Long-term landscape evolution: Linking tectonics and surface processes

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Collaboration

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- Academic and post-docs: Gordon Cook, Tim Dempster, Derek Fabel, Trevor Hoey, John Jansen, Fin Stuart, Peter van der Beek

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Natural Environment Research Council

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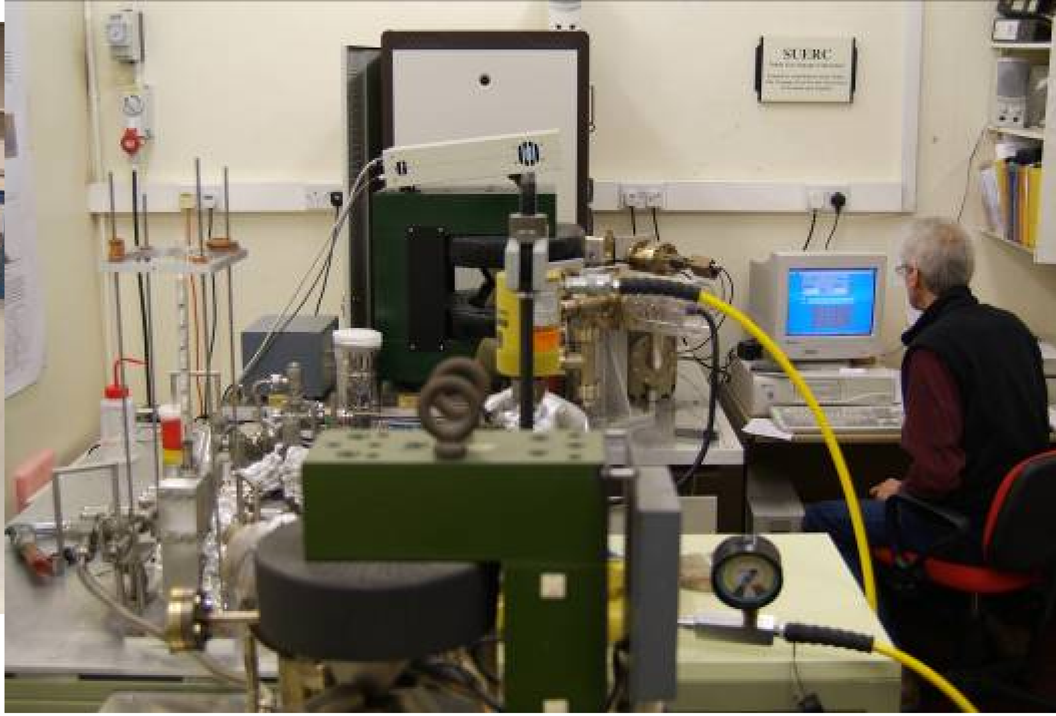
Constraining Regional Uplift Sedimentation & Thermochronology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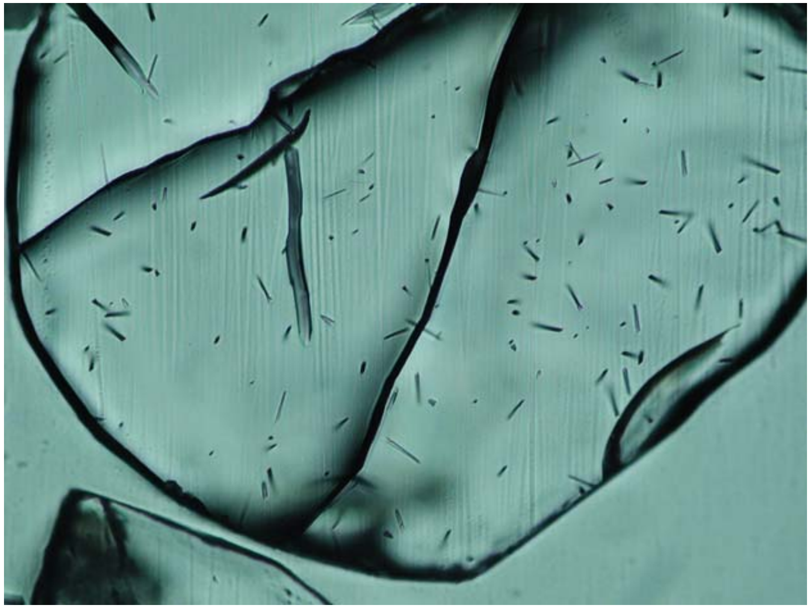

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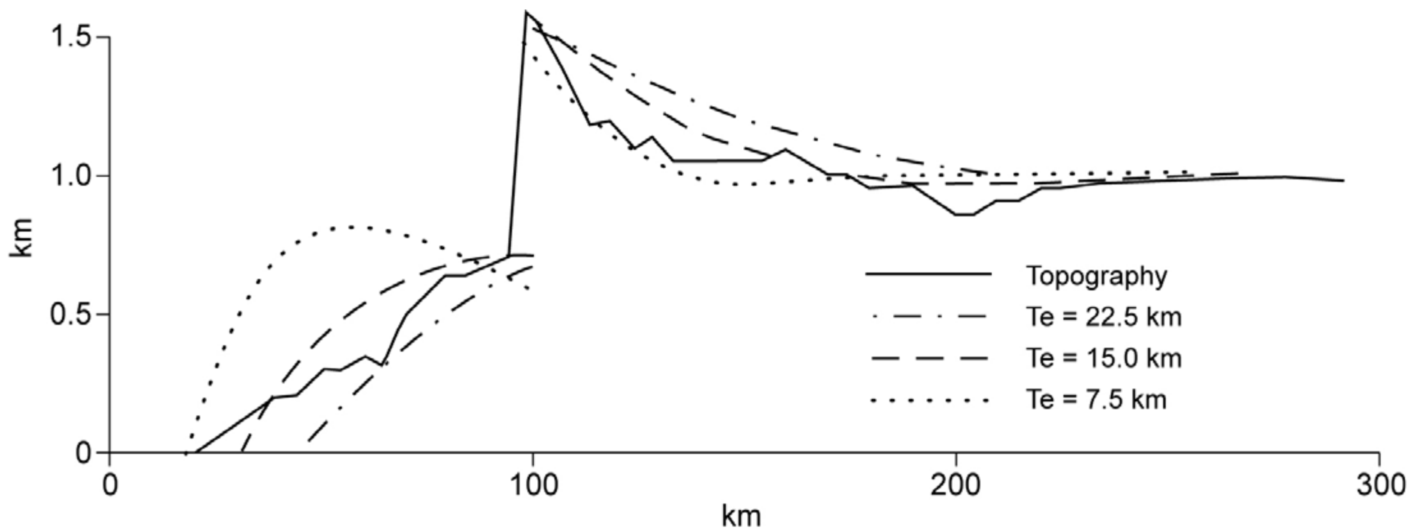
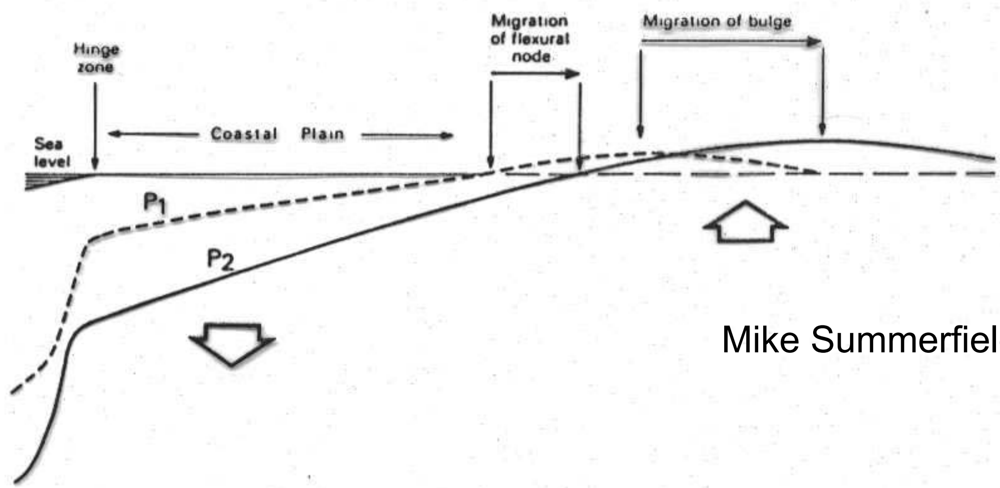
Overview

- The revolution in geomorphology
- Orogenic steady-state landscapes vs post-orogenic
- Bottom-up vs top-down processes & LP evolution
- Some unresolved issues
- Individual issues
  - Duration of transience
  - Novel applications of cosmo
  - Passive continental margin evolution

Flexure and geomorphology

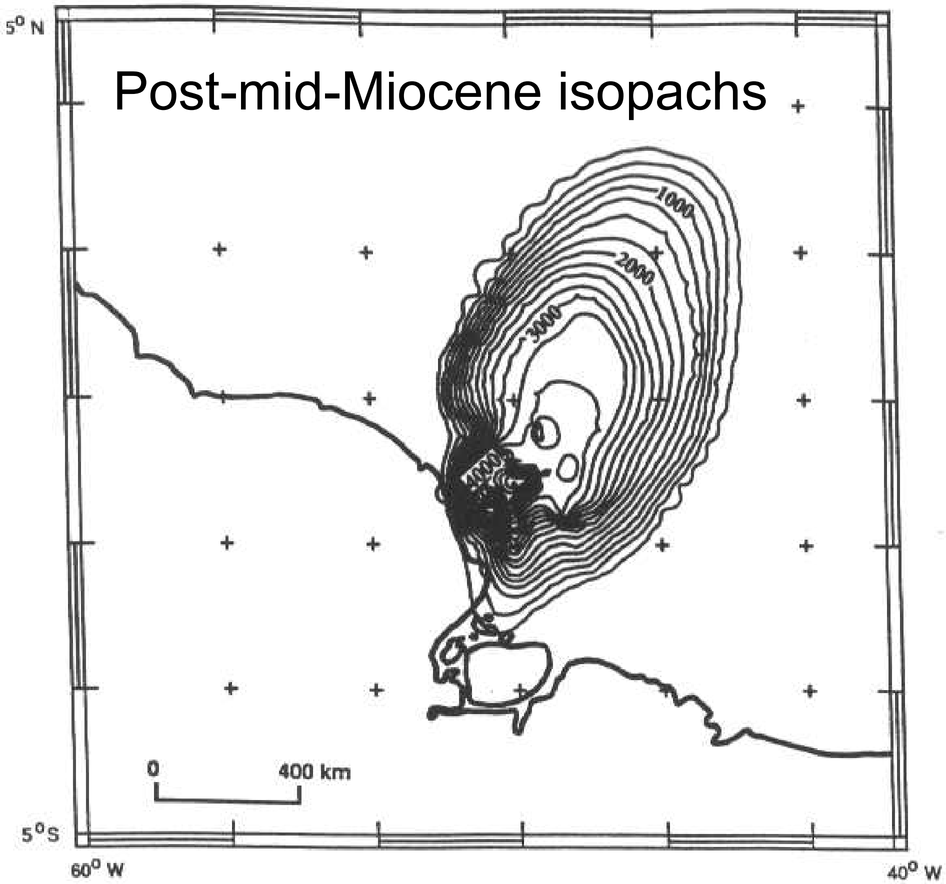


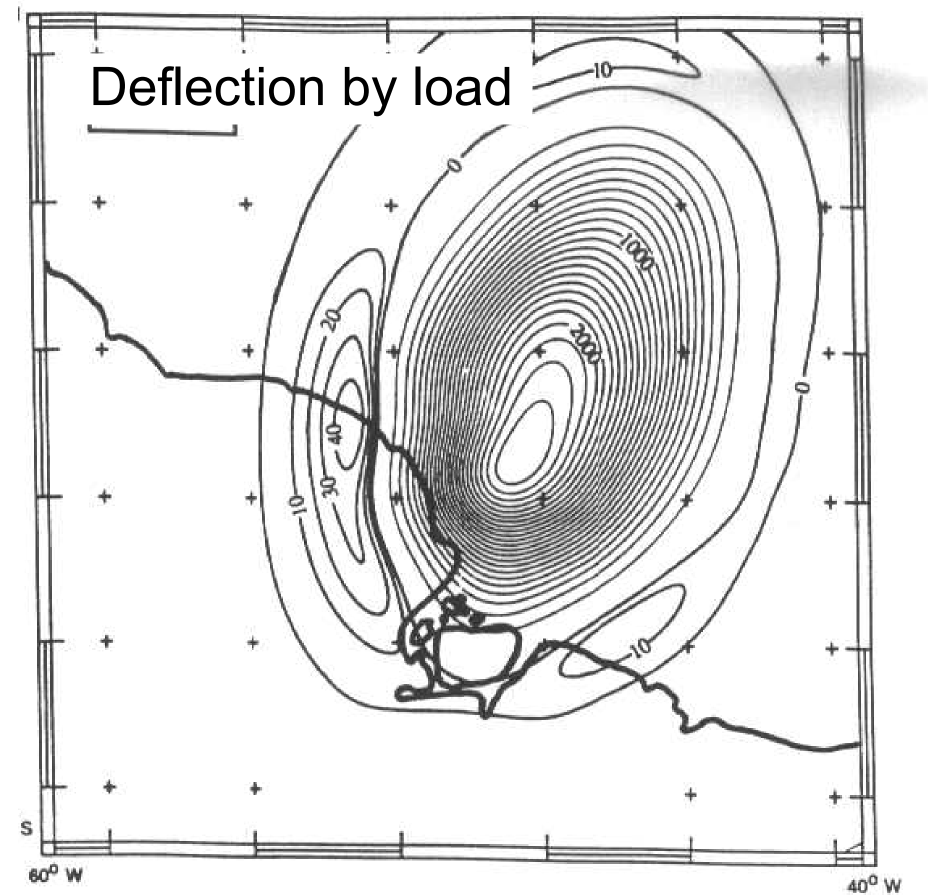
Gilchrist & Summerfield



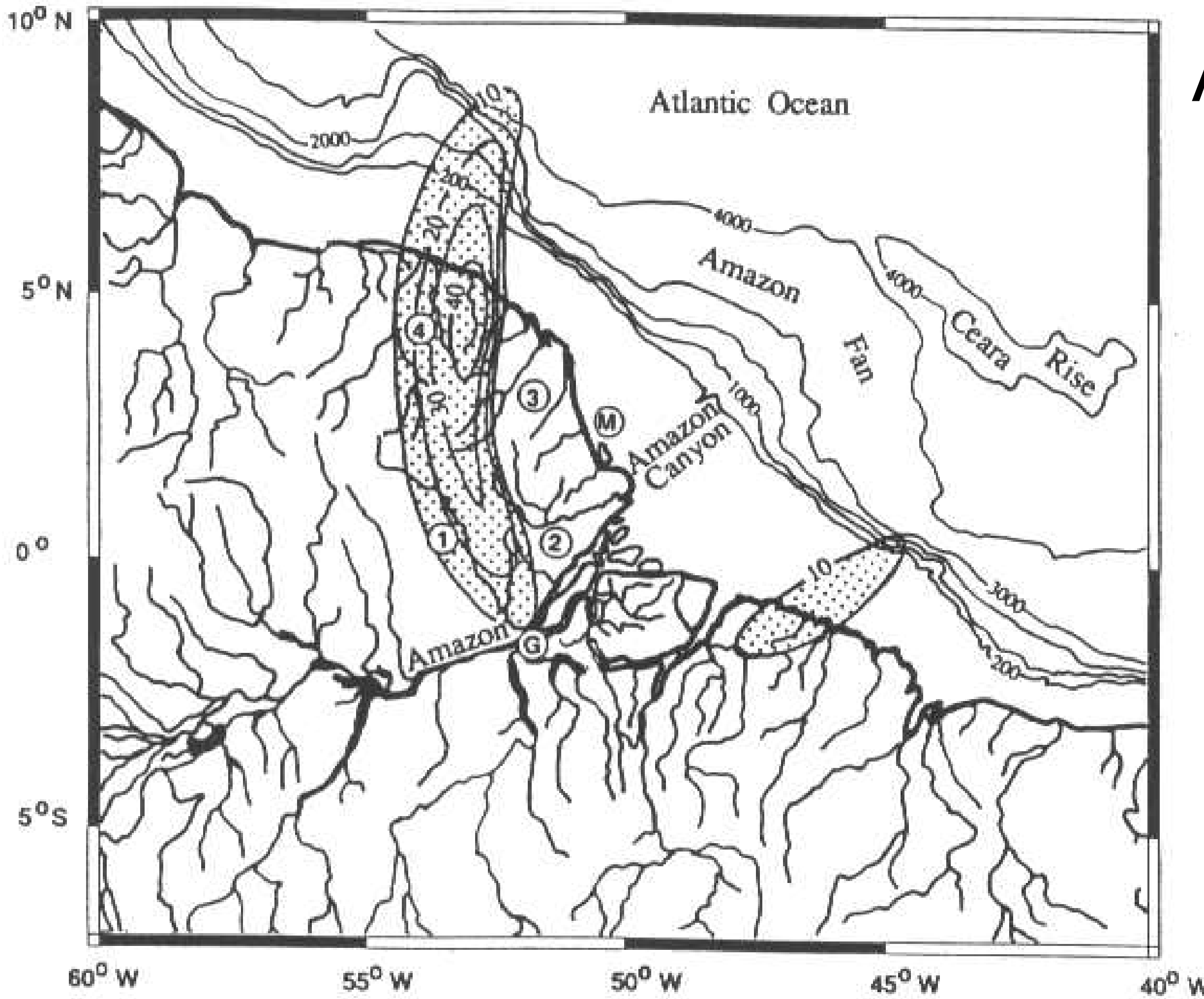
Mike Summerfield

Amazon delta





Flexure and geomorphology



Amazon delta

Calculated peripheral bulge

Dave Montgomery

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Plate tectonics and geomorphology

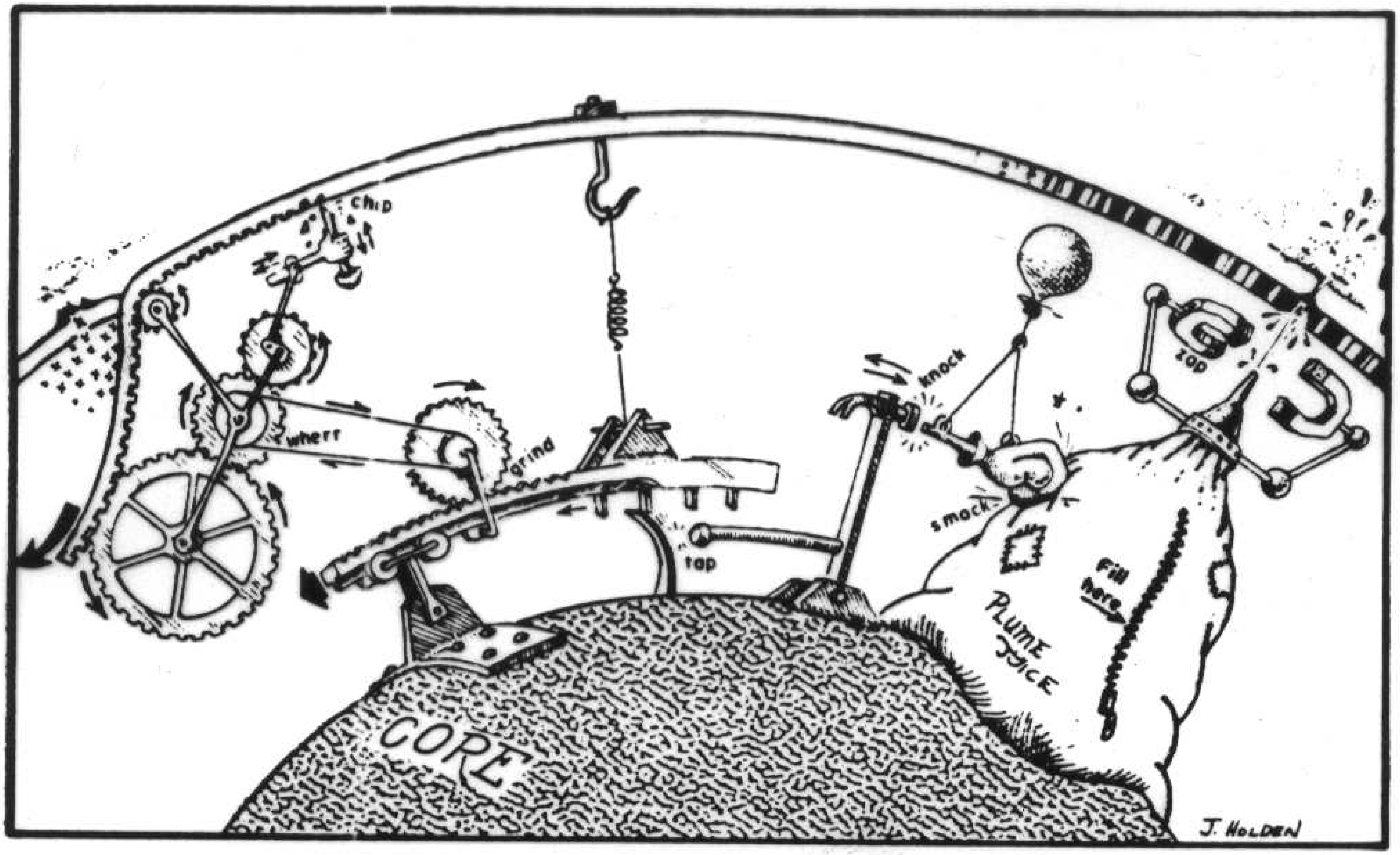

Fig. 9. Diagram hypothesizing the correlation between discharge of island arc and hot spot volcanoes. Mantle viscosity is assumed to be zero as a first approximation (with apologies to S. K. Runcorn).

EOS 1974?

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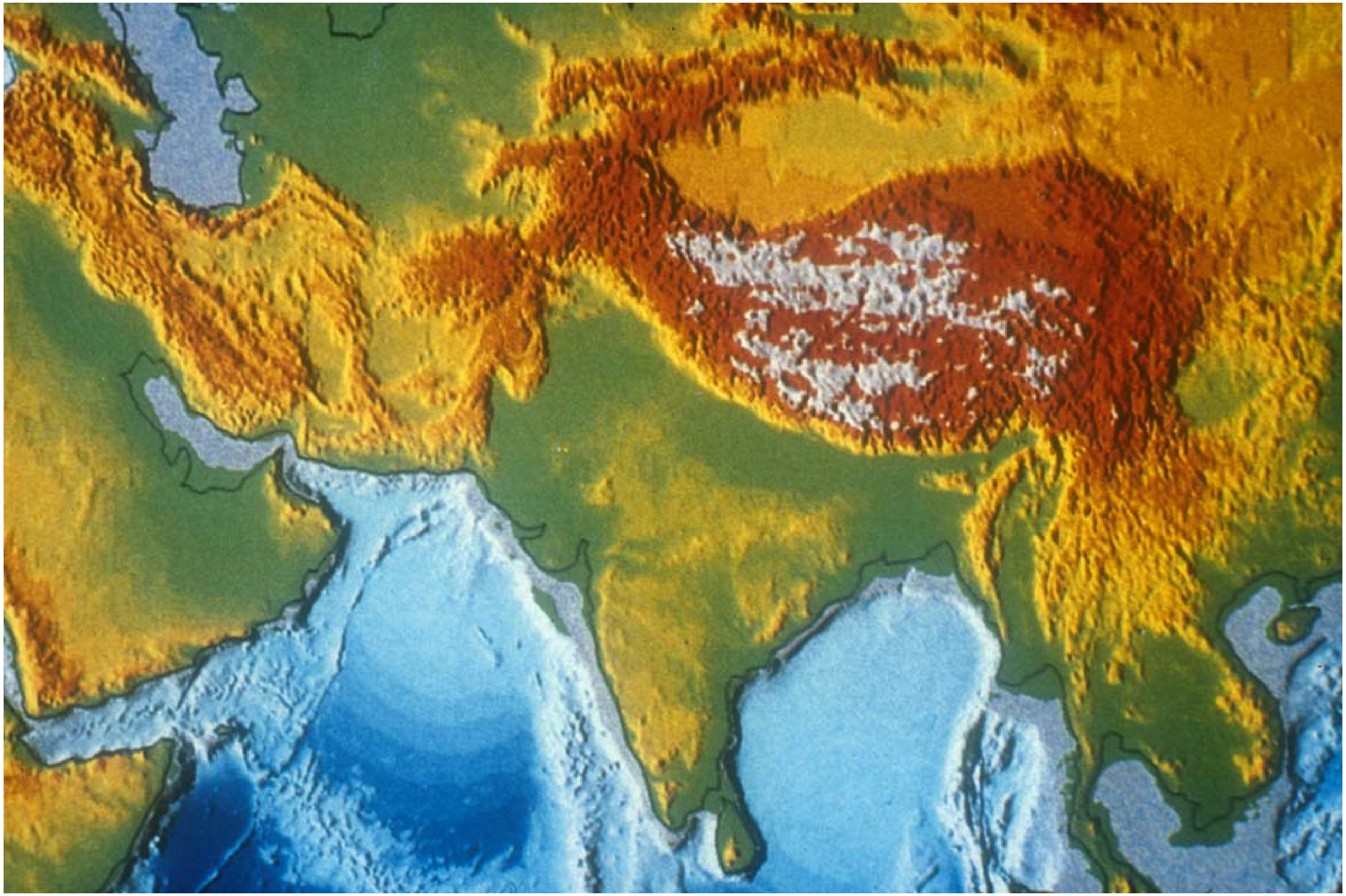
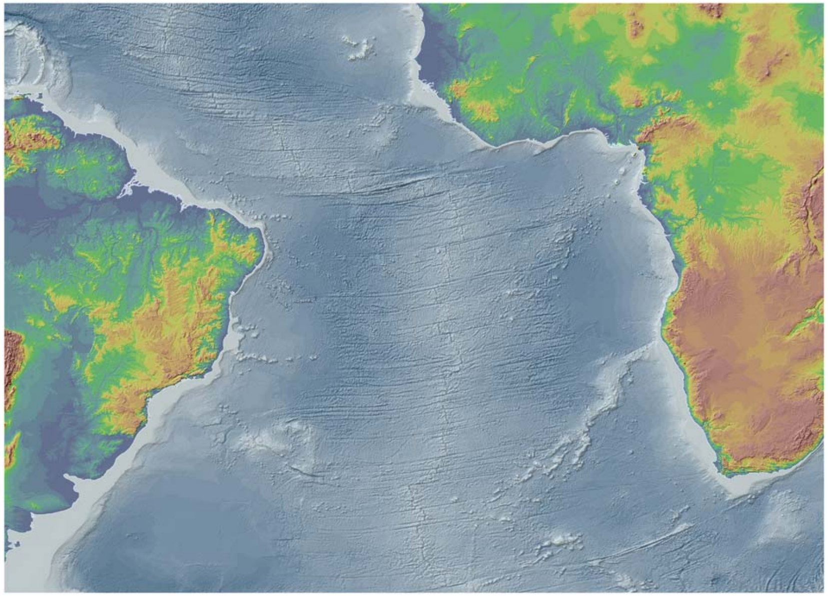
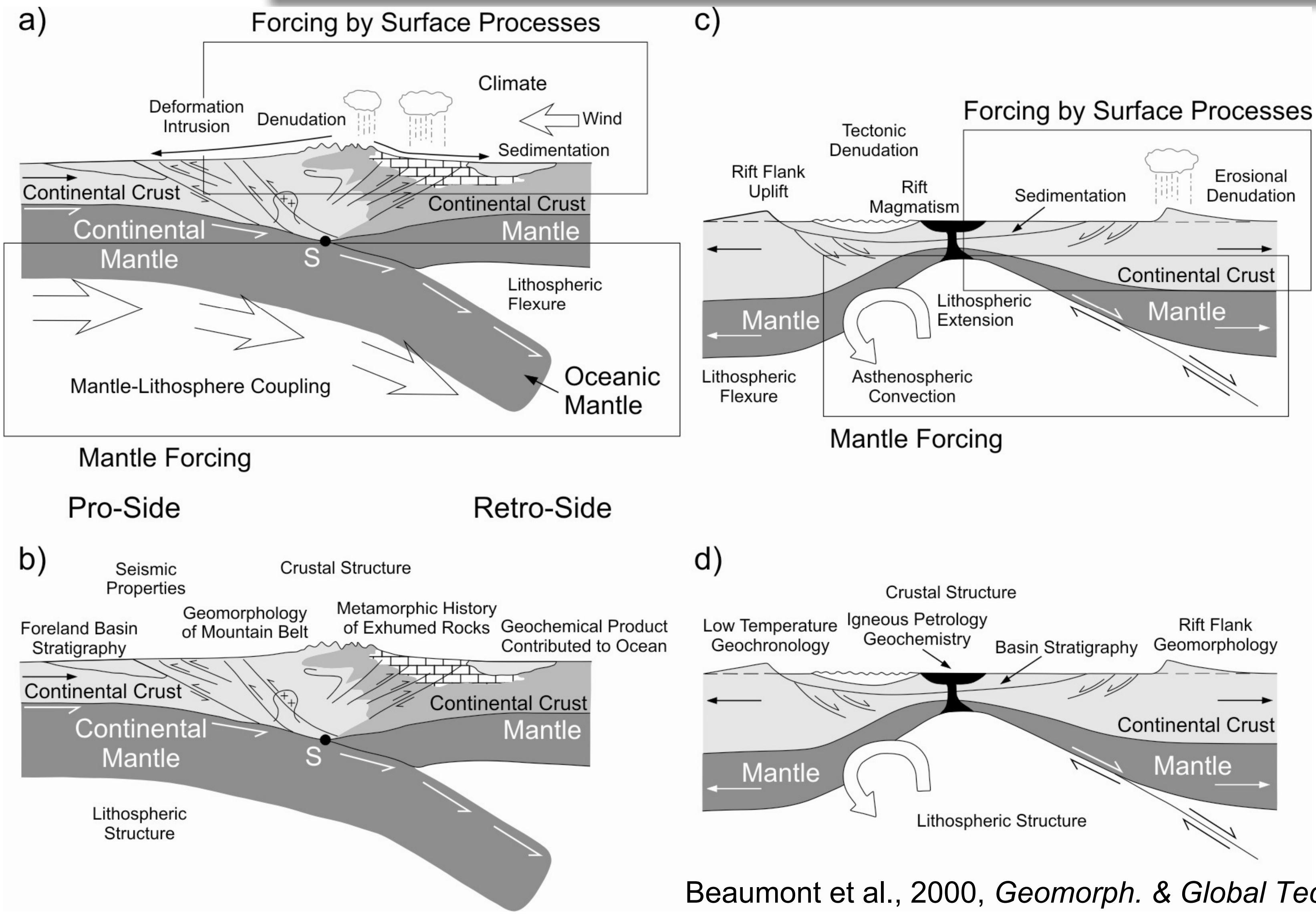
Active settings



High elevation passive continental margins



The whole shooting match



Beaumont et al., 2000, *Geomorph. & Global Tectonics*

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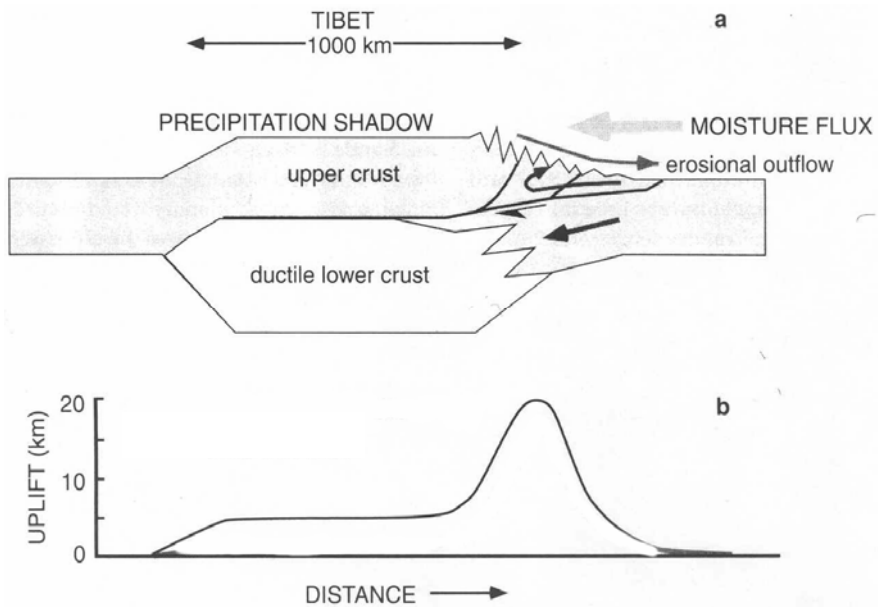
Surface processes DRIVING rock uplift



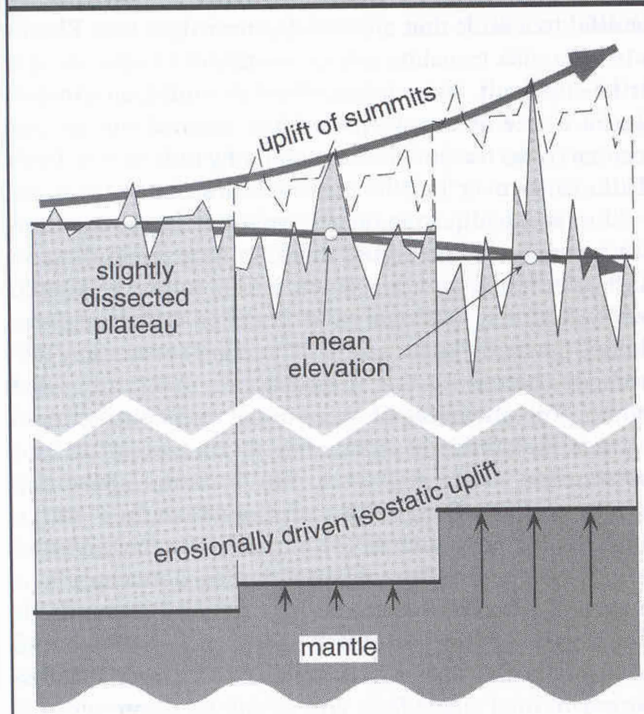
Surface processes DRIVING rock uplift

Surface processes DRIVING surface uplift & climate change

BUT … Eur Alps: denudational isostasy can a/c for ~1000m of elevation of highest peaks

Gilchrist et al., 1994, *Geology*

FIGURE 10.26. Schematic diagram of erosionally driven isostatic uplift of peaks



Mean elevations of the topography decrease to the right, but the heights of the summits (undissected remnants in the landscape) increase in this direction. Note that for each increment of lowering of the mean elevation, rock uplift is about 6 times greater than the amount of surface lowering, and in this scheme, uplift of some peaks is also about 6 times greater.

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Two critical implications

Isostatic response to denudation

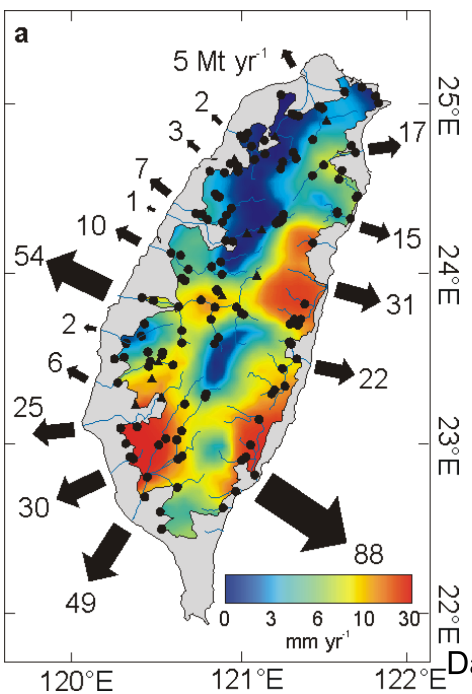
Low rates of denudation:

e.g., SE Oz: ~5-10m.Myr^{-1}

20Ma → 100-200 m denudation & ~80-160m rebound: rock uplift

High rates of denudation:

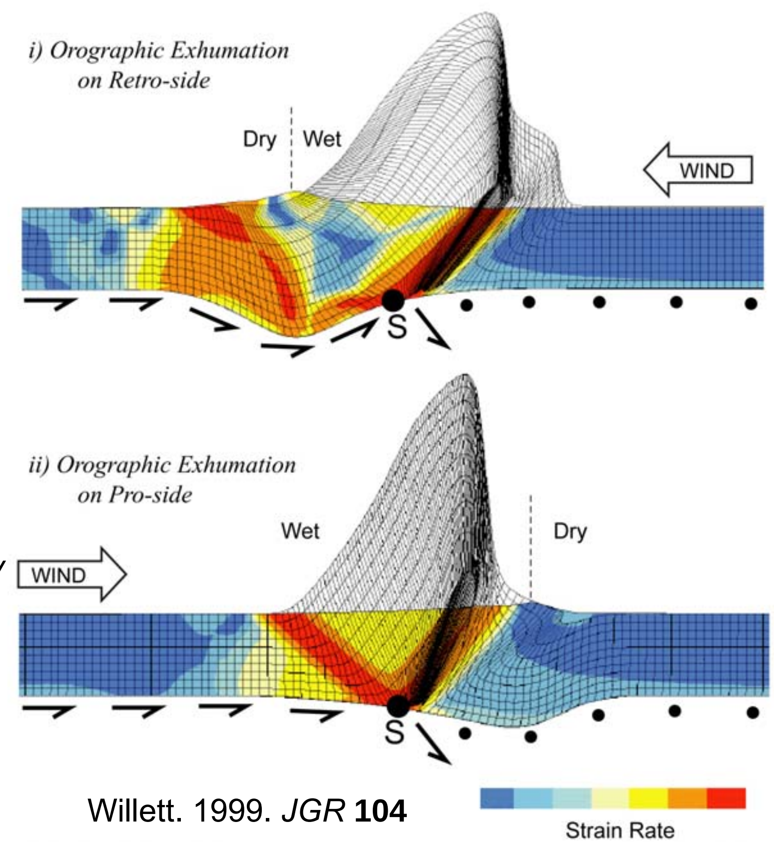
e.g., Taiwan: 5-10km.Myr^{-1}



“The geomorphology of metamorphism”

Zeitler et al., 2001, *GSA Today*

Dadson et al. 2003. *Nature* **426**



Willett. 1999. *JGR* **104**

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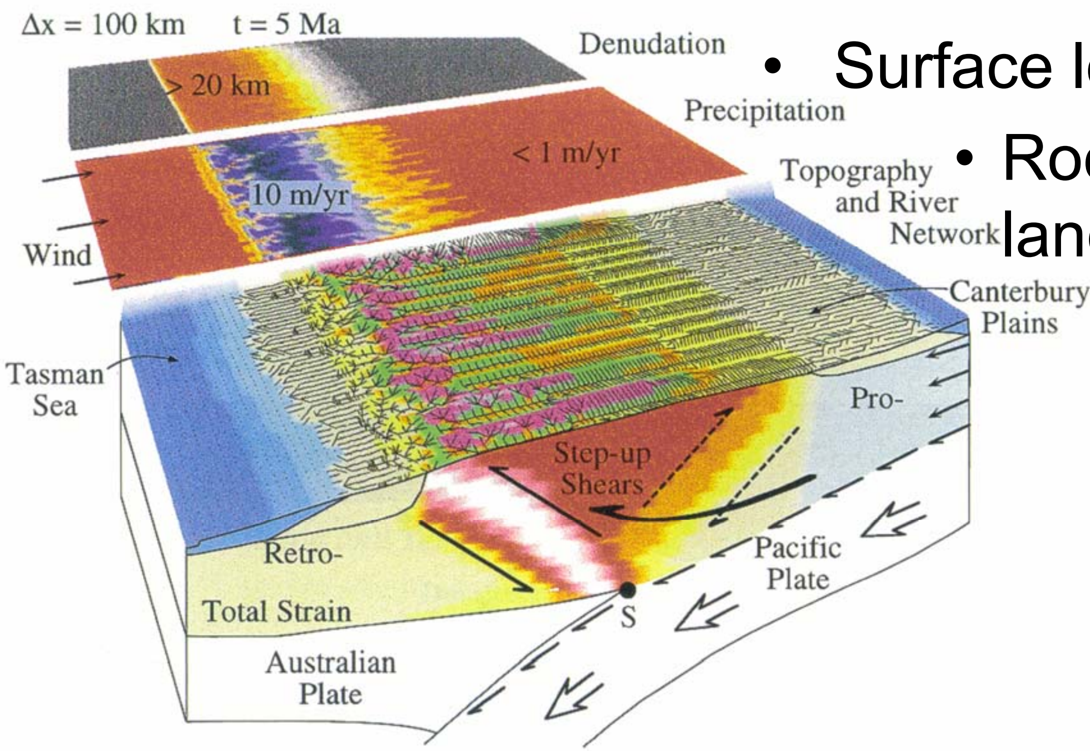
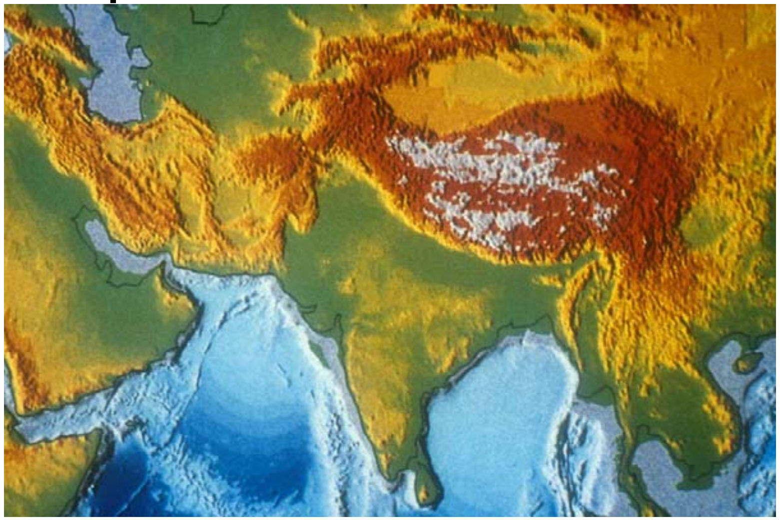
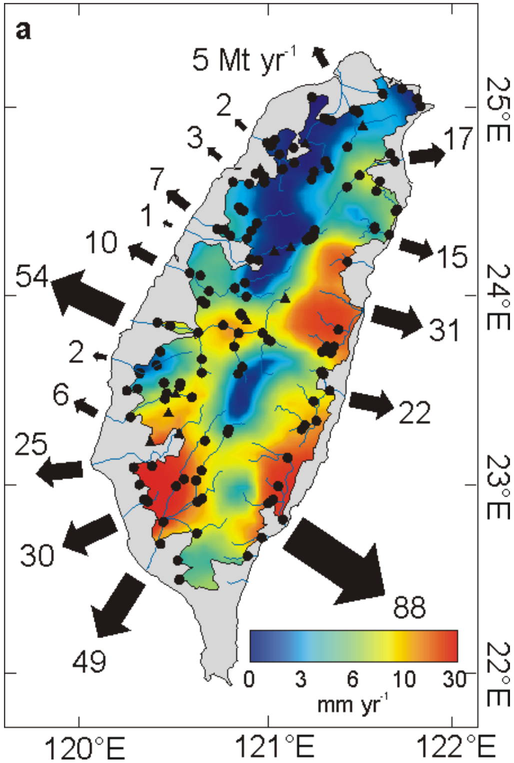
How do we track / know these things?

- Sediment fluxes
- Mass balance
- Numerical modelling
- Surface uplift - GPS
- Surface lowering – cosmo + lo-T
  - Rock uplift: steady state landscapes





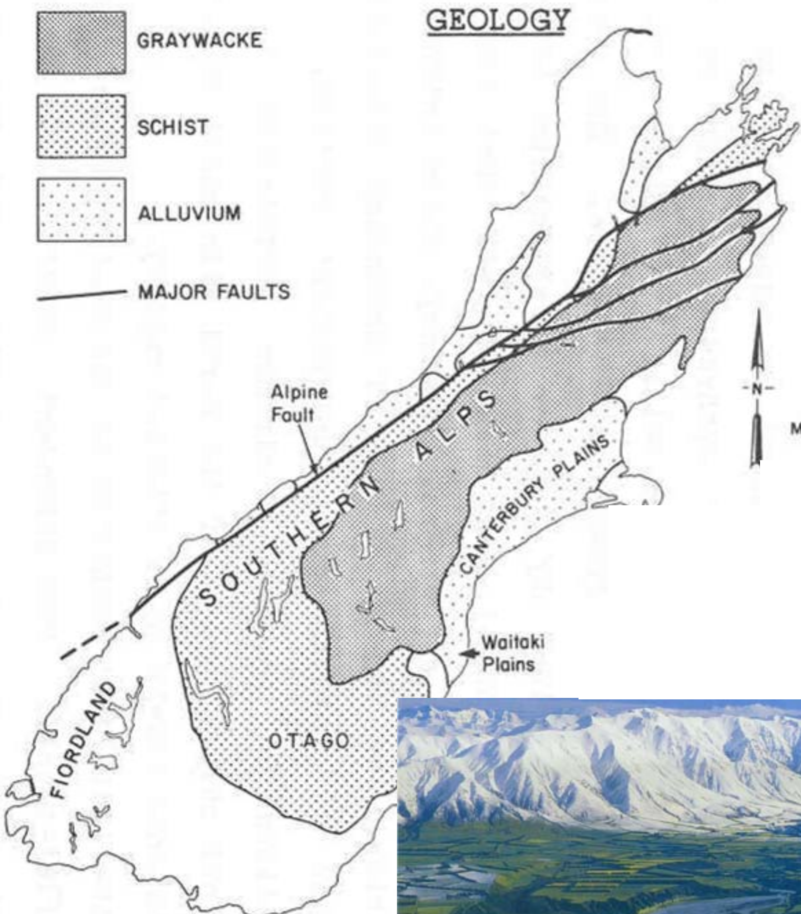
Orogenic landscapes

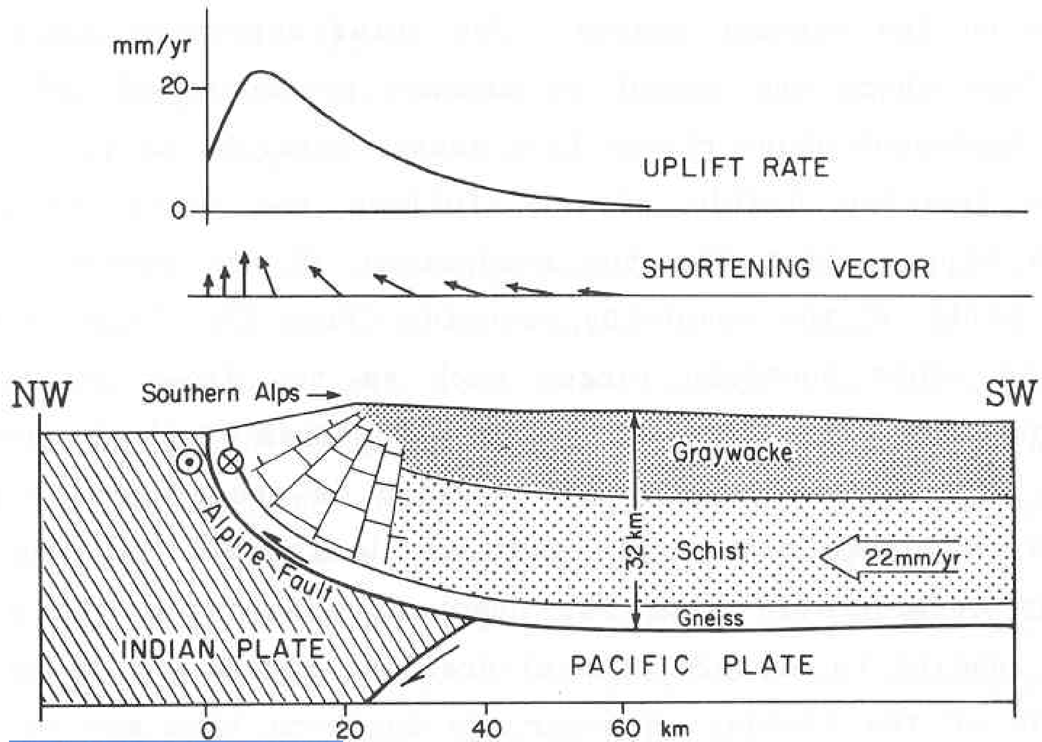


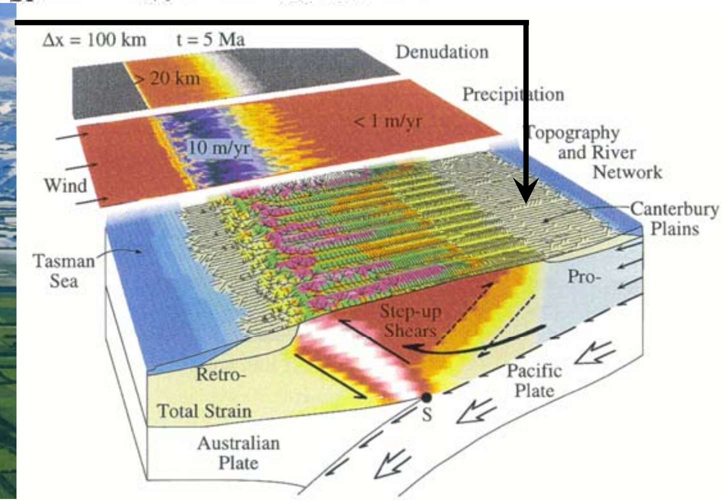
- Steady state landscapes
- Bedrock river incision = rock uplift
- Hack (regolith, rock)
- Time-independent landscapes

Dadson et al. 2003. *Nature* **426**

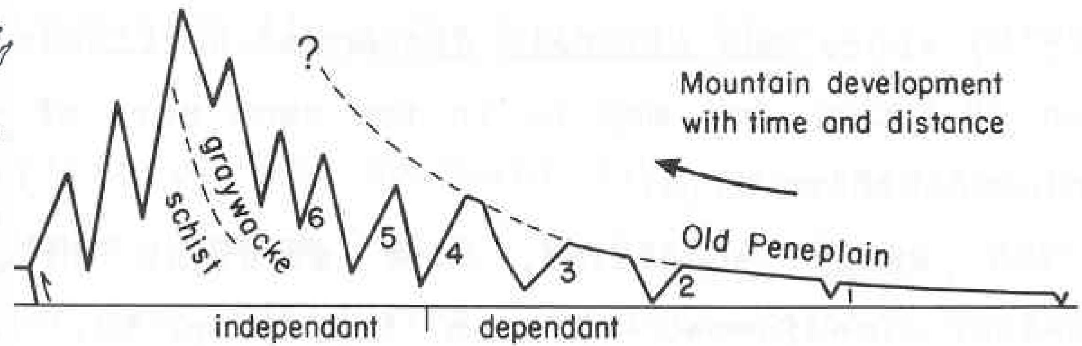
Pacific-Australia covergence

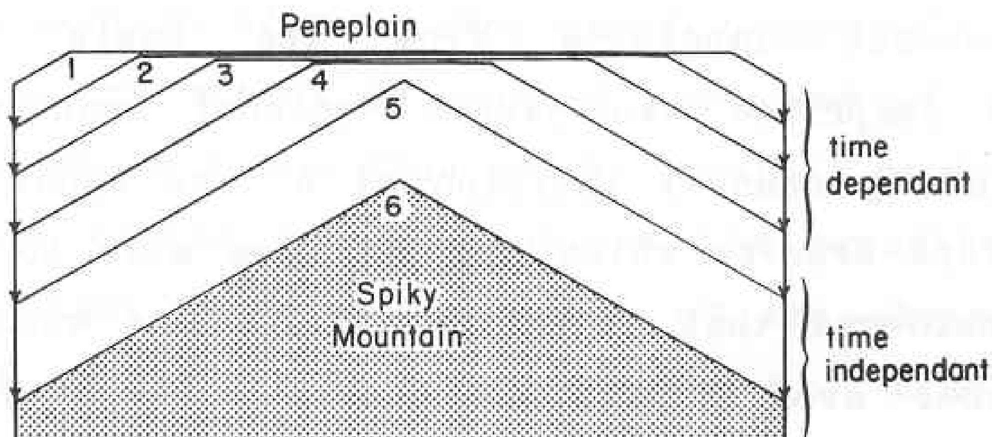




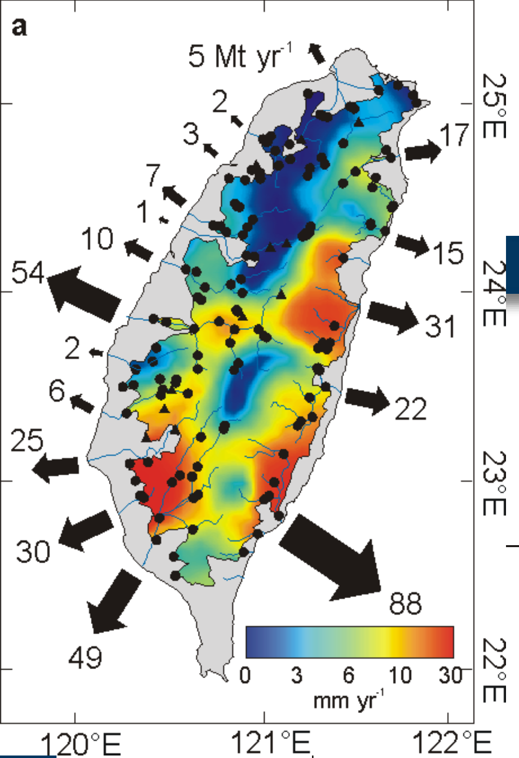


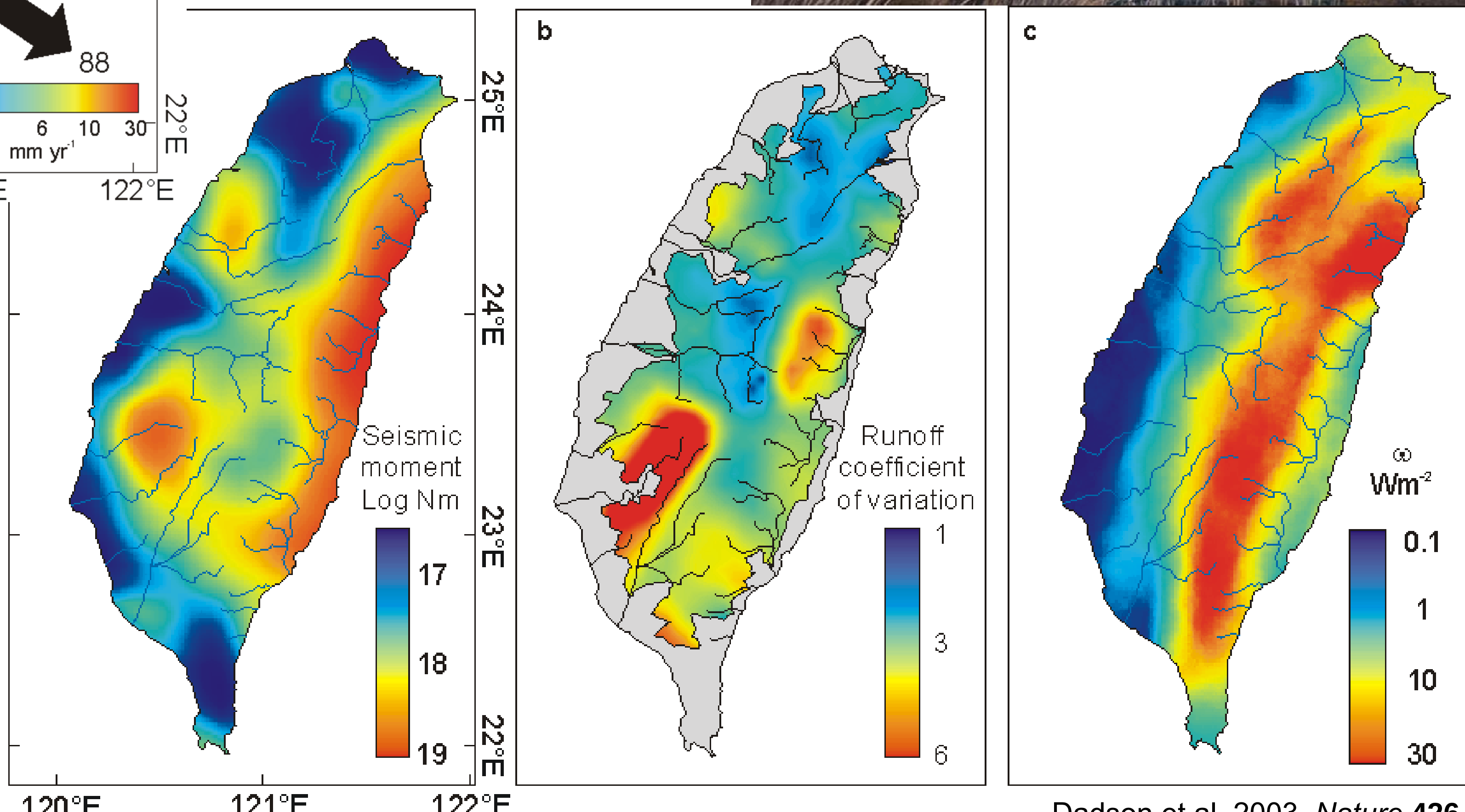
Southern Alps topography – the Adams scenario





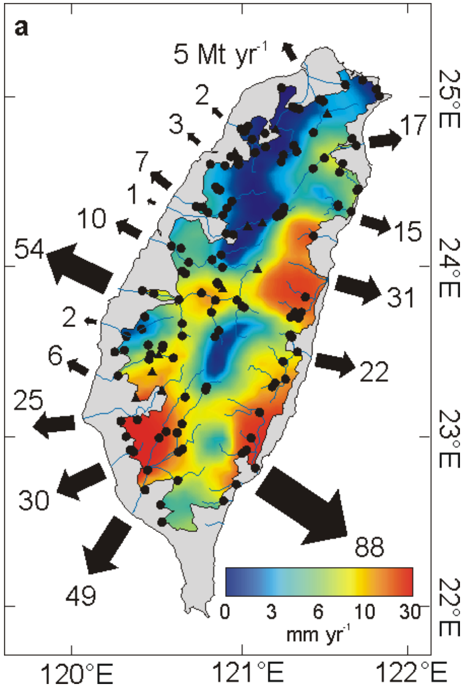
Taiwan

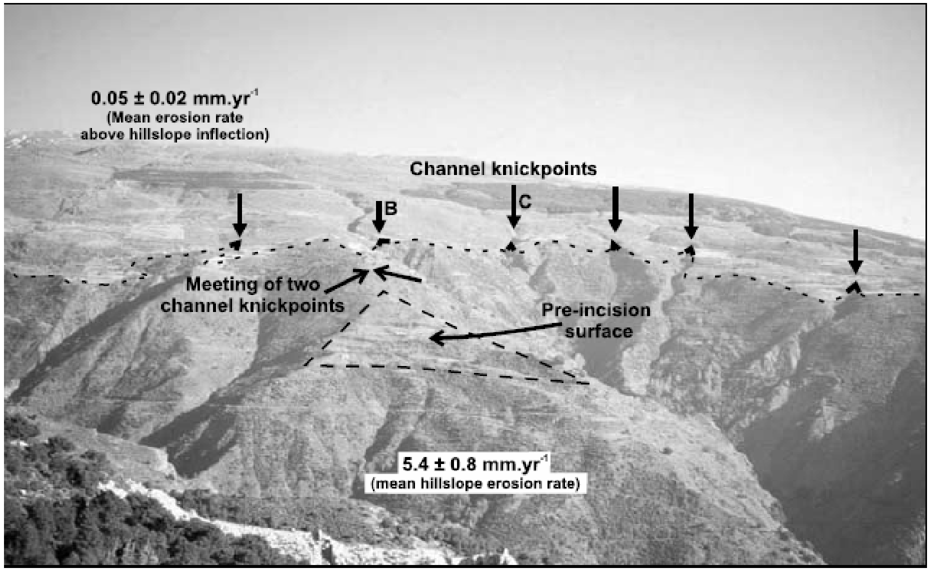




Dadson et al. 2003. *Nature* **426**

Top-down vs. bottom-up





- Two fundamentally different landscape response to rock uplift?:
- <u>Top-down</u>: continuous rock uplift, hi Q, Q_S, seismic shaking?, 'continuous' incision in response to rock uplift
- <u>Bottom-up</u>: channel response to rock uplift via KP retreat

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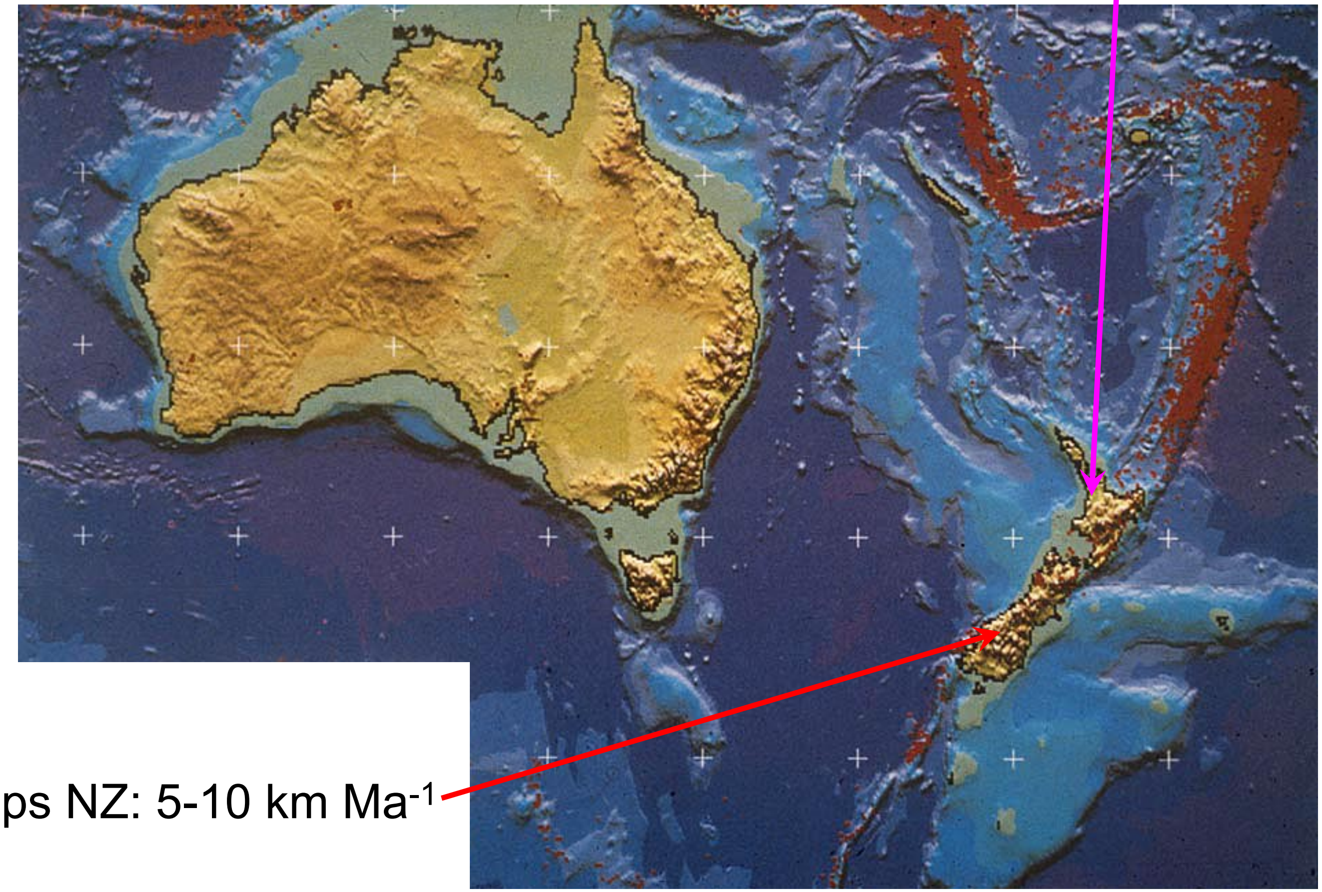
Passive & active settings

Taranaki Basin (Nth Isl., NZ): 7 km in ≤ 20 Ma

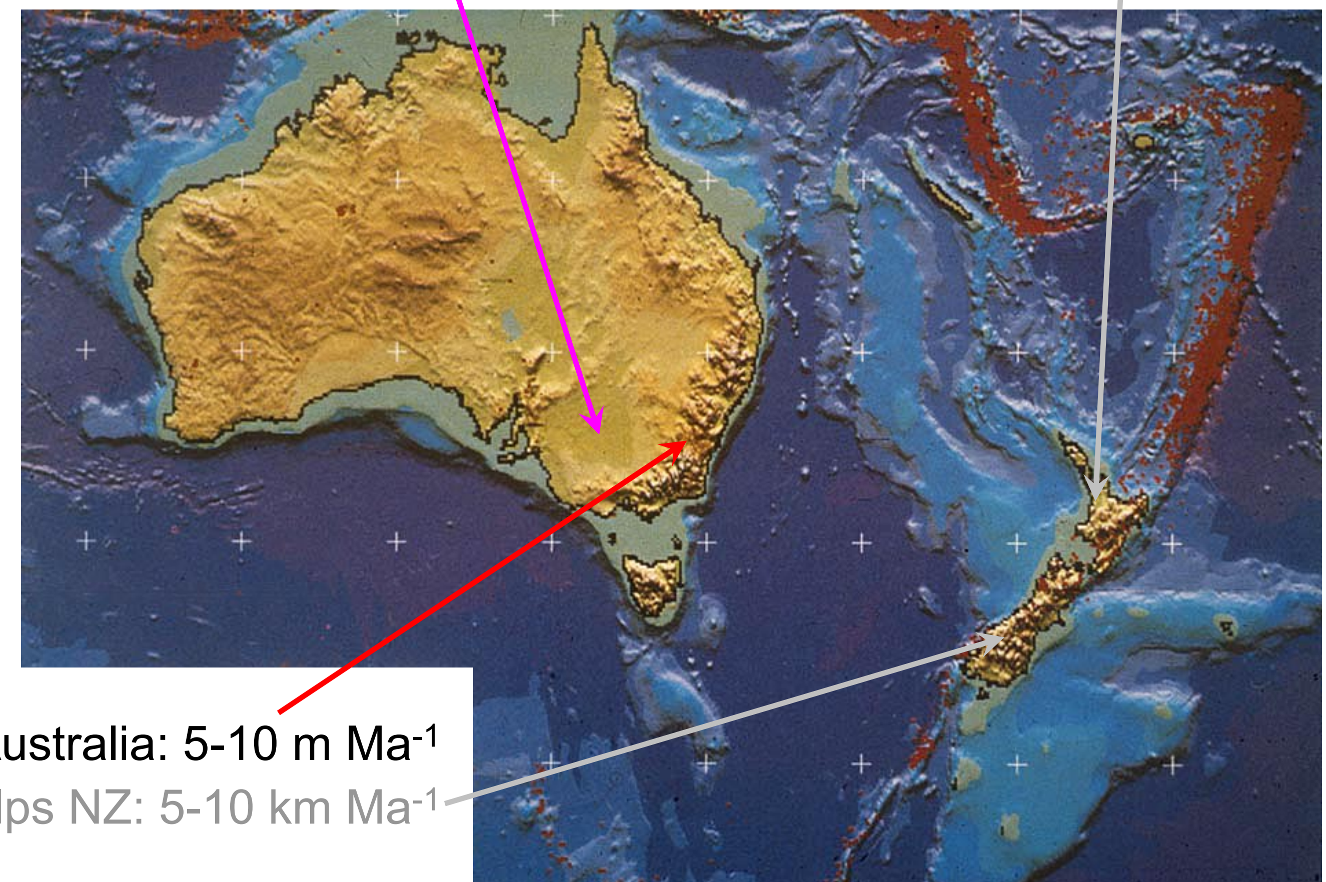


Southern Alps NZ: 5-10 km Ma^{-1}

Passive & active settings

Taranaki Basin (Nth Isl., NZ): 7 km in ≤ 20 Ma

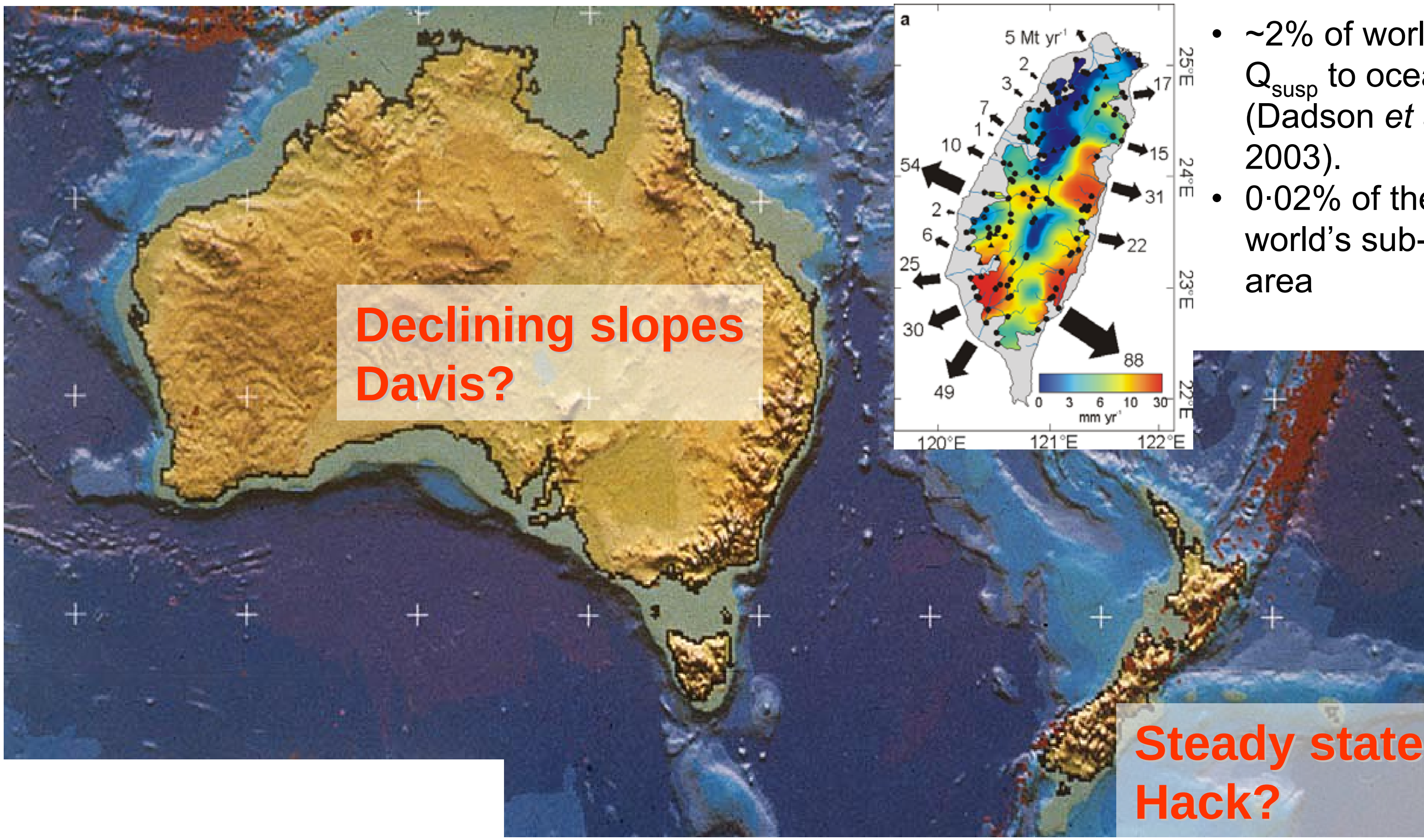
Murray Basin (SE Oz) : 0.5 km in 65 Ma



SE Australia: 5-10 m Ma^{-1}

Southern Alps NZ: 5-10 km Ma^{-1}

Orogenic vs non-orogenic settings



Declining slopes
Davis?

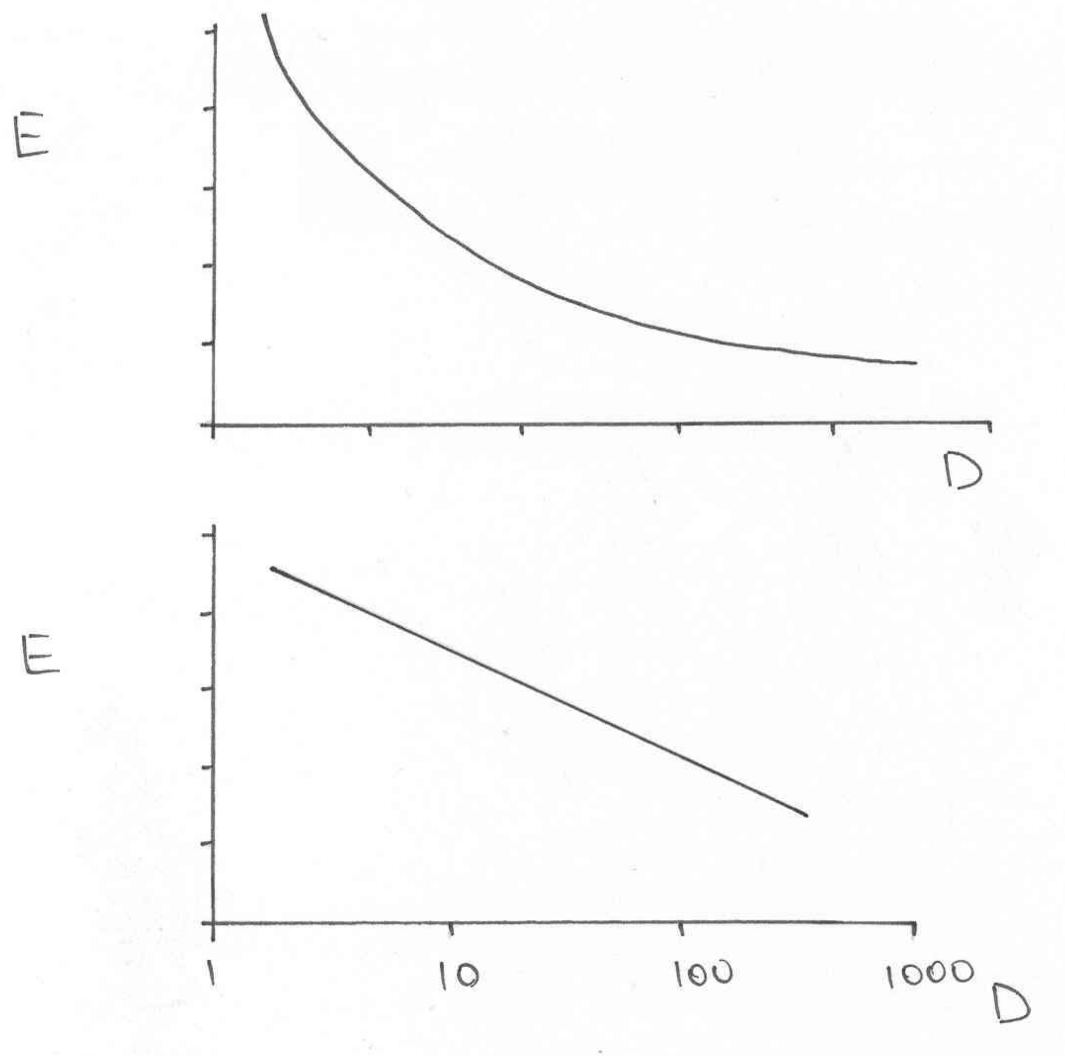
Steady state
Hack?

- ~2% of world's Q_{susp} to oceans (Dadson *et al.*, 2003).
- 0·02% of the world's sub-aerial area

Relative areal extents
Reconciliation?

Long profiles

- Concave-up 17th C
- John Hack; SL form
- Steeper on resistant lithologies
- SL index
- Also steeper in tectonically active areas



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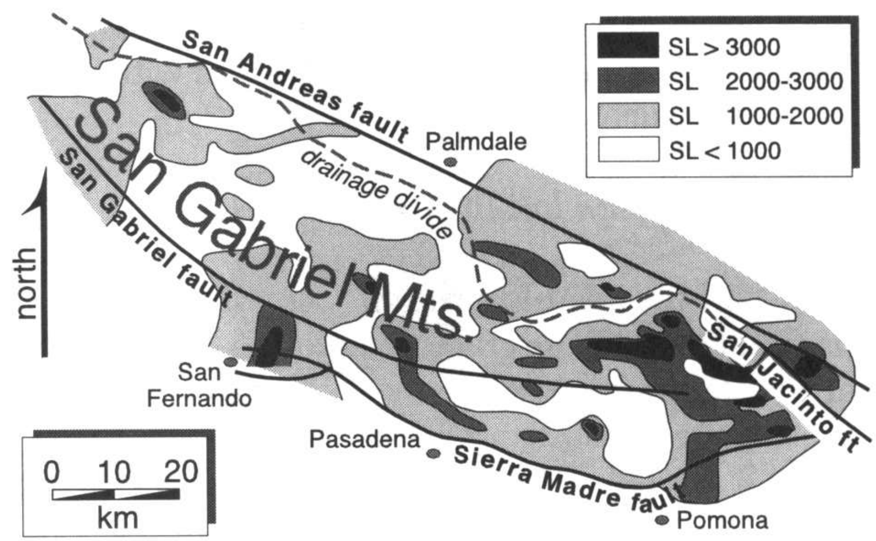
Long profiles & tectonics 1

Plot SL index & relate to tectonics (e.g., Keller & Rockwell, 1984)

FIGURE 9.12. Stream-gradient indices (SL) in the San Gabriel Mountains, southern California



Map of contoured indices identifies areas of known active uplift in the eastern and southern parts of the range, as well as anomalously high rates along the northern San Fernando valley, where the 1971 and 1994 earthquakes occurred. Such a map can point out areas where more detailed studies on active deformation could be warranted. Modified after Keller (1986).

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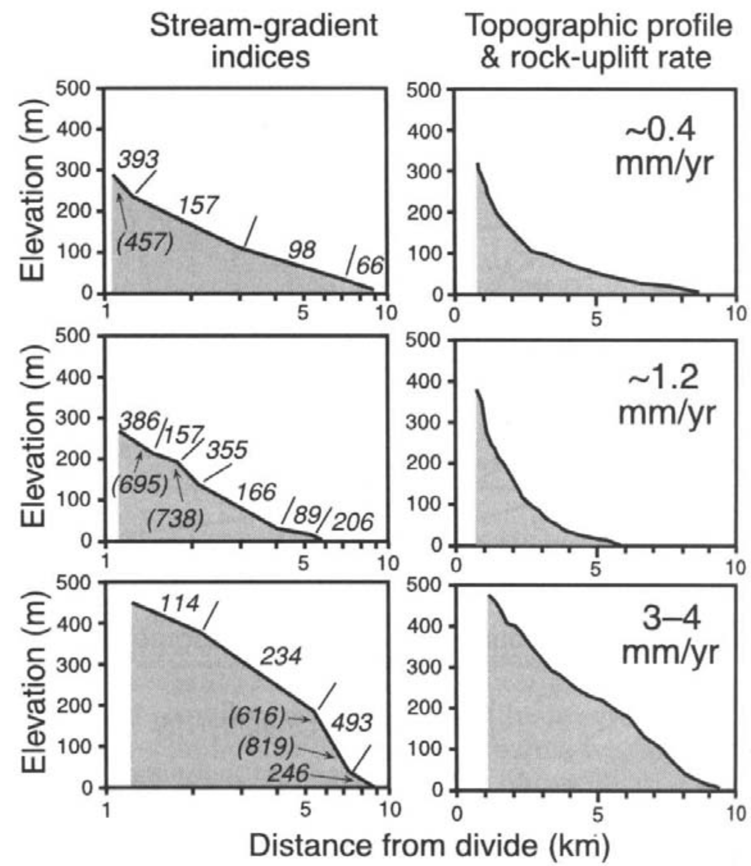
Long profiles & tectonics2

Plot LPs & SL values (e.g., Merrits & Vincent (1989, Mendocino): different uplift rates)

1. Low uplift rate:
   - Hi SL values in upper reaches (migrated KP?)
2. Intermed uplift:
   - Hi SL value at mouth (base-level?) & variable throughout
3. Hi uplift:
   - Hi SL values throughout; highest in middle and lower; convex SL plot

FIGURE 9.13. Stream-gradient indices, topographic profiles, and rock-uplift rates for rivers in northern California



Note that the zone of rapid rock uplift has a steeper gradient, higher relief, and higher gradient indices. Modified after Merritts and Vincent (1989)

BUT …

- Steepness — Lithology / Tectonics ?
- Stream power rule

$$I = K\,A^m\,S^n$$

I: fluvial incision

A: catchment area (≡ channel discharge)

S: channel gradient

K: dimensional coefficient of erosion

m, *n*: constants

DS form of long profile

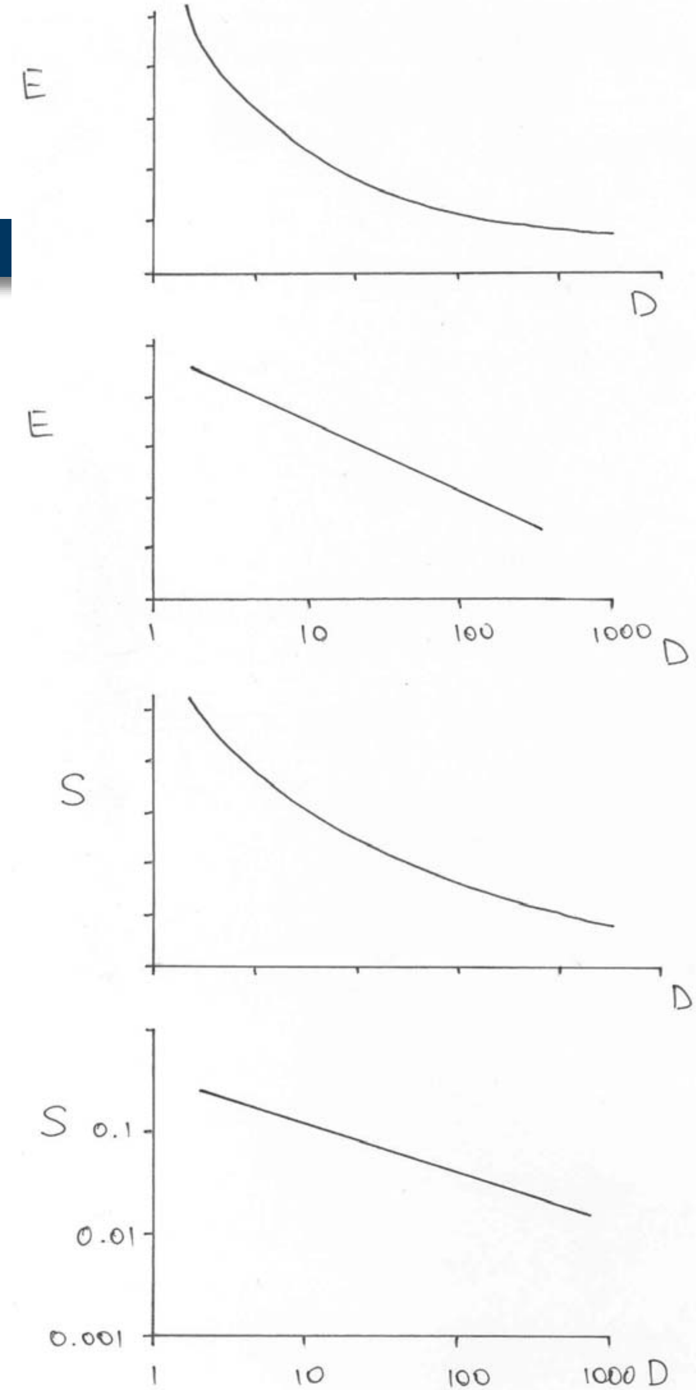
- $I = KSQ$ (or KSA)
- Discharge increases downstream:

$$Q = IL^{\lambda}$$

- Substitutions: $S = kL^{-\lambda}$ or

$$\log S = \gamma - \lambda \log L$$

- DS form ('distance – slope'): $\log S$, $\log D$



Goldrick & Bishop, 2007, *ESP&L*

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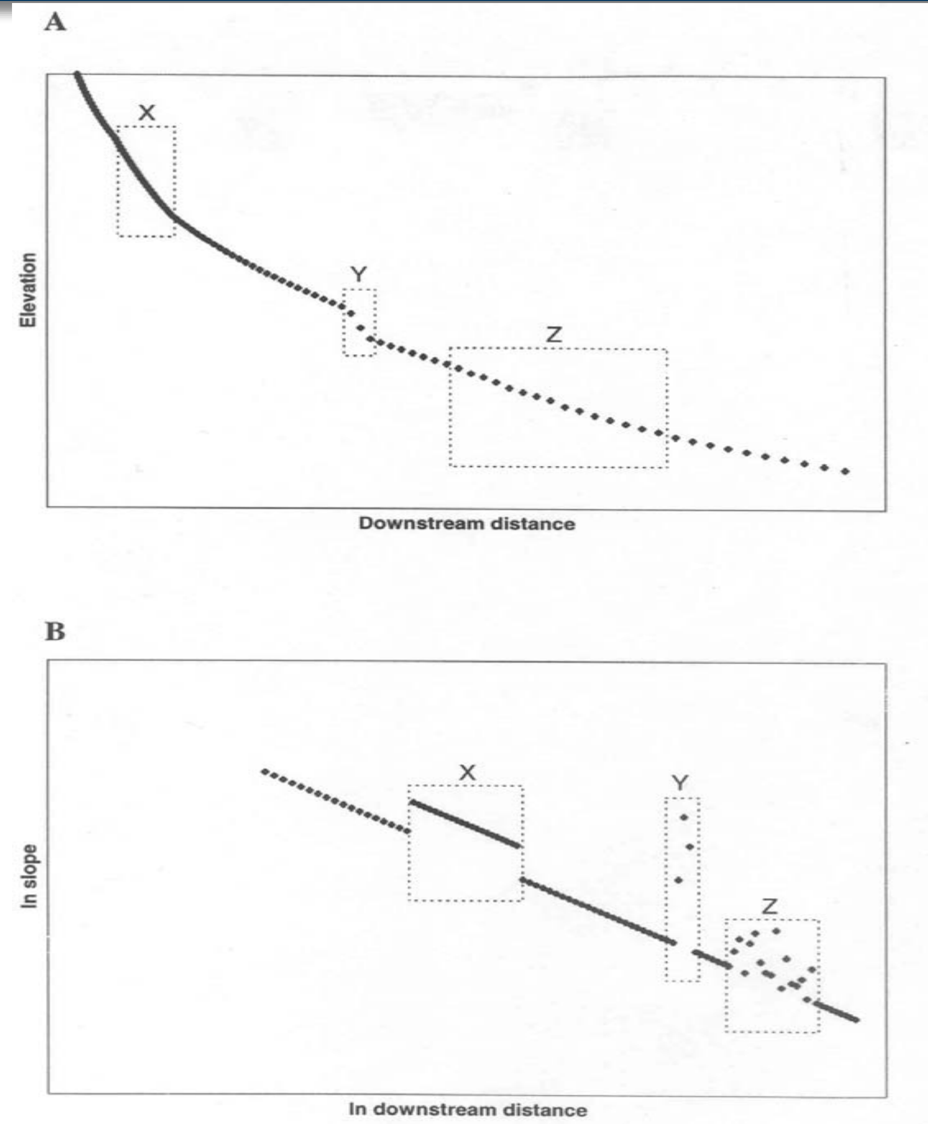
The equilibrium DS form

Equilibrium steepening on more resistant lithology = parallel upwards shift: X

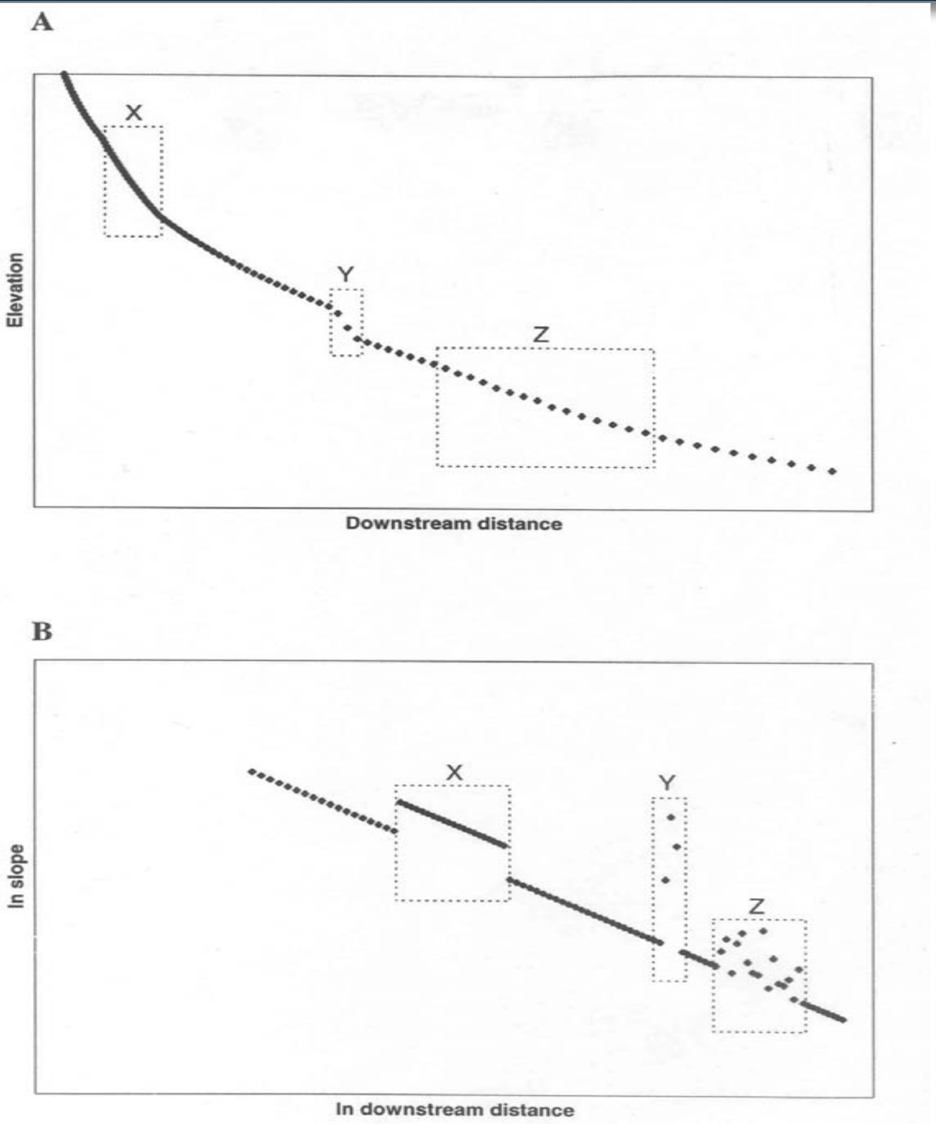


The equilibrium DS form

Disequilibrium steepening (knickpoint) = DS outlier

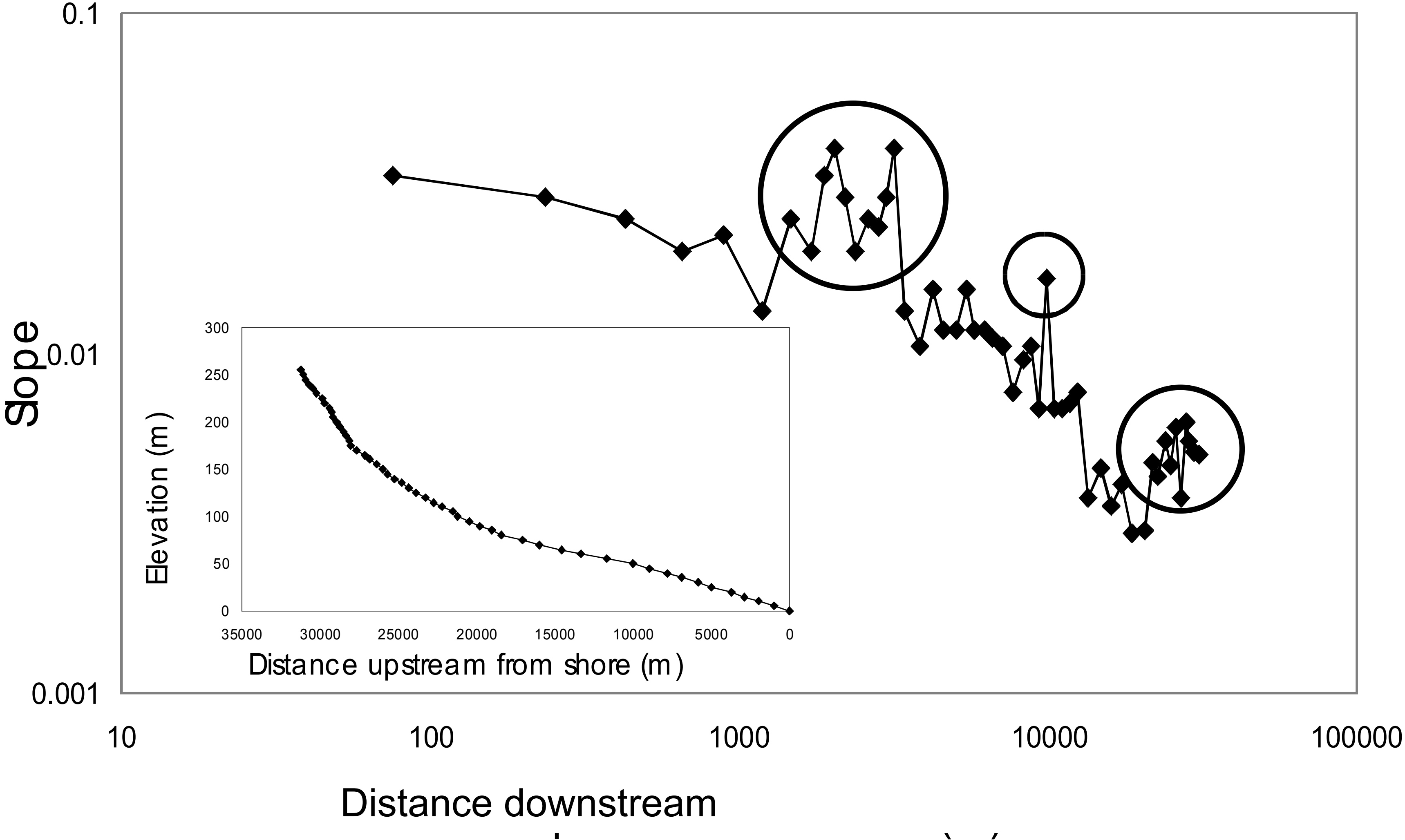
Y: ‘obvious’ KP

Z: diffuse KP or knickzone

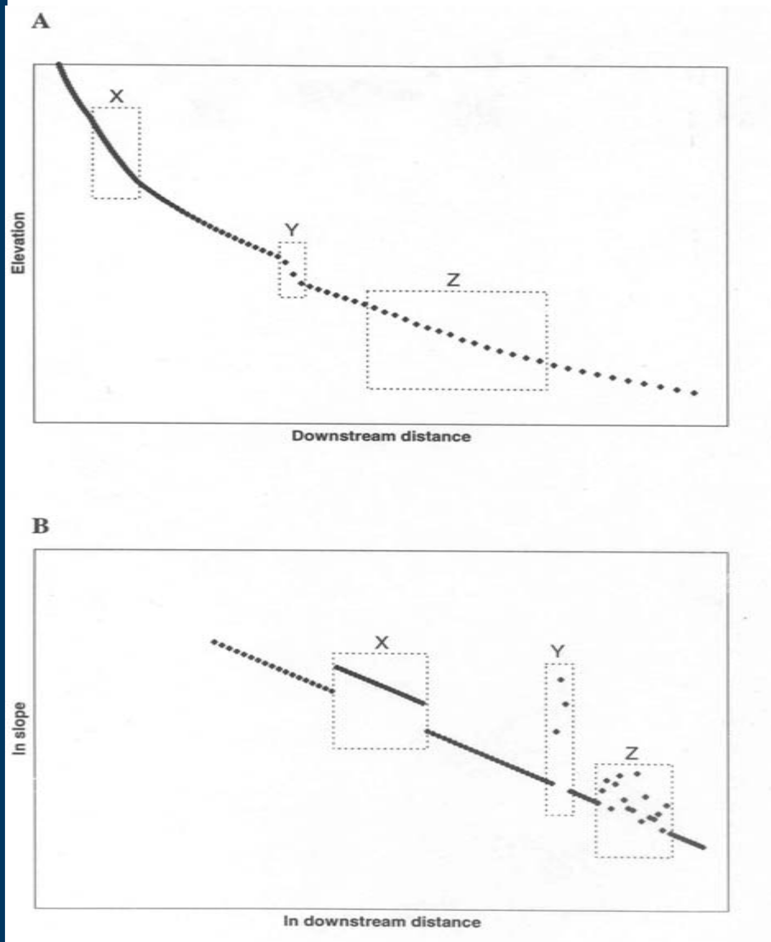


The equilibrium DS form

Even diffuse KPs



Long profiles



- Equilibrium long profiles
- SL
- DS (slope-distance) and Slope-Area forms:
  - Steepness = f(lithology, tectonics)
  - Concavity = f(rate of increase of Q with D or A)
  - Straight line on DS or SA ≡ equilibrium
  - Parallel shift = equilibrium response to Δ lithology
  - Outliers ≡ disequilibrium

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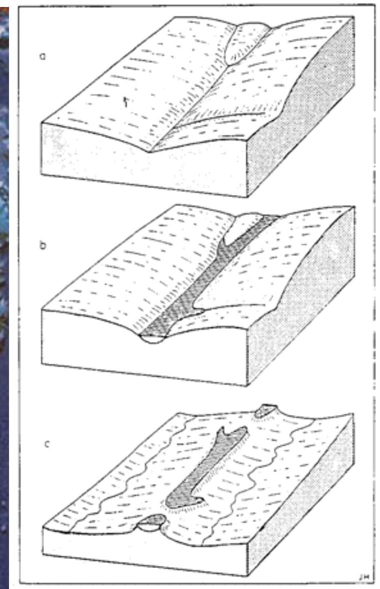
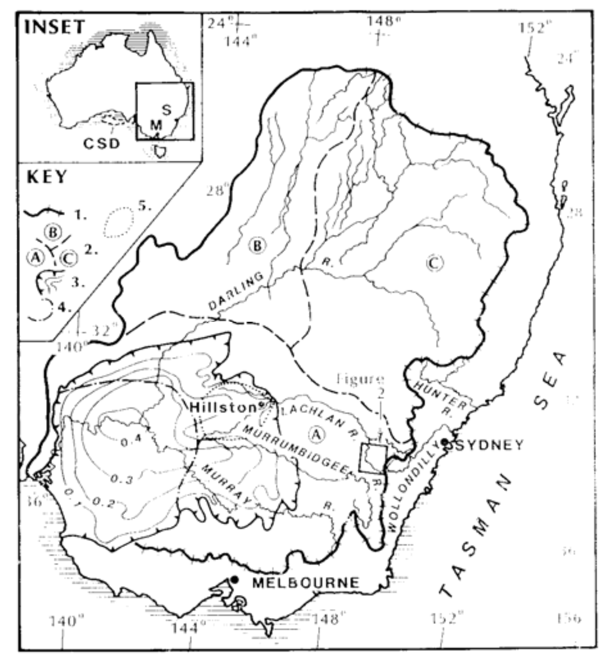
Post-orogenic landscape evolution





SE Australia: 5-10 m Ma^{-1}

→ denudational isostatic rebound

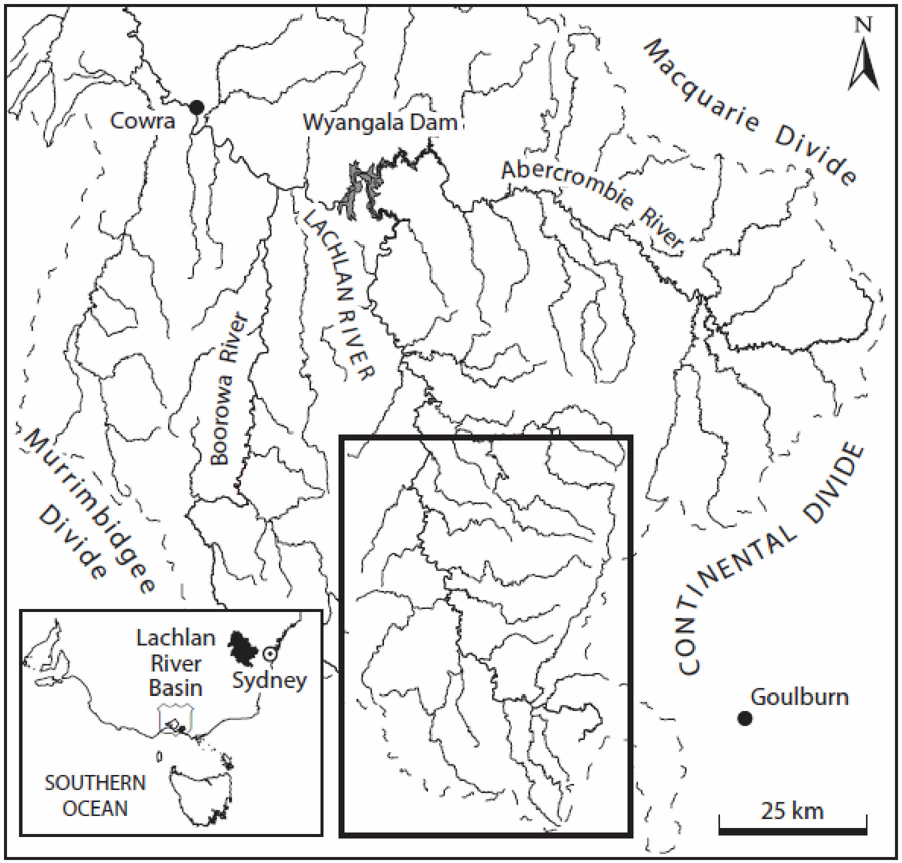
→ landscape evol’n via bottom-up processes

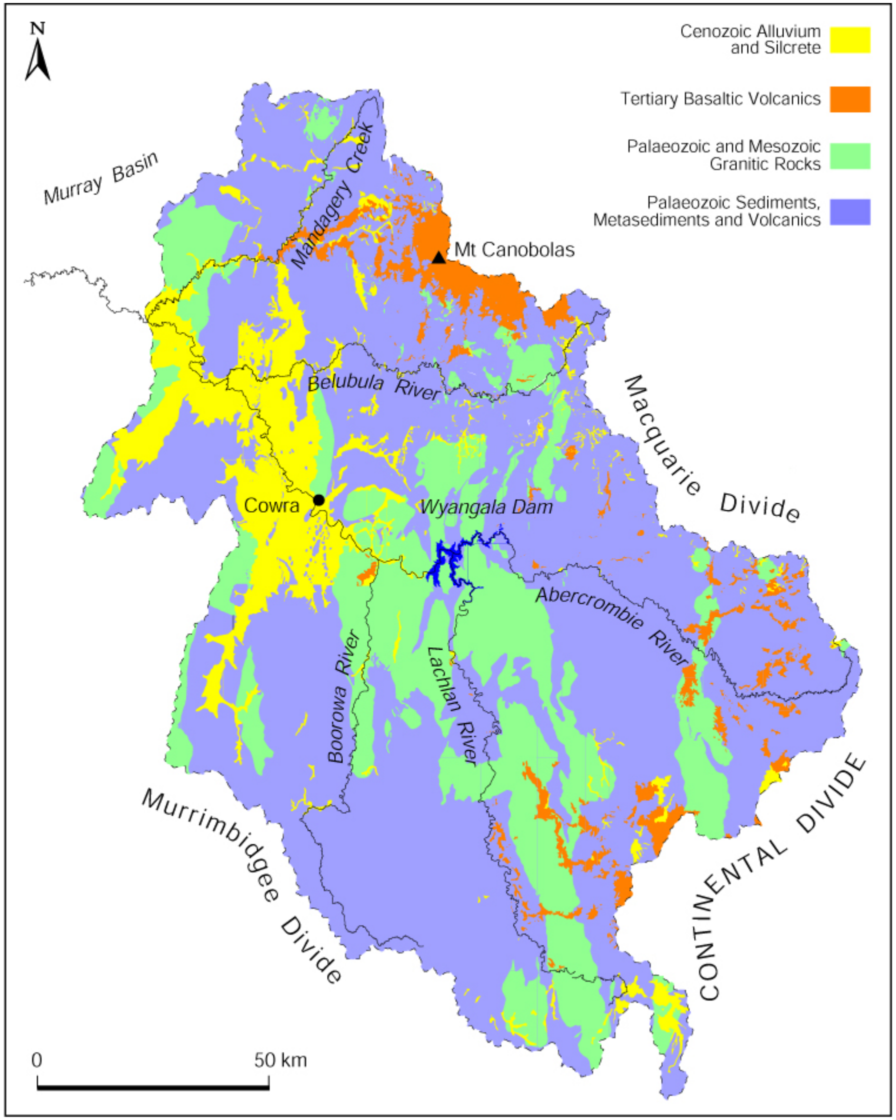
Bishop, 1985, *Geology*;
Bishop & Goldrick, 2000, *Geomorph & Global Tectonics*

Post-orogenic landscape evolution

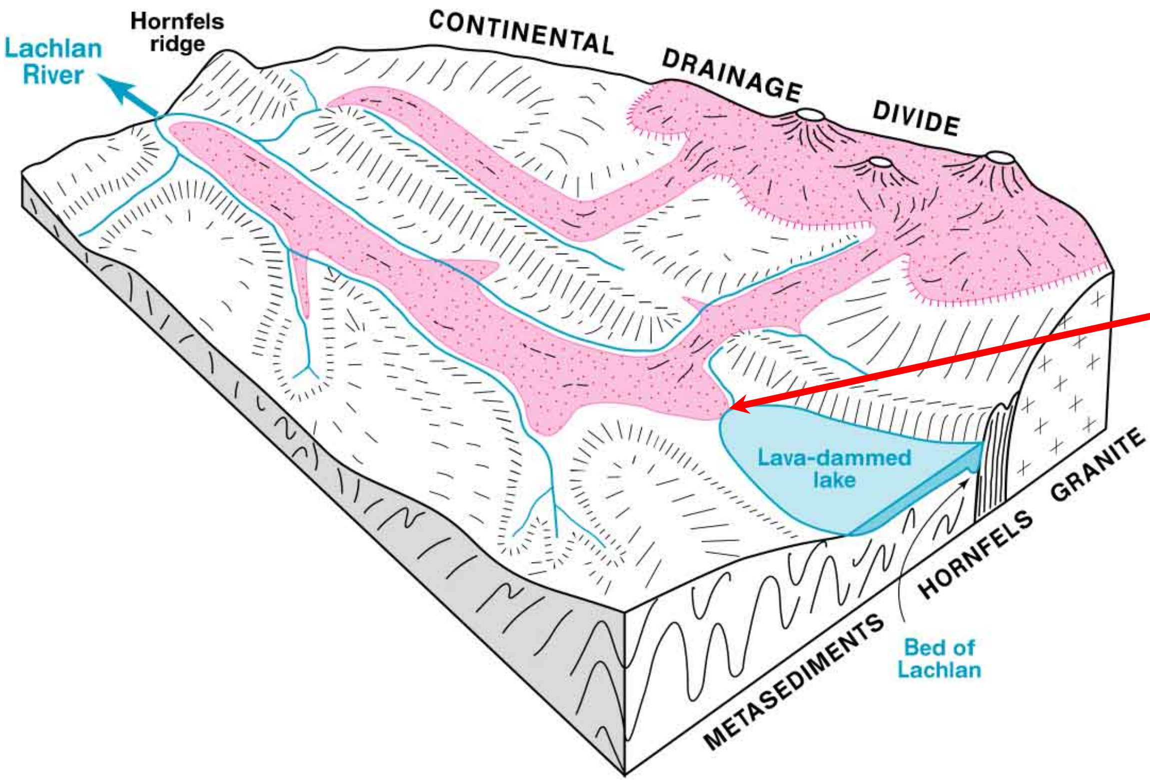
- Neglected: Baldwin et al., 2003, *JGR*: denudational isostasy; detachment-limited → transport-limited; Δing mag-frequ of large Q
- Bottom-up processes of KP retreat triggered by denudational isostatic rebound
- What role lithology?

Lithology and post-orogenic landscape evolution





Lachlan valley



21 Ma

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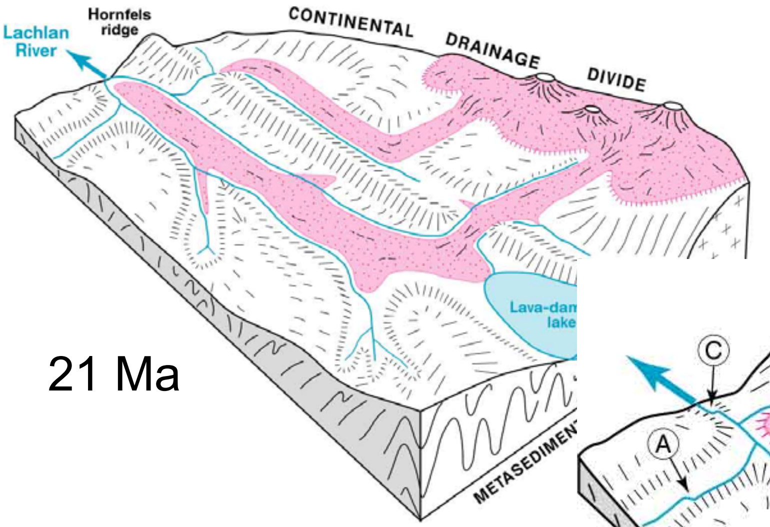
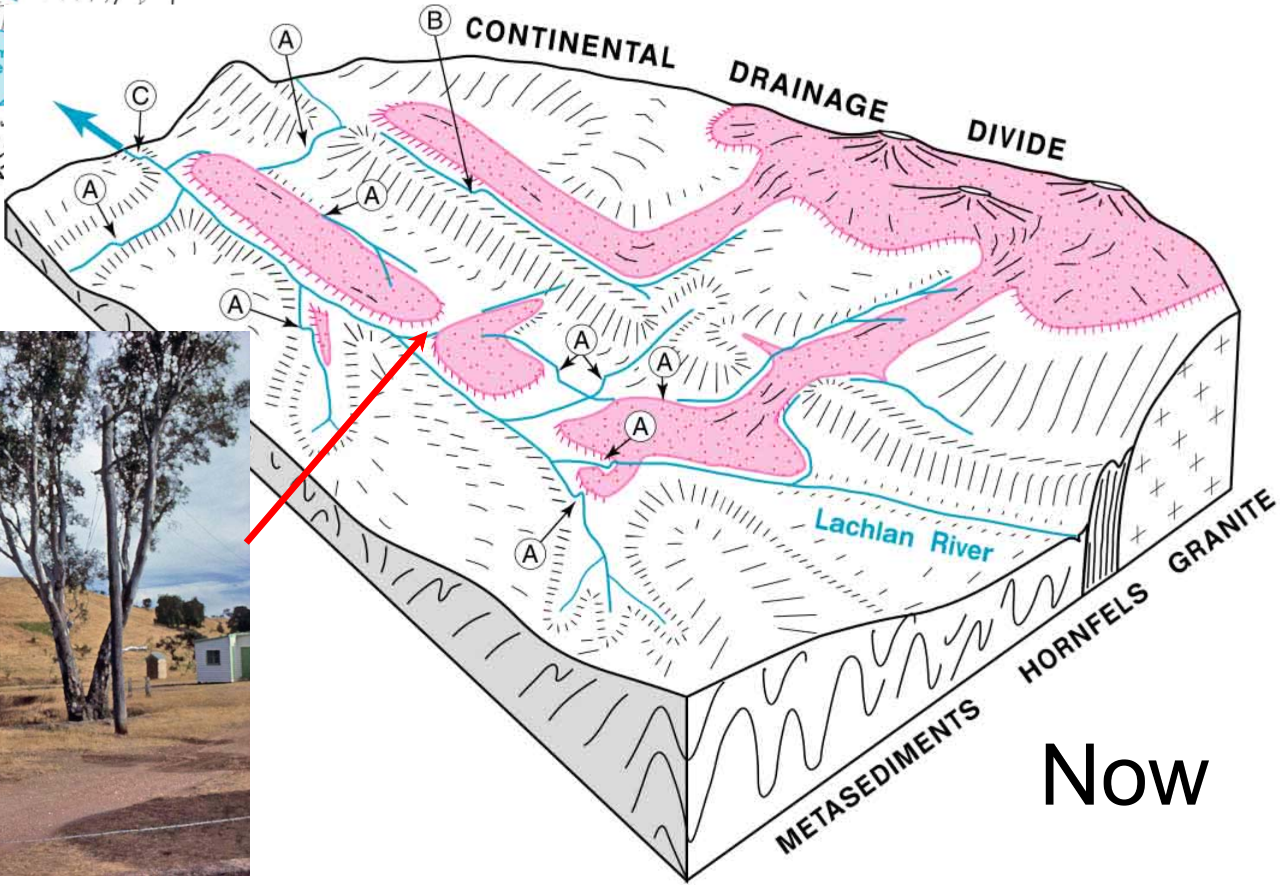
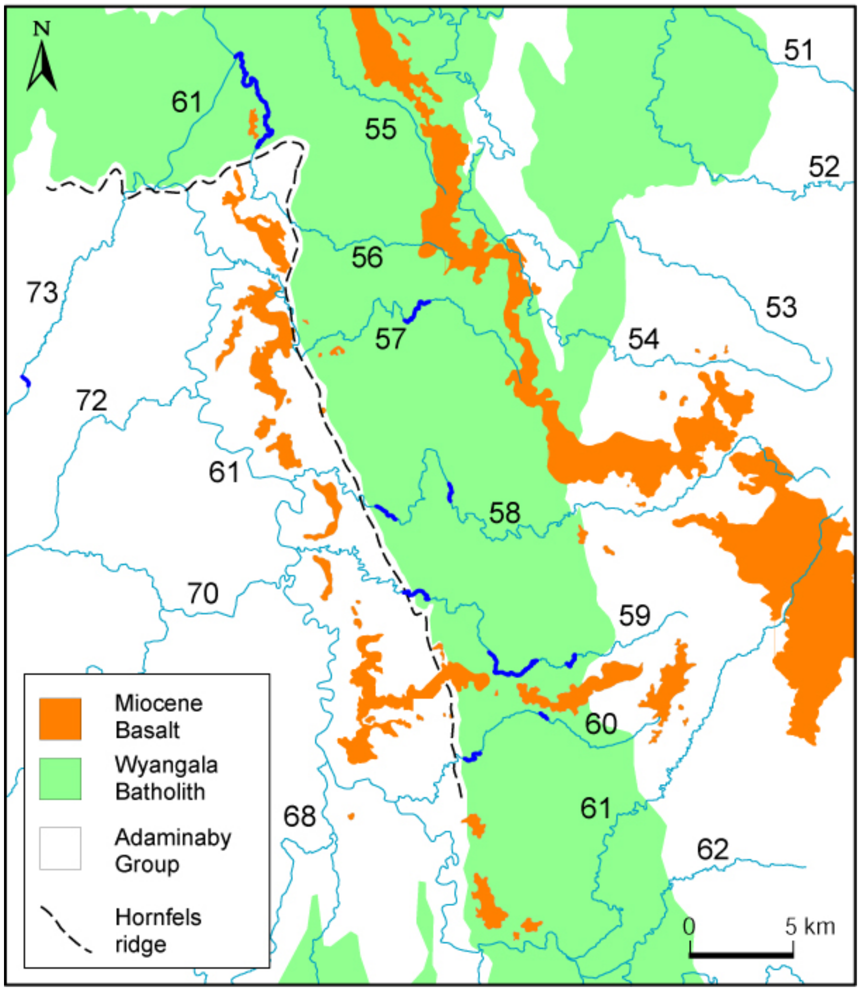
Lachlan valley





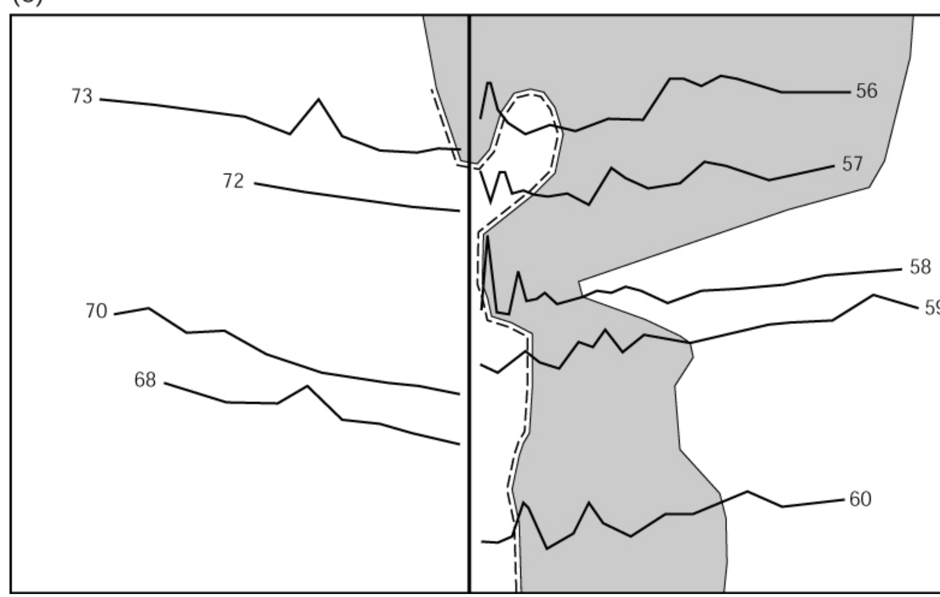
Lithology and post-orogenic landscape evolution

(a)



- KPs (DS outliers) closely associated with resistant granites and hornfels in right bank tribs
- Left-bank tribs tribs more regular long profiles

(c)



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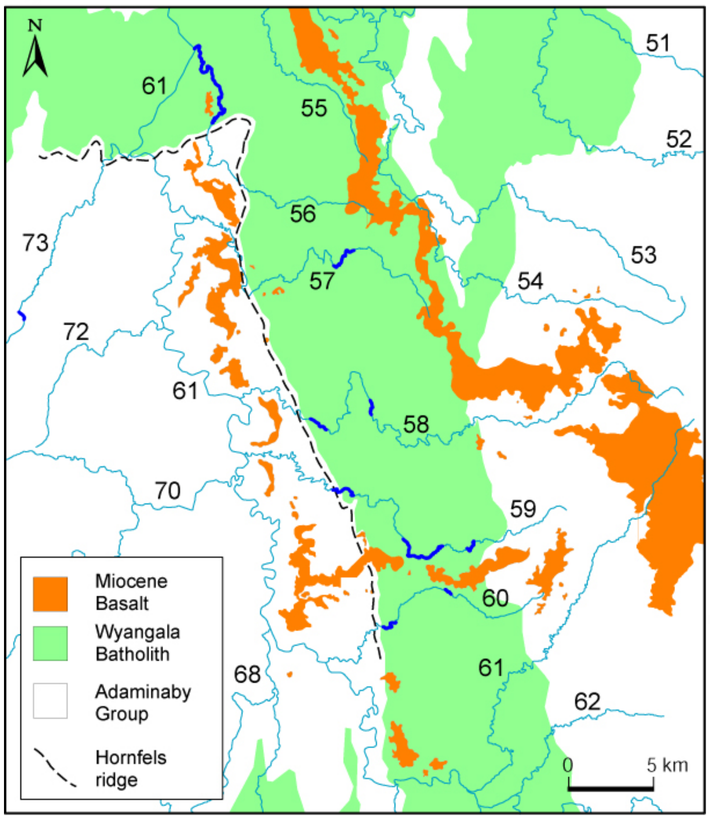
Lithology and post-orogenic landscape evolution

(a)



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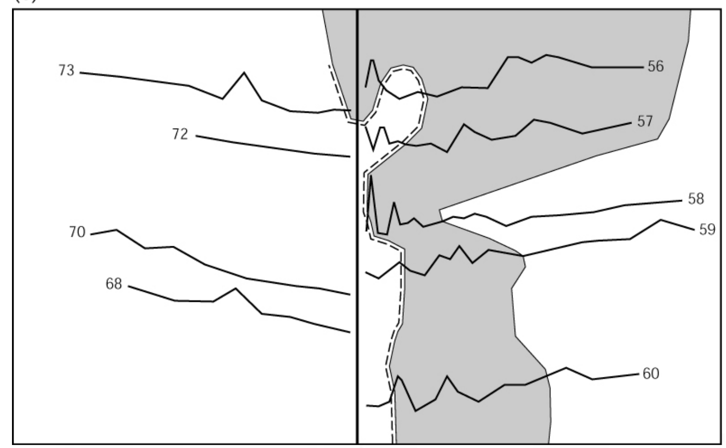

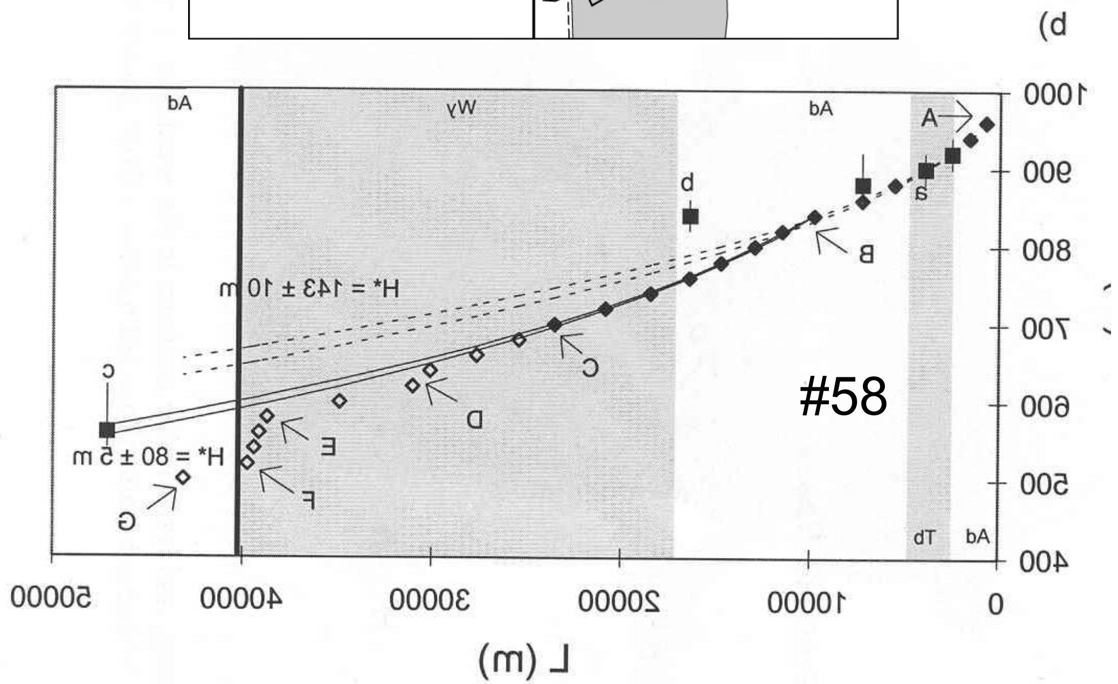

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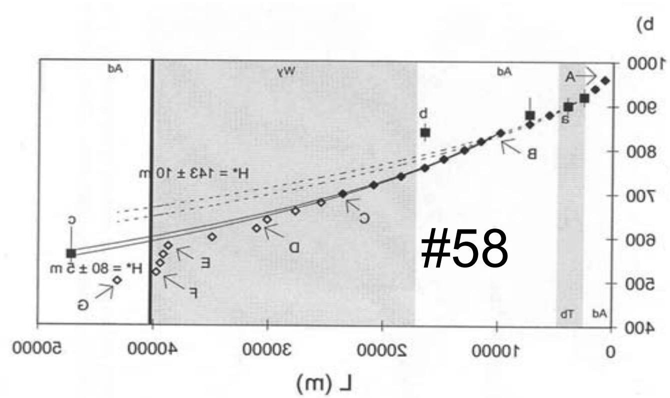
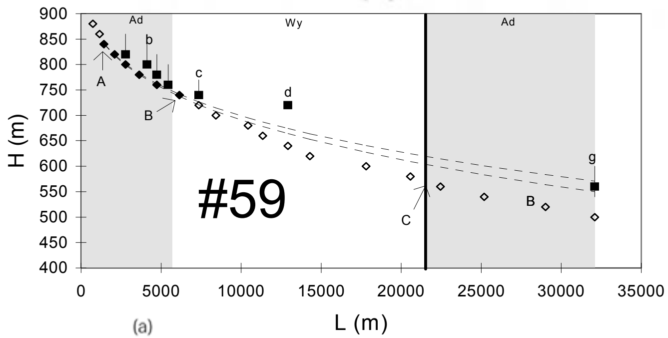
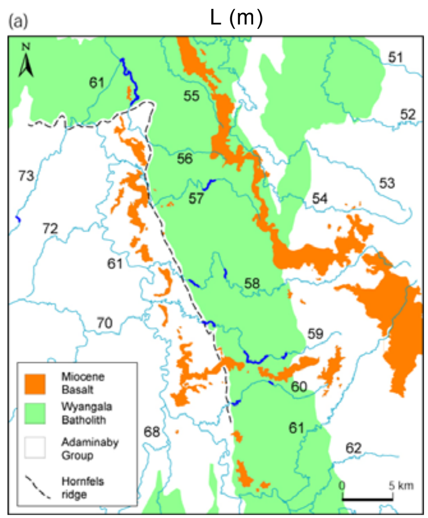
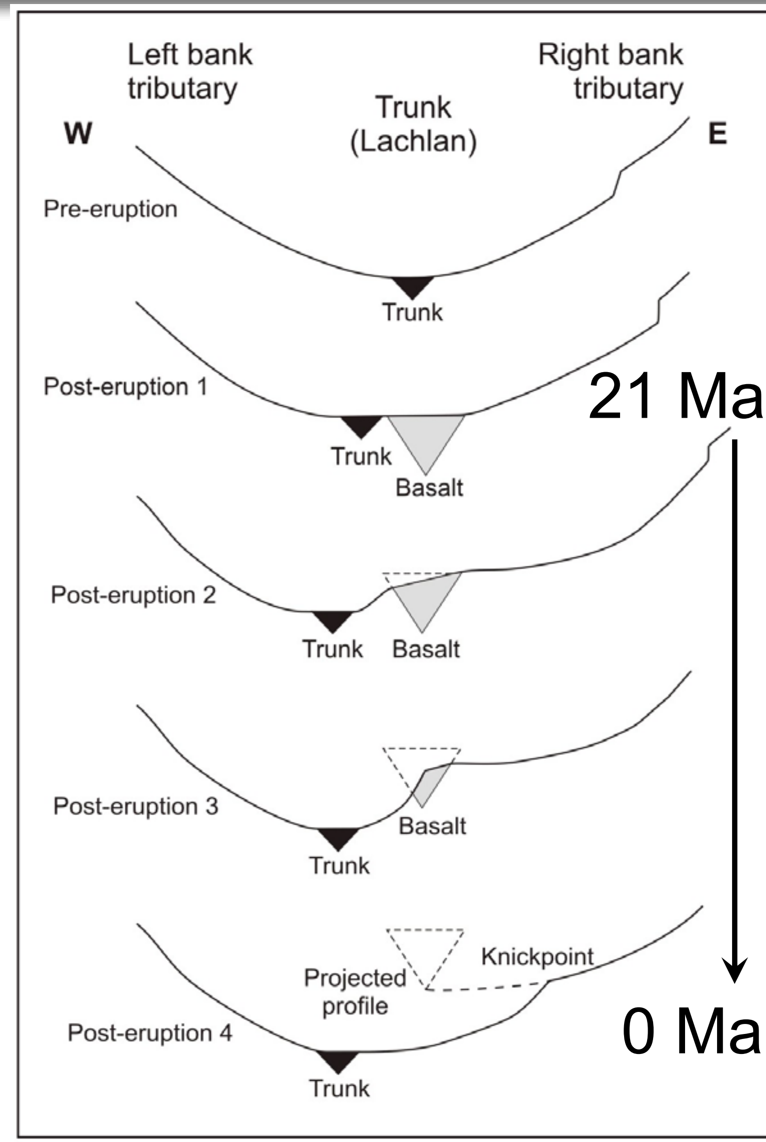
Role of basalt









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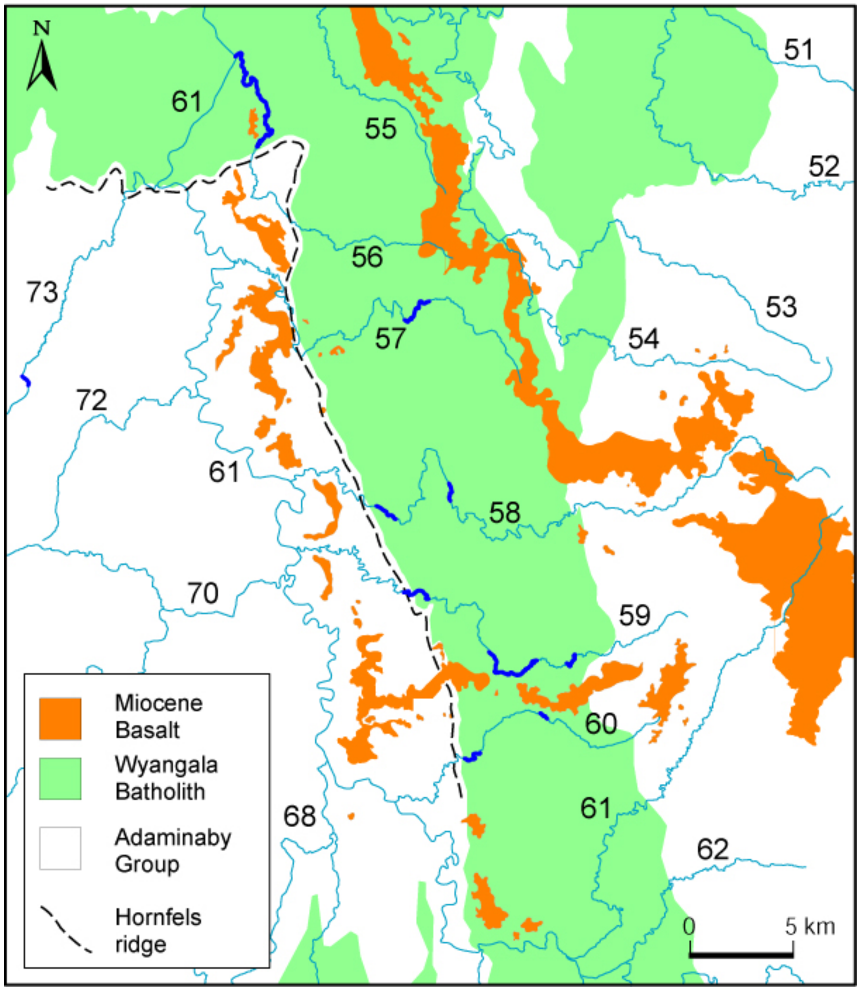
Lithology and post-orogenic landscape evolution

(a)



- Denudational rebound → headward propagating KPs ‘sending the signal upstream’
- Harder lithologies: KPs ‘stall’
- Signal ‘caught’ on resistant lithology
- Catchment relief increases over time
- Crickmay, not Davis

Controls on KP retreat

- Lithology
- What else?

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KP behaviour – Jansen, Castillo, Hoey, Schnabel

- Bedrock rivers set boundary conditions for:
  - hillslopes
  - catchment denudation
  - sediment flux
- Control(s) on bedrock river response to surface uplift?
- Bottom-up responses

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Motivation

- Bedrock river a conveyer belt of
  - Information up
  - Sediment down
- Knickpoint is key communication link

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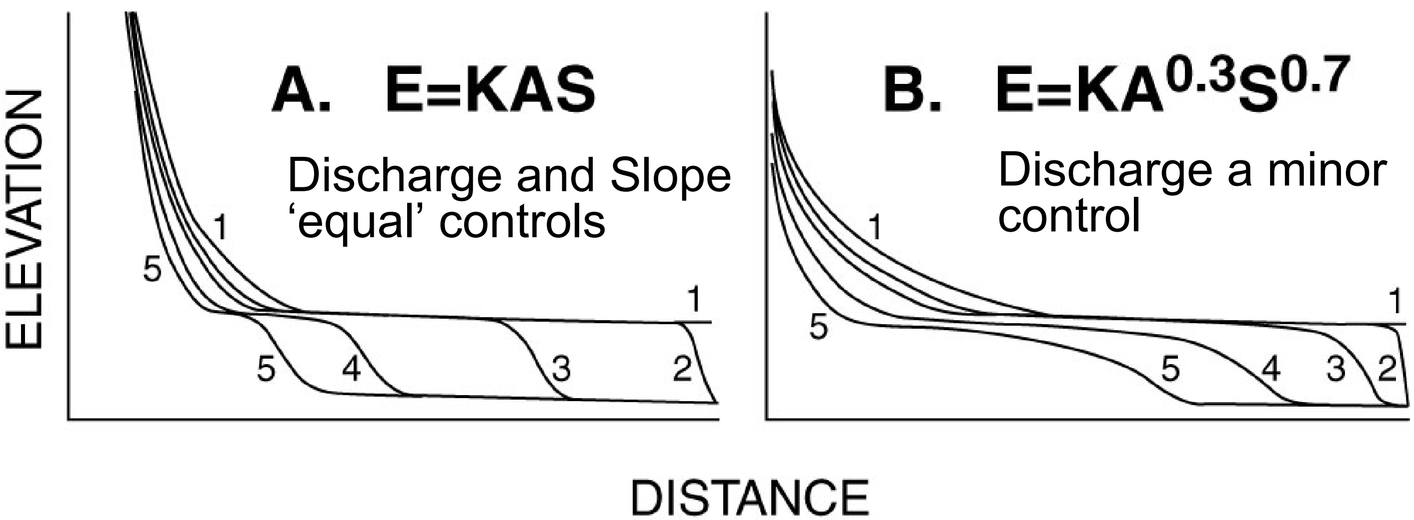
Knickpoint knowledge

- Processes poorly known; difficult to measure and model
- Simple numerical and physical models



Natural laboratory of rebound in Scotland

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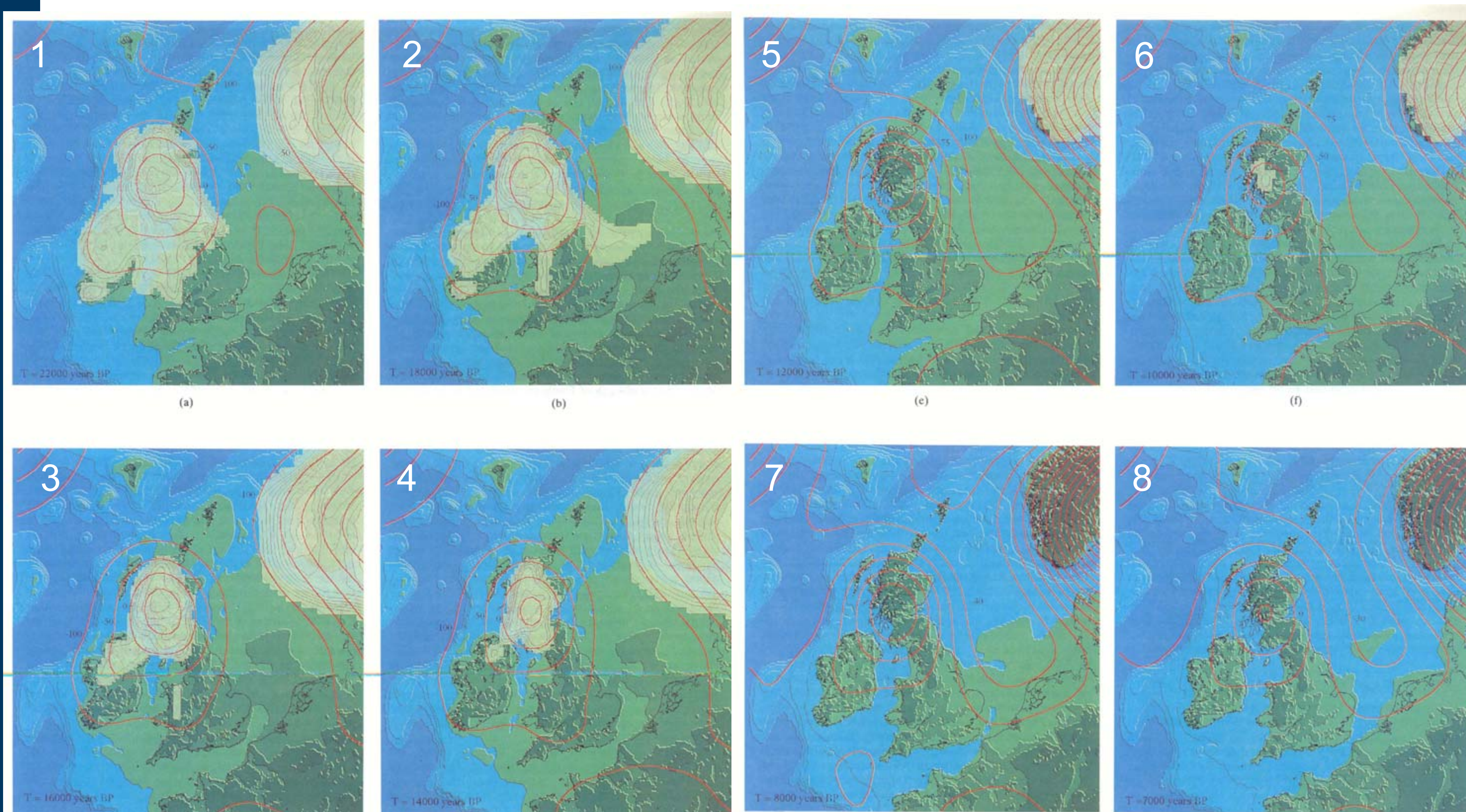
Glacio-isostatic uplift of Scotland



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Glacio-isostatic uplift of Scotland

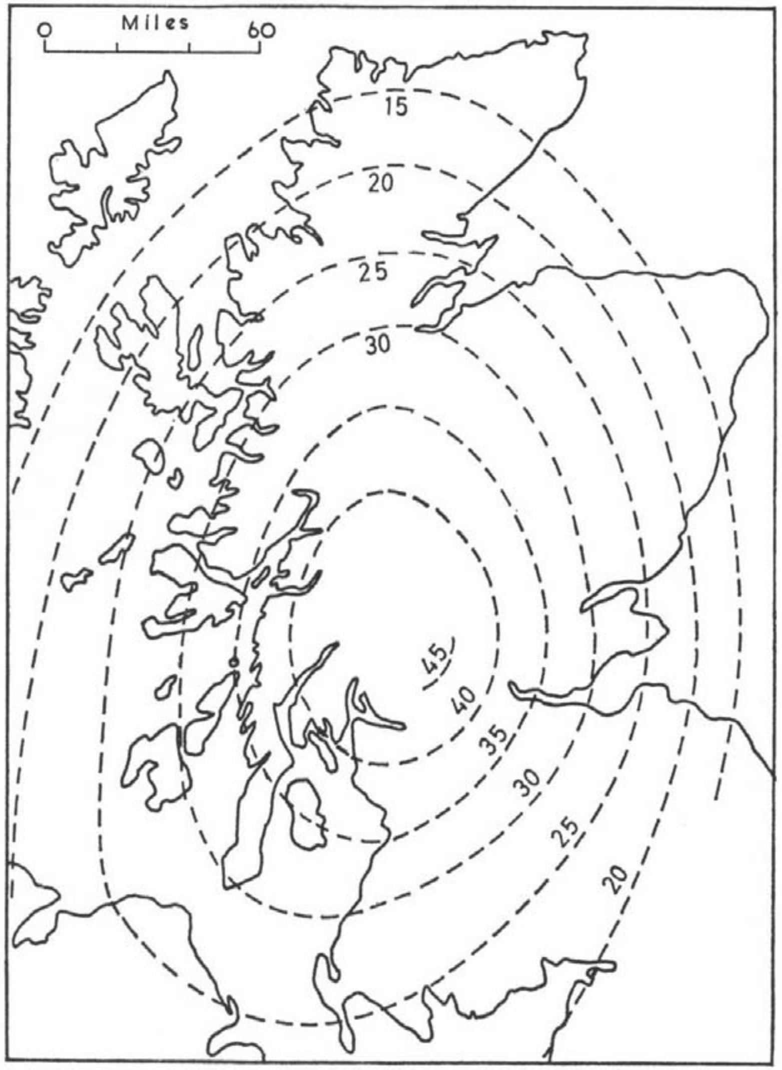

FIG. 87. Isobases for Main Postglac Shoreline. Based various sources.
(in feet)

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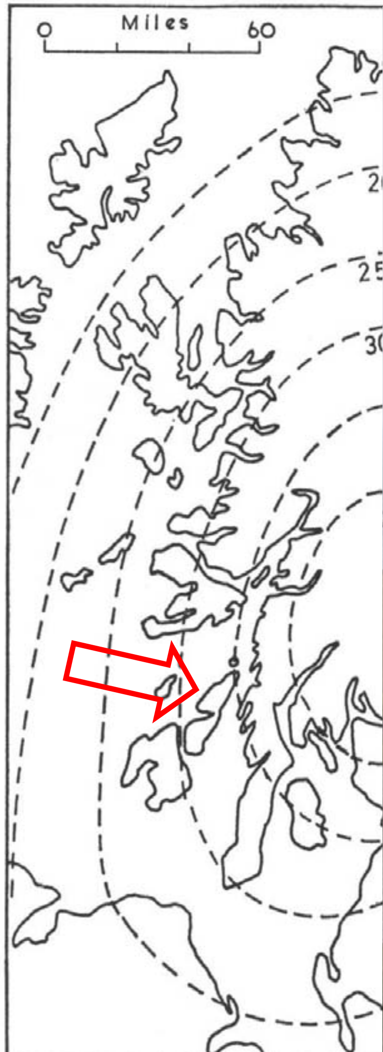
Glacio-isostatic uplift of Scotland

Raised beache of Jura



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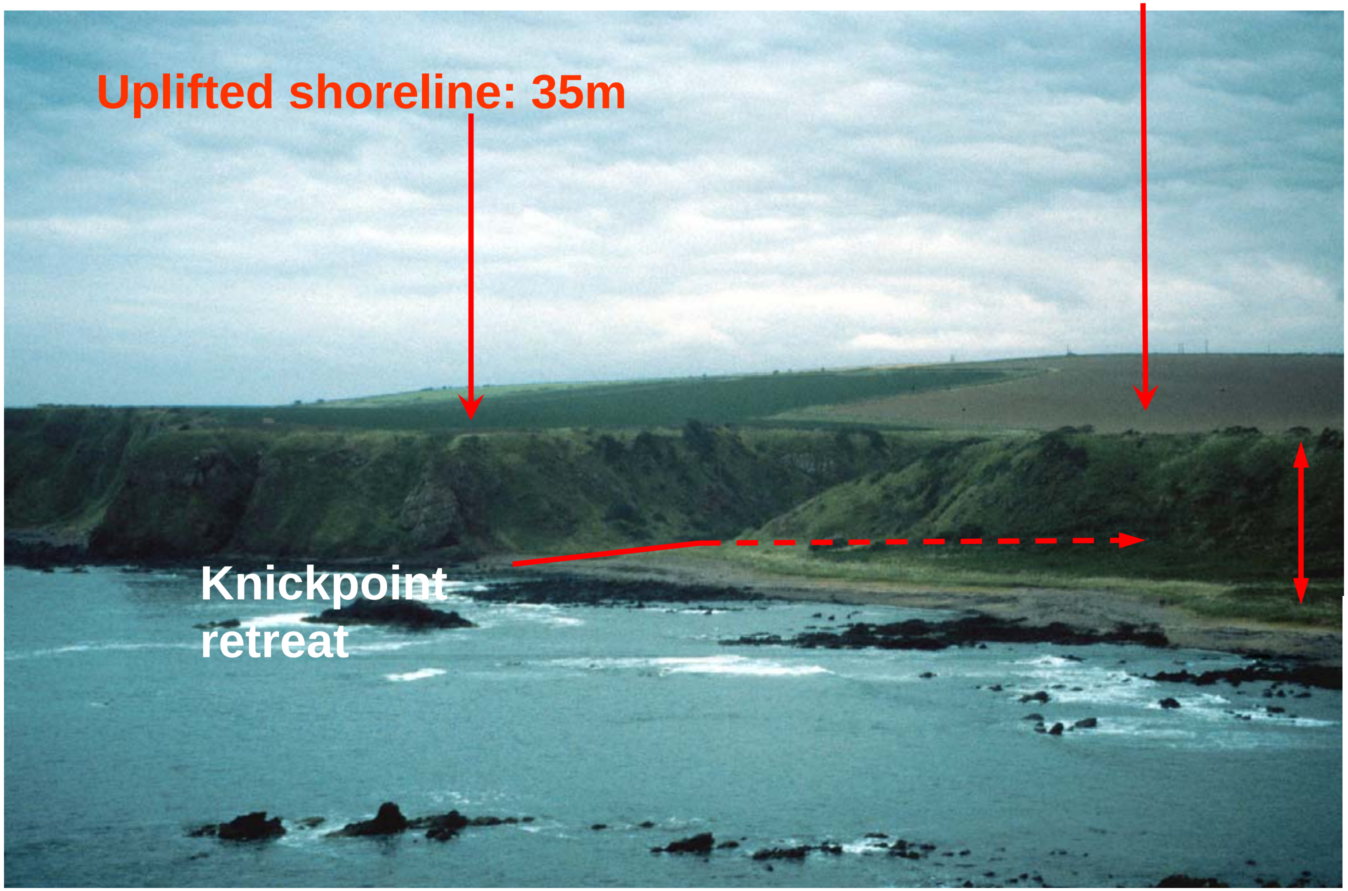
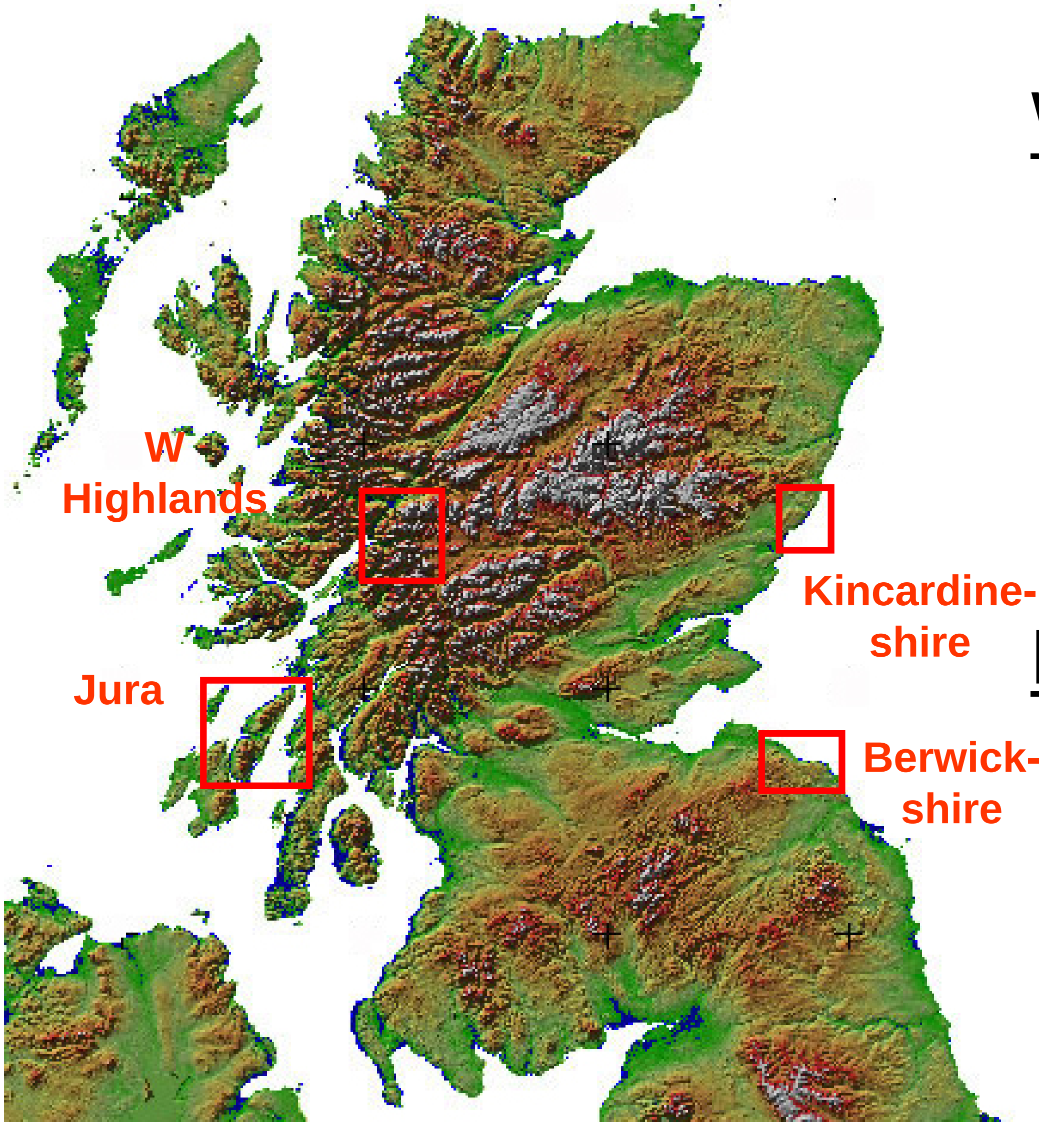
Knickpoint retreat on glacio-isostatically uplifted coast



Scotland study



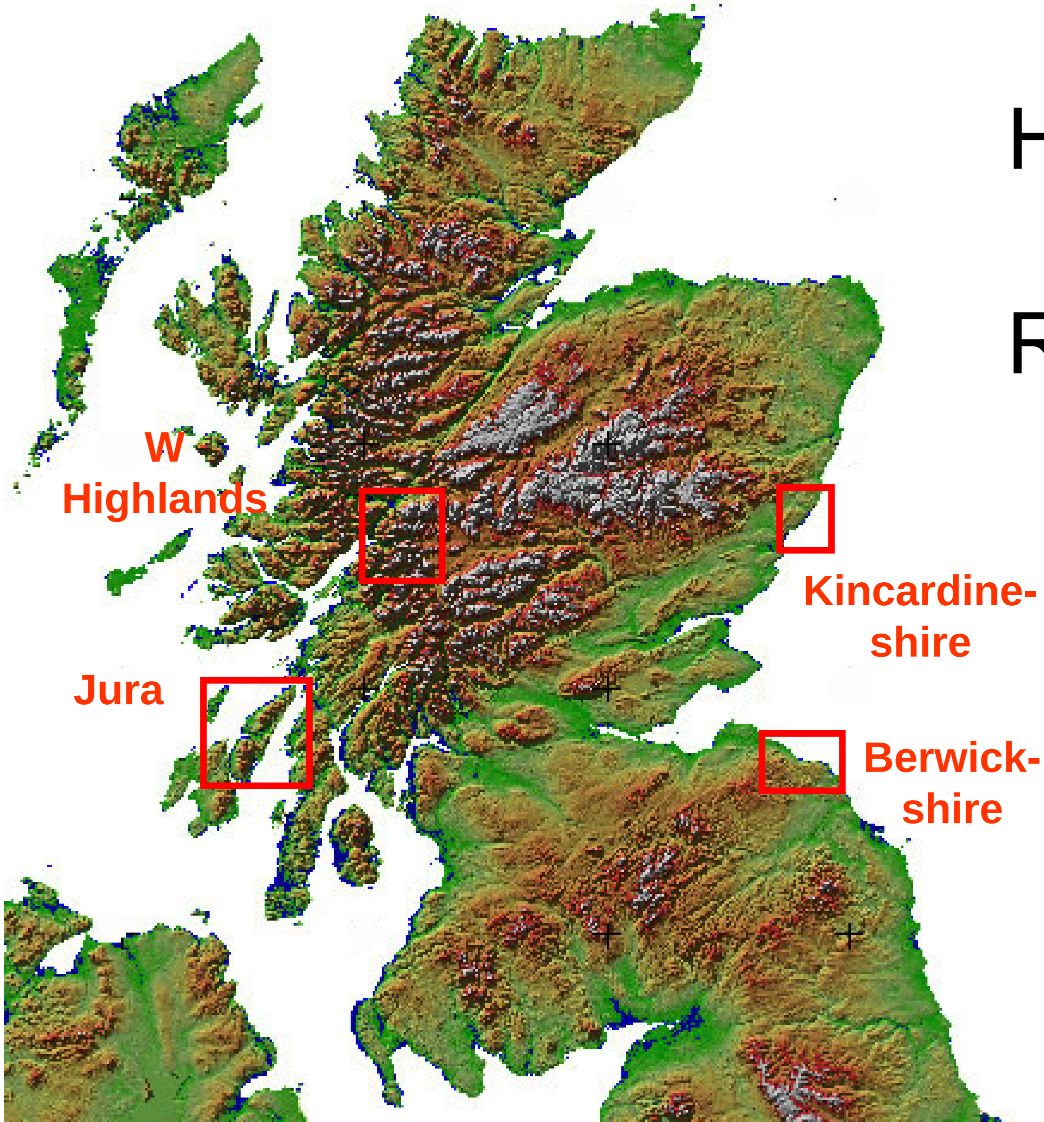
West:

- ≤3m pptn p.a.
- Metamorphics & granites (W Hilands) and quartzites (Jura)

East:

- ~0.7m pptn p.a.
- Mixed lithologies (but overall less resistant)

Scotland study



Hydrological controls (A = ~Q)

Role of lithology and structure

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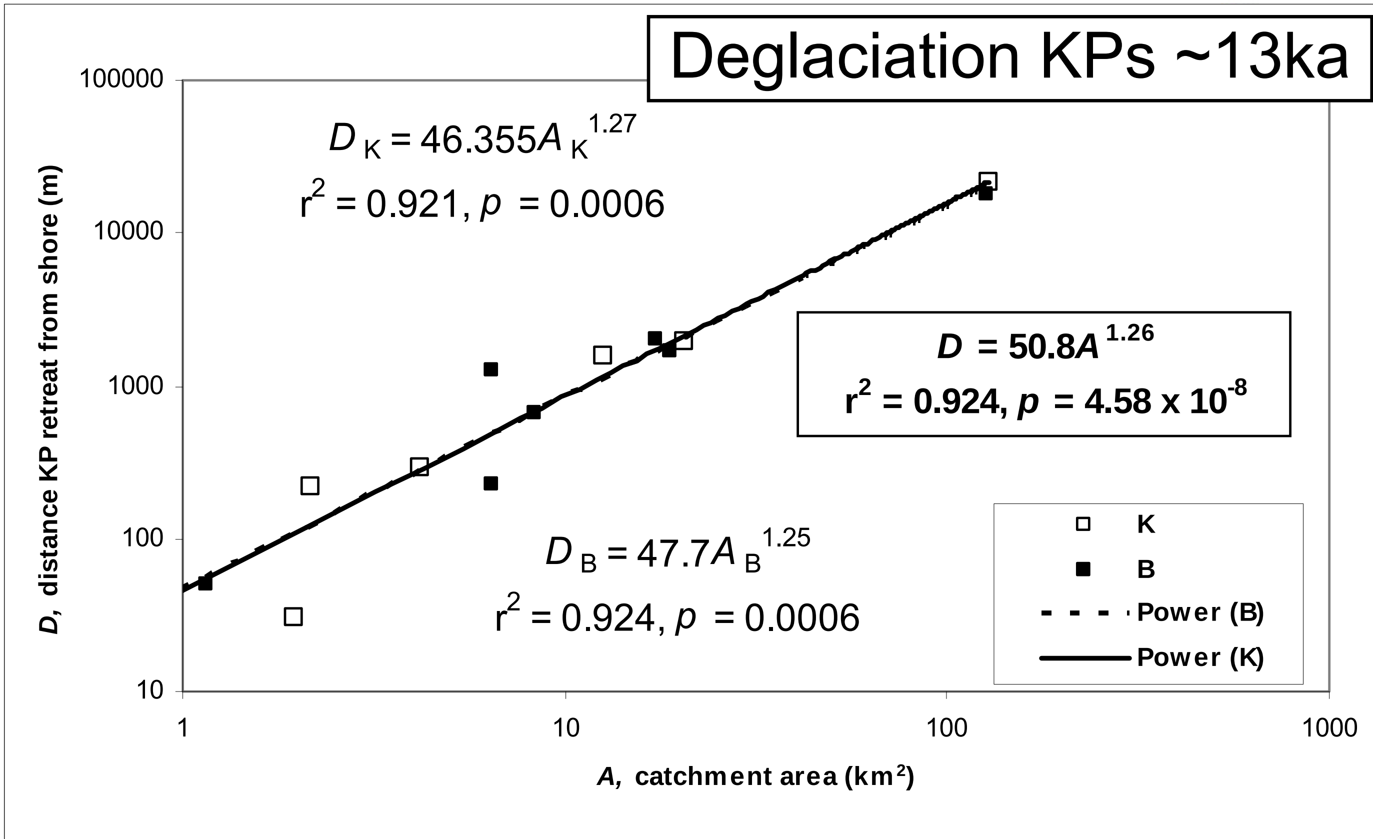
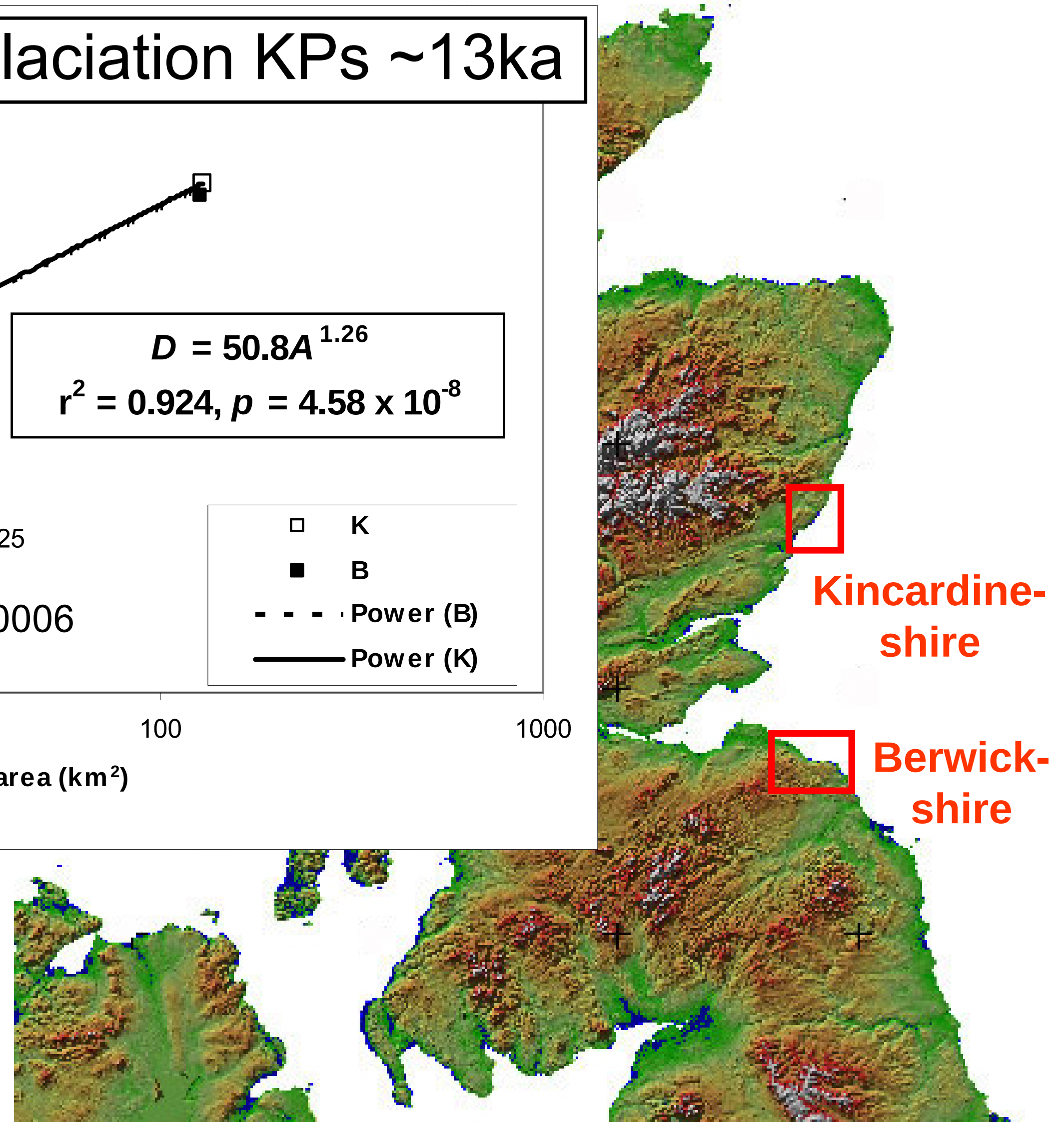
E Scotland study





Bishop et al. 2005. *ESPL*

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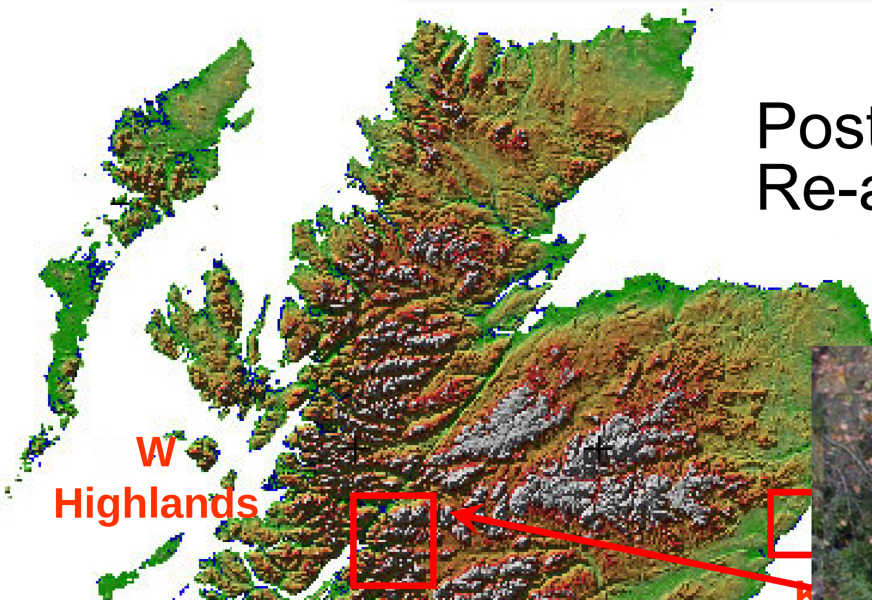
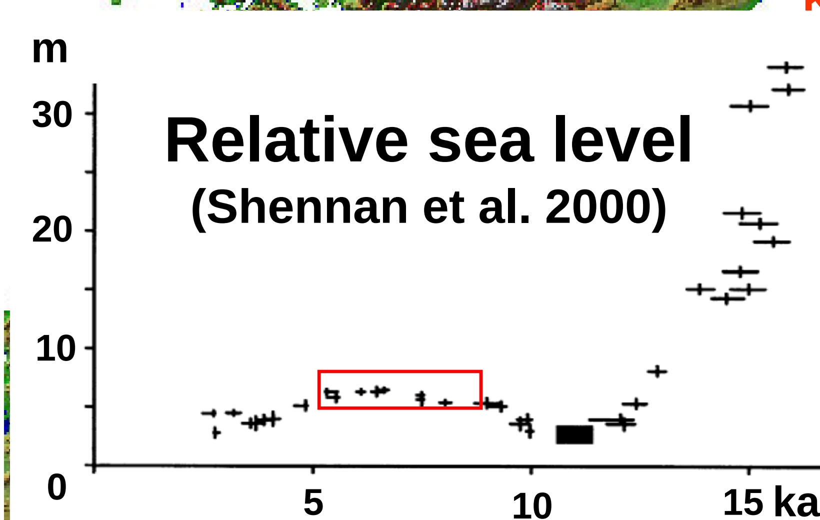
W Highlands study

Post-Younger Dryas (Loch Lomond Re-advance)





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Those upland surfaces

- Marine vs. sub-aerial
- Davis
- RW Young
- Cosmo from Highland Scotland:
  - Tertiary surface
  - Cold-based ice
  - Max ages 250kyr
- Morphology retained but surface lowers

Where are we?

- Exciting time
- New paradigms that link surface and sub-surface processes: plate tectonics
- New conceptual approaches: climate driving tectonics
- New techniques: cosmo, numerical modelling, lo-T thermochronology, combine all three
- Davis: instantaneous uplift, declining relief; Hack: ongoing rock uplift; constant relief

Last word…

"Classical conceptual geomorphic models may be valid under specific tectonic, climatic, and substrate conditions and at specific scales. These ideas imply that apart from some claims to universal applicability, there may be no conflict among the various classical conceptual models and that these models might be reconciled with modern concepts within a single numerical framework"

(Kooi & Beaumont. 1996. ***JGR***)

Transience – Reinhardt, Hoey, Freeman, Sanderson, Persano

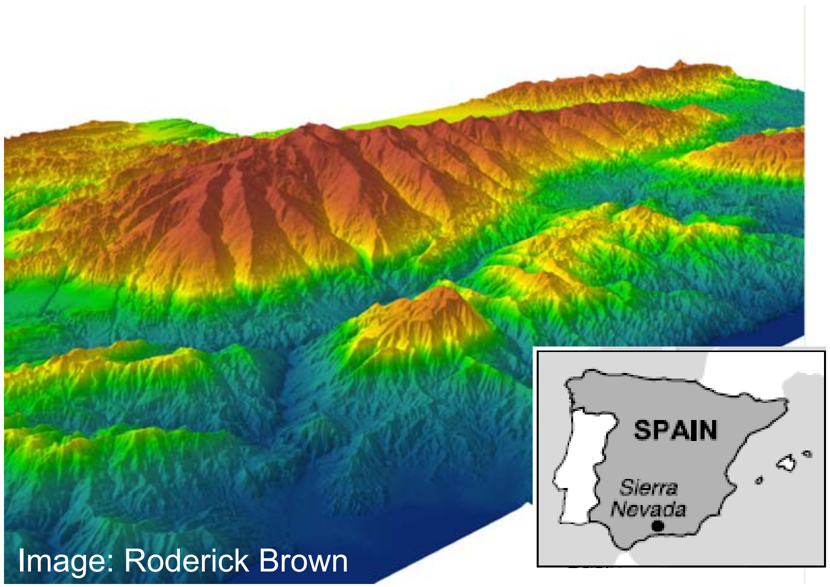

Image: Roderick Brown

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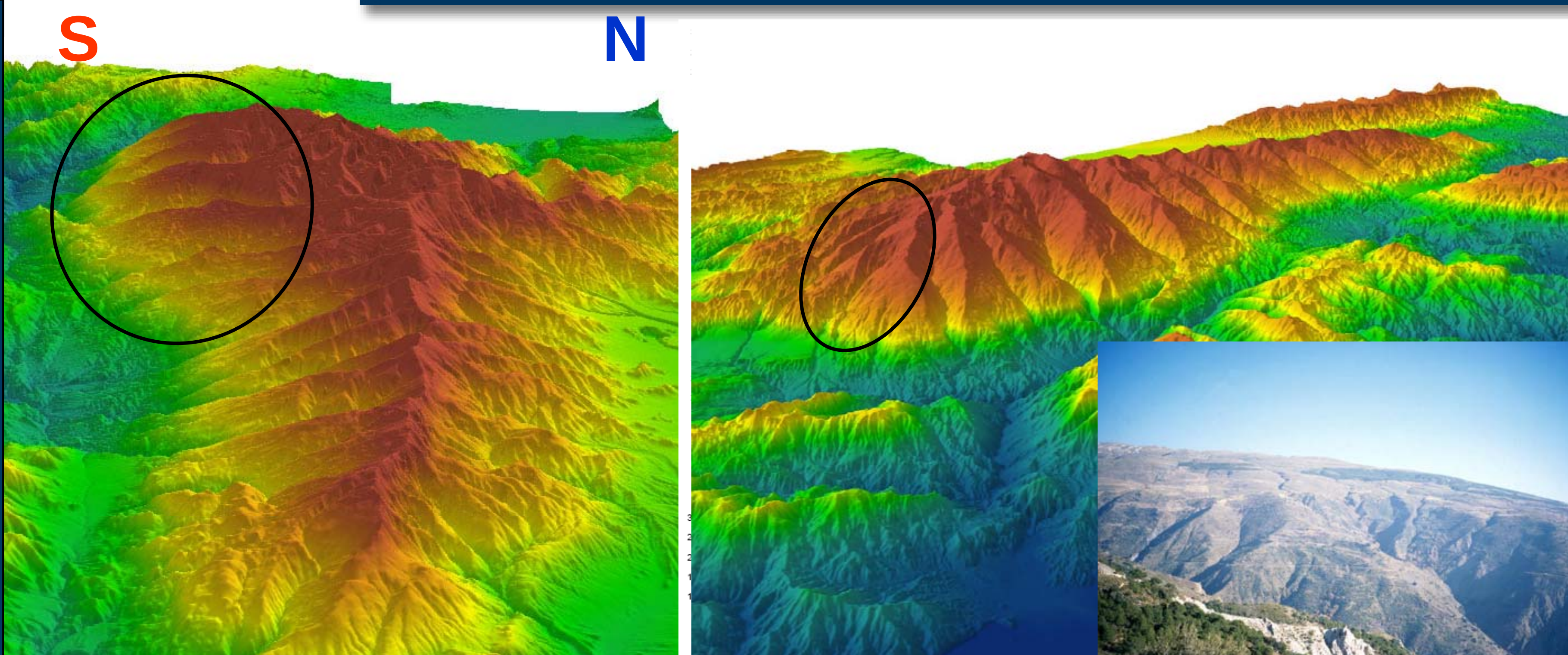
Transience



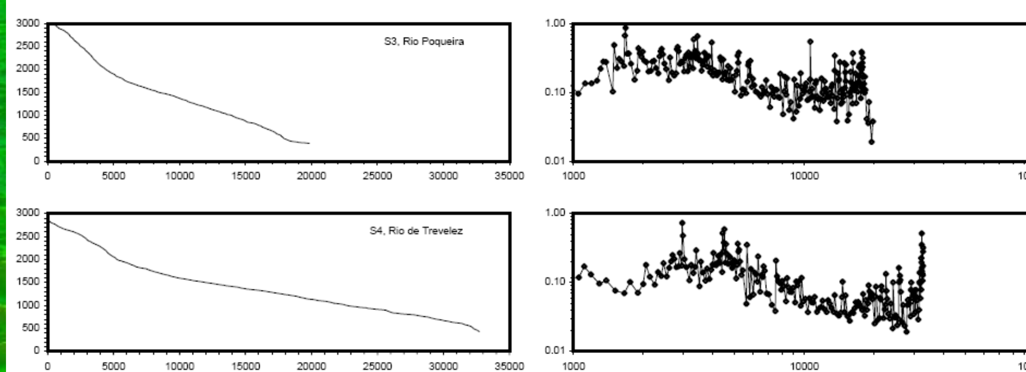


Image: Roderick Brown; Long profiles: John Jansen

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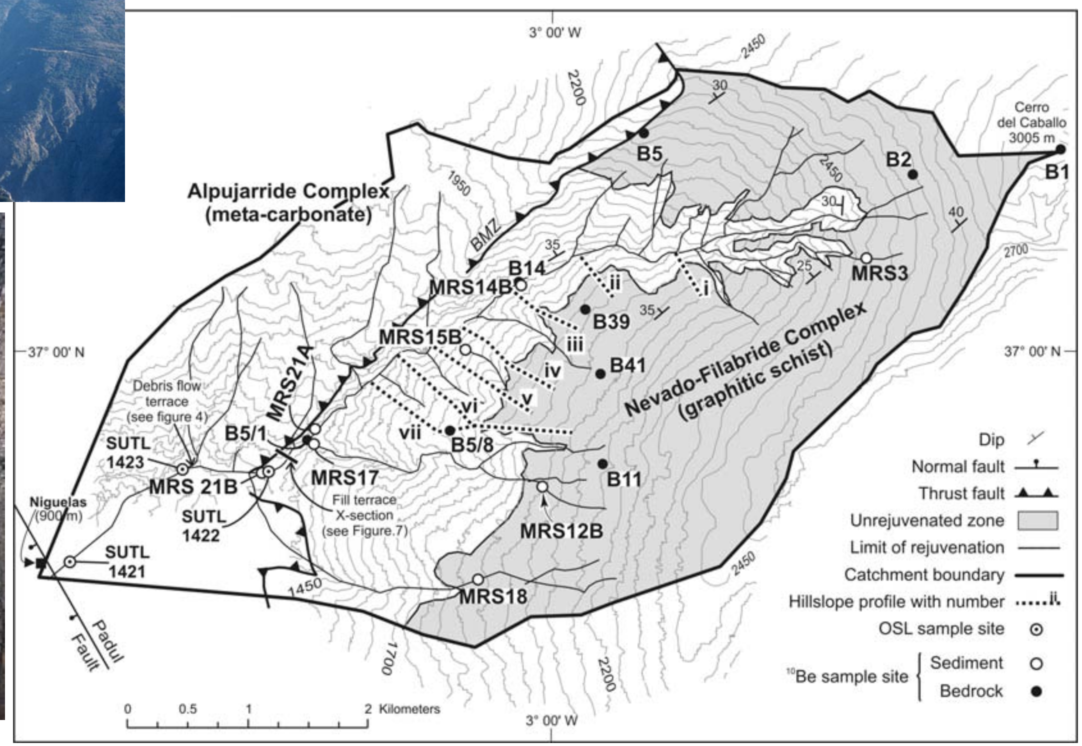
Transience

- OSL: KP retreat rate
- Cosmogenic ^{10}Be: ‘spot’ and catchment-averaged erosion rates

Reinhardt et al. 2007. *JGR*



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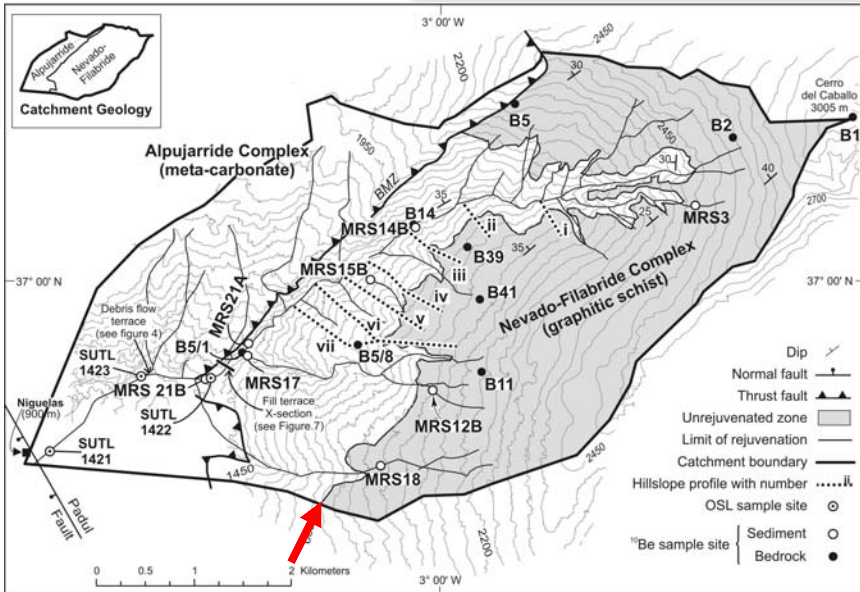
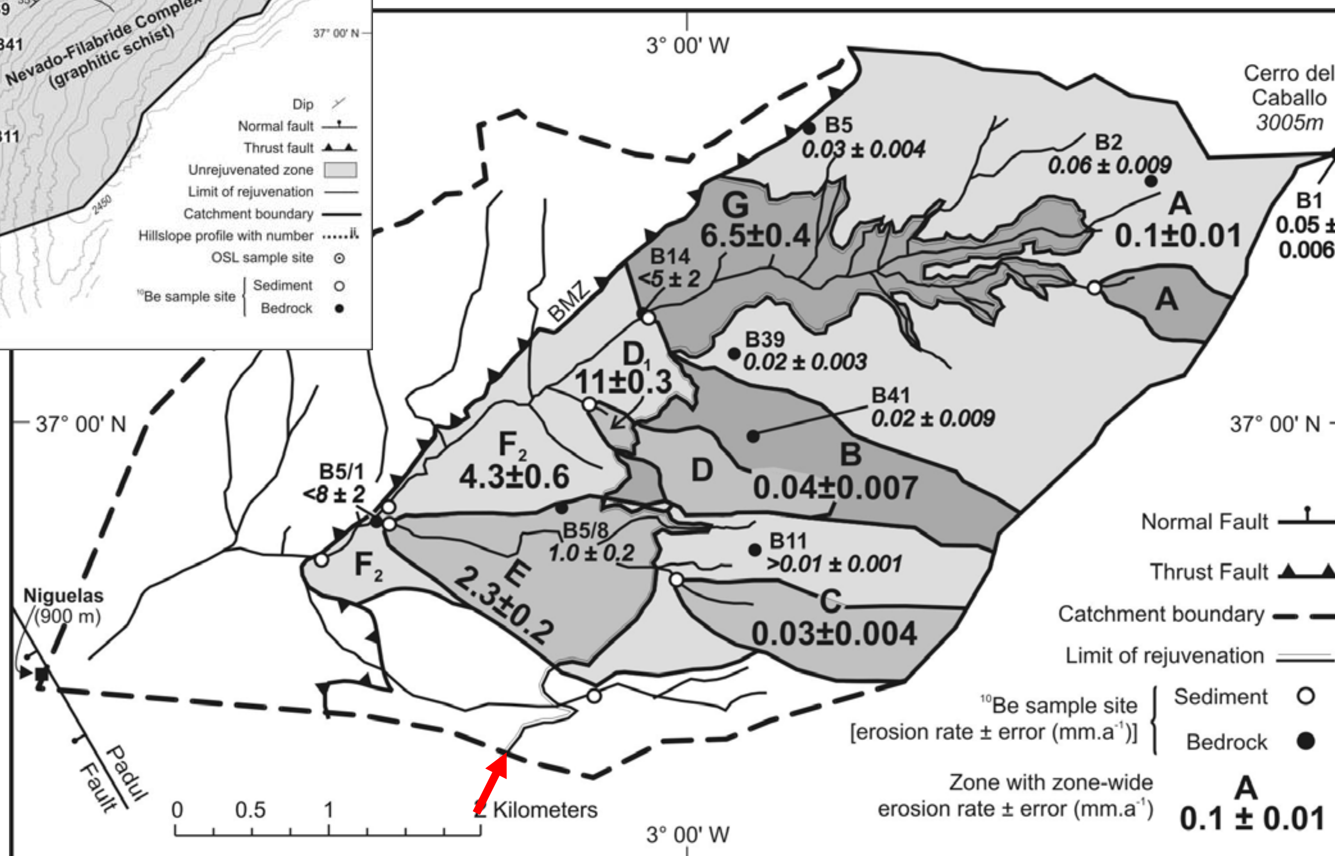
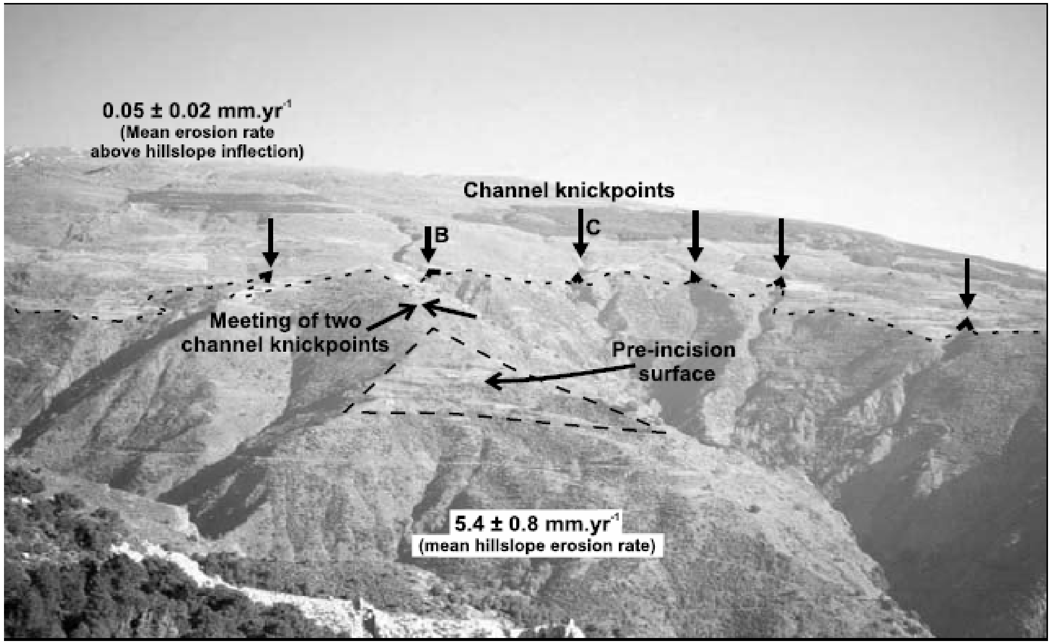
Transience

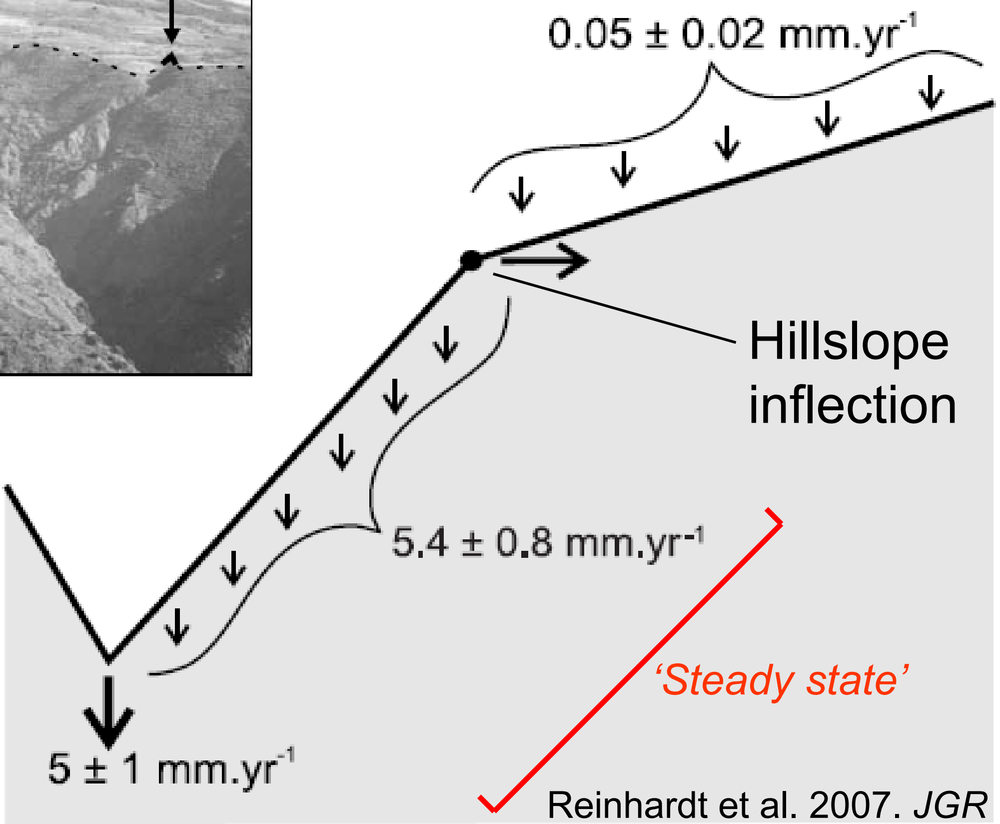




Reinhardt et al. 2007. *JGR*

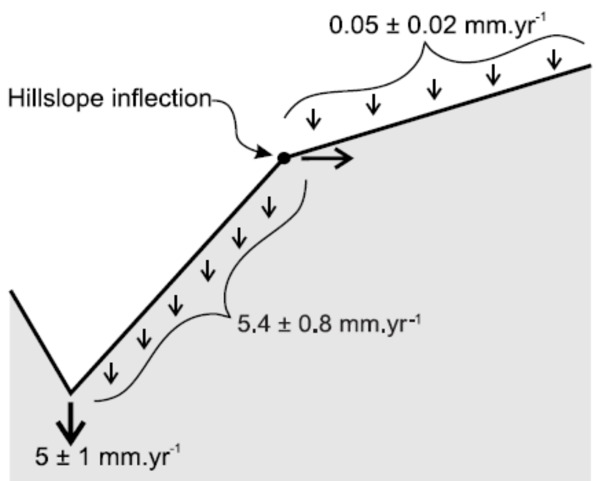
Transience



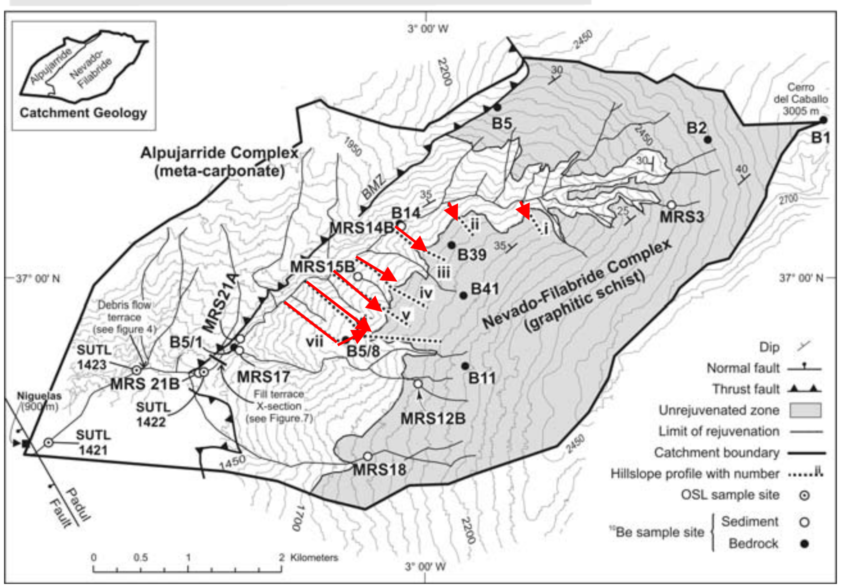


Reinhardt et al. 2007. *JGR*

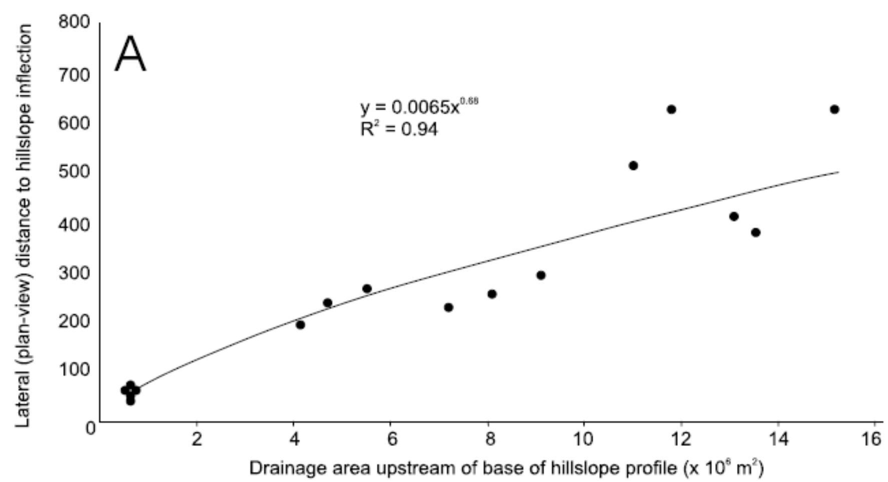
Top-down vs. bottom-up



- Trunk valleys hillslope lowering ‘tracks’ channels
- Rate of lateral migration of hillslope inflection α rate channel incision & slope angle
- KP_{HS} retreat distance = *f*(time since KP_{Ch} passed foot of slope)

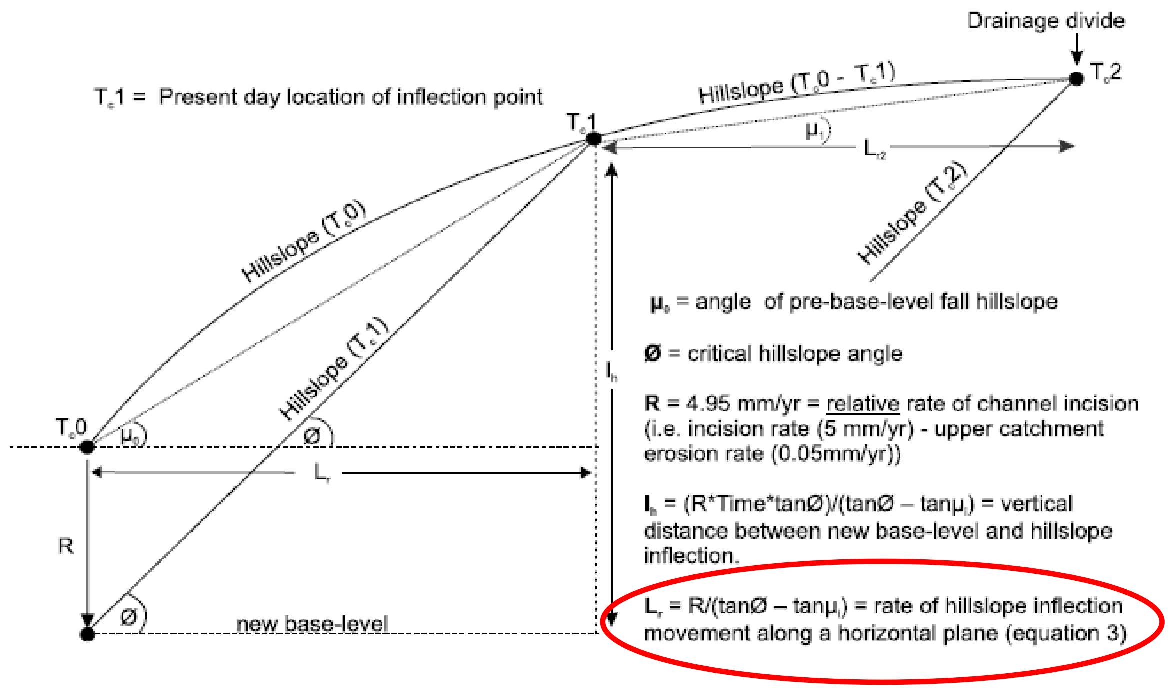


- i.e., scales to catchment area



Reinhardt et al. 2007. *JGR*

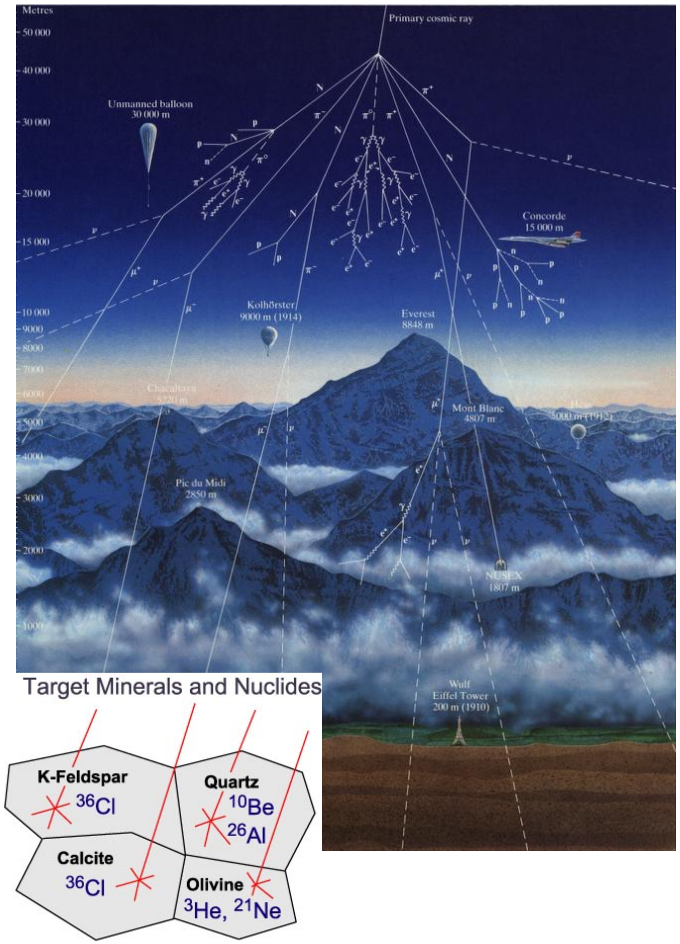
Duration of transience



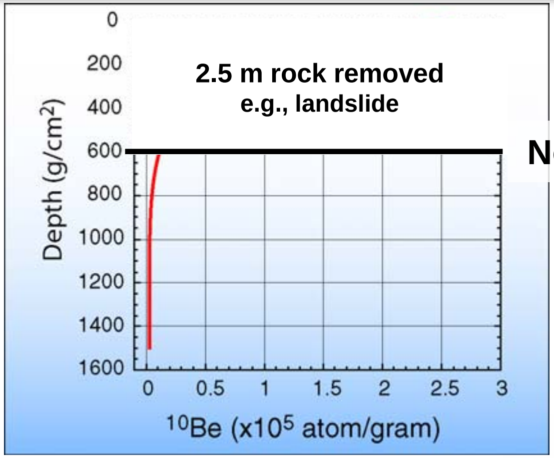
- Incision to acquire steady-state topography = 1140 m
- Time to acquire steady-state topography = 240 kyrs
- 50m of mountain front fault throw in 12 kyrs
- "Fast rivers, slow hillslopes"
- Steady-state topography?

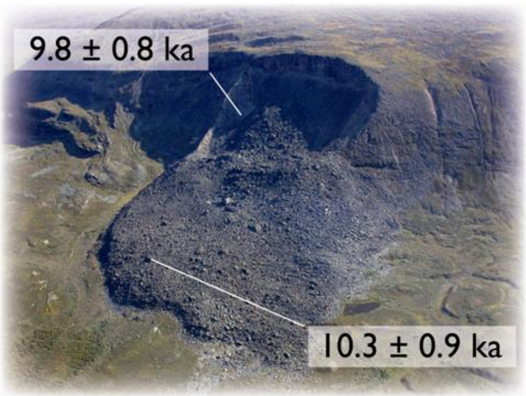
Reinhardt et al. 2007. *JGR*

‘Novel’ cosmo – Codilean, Fulop, Fabel, Stuart



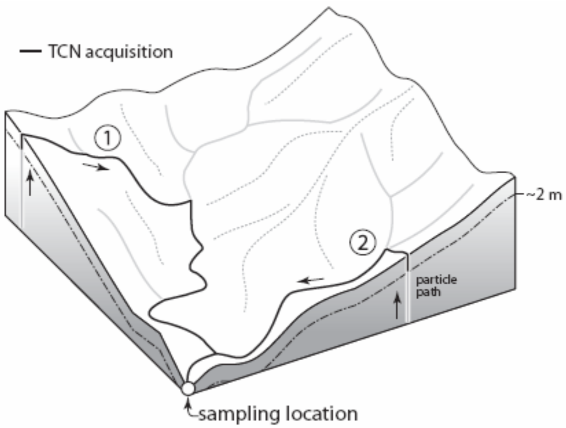
- ‘Garden’ variety of nuclides
- *In situ*





‘Exposure’ ages

Rates of surface lowering



Catchment-averaged erosion rates

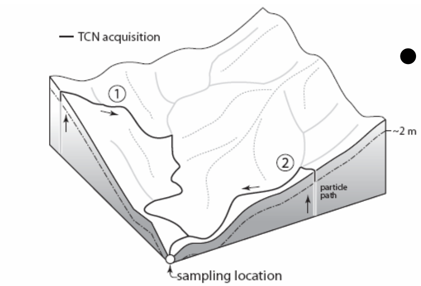
↓

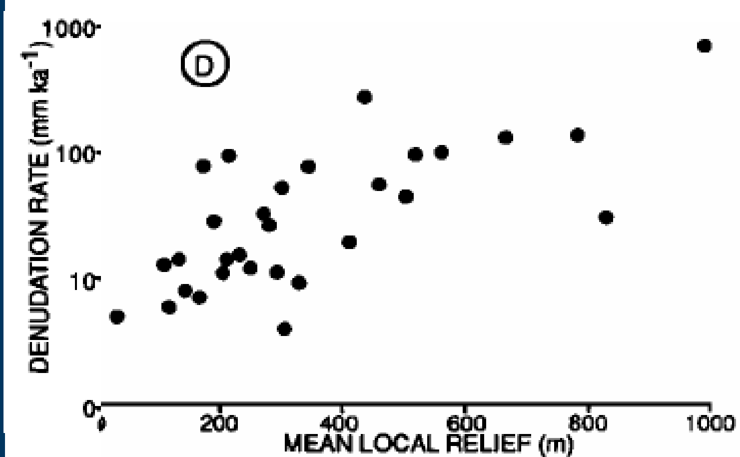
“Let Nature do the averaging”

Diagrams & images: Derek Fabel, Liam Reinhardt, Tibi Codilean

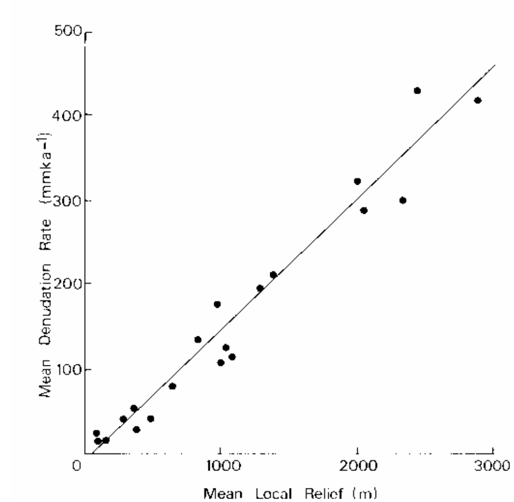
Novel applications of cosmogenic nuclides

- Beyond dates and rates?
- TCN production (concentration) = *f*(latitude, **altitude**, **dwell time in upper 2m of Earth's surface**)
- Dwell time = *f*(erosion rate)

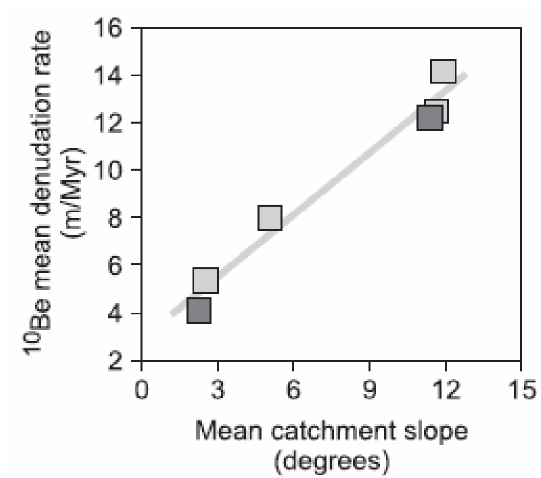




Summerfield & Hulton. 1994. *JGR*



Ahnert. 1970. *Amer. J Sci.*



Codilean et al. 2008. *Geology*

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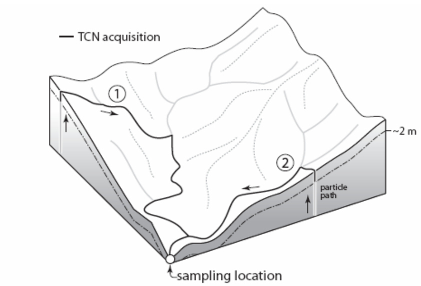
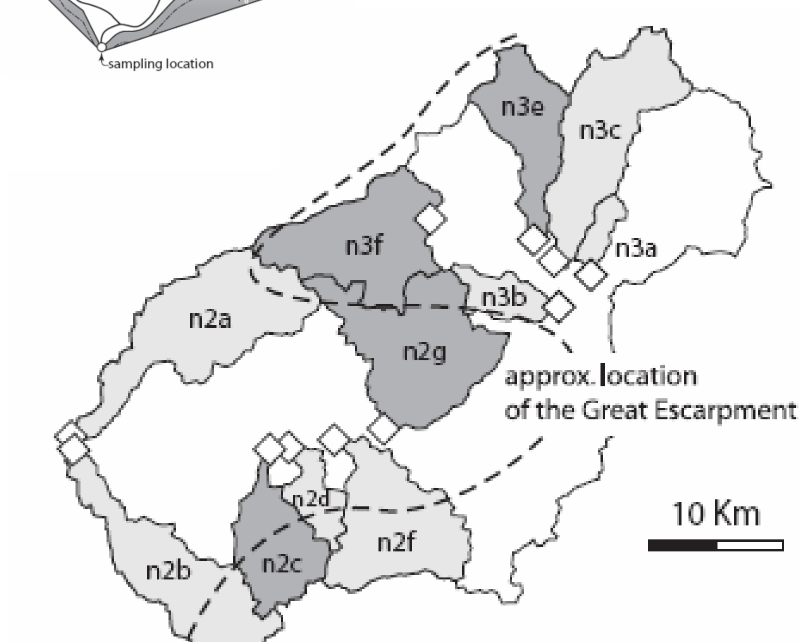
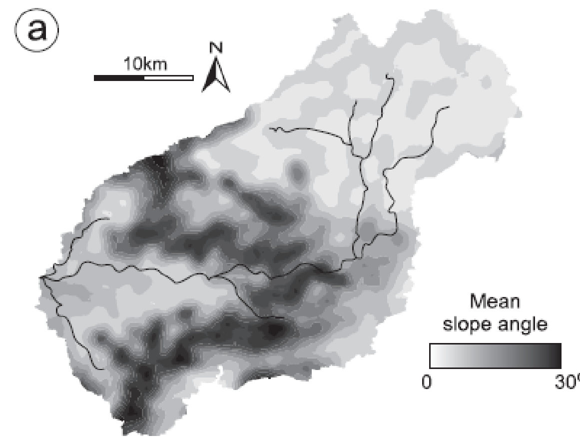
Novel applications of cosmogenic nuclides

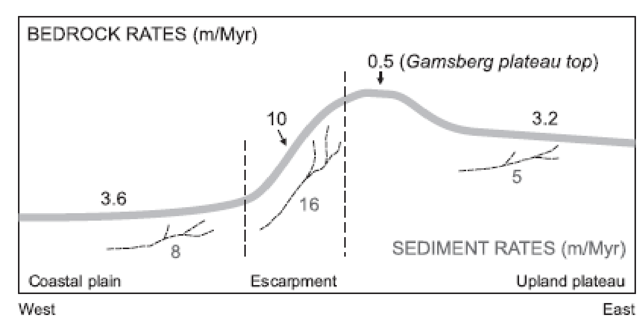
- Multiple (unique?) pathways for grains?
- Each grain's history → TCN concentration
- PDFs of cosmo concentrations, reflecting catchment geomorphology





Codilean et al. 2008. *Geology*





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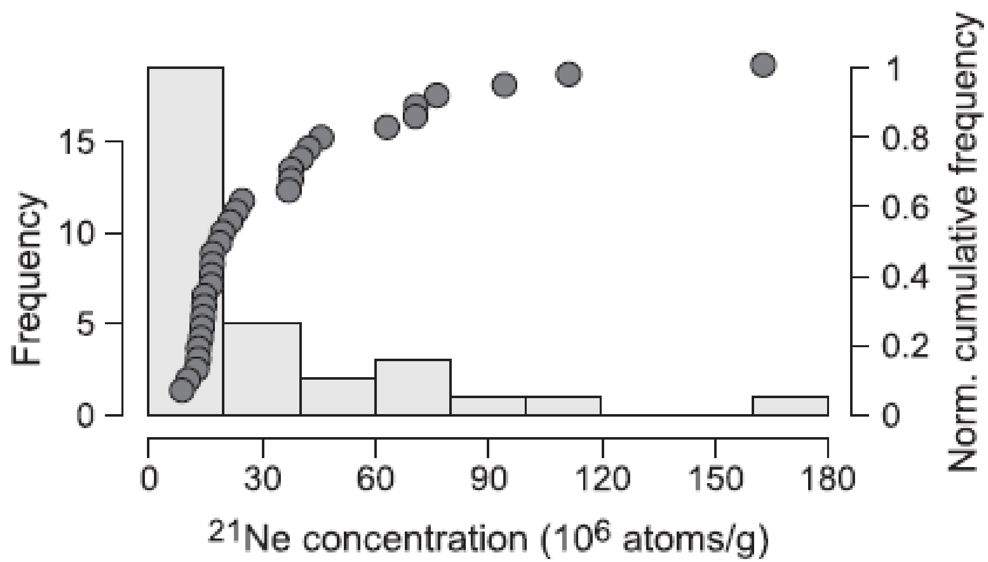
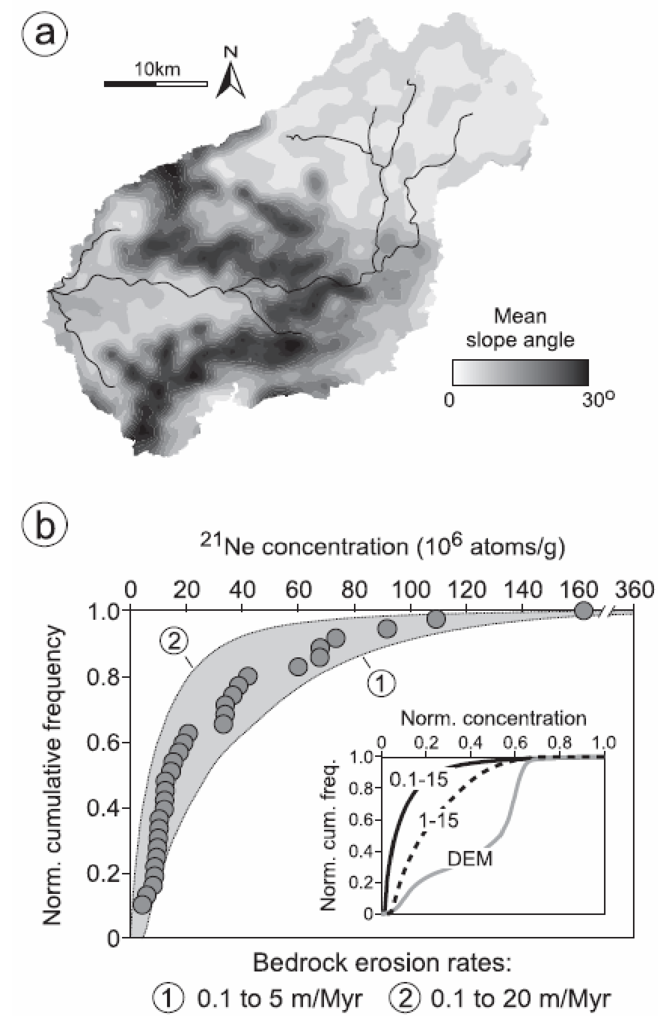
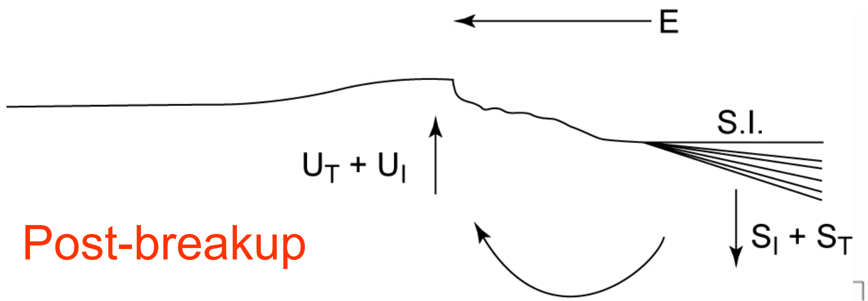
PDF of cosmogenic nuclide concentration

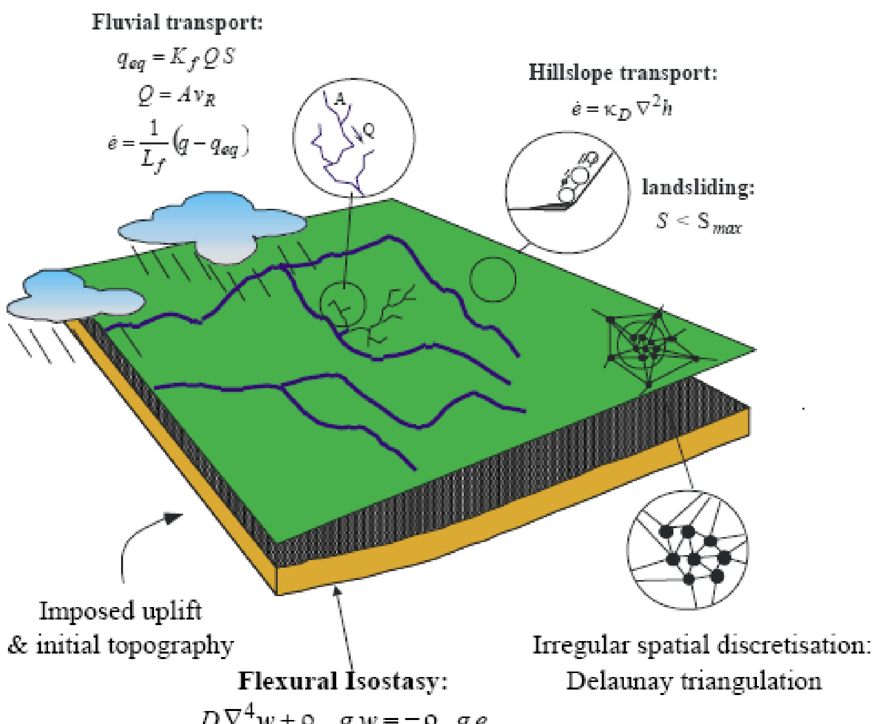




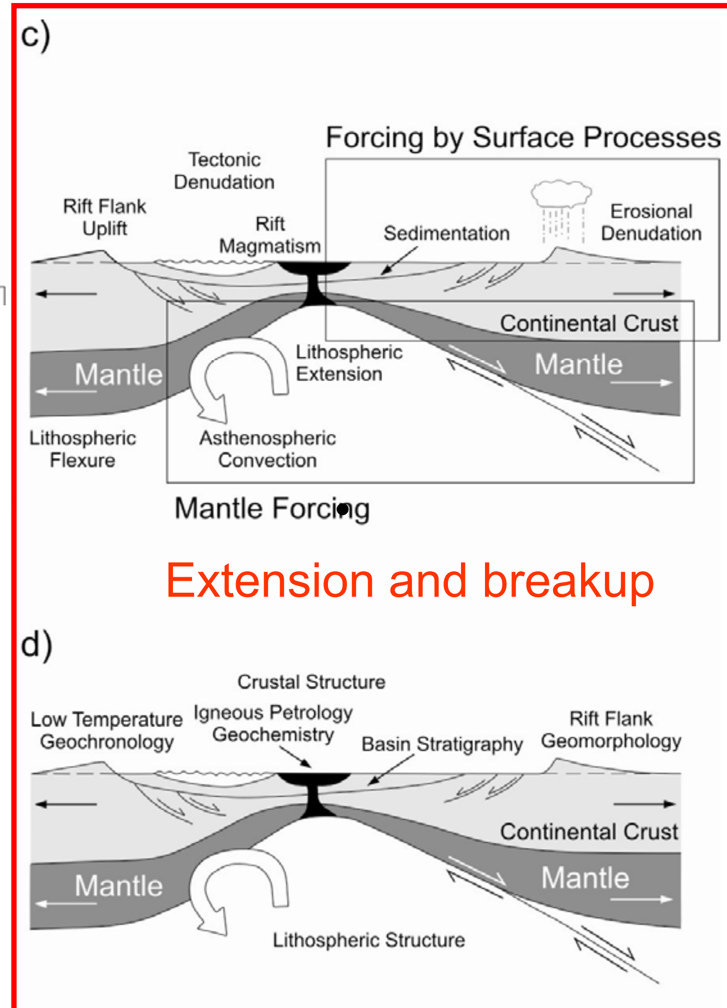
Codilean et al. 2008. *Geology*

Passive margin evolution – Persano, Campanile, Brown, Stuart





Braun & Sambridge. 1997. *Basin Research*



Beaumont *et al*. 2000. In *Geomorphology and Global Tectonics*

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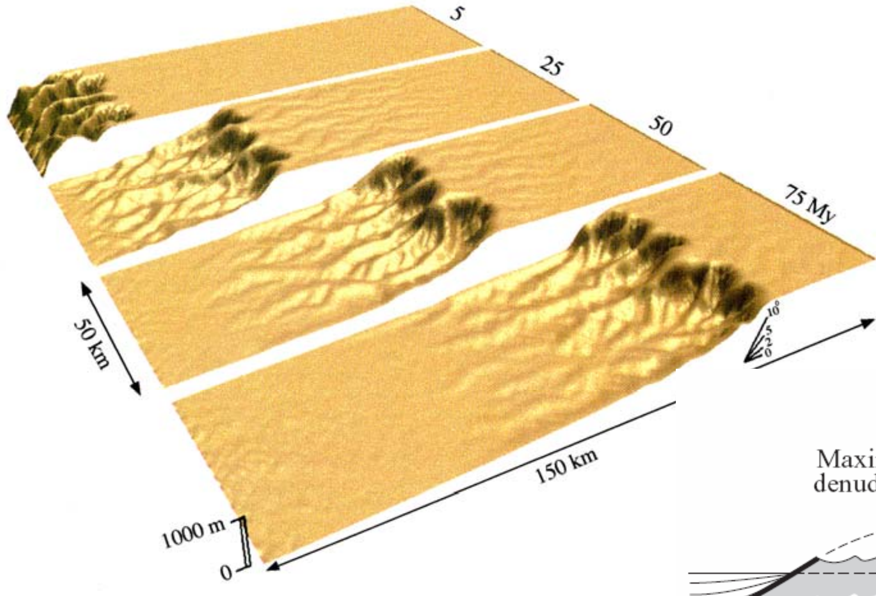
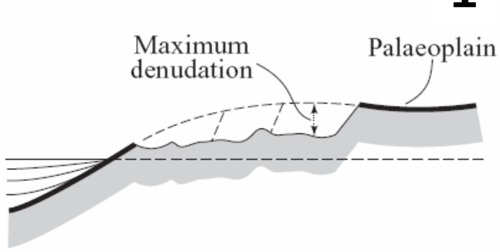
Numerical & conceptual modelling



Kooi & Beaumont. 1994. ***JGR***

1



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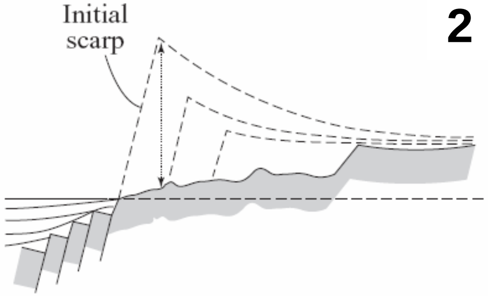
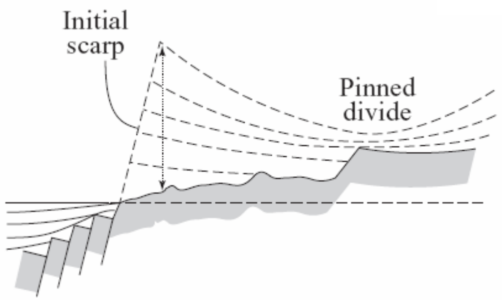
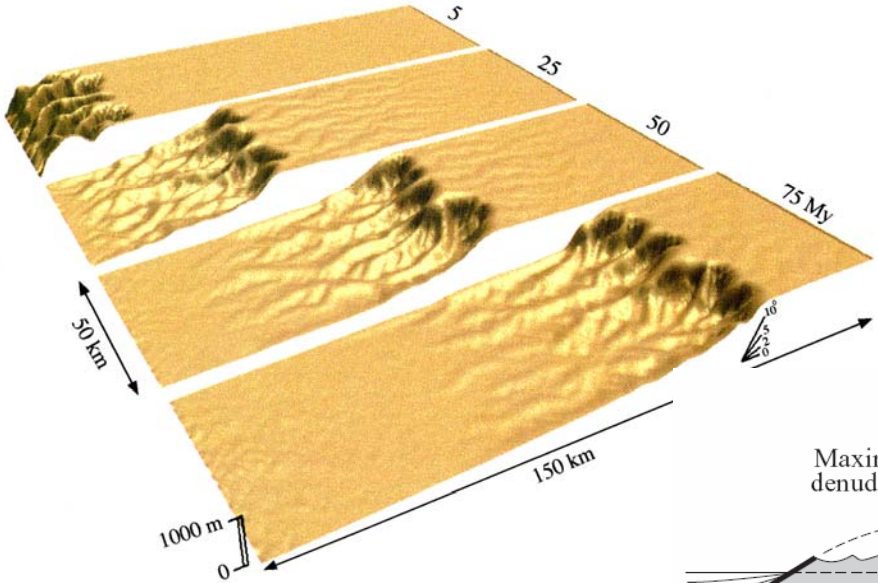


3

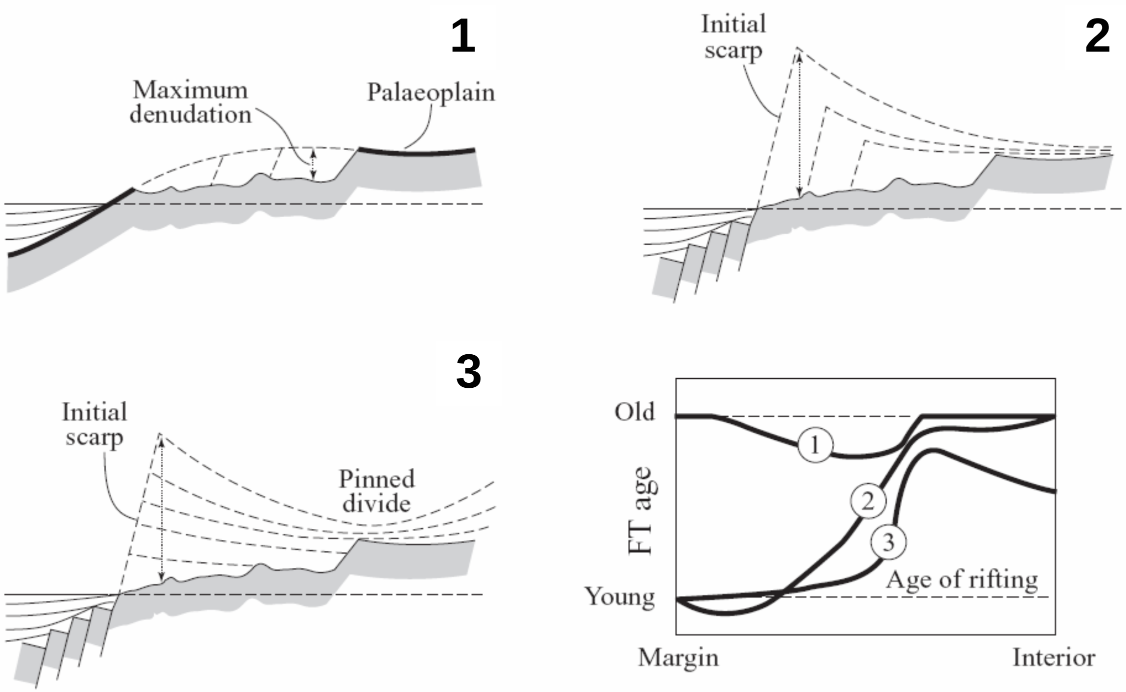


Gallagher *et al*. 1998. ***Ann. Rev. Earth & Planet. Sci.***

Numerical & conceptual modelling



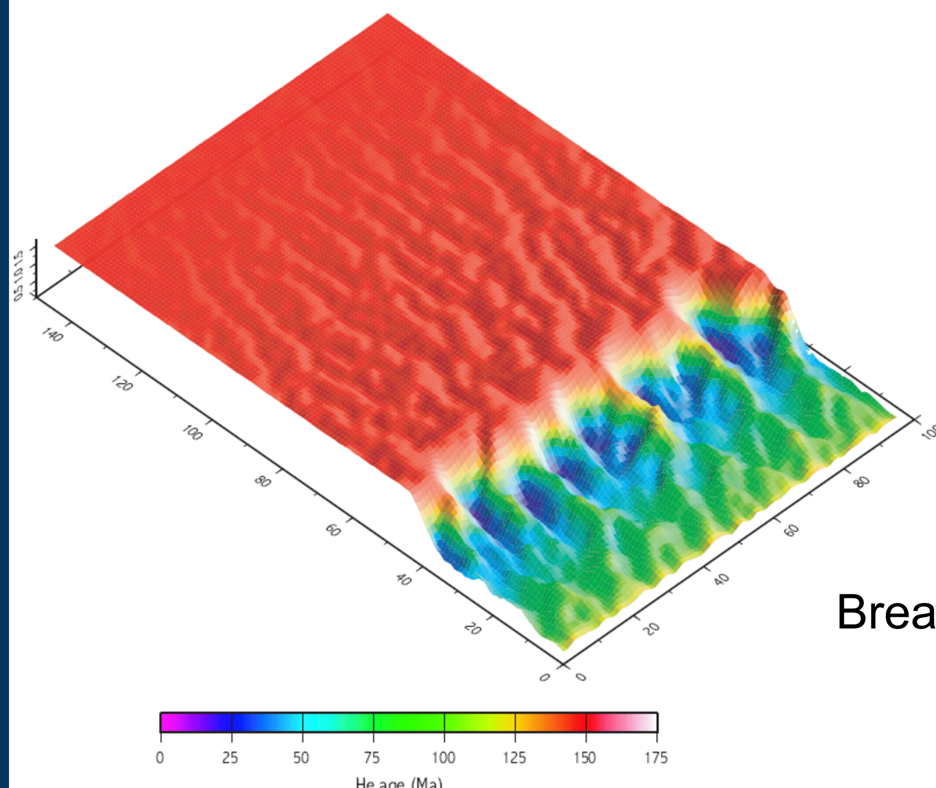
Kooi & Beaumont. 1994. ***JGR***



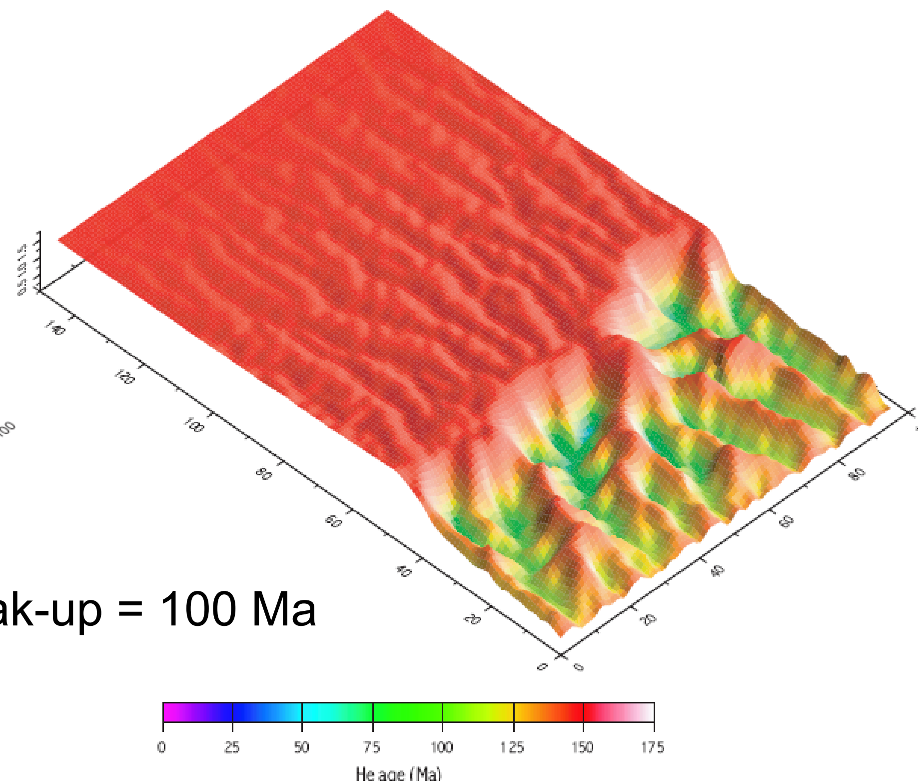
Gallagher *et al*. 1998. ***Ann. Rev. Earth & Planet. Sci.***

Numerical modelling

Escarpment retreat model



Plateau degradation model



Break-up = 100 Ma

Braun & van der Beek. 2004. ***JGR***

Lo-T thermochronology

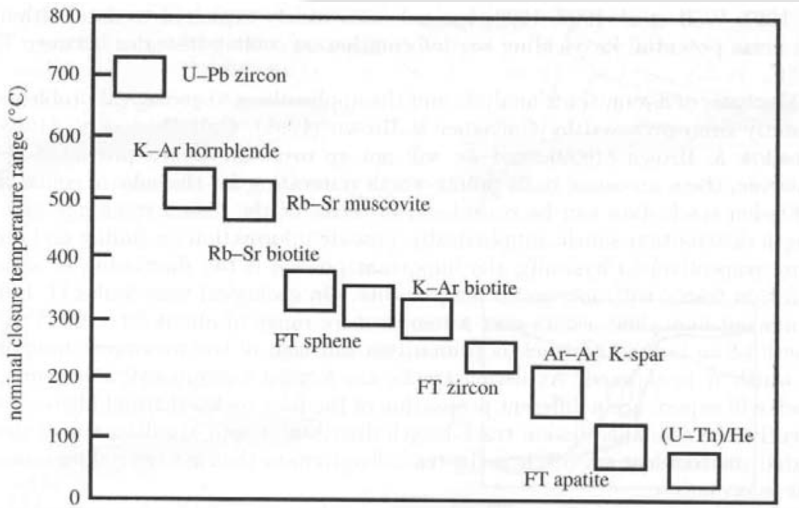
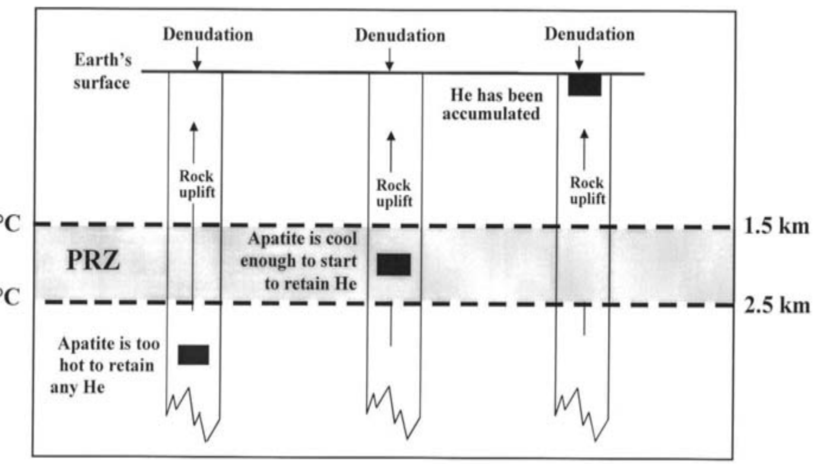
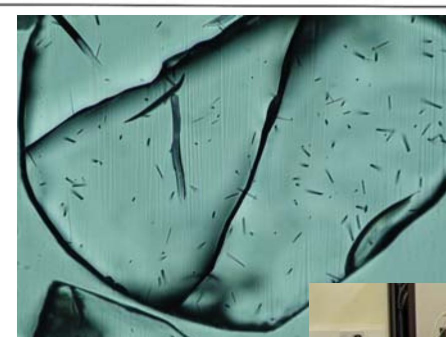
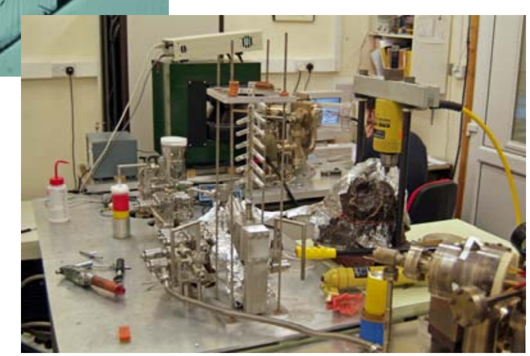


Figure 1. Nominal closure temperature ranges for a selection of mineral-isotope systems. The low-temperature systems such as apatite fission track analysis and (U–Th)/He are most suitable for constraining denudation and surface processes on geological time-scales.



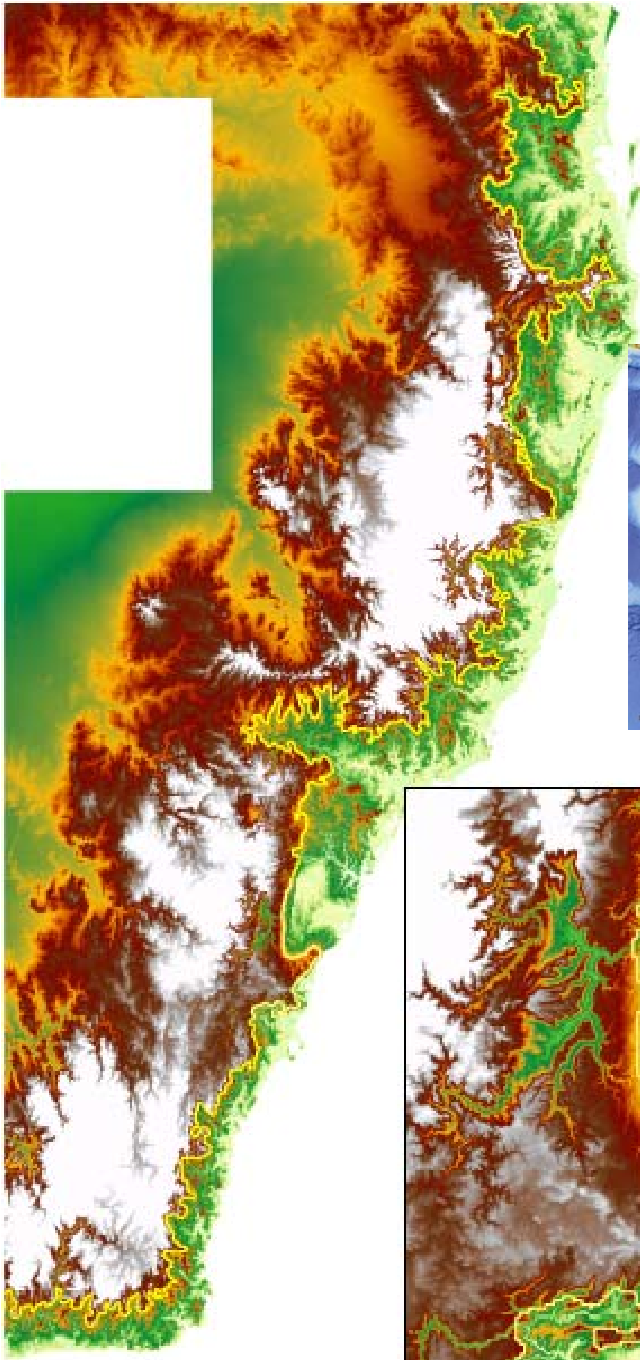


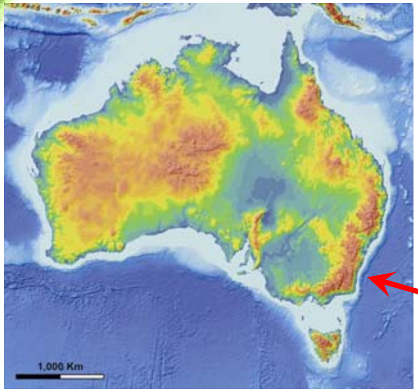


Tracking rocks to the surface from 'shallow' depths:

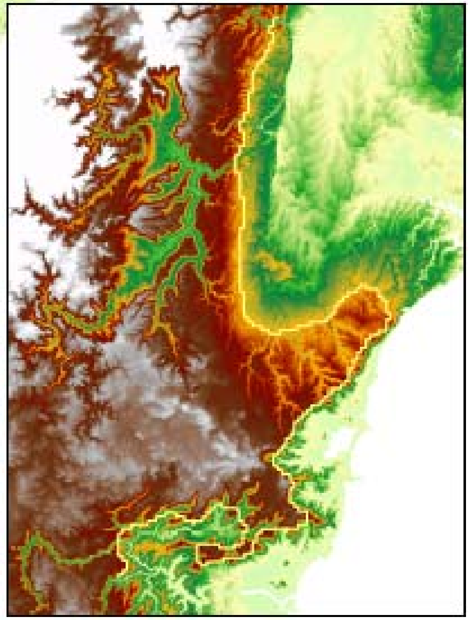
- ~4km depth: apatite fission track analysis
- ~2km depth: apatite-He analysis

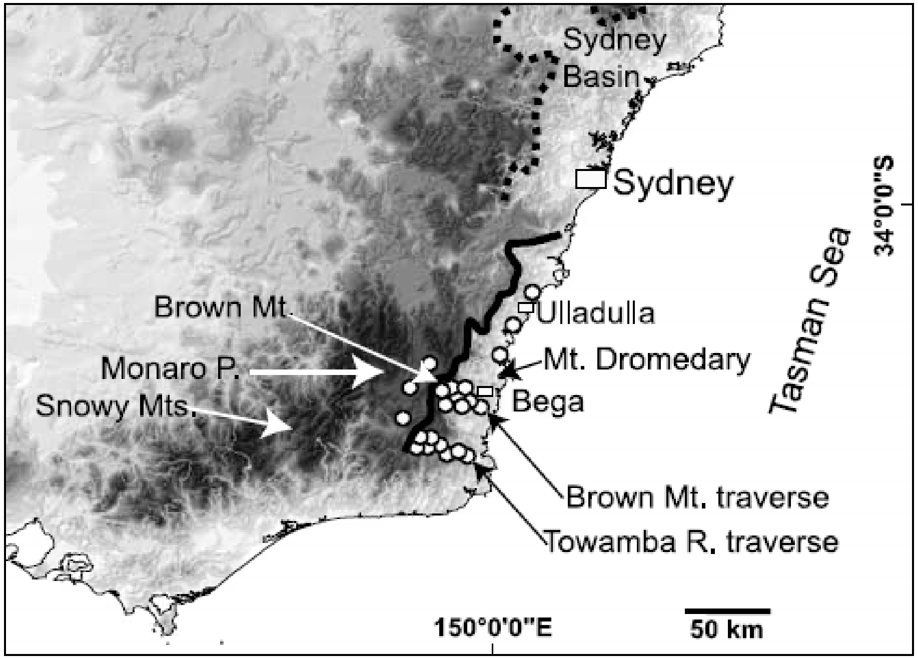
SE Australia





Tasman Sea breakup: 85-90 Ma





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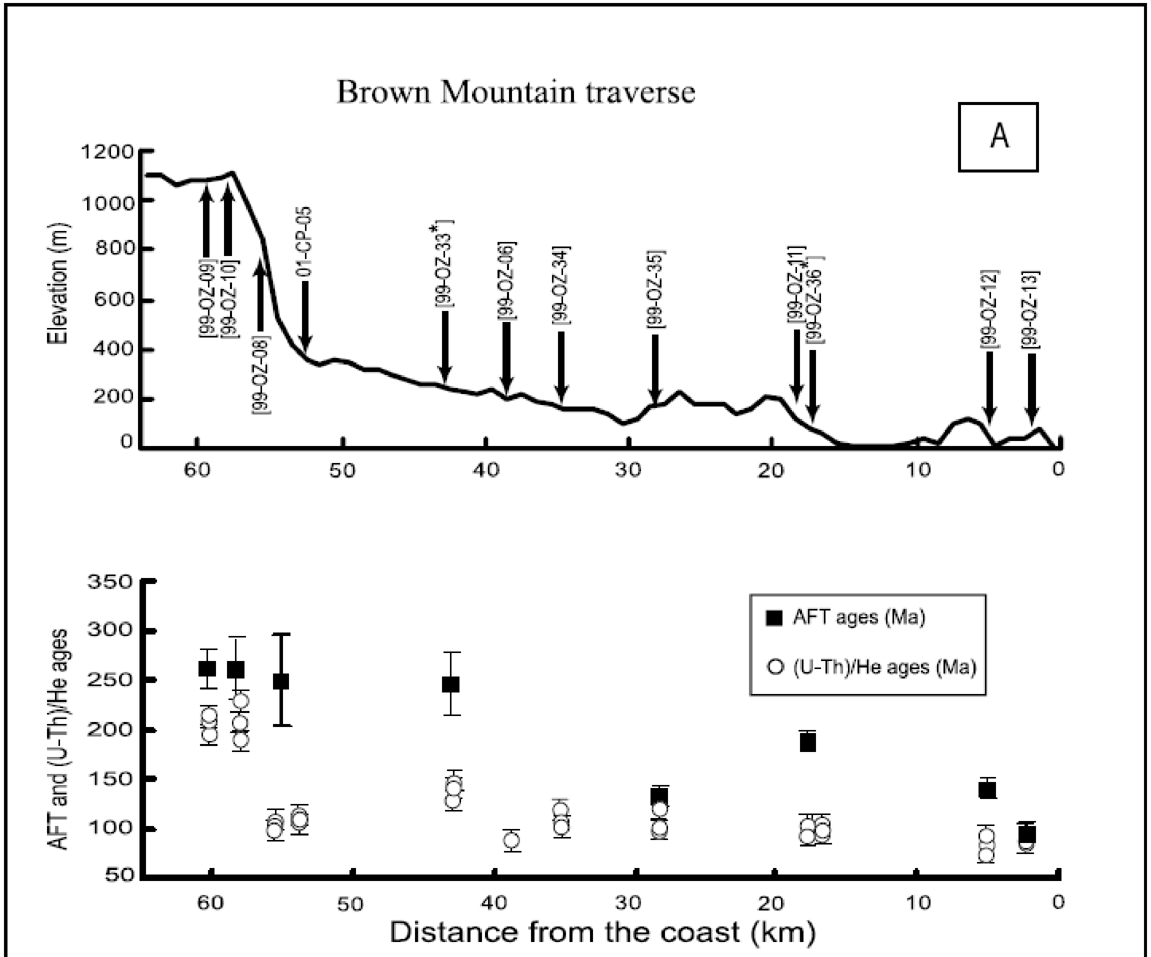
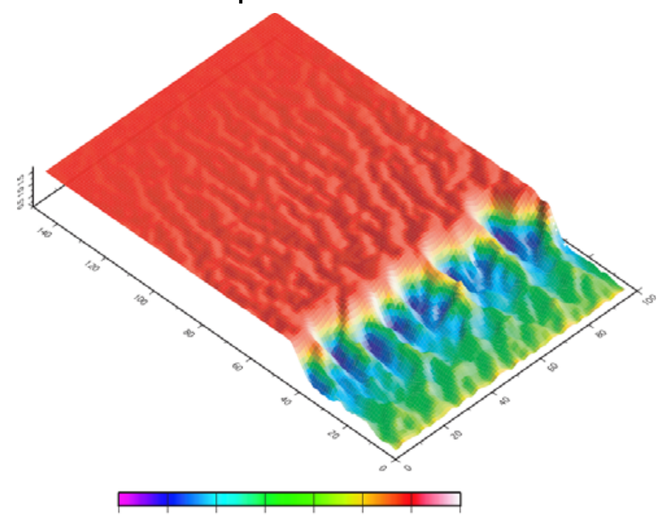
SE Oz lo-T thermochronology data

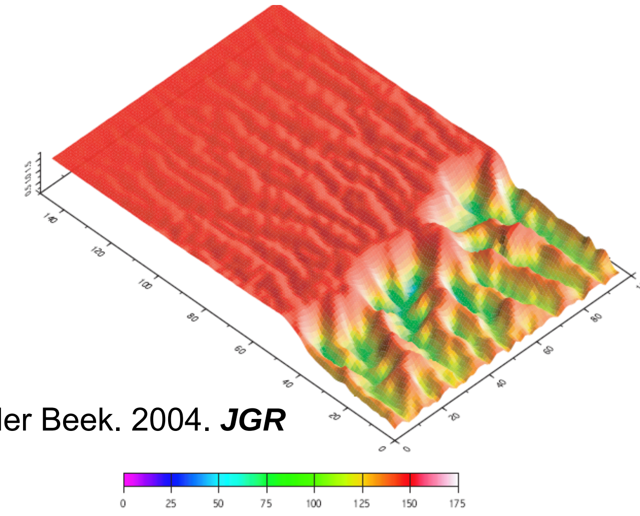


Persano et al. 2005. ***JGR***

Escarpment retreat

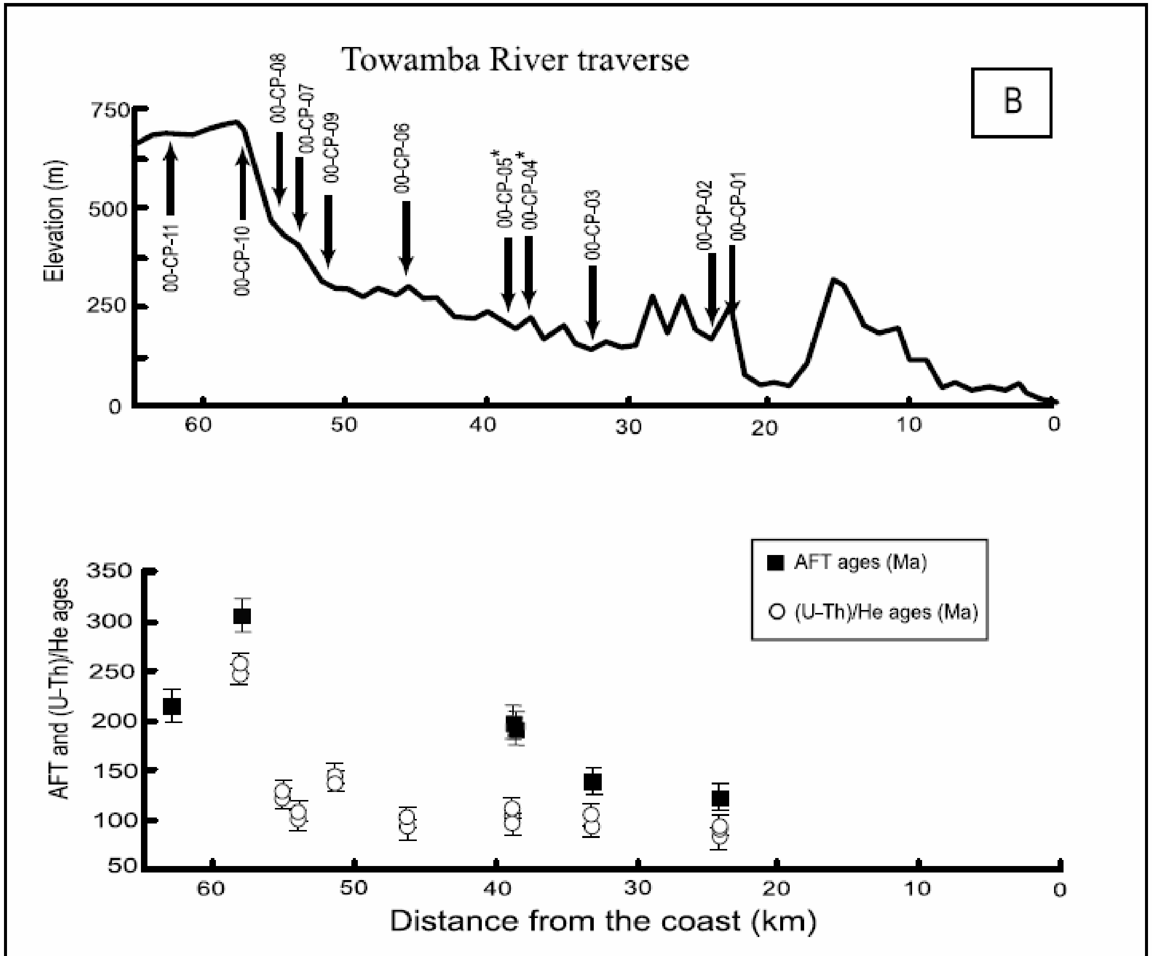


Plateau degradation



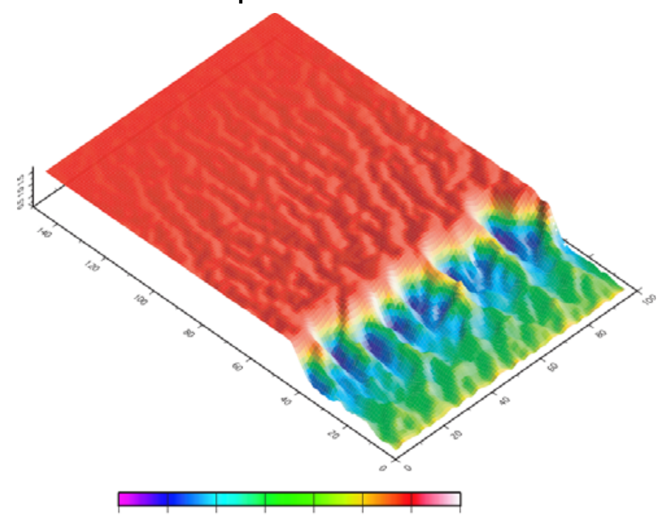
Braun & van der Beek. 2004. ***JGR***

SE Oz lo-T thermochronology data

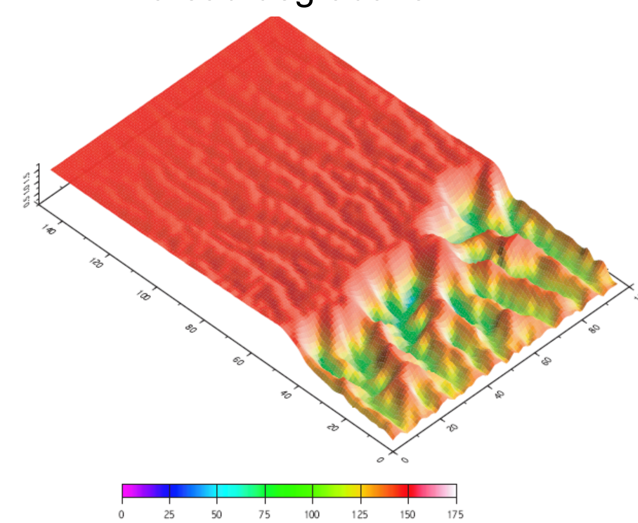


Persano et al. 2005. ***JGR***

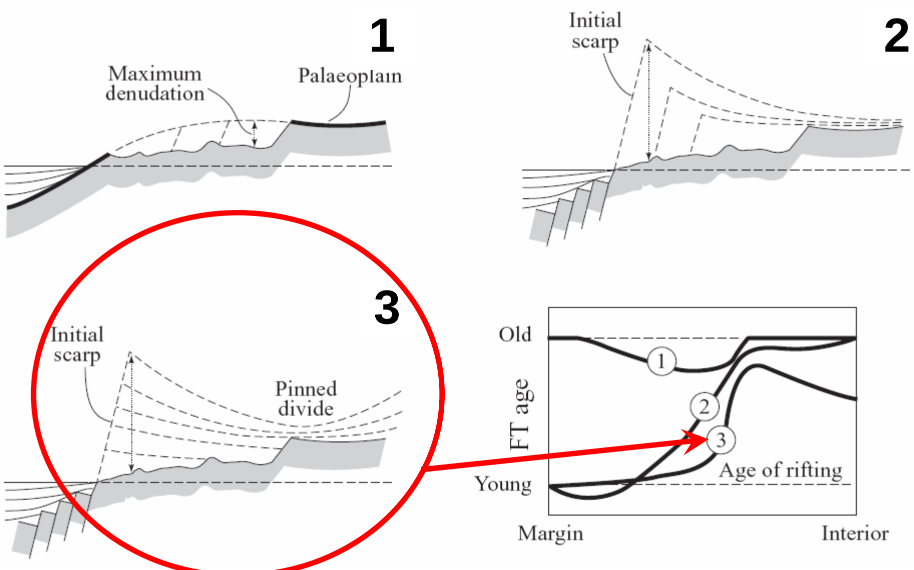
Escarpment retreat



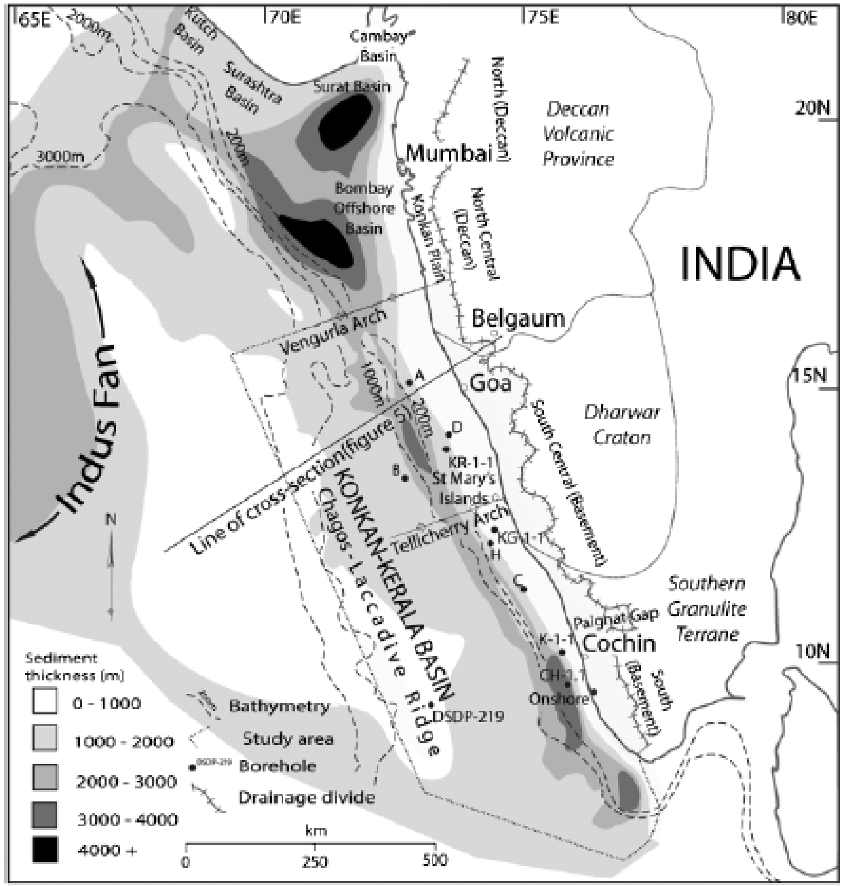
Plateau degradation



Downwarping or not?



Gallagher *et al*. 1998. *Ann. Rev. Earth & Planet. Sci.*



Western Indian Margin

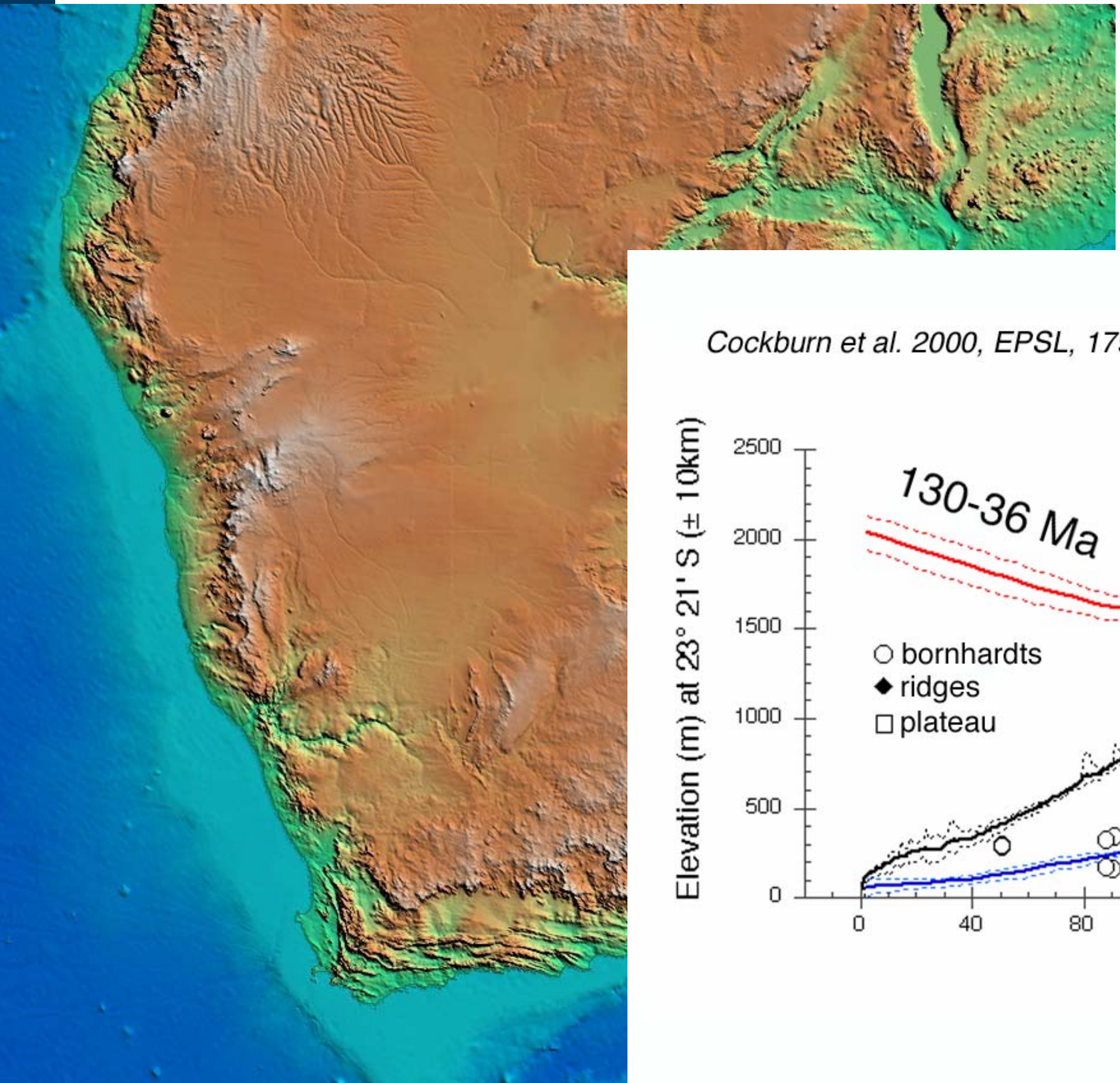
Onshore volume of denudation with flexural rebound: ~110 000 km^3

Onshore volume of denudation with downwarping only: ~38 000 km^3

Offshore volume sediment: 108 740 km^3

Campanile et al., 2008, *Basin Research*

Southern Africa



Fission track & cosmogenic nuclides

Cockburn et al. 2000, EPSL, 179, 429-435.