Tectonics from topography

Insights from high-resolution hillslope morphology analysis

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Une vie immense, très lente, mais terrible par sa force révélée, émeut le corps formidable de la terre, circule de mamelons en vallées, ploie la plaine, courbe les fleuves, hausse la lourde chair herbeuse.

Giono, Collines

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Earth Surf. Dynam., 8, 221–243, 2020
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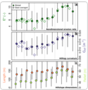
Research article 07 Apr 2020

Hillslope denudation and morphologic response to a rock uplift gradient



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Abstract

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Documenting the spatial variability of tectonic processes from topography is routinely undertaken through the analysis of river profiles, since a direct relationship between fluvial gradient and rock uplift has been identified by incision models. Similarly, theoretical formulations of hillslope profiles predict a strong dependence on their base-level lowering rate, which in most situations is set by channel incision. However, the reduced sensitivity of near-threshold hillslopes and the limited availability of high-resolution topographic data has often been a major limitation for their use to investigate tectonic gradients. Here we combined high-resolution analysis of hillslope morphology and cosmogenic-nuclide-derived denudation rates to unravel the distribution of rock uplift across a blind thrust system at the southwestern Alpine front in France. Our study is located in the Mio-Pliocene Valensole molassic basin, where a series of folds and thrusts has deformed a plateau surface. We focused on a series of catchments aligned perpendicular to the main structures. Using a 1 m lidar digital terrain model, we extracted hillslope topographic properties such as hilltop curvature C_{HT} and nondimensional erosion rates E^*. We observed systematic variation of these metrics coincident with the location of a major underlying thrust system identified by seismic surveys. Using a simple deformation model, the inversion of the E^* pattern allows us to propose a location and dip for a blind thrust, which are consistent with available geological and geophysical data. We also sampled clasts from eroding conglomerates at several hilltop locations for ^{10}Be and ^{26}Al concentration measurements. Calculated hilltop denudation rates range from 40 to 120 mm kyr^{-1}. These denudation rates appear to be correlated with E^* and C_{HT} that were extracted from the morphological analysis, and these rates are used to derive absolute estimates for the fault slip rate. This high-resolution hillslope analysis allows us to resolve short-wavelength variations in rock uplift that would not be possible to unravel using commonly used channel-profile-based methods. Our joint analysis of topography and geochronological data supports the interpretation of active thrusting at the southwestern Alpine front, and such approaches may bring crucial complementary constraints to morphotectonic analysis for the study of slowly slipping faults.

Tectonic from topography

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Tectonics from topography: Procedures, promise, and pitfalls

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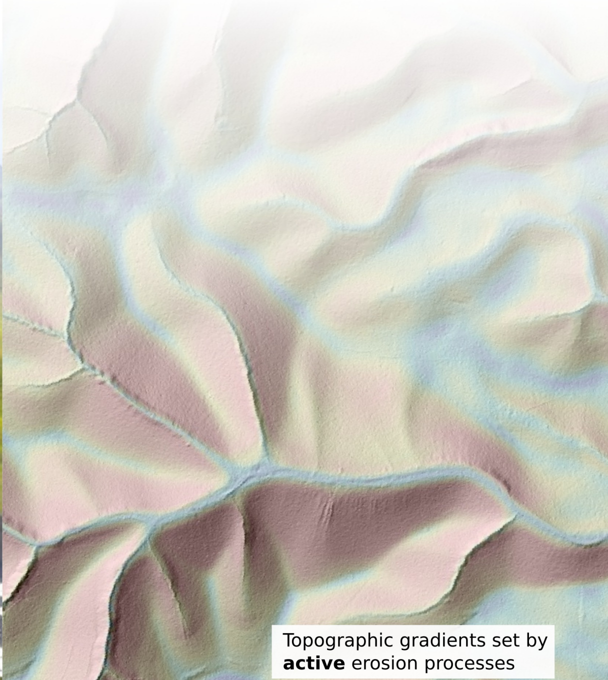
Tectonic from topography

Active *vs* passive tectonic geomorphology

Tectonic from topography

Active *vs* passive tectonic geomorphology



Tectonics from fluvial and hillslope processes

River profile response

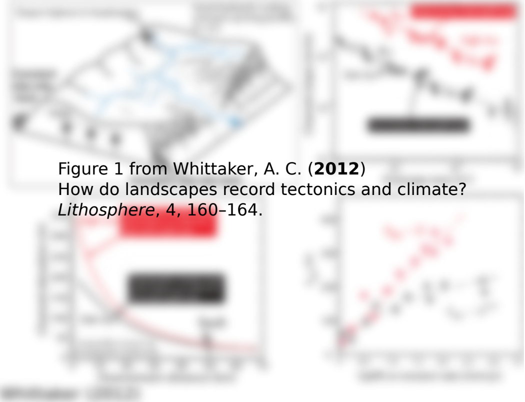
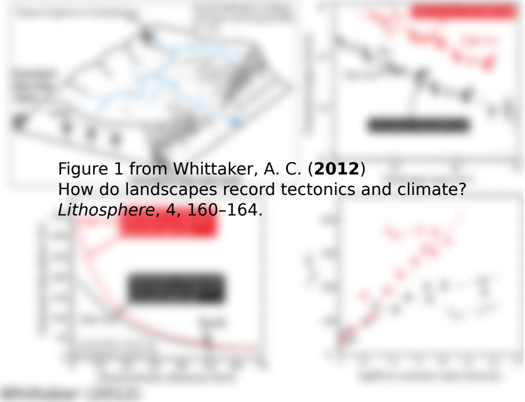


Figure 1 from Whittaker, A. C. (**2012**)
How do landscapes record tectonics and climate?
Lithosphere, 4, 160–164.

- Scales with uplift rate over large range
- Limitation from erodibility variations, knickpoints, structure of river networks

Tectonics from fluvial and hillslope processes

River profile response



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Hillslope gradient response

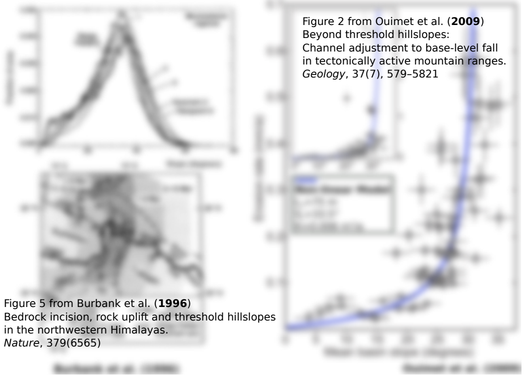


Figure 2 from Ouimet et al. (**2009**)
Beyond threshold hillslopes:
Channel adjustment to base-level fall
in tectonically active mountain ranges.
Geology, 37(7), 579–5821

Figure 5 from Burbank et al. (**1996**)
Bedrock incision, rock uplift and threshold hillslopes
in the northwestern Himalayas.
Nature, 379(6565)

- Potentially very high spatial density of information
- But hillslope gradient response limited by threshold angle S_c

Figure 6 from Hurst et al. (**2012**)
Using hilltop curvature to derive
the spatial distribution of erosion rates
Journal of Geophysical Research,
117(F2), F02017

Hillslope topographic profile

$$z(x) = \frac{KS_c^2}{2\beta E}\left(\ln\left(\frac{1}{2}\sqrt{1+\left(\frac{2\beta Ex}{KS_c}\right)^2}+\frac{1}{2}\right)-\sqrt{1+\left(\frac{2\beta Ex}{KS_c}\right)^2}+1\right)$$

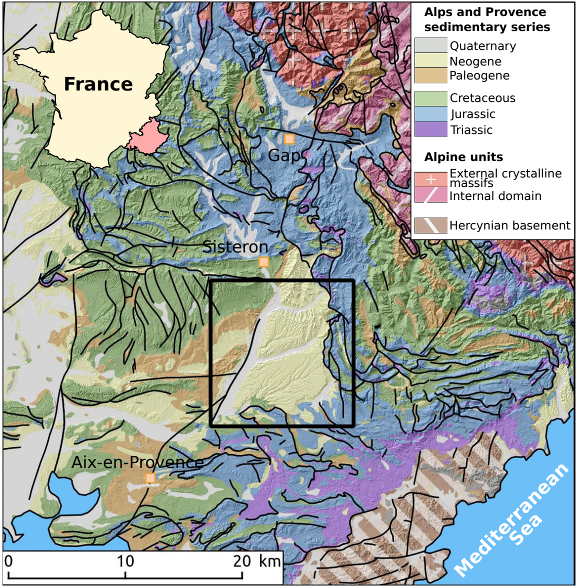
Non-dimensional form

$$R^* = \frac{R}{S_c L_H} \qquad E^* = \frac{2C_{HT}L_H}{S_c}$$

$$R^* = \frac{1}{E^*}\left(\sqrt{1+(E^*)^2} - \ln\left(\frac{1}{2}\left(1+\sqrt{1+(E^*)^2}\right)\right) - 1\right).$$

- Hilltop curvature $C_{HT} \Rightarrow$ proxy for erosion rate : $E = \frac{KC_{HT}}{\beta}$
- Possibility to retrieve tectonic information from hillslope morphology
- Limited number of case studies so far

Settings

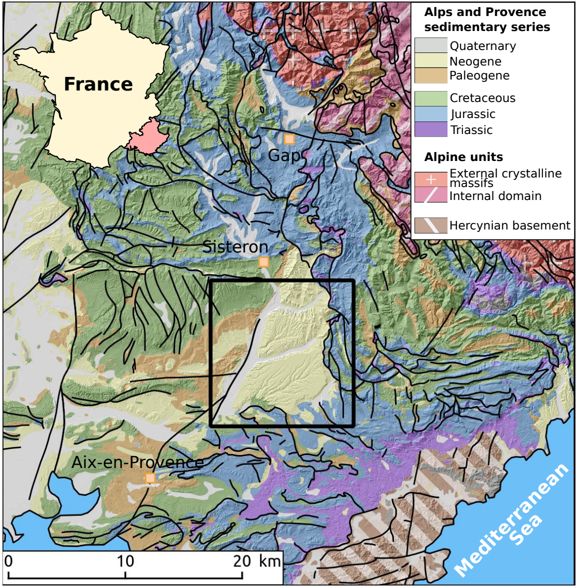


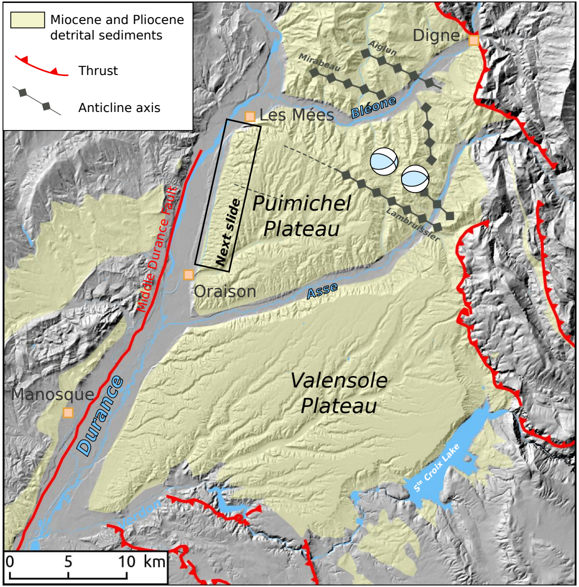
Provence and SW Alps

- Slow deformation
- Significant seismic hazard
- *e.g.* 1909 Lambesc Earthquake

Specific challenges for the identification of slow faults under temperate climate

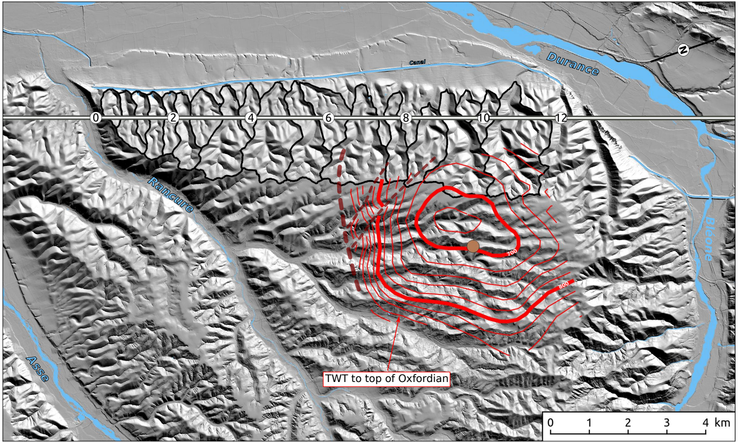
Settings


France
Alps and Provence sedimentary series
Quaternary
Neogene
Paleogene
Cretaceous
Jurassic
Triassic
Alpine units
External crystalline massifs
Internal domain
Hercynian basement
Gap
Sisteron
Aix-en-Provence
Mediterranean Sea
0
10
20 km


Miocene and Pliocene detrital sediments
Thrust
Anticline axis
Digne
Mirabeau
Aiglun
Les Mées
Bléone
Next slide
Puimichel Plateau
Lambruisser
Middle Durance Fault
Oraison
Asse
Manosque
Durance
Valensole Plateau
Ste Croix Lake
Verdon
0
5
10 km

Settings

- <u>Puimichel Plateau</u>
  - • Uplifted Mio-Pliocene mollassic deposits
  - • Major depocenter of the SW Alps
- <u>*Mées* structure</u>
  - • Csup-Eocene basement deformation (Pyrenean orogeny)
  - • Possible Alpine reactivation



Settings

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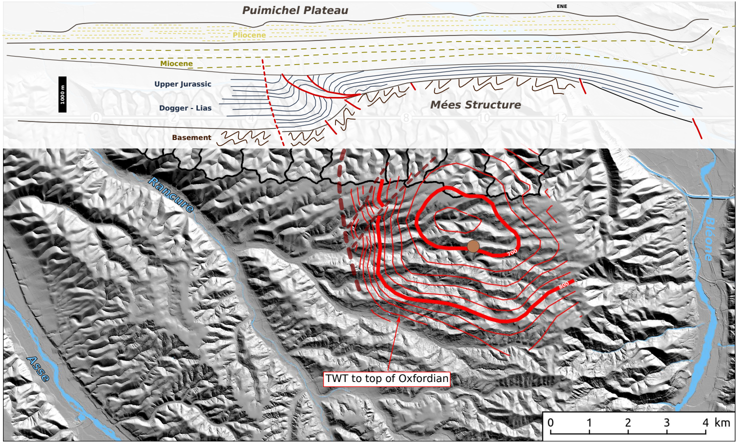
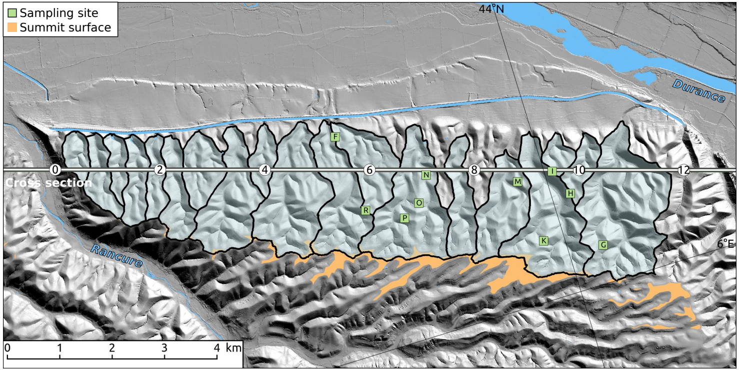


Settings

- Easily erodible conglomerates
- Pliocene relict summit surface
- Major warping of the surface (LiDAR data)



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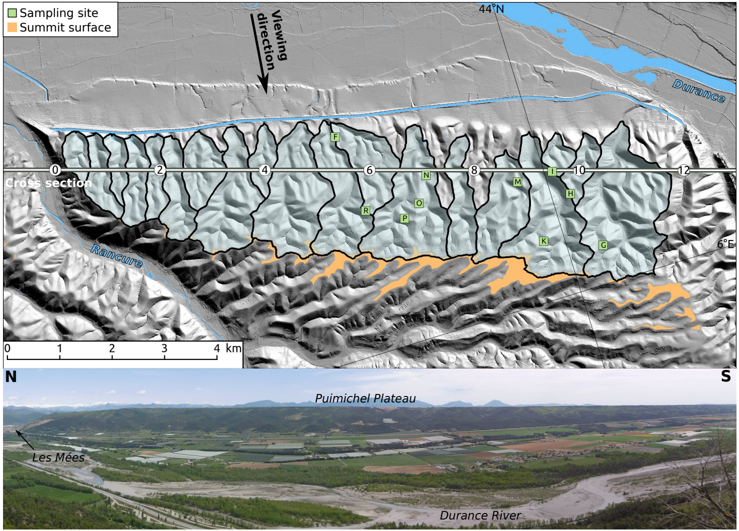

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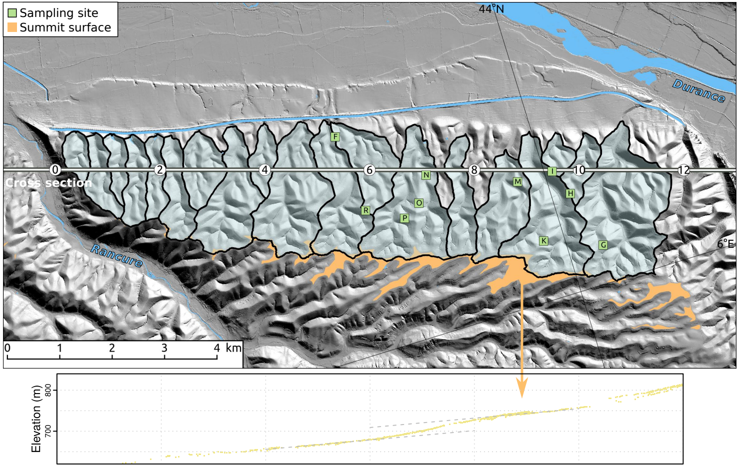

Methods

Hillslope parameters

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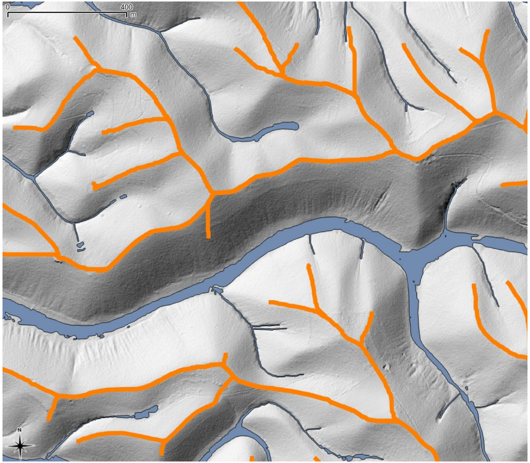

Methods

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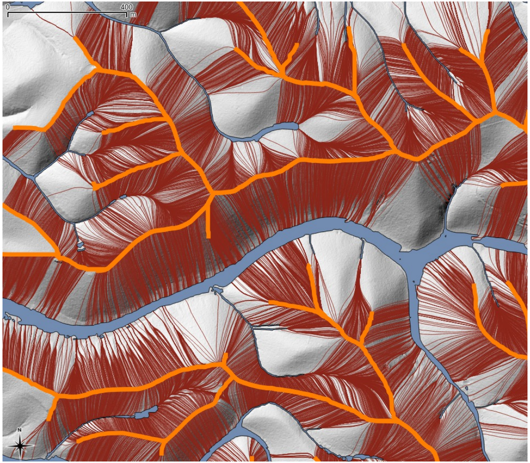
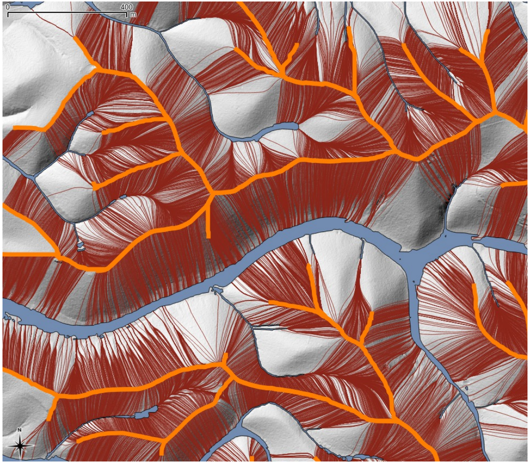


- Hilltops and flowlines ⇒ R, L_H and C_{HT}
- Hurst *et al.* (2012), Grieve *et al.* (2016), Clubb *et al.* (2017)

Methods

Hillslope parameters



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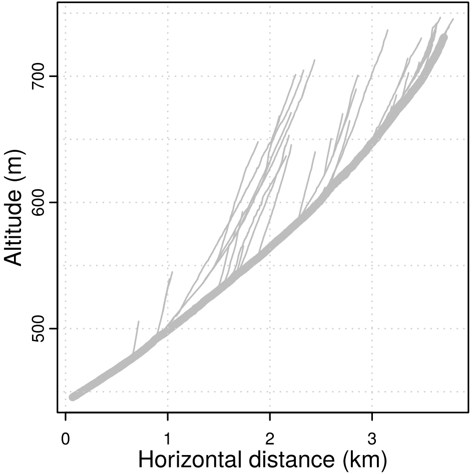
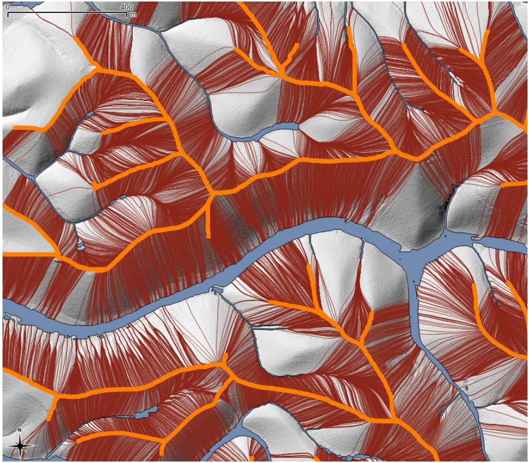
Fluvial parameters



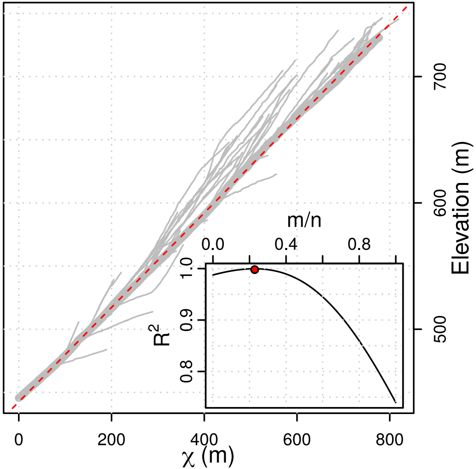
Methods

Hillslope parameters



- Hilltops and flowlines $\Rightarrow$ R, L_H and C_{HT}
- Hurst *et al.* (2012), Grieve *et al.* (2016), Clubb *et al.* (2017)

Fluvial parameters

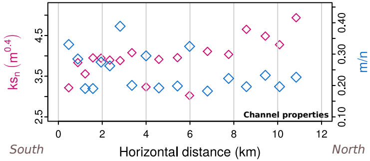


- Channel profiles $\Rightarrow$ θ and ks_n ($\theta_{ref} = 0.25$)
- Perron and Royden (2012)

Results

Spatial distribution of hillslope morphological properties

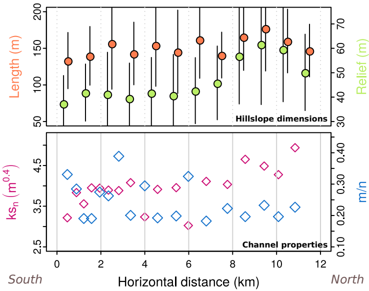
- A lot of scatter fluvial metrics (slight ks_n increase)



Results

Spatial distribution of hillslope morphological properties

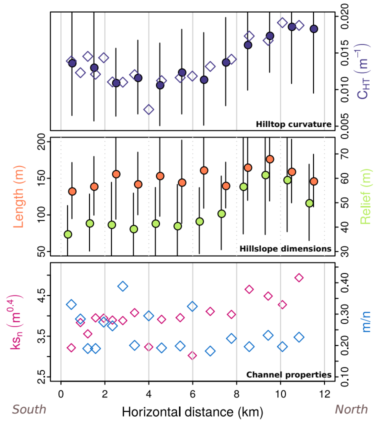
- Slight increase in relief (R), length (L_H) $\sim$ stable
- A lot of scatter fluvial metrics (slight ks_n increase)



Results

Spatial distribution of hillslope morphological properties

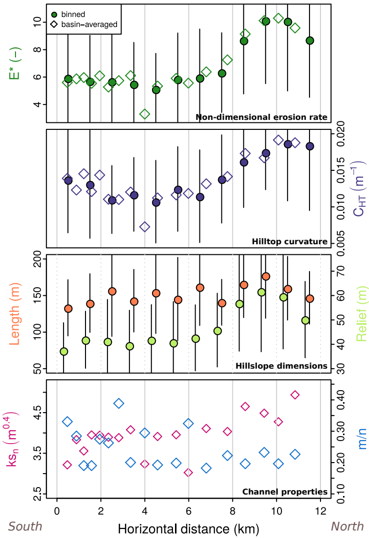
- 2-fold increase in hilltop curvature (C_{HT})
- Slight increase in relief (R), length (L_H) $\sim$ stable
- A lot of scatter fluvial metrics (slight ks_n increase)



Results

Spatial distribution of hillslope morphological properties

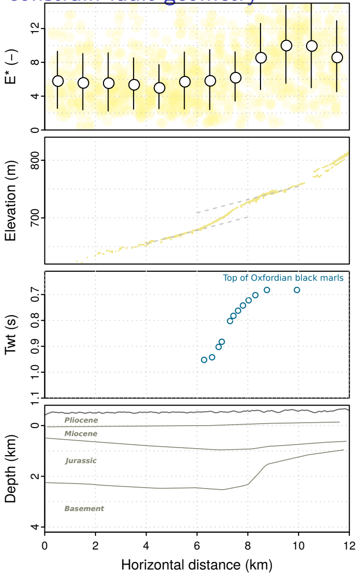
- Same pattern for $E^* \ (= 2C_{HT}L_H/S_c)$
- 2-fold increase in hilltop curvature (C_{HT})
- Slight increase in relief (R), length (L_H) $\sim$ stable
- A lot of scatter fluvial metrics (slight ks_n increase)



Results

Inversion of Non-Dimensional Erosion rate (E^*) pattern to constrain fault geometry

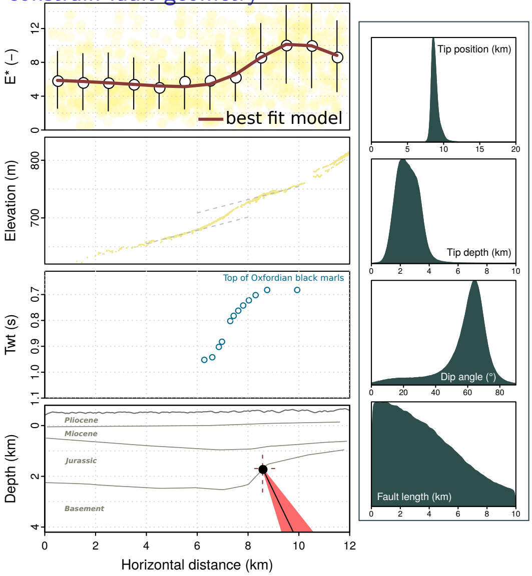
- Single planar dislocation into a semi-infinite elastic half-space
- MCMC inversion to retrieve dislocation parameters
  - Horizontal position
  - Depth
  - Dip angle



Results

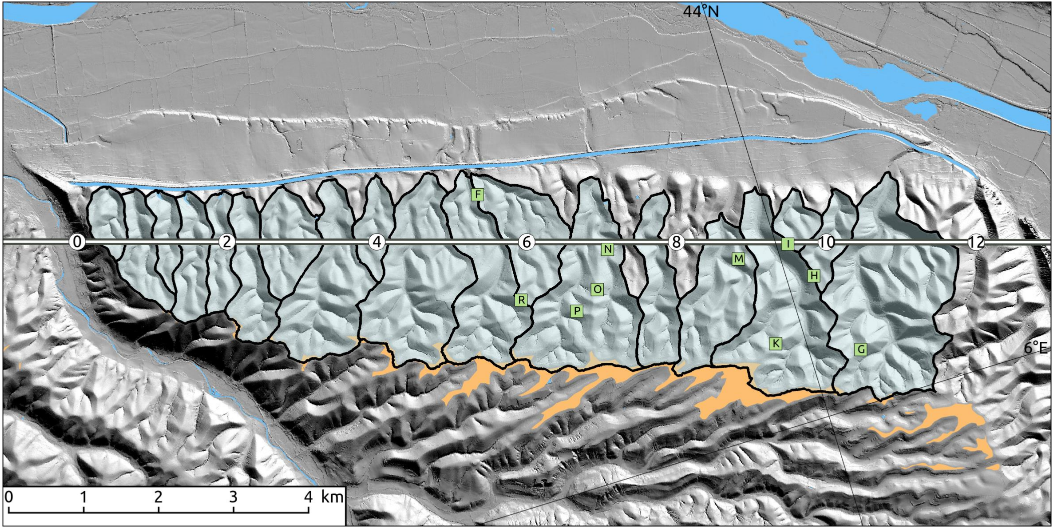
Inversion of Non-Dimensional Erosion rate (E^*) pattern to constrain fault geometry

- Single planar dislocation into a semi-infinite elastic half-space
- MCMC inversion to retrieve dislocation parameters
  - Horizontal position
  - Depth
  - Dip angle
- Globally consistent with available geological data
- Steep structure reactivated inside the basement
- Slip rate?



Denudation rates

^{10}Be and ^{26}Al concentrations at hilltop sites



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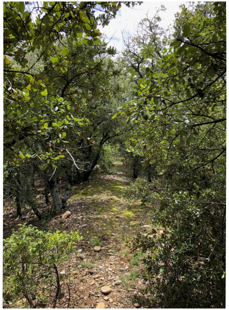


Denudation rates

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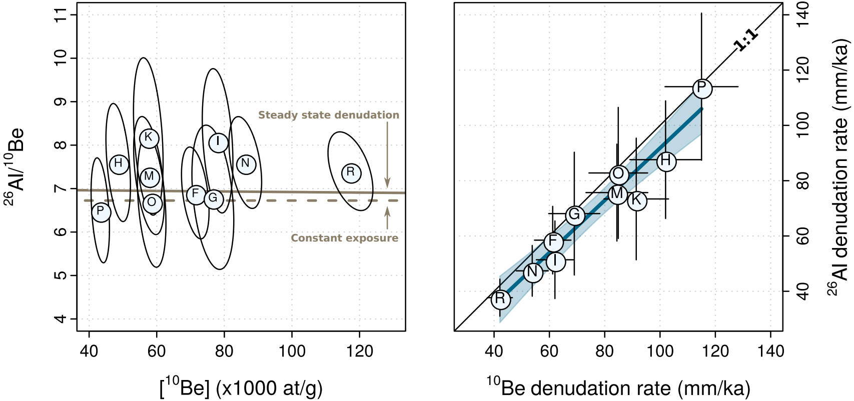
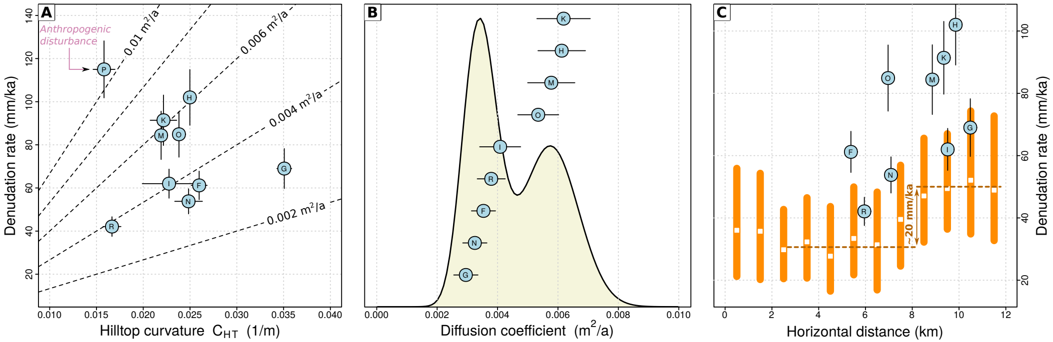


- No apparent inheritance from pre-deposition history
- Consistent denudation signal from ^{10}Be and ^{26}Al

Denudation rates *vs* hillslope properties

Converting C_{HT} into denudation rates



- At shallow slopes near hilltops : $E = \frac{KC_{HT}}{\beta}$
- $\sim$20 mm/ka differential denudation across the transect
- Similar amplitude for differential uplift and fault slip rate?

Conclusions

- HR hillslope morphology analysis allows to decipher denudation and uplift patterns (Hurst *et al.*, 2013, Grieve *et al.*, 2016)
- High potential in slow deformation areas
- Higher spatial resolving power than approaches based on river profiles analysis
- Blind thrust rooted in the basement, folding the Cenozoic cover of the N. Valensole Basin
- Active thrusting and deformation propagation at the SW Alpine front