Reconciling landscape models with reality: a spectrum of success

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Challenge: In what locations/spatial scales/timescales do the models we implement actually reveal information on how nature works?

- There are complexities in natural systems that either limit the applicability of our simplified models or require some adjustments
- There may not be a single equation/approach that will describe all river systems (and thus all landscapes!) in all environments.

Quantitative theory (i.e. where does the stream power model come from?):

Starting with a proxy model (i.e. phenomenological model), perhaps rooted in process mechanics

$$E = k_v \tau^{a}$$

$$E = k_v (\tau - \tau_c)^{a}$$

Howard and Kerby, 1983

$$\tau_b = \rho g \left(\frac{nQ}{w} \right)^{3/5} S^{7/10}$$

Water discharge
Channel width
Erosion efficiency (Kv)
-Dependent on **rock-type**

Channel slope

How well does all of this hold up when we look at 'the real world'?

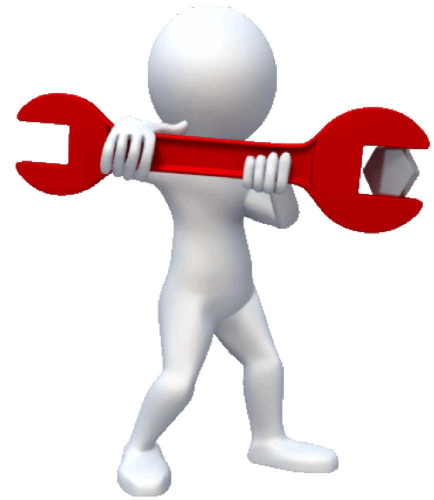
How does is scale?

What needs improvement?

$$w = k_w A^b$$

$$Q = k_Q A^c$$

$$E = KA^m S^n$$

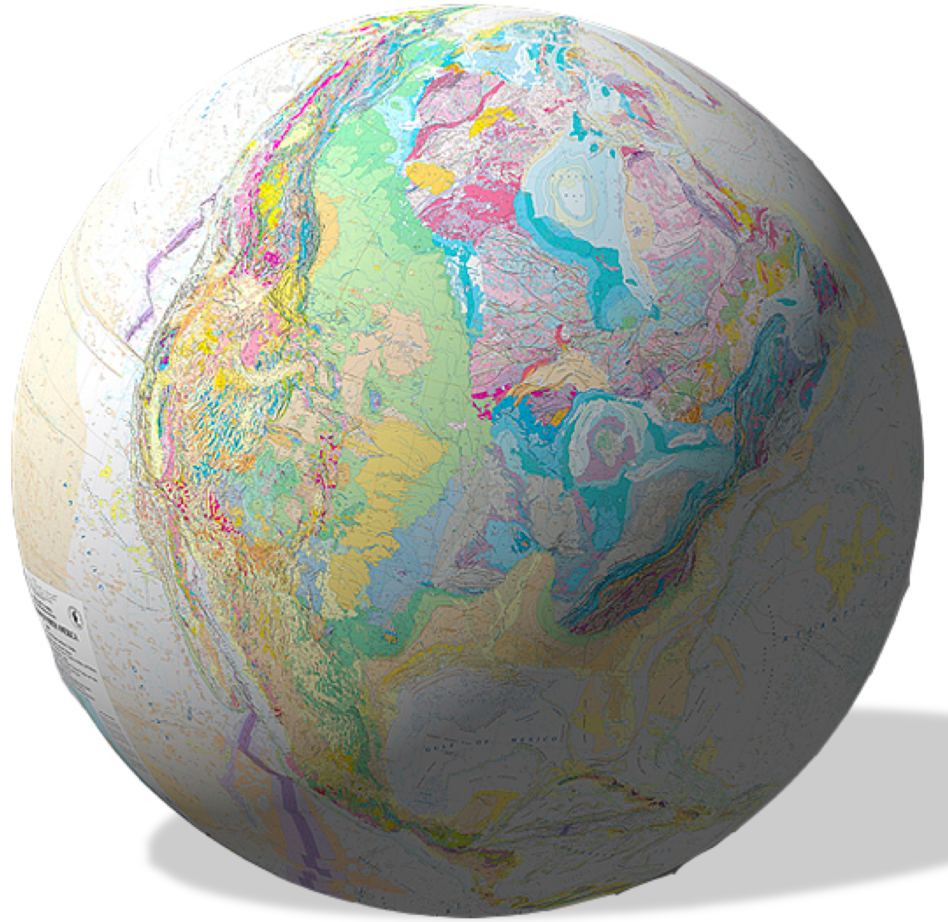


Talk outline

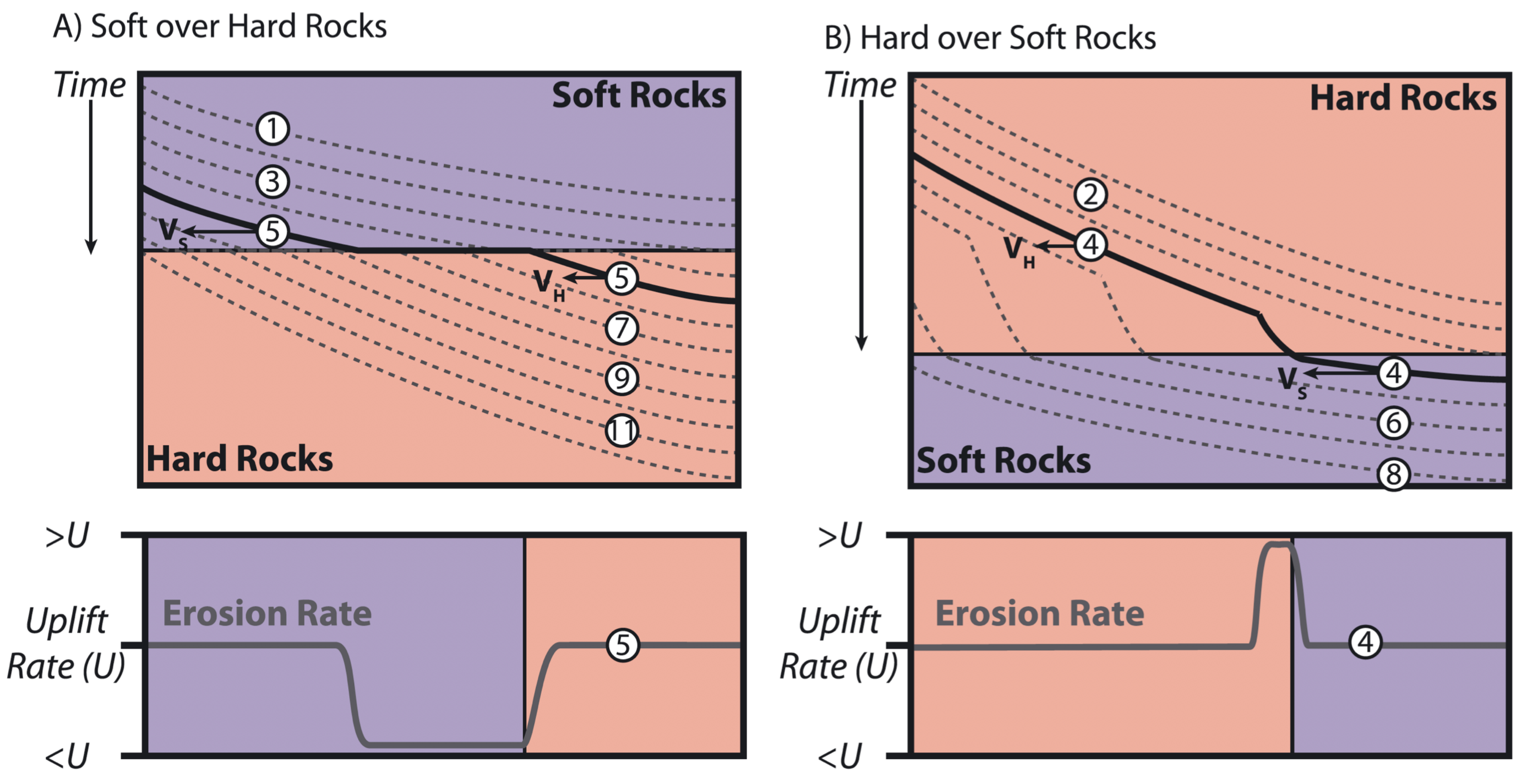
Rock-type Climate Channel width

Lithology

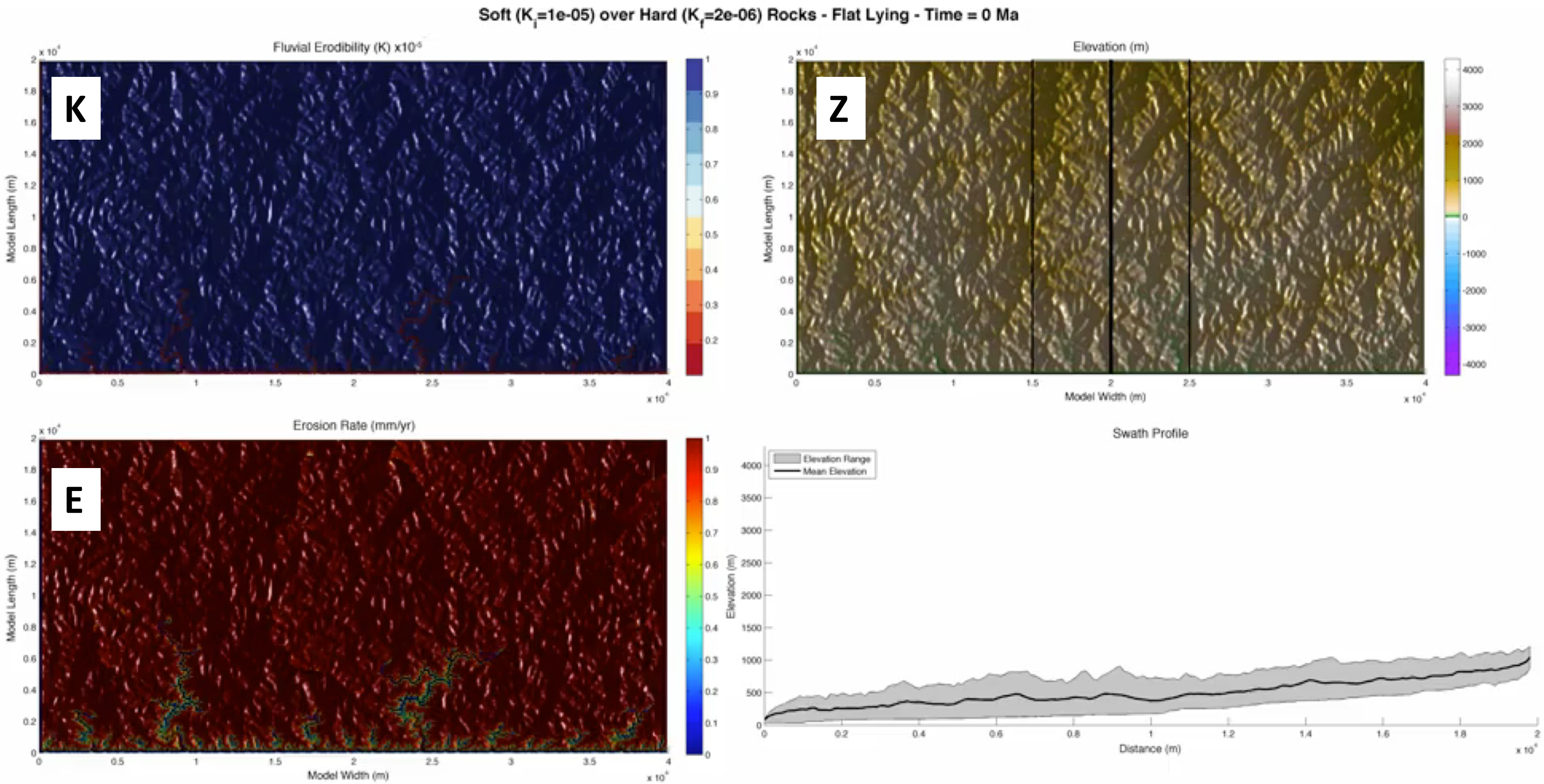
If we really want to understand the evolution of Earth's surface, we better understand how different rock-types influence erosion efficiency



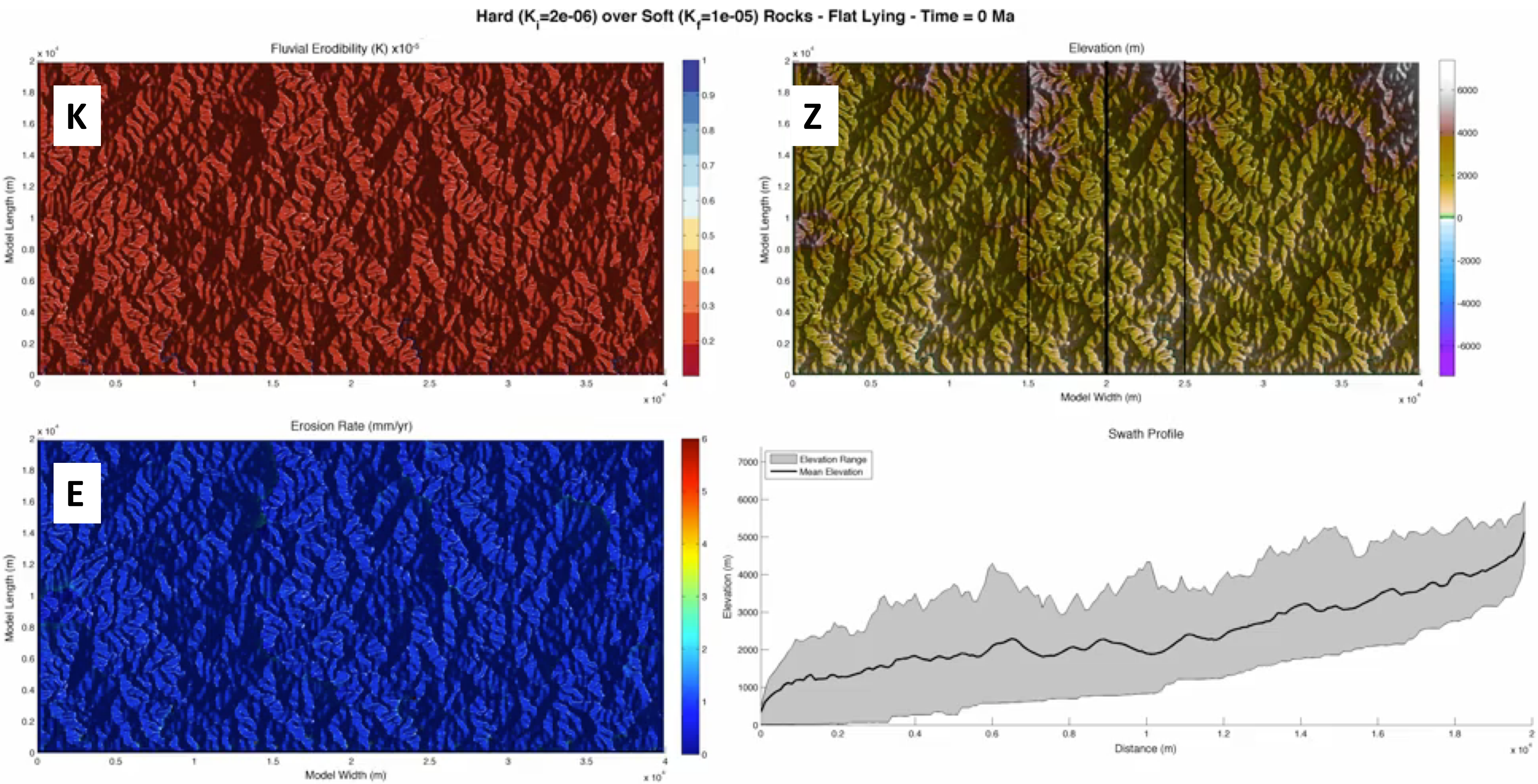
Significant, propagating effects of lithologic change



Forte et al., 2016



5x differences in K



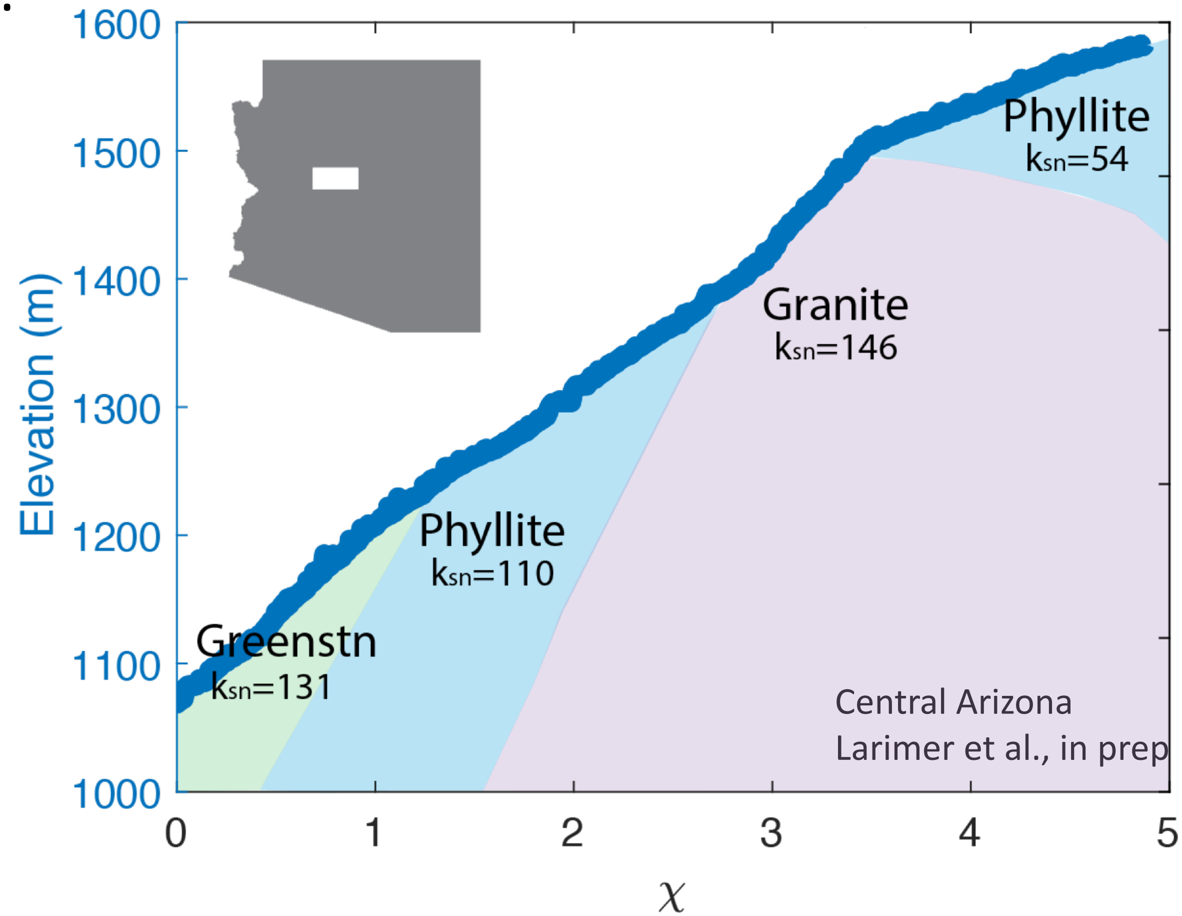
5x differences in K

Lithology challenge: How do we translate rock-type into erosivity ‘k’ terms?

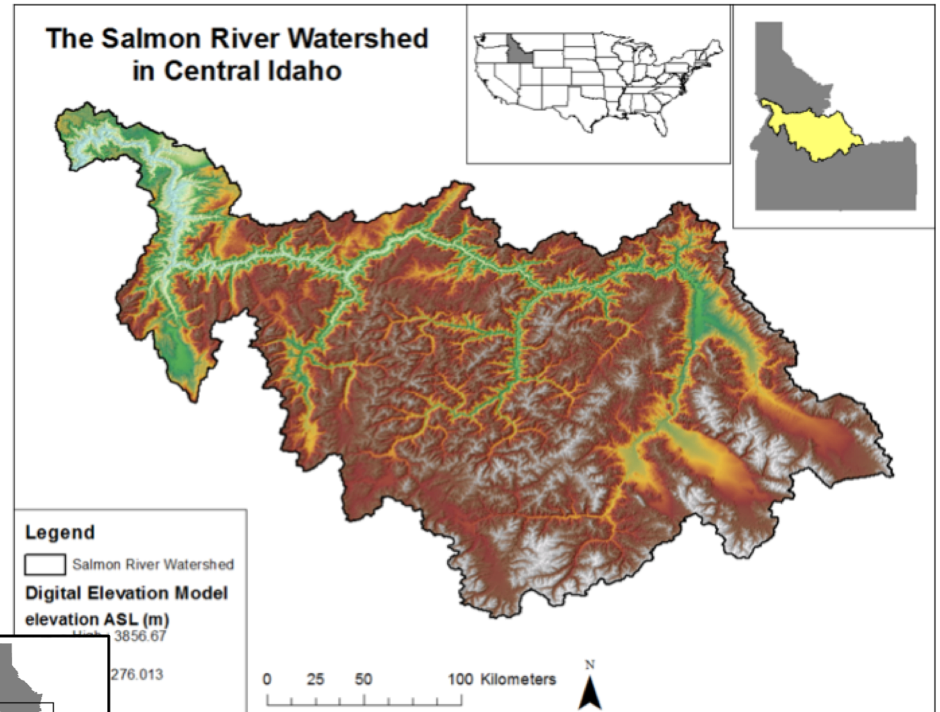
$$E = k_v \tau^{a}$$

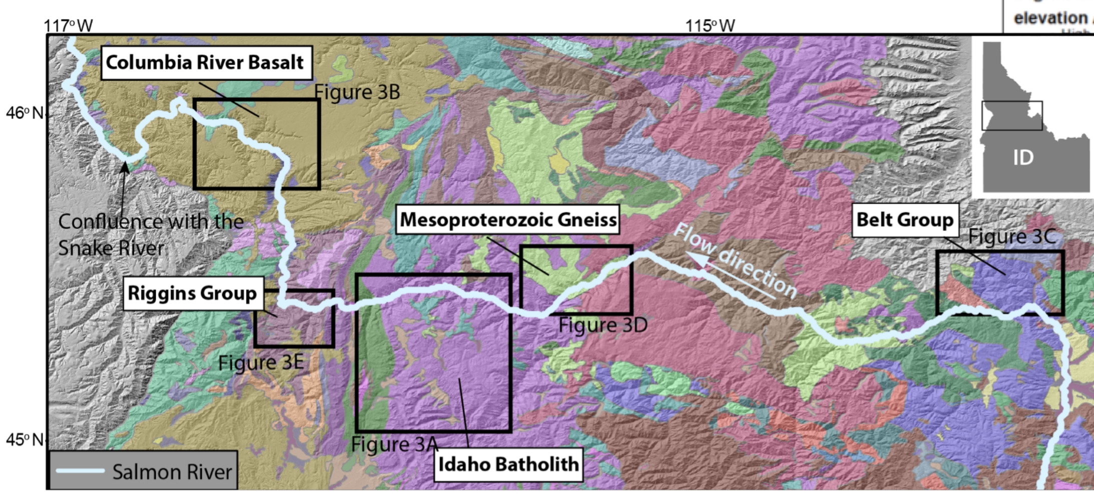
$$E = KA^m S^n$$

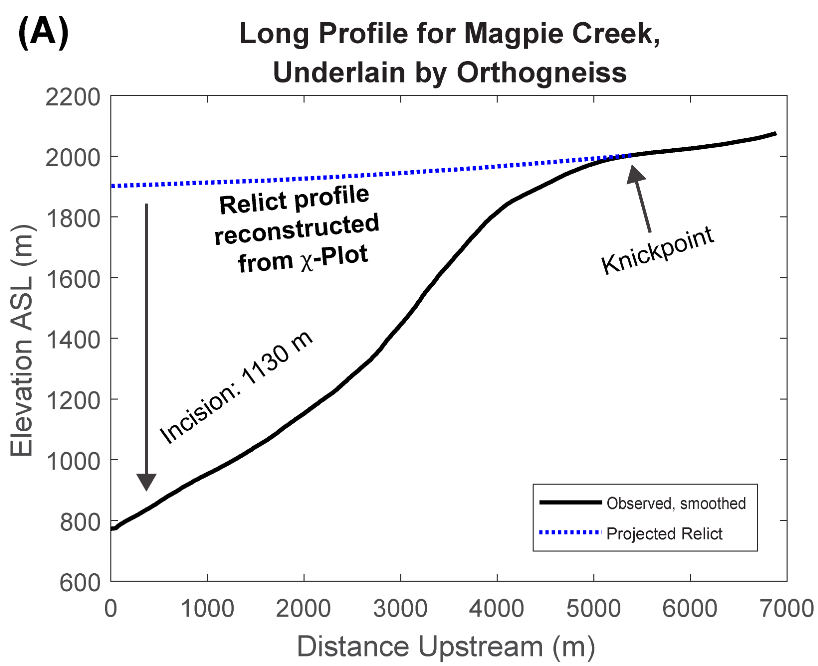
Differences in erosional efficiency have large implications both numerically and in field observations



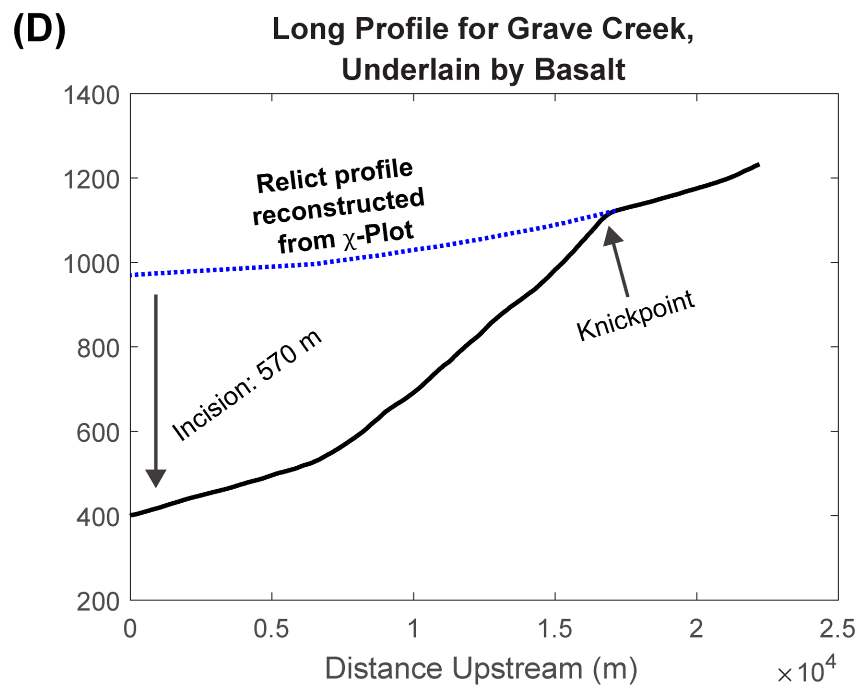
Rock-type modulates transient erosion in central Idaho







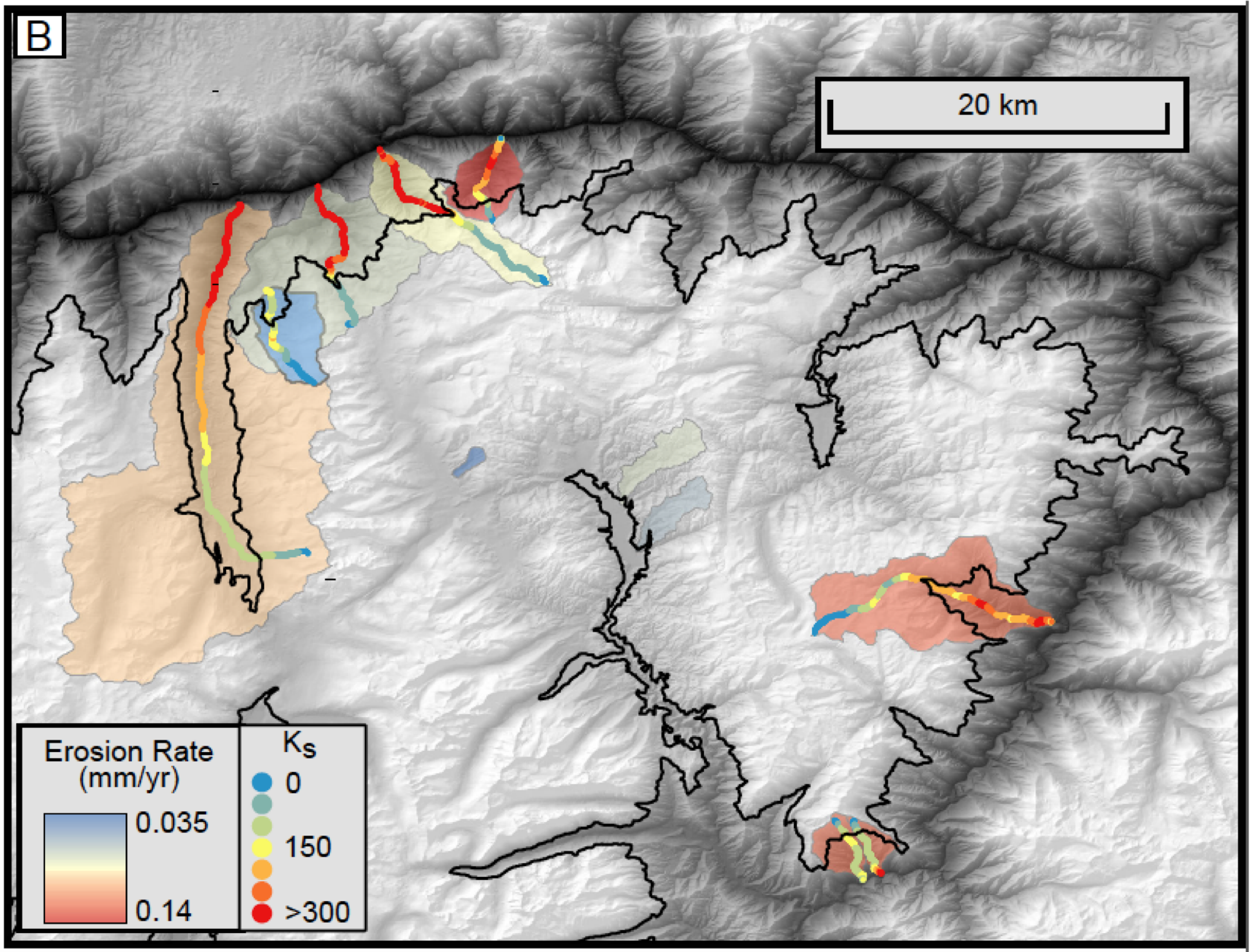
Granites and gneiss generate stretched out knick-'zones'



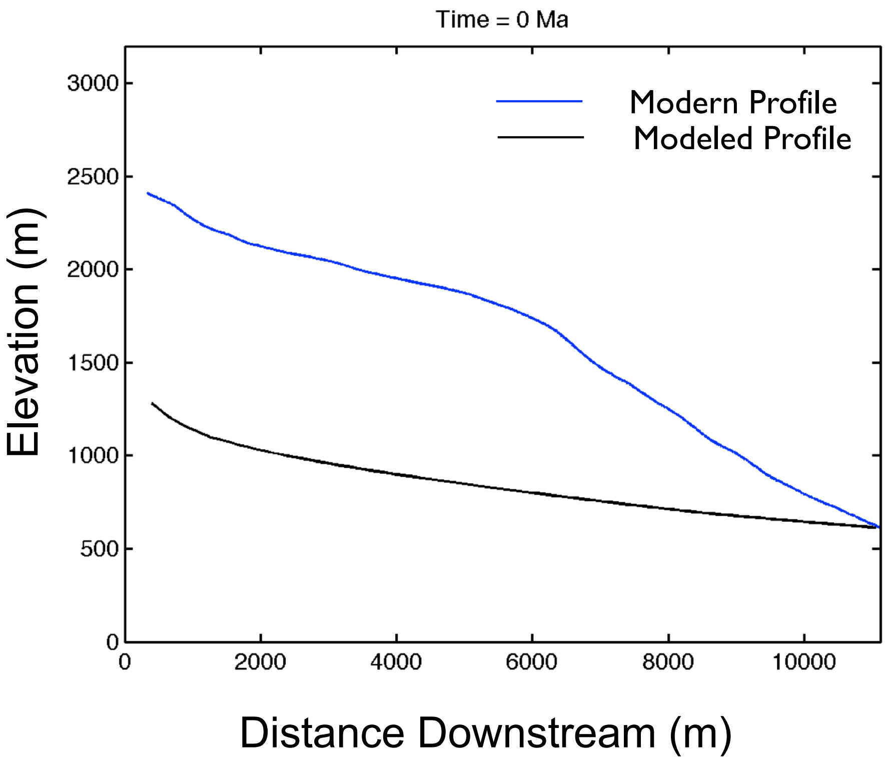
Basalt generates more discrete knickpoints'

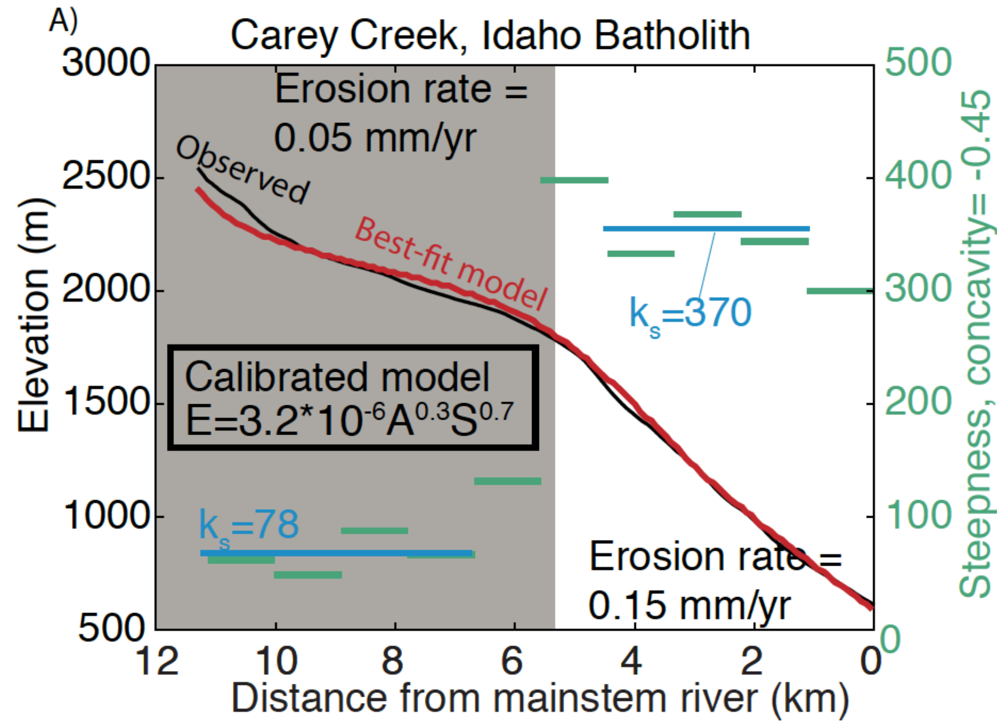
Mitchell et al., in prep

~3 fold difference in erosion rate from cosmogenic nuclide concentrations

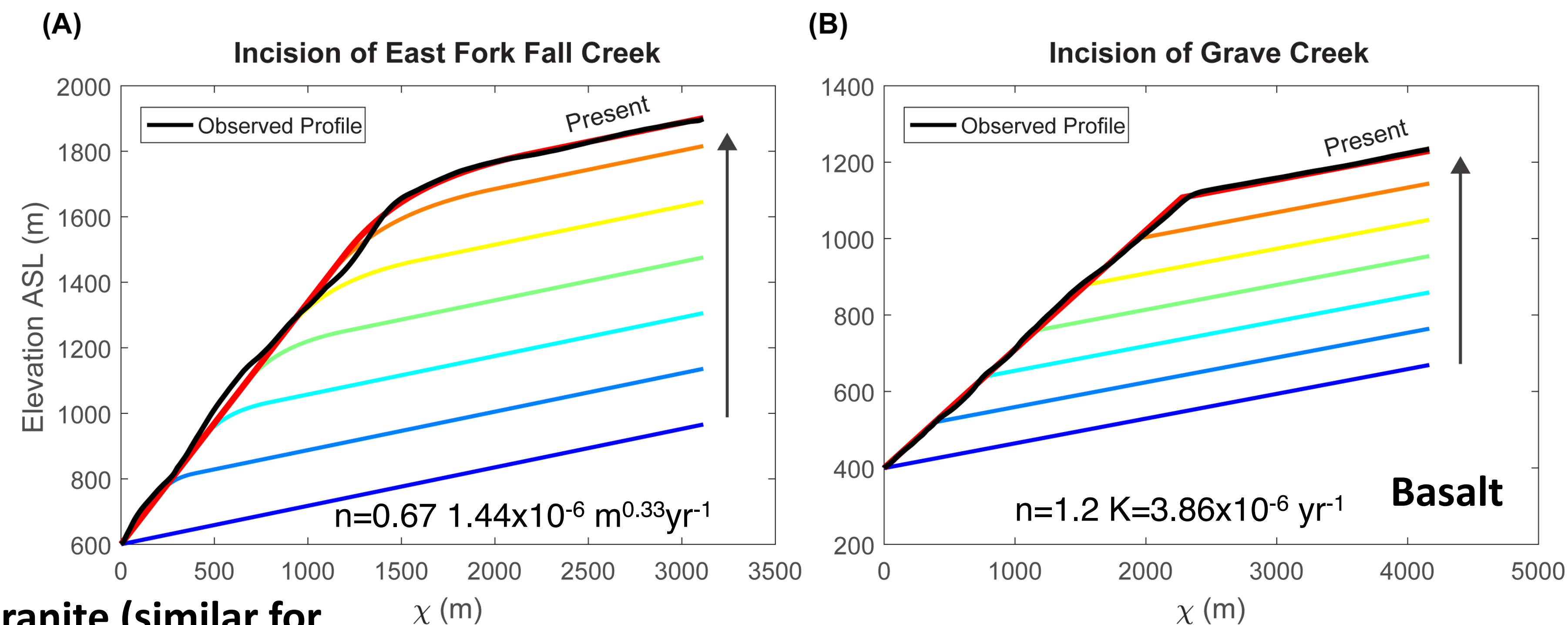


Calibrated river incision model





Slope exponent varies among rock-type



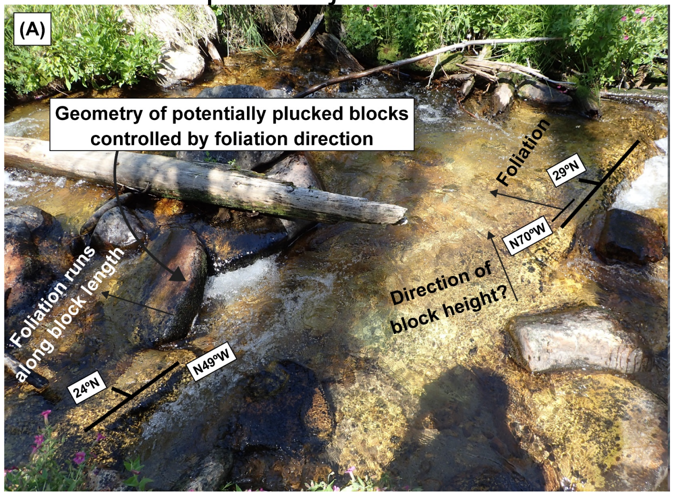
Granite (similar for gneiss as well)

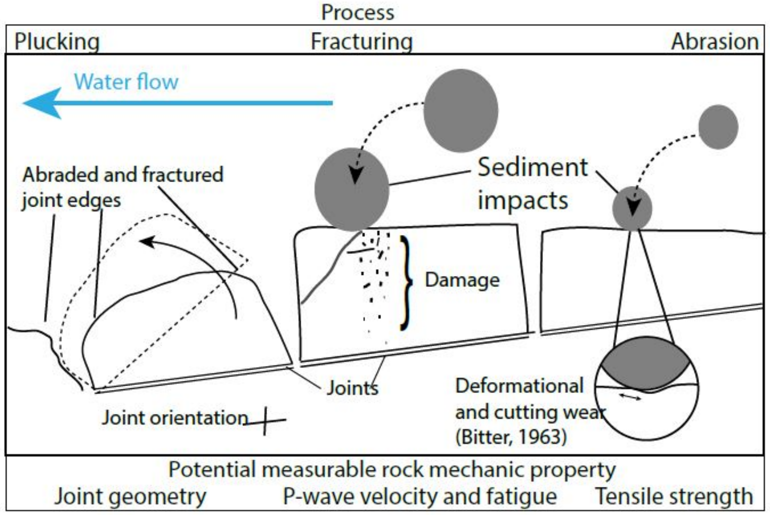
$$E = KA^m S^n$$

n<1 (consistently at ~0.6-0.7 for >30 profiles in gneiss and granite)

n>=1 (consistently at ~1.0-1.5 for >10 profiles in basalt)

Clear evidence of plucking along foliation parallel joints

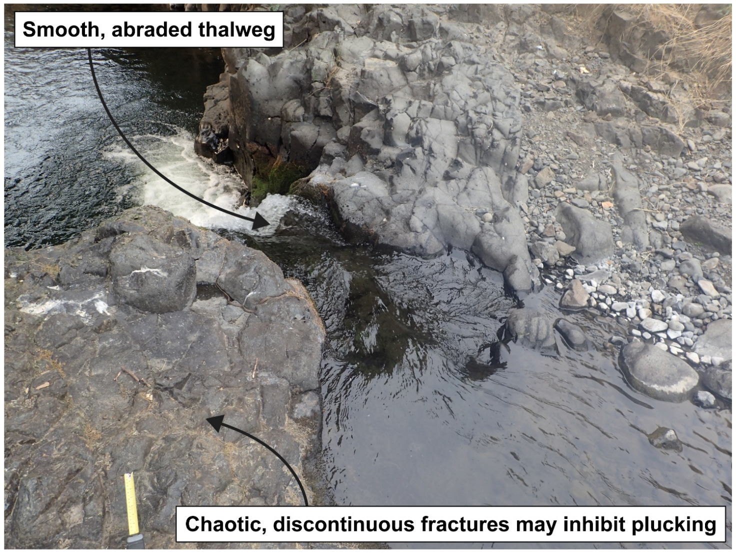




n ~ 2/3
(Whipple et al., 2000)

n ~ 3/2

Rock-type controls scaling between slope and erosion rate



Between a Rock **and a hard place**

- Rock-type variability has 1st order influences on the rate and style of landscape evolution, yet we are only beginning the unravel how to parameterize different rock-types in landscape evolution models

- Variation in rock type is not just differences in ‘K’. The exponent matters as well

- Rock-type dictates dominant erosion process, and thus erosion-stream power scaling.

Quantifying climate's impact on landscape evolution

Climatic forcing of erosion, landscape, and tectonics in the Bhutan Himalayas

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Decoupling of erosion and precipitation in the Himalayas

D. W. Burbank[1], A. E. Blythe[2], J. Putkonen[3], B. Pratt-Sitaula[1], E. Gabet[1], M. Oskin[1], A. Barros[4] & T. P. Ojha[5]

Dominance of tectonics over climate in Himalayan denudatic

Vincent Godard[1], Didier L. Bourlès[1], Françoise Spinabella[1], Douglas W. Burbank[2], Bodo Bookhagen[2], G. l
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Coupled spatial variations in precipitati erosion ra Washingtc

Peter W. Reiners[1], Todd A. Ehlers[2], Sara G. Mitchell[2]

Chemical weathering as a mechanism for the climatic control of bedrock river incision

Brendan P. Murphy[1], Joel P. L. Johnson[1], Nicole M. Gasparini[2] & Leonard S. Sklar[3]

river incision

Ken L. Ferrier, Kimberly L. Huppert & J. Taylor Perron

Nature **496**, 206–209 (11 April 2013) Received: 03 September 2012

Minimal climatic control on erosion rates in the Sierra Nevada, California

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A climate signal in exhumation patterns revealed by porphyry copper deposits

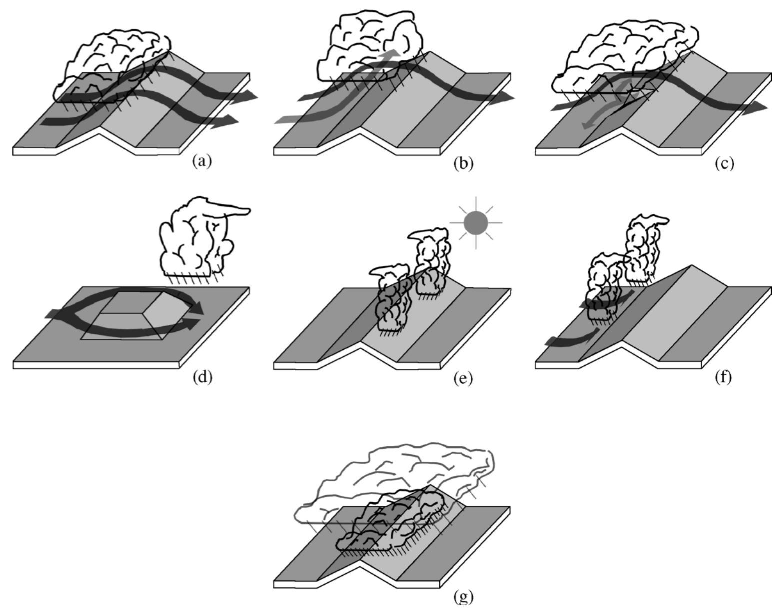
Brian J. Yanites & Stephen E. Kesler

Climate does matter!
Or does it?
I’m sorry. I got confused
and made of mess of things.

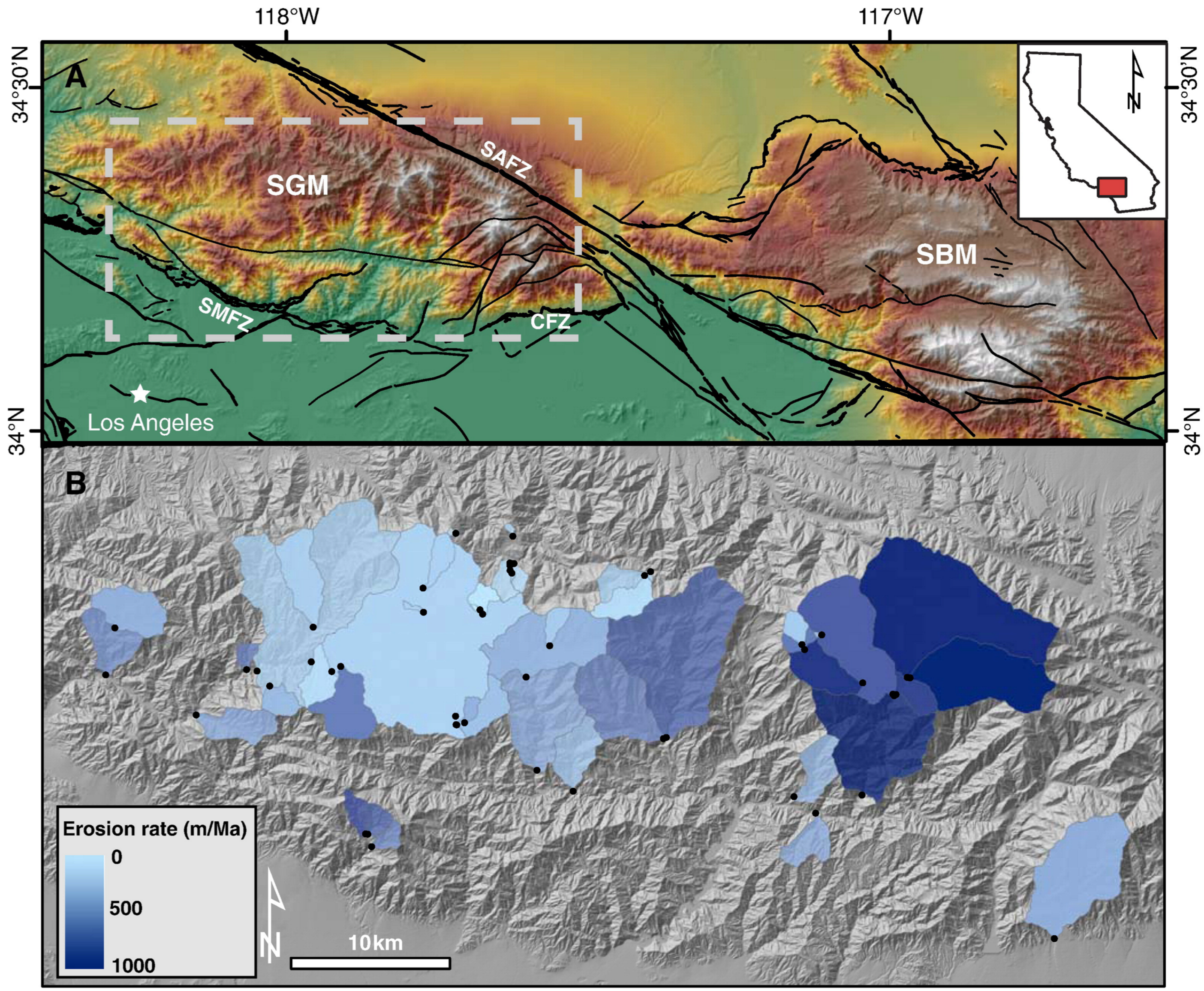
Safe to say that some serious adjustments are needed

Climate challenge #1 : weather erodes, not climate (see Jean Braun's talk)

Climate challenge #2: Climate changes for many reasons, including climate-topography coupling



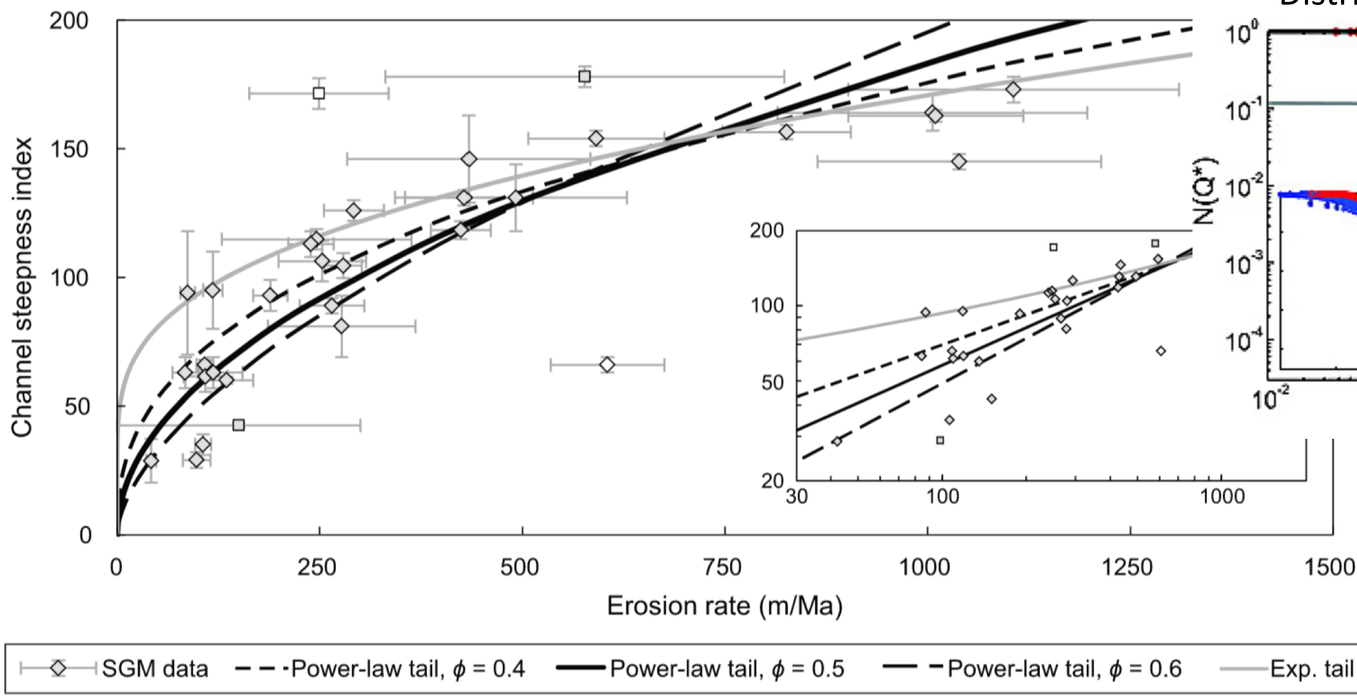
San Gabriel natural experiment



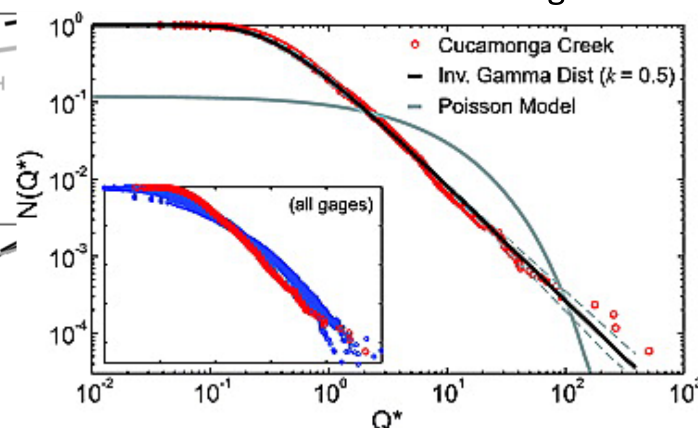
Dibiase et al., 2010

Observations require water discharge variability and an erosion threshold

Building on Tucker 2004; Lague et al 2005…



Distribution of water discharge

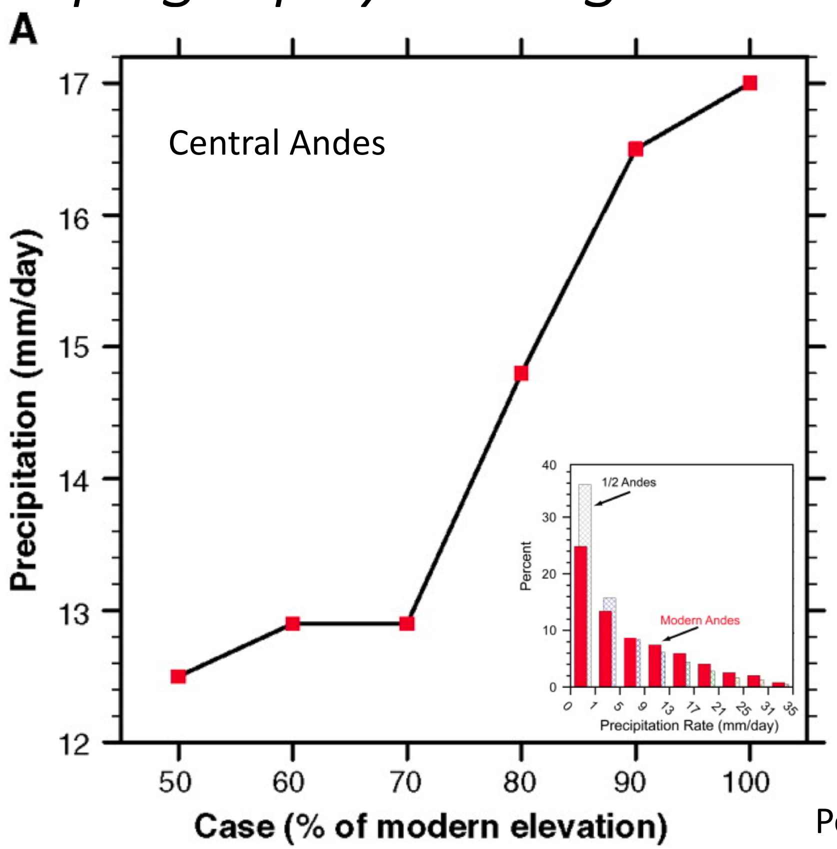


$$E = k_v(\tau - \tau_c)$$

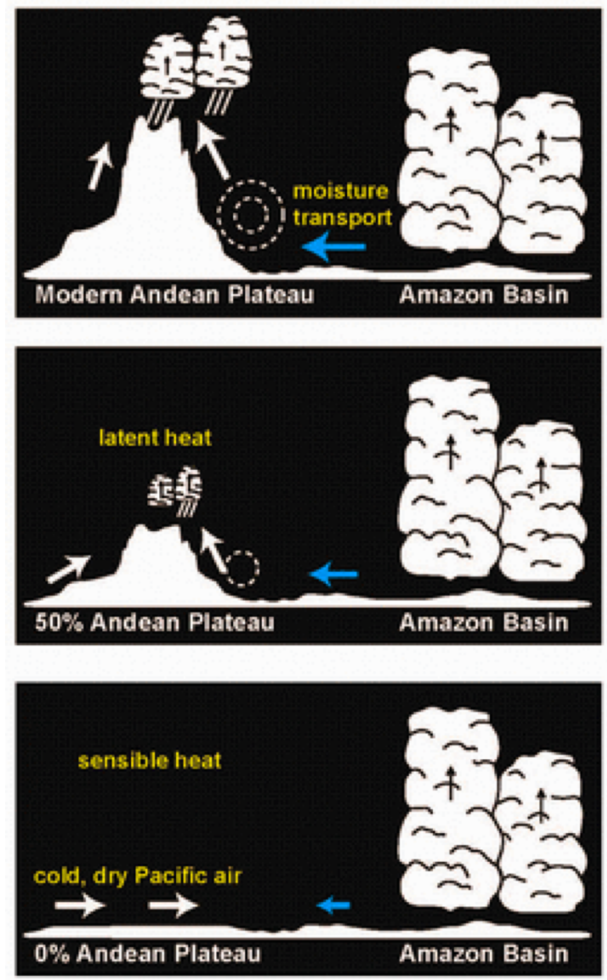
Steepness becoming less sensitive to rock-uplift rate

Dibiase and Whipple, 2011

Climate challenge #2: :
Topography changes climate



Poulsen et al., 2010

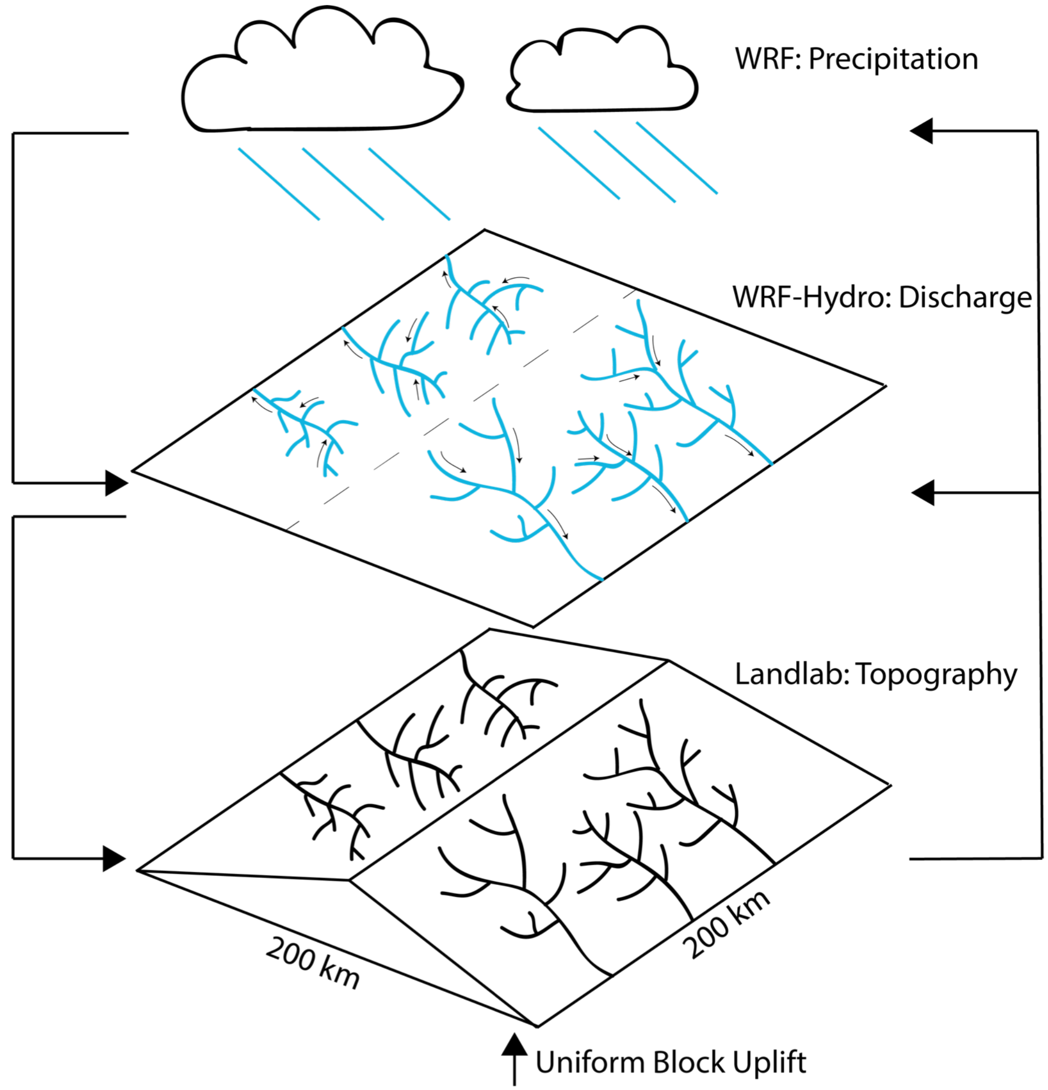


WRF THE WEATHER RESEARCH & FORECASTING MODEL

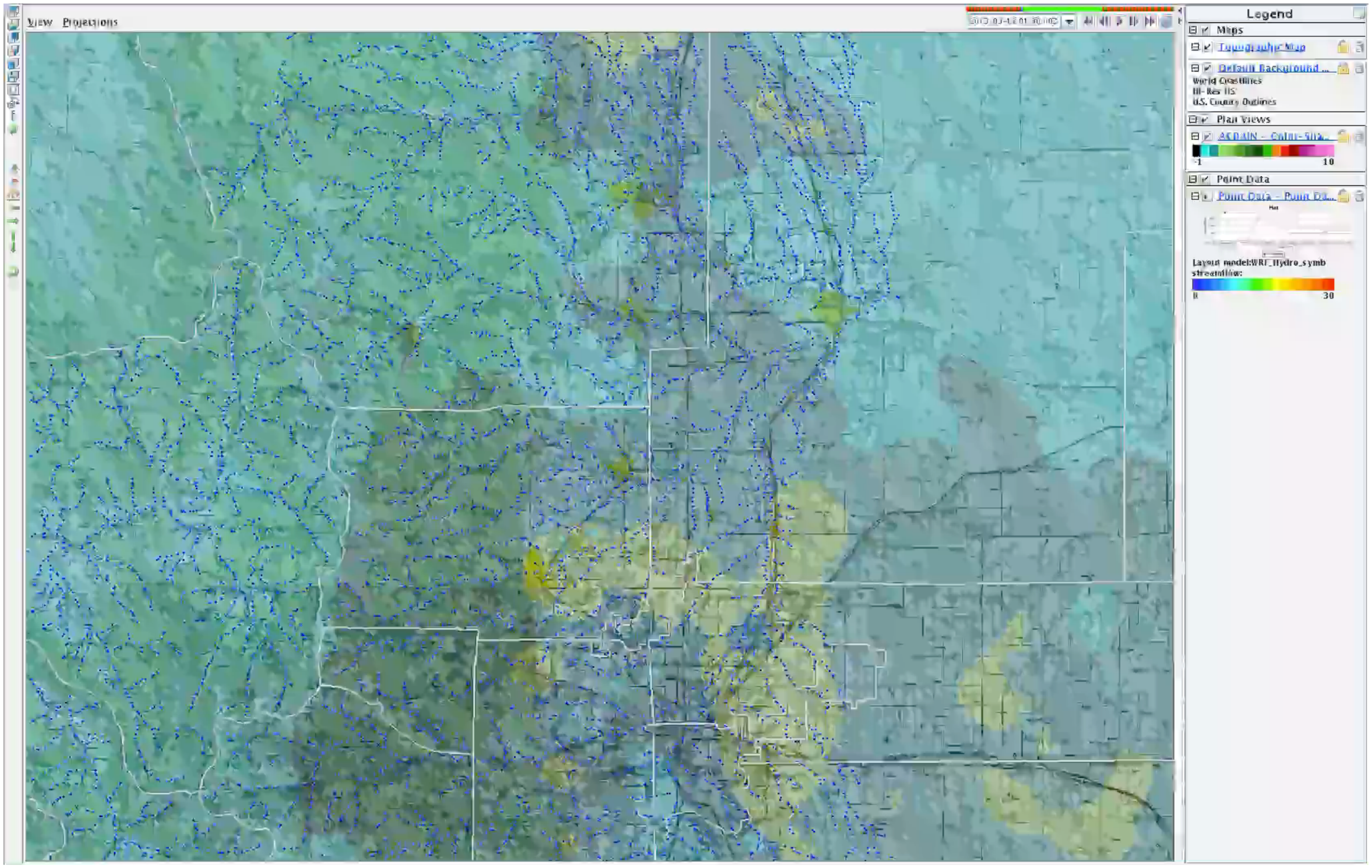
WRF-Hydro

LANDLAB

Lynch et al., in prep



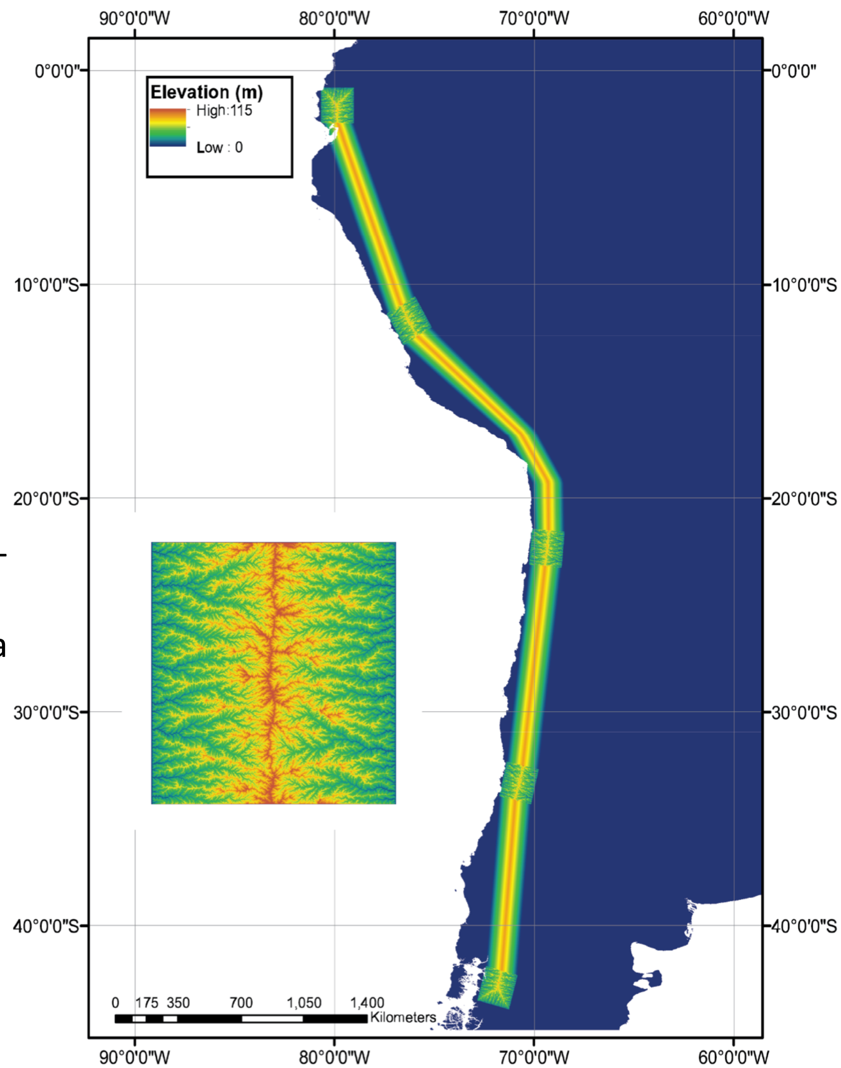
Front Range
storm of 2013

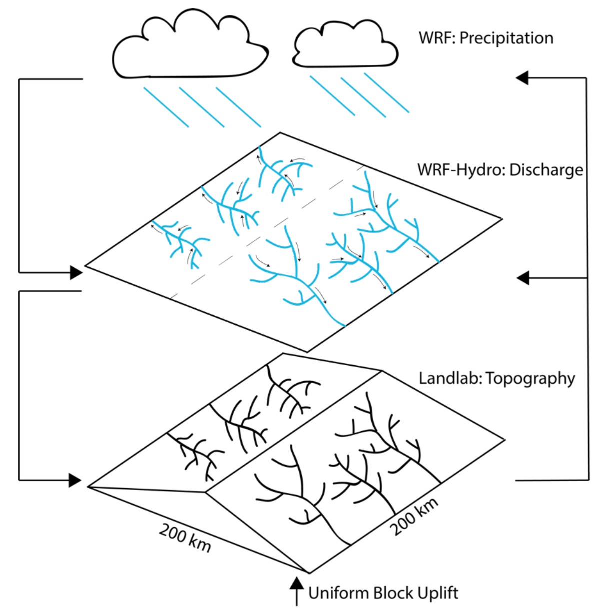


https://ral.ucar.edu/projects/wrf_hydro/overview

Utilizing the N-S latitudinal gradient

Allows us to apply modern boundary conditions (e.g. sea-surface temperature) to WRF model rather than nesting in a GCM

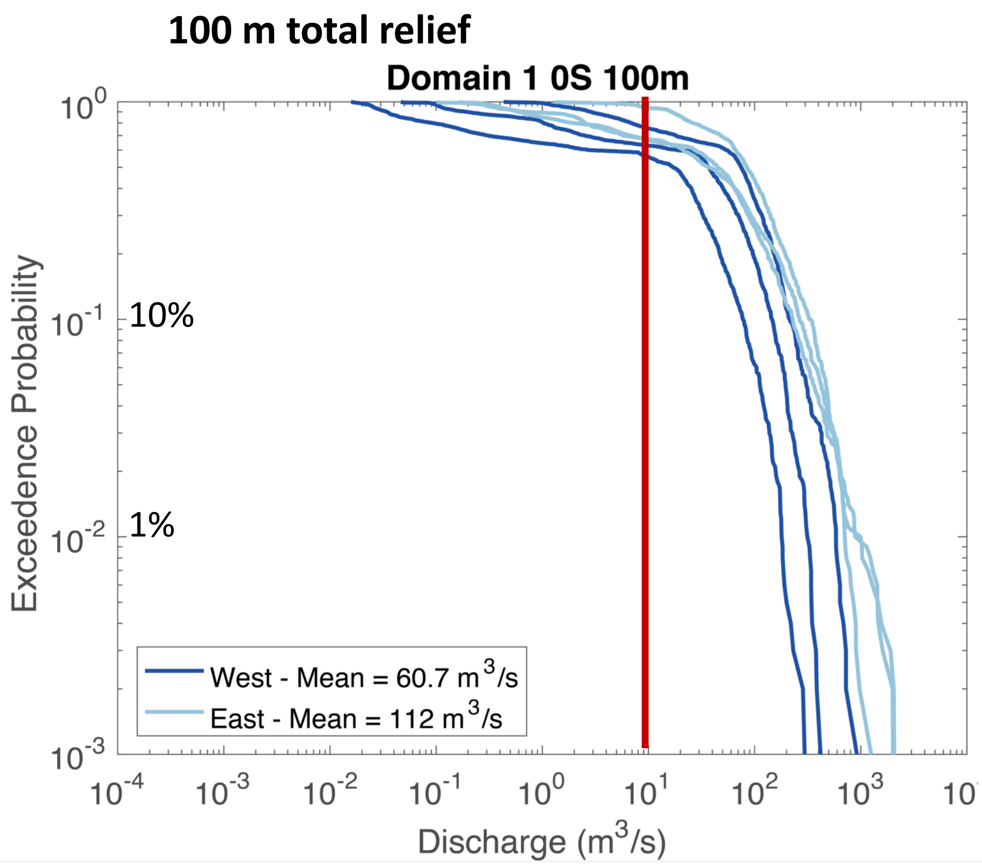


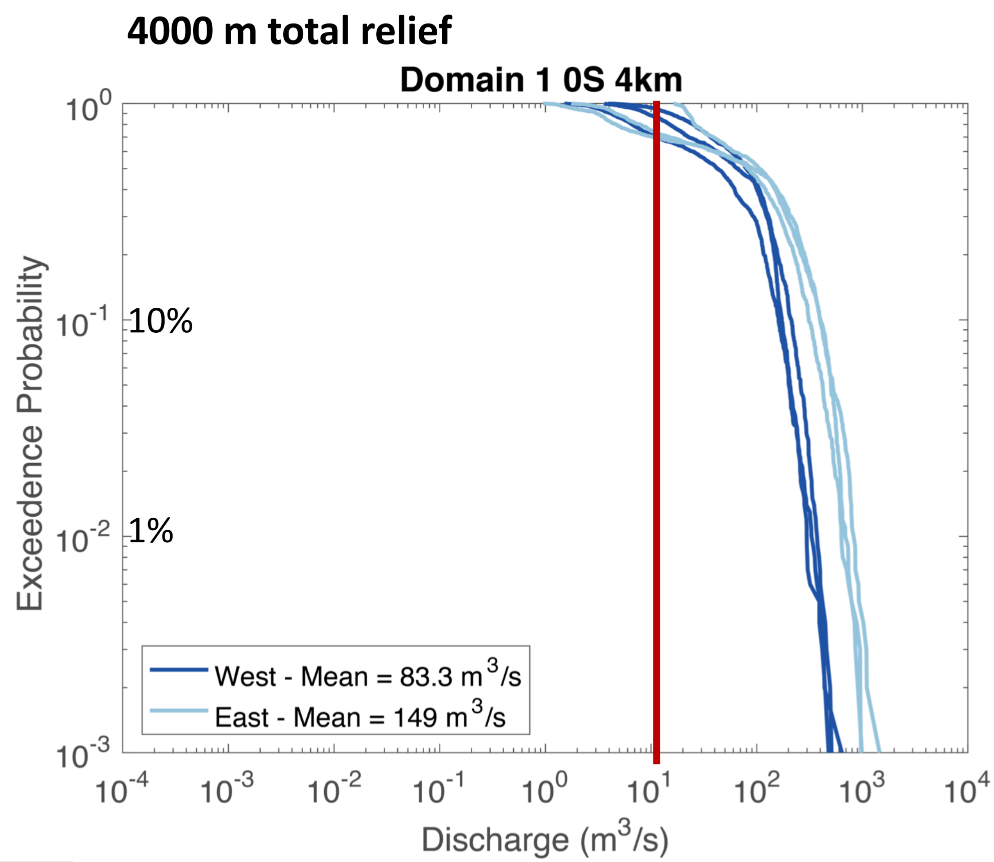


Lynch et al., in prep

Equatorial climate

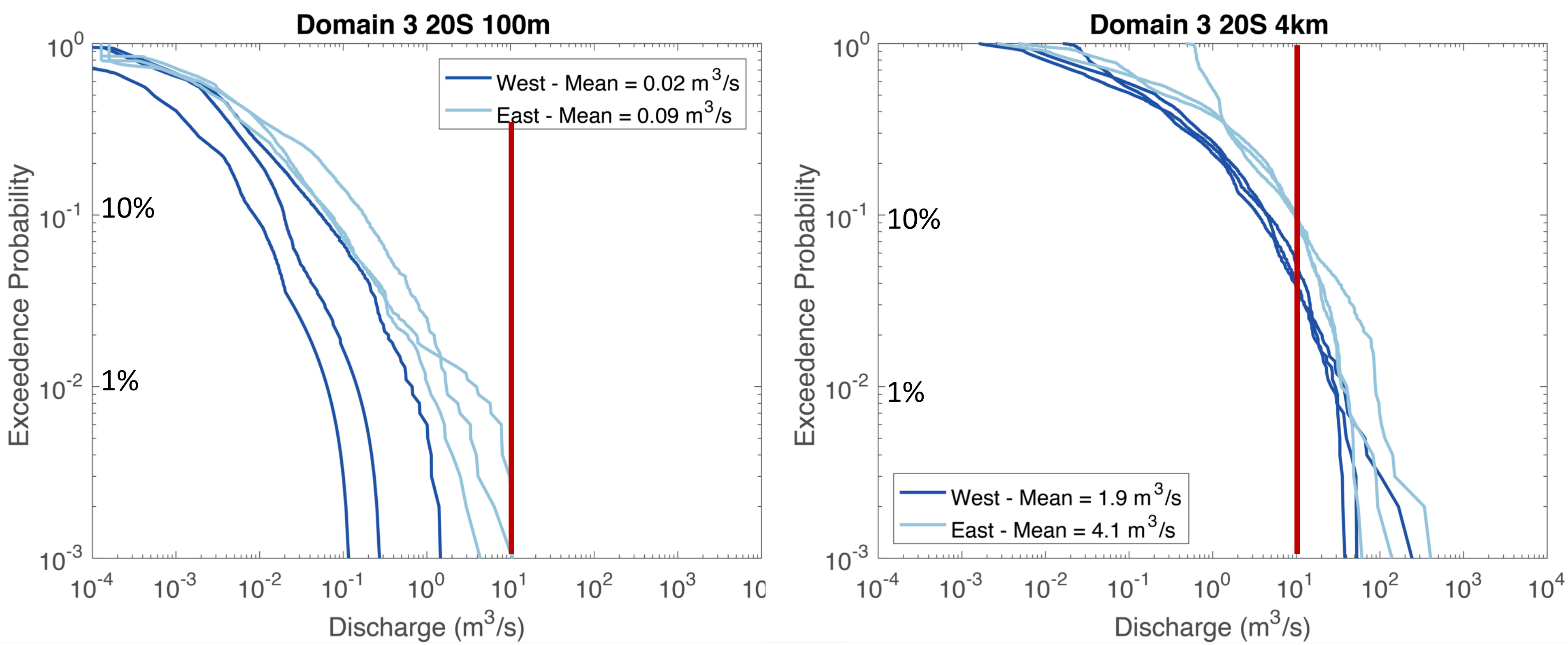
Baseflow (high probability flows) is higher, but not much change in extremes





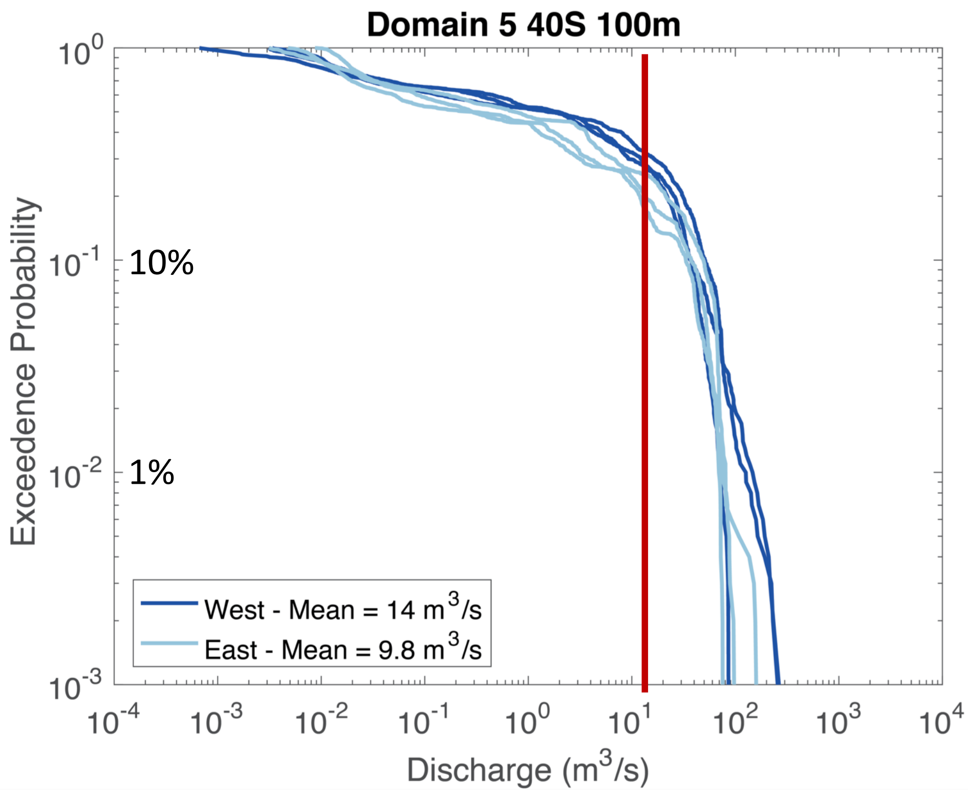
Sub-tropical

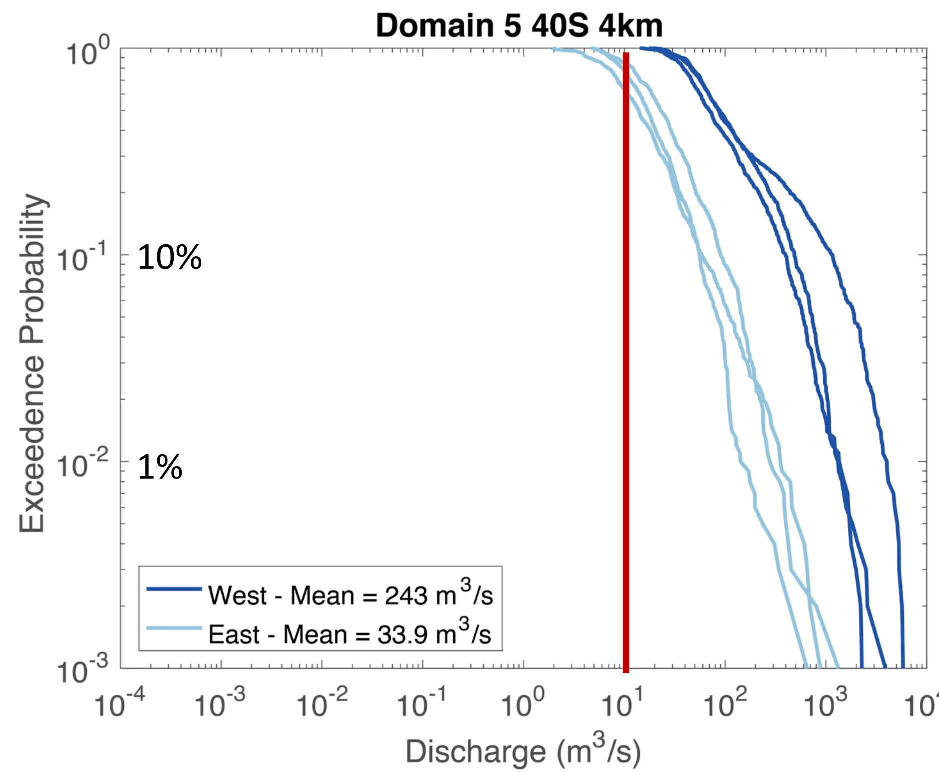
From 0 to >7-10% of time



Mid-latitude

Latitude matters in climate-topography coupling





Cleaning up the dog's breakfast

- Increasingly clear that a 'mean' climate state is difficult to translate into a geomorphic 'effectiveness'
  - Weather erodes, not climate
- Climate and resulting weather patterns change over a range of timescales
- Climate-topography coupling varies with latitude
  - We very well might expect a dog's breakfast of study conclusions

Channel geometry (think width)

- So far focused on models in which slope is the only free geomorphic variable to respond. Thus channels get steeper (less steep) and topography gets higher (lower) in response to any change.

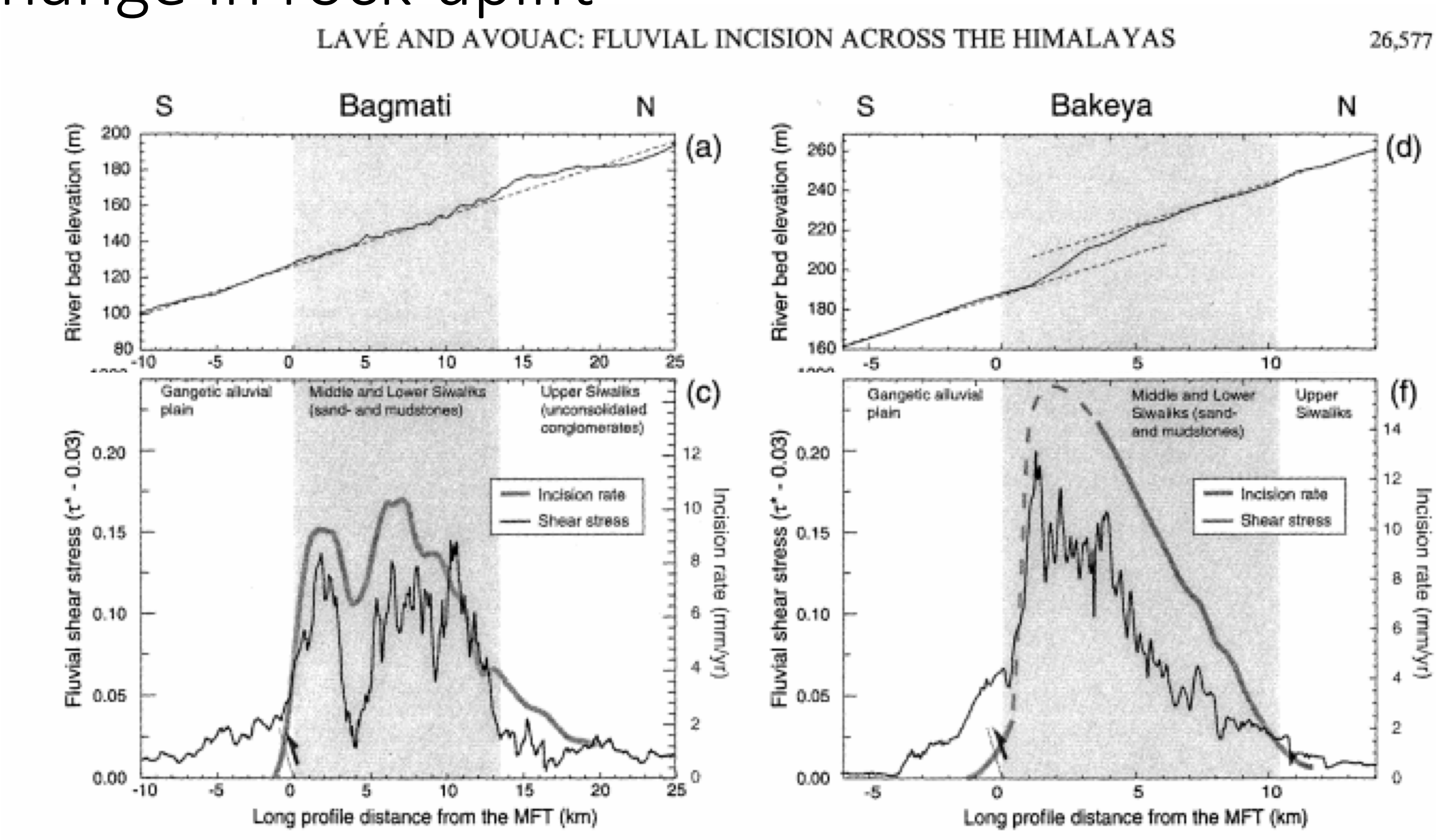
- That's not always the case

Channel geometry challenge: How do we maintain the power of simplicity while recognizing that rivers are more than 1-dimensional?

$$\tau_b = \rho g \left(\frac{nQ}{w} \right)^{3/5} S^{7/10}$$

10x change in rock-uplift

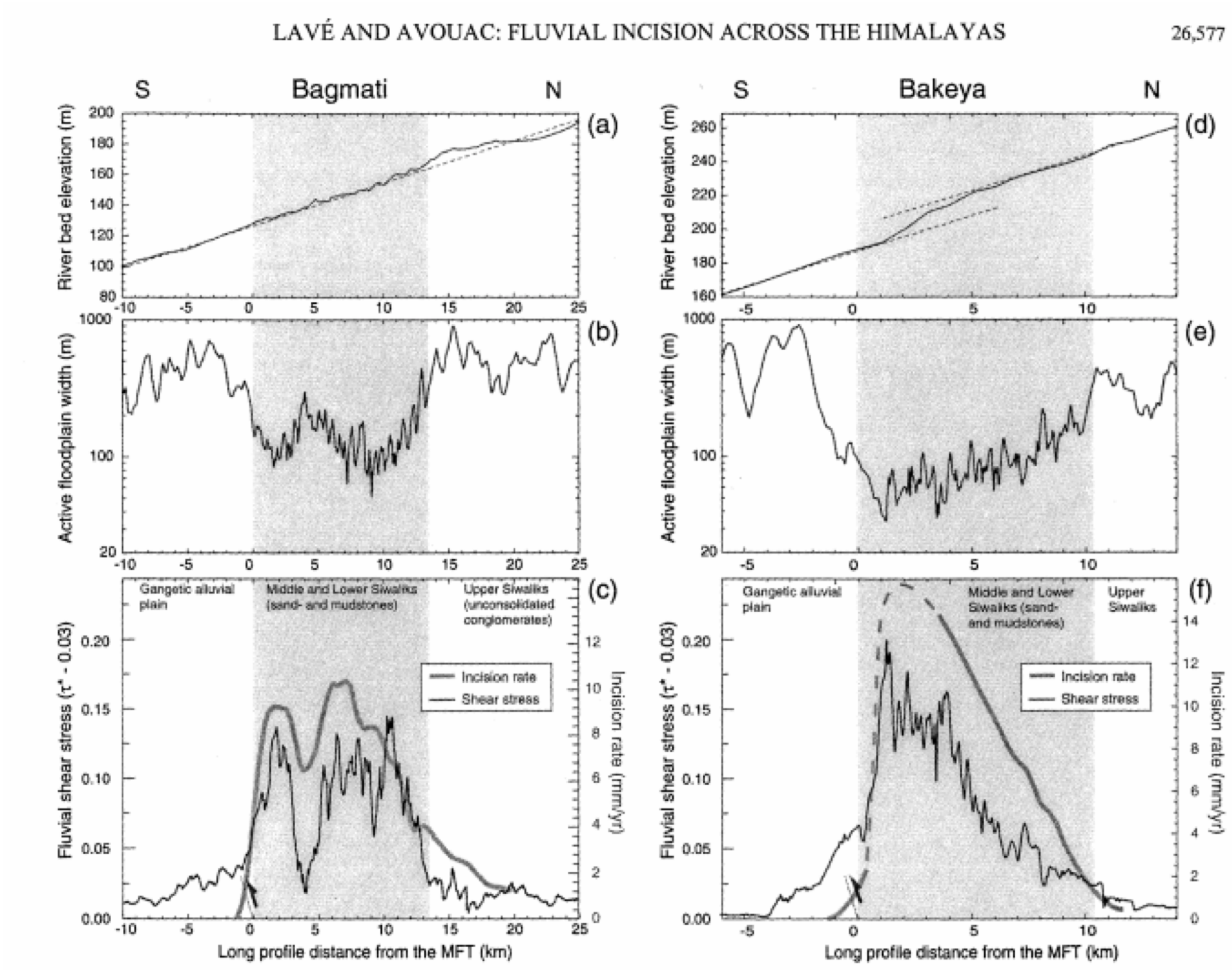
Siwaliks/'Sub -Himalaya'

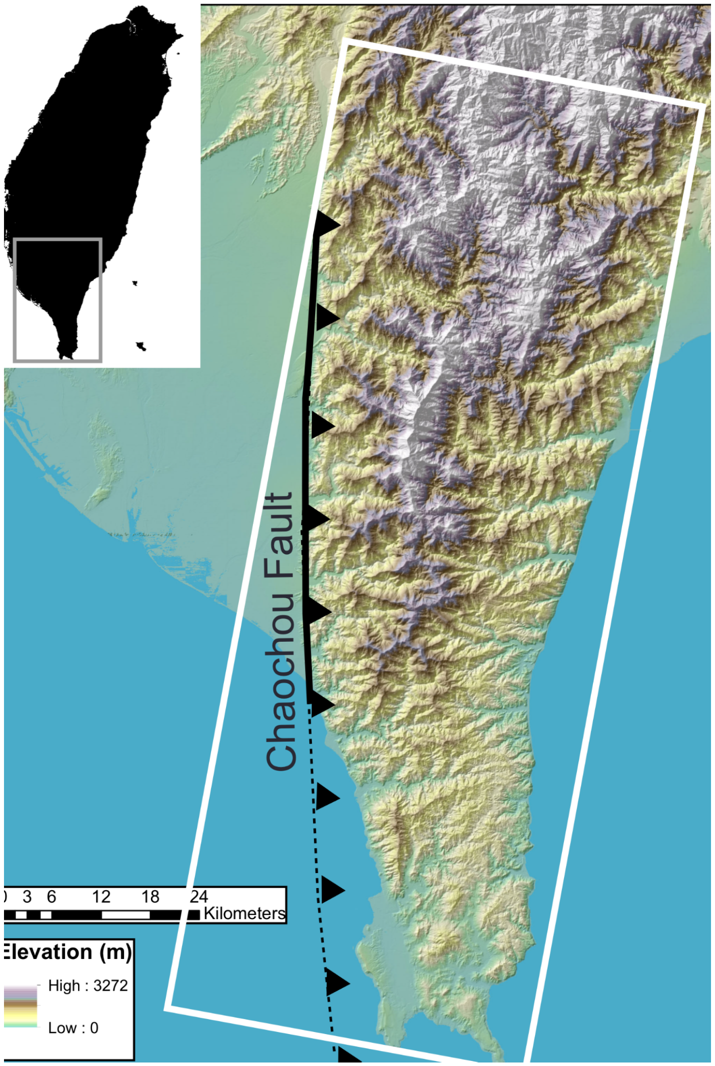


Lave and Avouac, 2001)

Channel width dominates the morphological response to variation in rock-uplift

$$E = KA^m S^n$$



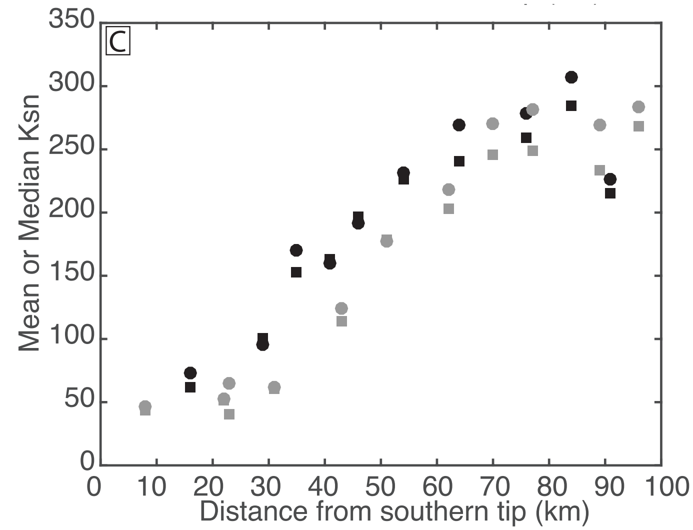


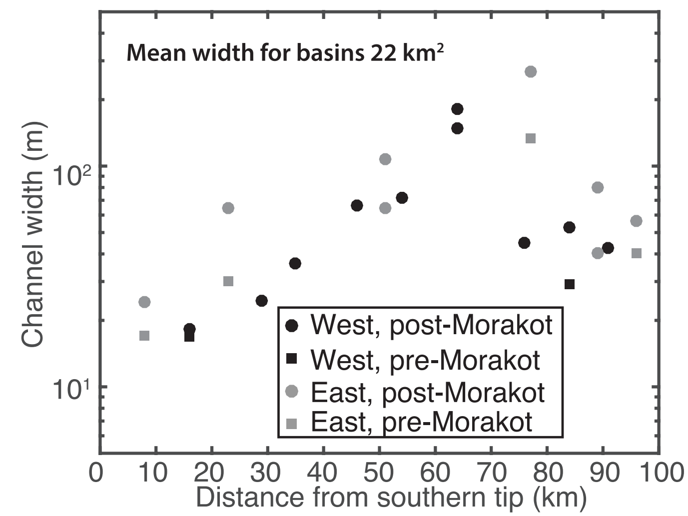
Yanites et al., 2018

$$\tau_b = \rho g \left(\frac{nQ}{w} \right)^{3/5} S^{7/10}$$

$$\cancel{w = k_w A^b}$$

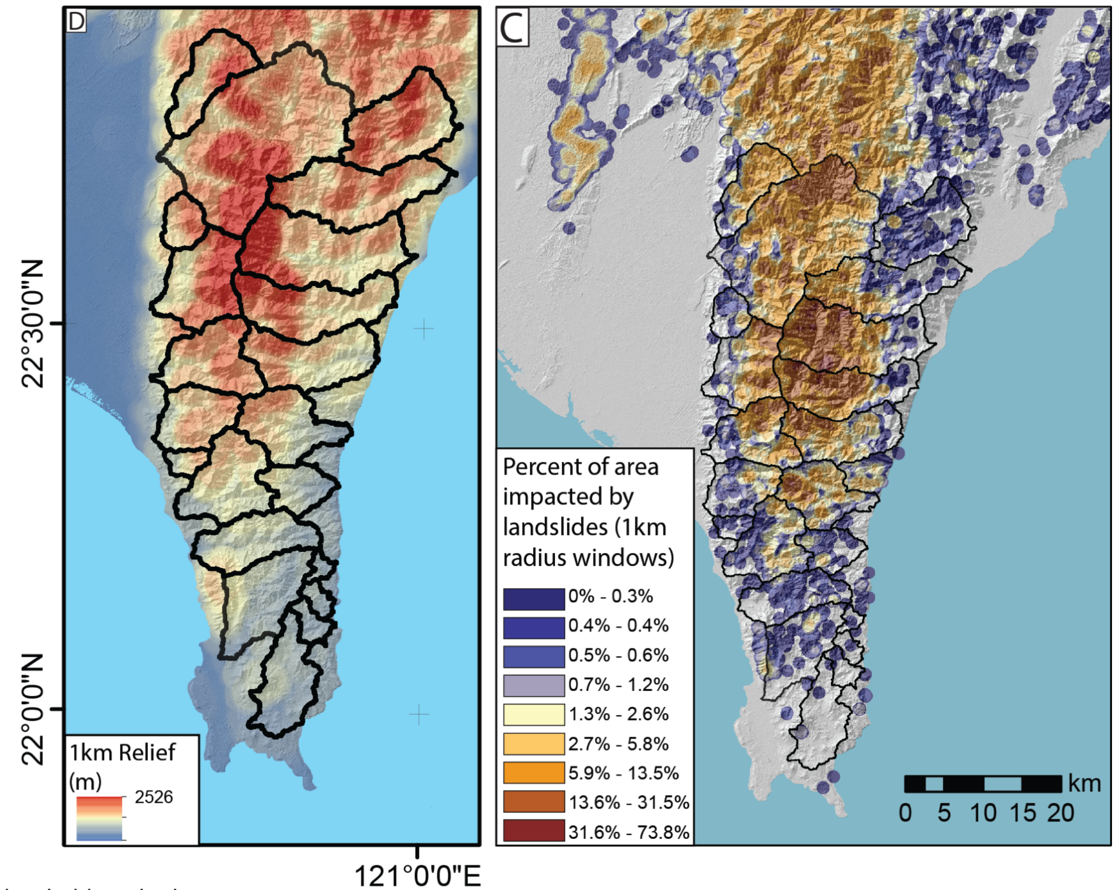
Southern Taiwan

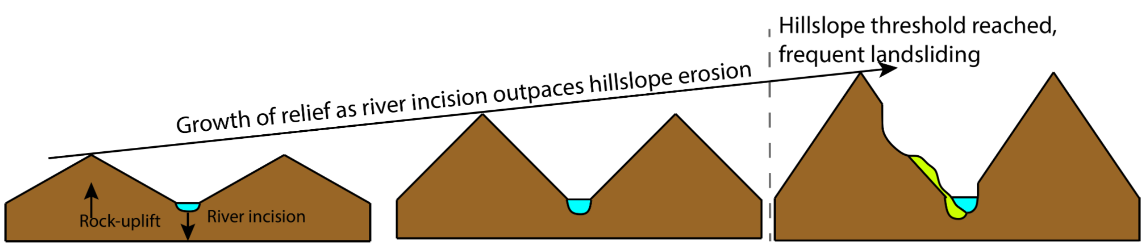




Rivers are wider where they are steeper?

Influence of sediment supply



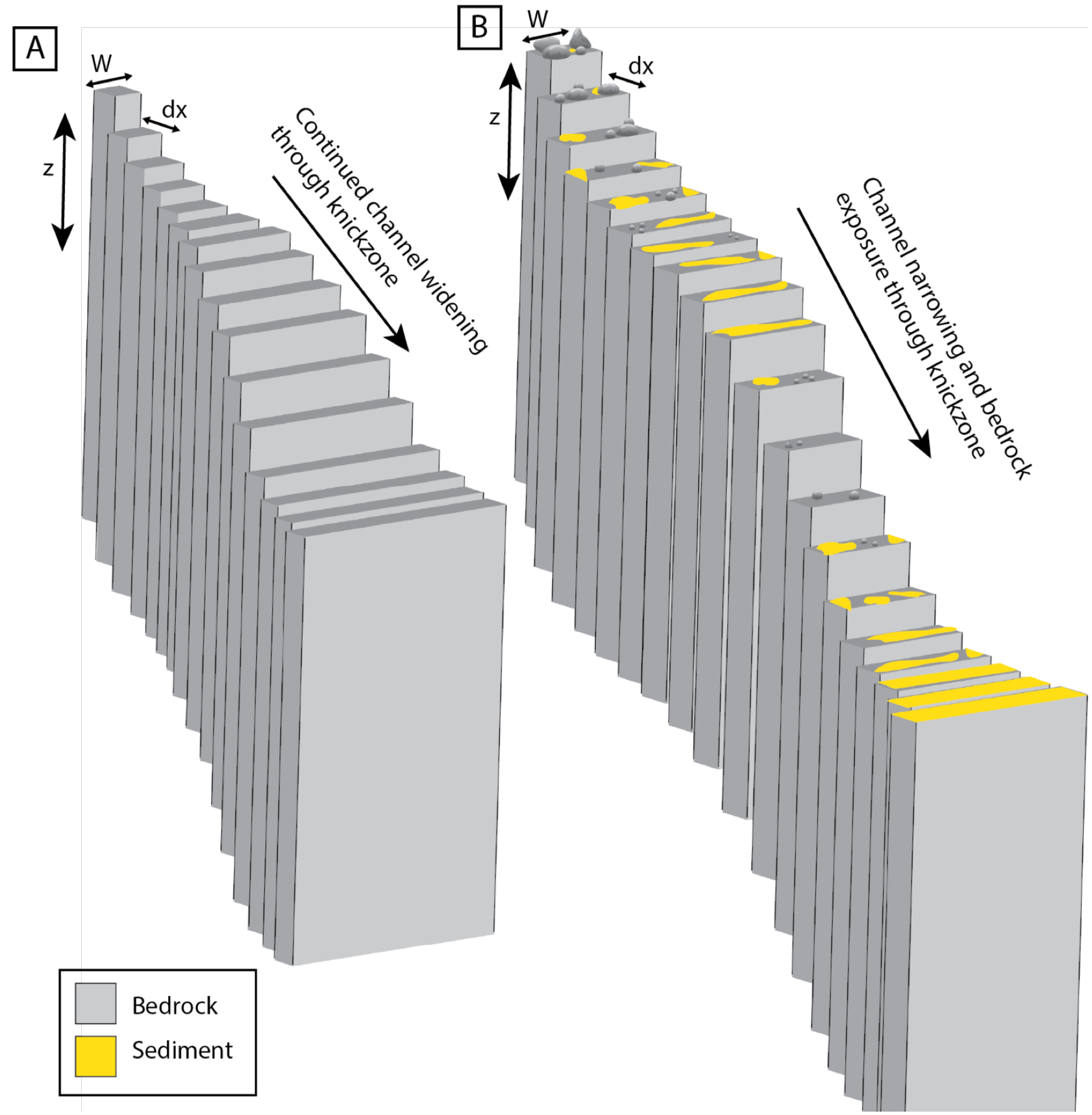


River channel optimization as a dynamic process

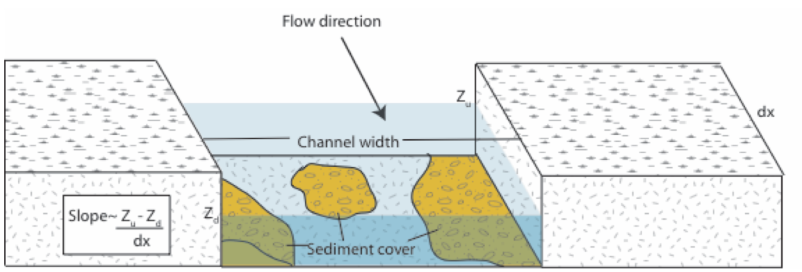
$$E = F k_f \tau^a$$

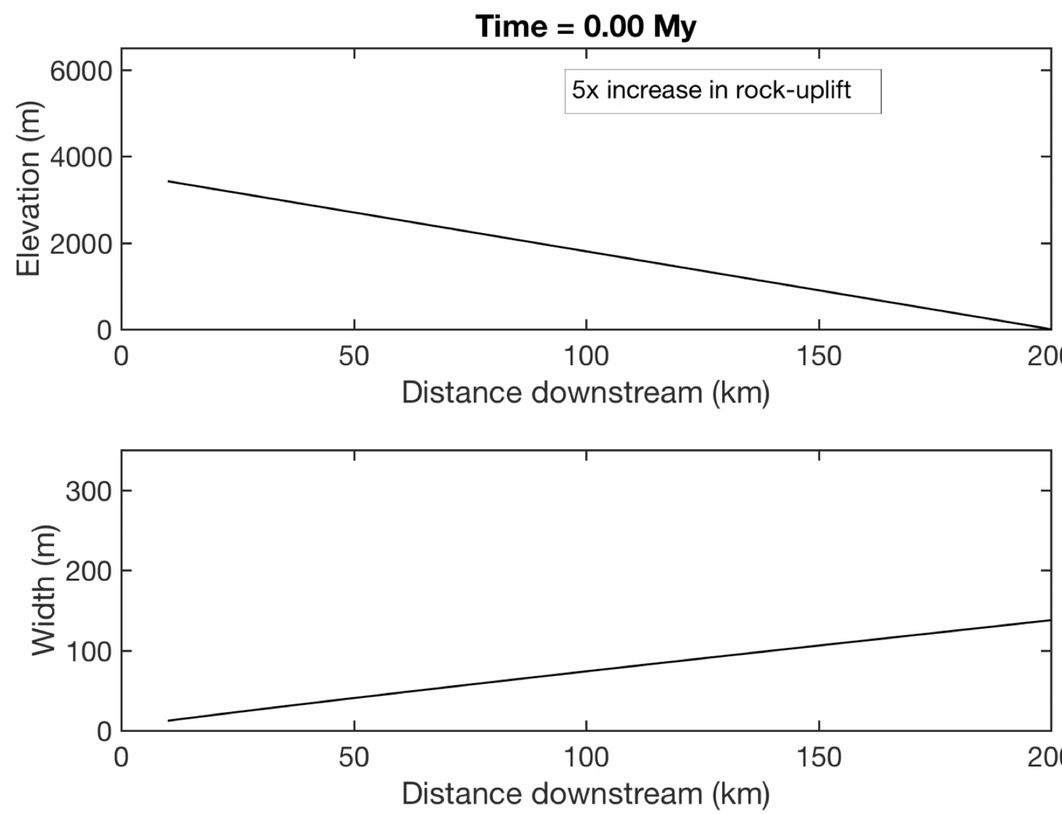
$$F = 1 - \frac{Q_s}{Q_t}$$

$$w_i = w_0 \pm k_b \tau$$



Dynamic width and sediment

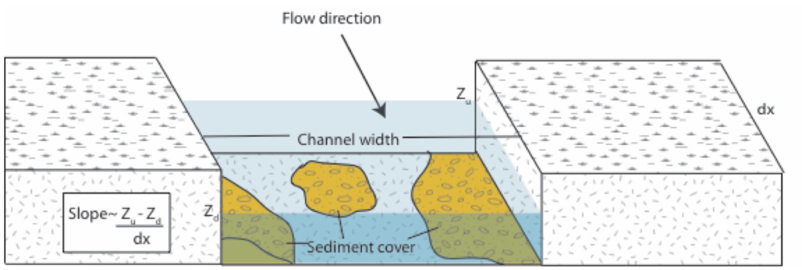


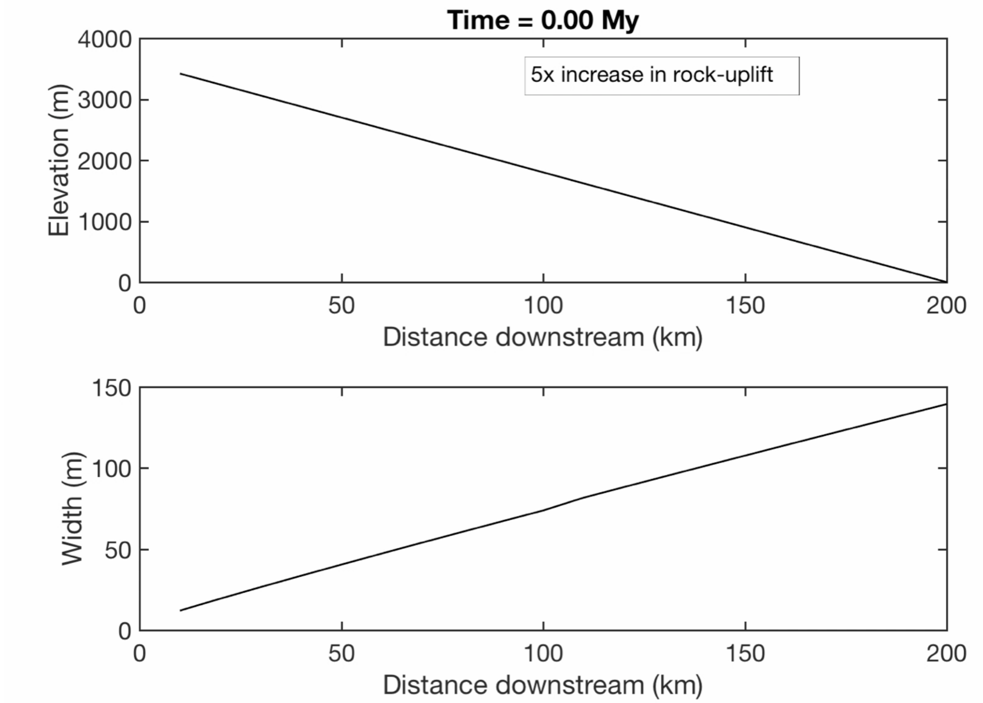


'Bedrock exposure limited'

Yanites, in press?
JGR-Earth Surface

Dynamic width and sediment

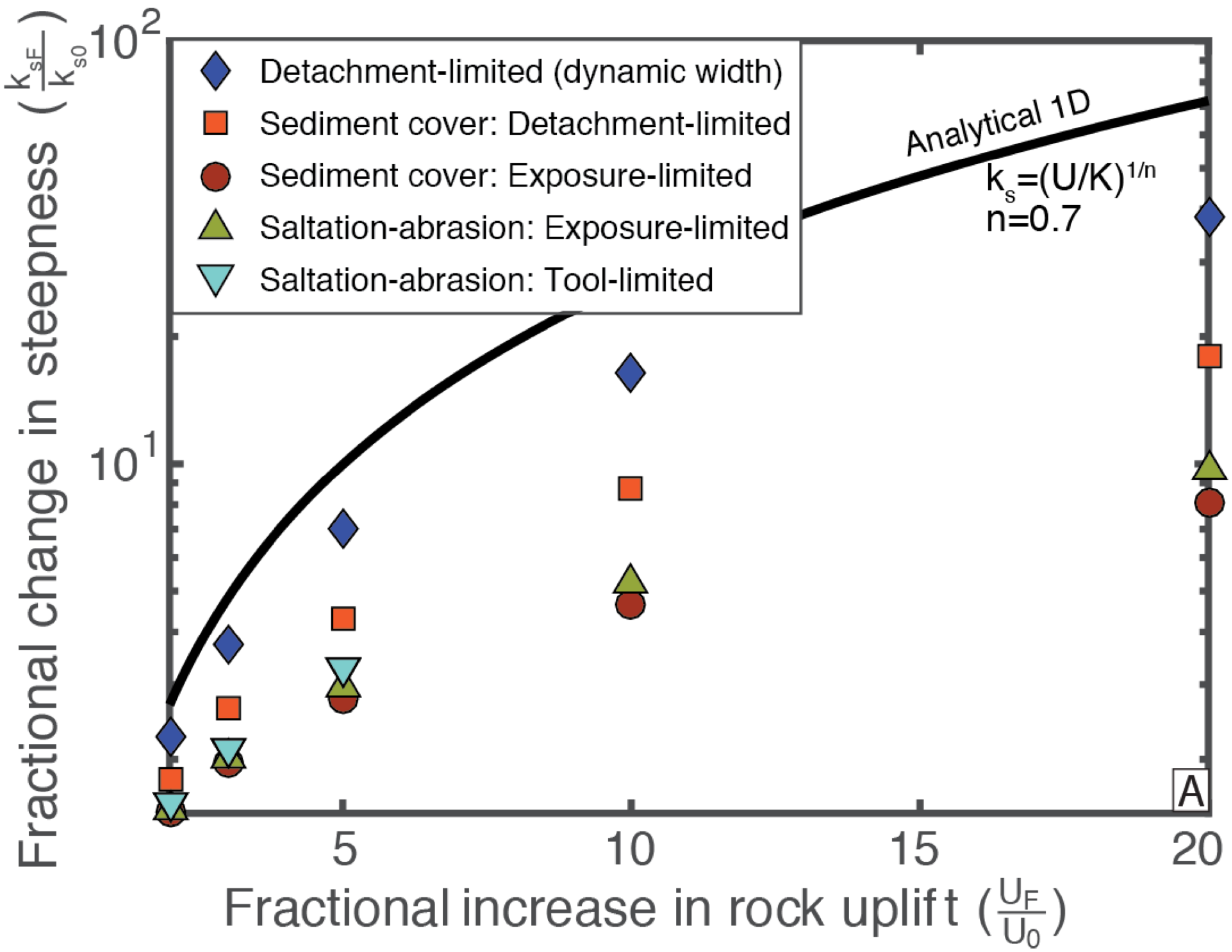




'Sed-cover detachment-limited'

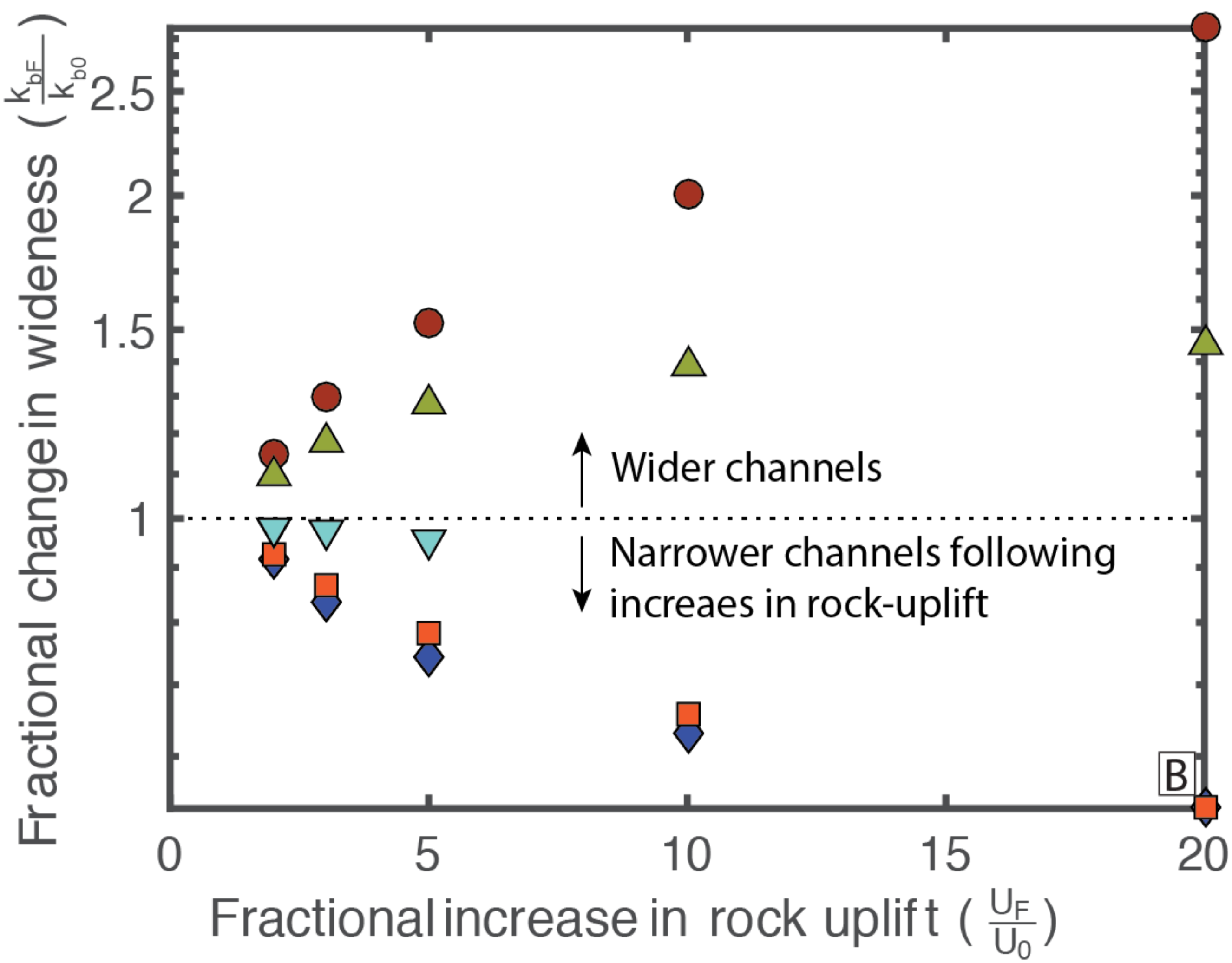
Yanites, in press?
JGR-Earth Surface

Channel geometry lowers topographic sensitivity to rock-uplift



U_0	Initial rock-uplift rate
U_F	Final rock-uplift rate
k_{S0}	Steady state channel steepness prior to increase in rock-uplift
k_{SF}	Steady state channel steepness following increase in rock-uplift
k_{b0}	Steady state channel wideness prior to increase in rock-uplift
k_{bF}	Steady state channel wideness following increase in rock-uplift

Yanites, in press?
JGR-Earth Surface



“Taiwan?”

Sediment transport dominated systems

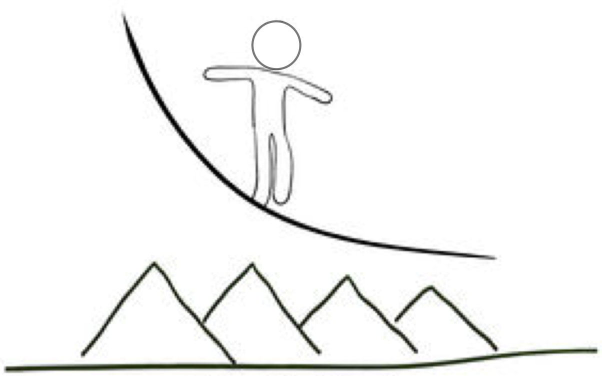
The ‘spectrum of success’ is because there is a spectrum of river systems

“Idaho?”

Bedrock detachment dominated systems

Geomorphologists walking a 1-dimensional tightrope

- In some environments, channel width can be as dominant of a control on erosional processes as slope
- Current 1-D ‘generalized’ stream power models do not capture this
- Simple modifications/assumptions can help overcome, but ultimately, mechanistic channel geometry models are needed



Summary

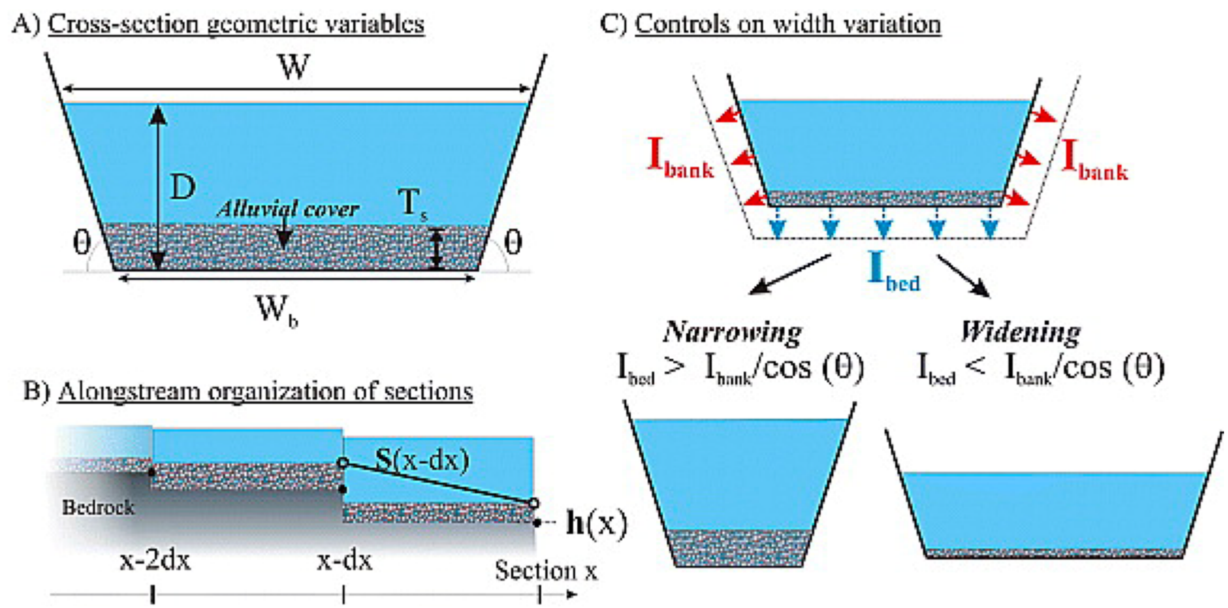
There are complexities in natural systems that can limit the applicability of our simplified models

There is no single equation that will describe all river systems (and thus landscapes!) in all environments.

This requires:

- Flexibility
- Situational awareness
- Innovative solutions

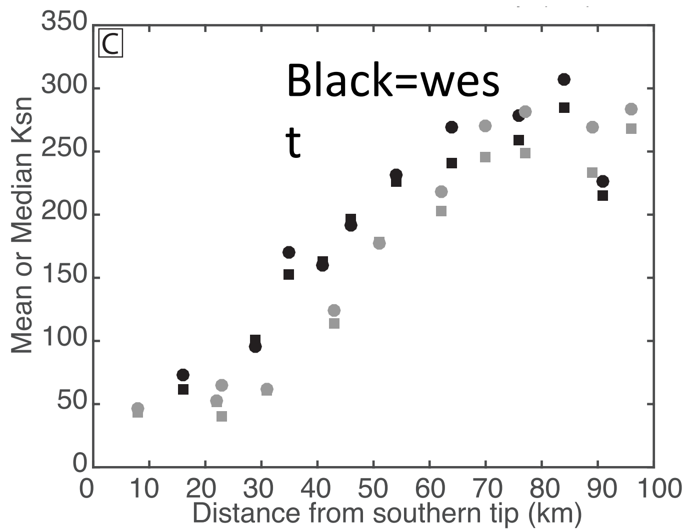
Thank you!   Questions or comments?

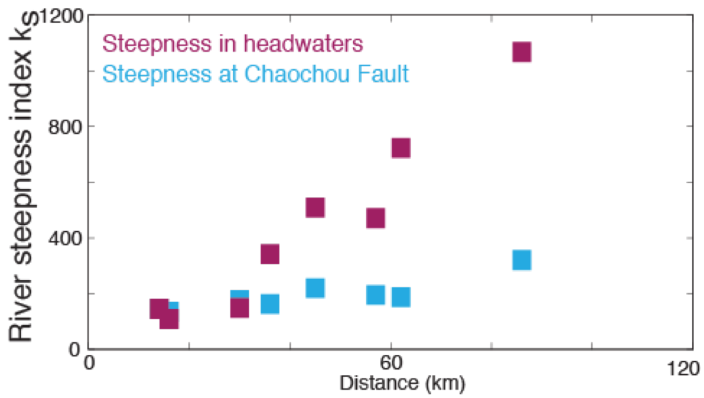

A) Cross-section geometric variables
W
D
Alluvial cover
T_s
θ
θ
W_b
B) Alongstream organization of sections
S(x-dx)
Bedrock
h(x)
x-2dx
x-dx
Section x
C) Controls on width variation
I_bank
I_bank
I_bed
Narrowing
I_bed > I_bank/cos (θ)
Widening
I_bed < I_bank/cos (θ)

Lague, 2010

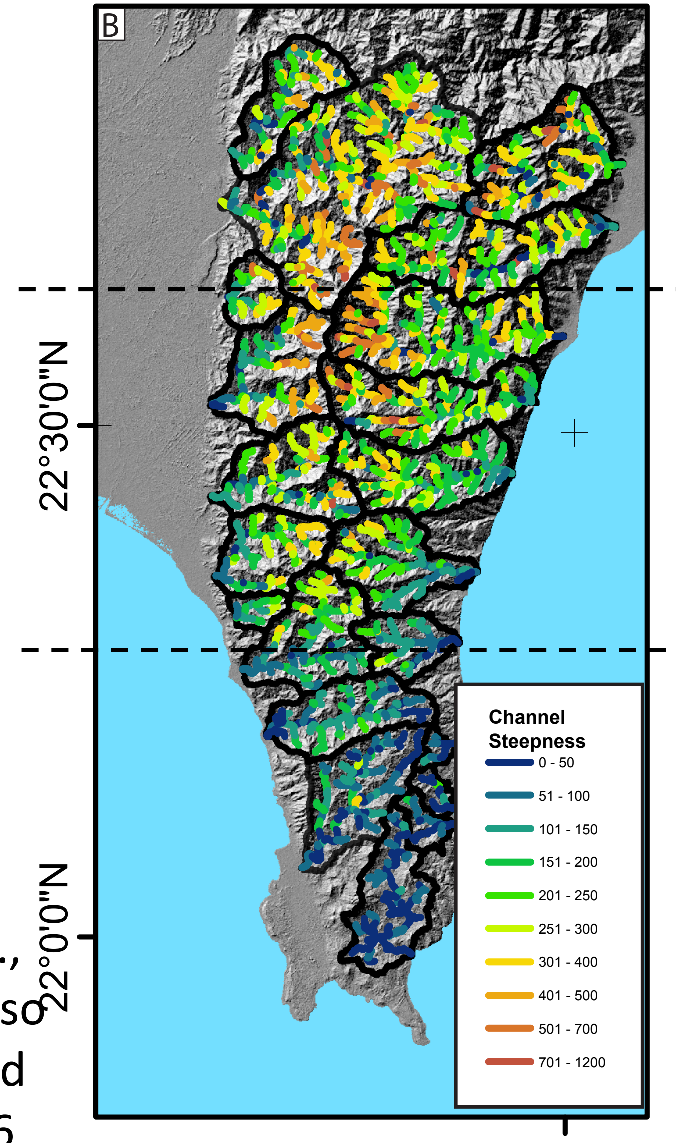
Channel steepness

$$S=k_sA^{-\theta}$$





~5x increase in steepness along strike

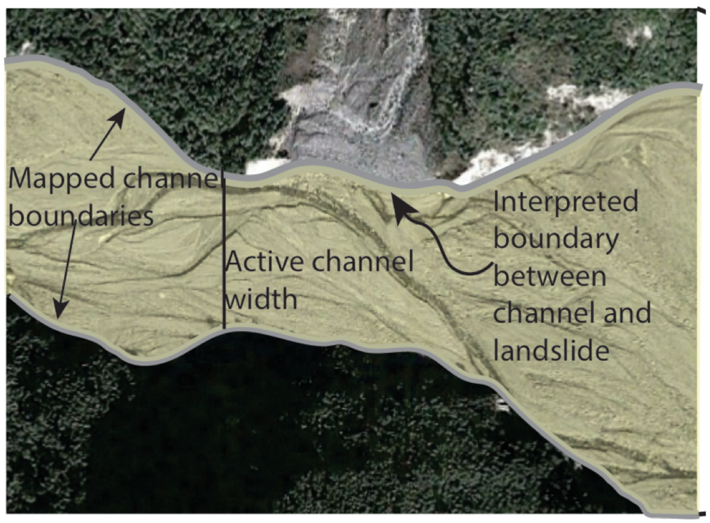


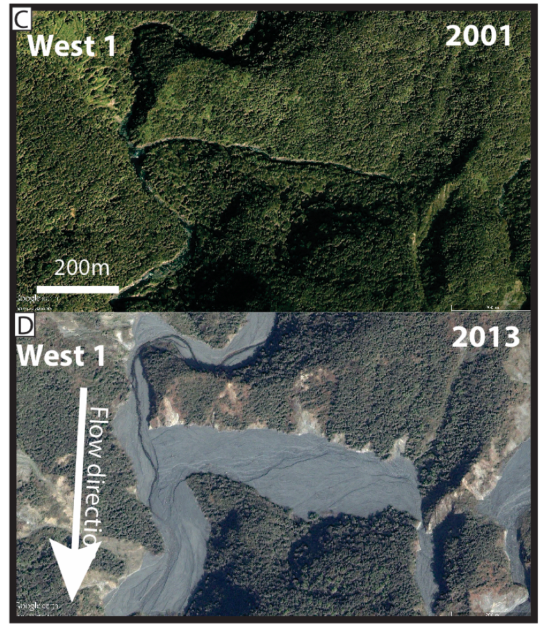
Yanites et al., in review. Also see Chen and Willett, 2016

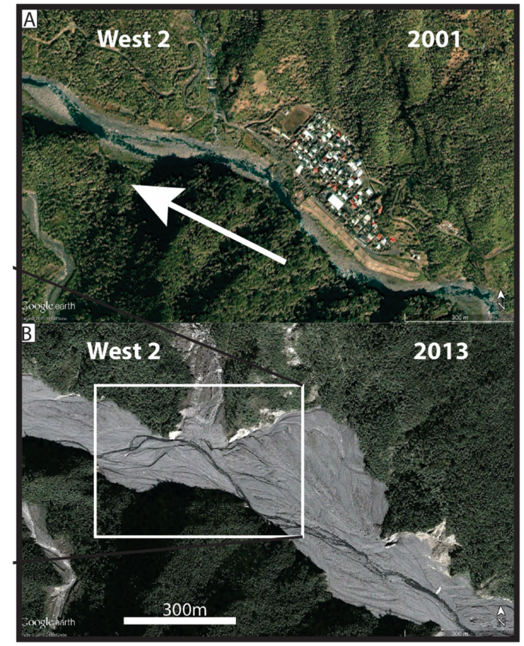
Channel width

Spatiotemporal dynamics

Channel bank delineation



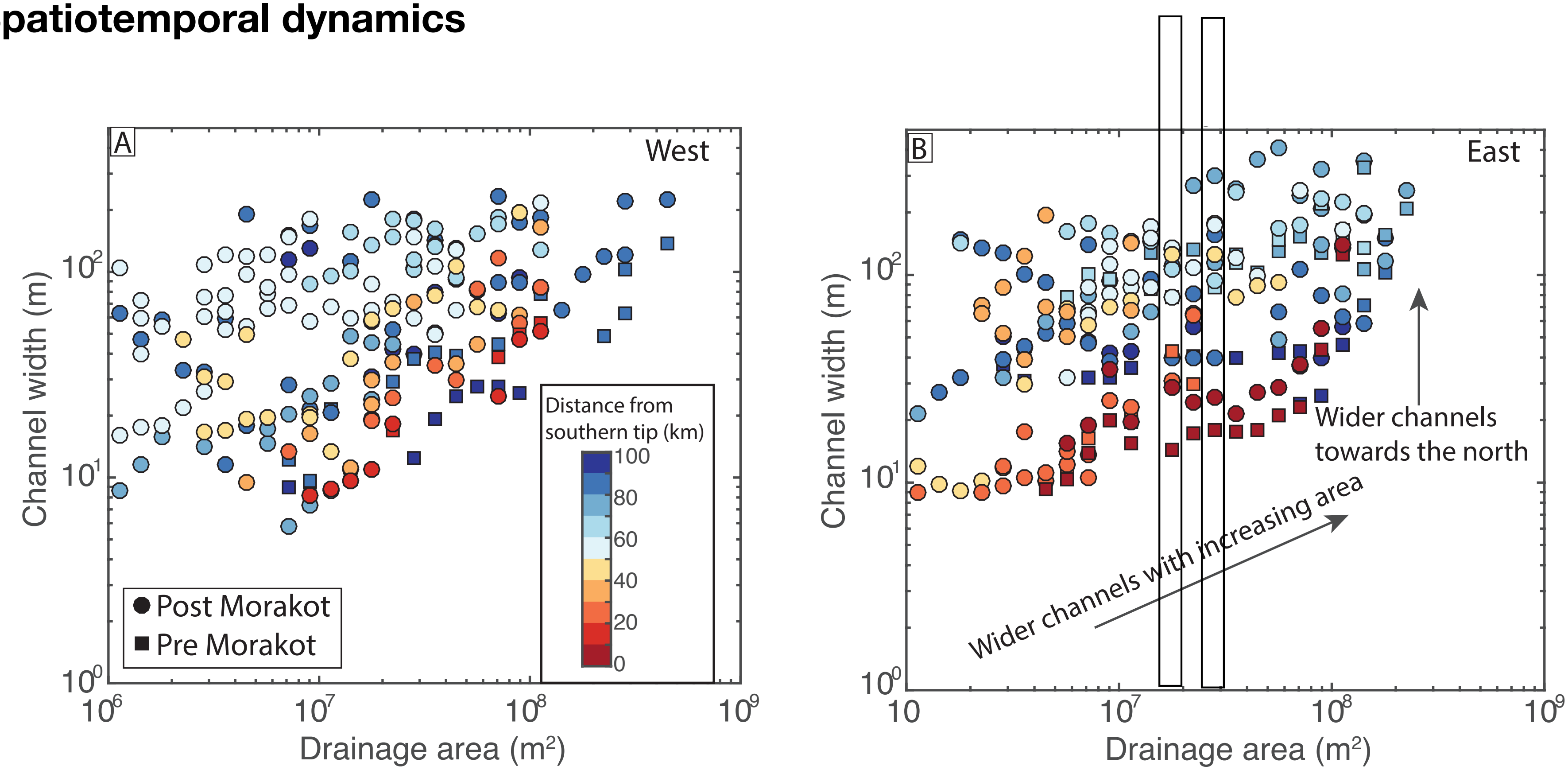


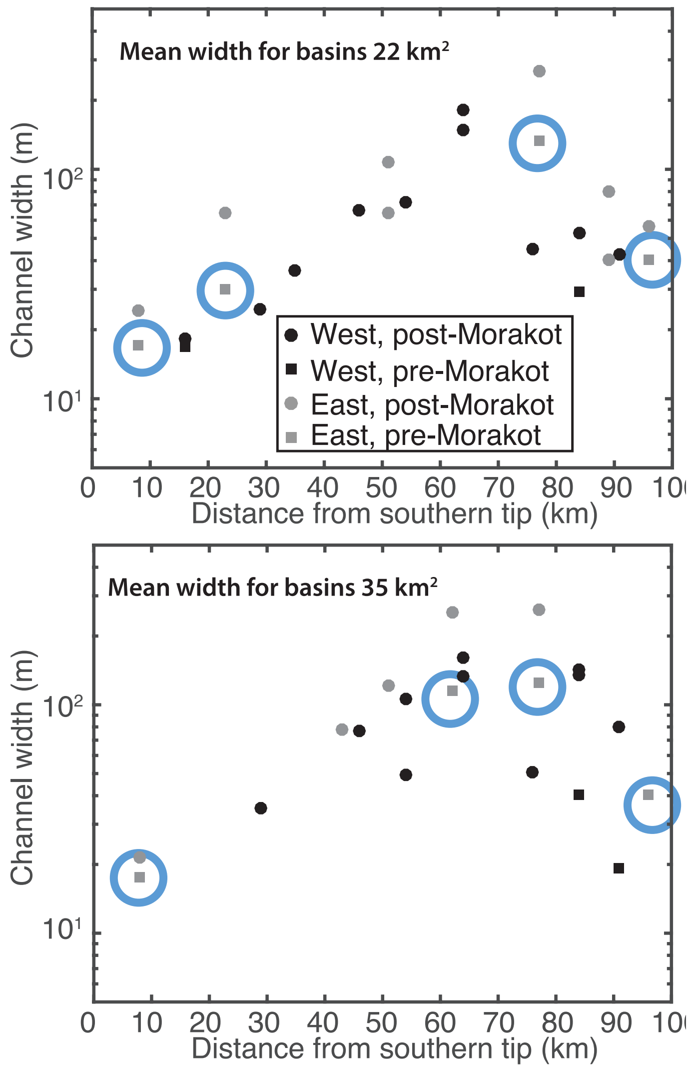


Need both pre and post Typhoon Morakot measurements

Channel width

Spatiotemporal dynamics





Width pattern was accentuated by Typhoon Morakot

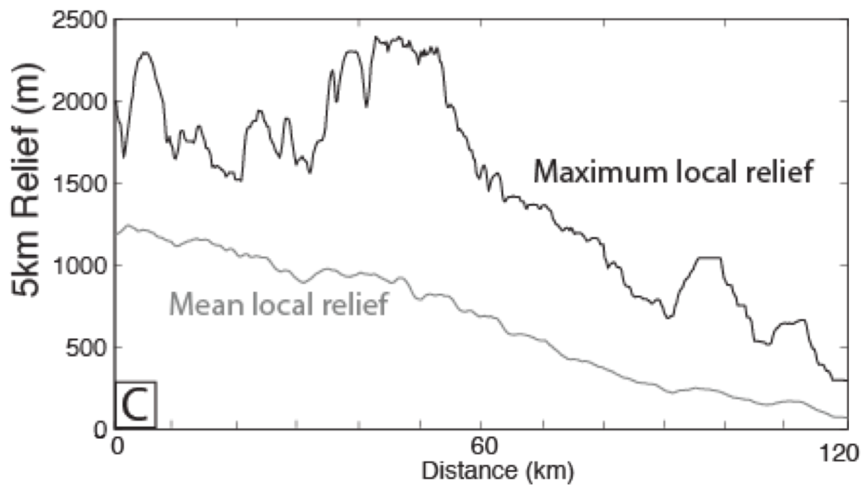
$$\tau_b = \rho g \left(\frac{nQ_w}{W} \right)^{\frac{3}{5}} S^{\frac{7}{10}}$$

Recall: ~5x increase in steepness along strike

So what is going on here?

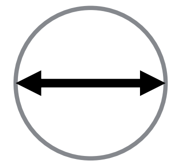
$$Q_T = 8\rho_s W \left[\frac{\tau_b}{(\rho_s - \rho)gD} - \tau_{c*} \right]^{3/2} D^{3/2} \sqrt{\frac{(\rho_s - \rho)}{\rho} g}$$

Spatial variations in hillslope morphology and sediment supply



Expectation from sediment cover effect: channels should become **wider** and steeper

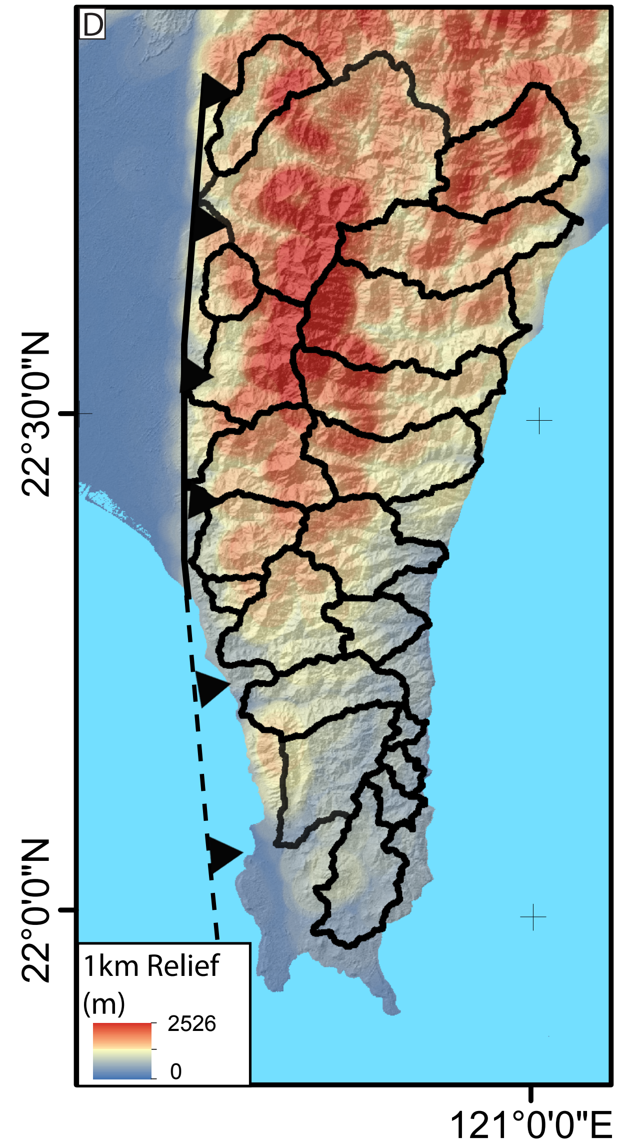
2 km relief

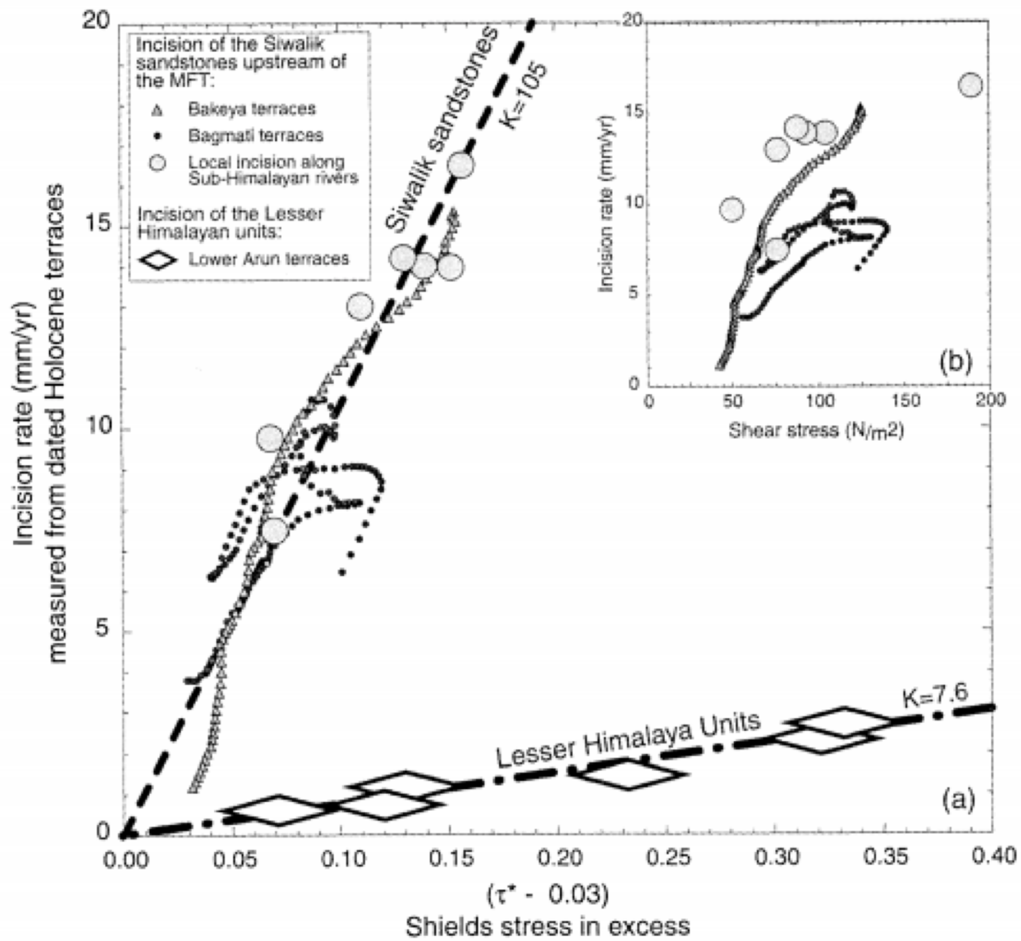


1000's meters

100's meters

10's meters

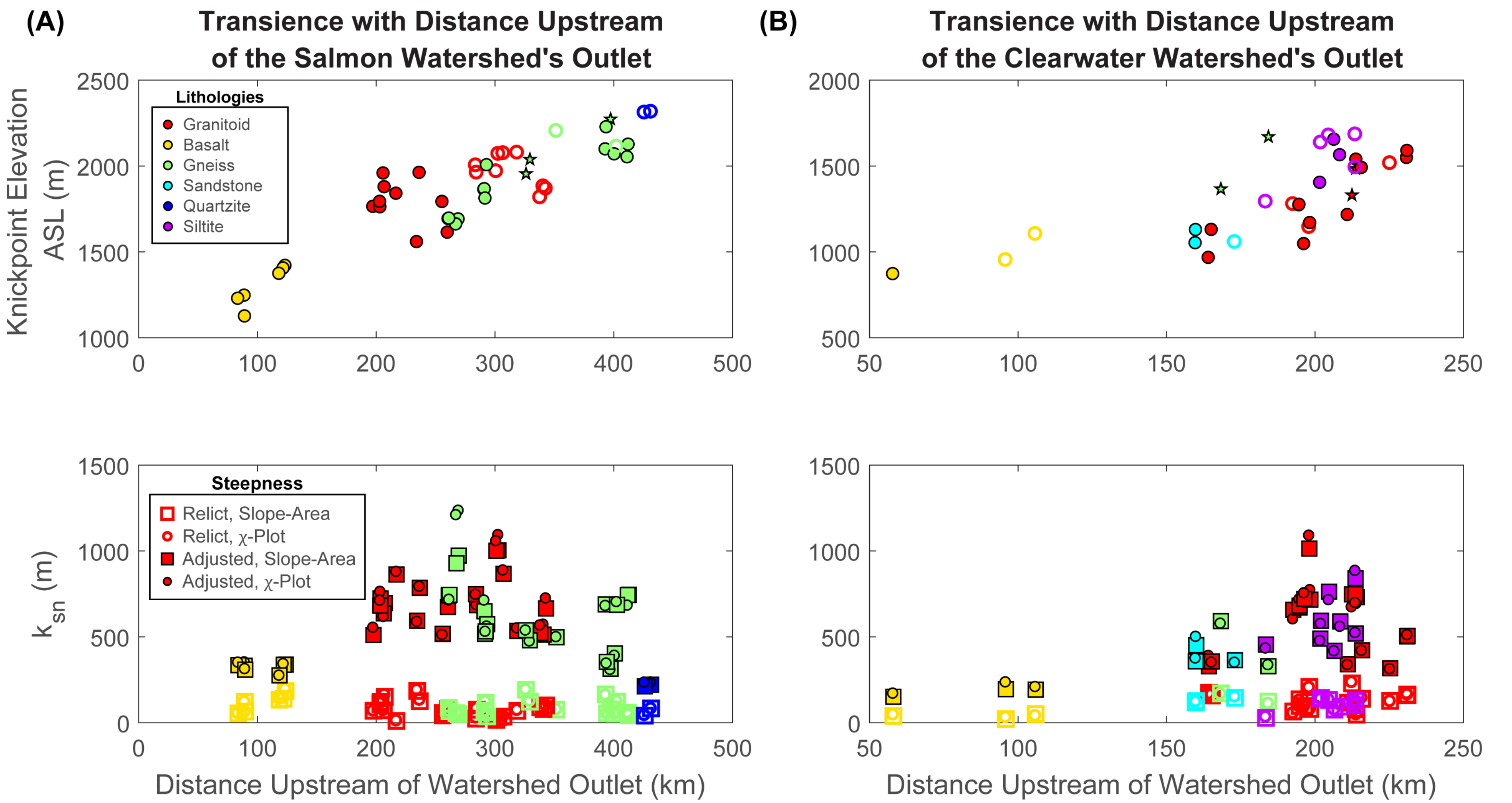


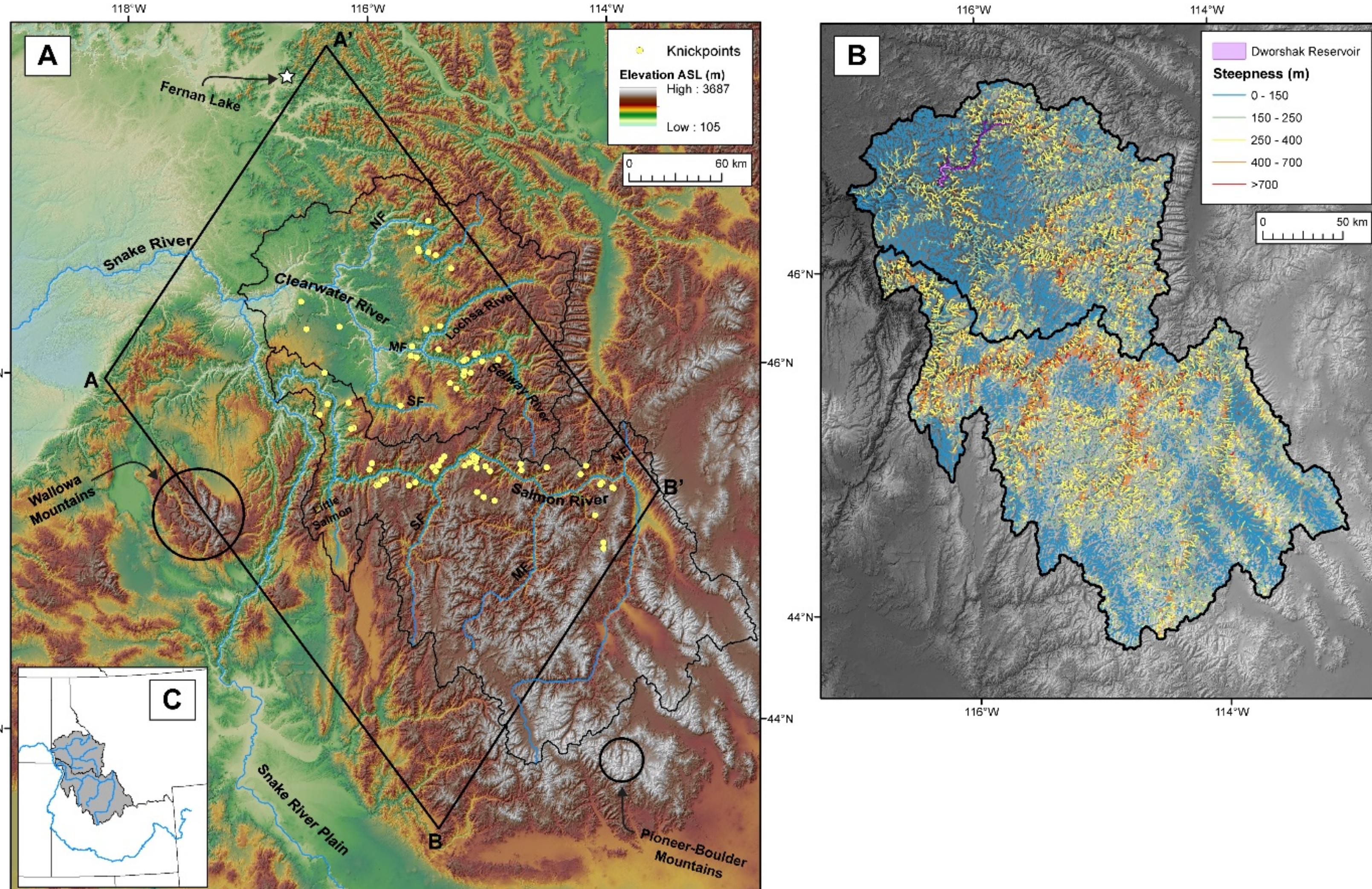


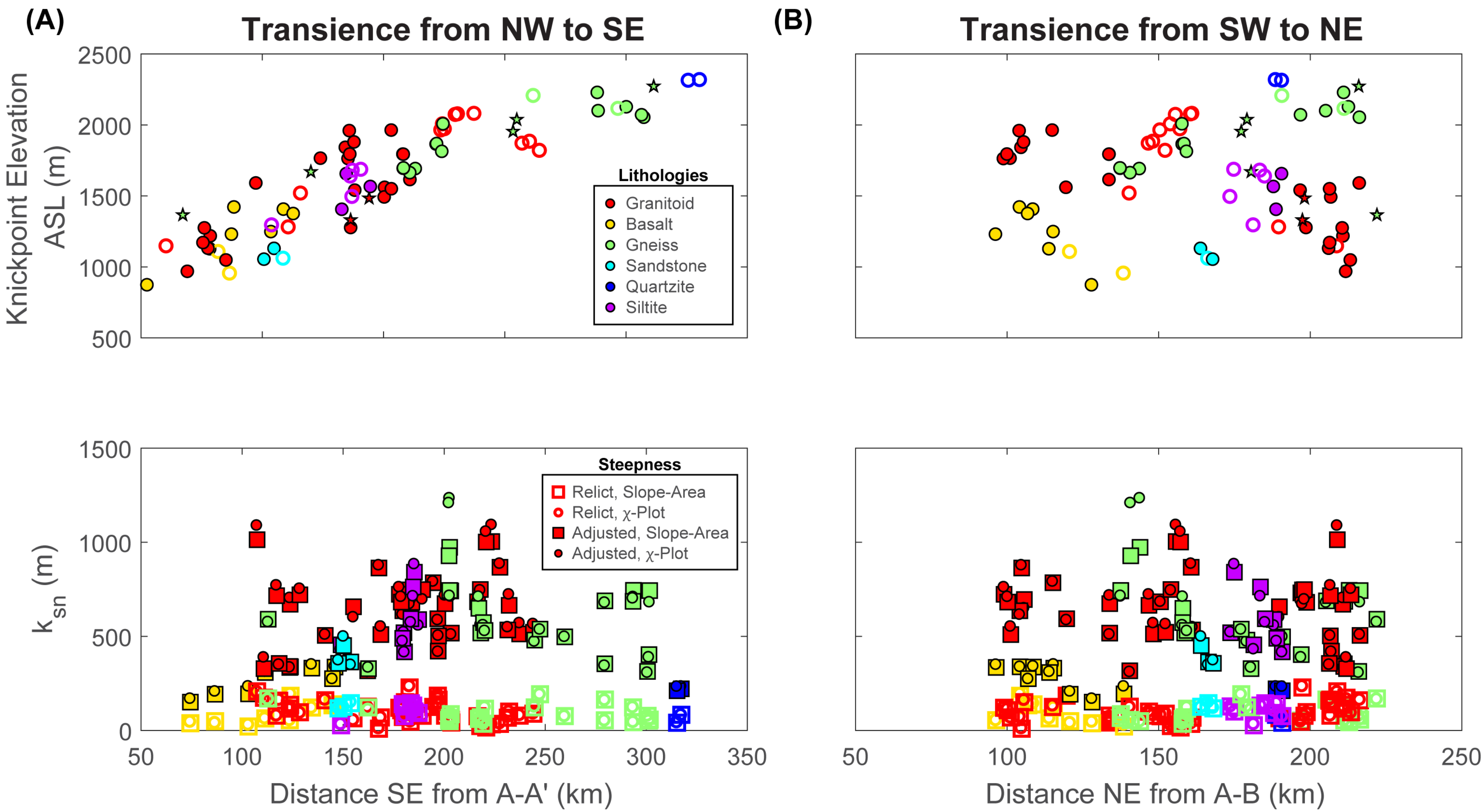
Incision of the Siwalik sandstones upstream of the MFT:
Bakeya terraces
Bagmati terraces
Local incision along Sub-Himalayan rivers
Incision of the Lesser Himalayan units:
Lower Arun terraces
Siwalik sandstones
K=105
Lesser Himalaya Units
K=7.6
(a)
Incision rate (mm/yr) measured from dated Holocene terraces
(τ* - 0.03)
Shields stress in excess
Incision rate (mm/yr)
Shear stress (N/m2)
(b)

The token/obligatory hillslope slide

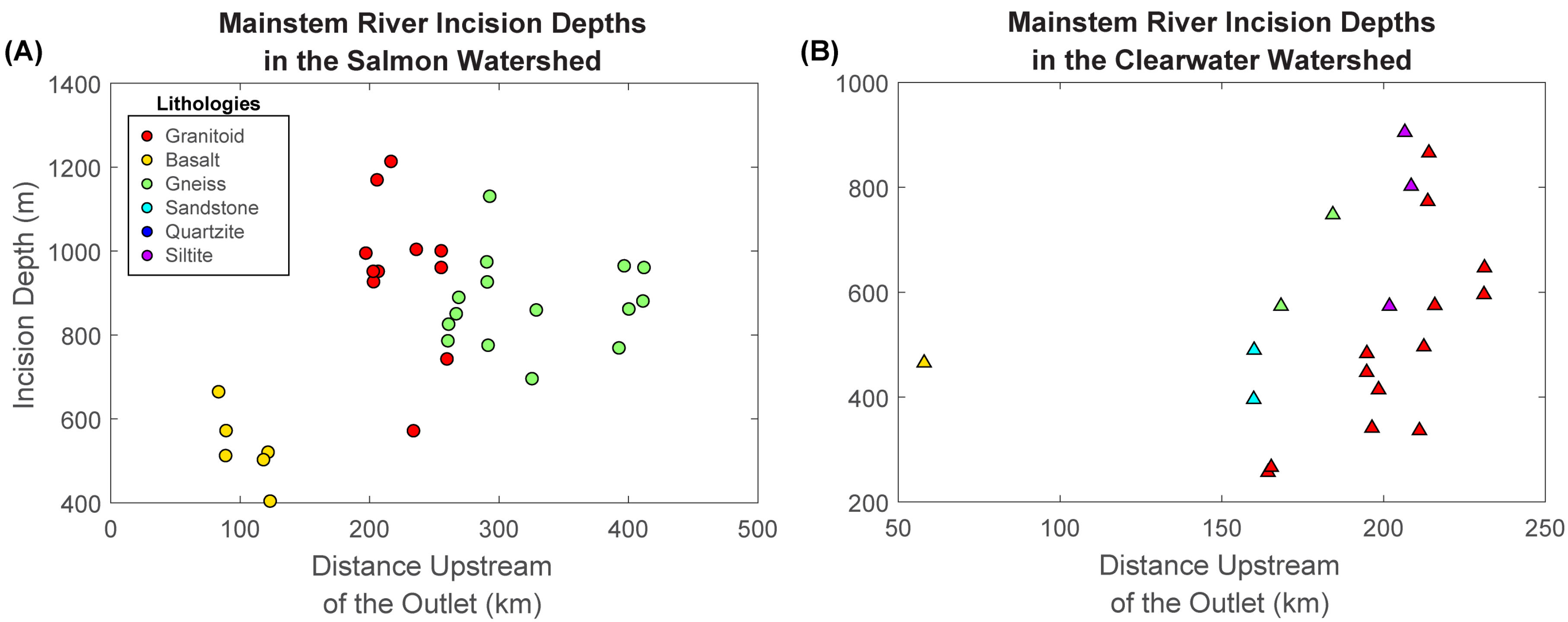
- Moon et al., fracturing, lithology (hilley student), Roering, etc

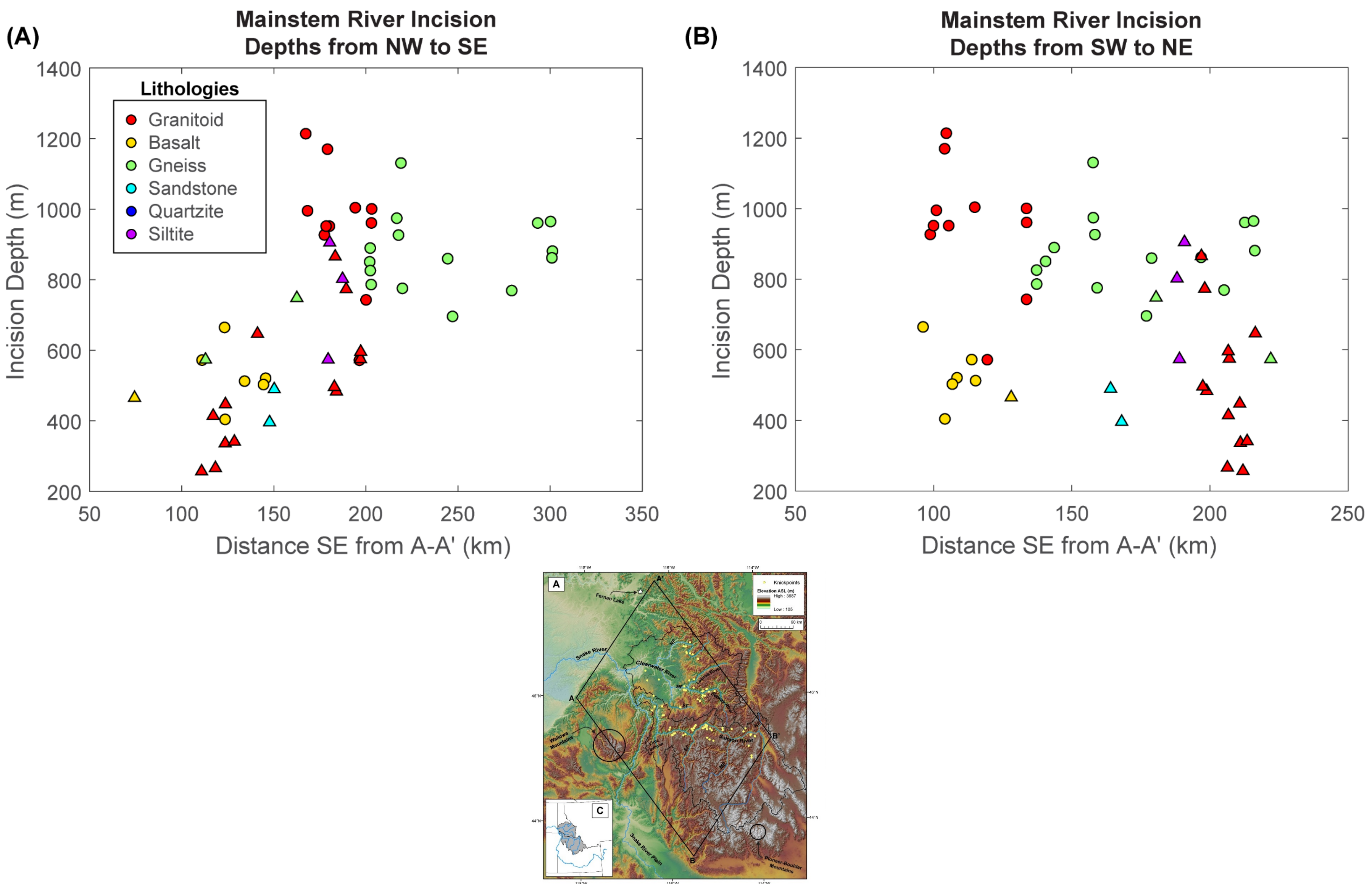

(A)
Transience with Distance Upstream of the Salmon Watershed's Outlet
(B)
Transience with Distance Upstream of the Clearwater Watershed's Outlet
Knickpoint Elevation ASL (m)
Lithologies
Granitoid
Basalt
Gneiss
Sandstone
Quartzite
Siltite
k_{sn} (m)
Steepness
Relict, Slope-Area
Relict, χ-Plot
Adjusted, Slope-Area
Adjusted, χ-Plot
Distance Upstream of Watershed Outlet (km)
Distance Upstream of Watershed Outlet (km)

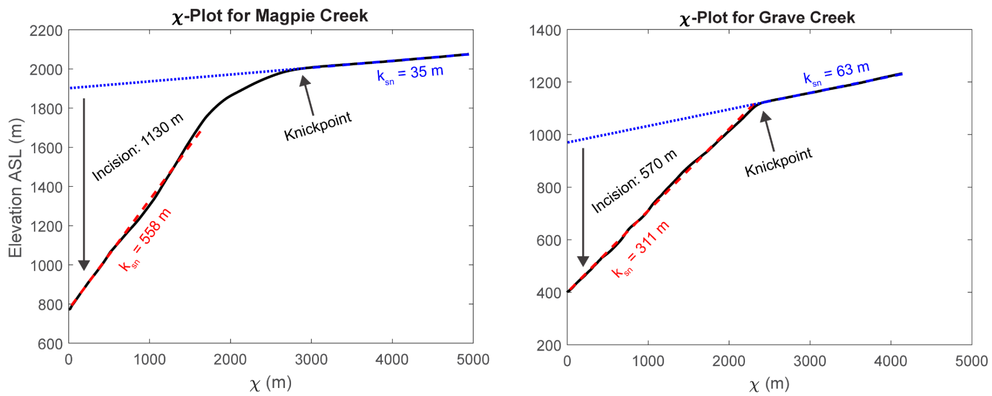

A
B
C
Knickpoints
Elevation ASL (m)
High : 3687
Low : 105
0
60 km
Fernan Lake
Snake River
Clearwater River
Lochsa River
Selway River
NF
MF
SF
Little Salmon
Salmon River
ME
Wallowa Mountains
Snake River Plain
Pioneer-Boulder Mountains
A
A'
B
B'
118°W
116°W
114°W
46°N
44°N
Dworshak Reservoir
Steepness (m)
0 - 150
150 - 250
250 - 400
400 - 700
>700
0
50 km

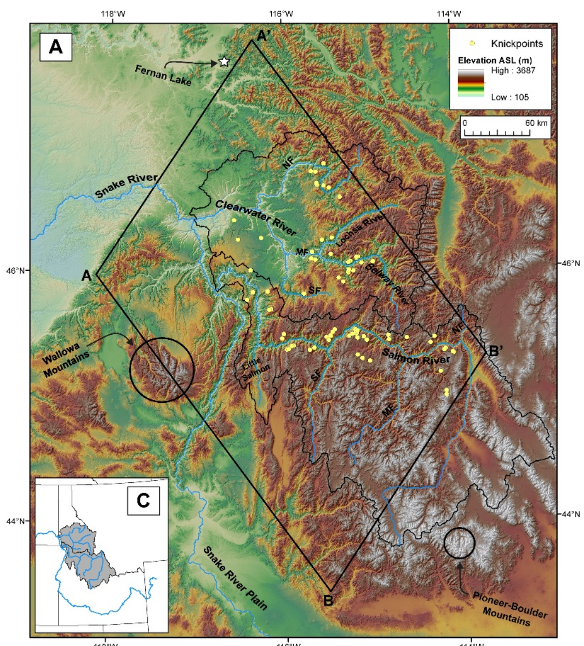


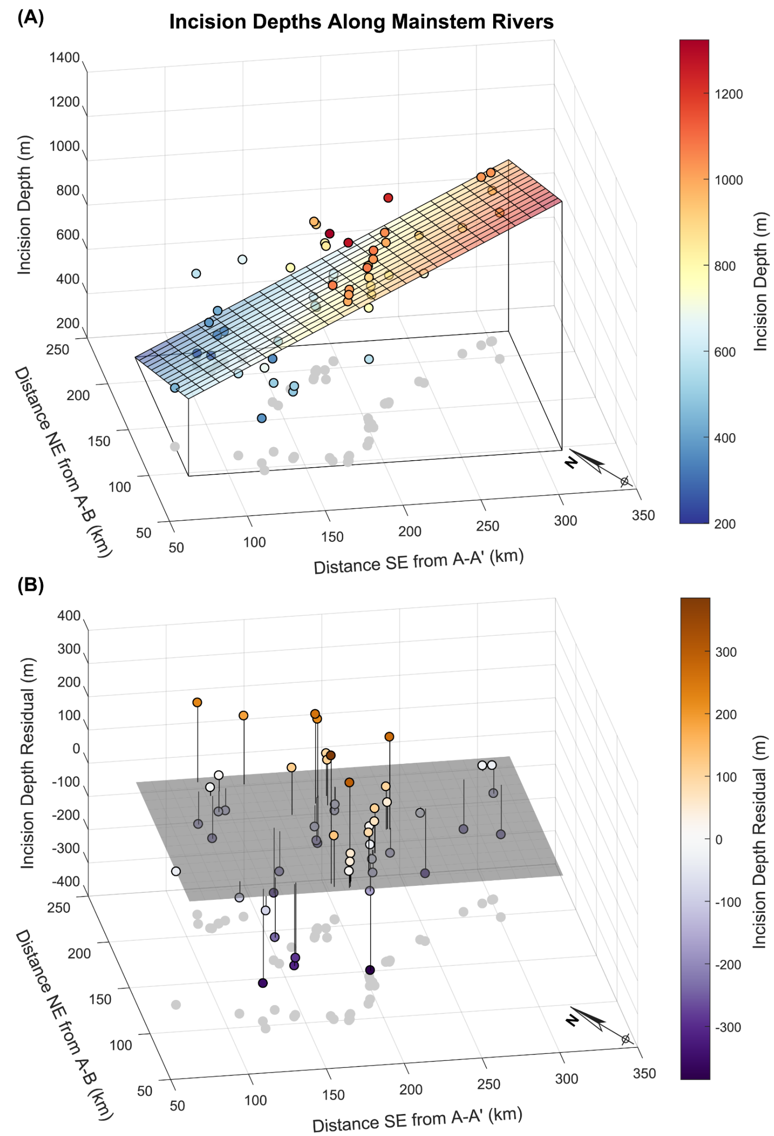
(A)
Transience from NW to SE
(B)
Transience from SW to NE
Knickpoint Elevation ASL (m)
2500
2000
1500
1000
500
Lithologies
Granitoid
Basalt
Gneiss
Sandstone
Quartzite
Siltite
1500
1000
500
0
k_{sn} (m)
Steepness
Relict, Slope-Area
Relict, χ-Plot
Adjusted, Slope-Area
Adjusted, χ-Plot
50
100
150
200
250
300
350
Distance SE from A-A' (km)
50
100
150
200
250
Distance NE from A-B (km)


(A)
Mainstem River Incision Depths
in the Salmon Watershed
Lithologies
Granitoid
Basalt
Gneiss
Sandstone
Quartzite
Siltite
Incision Depth (m)
1400
1200
1000
800
600
400
0
100
200
300
400
500
Distance Upstream
of the Outlet (km)
(B)
Mainstem River Incision Depths
in the Clearwater Watershed
1000
800
600
400
200
50
100
150
200
250
Distance Upstream
of the Outlet (km)


(A)
Mainstem River Incision
Depths from NW to SE
Lithologies
Granitoid
Basalt
Gneiss
Sandstone
Quartzite
Siltite
Incision Depth (m)
1400
1200
1000
800
600
400
200
50
100
150
200
250
300
350
Distance SE from A-A' (km)
(B)
Mainstem River Incision
Depths from SW to NE
Incision Depth (m)
1400
1200
1000
800
600
400
200
50
100
150
200
250
Distance SE from A-A' (km)
A
C


χ-Plot for Magpie Creek
Elevation ASL (m)
χ (m)
Incision: 1130 m
Knickpoint
k_{sn} = 35 m
k_{sn} = 558 m
χ-Plot for Grave Creek
Incision: 570 m
Knickpoint
k_{sn} = 63 m
k_{sn} = 311 m

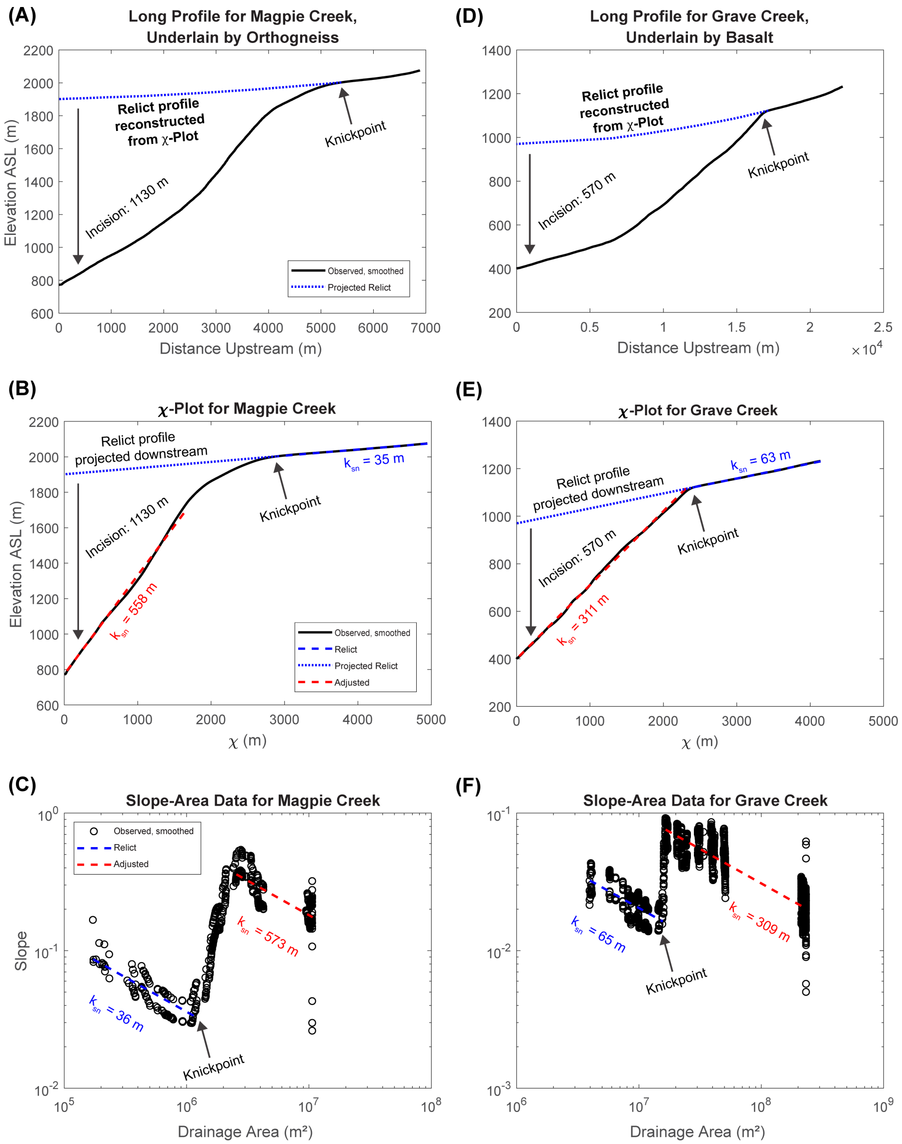

A
C
Knickpoints
Elevation ASL (m)
High : 3687
Low : 105
0
60 km
118°W
116°W
114°W
46°N
44°N
A
A'
B
B'
Fernan Lake
Snake River
Clearwater River
Lochsa River
Selway River
Salmon River
Wallowa Mountains
Snake River Plain
Pioneer-Boulder Mountains
NF
MF
SF


(A)
Incision Depths Along Mainstem Rivers
Incision Depth (m)
Distance NE from A-B (km)
Distance SE from A-A' (km)
N
(B)
Incision Depth Residual (m)
Distance NE from A-B (km)
Distance SE from A-A' (km)

Slope exponent n

$$n = \frac{\ln\left(\frac{U_2}{U_1}\right)}{\ln\left(\frac{k_{sn_2}}{k_{sn_1}}\right)}$$

- Only appropriate n values can reproduce:
  1. differences between relict and adjusted k_{sn}
  2. the curvature of a stretch zone
  3. the sharpness of a consuming knickpoint

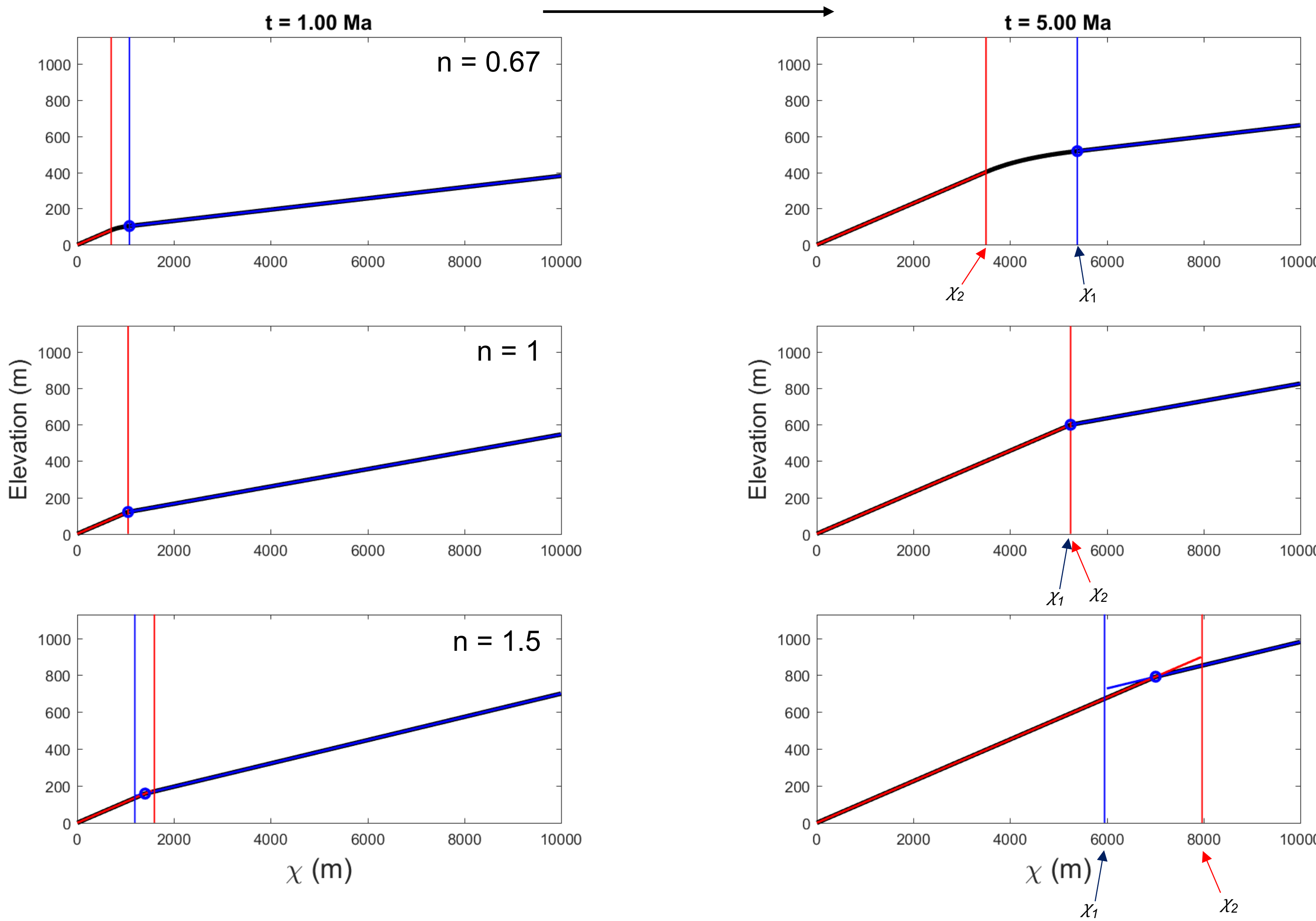


U_1 = 0.05 mm/yr

U_2 = 0.12 mm/yr

$$\chi_1 = \frac{nU_1 t}{\left(\frac{U_1}{K}\right)^{1/n} {A_0}^{-m/n}}$$

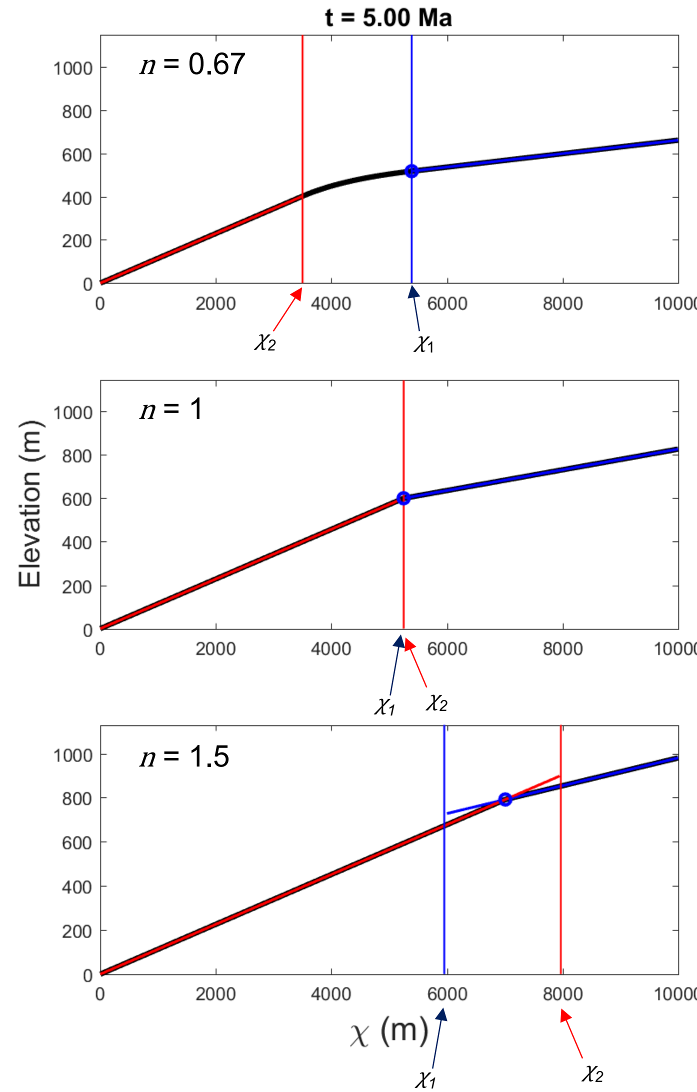
$$\chi_2 = \frac{nU_2 t}{\left(\frac{U_2}{K}\right)^{1/n} {A_0}^{-m/n}}$$



Royden and Perron (2013)

Transient Incision Modeling

$$z(\chi,t)=\begin{cases} z(\chi_b)+\left(\frac{U_1}{K}\right)^{1/n}{A_0}^{-m/n}\chi+(U_2-U_1)t & for\ \chi\geq\chi_1 \\ z(\chi_b)+\frac{n-1}{n}\left(\frac{\chi^n}{nKtA_0{}^m}\right)^{1/n-1}+U_2t & for\ \chi_2<\chi<\chi_1 \\ z(\chi_b)+\left(\frac{U_2}{K}\right)^{1/n}{A_0}^{-m/n}\chi & for\ \chi\leq\chi_2 \end{cases}$$



Here,

U_1 = 0.05 mm/yr

U_2 = 0.12 mm/yr

Boundaries of old and new slope patches

$$\chi_1=\frac{nU_1t}{\left(\frac{U_1}{K}\right)^{1/n}{A_0}^{-m/n}}$$

$$\chi_2=\frac{nU_2t}{\left(\frac{U_2}{K}\right)^{1/n}{A_0}^{-m/n}}$$

Model Assessment

$$\chi^2=\frac{1}{N-\nu-1}\sum_i^N\left(\frac{sim_i-obs_i}{tolerance}\right)^2$$

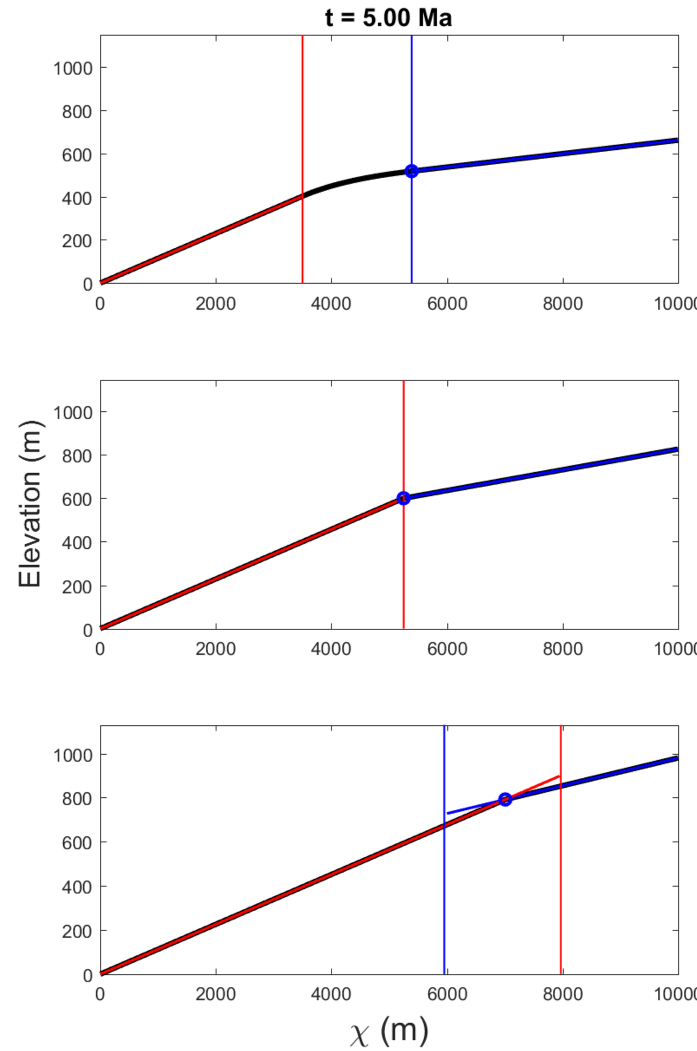
Royden and Perron (2013)

Jeffrey et al. (2013)

Knickpoint location and elevation

$$z_{KP}(t) = \begin{cases} z(\chi_b) + t(U_2 + (n-1)U_1) & for\ n < 1 \\ z(\chi_b) + nU_2 t & for\ n = 1 \\ z(\chi_b) + t(U_2 - U_1)\left(\dfrac{\left(\frac{U_2}{K}\right)^{1/n}}{\left(\frac{U_2}{K}\right)^{1/n} - \left(\frac{U_1}{K}\right)^{1/n}}\right) & for\ n > 1 \end{cases}$$

$$\chi_{KP}(t) = \begin{cases} \dfrac{nU_1 t}{\left(\frac{U_1}{K}\right)^{1/n} {A_0}^{-m/n}} & for\ n < 1 \\ nKt{A_0}^{m/n} & for\ n = 1 \\ \dfrac{t(U_2 - U_1)}{\left(\left(\frac{U_2}{K}\right)^{1/n} - \left(\frac{U_1}{K}\right)^{1/n}\right){A_0}^{-m/n}} & for\ n > 1 \end{cases}$$

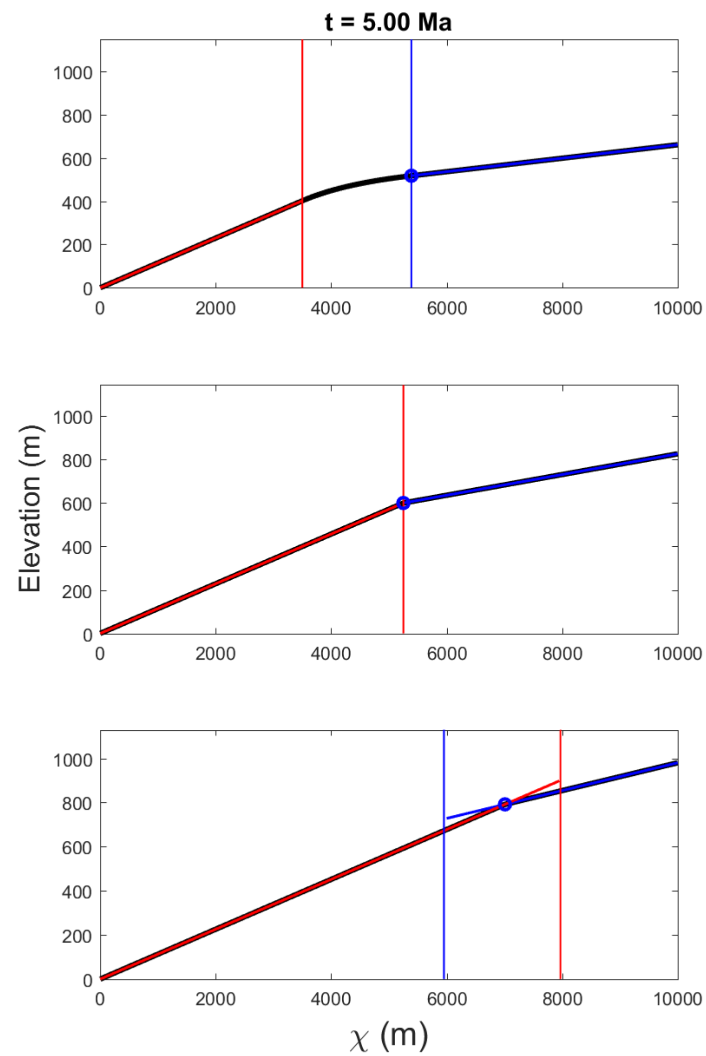


Royden and Perron (2013)

Knickpoint horizontal and vertical celerity

$$\frac{dz_{KP}}{dt} = \begin{cases} U_2 + (n-1)U_1 & for\ n < 1 \\ nU_2 & for\ n = 1 \\ (U_2 - U_1)\left(\dfrac{\left(\frac{U_2}{K}\right)^{1/n}}{\left(\frac{U_2}{K}\right)^{1/n} - \left(\frac{U_1}{K}\right)^{1/n}}\right) & for\ n > 1 \end{cases}$$

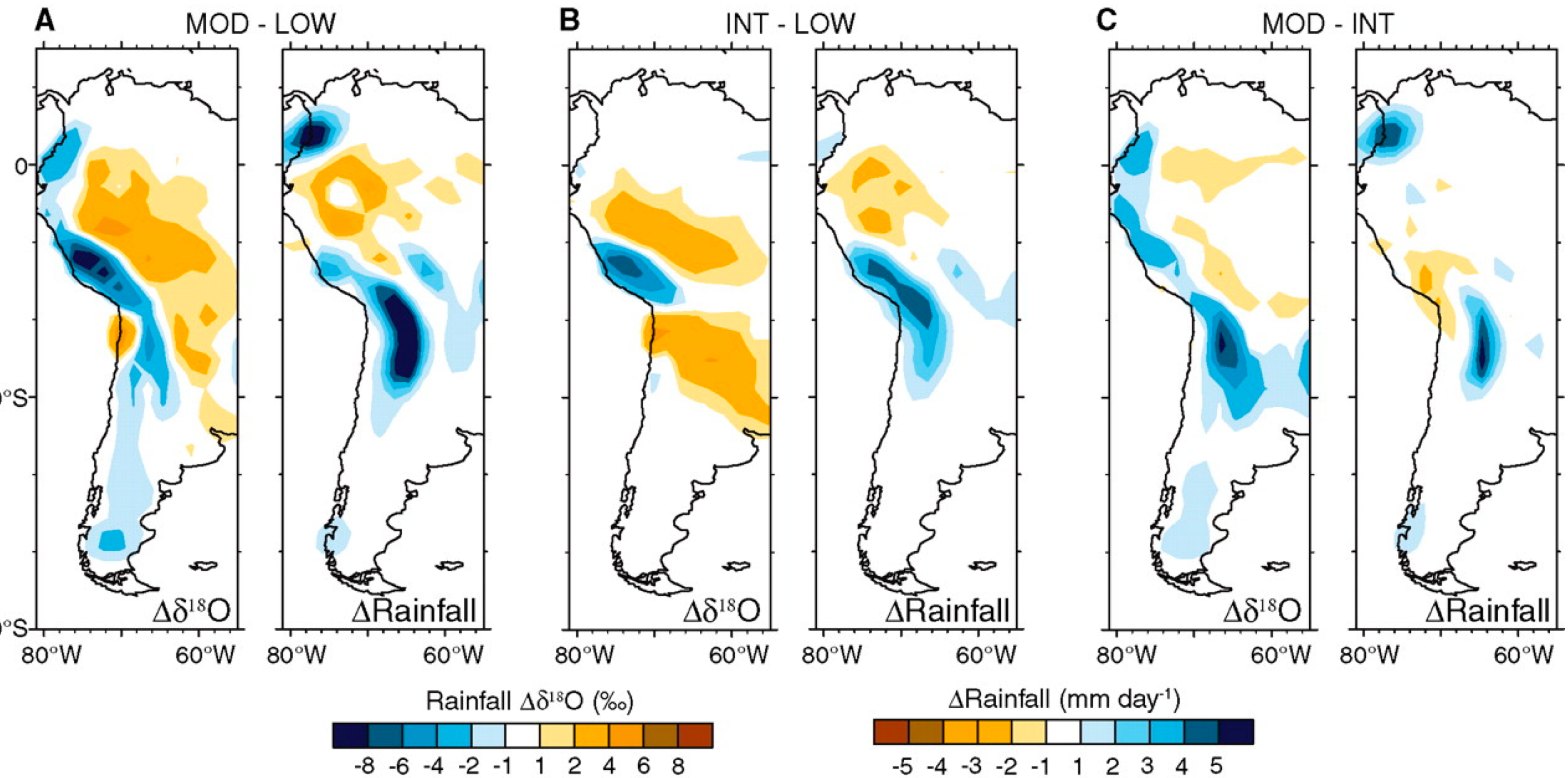
$$\frac{d\chi_{KP}}{dt} = \begin{cases} \dfrac{nU_1}{\left(\frac{U_1}{K}\right)^{1/n} {A_0}^{-m/n}} & for\ n < 1 \\ nK{A_0}^{m/n} & for\ n = 1 \\ \dfrac{U_2 - U_1}{\left(\left(\frac{U_2}{K}\right)^{1/n} - \left(\frac{U_1}{K}\right)^{1/n}\right) {A_0}^{-m/n}} & for\ n > 1 \end{cases}$$



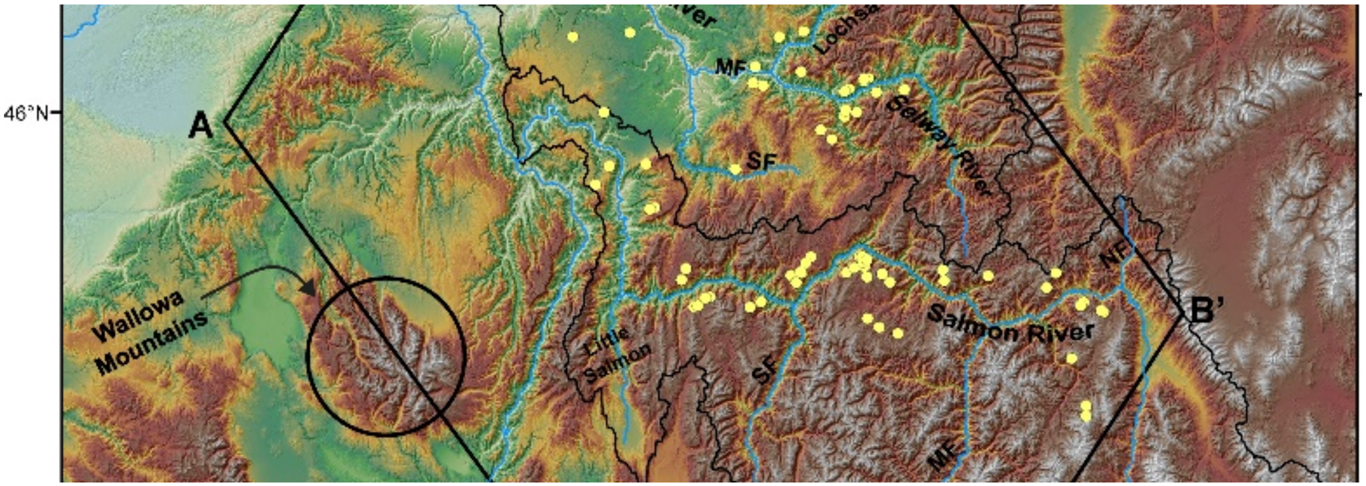
Royden and Perron (2013)

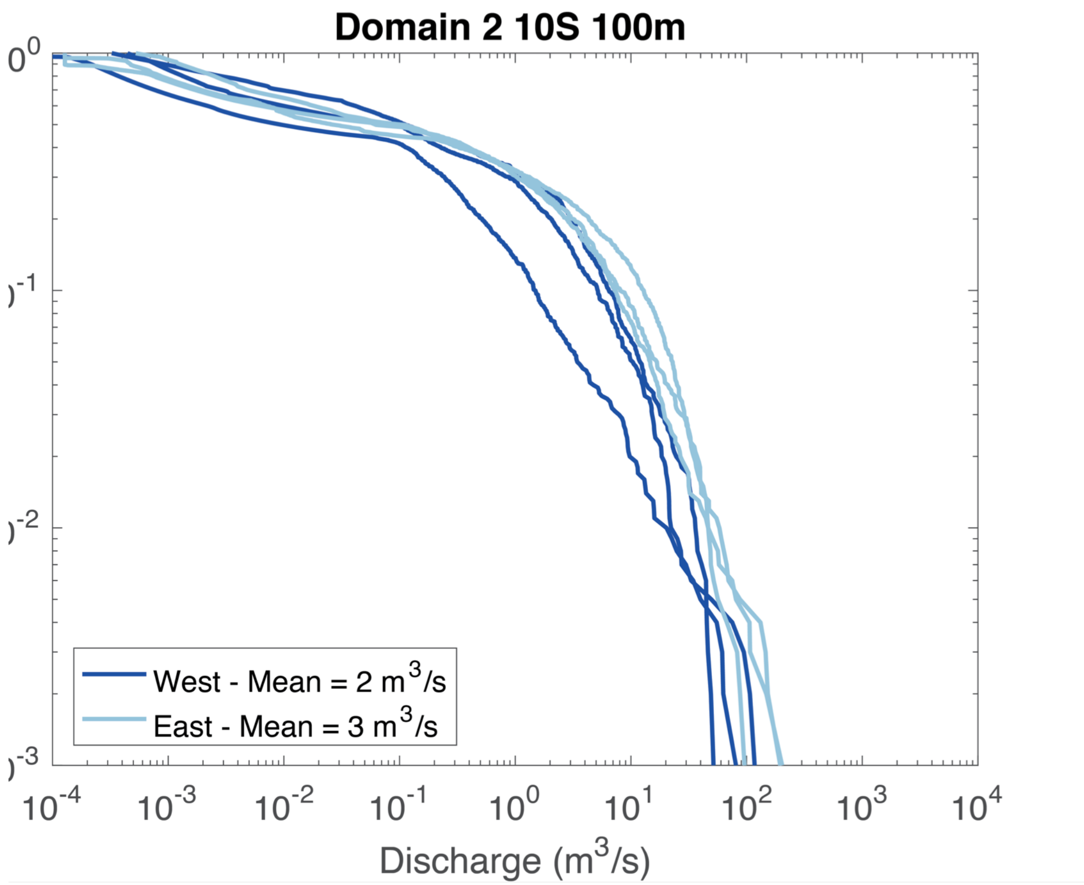
Two main takeaways from this talk

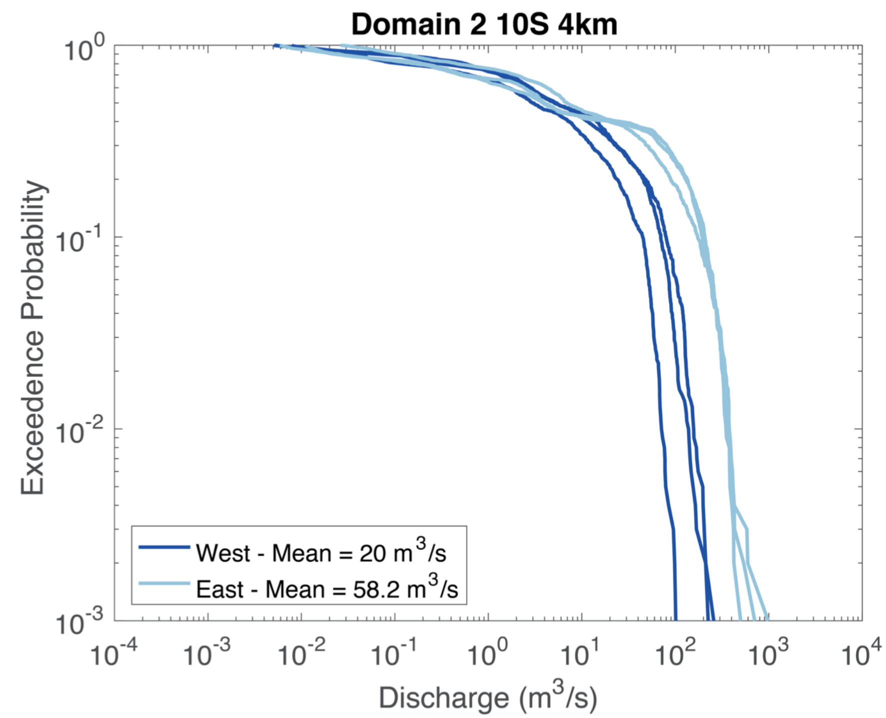
- There are complexities in natural systems that can limit the applicability of our simplified models to explain how nature works
- There is no single equation that will describe all river systems (and thus landscapes!) in all environments.

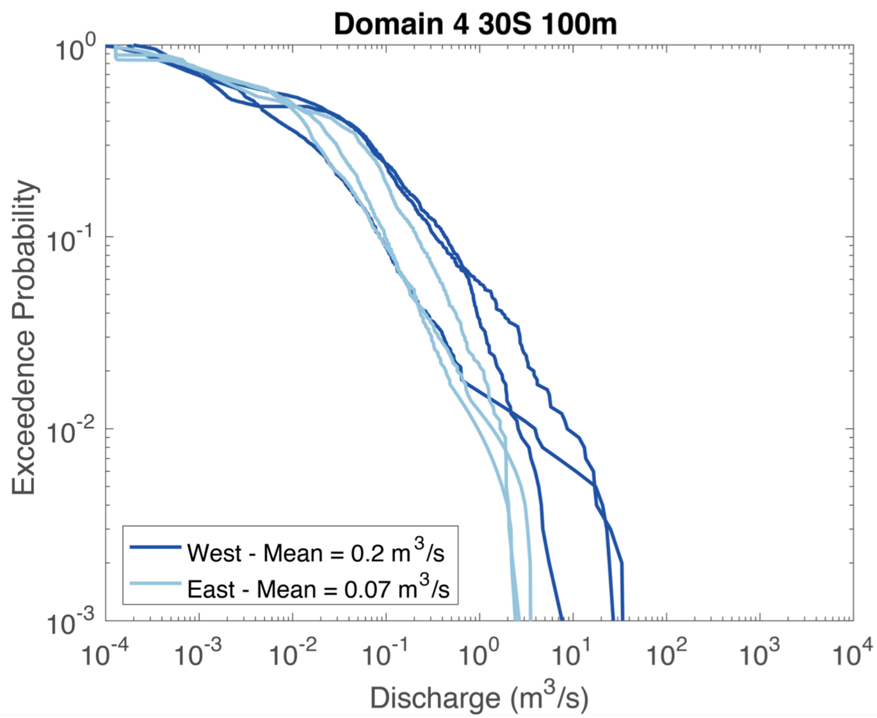

A
MOD - LOW
B
INT - LOW
C
MOD - INT
0
30°S
60°S
80°W
60°W
Δδ18O
ΔRainfall
Rainfall Δδ18O (‰)
-8 -6 -4 -2 -1 1 2 4 6 8
ΔRainfall (mm day-1)
-5 -4 -3 -2 -1 1 2 3 4 5

Rock-type modulates transient erosion in central Idaho

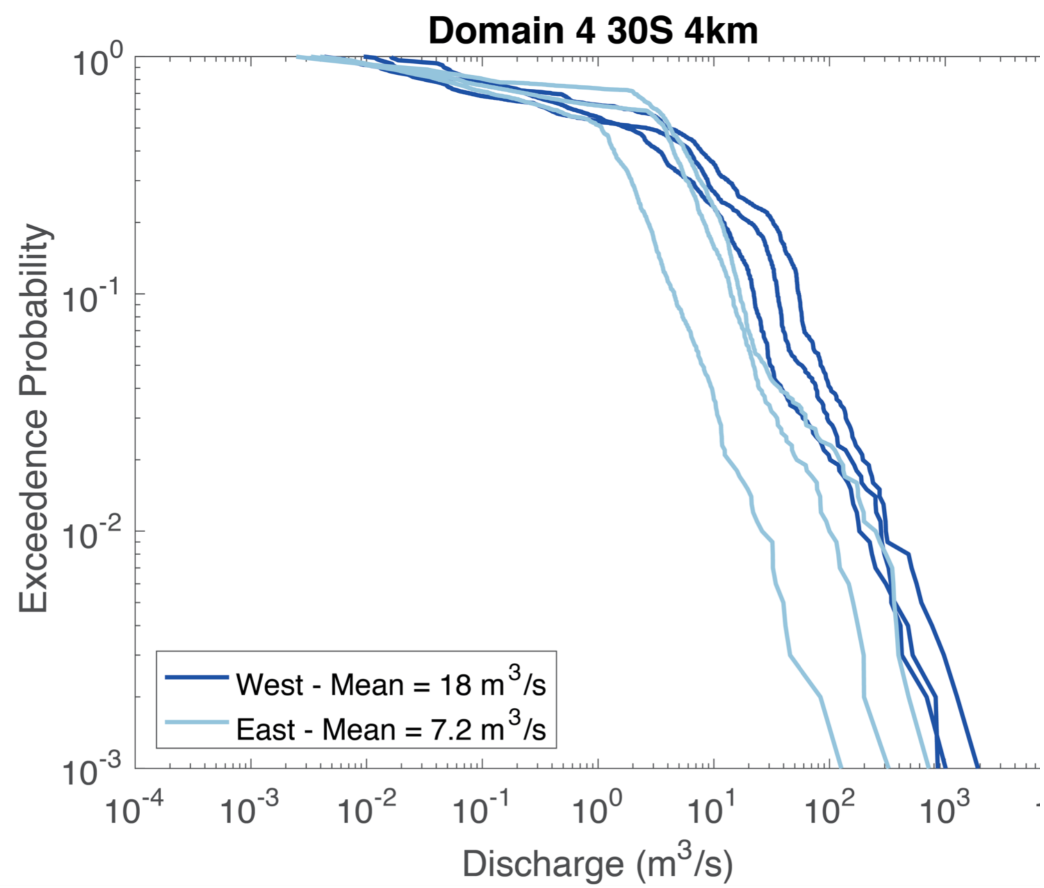



Domain 2 10S 100m
West - Mean = 2 m3/s
East - Mean = 3 m3/s
Discharge (m3/s)


Domain 2 10S 4km
Exceedence Probability
West - Mean = 20 m3/s
East - Mean = 58.2 m3/s
Discharge (m3/s)



Domain 4 30S 100m
Exceedence Probability
Discharge (m3/s)
West - Mean = 0.2 m3/s
East - Mean = 0.07 m3/s



Domain 4 30S 4km
Exceedence Probability
Discharge (m3/s)
West - Mean = 18 m3/s
East - Mean = 7.2 m3/s