Quantifying relationships among topography, climate, and erosion rate

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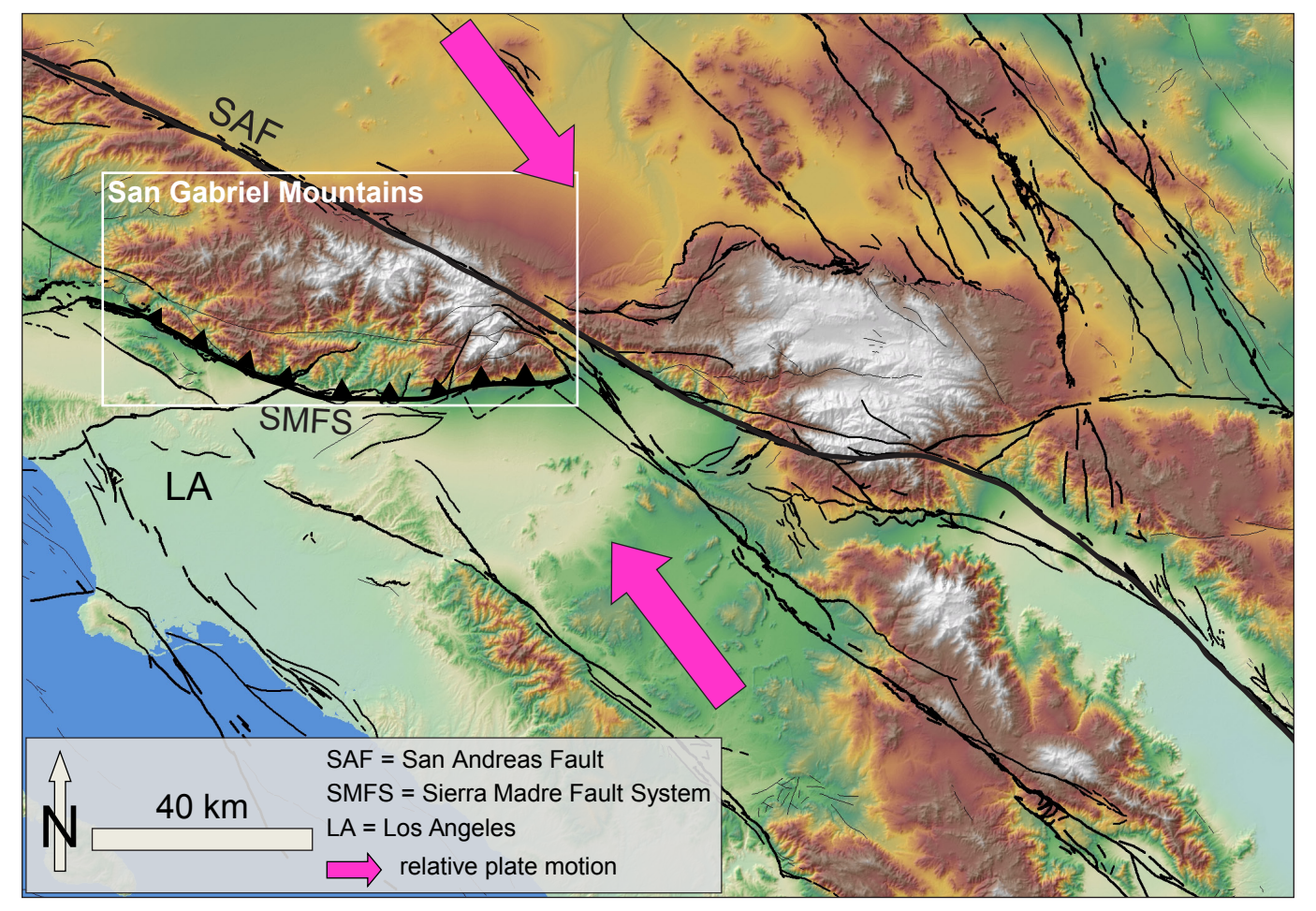
Motivation: what controls erosion?

Landscape-scale erosion rate depends generally on topographic relief, climate, and rock strength. To build a quantitative understanding of landscape dynamics, we must incorporate metrics of these variables into process-based erosion laws. Here I use cosmogenic erosion rates, DEM analysis, streamflow records, and field surveys to quantify the topographic controls on erosion rates in the San Gabriel Mountains of California, and explore the influence of climate on this relationship using a 1-D bedrock river incision model.

1. Study area: San Gabriel Mountains

- Compact mountain range just north of Los Angeles, CA, composed primarily of highly fractured granites and gneisses
- Large restraining bend in the San Andreas Fault creates a strong gradient in rock uplift rate
- Hold climate and lithology constant - isolate topographic controls on erosion rate



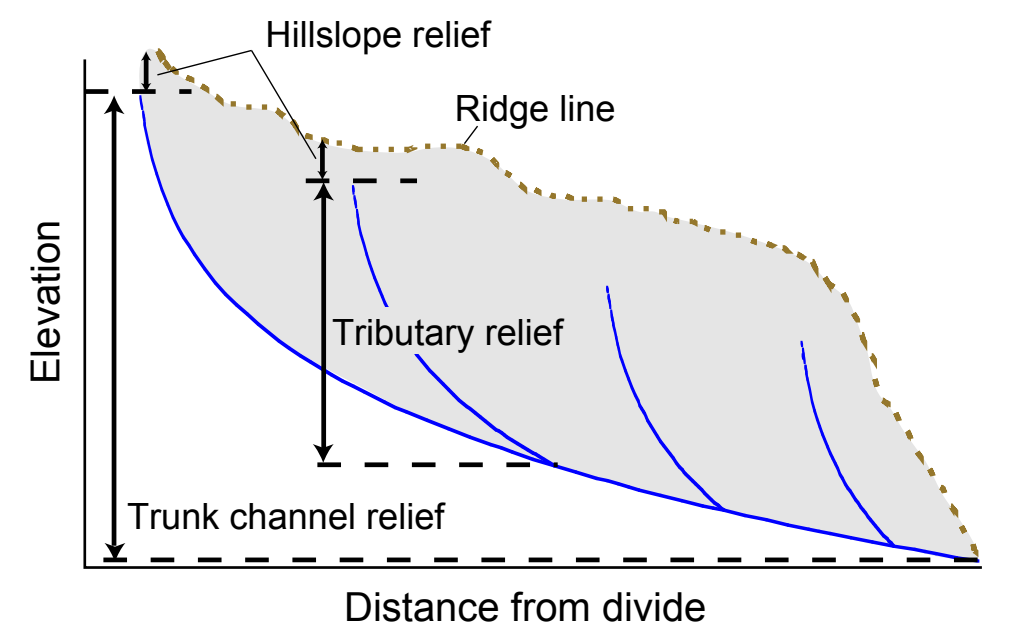
2. Defining topographic relief: the channel steepness index

- Bedrock channels define relief structure of unglaciated landscapes
- Flint's law relates channel slope to drainage area:

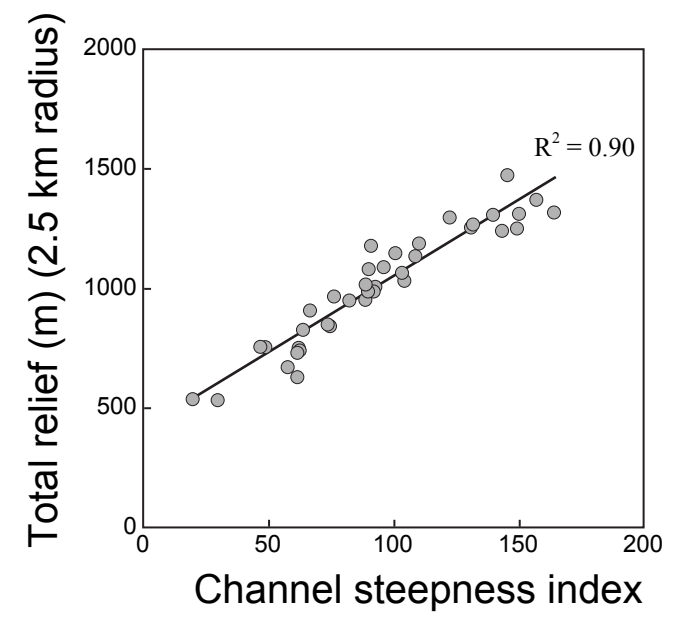
$$S = k_s A^{-\theta}$$

k_s = channel steepness index; θ = concavity index

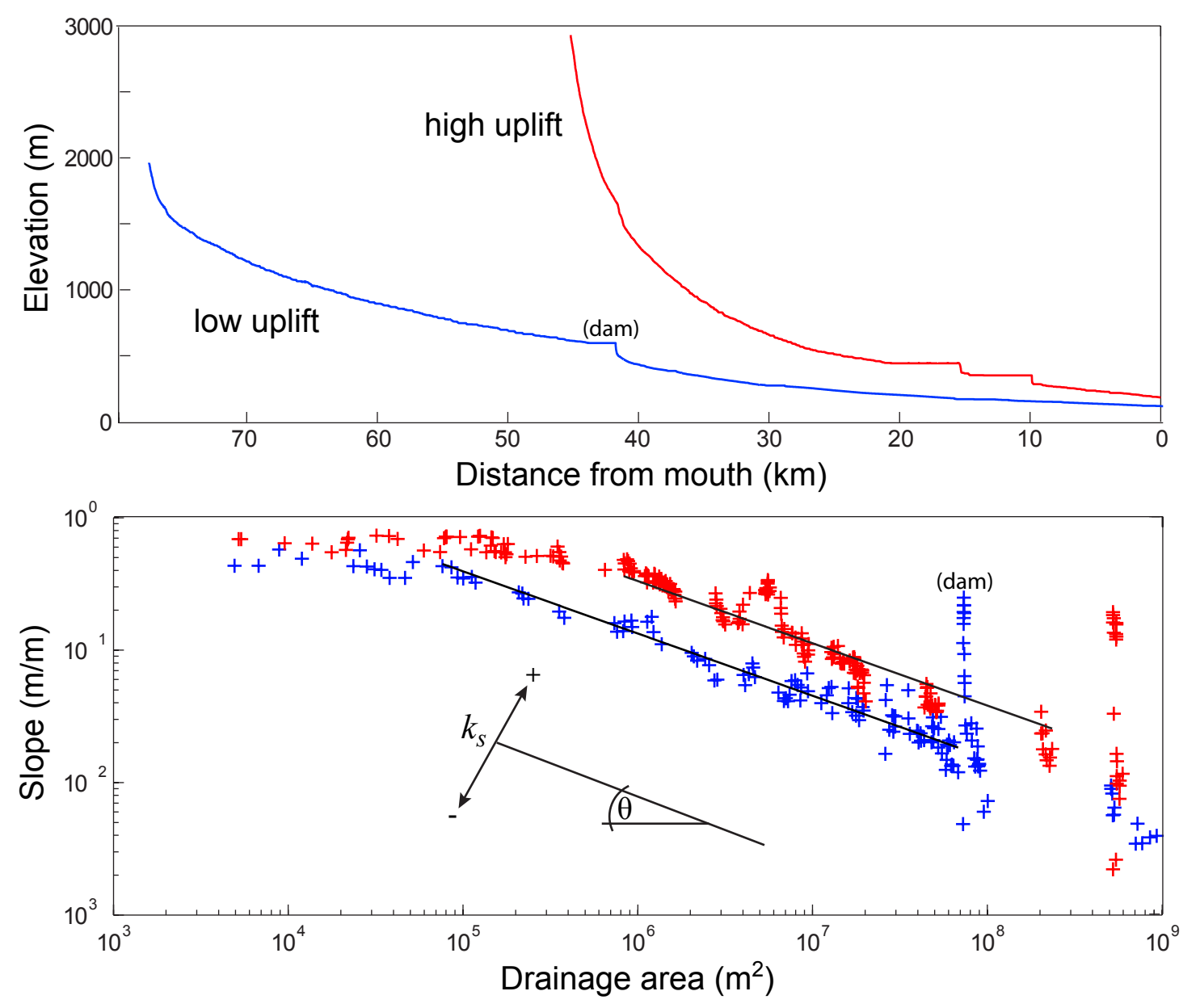
- Extract channel profile data from 10 m DEM (fix θ, fit k_s)



Side profile of catchment showing elements comprising relief. (Whipple et al., 1999)



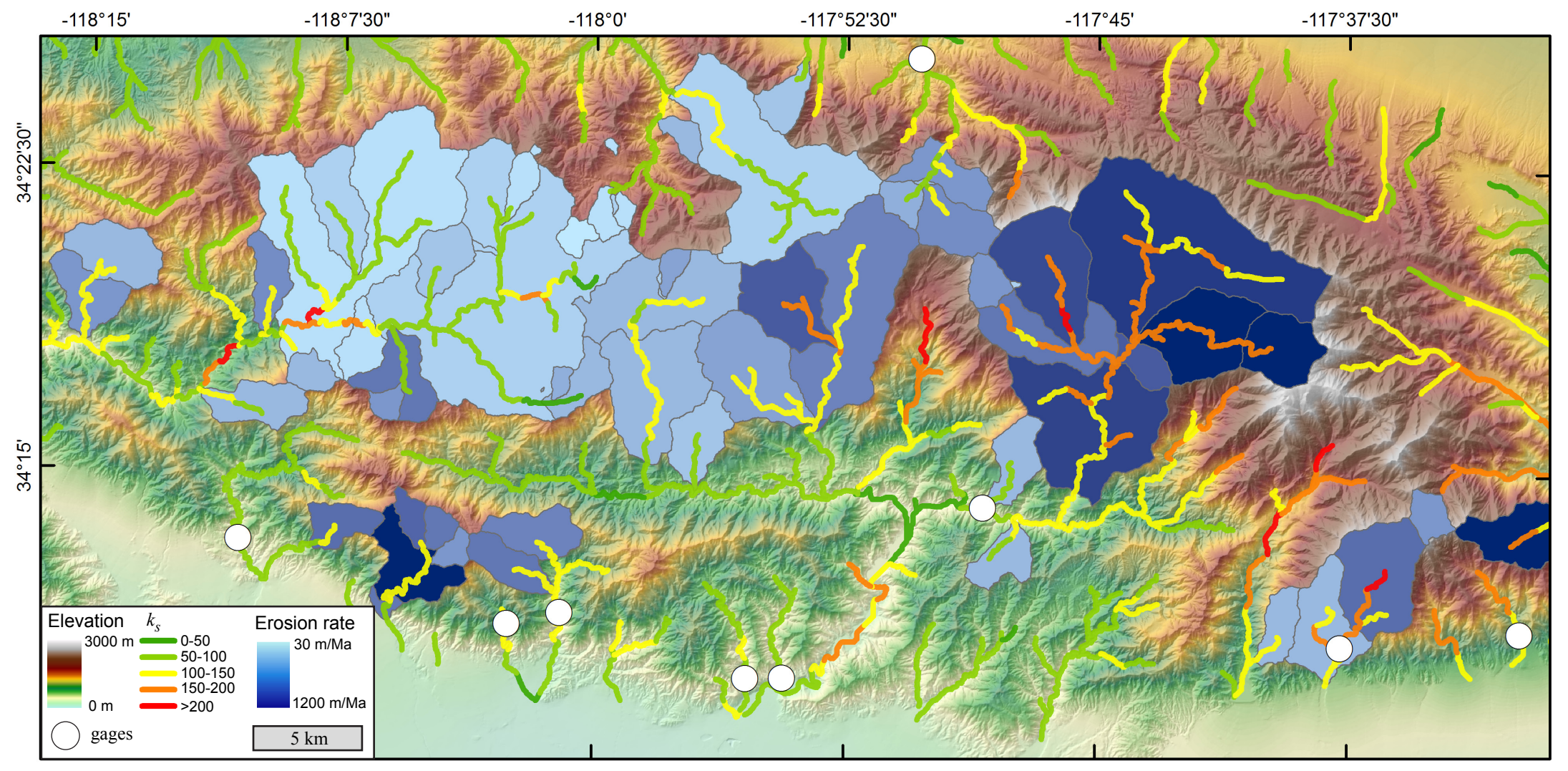
Channel steepness scales linearly with catchment-scale relief. (DiBiase et al., 2010)



Comparison of two channels in the San Gabriel Mountains showing long profile (top) and associated slope-area plot (bottom).

3. Quantifying erosion rates: detrital cosmogenic nuclides

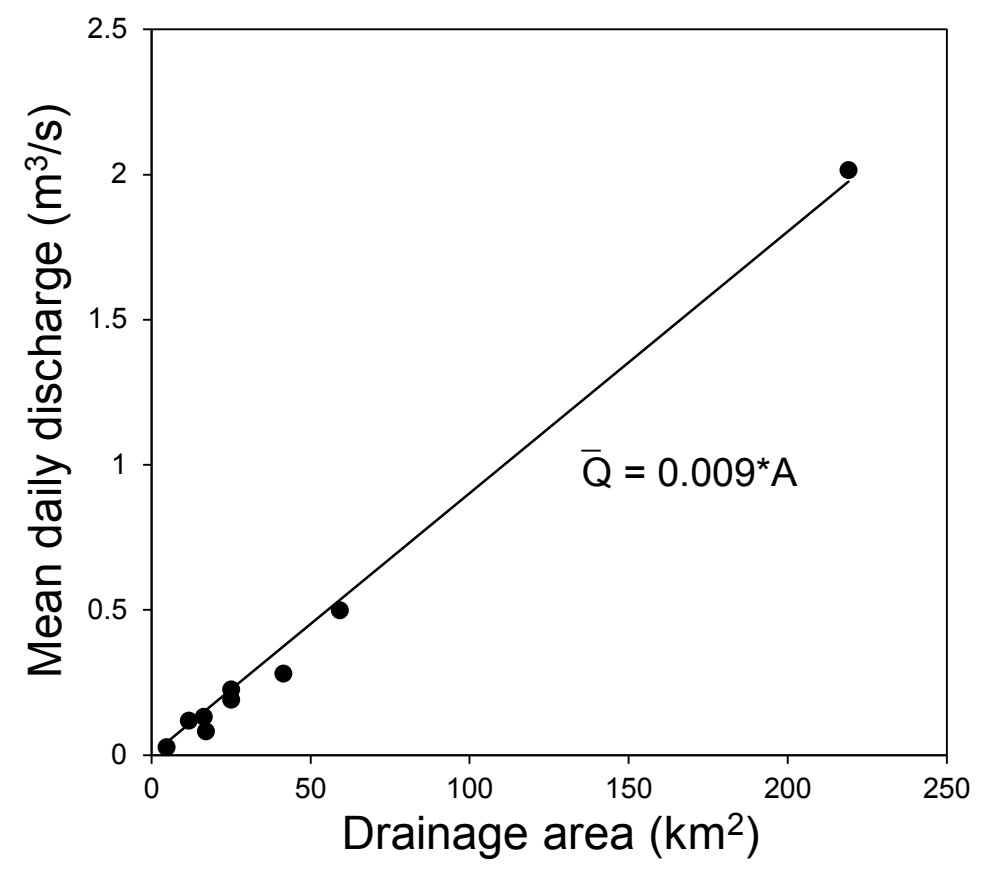
- Cosmogenic ^{10}Be concentrations in stream sands integrate exposure history of thousands of grains
- Key technique for measuring erosion rates over millennial timescales
- This study: 80 catchment-averaged erosion rates across San Gabriel Mountains
- Rates range from 30-1200 m/Ma, generally increase from west to east

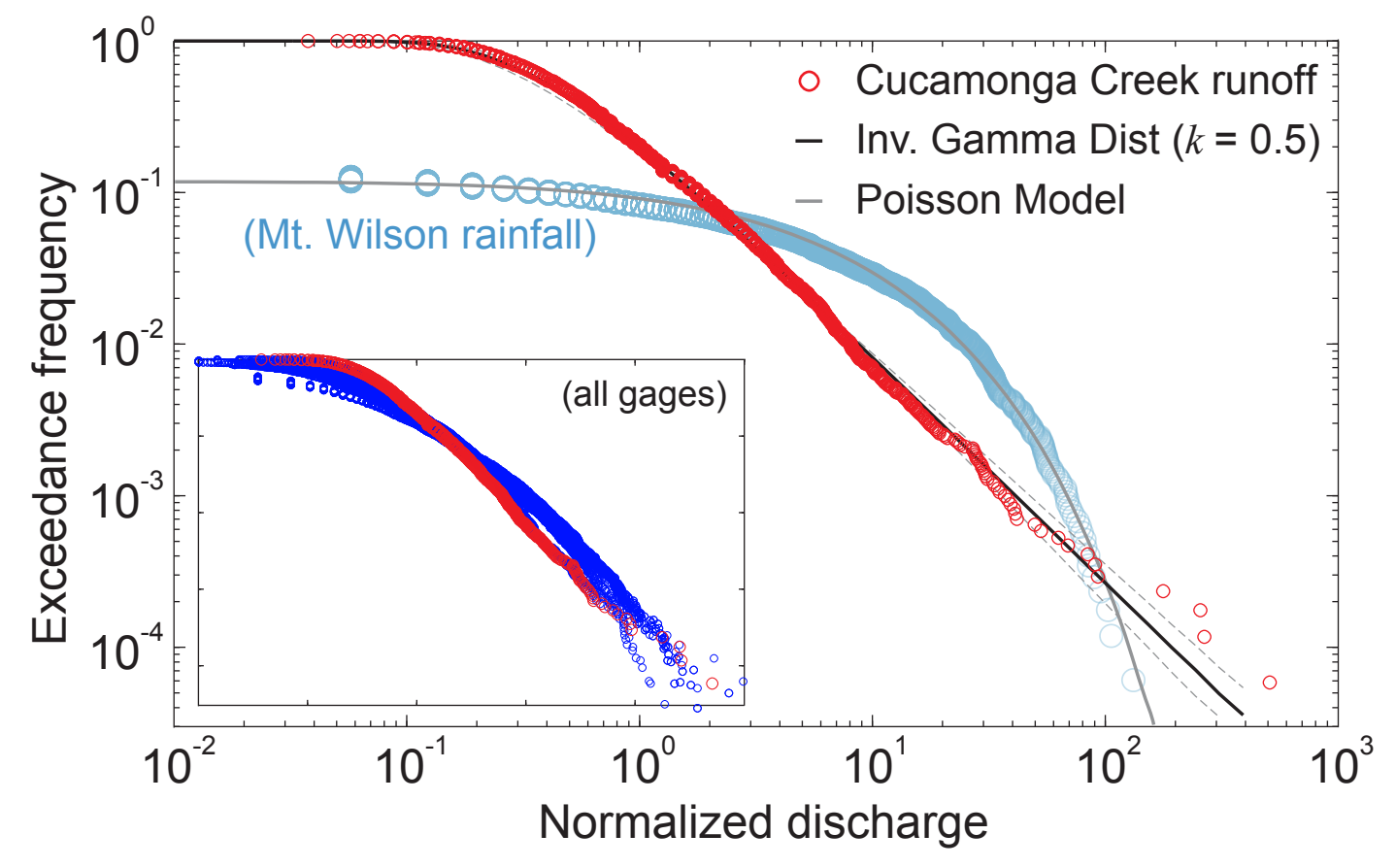


Catchment averaged erosion rates in the San Gabriel Mountains, showing channel network color-coded by steepness index.

4. Characterizing climate: flood frequency distributions

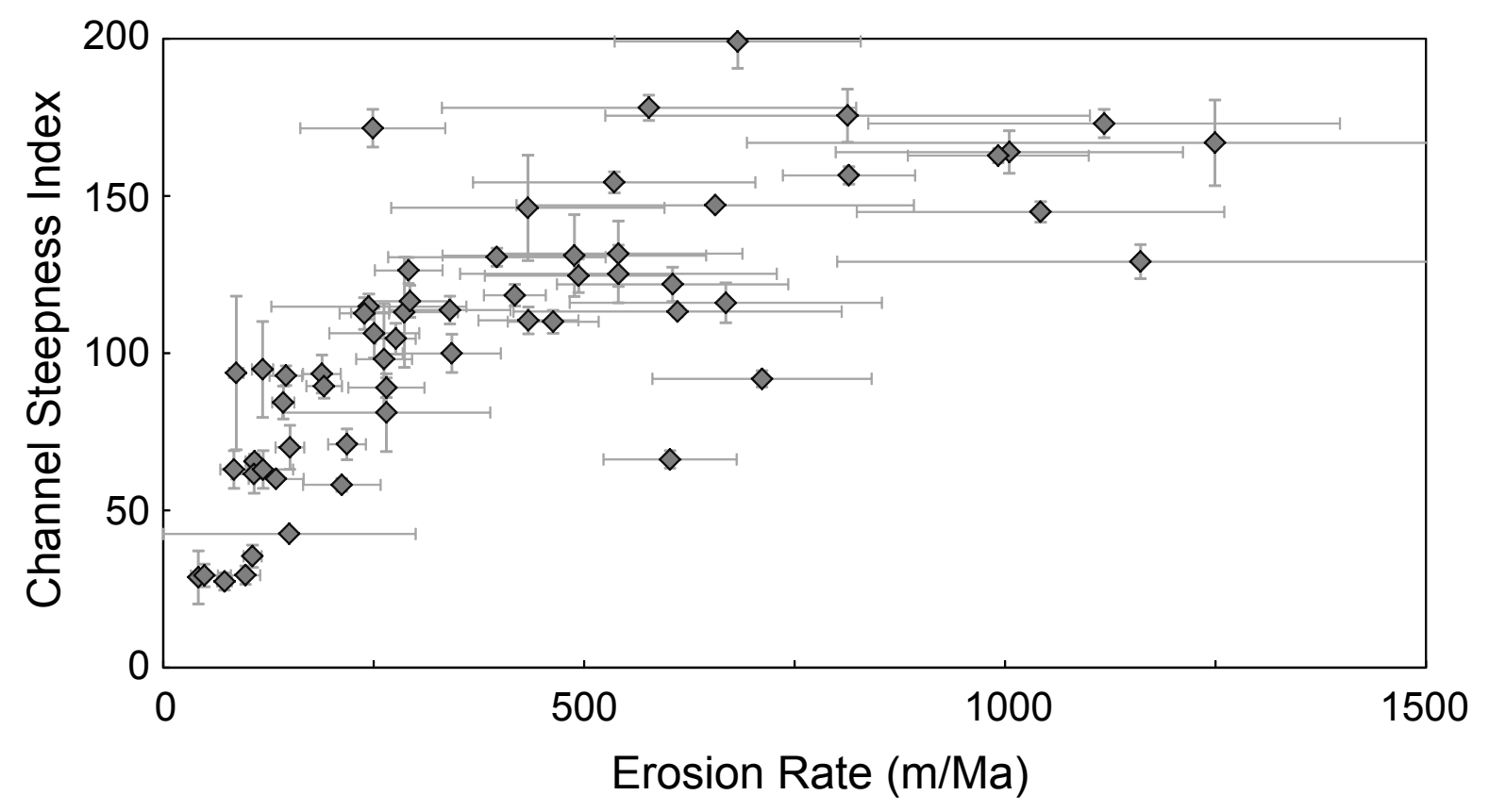
- Analyze USGS mean daily discharge records for 9 gages across SGM (40+ year records)
- Mean daily discharge scales linearly with drainage area over 3 orders of magnitude (mean runoff = 280 mm/yr)
- Distribution of large floods follows a power-law scaling that is consistent across the SGM
- Mean annual precipitation over catchments is ~700-1000 mm/yr; storms follows a poisson distribution



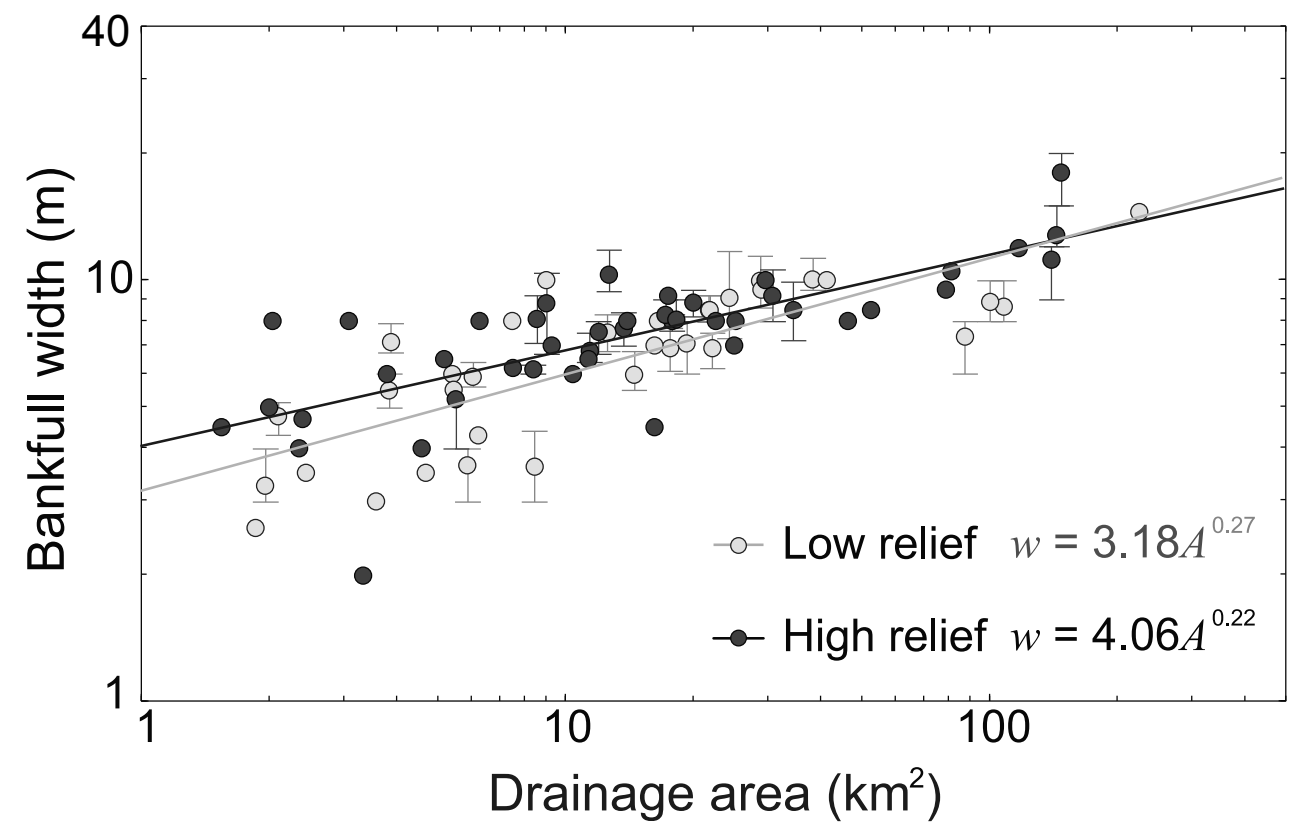


Exceedance plot of mean daily discharge normalized by the mean of all events for Cucamonga creek, showing power-law distribution of large floods.

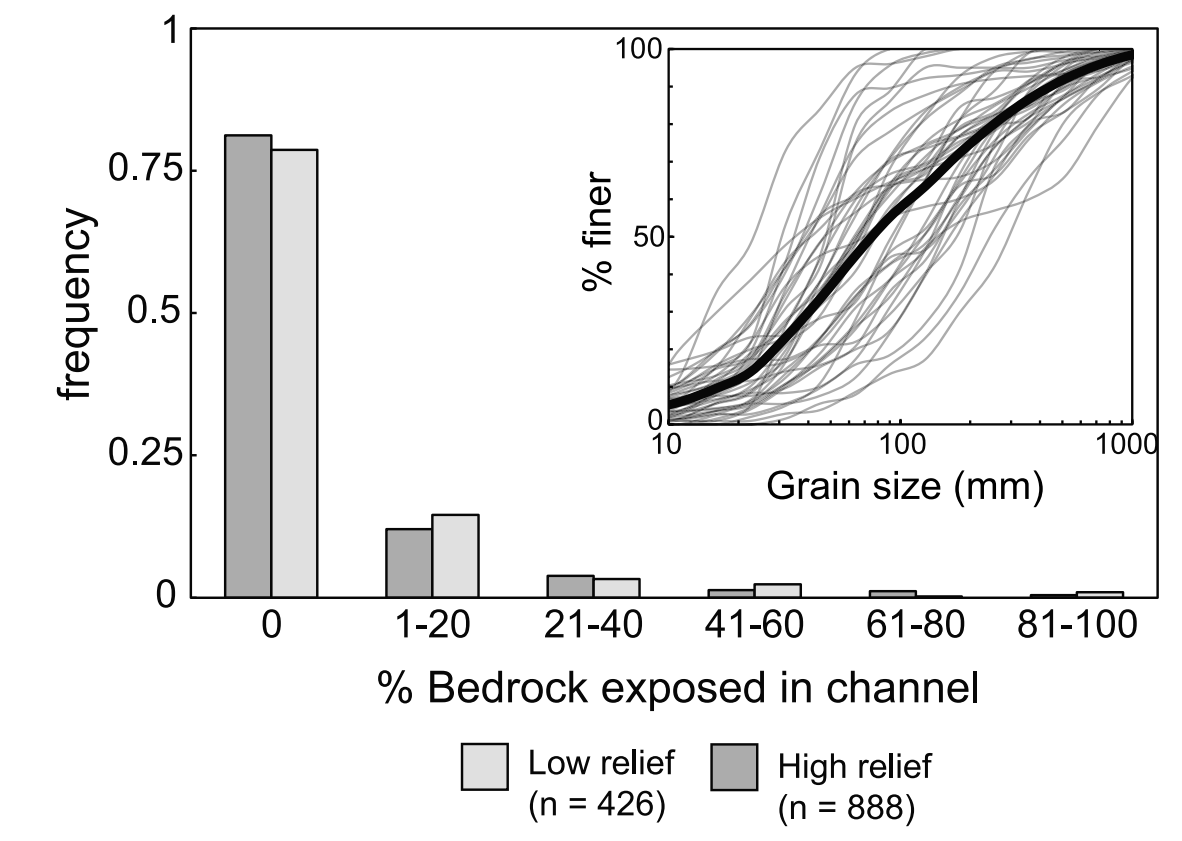
5. A non-linear relationship between channel steepness and erosion rate



- Channel steepness increases non-linearly with erosion rate, implies that steeper channels are more efficient
- Of the potential factors that may contribute to this roll-over, we use field measurements and USGS streamflow data to show that it is likely due to the influence of an erosion threshold that preferentially retards the incision of low steepness channels.



Summary of field survey data from SGM channels. Width scales similarly with drainage area across the range.



Channels in the SGM tend to be mantled with a thin layer of alluvium - bare bedrock channels are rare. We use pebble counts to estimate a minimum threshold shear stress based on incipient motion.

6. Stochastic-threshold incision model

Incorporate threshold term into stream power model, drive with full distribution of storm events (Tucker, 2004; Lague et al., 2005)

(normalized discharge $Q*$)

(threshold term)

(instantaneous incision)

$$I = K\left(\frac{Q}{Q_b}\right)^{\gamma} k_s^n - \Psi$$

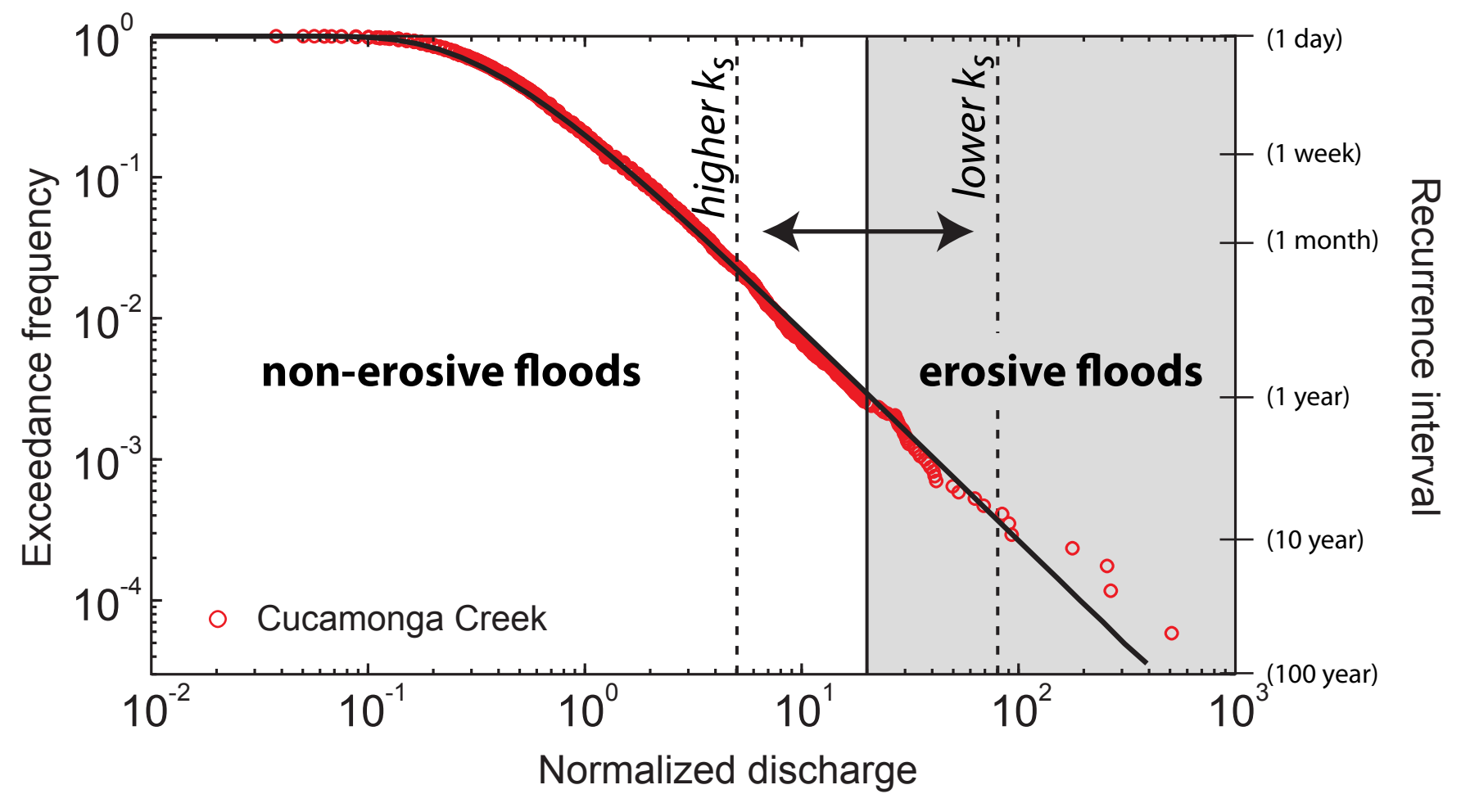
(long-term erosion: integrate over full pdf of discharges)

$$E = \int_{Q_c(k_s)}^{Q_m} I(Q, k_s)\,pdf(Q)\,dQ$$

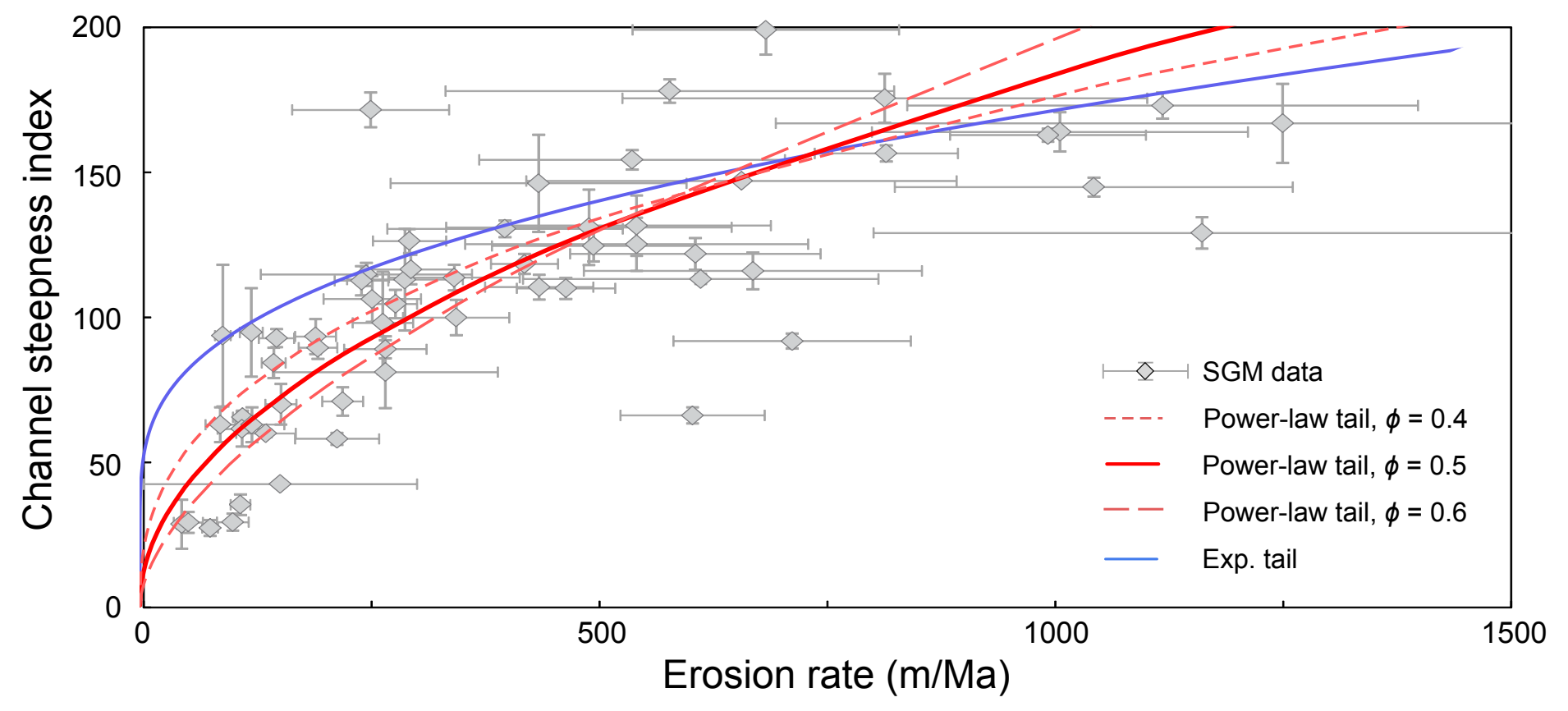
$$pdf(Q*) = \frac{k^{k+1}}{\Gamma(k+1)} \exp\left(-\frac{k}{Q*}\right) Q*^{-(2+k)}$$

(discharge distribution w/ power law tail)
(Lague et al., 2005)

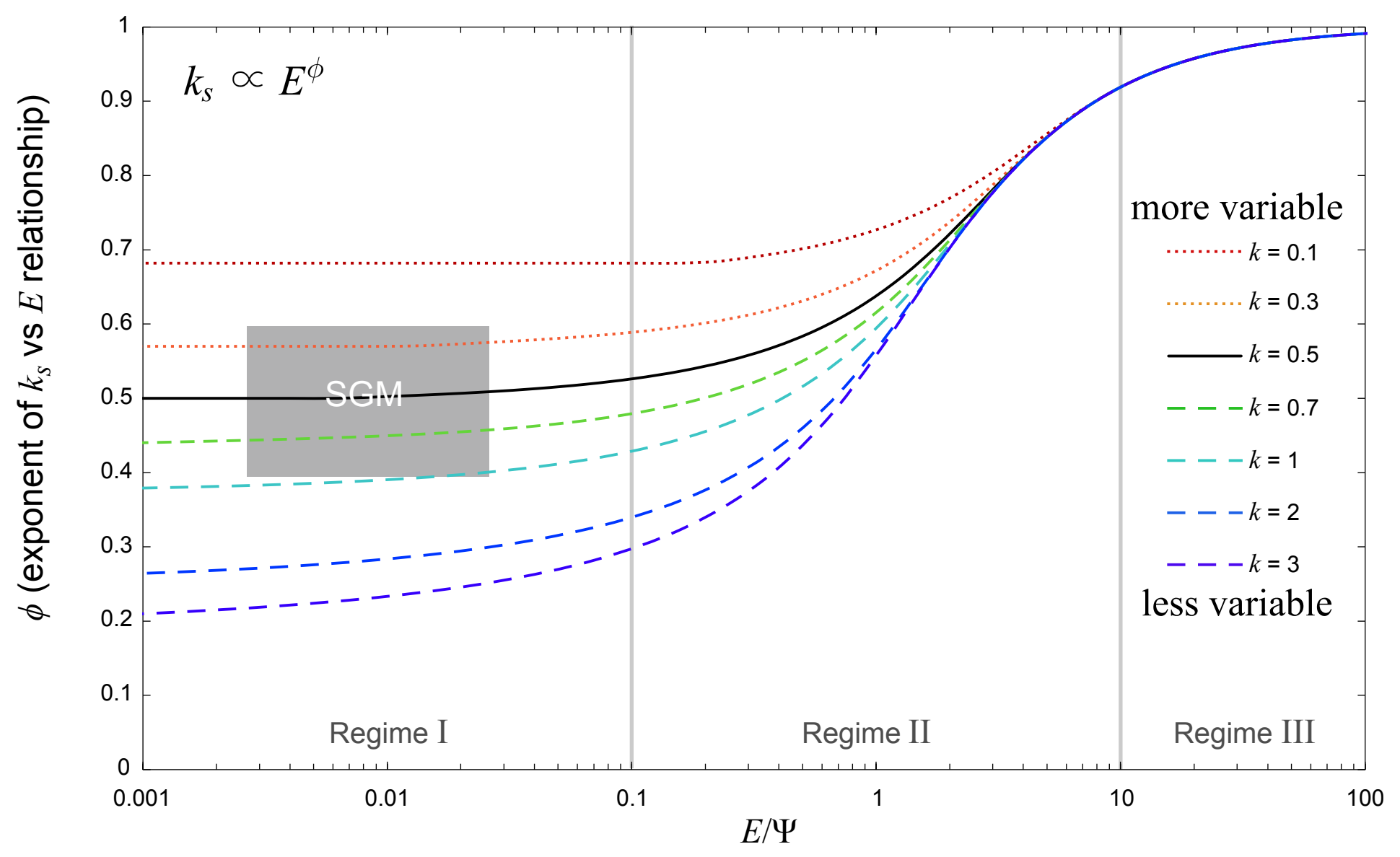
(k relates to discharge variability: low k = high variability)



Critical discharge depends on channel steepness index. Steeper channels incise more frequently.



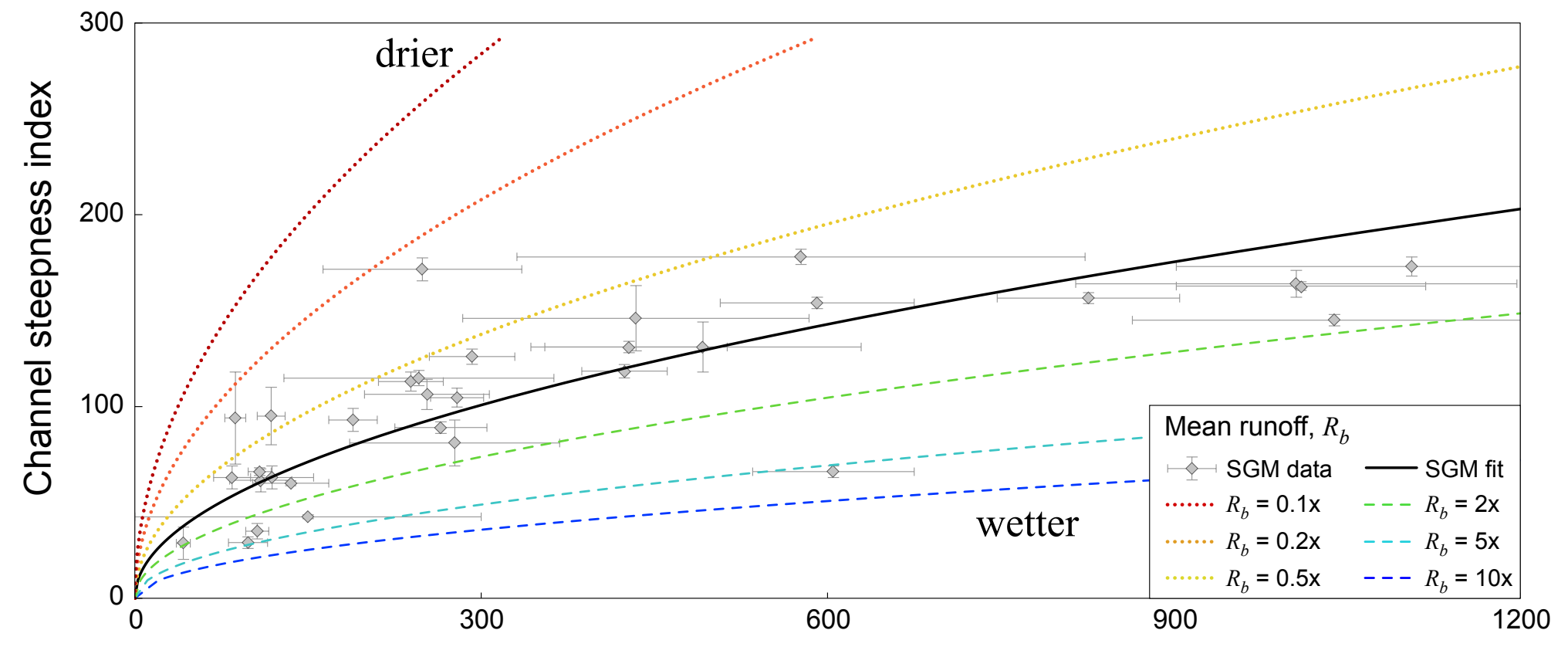
- Shape of k_s-E relationship depends on frequency of large floods
- Magnitude of curve depends on K (erodibility), which is tuned to SGM data
- Stochastic-threshold model fits SGM data to first order without accounting for sediment and geometry dynamics
- These effects become important in the transient case



- For high erosion rates (neglible threshold), above relationship collapses to standard stream power
- When the threshold term dominates, the shape of the k_s-E relationship is governed primarily by discharge variability
- Channels in the San Gabriel Mountains lie well within the threshold dominated regime

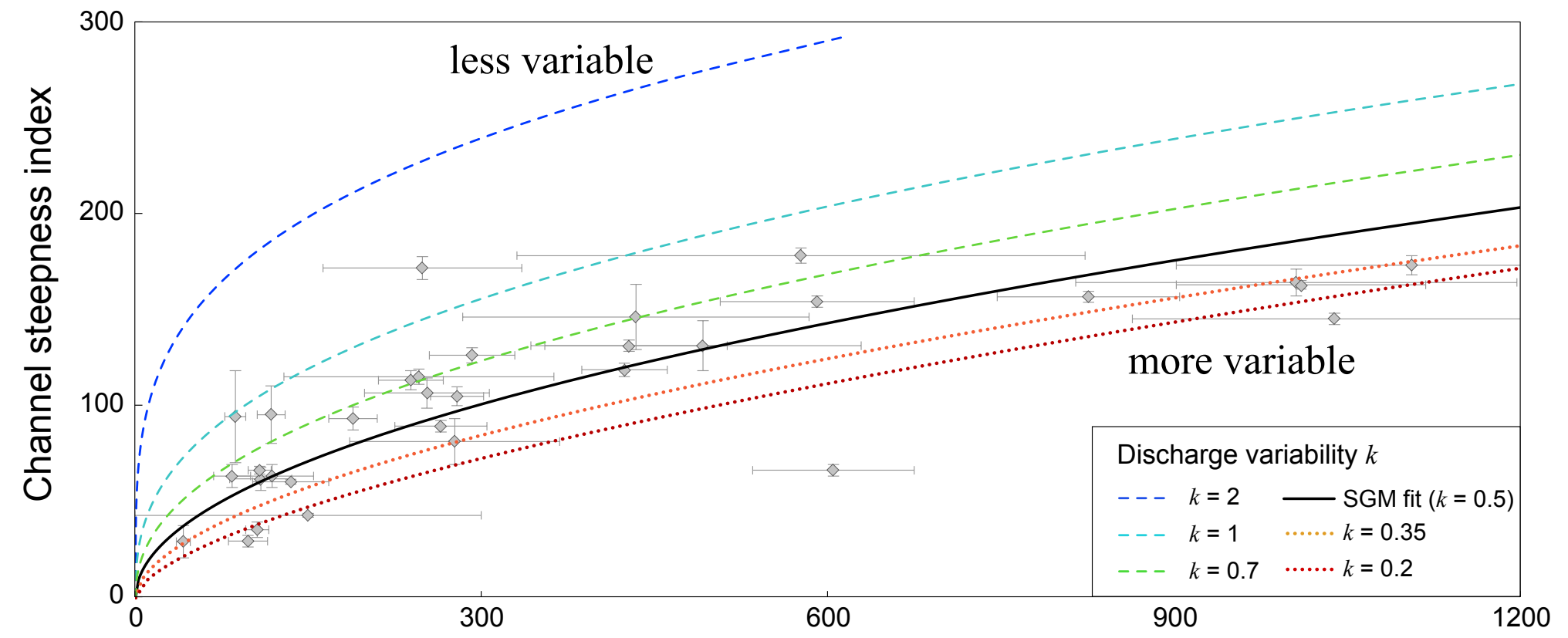
7. Climate and erosional efficiency

Start with SGM fit, and change climate variables to see influence on k_s-E relationship



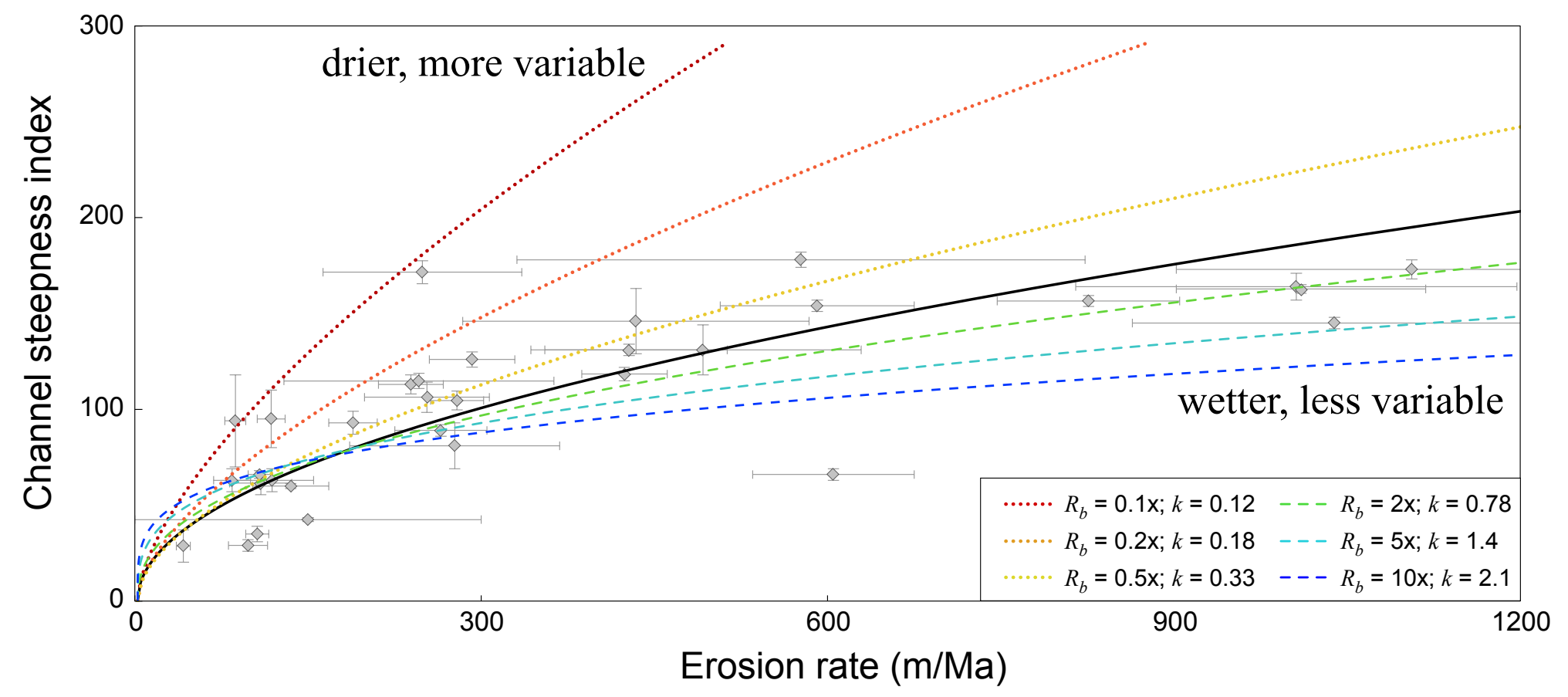
Change mean runoff only

- Decrease runoff = lower E (less efficient)
- Increase runoff = higher E (more efficient)
- "Shape" does not change, just magnitude



Change discharge variability only

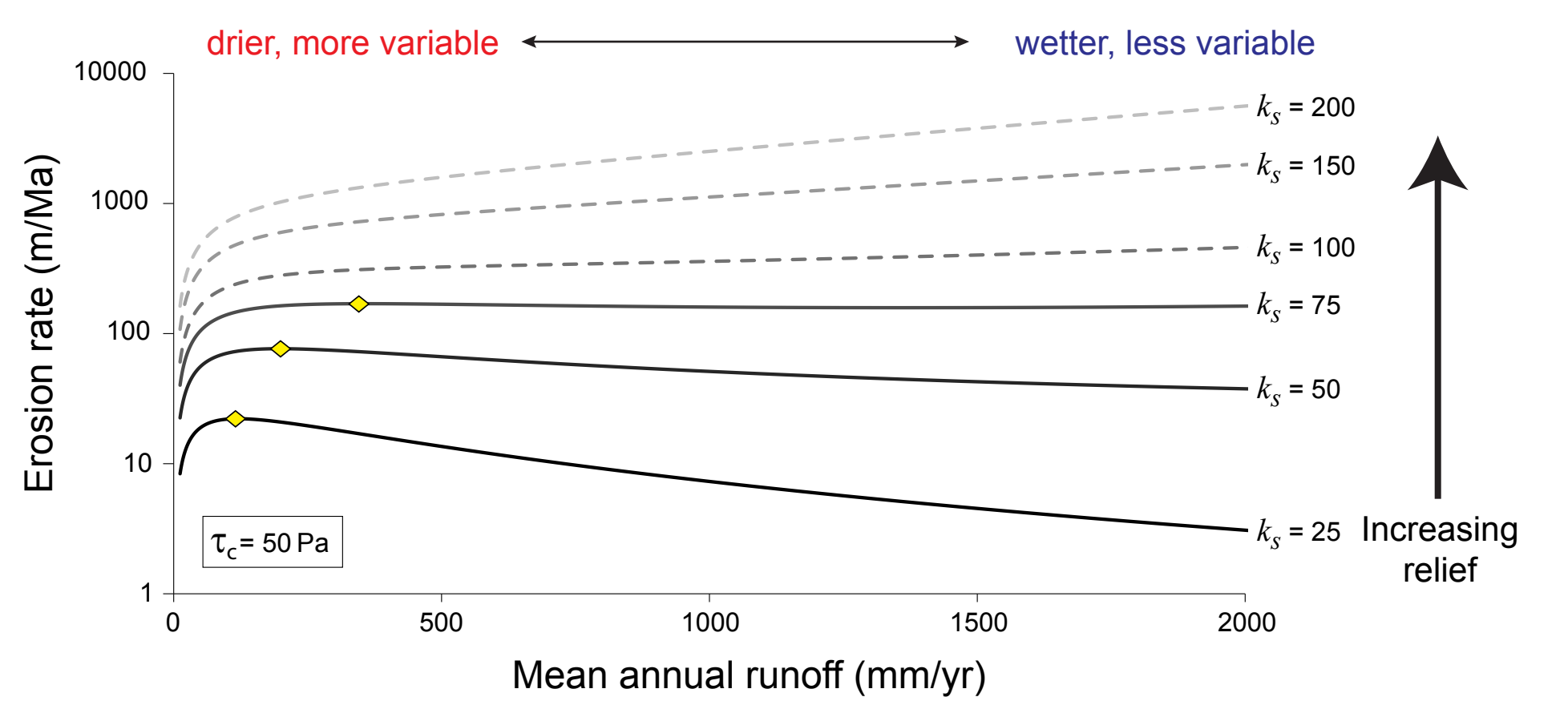
- Decrease variability = lower E (less efficient)
- Increase varibility = higher E (more efficient)
- Increasingly non-linear for high variability



Covary mean runoff and discharge variability
(Cont. US empirical relationship, Molnar et al., 2006)

- Inverse relationship between mean and variability
- For low E, dry, variable channels are more efficient
- For high E, wet, stable channels are more efficient

8. Implications for climate-tectonic feedbacks



- Humped relationship between erosion rate and runoff when threshold-dominated
- Erosion insensitive to increases in runoff beyond ~500 mm/yr for much of parameter space
- Suggests weak climate-tectonics link (dual effect of $\phi<1$ and weak runoff-E relationship (Whipple and Meade 2004))
- The most sensitive landscapes have steep channels, low threshold, and highly variable climate not offset by decreases in mean runoff (e.g., Taiwan)

9. Conclusions

- The channel steepness index serves as a metric of relief that can be directly tied to process-based erosion models
- Catchment average erosion rates in the San Gabriel Mountains range from 30-1200 m/Ma, reflecting a strong gradient in rock uplift rate (as opposed to climate or lithology)
- A non-linear relationship between channel steepness and erosion rate in the SGM can be explained by a stochastic-threshold incision model where thresholds of incision preferentially retard the erosion of low-steepness channels
- The relationship between channel steepness and erosion rate is sensitive to variations in climate and rock strength, and enables quantitative predictions of these influences on erosional efficiency.

Acknowledgements

We thank all those involved with the field surveys, including B. Adams, E. DiMaggio, N. Gasparini, B. Guralnik, M. Jungers, J. McDermott, D. Stolar, and J. Walsh. Funding was provided by the Geomorphology and Land Use Dynamics program at NSF (EAR-0724194 to KXW and EAR-0518998 to AMH).

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