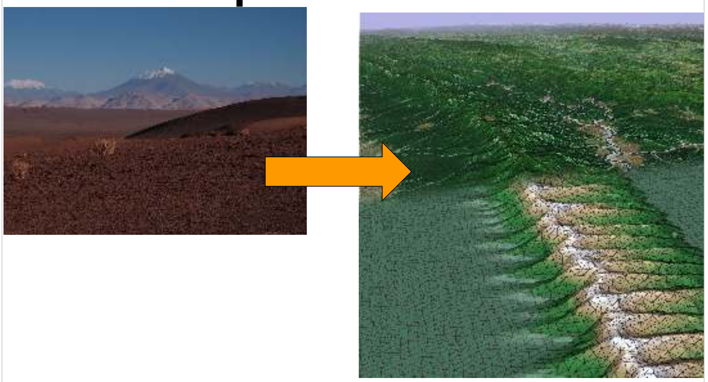
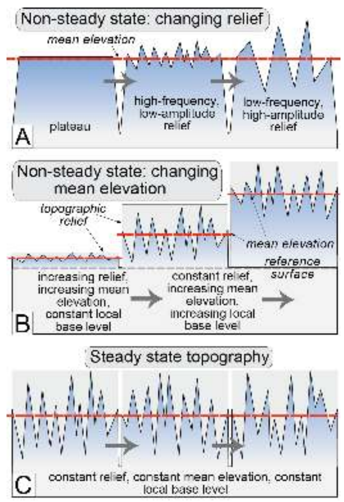
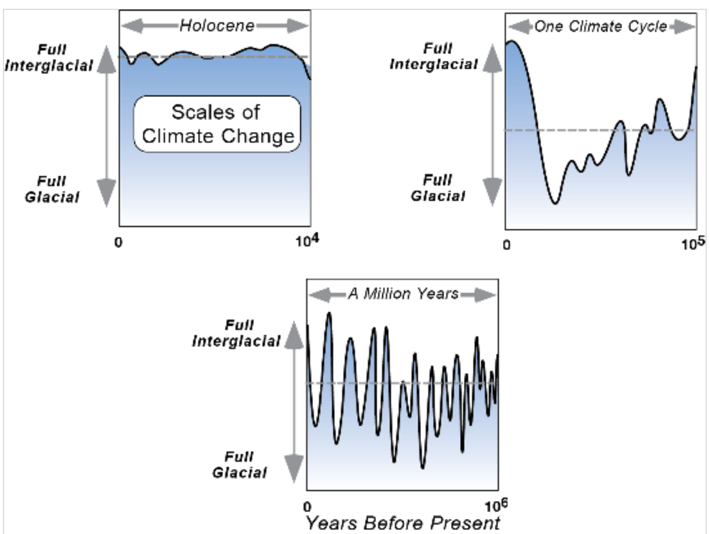
IITGn Workshop Quantitative Geomorphology:
Landscape Evolution Models

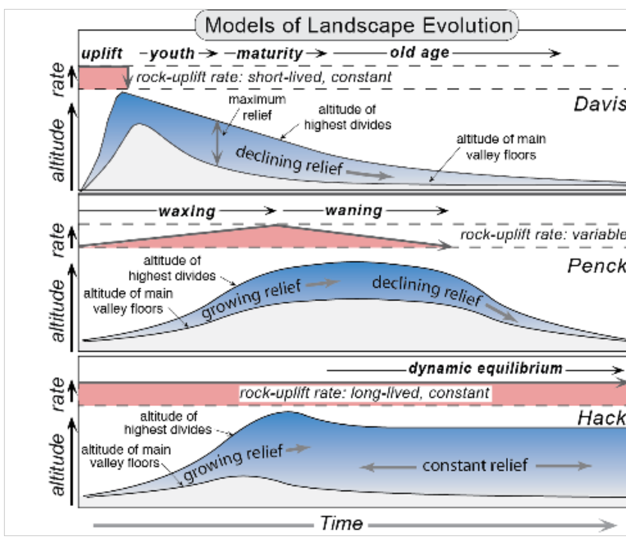


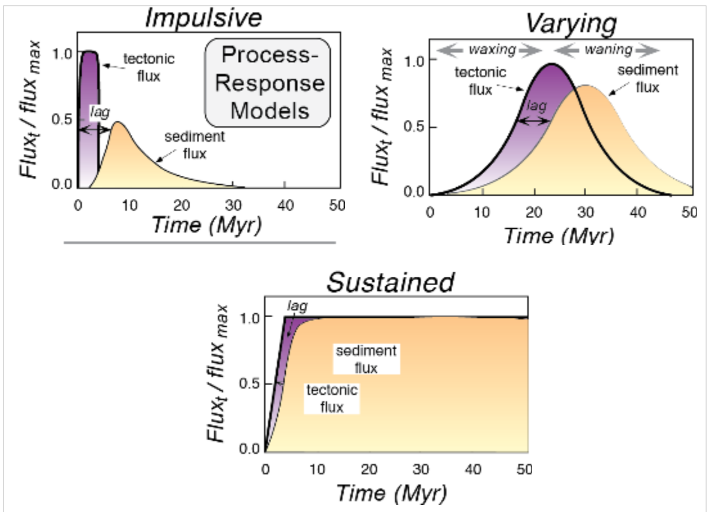
1. Landscape Evolution Models (LEMs)



Long-Timescale Changes with LEMs

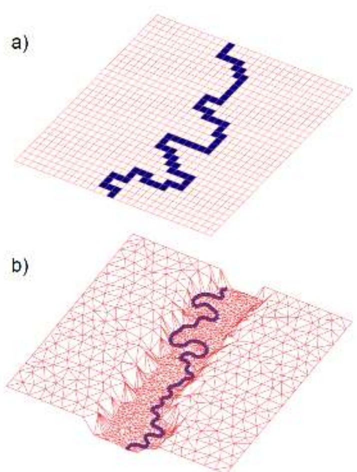






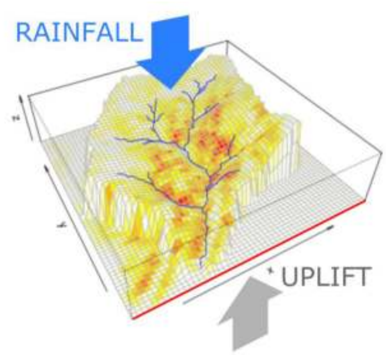
Useful Literature

- **Comparison and Summary:** http://geomorphology.org.uk/sites/default/files/chapters/5%206%2012_LEM.pdf
- http://onlinelibrary.wiley.com/doi/10.1002/esp.4162/full
- **Landlab website**: http://landlab.github.io/#/
- **SIGNUM:** http://www.sciencedirect.com/science/article/pii/S009830041100392X?via%3Dihub
  (simple, Matlab-based LEM)



Comparison of two terrain-discretization approaches:

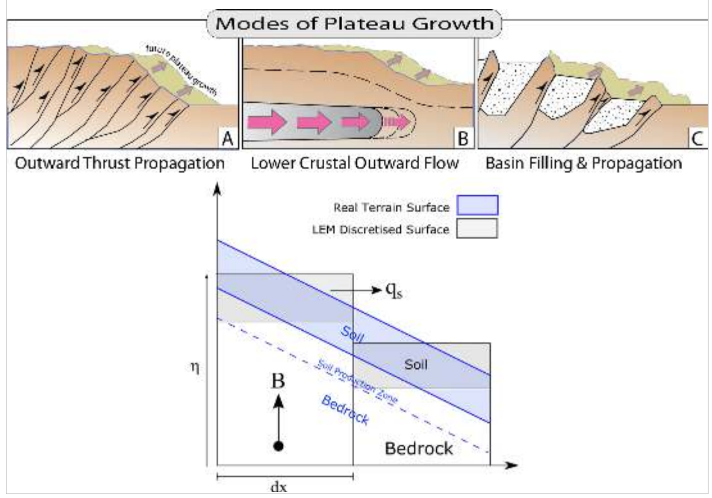
- Regular, rectangular gridded discretization
- TIN (Triangulated Irregular Network), with adaptive re-meshing (Tucker et al., 2001).



Main components and boundary conditions of a Landscape Evolution Model.

Table 1. Partial list of numerical landscape models published between 1991 and 2005.

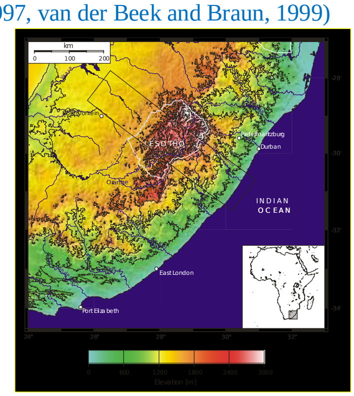
Model	Example reference	Notes
SIBERIA	*Willgoose et al.* (1991)	Transport-limited; Channel activator function
DRAINAL	*Beaumont et al.* (1992)	"Undercapacity" concept
GILBERT	*Chase* (1992)	Precipiton
DELIM/MARSSIM	*Howard* (1994)	Detachment-limited; Nonlinear diffusion
GOLEM	*Tucker and Slingerland* (1994)	Regolith generation; Threshold landsliding
CASCADE	*Braun and Sambridge* (1997)	Irregular discretization
CAESAR	*Coulthard et al.* (1996)	Cellular automaton algorithm for 2D flow field
ZSCAPE	*Densmore et al.* (1998)	Stochastic bedrock landsliding algorithm
CHILD	*Tucker and Bras* (2000)	Stochastic rainfall
EROS	*Crave and Davy* (2001)	Modified precipiton
TISC	*Garcia-Castellanos* (2002)	Thrust stacking
LAPSUS	*Schoorl et al.* (2002)	Multiple flow directions
APERO/CIDRE	*Carretier and Lucazeau* (2005)	Single or multiple flow directions



CASCADE

(Braun & Sambridge, 1997, van der Beek and Braun, 1999)

Example 1: SE African margin (van der Beek et al., 2002)



Margin formed during rifting 130 Ma ago. Height of topographic scarp ~1.5 km

CASCADE

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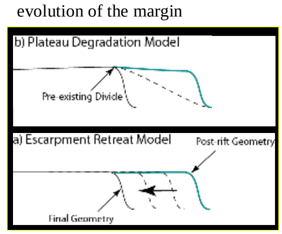
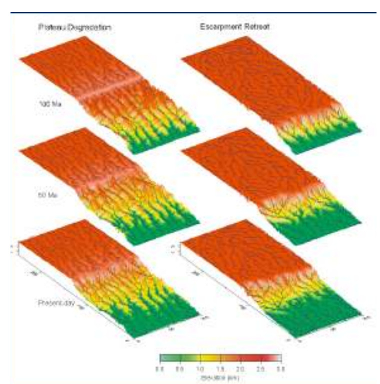
Example 1: SE African margin (van der Beek et al., 2002)

Aim: discrimination between 2 end-member models for the evolution of the margin





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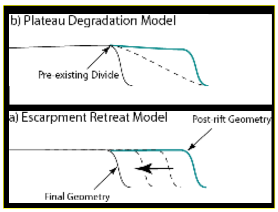

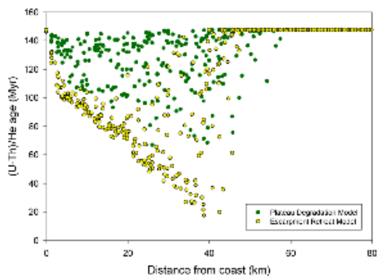

Coupling with thermal model for the lithosphere

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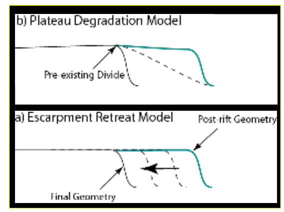

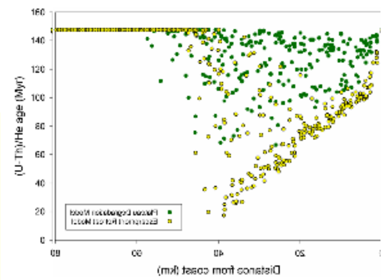

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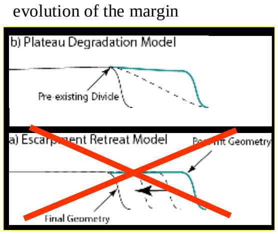
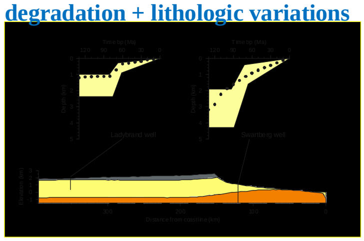
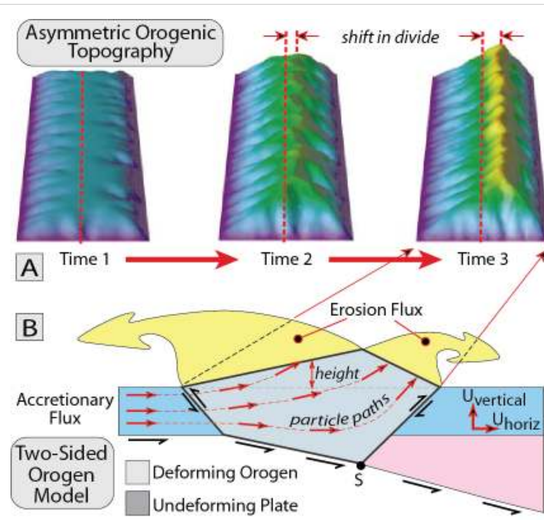
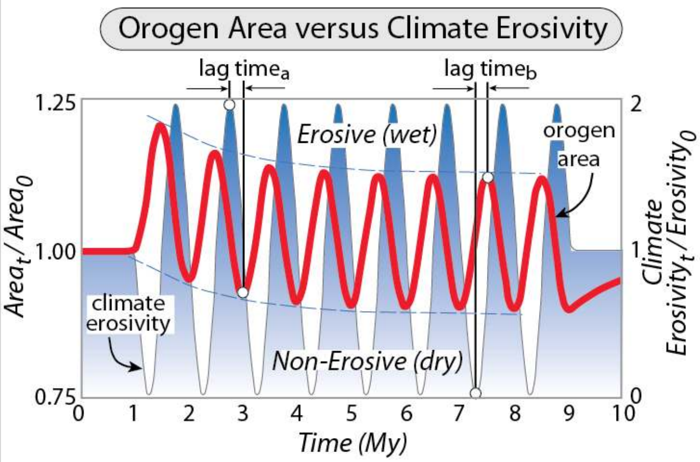


Preferred model: plateau degradation + lithologic variations





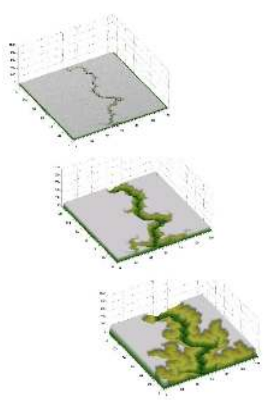


Components to Landscape Evolution Model

Formulations for:

1) Continuity of mass
2) Runoff generation and Routing of water
3) Erosion-Transport laws for hillslope sediment
4) Erosion-Transport laws for river sediment

Landscape evolution model



Continuity of mass:
(e.g., Kirkby, 1971)

$$\frac{\partial \eta}{\partial t} = U - \nabla \mathbf{q}_s$$

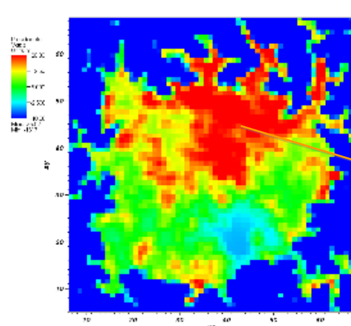
Transport / erosion laws:
(e.g., Dietrich et al., 2003)

$$\mathbf{q}_s = f_1(\eta, R) + f_2(Q, S, W, D, n)$$

Gravity-driven (e.g., landslides)

Water-driven (e.g., river networks)

Simple Case: Raster Model



Any cell receive water and mass flux from 'upstream' cells, so we need to know drainage pattern

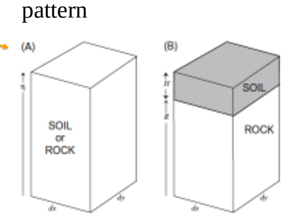


Figure 3. Two control volumes for continuity of mass. (A) Uniform substrate. (B) Division between regolith (or soil) and bedrock, with a regolith layer of time- and space-varying thickness.

'D8 Algorithm' for Drainage

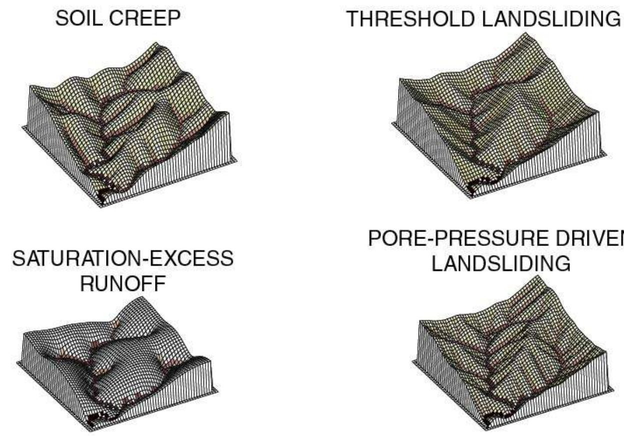
7	8	9
4	COI	6
1	2	3

We assume that water and mass flows into the direction of the steepest slope:

$$S = \arctan(\Delta z / d)$$

S = slope [-]
Δz= z_coi – z_neighbor [L]
d = distance [L]

What are the lengths, d, for the two potential drainage directions?



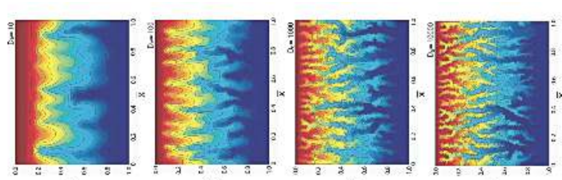
Tucker and Bras (1998)

Random Walk

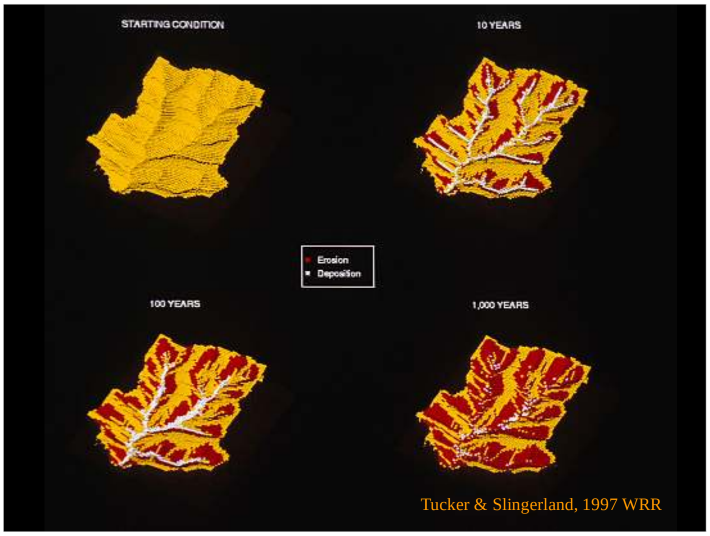
- Go out to a large open space and mark a spot on the ground. Take with you a coin.
- Stand on the spot and flip the coin. If the coin comes up heads, turn to the right and take a large step. If the coin comes up tails, turn to the left and take a large step.
- Keep doing this many times and see where you end up.

Smooth and rough landscapes

- Roughening: growth of rills and gullies
  - Less vegetation, more runoff, more erodible soils
- Smoothing: soil creep
  - Rapid soil mixing by plants and animals, ice growth in soil, and other processes

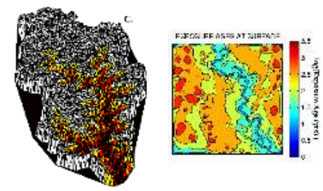


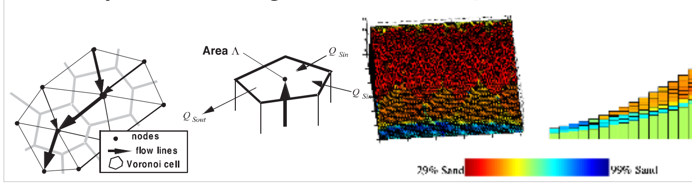
Simpson and Schlunegger (2003)



Channel-Hillslope Integrated Landscape Development (CHILD) model

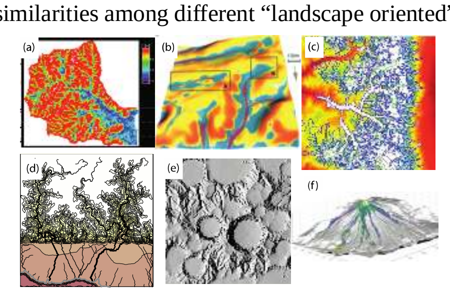
- MIT late 1990s
- Explore channel-hillslope coupling under varying climate
- Irregular mesh
- Written in C++
- Object-oriented design





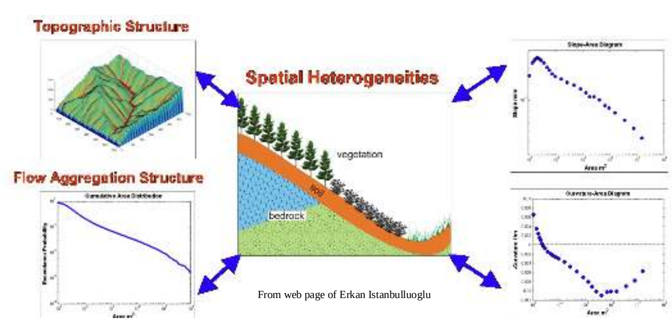
LANDLAB: landscape modeling library

Many similarities among different “landscape oriented” models

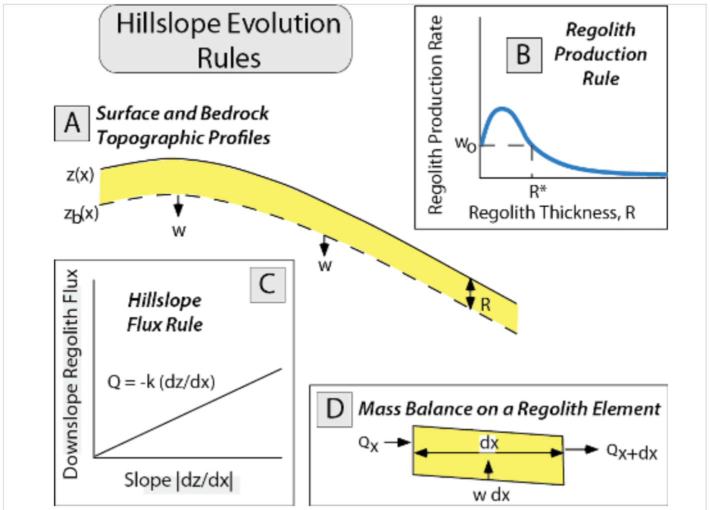


Use CHILD code to build common, shared components for mesh generation / management, water flow, erosion, vegetation, etc.

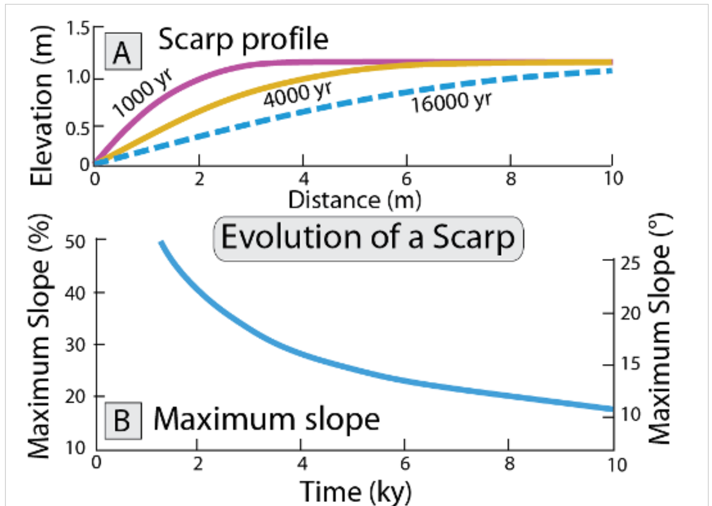
Interaction of vegetation, soil hydrology, and landscape evolution



Collins et al. (2004)
Istanbulluoglu and Bras (2005)



Burbank and Anderson, 2011, Tectonic Geomorphology, Chapter 11



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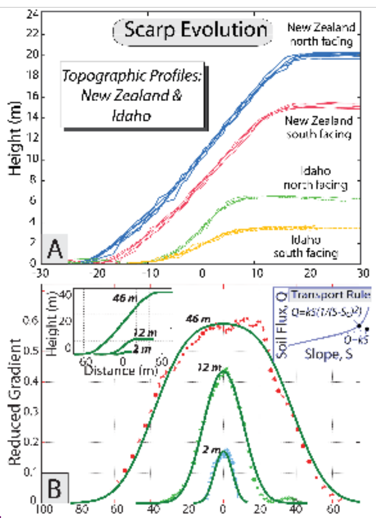

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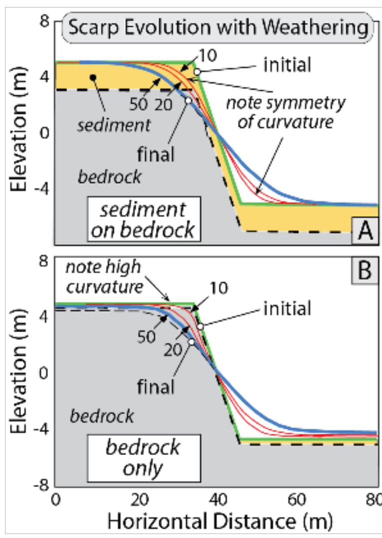

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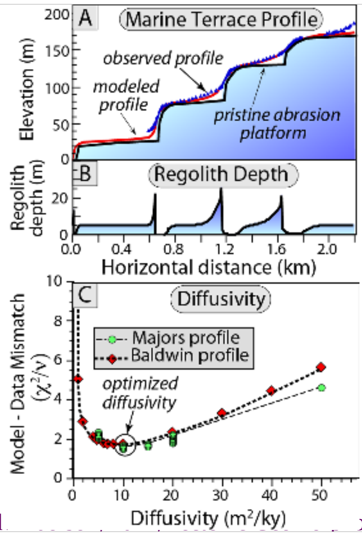

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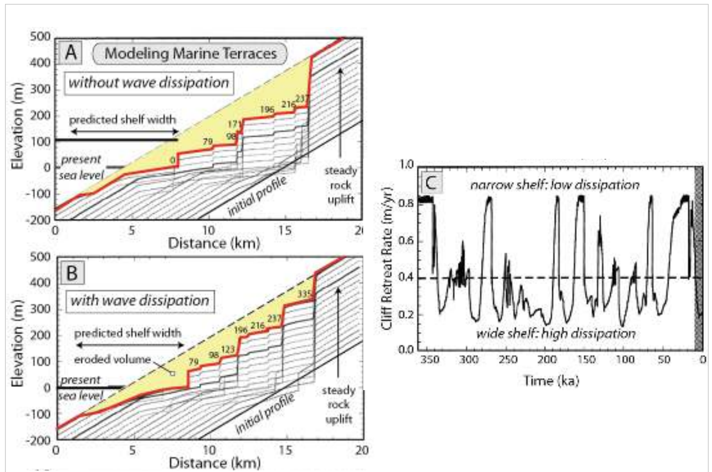

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Stochastic-threshold incision model
(Tucker & Bras, 2000)

- $K_{\tau c} = K_{\tau c}$ ($R_c/P \propto \tau_c/P$, A, S; varies from 0 to 1)

Bedrock Channel Incision Models

Basic Postulate

$$E = k_e(\tau - \tau_{cr})^a \quad \text{or} \quad E = k_e(\tau^a - \tau_{cr}^a)$$

$$E = K_{eff} A^m S^n$$

$$K_{eff} = K_r K_c \beta_{\tau_{cr}} \; ; \; n = \frac{2}{3}a \; ; \; m = \frac{2}{3}ac(1-b)$$

Stream Power Model

$$K_r = k_e k_w^{-2a/3} k_t^a$$
$$K_c = k_q^{2a/3(1-b)}$$
$$\beta_{\tau_{cr}} = 1$$

Empirical Relations

$$k_t = C_f^{1/3} \rho g^{2/3}$$
$$Q_r = k_q A^c$$
$$w_{bf} = k_w Q_{bf}^b$$
$$(w/w_{bf}) = (Q/Q_{bf})^s$$

Stochastic Model (Tucker and Bras)

$$K_r = k_e k_w^{2a/3} k_t^a$$
$$K_c = \langle P \rangle^{\gamma_b - \varepsilon_b} F_{var}^{\gamma_b - 1} \exp(-I/\langle P \rangle F_{var}) \Gamma(\gamma_b + 1)$$
$$\beta_{\tau_{cr}} = \frac{\left[\Gamma(\gamma_b + 1, R_c/P) - (R_c/P)^{\gamma_b} \exp(-R_c/P)\right]}{\Gamma(\gamma_b + 1)}$$

Exponents (Stochastic Model)

$$c = 1$$
$$\gamma_b = 2a(1-s)/3$$
$$\varepsilon_b = 2a(b-s)/3$$