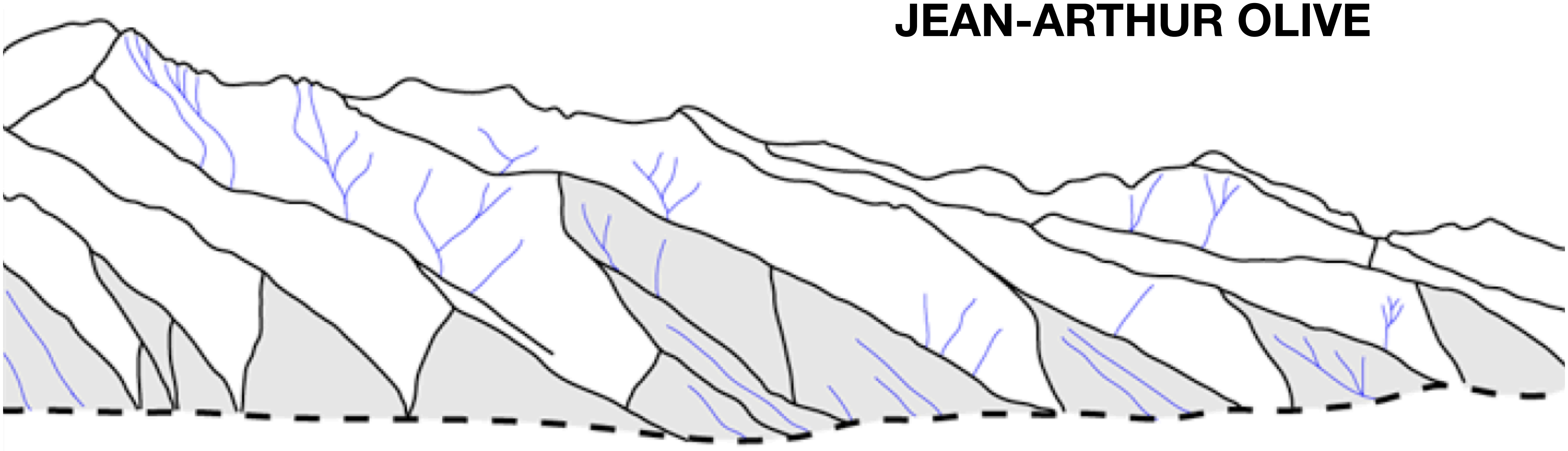
FEEDBACKS BETWEEN BRITTLE DEFORMATION AND SURFACE PROCESSES: **INSIGHTS FROM EXTENSIONAL SETTINGS**

JEAN-ARTHUR OLIVE



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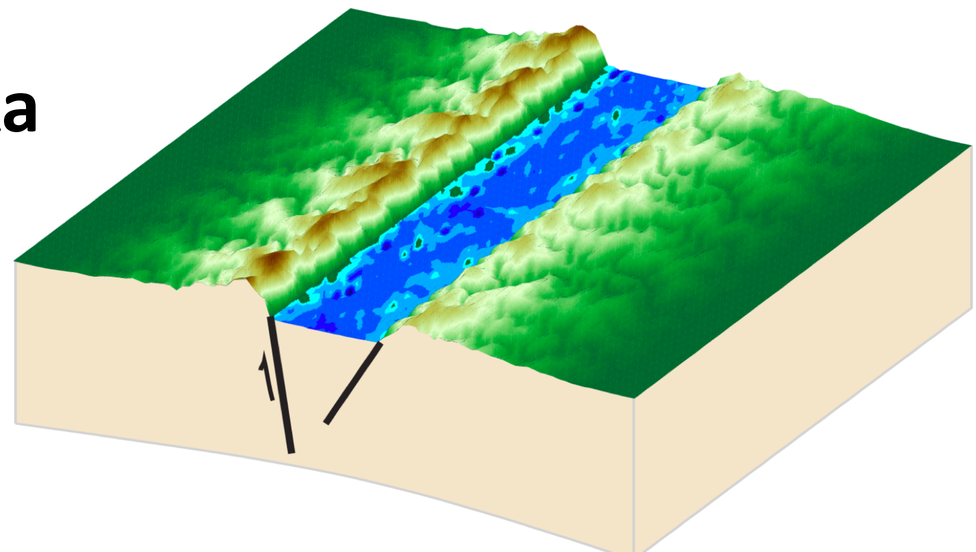

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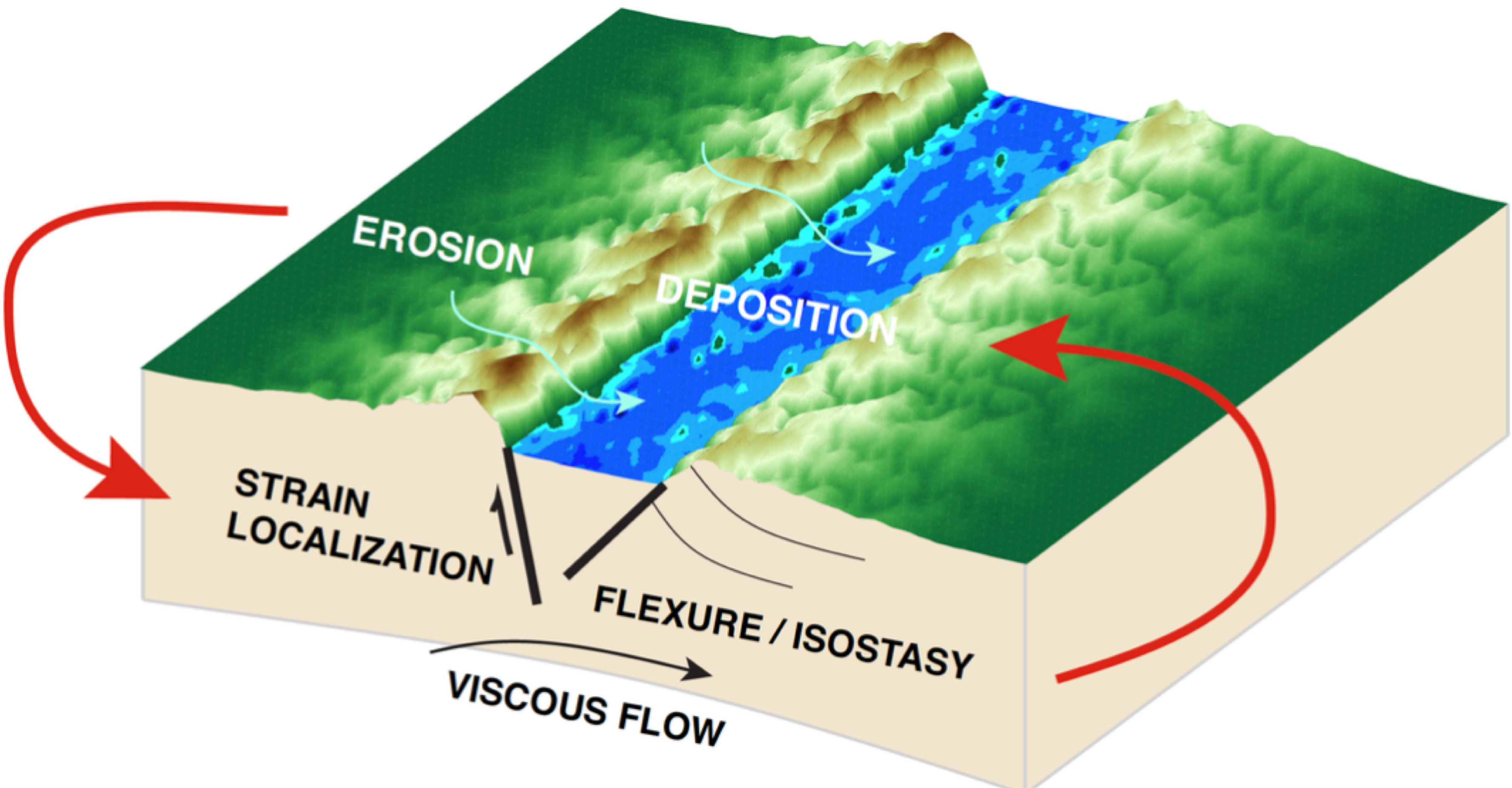
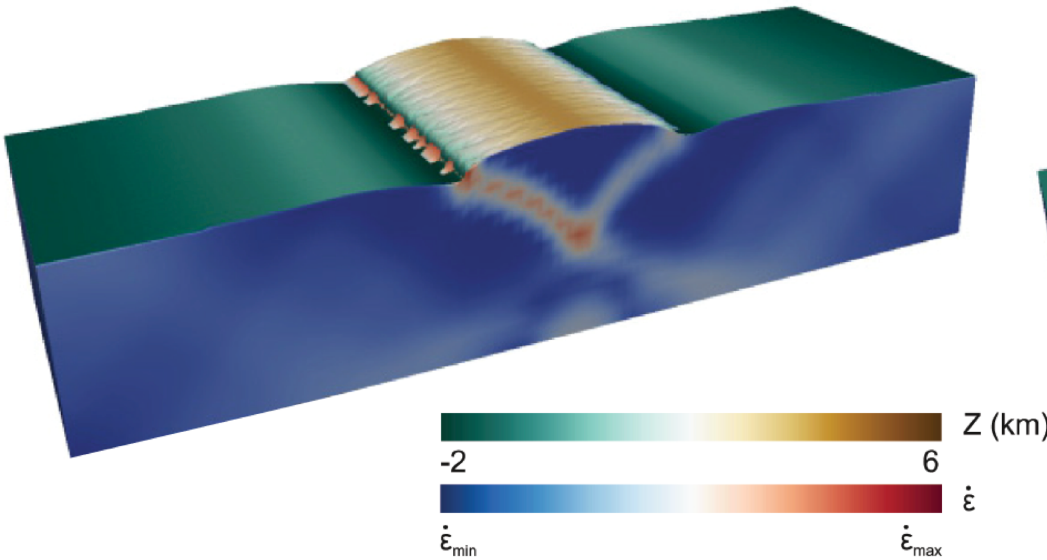
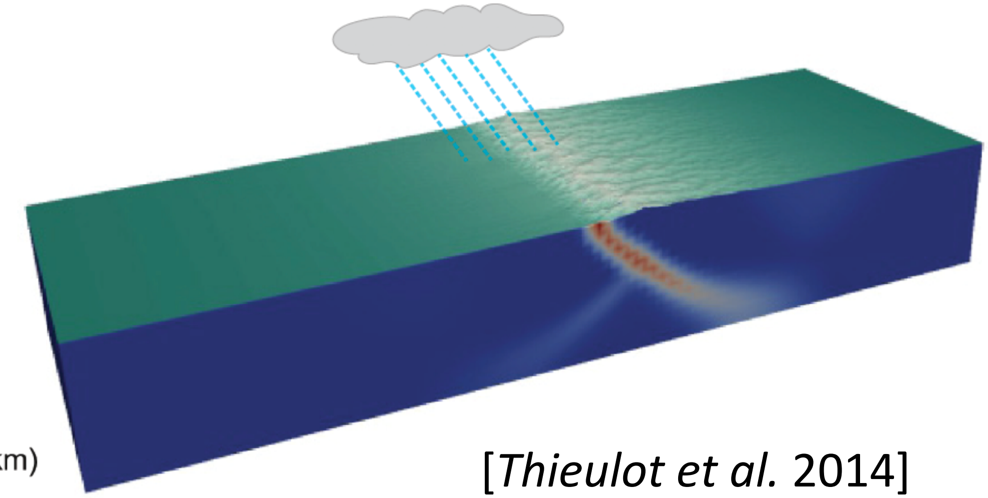
1930

Brittle deformation vs. surface processes



Surface processes promote strain localization



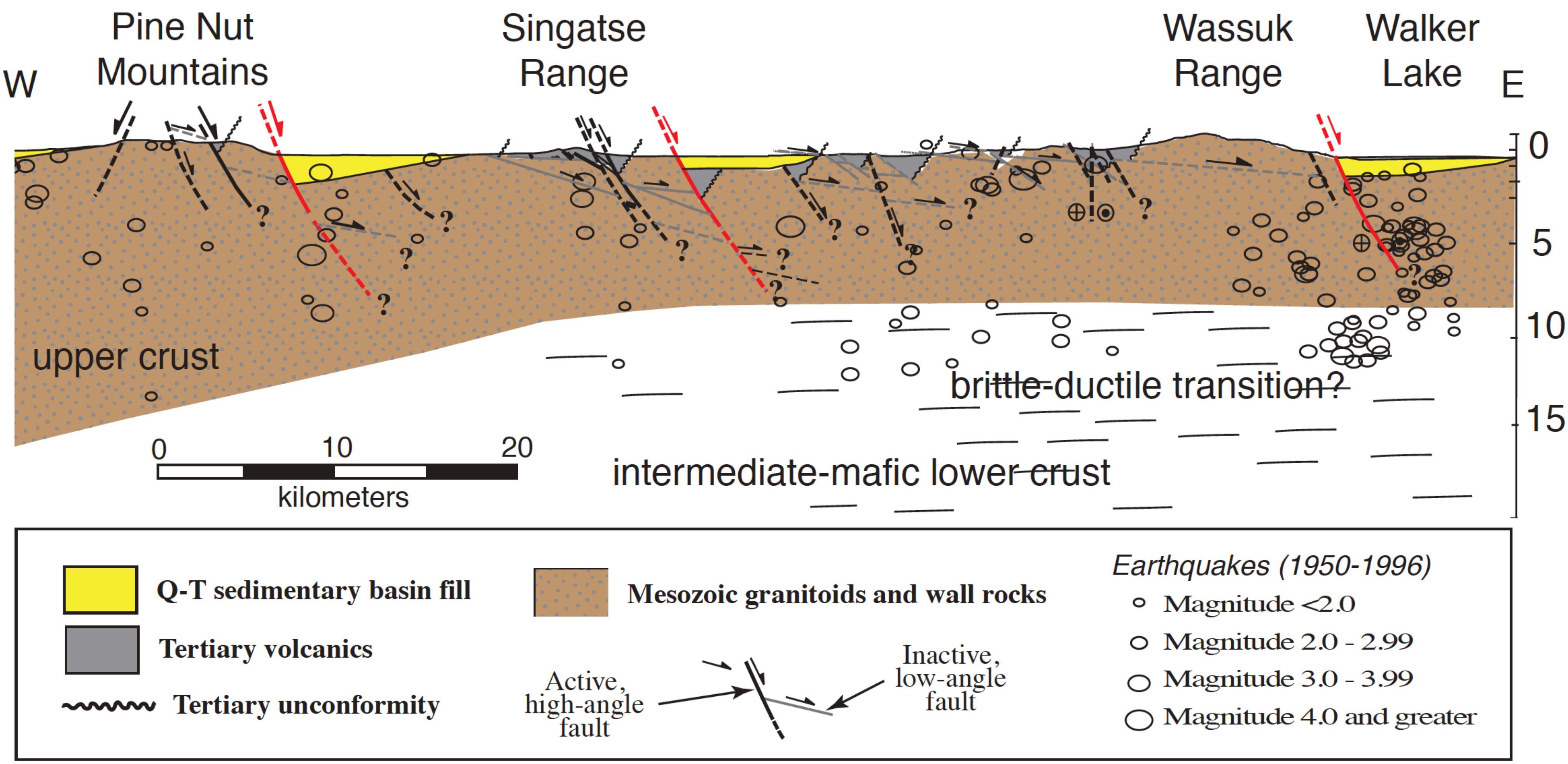


[*Thieulot et al.* 2014]

- What are the **underlying physics**?
- What controls the **sensitivity** of a tectonic system to surface processes?
- How **efficient** do surface processes need to be to impact long-term tectonic evolution?
- Can we find evidence for such modulation in **real landscapes**?

Half-grabens as natural laboratories

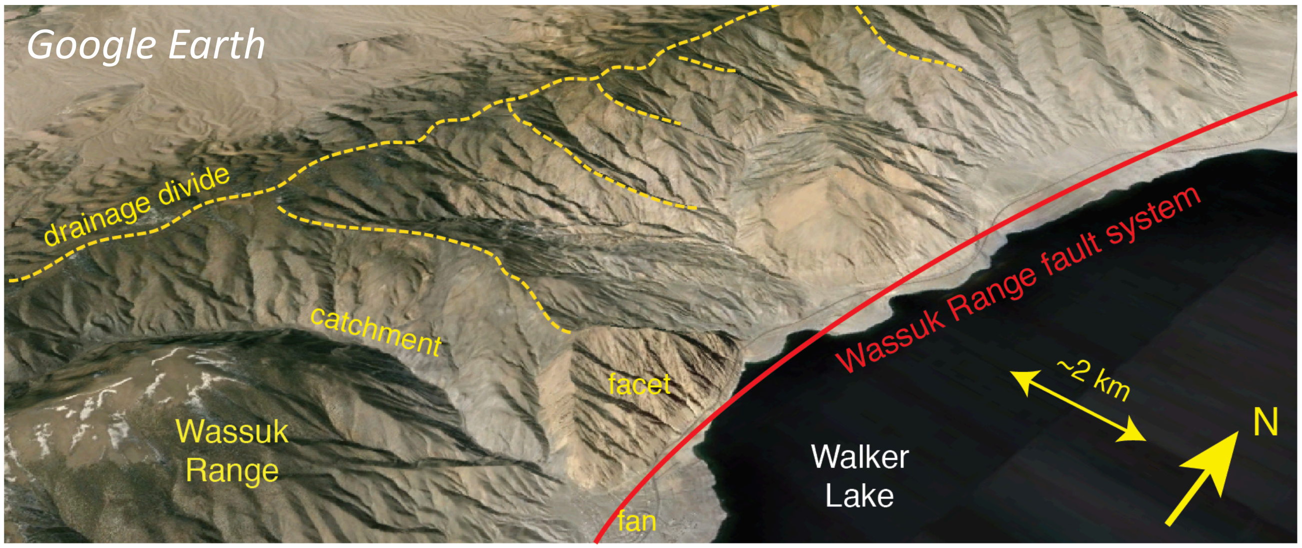
High degree of **strain localization** sustained over offsets as large as ≈ 10 km. **Relief** generally ≤ 1–2 km.



Surpless et al. 2002

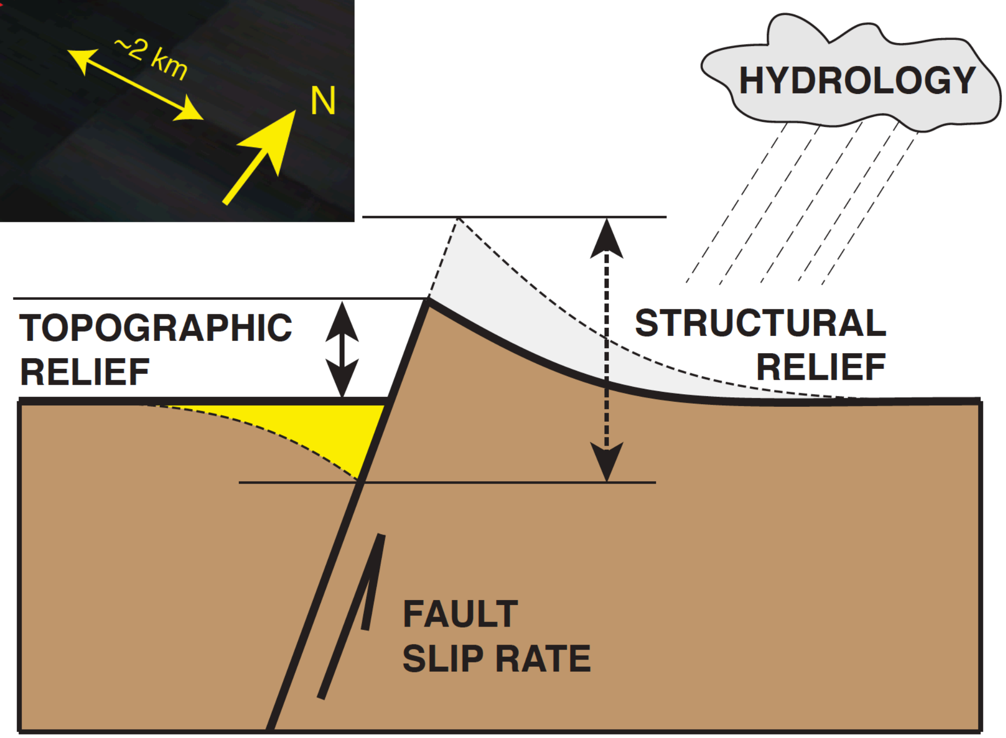
Half-grabens as natural laboratories

Flexure, **strain localization**, **topography** build-up
& **surficial mass redistribution** over ≈ 10s of km.



<u>e.g., Wassuk Range (NV):</u>

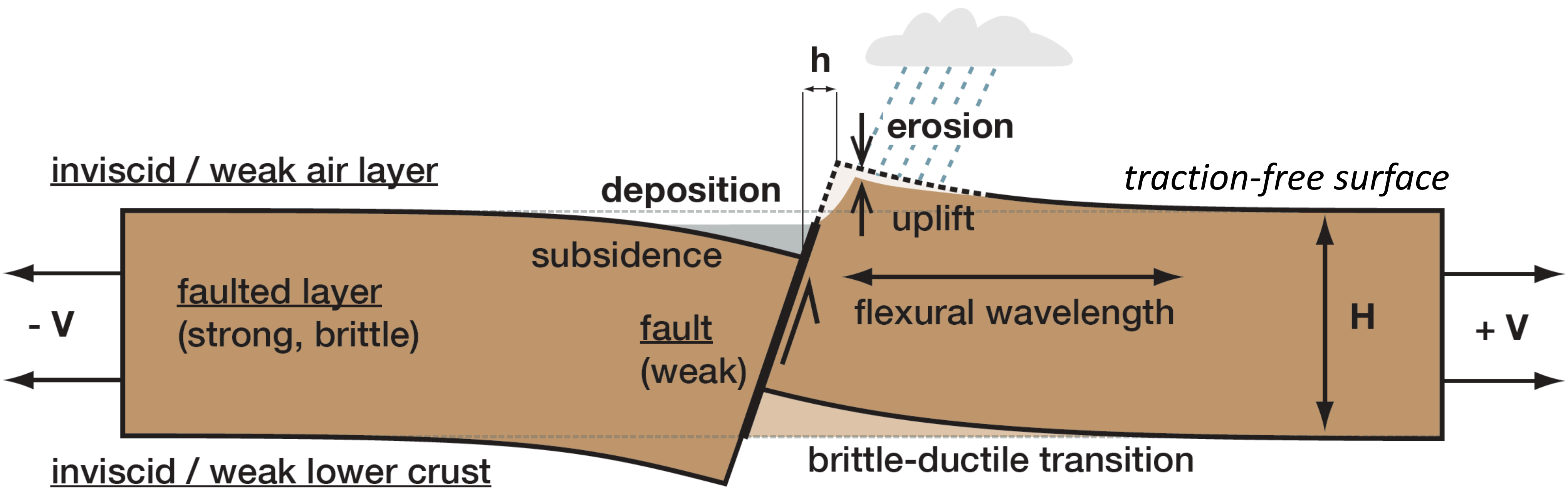
- Topographic relief ≈ 1.2 km
- Structural relief ≈ 8.5 km
- Slip rate ≈ 0.7 mm/yr



Coupled tectonic & surface evolution models

Tectonic evolution model:

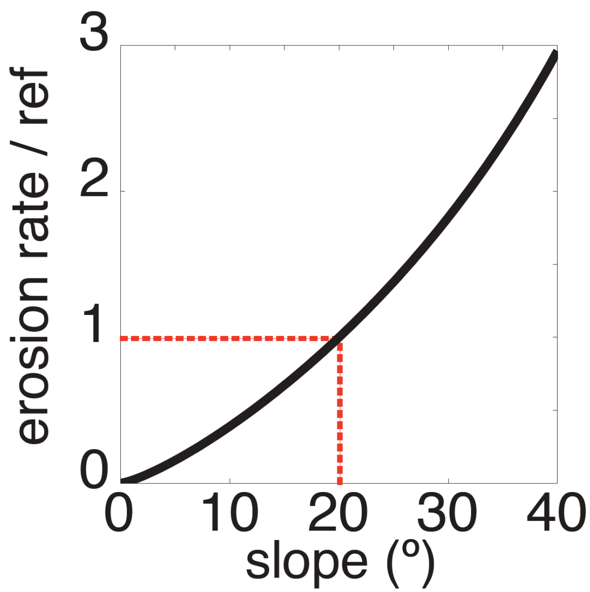
- Numerical simulations conducted with the ***SiStER*** code: ***Si**mple **St**okes solver with **E**xotic **R**heologies* [*Olive et al.*, 2016 GJI]. Available at github.com/jaolive/SiStER
- Solving conservation of **mass**, **momentum** and **energy** in a **visco-elasto-plastic** upper continental crust under extension. **Faults can localize spontaneously** when the Mohr-Coulomb criterion is met.



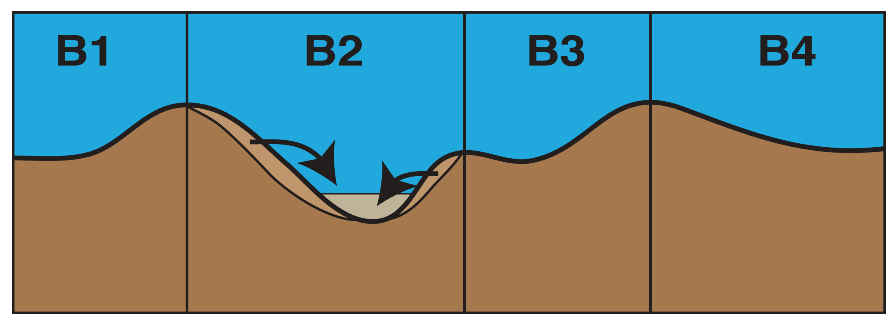
Coupled tectonic & surface evolution models

Surface evolution model (upper boundary condition):

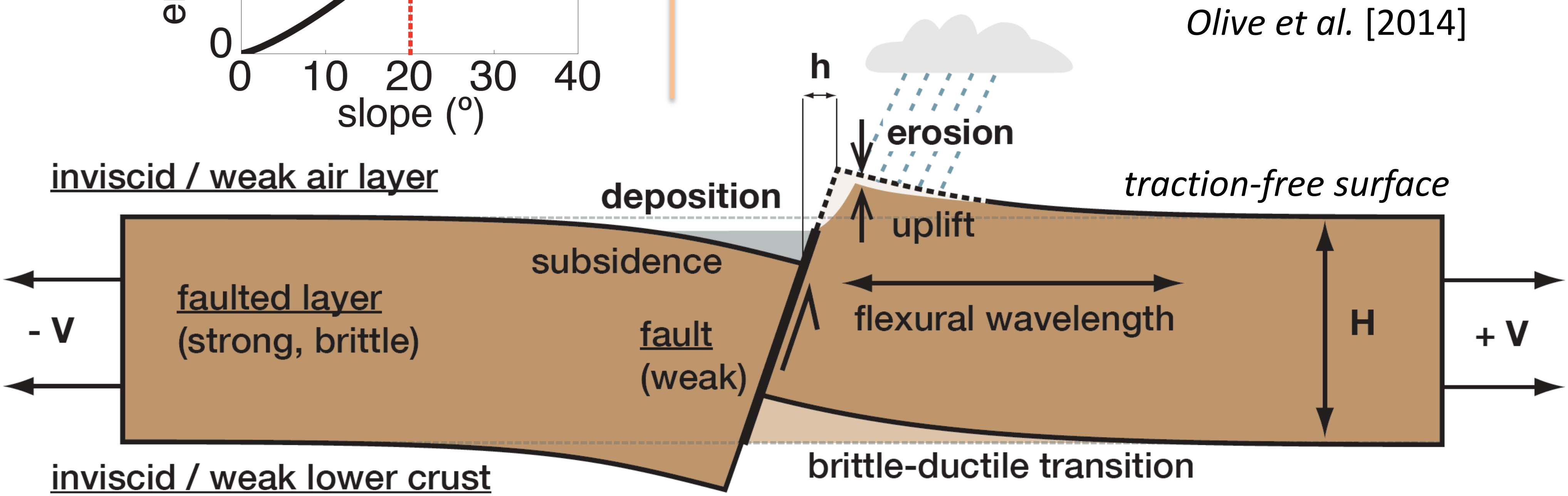
Step 1: **erode** material



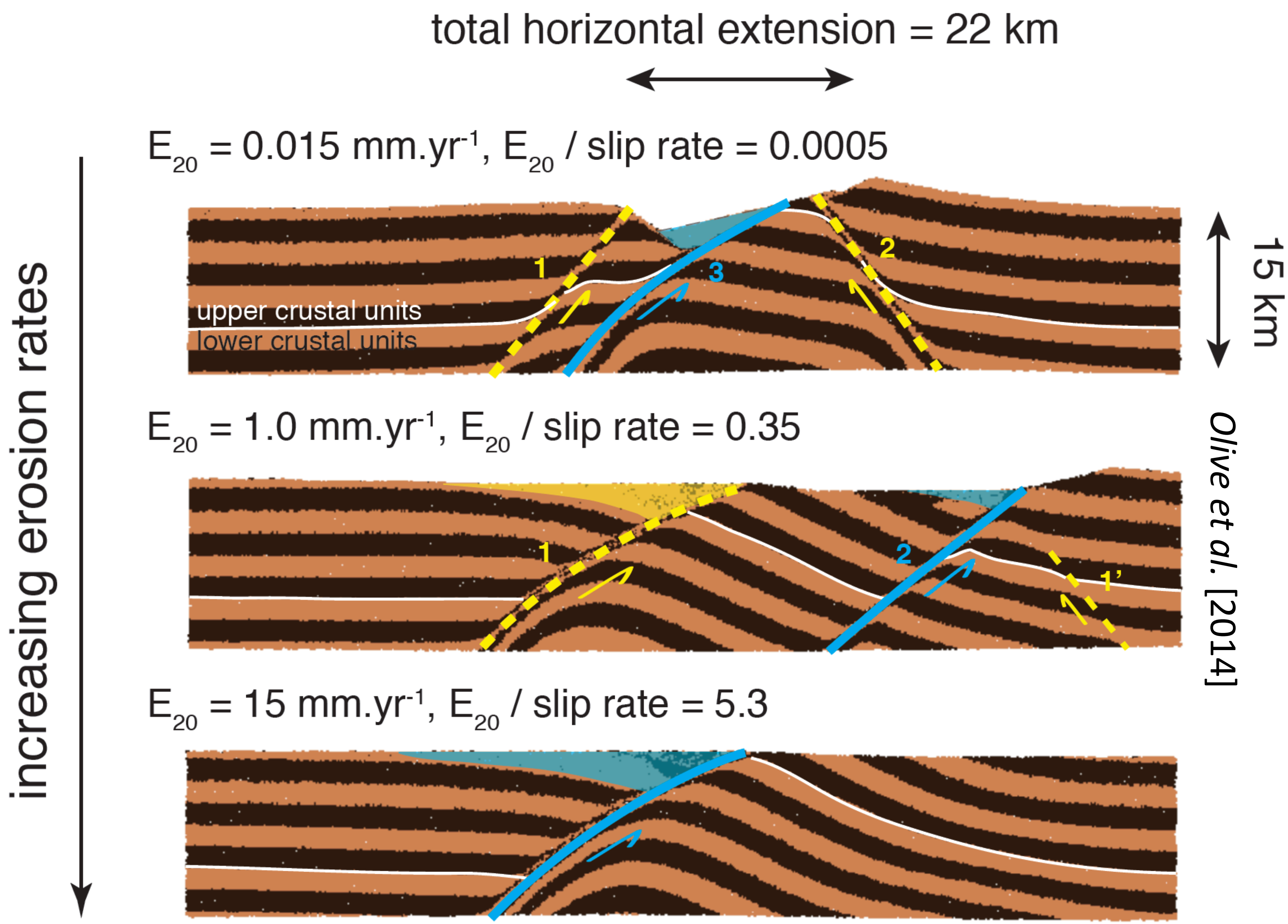
Step 2: **deposit** material flat in corresponding watershed



Olive et al. [2014]

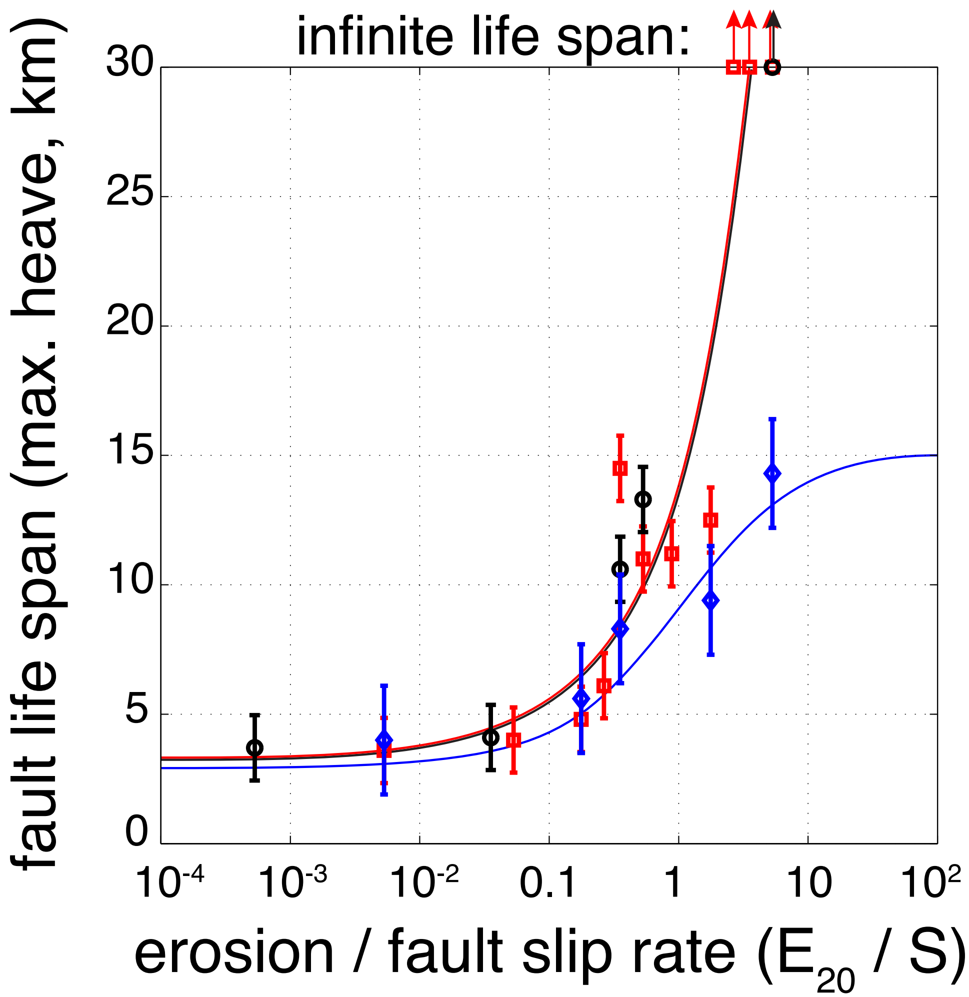


Surface processes promote strain localization

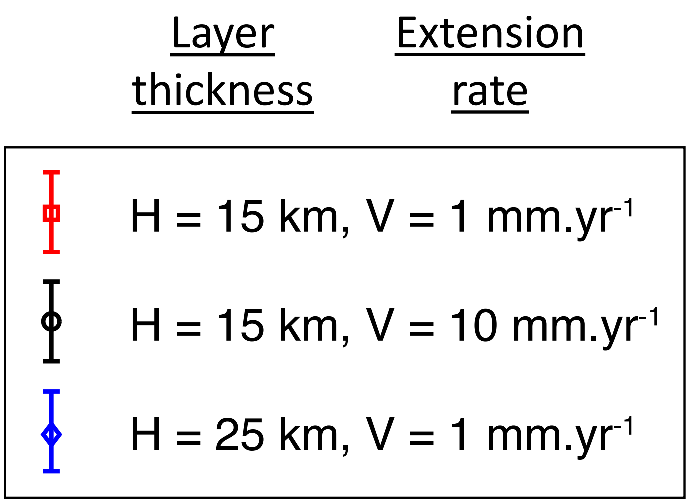


Surface processes promote strain localization

Surface processes **further enhance** fault life span
in **thinner / weaker** faulted layers for a given erosion / slip rate.



Underlying physics?



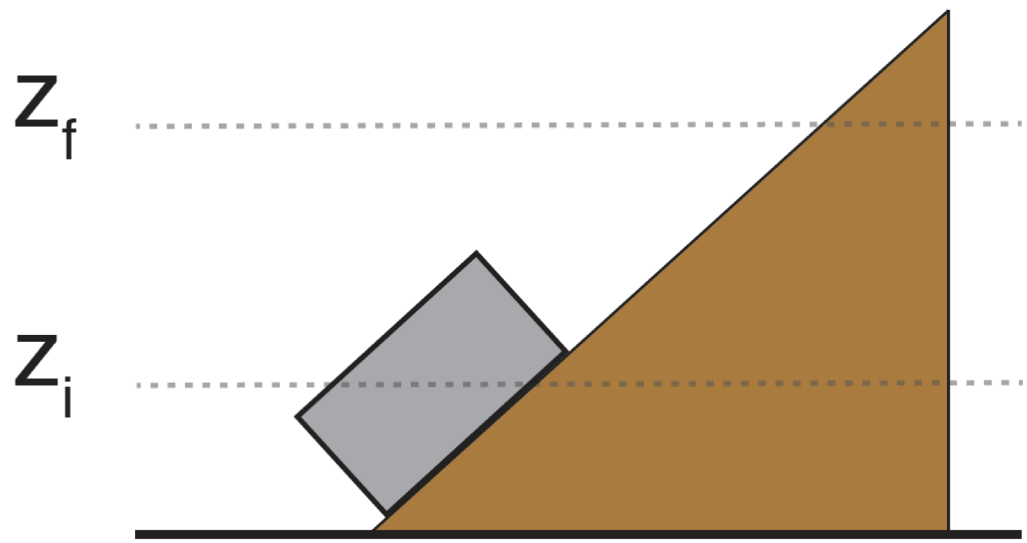
Olive et al. [2014]

Energy balance in tectonic systems

Consider a block at height $\mathbf{z_i}$ on an inclined plane.
How much energy does it take to move it to height $\mathbf{z_f}$?

Define the block's mechanical energy:

$$\Delta E_m = \Delta E_k + \Delta E_p$$

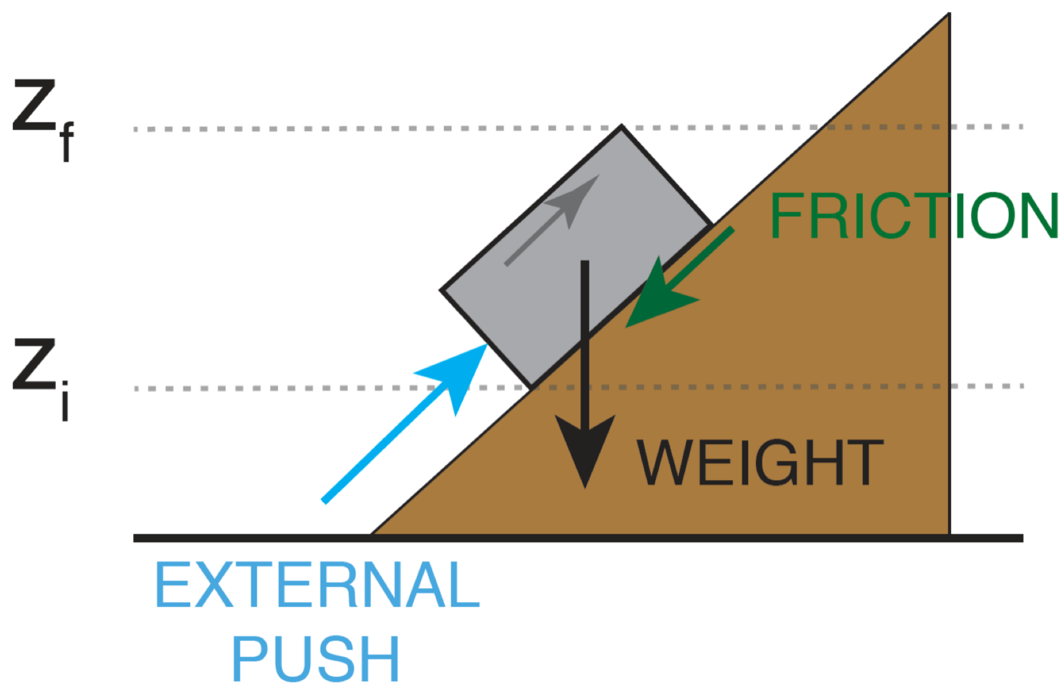


Energy balance in tectonic systems

Consider a block at height $\mathbf{z_i}$ on an inclined plane.
How much energy does it take to move it to height $\mathbf{z_f}$?

Change in mechanical energy: $$\Delta E_m = \sum W_{\text{dissipative forces}}$$

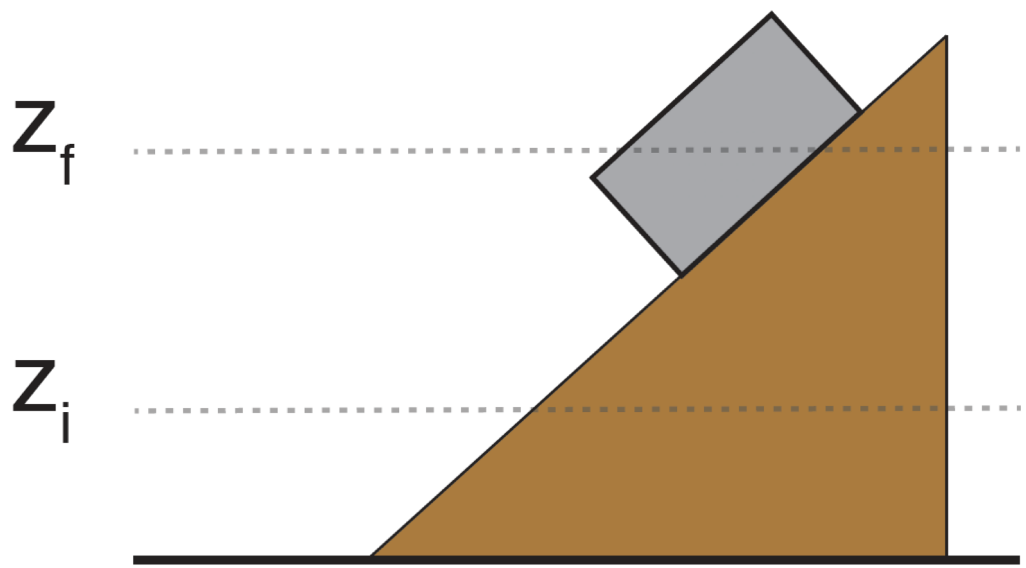
Change in potential energy: $$\Delta E_p = \underline{W_{\text{friction}}} + \underline{W_{\text{external}}}$$



Energy balance in tectonic systems

Consider a block at height $\mathbf{z_i}$ on an inclined plane.
How much energy does it take to move it to height $\mathbf{z_f}$?

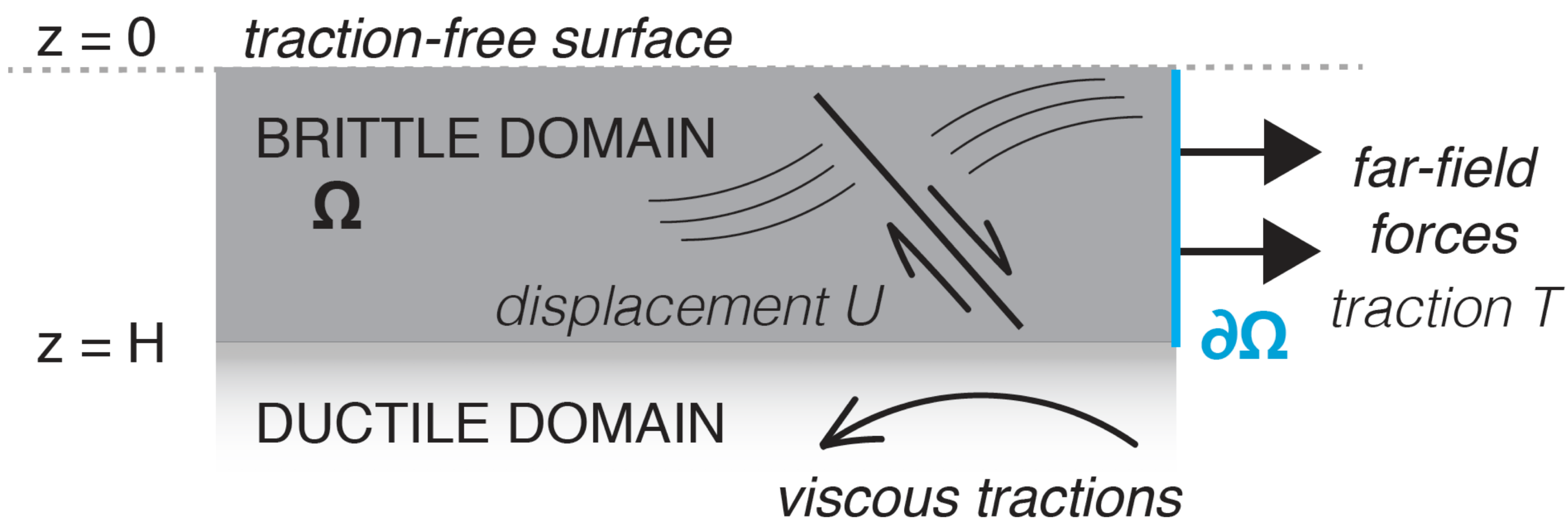
$$\boxed{W_{\text{external}} = \Delta E_p - W_{\text{friction}}}$$



Energy balance in tectonic systems

Force balance in the brittle upper crust (continuum):

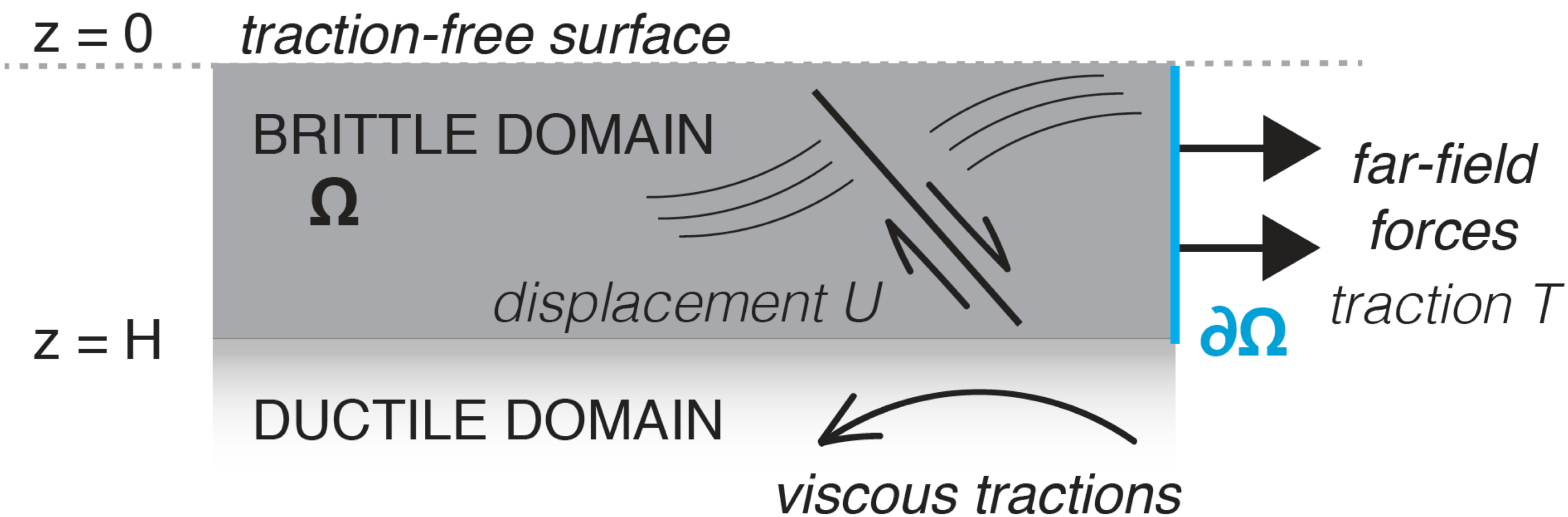
$$\underline{\mathrm{div}}\left(\underline{\underline{\sigma}}\right) + \rho \underline{g} = \underline{0}$$



Energy balance in tectonic systems

Force balance in the brittle upper crust (weak form):

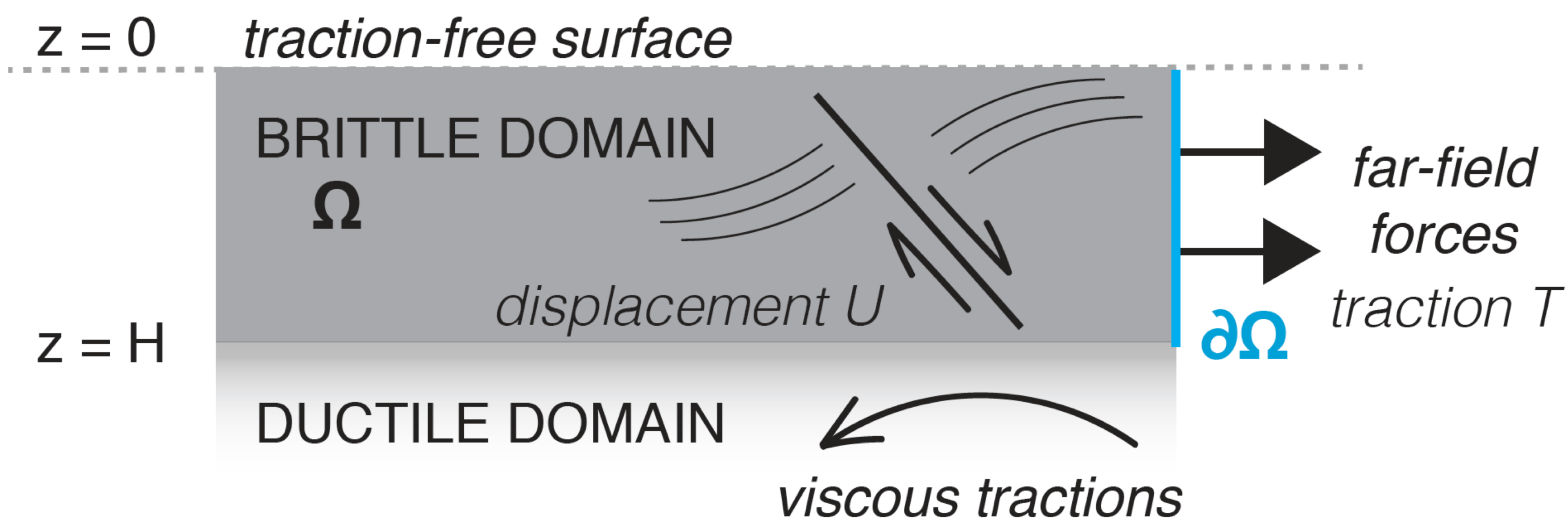
$$\underline{\mathrm{div}}\left(\underline{\underline{\sigma}}\right) + \rho \underline{g} = \underline{0} \longrightarrow \int_{\Omega} \left(\underline{\mathrm{div}}\left(\underline{\underline{\sigma}}\right) + \rho \underline{g}\right) \cdot \underline{U} \; d\Omega = 0$$



Energy balance in tectonic systems

Work balance in the brittle upper crust:

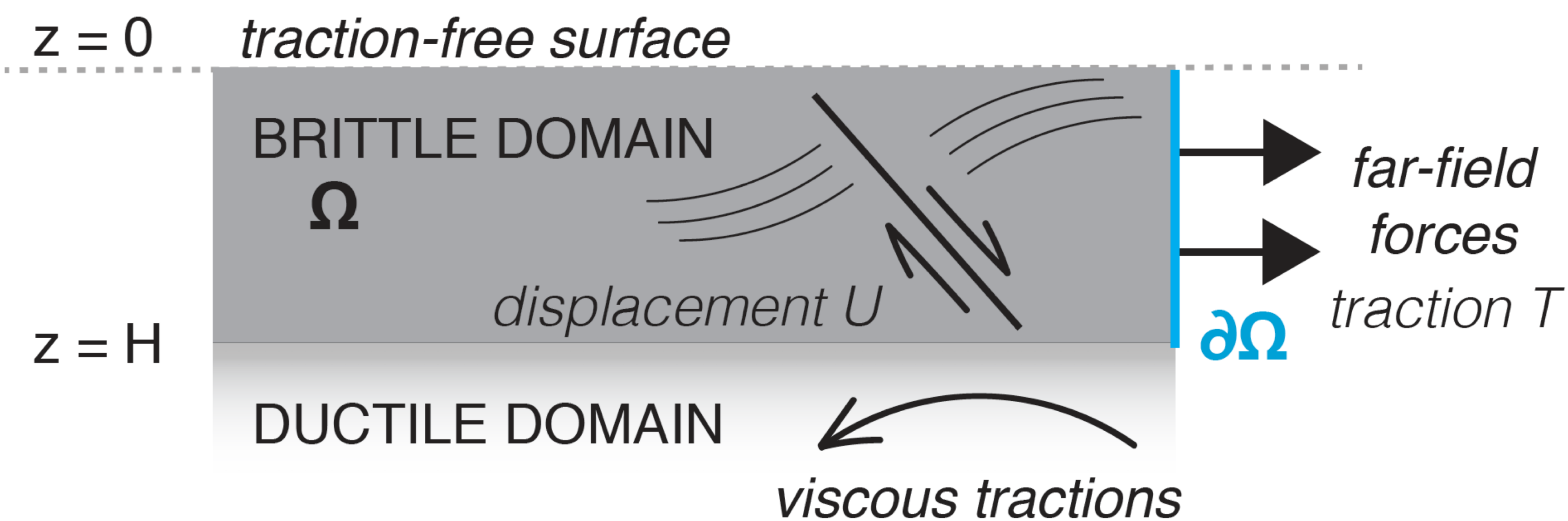
$$\int_{\partial\Omega} \underline{T} \cdot \underline{U}\, dS + \int_{\Omega} \rho \underline{g} \cdot \underline{U}\, d\Omega = \int_{\Omega} \underline{\underline{\sigma}} : \underline{\underline{\nabla}}\left(\underline{U}\right)\, d\Omega$$



Energy balance in tectonic systems

Work balance in the brittle upper crust:

$$\underbrace{\int_{\partial\Omega} \underline{T} \cdot \underline{U}\, dS}_{\text{EXTERNAL WORK}} + \underbrace{\int_{\Omega} \rho \underline{g} \cdot \underline{U}\, d\Omega}_{\text{GRAVITY WORK}} = \underbrace{\int_{\Omega} \underline{\underline{\sigma}} : \underline{\underline{\nabla}}\left(\underline{U}\right)\, d\Omega}_{\text{- INTERNAL WORK}}$$



Energy balance in tectonic systems

Work balance in the brittle upper crust:

$$\underbrace{\int_{\partial\Omega} \underline{T} \cdot \underline{U} \, dS}_{\text{EXTERNAL WORK}} + \underbrace{\int_{\Omega} \rho \underline{g} \cdot \underline{U} \, d\Omega}_{\text{GRAVITY WORK}} = \underbrace{\int_{\Omega} \underline{\underline{\sigma}} : \underline{\underline{\nabla}} \left(\underline{U}\right) \, d\Omega}_{\text{- INTERNAL WORK}}$$

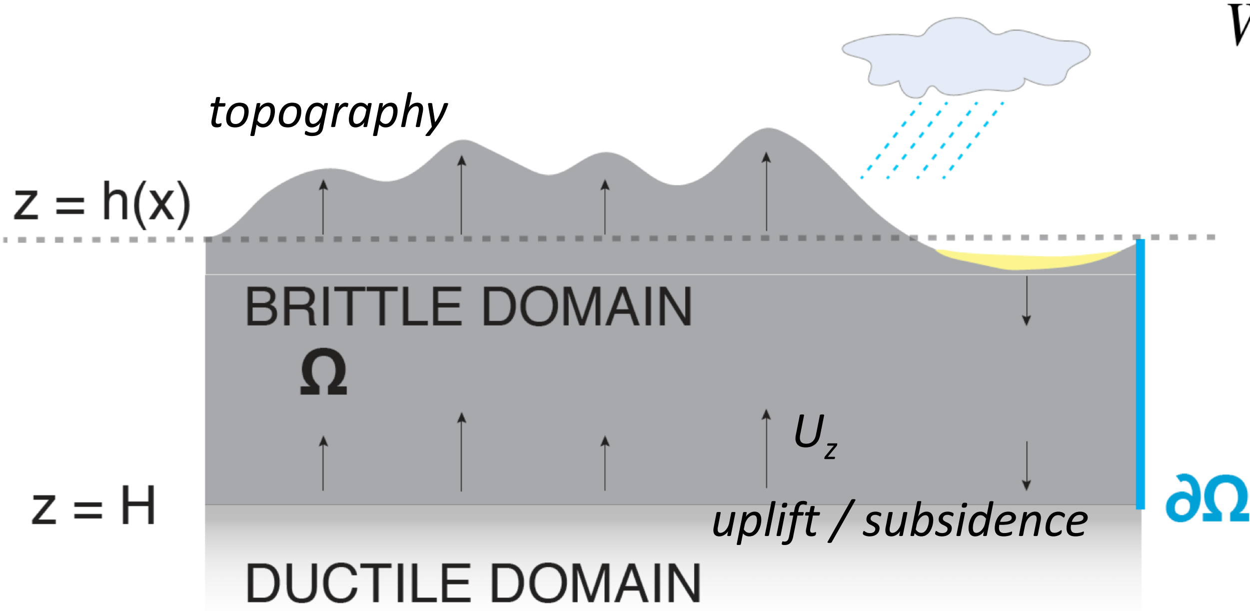
DISSIPATION
BY **LOCALIZED**
DEFORMATION
(faults)

DISSIPATION
BY **DISTRIBUTED**
DEFORMATION
(flexure, folding,
viscous creep…)

Energy balance in tectonic systems

Work balance in the brittle upper crust:

$$\underbrace{\int_{\partial\Omega} \underline{T} \cdot \underline{U}\, dS}_{\text{EXTERNAL WORK}} + \underbrace{\int_{\Omega} \rho \underline{g} \cdot \underline{U}\, d\Omega}_{\text{GRAVITY WORK}} = \underbrace{\int_{\Omega} \underline{\underline{\sigma}} : \underline{\underline{\nabla}}\left(\underline{U}\right)\, d\Omega}_{\text{- INTERNAL WORK}}$$



$$W_{GRAV} = \int_{-\infty}^{+\infty} \rho g H U_z\, dx + \int_{-\infty}^{+\infty} \rho g U_z h\, dx$$

SENSITIVE TO SURFACE PROCESSES !

Energy balance in tectonic systems

Work balance in the brittle upper crust:

$$\underbrace{\int_{\partial\Omega} \underline{T} \cdot \underline{U}\, dS}_{\text{EXTERNAL WORK}} + \underbrace{\int_{\Omega} \rho \underline{g} \cdot \underline{U}\, d\Omega}_{\text{GRAVITY WORK}} = \underbrace{\int_{\Omega} \underline{\underline{\sigma}} : \underline{\underline{\nabla}} \left(\underline{U}\right)\, d\Omega}_{\text{- INTERNAL WORK}}$$

$$W_{EXT} = \int \underline{F}_{EXT} \cdot \underline{dl}$$

$$F_{EXT} = \frac{\partial W_{EXT}}{\partial l} = \frac{\partial E_P}{\partial l} - \frac{\partial W_{INT}}{\partial l}$$

- F_{EXT} changes with increasing extension / shortening (*l*).
- Do systems evolve to minimize F_{EXT} ?
- A stable configuration can be maintained until $F_{EXT} \geq F_{BREAK}$

A simple force balance model for fault life span

FORCE REQUIRED TO KEEP A FAULT ACTIVE

=

FORCE REQUIRED TO...

OVERCOME THE FRICTIONAL RESISTANCE ON THE FAULT

+

FLEX THE FOOTWALL AND HANGING WALL BLOCKS

+

SUSTAIN THE GROWTH OF TOPOGRAPHY

[*Olive et al.* 2014]

A simple force balance model for fault life span

FORCE REQUIRED TO KEEP A FAULT ACTIVE = FORCE REQUIRED TO...

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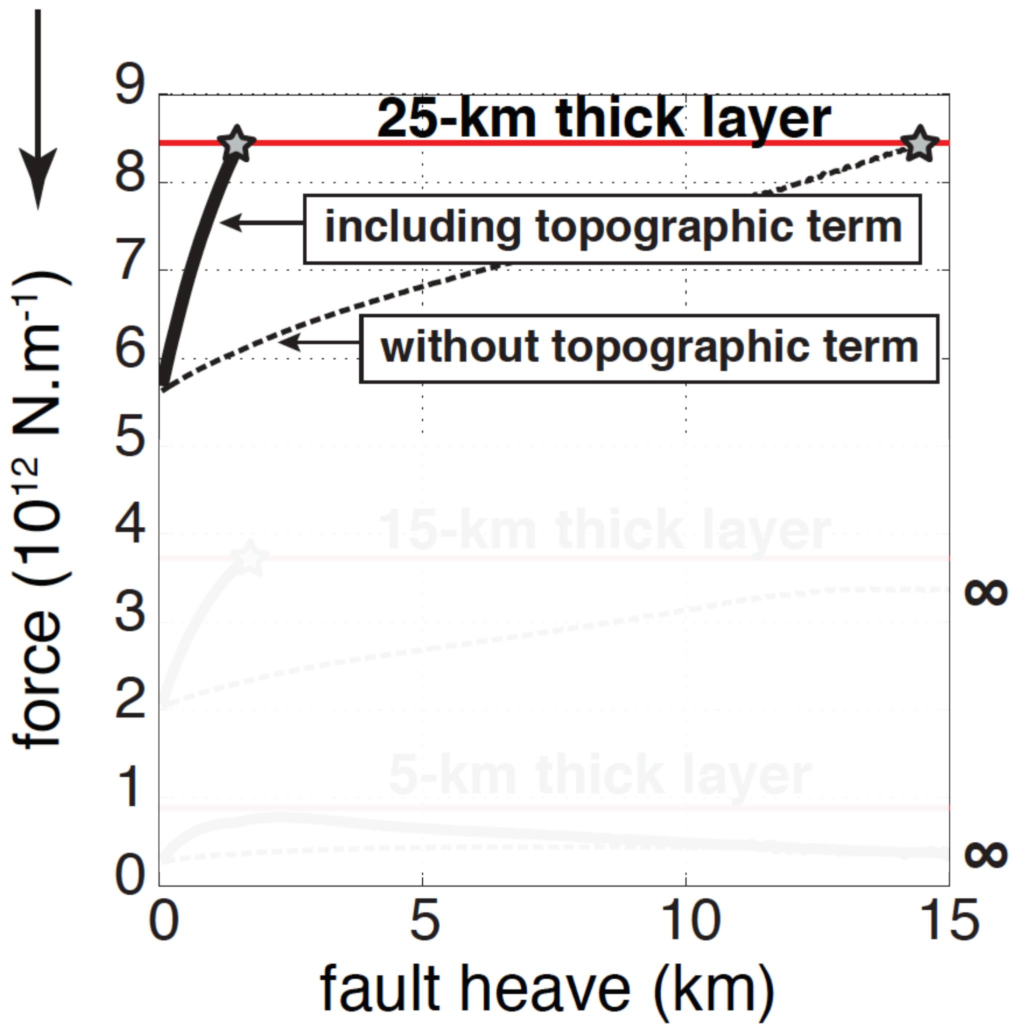

SUSTAIN THE GROWTH OF TOPOGRAPHY

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A simple force balance model for fault life span

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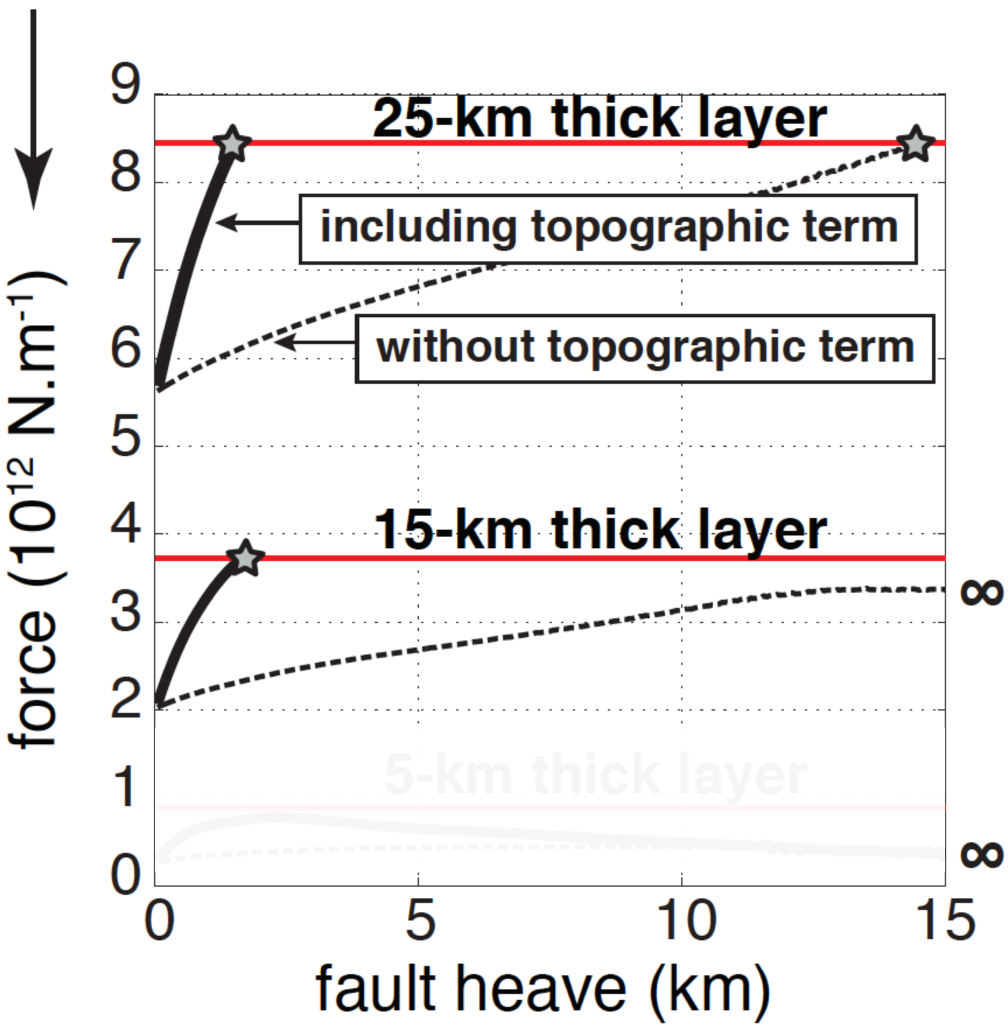


OVERCOME THE FRICTIONAL RESISTANCE ON THE FAULT

+

FLEX THE FOOTWALL AND HANGING WALL BLOCKS

+

ON / OFF

SUSTAIN THE GROWTH OF TOPOGRAPHY

[*Olive et al.* 2014]

How ”efficient” can surface processes be?

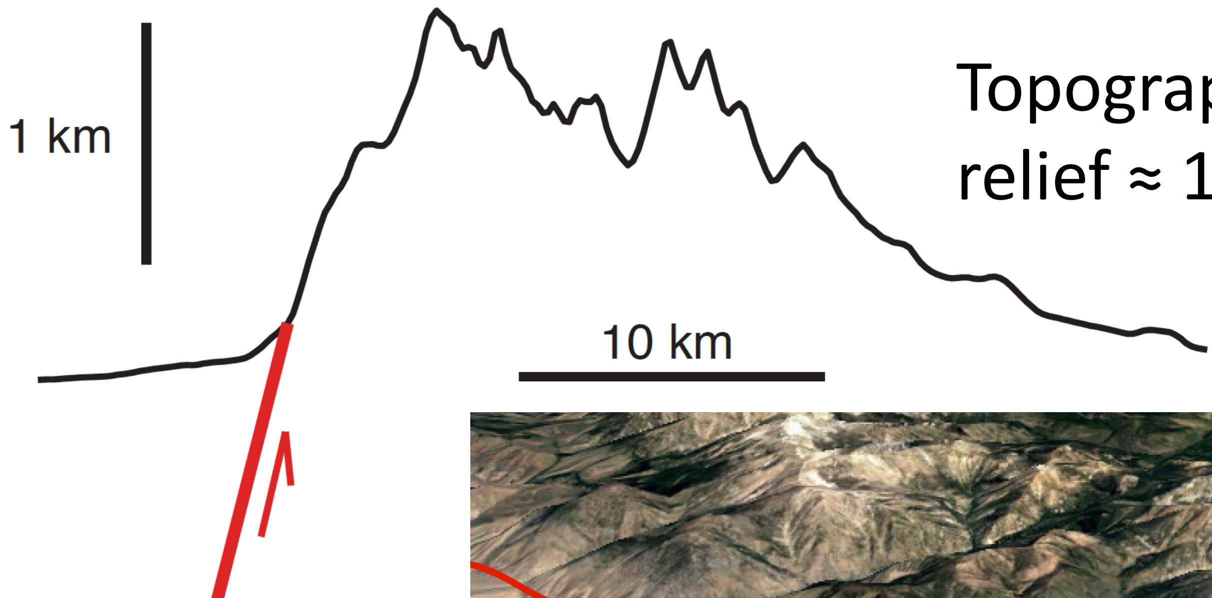
What constitutes a reasonable middle ground between unhindered topographic growth and total leveling?

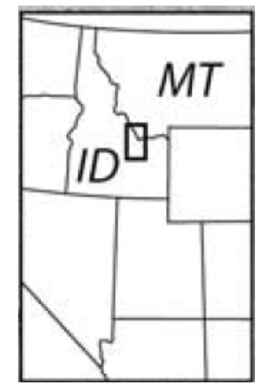
What do we need from a **landscape evolution model**?

- Capture the first-order physics, time and length scales of surficial mass redistribution.
- Allow some degree of benchmarking against real landscapes (e.g., calibrating coefficients, reproducing key morphological features…).

How is surficial mass redistributed ?

Lemhi Range, ID



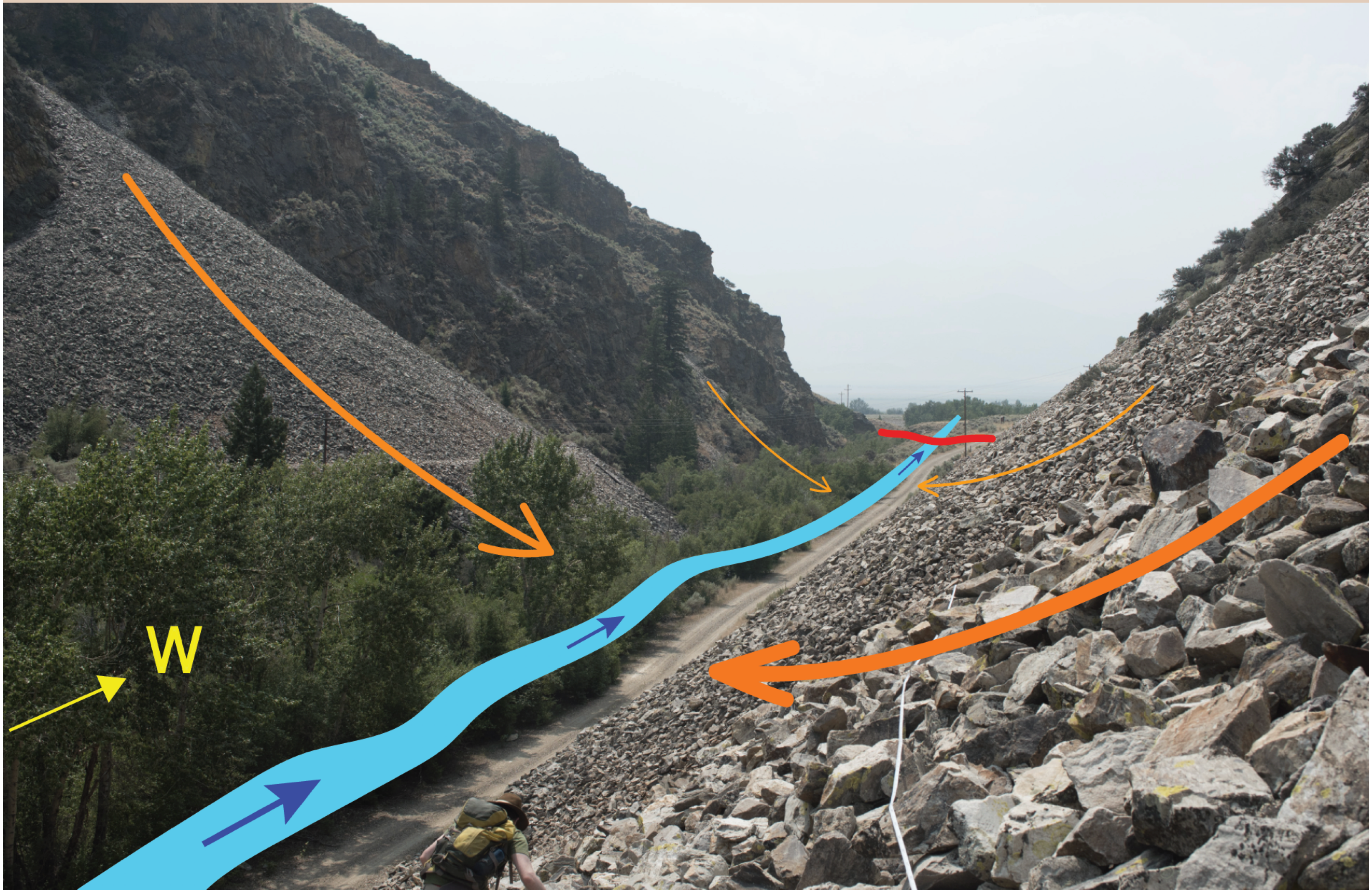


Topographic relief ≈ 1 km

Structural relief ≈ 4 km

[*Anders et al.*, 1993]

How is surficial mass redistributed ?



Coupled tectonic & surface evolution models

Landscape evolution model:

- **Deposition law**: Instantaneous infilling of subsiding areas.
- **Erosion law**: Stream power incision and hillslope diffusion.

$$\frac{\partial z}{\partial t} = \boxed{U} \boxed{- K A^m S^n} \boxed{+ D \nabla^2 z}$$

Stream power incision:
- erodibility (**K**)
- drainage area (**A**)
- local slope (**S**)

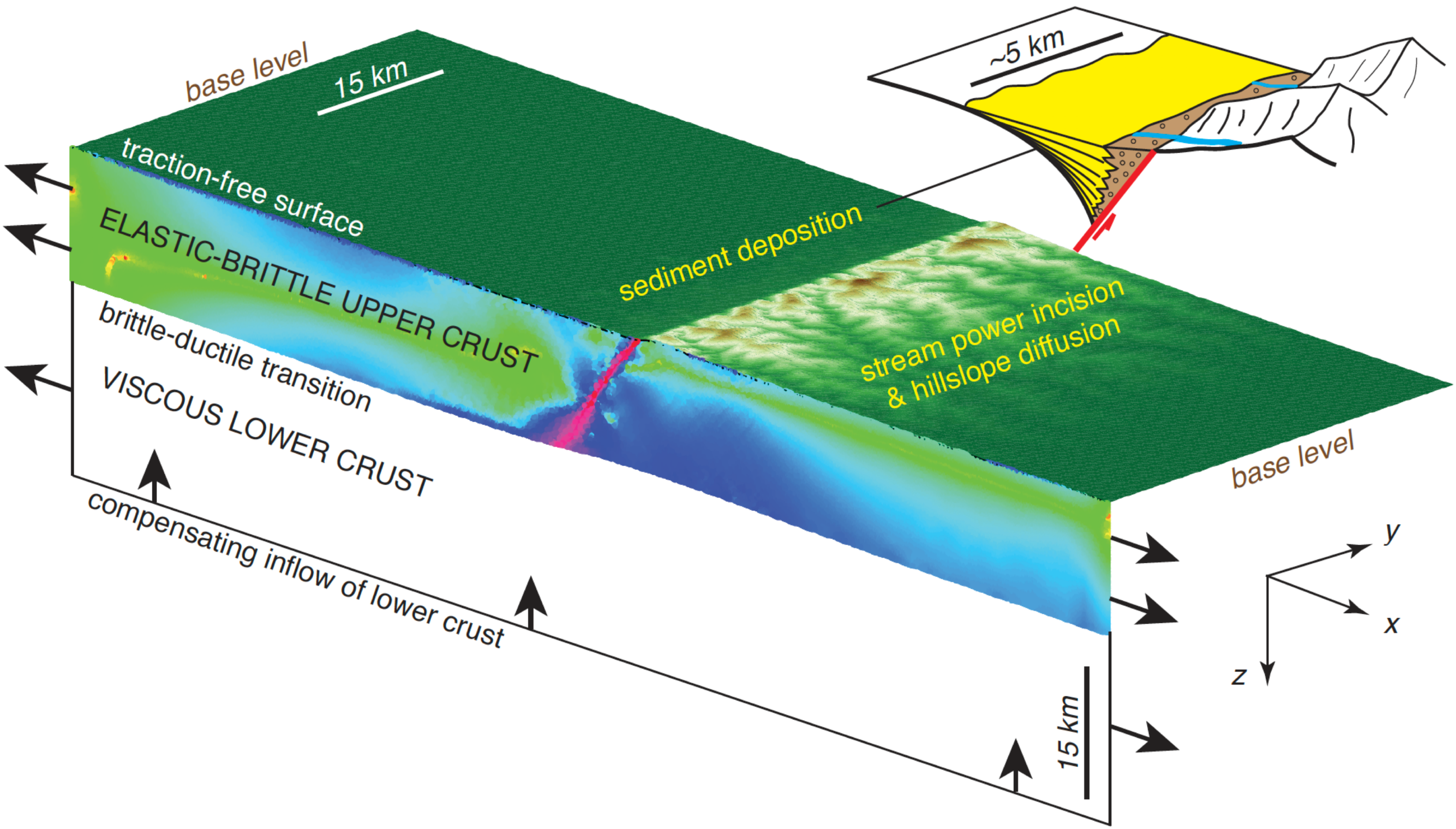
Hillslope diffusion:
- diffusivity (**D**)

Tectonic uplift

[*Anderson*, 1994; *Howard*, 1994; *Braun and Willett*, 2013]

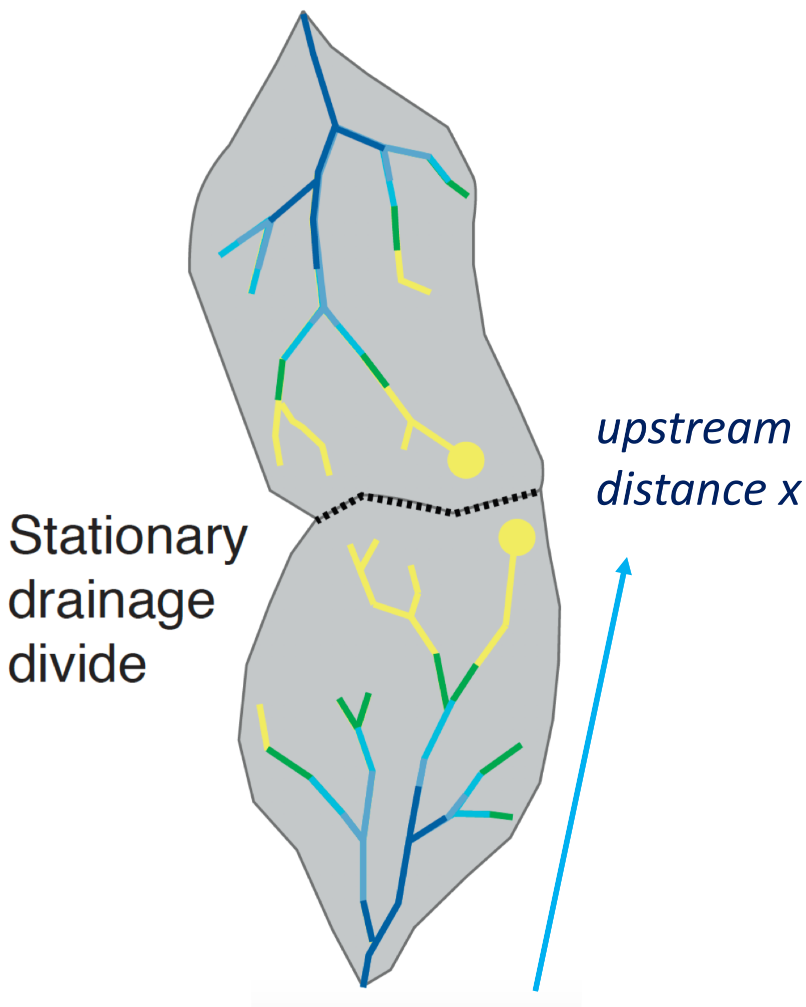
Numerical implementation by S. Castelltort & B. Kaus, available at www.topomod.eu

Coupled tectonic & surface evolution models

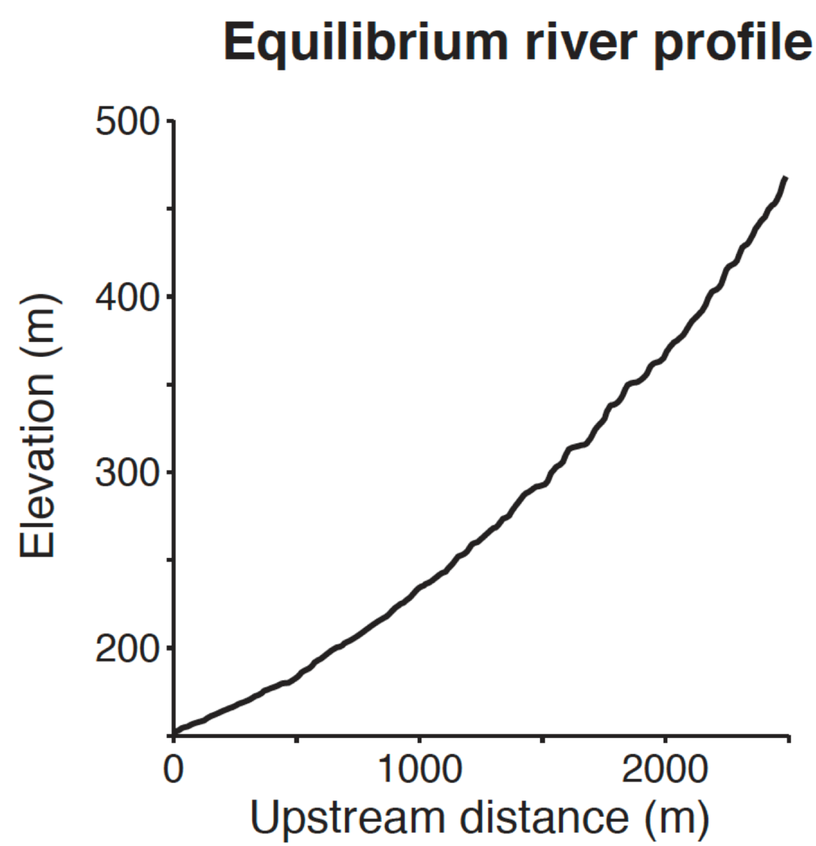


Calibrating stream power incision parameters

χ-analysis: $$\frac{\partial z}{\partial t} = U - KA^m S^n \xrightarrow{\text{steady state}} \left|\frac{\partial z}{\partial x}\right| = \left(\frac{U}{KA^m}\right)^{\frac{1}{n}}$$



[*Willett et al.*, 2014]



[*Perron & Royden*, 2013]

Calibrating stream power incision parameters

χ-analysis:

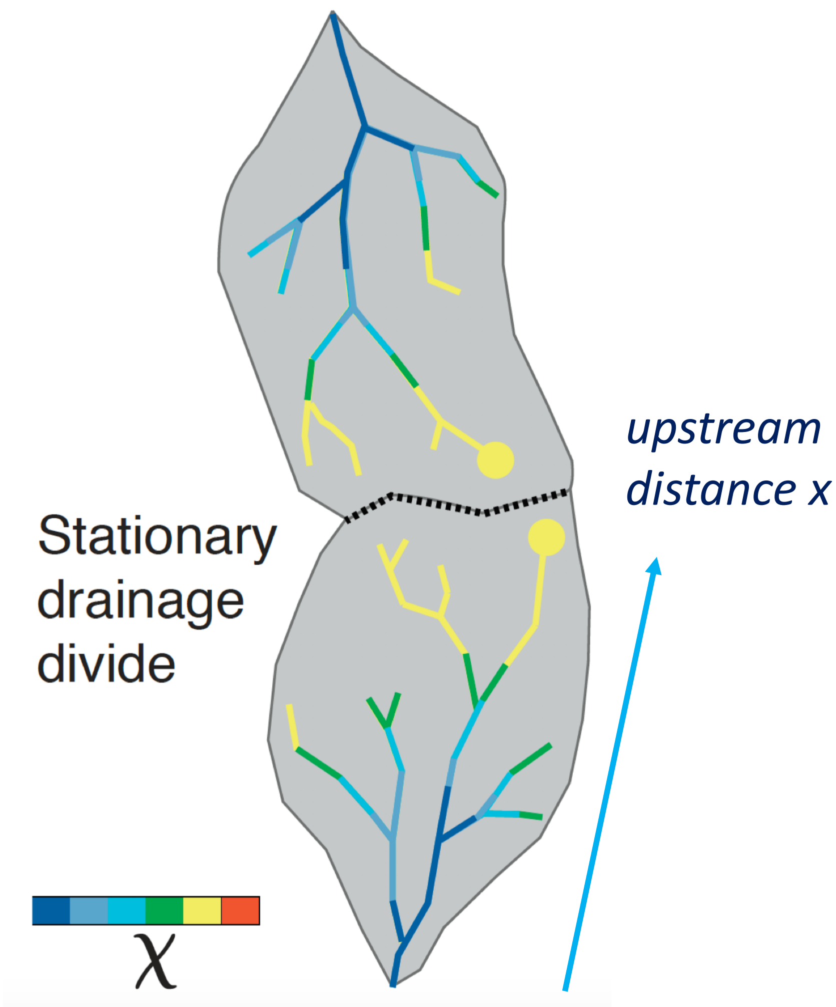
$$\frac{\partial z}{\partial t} = U - K A^m S^n \xrightarrow{\text{steady state}} \left|\frac{\partial z}{\partial x}\right| = \left(\frac{U}{K A^m}\right)^{\frac{1}{n}}$$

integrate upstream

$$\int_{z_b}^{z} dz = \int_{x_b}^{x} \left(\frac{U}{K A^m}\right)^{\frac{1}{n}} dx$$

define χ: upstream distance corrected for decrease in drainage area

$$z = z_b + \left(\frac{U}{K A_0^m}\right)^{\frac{1}{n}} \underbrace{\int_{x_b}^{x} \left(\frac{A_0}{A(x)}\right)^{\frac{m}{n}} dx}_{\chi}$$



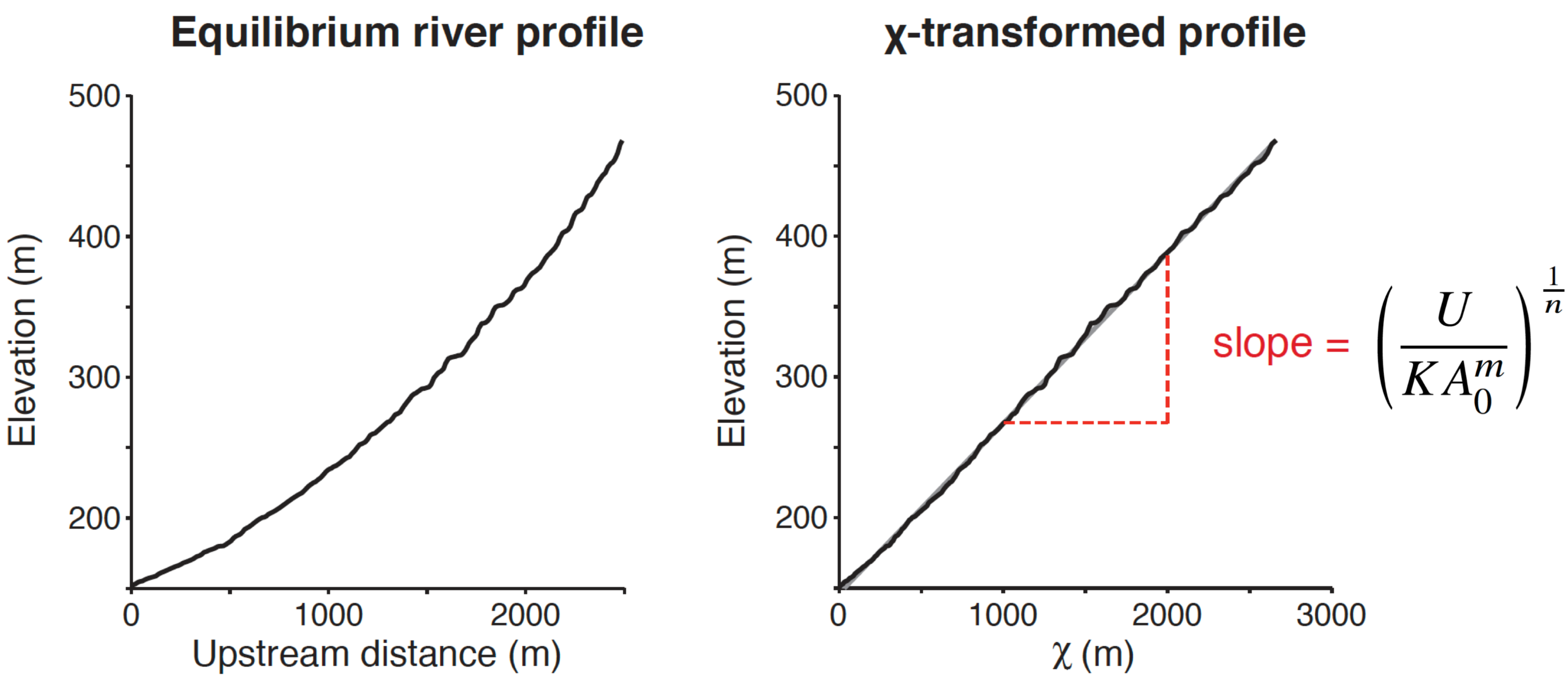
[*Willett et al.*, 2014]

[*Perron & Royden*, 2013]

Calibrating stream power incision parameters

χ-analysis:

Slope of χ-plot contains relative information on uplift vs. erodibility.



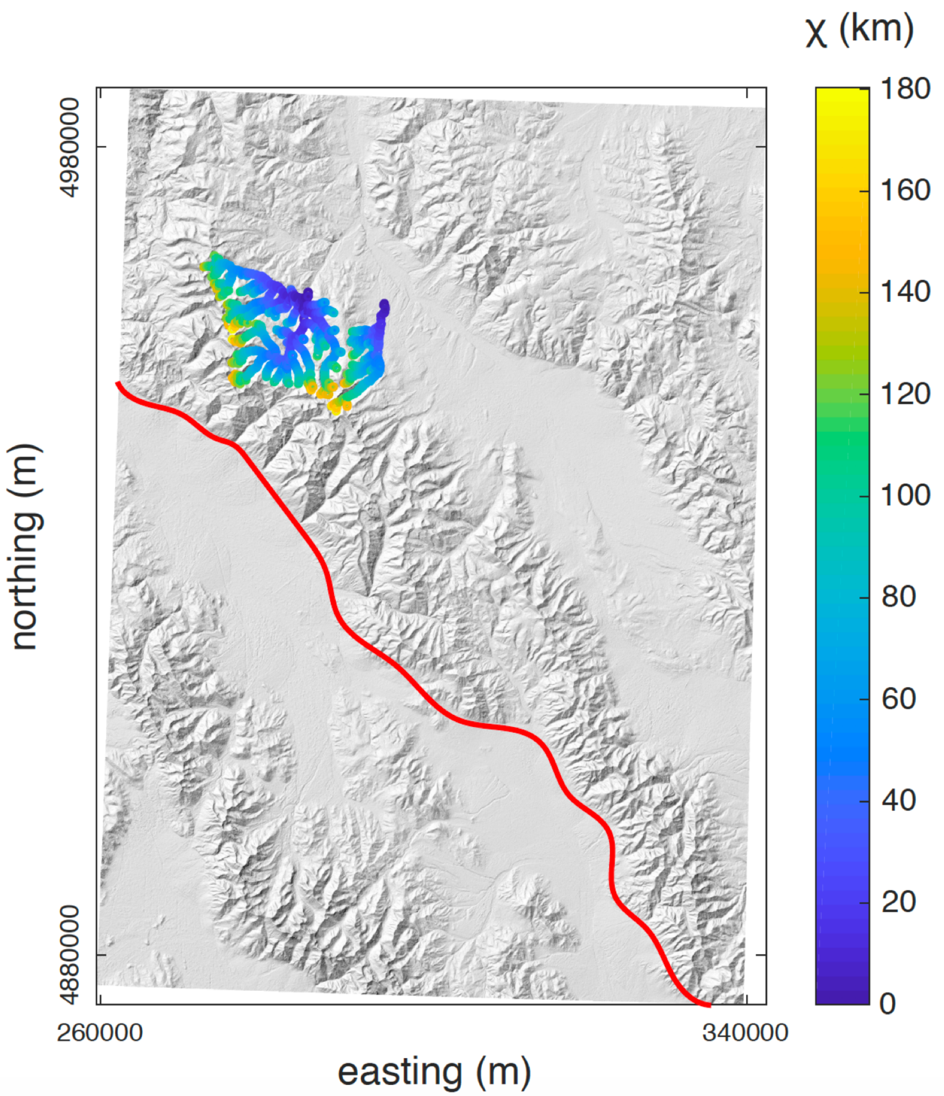
[*Perron & Royden*, 2013]

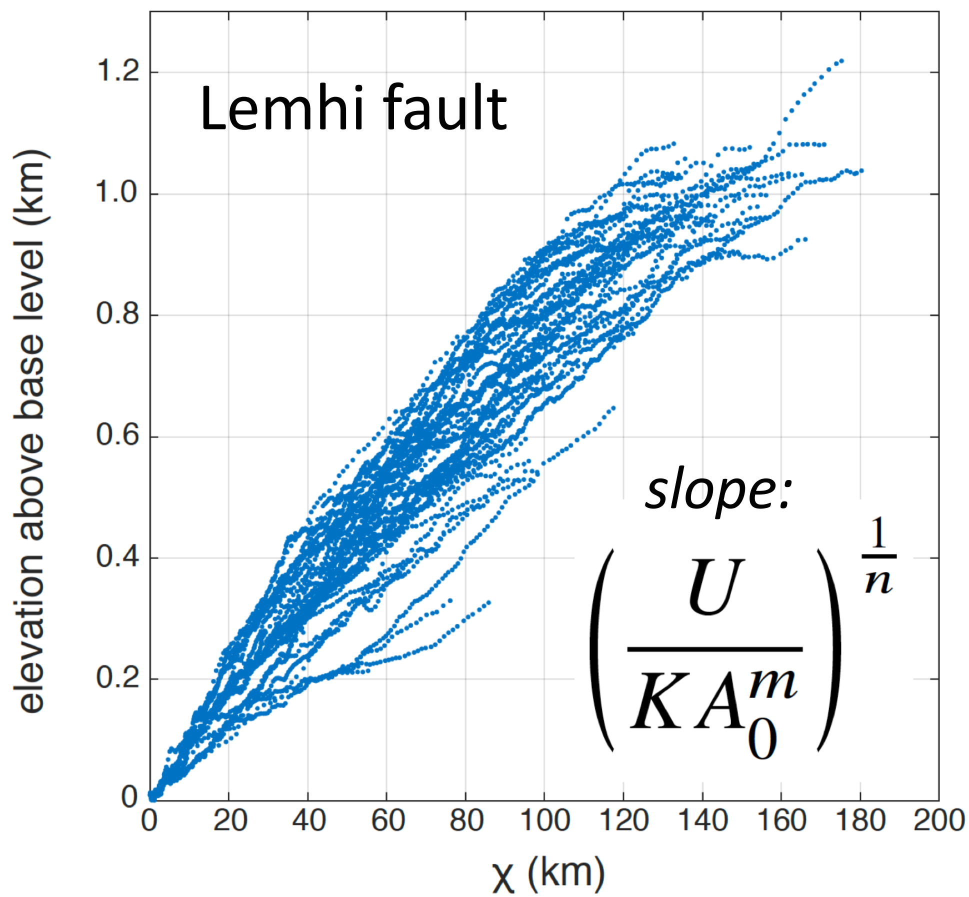
Calibrating stream power incision parameters

χ-analysis:

TopoToolbox suite available at topotoolbox.wordpress.com

[*Schwanghart & Scherler*, 2014]





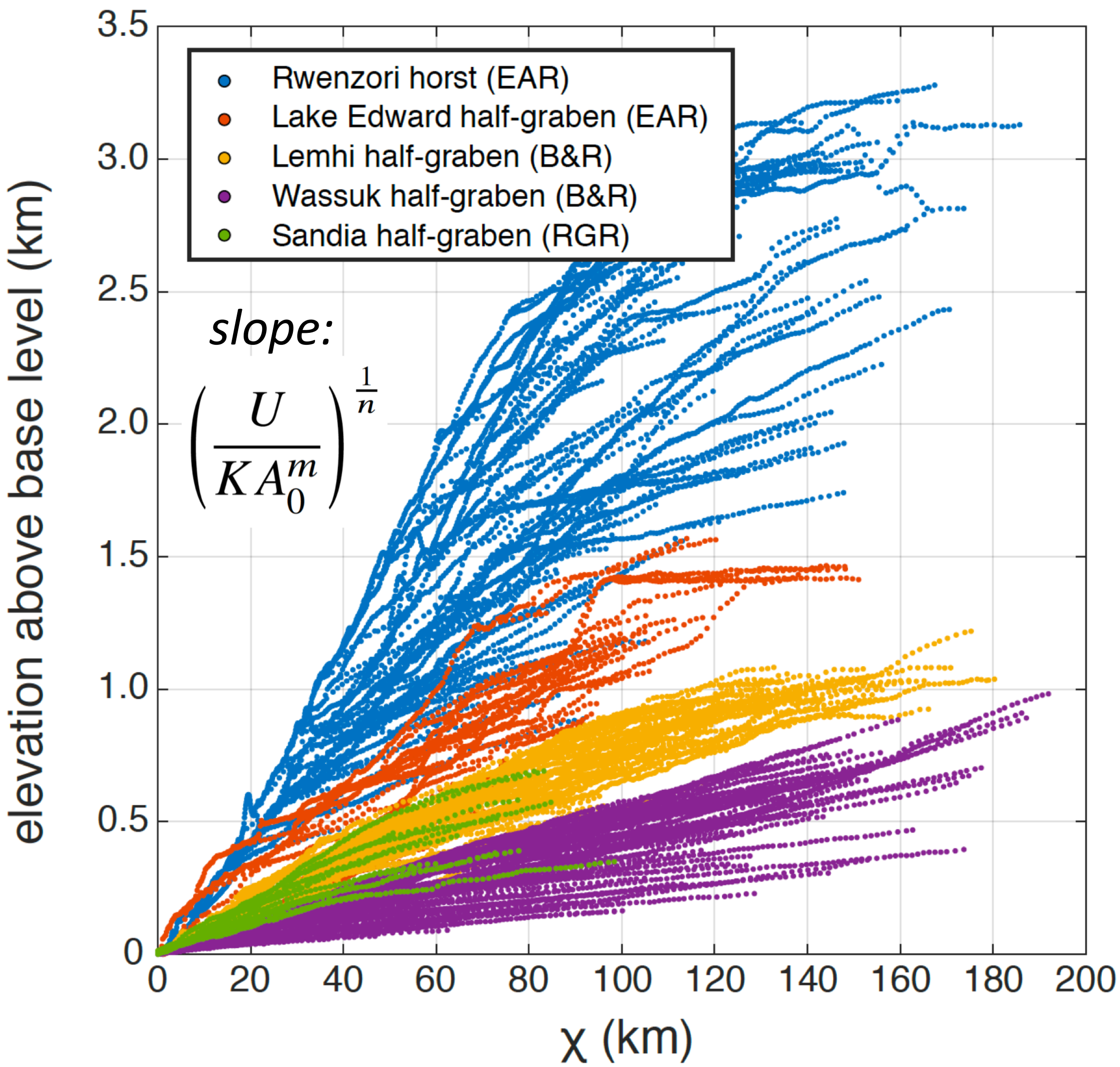
$$\left(\frac{U}{KA_0^m}\right)^{\frac{1}{n}}$$

U ≈ 0.1 mm/yr → K ≈ 10^{-5} yr^{-1}

(assuming n = 1, m = 0.5)

Calibrating stream power incision parameters

χ-analysis:



Range of erodibility coefficients:

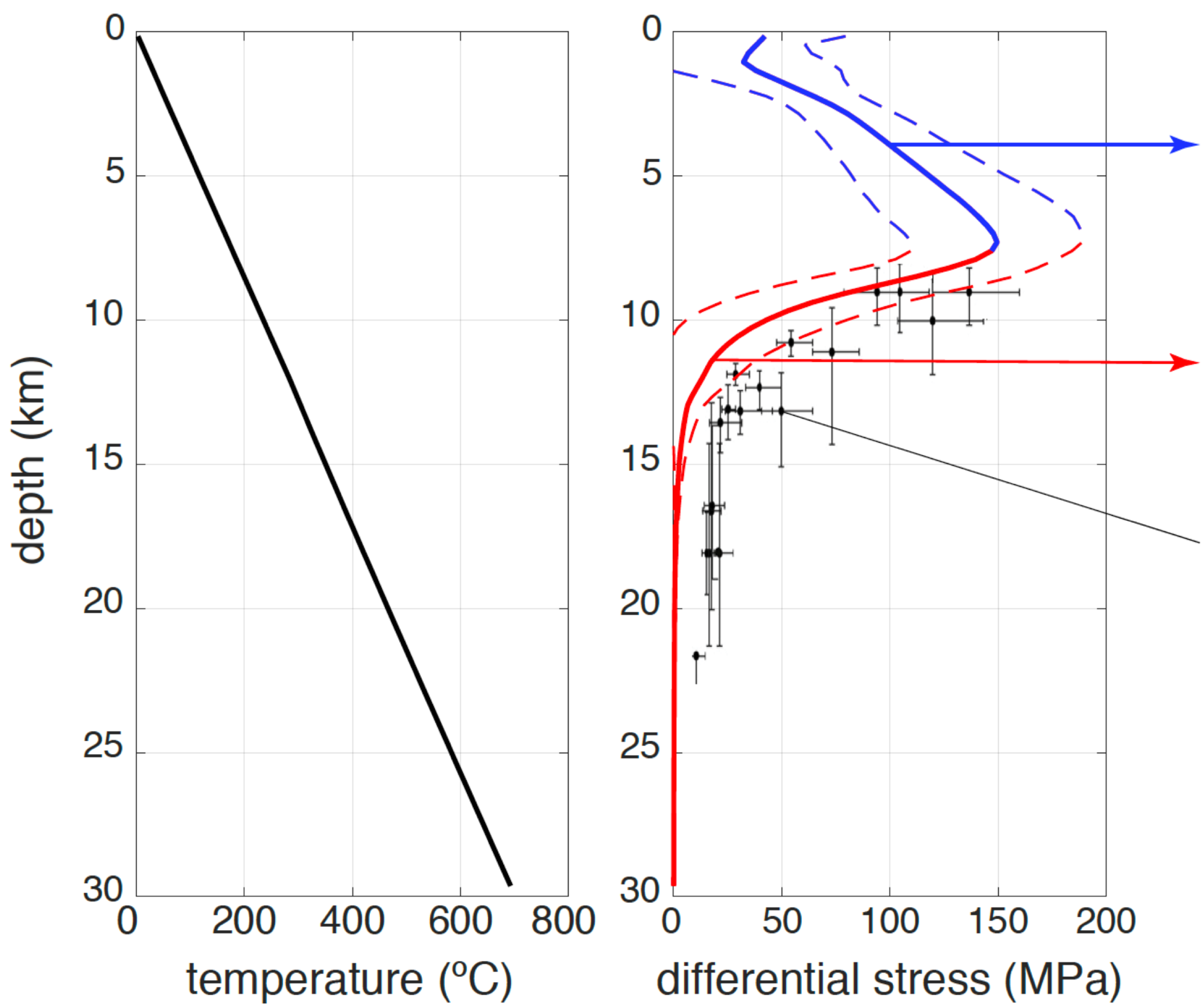
$K \approx 10^{-6} - 10^{-4}\ yr^{-1}$

Limitations:

- Ignores spatial variability.
- Assumes steady state.
- Only valid within stream power framework.

Realistic crustal strength profiles

Combining laboratory and field constraints:



Elastic-brittle:
$\mu = 0.6$
C = 30 MPa
Strain-weakening of cohesion

Visco-elastic:
Wet quartzite flow law
[*Ranalli*, 1995]

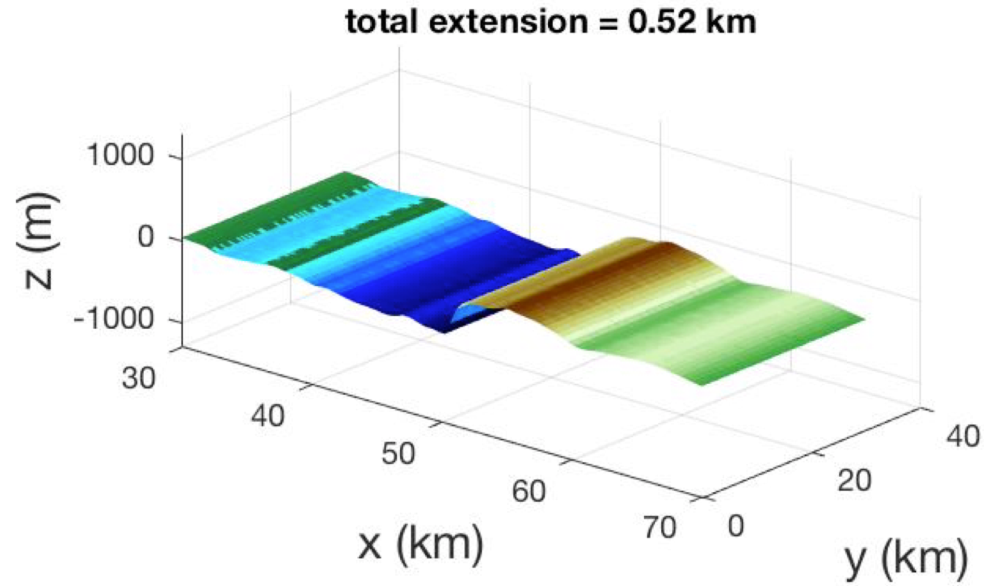
Middle crustal stresses inferred from paleopiezometry in the Whipple Mountains MCC.
[*Behr & Platt*, 2011]

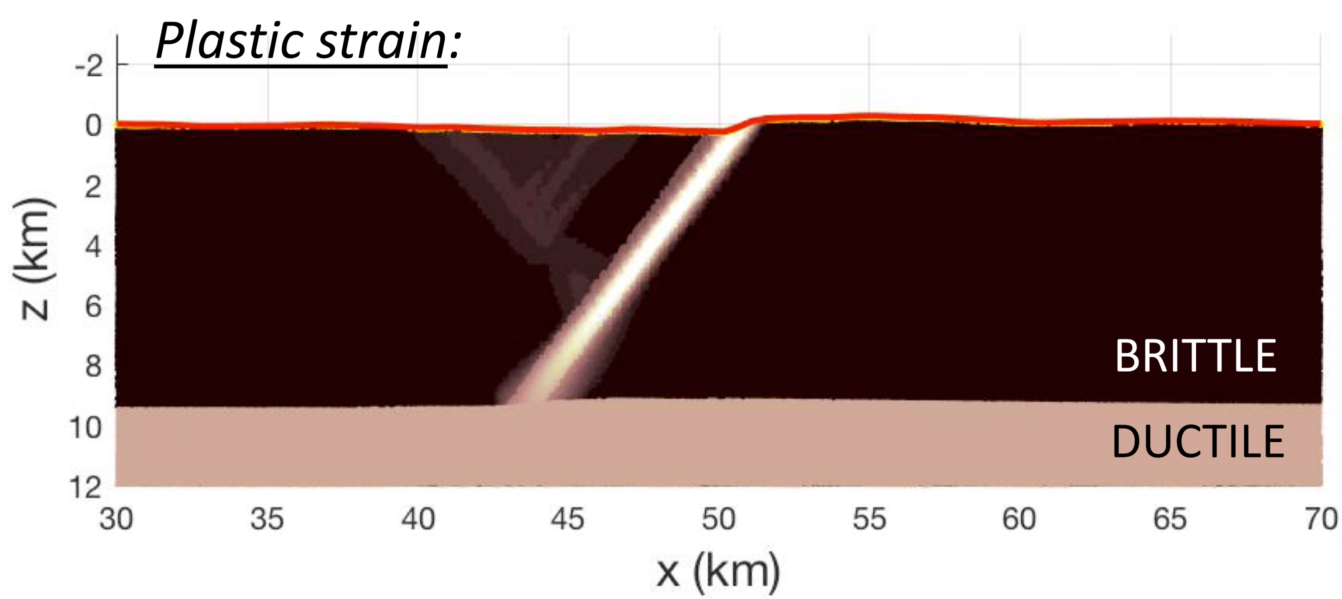
Imposed extension rate: 1 mm/yr

Half-graben growth with reasonable strength & SPs

- $K = 10^{-7}$ yr^{-1}
- No sedimentation

*Half-graben to **graben** after 3 km of extension.*

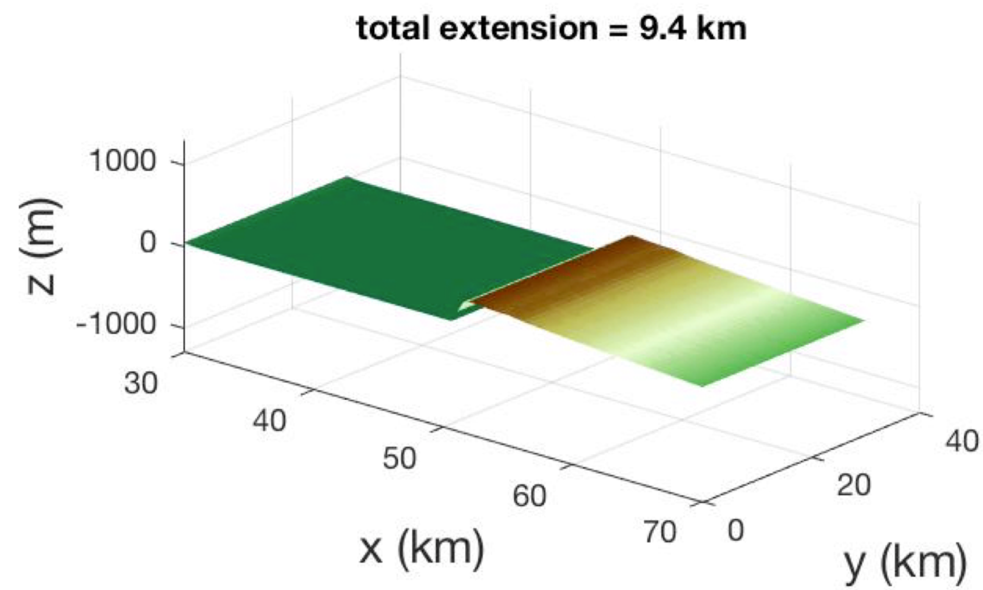


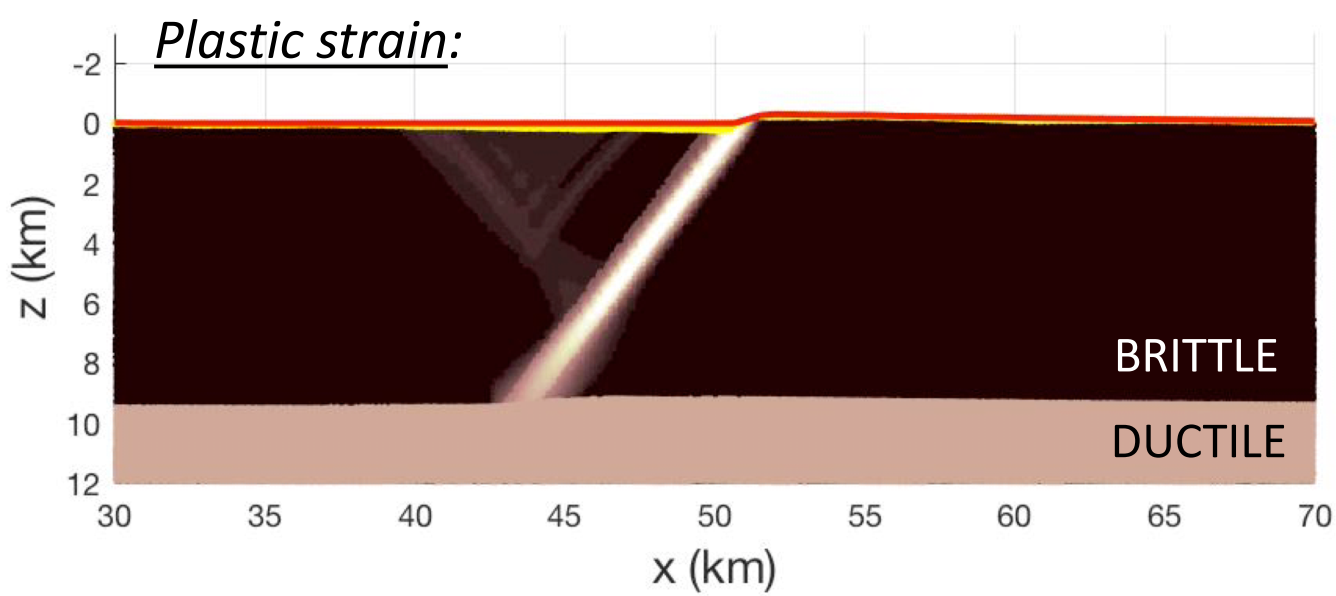


Half-graben growth with reasonable strength & SPs

- $K = 10^{-7}\ yr^{-1}$
- Sedimentation

*Half-graben to **graben** after 4 km of extension.*

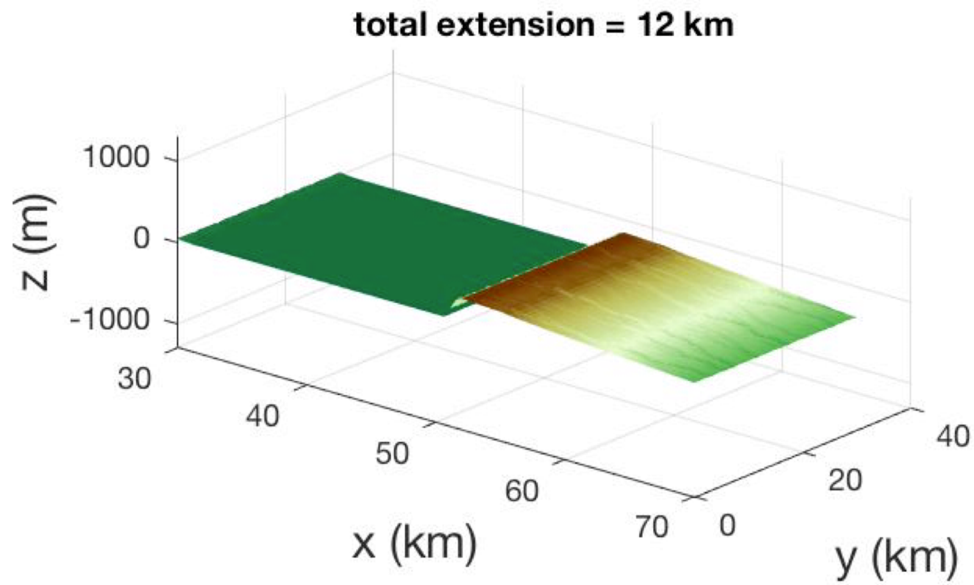


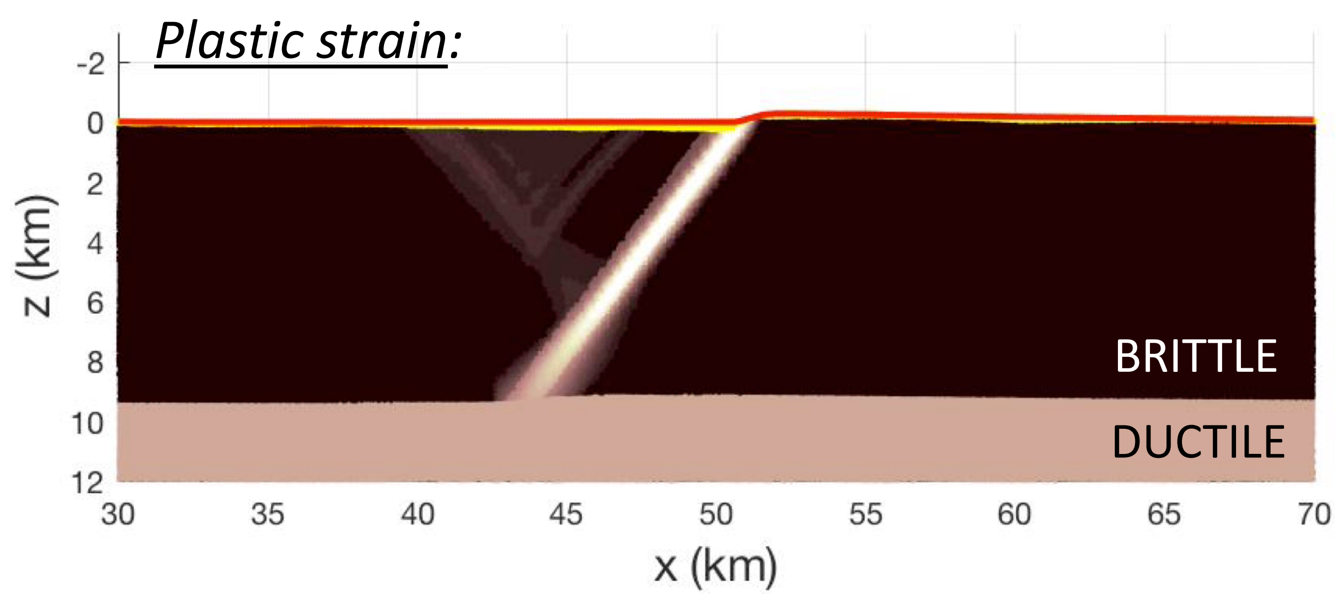


Half-graben growth with reasonable strength & SPs

- $K = 10^{-6}\ yr^{-1}$
- Sedimentation

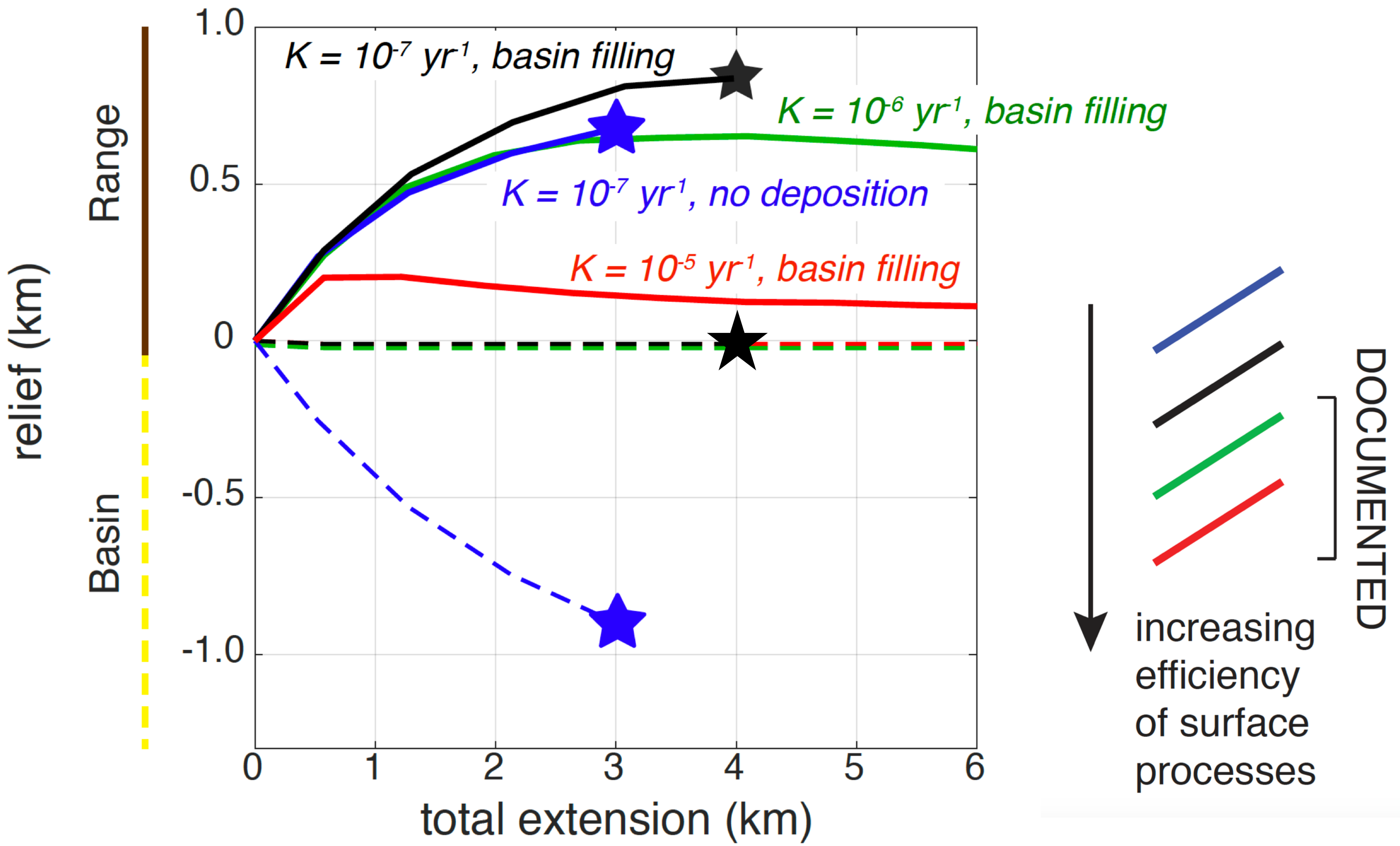
Stable half-graben.





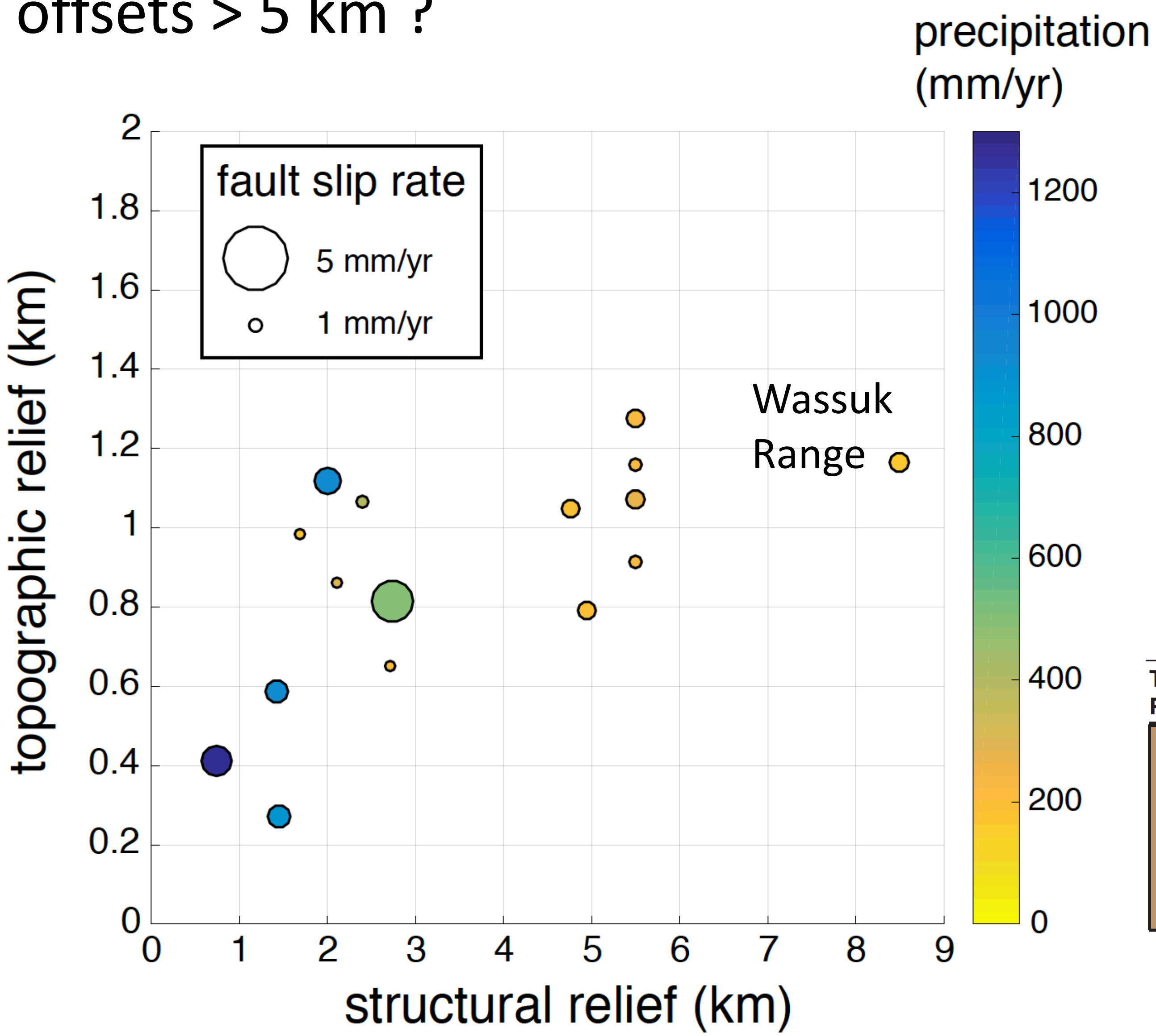
Stabilizing half-grabens with surface processes

Quickly reaching **topographic steady state** keeps half-grabens stable.

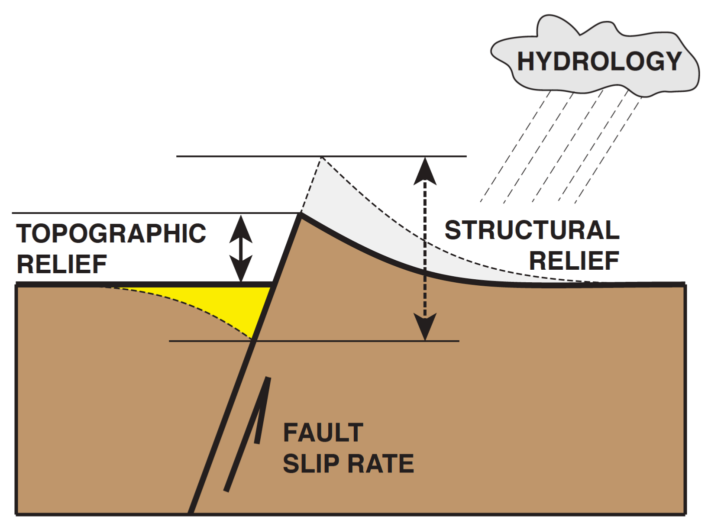


Half-graben lifespan and topographic steady state

Rapidly attained topographic steady state allowing half-graben offsets > 5 km ?



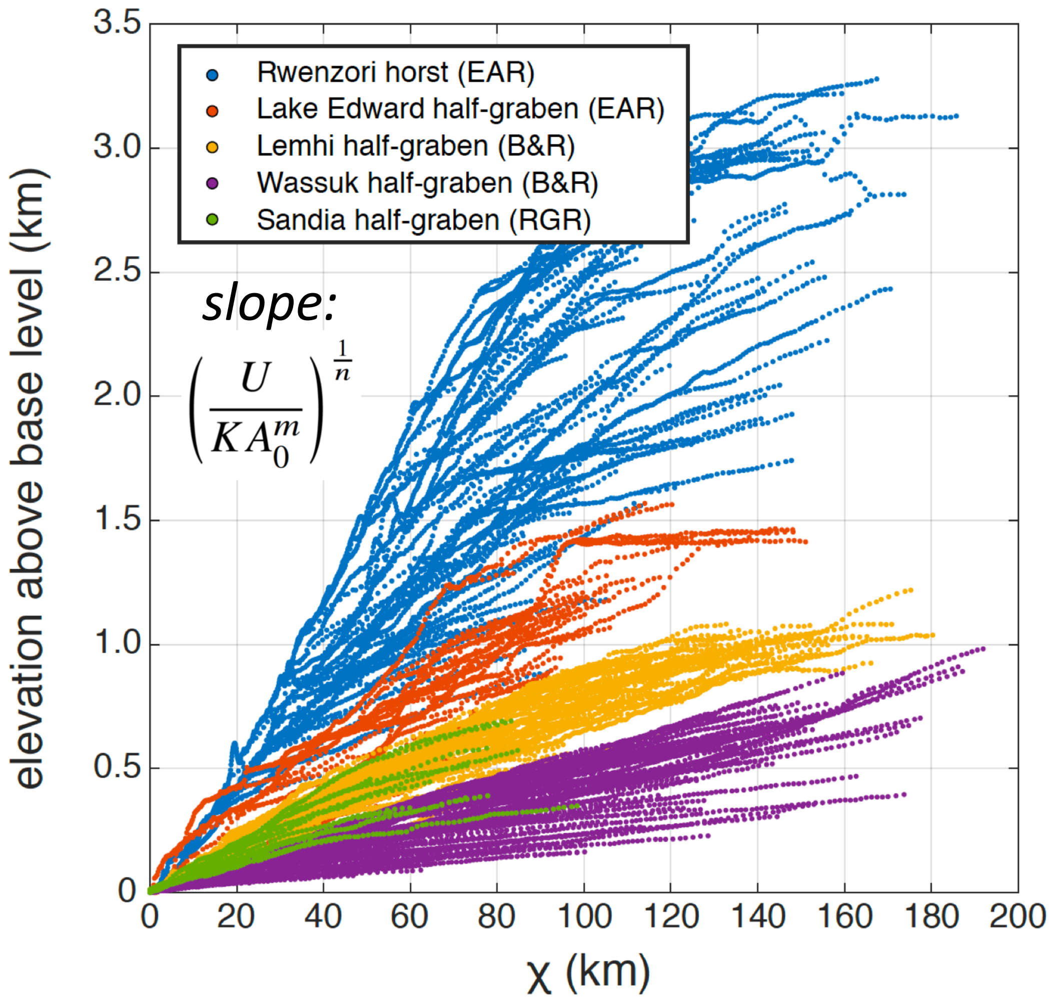
Global compilation of half-graben characteristics
[*Ellis & Barnes*, 2015]

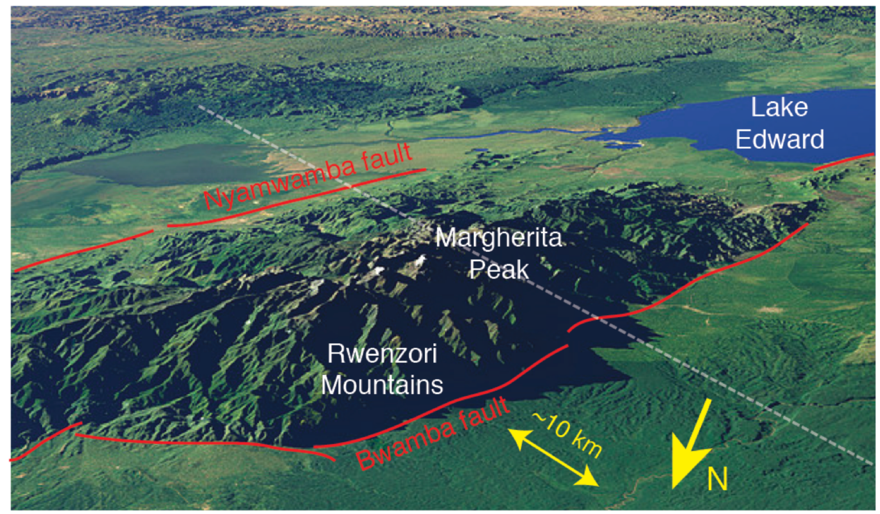


Half-graben lifespan and topographic steady state

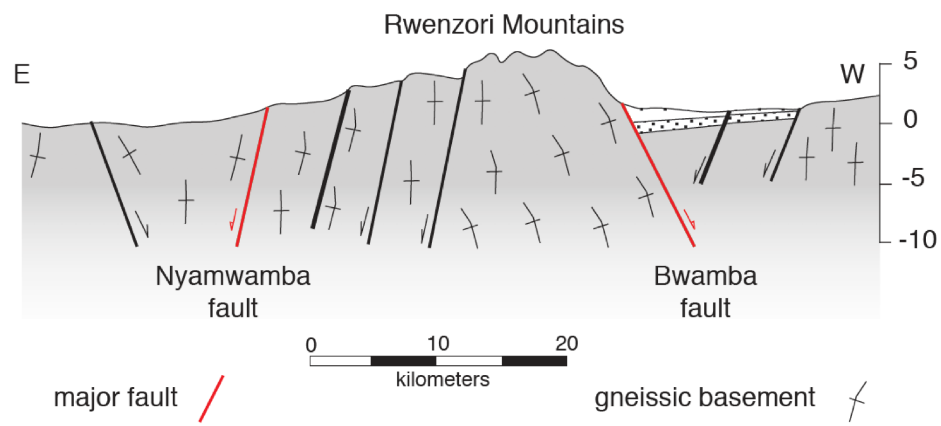
Stable vs. unstable half-grabens in the Albertine Rift (West-EAR)?

A form of **tectonic inheritance** through surface processes?





[*Ring*, 2008]



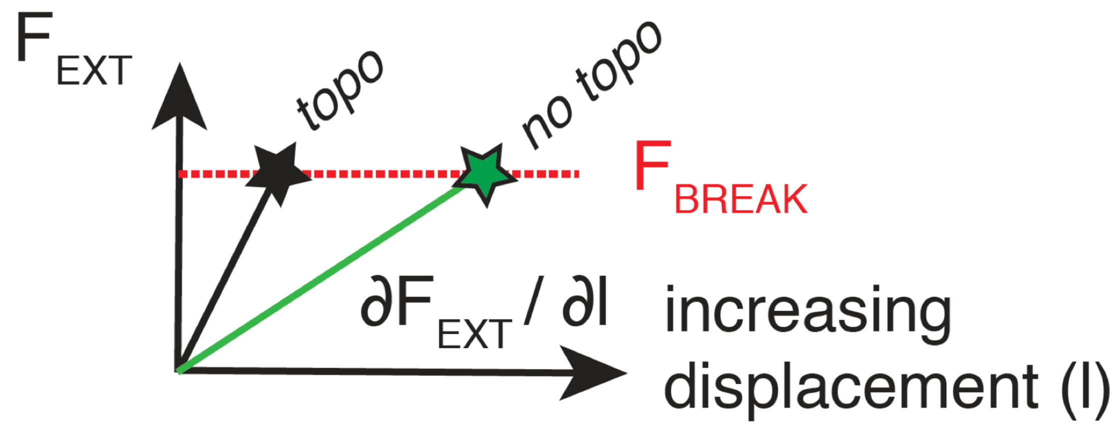
Recap: relevant time and length scales

<u>Is a tectonic system sensitive to topographic growth?</u>

Recall $F_{EXT} = F_{INT} + F_{GRAV}$ increases with increasing deformation, and a system is stable until $F_{EXT} \geq F_{BREAK}$

Topographic sensitivity:

$$S_T = \frac{\left(\frac{\partial F_{GRAV}}{\partial l}\right)}{\left(\frac{\partial F_{INT}}{\partial l}\right)}$$



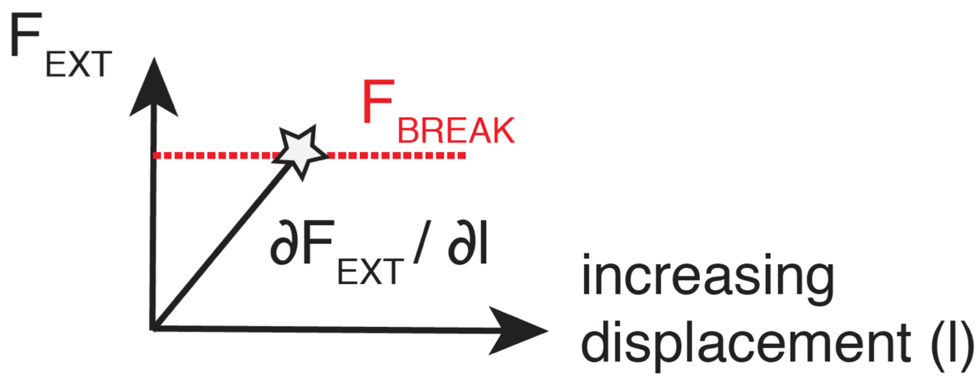
Primarily controlled by the integrated strength of the crust:

weaker crust ⟶ $S_T >> 0$ Increased sensitivity

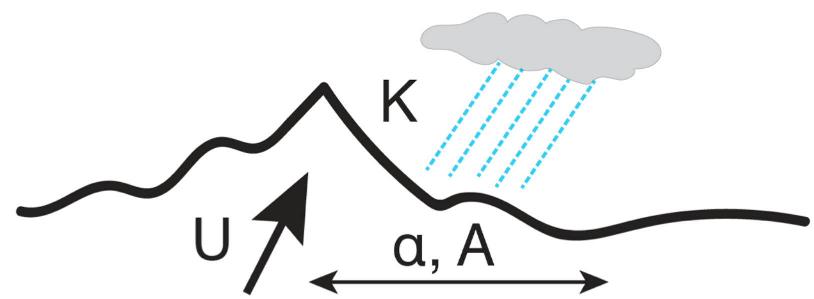
Recap: relevant time and length scales

If a tectonic system is sensitive to topographic evolution ($S_T >> 0$)

<u>How much influence do surface processes have on localization?</u>



Internal time scale for fault stability



Time to topographic steady state

Localizing efficiency

$$L_{SP} = \tau_{BREAK} \,/\, \tau_{TSS} = \left(\frac{F_{BREAK}}{U \frac{\partial F_{EXT}}{\partial l}} \right) \,/\, \left(\frac{\alpha}{K\sqrt{A}} \right)$$

Controlled by strength and intensity of mass redistribution:

- weaker crust
- slower tectonic rates
- greater erodibility and fast deposition

$\longrightarrow$ $L_{SP} >> 1$

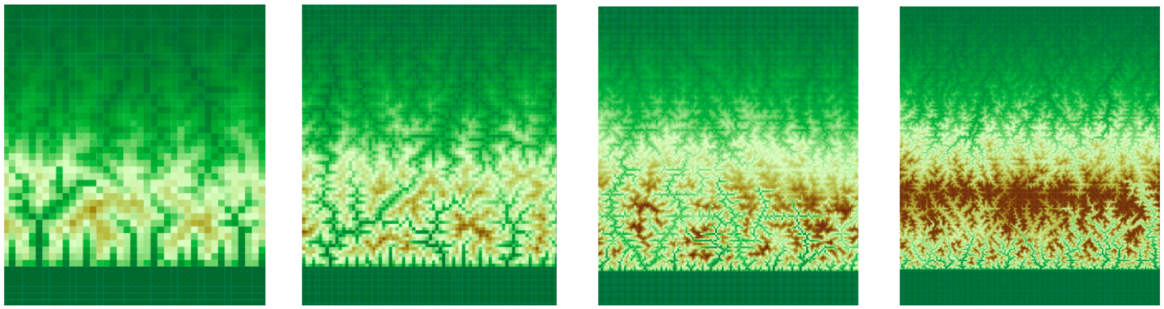
enhanced localization

So, what do we need from coupled models?

Capture the time / length scales of surficial mass redistribution:

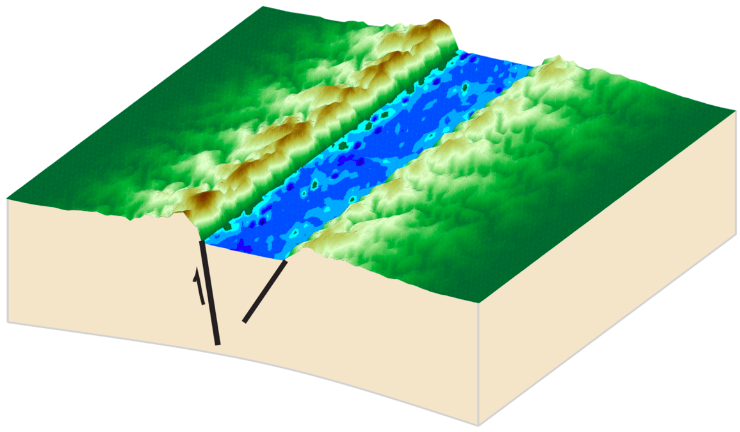
- time to topographic steady state, rates of topography build-up
- "height & width" of topographic steady state
- reproduce key morphological features?

Have limited sensitivity to grid resolution:



Use parameterizations that can be benchmarked against real landscapes & processes:

- fluvial incision
- hillslope diffusion
- glacial erosion
- sediment transport & deposition



Conclusions

- How do surface processes affect normal fault evolution?

  By alleviating the energy cost of topography build-up. Preliminary simulations further suggest importance of reaching ***topographic steady state*** *in stabilizing major fault systems.*

- A signature of surface processes in rift architecture?

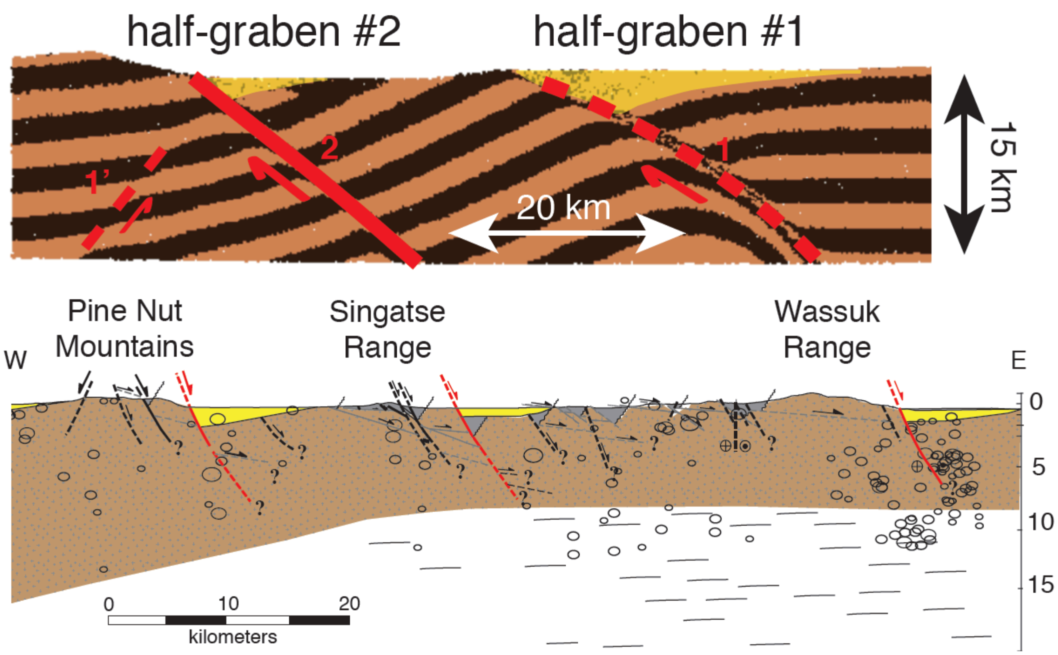
  Fluvial incision & hillslope diffusion *acting at "reasonable" rates (i.e., consistent with observed half-graben morphologies) could be a* ***key ingredient to stabilize half-graben structures*** *over large amounts of extension (1–10 km).*

- Novel research questions

  Specific effects of sediment deposition? of glacial erosion (threshold effects)? Of climatic & lithological variability? Tectonic inheritance through erodibility gradients?

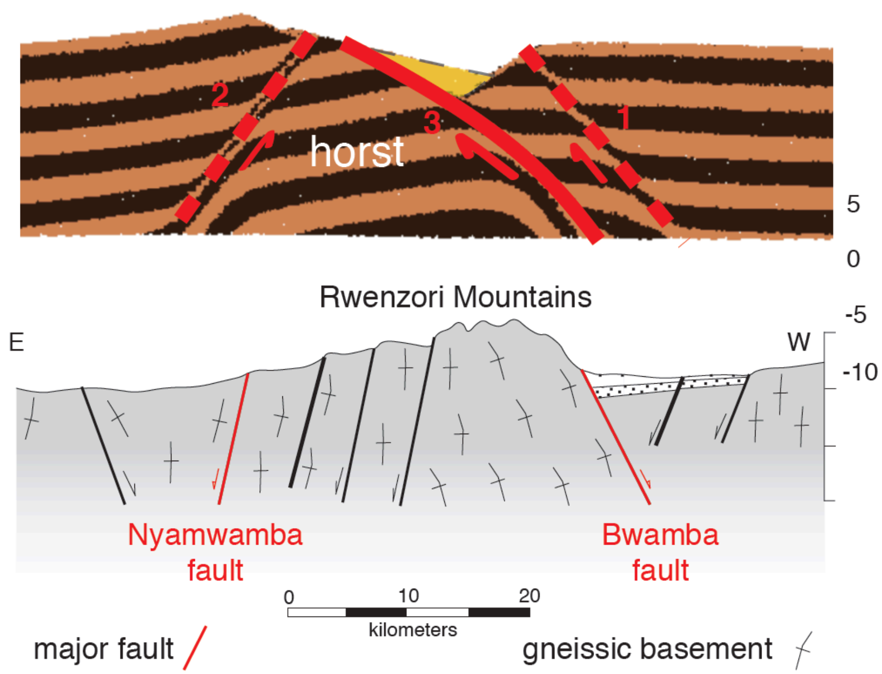
Conclusions

Surface processes enabling rapid topographic steady state (over ~3 km of fault offset) at a moderate relief (~1–2 km)



Surpless et al. [2002]

Inefficient surface processes due to fast tectonic uplift, or unerodable lithologies ?



Ring [2008]

Conclusions

- **Fluvial incision & hillslope diffusion** acting at "reasonable" rates (i.e., consistent with observed half-graben morphologies) could be a **key ingredient to stabilize half-graben structures** over large amounts of extension (1–10 km), as seen in the Basin & Range.
- **Future efforts** to investigate:
  - the specific effect of **sediment deposition** relative to erosion
  - the specific effect of **glacial erosion**, and climate **variability**
  - the potential delocalizing effect of **a strong lower crust**
  - the **interactions** between distant faults