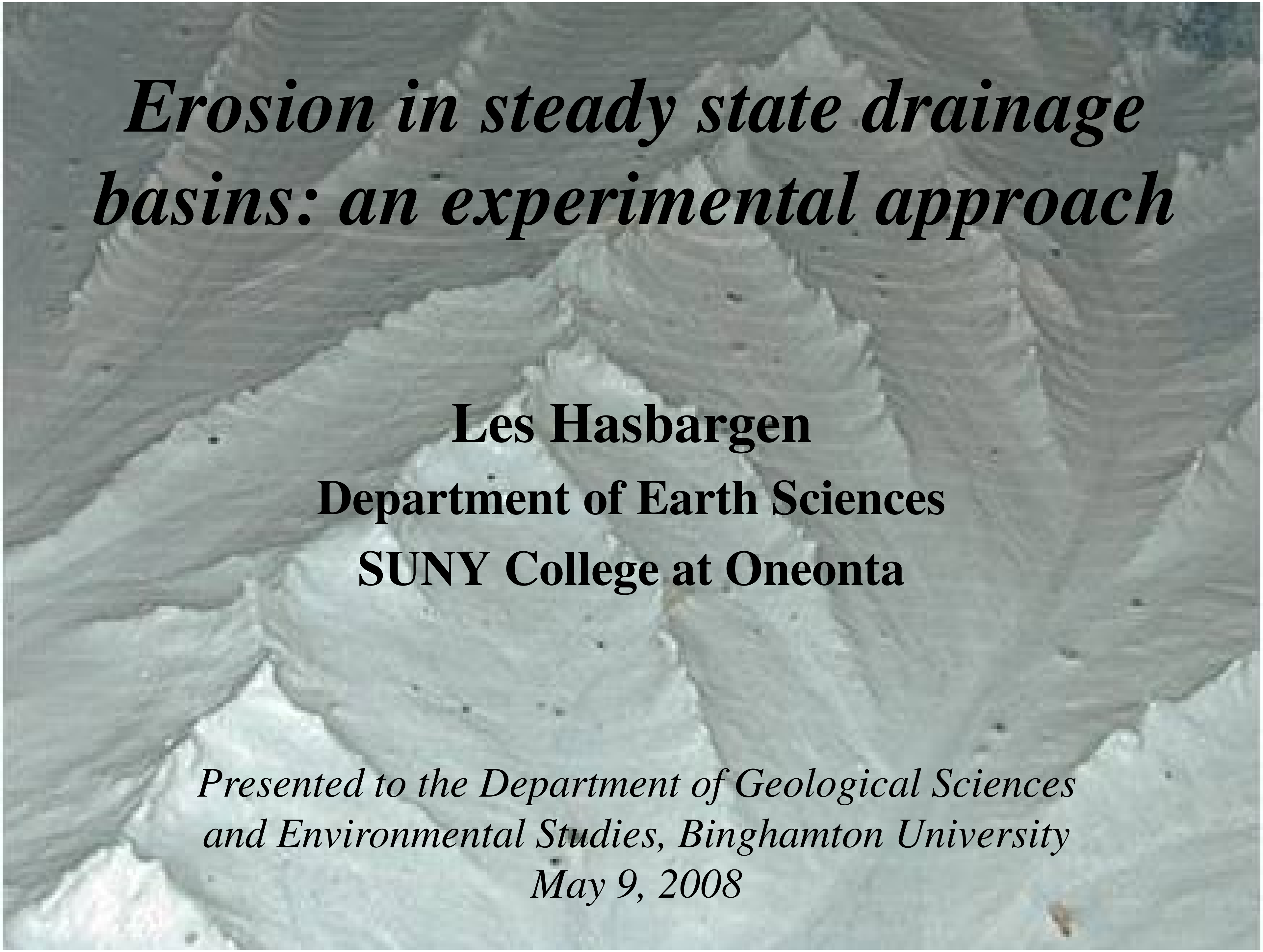

Erosion in steady state drainage basins: an experimental approach

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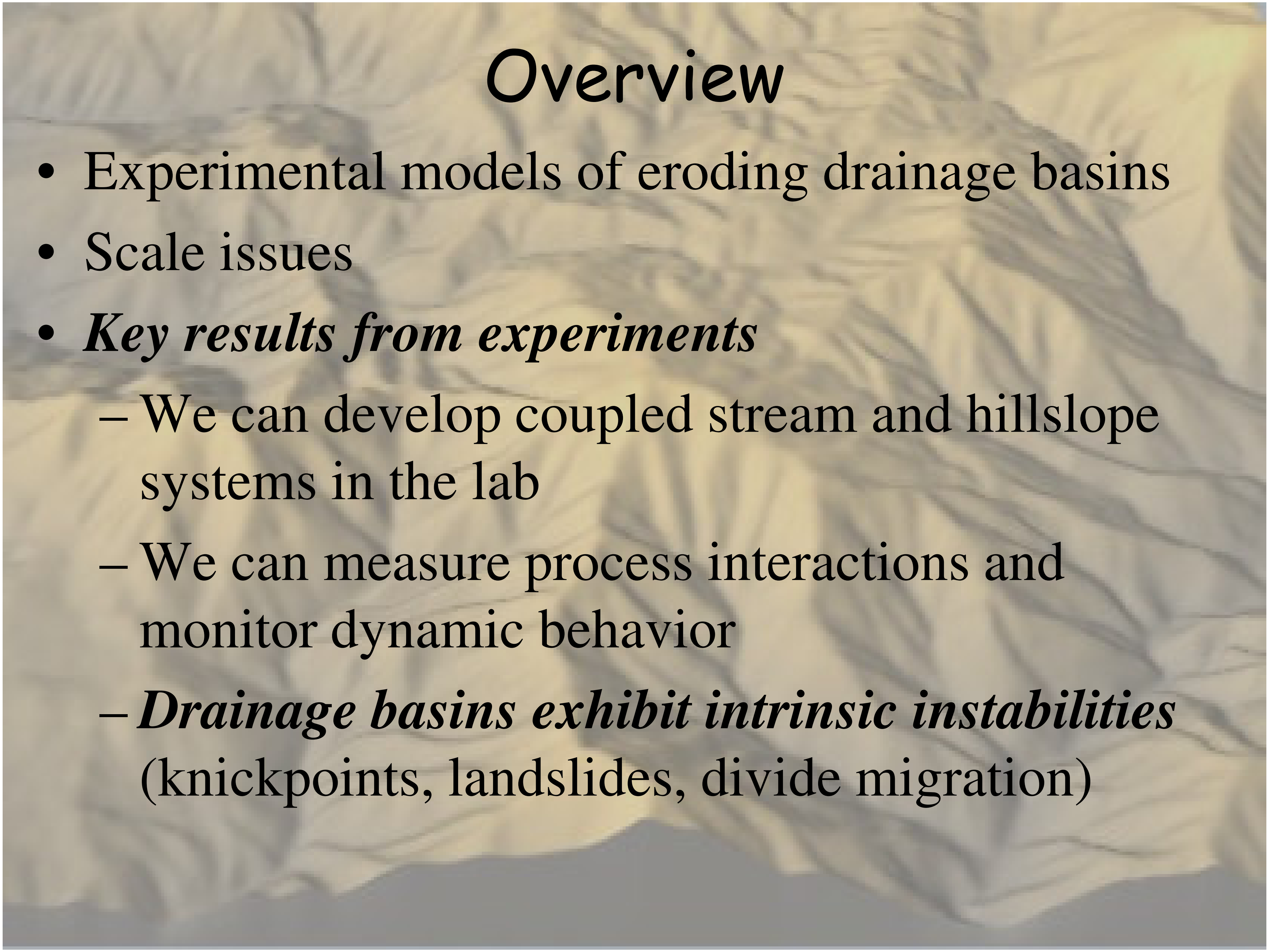
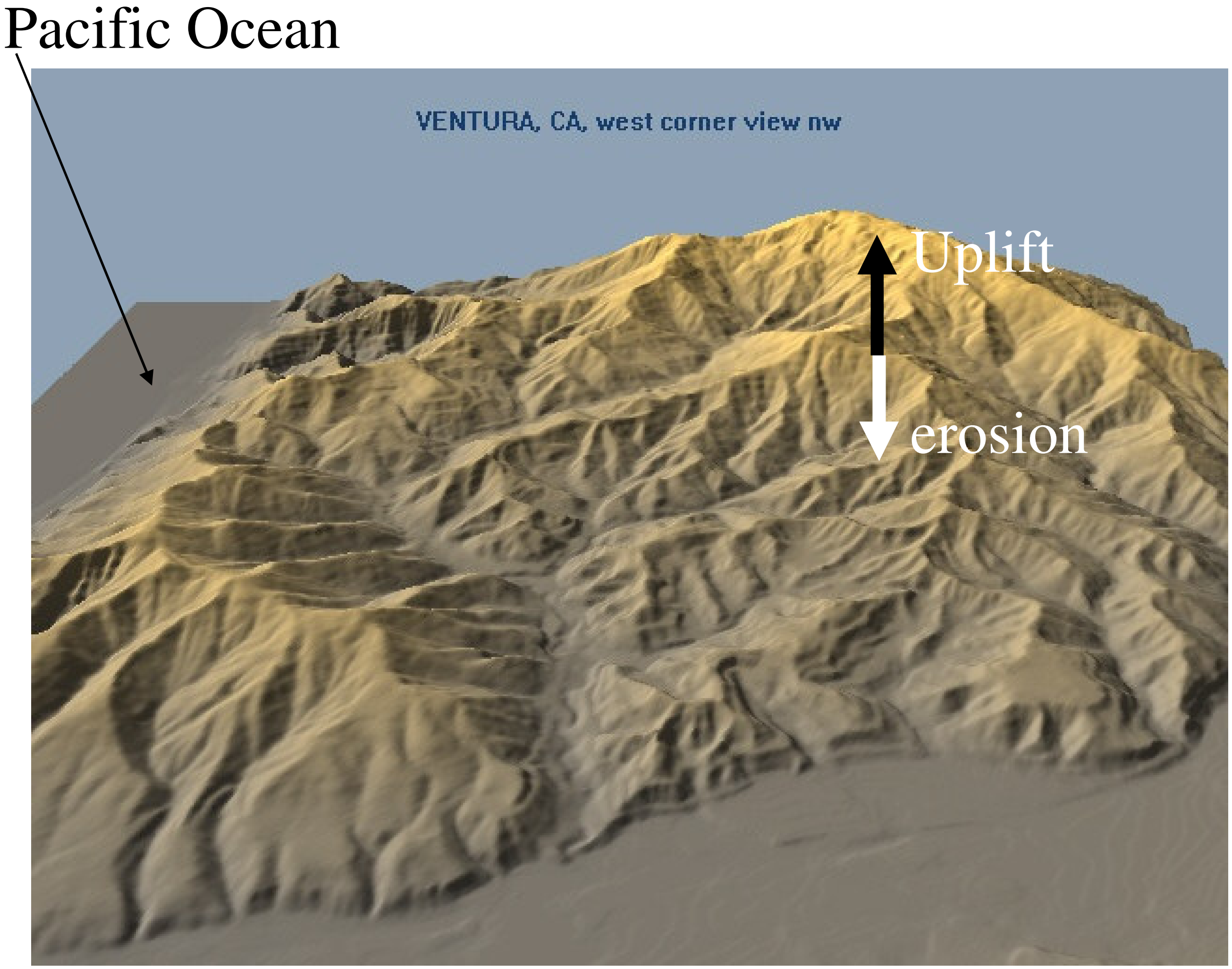


Overview

- Experimental models of eroding drainage basins
- Scale issues
- ***Key results from experiments***
  - We can develop coupled stream and hillslope systems in the lab
  - We can measure process interactions and monitor dynamic behavior
  - ***Drainage basins exhibit intrinsic instabilities*** (knickpoints, landslides, divide migration)

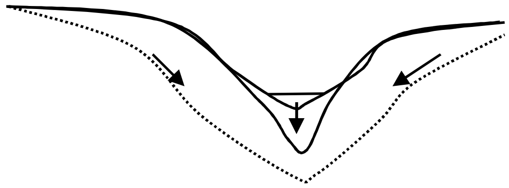
Drainage basins are erosional structures: an interacting system of hillslopes and channels



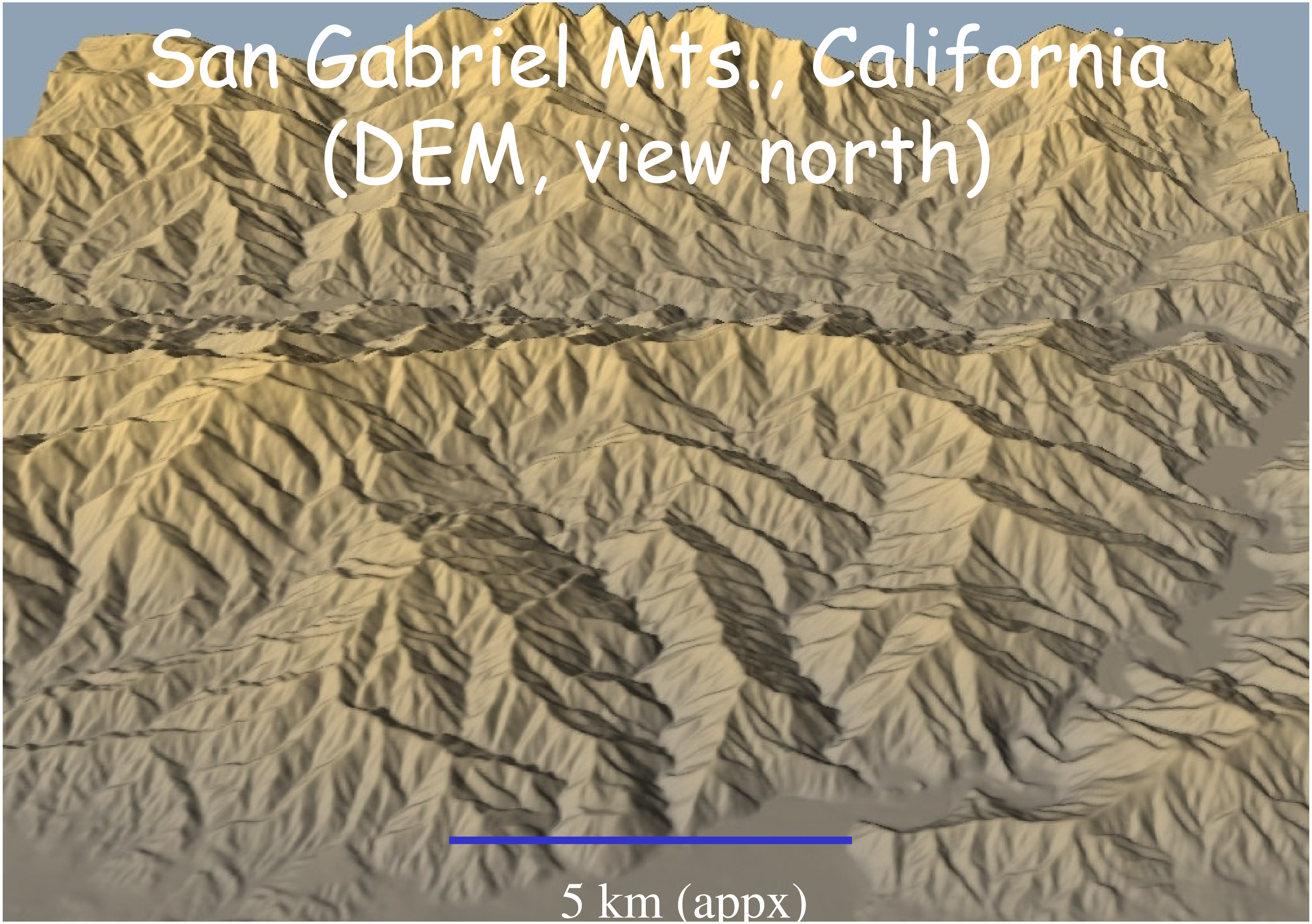
Streams initially erode faster than hillslopes, which then start eroding faster to keep up with channel incision

Key prediction:

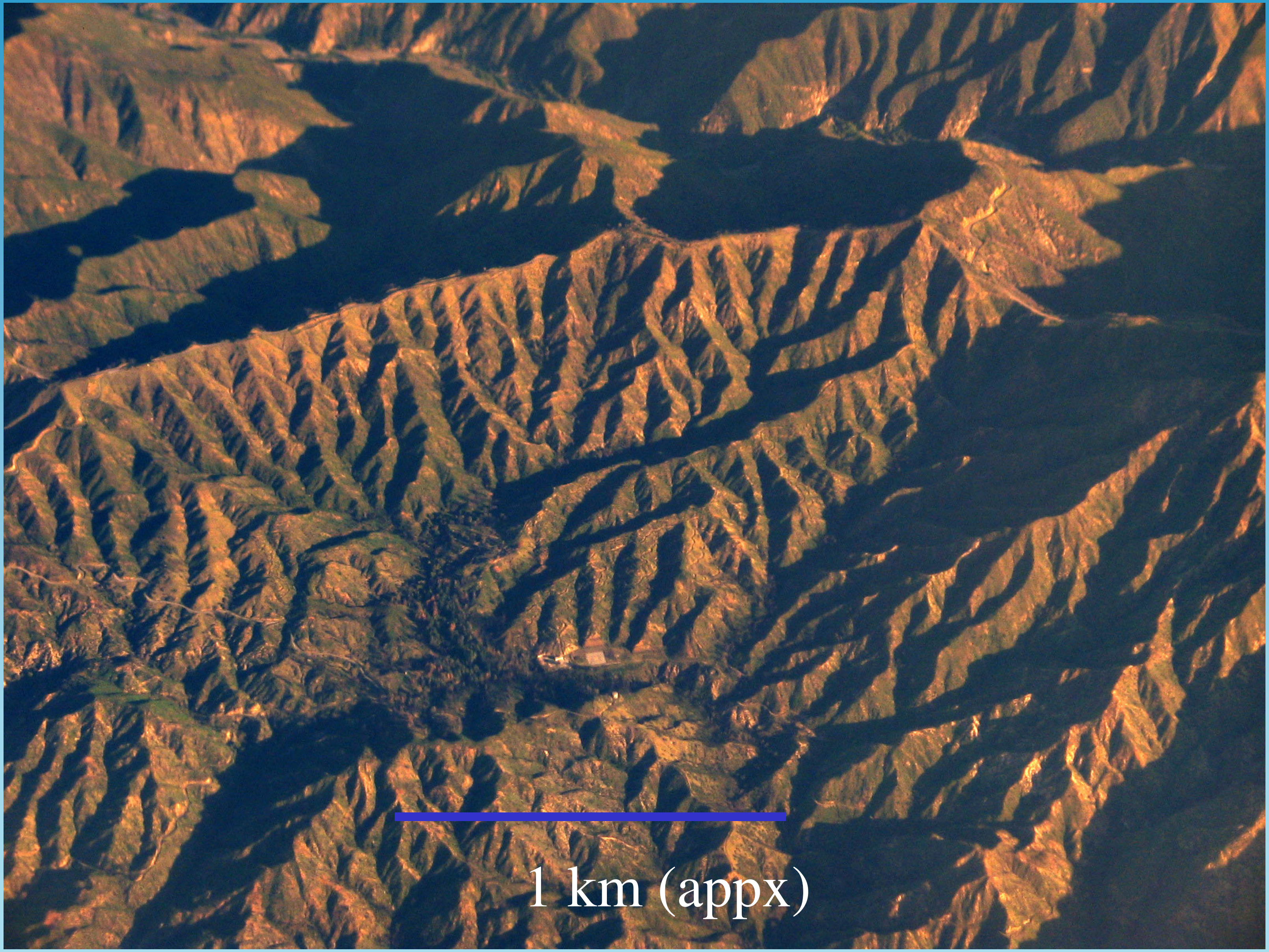
at steady state, erosion is everywhere constant and = uplift



San Gabriel Mts., California (DEM, view north)



San Gabriel Mts., California



Cuyama Badlands, California

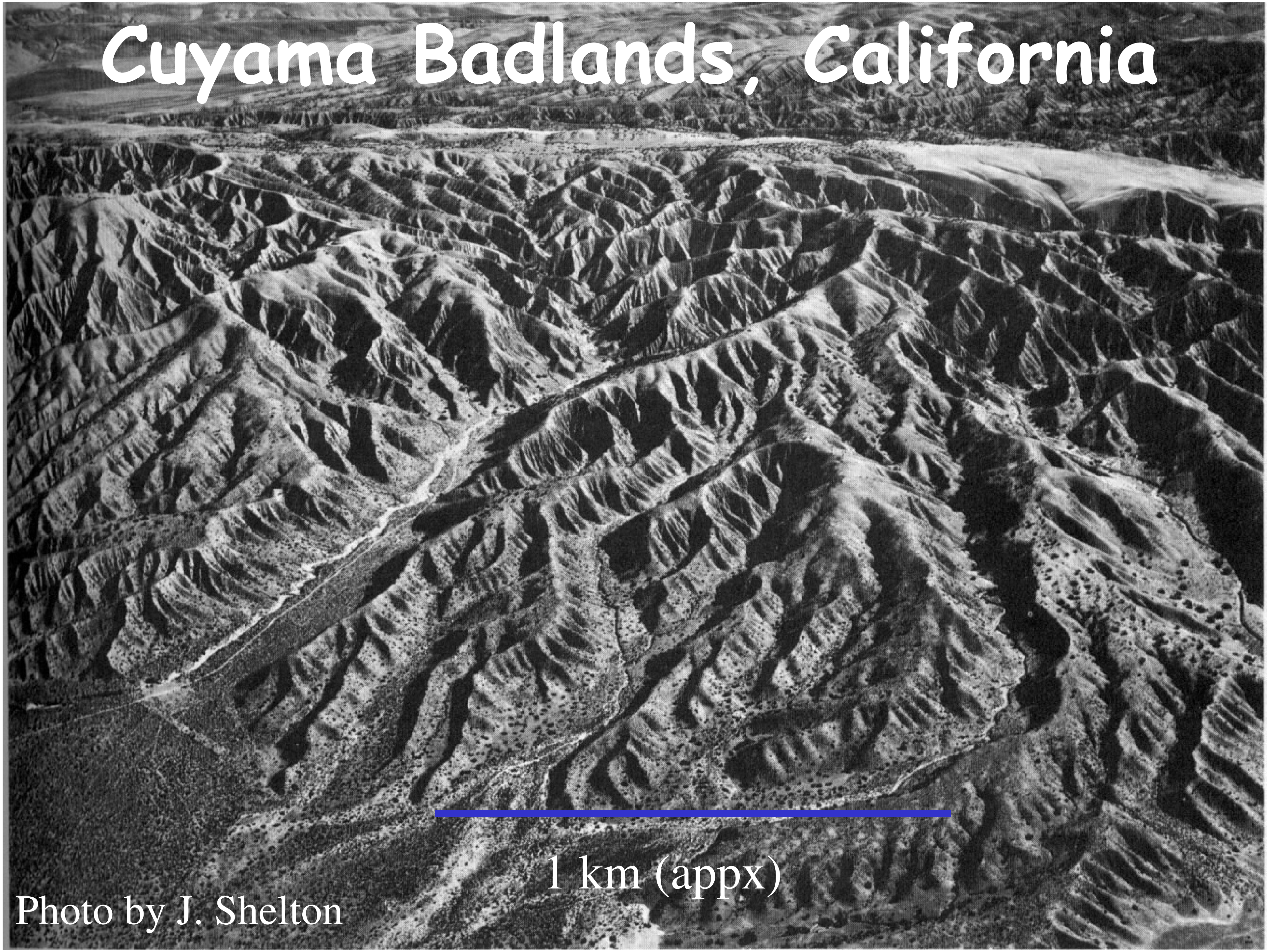
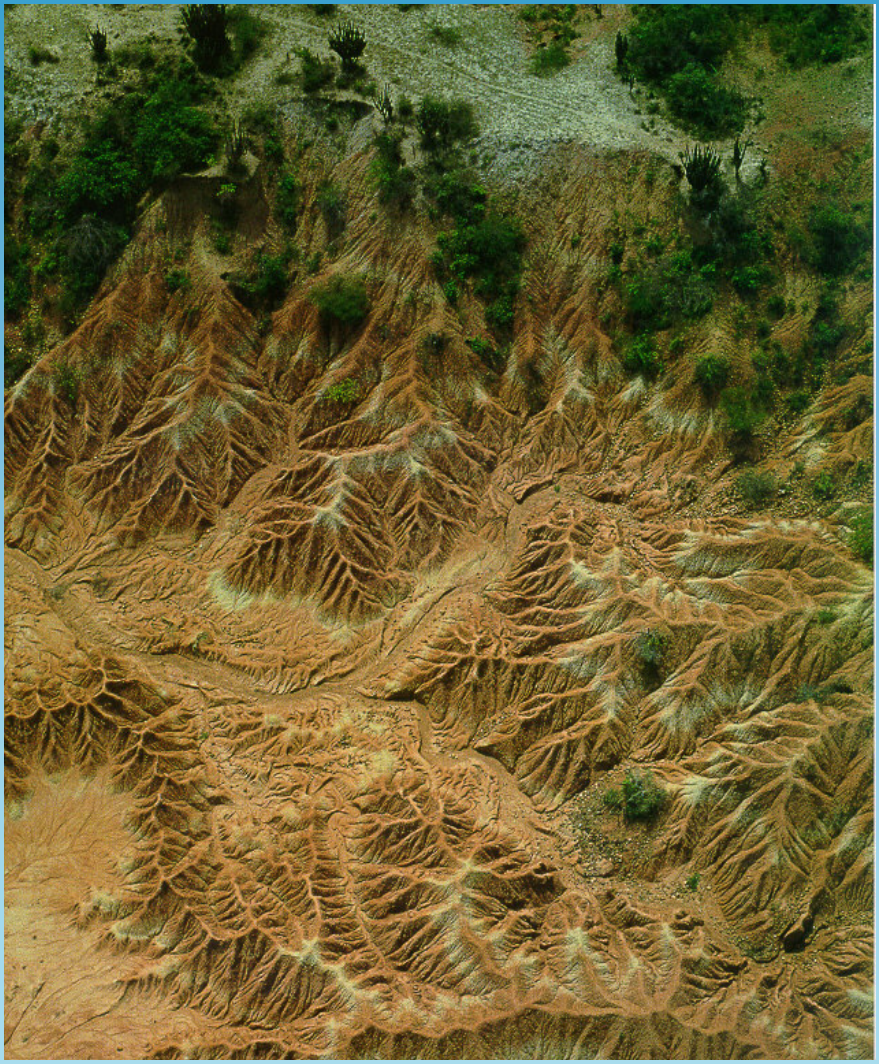


Photo by J. Shelton

Badlands, Columbia, S. America



Note
bushes for
scale

Exhumation depths for rocks currently exposed at Earth's surface

Location	Lithostatic load (km)	Reference
European Alps (Dora Maira)	10-75	Rubatto and Hermann (2001)
European Alps (Zermatt-Saas)	6-65	Amato et al. (1999)
Irian Jaya Indonesia	>4	Weiland and Cloos (1996)
Crete Greece	25	Thomson et al. (1999)
Nepalese Himalaya	25	Harrison et al. (1997)
K2 Karakoram	>3	Foster et al. (1994)
Kokchetav Kazakhstan	160	Hacker et al. (in review)
Nanga Parbat Pakistan	15-20	Zeitler et al. (2001)
Southern Alps New Zealand	10-20	Tippett and Kamp (1995)
Basin and Range USA	10-15	Foster and John (1999)
Denali Alaska	6	Fitzgerald et al. (1995)
Olympic Range Washington	9	Brandon et al. (1998)

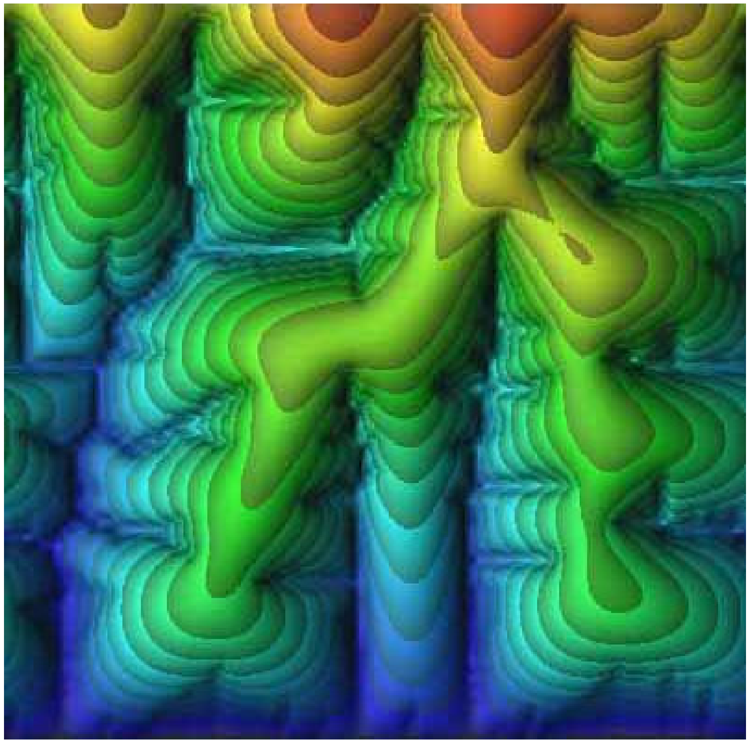
Location	Erosion rate (m/Myr)	Reference
Great Smoky Mountains, USA	19-37	Matmon et al. (2001)
Santa Monica Mountains, USA	500	Meigs et al. (1999)

top table from Burbank, D. W., Rates of erosion and their implications for exhumation, Mineralogical Magazine, February 2002, Vol. 66(1), pp. 25-52.

Modeling drainage basin scale erosion

- Simplified physics approach
  - Erosion rate ε depends on erosion processes (stream power, soil creep, landslides, etc) and rock resistance
- Couple erosion processes with uplift in a time evolving grid: $z_{(i,j,t+1)} = z_{(i,j,t)} + \Delta t(U_{(i,j)} - \varepsilon_{(i,j)})$
- Models successfully capture planform statistics, and area-slope relations
- **Key result: At steady forcing, models evolve to a uniformly eroding (static) surface**
  - **Requires 1 to 3 'reliefs' of erosion**

Numerical model landscapes



Howard's 1994 model

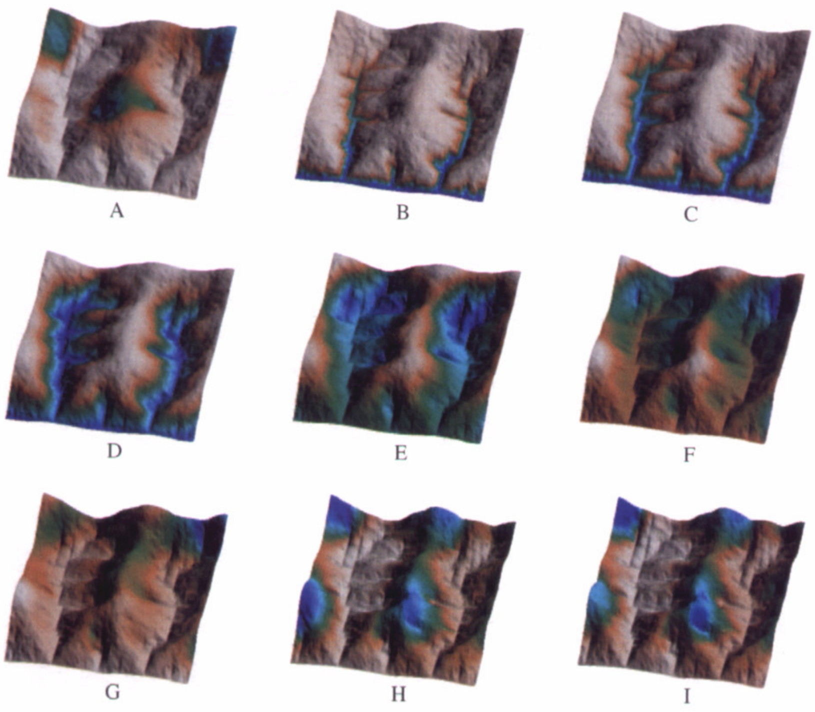
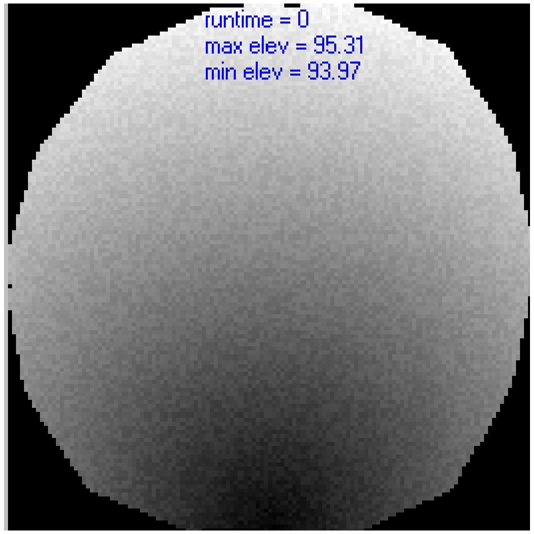
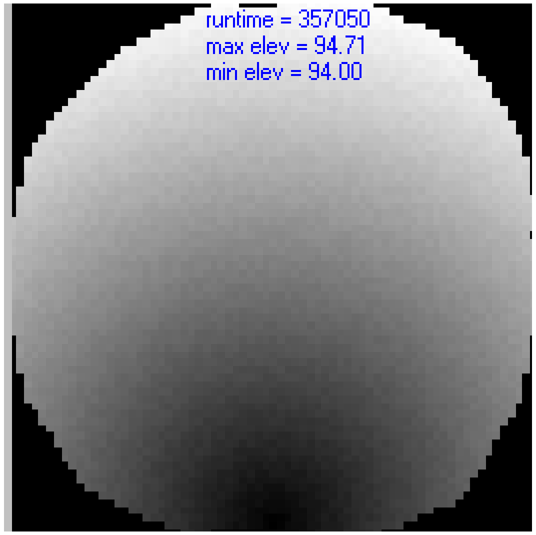


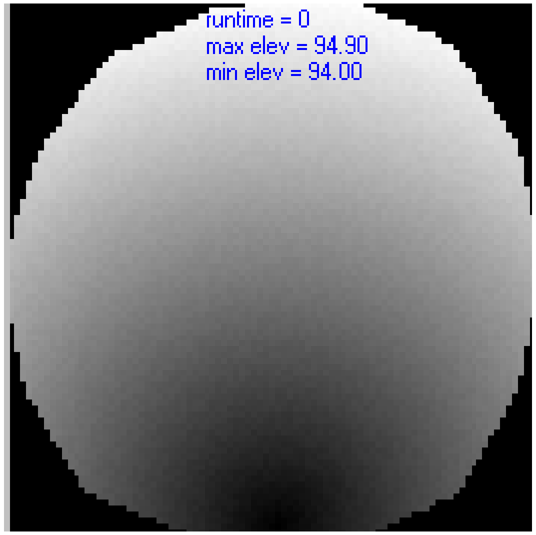
Fig. 10. Response of a steady-state landscape to an increase in uplift rate. A wave of increased erosion rate propagates up the stream network and dissipates slowly on the hillslopes. (in Stark and Stark, 2001; Am. Journal of Science)

Stark and Stark, 2001; time series erosion rate following uplift rate increase

Landscape evolution in numerical models...







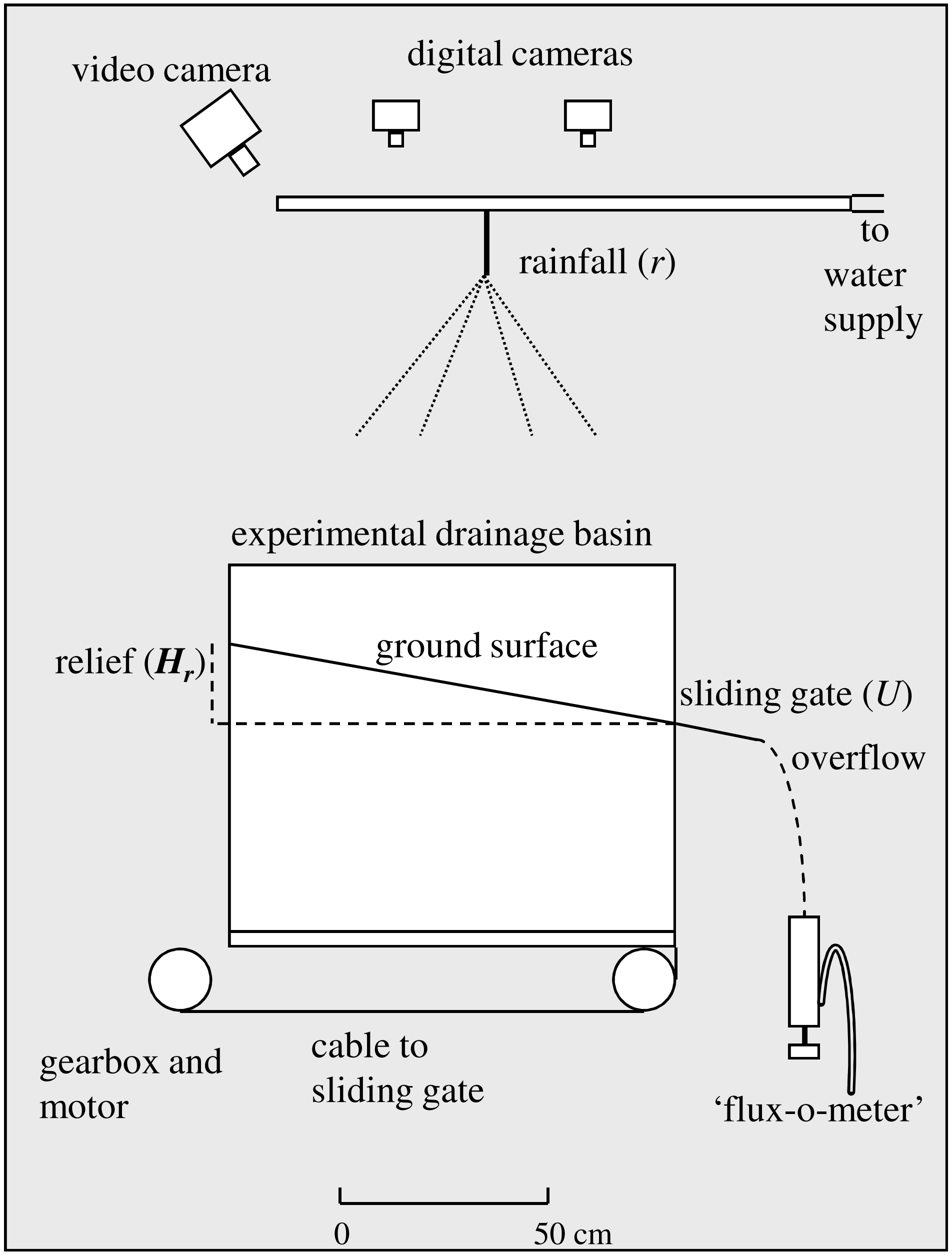
- Original surface is flat with random roughness
- System is energized by lowering base level (flow leaves basin at a single point)
- Erosion Rules: water flows down the steepest slope, and erodes according to stream power
- Repeatedly rain/route water over surface (a bizzillion times!)
- Feedback between erosion and flow capture creates a dendritic pattern
- The rules above lead to a stable (i.e., static) network

Testing numerical models

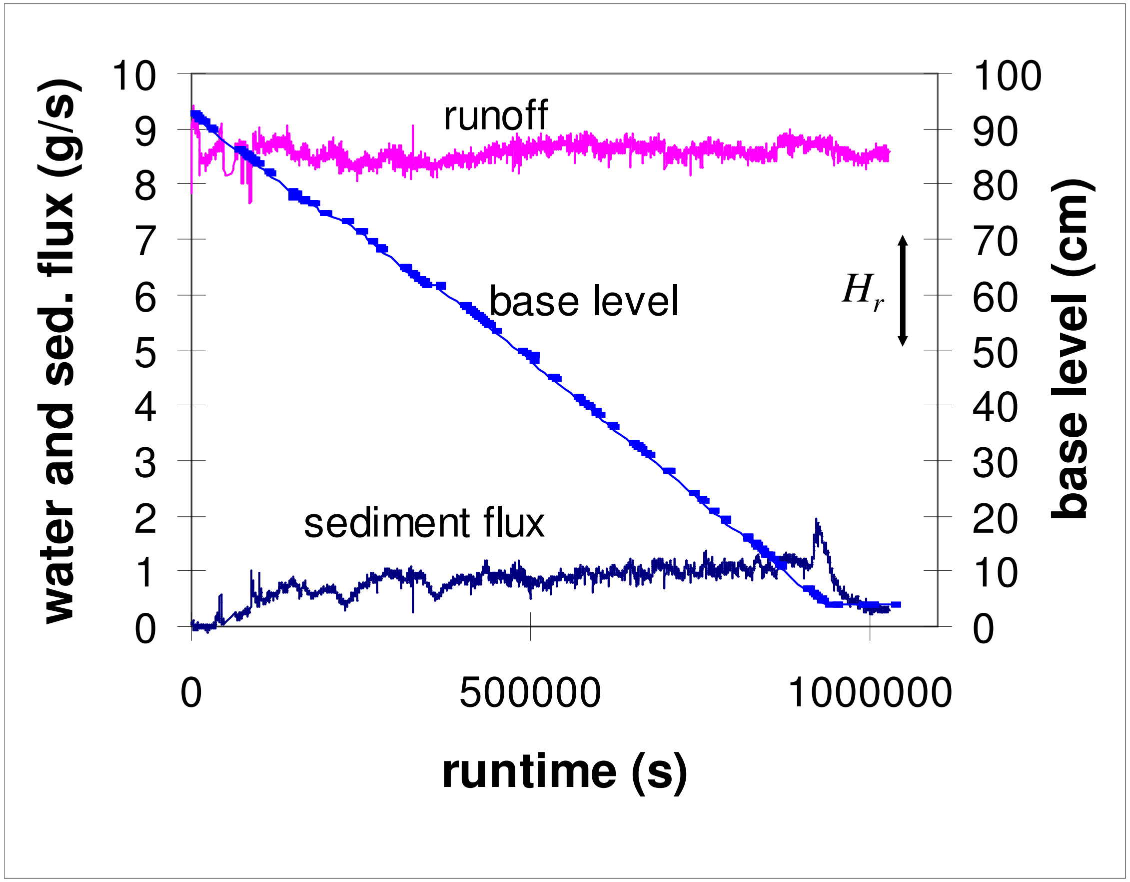
- The **stability** achieved by models is ***very difficult to test*** in field settings
  - Requires 1-3 relief units of erosion (H_r) to achieve stability in numerical simulations
  - e.g., to erode 1 km relief at 1 mm/yr requires 1 Myr
  - Over this time scale, climate and tectonic forcing vary
- **The Test**: Will a *physical* model with similar simplifying assumptions achieve a stable (static) arrangement of ridges and valleys?

Erosion facility

view from digital camera



Steady Forcing Conditions



Experimental drainage basins…

- *Rain on the surface*
- *Rower the outlet at a constant rate*
- *Substrate erodes via surface runoff and hillslope failures!*

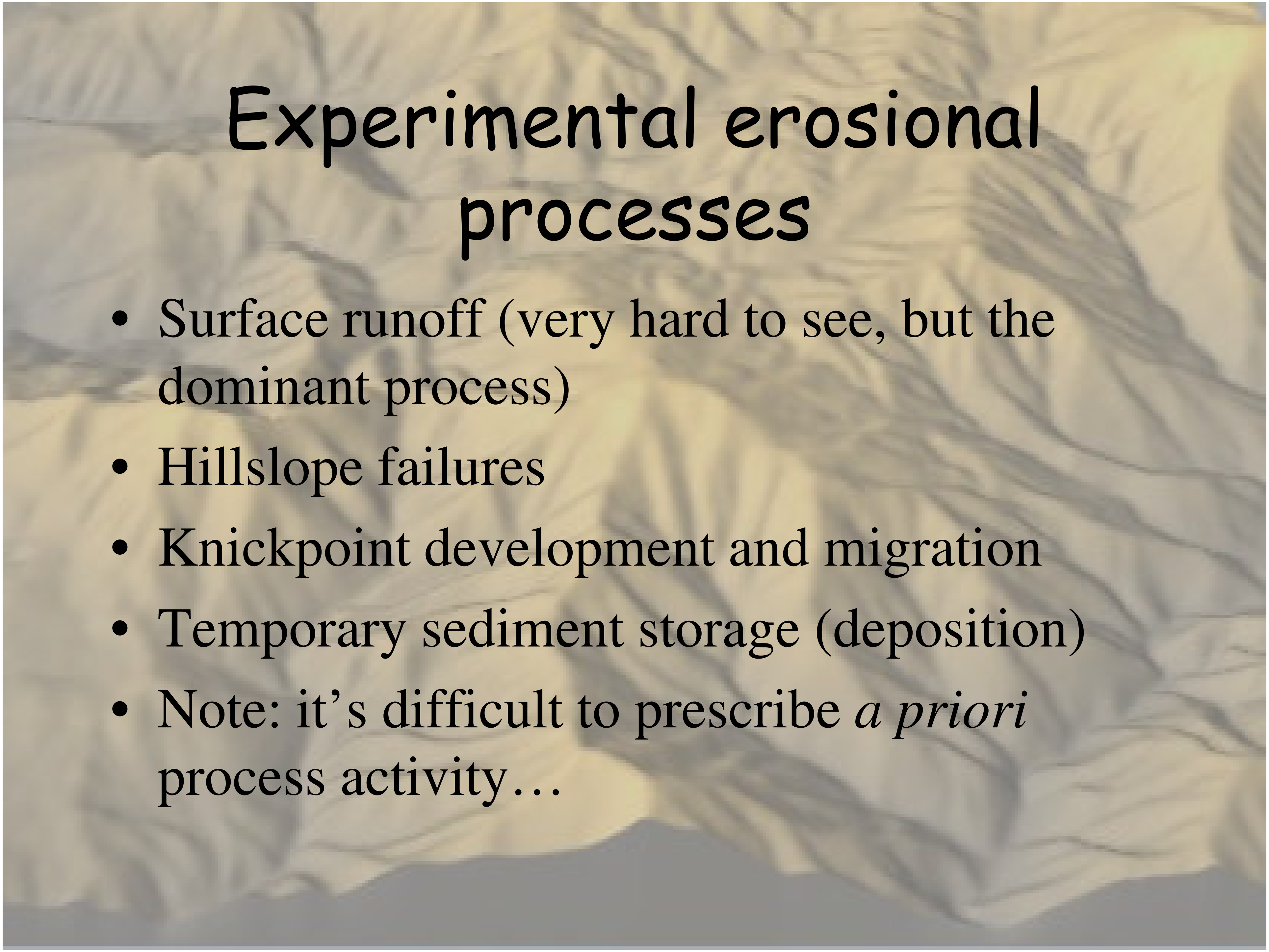
90 cm

~ 60 hours of erosion

100 cm

~ 90 hours of erosion

Experimental erosional processes



- Surface runoff (very hard to see, but the dominant process)
- Hillslope failures
- Knickpoint development and migration
- Temporary sediment storage (deposition)
- Note: it’s difficult to prescribe *a priori* process activity…

The water-to-rock ratio (*r/u*)

- Uplift (*u*) and rainfall (*r*) rates were varied between several experiments
- Water-to-rock ratio, *r/u*, is a convenient way to measure forcing

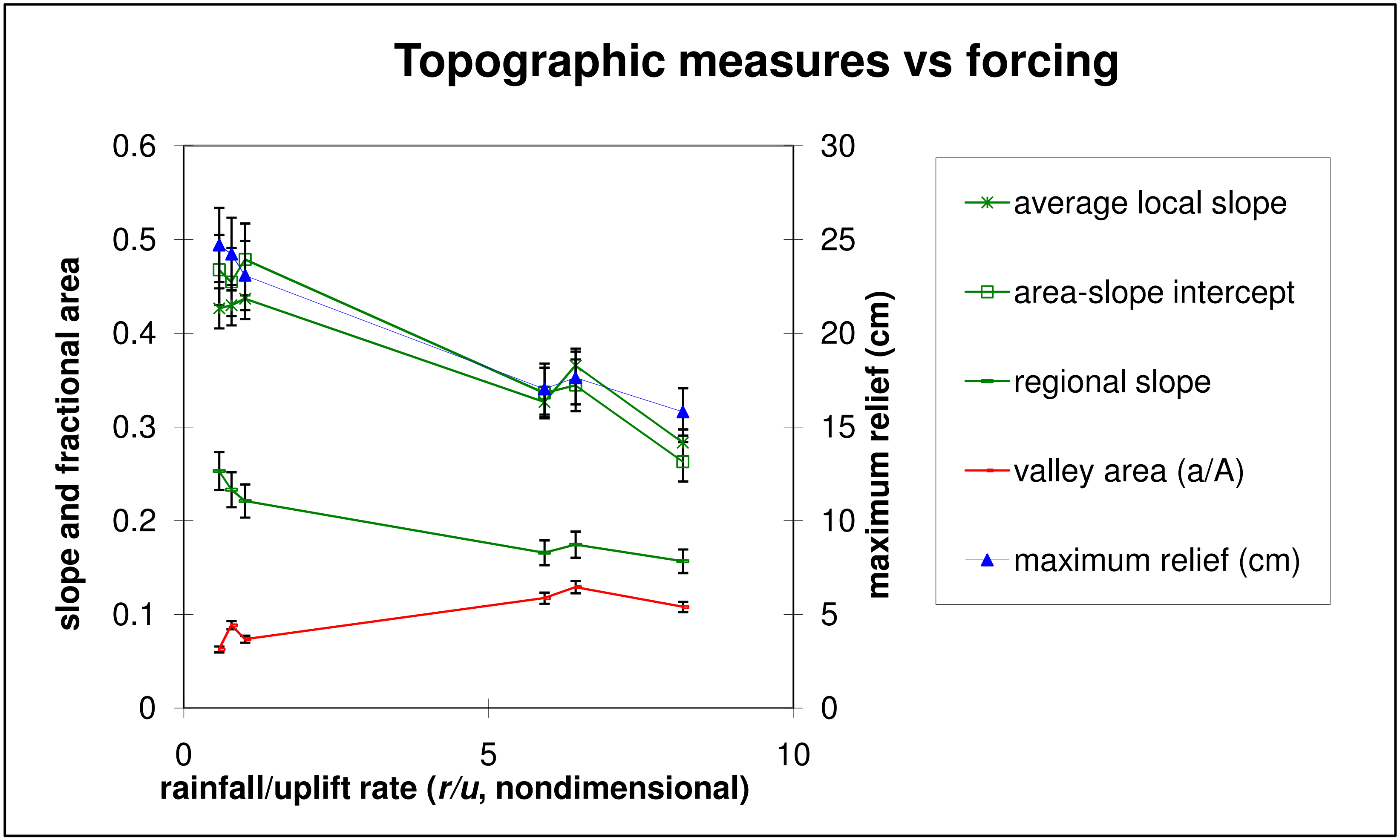
$r = R\rho_w$ where R is rainfall rate [L/T], ρ_w is water density [M/L^3]

$u = U\rho_r$ where U is uplift rate [L/T], ρ_r is substrate density [M/L^3]

$\frac{r}{u} = \frac{R\rho_w}{U\rho_r}$ where *r/u* is a dimensionless forcing parameter

- As *r/u* increases, surface runoff dominates erosion
- At low *r/u,* mass movements play a larger role

Uplift and rainfall rates control overall topographic expression



r/u = 1 (slope failure and runoff dominated)

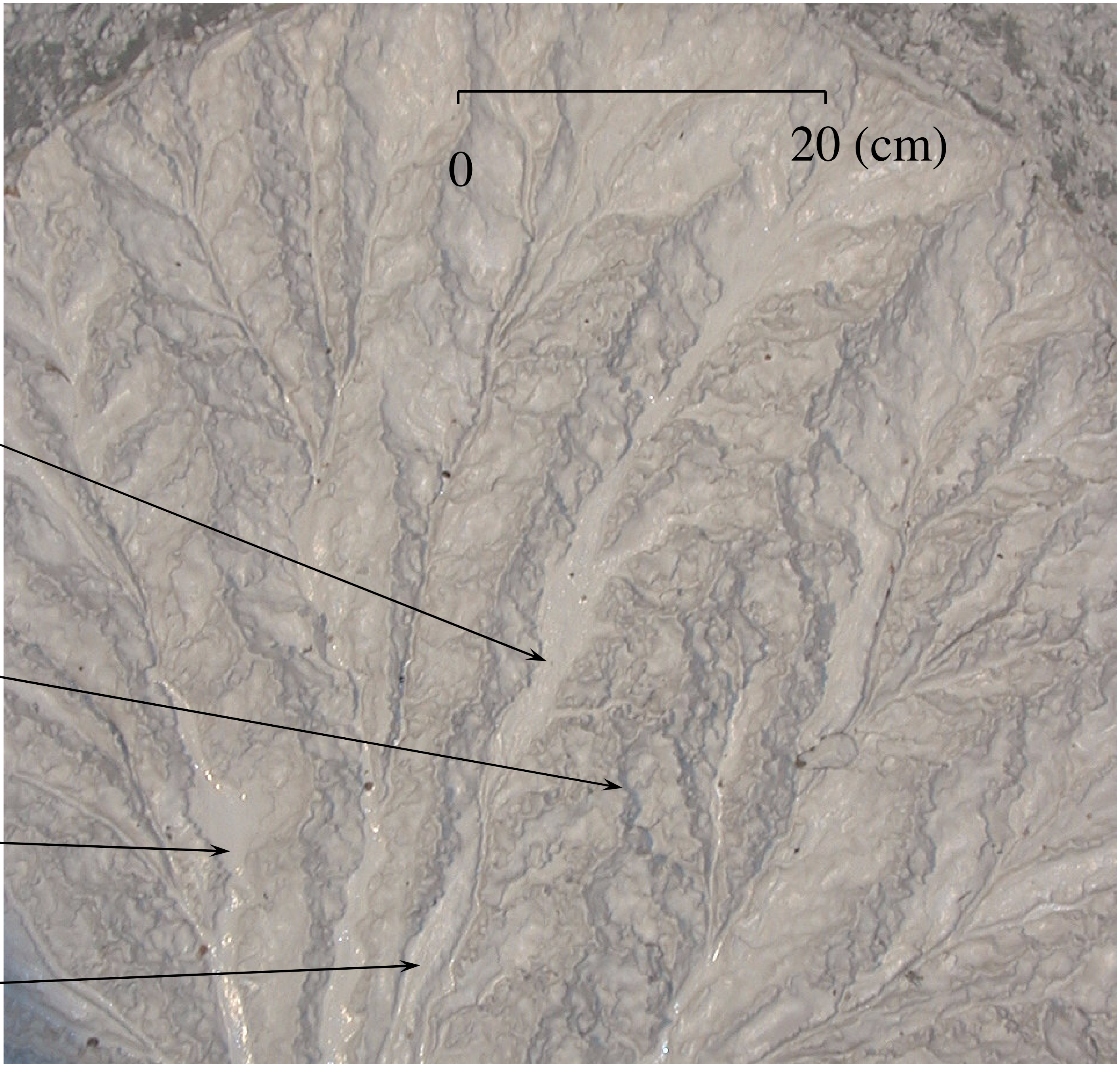
initial surface remnant

slope failure

smooth hillslopes

smooth valley floor (deposition/transport/ erosion)

r/u = 6 (runoff dominated)



deposition

crenulated ridge crests

failure and dam

terrace

r/u = 8
(runoff
dominated)

smooth
valleys

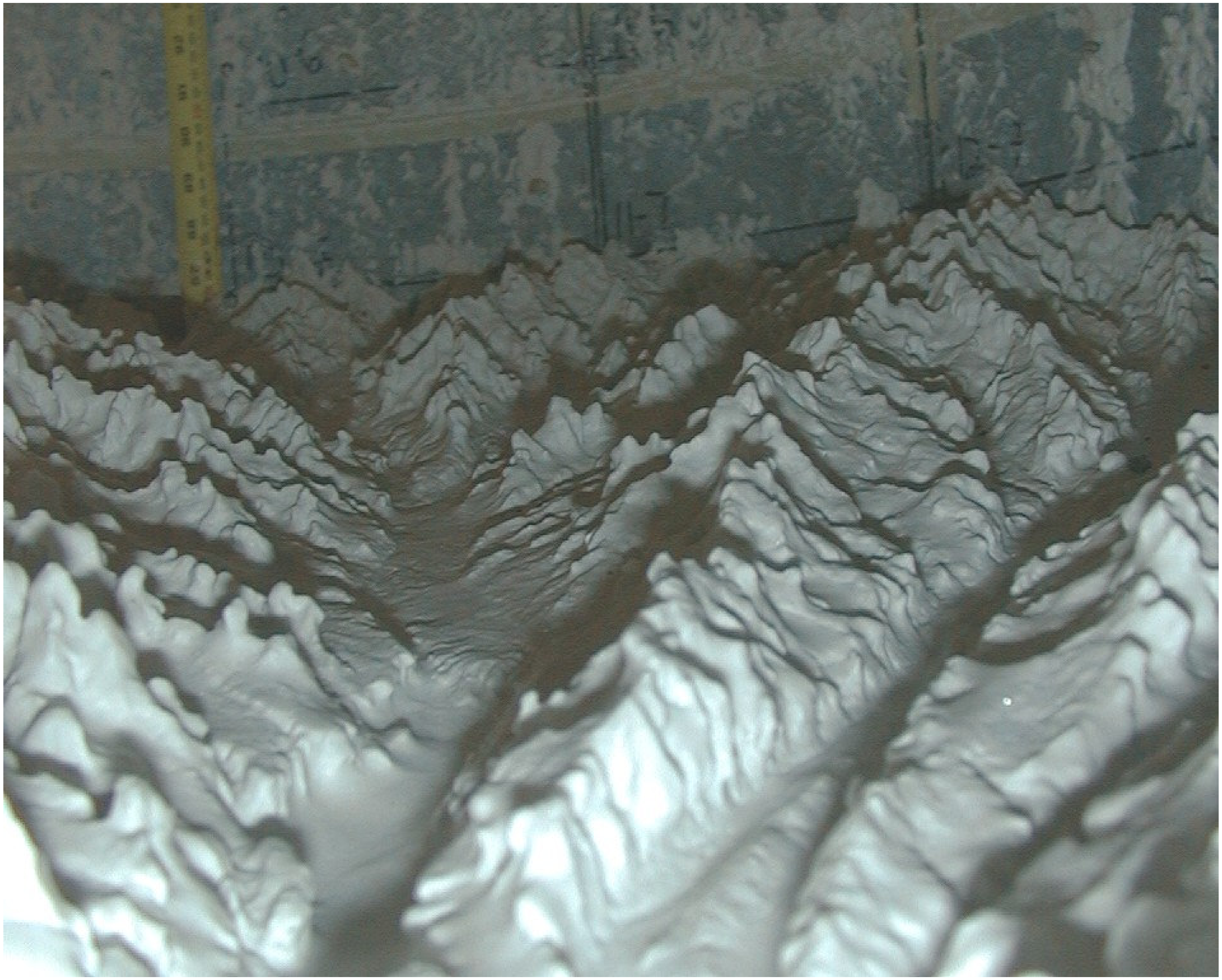
‘peaky’,
irregular
ridge crests

concave
hillslopes

knickpoint

Decaying landform, fixed base level

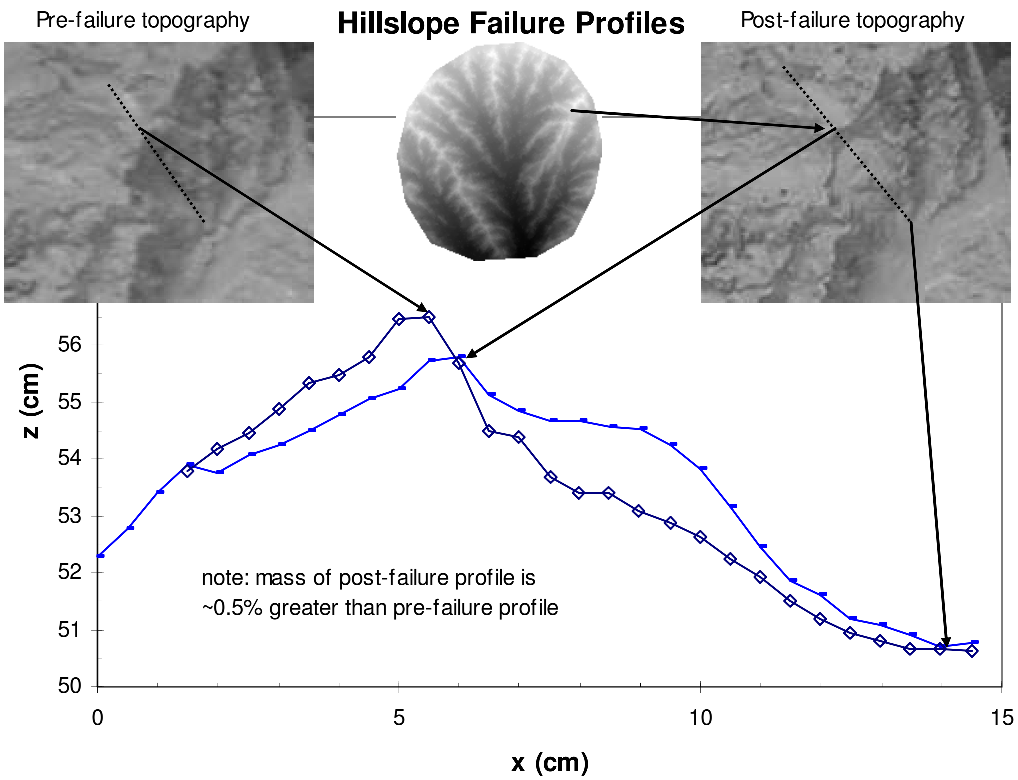
Low angle photo of knickpoint



Vertical photo of knickpoint incision

Sediment Storage and Excavation

Time between photos: 10 minutes (base level fall of 3 mm);
Width of view is ~30 cm; Local relief ~ 6 cm



Hillslope profile before and after a significant slump occurred. Approximately 5 minutes elapsed between the photographs. Topographic profiles were extracted from DEMs derived from stereophotogrammetry.

What’s the scale!!??

- There isn’t one…
- At least not for fluid forces
  - Re and Fr are typically used for scaling flows
  - Specifying Re and Fr uniquely sets flow velocity and depth—no scaling is possible without changing viscosity or gravity
  - However, relative strength of fluid forces are approximately satisfied by thin film flows (gravity and inertial forces dominate; viscosity less important)

What's the scale!!?? (cont.)

$$\mathrm{Re} = \frac{UD}{\nu}$$

Where *U* is velocity, *D* is depth
ν is kinematic viscosity, *g* is gravity

$$Fr = \frac{U}{\sqrt{gD}}$$

Reynolds number gives the ratio of inertial forces to viscous forces; large numbers imply viscous forces are not important;

Rivers are always turbulent; thin flows can be…

Froude number gives the ratio of inertial forces to gravity; most **river flows are dominated by gravity**, but can roughly balance inertial and gravitational forces

Drainage basins have large spatial changes in fluid forces (flow accumulates downstream; flows vary in time)

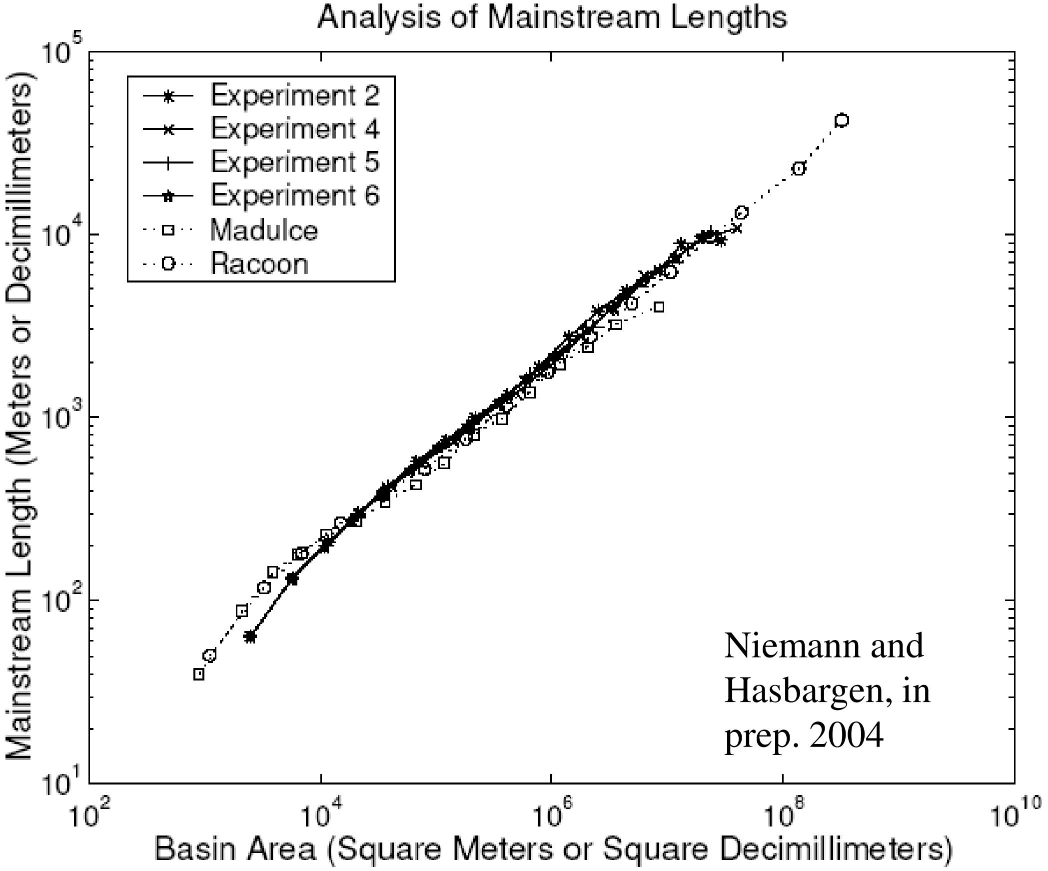
How do experiments scale?

For basins of 3rd to 5th stream order…

Feature	Natural	Experiment
– *length scale*, $L \sim A^{1/2}$	($10^3 – 10^4$ m)	(10^0 m)
– *relief*, H_r	($10^2 – 10^3$ m)	(10^{-1} m)
– regional *slope*, H_r/L	(10^{-1})	(10^{-1})
– *hill slopes*, h/l	(10^{-1} - 10^0)	(10^{-1} - 10^0)
– *knickpoint height*, h/H_r	(10^{-5} - 10^{-1})	(10^{-2} - 10^{-1})
– *landslide size*, a/A	(10^{-5} - 10^{-1})	(10^{-3} - 10^{-1})
– *ridge area*, a/A	(10^{-2} - 10^{-1})	(10^{-2} - 10^{-1})
– *valley area*, a/A	(10^{-2} - 10^{-1})	(10^{-2} - 10^{-1})

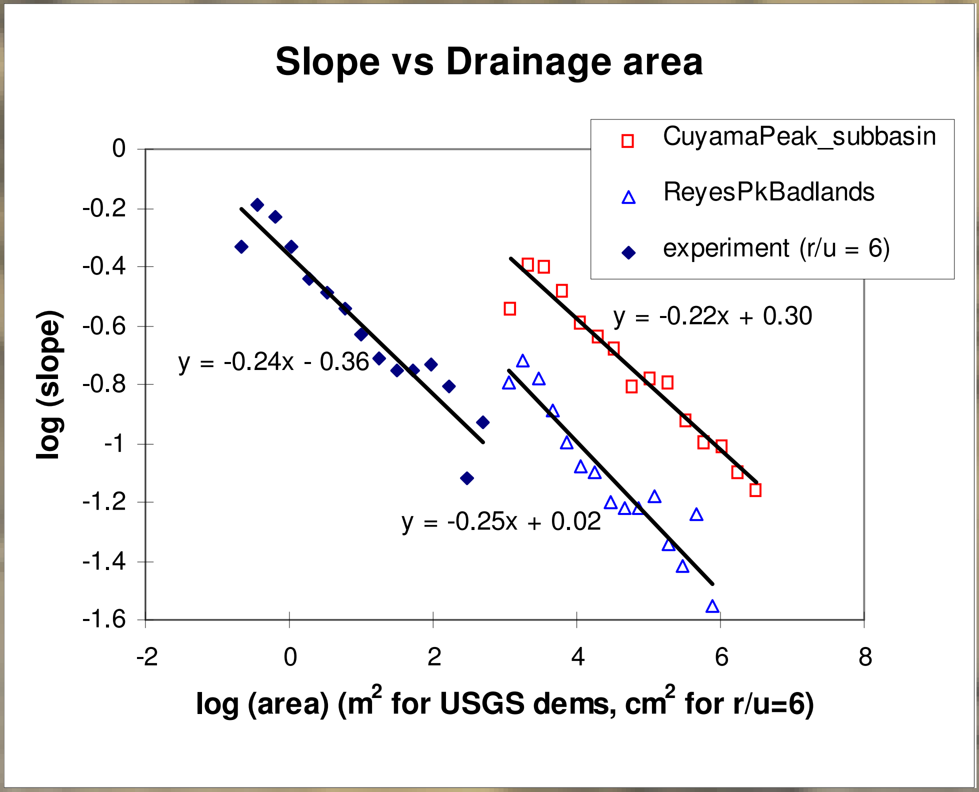
Note: key difference is slope, which is typically 2-3 x steeper in experimental basins

Hack's law: Sub-basin length increases with drainage area

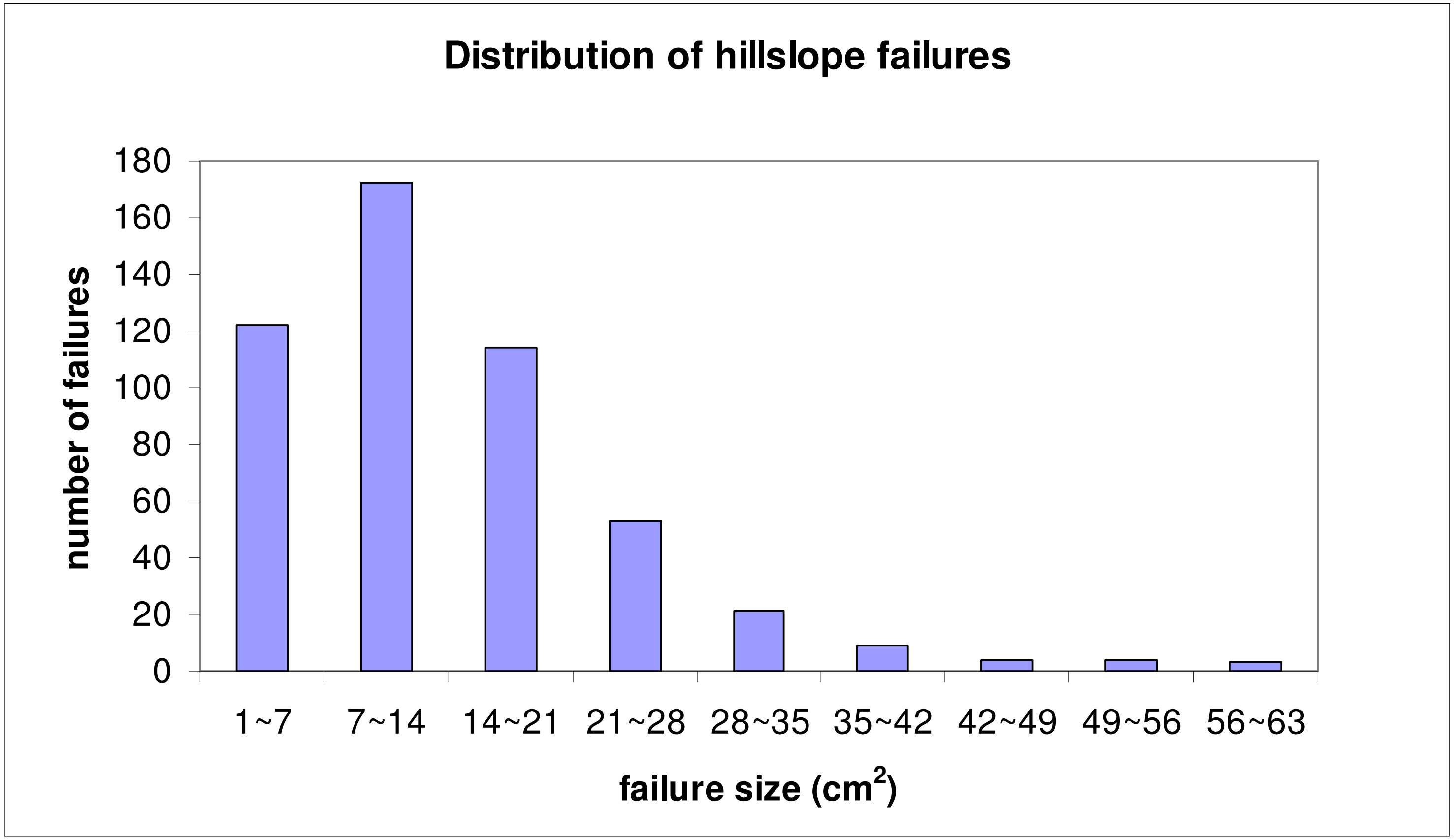


Niemann and Hasbargen, in prep. 2004

Area-Slope comparison

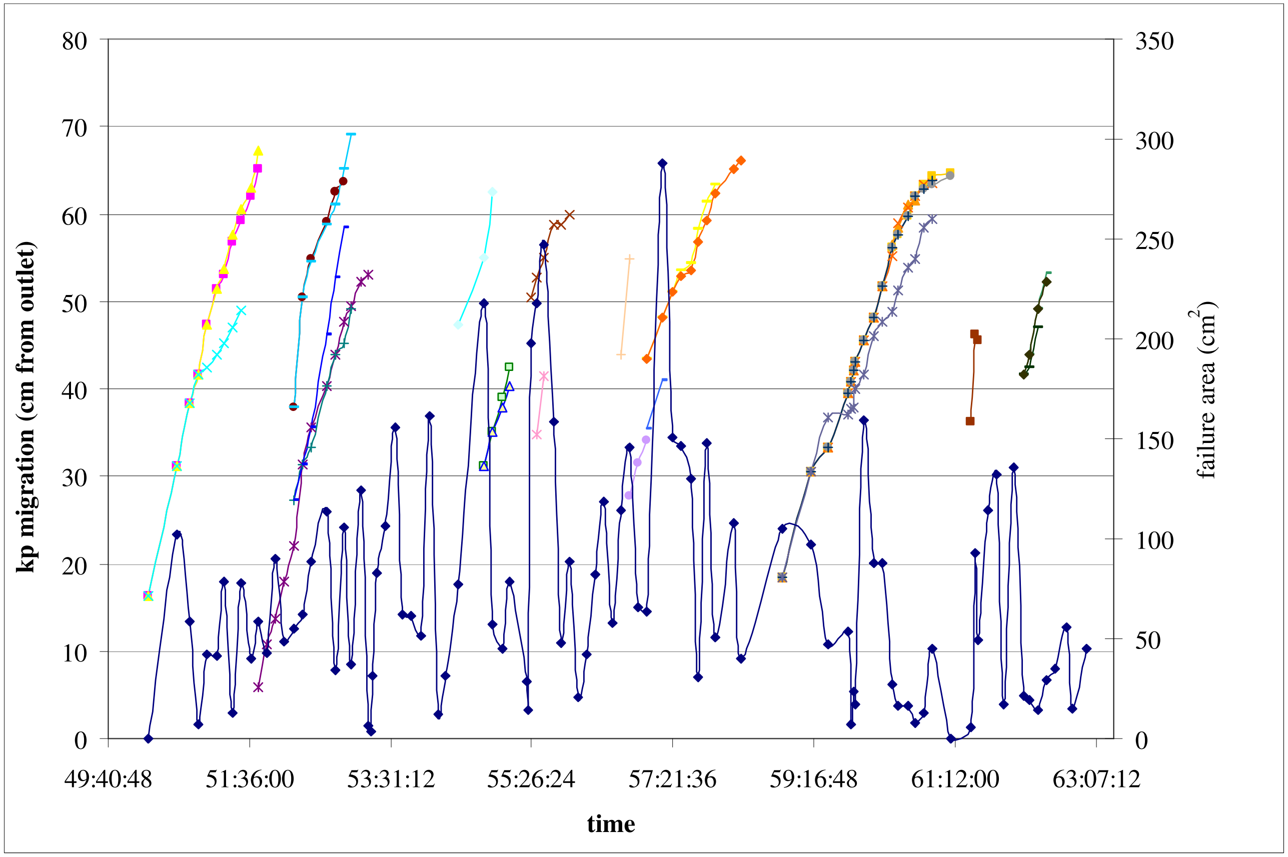


Experimental landscape activity: Hillslope failure distribution



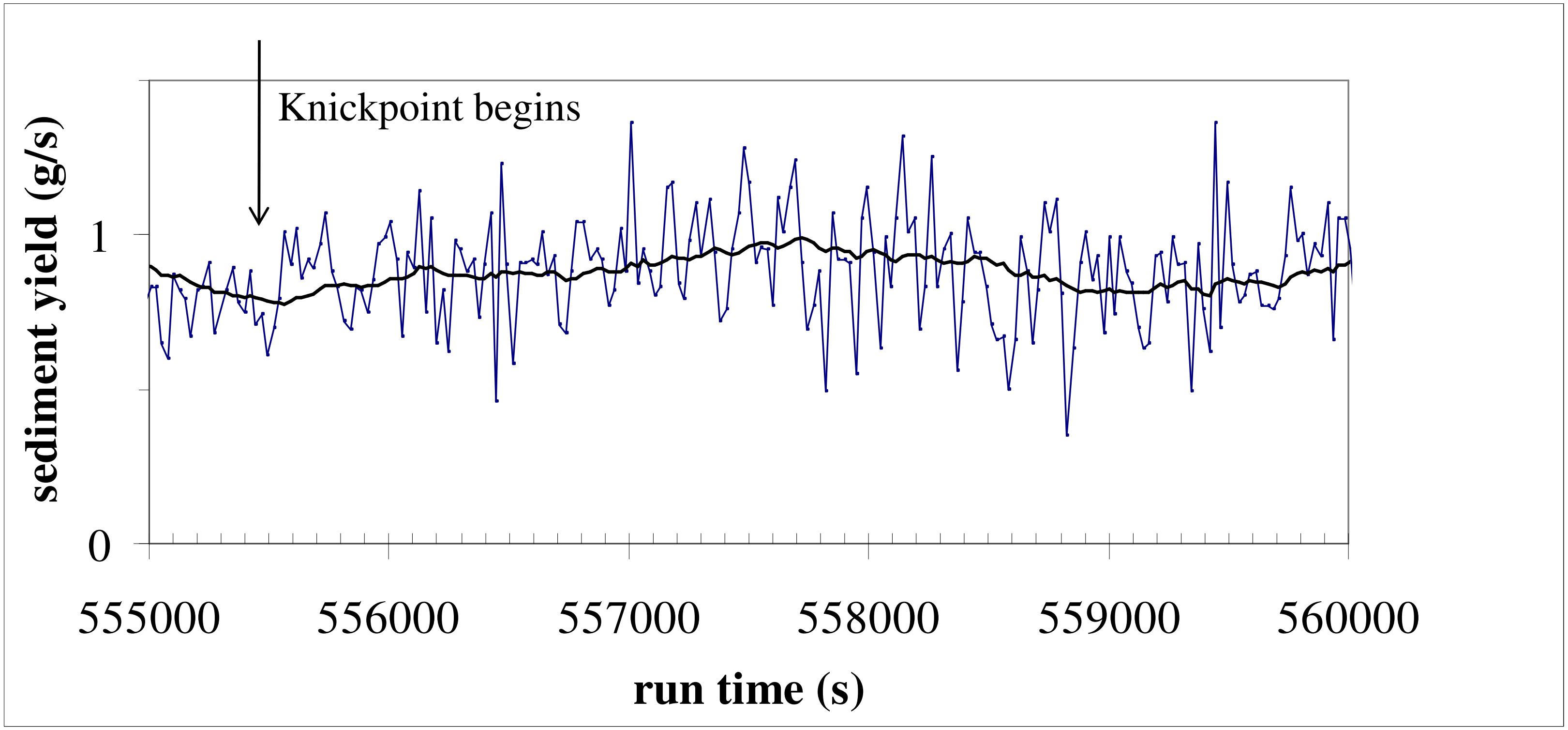
Bigi et al., 2006

Experimental landscape activity: Knickpoint propagation and hillslope failures



Bigi et al., 2006

Experimental landscape activity: Sediment yield and knickpoint propagation

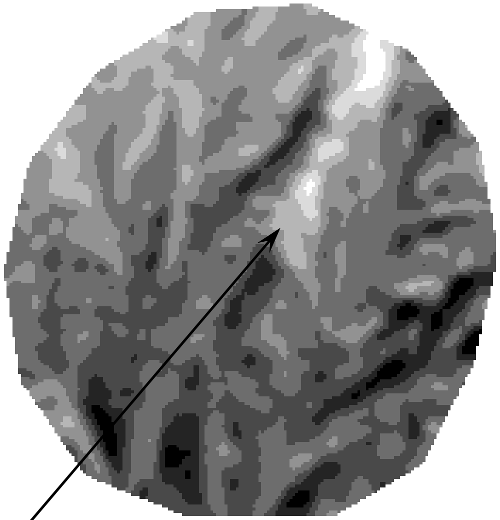


Measuring landscape dynamics: erosion rate variability

- Compute local erosion rates by differencing elevation grids
- Determine the variability in erosion rates as distance between surfaces increases
- **Remember: Numerical landform erosional variability is nil**

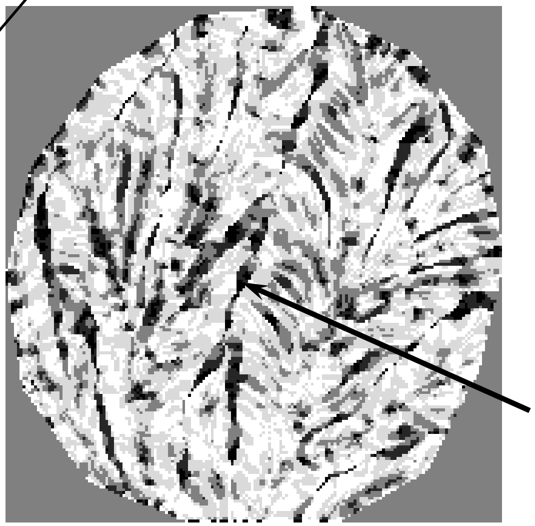
Sequential elevations, spatial erosion rates, and flow changes

Elevation, T_i



Large variation in erosion rates

+/- 1.5 *U*



Elevation T_{i+1}

($h/H_r = 0.3$)

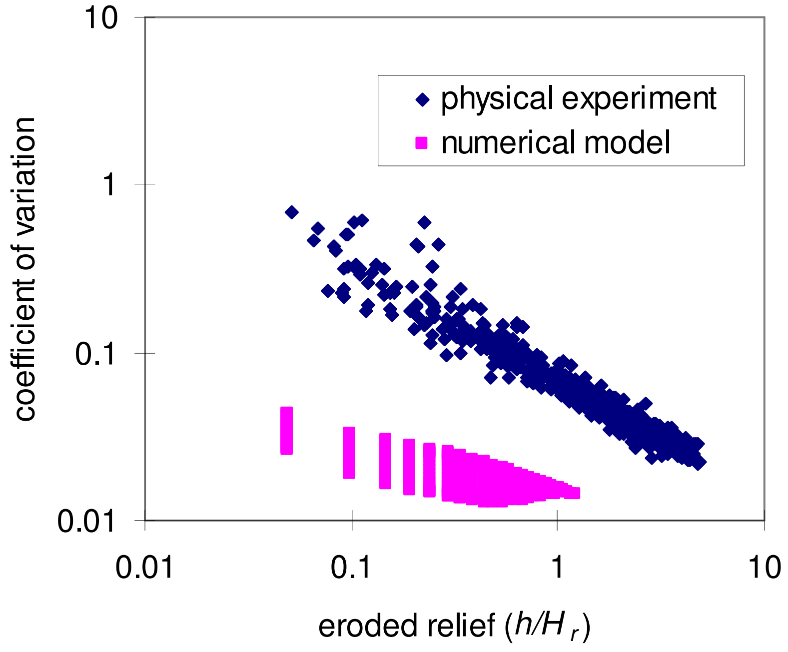
Organized

<u>flow path change</u>

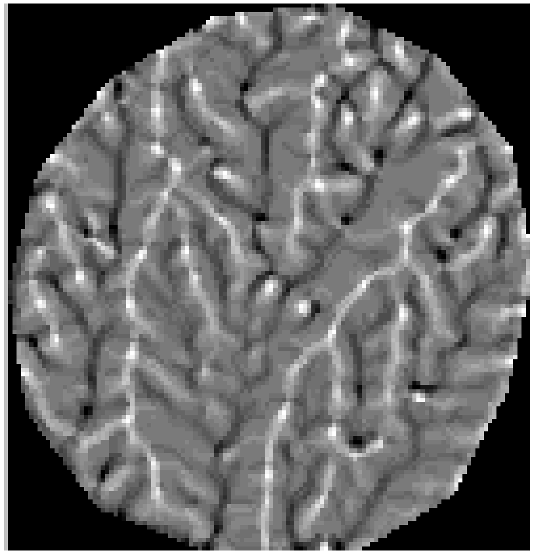
black = flow reversal

white = same flow path

Numerical vs experimental erosion rate variability



Divide Migration: Spatial Organization of Erosion



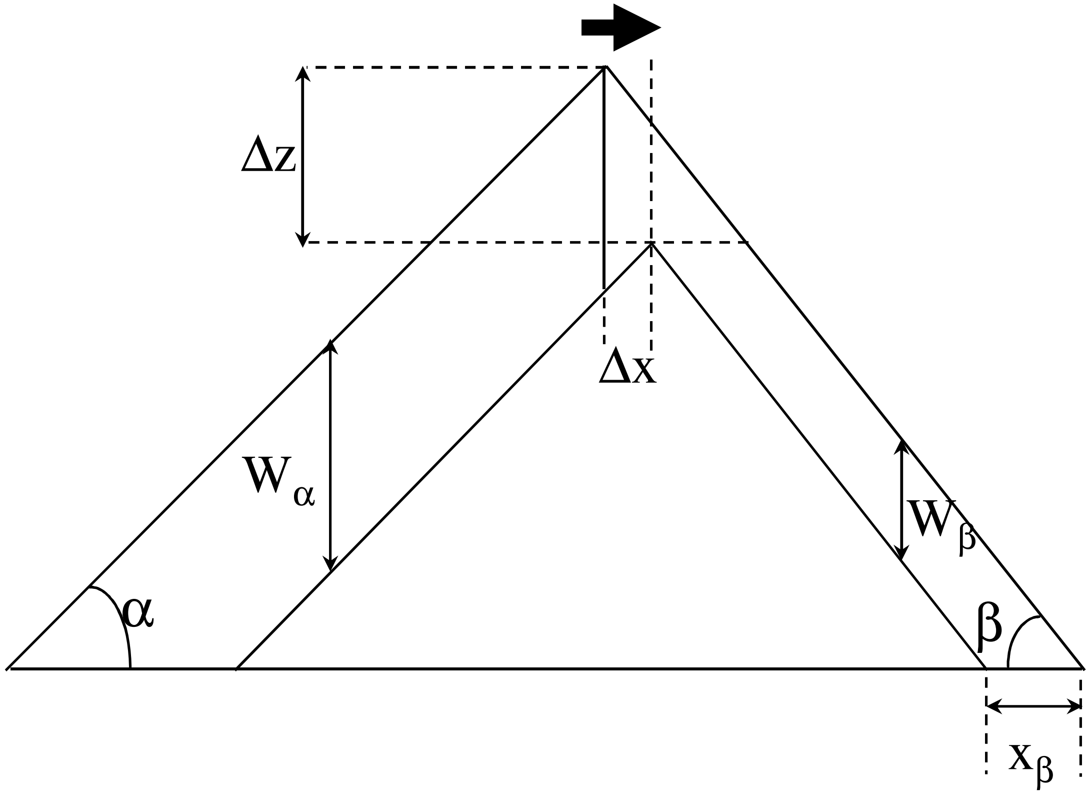
Relative height time series for a landscape at complete dissection

Erodes through ~3 units of relief (this took several days at continuous forcing!)

DivideMigration:

an inevitable result of erosion rate variability

$$\frac{\Delta x}{\Delta t} = \frac{W_\alpha - W_\beta}{\tan\alpha + \tan\beta}$$



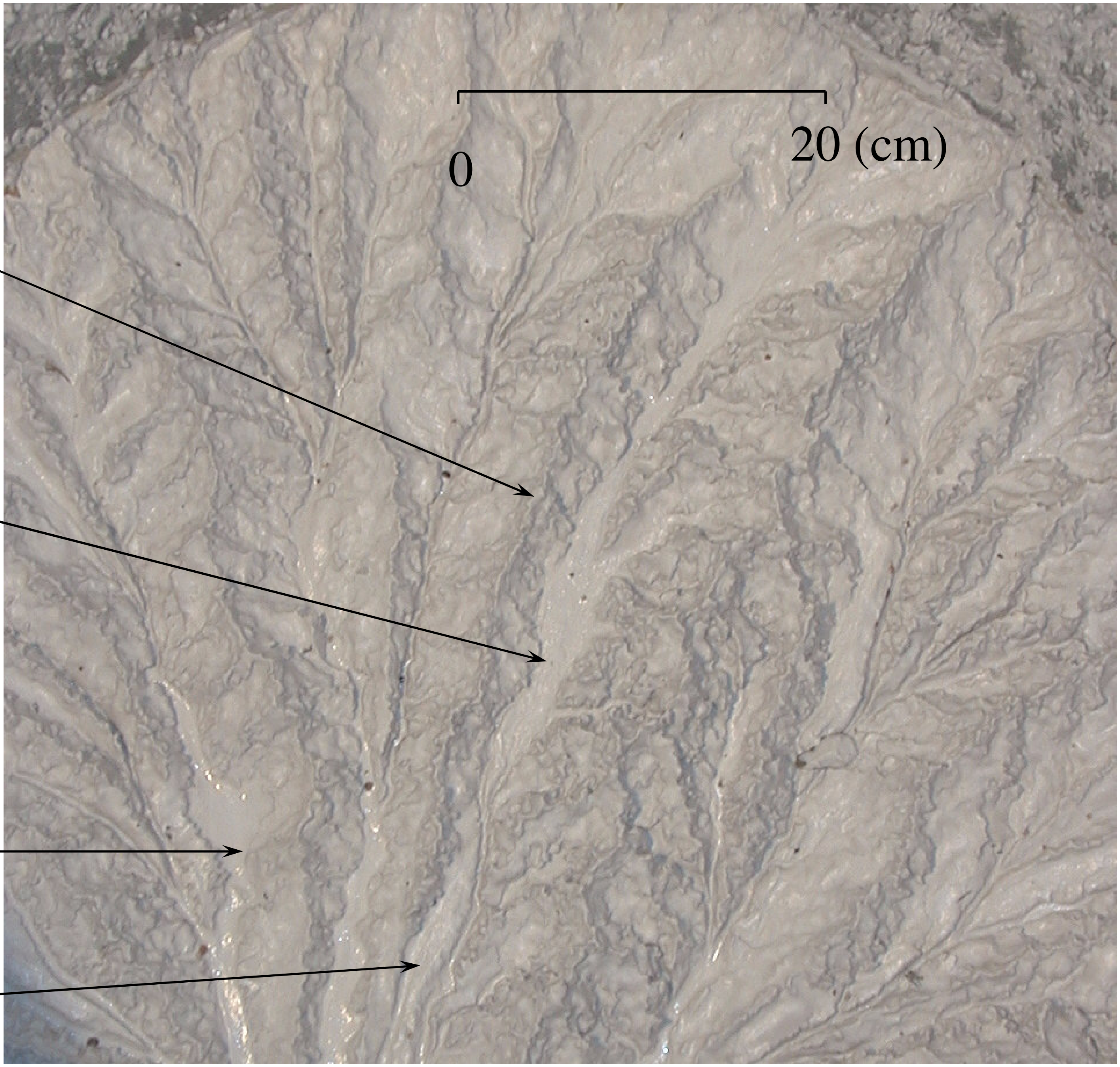
Divide migration is a function of erosion rates on either side of the divide (W_α and W_β), and hillslope angles α and β

When erosion rates on either side of divide are equal, regardless of asymmetry of hillslopes, there is no migration…

Divide Migration in natural settings: Is it recognizable?

Here's some possible characteristics

- **Asymmetric ridges**
  - **Migratory scarps**
- **Long narrow perched valleys**
- ***Organized* spatial erosion rate patterns**
- **Sediment flux variations between adjacent sub-basins**



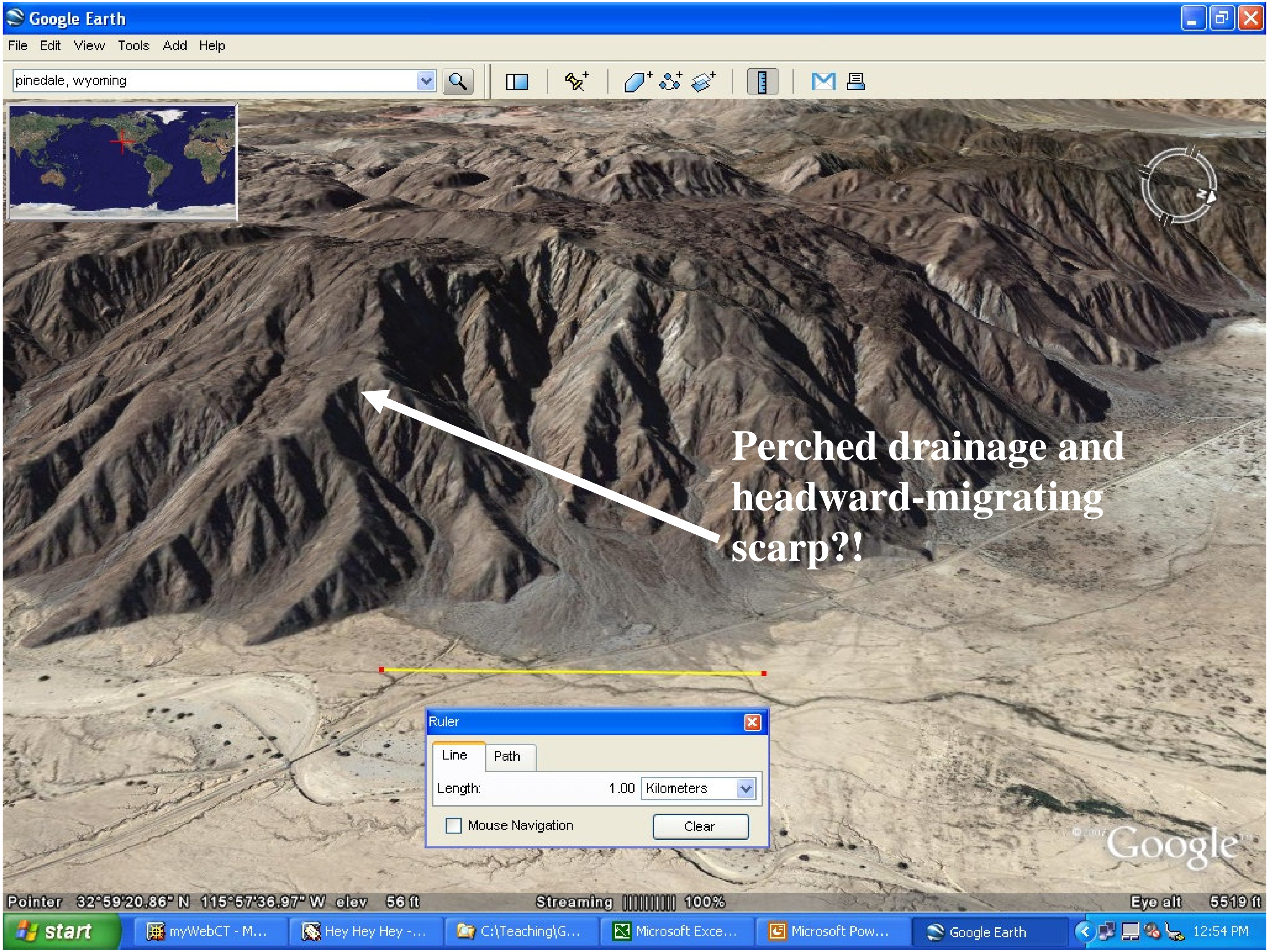
Ridge asymmetry

Deposition

Slope failure and dam

Terrace

Imminent capture and divide migration?
Mountains near Ojai, CA



Perched drainage and headward-migrating scarp?!

pinedale, wyoming

Ruler

Line | Path

Length: 1.00 Kilometers

☐ Mouse Navigation

Clear

Pointer 32°59'20.86" N 115°57'36.97" W elev 56 ft

Streaming 100%

Eye alt 5519 ft

Hypothesis for divide migration: positive feedback

- Migrating divide captures runoff from adjacent basin
- Increases runoff and erosion on advancing side
- Decreases runoff and erosion on the scavenged side, which
- Drives more migration

- *Migrating scarps*

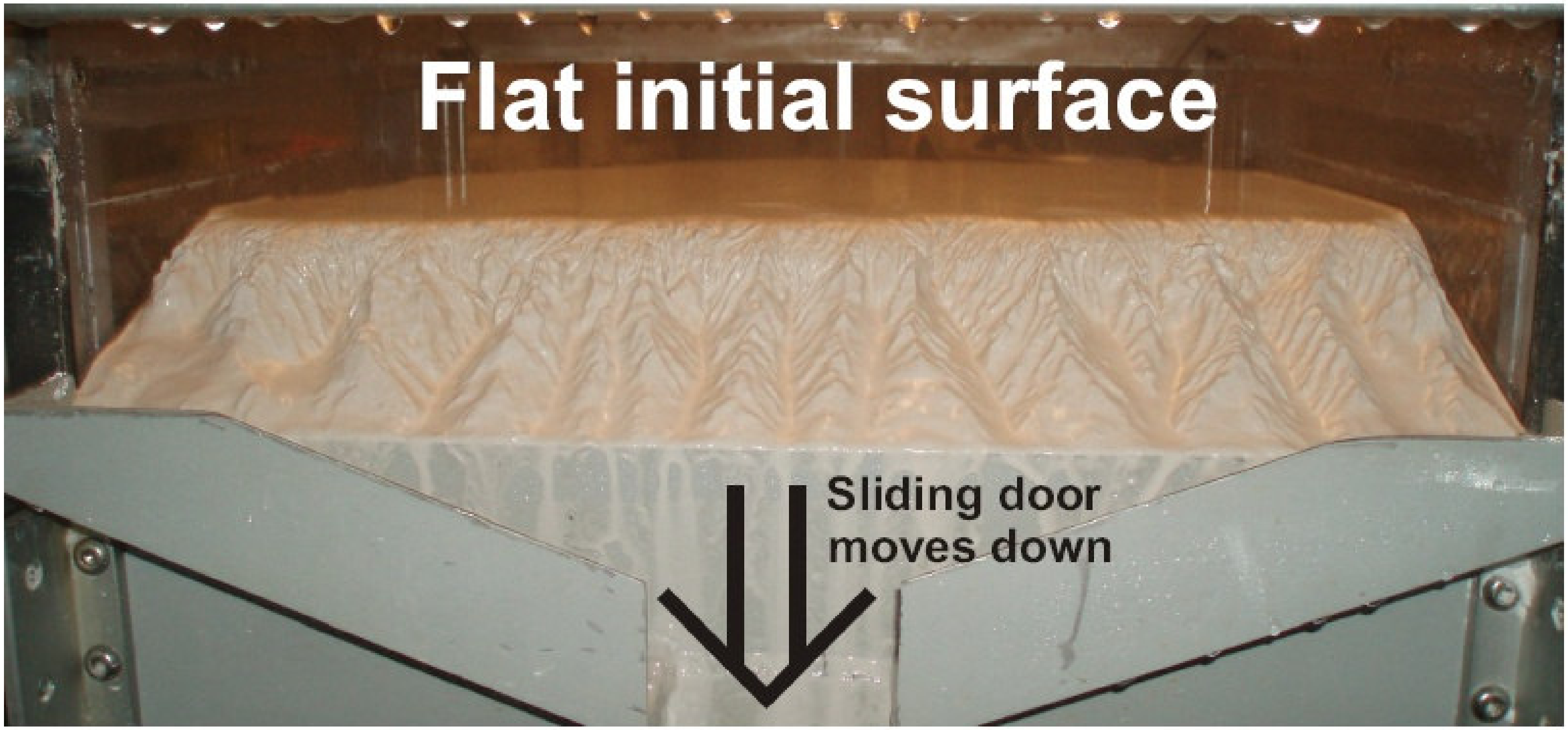
Mechanisms for instability

- Hillslope failures: streams near capacity are locally ‘overloaded’ with sediment
  - Triggers deposition, stream slope increases, and incision ensues (knickpoint development?)
- Out of phase erosion in adjacent drainages due to knickpoint propagation
- Drainage area capture (positive feedback)
  - Occurs in numerical models as well
  - Migrating divide increases runoff to the rapidly eroding side; decreased runoff on the scavenged side
  - Increased runoff increases erosion, which drives further migration

Future Work

- Expand work with natural settings
  - Characterize form/drainage structure around actively migrating ridges
  - Surface exposure dating to determine erosion rates
- Explore physical experiments further
  - Test effects of substrate resistance on stream geometry, landscape form, and dynamics
  - Incorporate control over groundwater
  - Investigate influences of rainfall/runoff variability
  - Focus on form in various tectonic styles (tilting, folding)
- Incorporate additional processes into numerical models
  - Better treatment of deposition
  - Concentration limits in stream erosion law

The next generation of experimental basins



Liam Reinhardt and Mike Ellis recent work at U. of Memphis
(ongoing at St. Anthony Falls, U of MN)

Uniform uplift at all boundaries

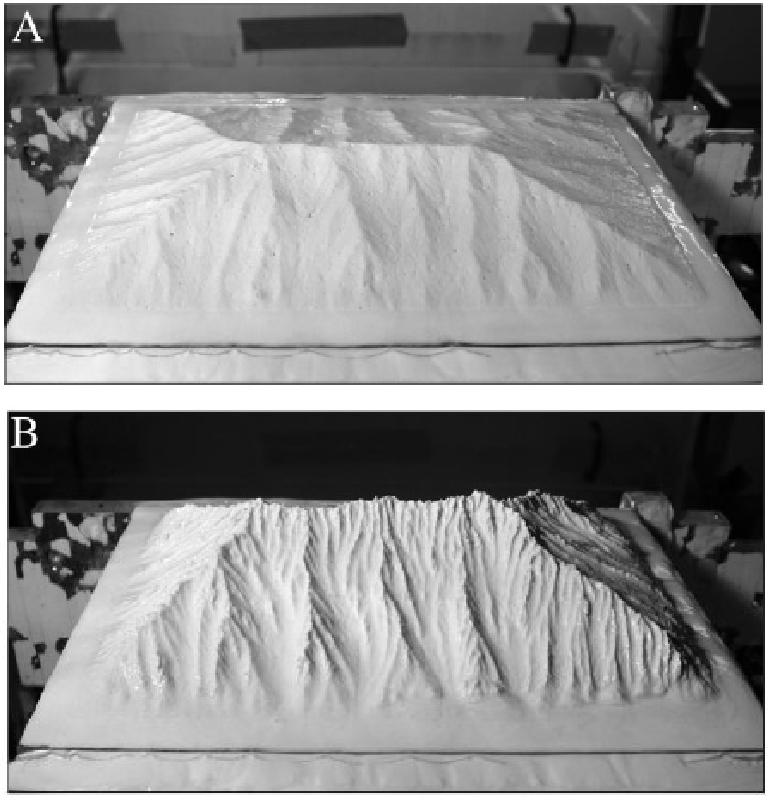


Figure 3. Oblique views of experiment TC18 (cf. Fig. 2). A: t = 240 min. B: t = 480 min. Topographies are at steady state with uplift rate of 1.5 cm/h and under high rainfall rate conditions (top: mean rainfall rate 166 ± 5 mm/h) and low rainfall rate conditions (bottom: mean rainfall rate 98 ± 7 mm/h).

Stephan Bonnet and Alain Crave, **Landscape response to climate change: Insights from experimental modeling and implications for tectonic versus climatic uplift of topography**, *Geology; February 2003; v. 31; no. 2; p. 123–126; 4 figures.*

Lateral shortening and erosion

328 *F. Graveleau, S. Dominguez / C. R. Geoscience 340 (2008) 324–333*

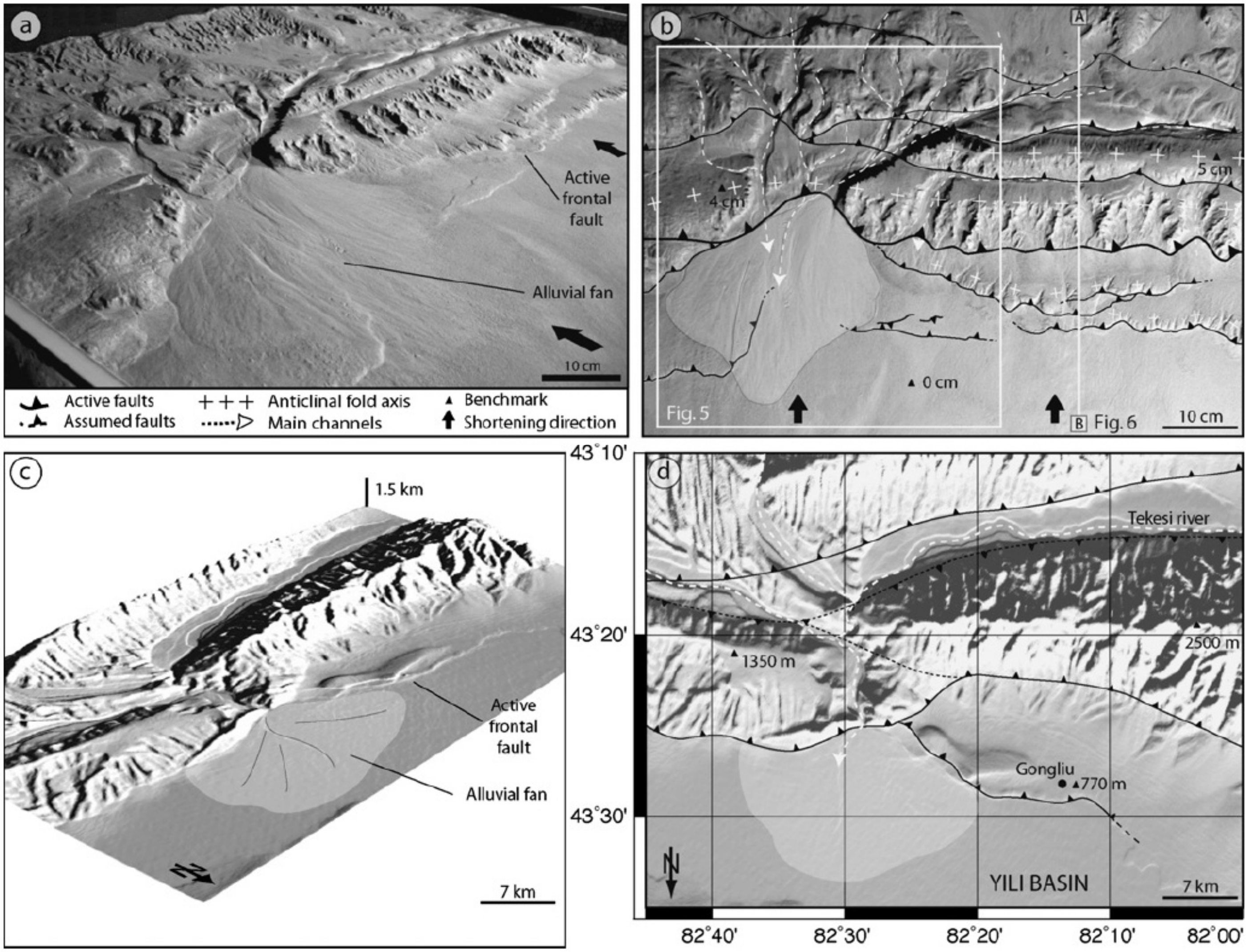


Fig. 3. Experiment of piedmont formation in frontal convergence compared to the Tian-Shan mountain. (**a**) Oblique and (**b**) map views with structural sketch. White frame corresponds to Fig. 5. Cross-section **A**–**B** corresponds to Fig. 6. (**c**) Oblique and (**d**) map views with structural sketch of the Tekesi River flowing down to the intramontaneous Yili basin (SRTM data, NASA). Note that north is oriented downward.

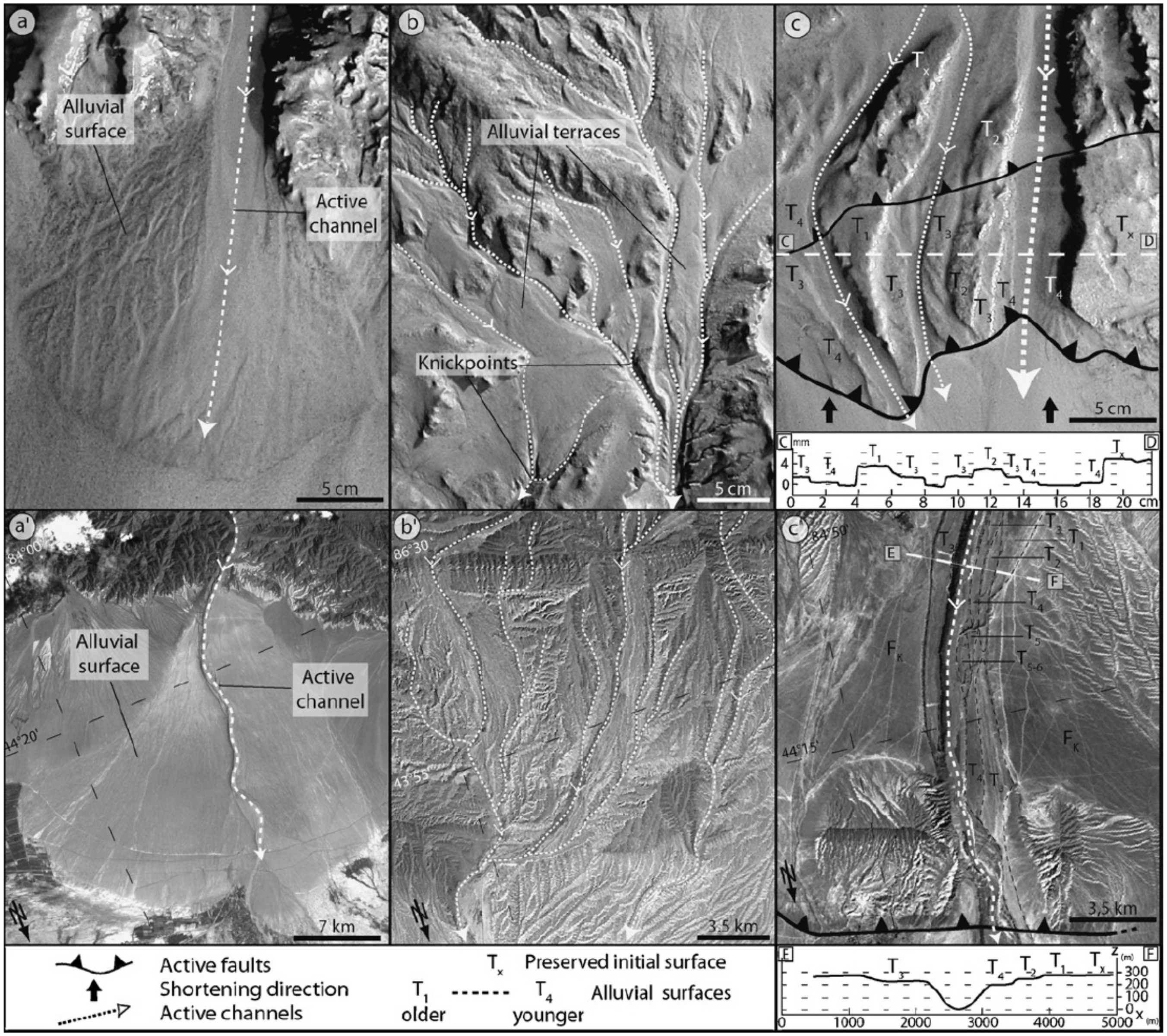


Fig. 4. Pictures of morphological features in experiment and equivalents in nature from Tian Shan northern piedmont (Landsat 7 satellite images). (**a**,**a′**) Alluvial fans. Note active channels and old alluvial surfaces; (**b**,**b′**) channel network with sub-parallel channel patterns in piedmont drainage basins. Note alluvial surfaces and knickpoints in experiments; (**c**,**c′**) stair-step fluvial terraces. Several successive levels are preserved on both sides of active channels. Topographic profiles show the vertical height of each terrace. Note downward orientation of north for satellite pictures.

Summary of *behavior* in experimental landscapes…

- Very noisy erosion rates at short time scales!!
  - Short term variability in erosion rate due to
    - propagating knickpoints, slope failures, temporary sediment storage
- Divide migration can impose spatially correlated erosion rate patterns on landscape
- If a small basin looks like a duck (channels and hillslopes) and walks like a duck (surface runoff erosion, landslides, knickpoints), **Is it a duck**? ***Dynamic*** questions…

Implications…

- Small drainage basins exhibit striking similarity to natural settings, suggesting a cost effective tool for process exploration and model testing
- Terrace development, often blamed on climate change, may be ***intrinsic*** behavior
- Knickpoint development (often attributed to changes in tectonic uplift/climate change) may be ***intrinsic*** behavior
- Drainage realignment may persist indefinitely, so long as erosion is occurring
- Are natural landscapes as dynamic?!?

Thanks for your attention!

Questions?