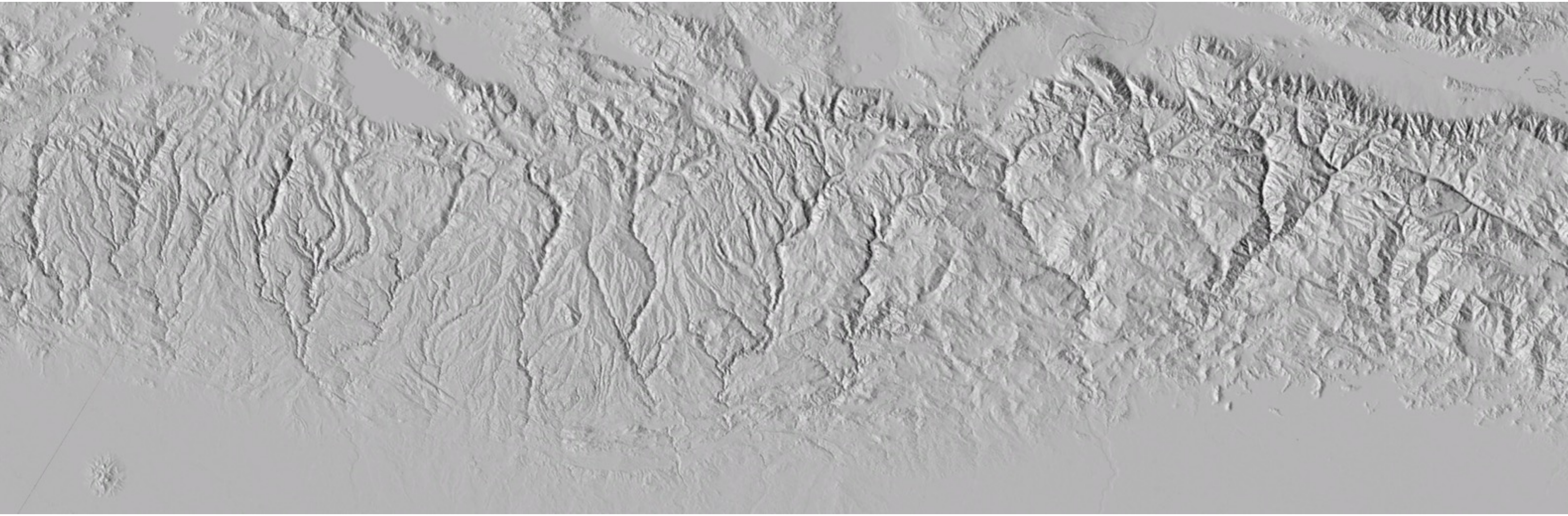
# Disequilibrium river networks dissecting the western slope of the Sierra Nevada, California record significant late Cenozoic tilting and associated surface uplift



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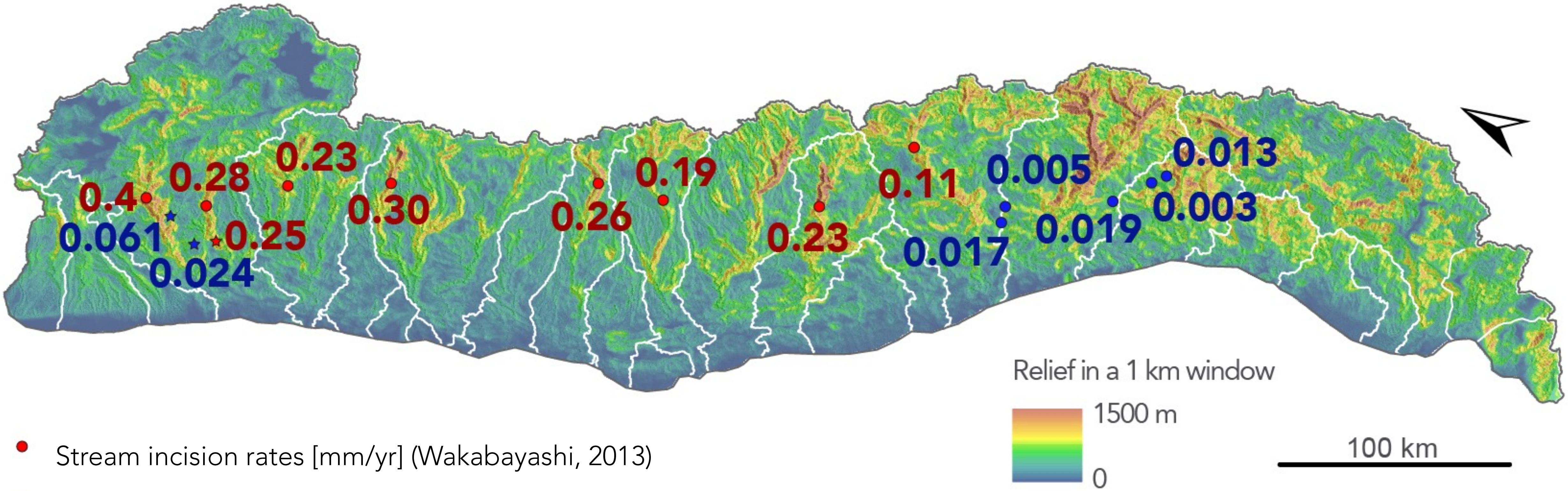
# Deeply incised canyons separated by broad low-relief surfaces

## Stream erosion rates compared with upland surface rates indicate **landscape transience**




Stream incision rates [mm/yr] (Wakabayashi, 2013)

Erosion rates from bedrock surfaces [mm/yr] (Stock et al., 2004; 2005; Callahan et al., 2019)

Catchment-avg erosion rates [mm/yr] (Hurst et al., 2012; Riebe et al., 2001)

# Question: To what degree do river networks dissecting the western slope of the Sierra Nevada record late Cenozoic tectonic forcing?

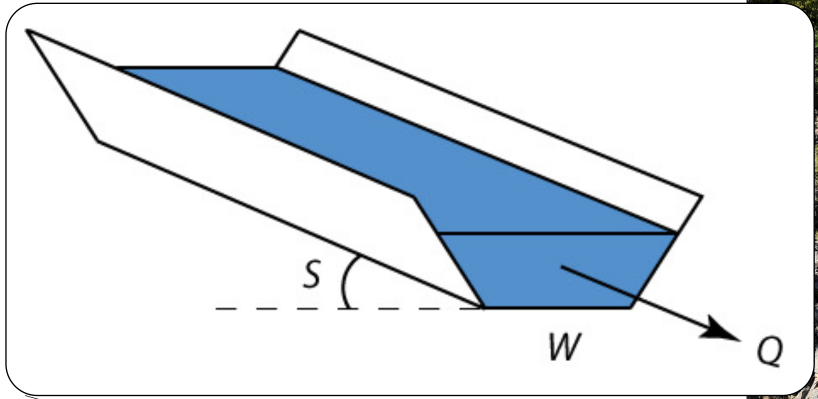
Methods:

- Numerical modeling of transient river response to perturbations
- Systematic river profile analysis of rivers draining western slope of Sierra Nevada

# Stream power model of bedrock river incision

Erosion rate *E* scales with rate of work done by the flow per unit area of river bed

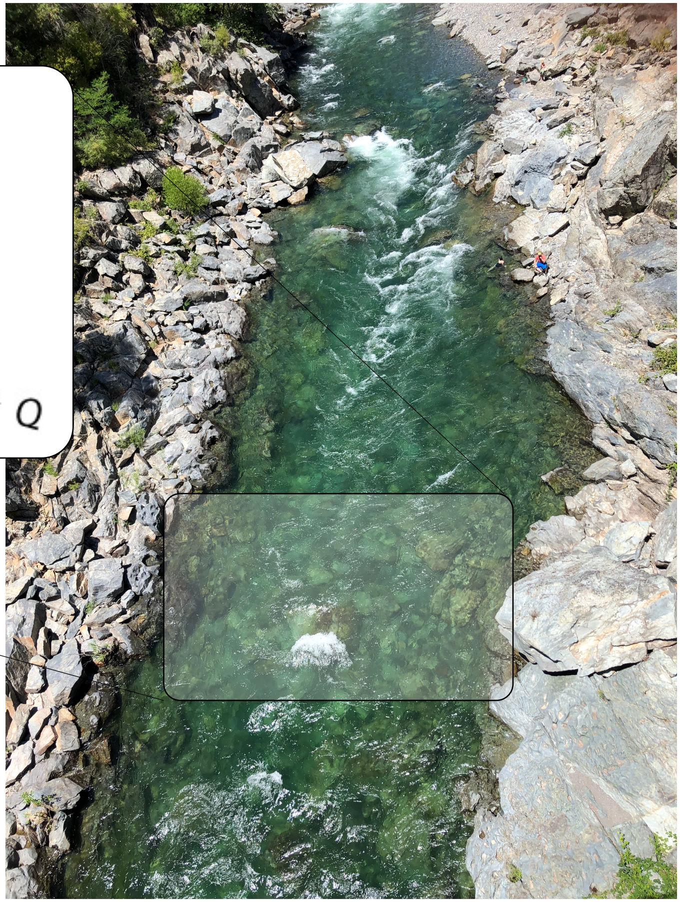
$$E = k\left(\rho g \frac{Q}{W} S\right)^{a}$$




$$E = KA^{m}S^{n}$$

Erosional efficiency

Drainage basin area used as a proxy for discharge and channel width



Howard, 1994; Howard and Kerby, 1983; Siedl and Dietrich, 1992

# Stream power model of bedrock river incision

$$\underbrace{\frac{\partial z}{\partial t}}_{\text{Rate of change in river elevation}} = \underbrace{U}_{\text{Rock uplift rate}} - \underbrace{KA^m \left| \frac{\partial z}{\partial x} \right|^n}_{\text{Rock erosion rate}}$$

*K* = erosional efficiency
*A* = drainage area
*z* = river channel elevation
*x* = distance along stream
*m*, *n* = river concavity
$A_0$ = scaling parameter (=1)

Howard, 1994; Howard and Kerby, 1983; Siedl and Dietrich, 1992

# Stream power model of bedrock river incision

Rate of change in river elevation

$$\frac{\partial z}{\partial t} = U - \underbrace{KA^m \left| \frac{\partial z}{\partial x} \right|^n}_{\text{Rock erosion rate}}$$

Rock uplift rate

$K$ = erosional efficiency
$A$ = drainage area
$z$ = river channel elevation
$x$ = distance along stream
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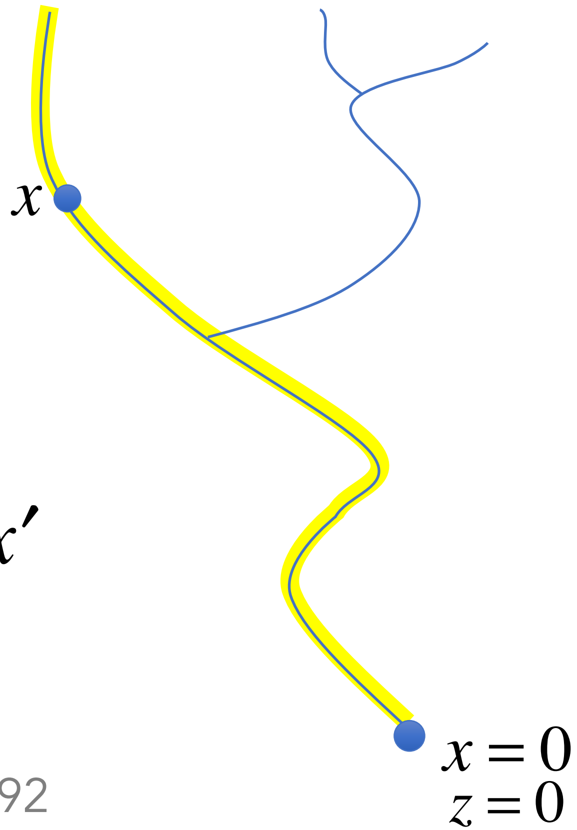


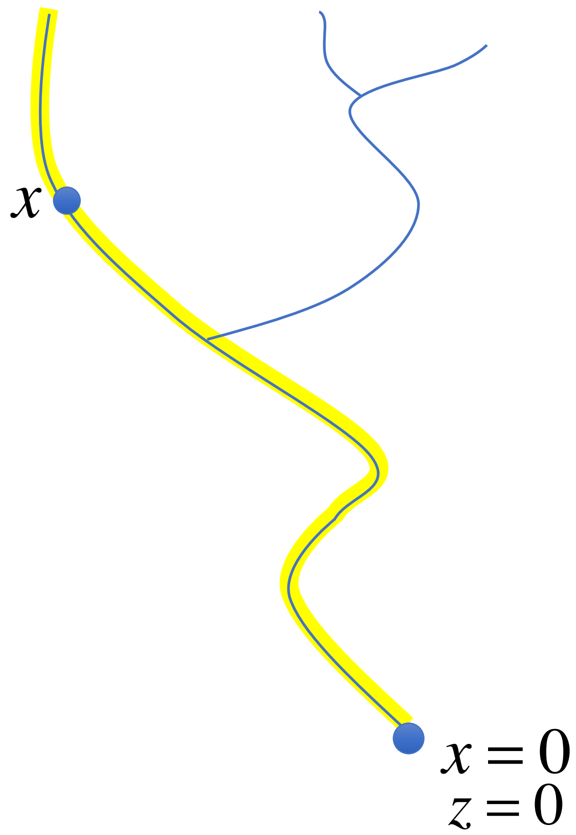

Steady-state solution for uniform $U$ and $K$:

$$z(x) = z_b + \left( \frac{U}{KA_0^m} \right)^{\frac{1}{n}} \chi \qquad \text{where} \qquad \chi = \int_0^x \left( \frac{A_0}{A(x')} \right)^{\frac{m}{n}} dx'$$

Perron and Royden, 2013; Howard, 1994; Howard and Kerby, 1983; Siedl and Dietrich, 1992

# $\chi$ is a key geometric parameter of a river network

$$z(x) = z_b + \left(\frac{U}{KA_0^m}\right)^{\frac{1}{n}} \chi \quad \text{where} \quad \chi = \int_0^x \left(\frac{A_0}{A(x')}\right)^{\frac{m}{n}} dx'$$




# What is it?

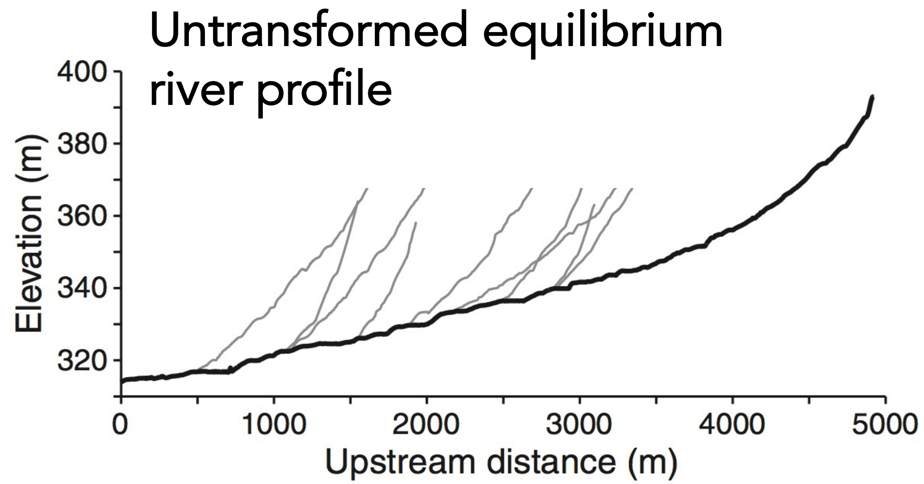
- It is distance upstream scaled for drainage area
- It can be converted to the channel response time:

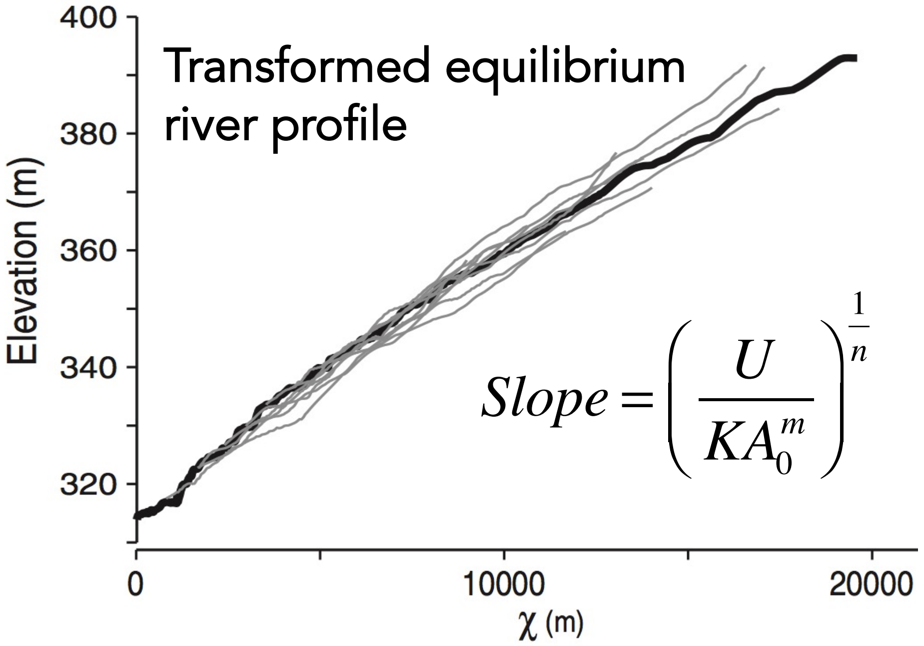
$$\tau = \int_0^x \frac{1}{KA(x')^m} \, dx'$$

Perron & Royden, 2013

# $\chi$ as a distance upstream scaled for drainage area

$$z(x) = z_b + \left(\frac{U}{KA_0^m}\right)^{\frac{1}{n}} \chi \qquad \chi = \int_{x_b}^{x} \left(\frac{A_0}{A(x')}\right)^{\frac{m}{n}} dx'$$




- All elevations in equilibrium river network collapse onto one line
- Slope of $\chi$ plot is channel steepness ($k_s$), a measure of erosion rate

Perron & Royden, 2013

# $\chi$ as the channel response time, $\tau$

$$\tau = \int_0^x \frac{1}{KA(x')^m}\, dx'$$

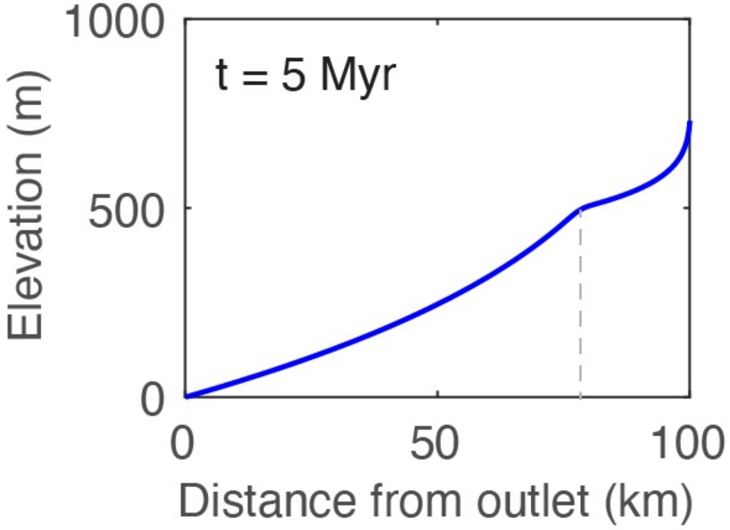
If $K$ is uniform: $\tau = \dfrac{\chi}{K}$

$$\chi = \int_{x_b}^{x} \left( \frac{A_0}{A(x')} \right)^{\frac{m}{n}} dx'$$

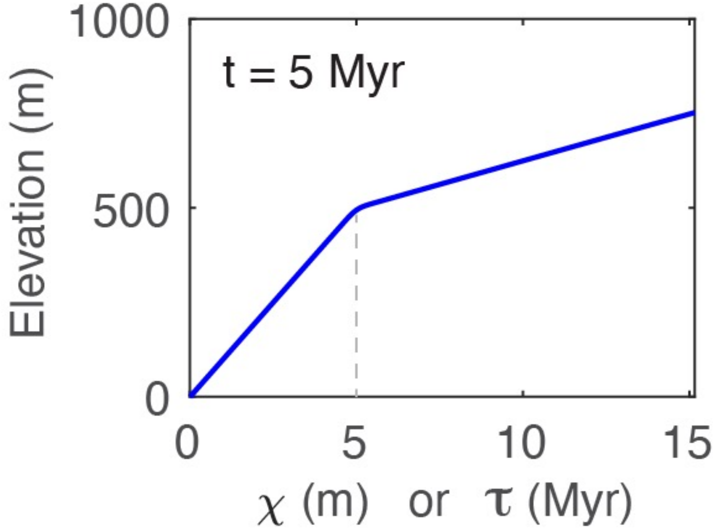
When erosional efficiency, $K = 1\text{x}10^{-06}$, $\chi$ can be read as time in Myr

River profiles 5 Myr after a step increase in rock uplift rate

Untransformed transient river profile




Transformed transient river profile




- The $\tau$ value of a knickpoint tracks the timing since channel perturbation

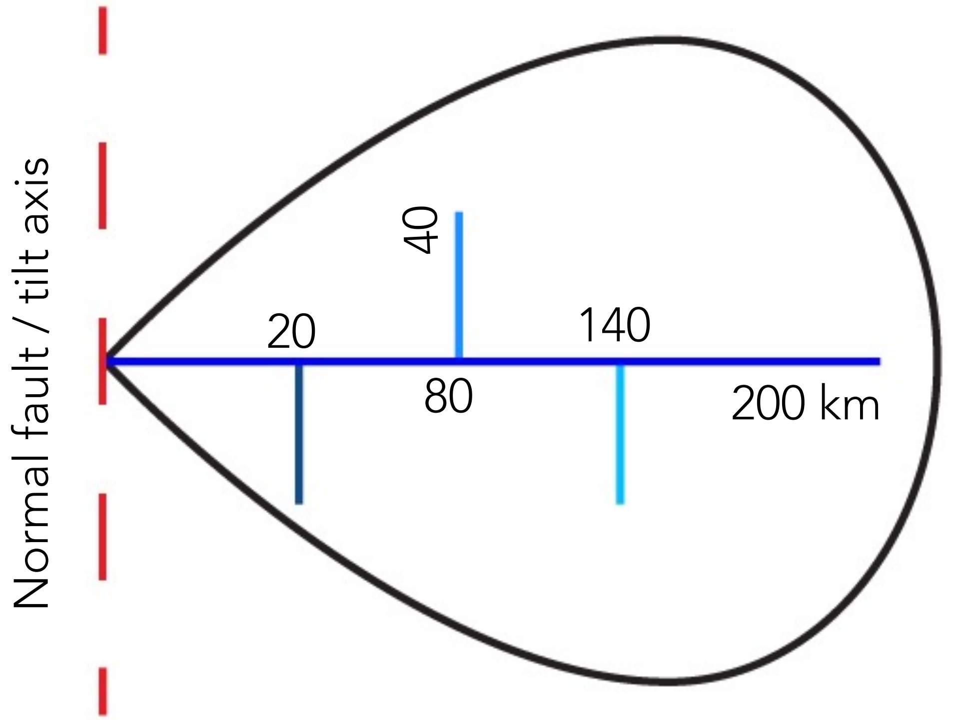
Perron & Royden, 2013, Willett et al., 2014

# 1-D numerical modeling to visualize 1st order fluvial response to geologically feasible perturbations:

1. Uniform pulse of rock uplift
2. Step increase in erodibility/decrease in uplift rate
3. Mainstem truncation
4. Nonuniform pulse of uplift due to tilting
5. Nonuniform pulse of uplift due to tilting with heterogeneous lithology

**Governing equation:**

$$\frac{\partial z}{\partial t} = U - KA^m \left| \frac{\partial z}{\partial x} \right|^n$$



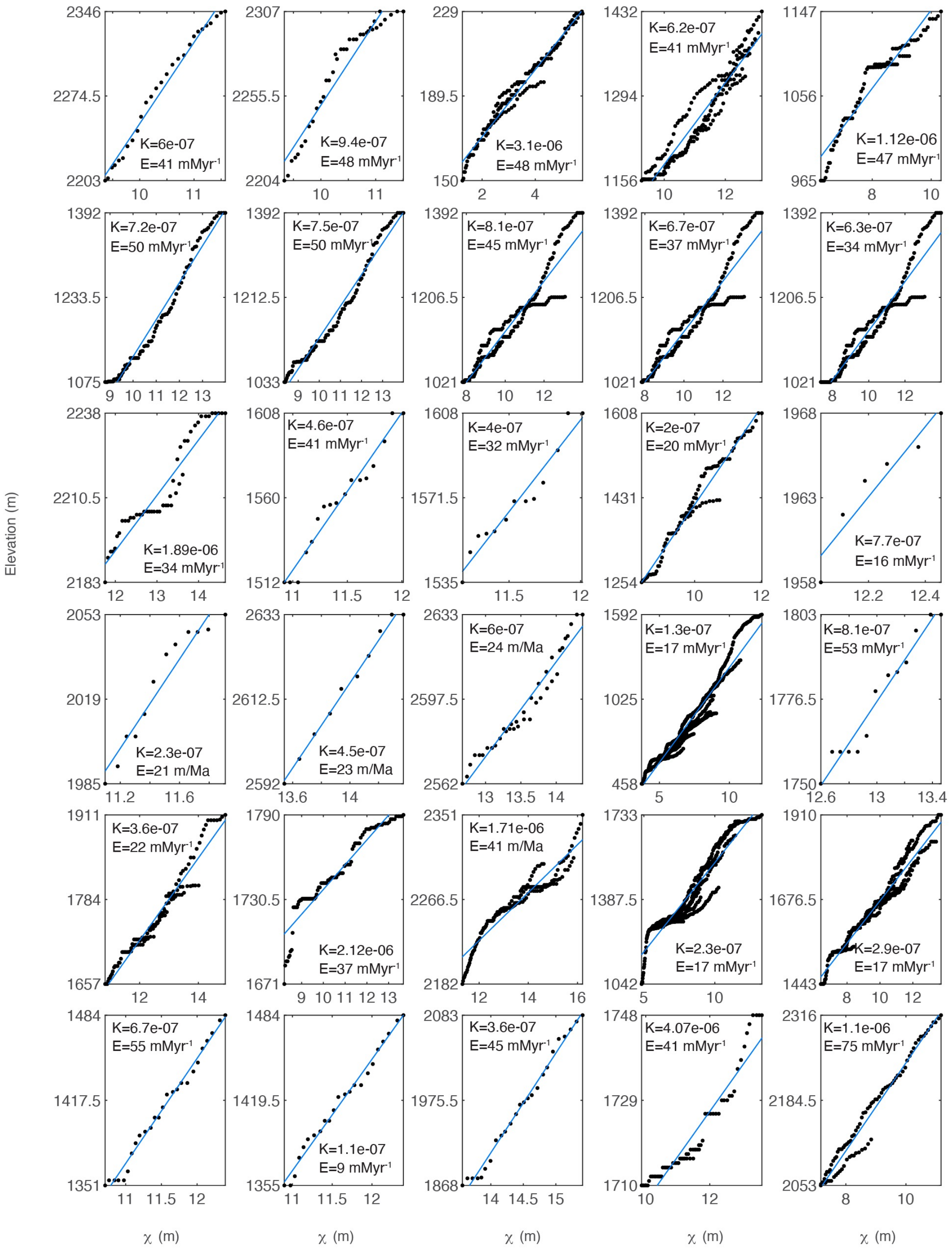
# Calibrate model parameters approximately to Sierra rivers

$$\frac{\partial z}{\partial t} = U - KA^m \left|\frac{\partial z}{\partial x}\right|^n$$ **model governing equation**

- Used published dataset of erosion rates from near-equilibrium upland granitic subbasins of San Joaquin and Kings Rivers (Callahan et al., 2019)

$$K = {}^{U}/_{k_{sn}}$$

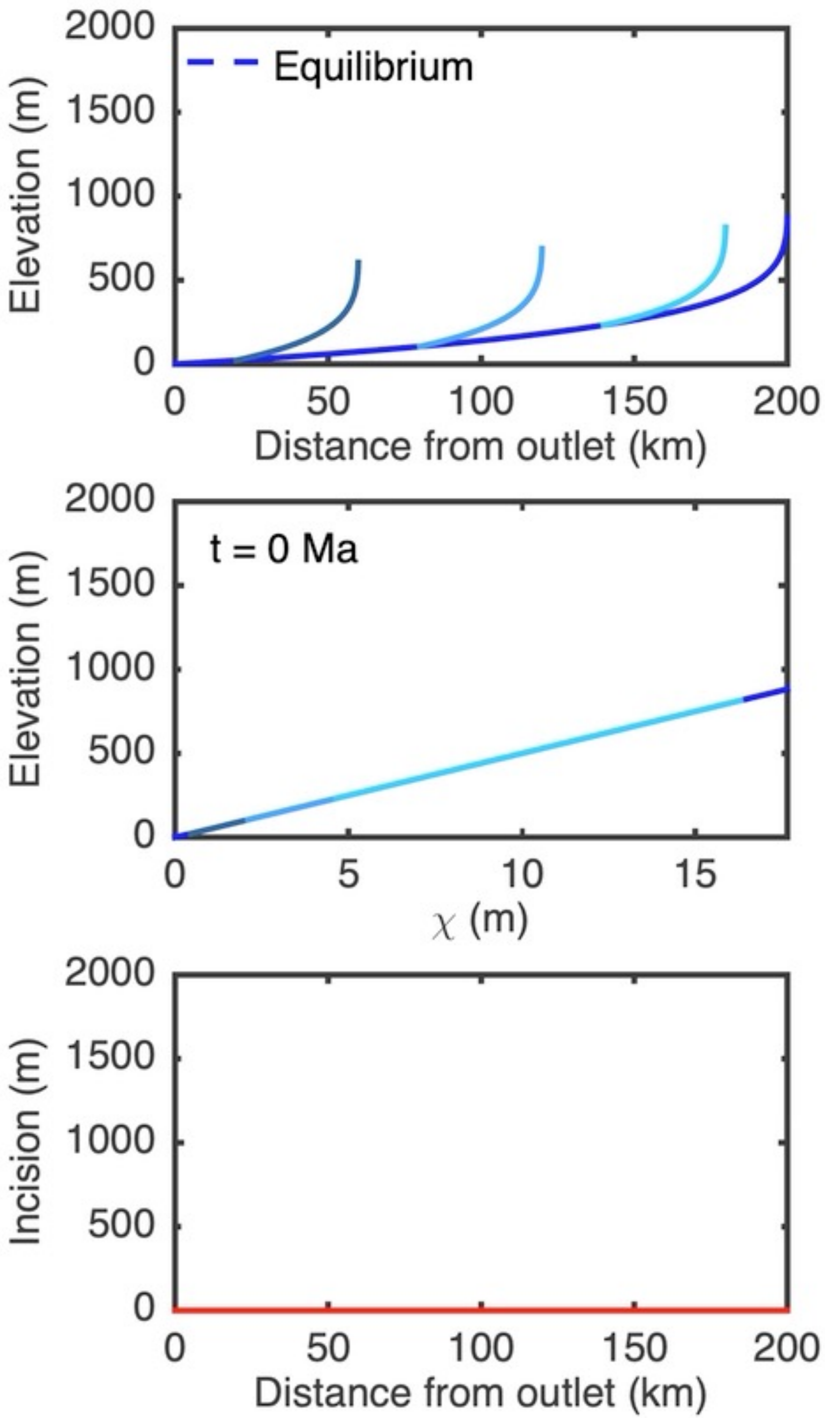
| Parameter values derived for Sierra: | Parameter values used in model: |
|---|---|
| $K$=9.0x10$^{-7}$ ± 3.3x10$^{-7}$ m$^{0.1}$/yr | $K$=1x10$^{-06}$ m$^{0.1}$/yr |
| $U$=36 m/Myr | $U$=50 m/Myr |
| $m/n$=0.45 (slope-area plots) | m/n=0.45 |
| Insufficient data | n=1 |



River response to nonuniform rock uplift due to **rapid tilting**, with steady, uniform background uplift rate

**Distinct mainstem response:**

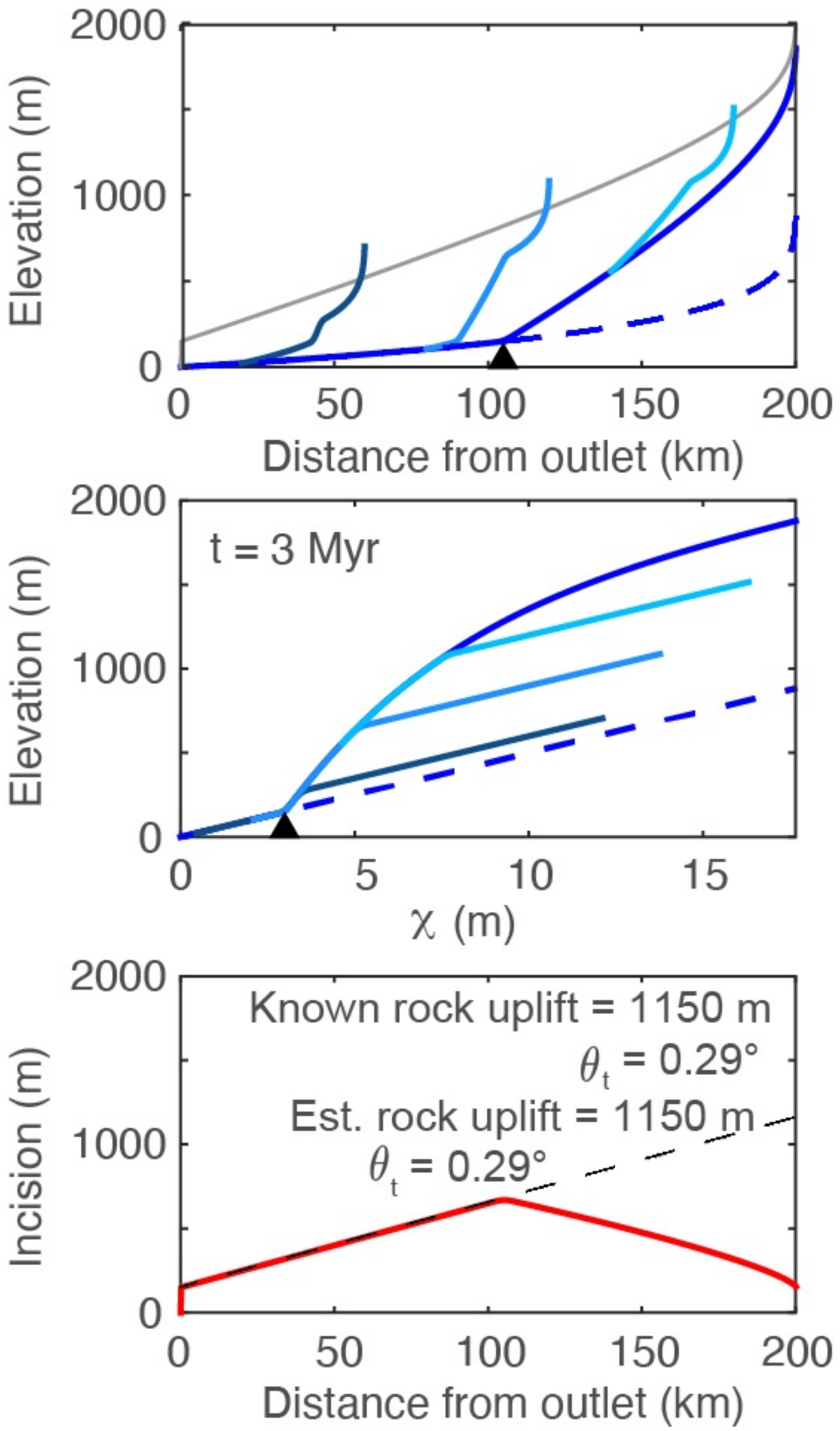
- Positive-curvature slope-break knickpoint forms at outlet
- Knickpoint progresses in wave-like manner to lower profile
- Steepness everywhere more than required to balance uplift
- Negative curvature in mainstem chi-plot
- Tributaries are closer to equilibrium than mainstem thus plot below mainstem in chi-plot
- Incision increases linearly upstream up to KP, then decreases



River response to nonuniform rock uplift due to **rapid tilting**, with steady, uniform background uplift rate

**Distinct mainstem response:**

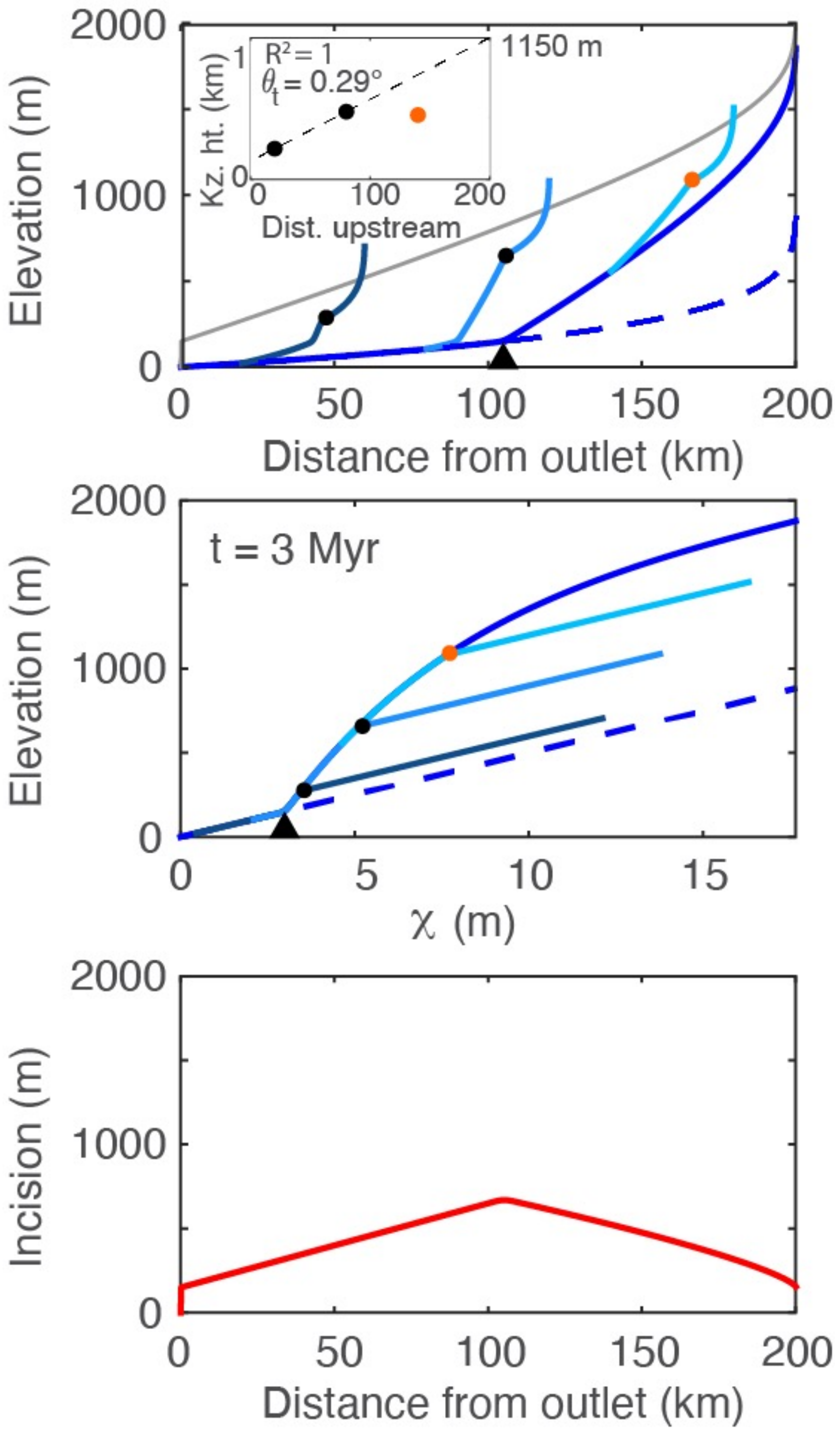
- Incision records the magnitude of rock uplift (tilt + uniform rock uplift since tilting event)



River response to nonuniform rock uplift due to **rapid tilting**, with steady, uniform background uplift rate

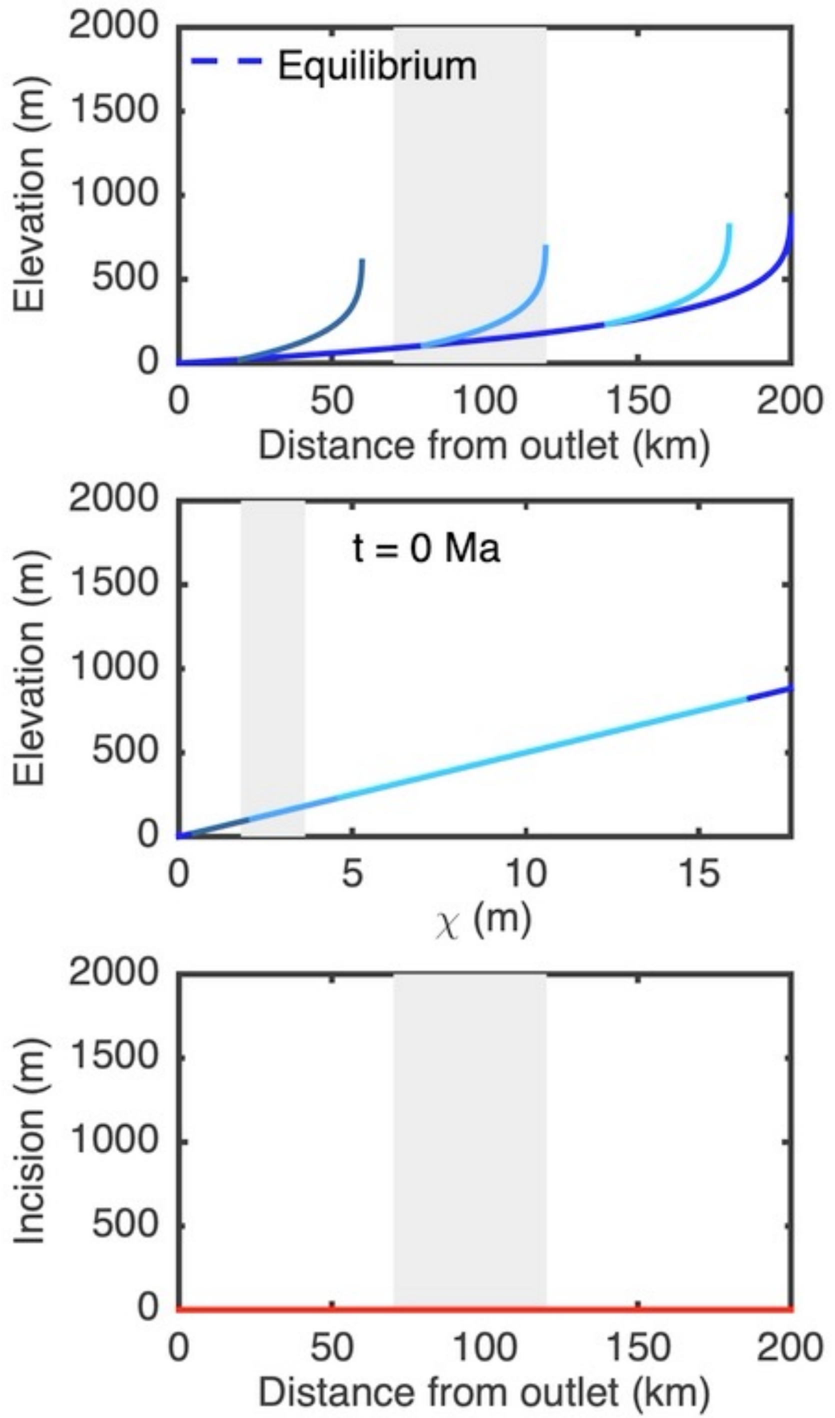
**Forms tributary knickzones with unique properties:**

- Initiated instantaneously at every tributary junction upon tilt so records timing of tilt
- Tributary knickzones have nonuniform $k_{sn}$ and collapse with mainstem chi-plot
- Grows in drop height until mainstem knickpoint passes so drop height increases upstream to knickpoint, then decreases. Knickzone drop height records magnitude of surface uplift

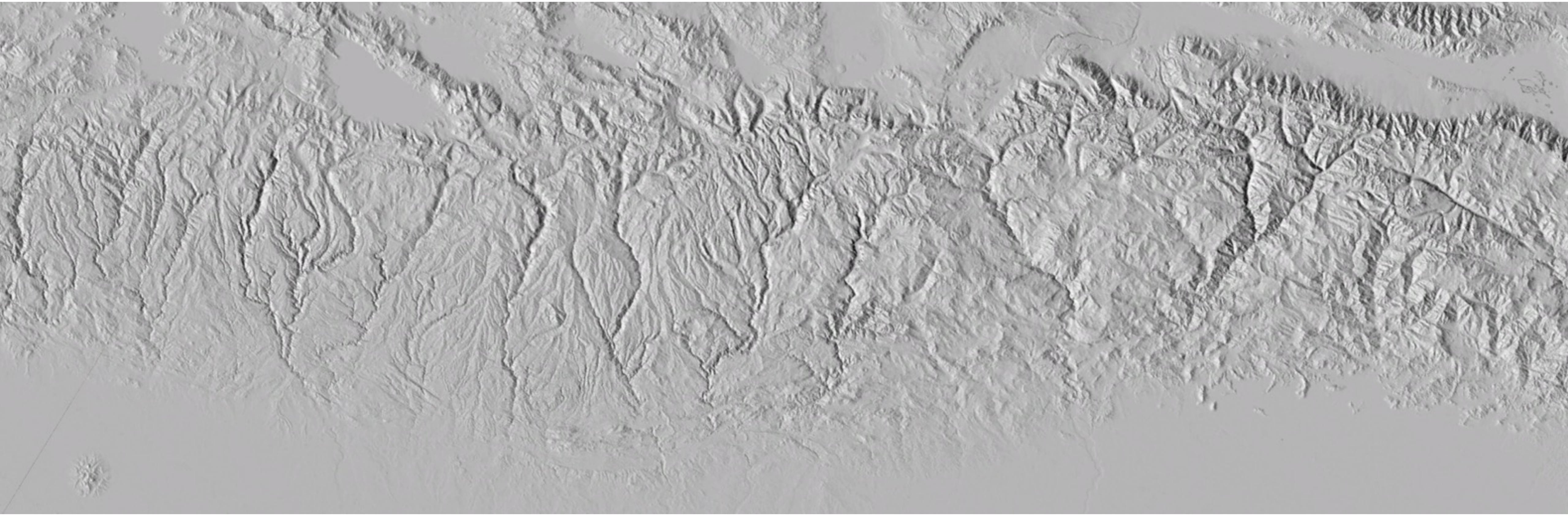


River response to nonuniform rock uplift due to **rapid tilting**, but with a band of **more erodible rock** at 70-120 km upstream

- Additional slope-break knickpoint initiated instantaneously at downstream end of band of soft rock
- Forms same tributary knickzones as mainstem slope-break knickpoint, but upstream
- Creates deviations in patterns in tributary knickzone drop height and incision below paleotopography



# What perturbation(s) did the Sierra Nevada experience?



From Feather River in the northern Sierra south to Tehachapi River in the southern Sierra

# What perturbation(s) did the Sierra Nevada experience?

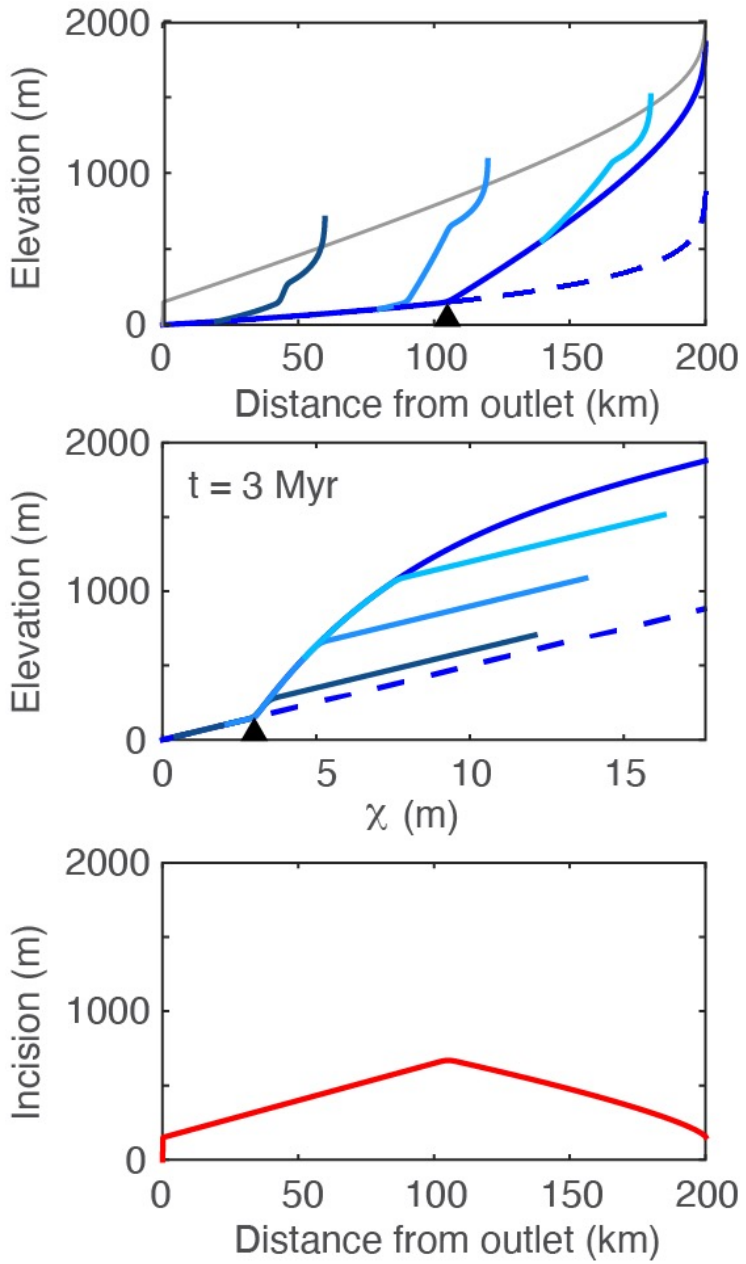
- Mainstems

- Tributaries

- Incision patterns

    - northern Sierra: measured incision below late Cenozoic volcanic deposits

    - southern Sierra: measured valley relief below smoothed ridge elevation



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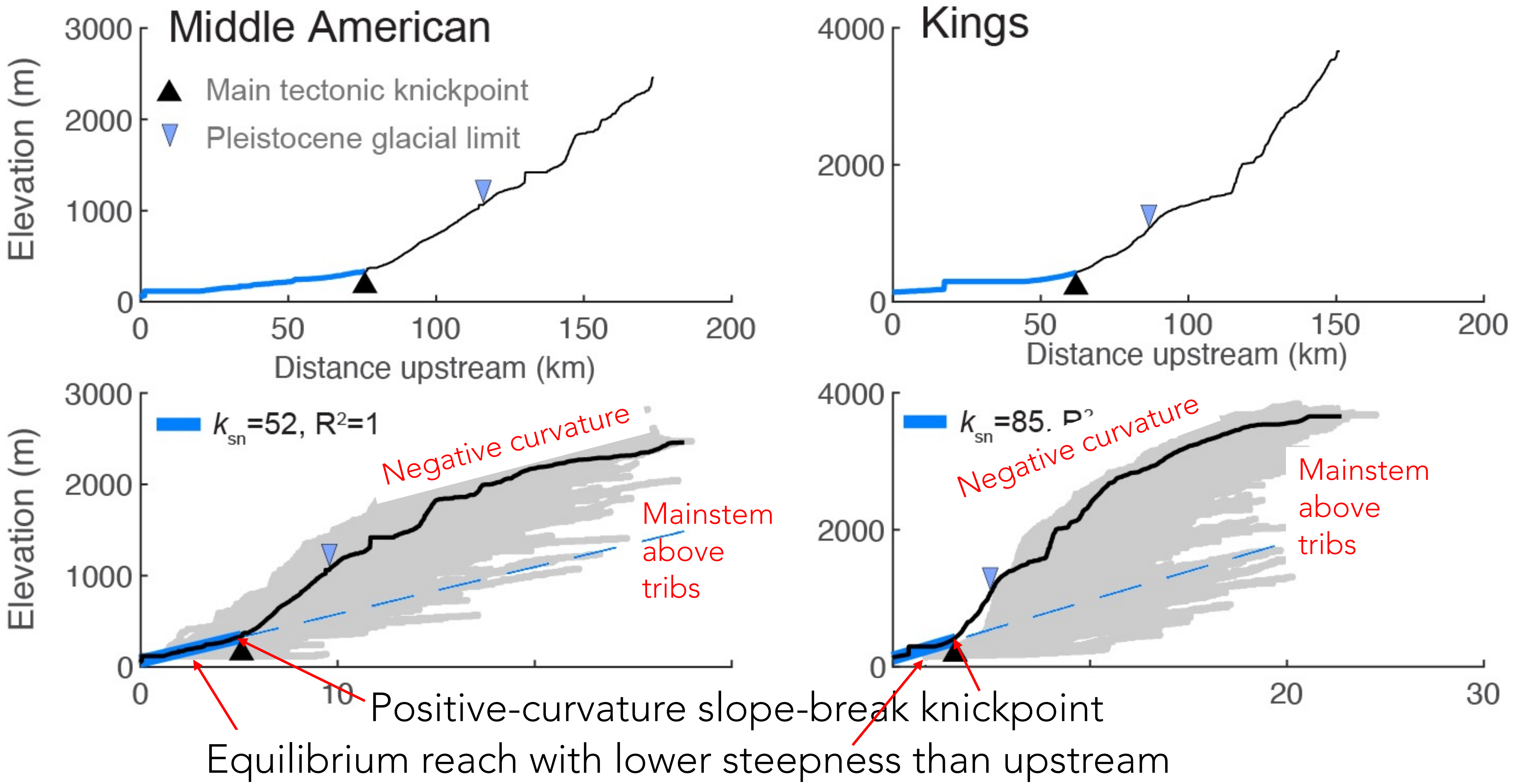

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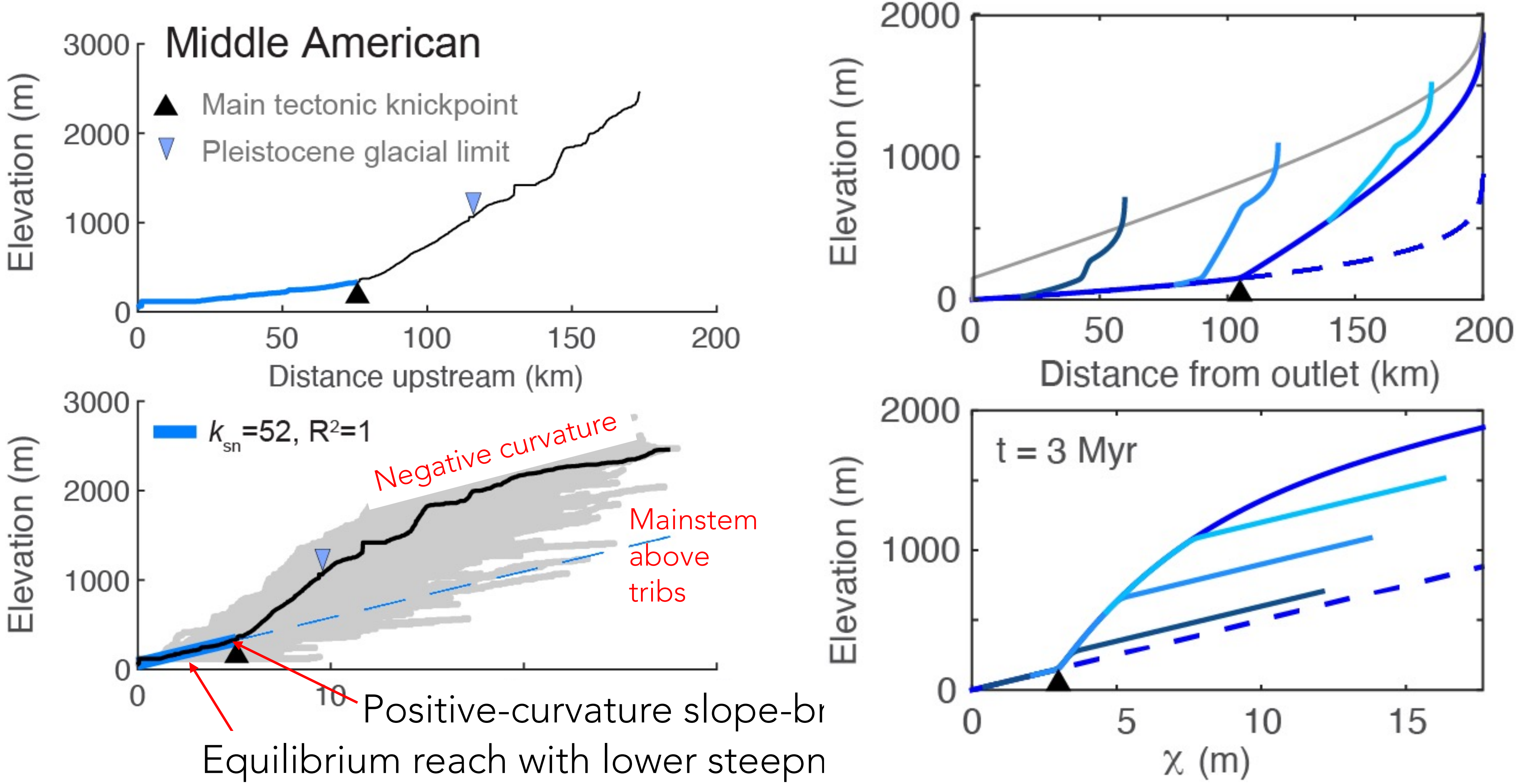

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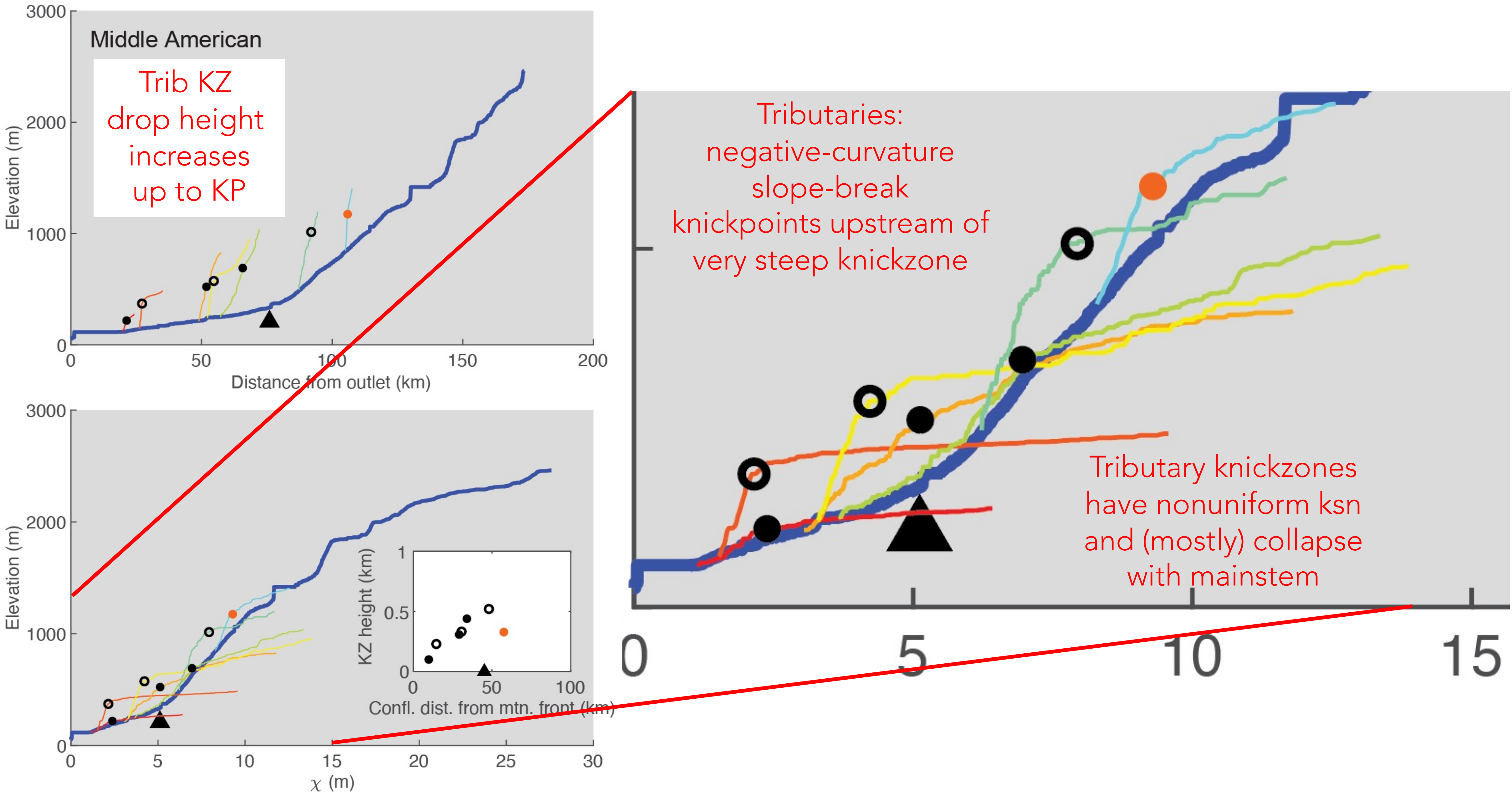

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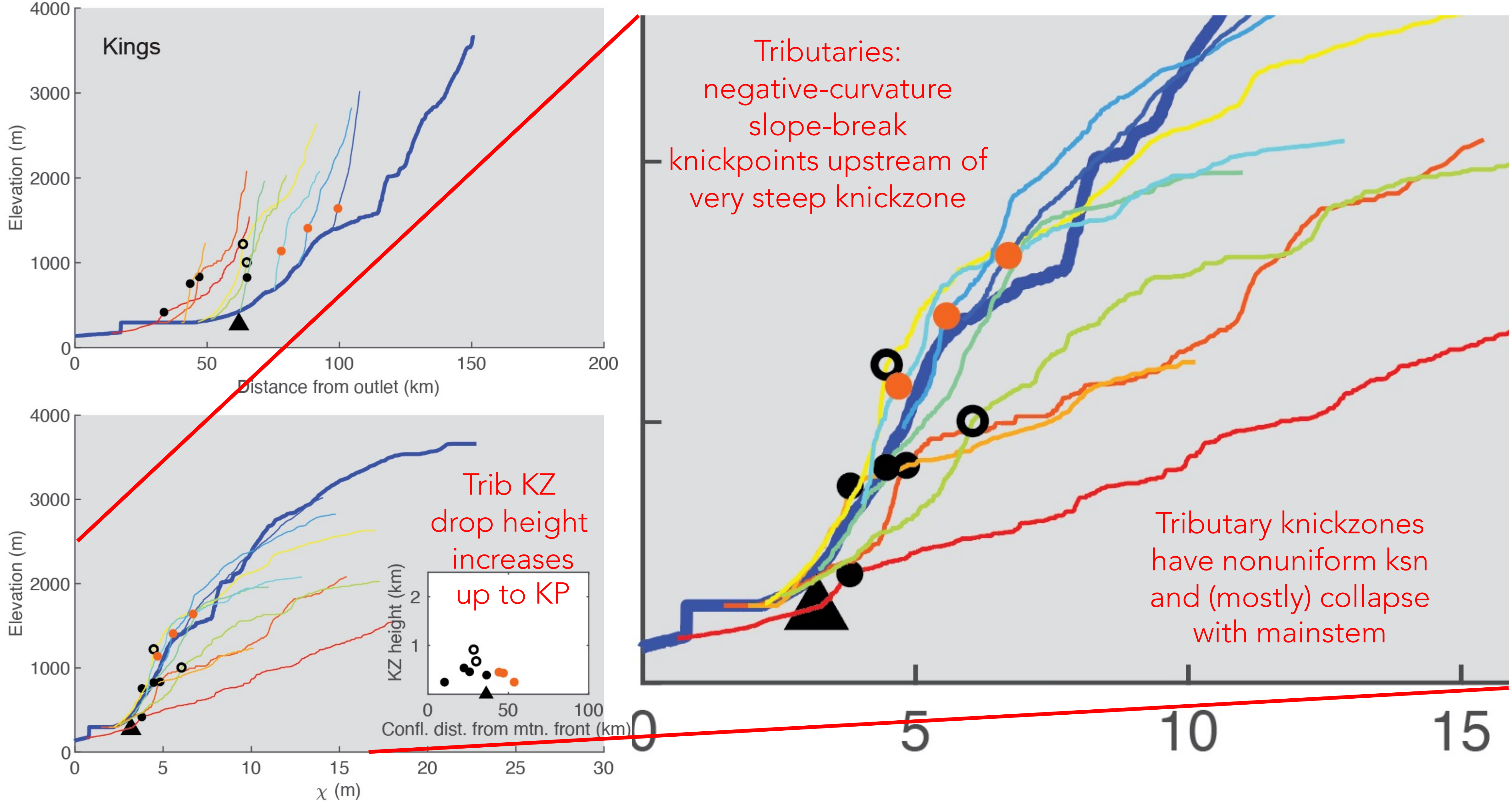

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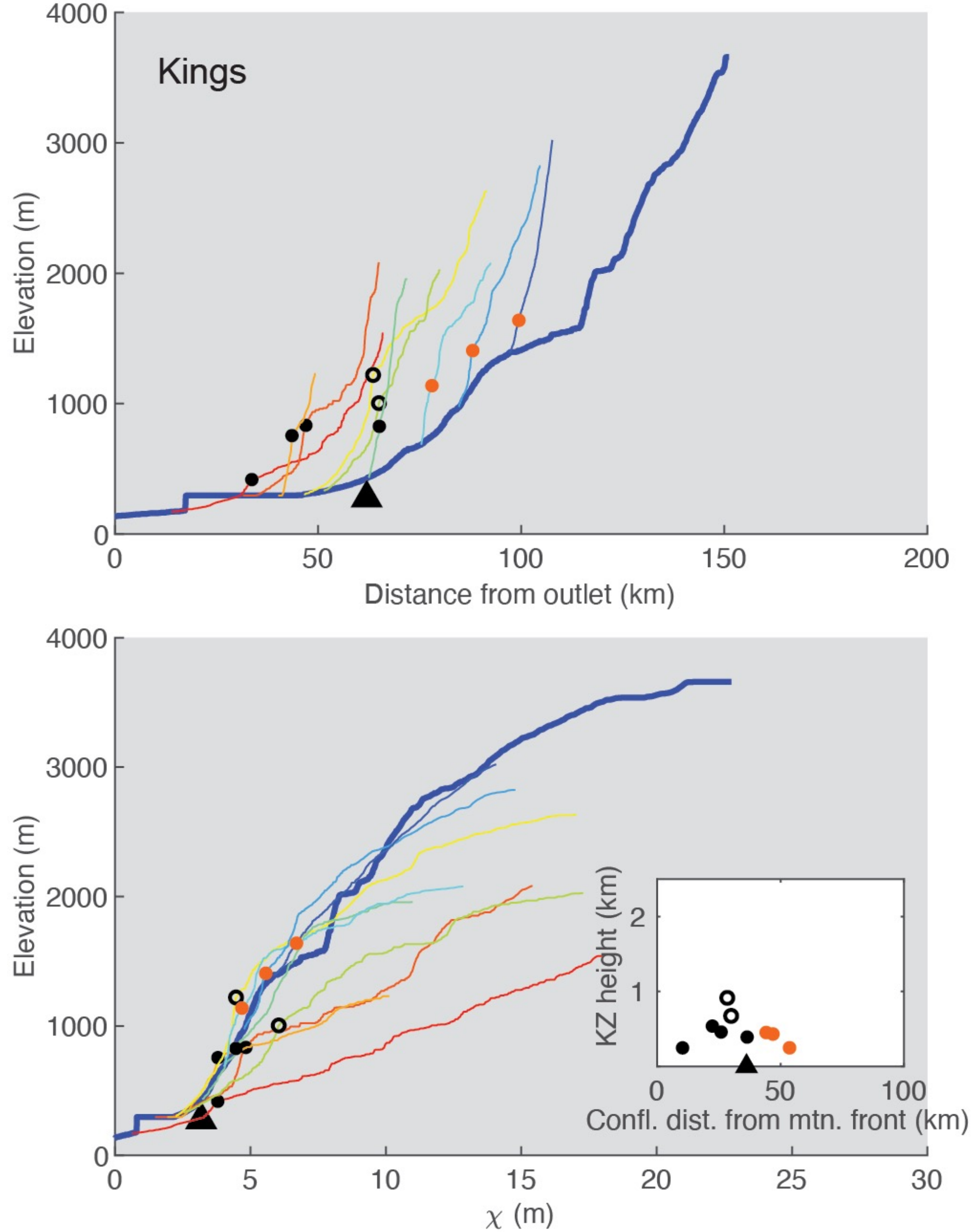


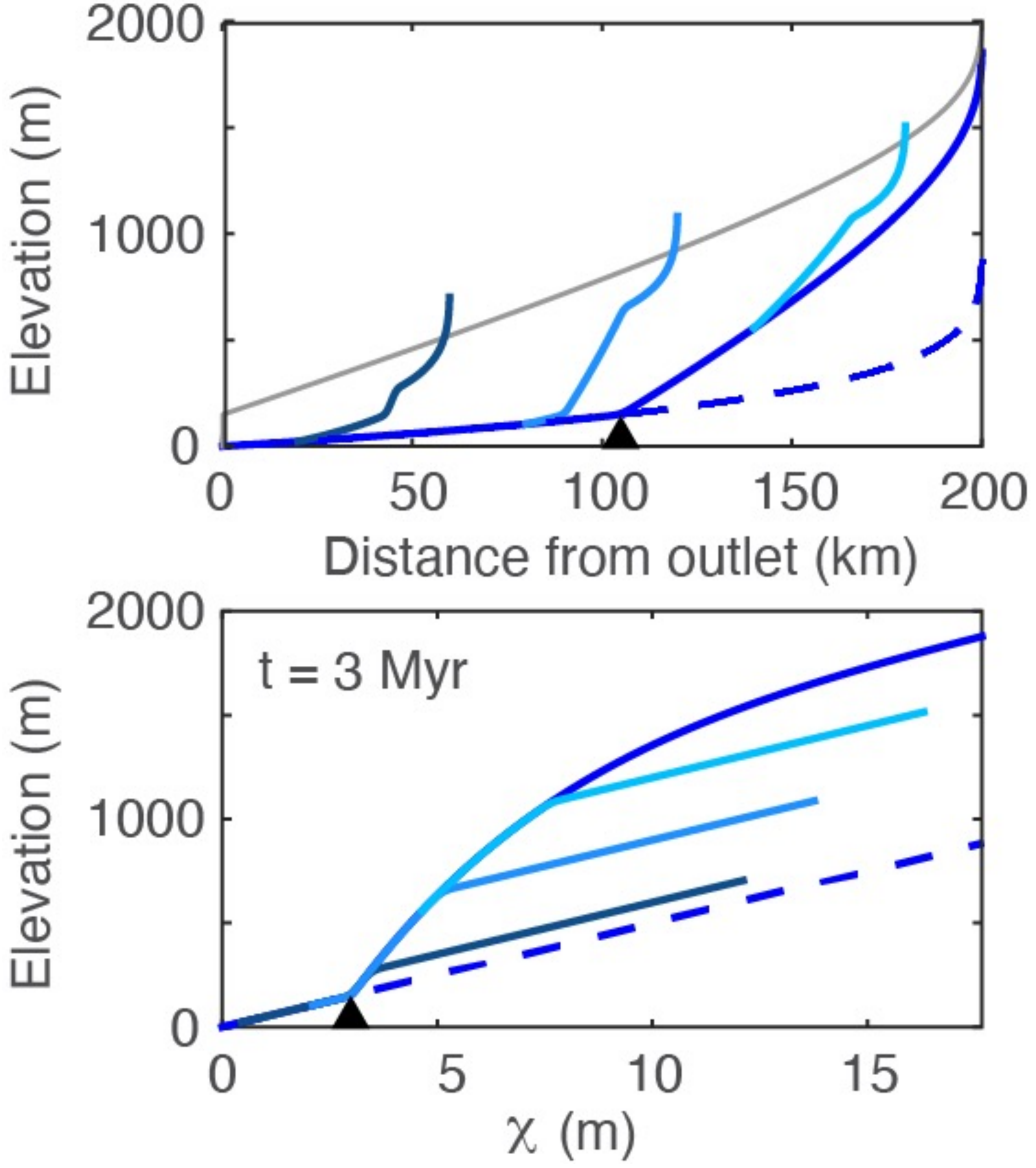

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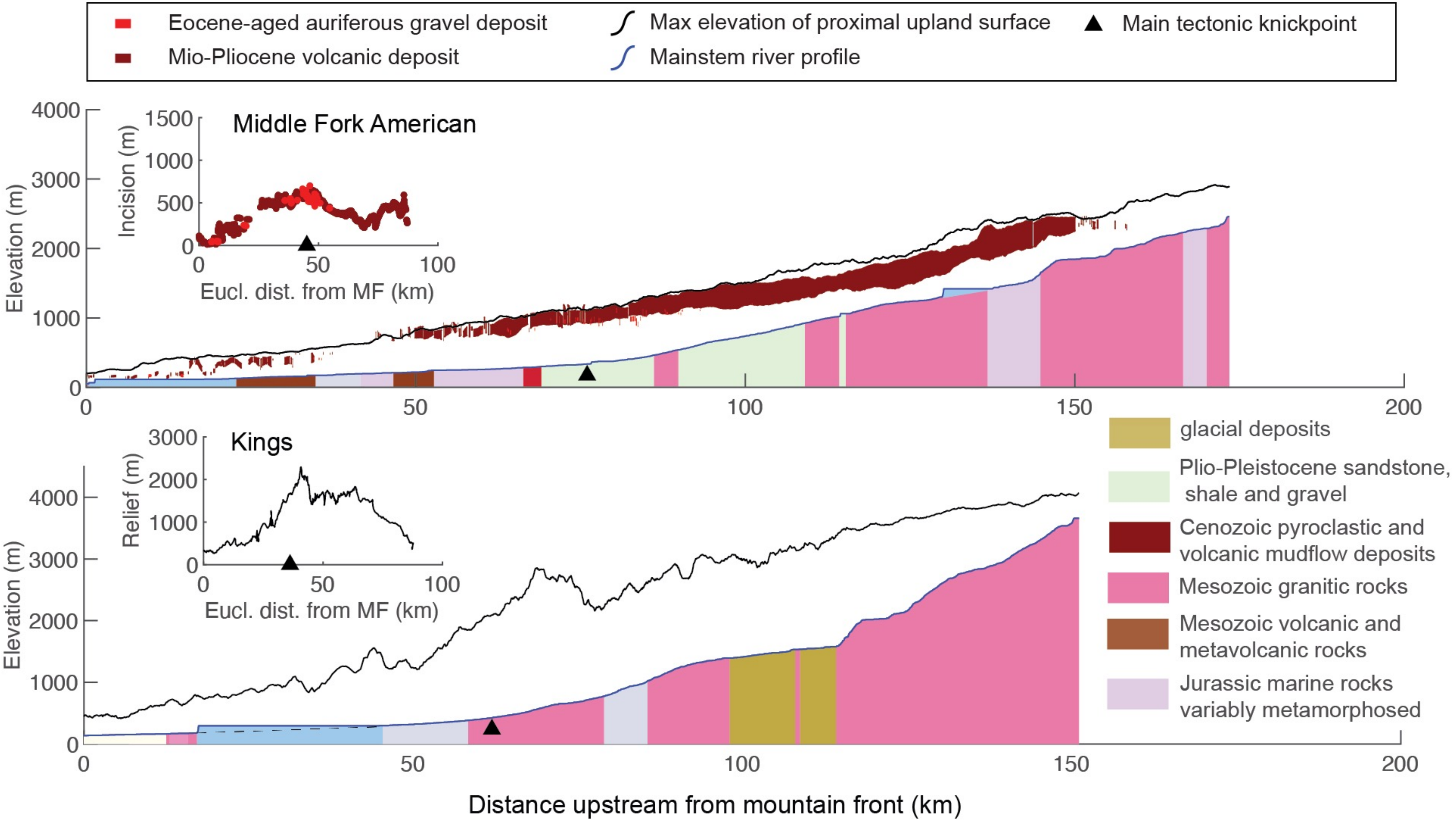
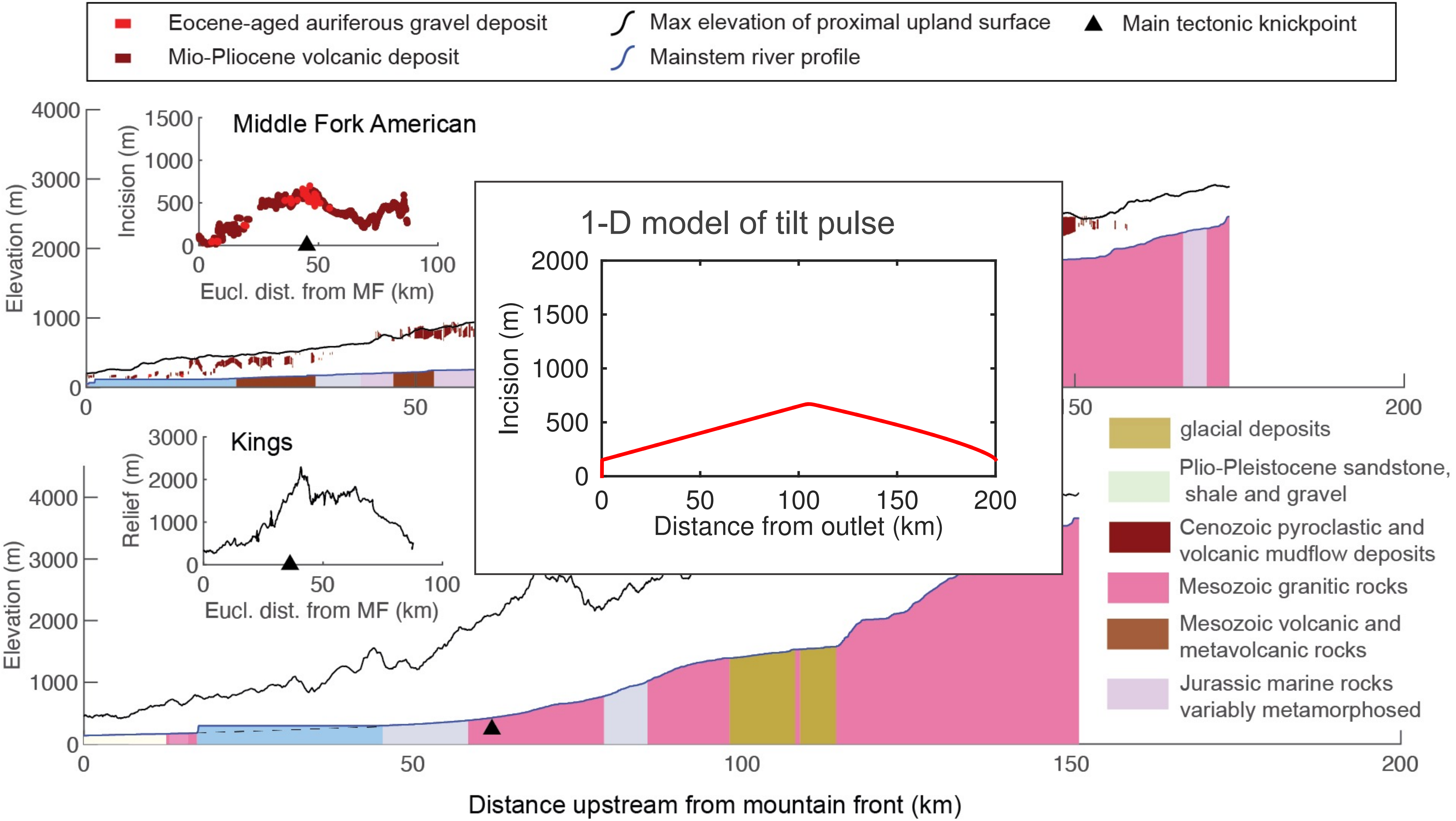



Simplified geology from 1:500K map (Ludington et al., 2005)

# What perturbation(s) did the Sierra Nevada experience?

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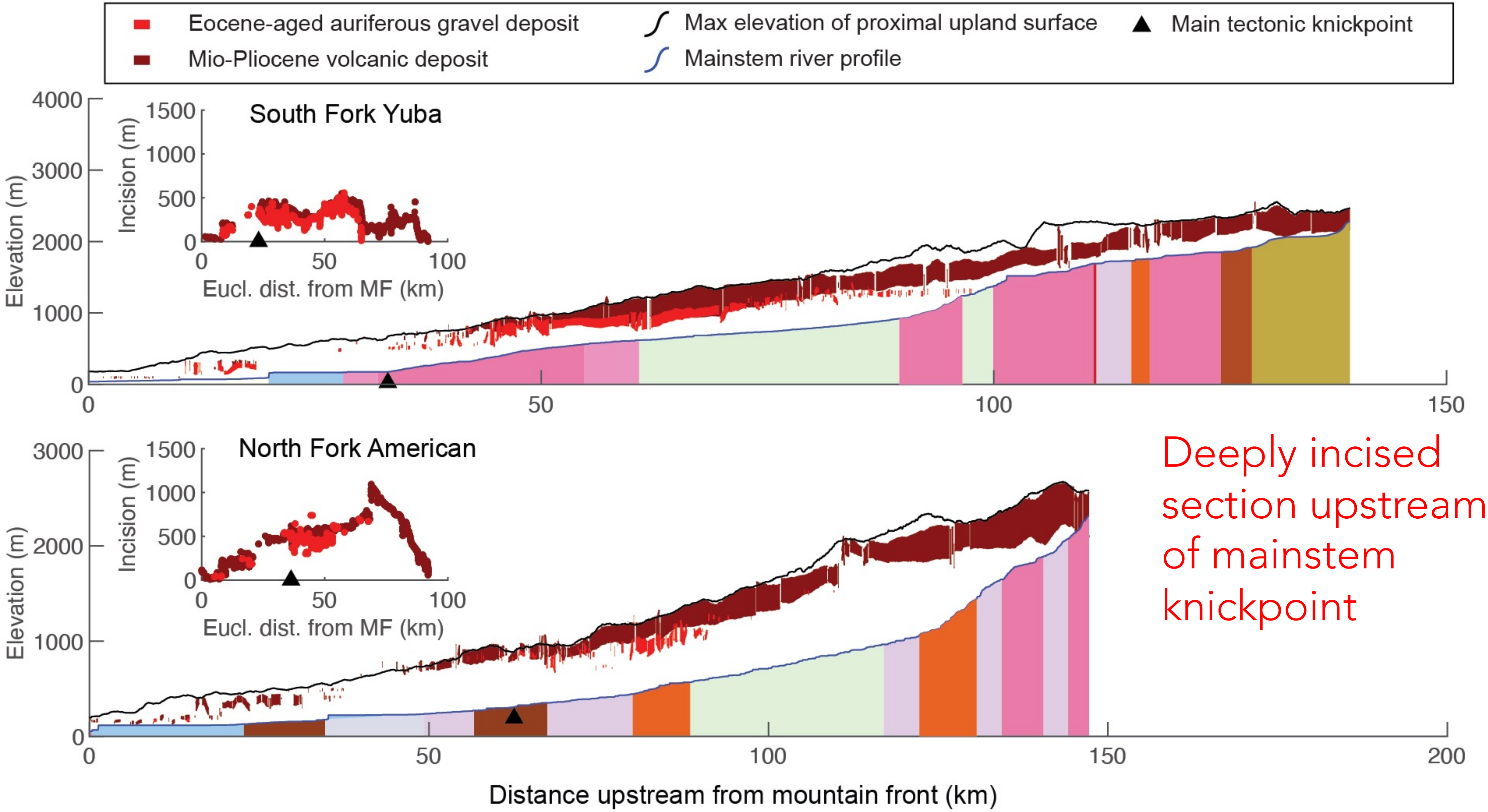
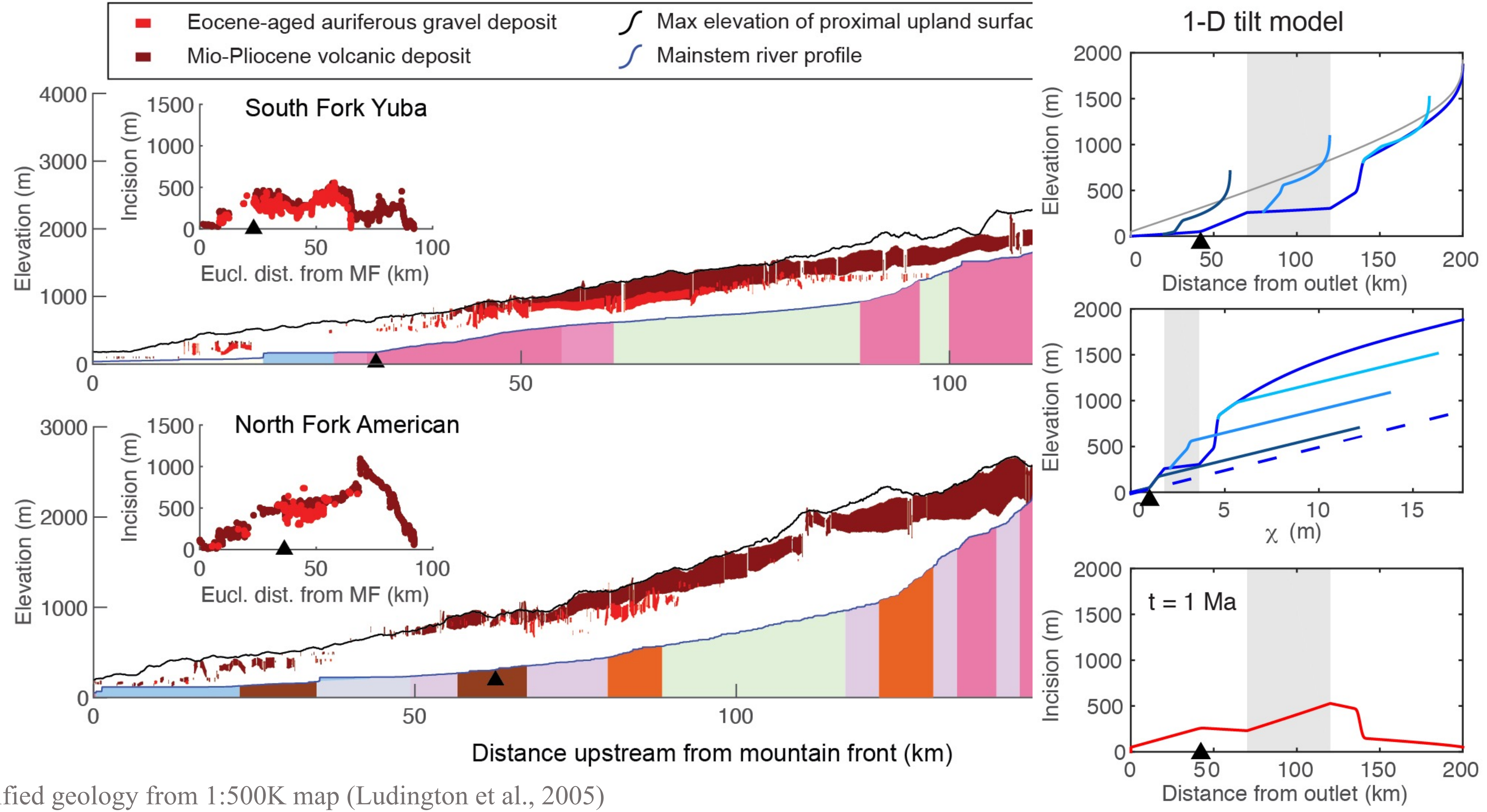



Deeply incised section upstream of mainstem knickpoint

Simplified geology from 1:500K map (Ludington et al., 2005)

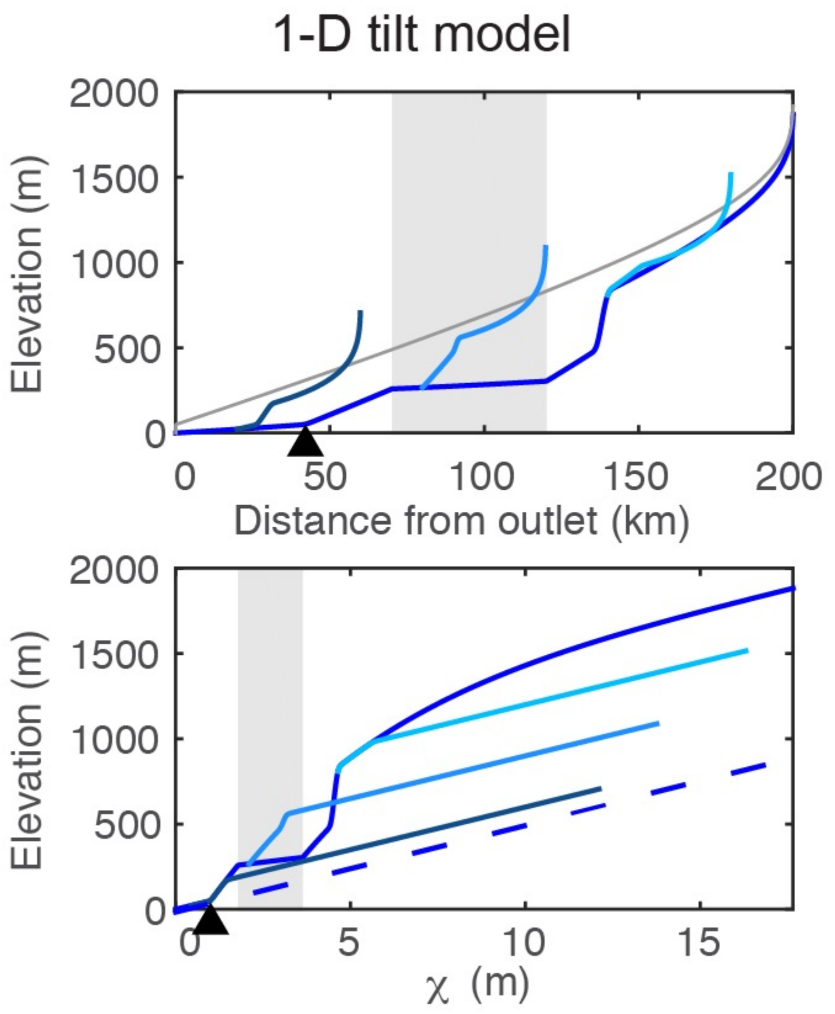
# What perturbation(s) did the Sierra Nevada experience?




Simplified geology from 1:500K map (Ludington et al., 2005)

# What perturbation(s) did the Sierra Nevada experience?

- Transient river profiles in the Sierra are consistent with a rapid tilting event that in many rivers is modulated by heterogeneous lithology.
- Can explain the observed variability in canyon incision both within the same river and between adjacent rivers.




We focused on rivers from and including the **Yuba** River south through the **Kings** River (~**39.3-36.5 N**) as they reflect the clearest signatures of a rapid tilting event.

# What was the timing of tilt?

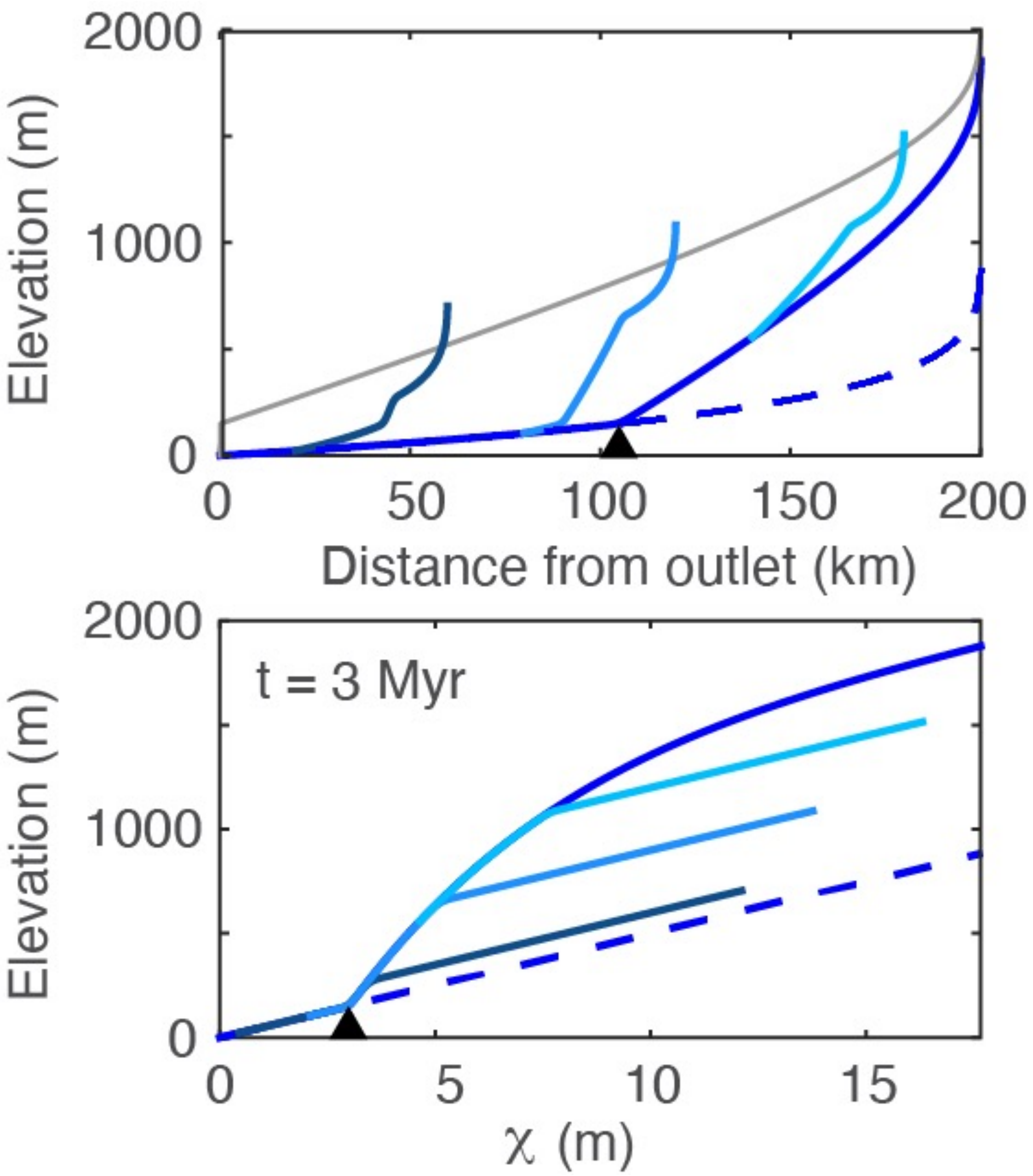
$$\tau = \frac{1}{K}\chi \qquad \chi = \int_{x_b}^{x} \left( \frac{A_0}{A(x')} \right)^{\frac{m}{n}} dx'$$

When K ≅ $1e^{-06}$, $\chi$ can be read as time in Ma

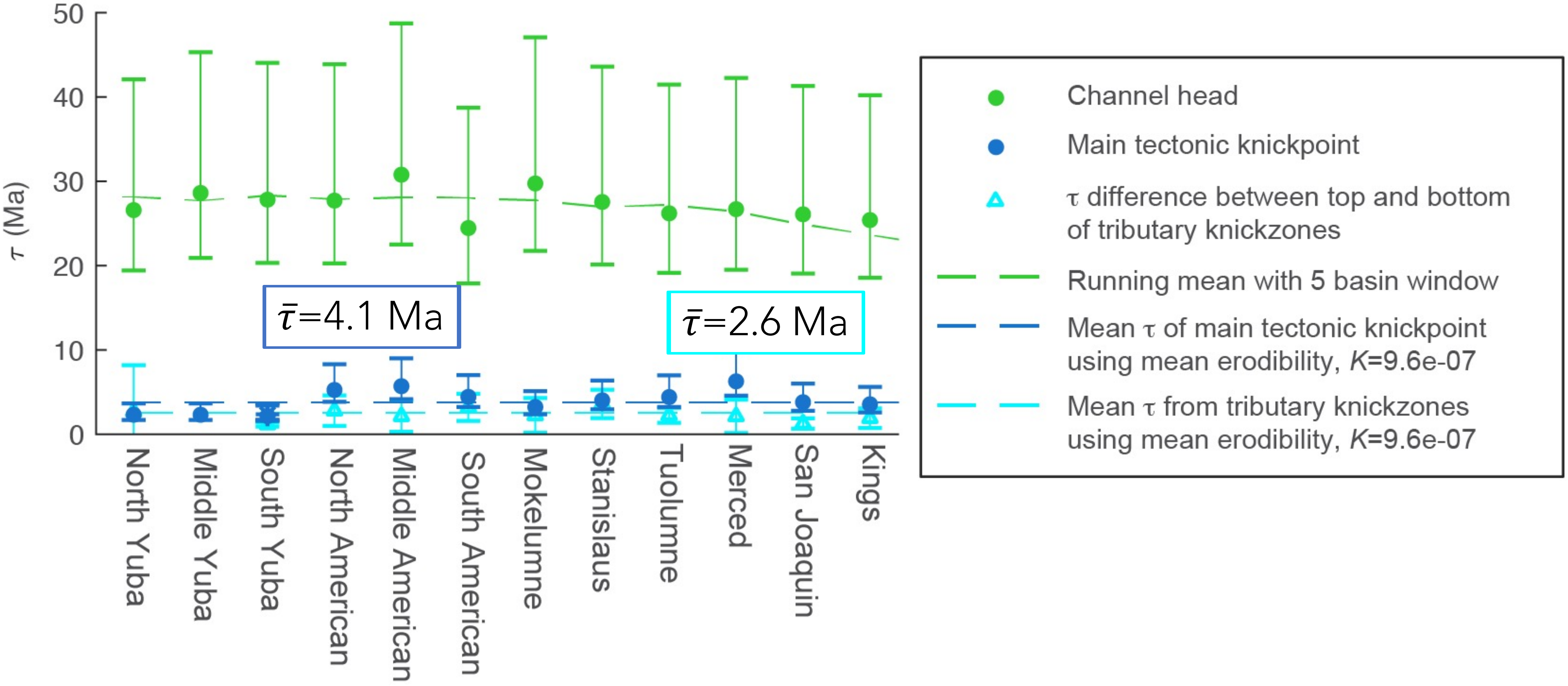
- Location of mainstem slope-break knickpoint records time since **cessation** of rapid tilting event

- Top of tributary knickzones record time since **cessation** of rapid tilting event:

$\boldsymbol{\tau}_{\text{top of kz}} - \boldsymbol{\tau}_{\text{junction}}$

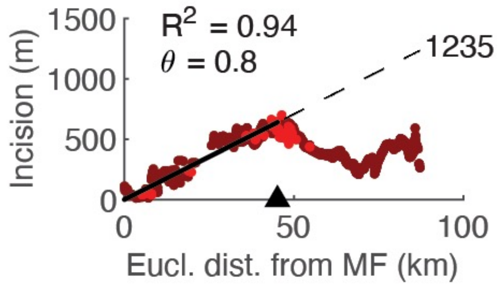


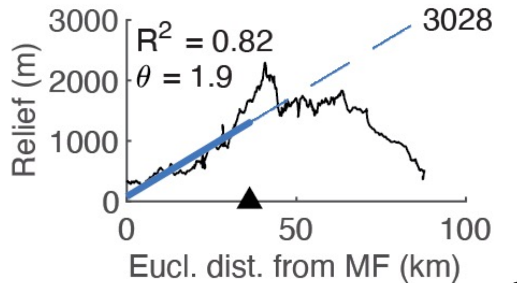
# Summary of constraints on tilt timing from knickpoint travel times



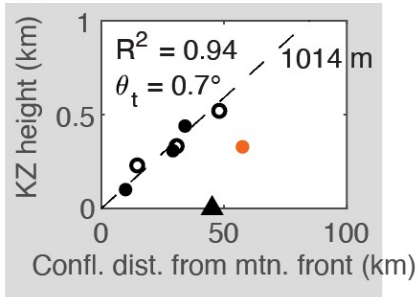
# What was the magnitude of tilt?

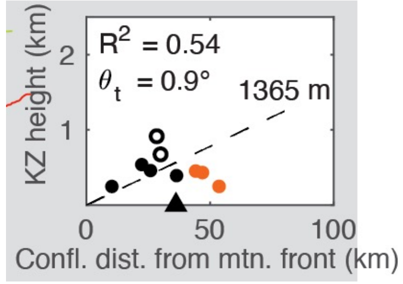
- Constraints from pattern of incision depth



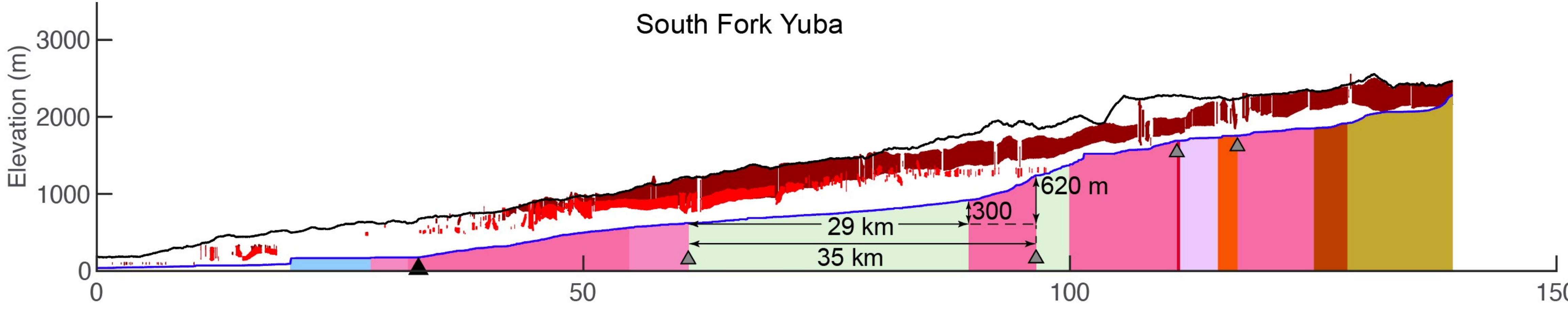




- Constraints from pattern in tributary kz drop height

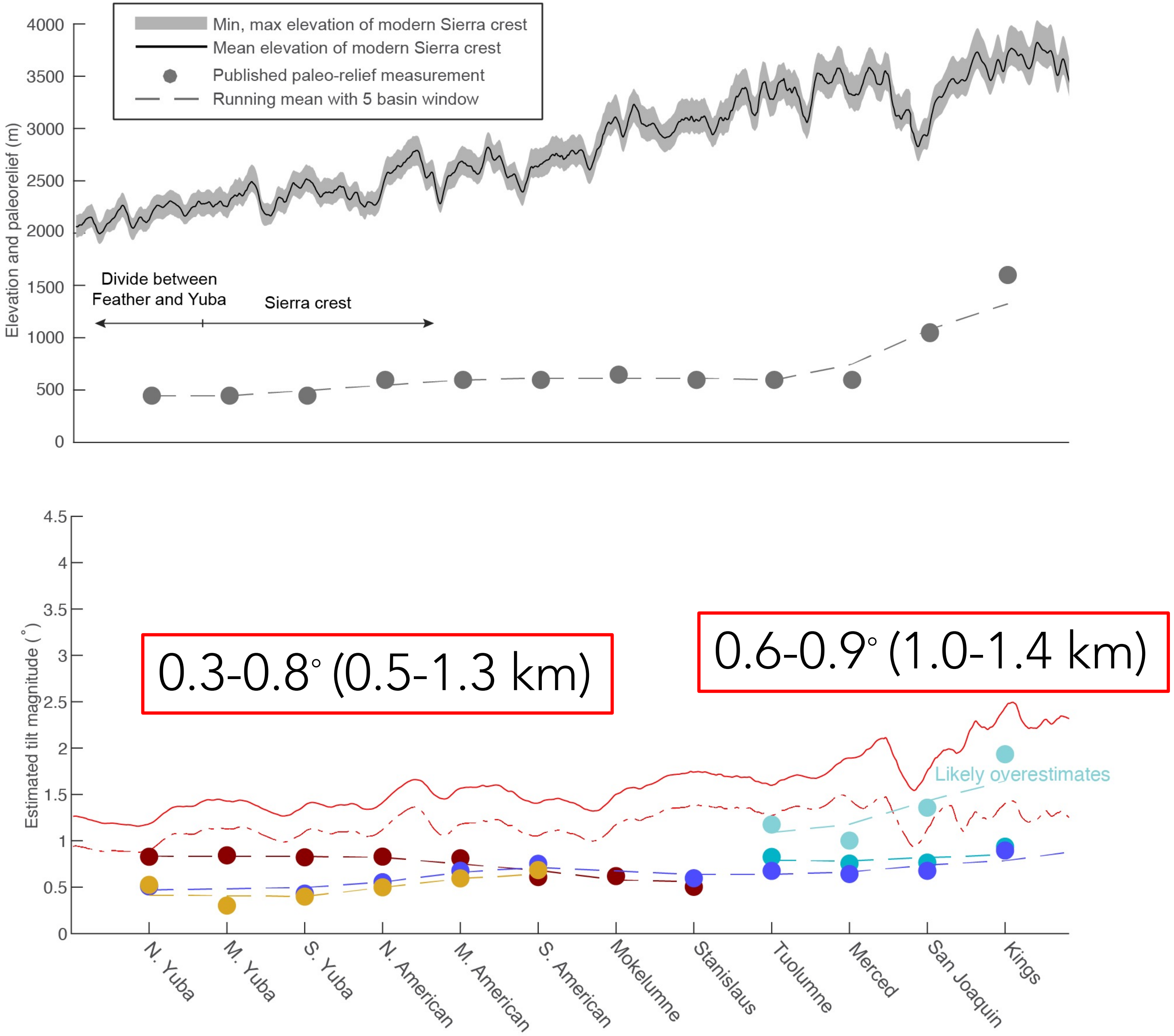



- Geometry of deeply-incised knickzones in more erodible rock



# What was the magnitude of tilt?




- Rigid-block tilt
- Rigid-block tilt accounting for estimated paleorelief
- Spatial gradient in mainstem basement incision below Mio-Pliocene volcanics and Eocene auriferous gravels
- Spatial gradient in mainstem canyon relief (incl. paleorelief)
- Spatial gradient in mainstem canyon relief minus paleorelief
- Spatial gradient in tributary knickzone drop height
- Geometry of knickzones formed as transient response in more erodible rock

Paleorelief from Wakabayashi, 2013

Transient river profiles in the Sierra are consistent with a rapid tilting event that **began <11 Ma and slowed between 2-6 Ma** and raised Sierra crest **0.5-1.4 km**

**Thanks for your attention!**

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