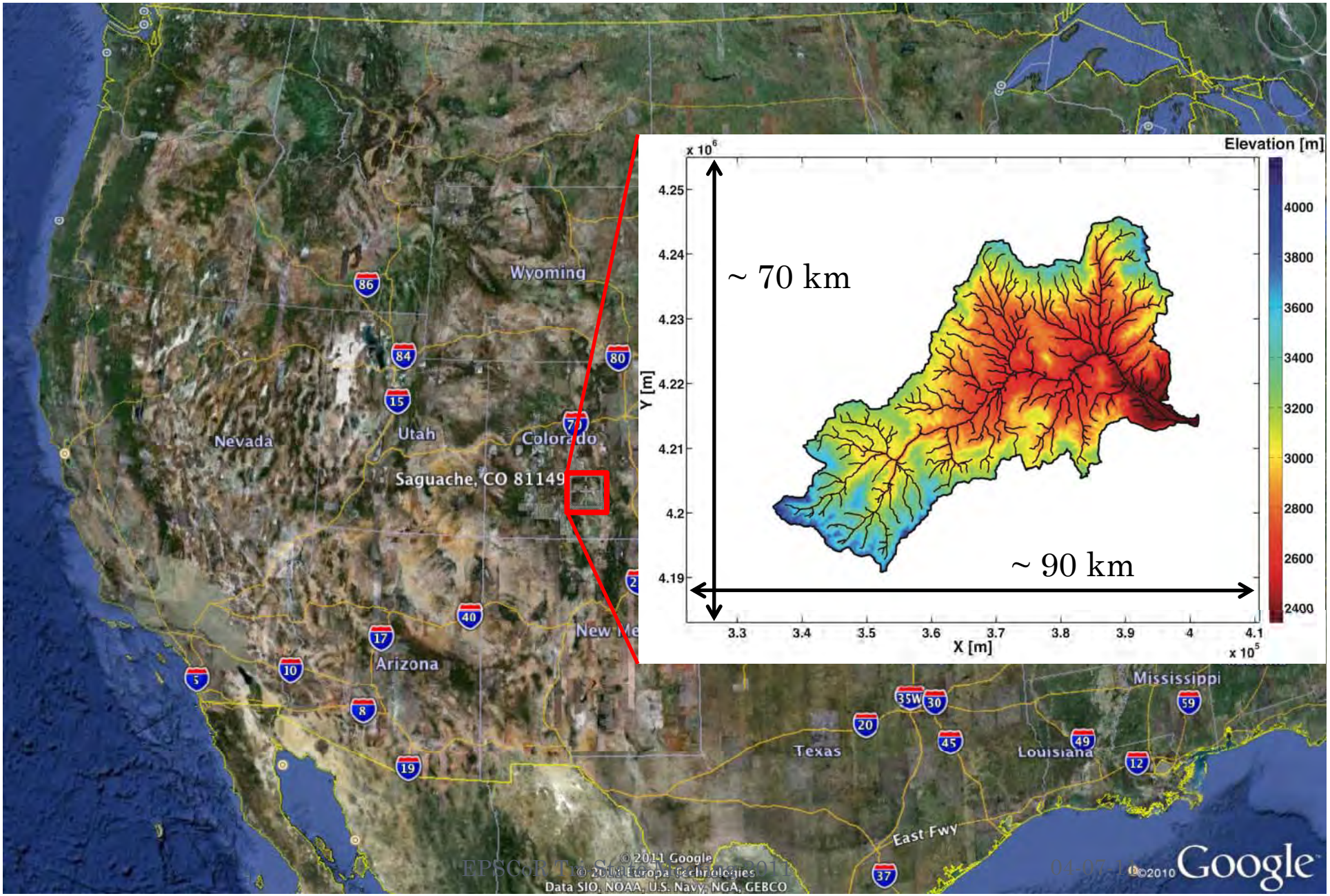
This difference depends on
the tracer, mixing, and flow dynamics

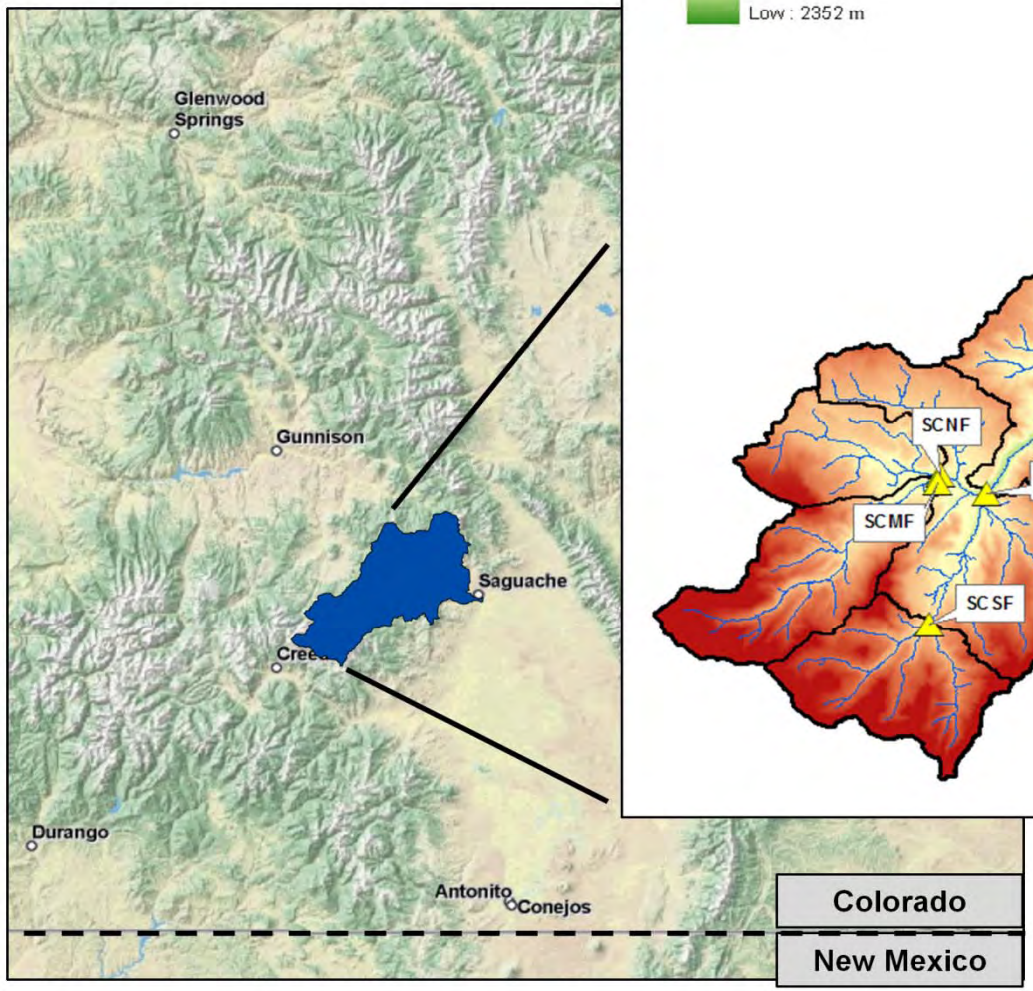


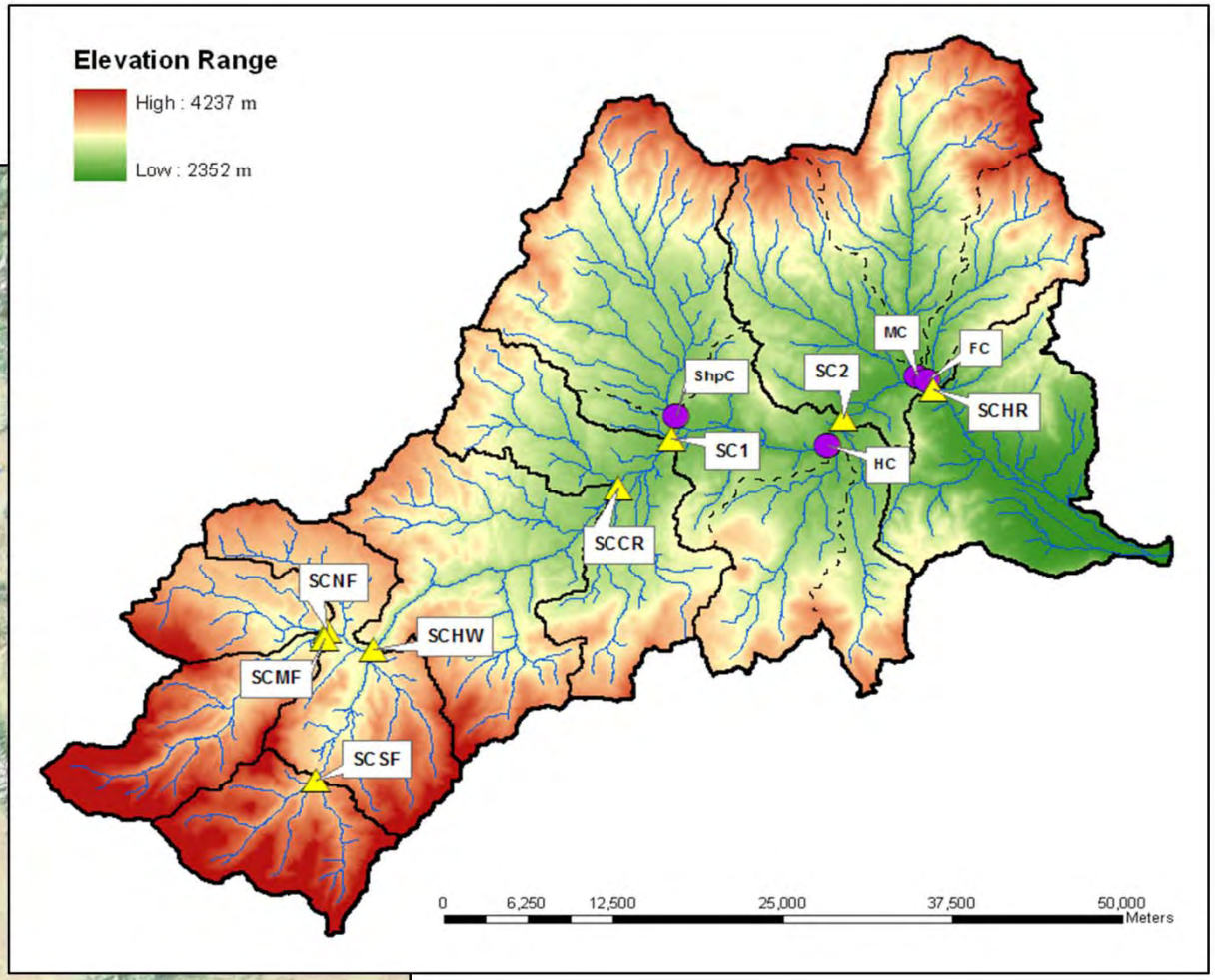
A_{et} = age estimated from environmental tracer

A = mean age (first moment of the age distribution)

SAGUACHE CREEK WATERSHED

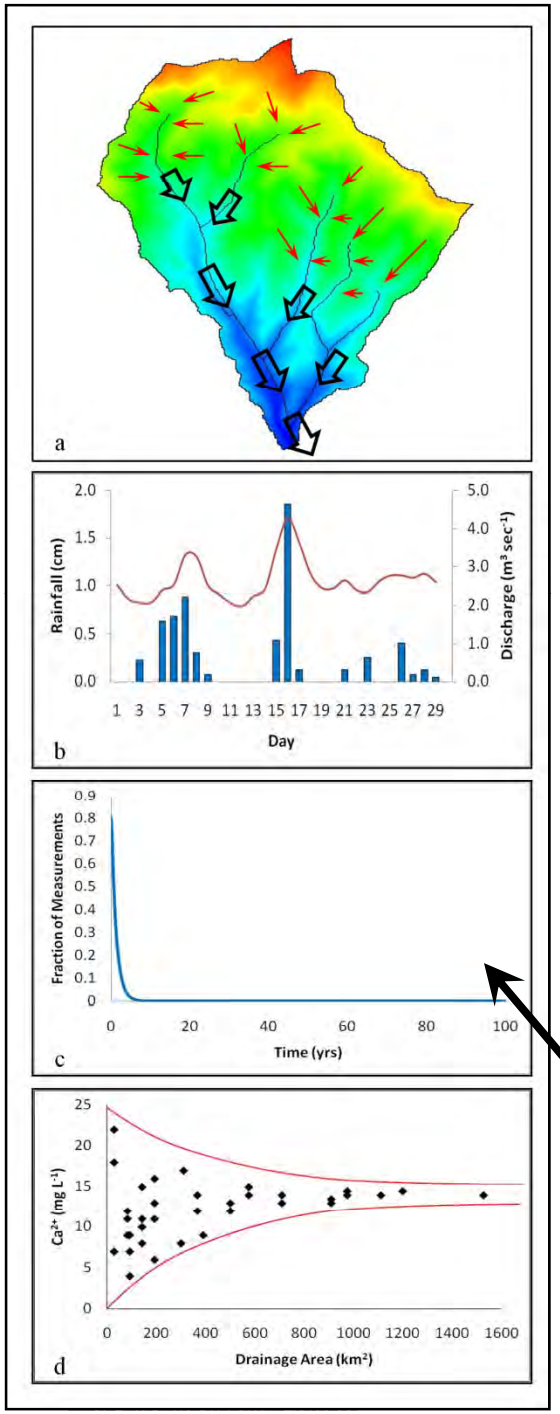






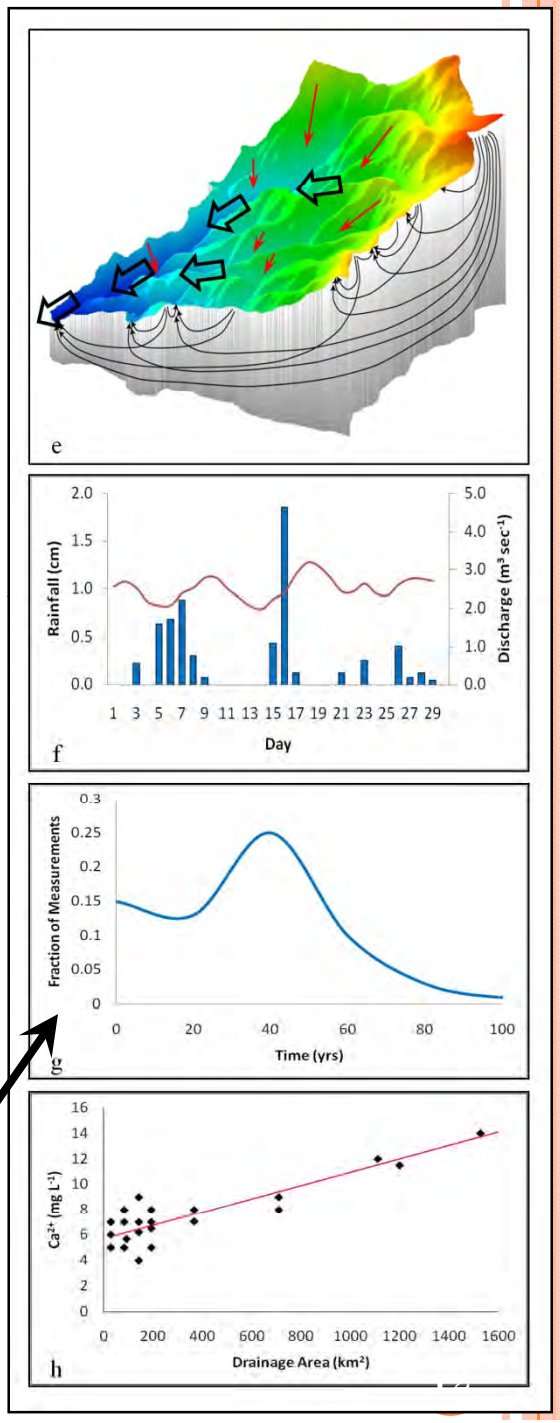
Marty Frisbee with
Fred Phillips, John Wilson, and Jesus Gomez

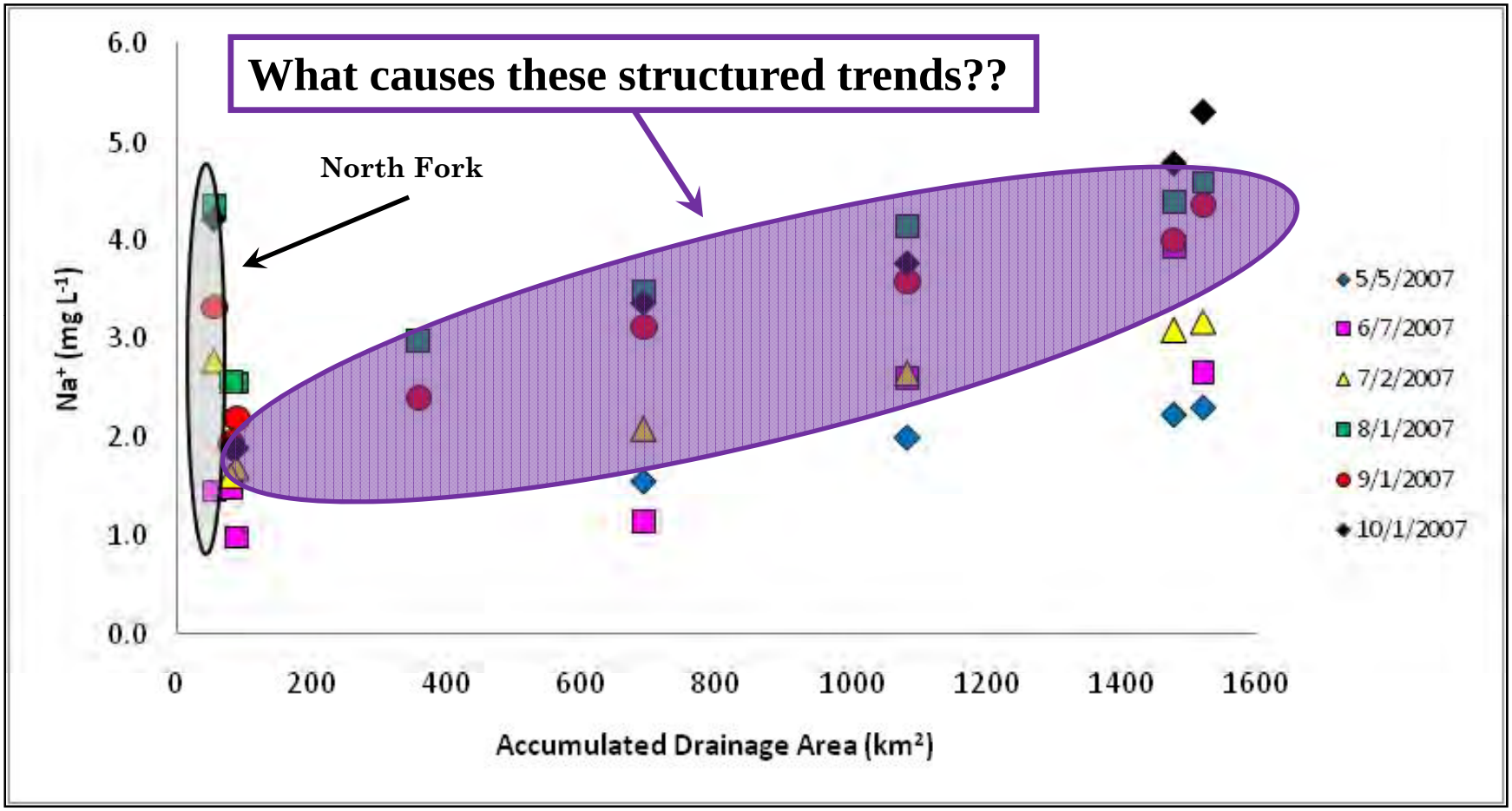
Saguache Creek Watershed - San Juan Mountains

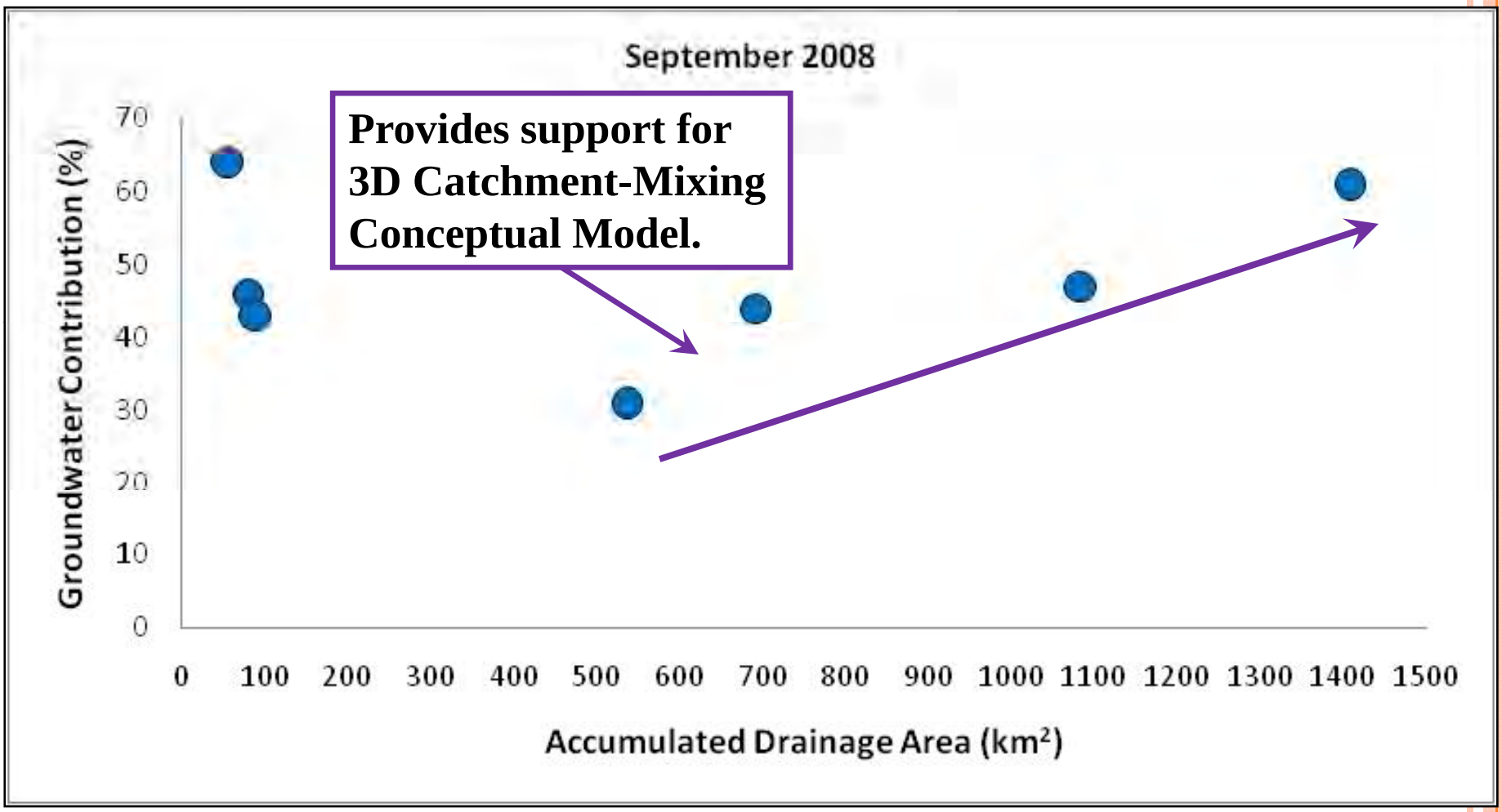


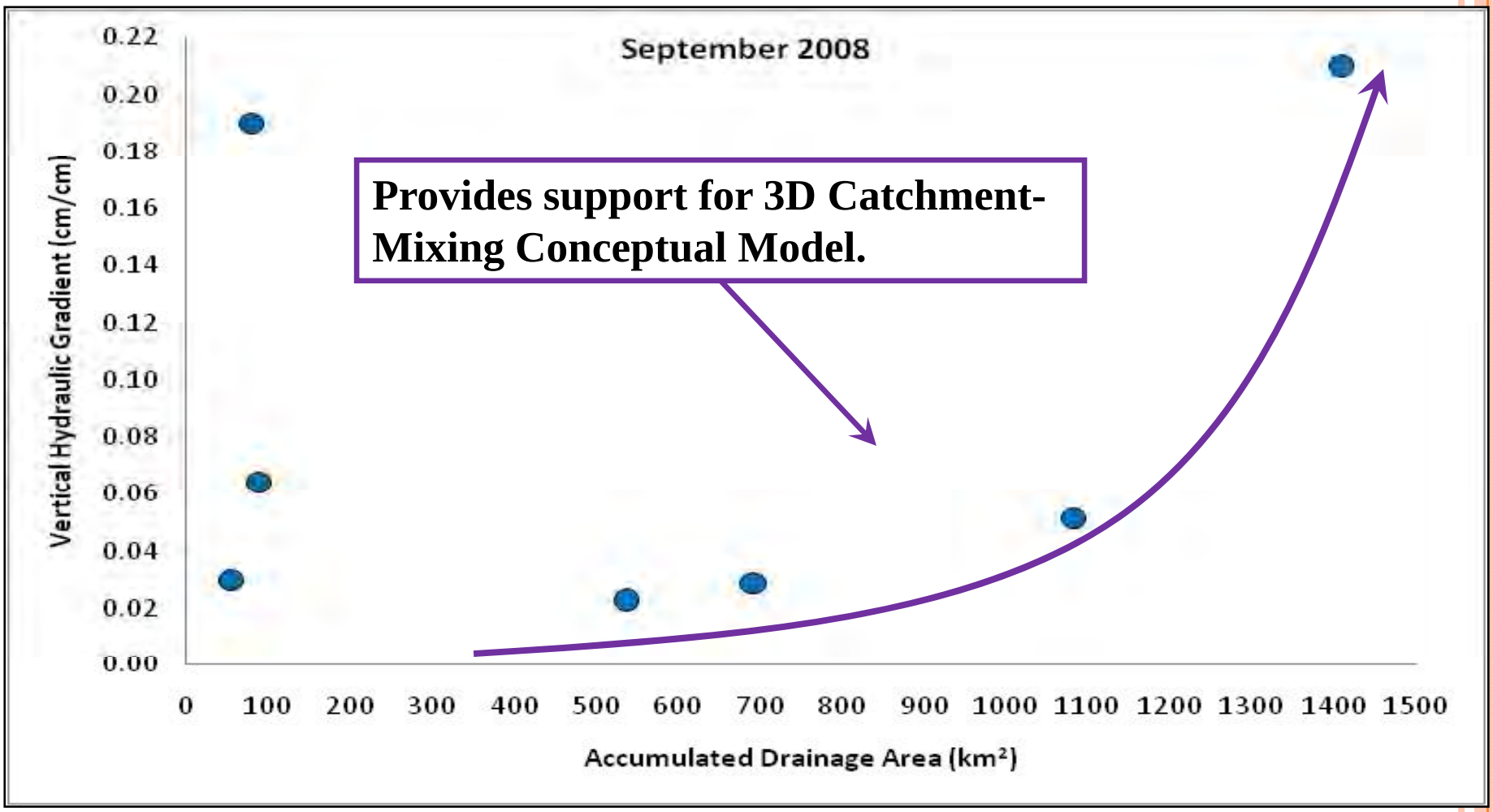
- **Two Competing Conceptual Models**
- **How do we distinguish between these two conceptual models?**
  - **<u>Groundwater:</u>**
    - Magnitude and Structuring of Contributions in Streamflow,
    - Use EMMA and measurements of vertical hydraulic gradients (VHG) in streamflow.
- **These Conceptual Models Have Far-Reaching Implications…**

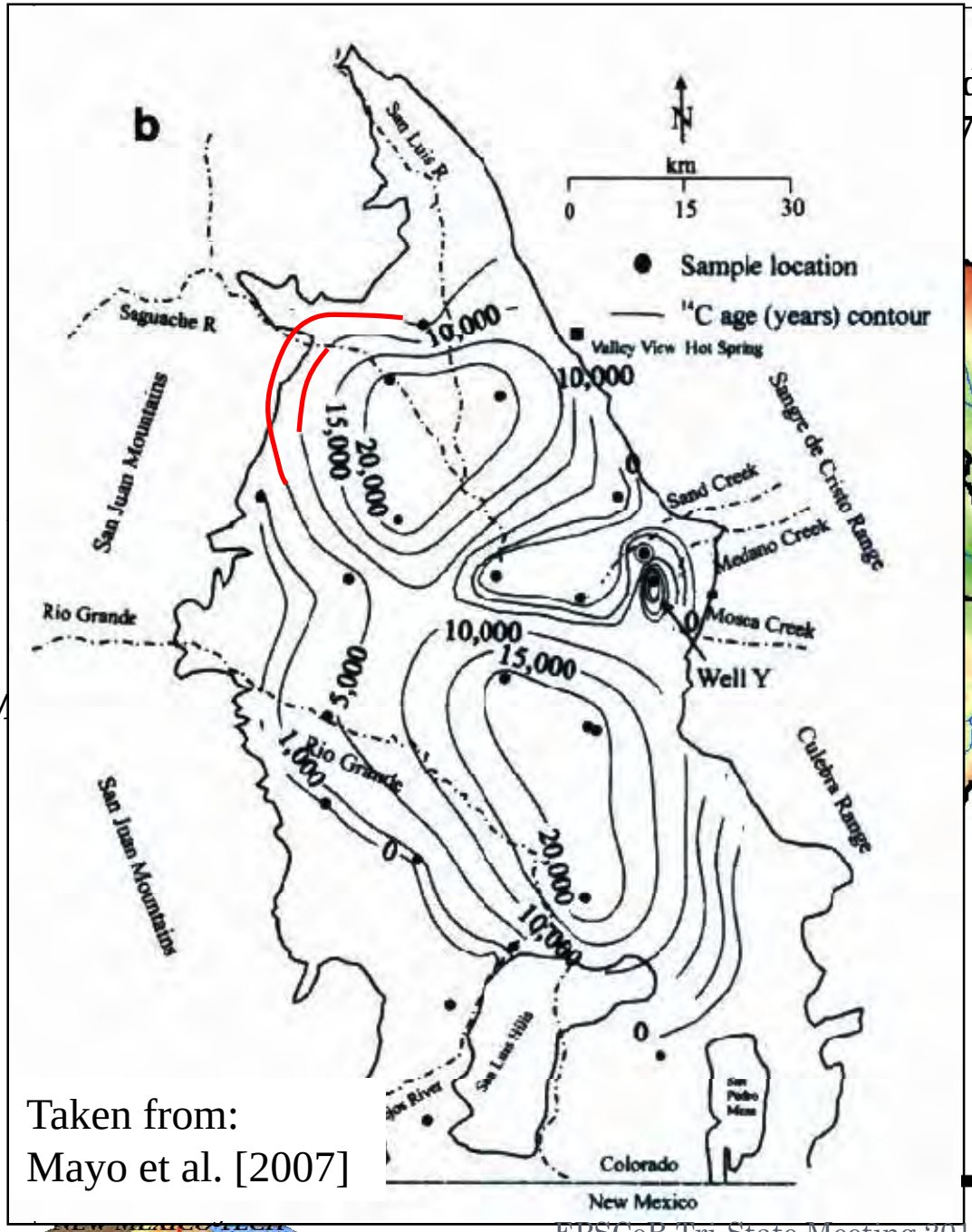
Frisbee, 2010



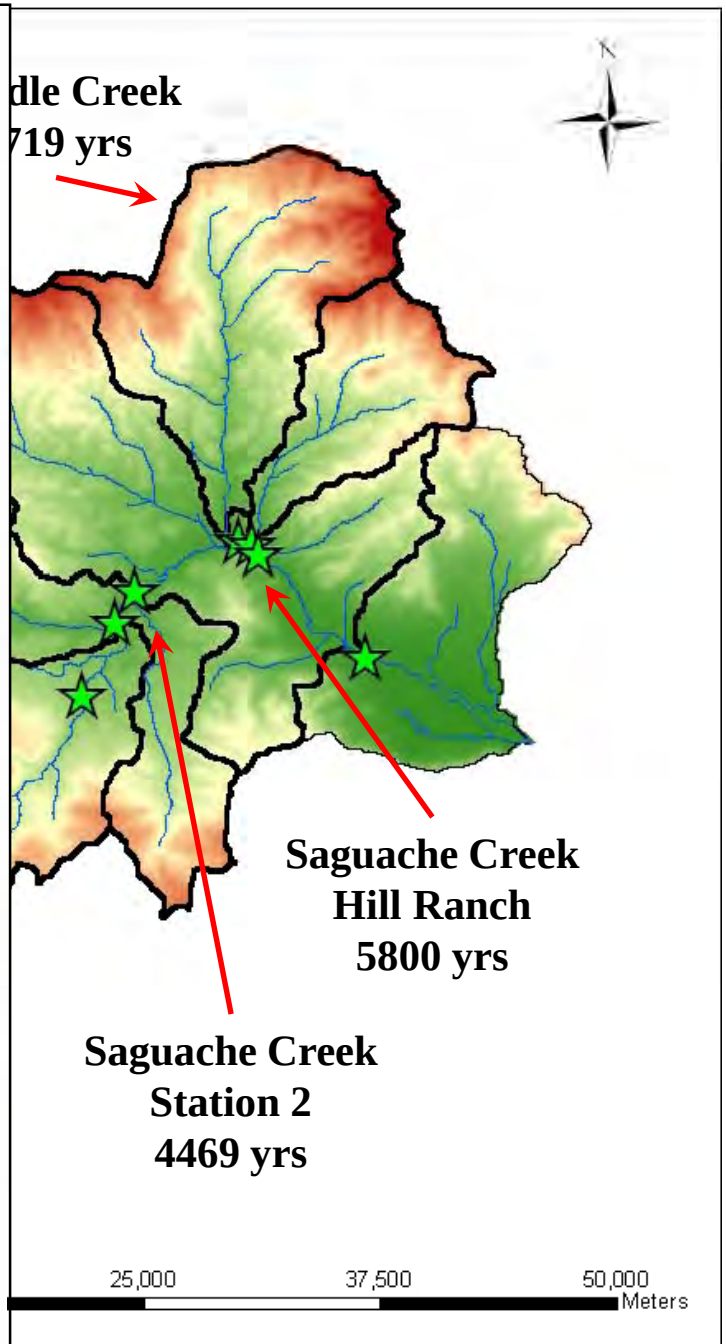

What causes these structured trends??
North Fork
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Na+ (mg L-1)
0
200
400
600
800
1000
1200
1400
1600
Accumulated Drainage Area (km2)
5/5/2007
6/7/2007
7/2/2007
8/1/2007
9/1/2007
10/1/2007

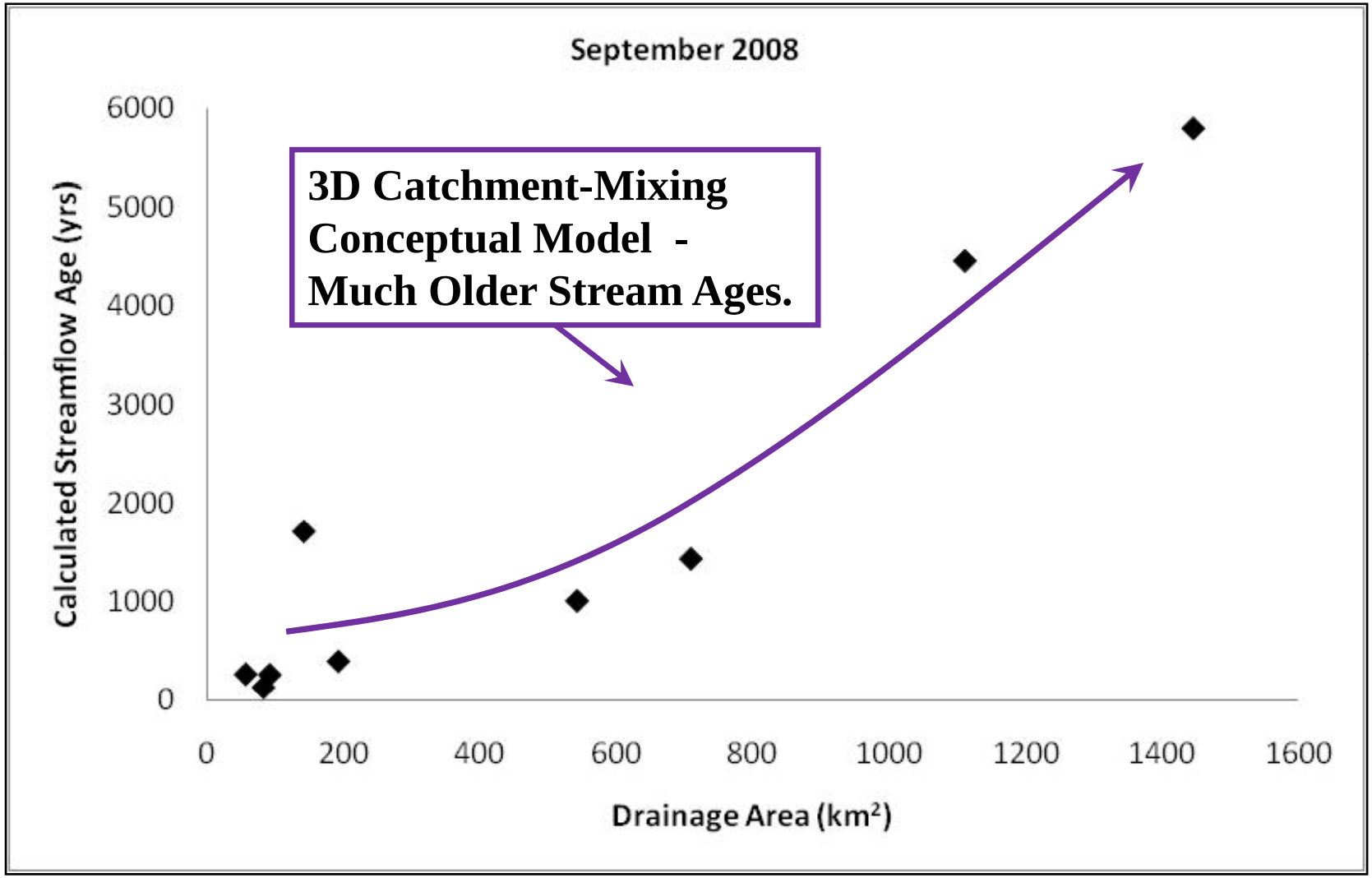

September 2008
Provides support for 3D Catchment-Mixing Conceptual Model.
Groundwater Contribution (%)
70
60
50
40
30
20
10
0
0 100 200 300 400 500 600 700 800 900 1000 1100 1200 1300 1400 1500
Accumulated Drainage Area (km²)

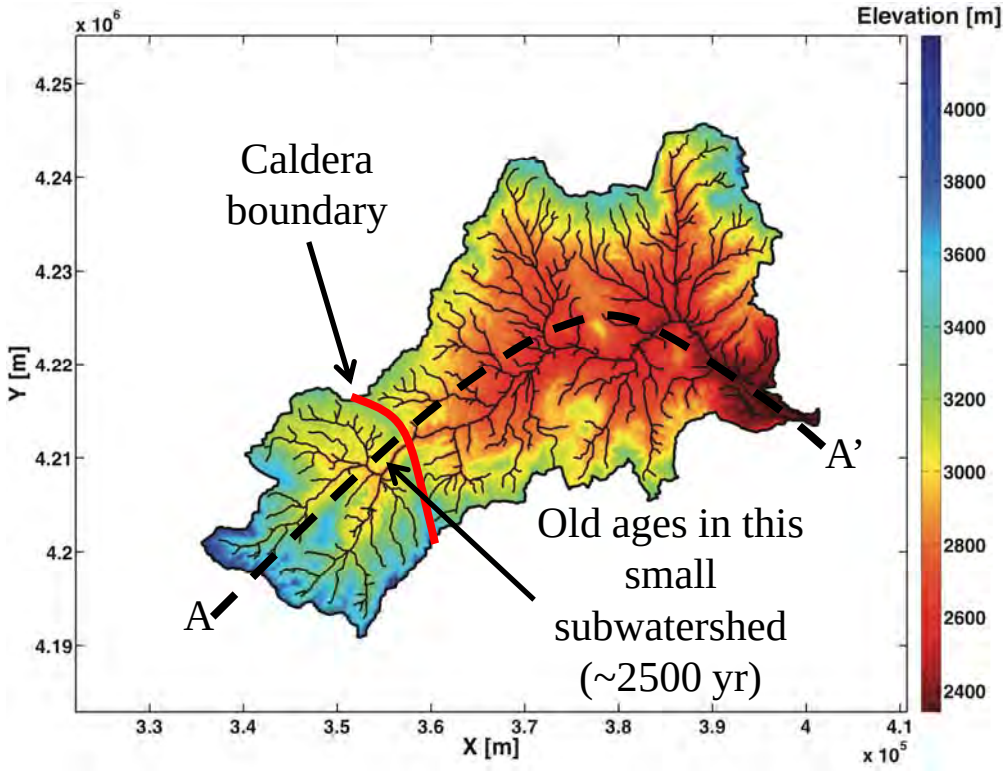

September 2008
Provides support for 3D Catchment-Mixing Conceptual Model.
Vertical Hydraulic Gradient (cm/cm)
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
0
100
200
300
400
500
600
700
800
900
1000
1100
1200
1300
1400
1500
Accumulated Drainage Area (km²)



Taken from:
Mayo et al. [2007]




September 2008
Calculated Streamflow Age (yrs)
6000
5000
4000
3000
2000
1000
0
0
200
400
600
800
1000
1200
1400
1600
Drainage Area (km²)
3D Catchment-Mixing Conceptual Model - Much Older Stream Ages.

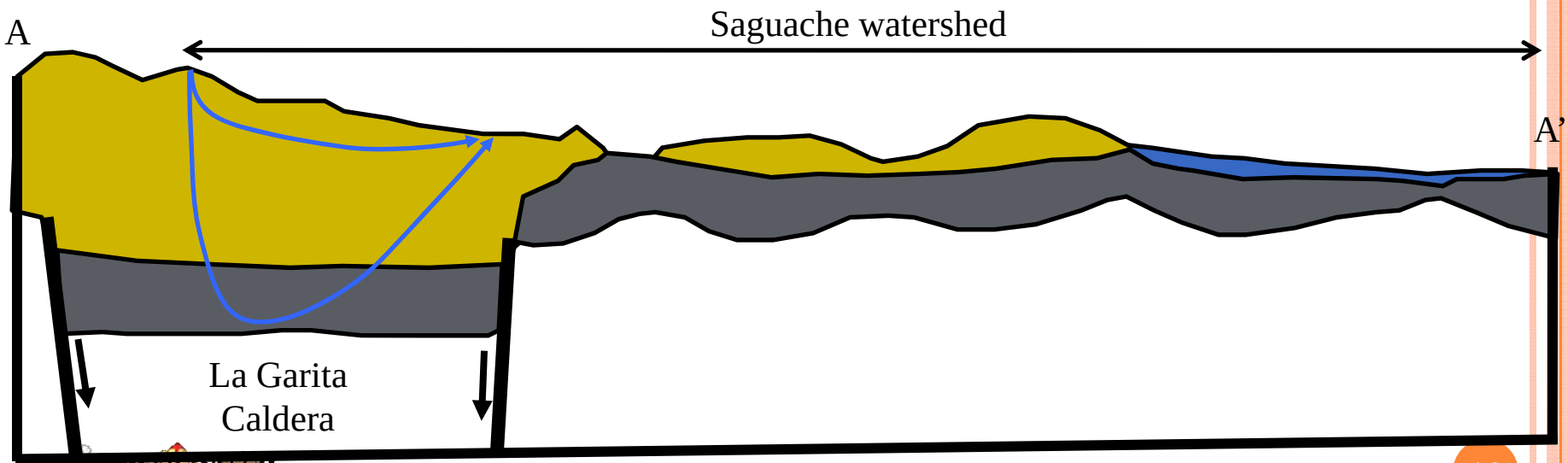


Conejos formation

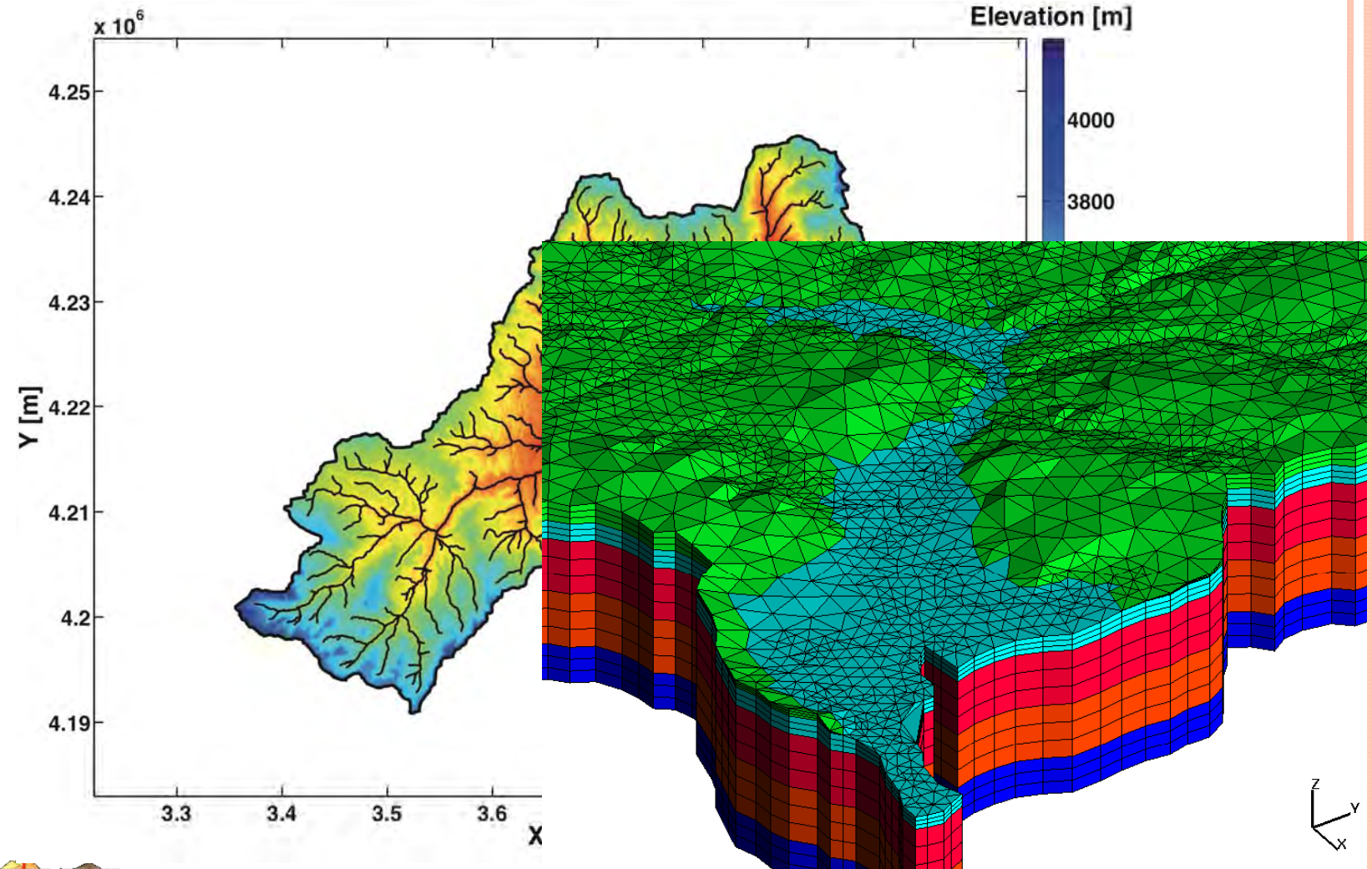
Saguache Creek + Fish Canyon tuffs + postcaldera lava

Pre-tertiary rocks

Alluvium

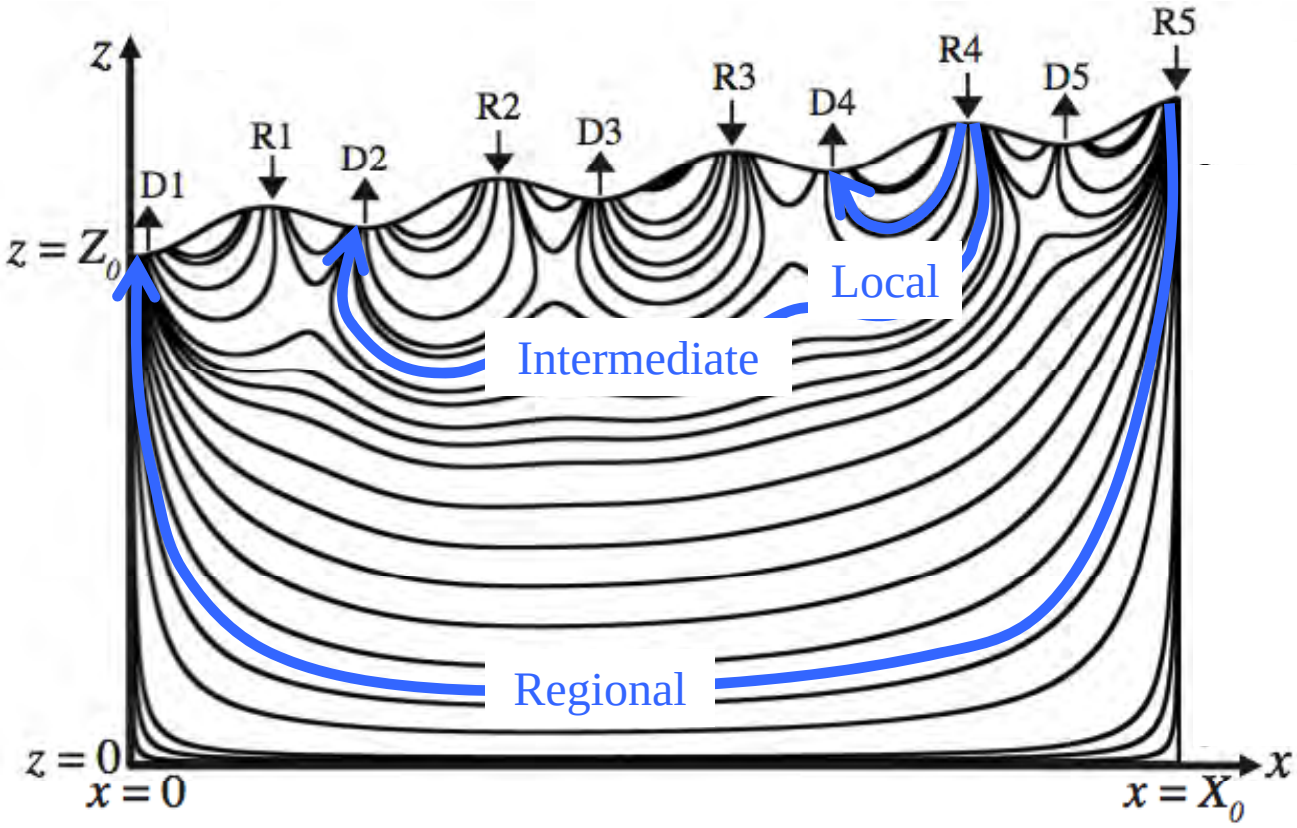


3-D FINITE ELEMENT MODEL TO EXPLORE FLOW AND TRANSPORT IN THE SYSTEM



Regional groundwater flow: a Tothian-like domain with nested scales of interaction

Change the scale and you have an analog for hyporheic zones



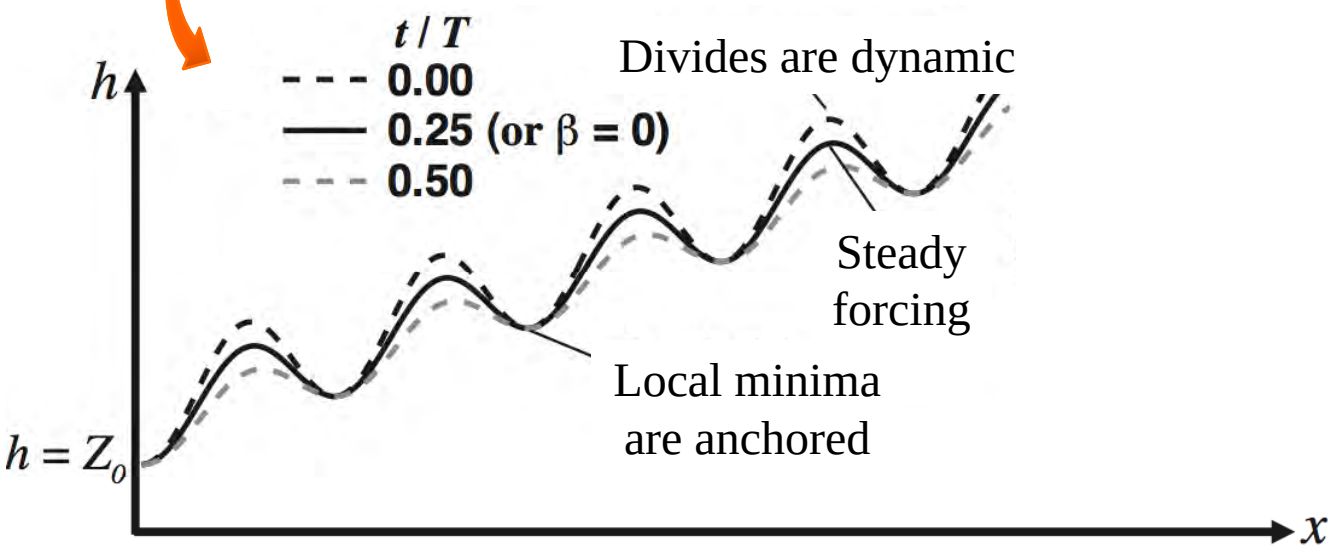
LET'S USE A DYNAMIC FORCING

Regional slope

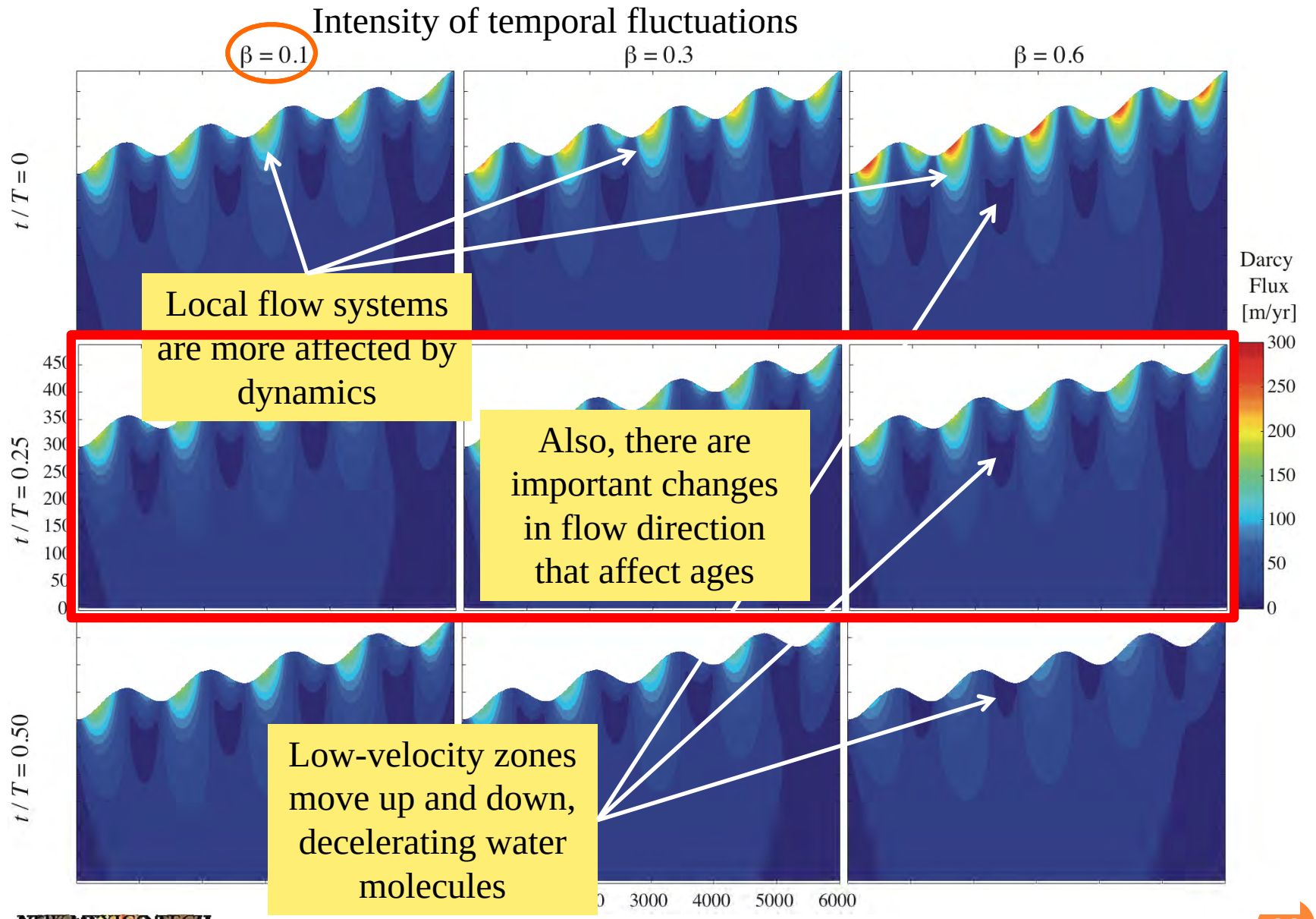
Displacements to anchor the minima

$$h(x,t) = Z_0 + m\,x + a(t)\sin\left[\frac{2\pi\left(x+\delta_x(t)\right)}{\lambda} - \frac{\pi}{2}\right] + \delta_z(t)$$

Time-varying amplitude



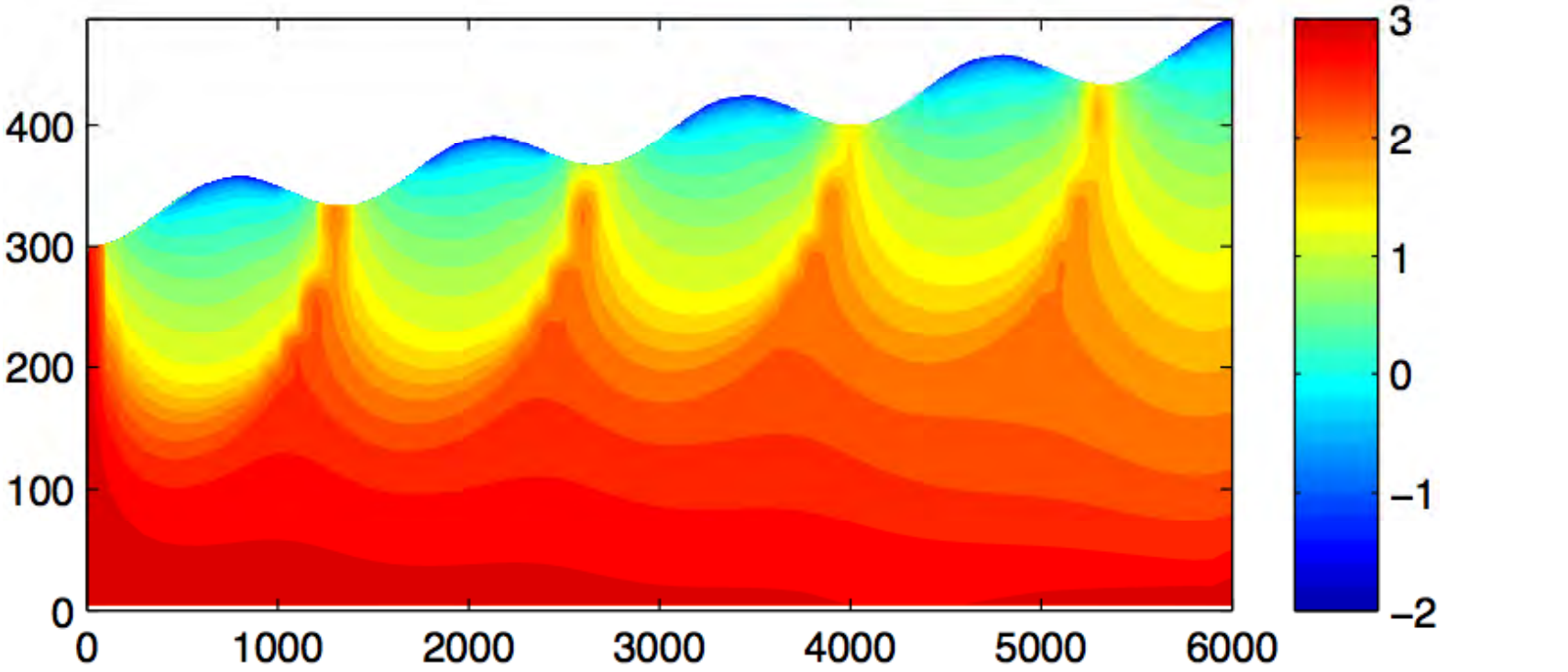
How does the flow field change over time?



SO, WHAT IS THE EFFECT ON AGES?

Mean age under the steady forcing

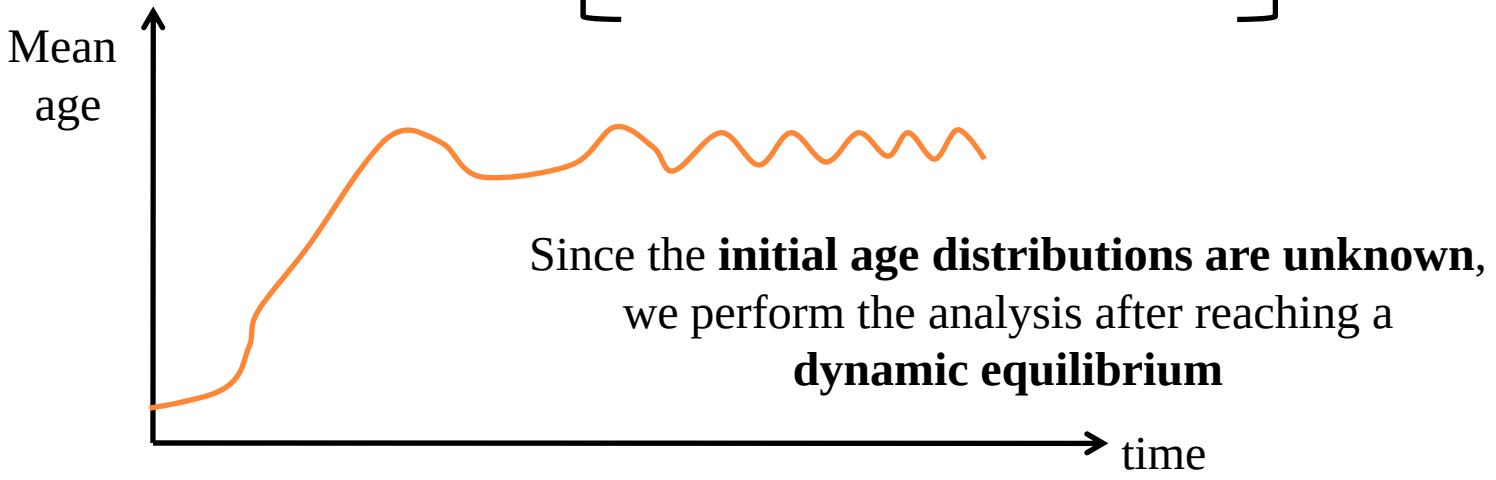
(A = 0.01 [1/m], a_l = 10 [m], a_t/a_l = 0.1)



METRIC FOR COMPARISON

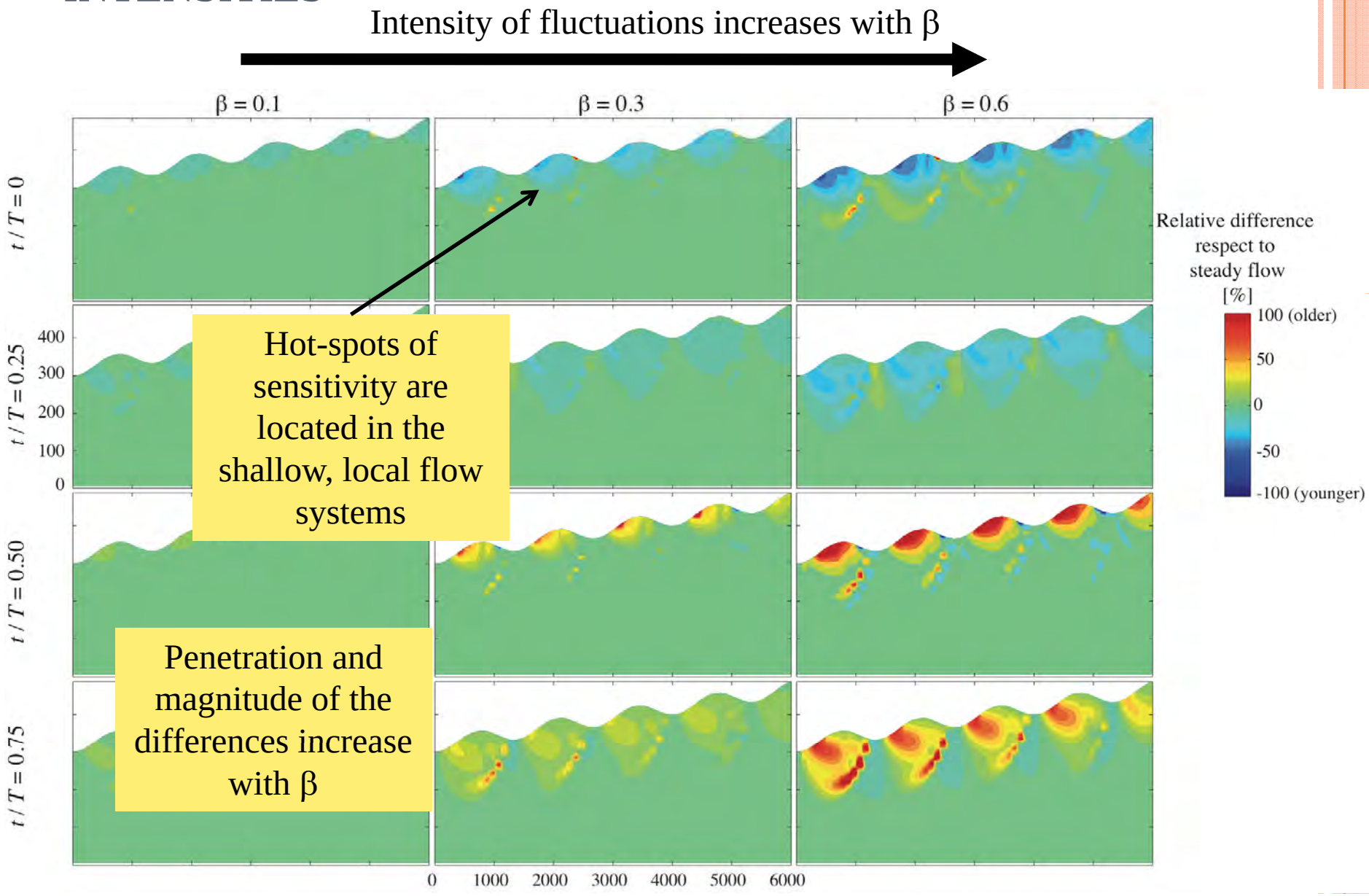
We will use the **relative difference respect to the mean age under steady forcing** as a metric to evaluate the effect of flow dynamics on ages

$$\text{Relative difference at time } t = \left[\frac{\text{Mean age at time } t - \text{Mean age steady forcing}}{\text{Mean age steady forcing}} \right] \times 100$$

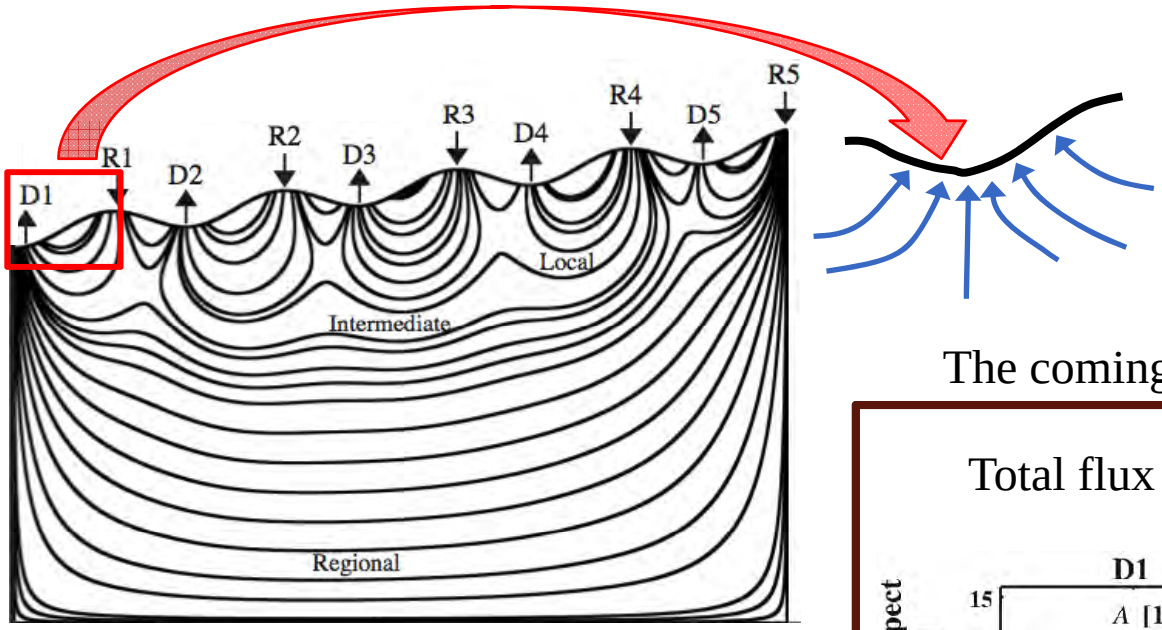


Since the **initial age distributions are unknown**, we perform the analysis after reaching a **dynamic equilibrium**

DIFFERENCES FOR DIFFERENT TIMES UNDER DIFFERENT INTENSITIES



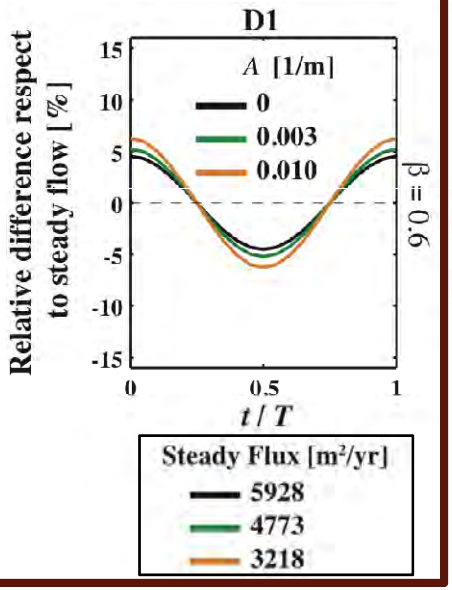
WHAT HAPPENS AT THE DISCHARGE ZONES?



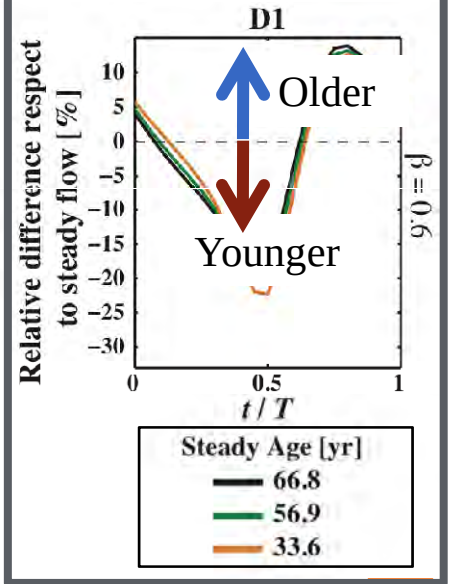
Integrate over the discharge zones to estimate the <u>total flux</u> and <u>flux-weighted mean age</u>

The coming figures will look like these:

Total flux at D1



Flux-weighted mean age at D1



The faster the decrease in *K*, the smaller the discharge and the younger the water along D1

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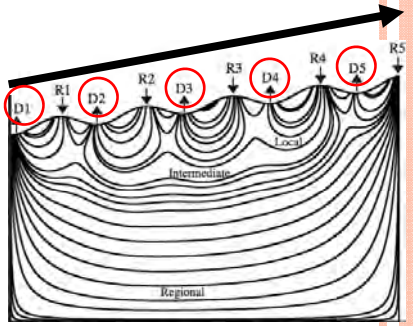
WATER FLUXES



Moving uphill along the discharge zones

Range increases as we increase β

D1 D2 D3 D4 D5 Total discharge

A [1/m]
0
0.003
0.010

Relative difference respect to steady flow [%]

Steady Flux [m²/yr]
5928
4773
3218

Steady Flux [m²/yr]
6785
5788
4378

Steady Flux [m²/yr]
6351
5609
4356

Steady Flux [m²/yr]
5857
5426
4339

Steady Flux [m²/yr]
3825
4106
3818

Steady Flux [m²/yr]
28746
25703
20109

β = 0.3

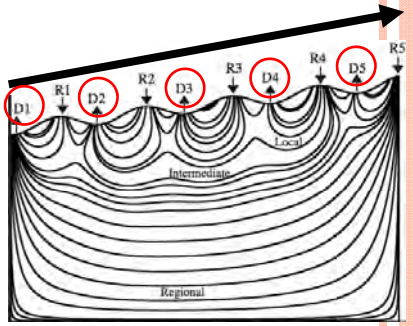
β = 0.6

t / T

Relative differences in water fluxes are not affected by changes in the conductivity decay rate *A*. However, flux magnitudes are different

The faster the decrease in *K*, the smaller the flux along discharge zones

FLUX-WEIGHTED AGES



Moving uphill along the discharge zones

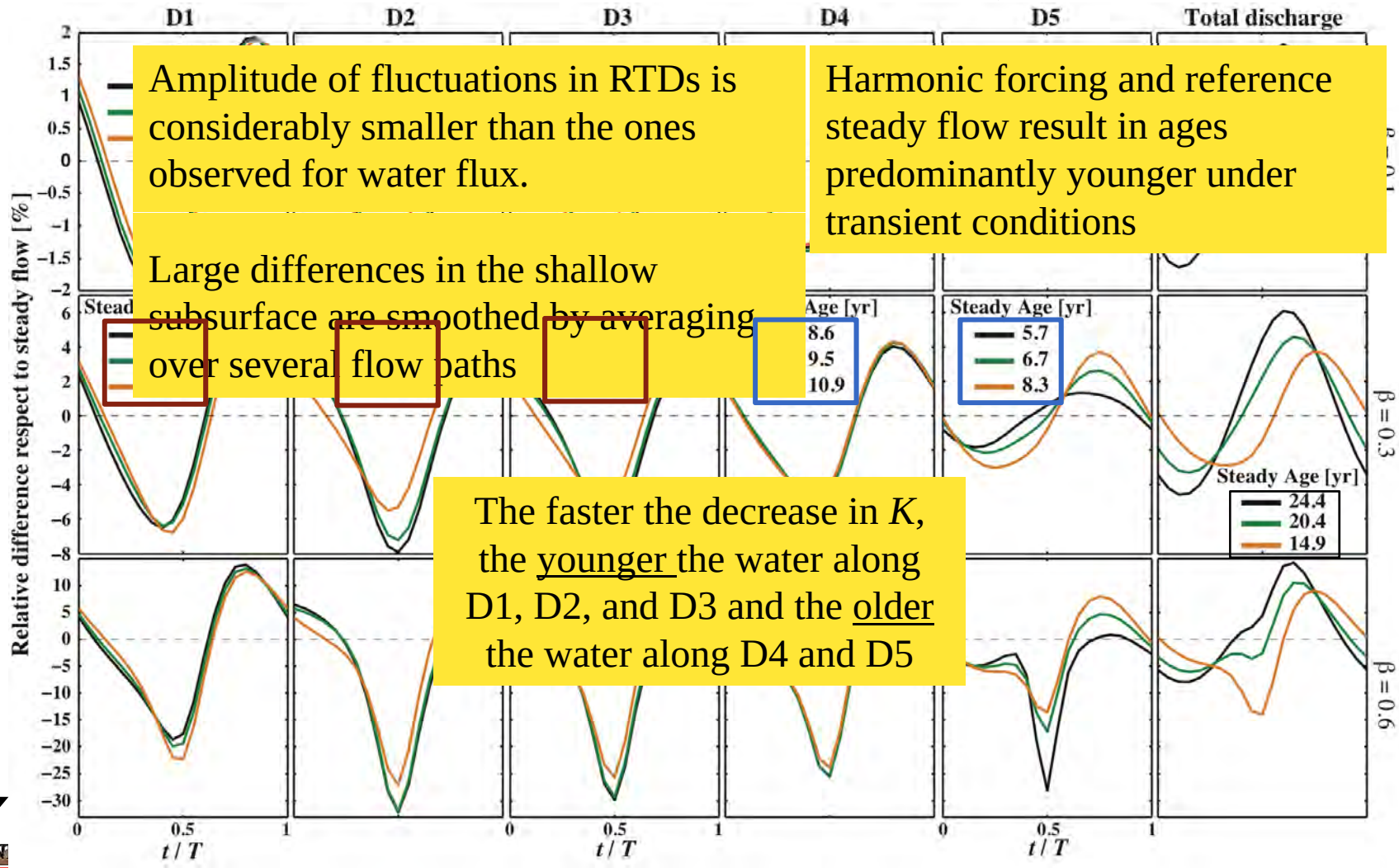
Range increases as we increase β

Amplitude of fluctuations in RTDs is considerably smaller than the ones observed for water flux.

Harmonic forcing and reference steady flow result in ages predominantly younger under transient conditions

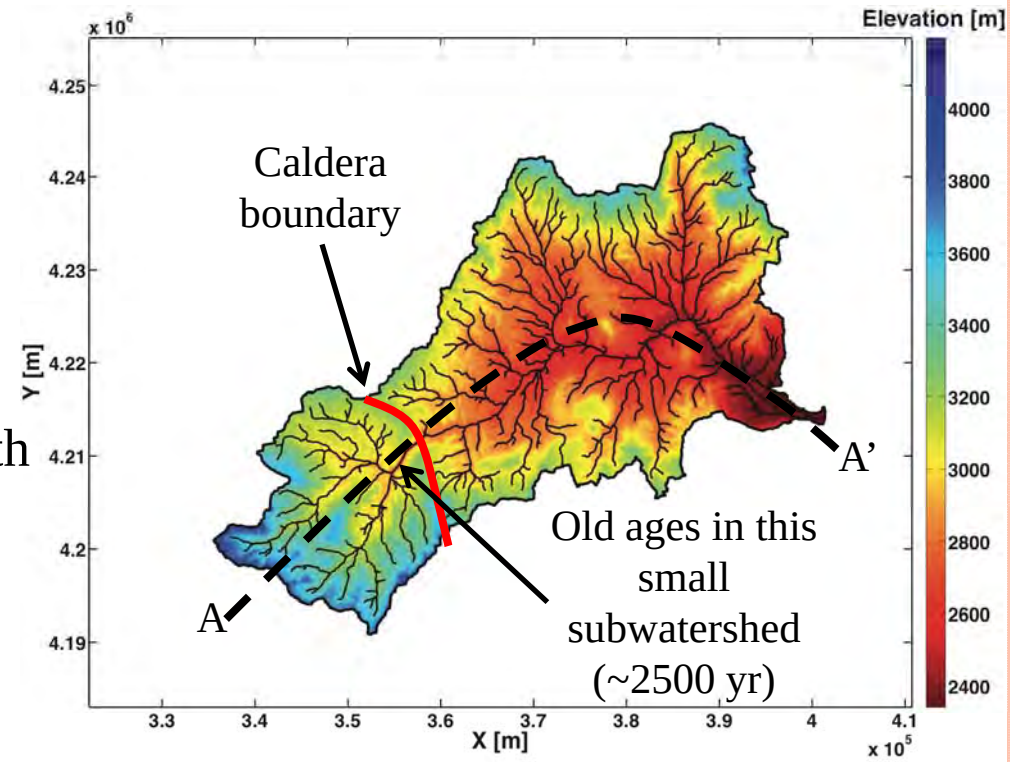
Large differences in the shallow subsurface are smoothed by averaging over several flow paths

The faster the decrease in *K*, the younger the water along D1, D2, and D3 and the older the water along D4 and D5



Implications for age measurements and modeling of Saguache Creek Watershed

- Mean ages in the local flow systems (shallow subsurface) are strongly affected by forcing variability (recall high-sensitivity zones).
- Averaging over flow paths smoothes out the effects of transient forcing on mean ages (e.g., discharge zones or wells with large screens).
- Can we measure these changes in mean ages? Transient flow enhances mixing, which at the same time biases the ages estimated with env. tracers.
- Next step is to look at the changes in the full age distribution, not just the mean.



THE END