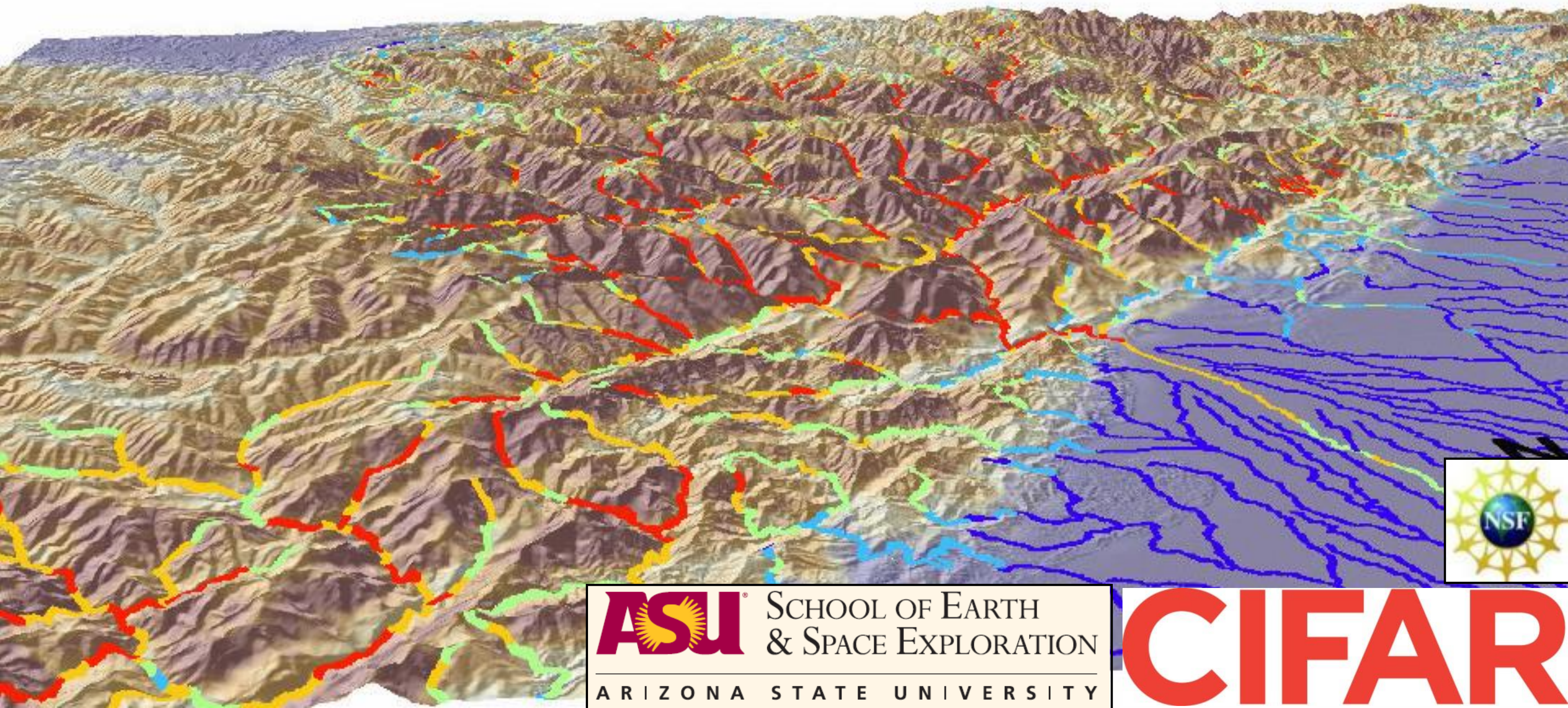
Topography, Climate, Erosion Rates and Tectonics

K. Whipple, R. DiBiase, M. Rossi, B. Adams



ASU SCHOOL OF EARTH & SPACE EXPLORATION
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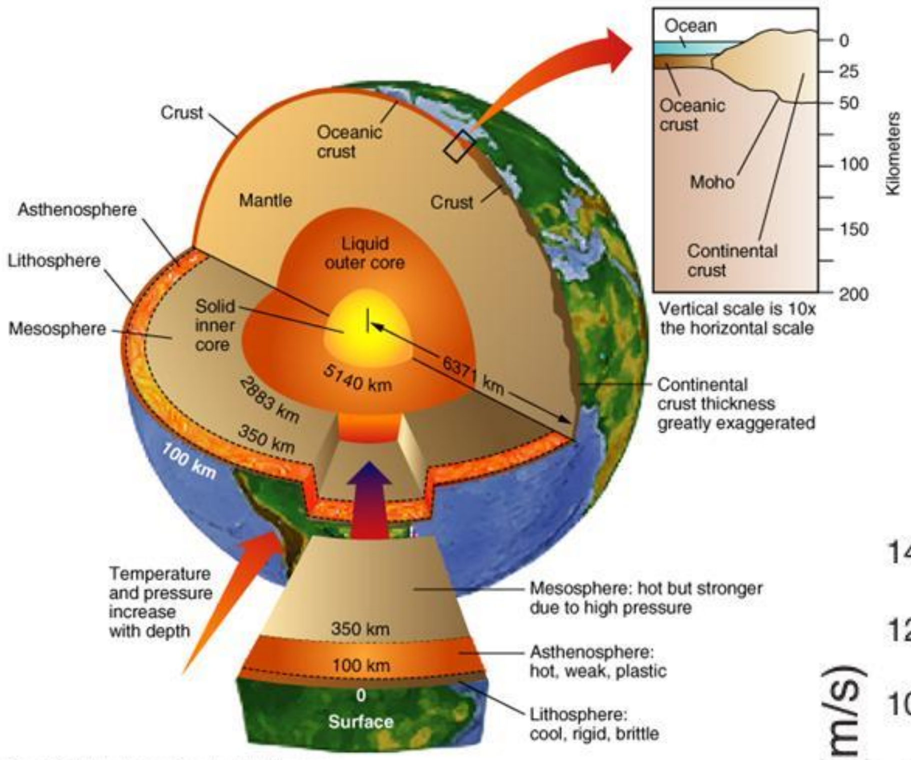
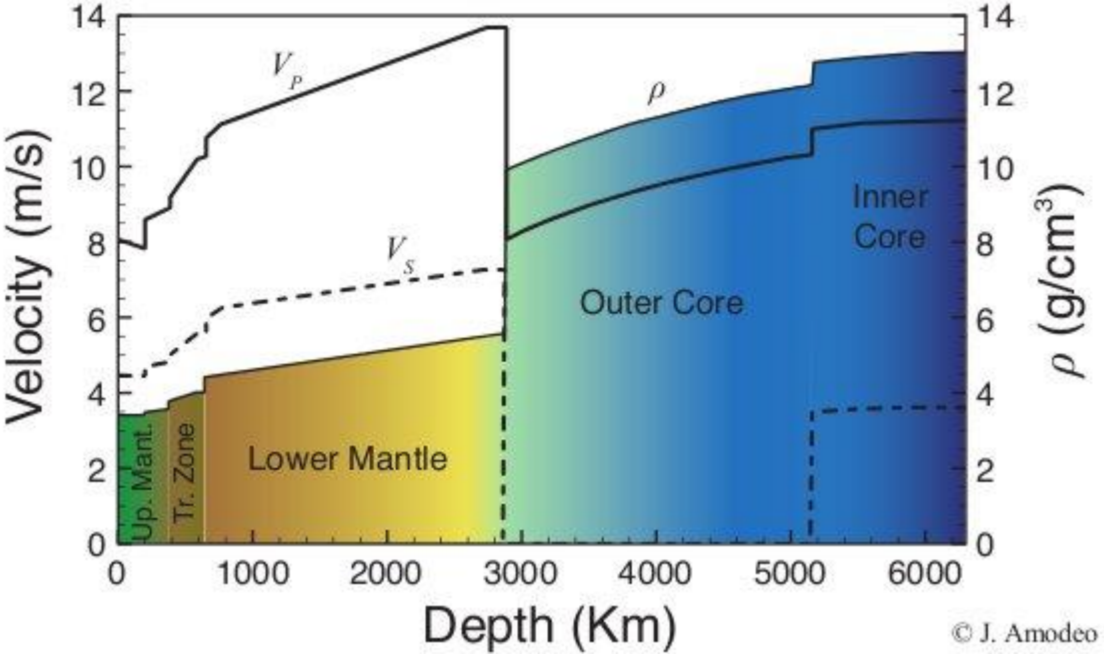
CIFAR

Topography Matters

- Locus of Active Uplift (*Tectonics, Hazards*)
- Temporal History of Rock Uplift (*Miocene*)
- Differential Stresses – *Fracture Rock, Influence Patterns of Deformation*
- Erosion Rates/Patterns – *Unloading and Deformation Response*
- *Erosion Rule Matters – Sensitivity to Relief, Climate, Rock Type, Drainage Area*


Crust
Oceanic crust
Mantle
Crust
Asthenosphere
Lithosphere
Mesosphere
Liquid outer core
Solid inner core
5140 km
6371 km
2883 km
350 km
100 km
Ocean
Oceanic crust
Moho
Continental crust
0
25
50
100
150
200
Kilometers
Vertical scale is 10x the horizontal scale
Continental crust thickness greatly exaggerated
Temperature and pressure increase with depth
350 km
100 km
0
Surface
Mesosphere: hot but stronger due to high pressure
Asthenosphere: hot, weak, plastic
Lithosphere: cool, rigid, brittle


V_P
V_S
ρ
Up. Mant.
Tr. Zone
Lower Mantle
Outer Core
Inner Core
Velocity (m/s)
ρ (g/cm^3)
Depth (Km)
0
2
4
6
8
10
12
14
0
1000
2000
3000
4000
5000
6000

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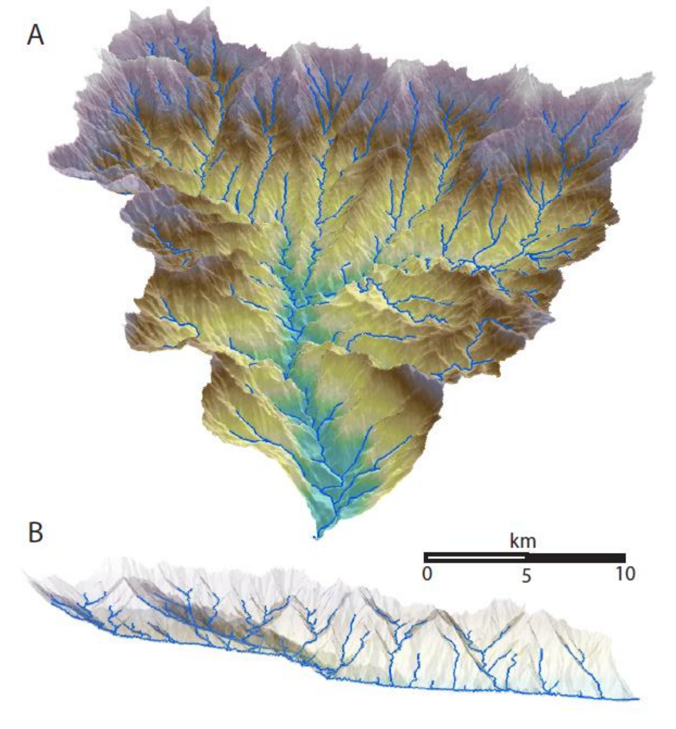
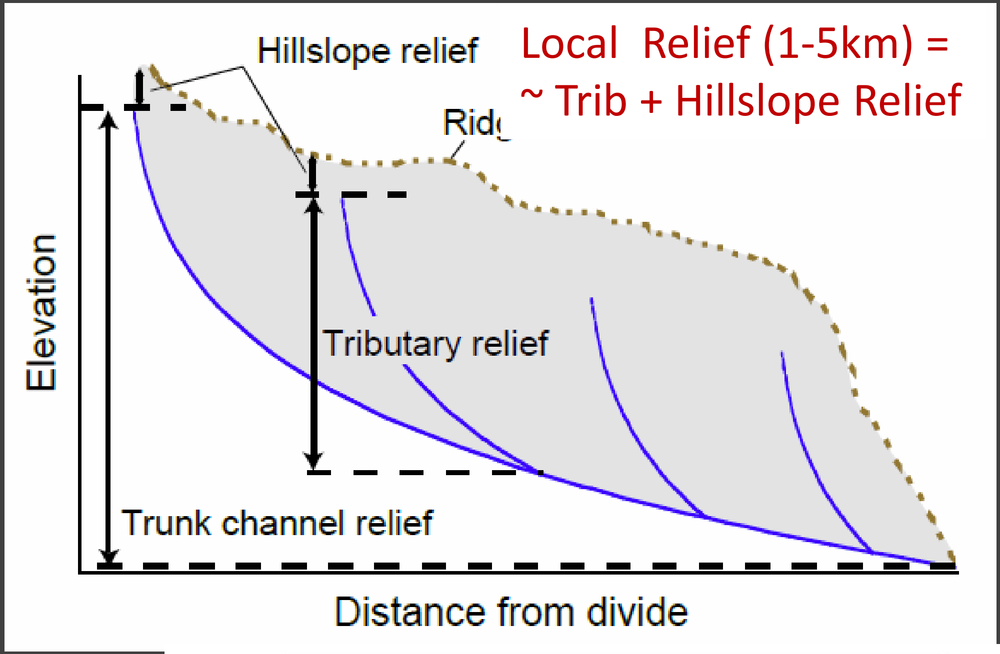
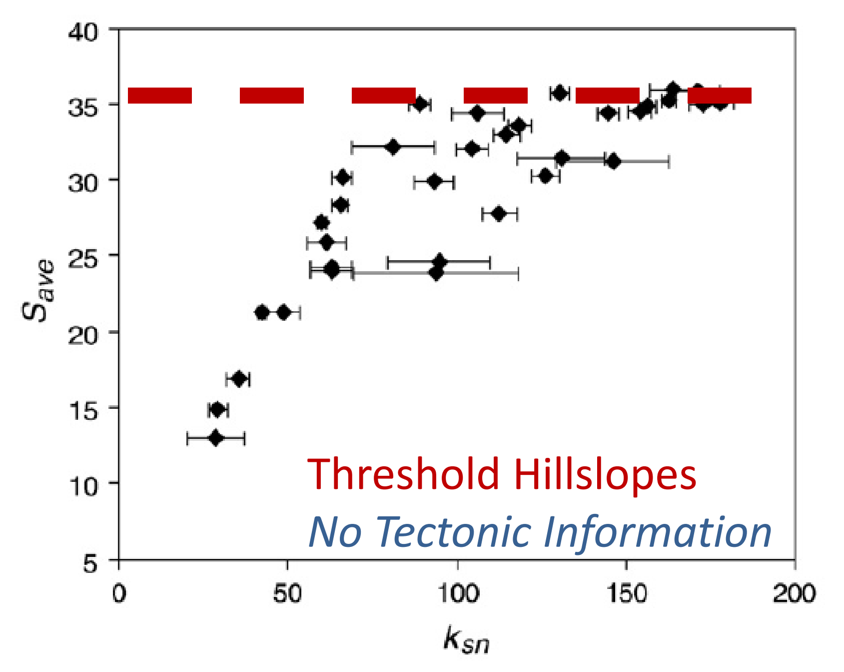


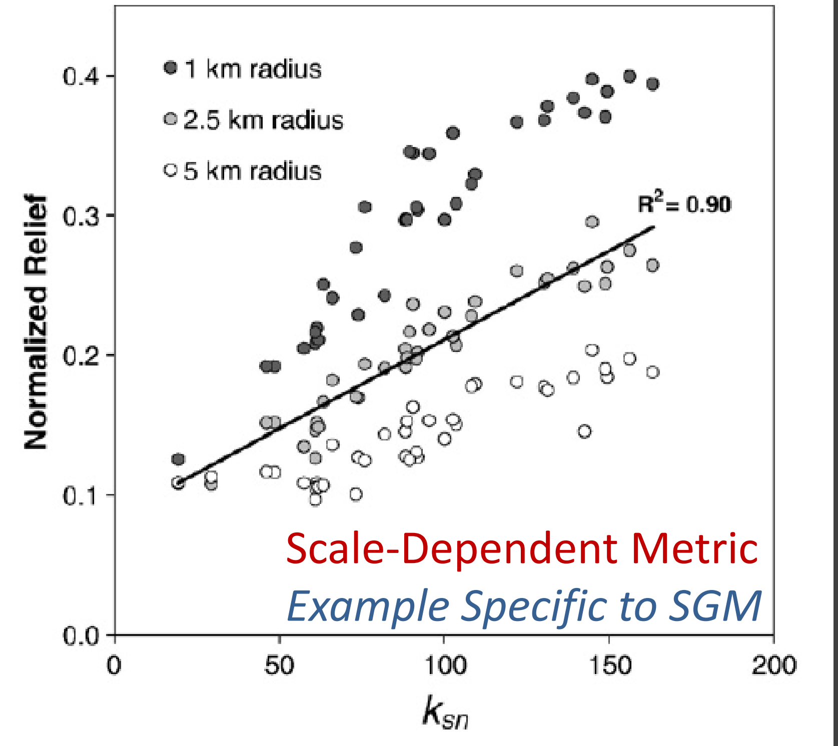


Local Relief (1-5km) =
~ Trib + Hillslope Relief



Threshold Hillslopes

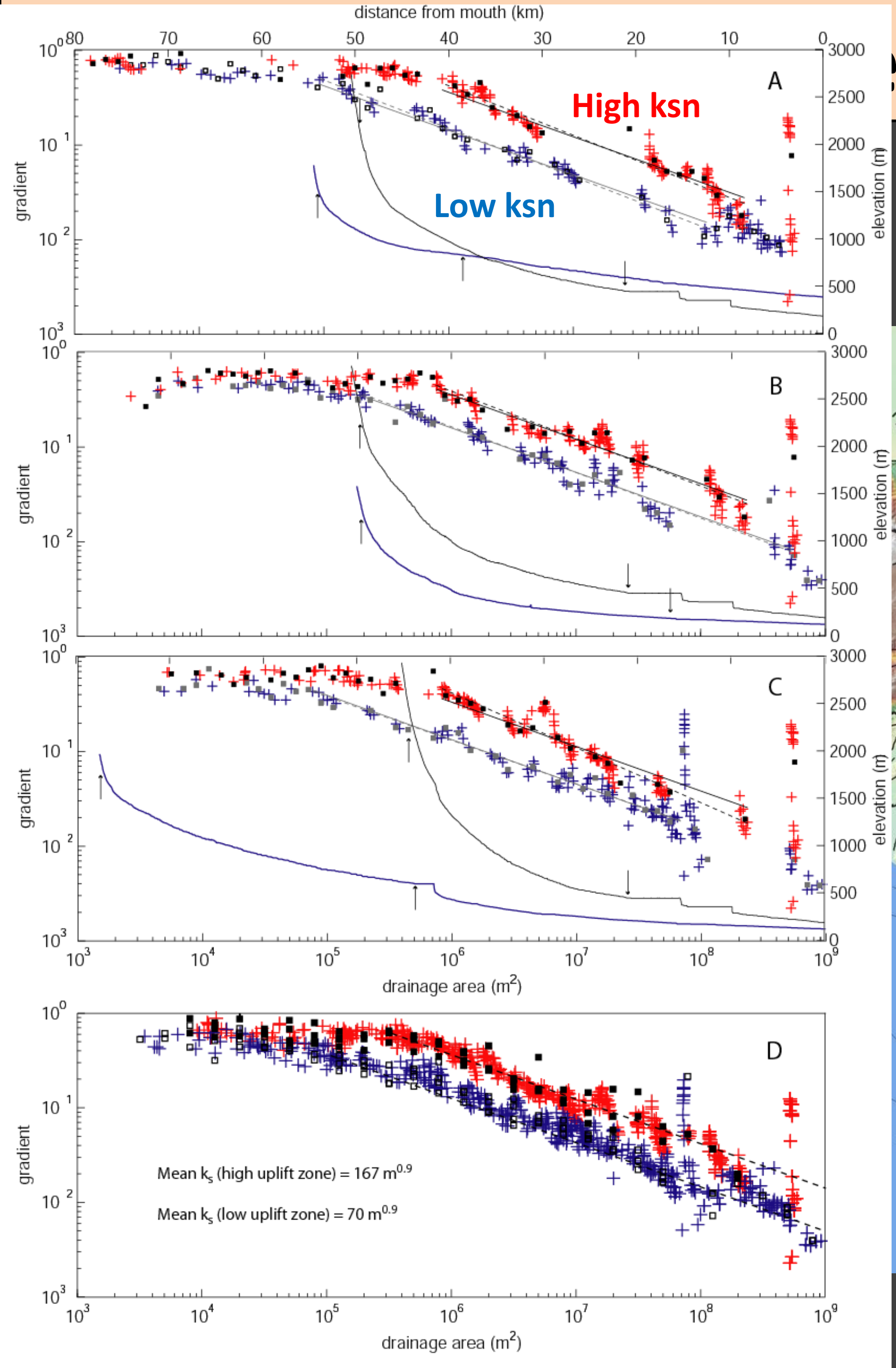
No Tectonic Information



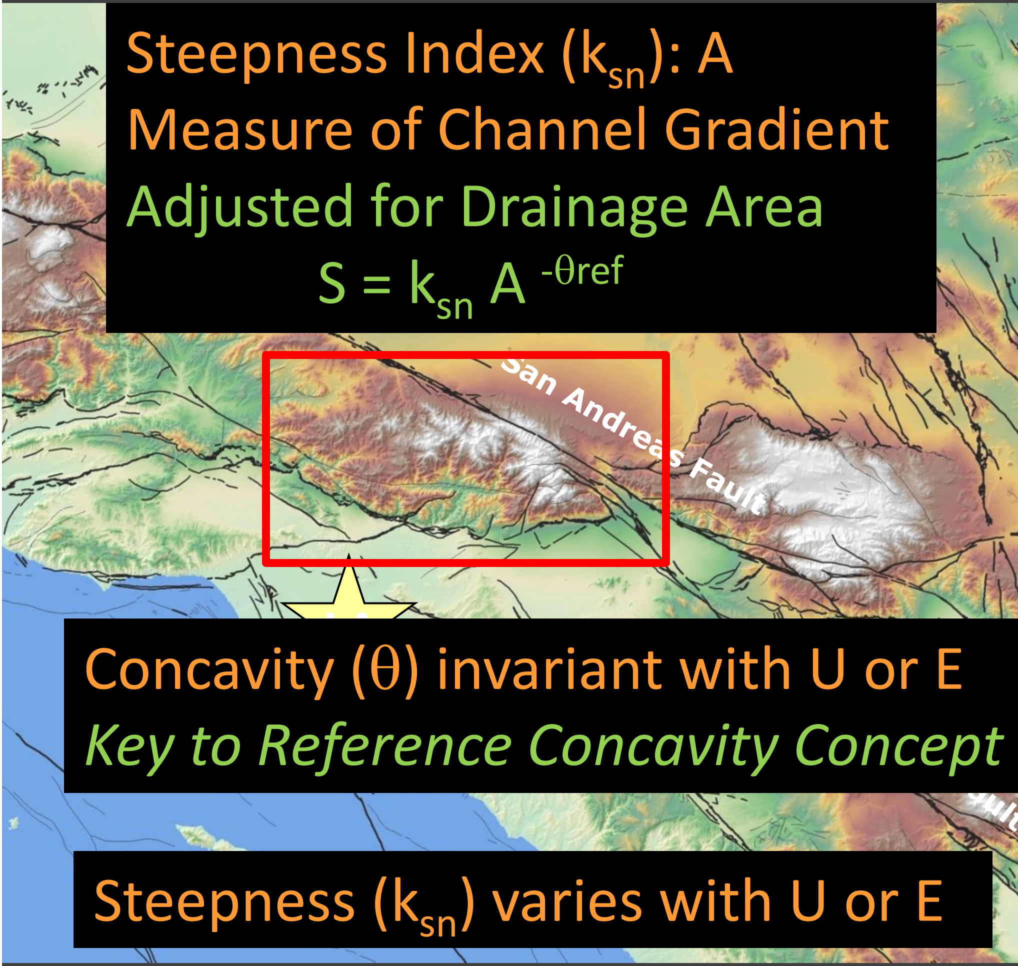
Scale-Dependent Metric

Example Specific to SGM

l Steepness Index (k_{sn})



Wobus et al., Figure 5



San Gabriel Mountains, CA

Steepness Index (k_{sn}): A Measure of Channel Gradient Adjusted for Drainage Area

$$S = k_{sn} A^{-\theta ref}$$

Concavity (θ) invariant with U or E

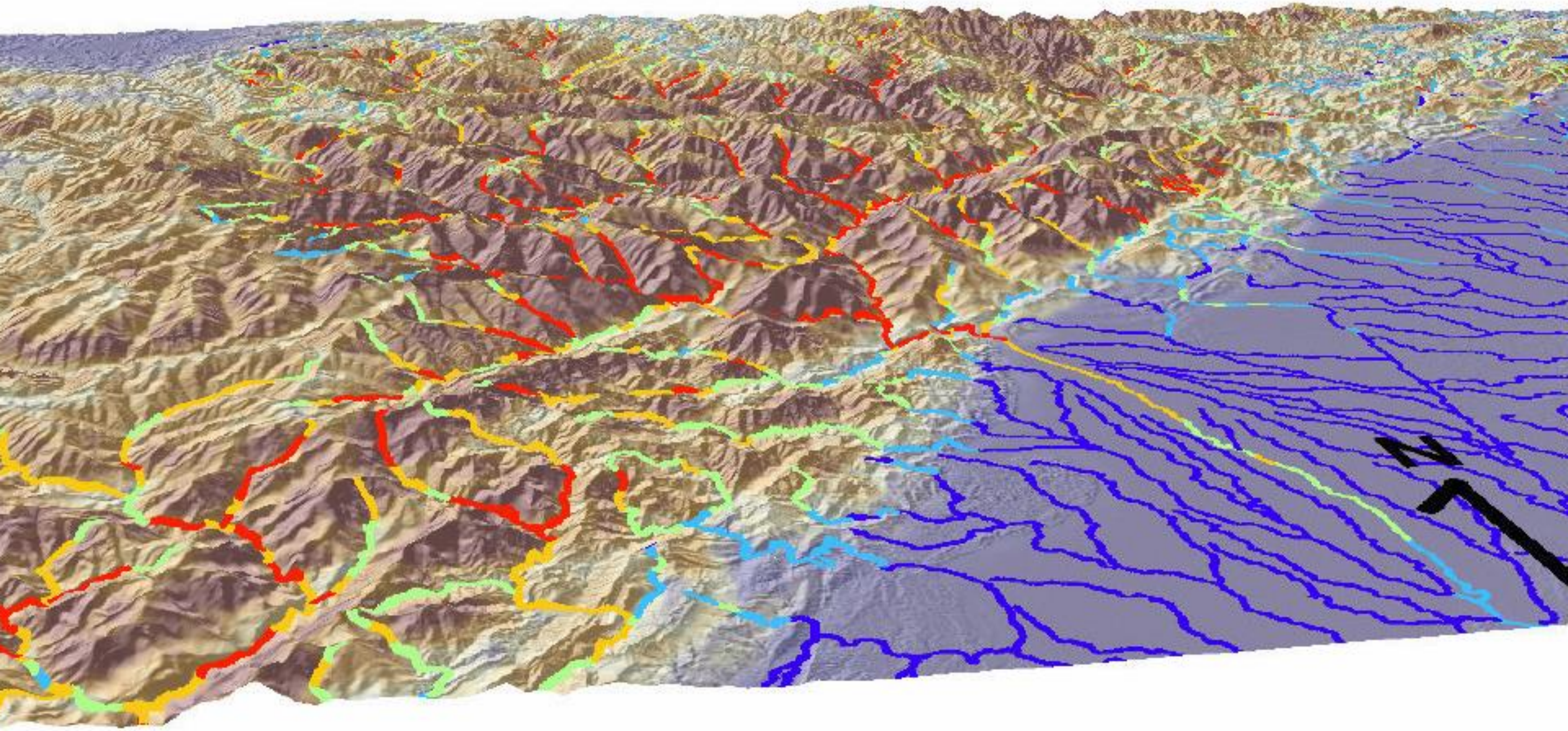
Key to Reference Concavity Concept

Steepness (k_{sn}) varies with U or E

$$k_{sn} \sim U^f$$

Qualitative: Is There an Active Fault? Where?

Perspective: local relief and ksn



Qualitative: Is There an Active Fault? Where?

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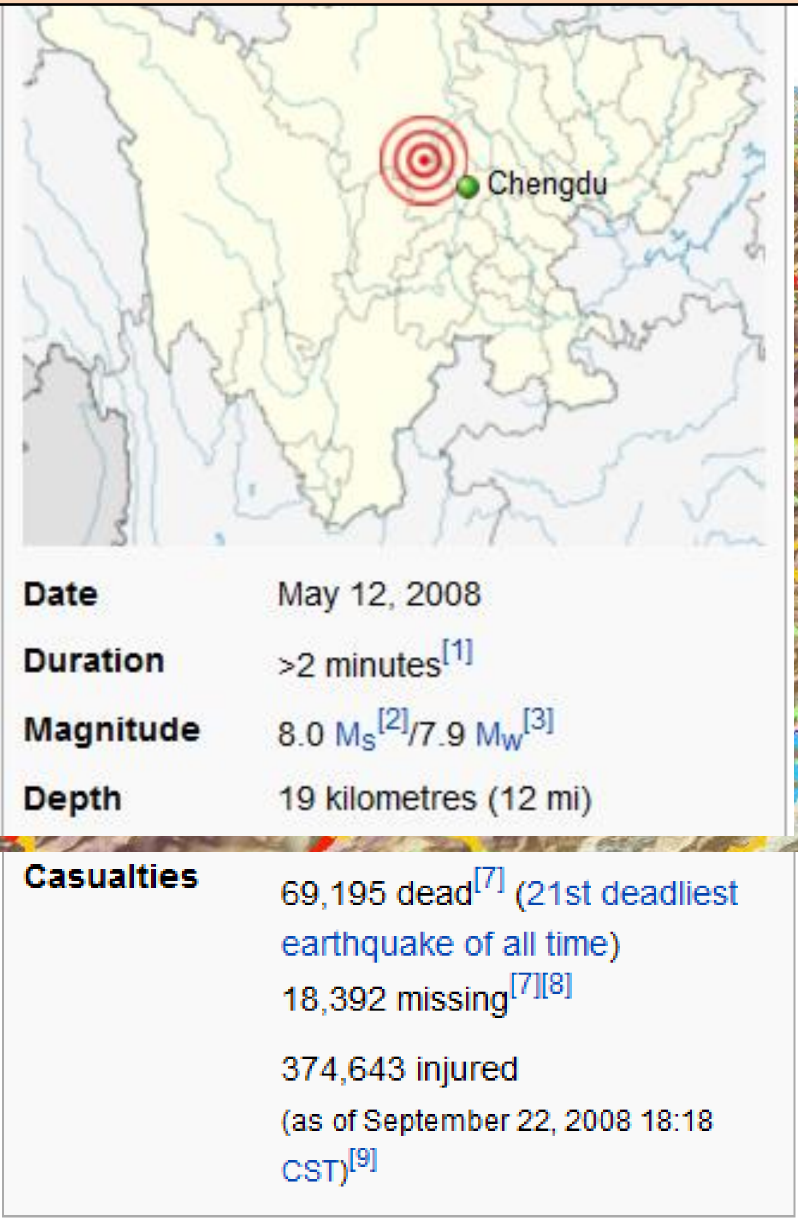
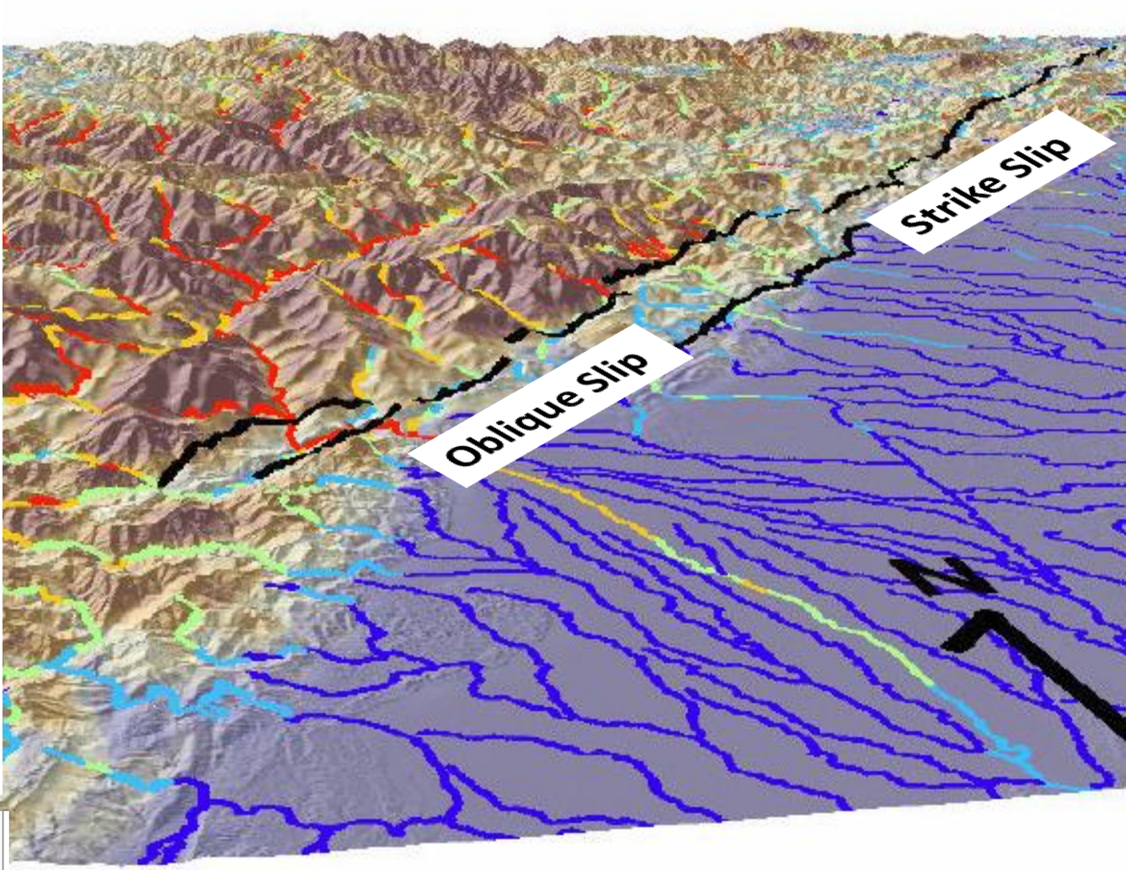
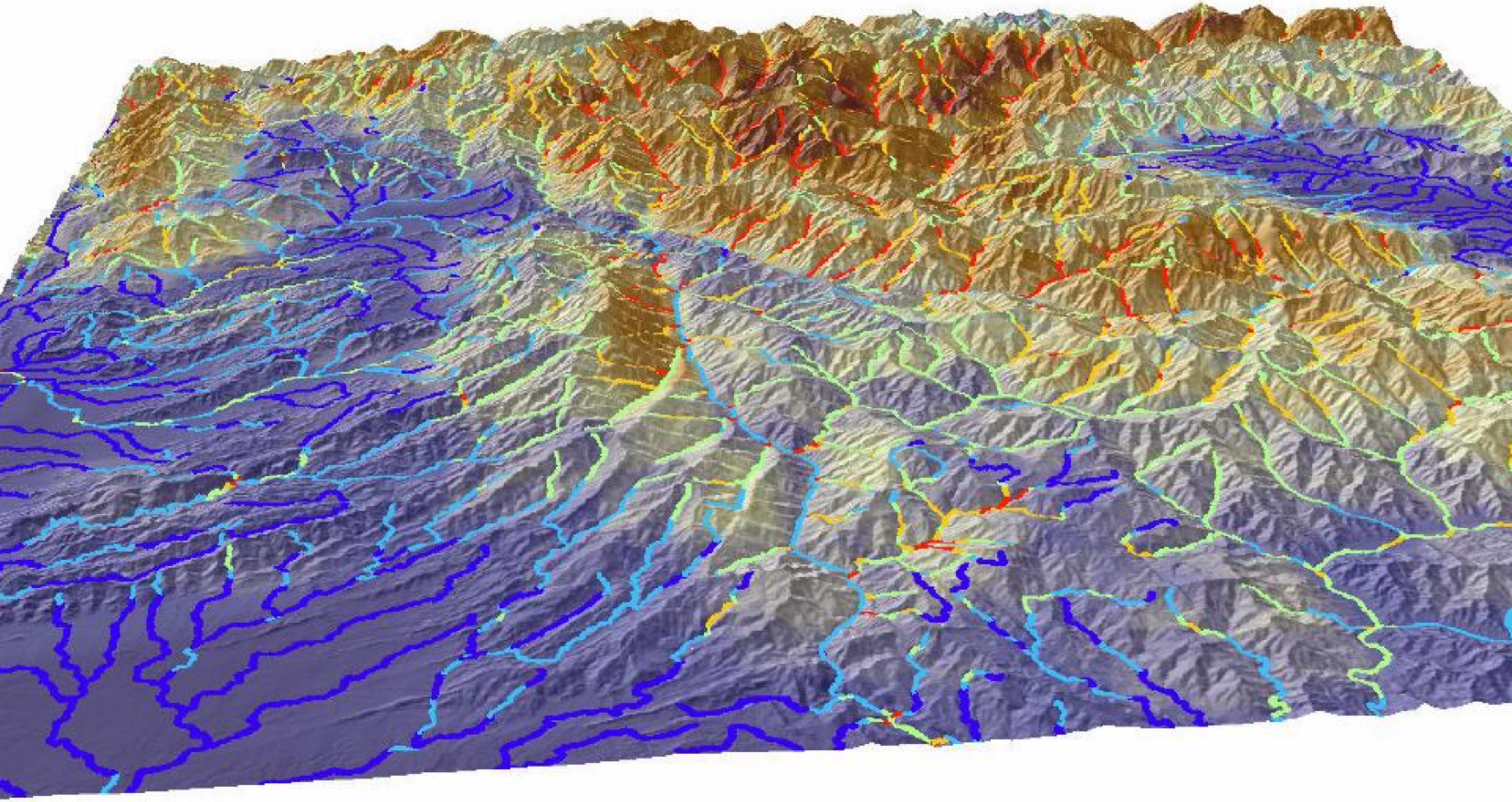


Date	May 12, 2008
Duration	>2 minutes[1]
Magnitude	8.0 M_S[2]/7.9 M_W[3]
Depth	19 kilometres (12 mi)
Casualties	69,195 dead[7] (21st deadliest earthquake of all time) 18,392 missing[7][8] 374,643 injured (as of September 22, 2008 18:18 CST)[9]



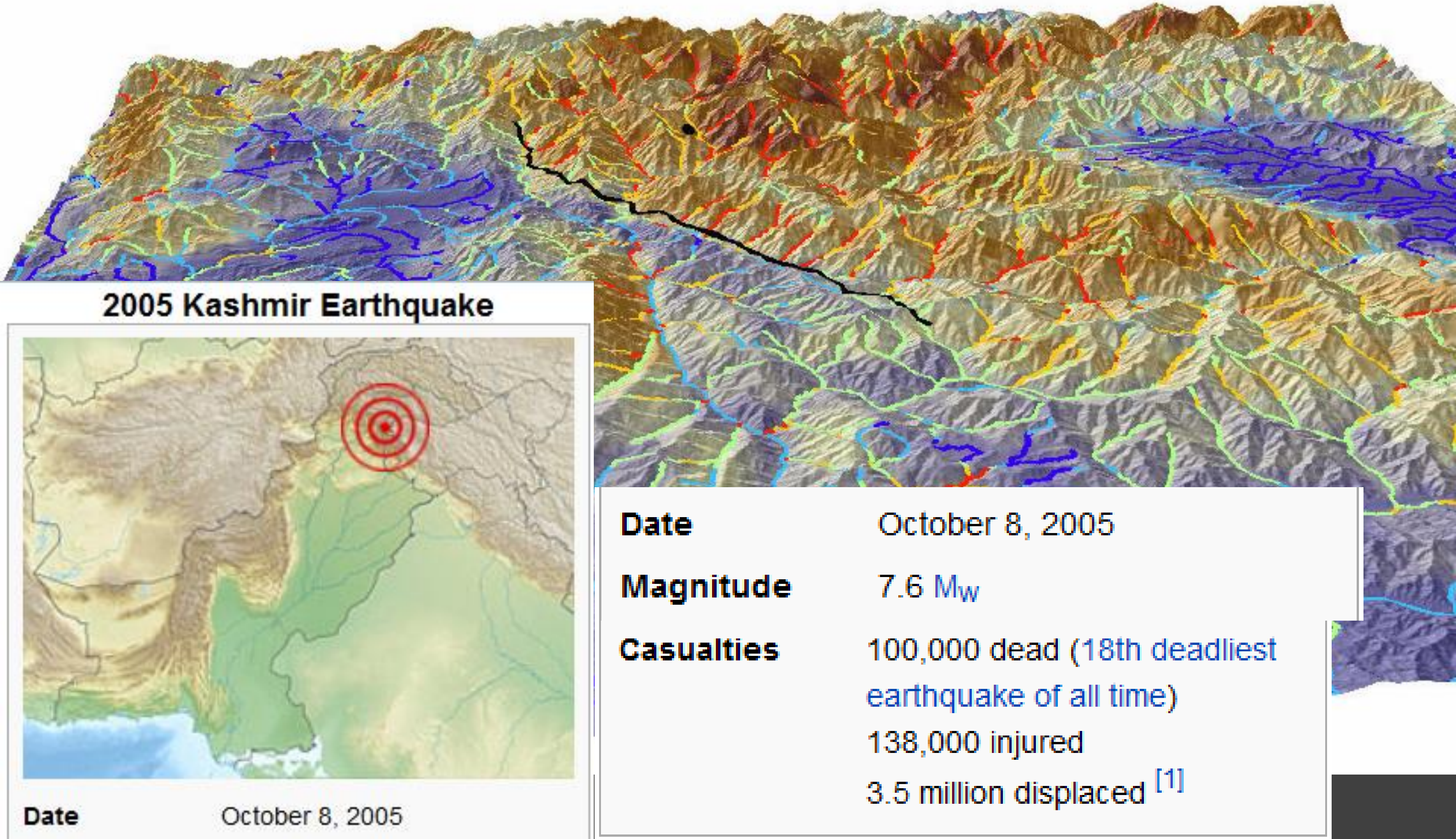
Qualitative: Is There an Active Fault? Where?

Perspective: local relief and ksn



Qualitative: Is There an Active Fault? Where?

Perspective: local relief and ksn

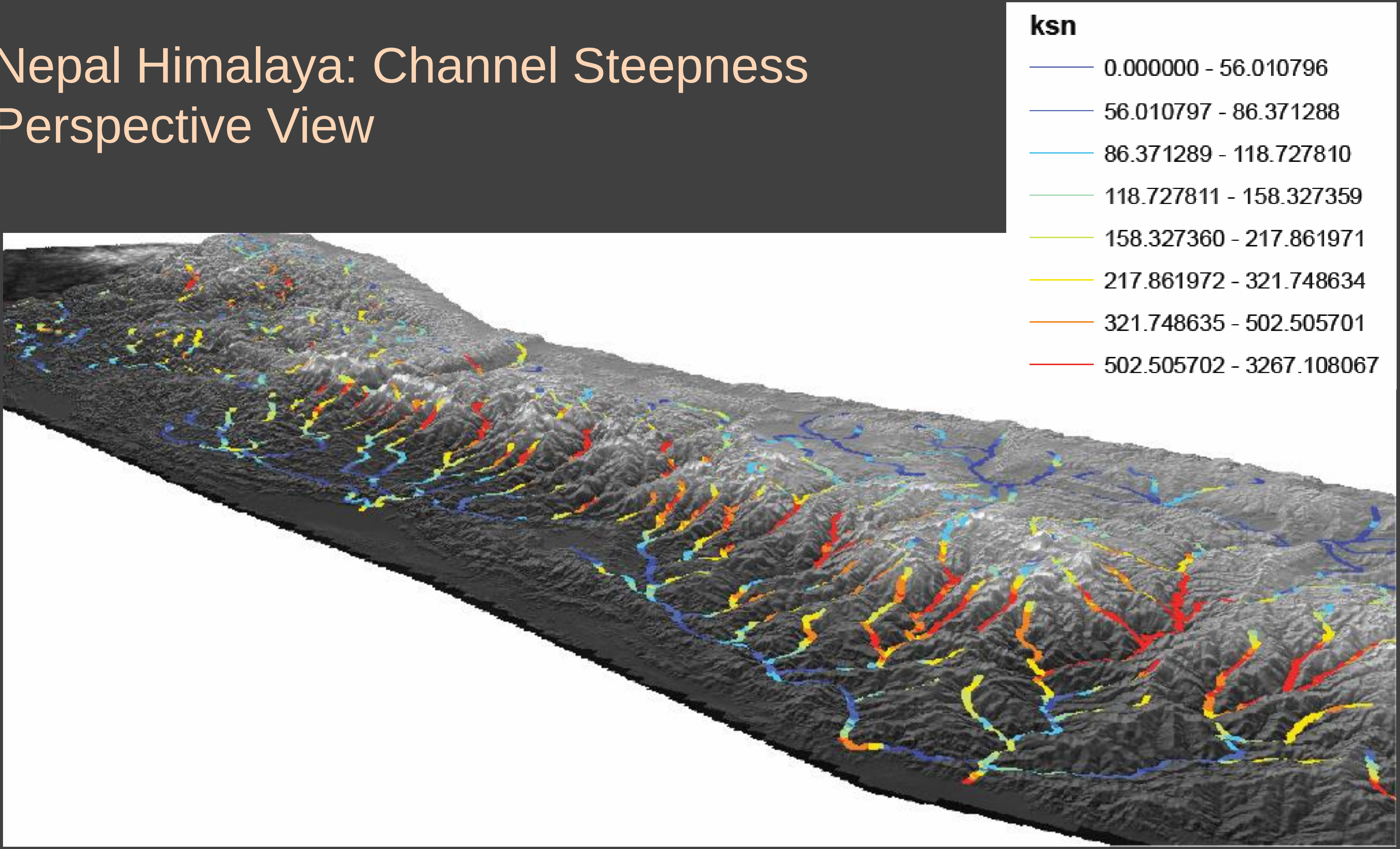


2005 Kashmir Earthquake

Date October 8, 2005

Date	October 8, 2005
Magnitude	7.6 M_W
Casualties	100,000 dead (18th deadliest earthquake of all time) 138,000 injured 3.5 million displaced [1]

Nepal Himalaya: Channel Steepness Perspective View



Tectonic controls of transient landscapes in the Bhutan Himalaya

Byron A. Adams
Kelin X Whipple
Kip V. Hodges
Matthijs C. van Soest
Arjun M. Heimsath

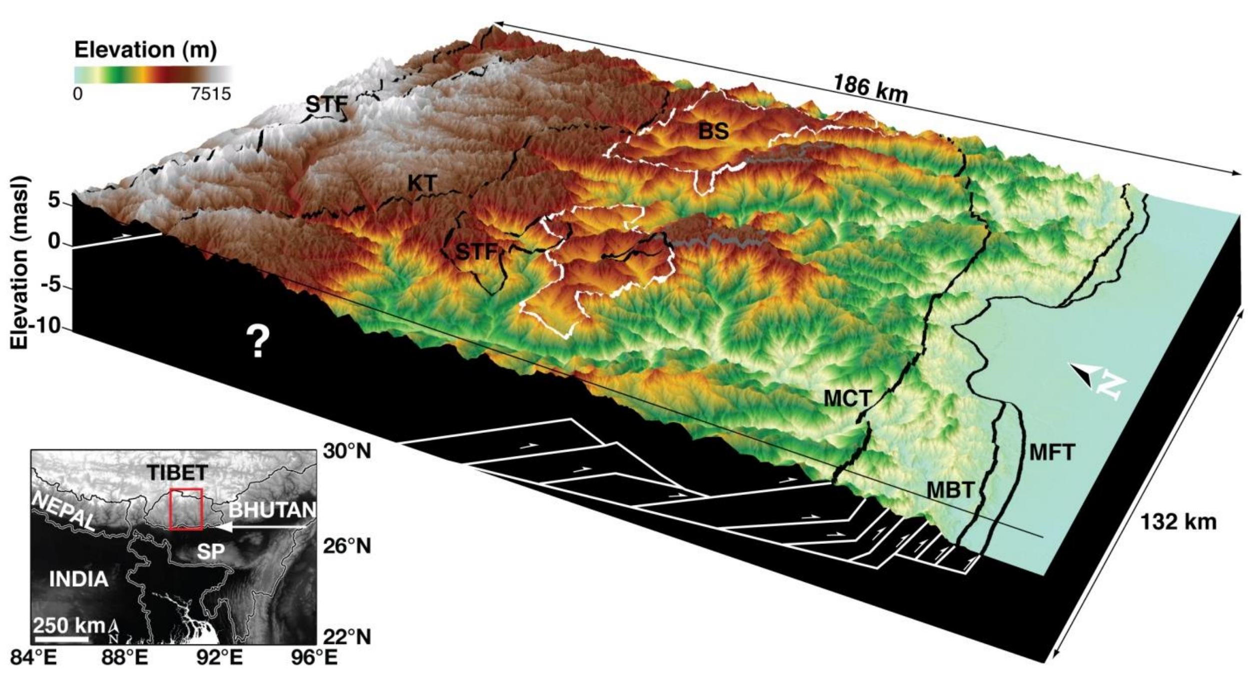
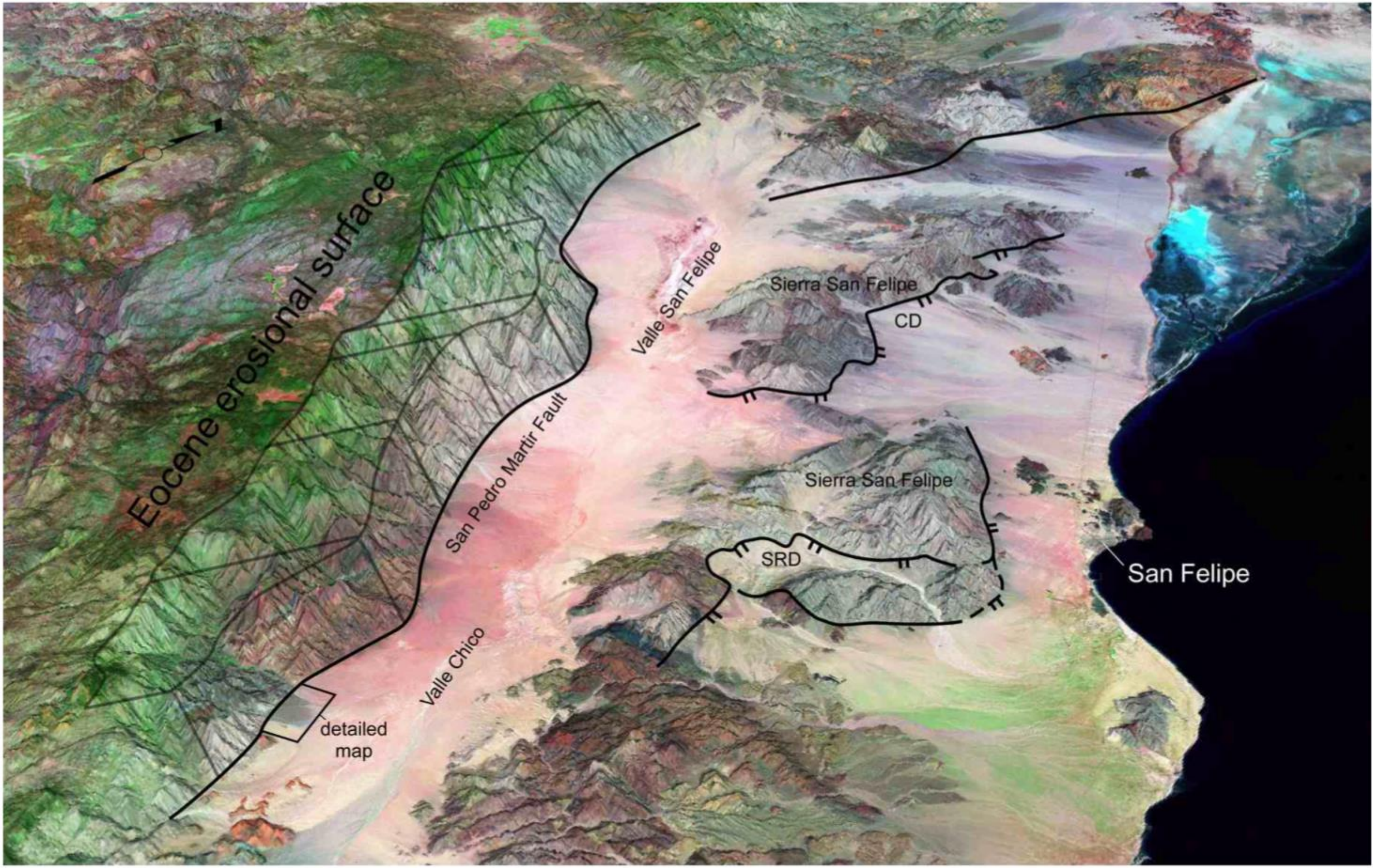


photo courtesy Kelin Whipple

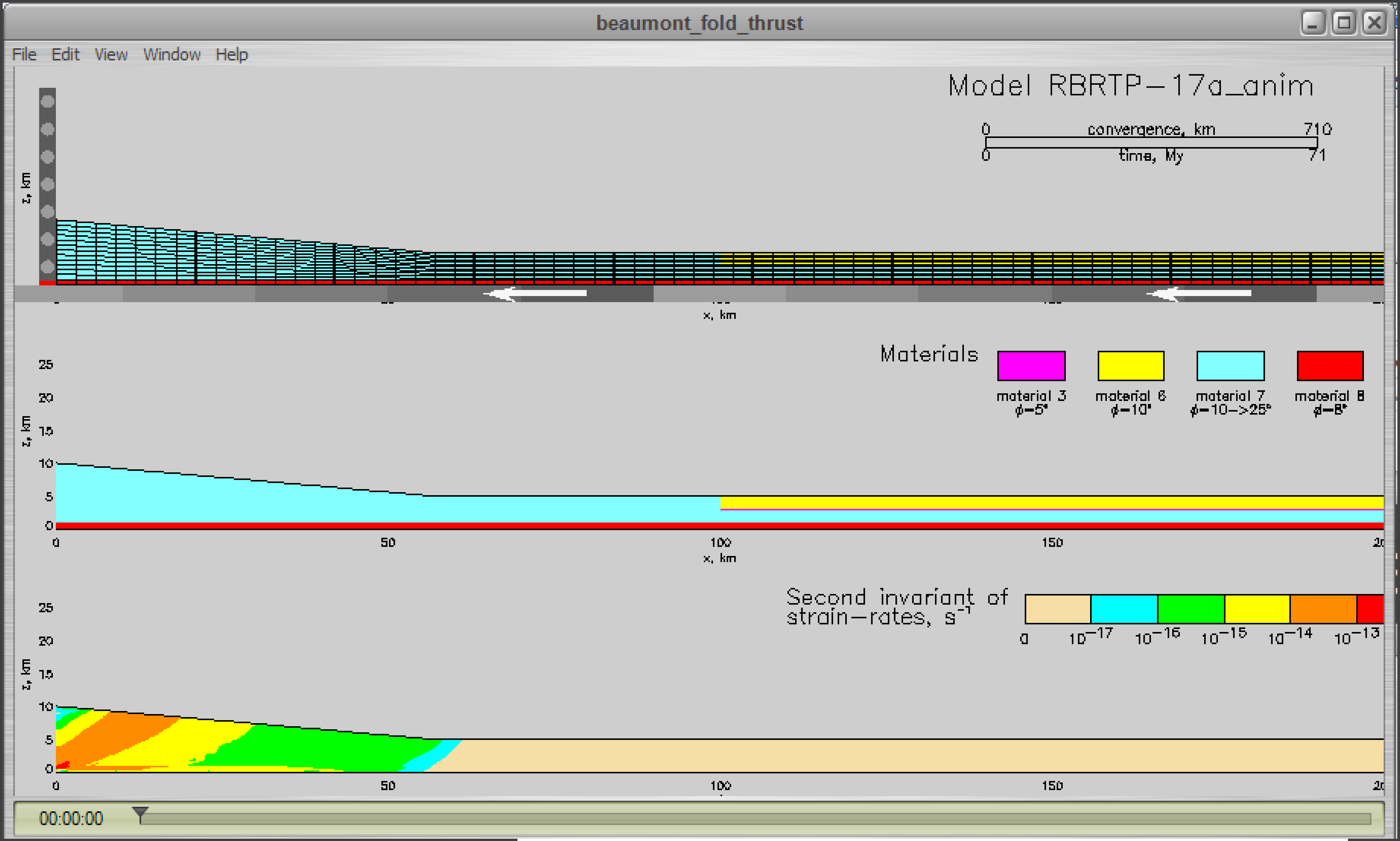
Sierra San Pedro Martir



Big-Picture Implications

- Interaction Between Climate and Tectonics
  - Tectonics -> Topography -> Climate
    - Global circulation, orographic effects
    - Myr timescale: Δtopo, ΔCO_2 -> Δclimate
    - Long-term Water Cycle
  - Topography + Climate -> Erosion -> Tectonics
    - Isotasy + Influence Deformation style/pattern/rate?
    - Thus Climate -> Tectonics (Myr timescale)
  - Erosion Patterns Influence Deformation
  - The Modulation of Erosion by Climate May be Weaker than Represented in Most Models
    - Interaction of Thresholds and Frequency of Extreme Events
    - Inverse Correlation between Runoff Mean and Variability

Fold and Thrust Belt Deformation



Mechanics of thin-skinned fold-and-thrust belts: Insights from numerical models

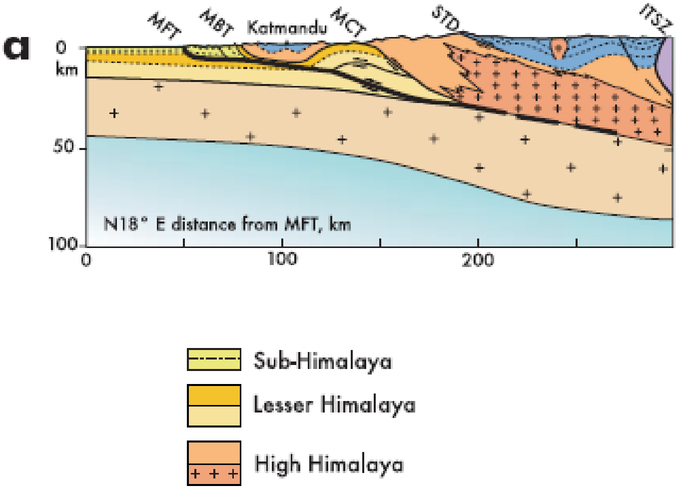
Glen S. Stockmal, Christopher Beaumont, Mai Nguyen and Bonny Lee

Geological Society of America Special Papers 2007;433;63-98
doi: 10.1130/2007.2433(04)

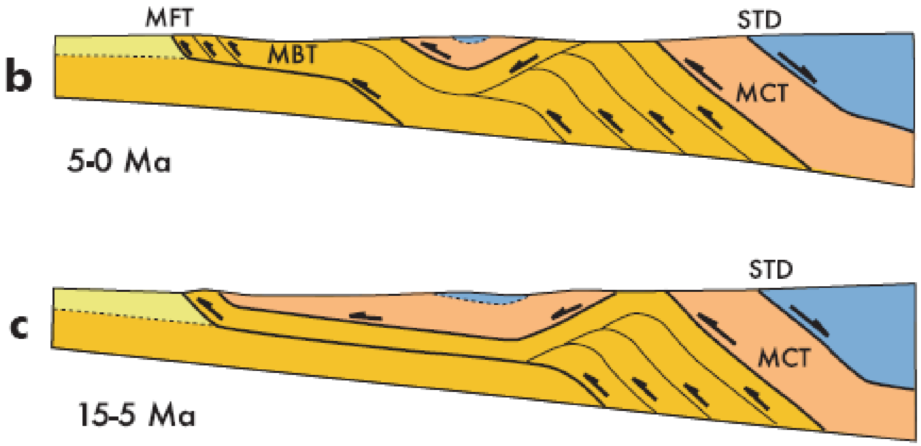
Add Erosion to Fold and Thrust Belt:

Konstantinovskaia_Malavielle_2005

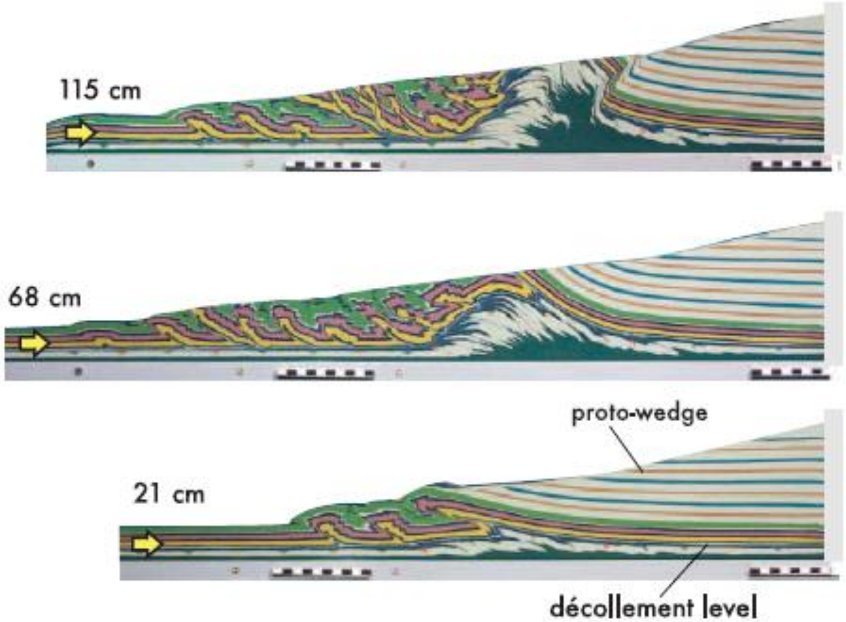
Geological section across central Nepal Himalaya

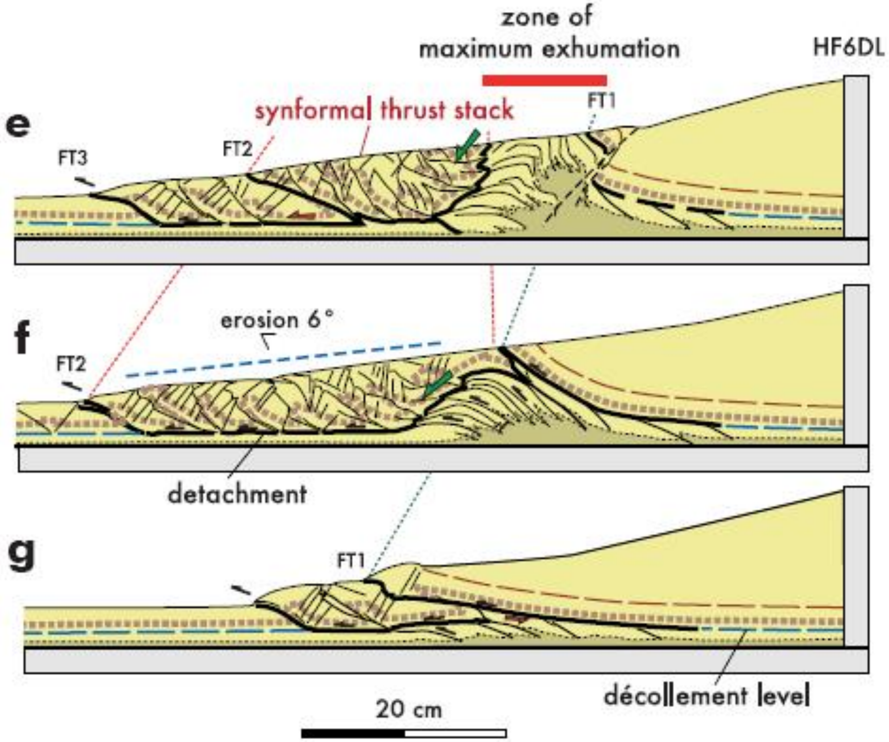


Structural evolution of the Himalayan orogen (Avouac, 2003)



Deformation stages for model thrust wedge with décollement level (HF6DL).





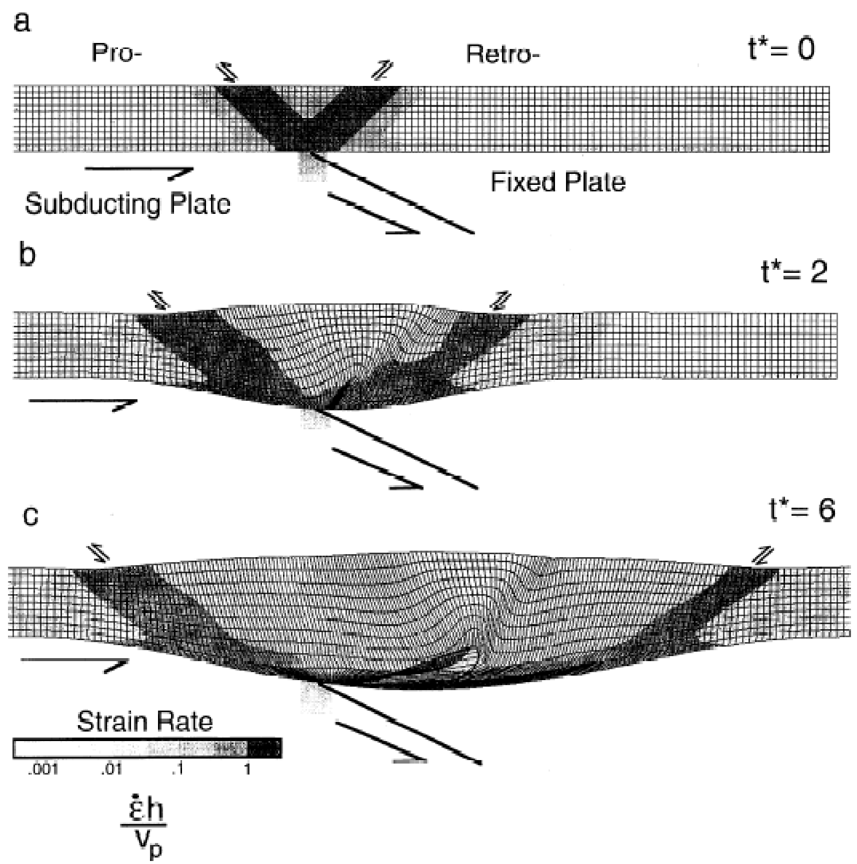
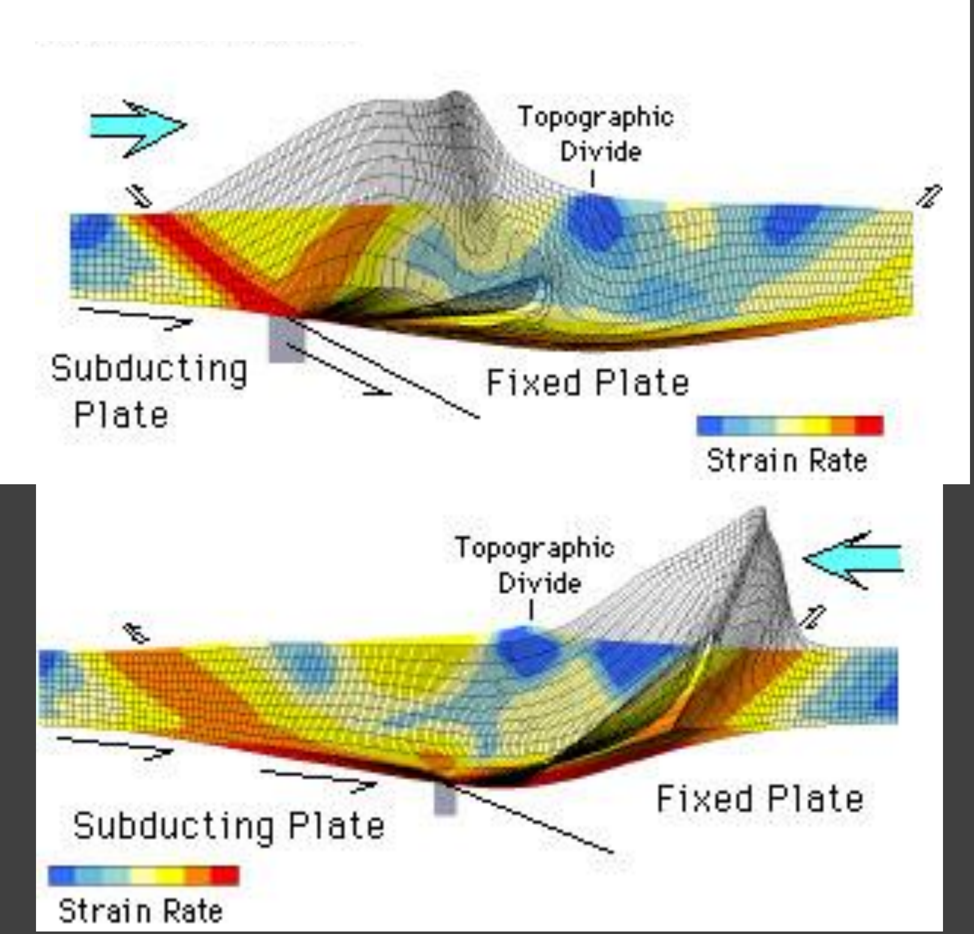


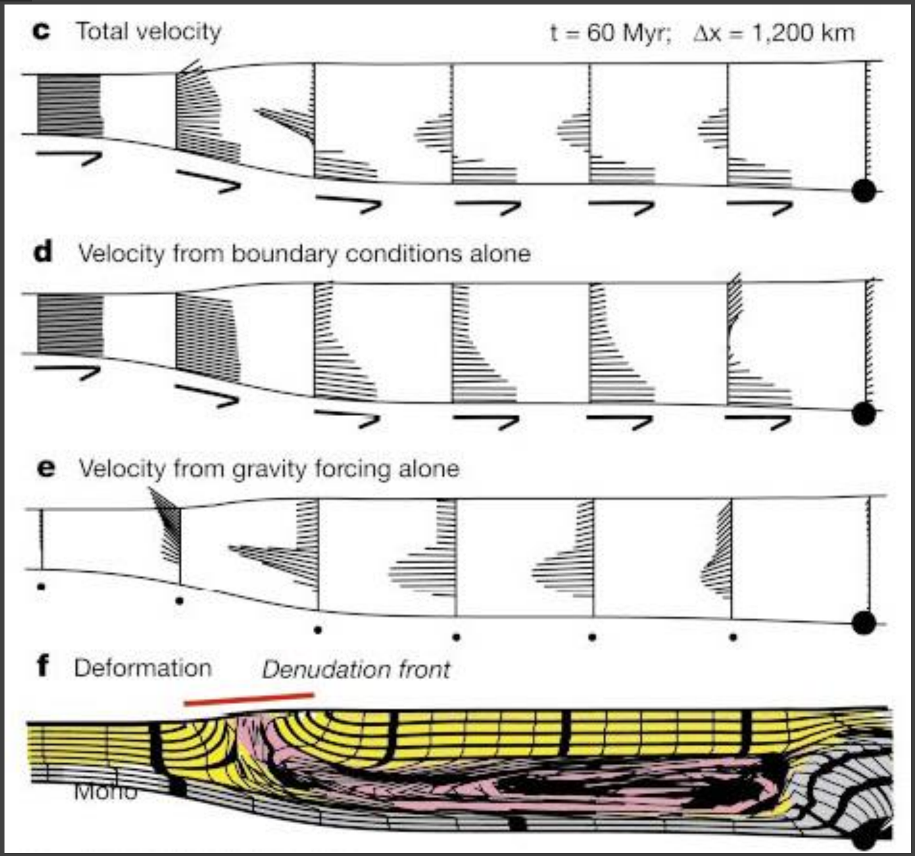
Figure 3. Finite element model for viscous-plastic deformation during convergence with no erosion and the boundary conditions shown in Figure 2. Model results are shown at nondimensional times t^* of 0, 2 and 6. The following features apply to this and all subsequent models. Substrate detachment point is given by the grey rectangular block. Crust deforms according to a temperature-dependent viscous constitutive law below the Coulomb yield stress. Viscous strength is characterized by an Argand number of 0.5 at the base of crustal layer prior to deformation. A Coulomb friction angle of 15° is used. Instantaneous deformation is given by shaded levels of the second invariant of nondimensional strain rate. Total deformation is shown by the Lagrangian tracking mesh. Note that no calculations are made on the Lagrangian mesh. The upper surface of the model is indicated by the top of the shaded region and the bold line. Surface does not coincide with the top of the Lagrangian mesh in the presence of erosion or sedimentation.

Willett, 1999 *JGR:* No Erosion Case

Numerical Simulations: Strong Climate-Tectonics Coupling



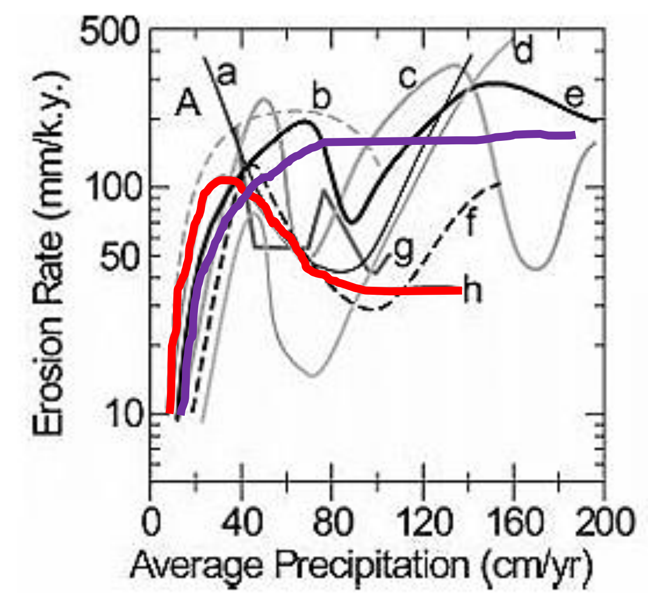
Willett, 1999 *JGR*



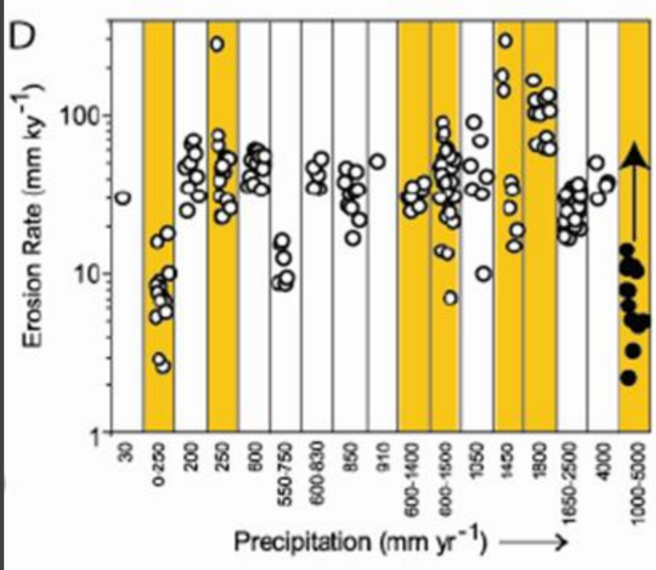
Beaumont et al., 2001
Nature

Climate, sediment transport and erosion

- How does climate influence erosion rate?
  - fundamental problem, yet no consensus on even first-order relationships
- Need to link measureable climate parameters to surface process models
- How strong is the climatic control on erosion rates relative to that of topography, rock strength?
- To Simulate Deformational Response to Erosion, especially to Climate, you need an Accurate Erosion Model

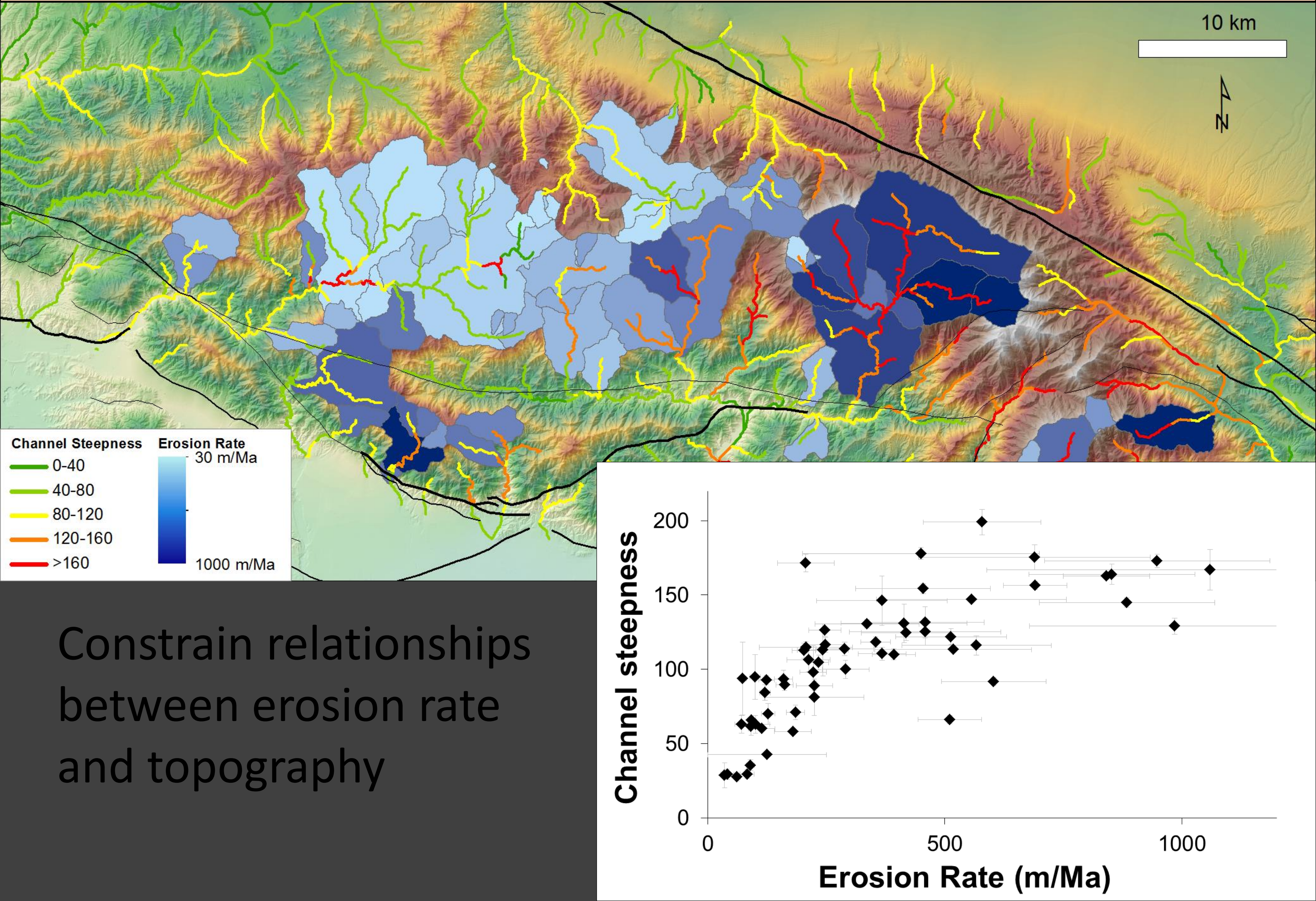


Riebe et al. 2001 Geology



Von Blankenburg 2004 EPSL

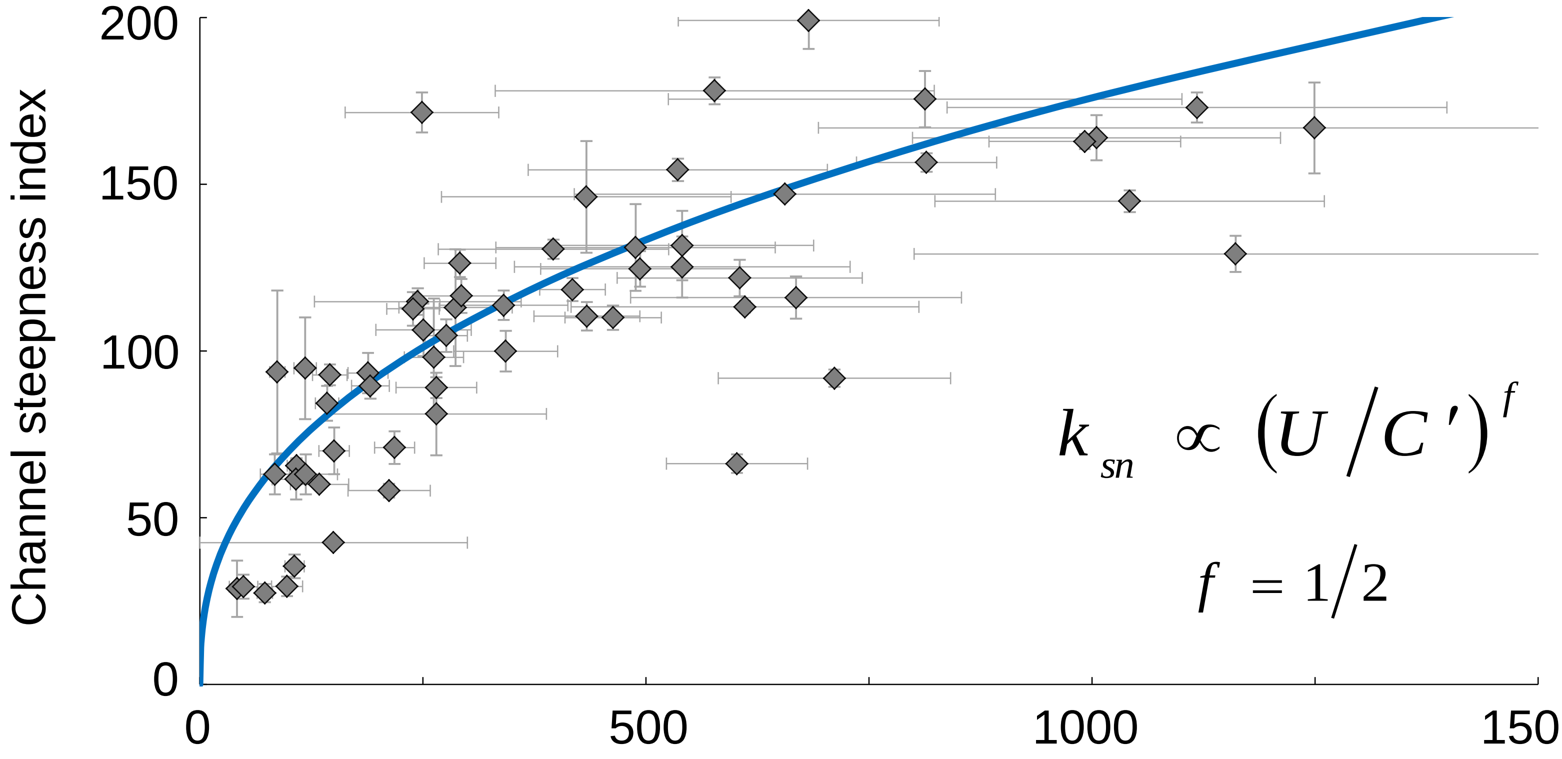
Quantifying the SGM Example (DiBiase, 2010)



Constrain relationships between erosion rate and topography

Model fit to SGM data

Calibrate model *(Lague et al., 2005 JGR)* to field data, discharge records from SGM



$$k_{sn} \propto (U/C')^{f}$$

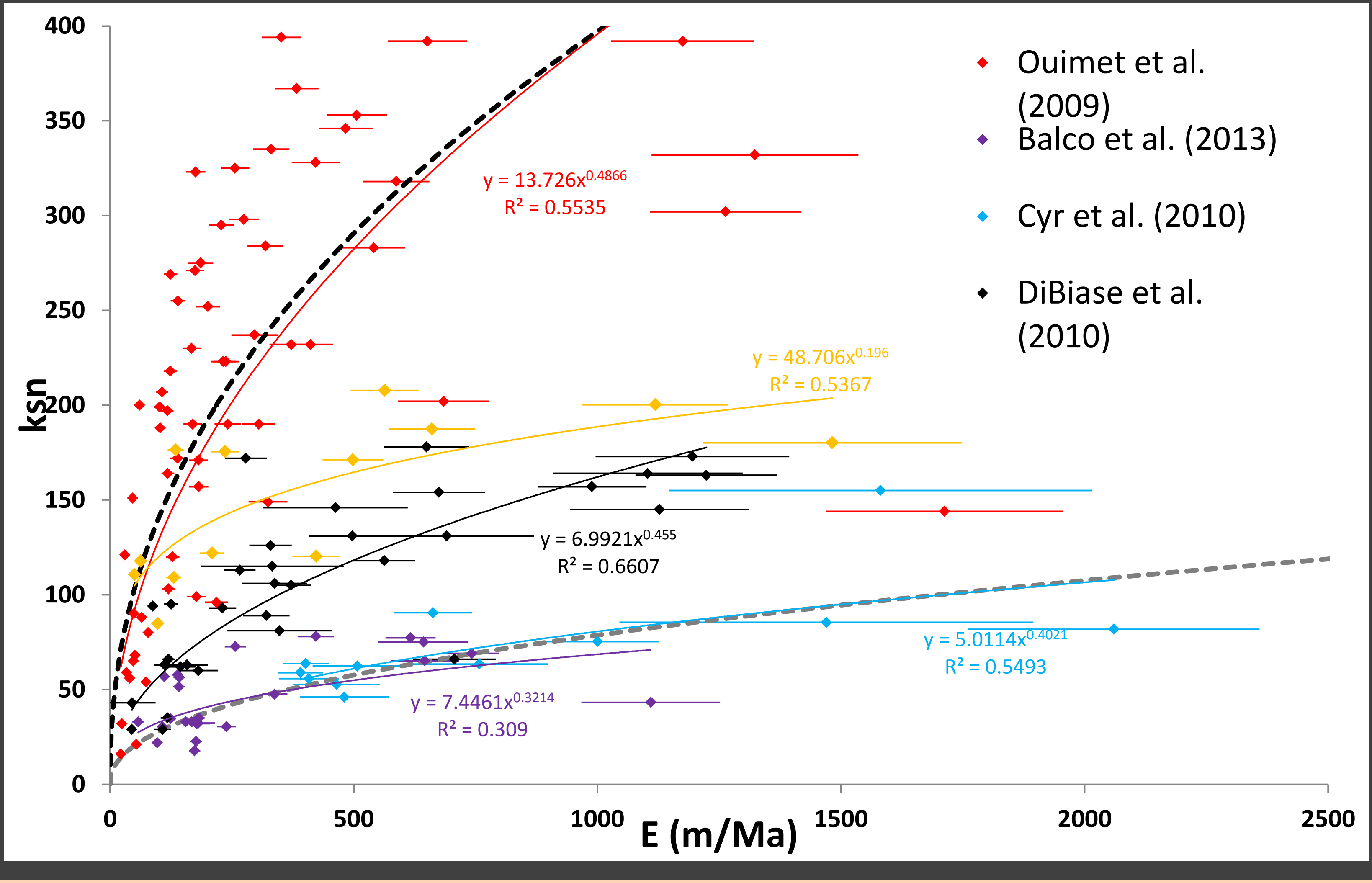
$$f = 1/2$$

DiBiase and Whipple, JGR 2011

Discharge Variability Sets Curvature of the Relationship (f)

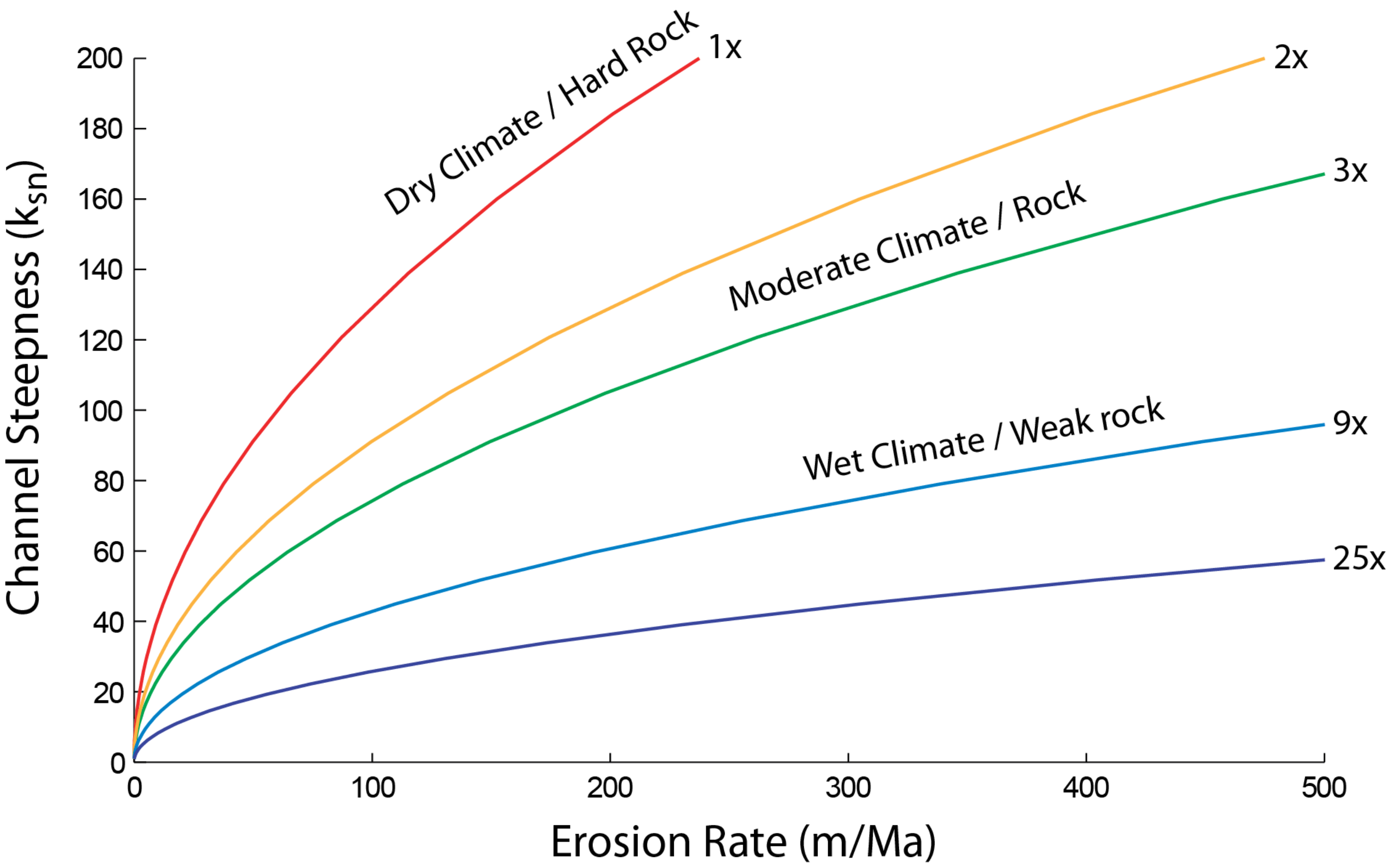
Acceptable Fit with no Tweaking

Rapidly Accumulating Detrital CRN Data



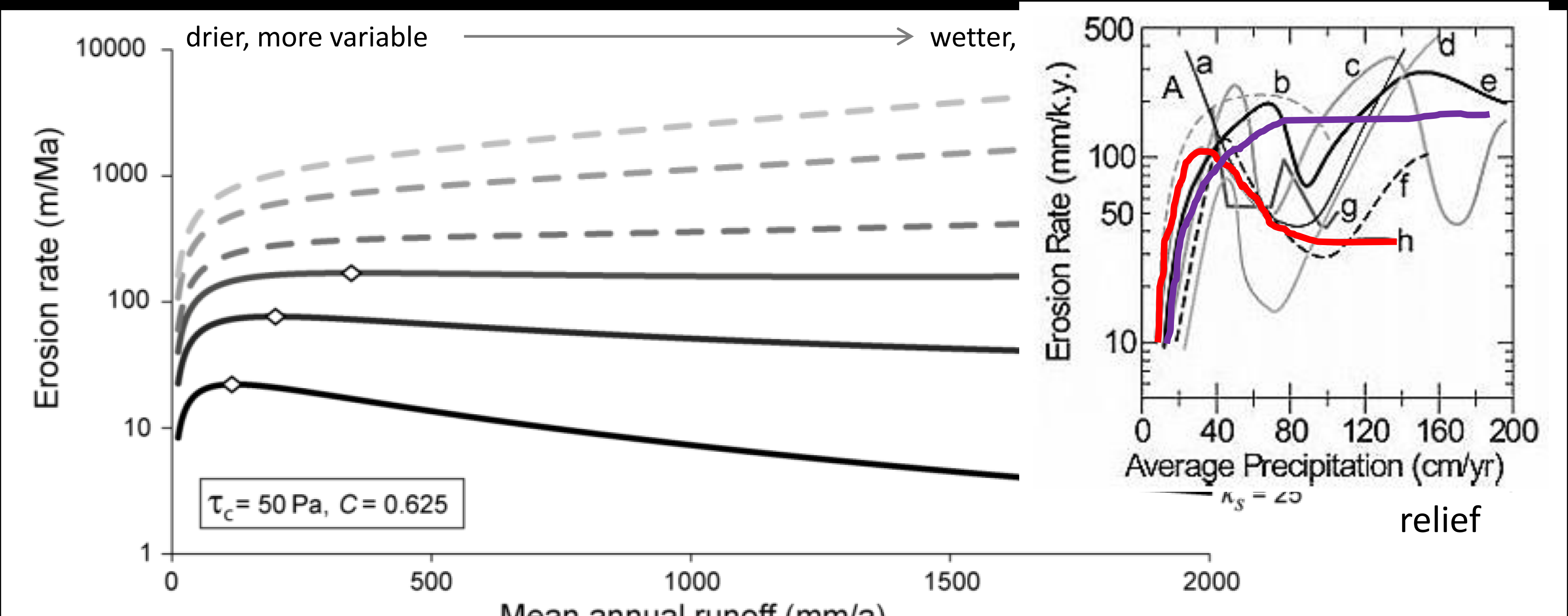
Similar Monotonic Relationships – Potential to Resolve Climatic, Lithologic Influences

Theory: Climate/Rock Strength at Steady State



Differences Reflect a Combination of Climate and Rock Properties (*Discharge Variability Held Constant Here*)

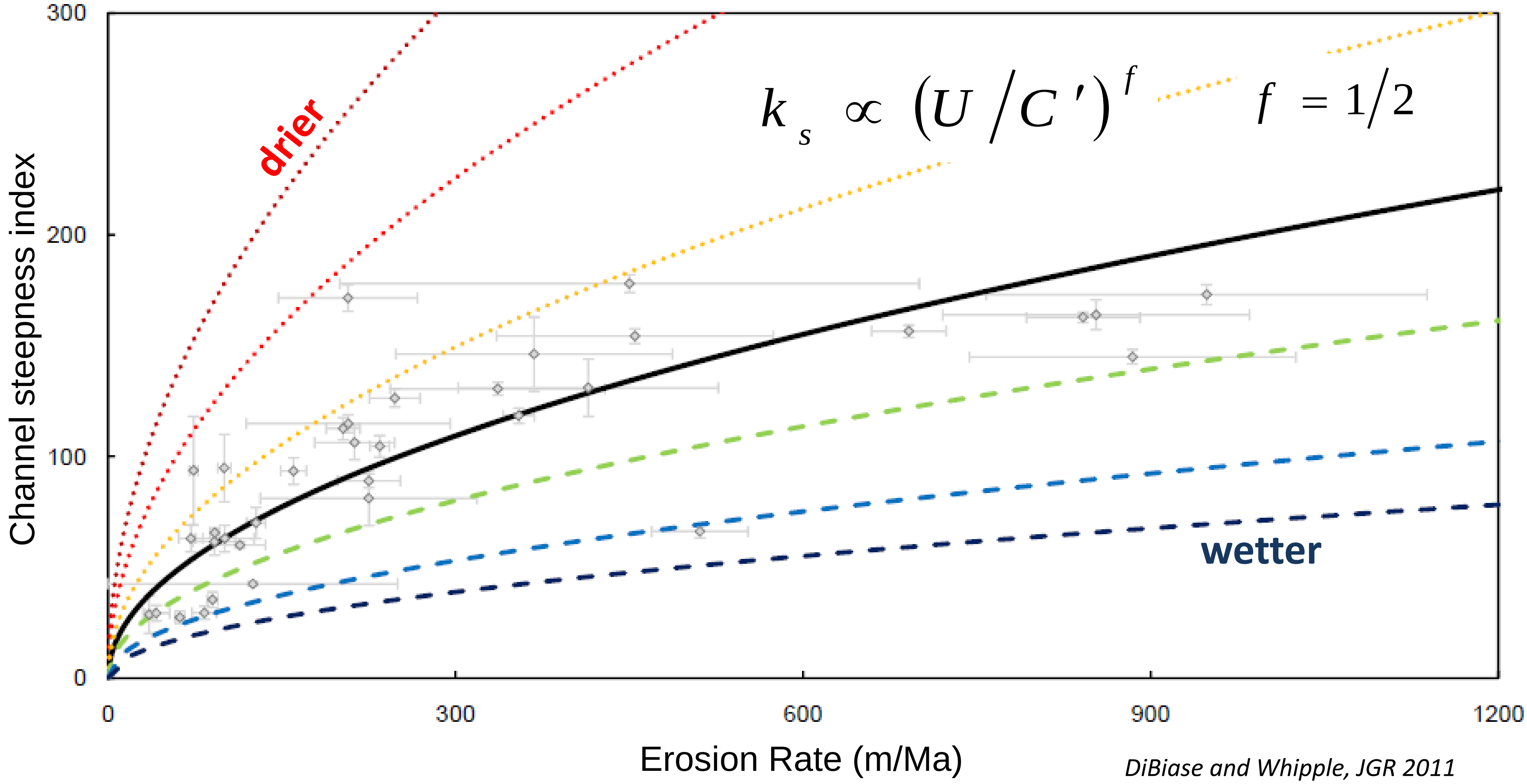
Consequences: Erosion rate and mean runoff



DiBiase and Whipple, JGR 2011

- “Humped” relationship between erosion rate and runoff for either low steepness or high threshold
- For a wide range of parameter space, dependence on runoff is muted above ~500 mm/a
- Erosion rate most sensitive to climate in steep landscapes (k_s>150)

Influence of Runoff under Uniform Variability (C_r)



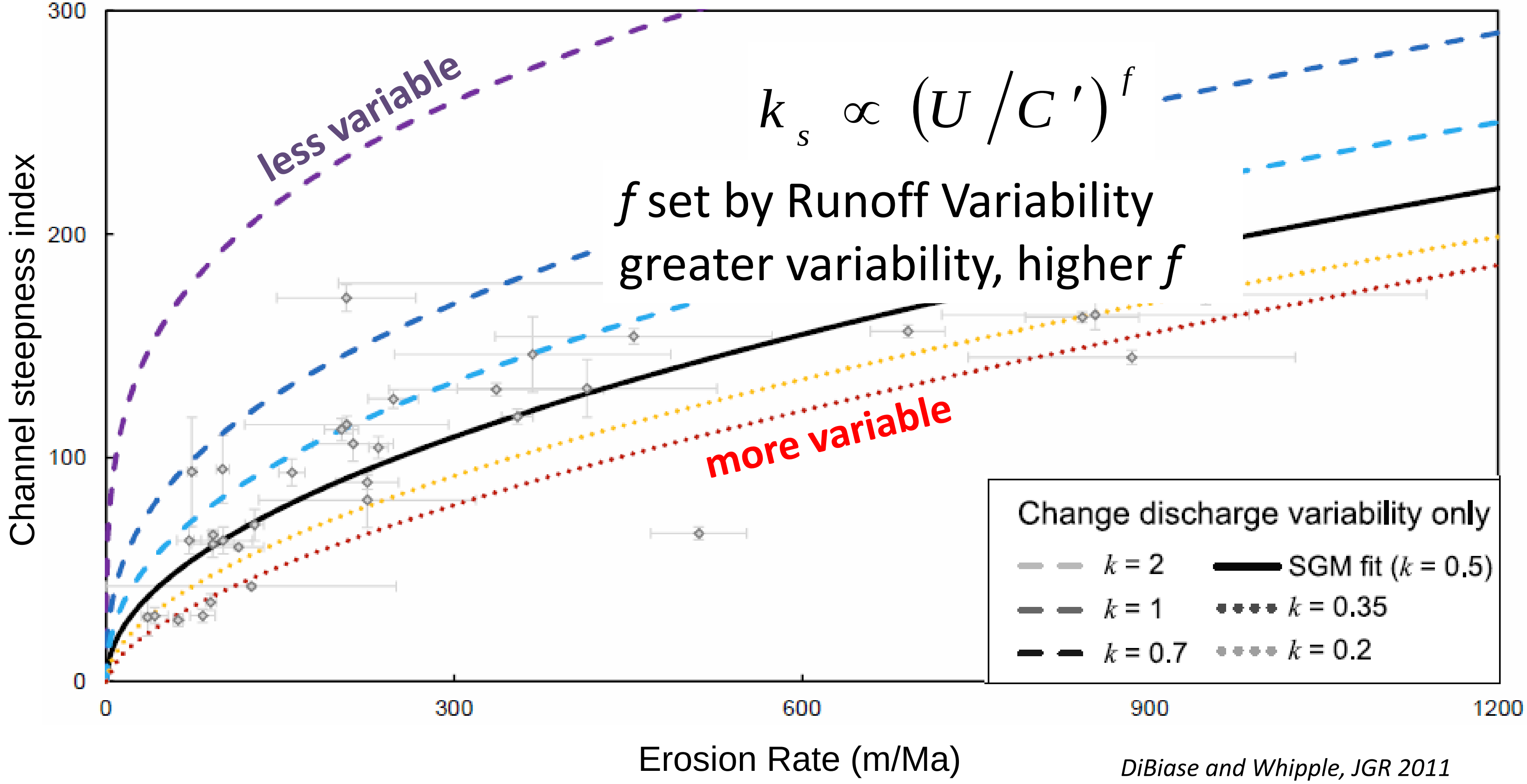
DiBiase and Whipple, JGR 2011

Start with SGM case (black line): how does climate influence the k_s-E relationship?

Wetter climates are more efficient

f **set by variability, smaller if less variable (Lague et al., 2005)**

Influence of Variability Runoff Alone



$$k_s \propto (U/C')^f$$

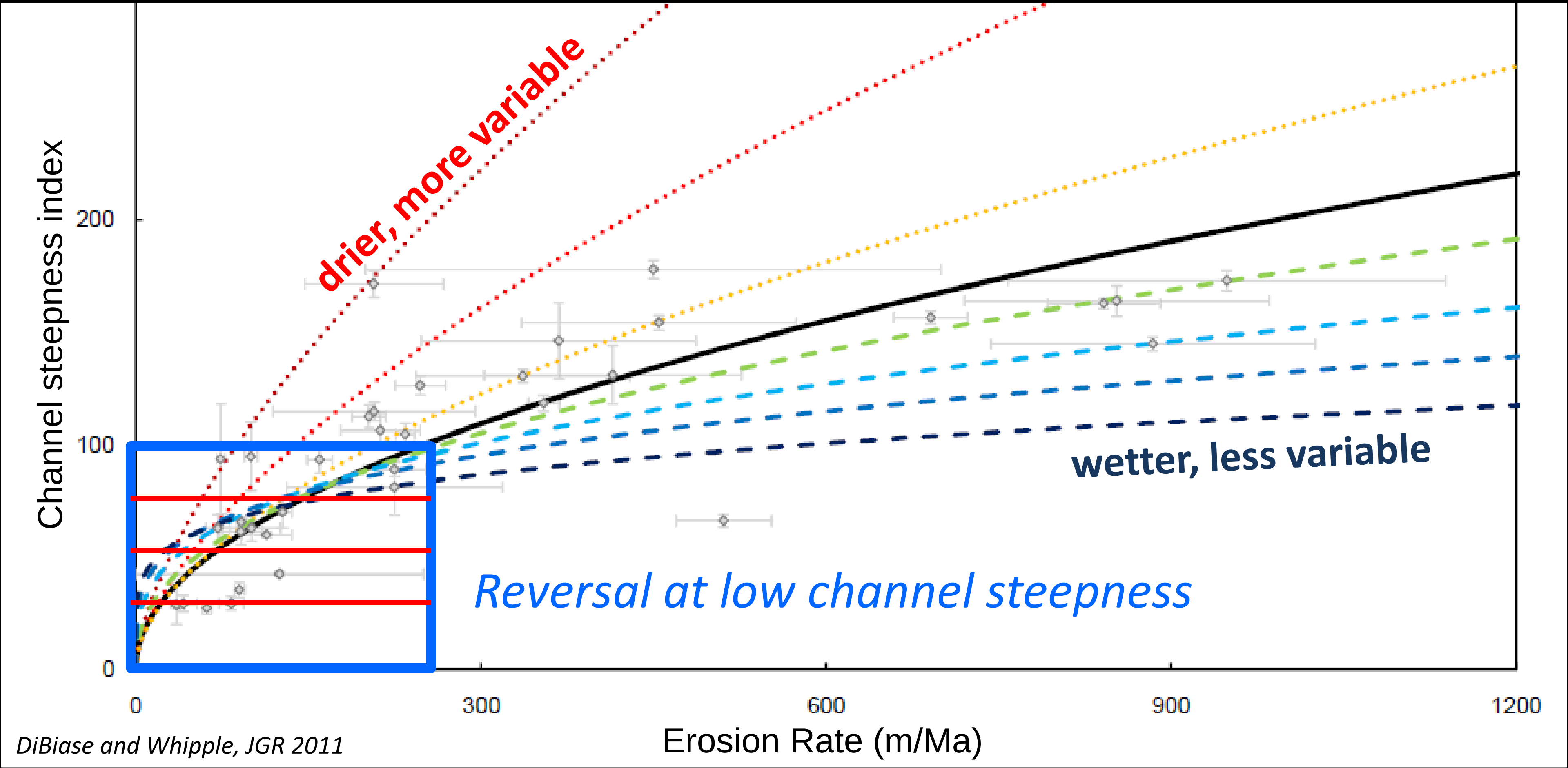
f set by Runoff Variability

greater variability, higher *f*

DiBiase and Whipple, JGR 2011

More variable climates are more efficient, and the ksn-E relationship is more Linear (*thresholds have less impact*)

Influence of Runoff with Co-Variation of *MAR* and C_r (Molnar, 2006)

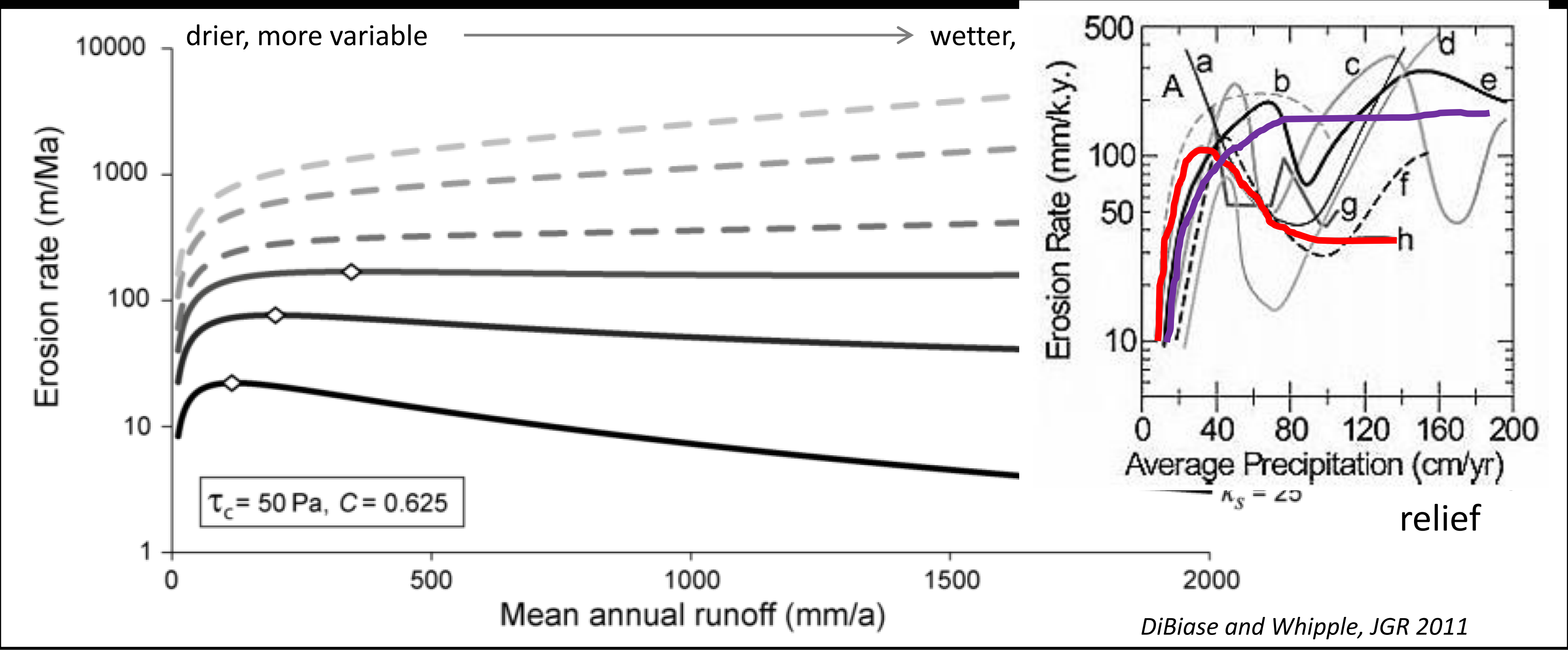


DiBiase and Whipple, JGR 2011

Dampens Response to MAP, but non-trivial relation:

Depends on channel steepness, threshold magnitude, and strength of mean-variability relationship

Consequences: Erosion rate and mean runoff



DiBiase and Whipple, JGR 2011

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Conclusions

- Channel Steepness (Ksn): Most Effective Metric
- Growing Database of Detrital CRN Erosion Rate Estimates
- Non-linear Dependence on Erosion (Uplift) Rate
- Ksn(E) Set Primarily by Erosion Threshold and Discharge Variability
- Quantitative Links to Measurable Climate and Rock Property Parameters are Needed