GEOS 28600

The science of landscapes:
Earth & Planetary Surface Processes

Lecture 14

Monday 24 Feb 2020

Summing up controls on longitudinal profiles: hypotheses

(1) Gross topography (set by tectonics)

(2) Threshold rivers (intent: gravel-bed rivers)

(3) Power-law relation between sediment transport flux and basal shear stress (intent: sand-bed rivers)

(4) Selective transport

(5) Bedrock incision in canyons:

(5a) Streampower

(5b) Tools-and-cover (Leonard Sklar)

Large boulders: effectively rough pieces of bedrock (abraded in pace)
Sourcing may change from coarse to fine downstream.

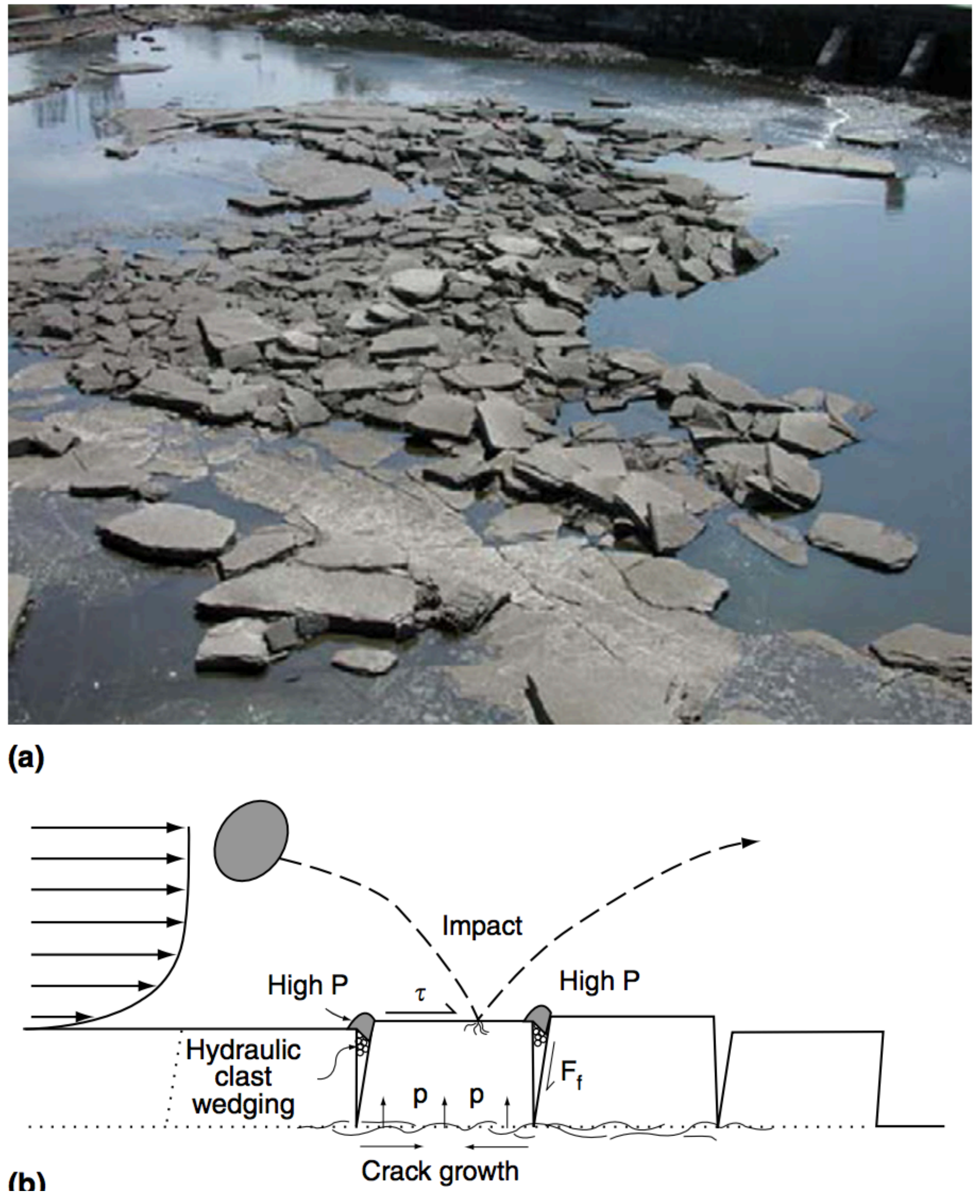
BASIC EQUATIONS GOVERNING BED ELEVATION

WHAT SETS RIVER PLANFORM?

WHAT SETS RIVER LONG PROFILE?

BEDROCK RIVER EROSION

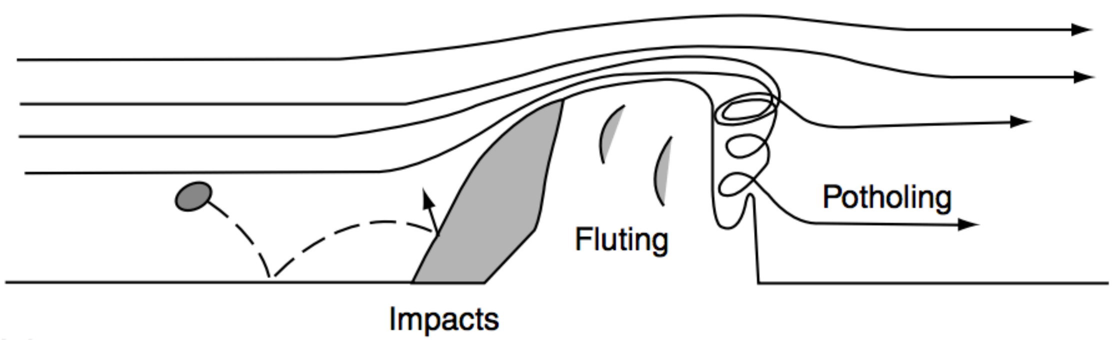
Mechanisms of bedrock erosion: plucking



Whipple et al., Treatise on Geomorphology 2013

Mechanisms of bedrock erosion: abrasion

(c)



Whipple et al., Treatise on Geomorphology 2013

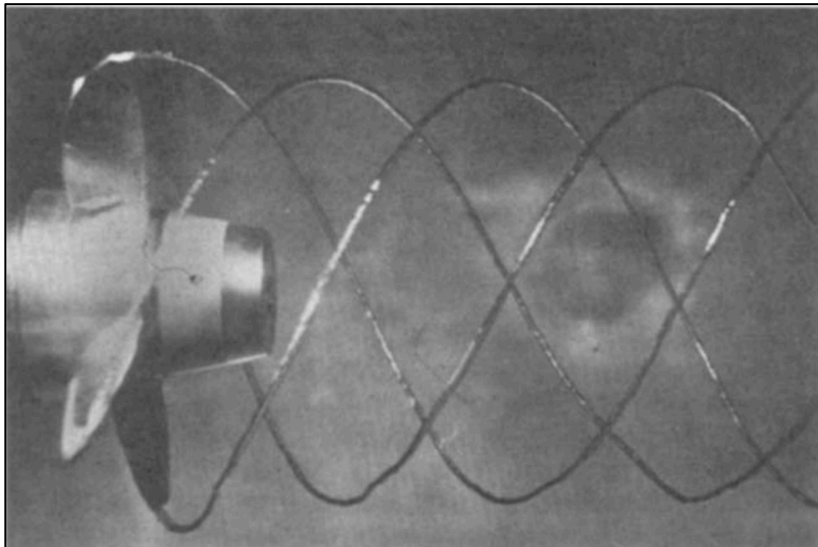
Mechanisms of bedrock erosion: corrosion (= weathering + dissolution)

Tsingy de Bamaraha, Madagascar (UNESCO World Heritage site)

Lighthouse Reef Atoll Blue Hole, Belize.

Mike Malaska (JPL)

Mechanisms of bedrock erosion (?): cavitation?



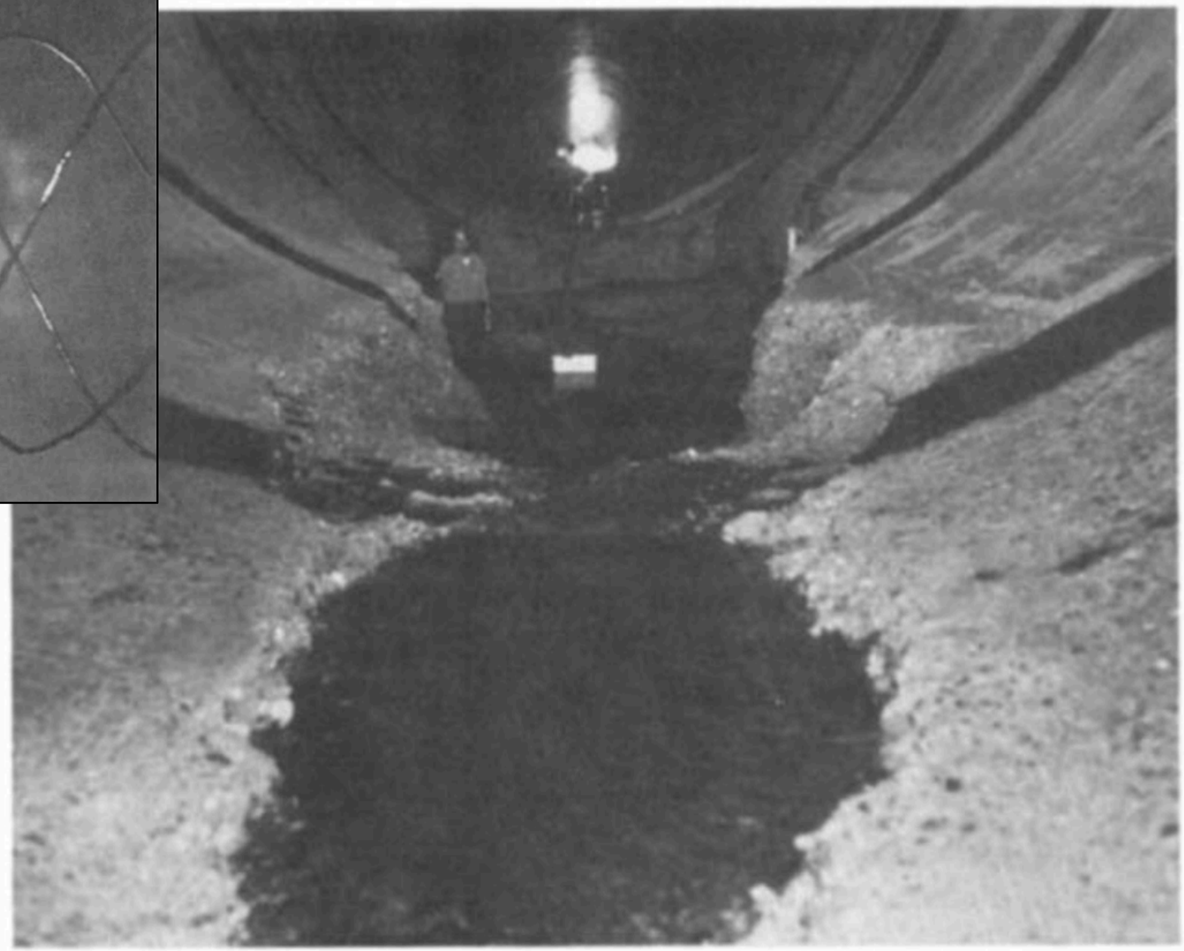


Figure 1 Cavitation damage in the spillway tunnel of the Yellowtail Dam in Montana. Courtesy of US Bureau of Reclamation.

Arndt, Annual Reviews of Fluid Mechanics, 1981

Key points from 'intro. to rivers and landscape evolution'

- Advective vs. diffusive channel profile evolution
- Hypotheses for controls on concavity
- Know the streampower equation
- Know bedrock erosion processes

Next lecture: Landscape-scale responses to forcing

Fluvial sediment transport vs. hillslope processes: what controls the spacing of rivers?

SETTING THE SPACING OF STREAMS

HILLSLOPE EROSION PROCESSES

SOIL PRODUCTION FUNCTION

SYNTHESIS: PERRON ET AL. 2009

Focus on <u>gently-uplifting</u> landscapes (no landslides) on <u>Earth</u>

Key points from today's lecture

- Explain mechanistically how streampower landscapes can act as a tectonic tape-recorder
- Explain why steady-state hillslopes are convex.
- Explain 2 or more hillslope transport processes.
- Know 2 or more physical and 2 or more chemical weathering processes.
- Understand how Peclet number can quantify competition between hillslope processes and fluvial channelization (see also required reading).

Fluvial sediment transport vs. hillslope processes: what controls the spacing of rivers?

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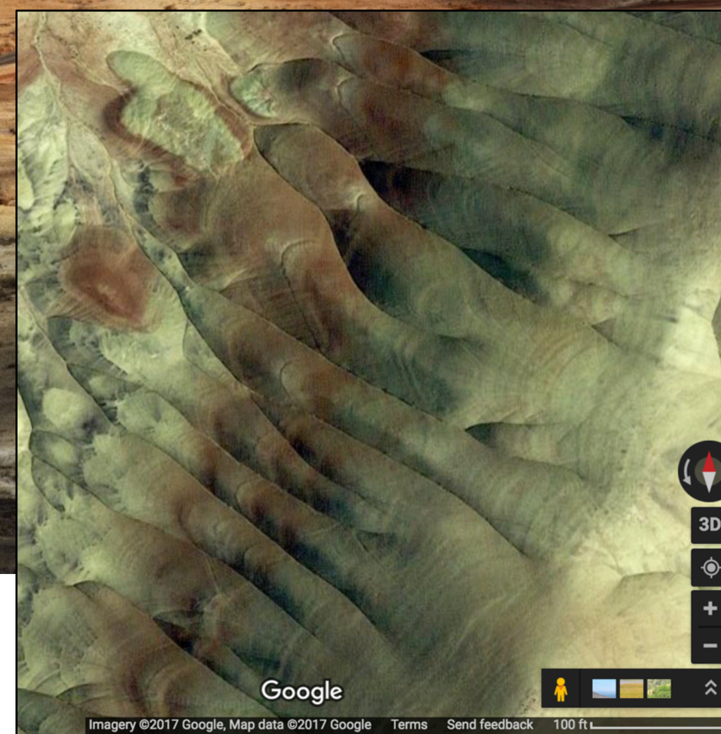
SYNTHESIS: PERRON ET AL. 2009

Painted Hills, Oregon: badlands, fine-grained material, micro-channeling, rilling



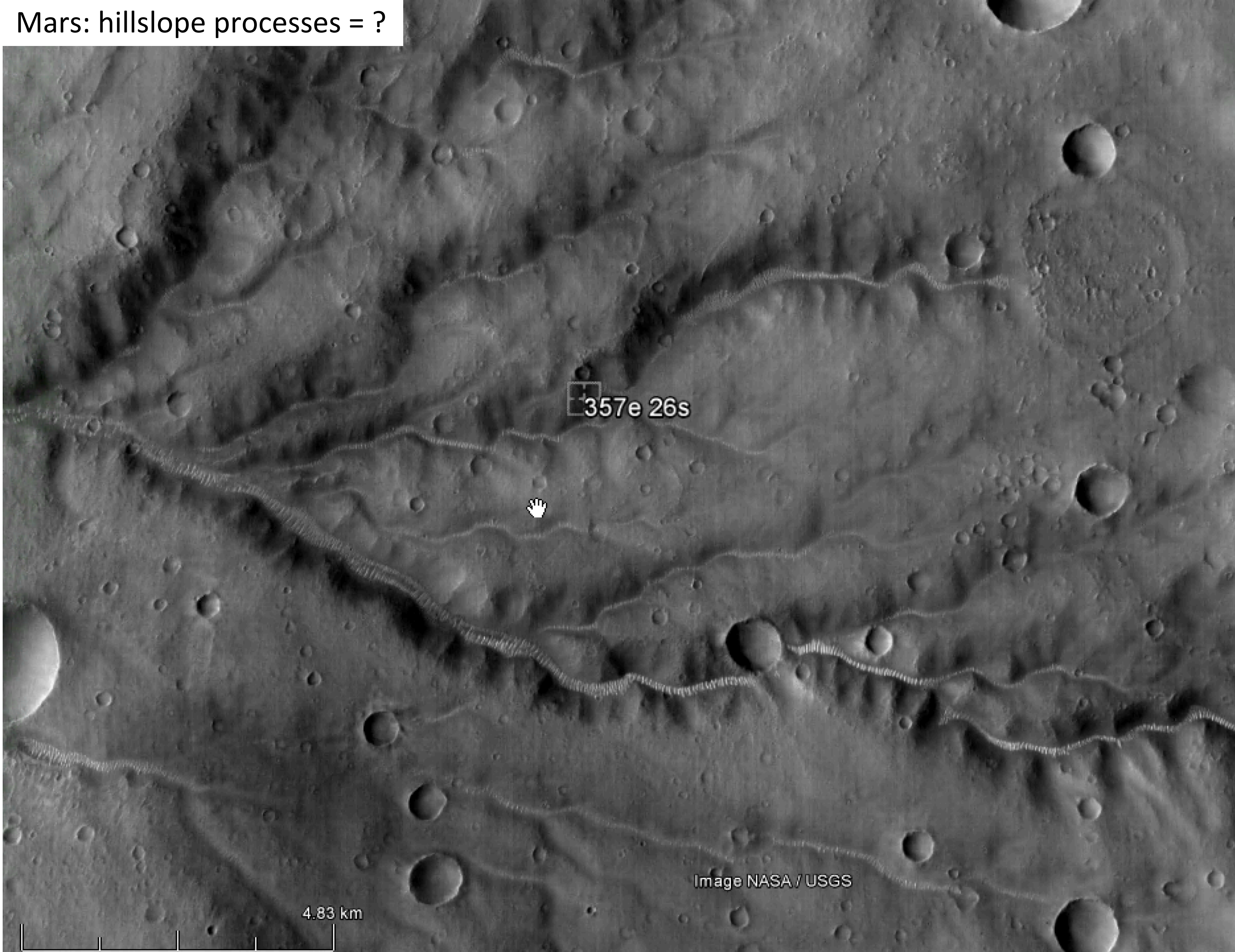
drainage density,

D_d = L/A (dimensions m^{-1})

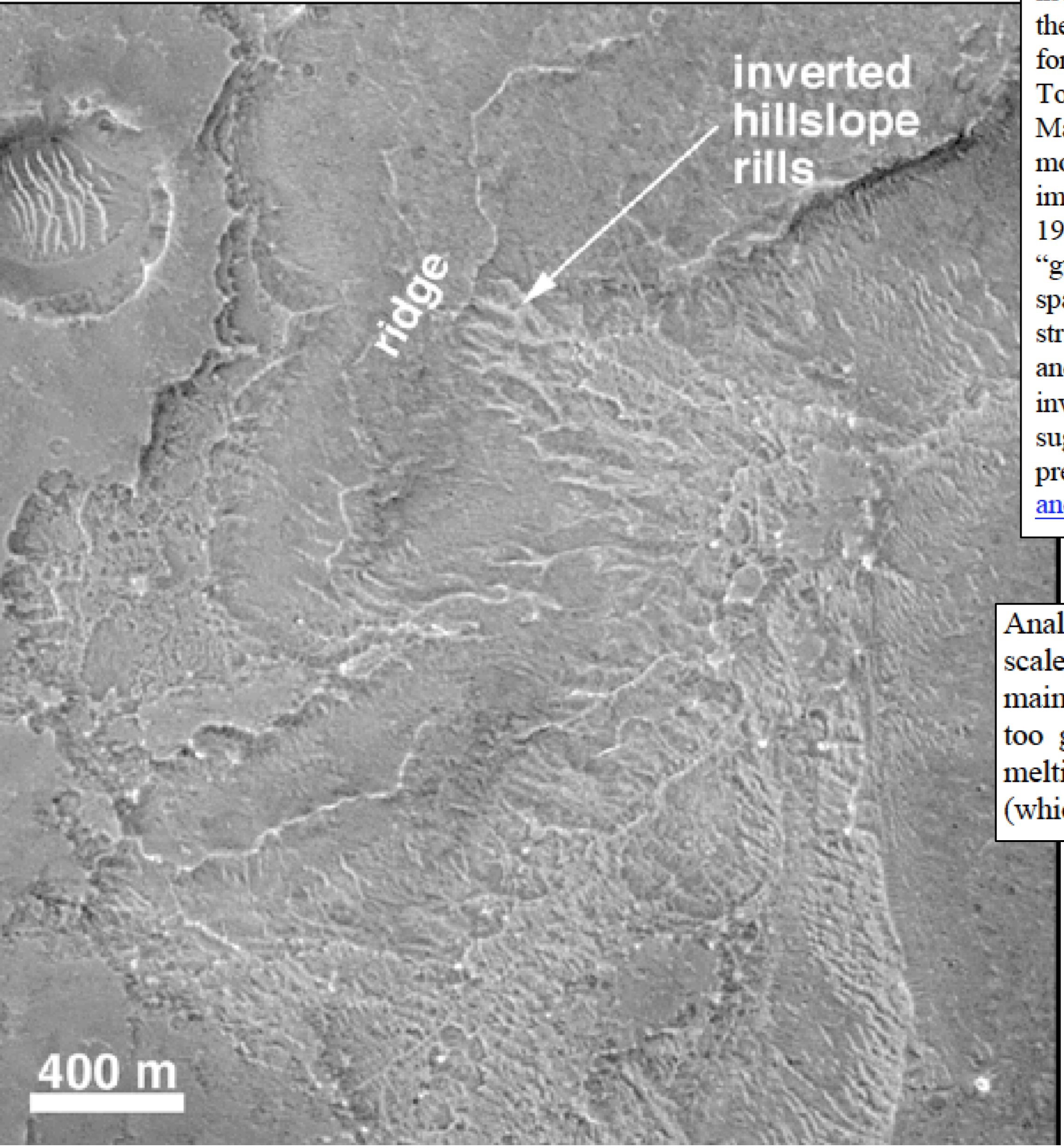
Central California: uniform lithology; saturation overland flow

Perron et al. Nature 2009 (required reading)

Mars: hillslope processes = ?



Drainage density D_d as a Mars process indicator?



Ancient streams and evidence for rainfall

Since their initial discovery in Mariner 9 images, many investigators have discussed and debated whether some of the fluvial valleys and their channels on Mars might have formed from precipitation-fed runoff (rainfall or snowmelt). To have "smoking gun" evidence that it once rained on Mars, one would need to find a mudstone or siltstone (or, more rarely, a sandstone) in which the crater-like impressions of raindrops have been preserved (Twenhofel 1926). From orbit, the best that can be hoped for—*i.e.*, a "gun," although not a "smoking gun"—is to locate high spatial density hillslope rills that merged to form larger streams, which in turn were tributaries to still larger streams, and so forth. This was a major objective of the MOC investigation when it was proposed in 1985, but initial results suggested that no such rills and low-order streams had been preserved at the planet's surface (Malin and Carr 1999, Carr and Malin 2000).

Analysis and comparison to terrestrial streams of the same scale indicate that the volumes of liquid needed to form and maintain runoff streams on these hillslopes would have been too great for them to have formed by the slow trickle of melting snow (Williams et al. 2005). Rainfall or springs (which require precipitation for recharge) are more likely.

Malin et al. 2010 *Mars Journal*

Steady state hillslope

What is soil? → Horizontally mobile layer
→ practical: No relict bedrock texture visible

$Q_{soil} = c\ S$

$dz/dt = k_1 * (Q_{in} - Q_{out})$

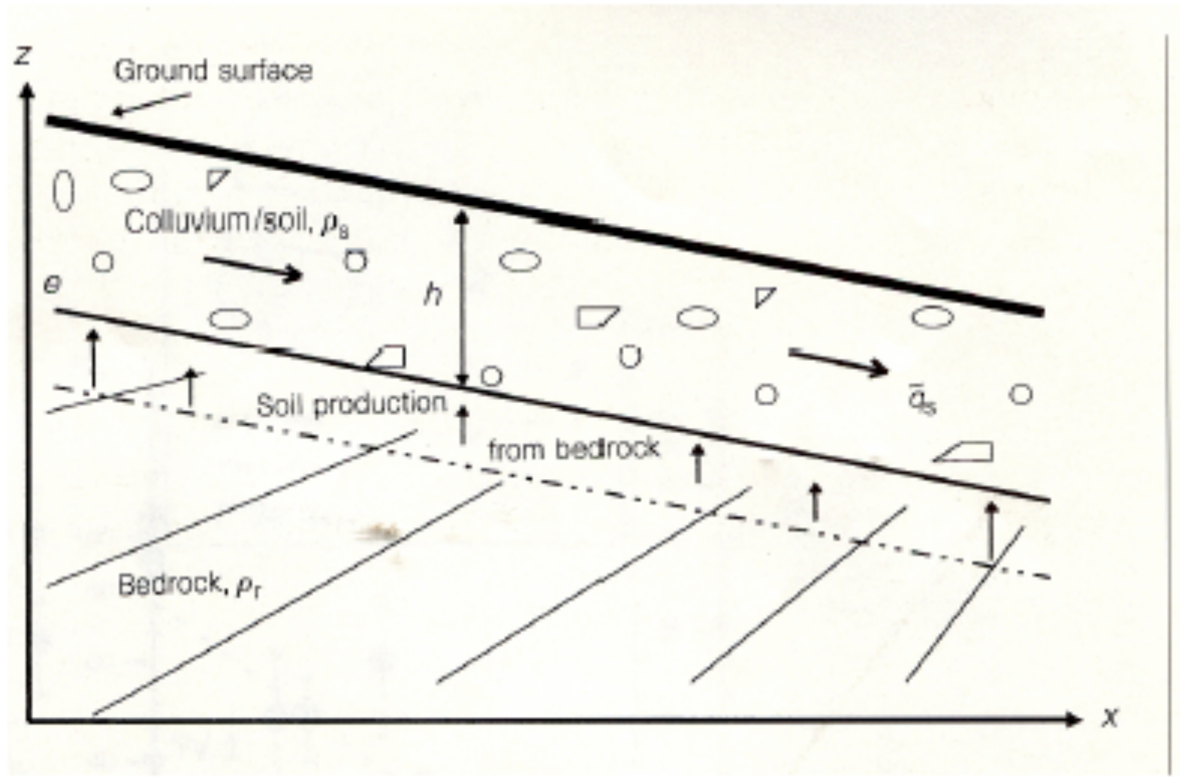
$dz/dt = k_2 * (c\ S_{up} - c\ S_{down})$

Topographic change is proportional to curvature.

$$\frac{\partial z}{\partial t} = -\nabla \cdot \mathbf{q}$$

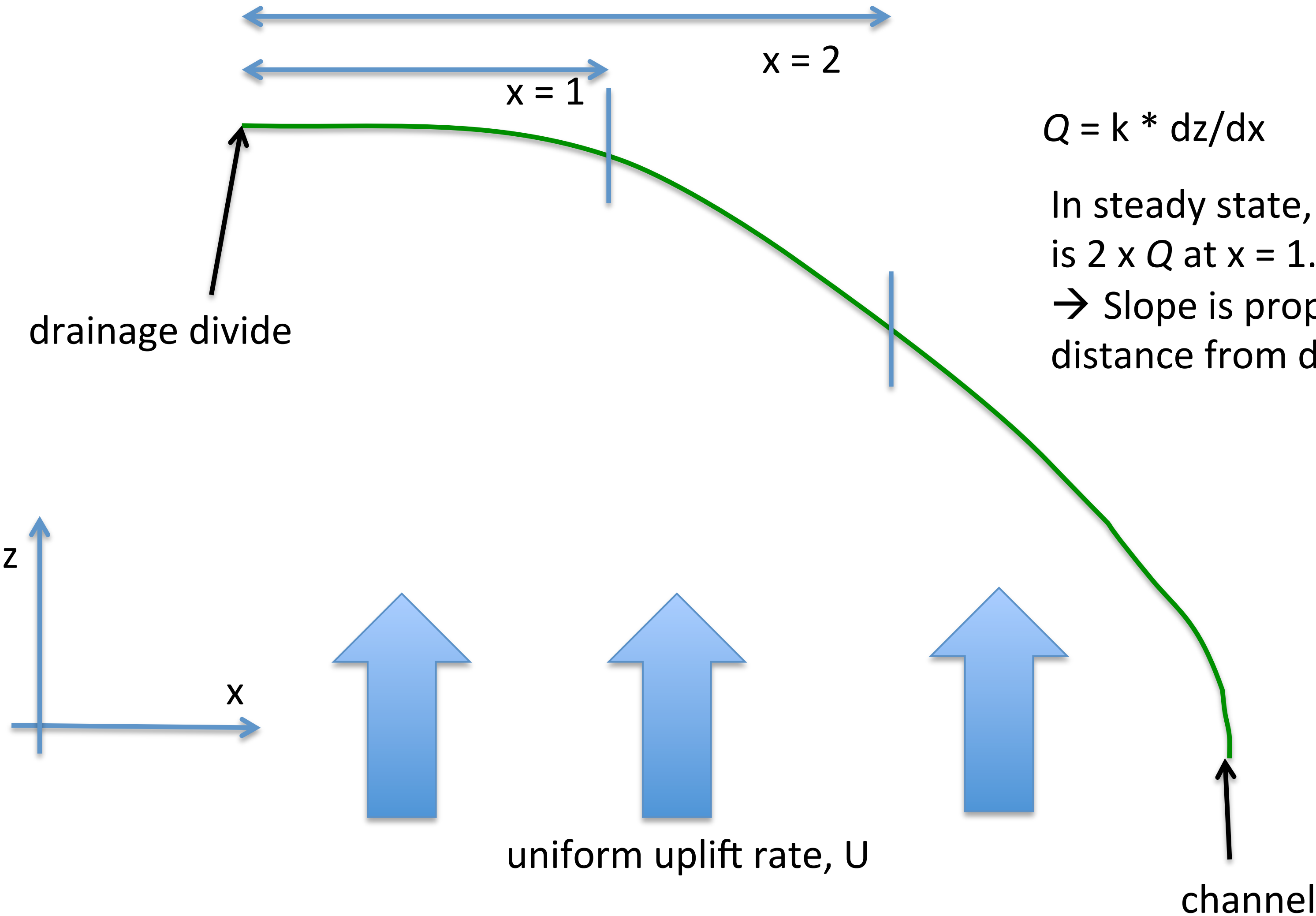
All the interesting processes are buried in k_0!

$$\frac{\partial z}{\partial t} = k_0 \nabla^2 z$$



Nonlinear hillslope diffusion can occur (not emphasized in this course.)

Steady state hillslopes are convex



Q = k * dz/dx

In steady state, *Q* at x =2
is 2 x *Q* at x = 1.
→ Slope is proportional to distance from drainage divide.

Drainage density is set by a competition between diffusive (hillslope) and advective (channelizing) processes

hillslope processes

fluvial erosion

eroding part of the landscape

$$\frac{\partial z}{\partial t} = k_0 \nabla^2 z - K A^m \left|\nabla z\right| + U$$

diffusivity

contributing area

n=1

tectonic uplift

For large *A* (and +ve *m*), 2nd term >> 1st term: fluvial erosion control → concave profile.
For small *A* (and +ve *m*), 1st term >> 2nd term: hillslope processes → convex profile.

Fluvial sediment transport vs. hillslope processes: what controls the spacing of rivers?

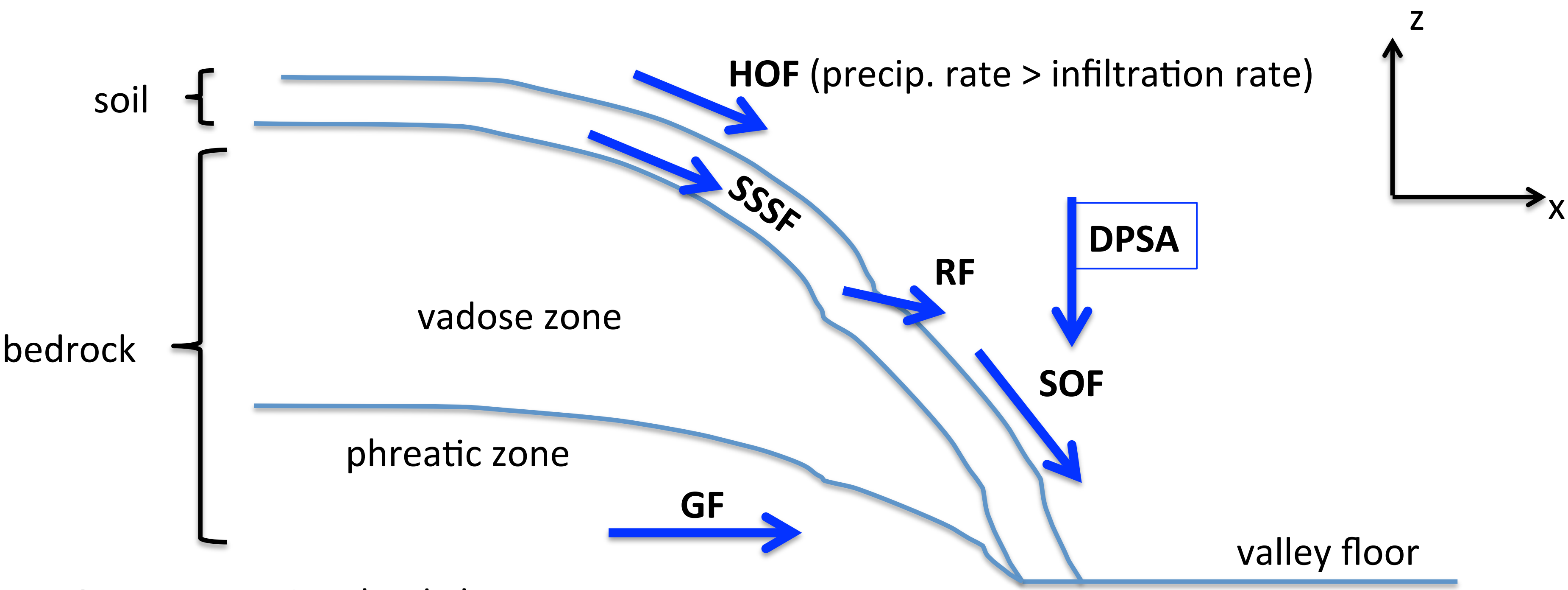
SETTING THE SPACING OF STREAMS

HILLSLOPE EROSION PROCESSES

SOIL PRODUCTION FUNCTION

SYNTHESIS: PERRON ET AL. 2009

The path of water dictates the process that erodes the landscape: Hillslope Hydrology



HOF – Horton Overland Flow
SSSF – Shallow Subsurface Storm Flow (*usually at soil-bedrock boundary*)
DPSA – Direct Precipitation on Saturated Areas
RF – Return Flow
GF Groundwater Flow
SOF – Saturated Overland Flow

Seasonal variation in flow mechanism may occur – e.g. some tuffs form clays when wet and deep

HOF – **Horton Overland Flow**

Badlands – fine-grained material

Australia – mature landscape – silcretes, gypcrete, calcrete.

Dirt roads

Cattle grazing

SOF – Saturated Overland Flow

Favored in poorly-drained valleys

SSSF – Shallow Subsurface Storm Flow (*usually at soil-bedrock boundary*)

Oregon - Coastal Oregon – Holes due to tree roots and mountain beaver. Steep, relatively straight slopes. Low-density (porous) soil.

(DPSA – Direct Precipitation on Saturated Areas)

GF Groundwater Flow

(Hawaii: fractured, permeable lavas Localised SSSF. No HOF).

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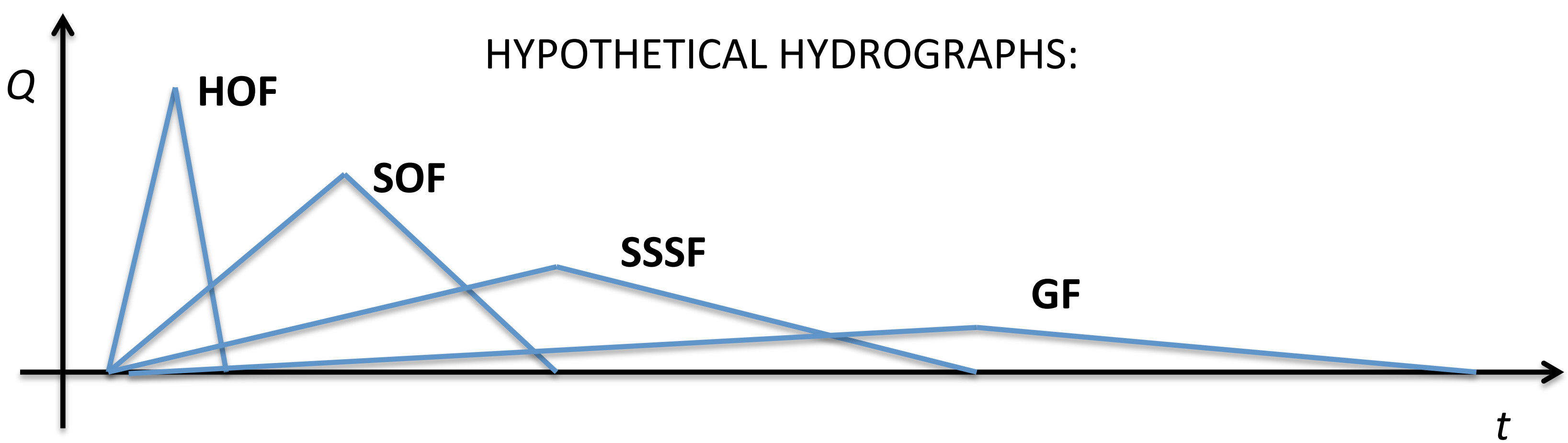
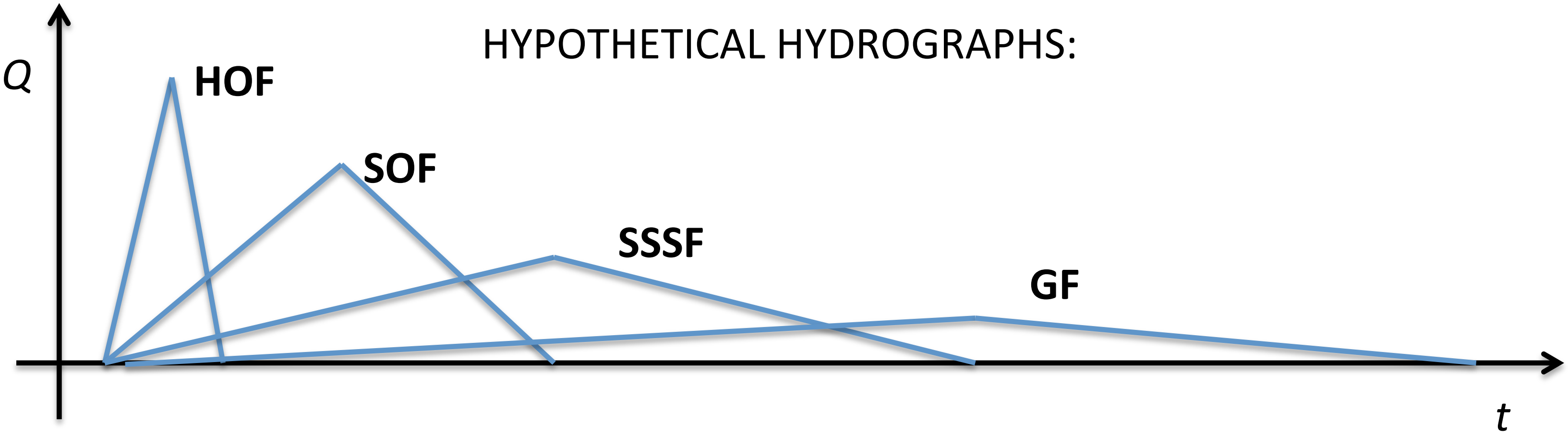
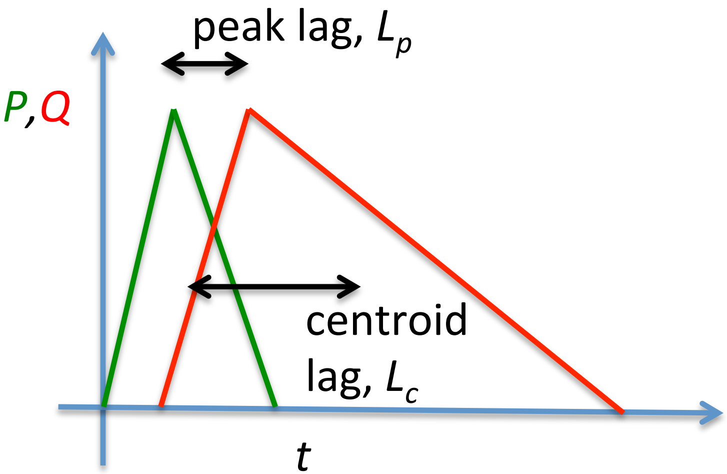
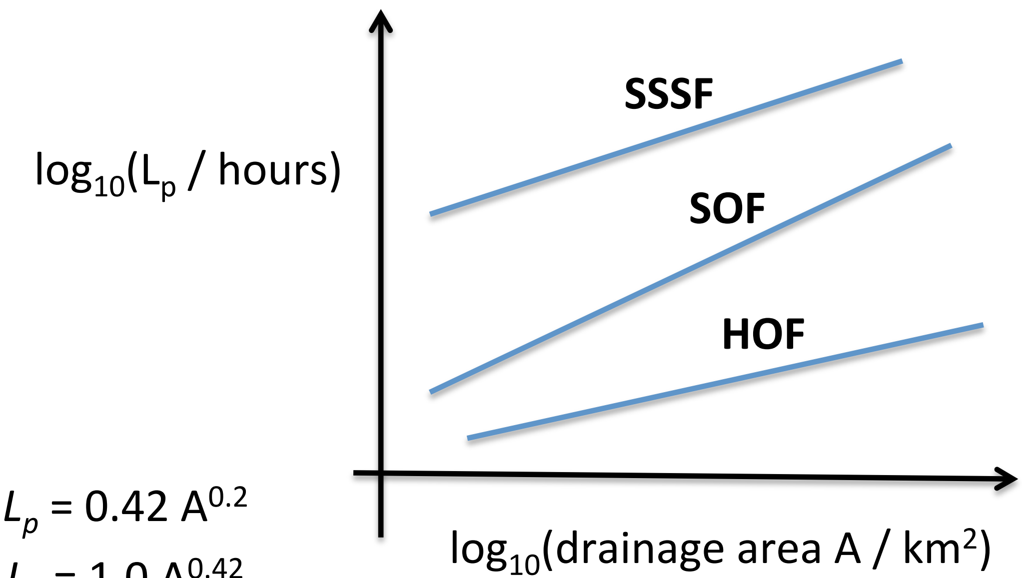


Hydrologic processes can be related to hydrograph shape





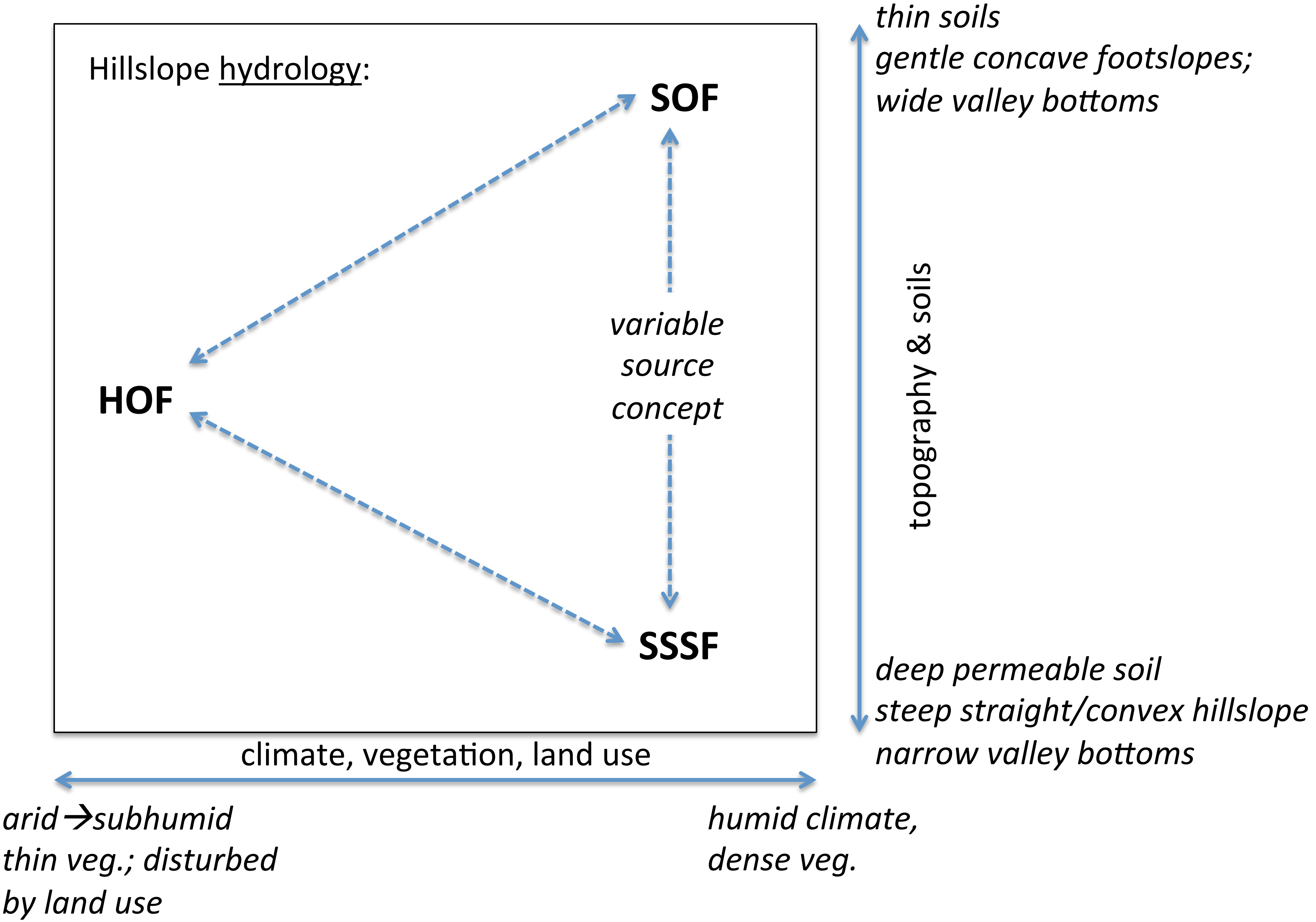


HOF: $L_p = 0.42\ A^{0.2}$

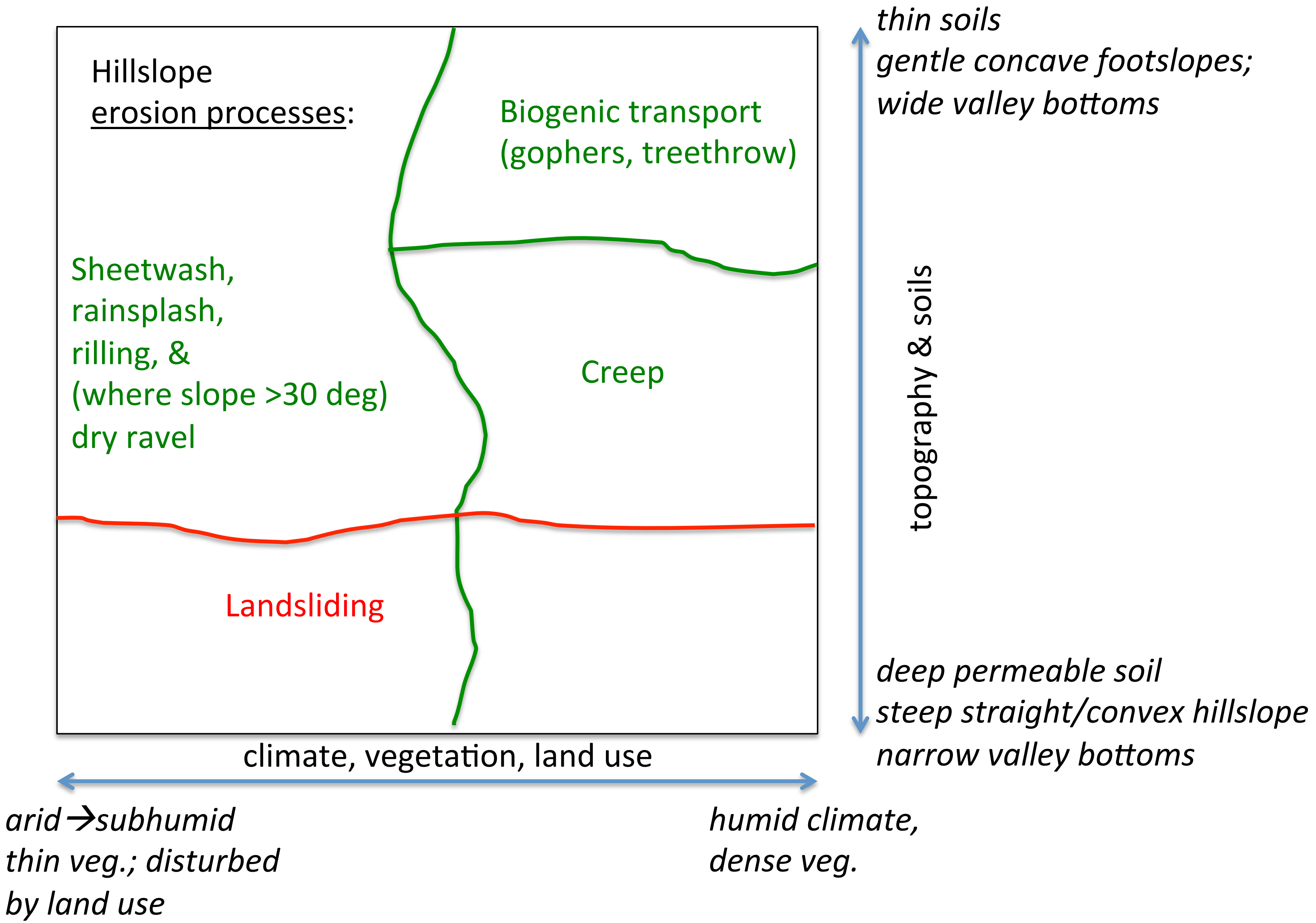
SOF: $L_p = 1.0\ A^{0.42}$

SSSF: $L_p = 18\ A^{0.26}$

compilation by Tom Dunne (UCSB)

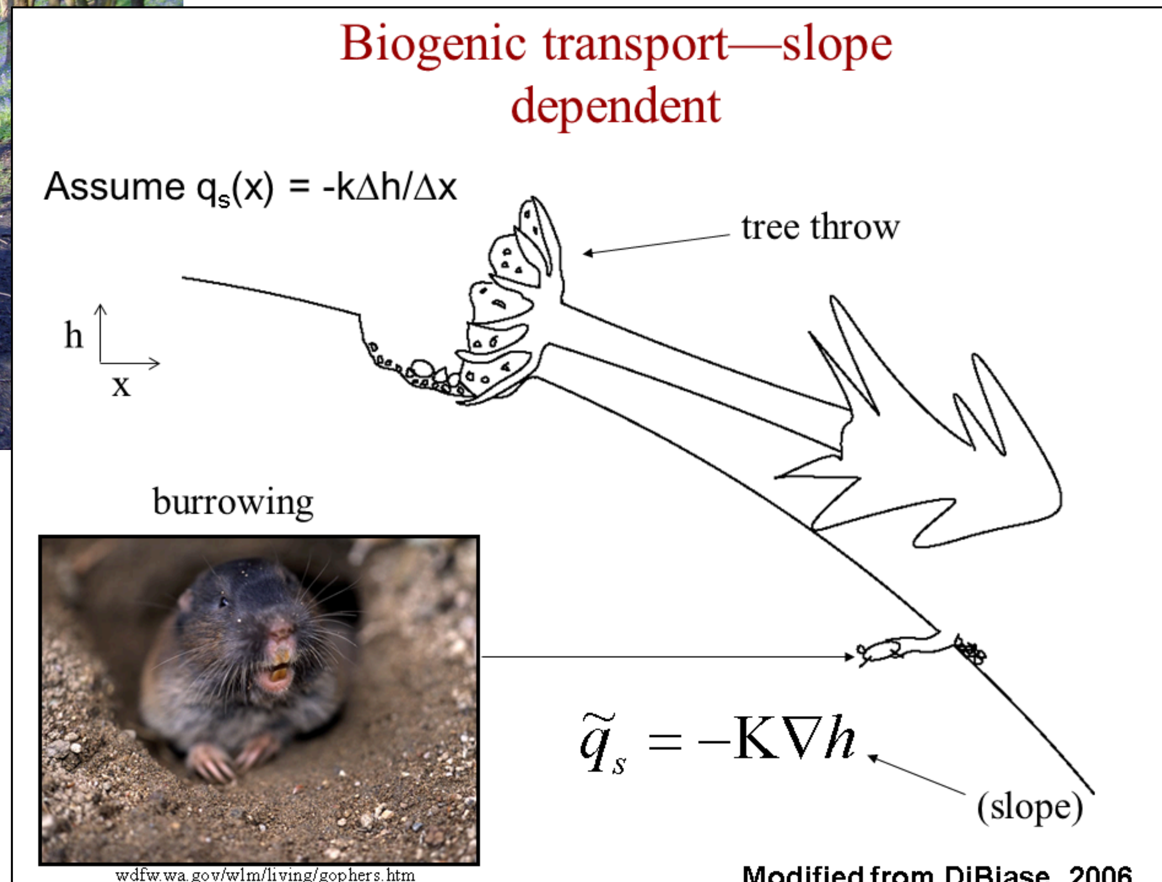


ideas by Tom Dunne (UCSB)



ideas by Tom Dunne (UCSB)

Biogenic transport: gophers + treethrow



Treethrow soil velocity of ~2 mm/yr for Pacific NW, Appalachians, Europe.
Soil thickness ~0.5 m, drainage density 6 km^{-1}
→ 20 tons / km^2 / yr

Ramon Arrowsmith

Global average erosion rate ~ global average uplift rate U = 0.05 mm/yr

Soil creep

Wetting/drying cycles
Clays expand perpendicular to slope; contract parallel to gravity.

Solifluction

Granular flow (dry ravel)

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HILLSLOPE EROSION PROCESSES

SOIL PRODUCTION FUNCTION

SYNTHESIS: PERRON ET AL. 2009

Weathering

="alteration of rocks and minerals by processes acting near or at the Earth's surface."

→ Changes in factors such as surface strength, permeability, particle size – which in turn affect the rate of mass removal.

Physical weathering processes: (1) stress release in rocks subject to high tectonic or overburden pressure

“curvature fracturing”(?) – Martel GRL 2006
Valley-bottom fracturing
Tensile secondary unloading joints
St. Clair et al. Science 2015

Physical weathering processes: (2) thermal cycling (hot day, cold night → stress gradient)

Eppes et al. Nature Communications 2015

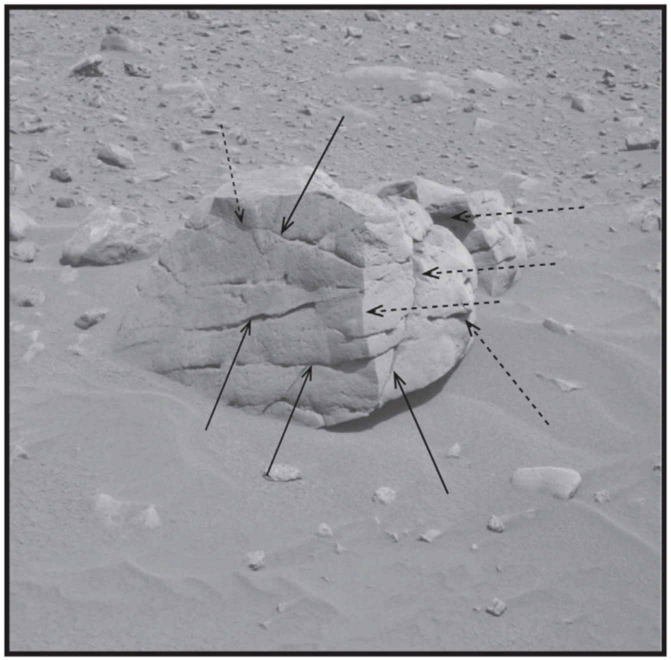


Figure 1 | Cracked rock on Mars. Example of a MER Spirit PANCAM image (data product 2p130443923eff0900p2555l7m1.img, Courtesy NASA/JPL-Caltech Planetary Data System) of a rock with visible cracks from the Martian surface. Image azimuth: 292°. Local True Solar Time: 10:45:08. Sol 46. Site 9. Solid arrows point to linear features that would meet our criteria for a crack (Methods). Dashed arrows point to features such as edges or wide voids that would not meet our criteria for a crack.

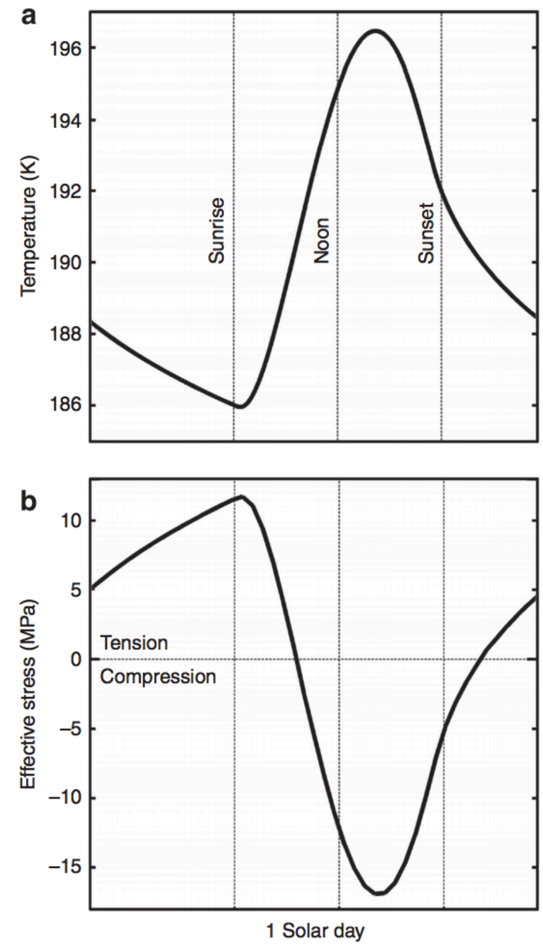


Figure 7 | Numerical model results. Results from our modification of a pre-existing model[38] to calculate solar-induced thermal stresses arising in the surface of a subaerially exposed Martian rock (see Methods for details). (**a**) Surface temperatures calculated over one solar day for a microstructure found in an idealized basalt located at a longitude of 0° and the latitude (15°S) of the Spirit traverse. (**b**) Calculated thermoelastic stresses induced within the microstructure throughout the solar day for the same rock using the temperatures derived for **a** above as inputs.

Physical weathering processes: (3) hydration (wetting and drying)

Swelling of micas → gruss on granites

Swelling of mudstones → clay

(4) growth in voids (frost, salt)

Hydrofracturing: thermochemical process at frost tip, not volume change

(5) Physical breakdown due to biota

Root growth, tree throw, burrowing

(6) Abrasion and comminution during transport

Discussed in previous lectures.

Chemical weathering processes:

(1) solution

Partial or complete dissolution of a mineral in a solvent; $NaCl \rightarrow Na^+ + Cl^-$

(2) hydration

Hydrolysis: addition of H2O to mineral; CaSO4 + nH2O → CaSO4.nH2O

(3) hydrolysis

Chemical reaction due to H+ or OH- ions in water; i.e., water is reactant not just a solvent. E.g. albite $NaAlSi_3O_8 + nH_2O \rightarrow Na^+ + OH^- + 2H_4SiO_4 + (1/2)Al_2Si_2O_5(OH)_4$ kaolinite.

(4) chelation

Organic process by which metallic cations are incorporated into hydrocarbon molecules.

(5) oxidation/reduction

e.g. reddening of soils (ferrous → ferric)

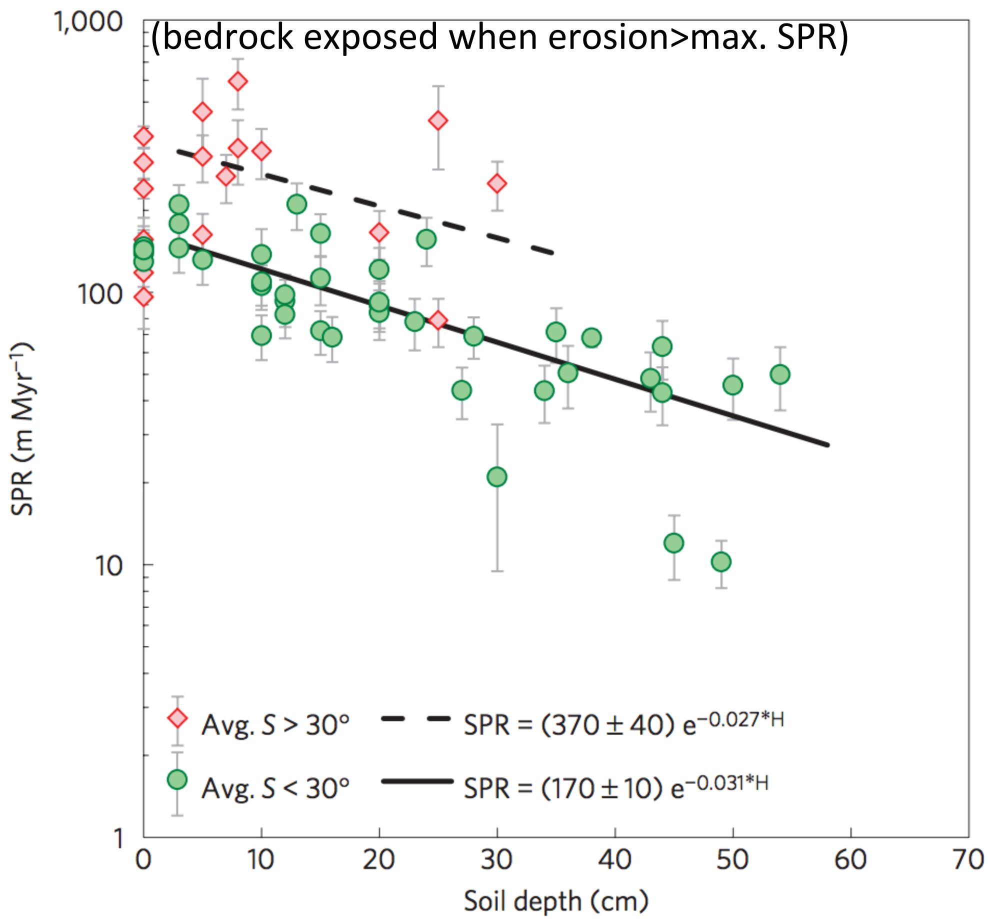
(6) carbonation

generation of bicarbonate ion and carbonic acid and its reaction with minerals.

Also: microbially mediated processes; pH due to respiration can be as low as pH 4.5 (this accelerates silicate weathering).

Soil Production Rate (SPR)

Heimsath et al., Nature Geoscience 2012



Soil production rates quantified using cosmogenic ^{10}Be
(5 atoms/g/yr at sea level)

Earlier “humped” SPR functions now considered dubious

Transport-limited hillslope evolution is well understood;
Weathering-limited hillslopes (e.g., Sierra Nevada) not well understood.

but see Larsen et al. Science 2014 for the claim that there is no speed limit on soil production

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HILLSLOPE EROSION PROCESSES

SOIL PRODUCTION FUNCTION

SYNTHESIS: PERRON ET AL. 2009

$$\frac{\partial z}{\partial t} = D\nabla^2 z - KA^m\left|\nabla z\right| + U$$

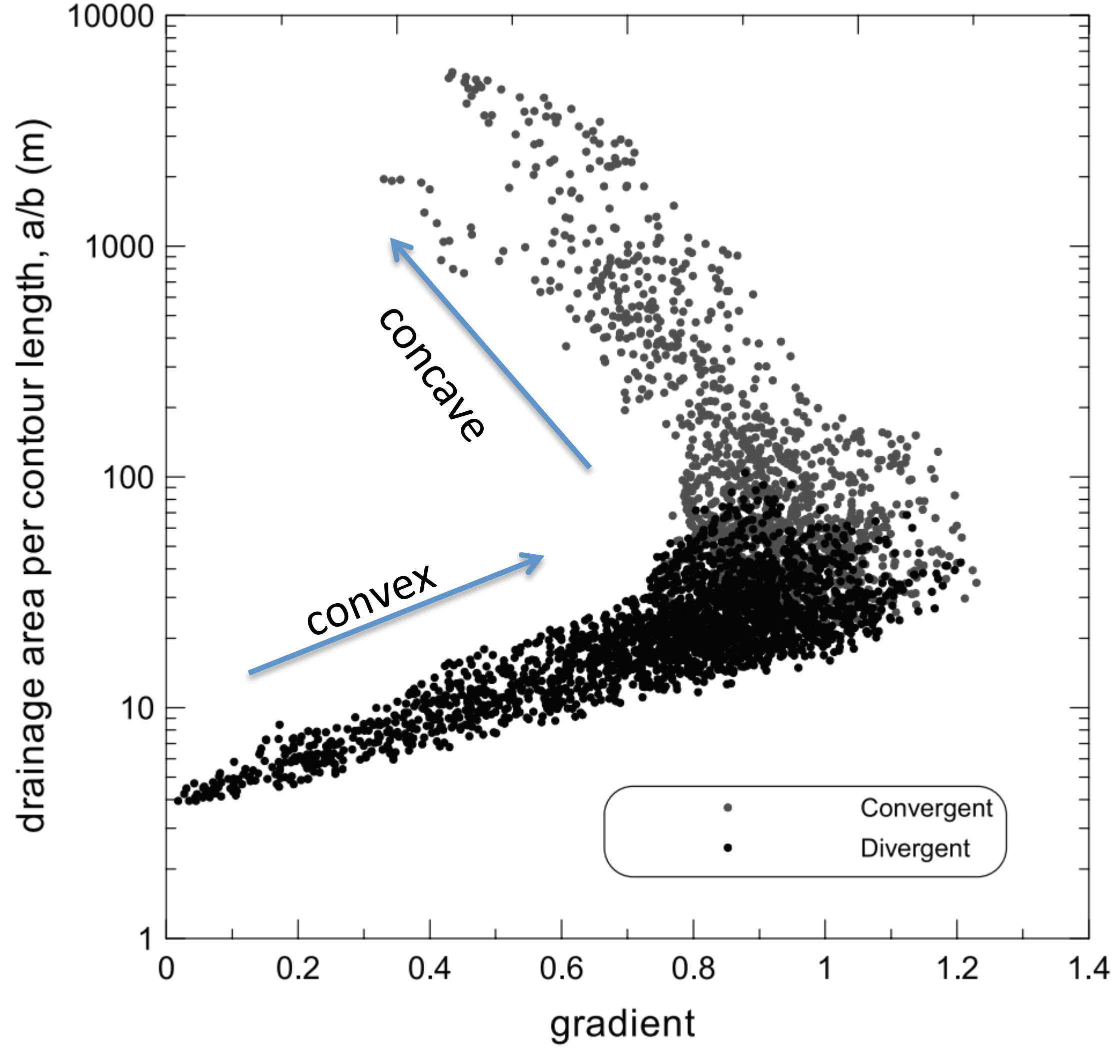


Figure 3. The variation of drainage area per grid cell size with local gradient for an entire small basin. Black dots represent terrain with divergent curvature, which are the hillslopes, and the gray dots are the convergent terrain. Values are calculated from topography gridded to 4m, hence the smallest a/b is 4m (from Roering et al., 1999).

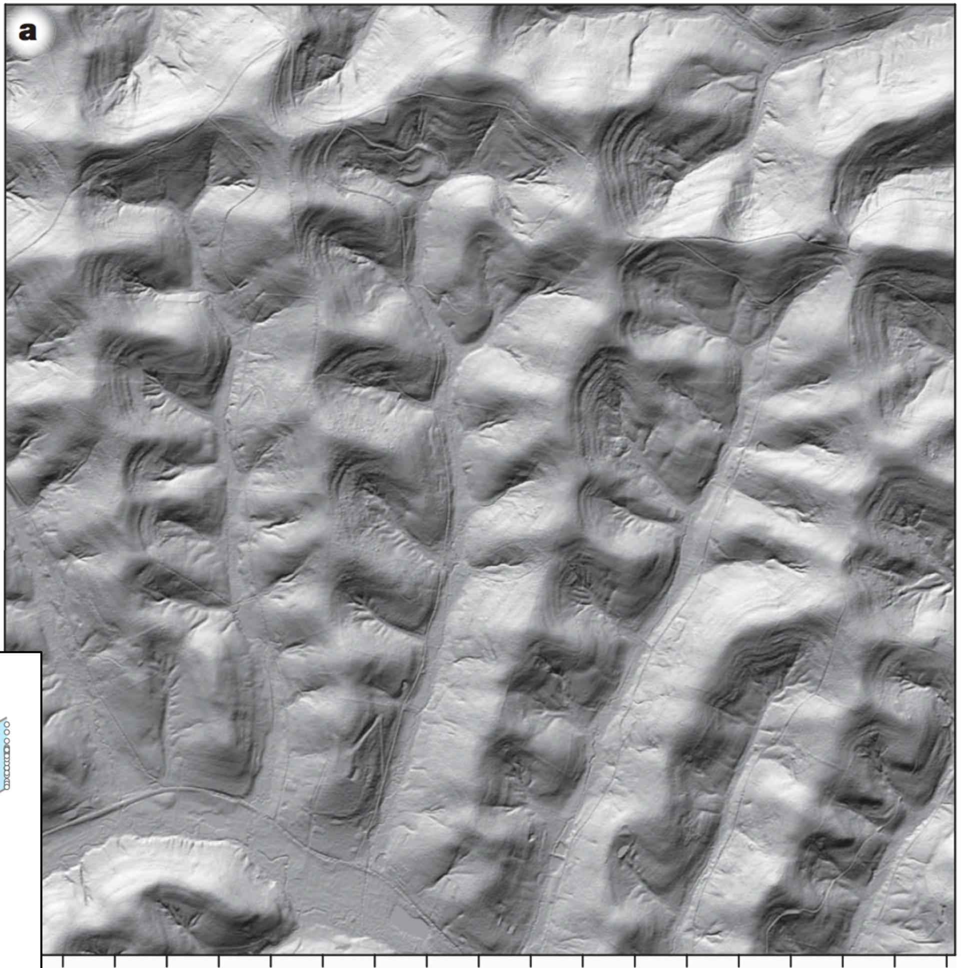
Dietrich et al. 2003
(supplementary reading)

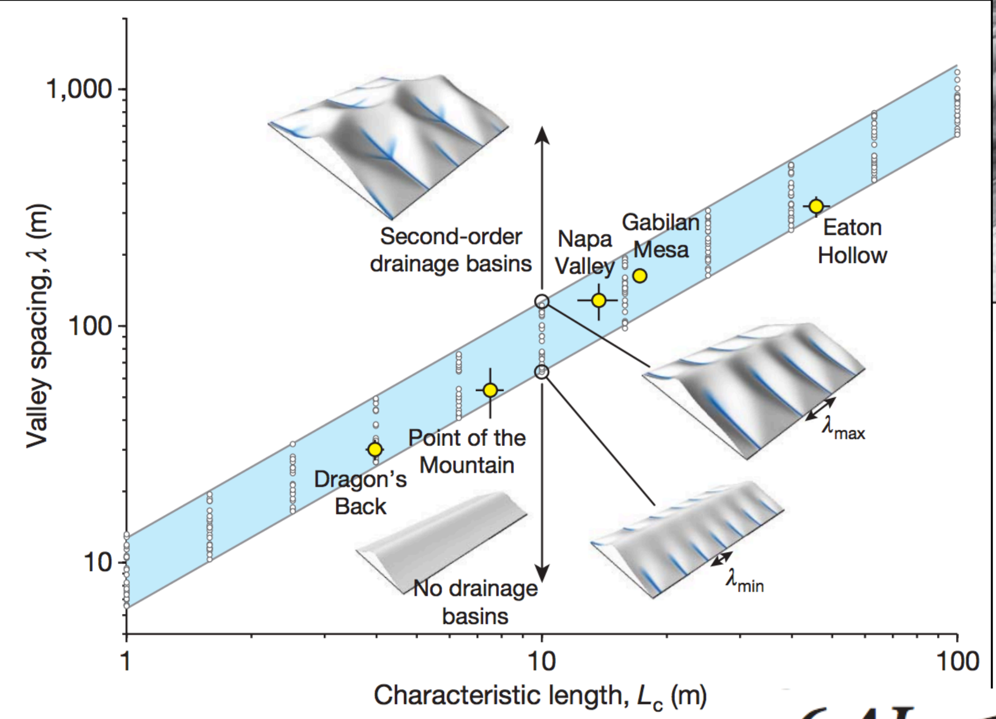
$$\frac{\partial z}{\partial t} = D\nabla^2 z - KA^m |\nabla z| + U$$

$$\mathrm{Pe} = \frac{KL^{2m+1}}{D}$$

Set Pe = 1, solve for *L*:

$$L_c = \left(\frac{D}{K}\right)^{\frac{1}{2m+1}}$$





$$6.4L_c \leq \lambda \leq 12.7L_c$$

Key points from today's lecture

- Explain mechanistically how streampower landscapes can act as a tectonic tape-recorder Explain why steady-state hillslopes are convex.
- Explain 2 or more hillslope transport processes.
- Know 2 or more physical and 2 or more chemical weathering processes.
- Understand how Peclet number can quantify competition between hillslope processes and fluvial channelization (see also required reading).

Backup slides

Transient hillslope evolution

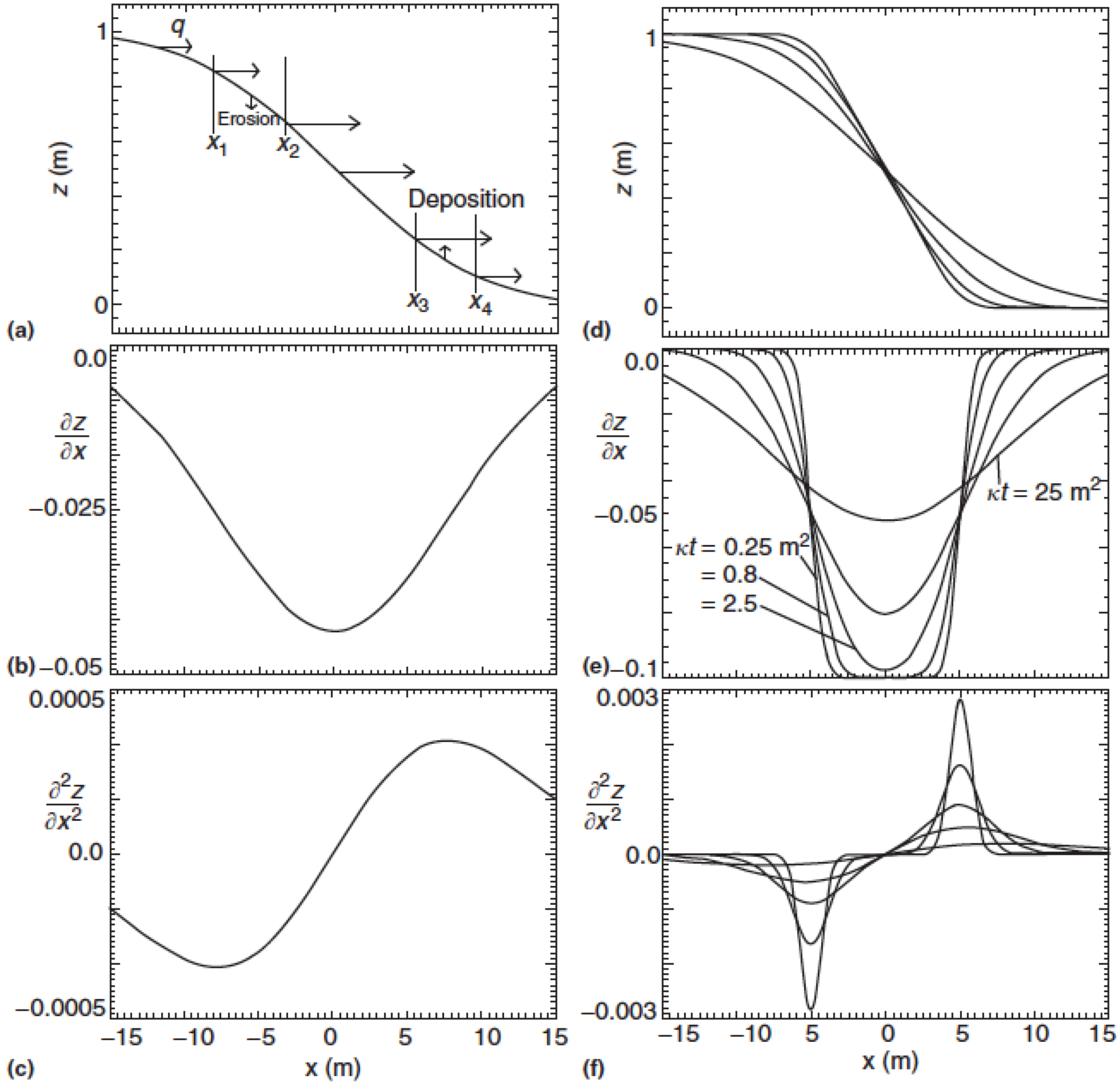


Figure 2 Evolution of a topographic scarp, illustrating (a) elevation, (b) slope, and (c) curvature. In (a), arrows of varying length represent the sediment flux at each point. In the diffusion model, the flux is proportional to the local slope, and the resulting raising or lowering rate of the surface is proportional to the change in flux per unit length, which, in turn, is proportional to the curvature. (d)–(f) Graphs of elevation, slope, and curvature for 5 times following scarp offset ($\kappa t = 0.25$, 0.8, 2.5, 8, and 25 m^2). Modified with permission from Pelletier, J.D., 2008. Quantitative Modeling of Earth Surface Processes. Cambridge University Press, Cambridge.

Pelletier, 2008, ch. 2; also Pelletier, 2013