Utagawa Kokunimasa, woodblock print, 1896

A Tale of Earthquakes and Landscapes

What landscapes can tell us about subduction zone earthquake cycles

 Bar Oryan
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Scripps Institution of Oceanography, UCSD

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GREAT MEGATHURST EARTHQUAKES IN THE PAST 20 YEARS

1. 2004 Sumatra-Andaman Earthquake (Mw 9.3)

- **Date:** December 26, 2004
- **Location:** Off the west coast of northern Sumatra, Indonesia
- **Impact:** Triggered a catastrophic tsunami, causing over 230,000 deaths across 14 countries

2. 2010 Maule Earthquake (Mw 8.8)

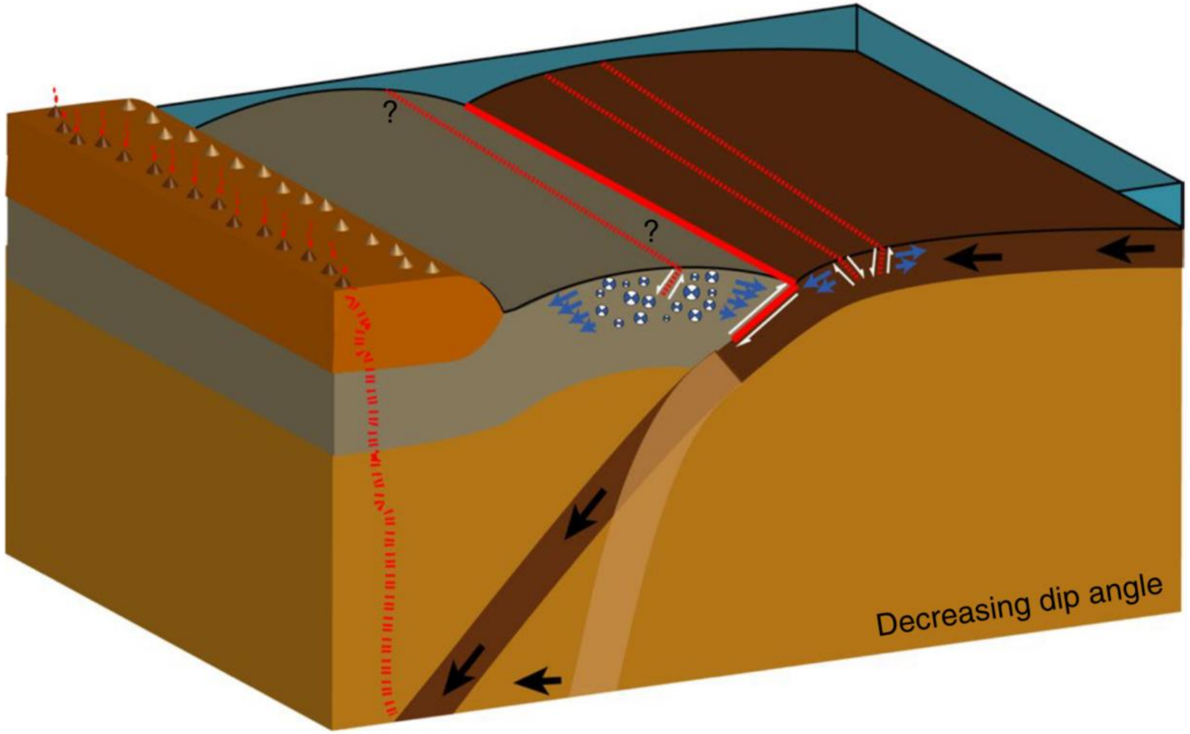
- **Date:** February 27, 2010
- **Location:** Offshore Maule region, Chile
- **Impact:** Over 500 fatalities and extensive infrastructure damage

3. 2011 Tōhoku Earthquake (Mw 9.1)

- **Date:** March 11, 2011
- **Location:** Off the east coast of Honshu, Japan
- **Impact:** Generated a massive tsunami, leading to nearly 16,000 deaths and the Fukushima nuclear disaster

MY RESREACH INTRESTS

Thermomechanical numerical modeling and study how slow changes of subducting slabs geometry over millions of years affect megathrust hazard



Oryan & Buck,2020, *Nature geoscience*

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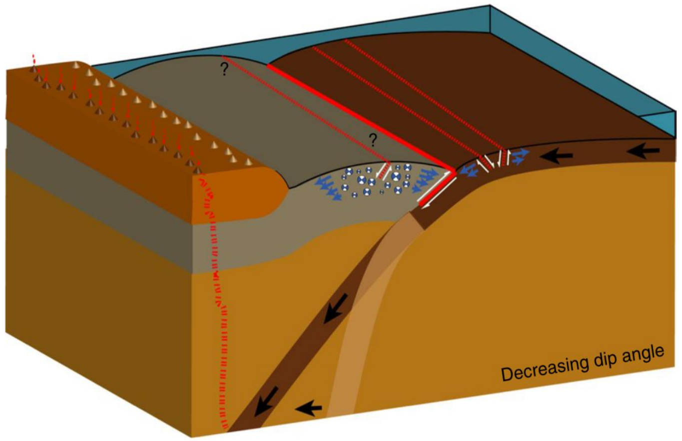

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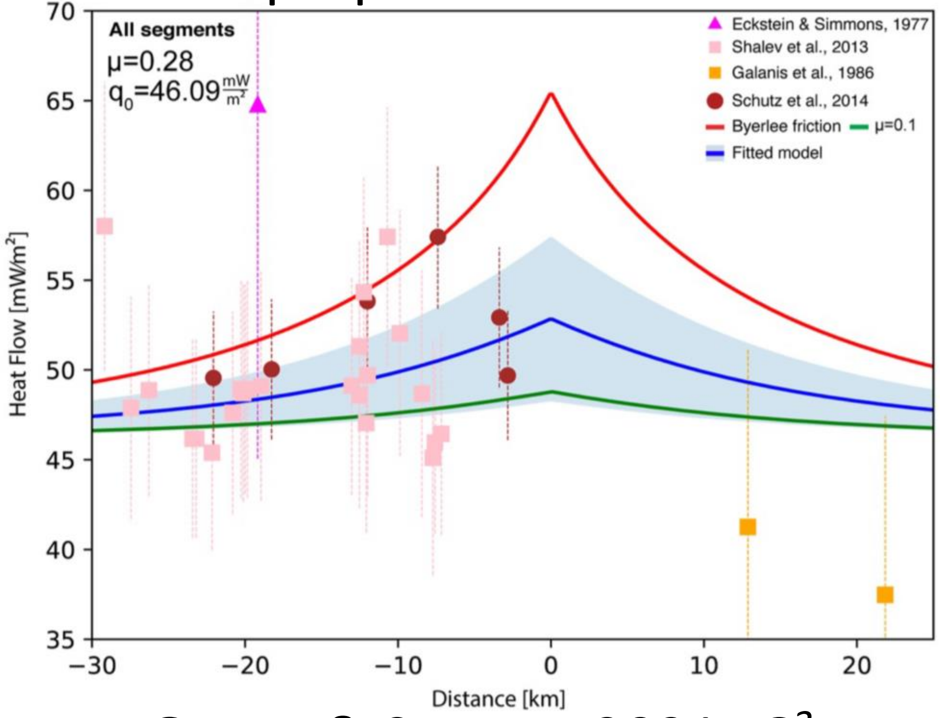
Analysis of **heat flow** data to constrain frictional properties of faults



Oryan & Savage ,2021, *G*[3]

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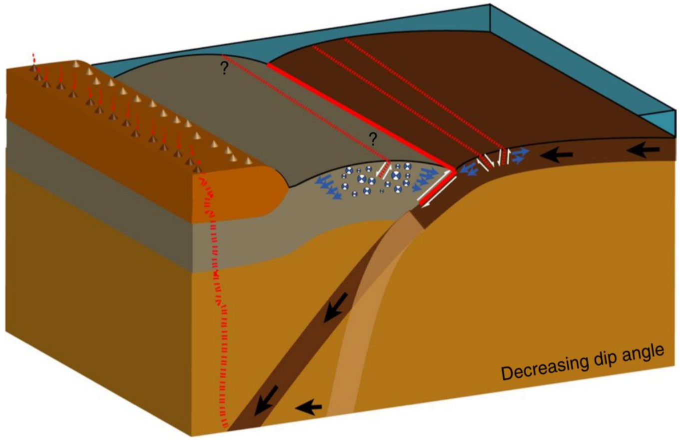

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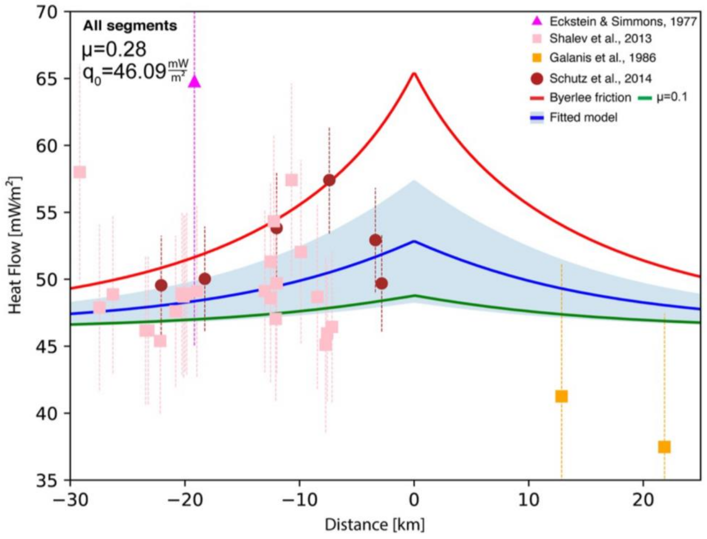
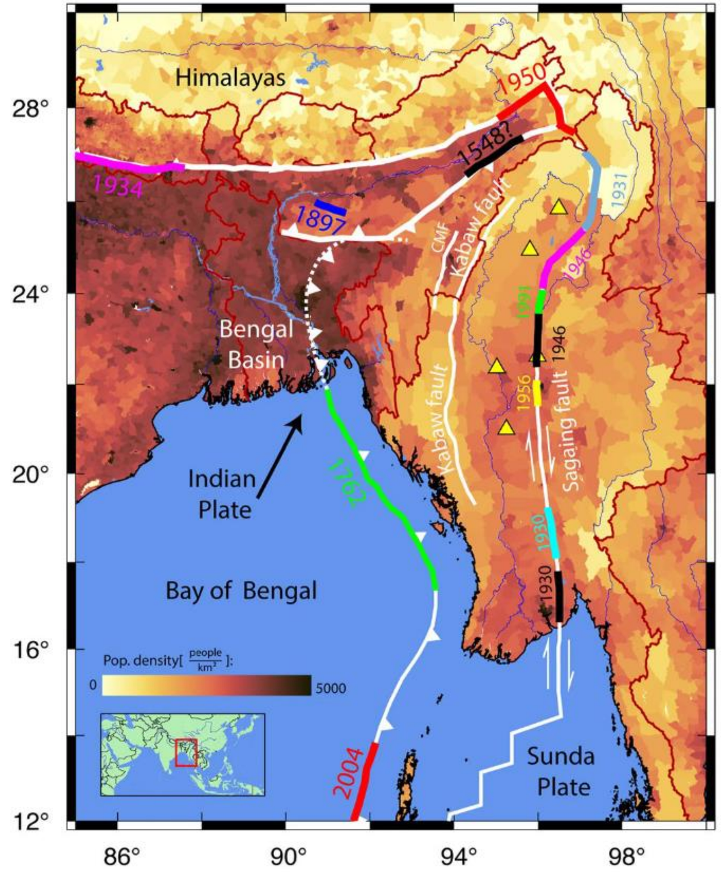


Oryan & Savage ,2021, *G*^{3}

Inversion of Indo-Burma **geodetic** data to constrain megathrust hazard

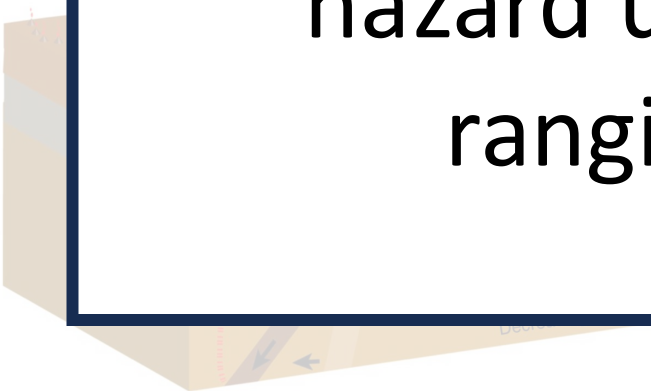


Oryan et al., 2023, JGR

MY RESREACH INTRESTS

Inversion of Indo-Burma **geodetic** data to constrain

I am a **geophysicist** interested in studying subduction earthquake cycles and associated hazard using an **interdisciplinary** approach ranging **a broad range of timescales**



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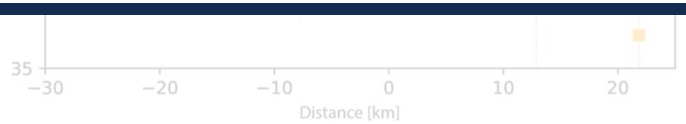

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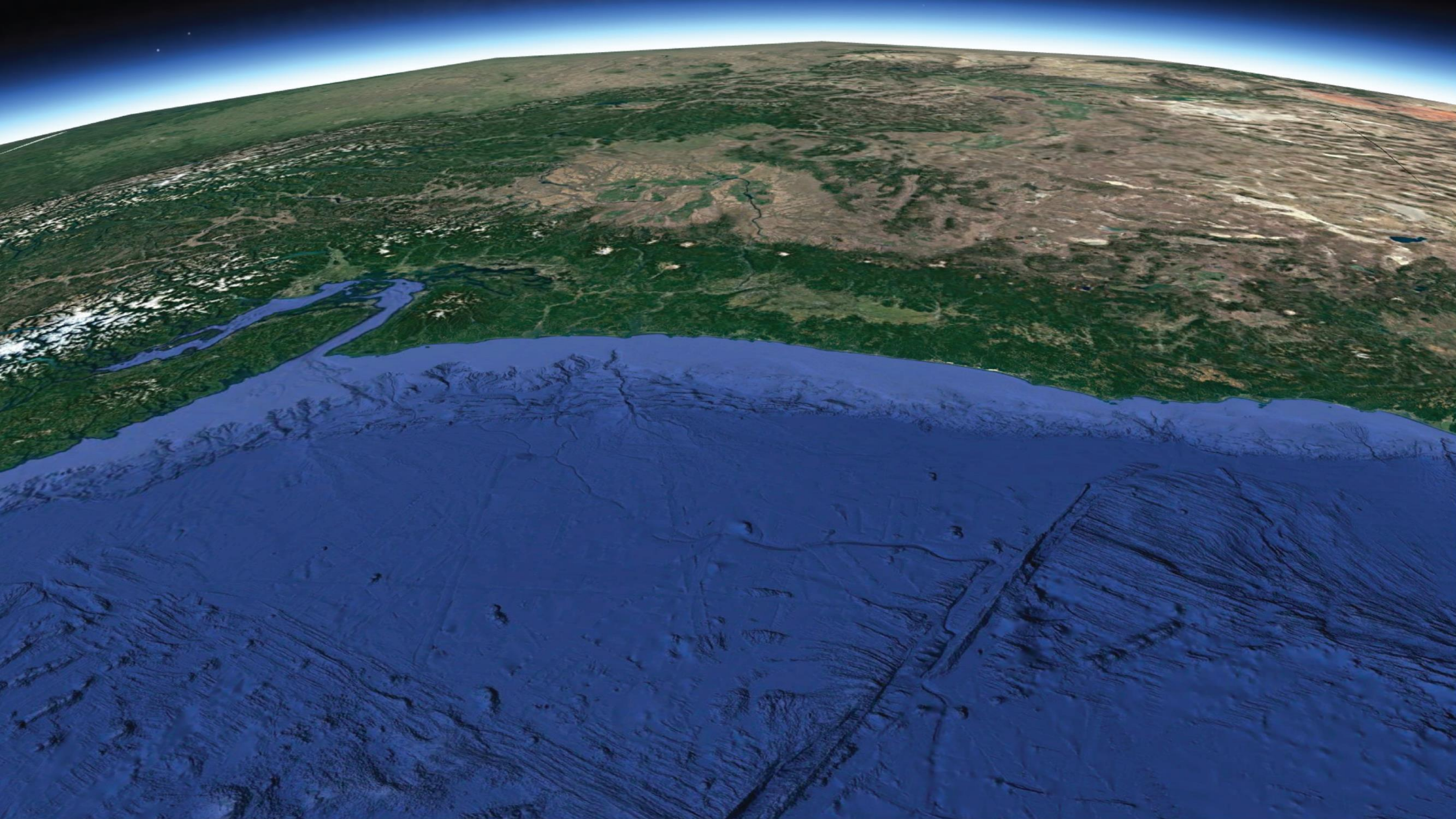
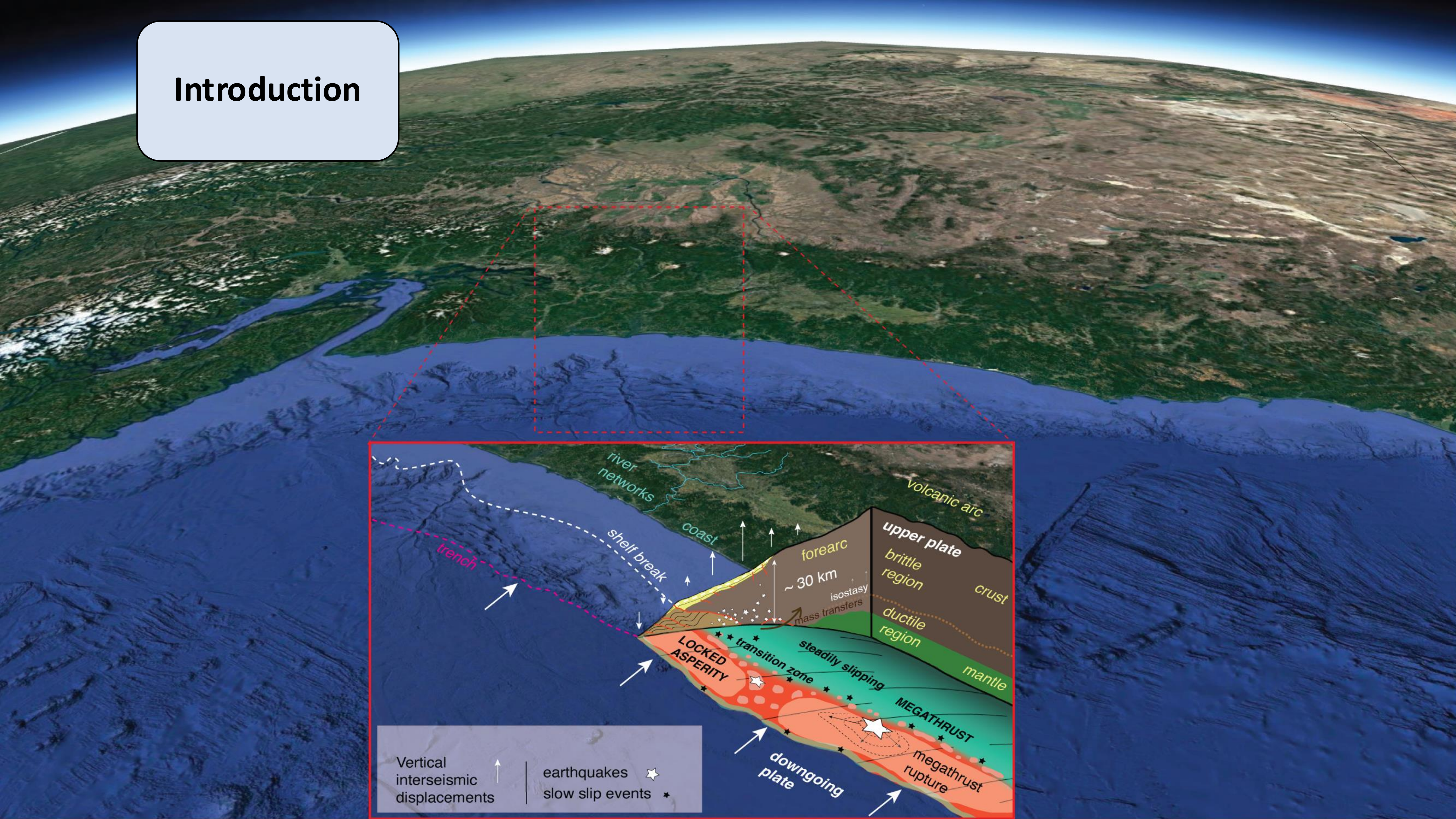
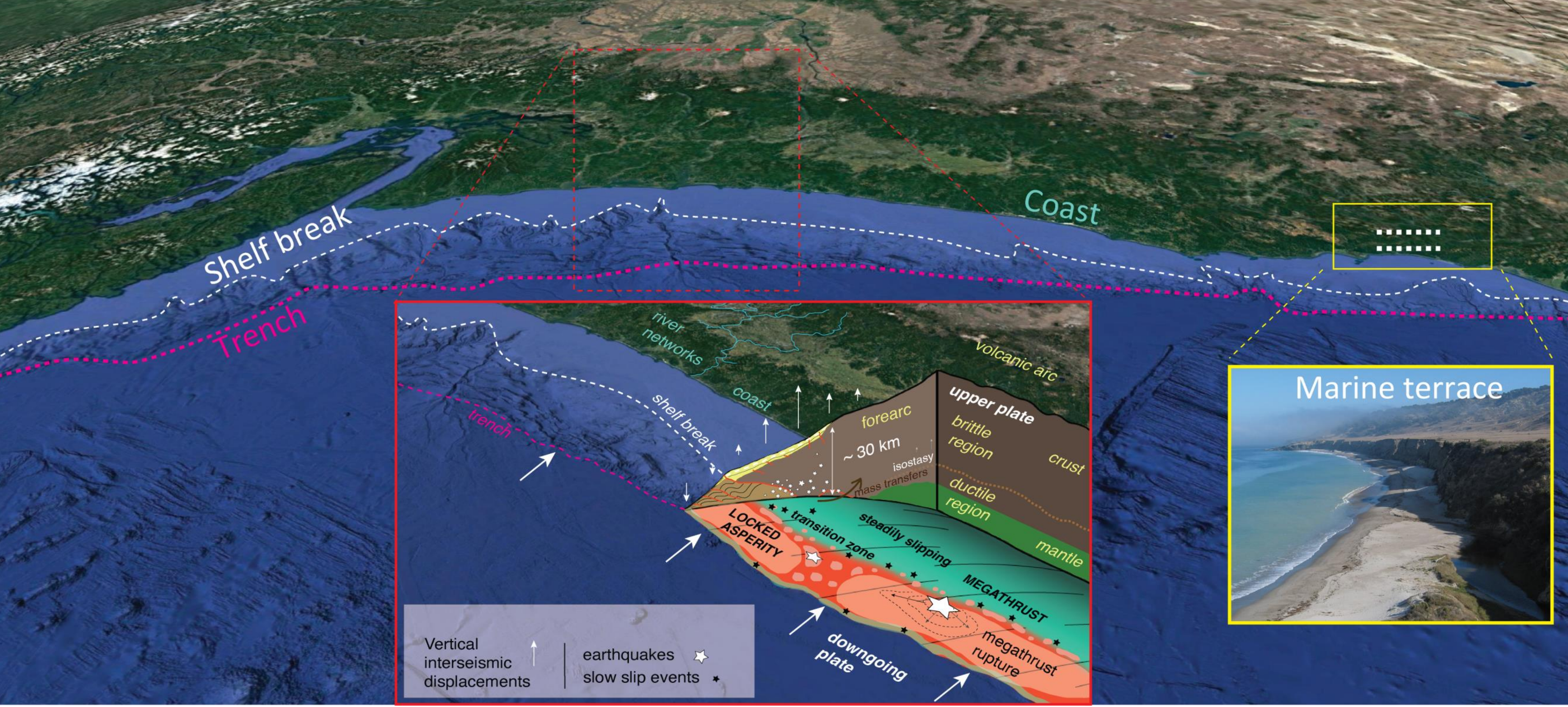


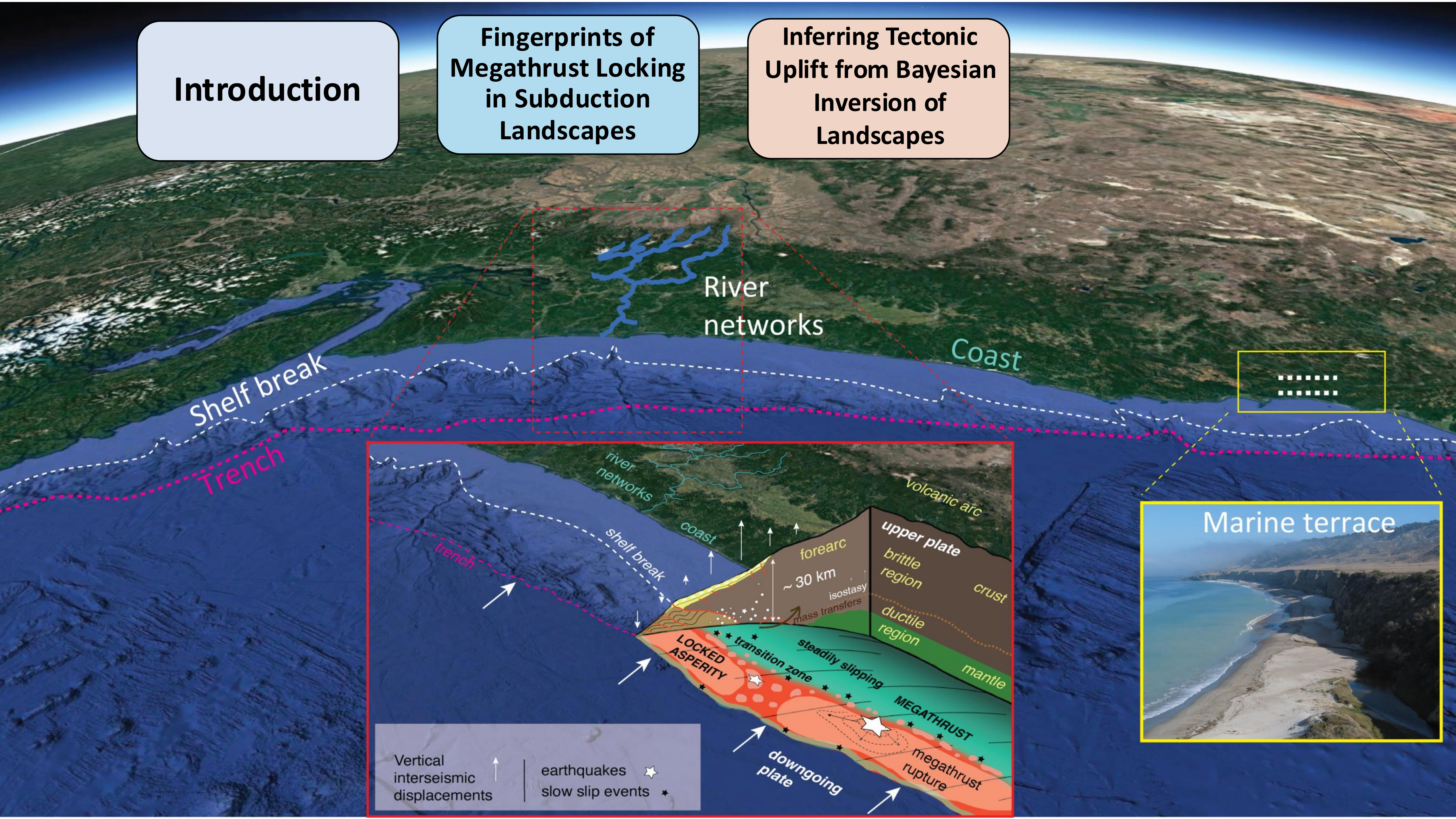
Introduction



Introduction

Fingerprints of Megathrust Locking in Subduction Landscapes





Introduction
Fingerprints of Megathrust Locking in Subduction Landscapes
Inferring Tectonic Uplift from Bayesian Inversion of Landscapes
River networks
Coast
Shelf break
Trench
river networks
volcanic arc
coast
shelf break
trench
forearc
upper plate
brittle region
crust
~ 30 km
isostasy
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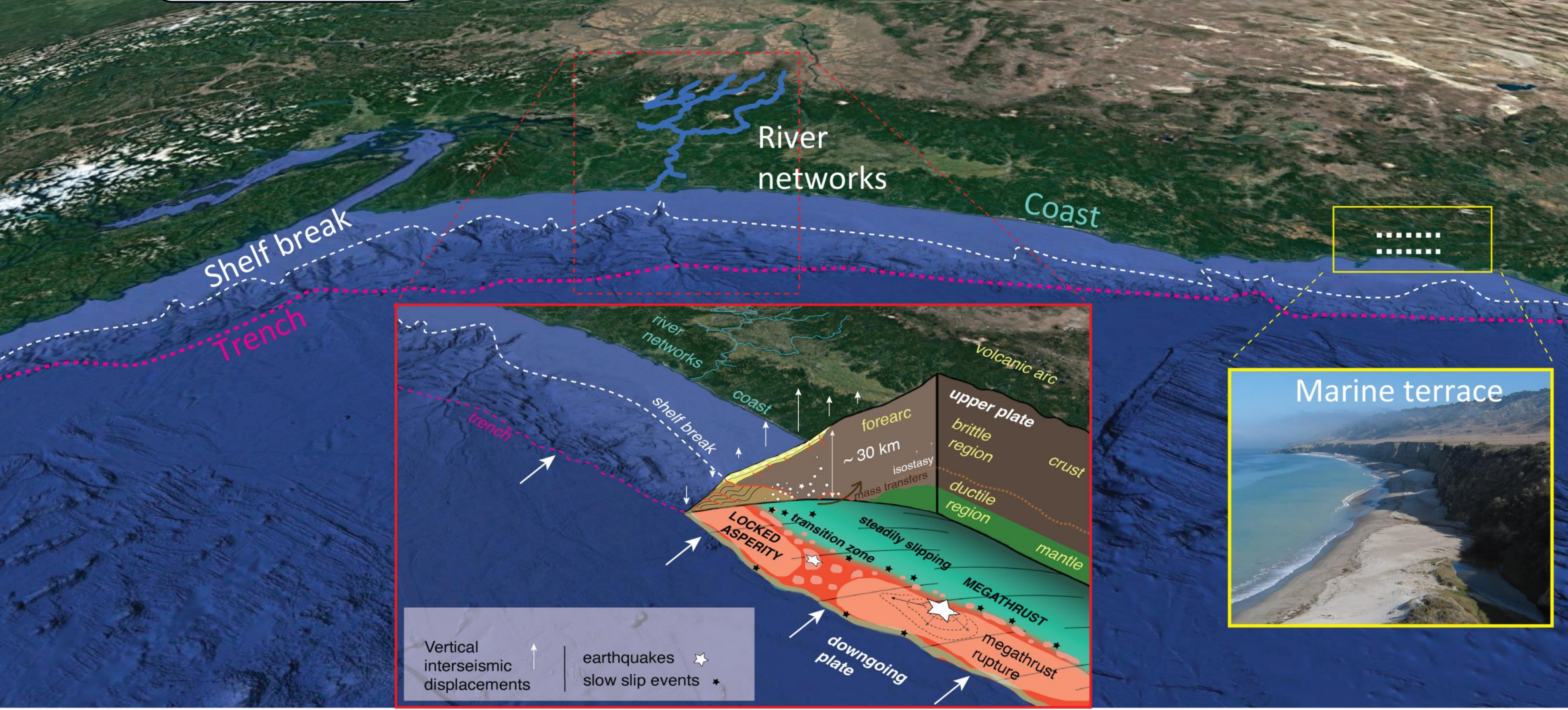
transition zone
steadily slipping
MEGATHRUST
megathrust rupture
downgoing plate
Vertical interseismic displacements
earthquakes
slow slip events
Marine terrace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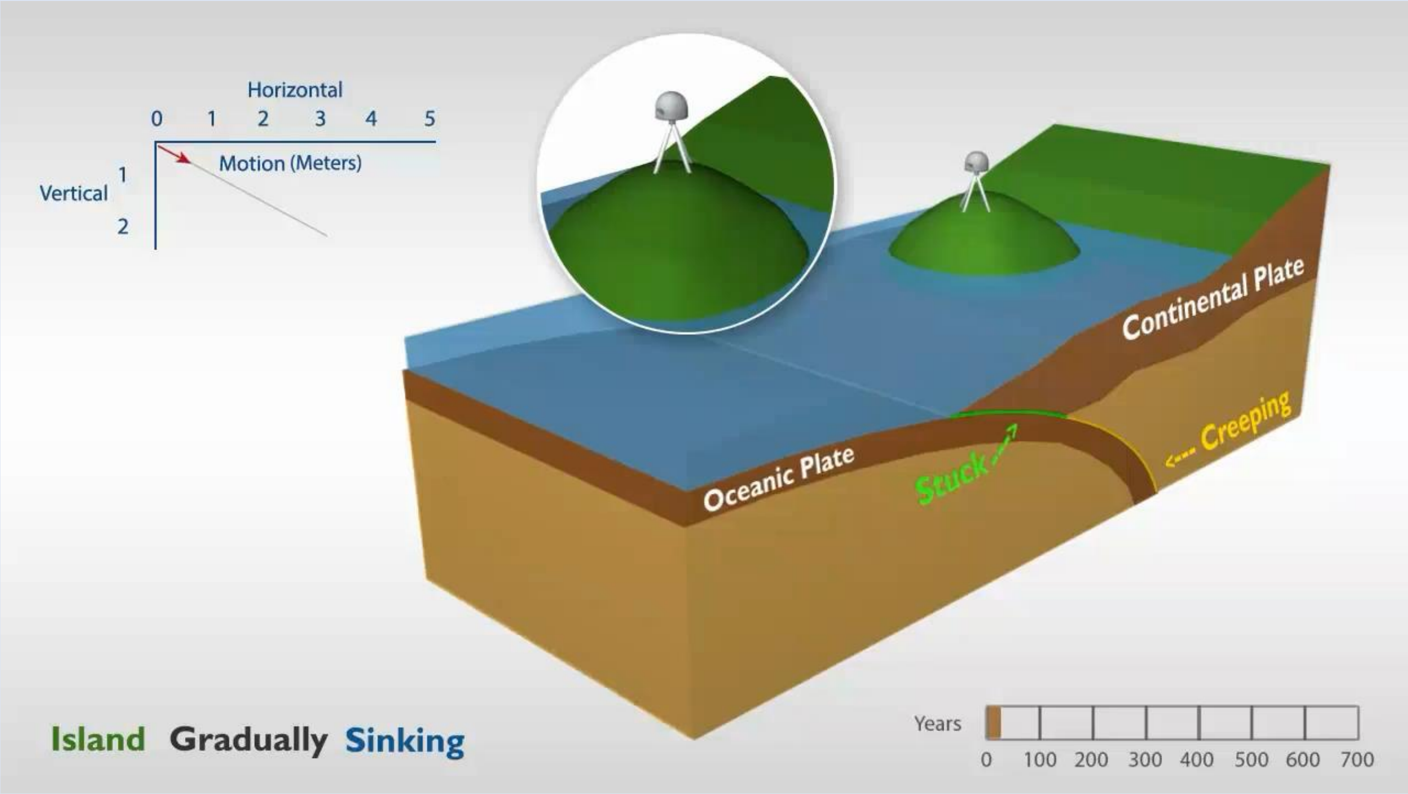
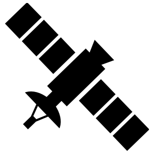
Scan me for slides and references.

Section 1 - Introduction



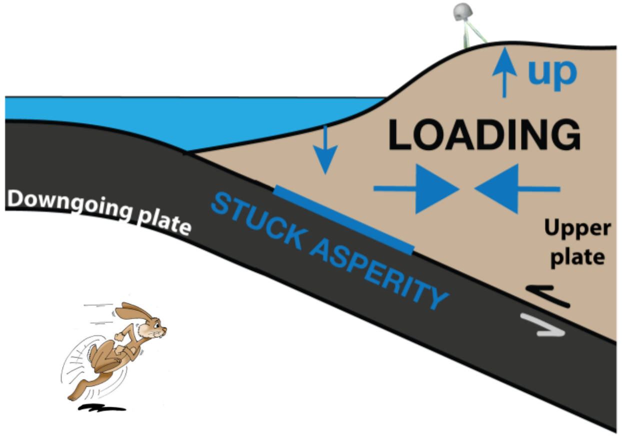
EARTHQUAKE CYCLES IN SUBDUCTION ZONES

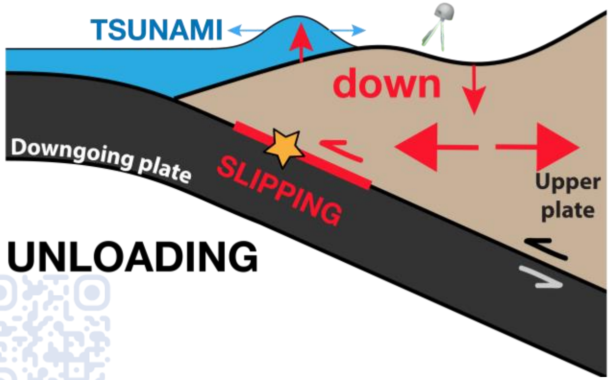


Long-term: downgoing plate descends beneath the upper plate in stick-slip fashion.

Interseismic: locked section is "stuck". Creeping section moves slowly.

Stress build up





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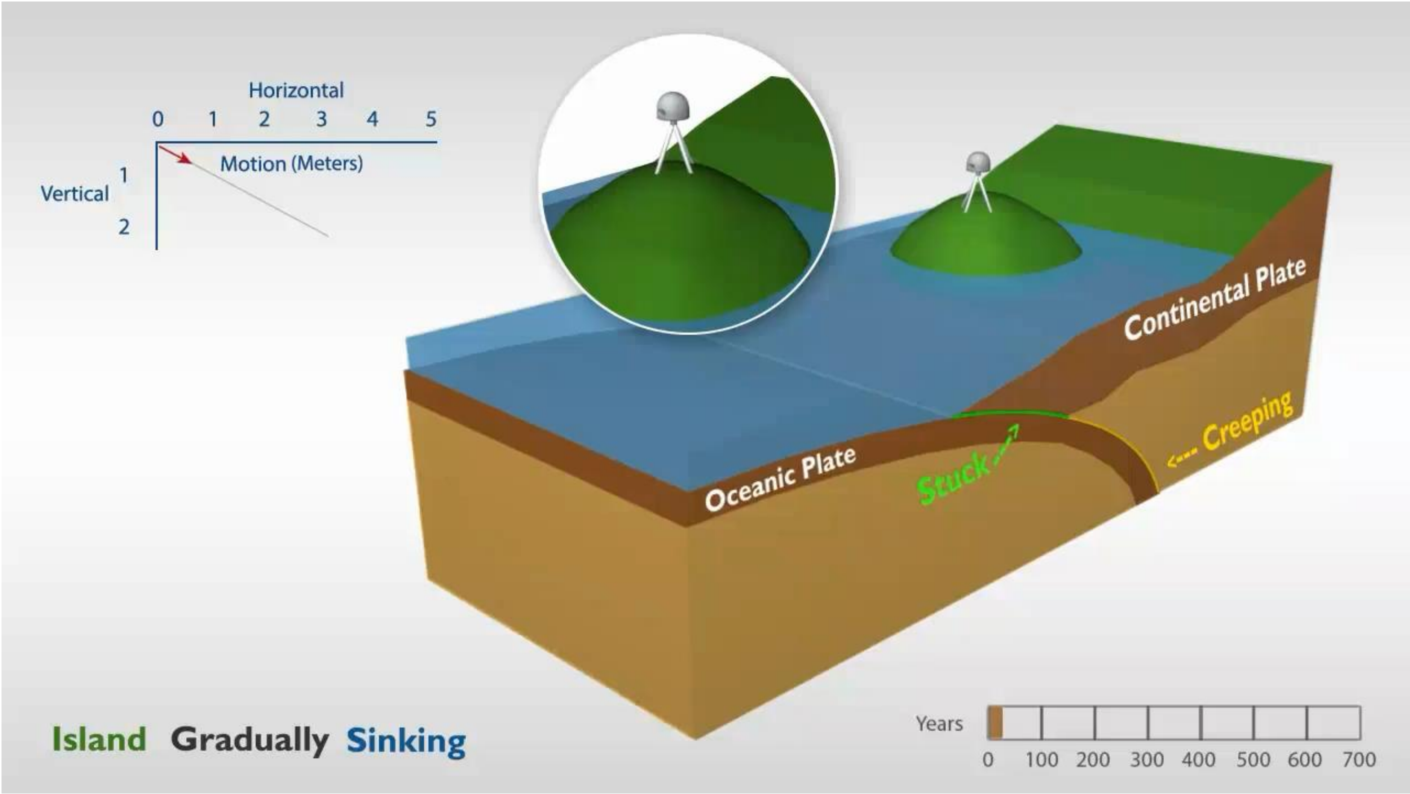

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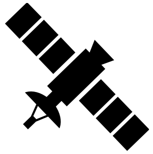

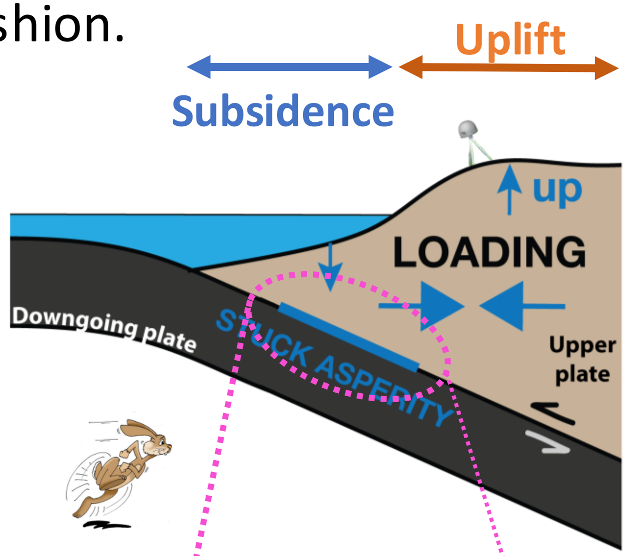

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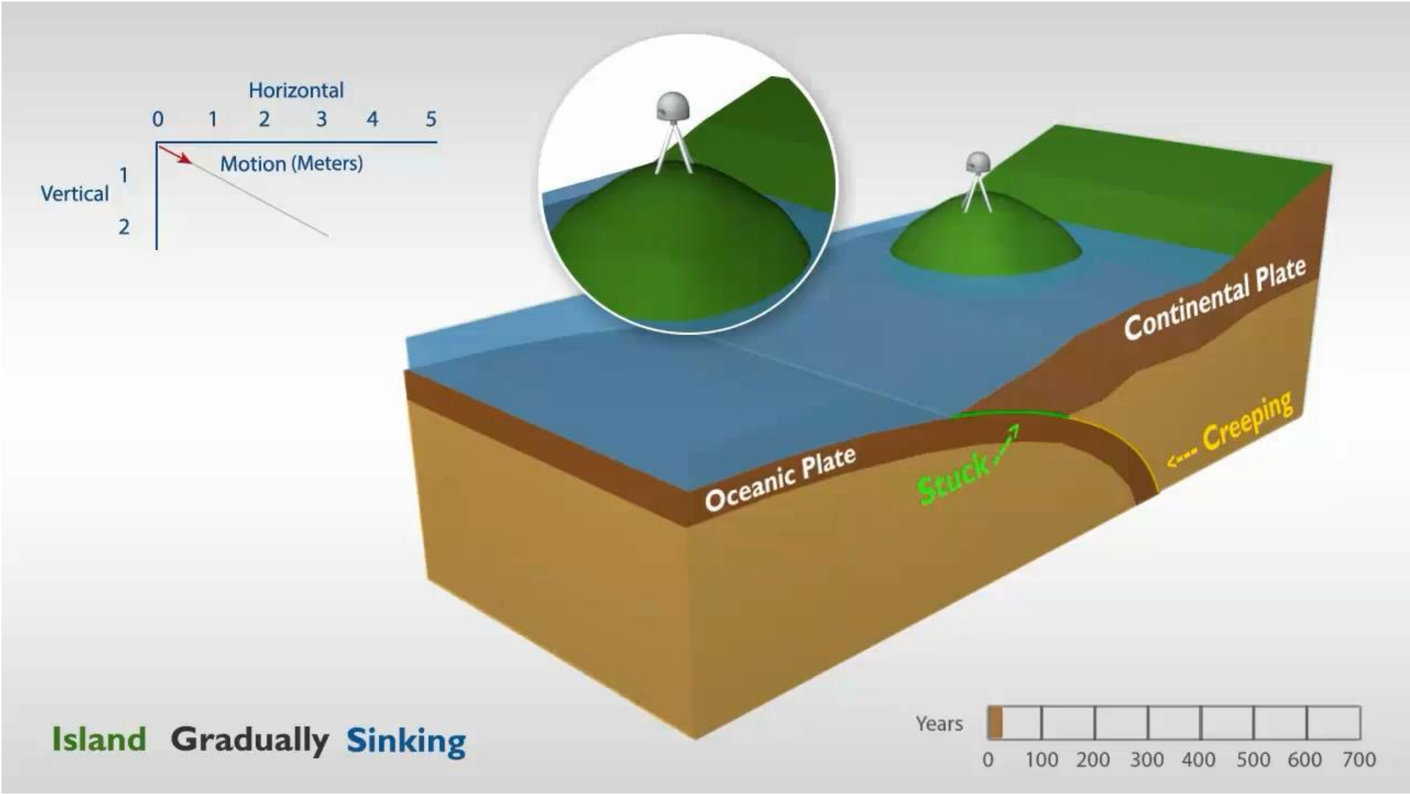

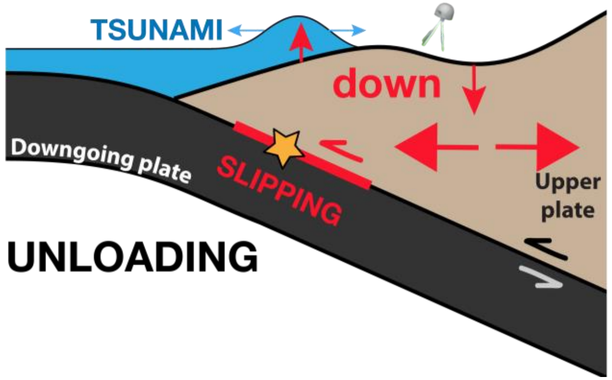

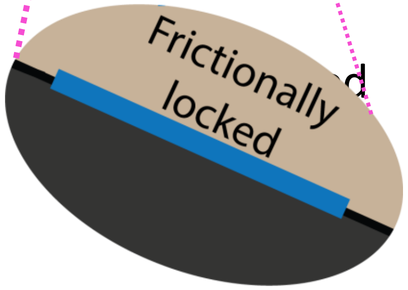

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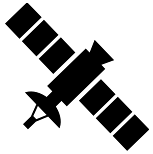

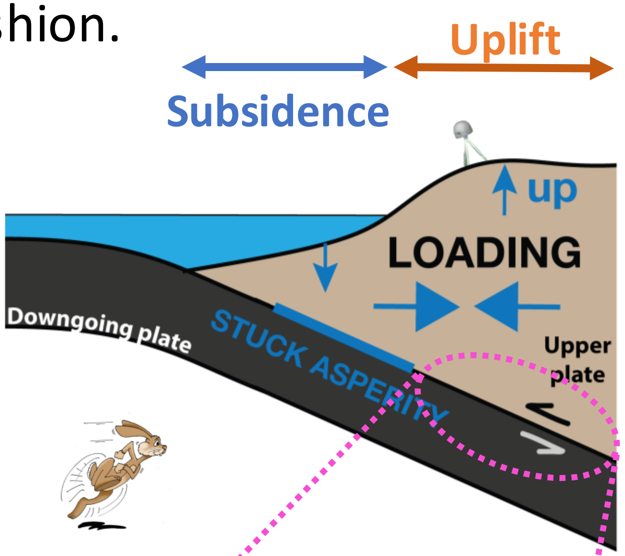

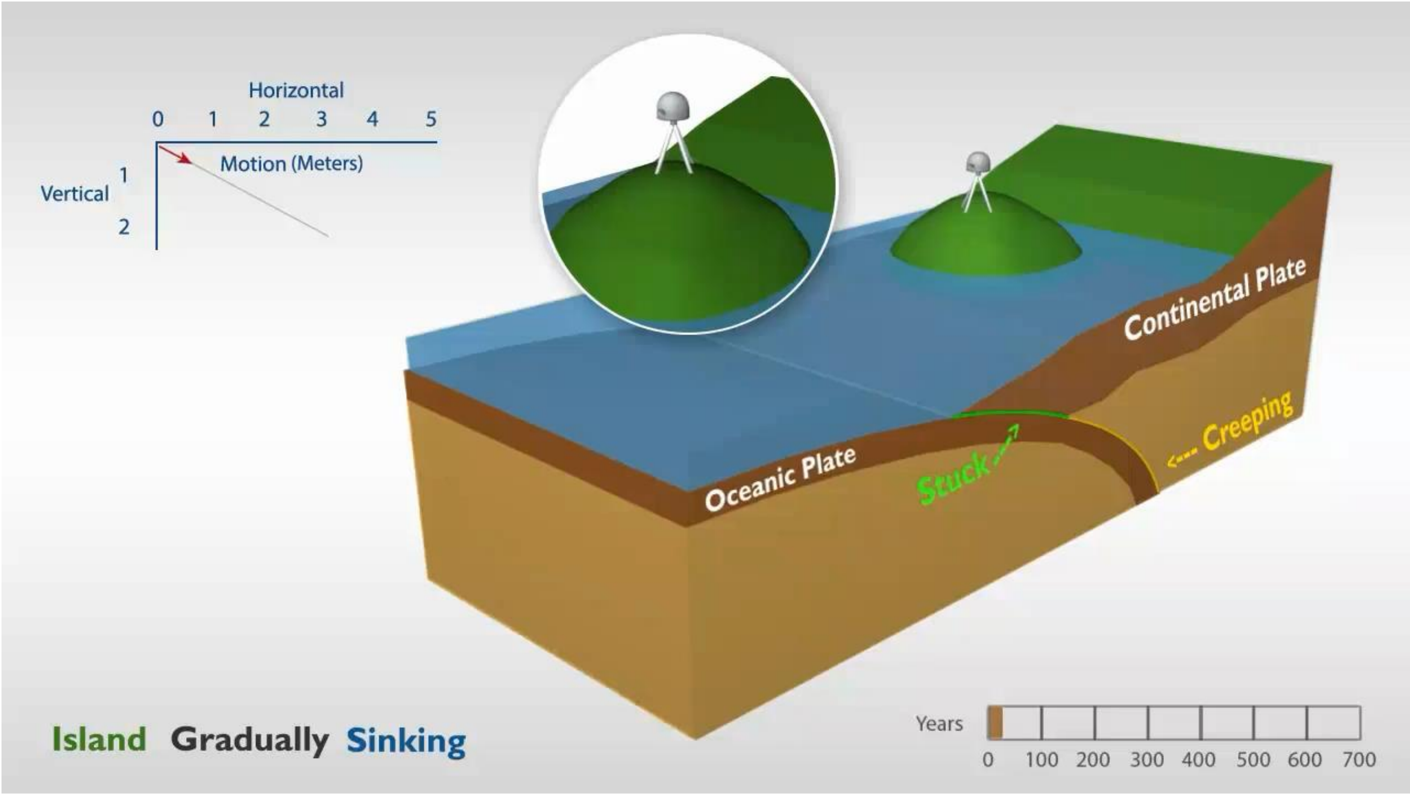

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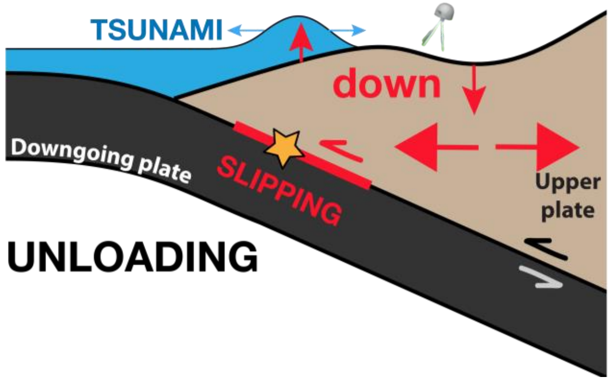

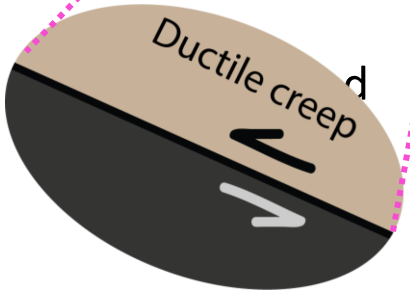

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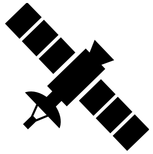

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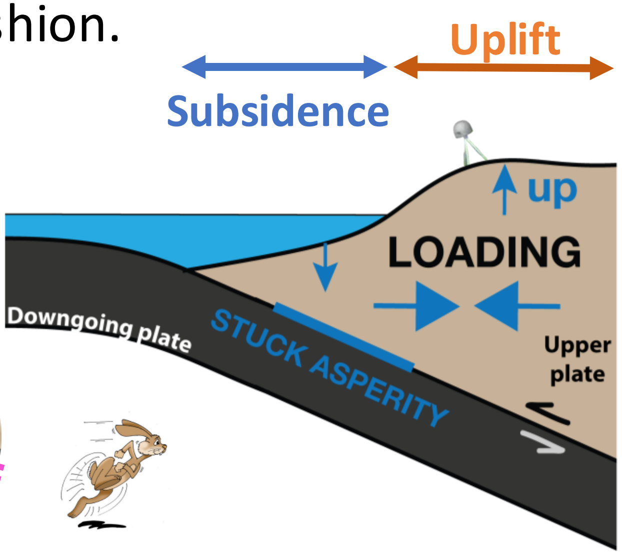

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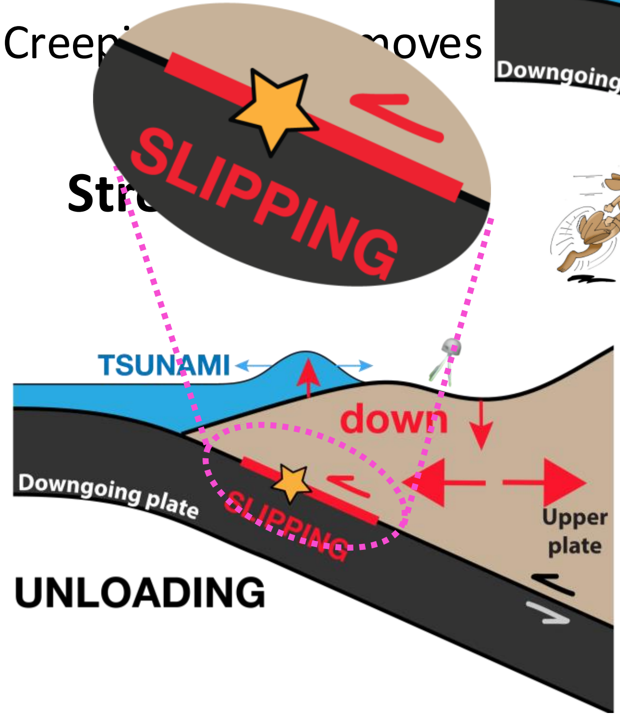

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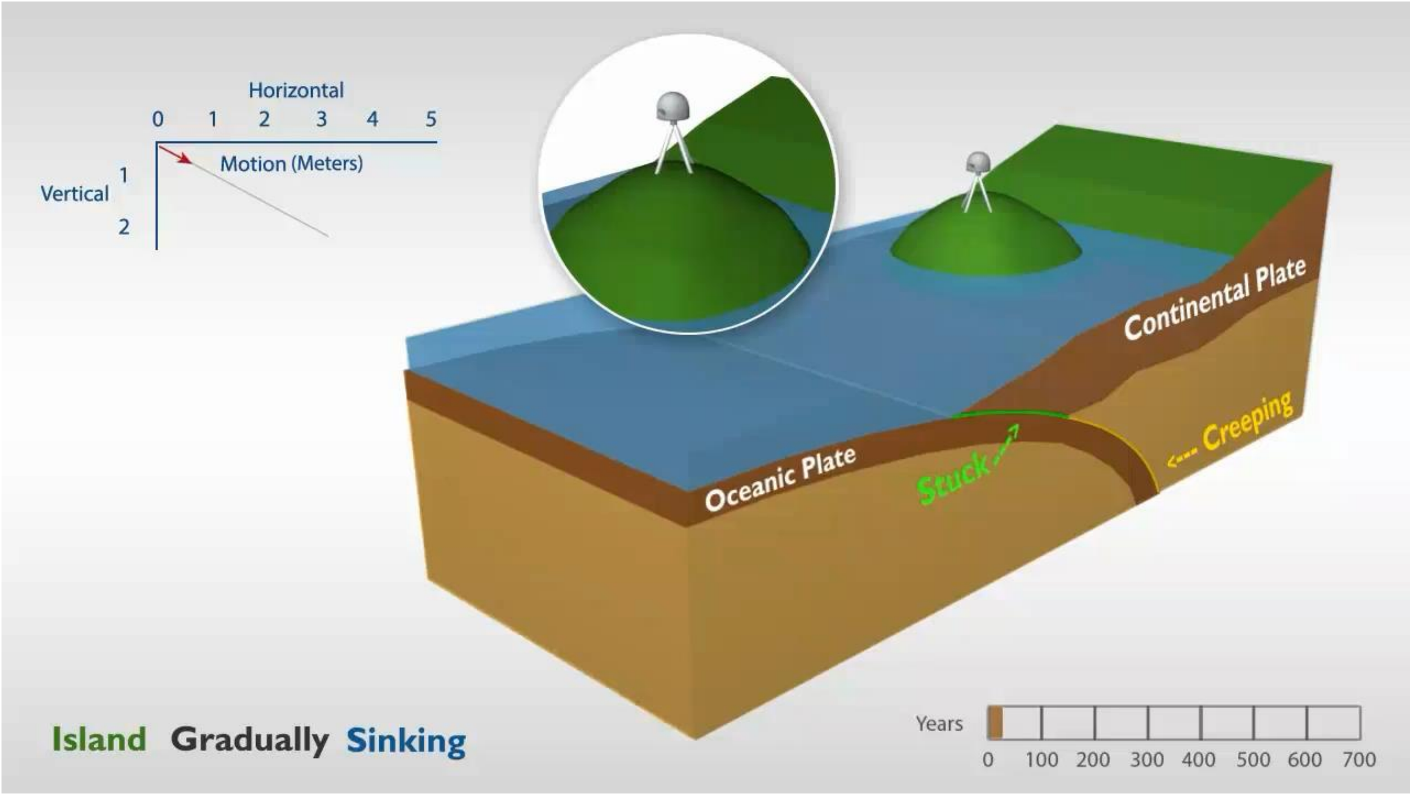
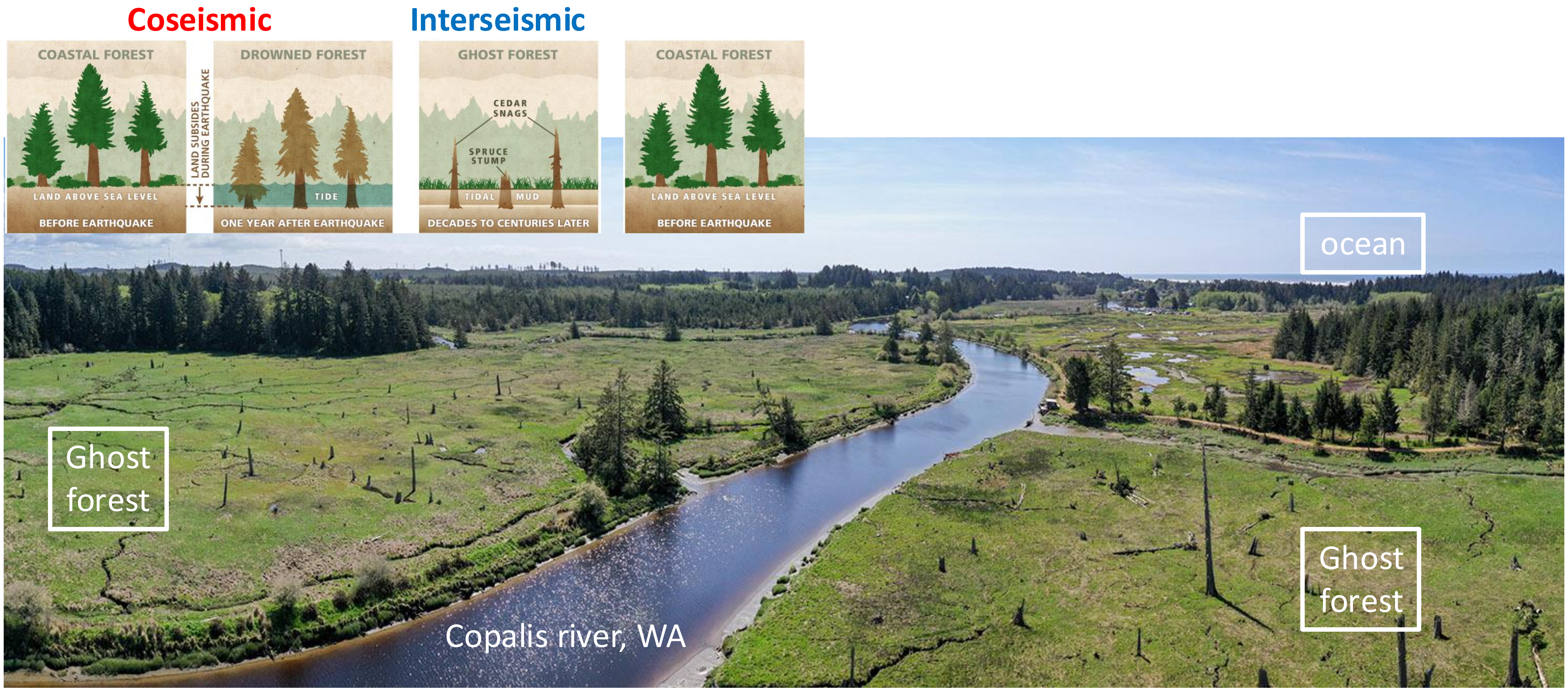


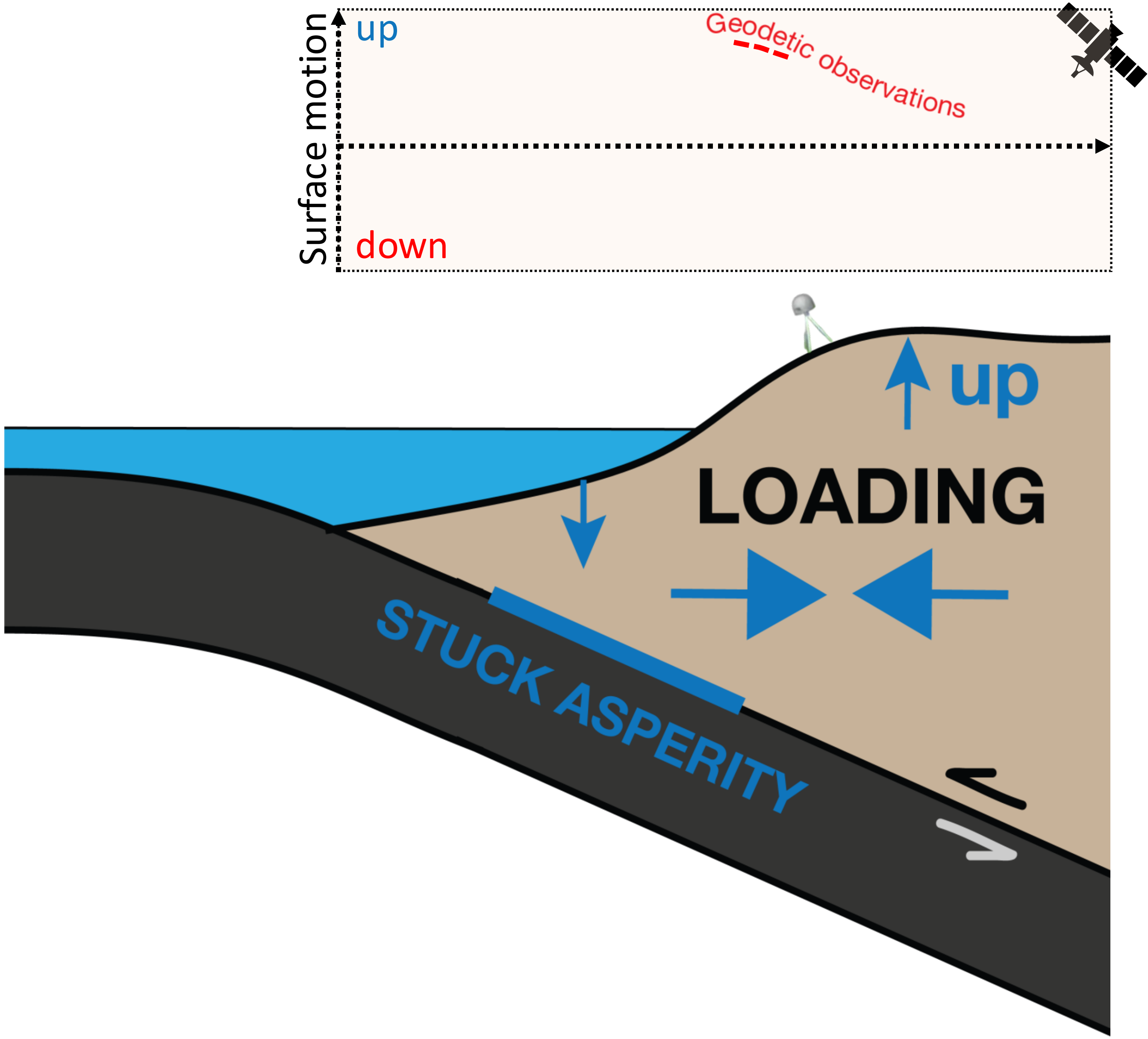
EARTHQUAKE CYCLES IN SUBDUCTION ZONES

Cascadia January 26th 1700 megathrust earthquake **killed forests** along the coast



CONSTRAINING MEGATHRUST HAZARD IN SUBDUCTION ZONES

- Deployment of GNSS stations and InSAR data collection have greatly **improved** the **availability** of **geodetic** data in recent decades.



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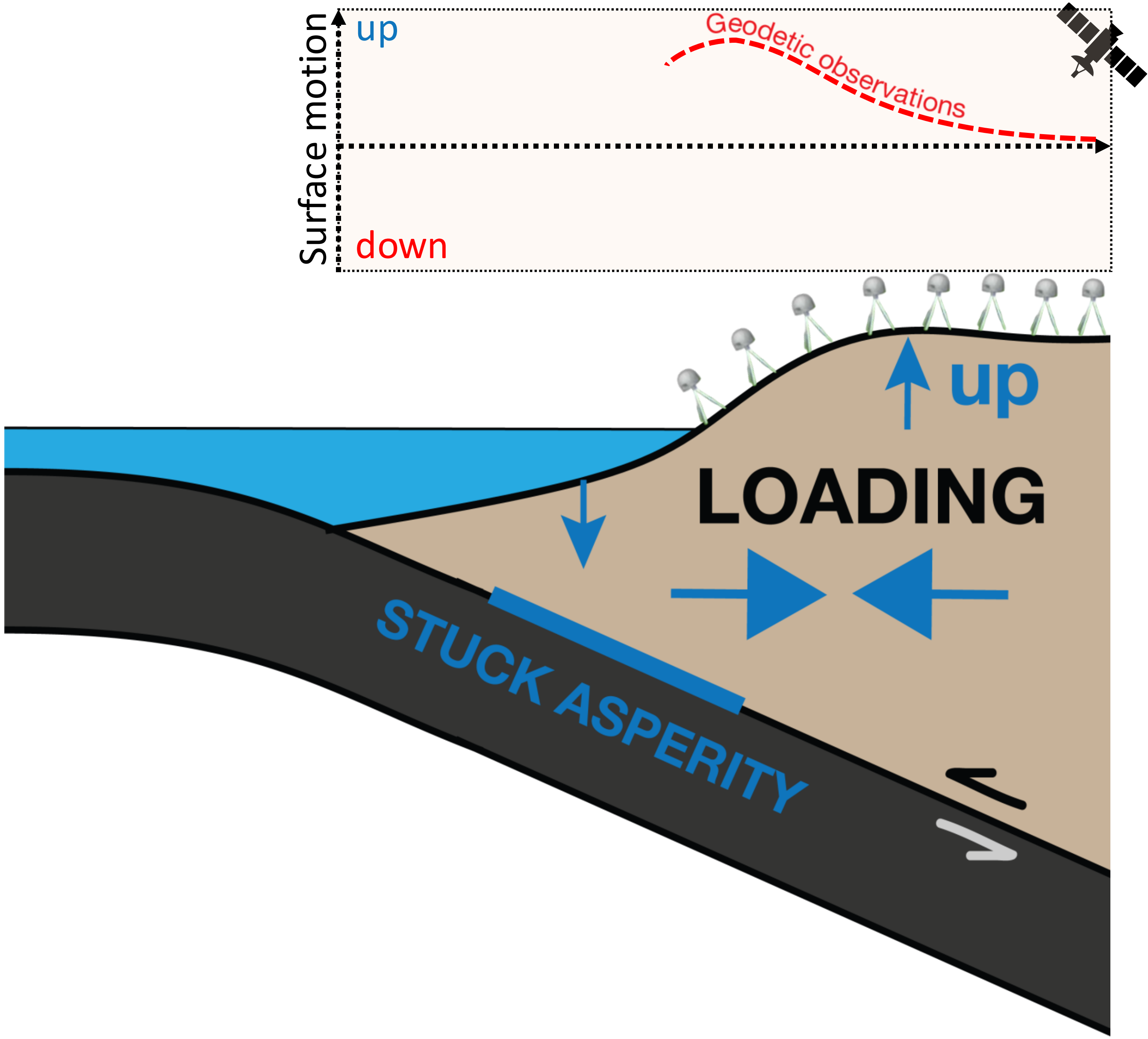

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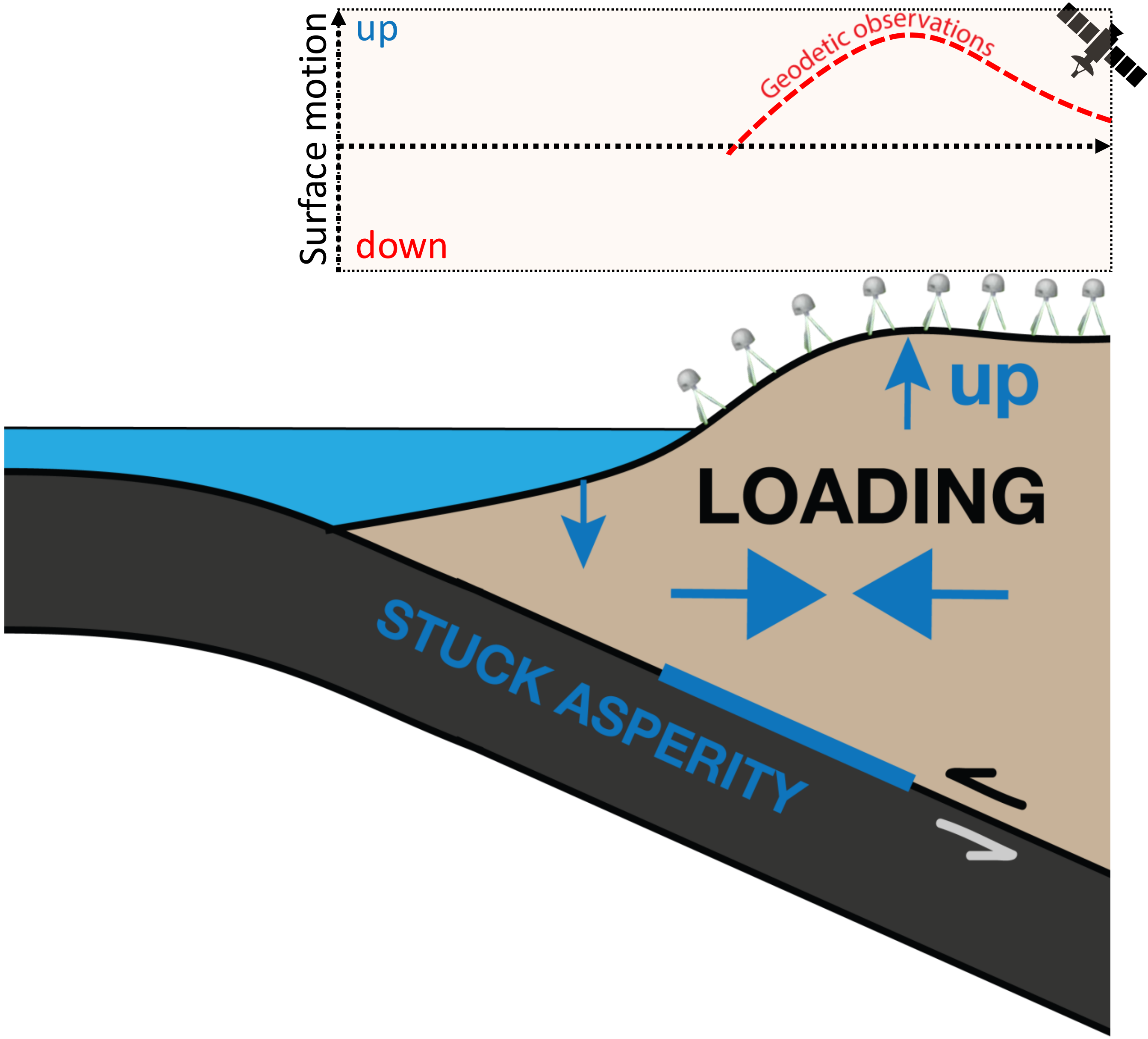

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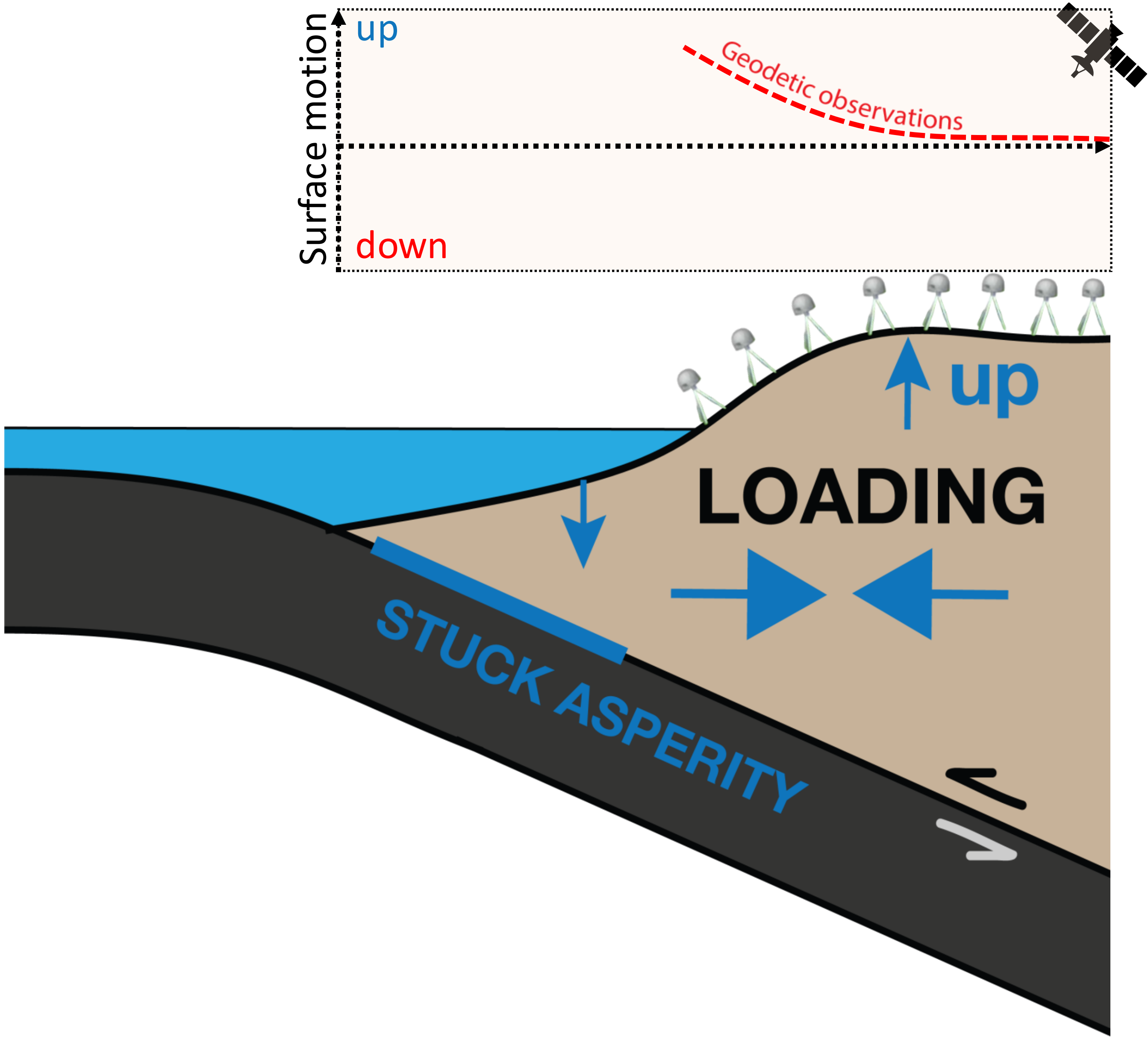

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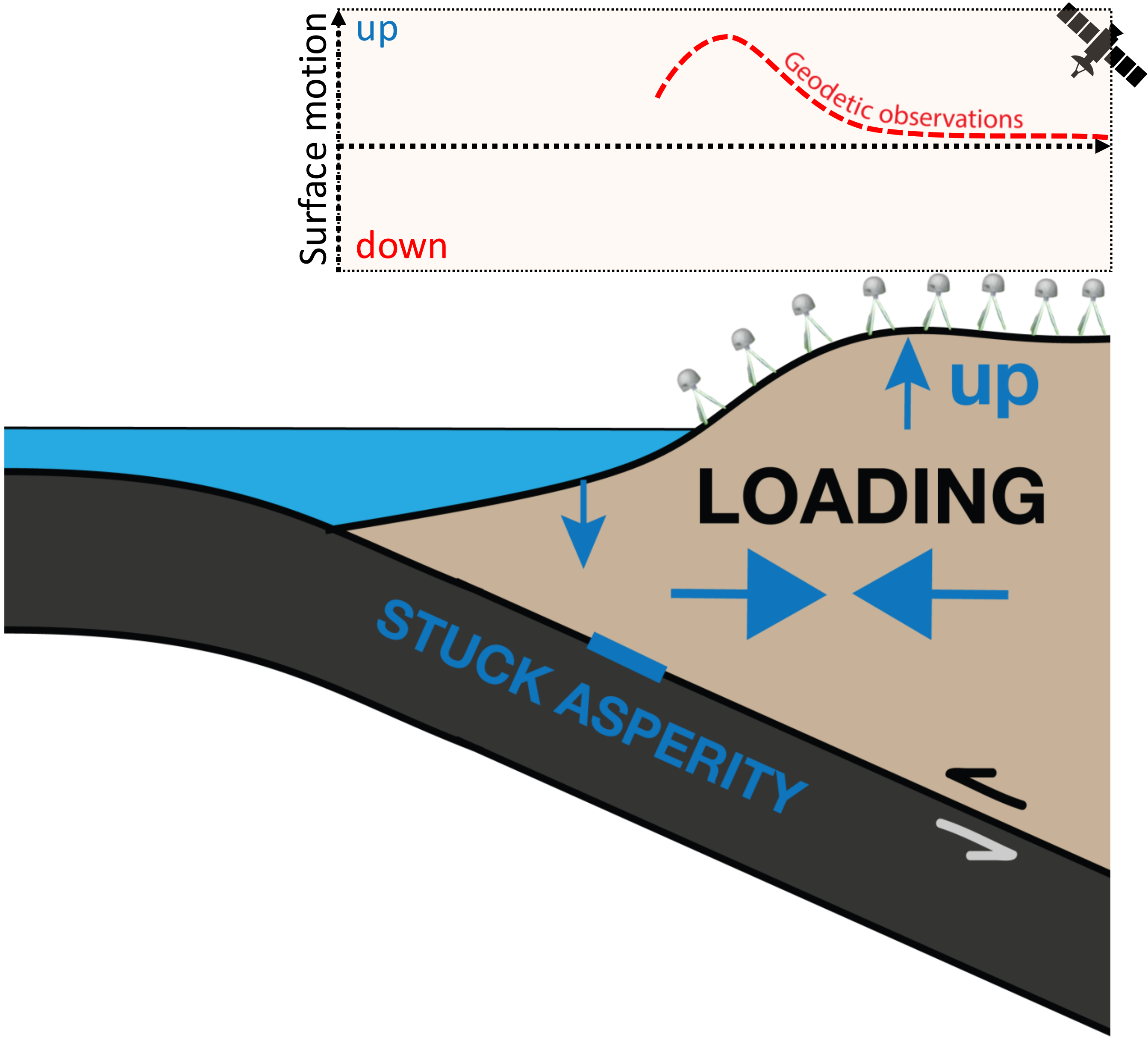

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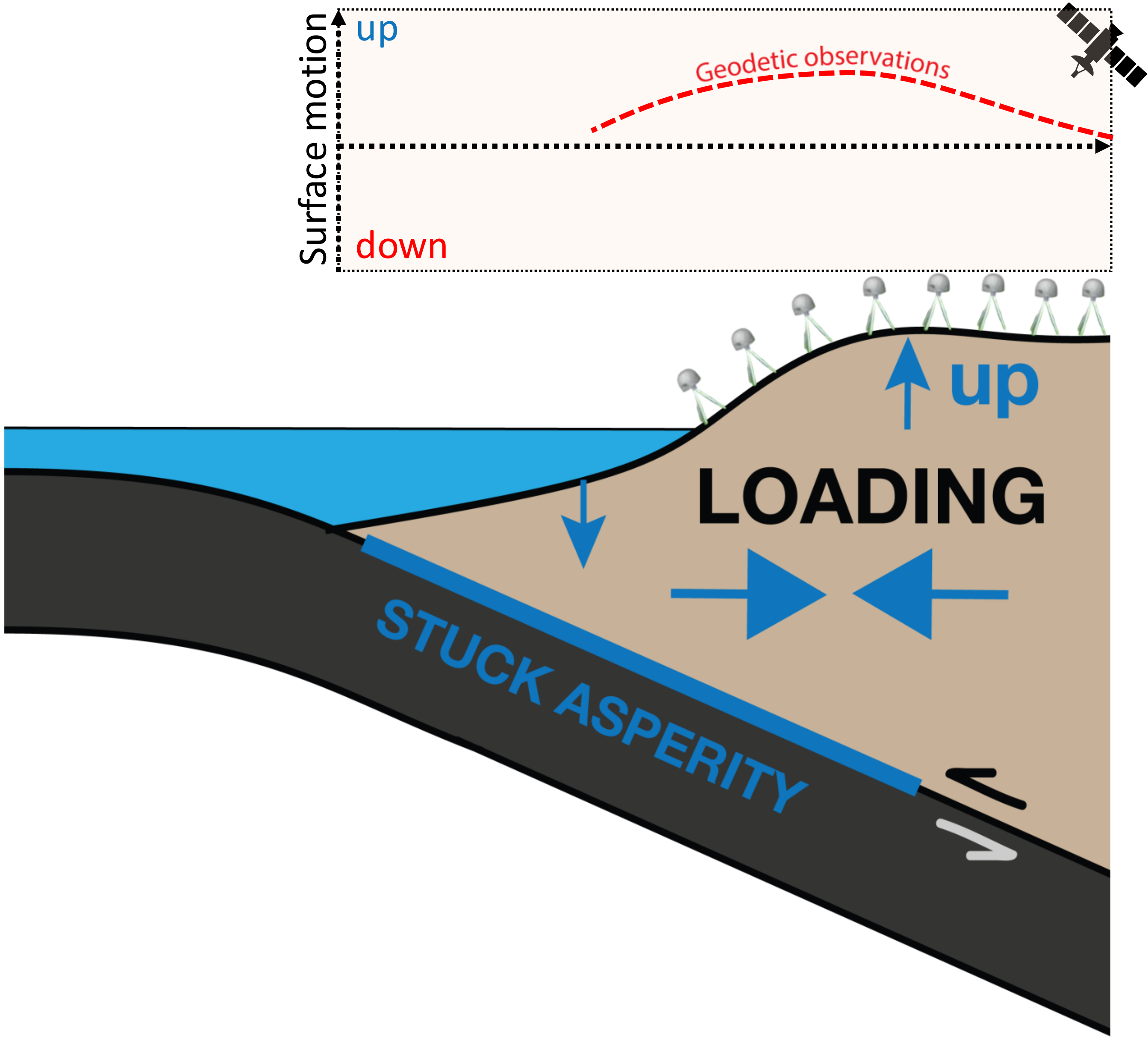

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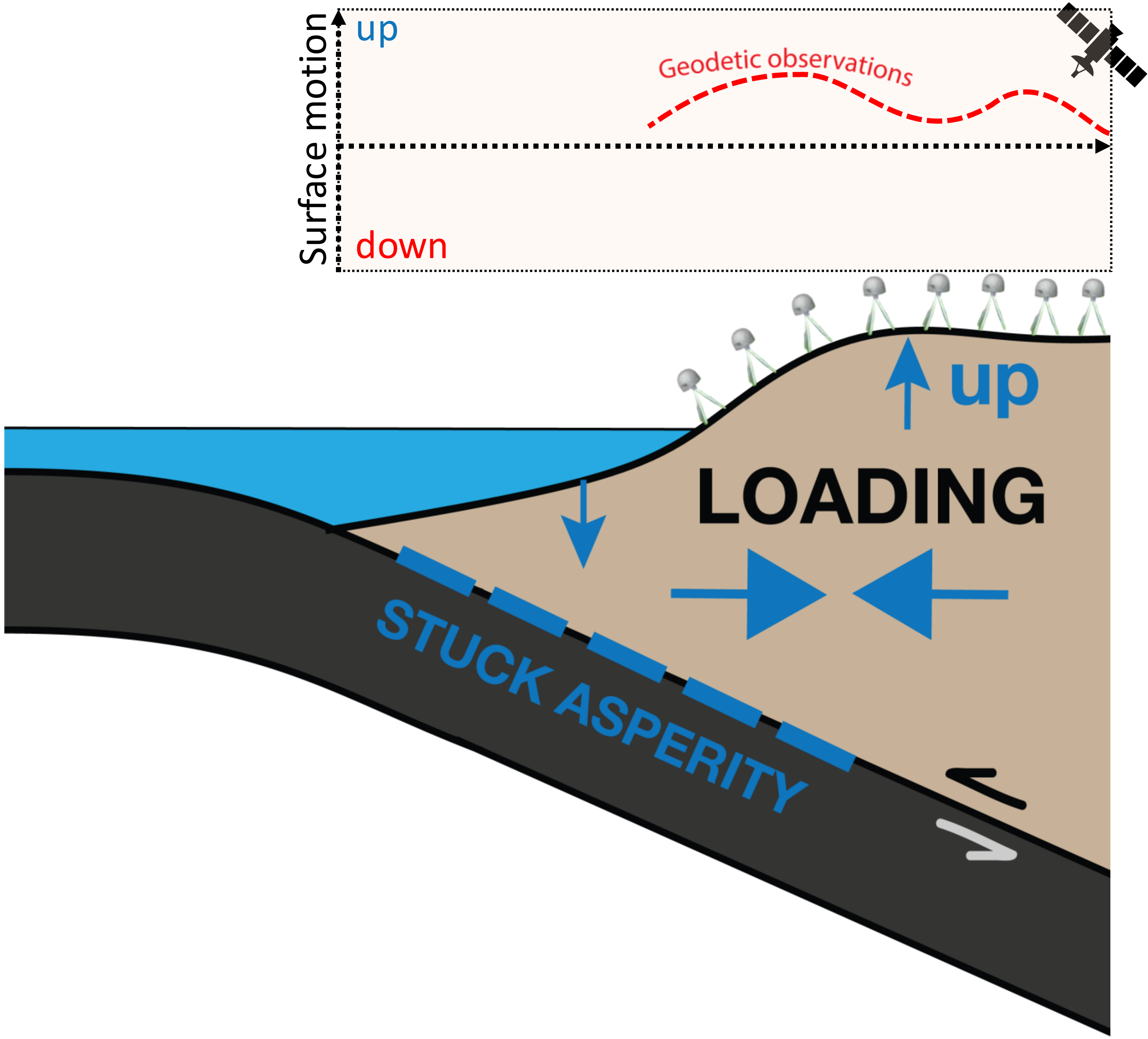

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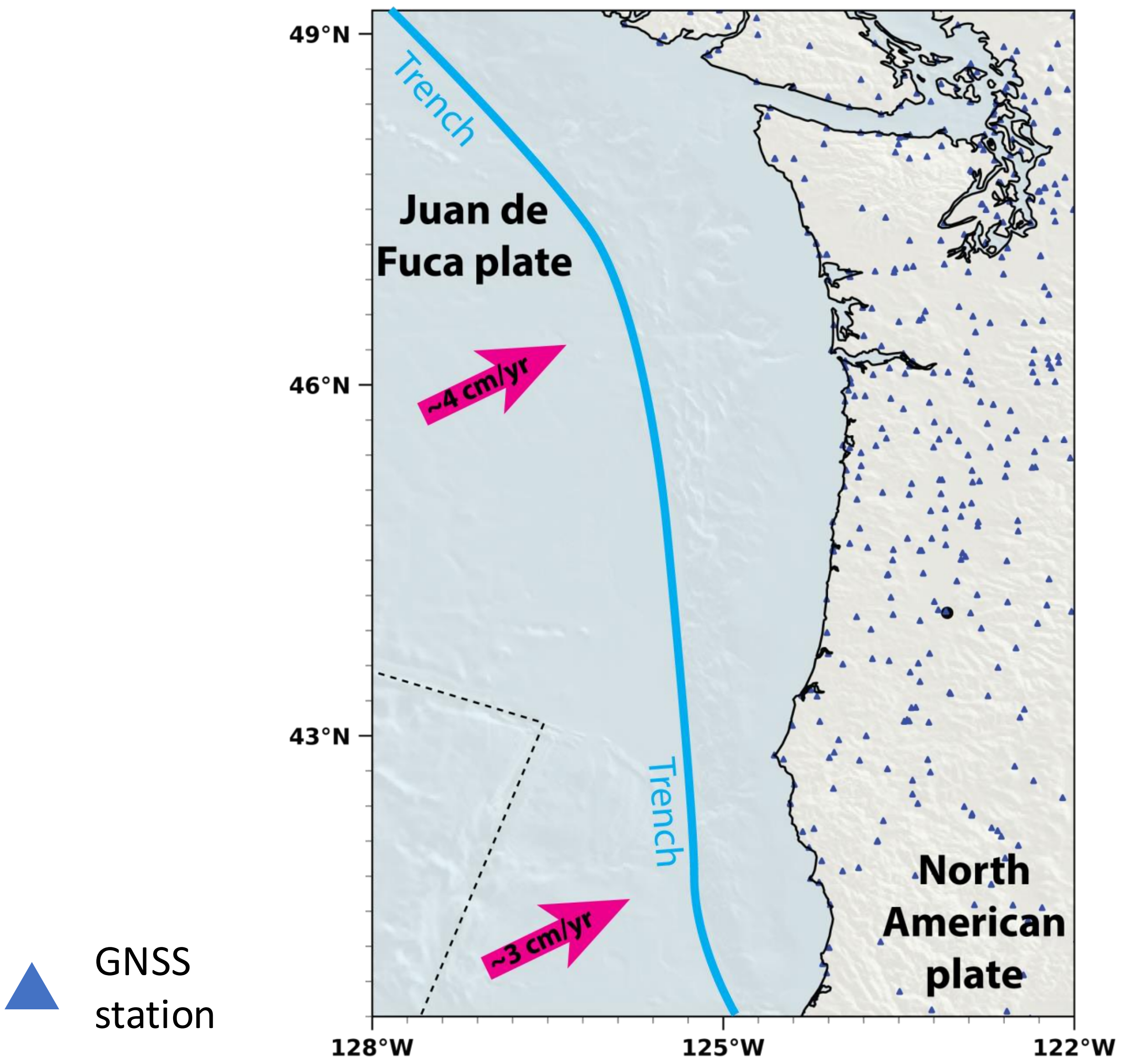
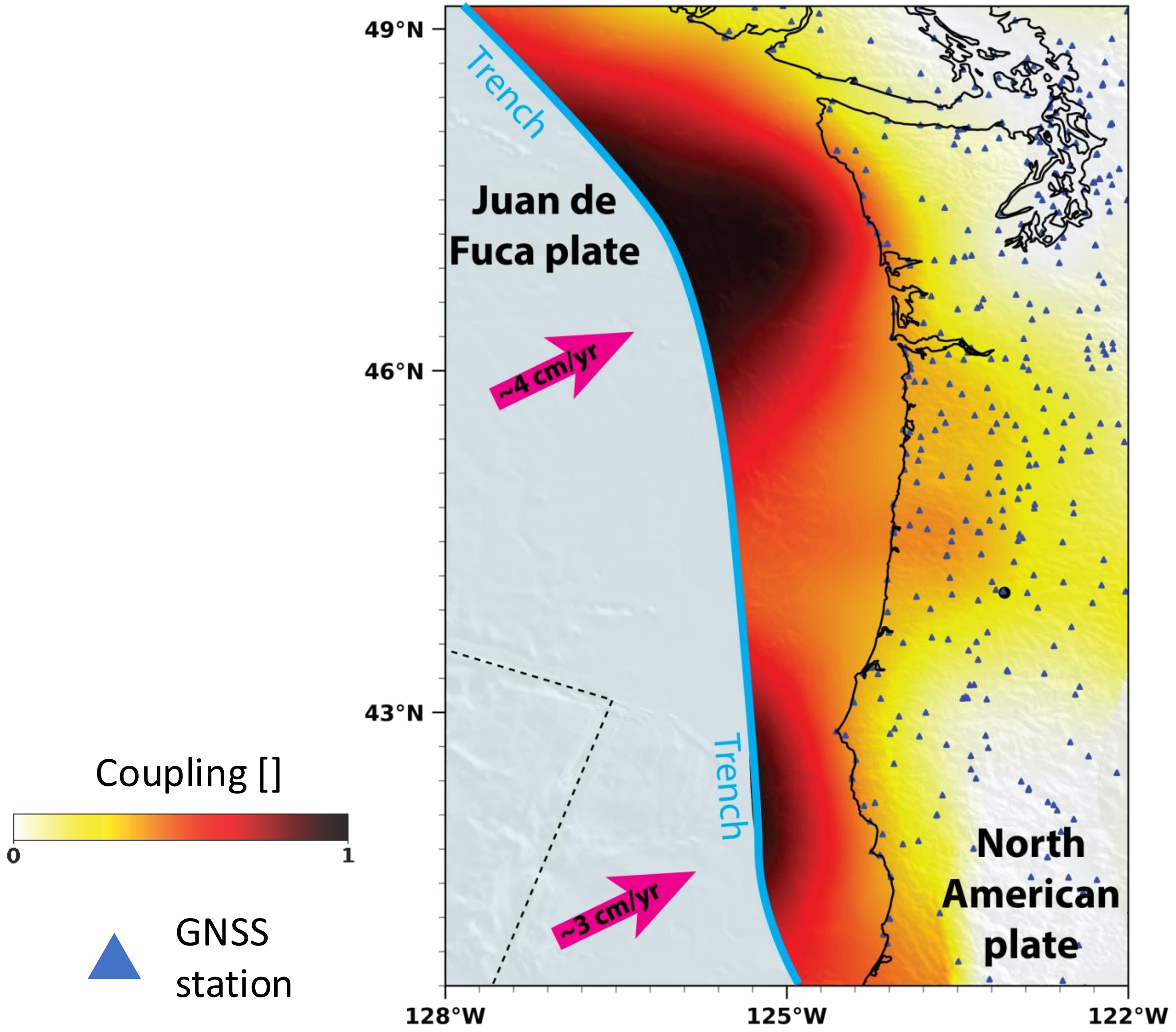


CONSTRAINING MEGATHRUST HAZARD IN SUBDUCTION ZONES

- Locked asperities along the megathrust are often represented using coupling maps.

Coupling in Cascadia [Lindsey et al., 2021]



CONSTRAINING MEGATHRUST HAZARD IN SUBDUCTION ZONES

- Locked asperities are often represented using coupling maps.
- Regions with high coupling values are considered locked and stationary.

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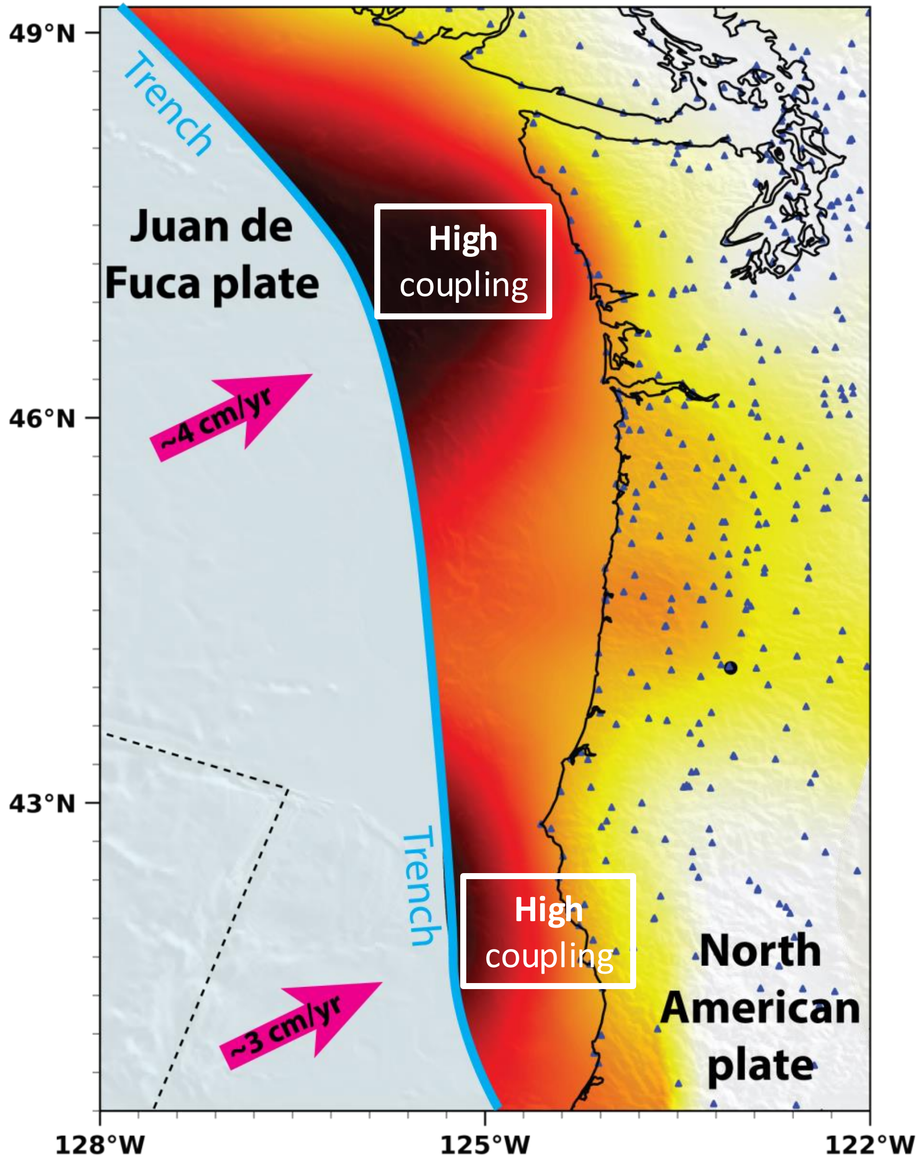

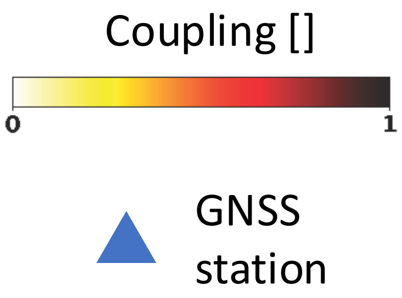

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- Locked asperities are often represented using coupling maps.
- Regions with high coupling values are considered locked and stationary.
- These locked regions are believed to accumulate interseismic stresses and are more likely to generate megathrust events.

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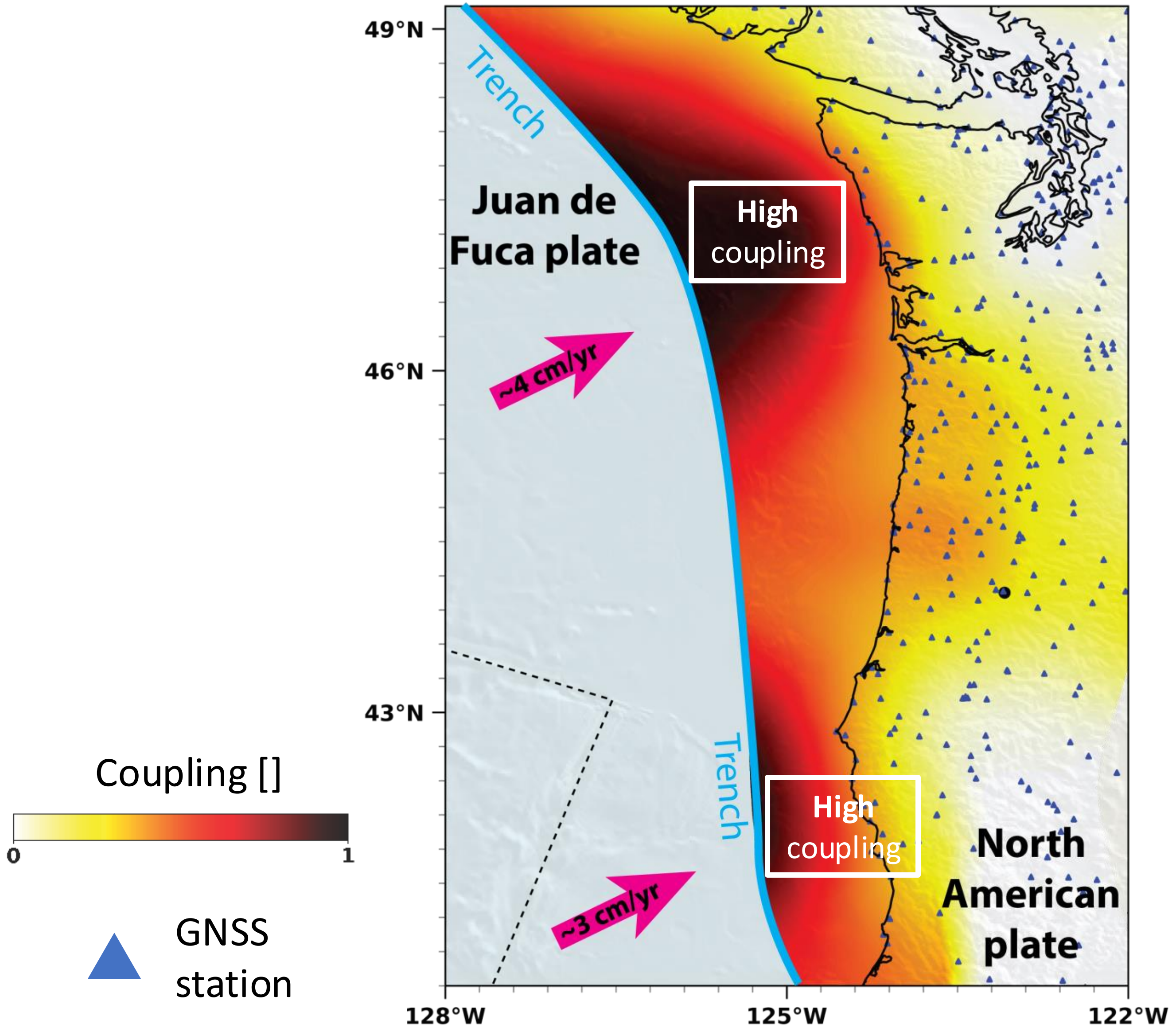
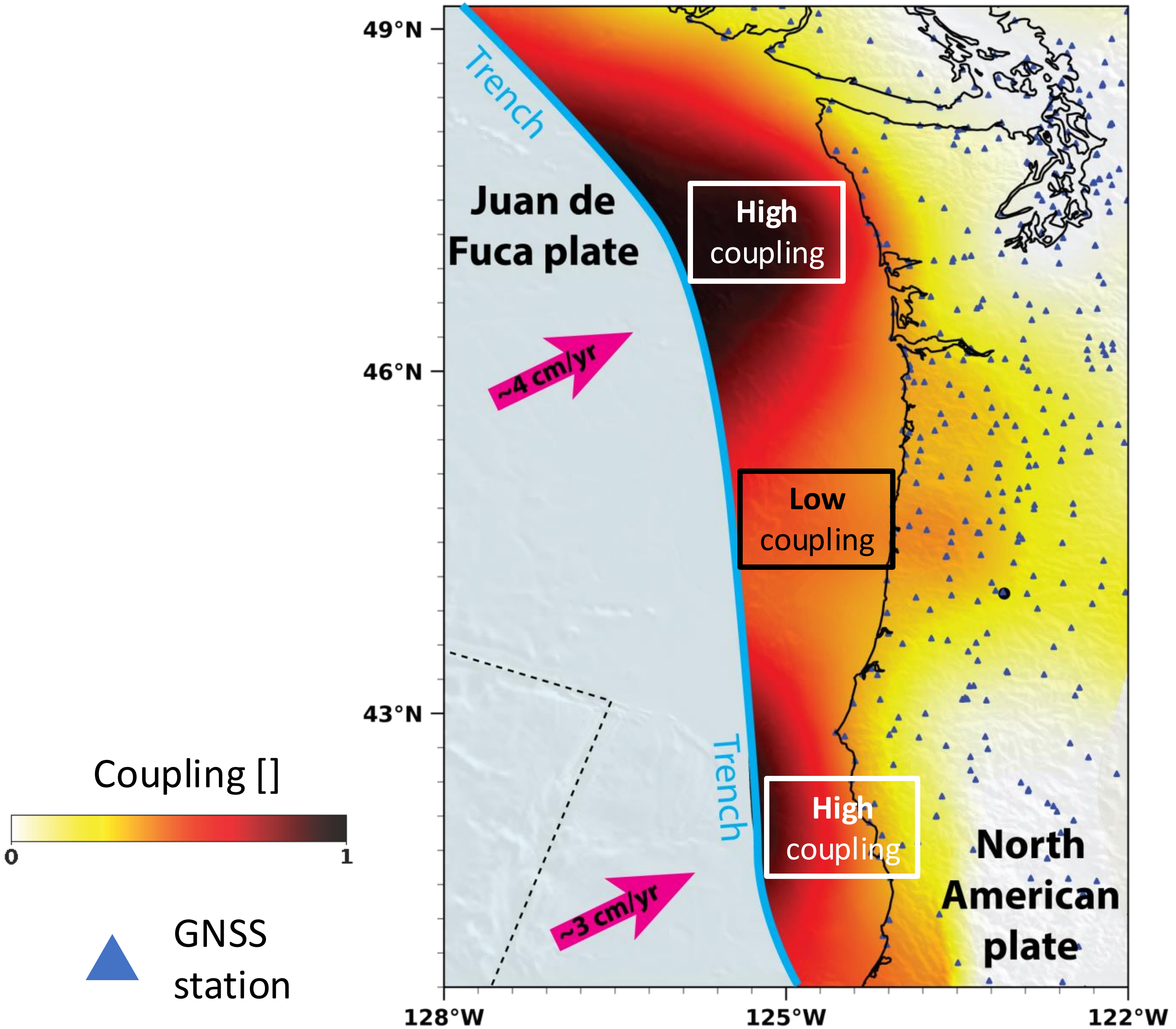


CONSTRAINING MEGATHRUST HAZARD IN SUBDUCTION ZONES

- Locked asperities are often represented using coupling maps.
- Regions with high coupling values are considered locked and stationary.
- These locked regions are believed to accumulate interseismic stress and are more likely to generate megathrust events.
- In contrast, regions with low coupling values are thought to creep during the interseismic period and are less likely to rupture.

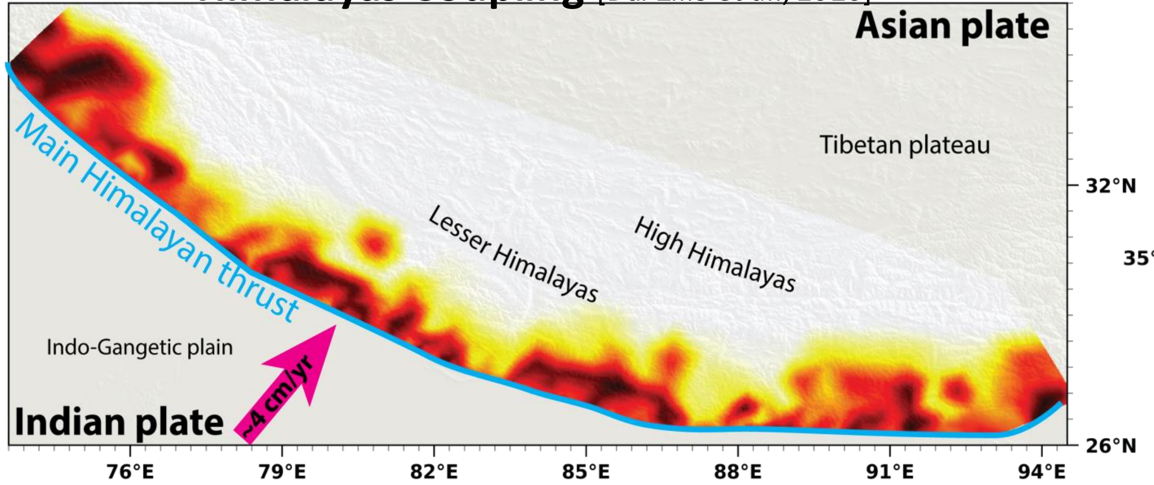
Coupling in Cascadia [Lindsey et al., 2021]



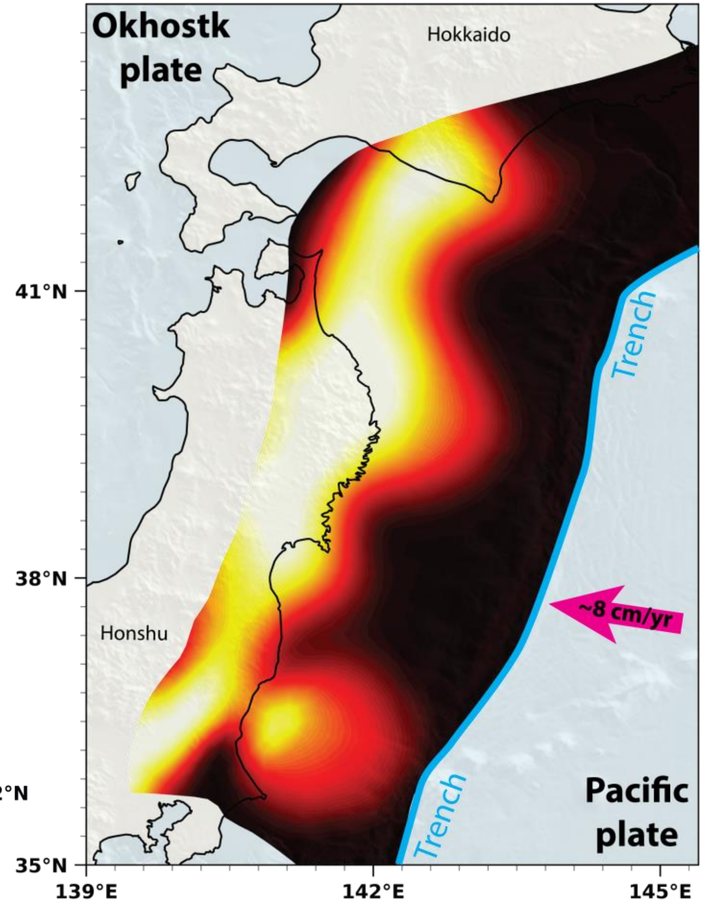
CONSTRAINING MEGATHRUST HAZARD IN SUBDUCTION ZONES

Coupling maps are used to illustrate fault locking variability across **nearly all megathrusts where geodetic data is available.**

Himalayas Coupling [Dal Zilio et al., 2020]

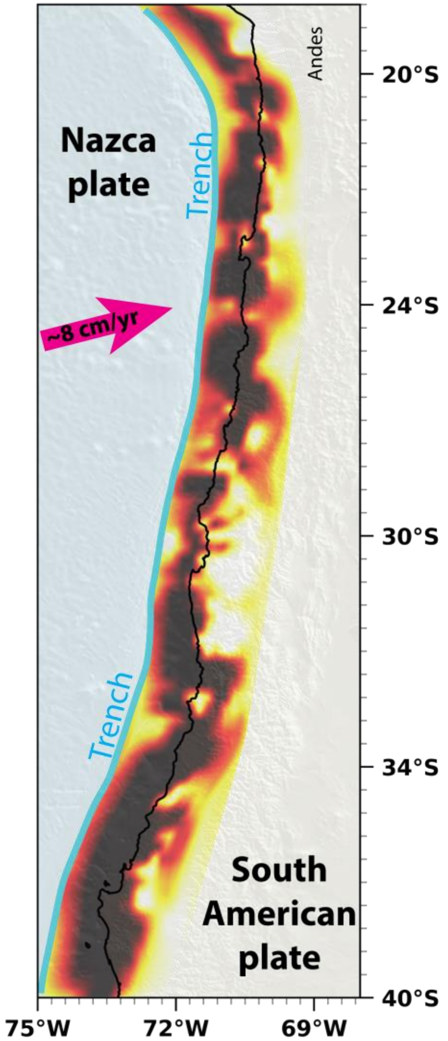


Japan Coupling [Lindsey et al., 2021]

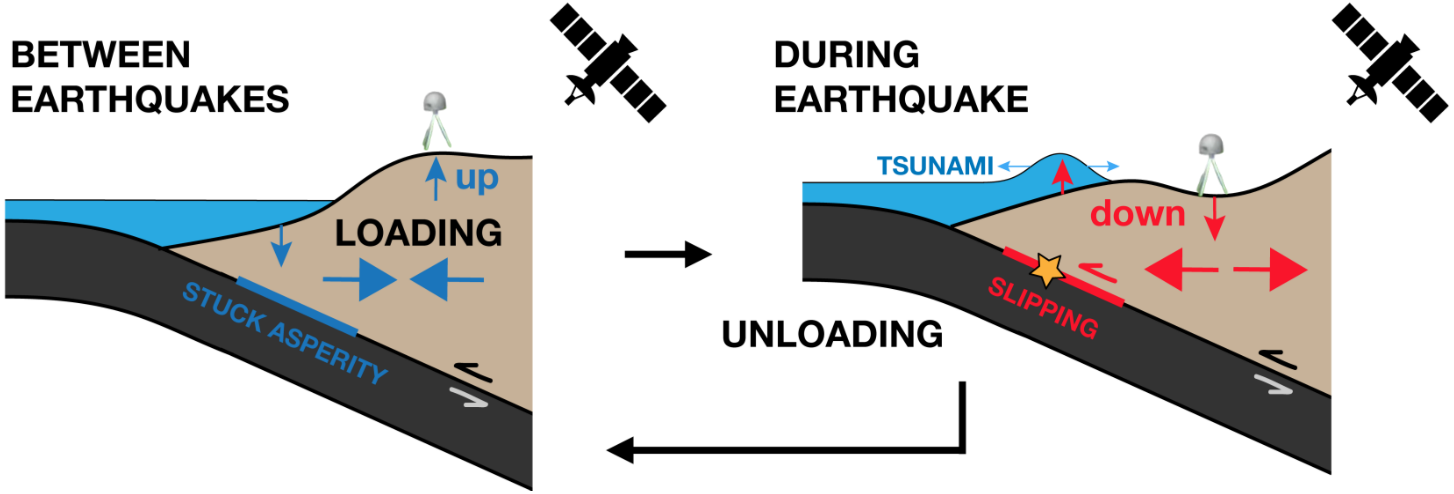


Chile Coupling

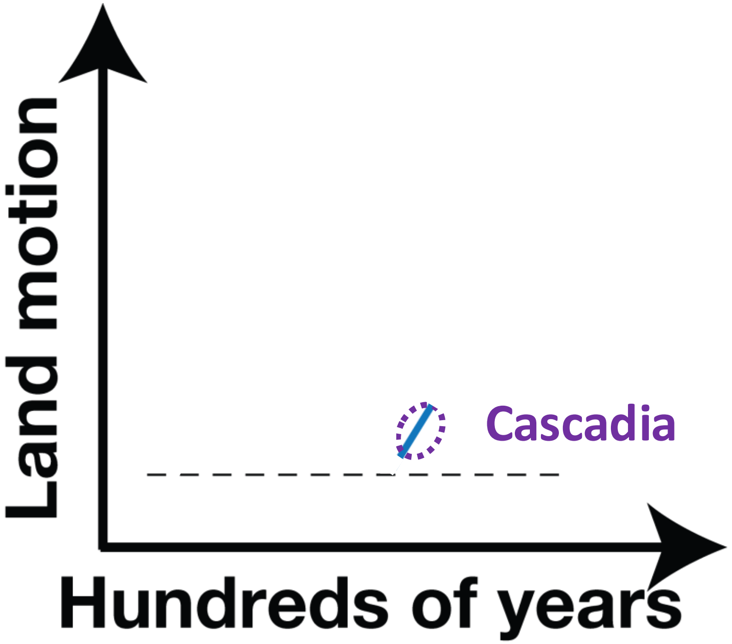
[Métois et al., 2016]



TEMPORAL LIMIATIONS OF GEODETIC DATA COVERAGE



- Geodetic data only captures a **small fraction** of the timescale over which **earthquake cycles operate.**



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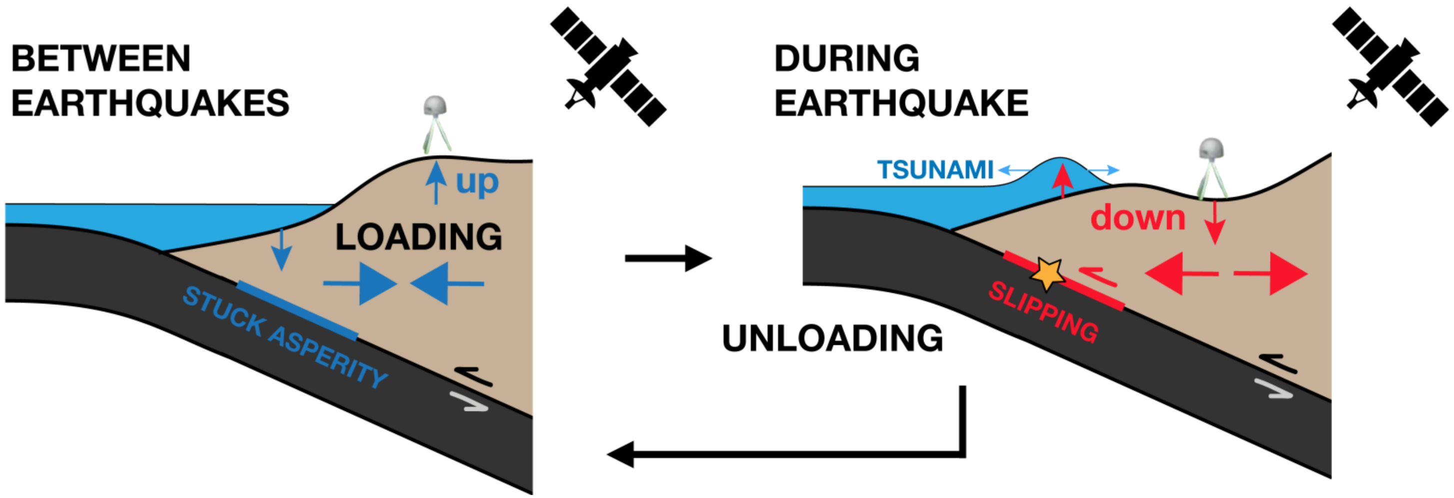

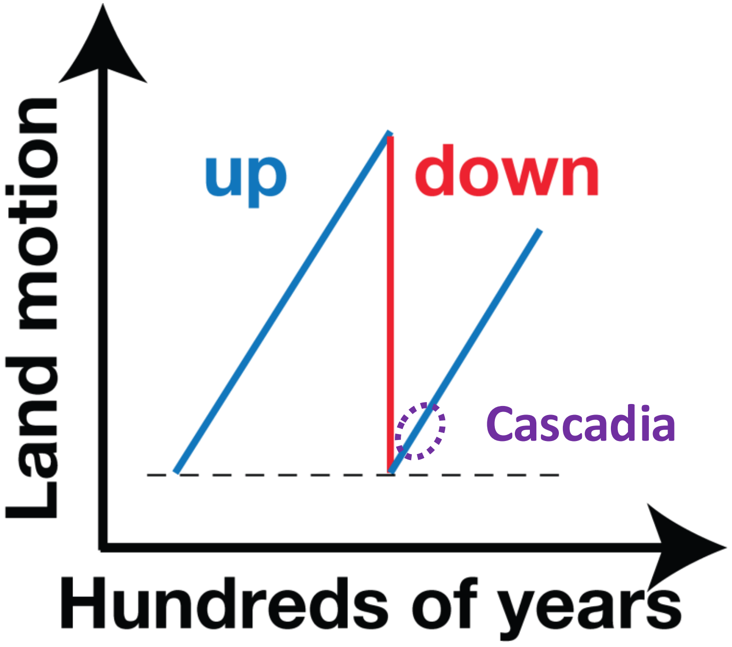

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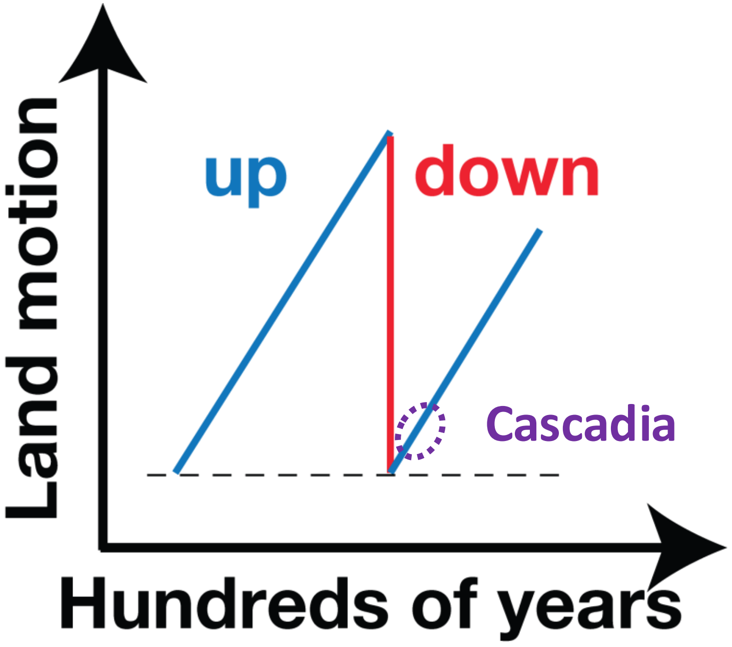
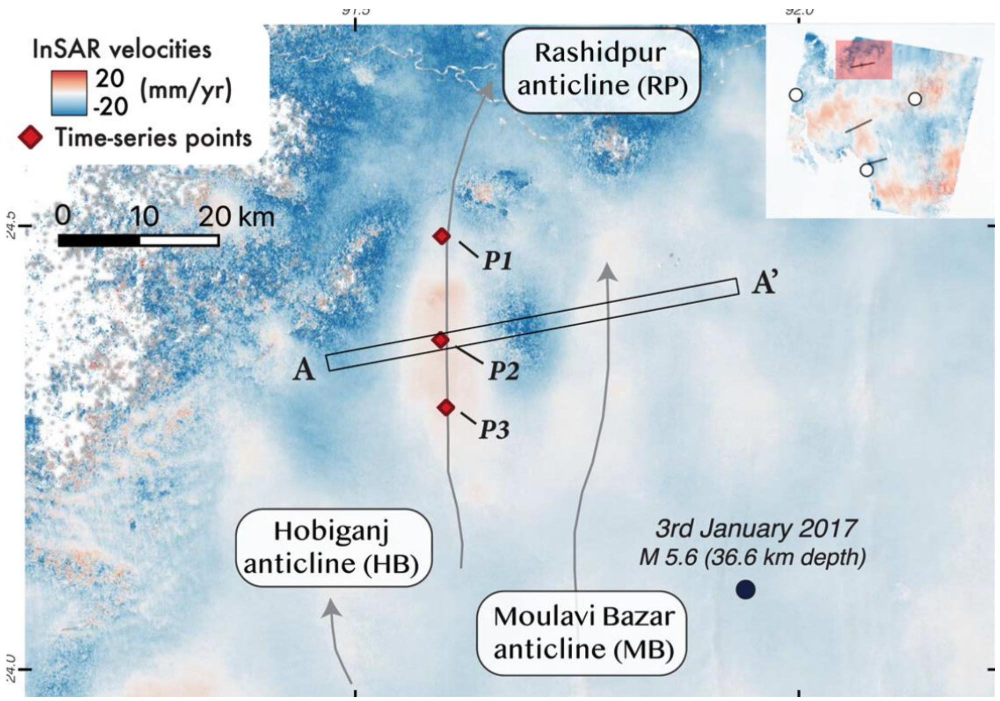


Viscous interseismic uplift of anticlines in the Indo-Burma subduction zone [Chong , **Oryan**, et al., 2024]



Geodetic observations indicate that the state of **coupling may evolve through time.**

TEMPORAL LIMITATIONS OF GEODETIC DATA COVERAGE

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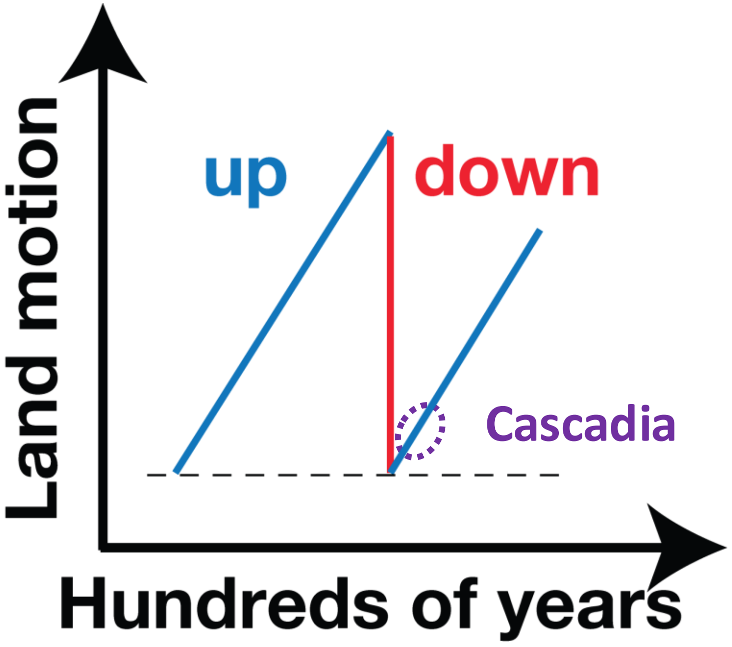
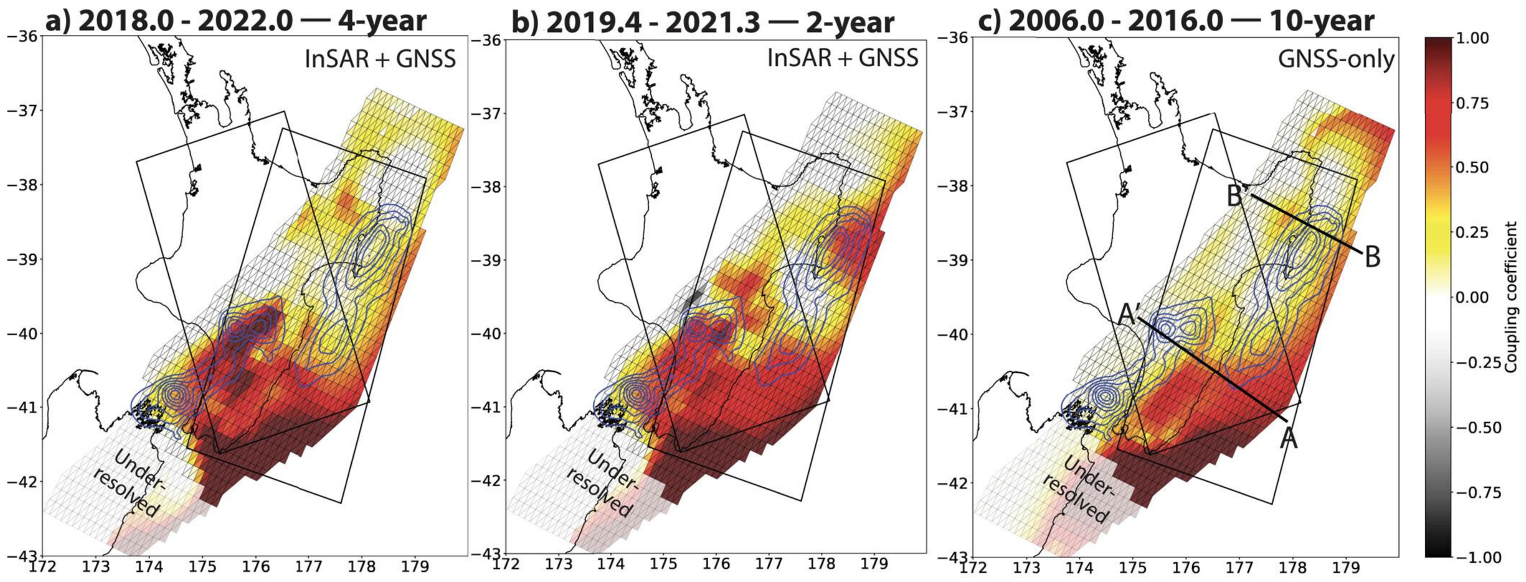


Locking in Hikurangi Subduction Zone varations based on different temporal resolution [Maubant et al., 2023].



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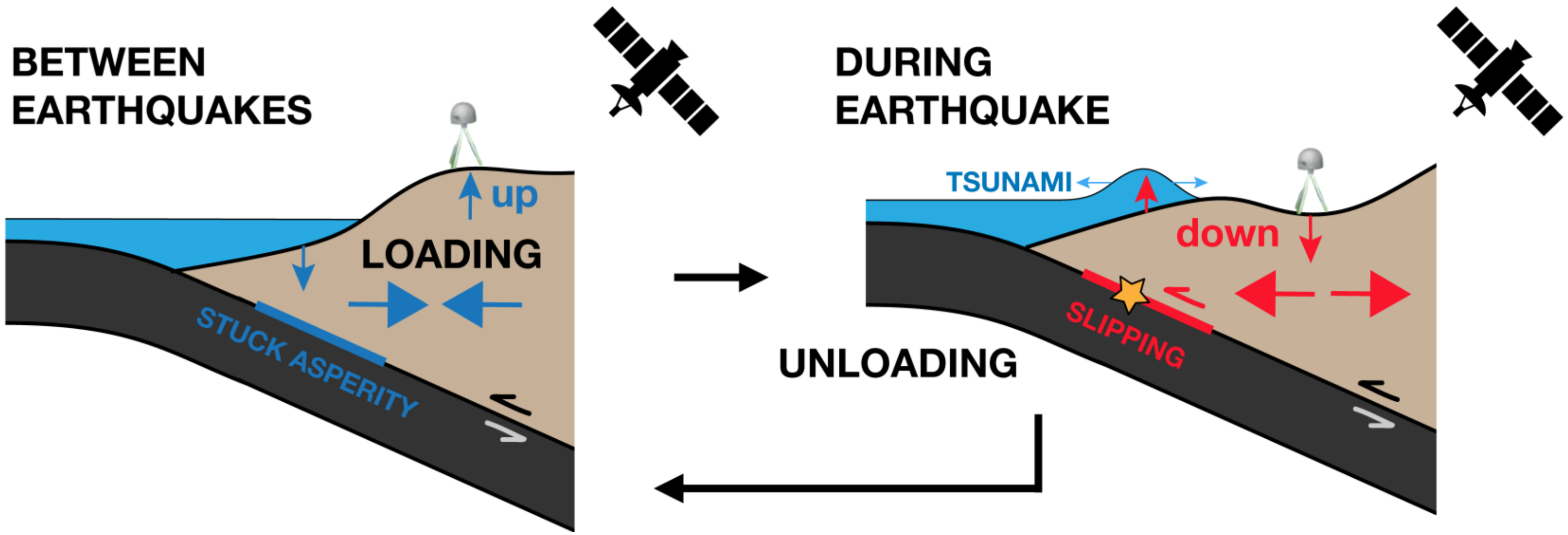
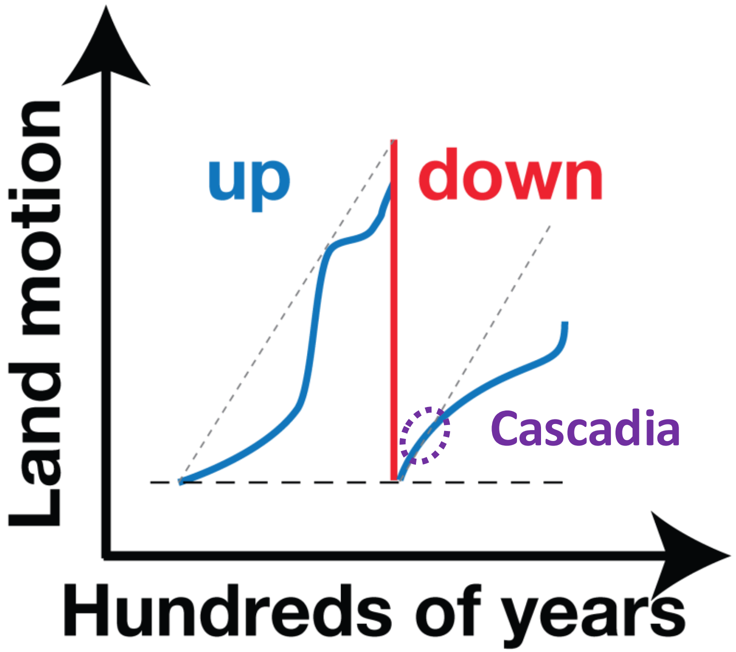




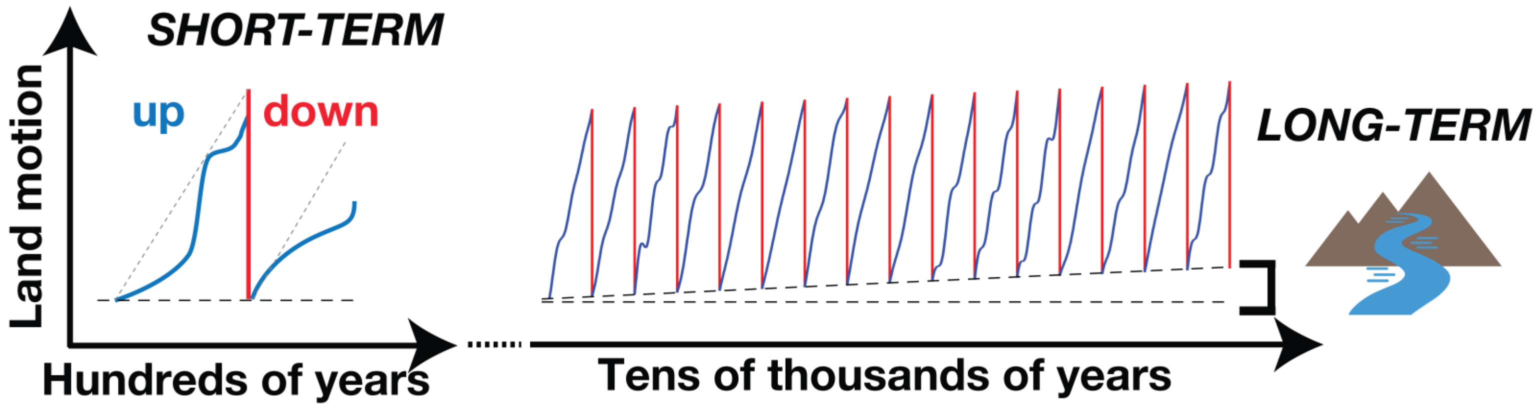
Current geodetic efforts to constrain coupling may be **overlooking key deformation components.**

TEMPORAL LIMITATIONS OF GEODETIC DATA COVERAGE

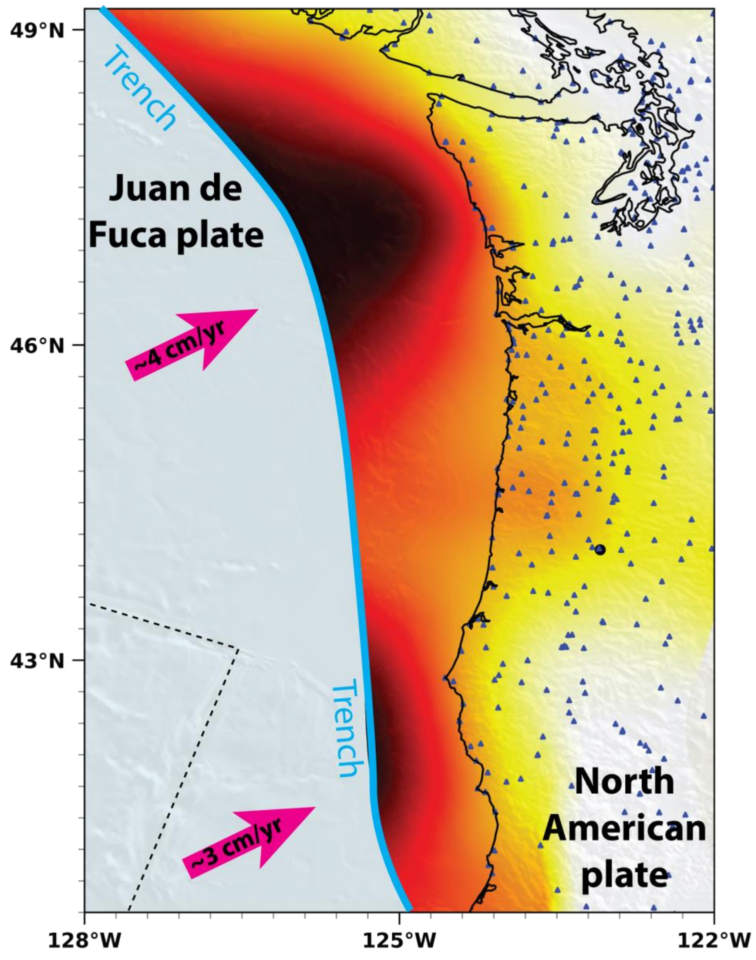
- Geodetic d... **small fract...** over which... **operate.**
- The recode... often **extra...** the **entire**...

KEY POINTS SO FAR

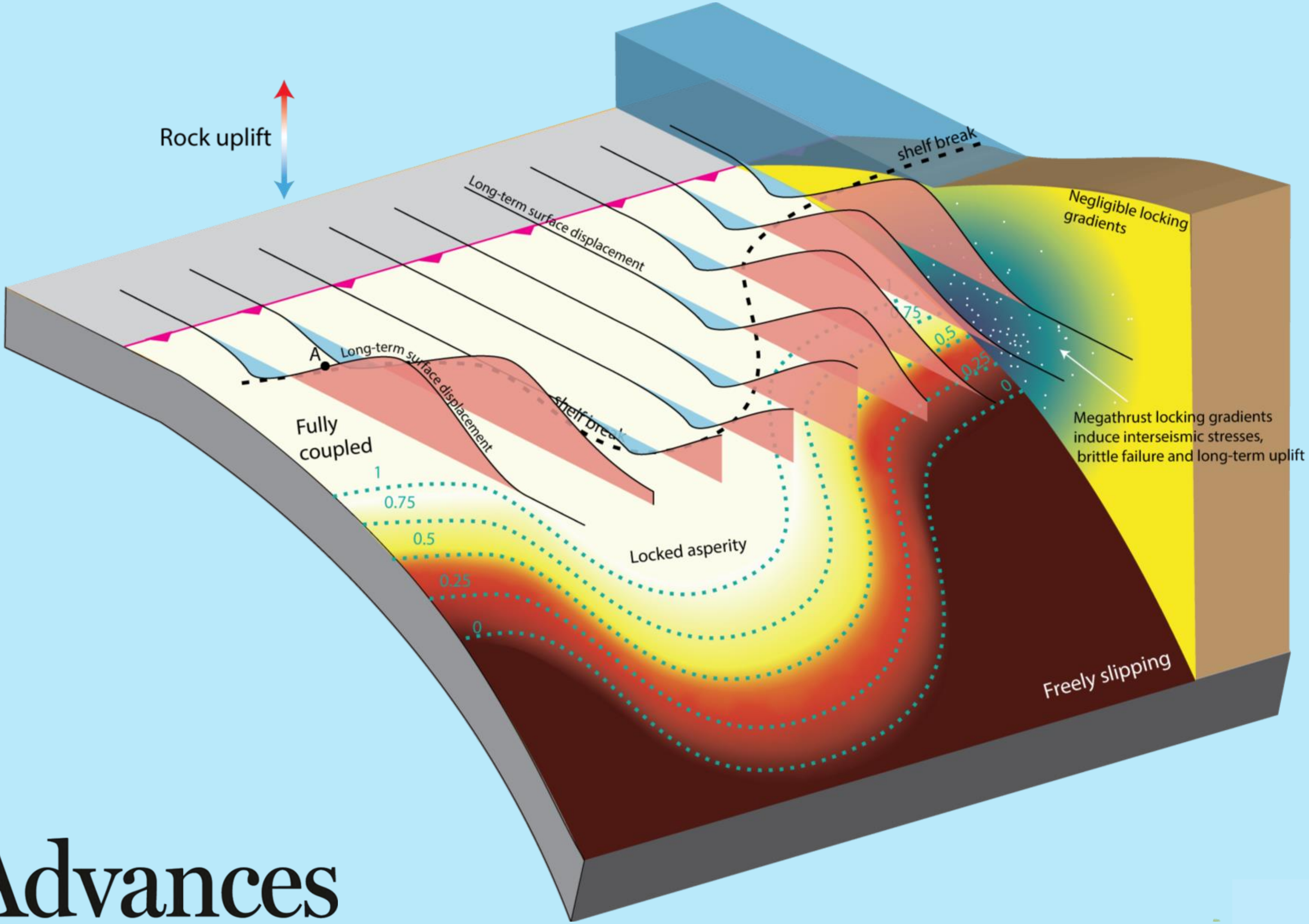
- Geodetic documentation of upper plate deformation help constrain the hazard associated with megathrust earthquakes.
- Geodetic data captures only a **small fraction** of the timescale over which **earthquake cycles operate.**
- **Landscapes record deformation** on time-scales of **hundreds of thousands of years and** could point to the **persistent plate locking.**



Coupling in Cascadia [Lindsey et al., 2021]



Section 2 - Fingerprints of Megathrust Locking in Subduction Landscapes

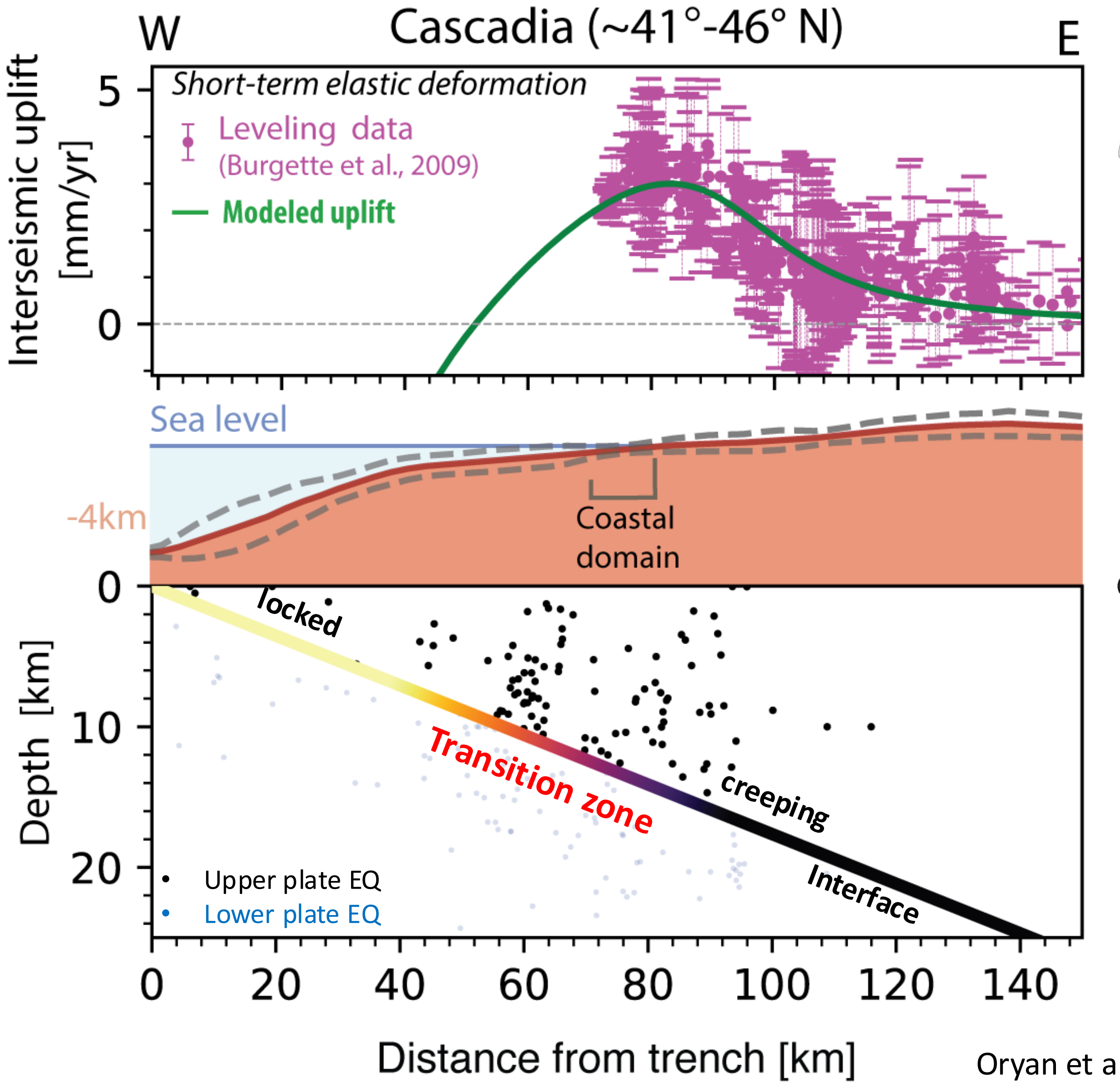


Science Advances

Oryan et al., 2024

SHORT-TERM DEFORMATION IN CASCADIA

- **Short-term (geodetic)** uplift shows a peak above the transition zone.



Oryan et al., 2024

SHORT- AND LONG-TERM DEFORMATION IN CASCADIA

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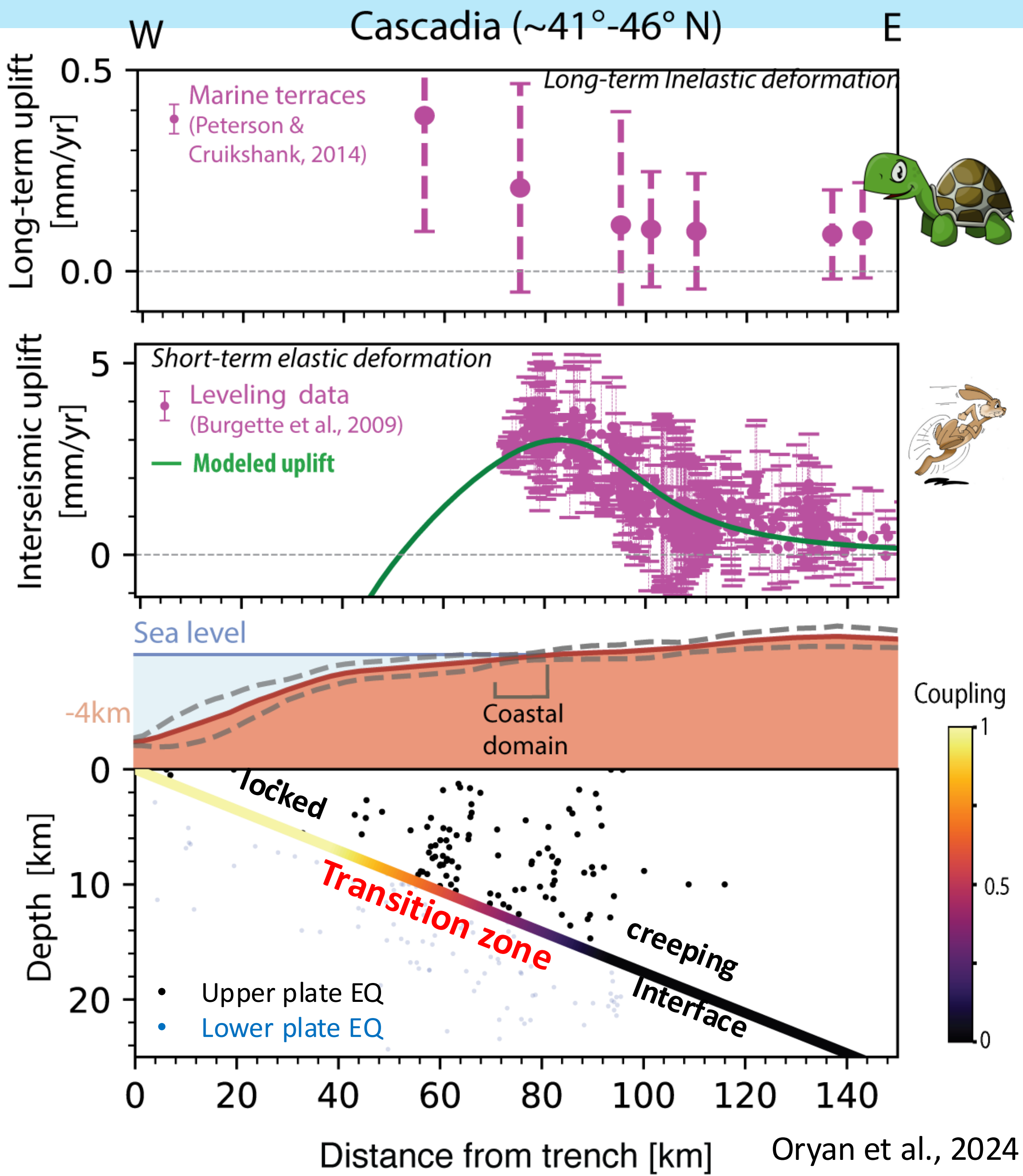

Oryan et al., 2024

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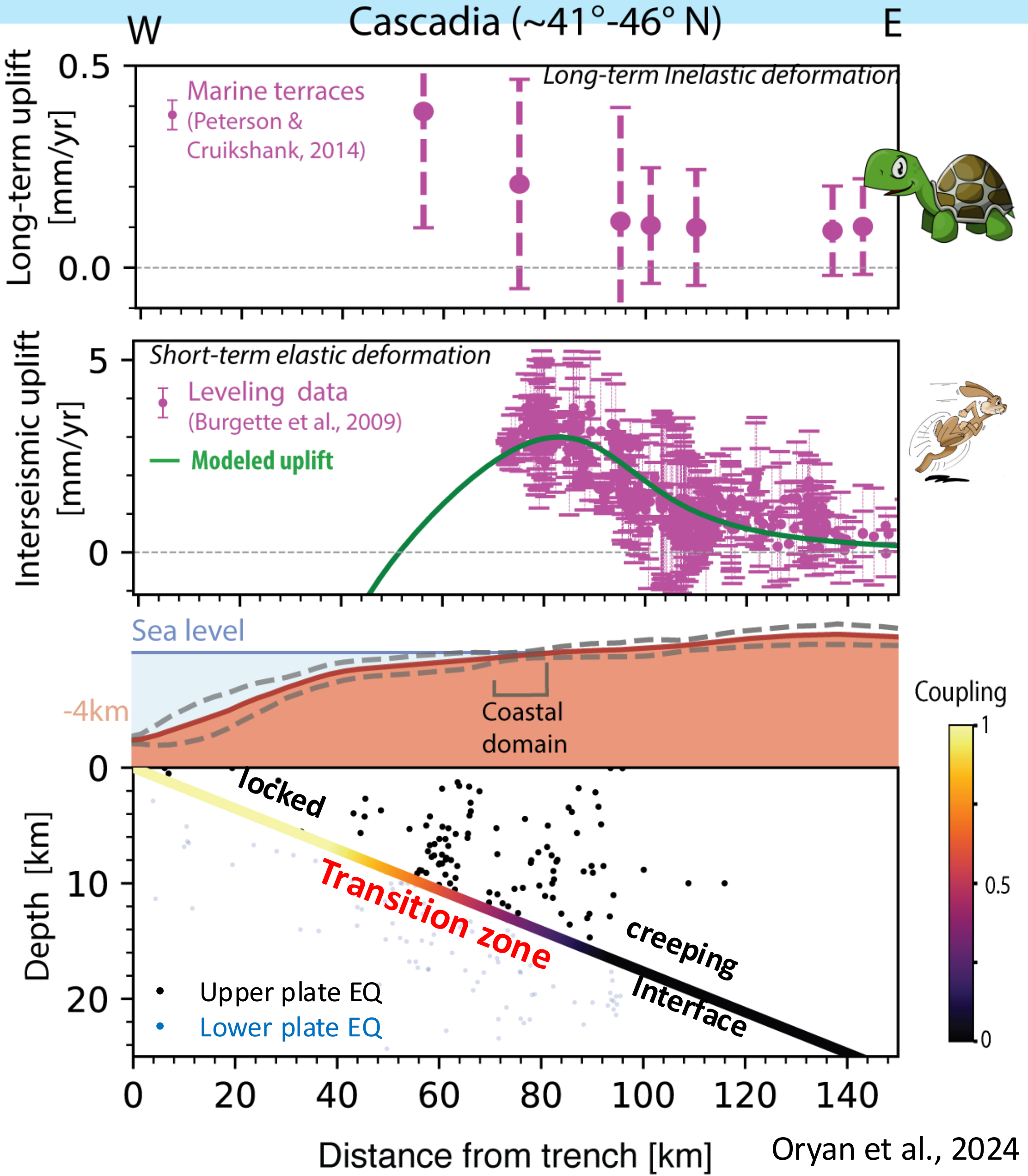

Oryan et al., 2024

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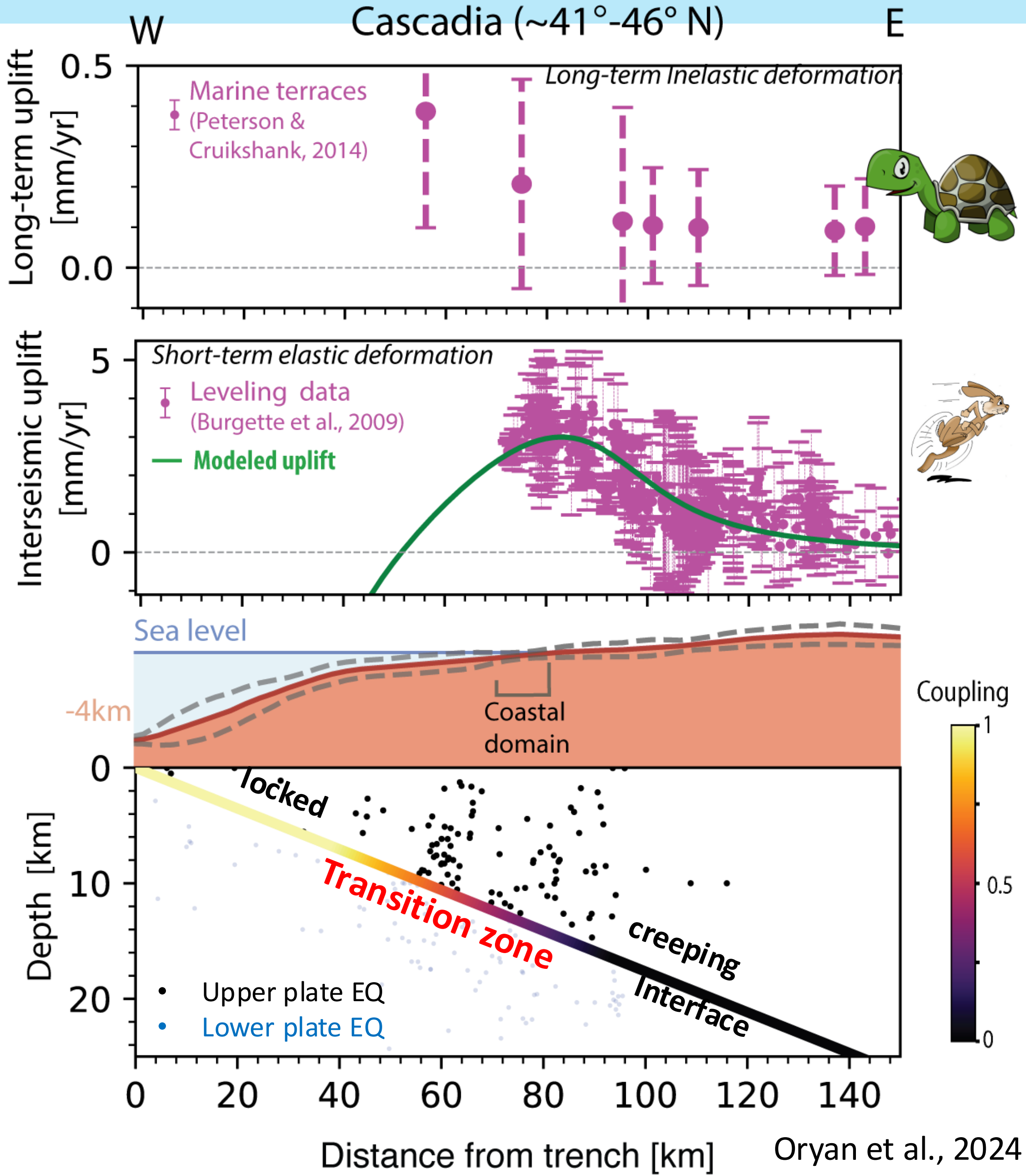

Oryan et al., 2024

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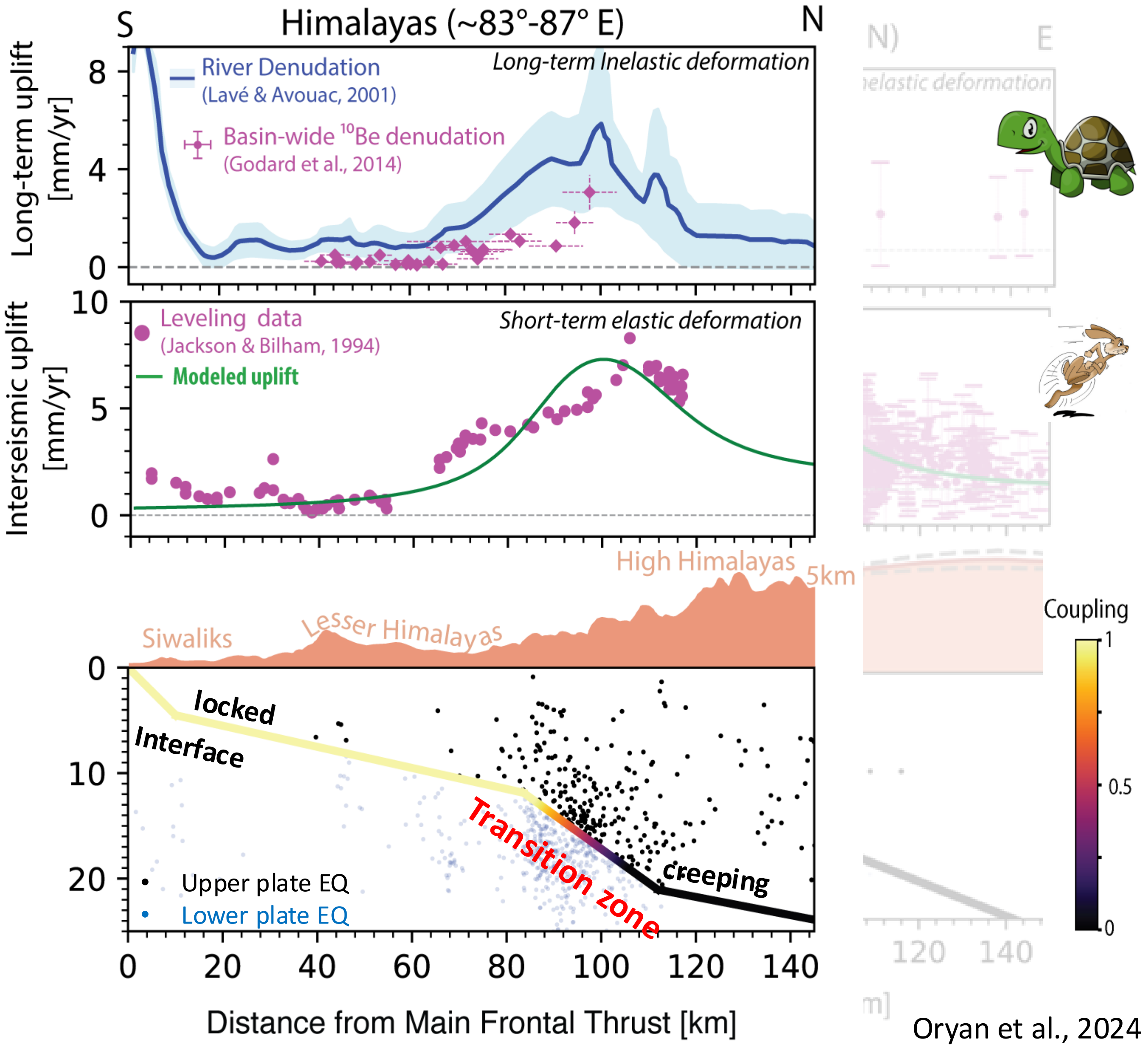

Oryan et al., 2024

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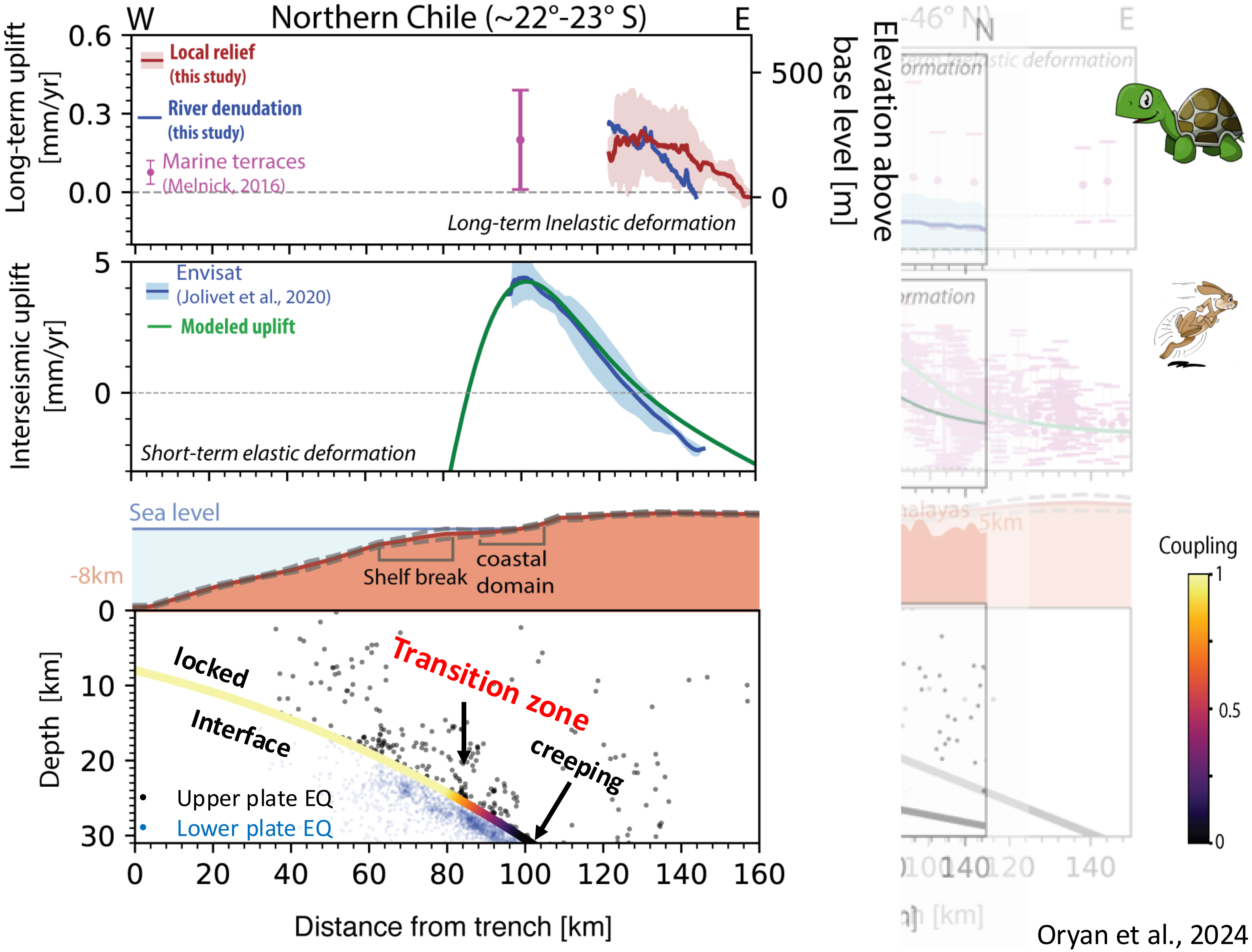


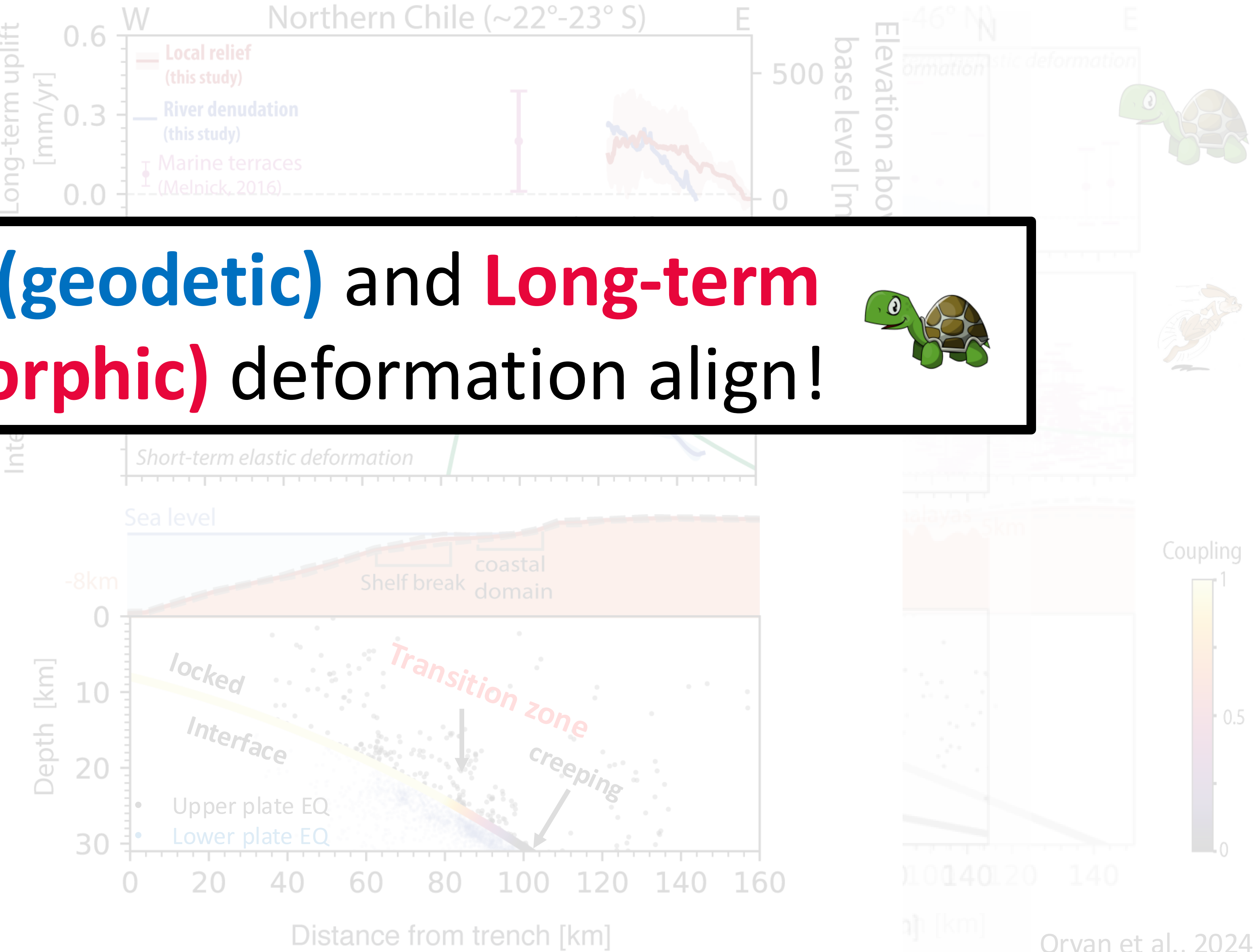
Short- (geodetic) and **Long-term (geomorphic)** deformation coincide.

Oryan et al., 2024

SHORT- AND LONG-TERM DEFORMATION IN CHILE

- **Short-term (elastic)** uplift shows a peak above the transition zone.
- **Long-term** … aligns with … deformatio… the transiti… zone.
- **Upper plate seismicity (inelastic)** is concentrated above the transition zone.

Short- (elastic) and **Long-term (inelastic)** deformation coincide.

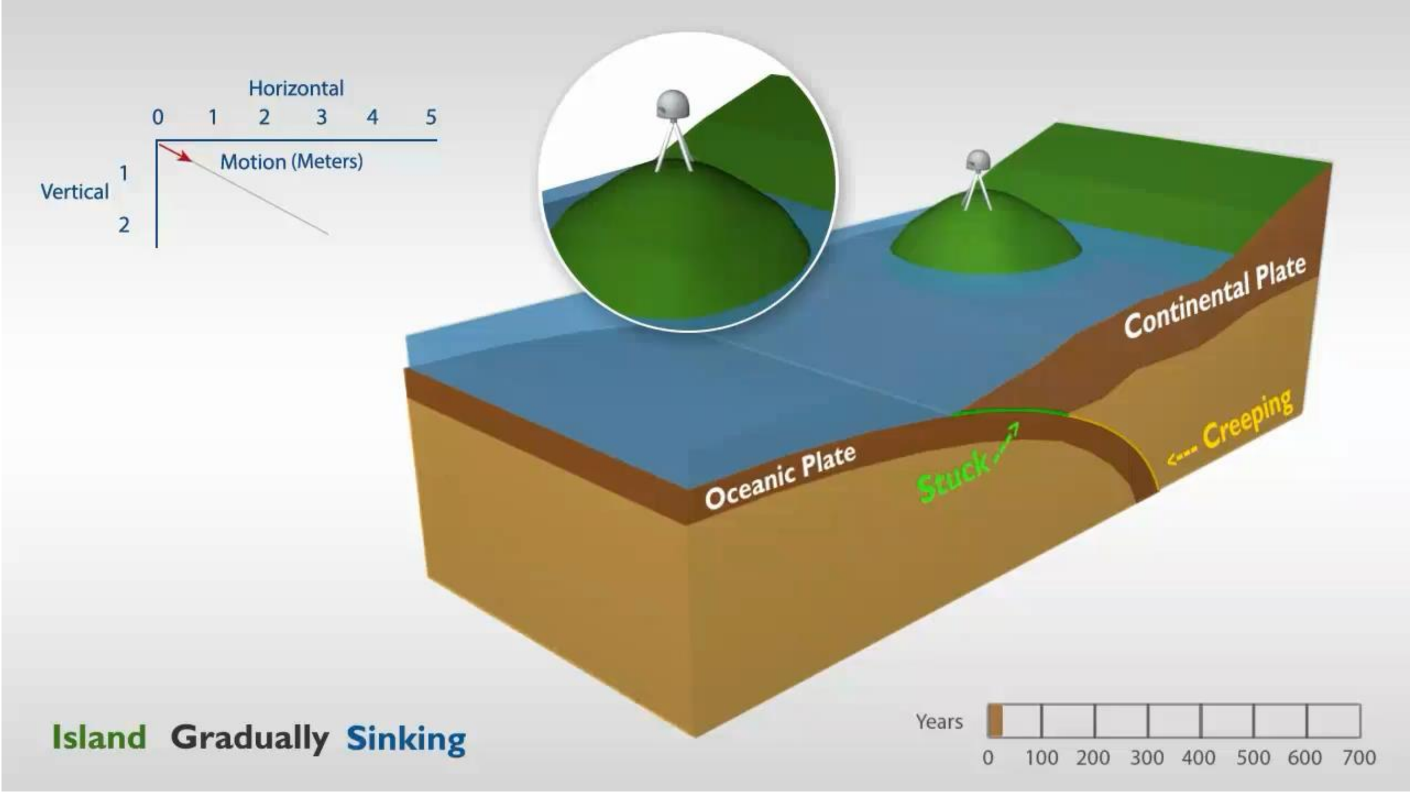


Short- (geodetic) and **Long-term (geomorphic)** deformation align!

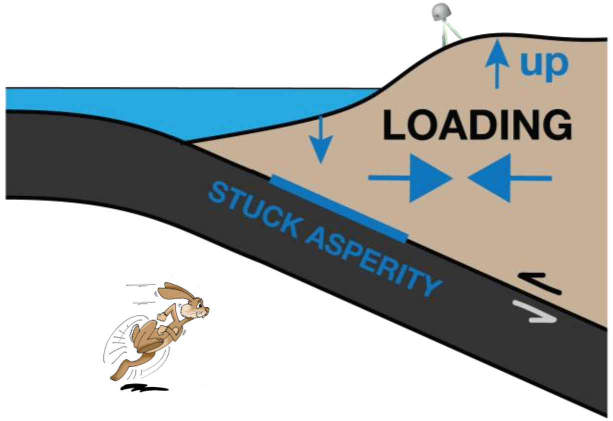
Oryan et al., 2024

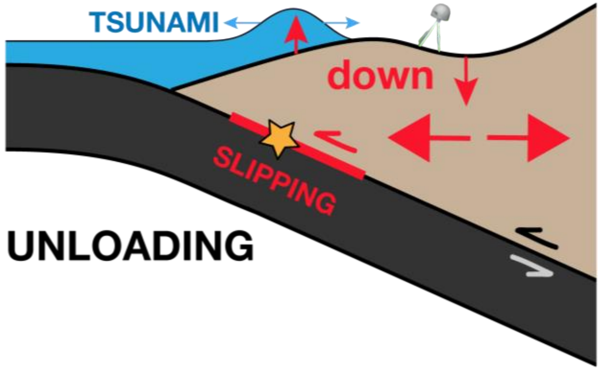
ELASTIC EARTHQUAKE CYCLES IN SUBDUCTION ZONES

Long-term: downgoing plate descends beneath the upper plate in stick-slip fashion.



Interseismic: locked section is "stuck". Creeping section moves slowly. Upper plate deform **elastically**

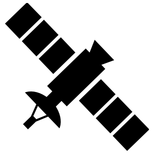




Coseismic: locked section moves abruptly. Upper plate deform **elastically** in an opposite sense.

ELASTIC EARTHQUAKE CYCLES IN SUBDUCTION ZONES

Long-term: downgoing plate descends beneath the upper plate in stick-slip fash



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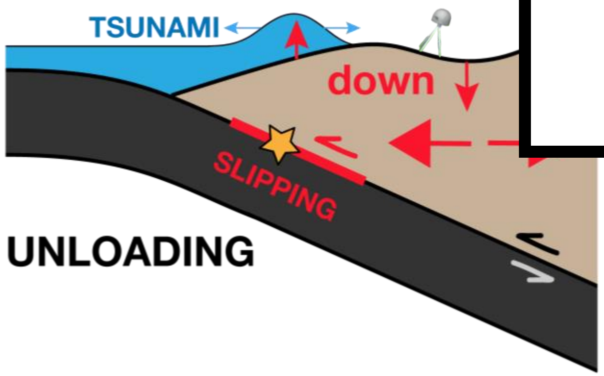

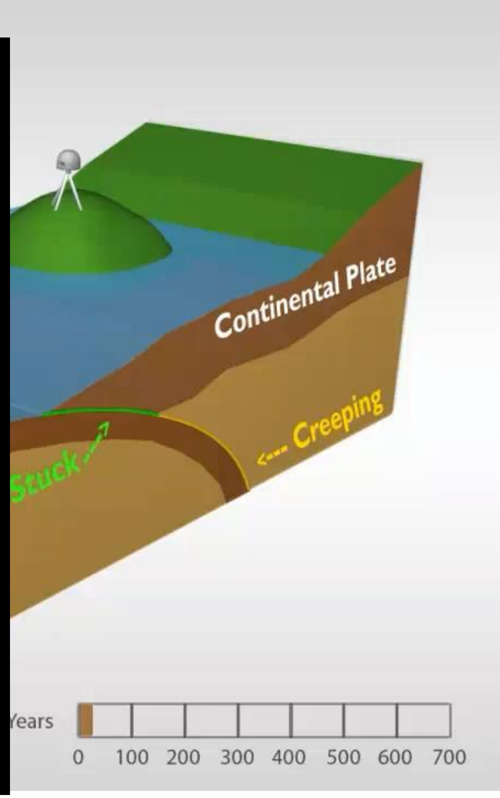

Elastic deformation is **reversible**

plate deform **elastically** in an opposite sense.

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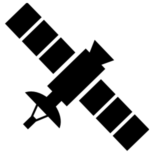

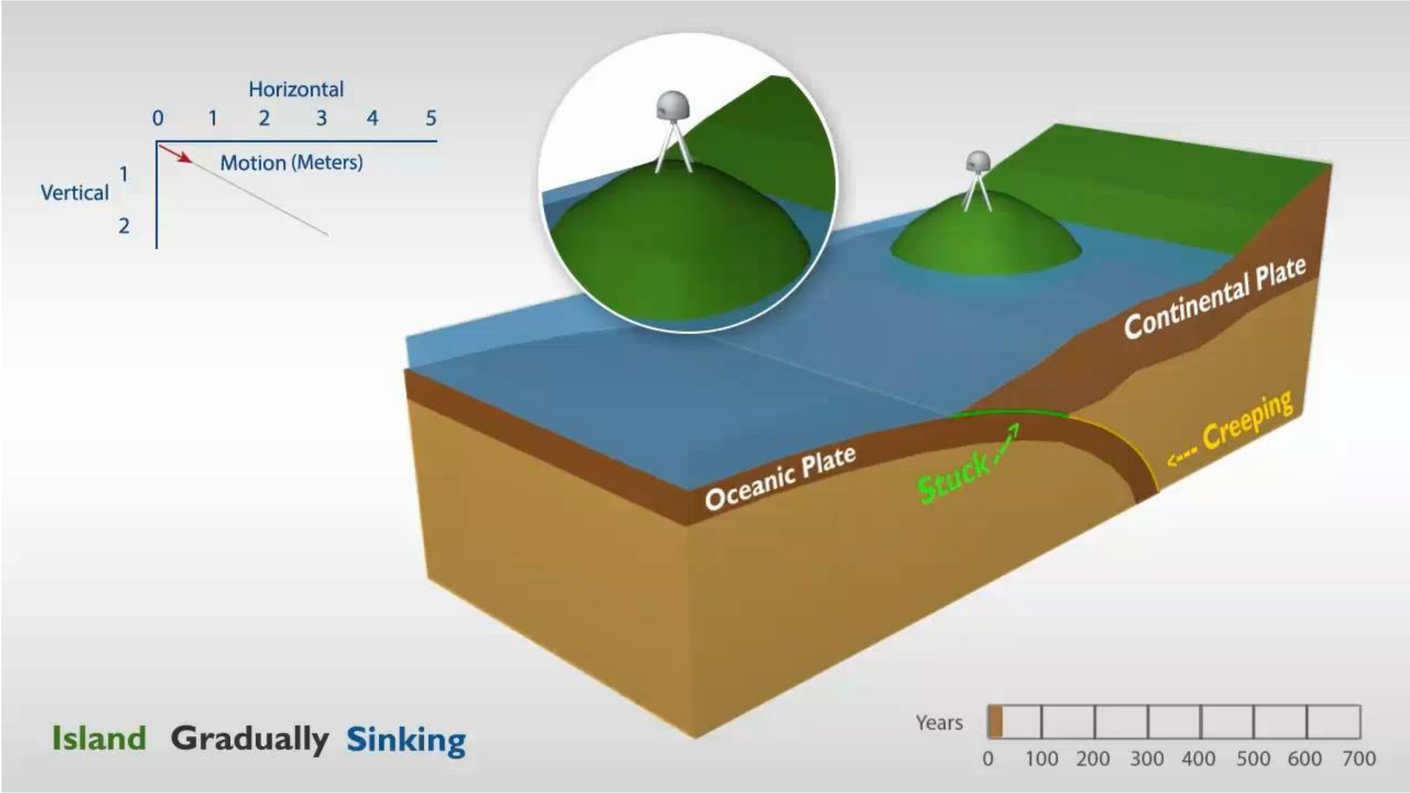

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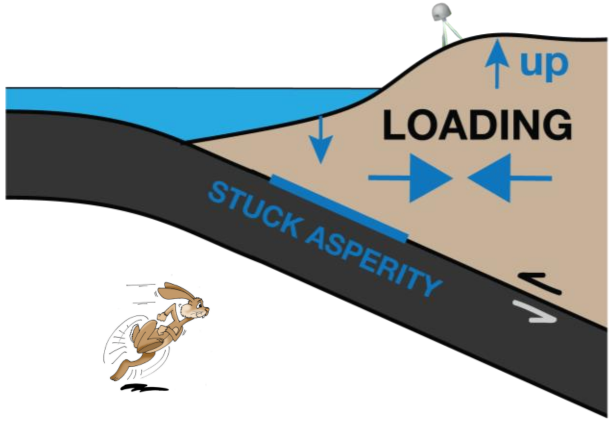

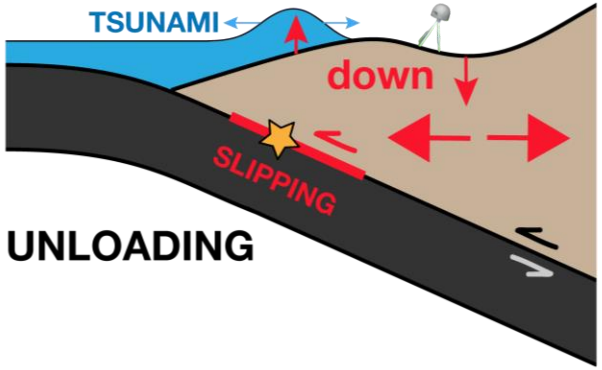

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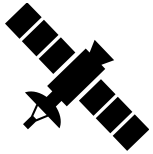

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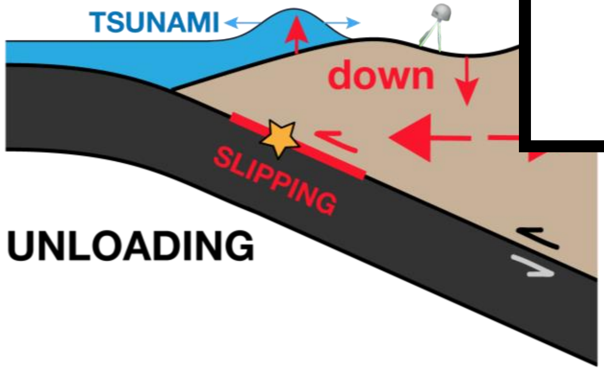

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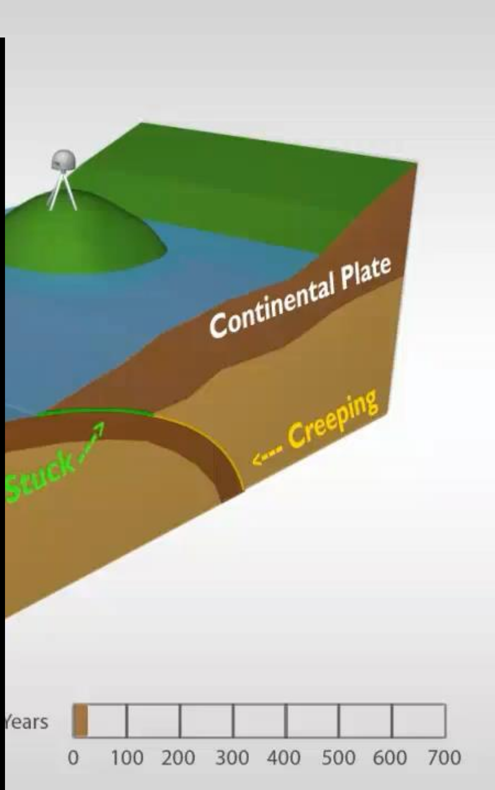

Plastic deformation is **permanent/irreversible**

HOW INTERSEISMIC FAULT LOCKING IMPRINTS SUBDUCTION LANDSCPES ?

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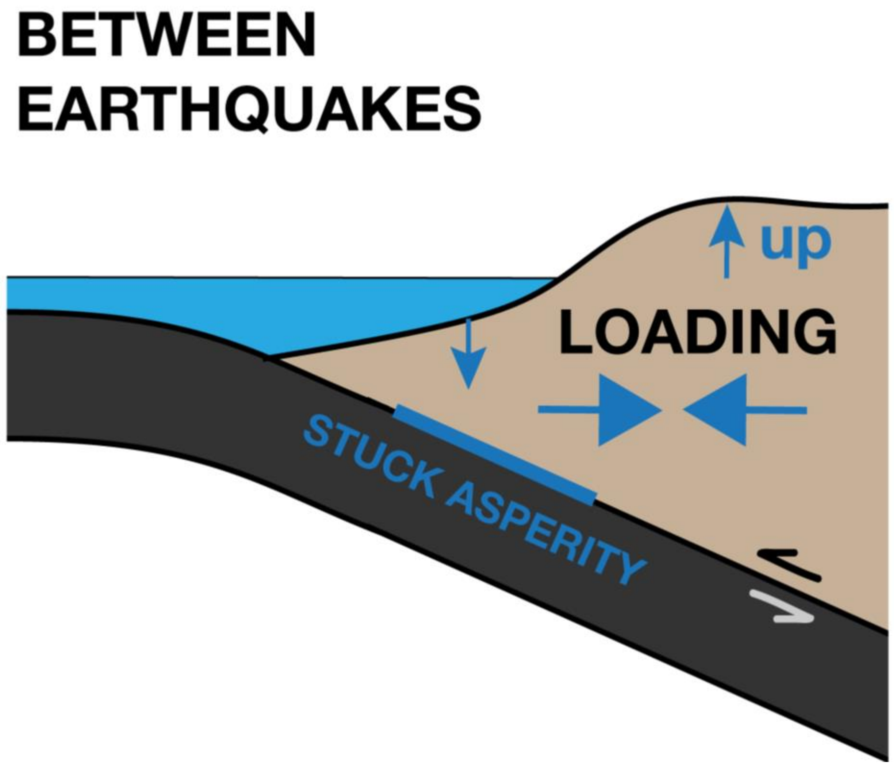
Bending



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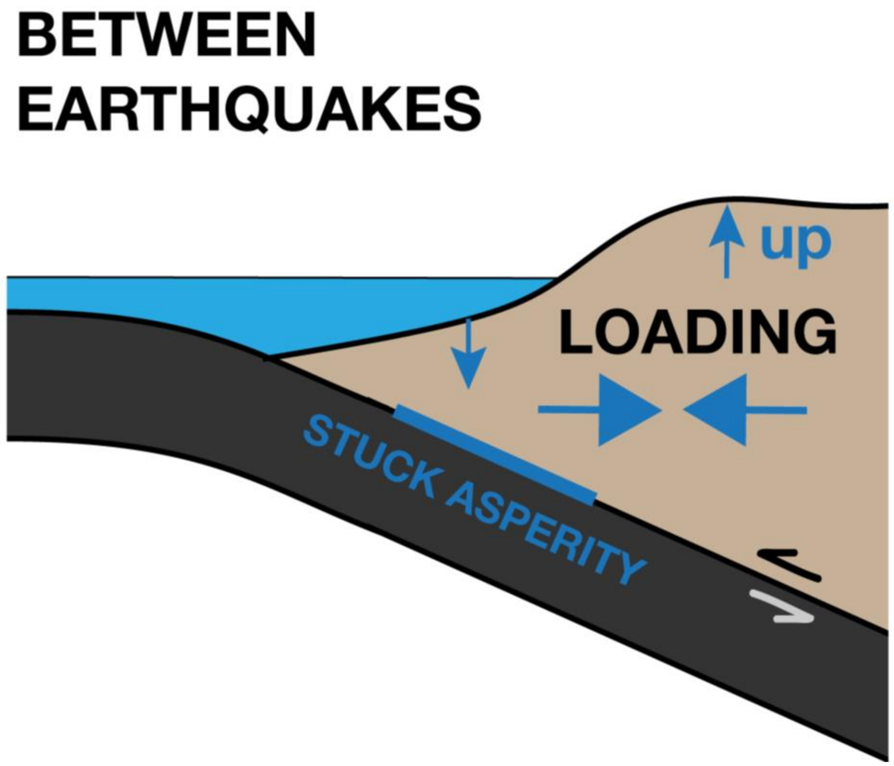
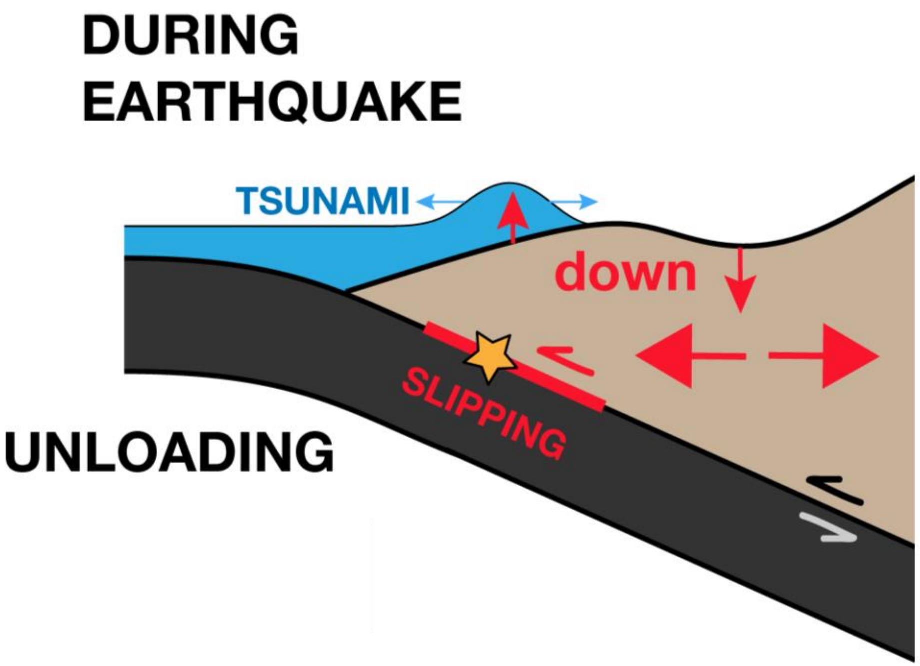
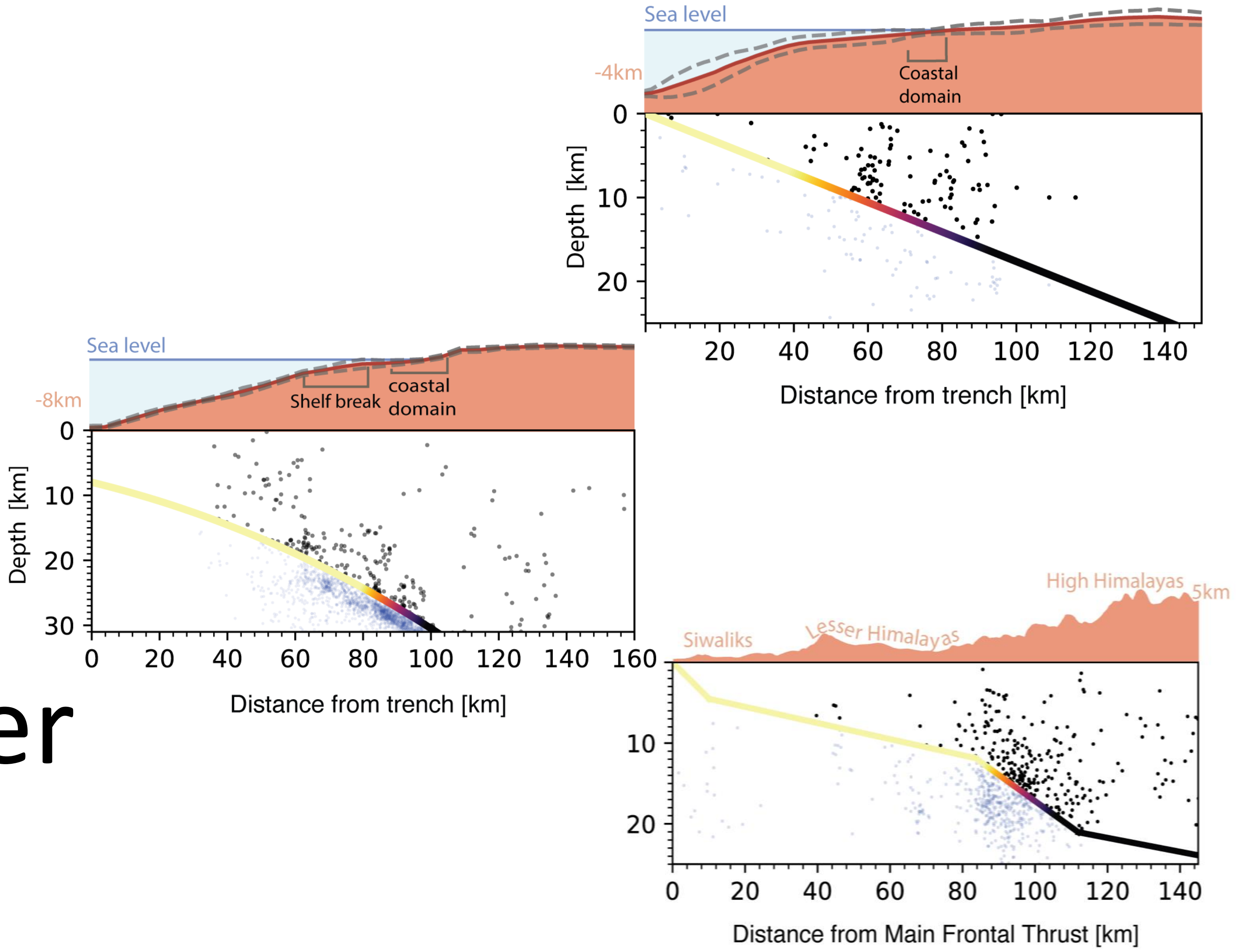


Unbending



HOW INTERSEISMIC FAULT LOCKING IMPRINTS SUBDUCTION LANDSCPES ?

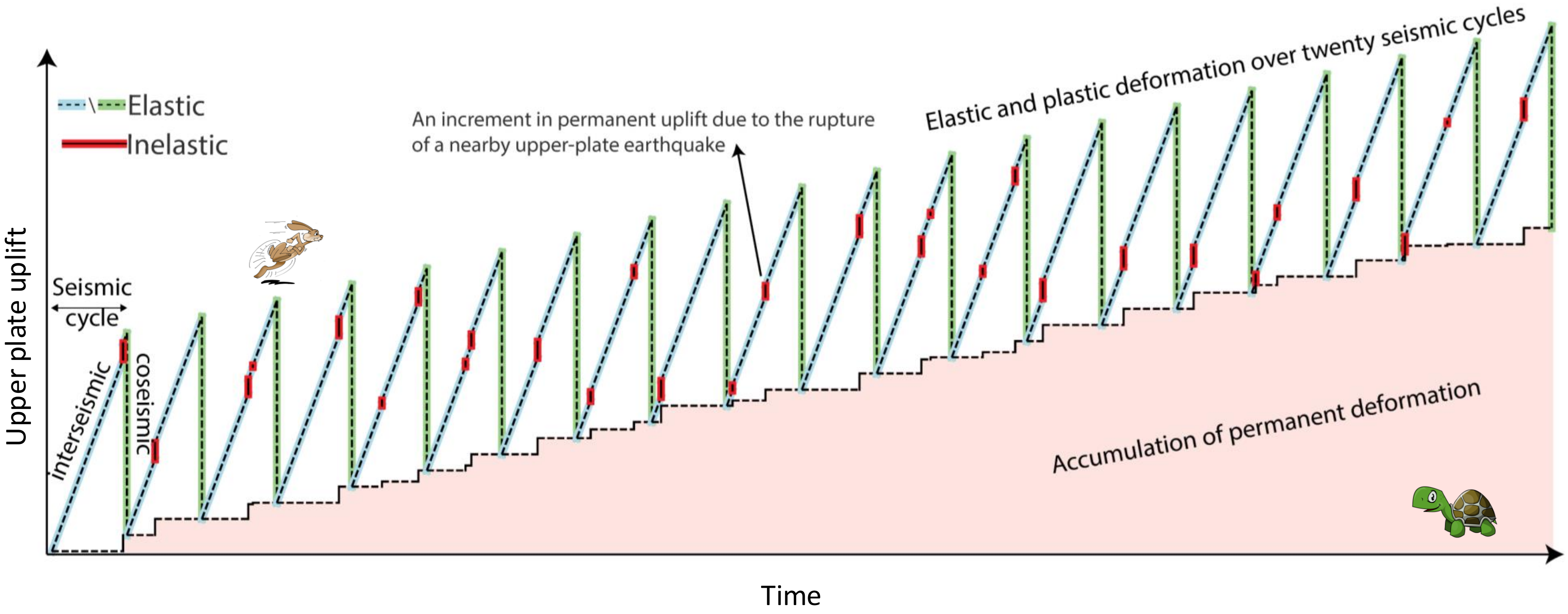
Upper plate interseismic earthquakes **permanently** shape the upper plate.



Oryan et al., 2024

HOW INTERSEISMIC FAULT LOCKING IMPRINTS SUBDUCTION LANDSCPES ?

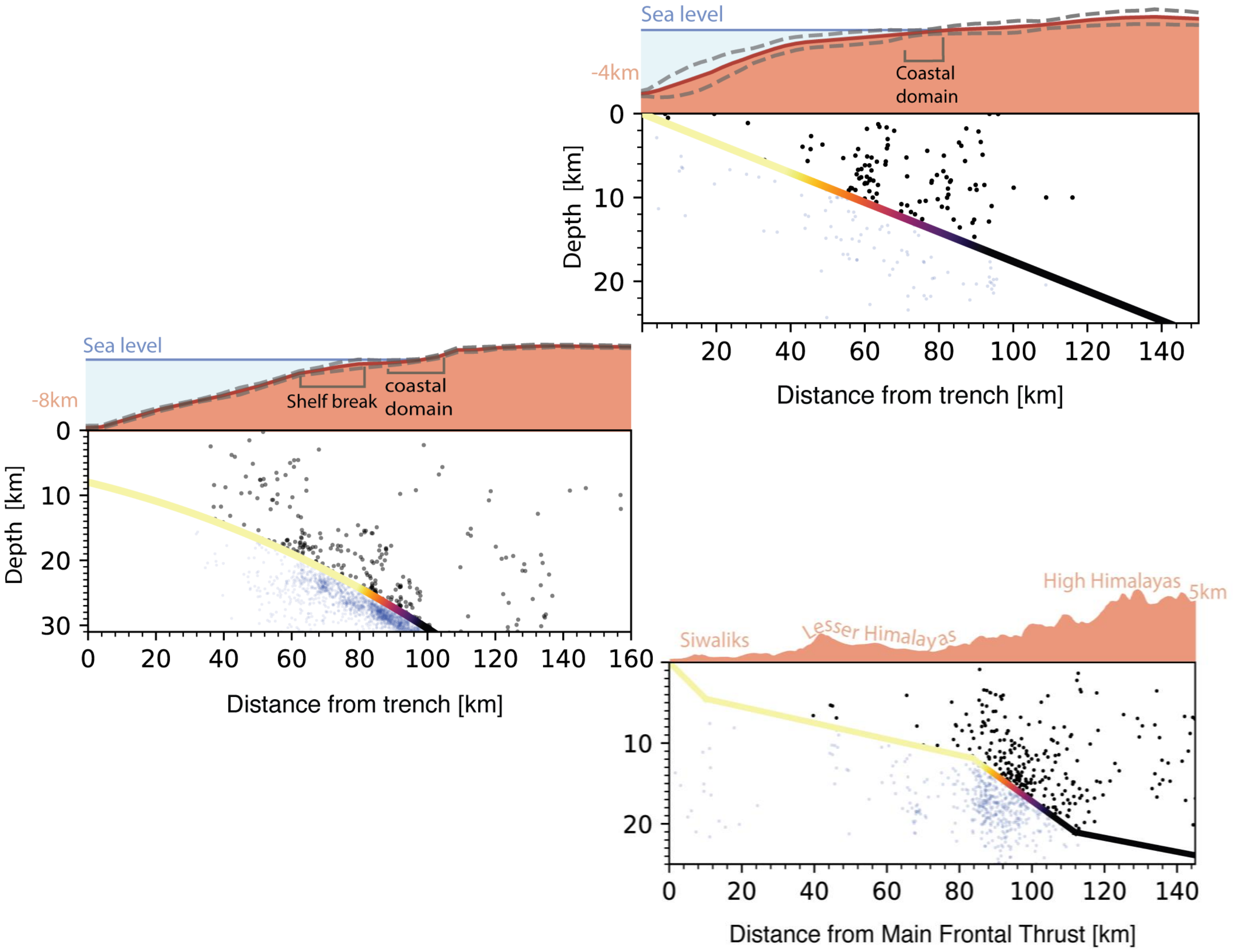
- **Interseismic upper plate stresses** induced by locking gradients push parts of the upper plate to **failure** generating overriding plate earthquakes.
- Repeated **failure** over multiple earthquake cycles explains the overlap between short- and long-term deformation.



Oryan et al., 2024

MODELING INTERSEISMIC INELASTIC DEFORMATION ACROSS UPPER PLATES

- Current interseismic recorded seismicity represents a **snapshot of the long-term processes** that gradually shape topography.
- We extend the upper plate seismic record by generating upper plate earthquakes, **representing the complete signature of earthquake cycles**.



Oryan et al., 2024

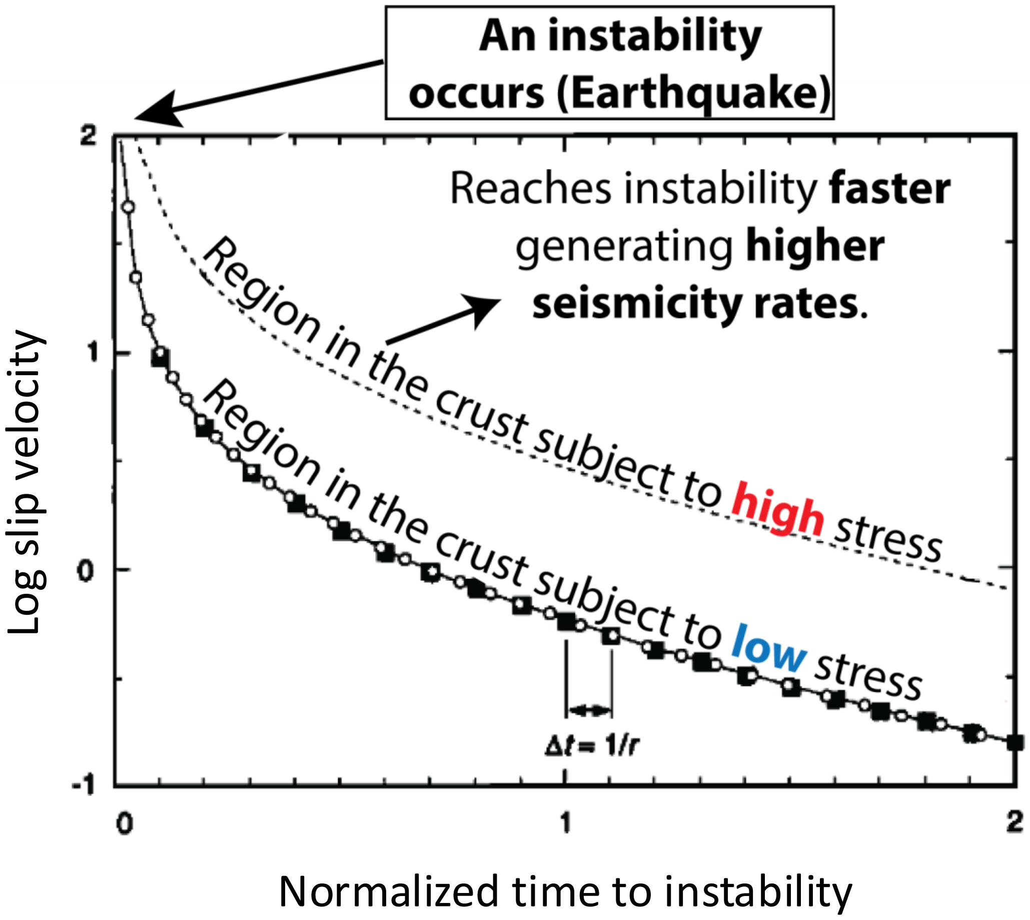
MODELING INTERSEISMIC INELASTIC DEFORMATION ACROSS UPPER PLATES

- The Dieterich approach models the crust as a series of independent nucleation points governed by rate-and-state friction, progressing toward instability.
- Higher stressing rate will reduce the time to reach instability.

Underlying assumption:

The state variable, θ, in rate-and-state friction follows $\frac{\theta\dot{\delta}}{D_c}$>>1 so θ=$\theta_0\exp(-\frac{\delta}{D_c})$ and as such the slip velocity:

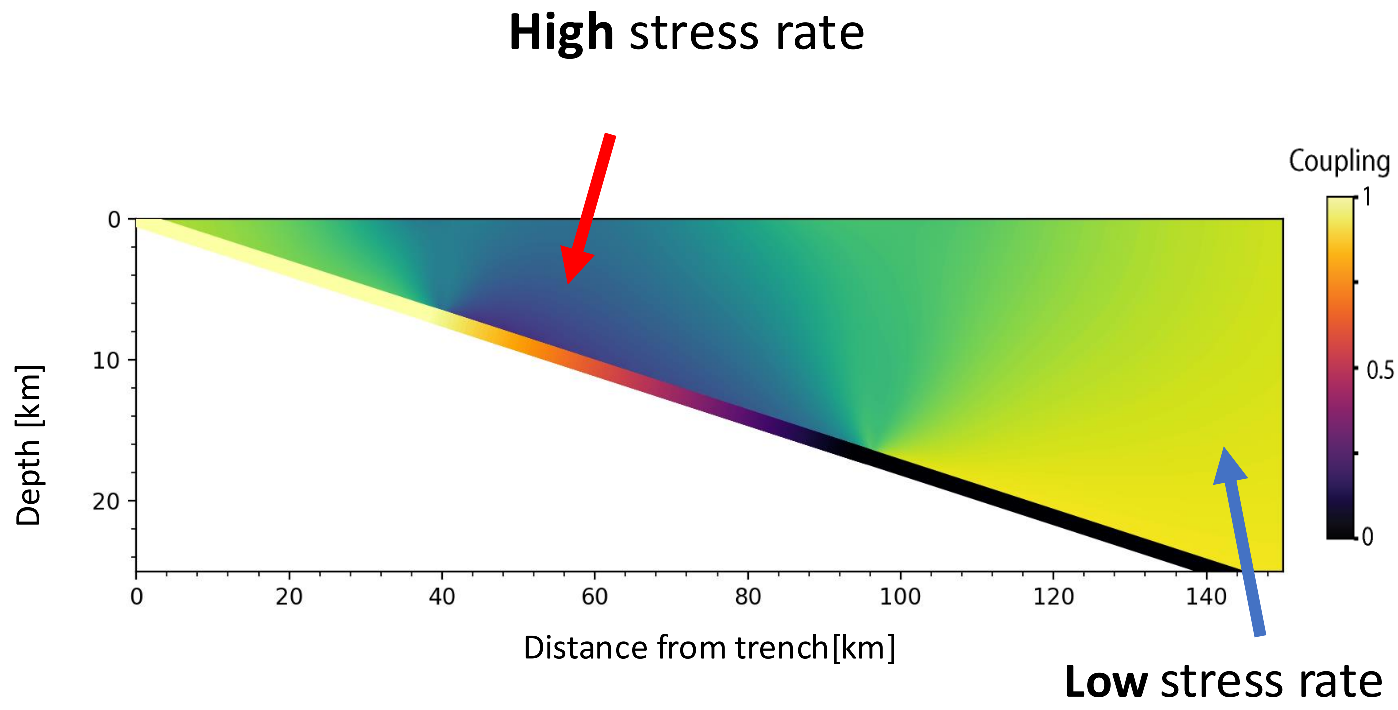
$$\dot{\delta} = \left\{\left[\frac{1}{\dot{\delta}_0} + \frac{H\sigma_n}{\dot{\tau}}\right]\exp\left(-\frac{\dot{\tau}t}{A\sigma_n}\right) - \frac{H\sigma_n}{\dot{\tau}}\right\}^{-1}.$$



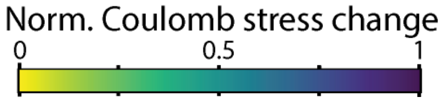
Dieterich 1994

MODELING INTERSEISMIC INELASTIC DEFORMATION ACROSS UPPER PLATES

- Compute the stress rate imparted by **locking gradients.**
- **Populate millions of synthetic earthquakes** spanning thousands of years and dozens of seismic cycles according to the **stress rate**.
- Estimate **cumulative long-term surface** displacement from the synthetic seismic events using the Okada solution.



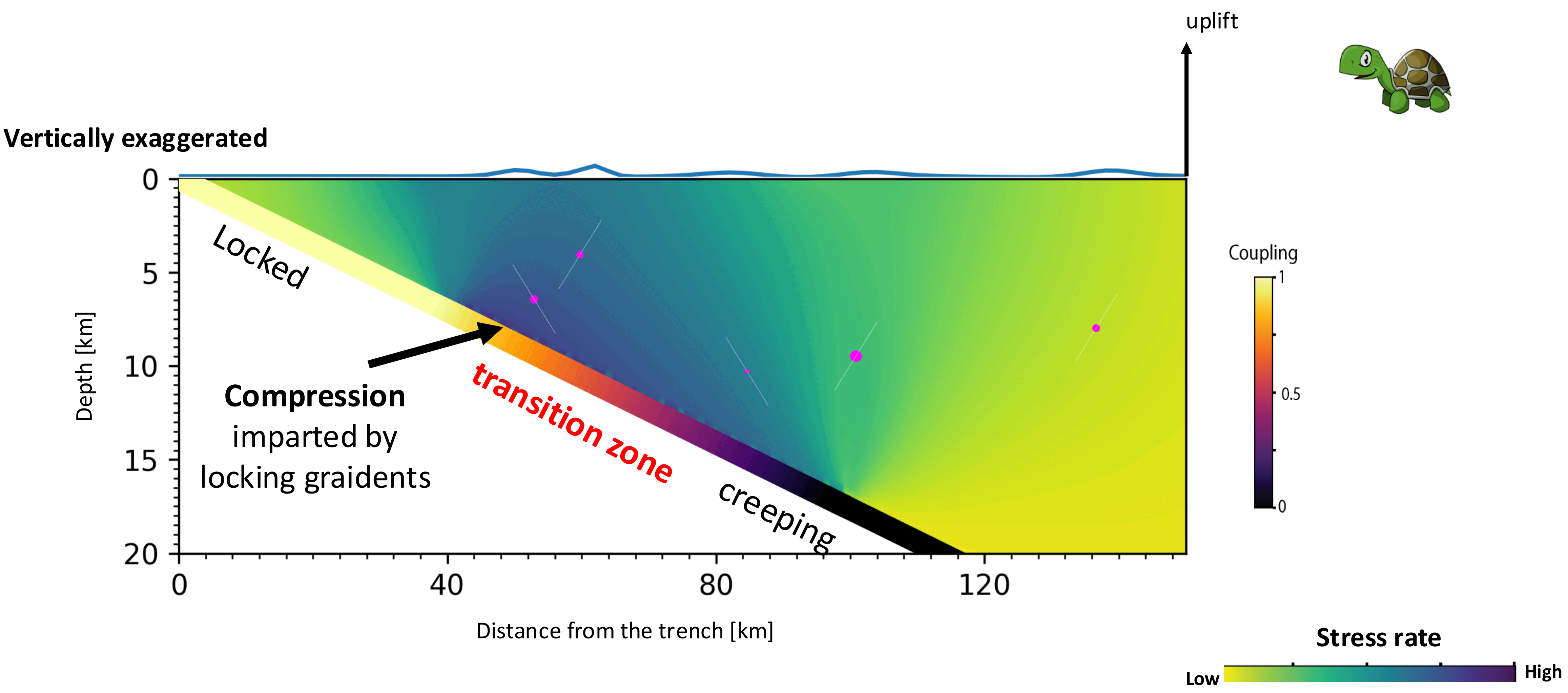
stress rate = Coulomb stress change assuming optimally orientated thrust faults (30°)



MODELING INTERSEISMIC INELASTIC DEFORMATION ACROSS UPPER PLATES

10 degree dip, fully locked to 40km

Uplift during three seismic cycles producing average **long-term** rate of 0.1 mm/yr



MODELING INTERSEISMIC INELASTIC DEFORMATION ACROSS UPPER PLATES

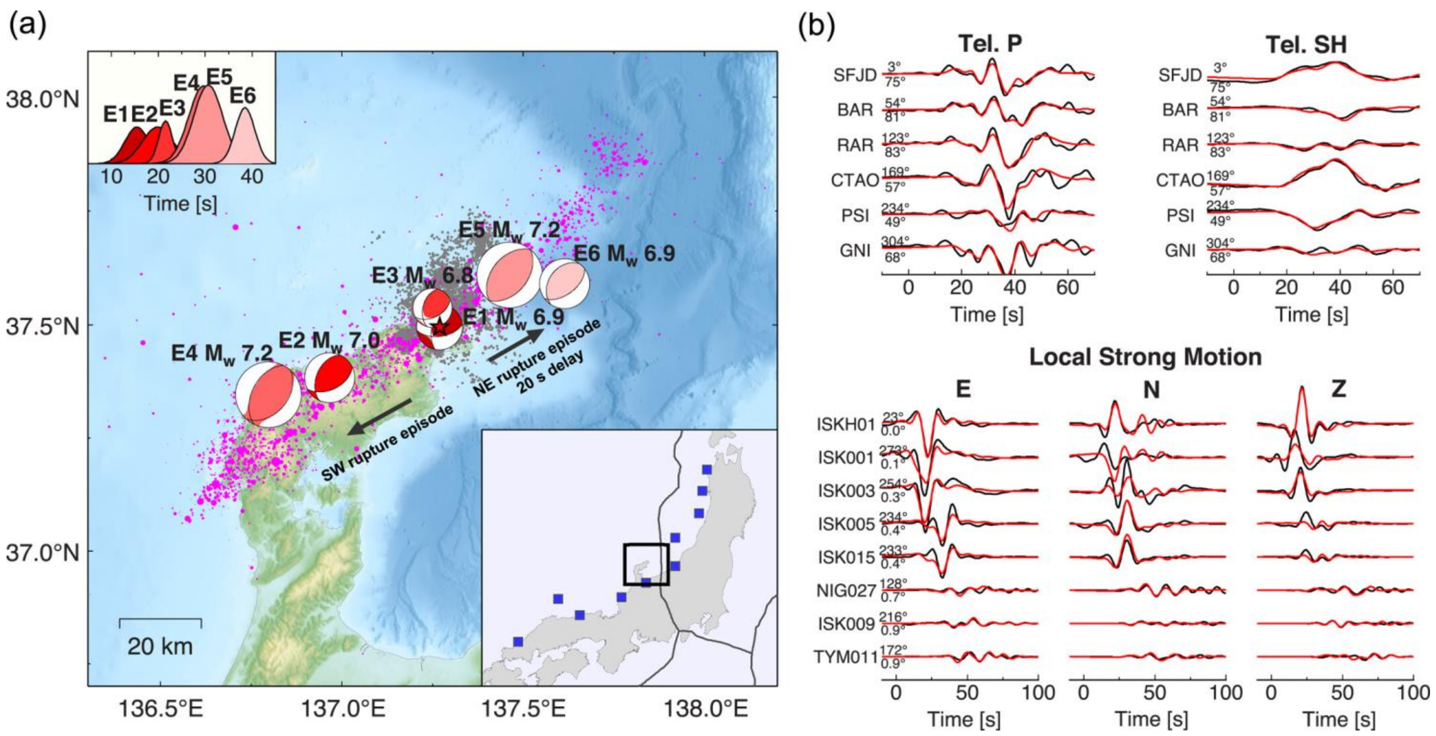
10 degree dip, f ... ing

locked to 40kr ... yr

Vertically

The approach of generating multiply synthetic **events** based on a probability density function has been utilized in other studies.

Bayesian inversion of seismic data is used to generate earthquakes and estimate the surface deformation for the **2024 Noto earthquake.**



Depth [km]

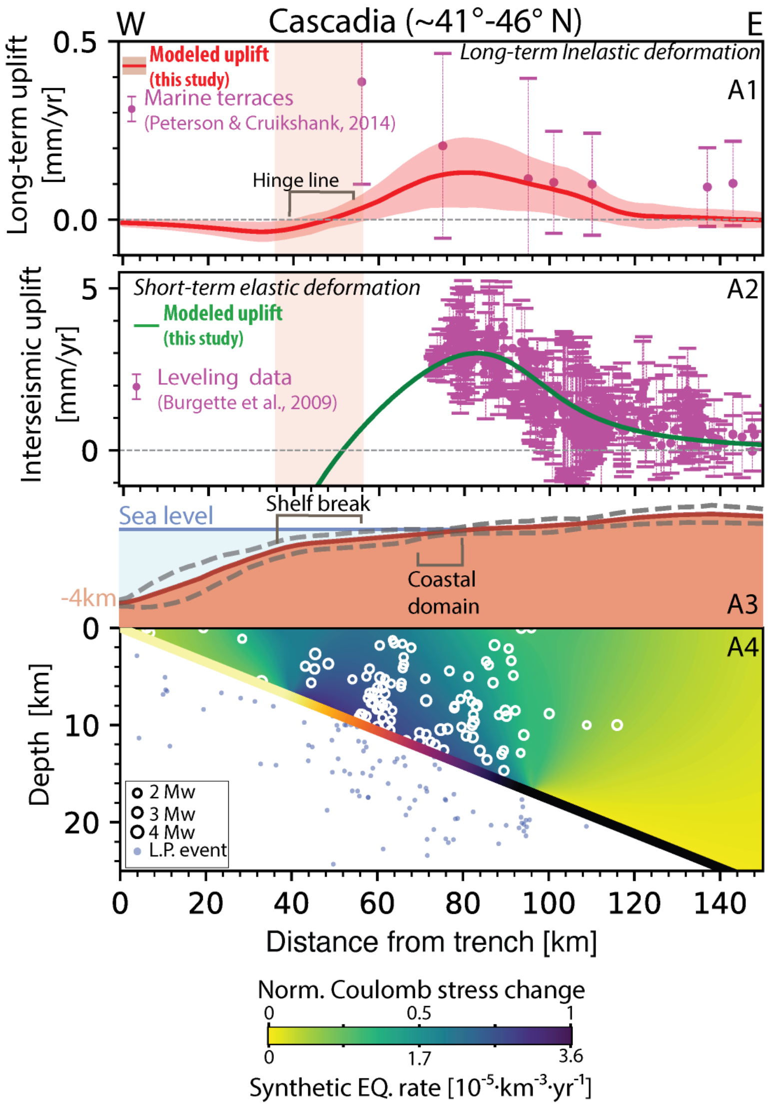
Kutschera, Jia, **Oryan** et al., [2024]

Distance from the trench [km]

Upper plate Coulomb stress change

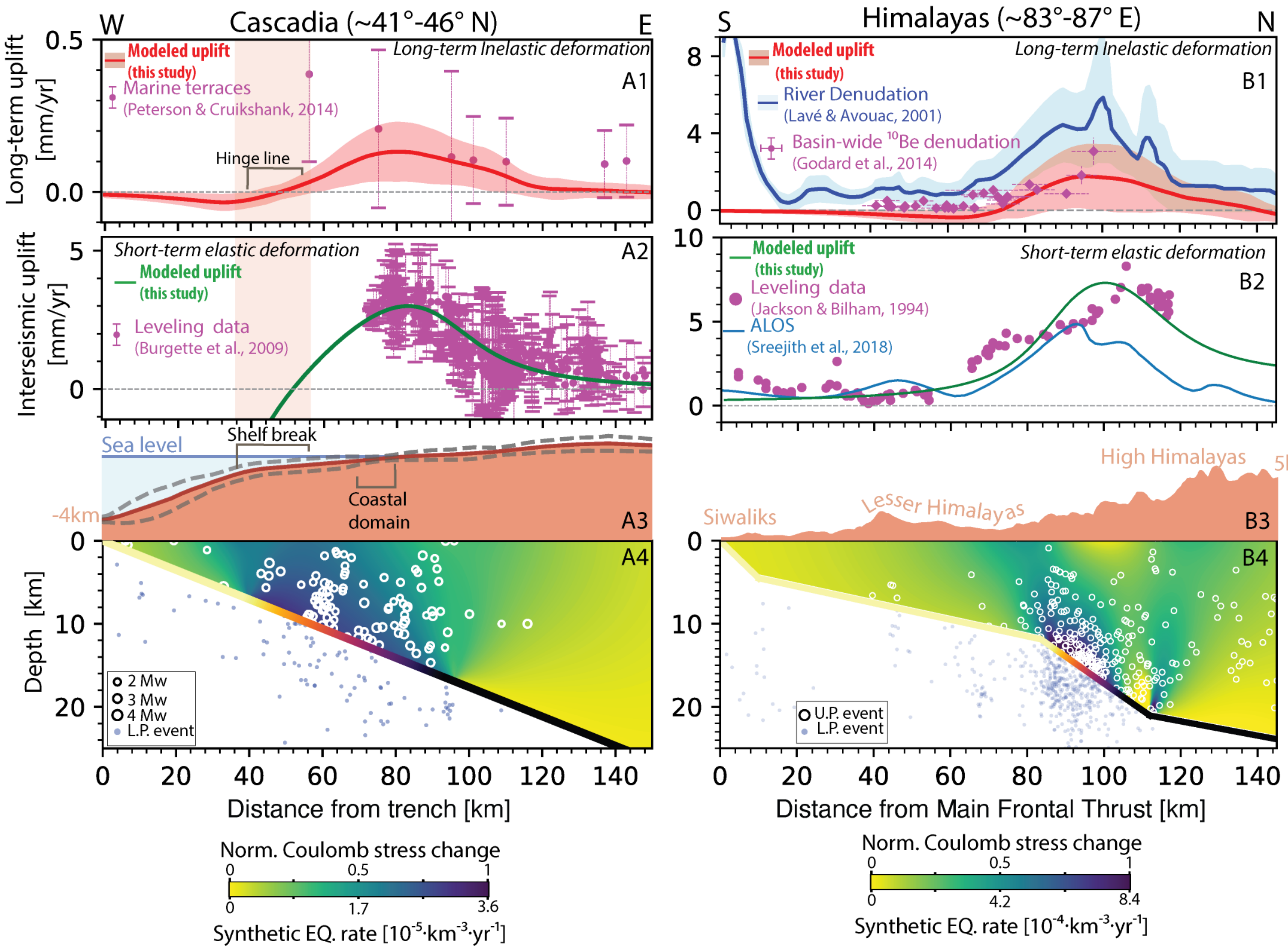
Low High

DEFORMATION IN CASCADIA,HIMALYAS AND CHILE



Oryan et al., 2024

DEFORMATION IN CASCADIA,HIMALYAS AND CHILE



Oryan et al., 2024

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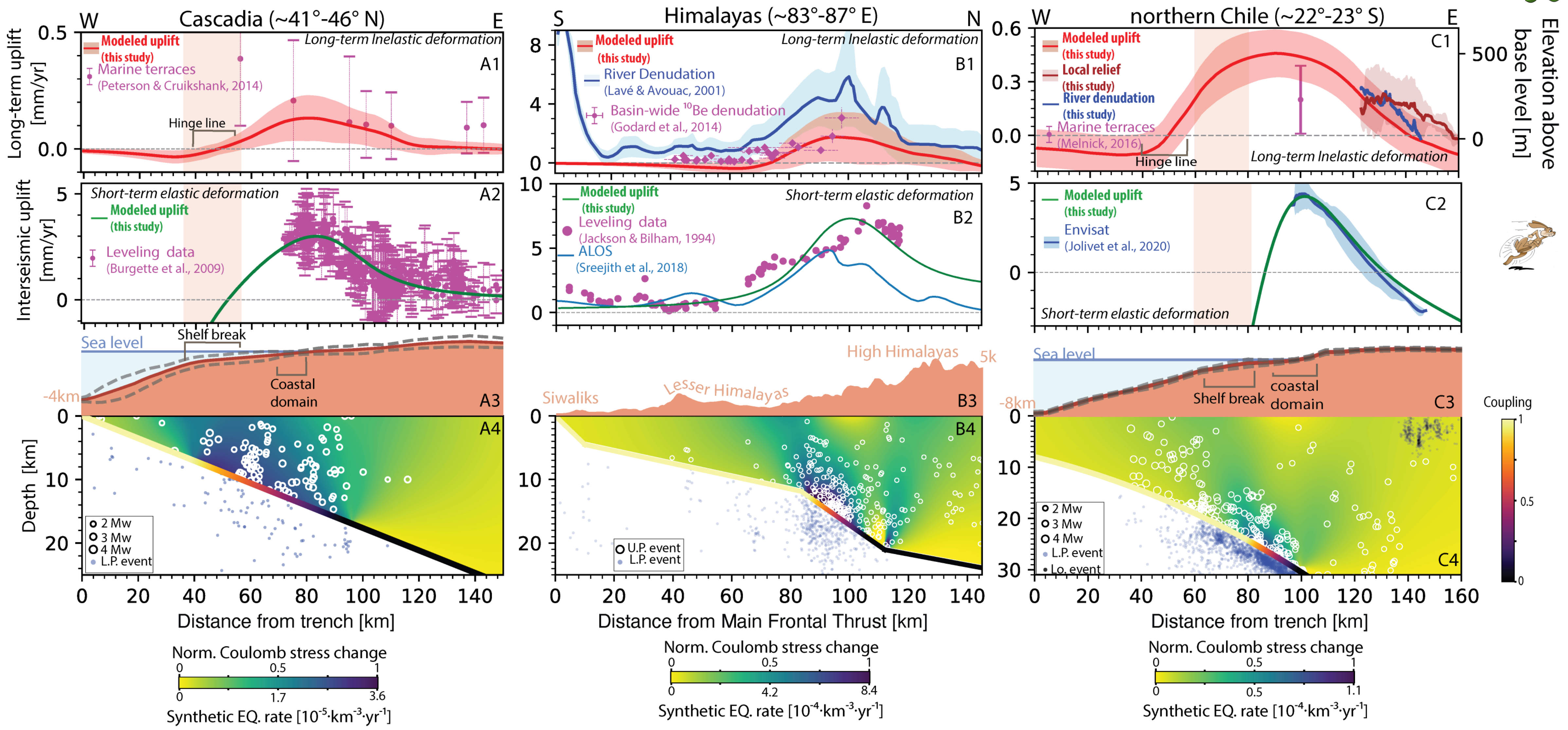
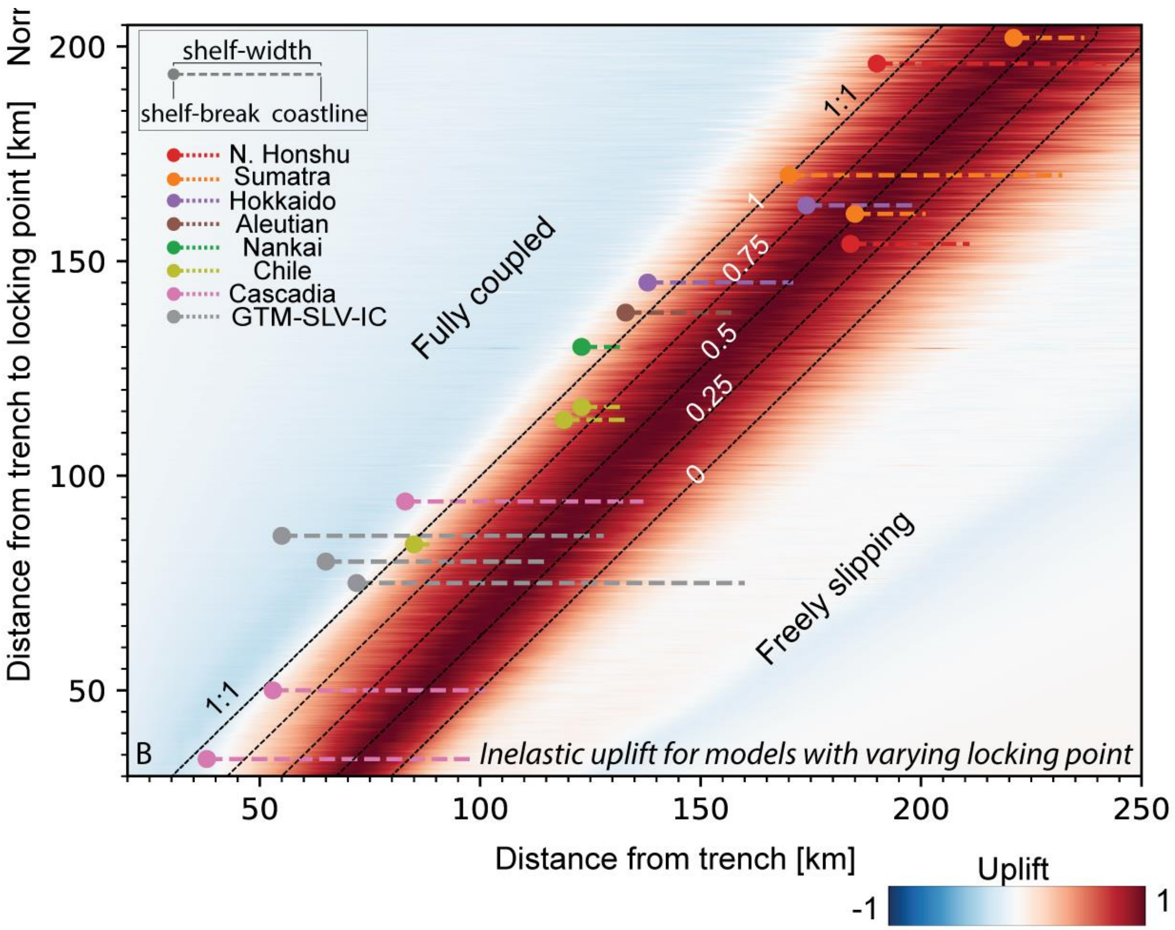
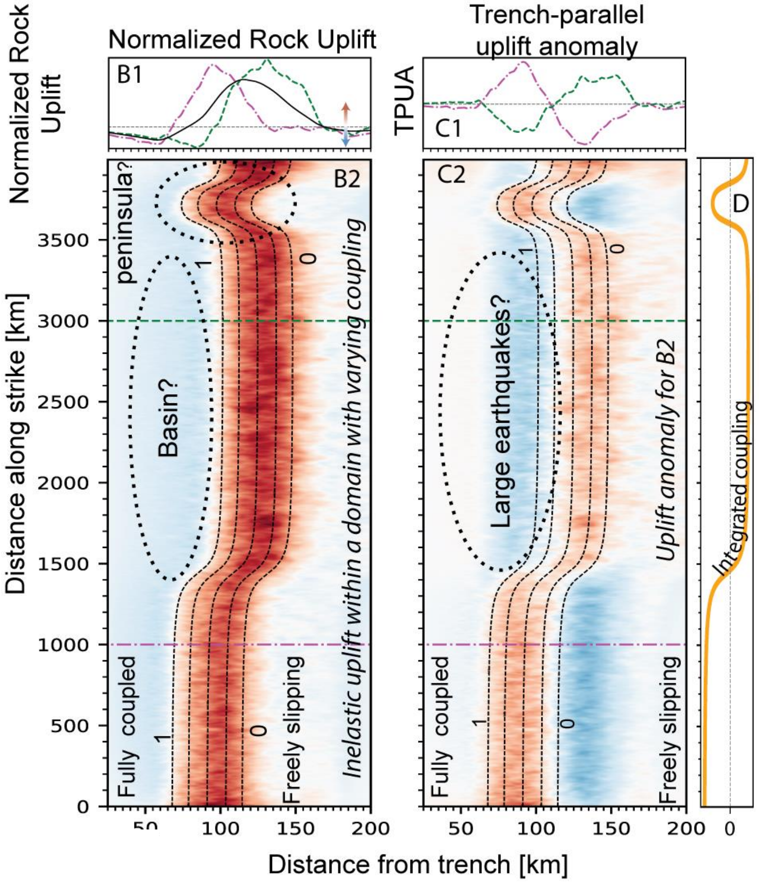


Oryan et al., 2024

MODELING GLOBAL TRENDS IN SUBDUCTION LANDSCAPES

Our model also explains first-order observations of the correlations found between long-term fields such as **gravity anomalies**, **shelf breaks**, and **peninsulas** with short term processes like **megathrust earthquakes** and **fault locking**.



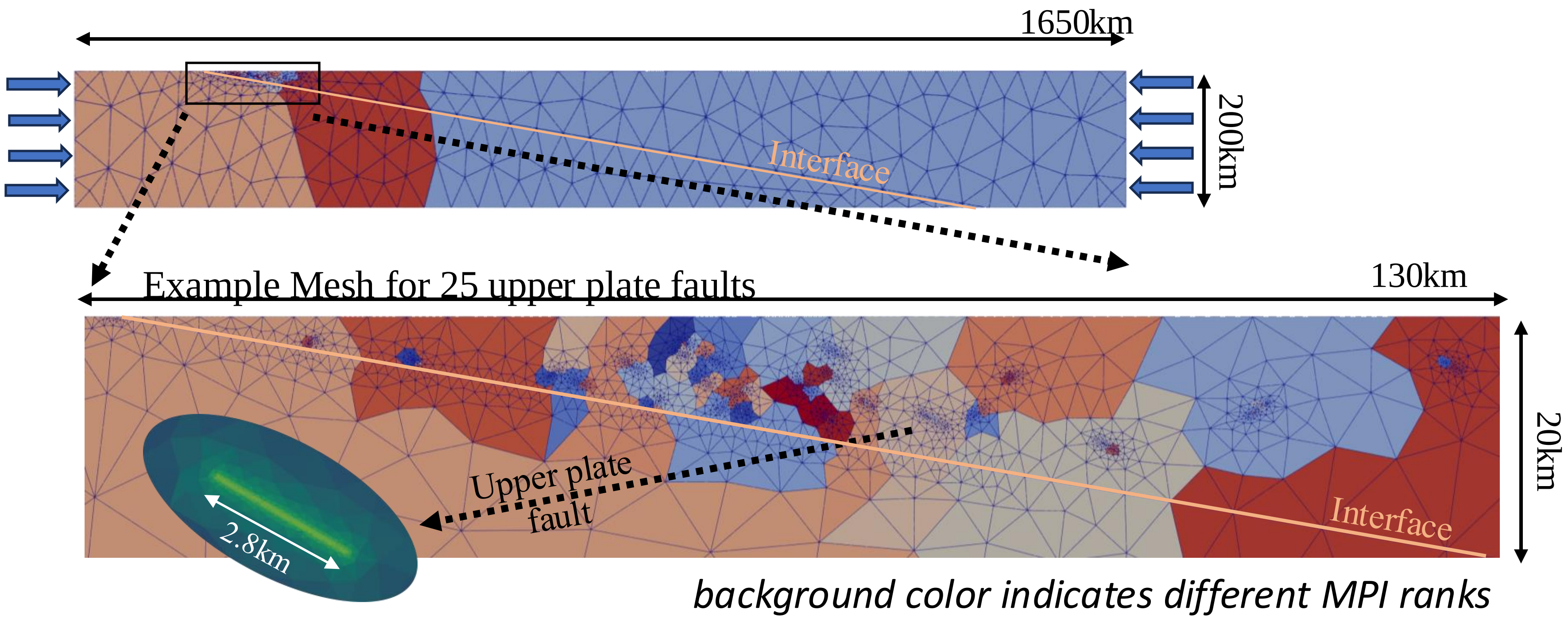


Oryan et al., 2024

MODELING INTERSEISMIC INELASTIC DEFORMATION ACROSS UPPER PLATES

- Simulations of megathrust cycles combined with discrete, randomly distributed upper plate faults governed by rate-and-state friction laws provide a comprehensive and realistic physics base numerical model of the problem.

Unstructured triangular mesh used to model **megathrust and upper plate faults** using Discontinuous Galerkin method

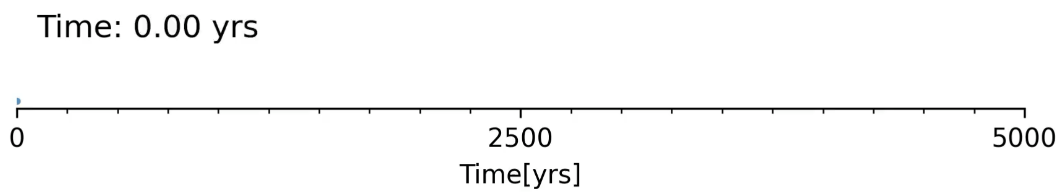


background color indicates different MPI ranks

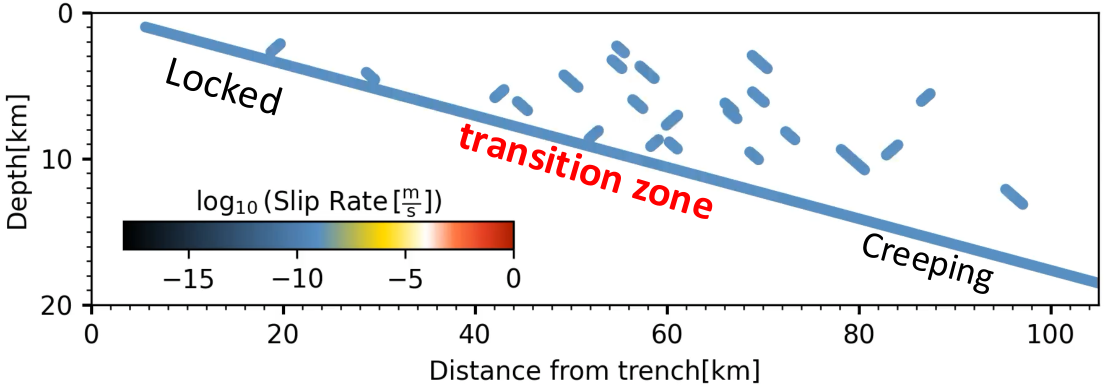
Oryan et al., in prep.

MODELING INTERSEISMIC INELASTIC DEFORMATION ACROSS UPPER PLATES

- Simulations of seismic cycles along a megathrust fault, combined with discrete, randomly distributed upper plate faults governed by rate-and-state friction laws, reveal that:
    - Upper plate faults can **fail interseismically** and generate earthquakes.



Simulation of sequences of earthquakes along a 10 degree megathrust and **25 upper plate faults**



Oryan et al., in prep.

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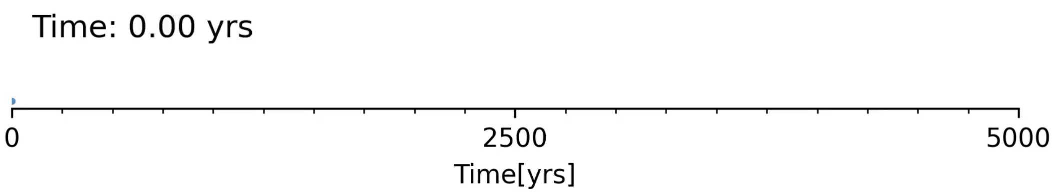

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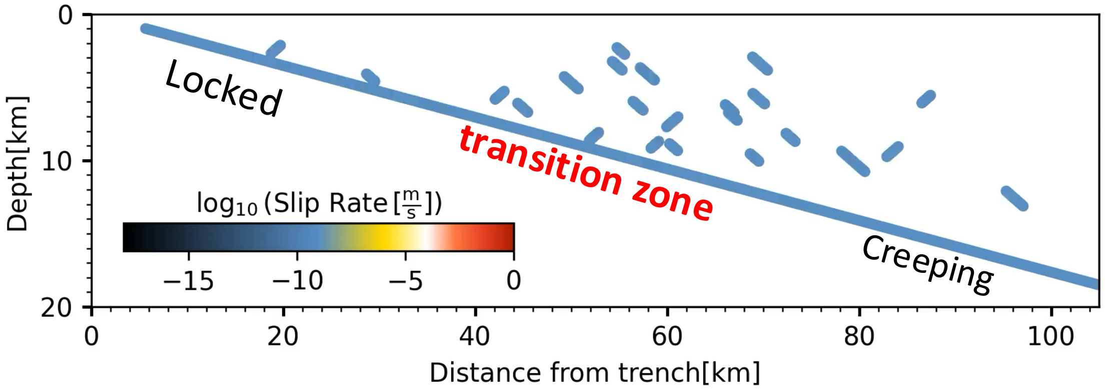

Oryan et al., in prep.

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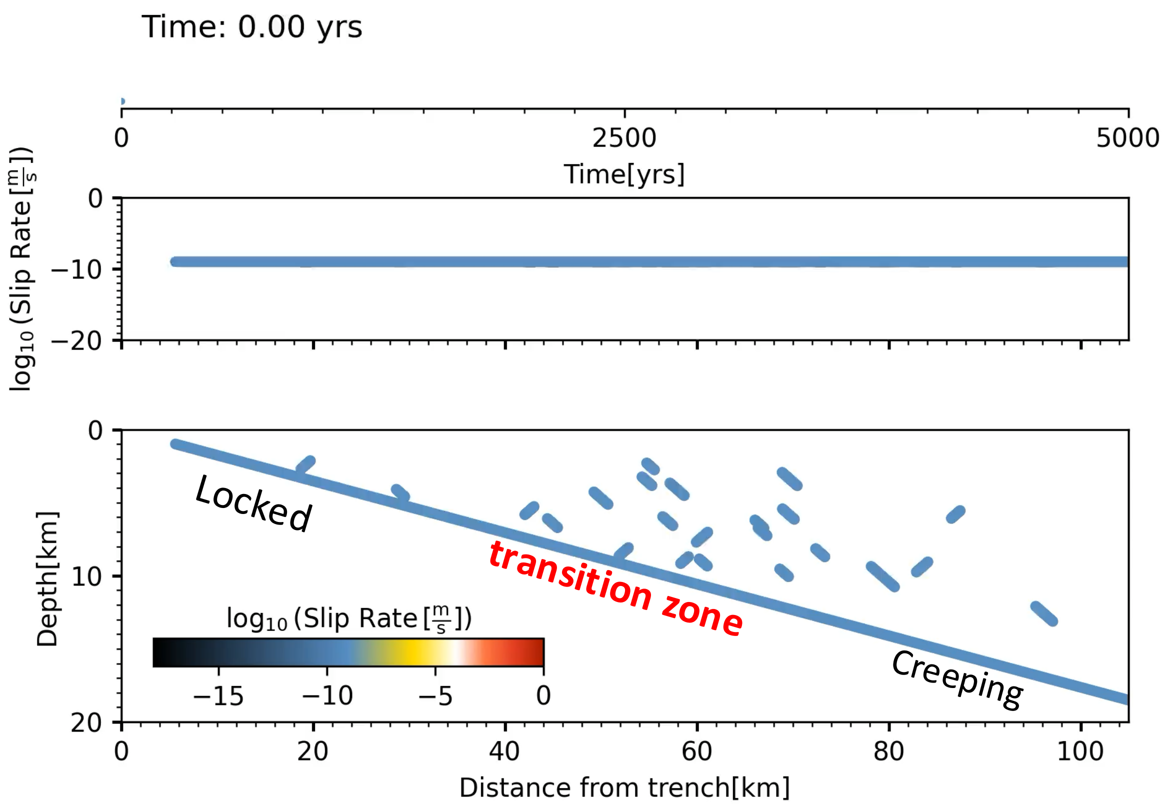
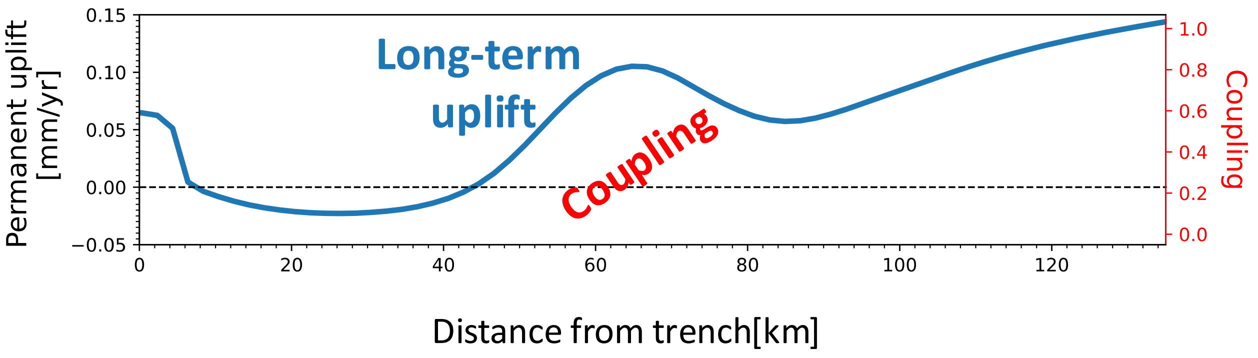
Simulation of sequences of earthquakes along a 10 degree megathrust and **25 upper plate faults**

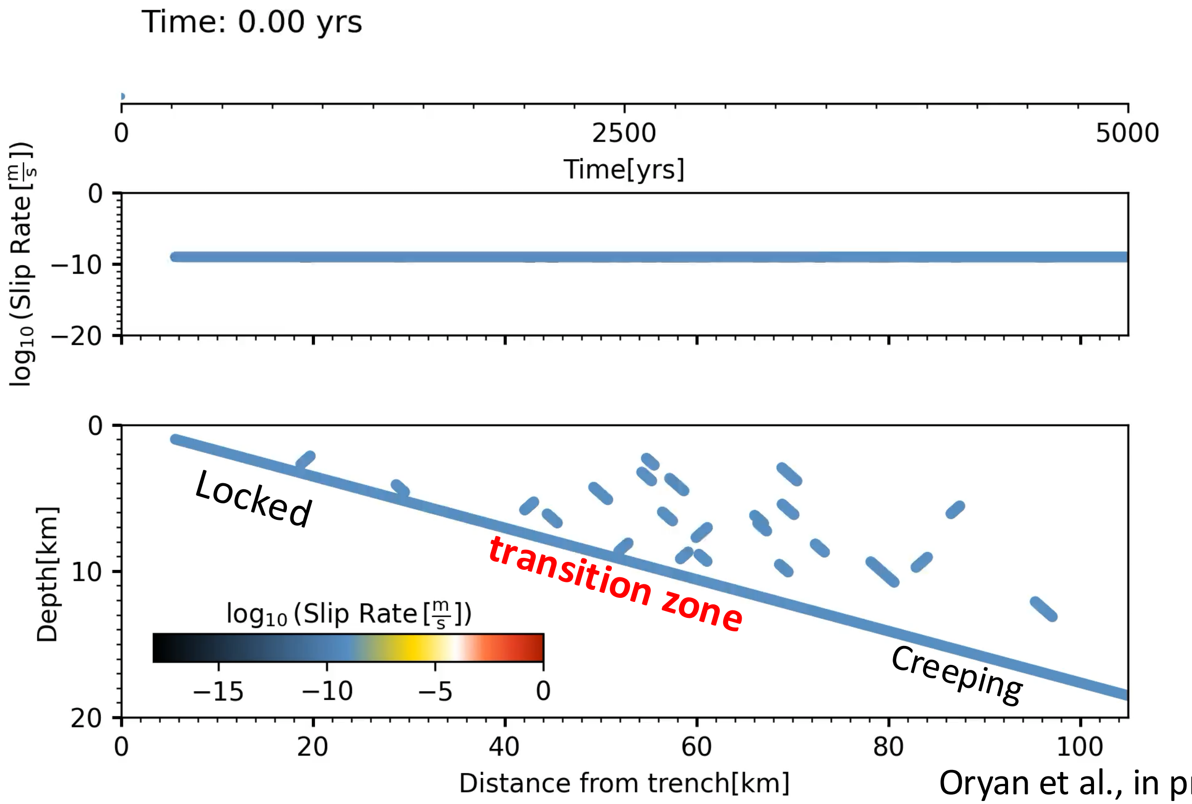


Oryan et al., in prep.

MODELING INTERSEISMIC INELASTIC DEFORMATION ACROSS UPPER PLATES

- Simulations of seismic cycles along a megathrust fault, combined with discrete, randomly distributed upper plate faults governed by rate-and-state friction laws, reveal that:
  - Upper plate faults can **fail interseismically** and generate earthquakes.
  - **Permanent uplift**, observed after four seismic cycles, **peaks above the transition zone**.



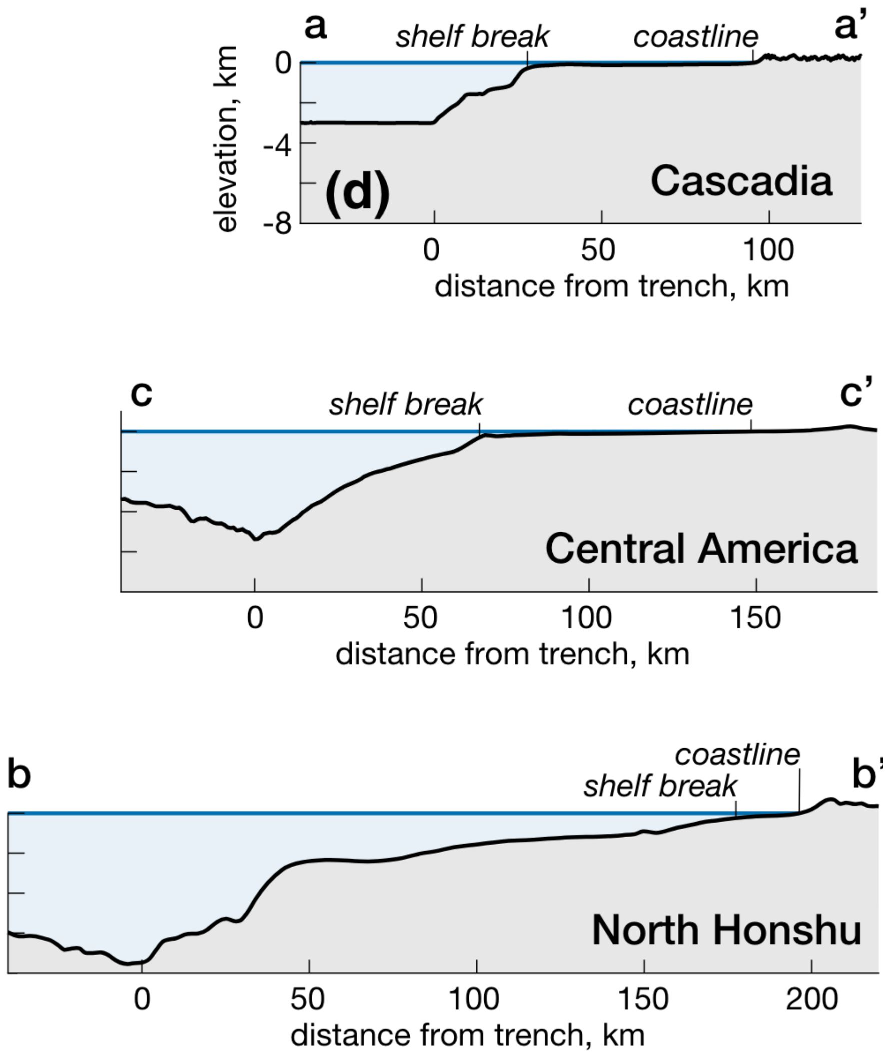


Oryan et al., in prep.

Oryan et al., in prep.

IMPLICATIONS FOR LONG-TERM PLATE COUPLING

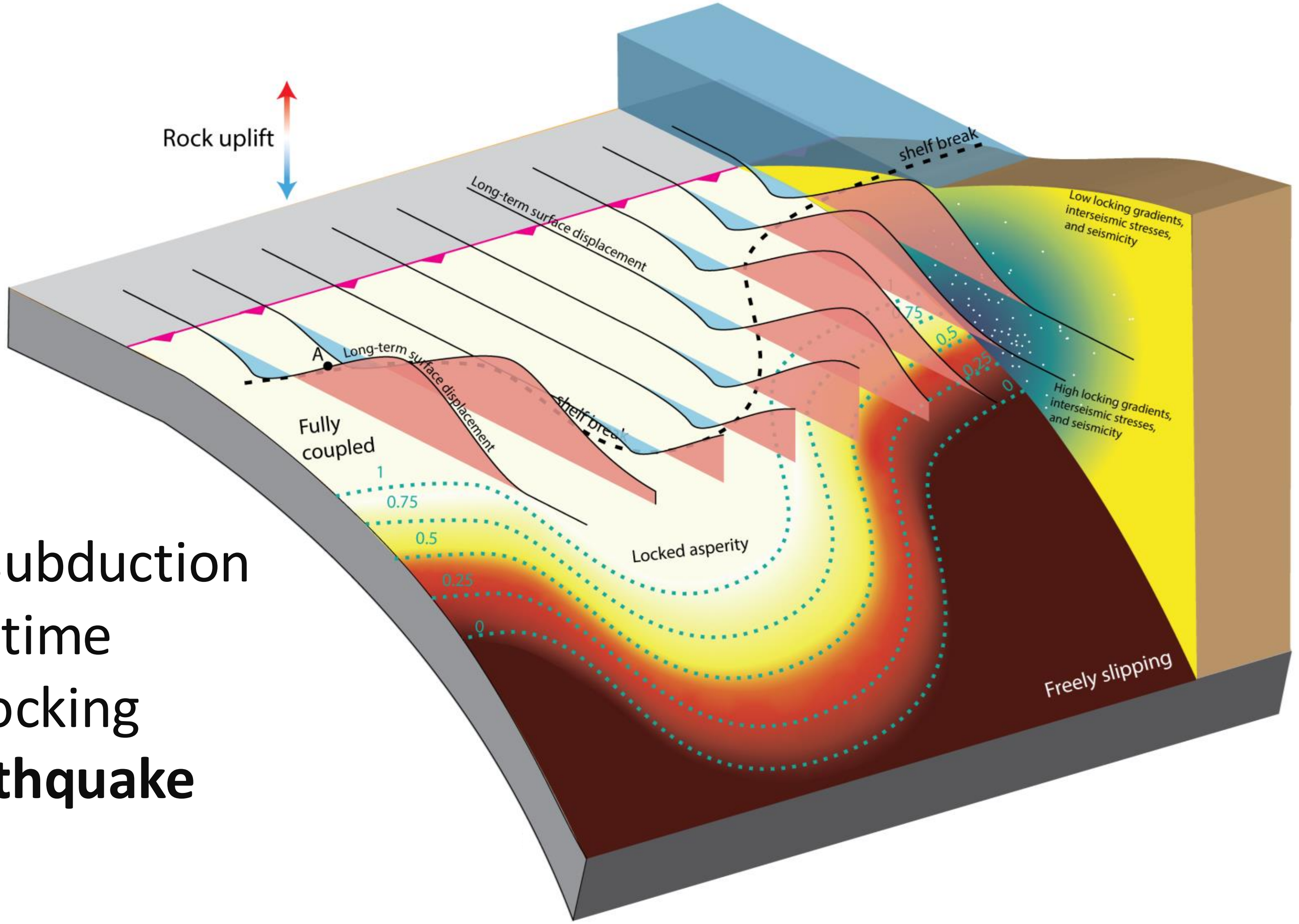
- Our results imply that the downdip pattern of megathrust locking tends to **remain steady over hundreds of thousands of years**.
- Our results provide limited insight into the **along strike pattern** of **megathrust locking.**



Malatesta et al [2021]

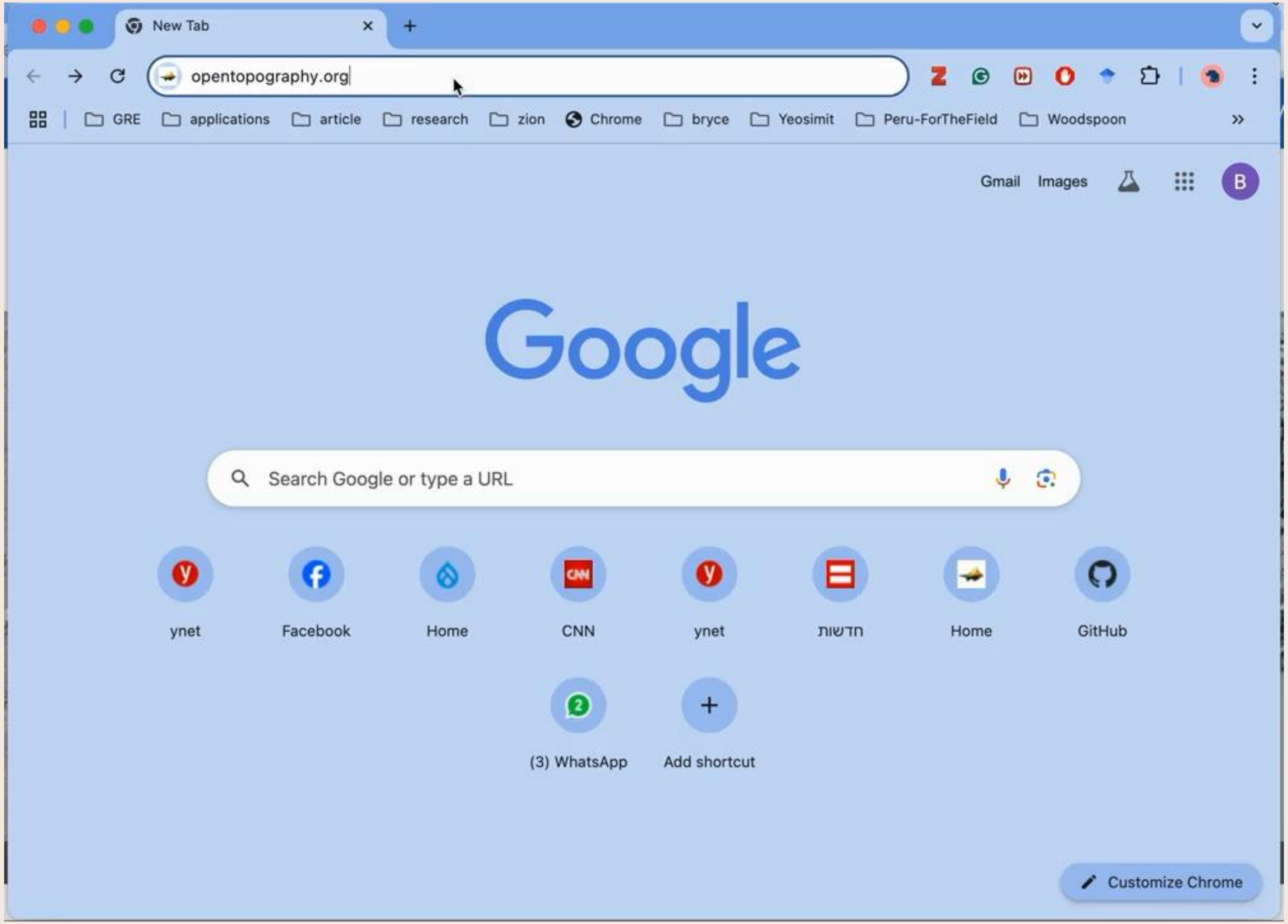
KEY POINTS SO FAR

- Variations in the degree of **megathrust locking** generate increments of **non-recoverable brittle deformation** within the overriding plate.
- This is expressed primarily as interseismic **upper plate seismicity**.
- Over time, this process **imprints** subduction landscapes one seismic cycle at a time
- Downdip pattern of megathrust locking **remains stable over multiple earthquake cycles**.



Oryan et al., 2024

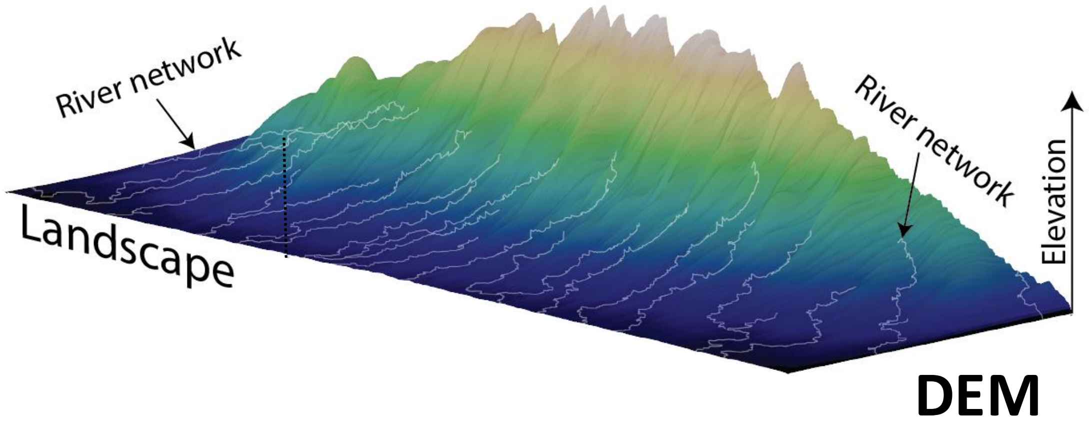
Section 3 - Inferring Long-Term Tectonic Uplift from Bayesian Inversion of Landscapes



Oryan et al., in review , https://doi.org/10.31223/X5T407

INFERRING LONG-TERM TECTONIC UPLIFT FROM BAYESIAN INVERSION OF LANDSCAPES

- Landscapes encode the forcing of **tectonic uplift**



Oryan et al., 2024 (in review)

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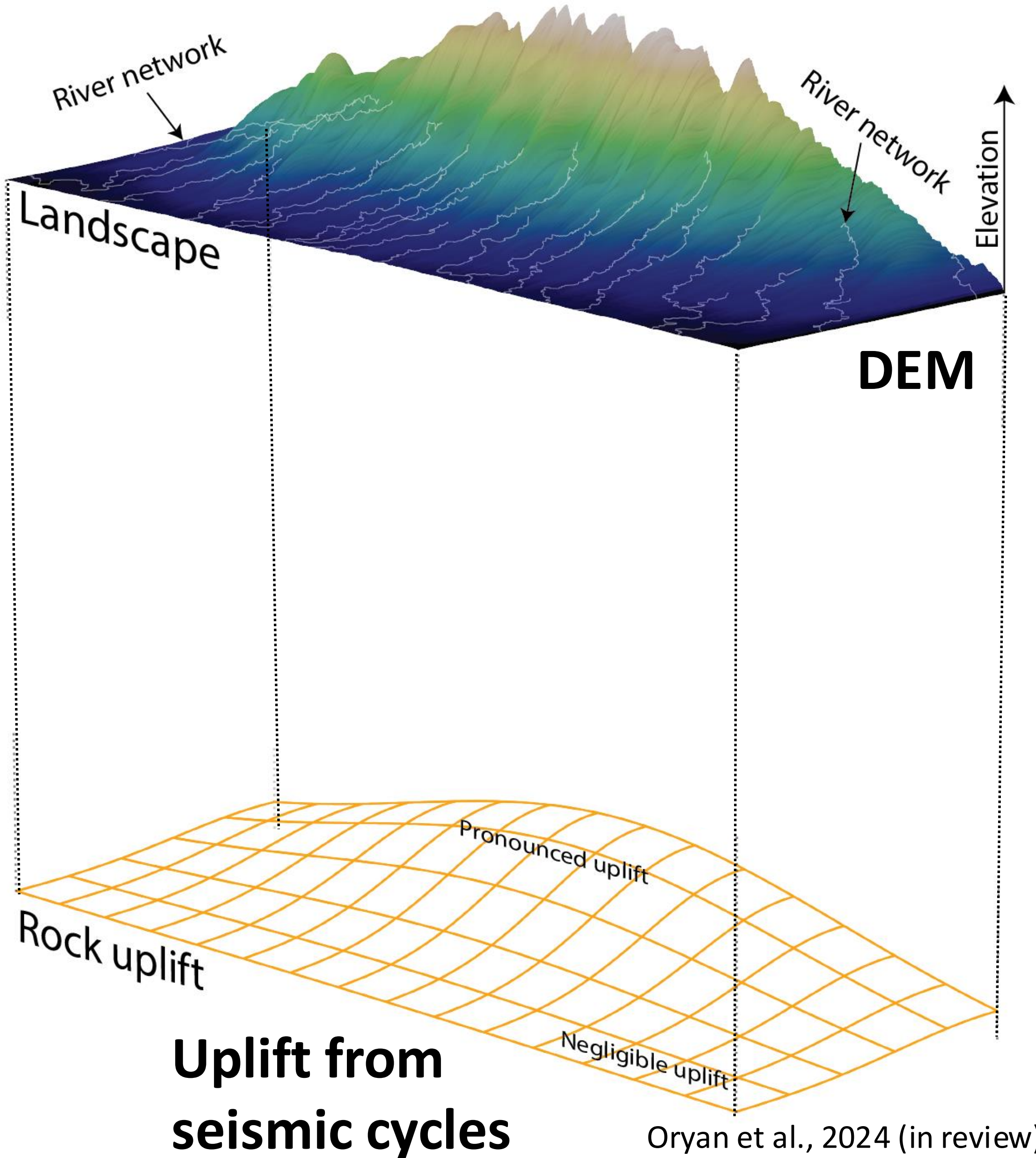
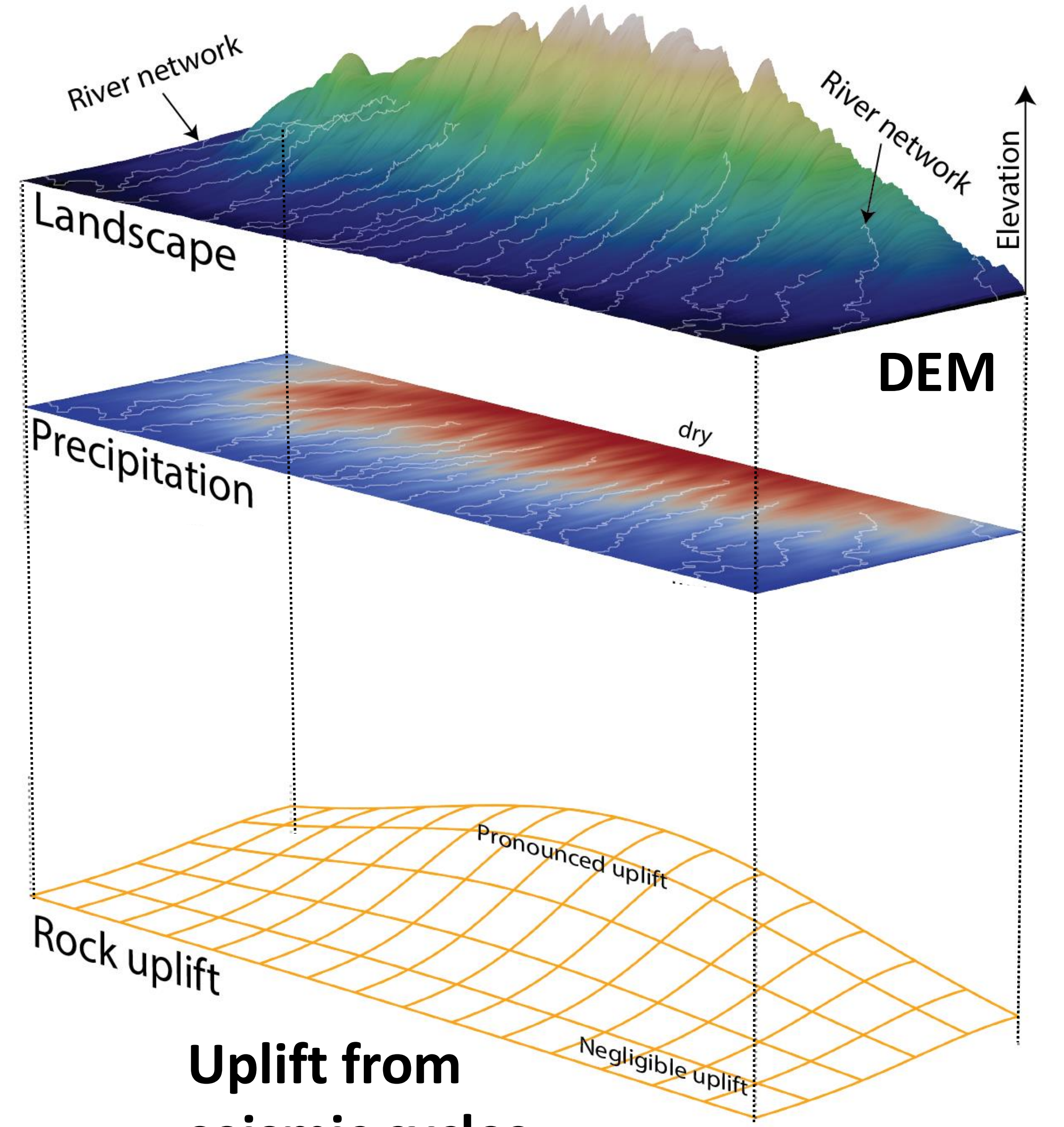


Oryan et al., 2024 (in review)

INFERRING LONG-TERM TECTONIC UPLIFT FROM BAYESIAN INVERSION OF LANDSCAPES

- Landscapes encode the combined forcing of **tectonic uplift** and erosion driven by **climate**

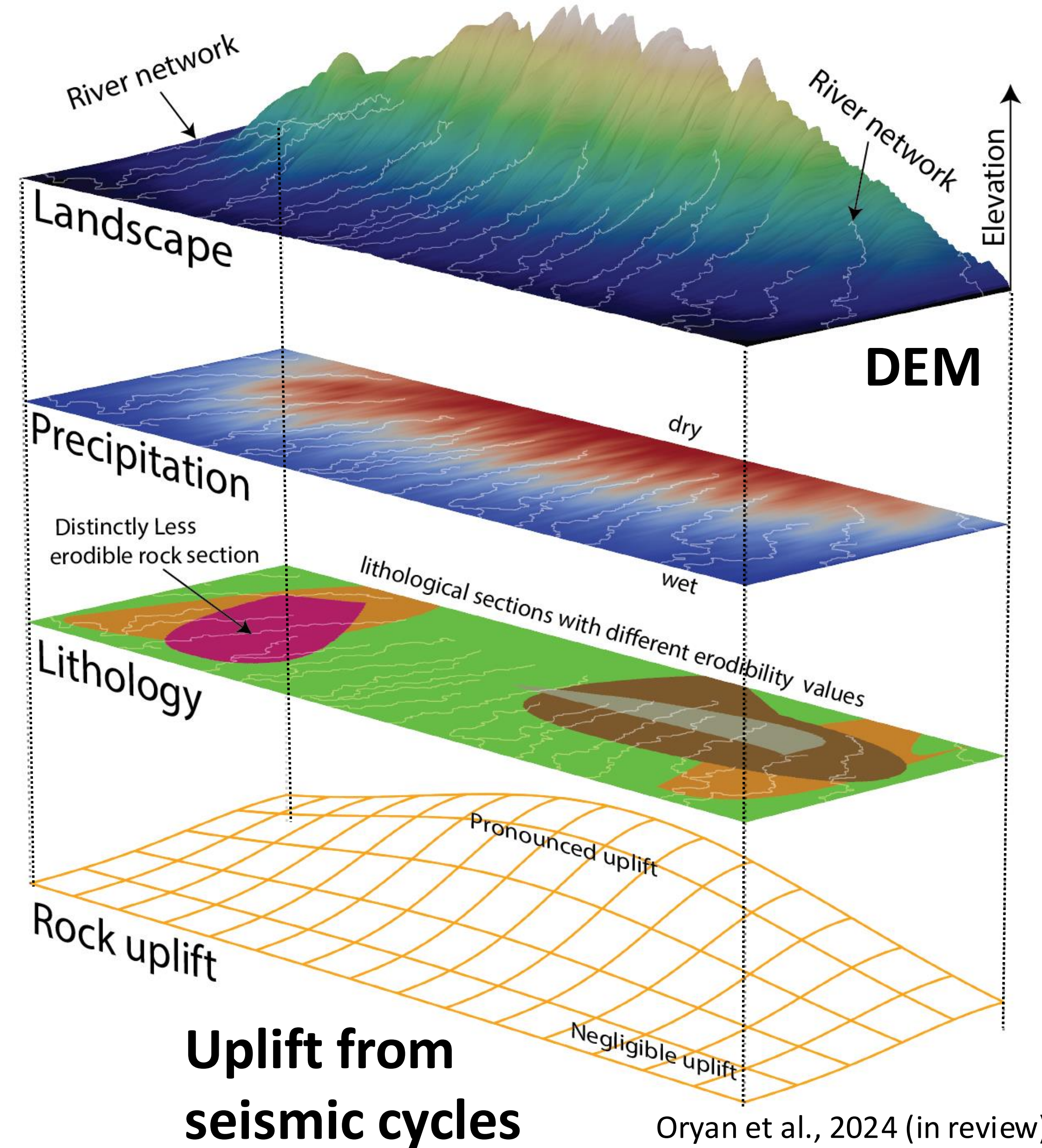


Uplift from seismic cycles

Oryan et al., 2024 (in review)

INFERRING LONG-TERM TECTONIC UPLIFT FROM BAYESIAN INVERSION OF LANDSCAPES

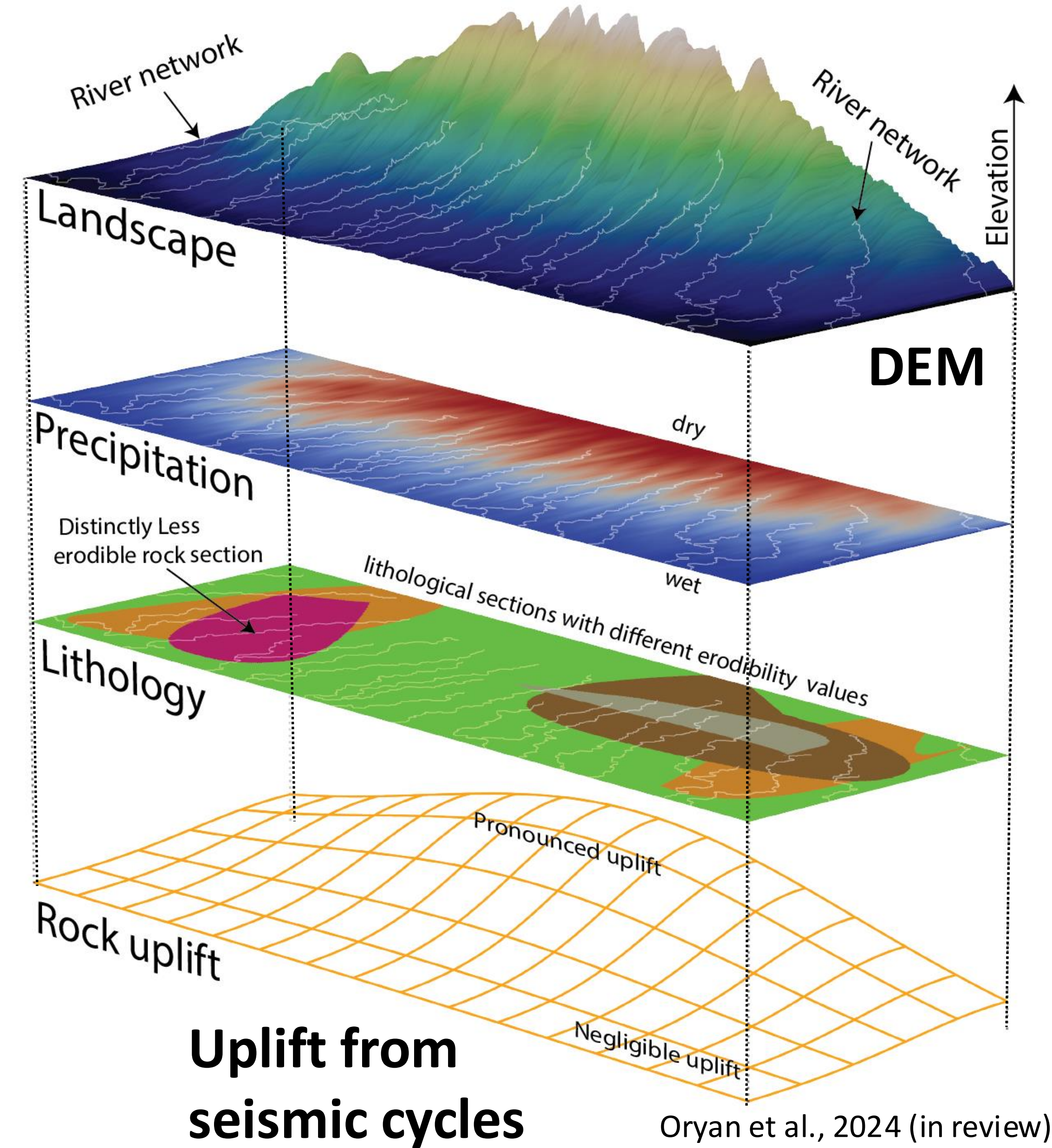
- Landscapes encode the combined forcing of **tectonic uplift** and erosion driven by **climate** and **rock erodibility**.



Oryan et al., 2024 (in review)

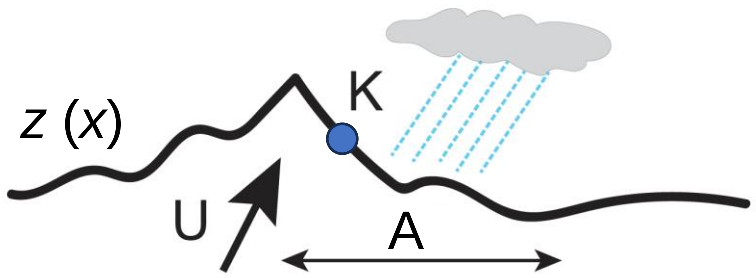
INFERRING LONG-TERM TECTONIC UPLIFT FROM BAYESIAN INVERSION OF LANDSCAPES

- Landscapes encode the combined forcing of **tectonic uplift** and erosion driven by **climate** and **rock erodibility**.
- Disentangling their contributions is essential for using landscapes as quantitative records of crustal deformation.



Oryan et al., 2024 (in review)

RIVER INCISION AT STEADY STATE



$$\boxed{U(X)} = \boxed{K(x)A^m(x)S^n(x)}$$

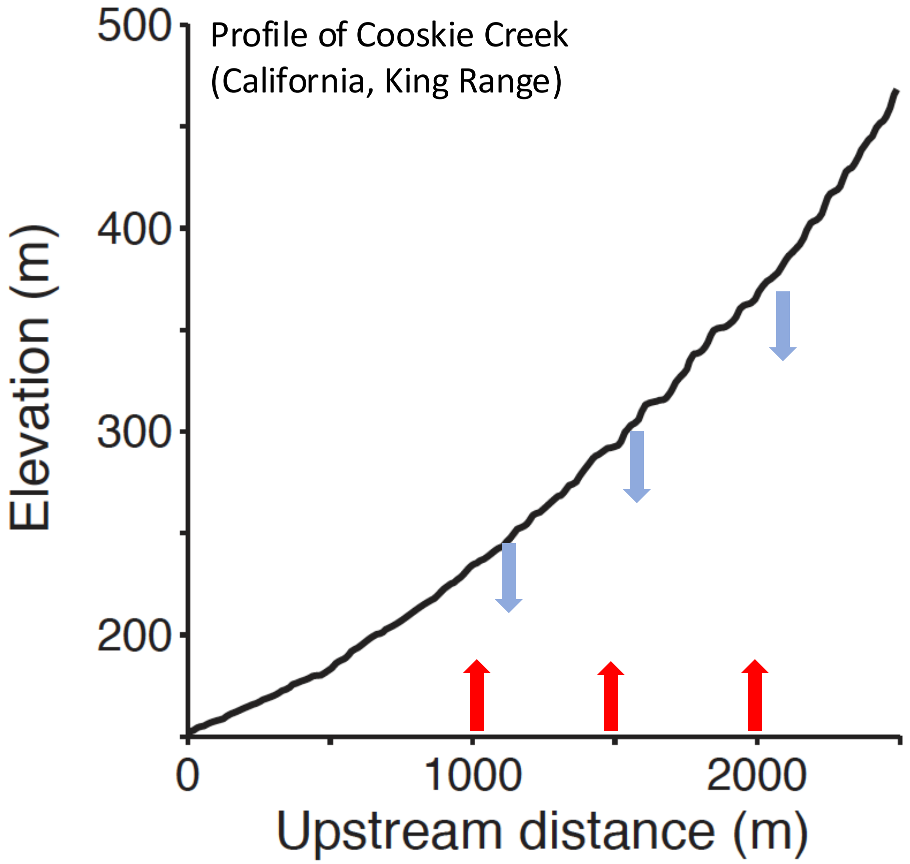
Tectonic uplift

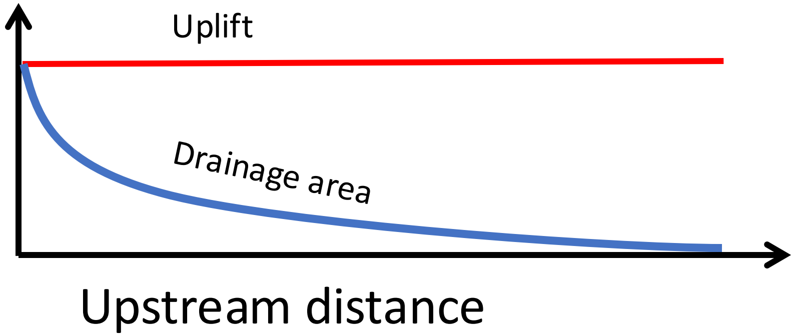
Local incision rate *(faster for steeper slope* ***S****, with more water flowing and larger erodibility)*

Parameters:

- erodibility (**K**)
- drainage area (**A**)
- exponents (**m**, **n**)

RIVER INCISION AT STEADY STATE





$$\boxed{U(X)} = \boxed{K(x)A^m(x)S^n(x)}$$

<u>Tectonic uplift</u>

<u>Local incision rate</u>
*(faster for steeper slope **S**, with more water flowing and larger erodibility)*

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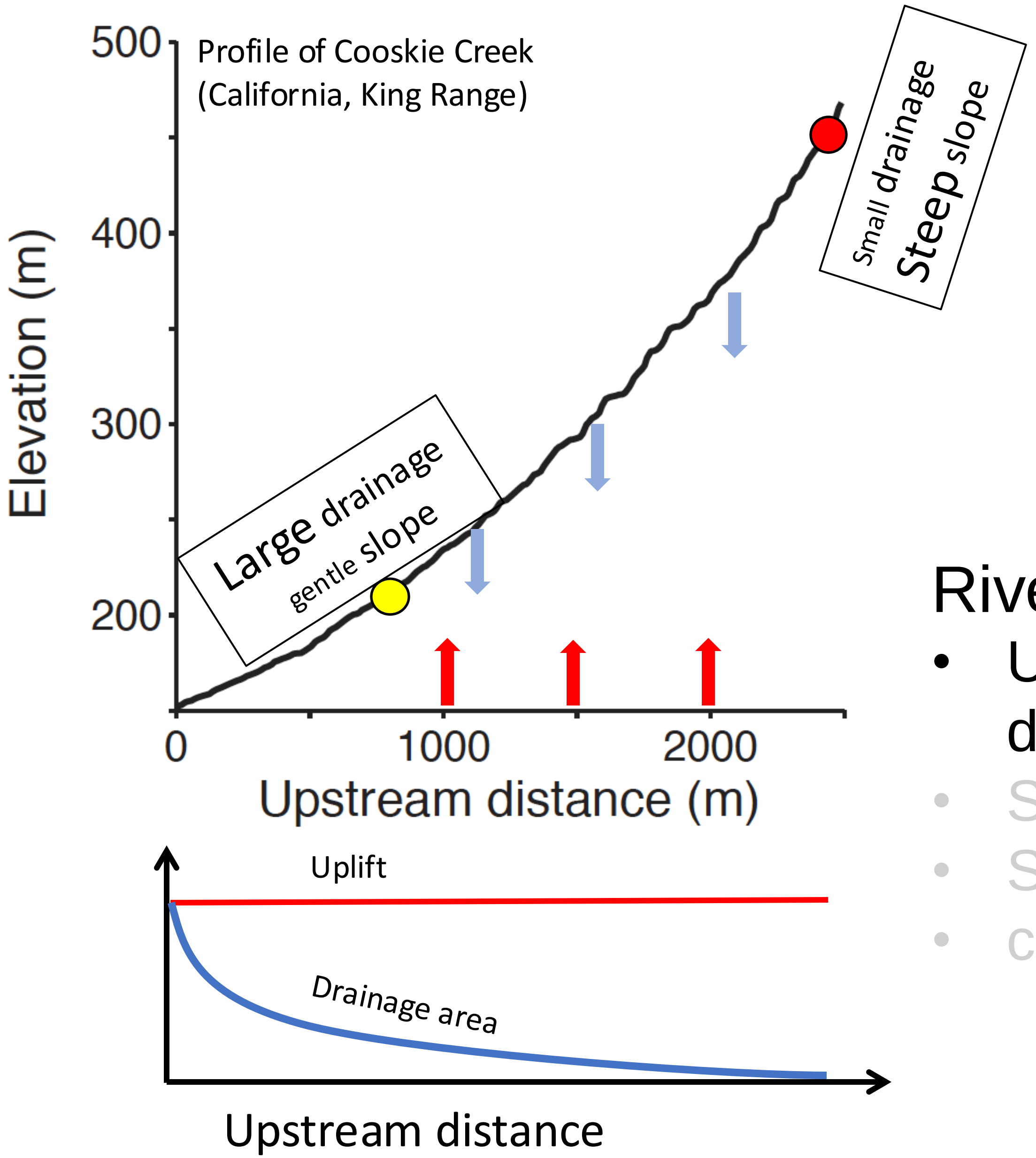
River concavity reflects:
- Upstream decrease in drainage area
- Shape of uplift
- Spatially variable erodibility
- climate

Perron & Royden, 2013

RIVER INCISION AT STEADY STATE



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Perron & Royden, 2013

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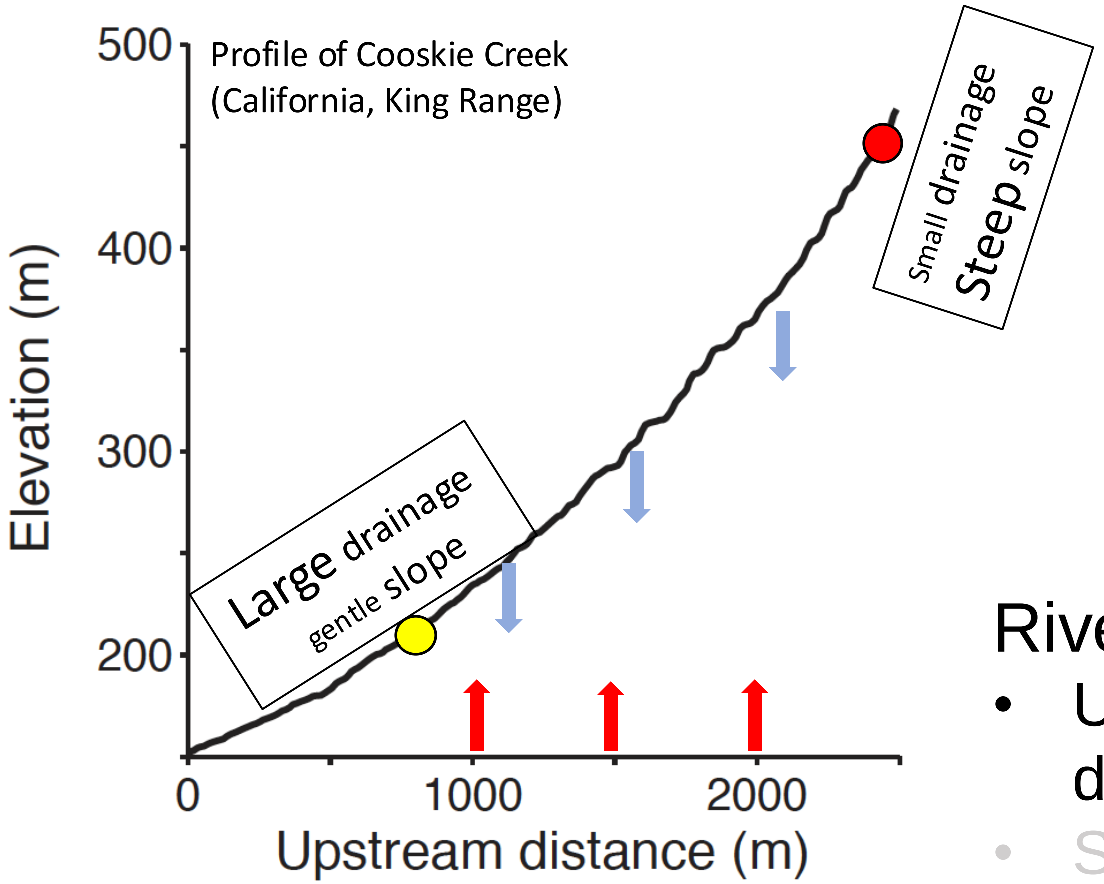
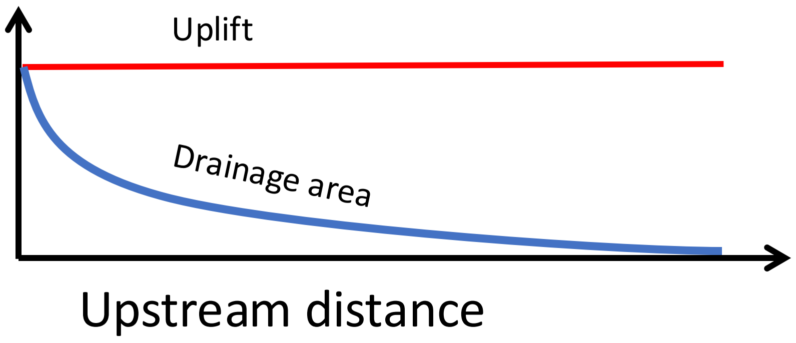
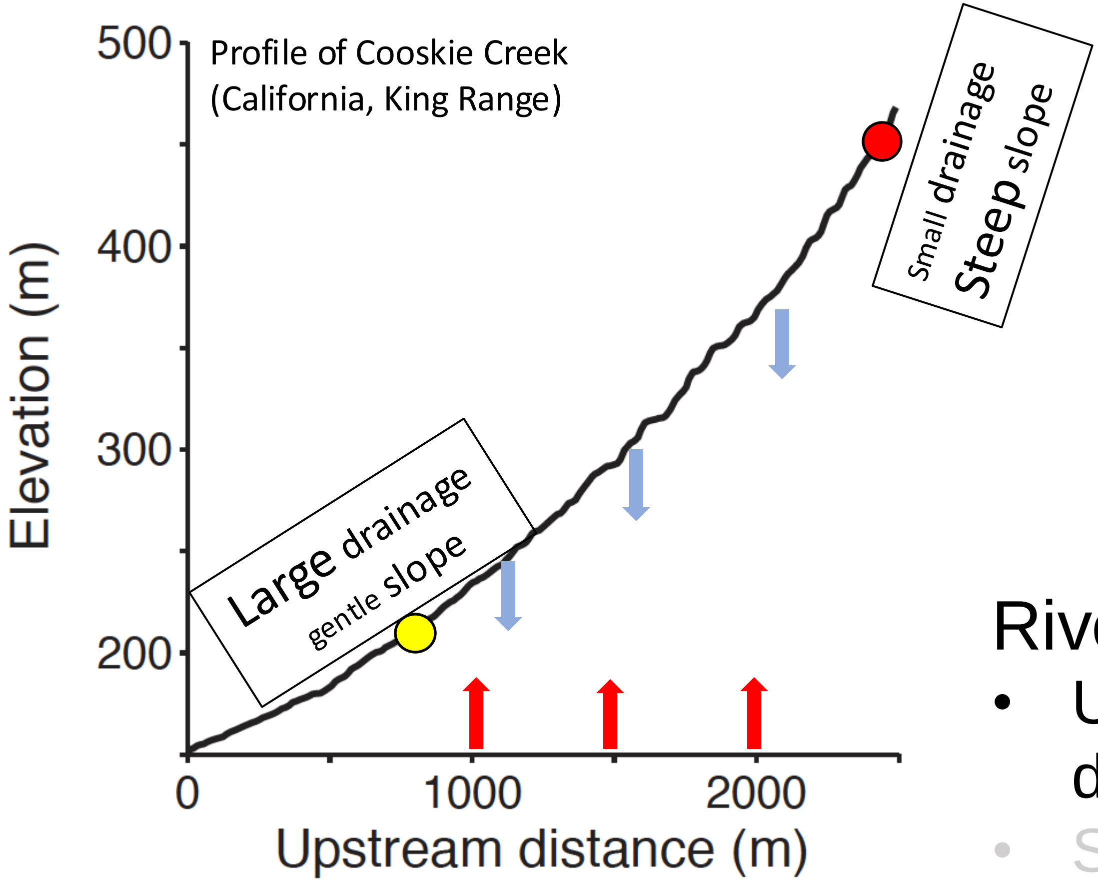


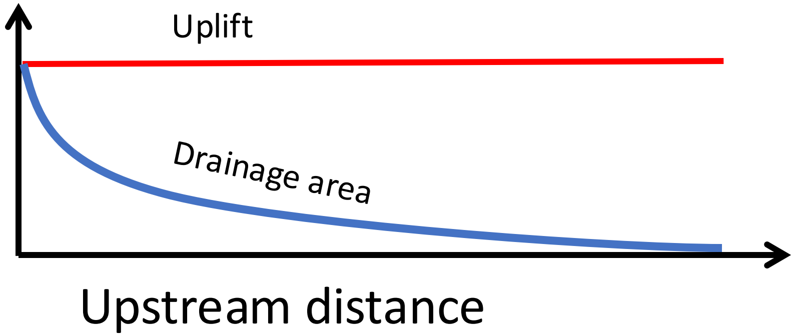


Rive
- U
d
- S
- S
- cl

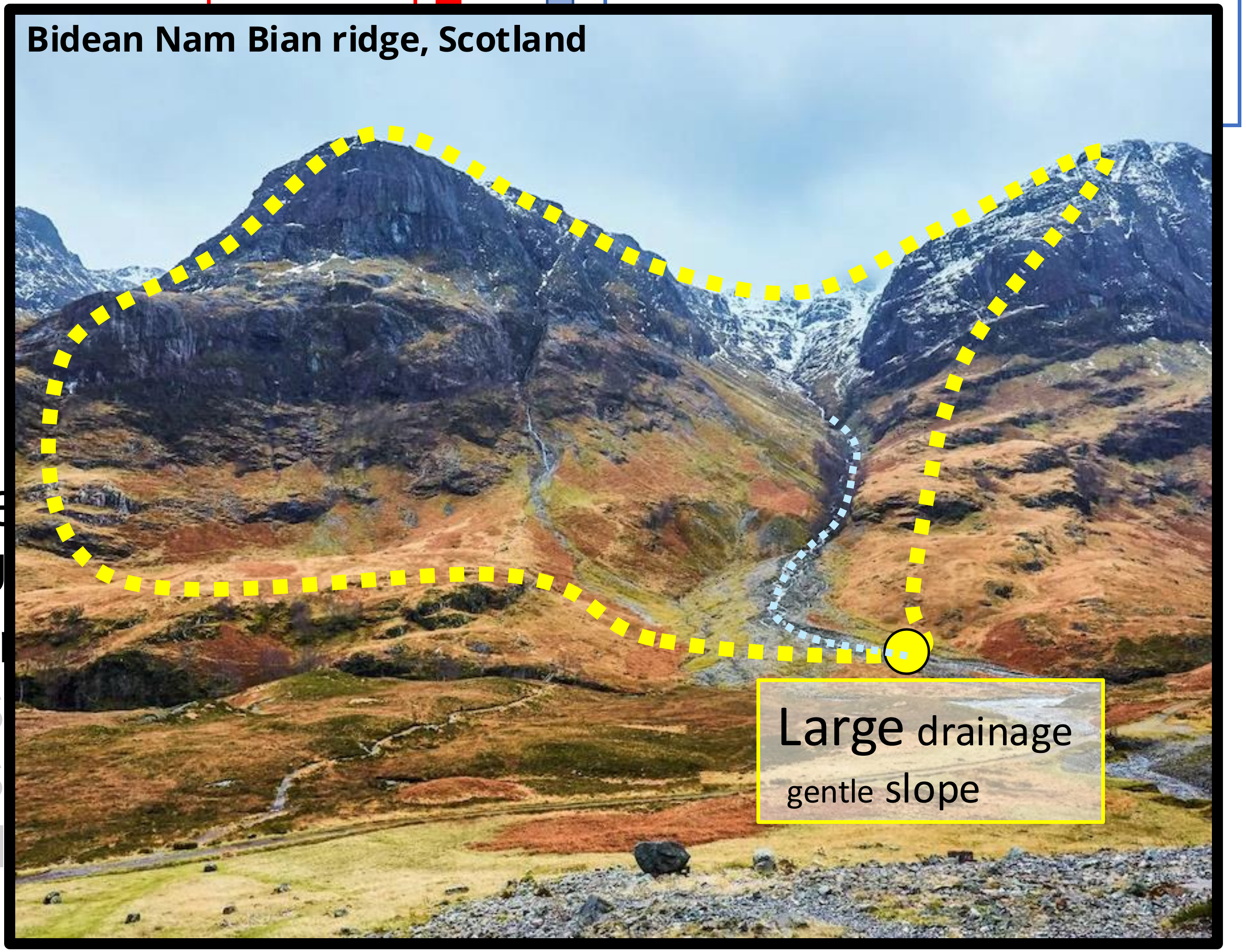
Perron & Royden, 2013

RIVER INCISION AT STEADY STATE



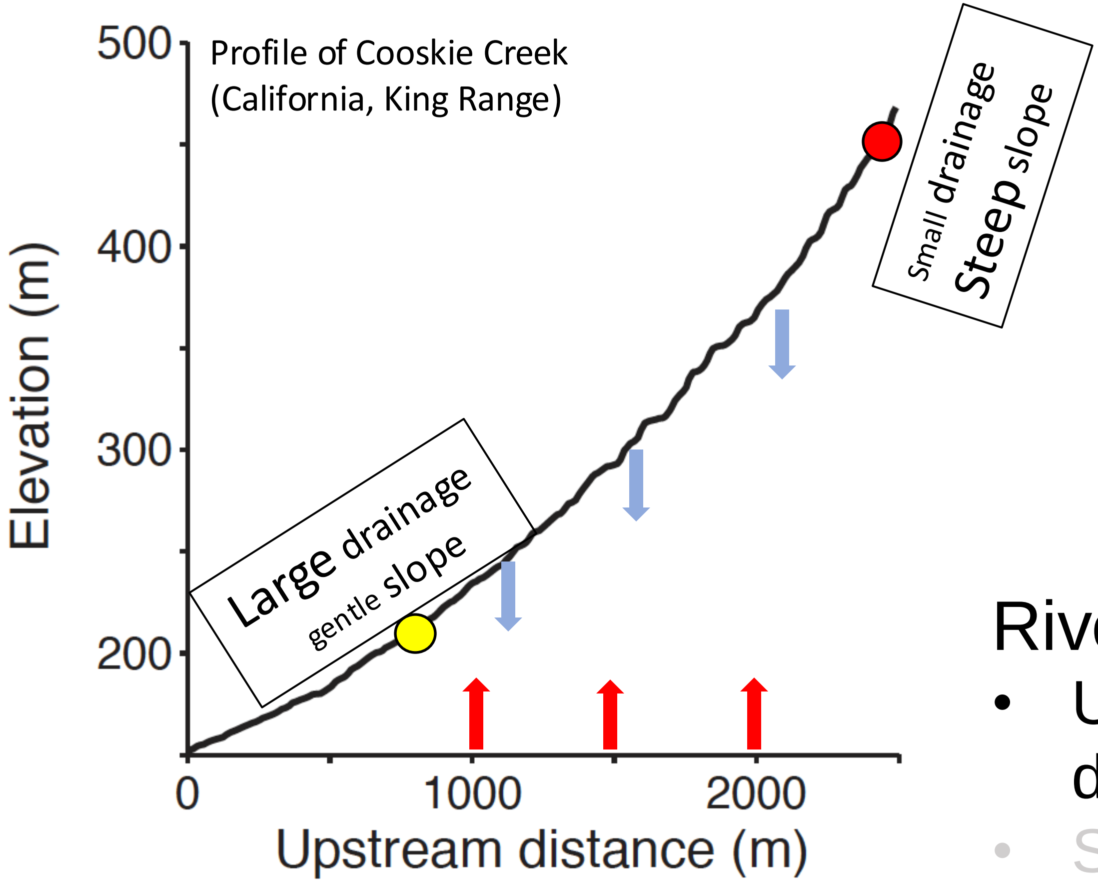


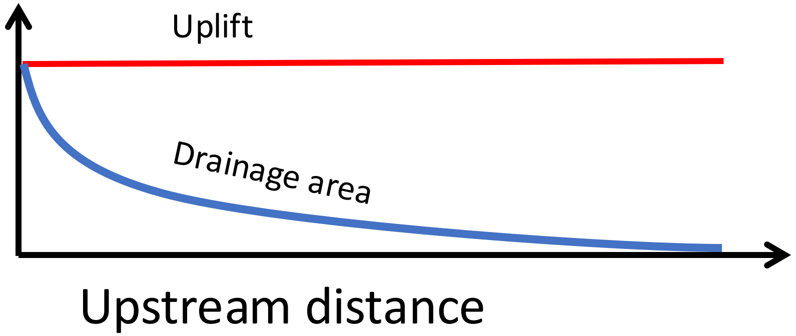
Rive
- U
d
- S
- S
- cl



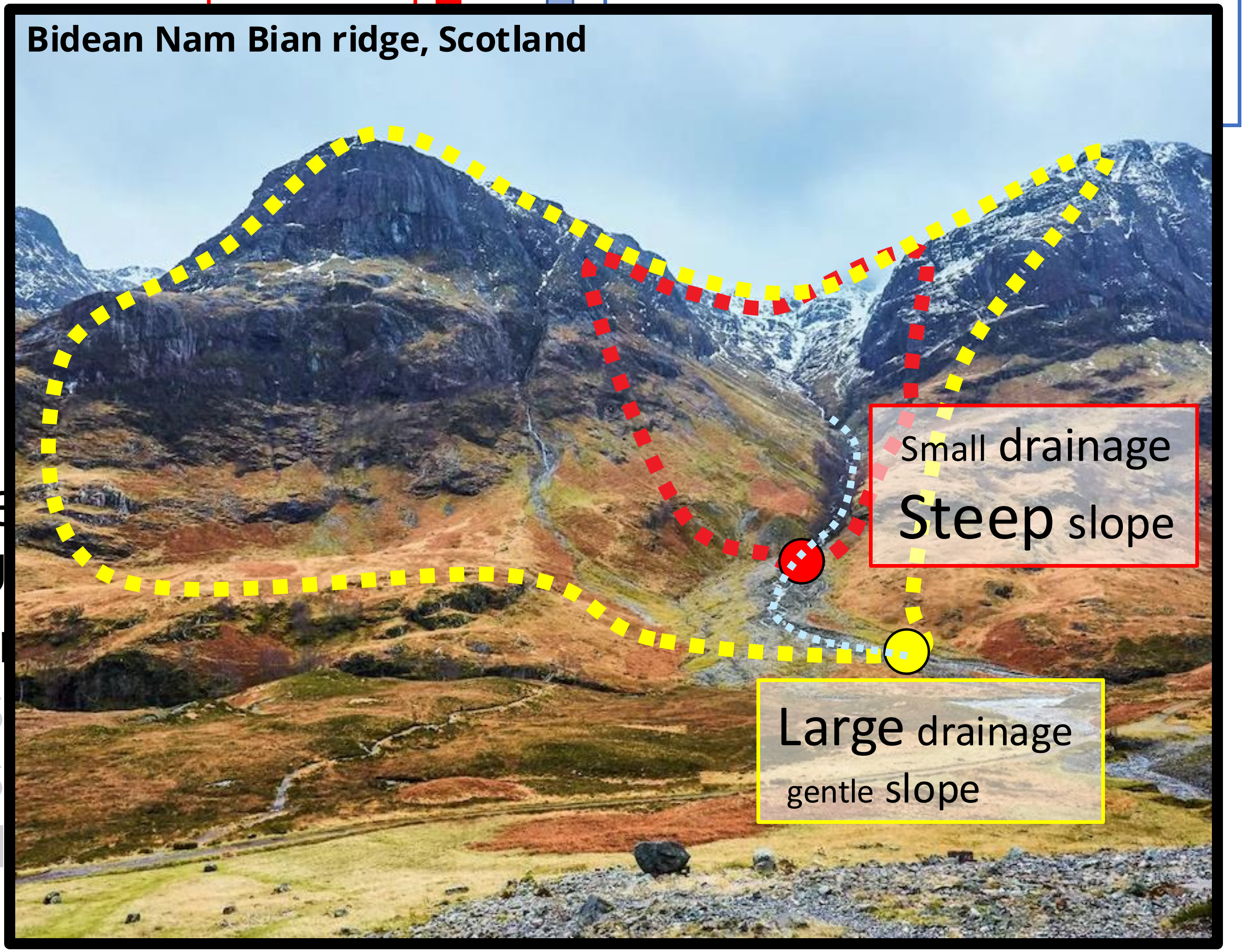
Perron & Royden, 2013

RIVER INCISION AT STEADY STATE



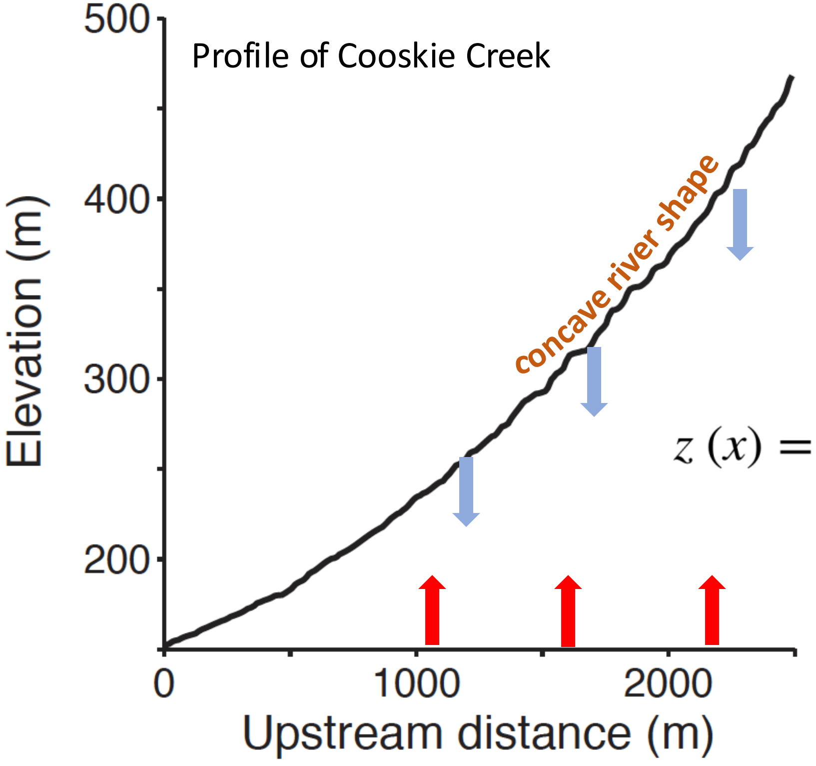


Rive
- U
d
- S
- S
- c



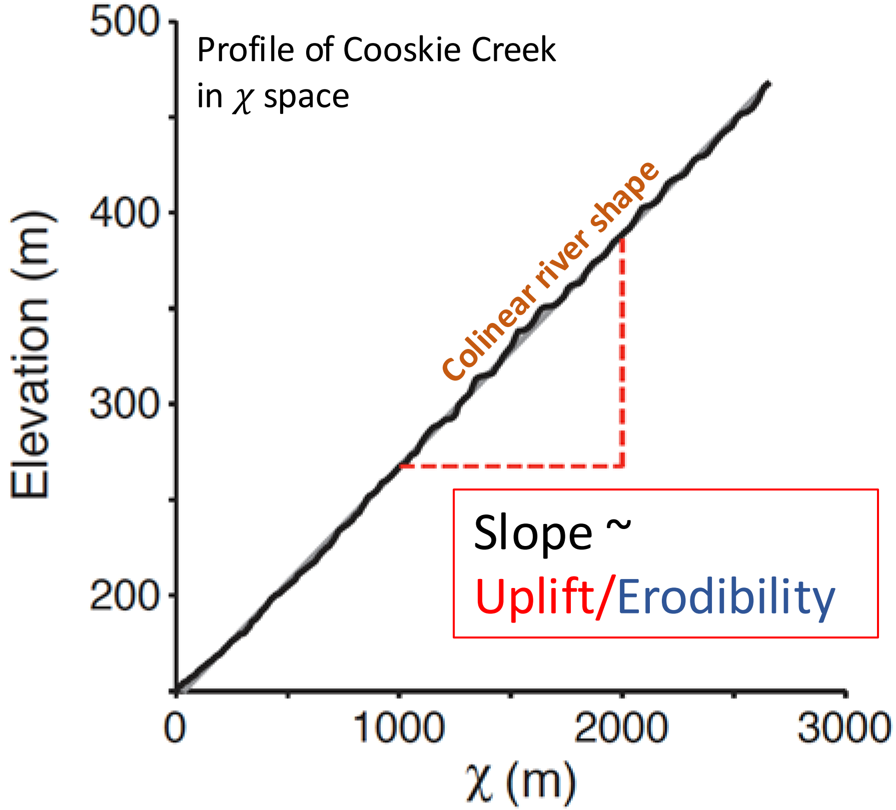
Perron & Royden, 2013

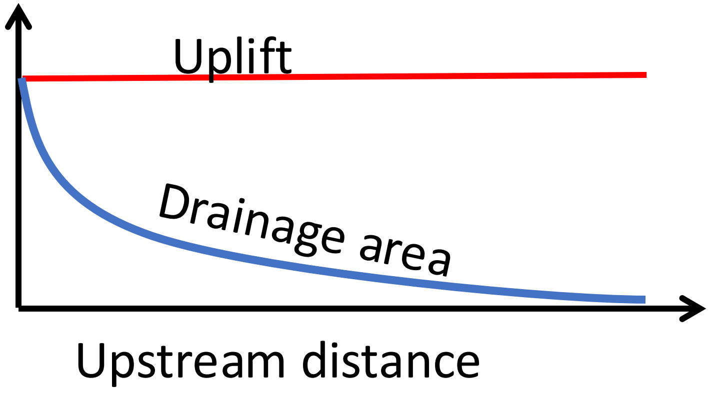
χ – TRANSFORMATION OF RIVERS



$$z(x) = z_b + \left(\frac{U_0}{K_0 A_0}\right)^{\frac{1}{n}} \underbrace{\int_{x_b}^{x} \left(\frac{A_0}{A^*(x)}\right)^{\frac{m}{n}} dx}_{\chi}$$

χ – TRANSFORMATION

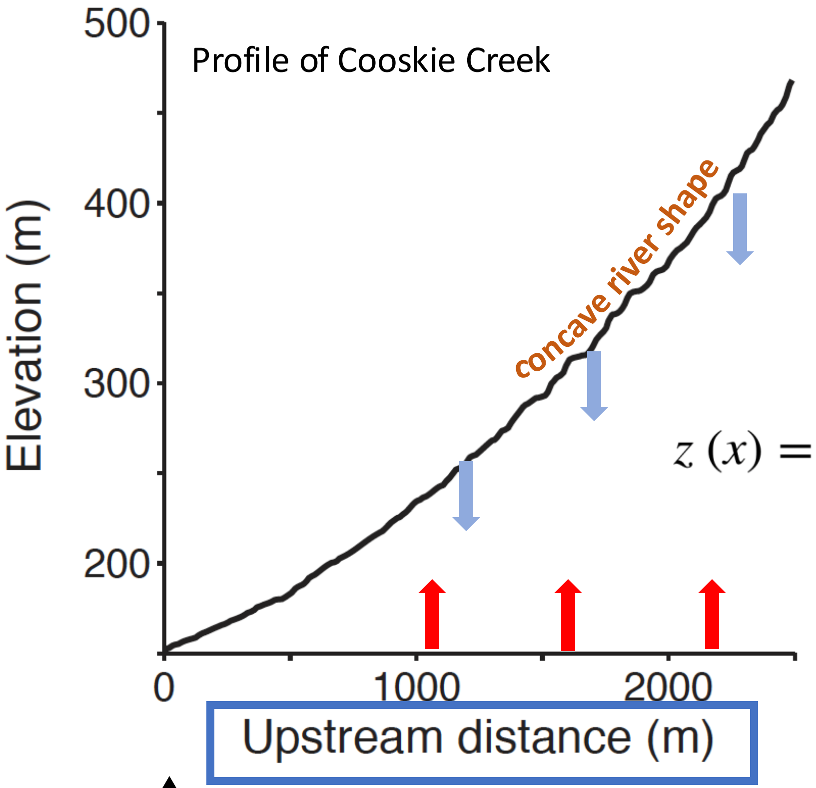




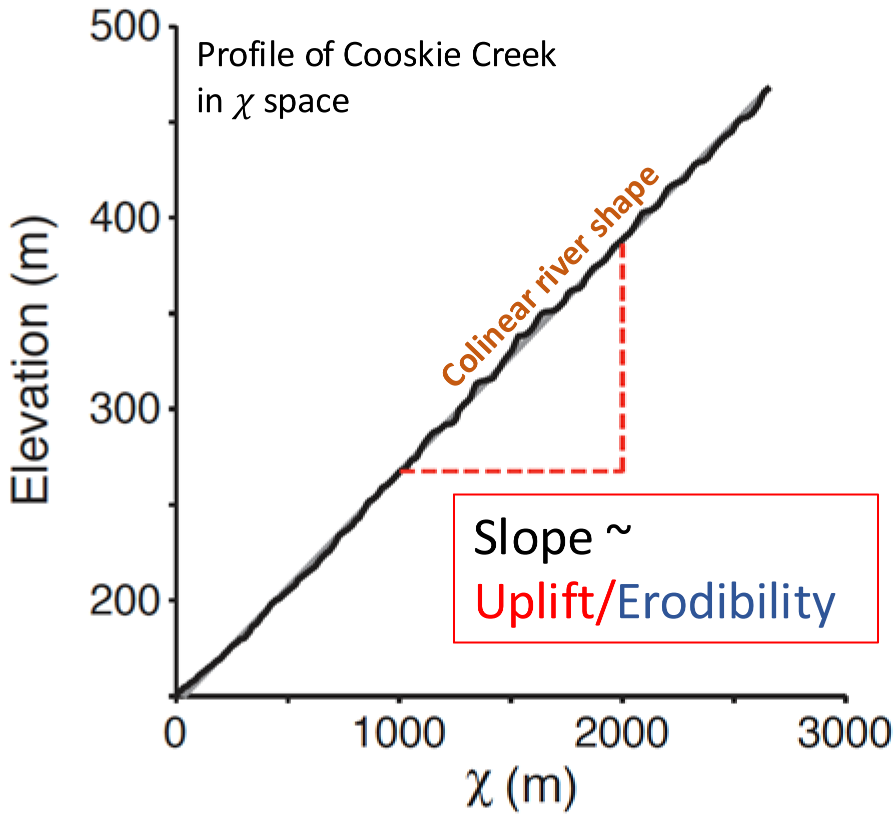
Corrects for upstream decrease in drainage area while assuming uniform spatial uplift

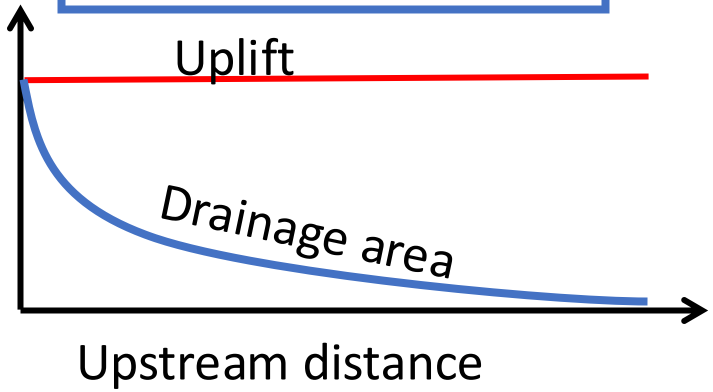
Perron & Royden, 2013

χ – TRANSFORMATION OF RIVERS



$$z\,(x) = z_b + \left(\frac{U_0}{K_0 A_0}\right)^{\frac{1}{n}} \underbrace{\int_{x_b}^{x} \left(\frac{A_0}{A^*\,(x)}\right)^{\frac{m}{n}} d\,x}_{\chi}$$





Corrects for upstream decrease in drainage area while assuming uniform spatial uplift

Perron & Royden, 2013

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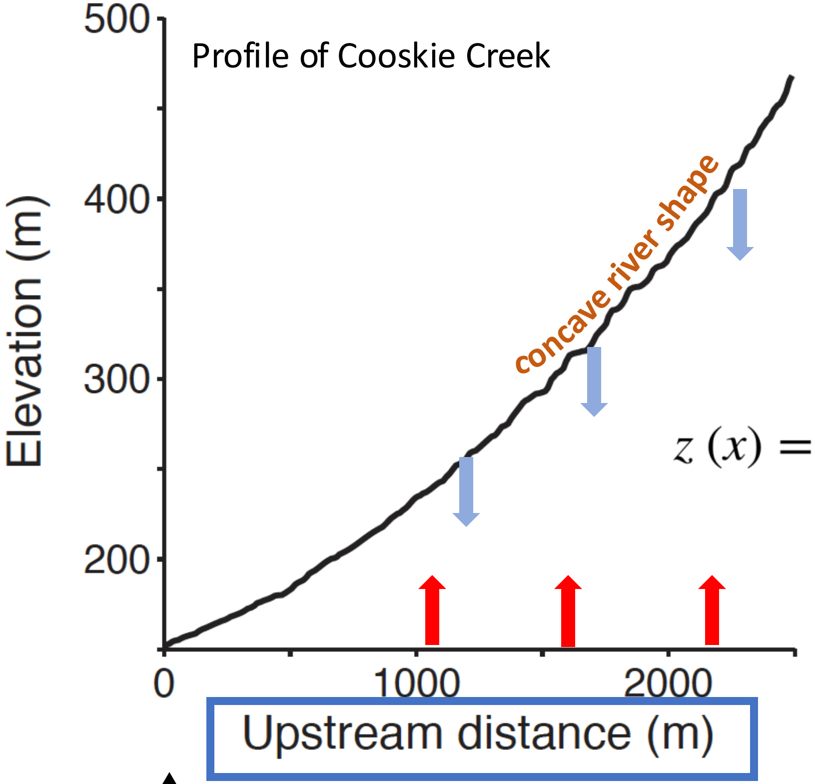
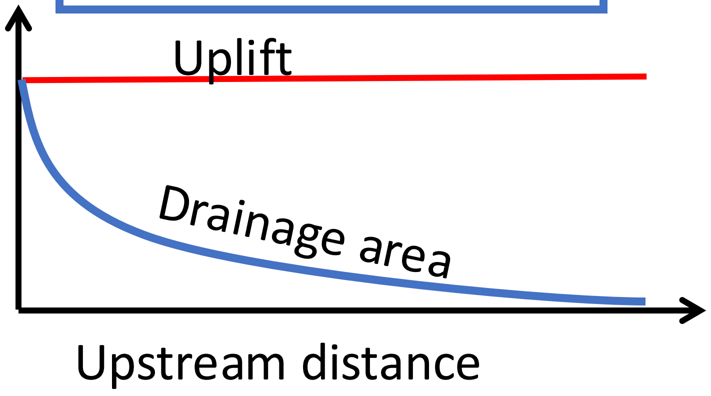
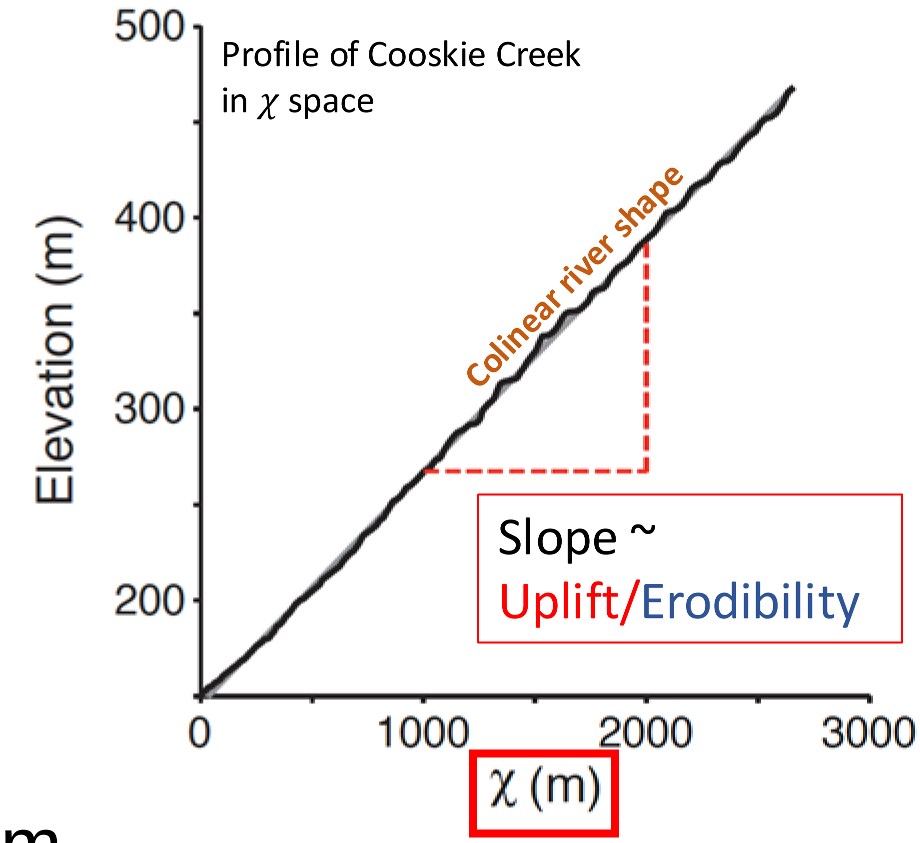




$$z\left(x\right) = z_b + \left(\frac{U_0}{K_0 A_0}\right)^{\frac{1}{n}} \underbrace{\int_{x_b}^{x} \left(\frac{A_0}{A^*\left(x\right)}\right)^{\frac{m}{n}} dx}_{\chi}$$

χ – TRANSFORMATION

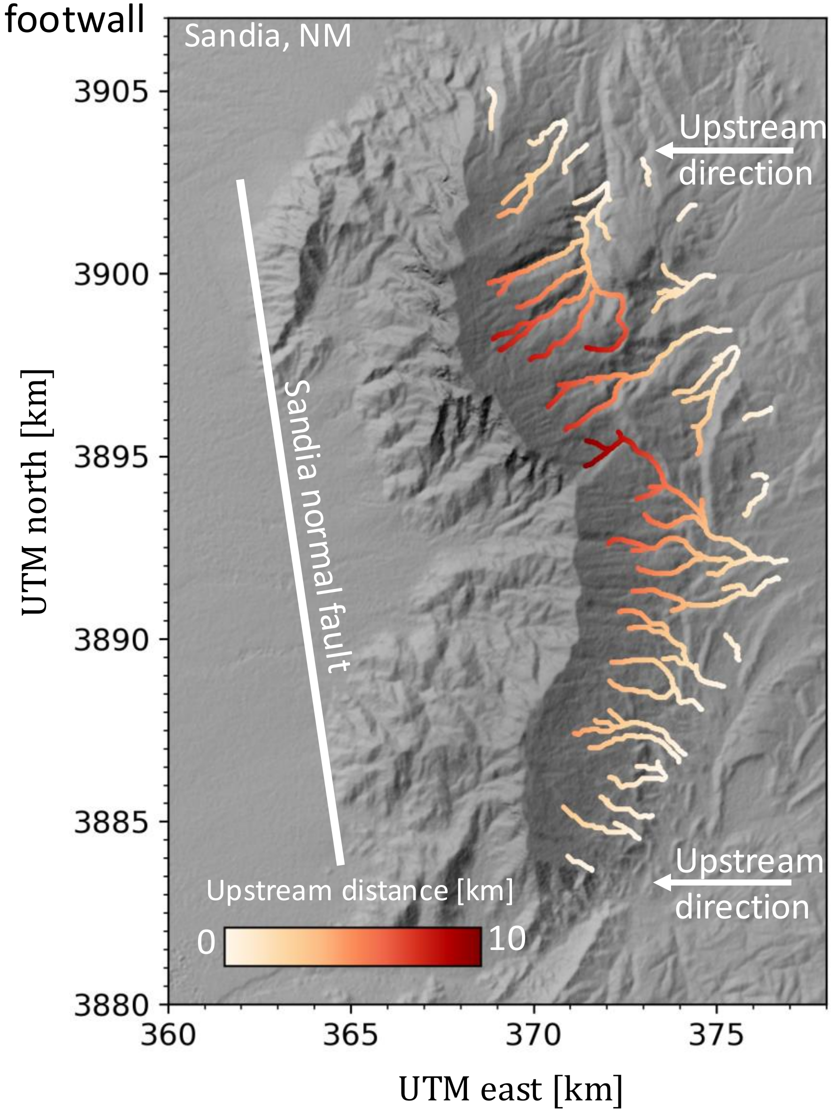


Corrects for upstream decrease in drainage area while assuming uniform spatial uplift

Perron & Royden, 2013

χ – TRANSFORMATION OF RIVER PROFILES IN SANDIA

Application to simple tectonic settings - normal fault footwall

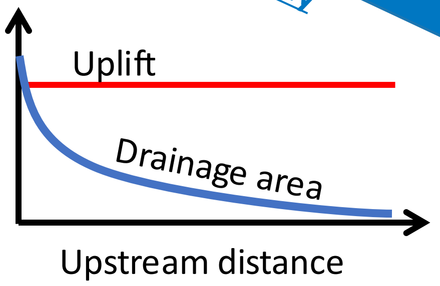


River concavity reflects:

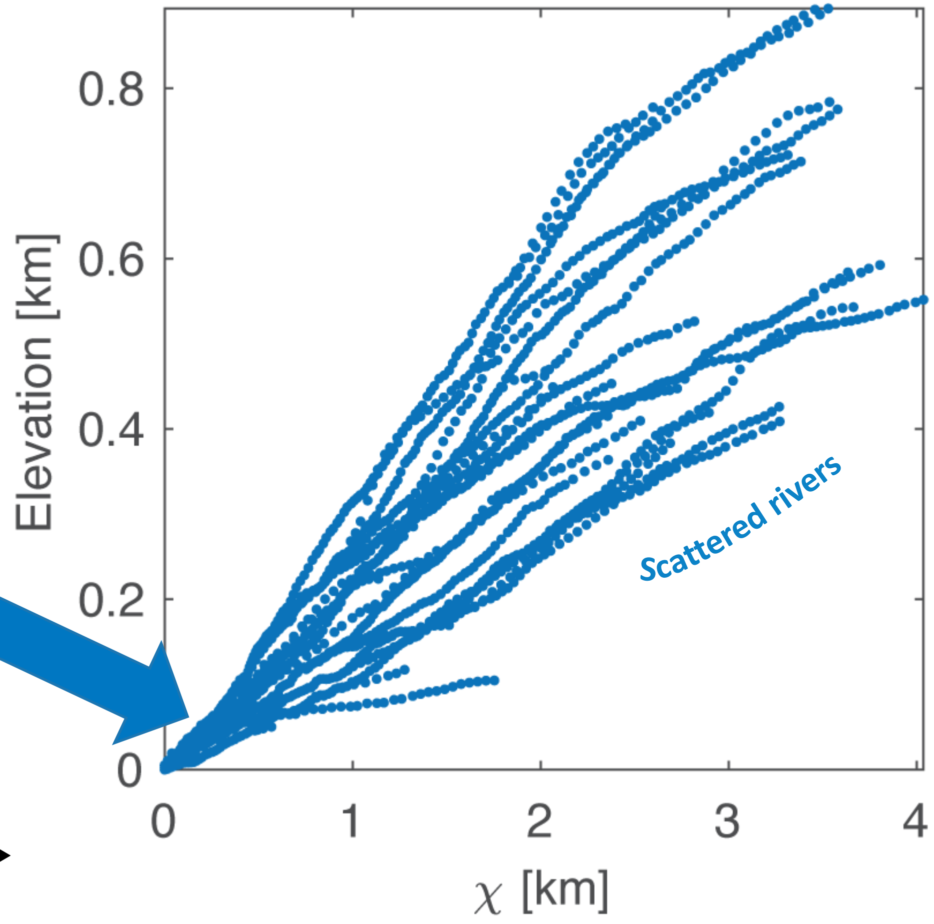
- Upstream decrease in drainage area
- Shape of uplift
- Spatially variable erodibility and climate

χ – TRANSFORMATION

Corrected for area only



χ *space* —Sandia rivers



Olive et al., 2022

χ – TRANSFORMATION OF RIVER PROFILES IN SANDIA

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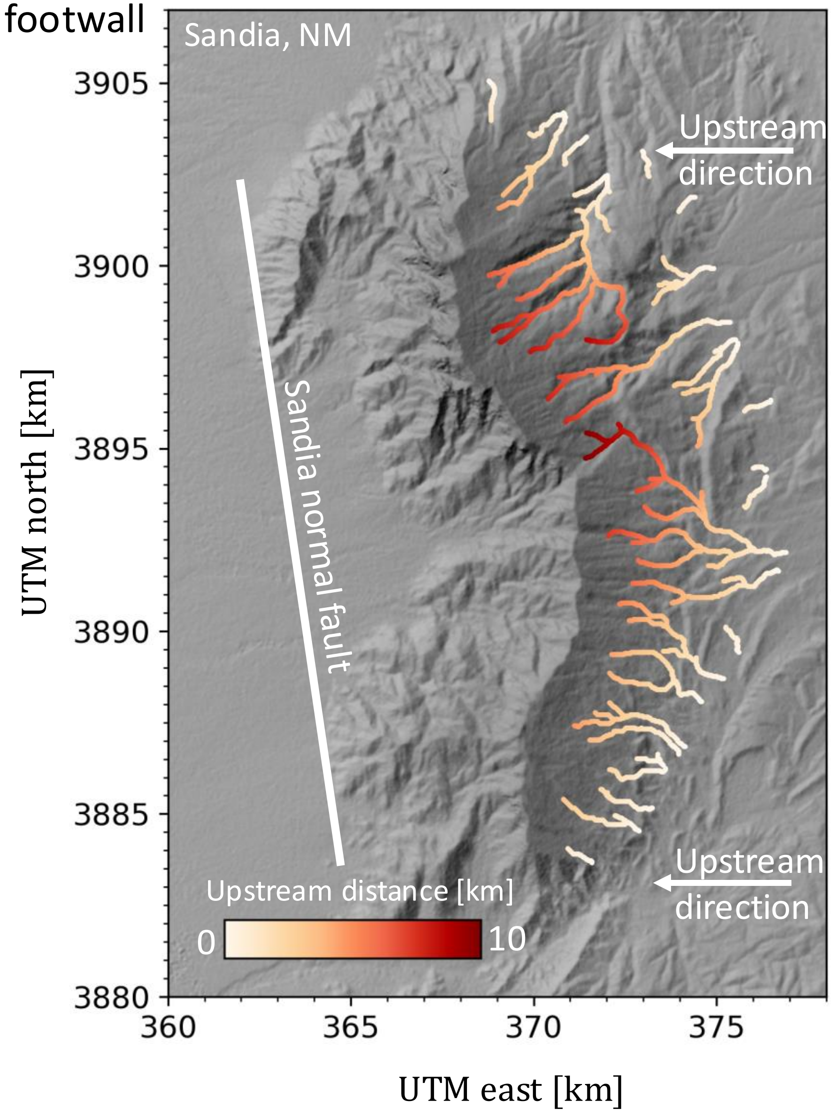

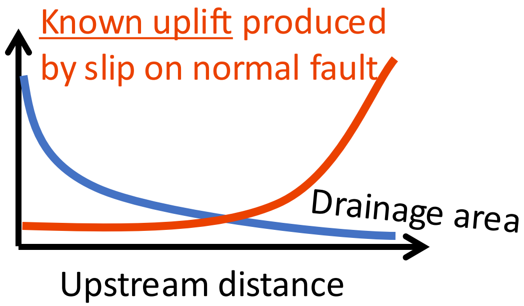

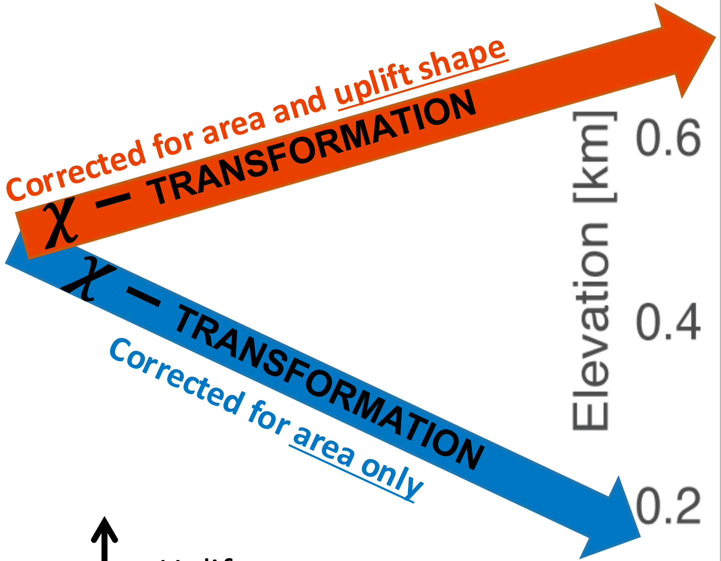

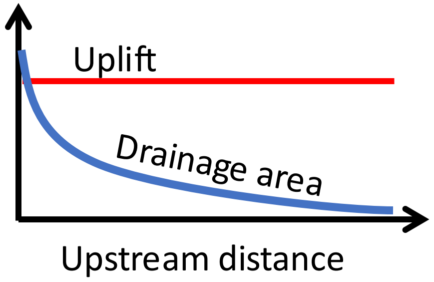

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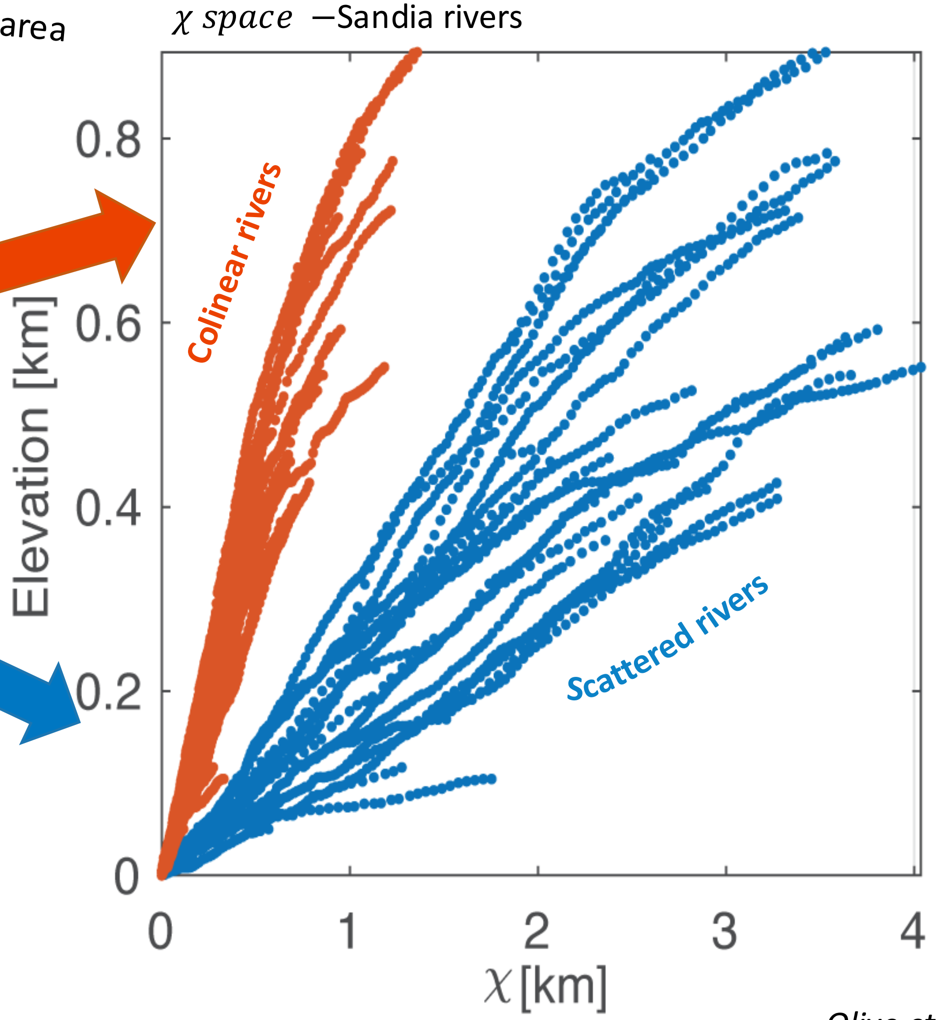
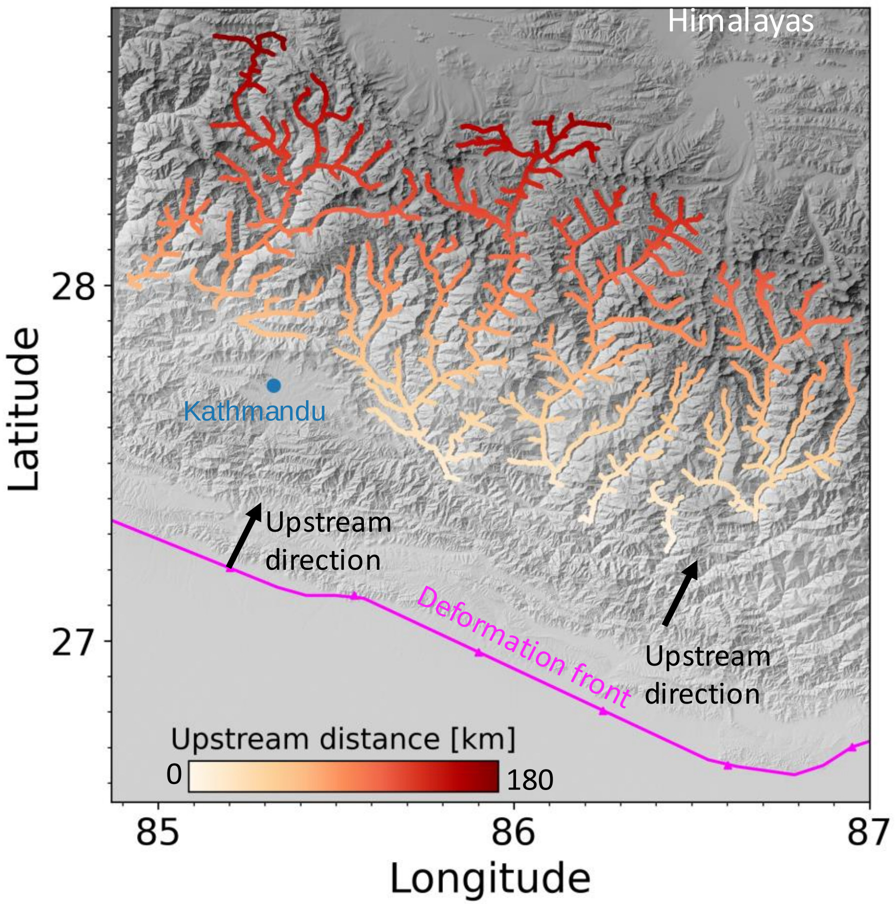


Olive et al., 2022

χ – TRANSFORMATION OF RIVER PROFILES IN THE HIMALAYAS



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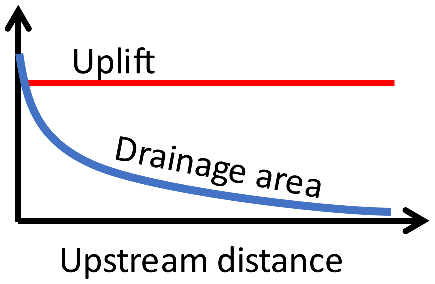
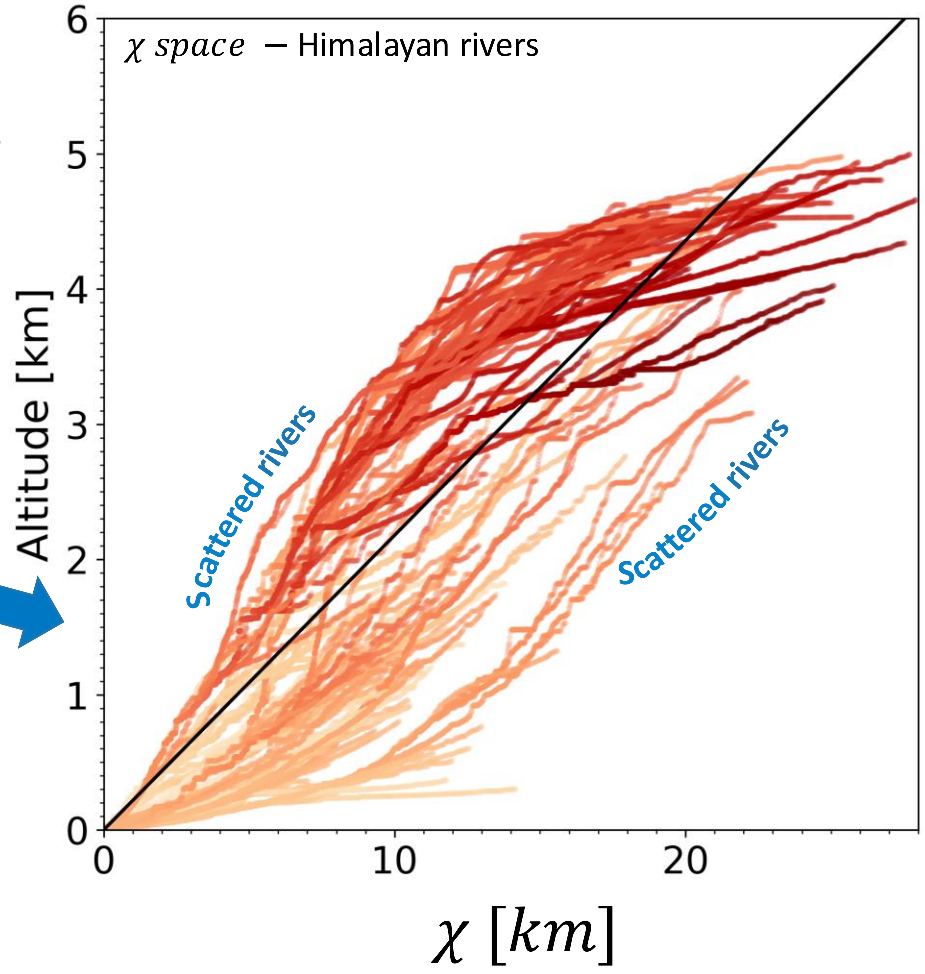
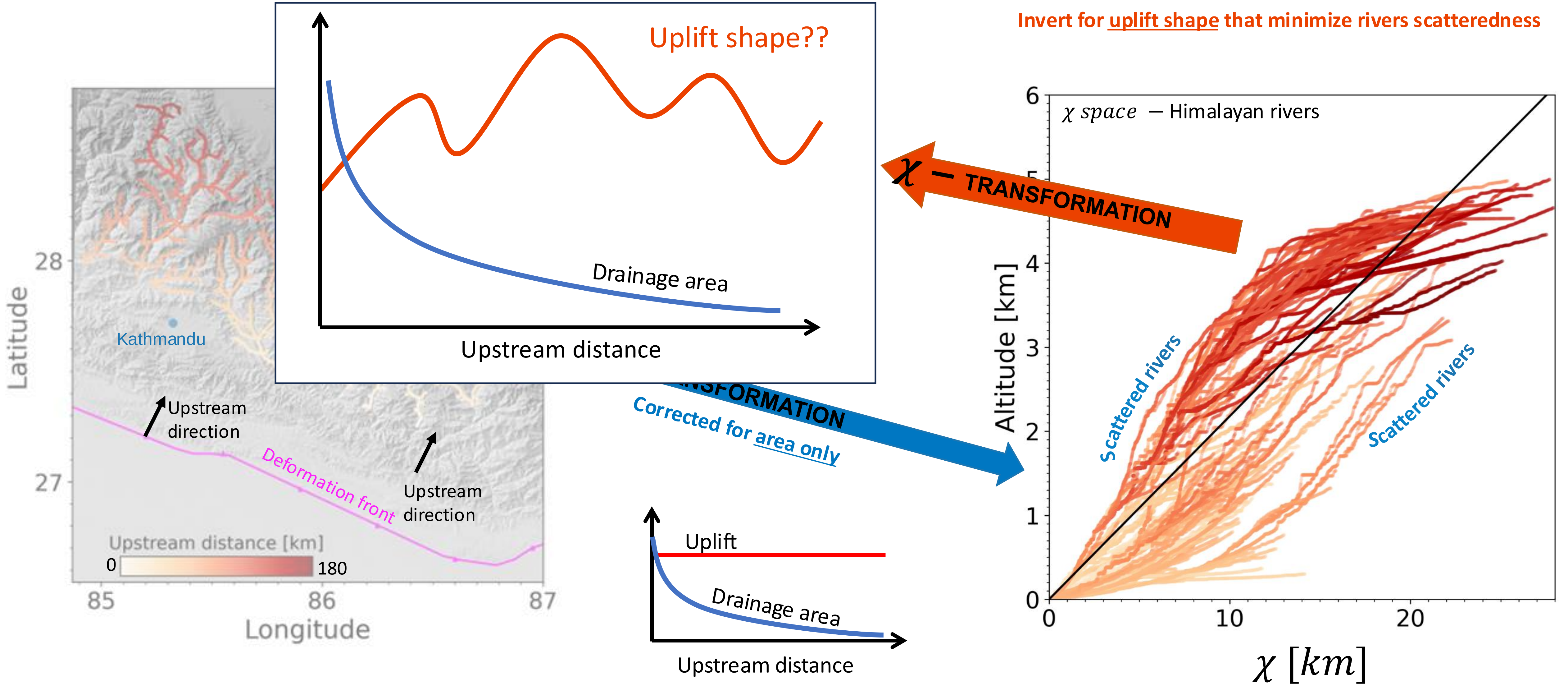
χ – TRANSFORMATION

Corrected for area only





χ – TRANSFORMATION OF RIVER PROFILES IN THE HIMALAYAS



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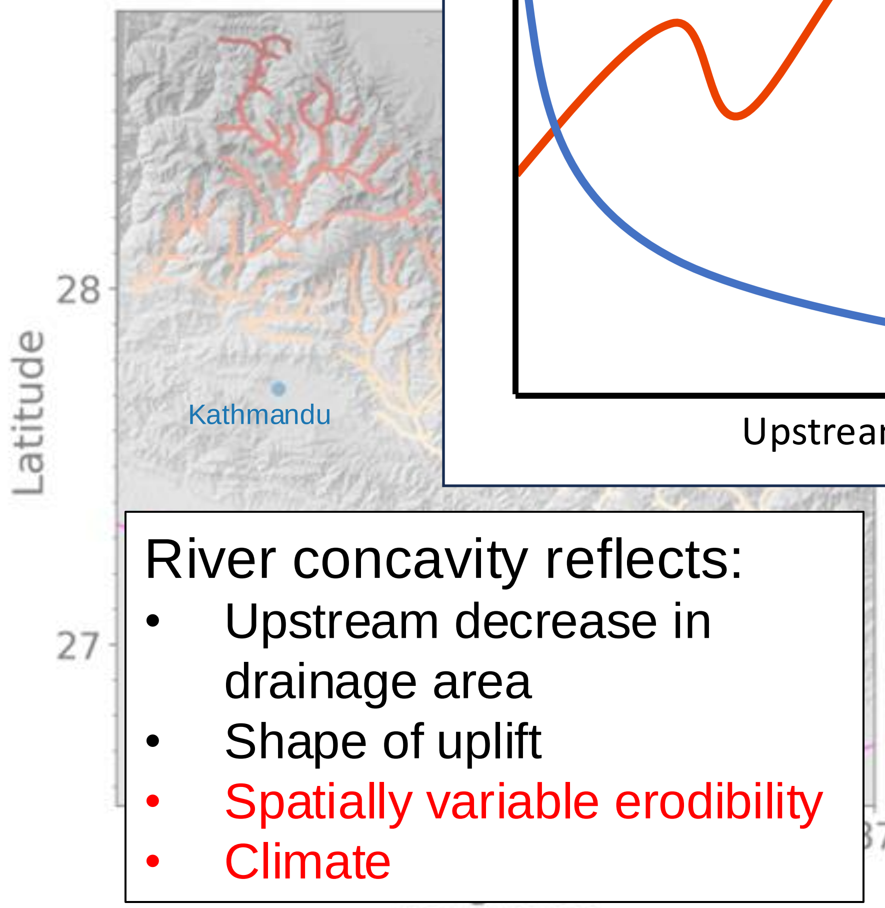

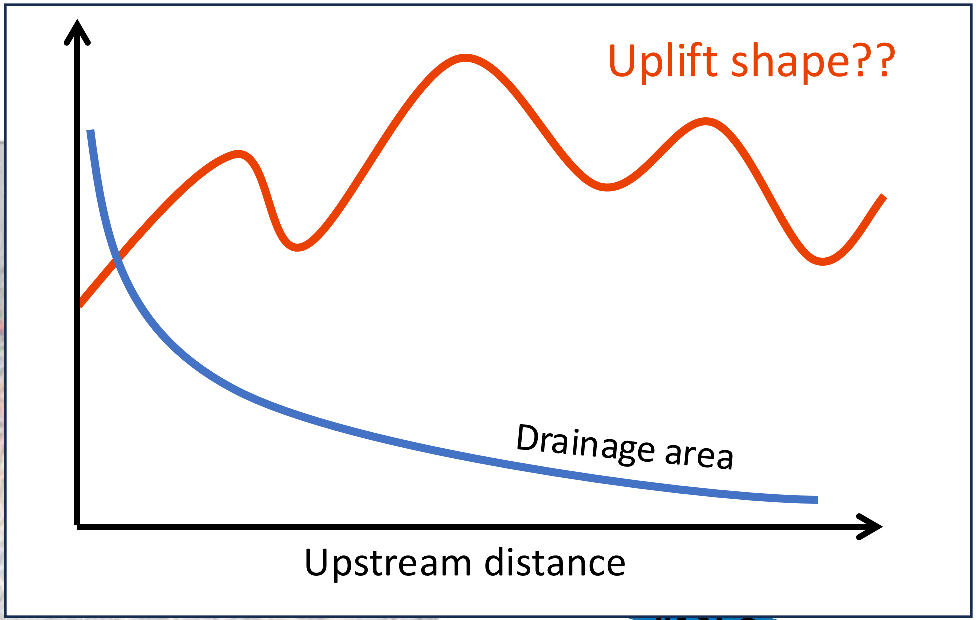

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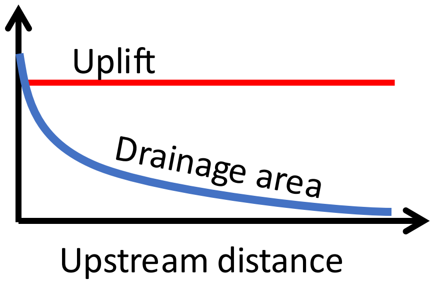
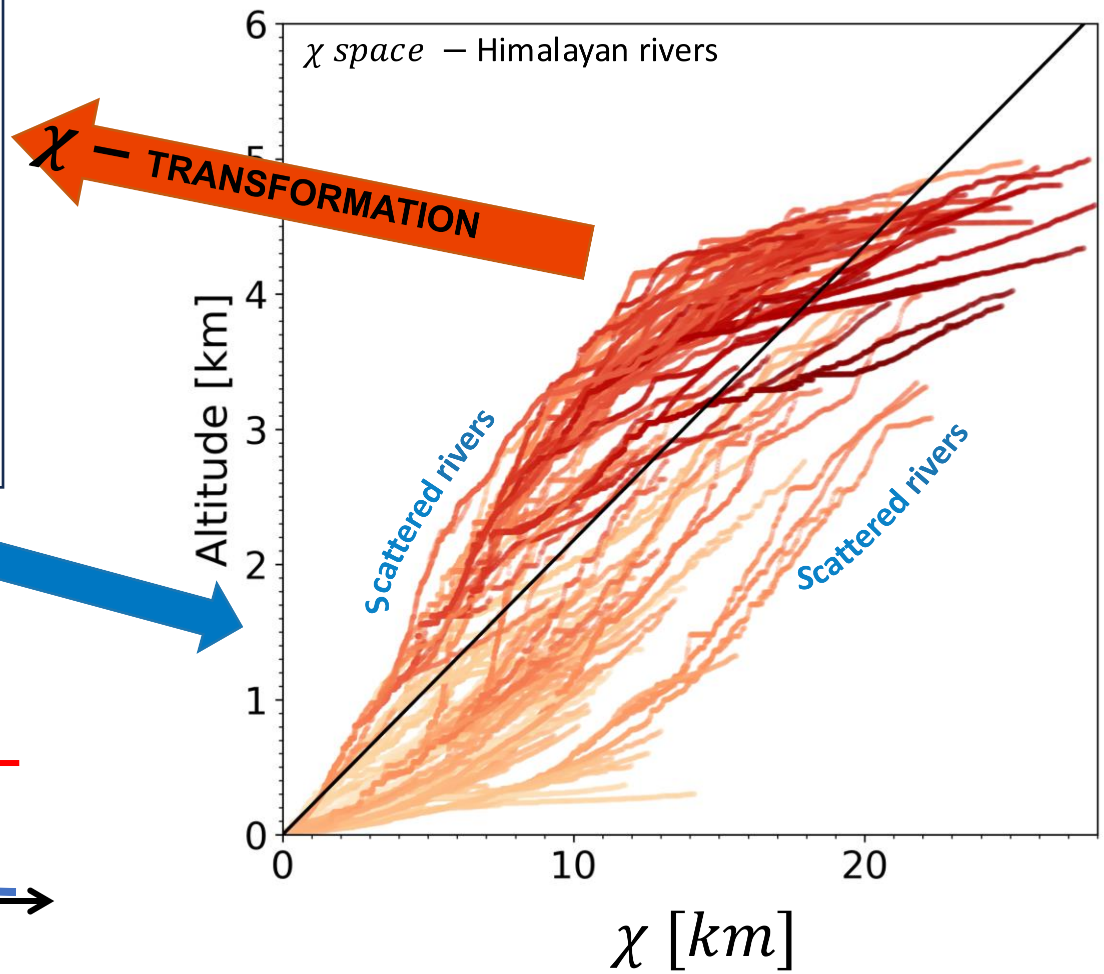
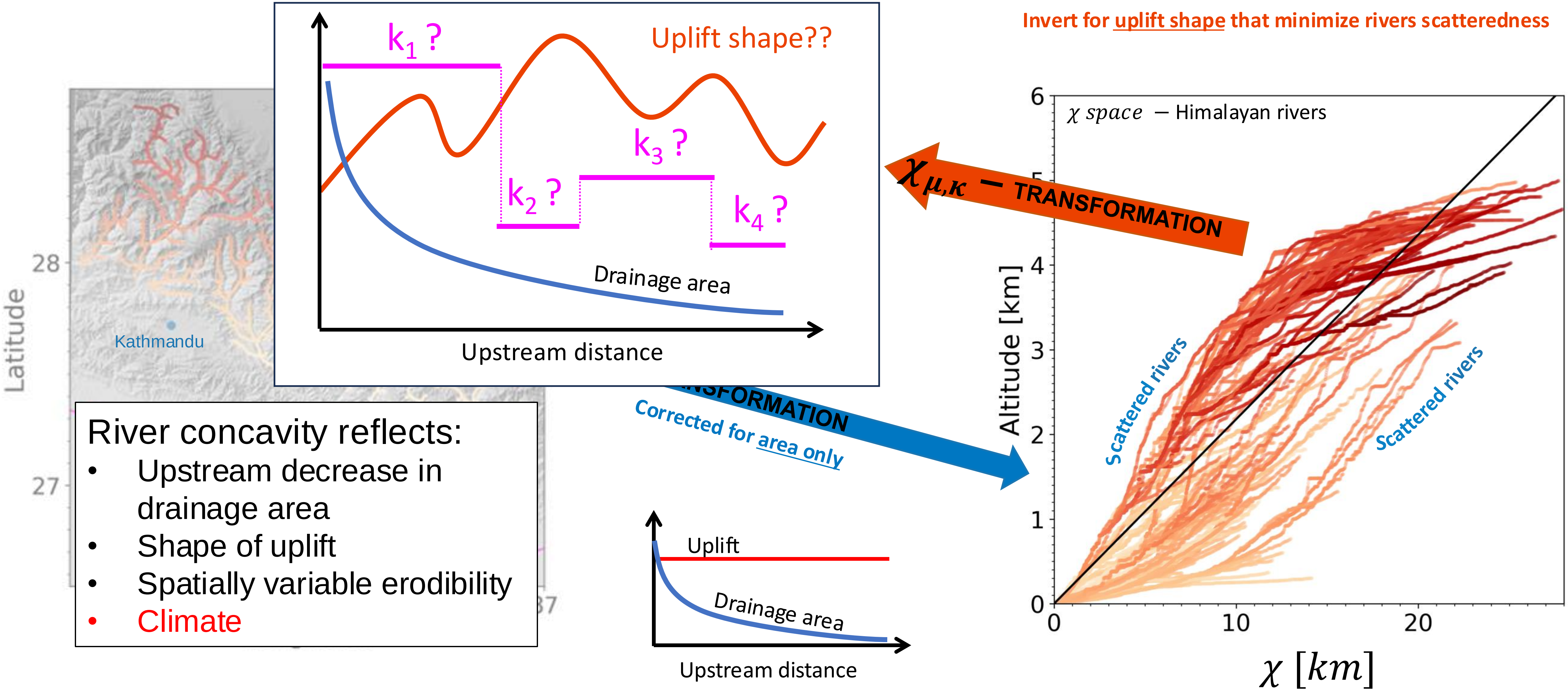


Invert for uplift shape that minimize rivers scatteredness



χ – TRANSFORMATION OF RIVER PROFILES IN THE HIMALAYAS



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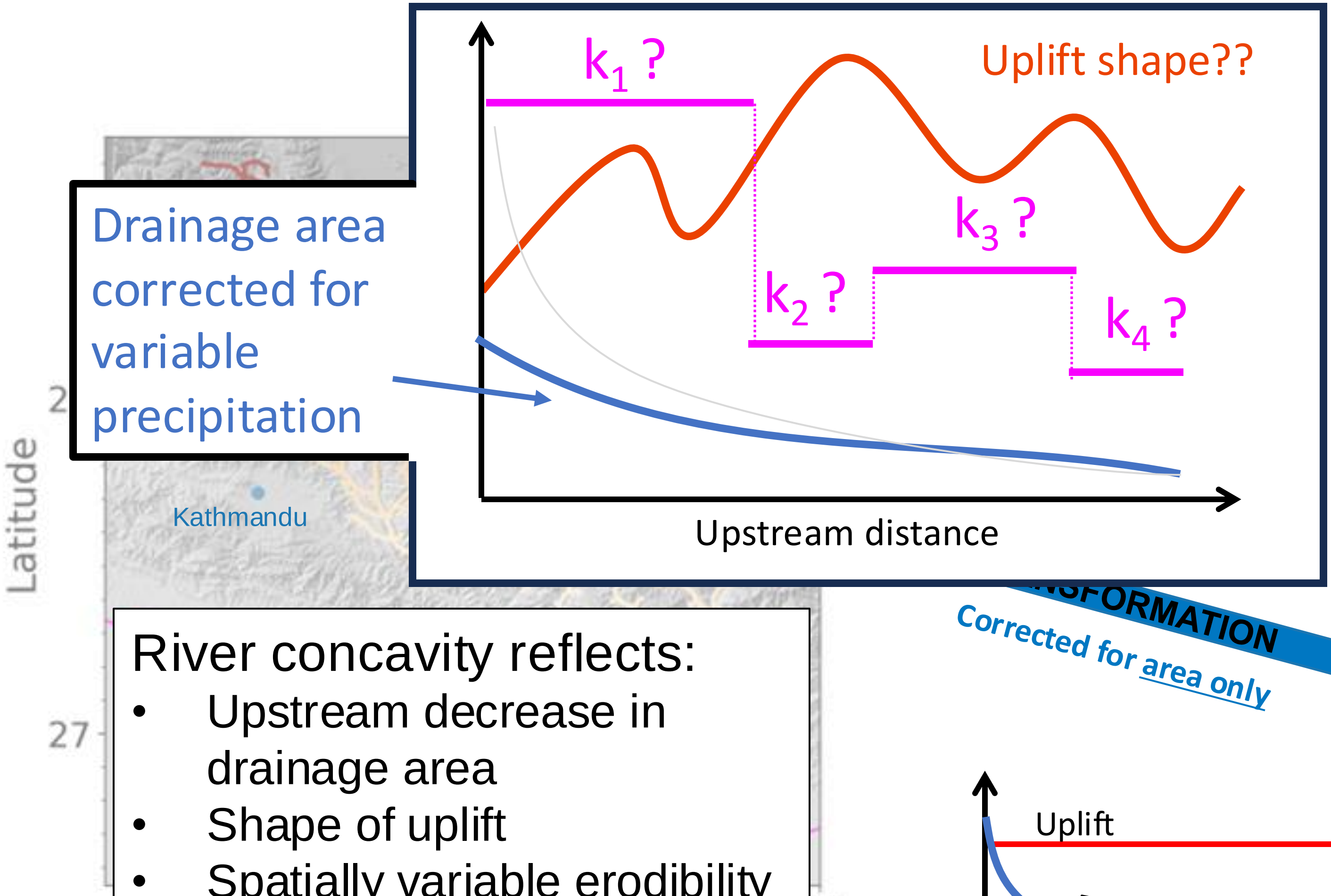
$\chi_{u,k}$ – TRANSFORMATION OF RIVER PROFILES IN THE HIMALAYAS



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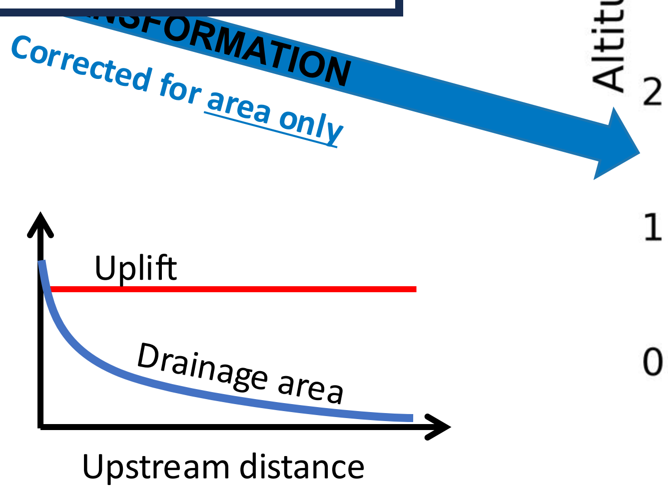

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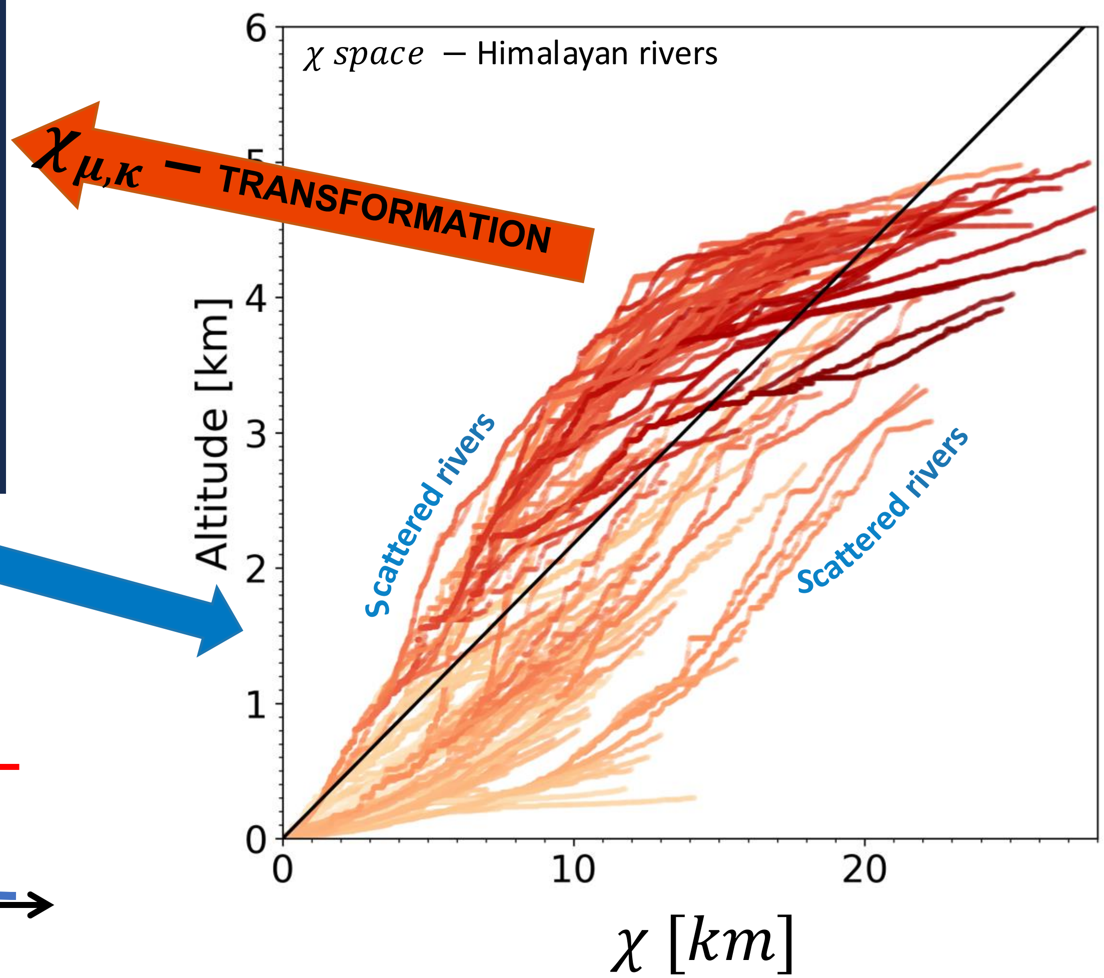
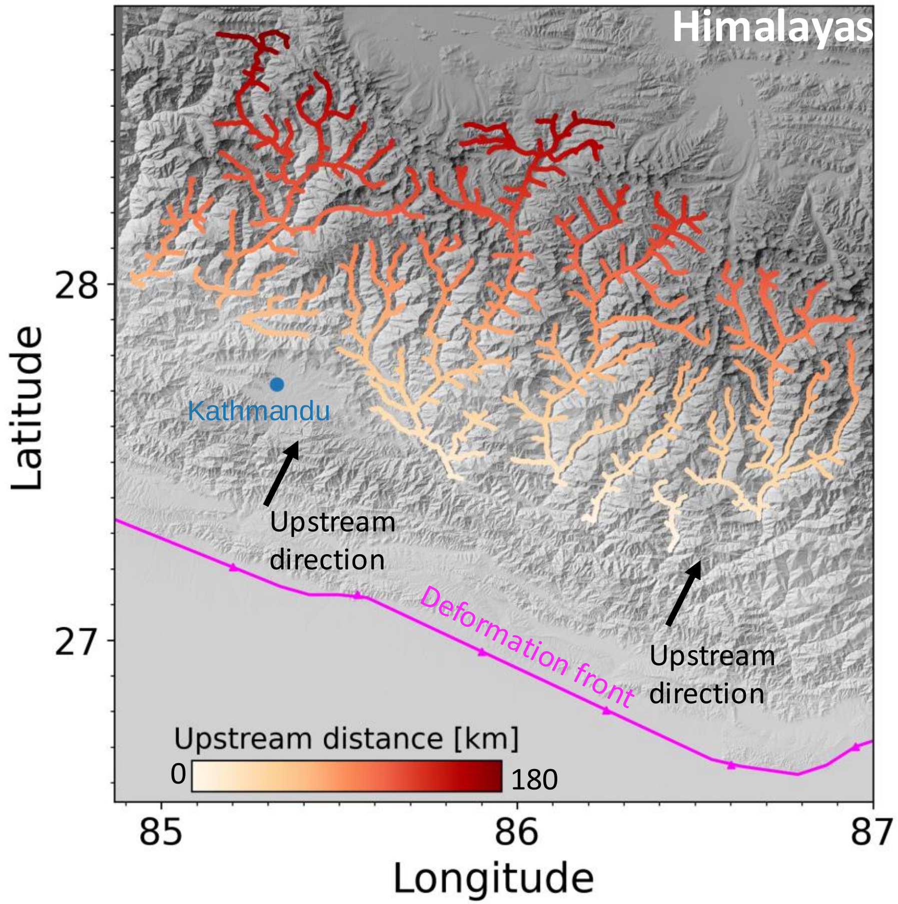


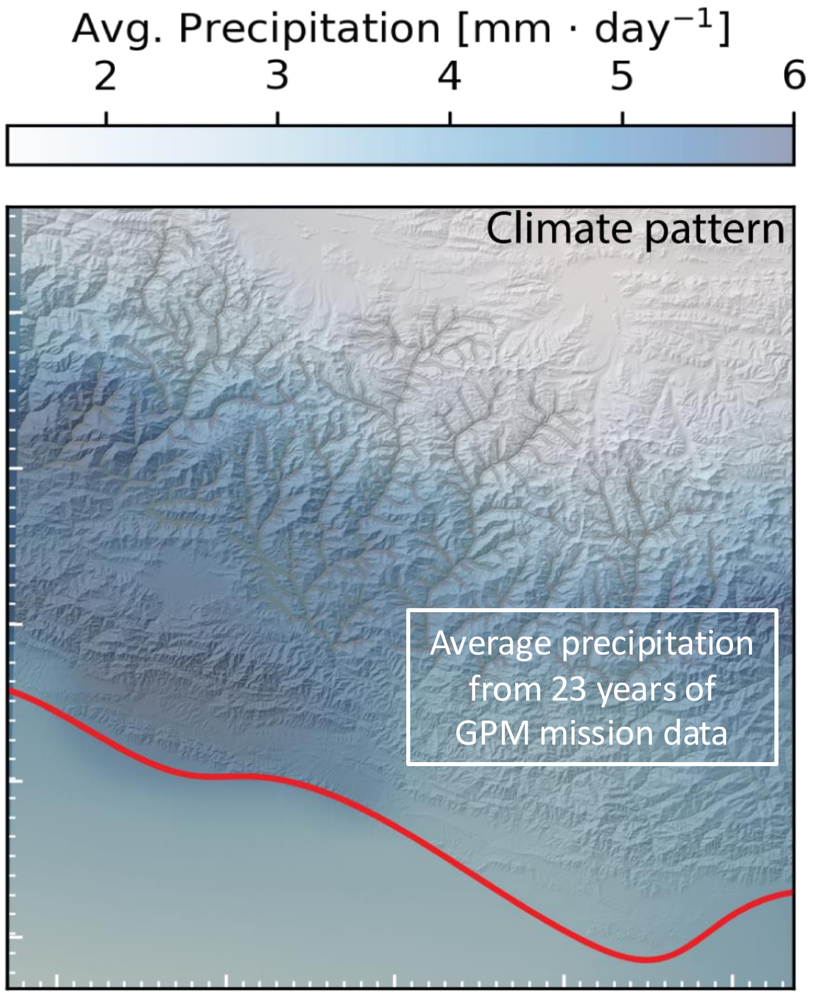
INVERTING HIMALAYAS USING $\chi_{u,k}$ TRANSFORMATION

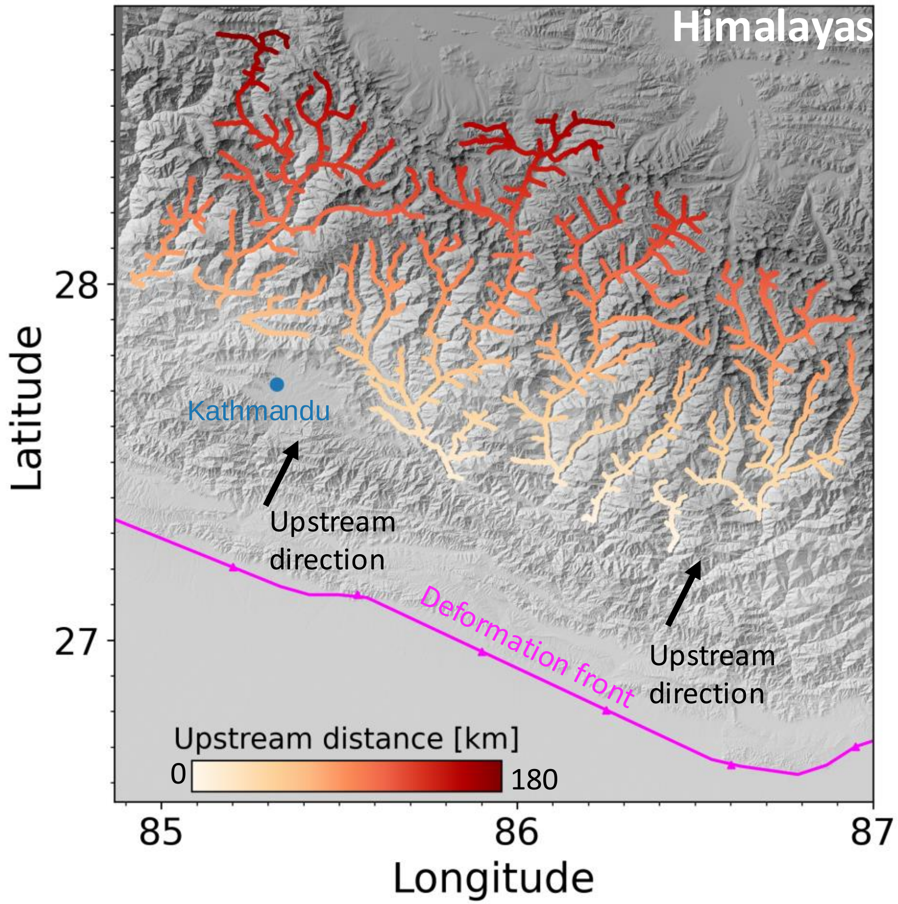


Oryan et al., 2024 (preprint)

INVERTING HIMALAYAS USING $\chi_{u,k}$ TRANSFORMATION

1. Download a DEM and compute drainage area corrected for climate.

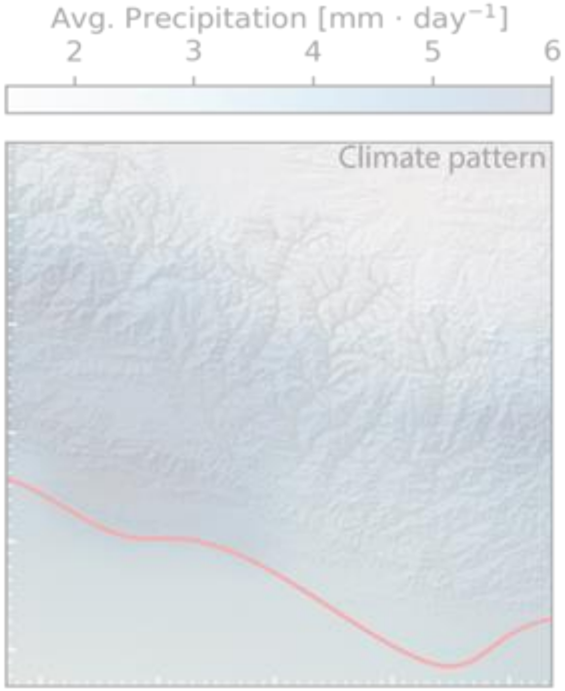




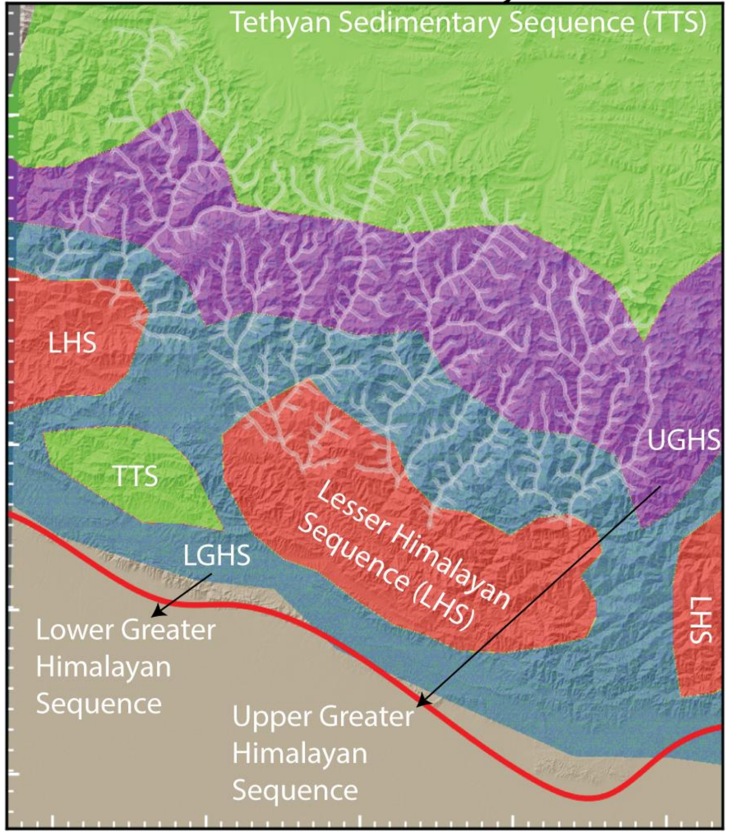
Oryan et al., in review

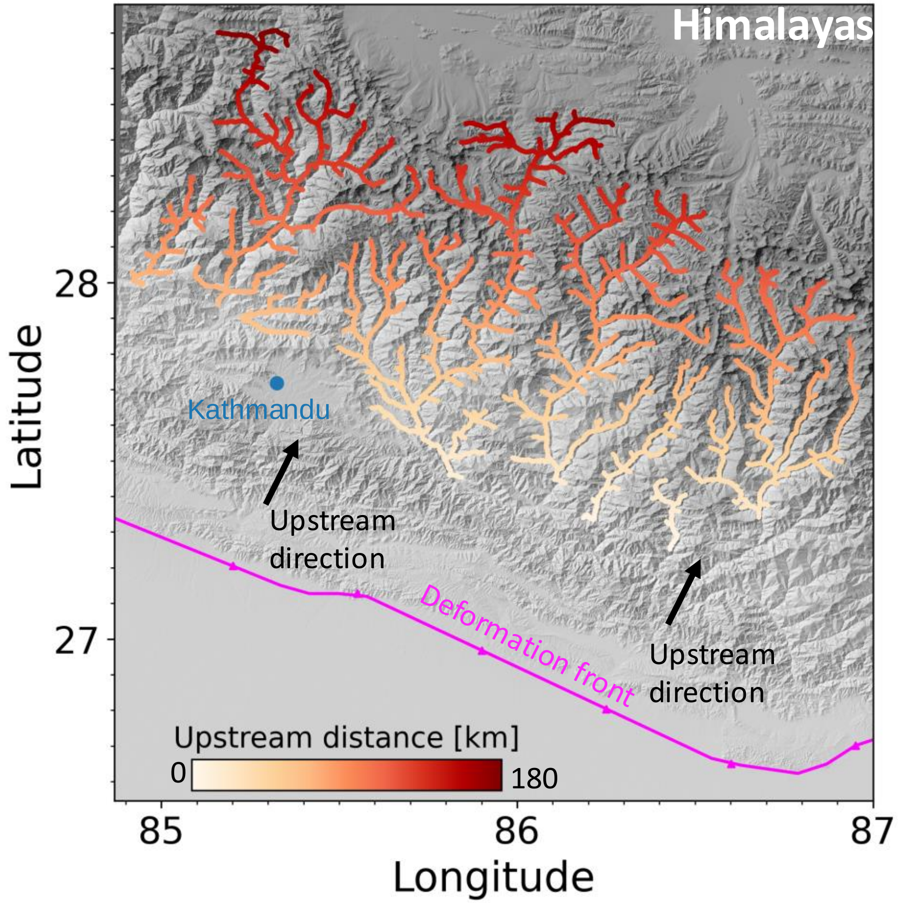
INVERTING HIMALAYAS USING $\chi_{u,k}$ TRANSFORMATION

1. Download a DEM and compute drainage area corrected for climate.
2. Map the spatial distribution of major lithological sections for piecewise rock erodibility values.



Four inverted erodibility sections

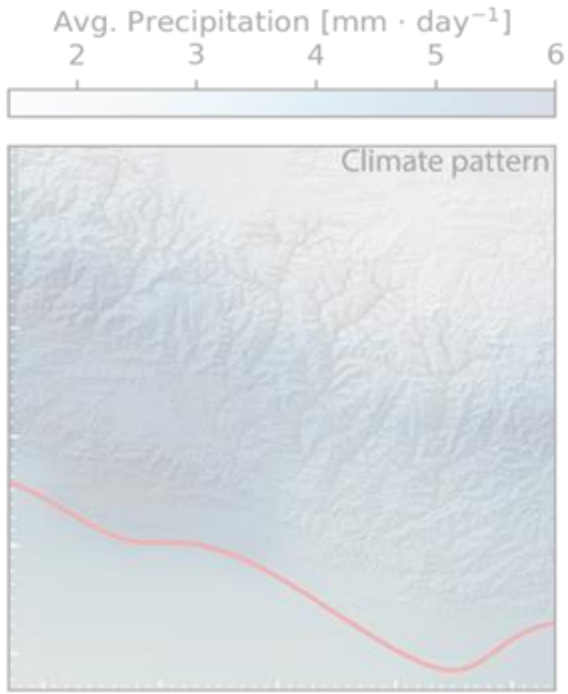


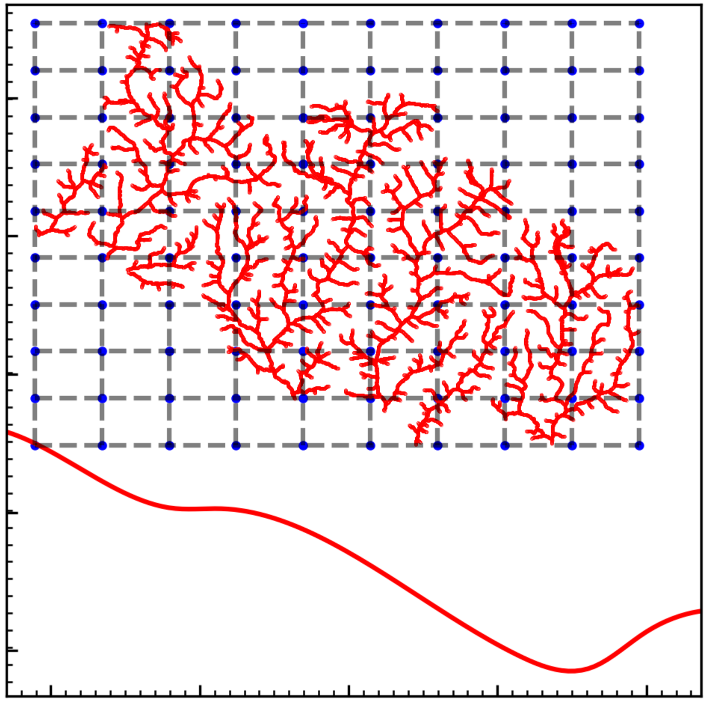


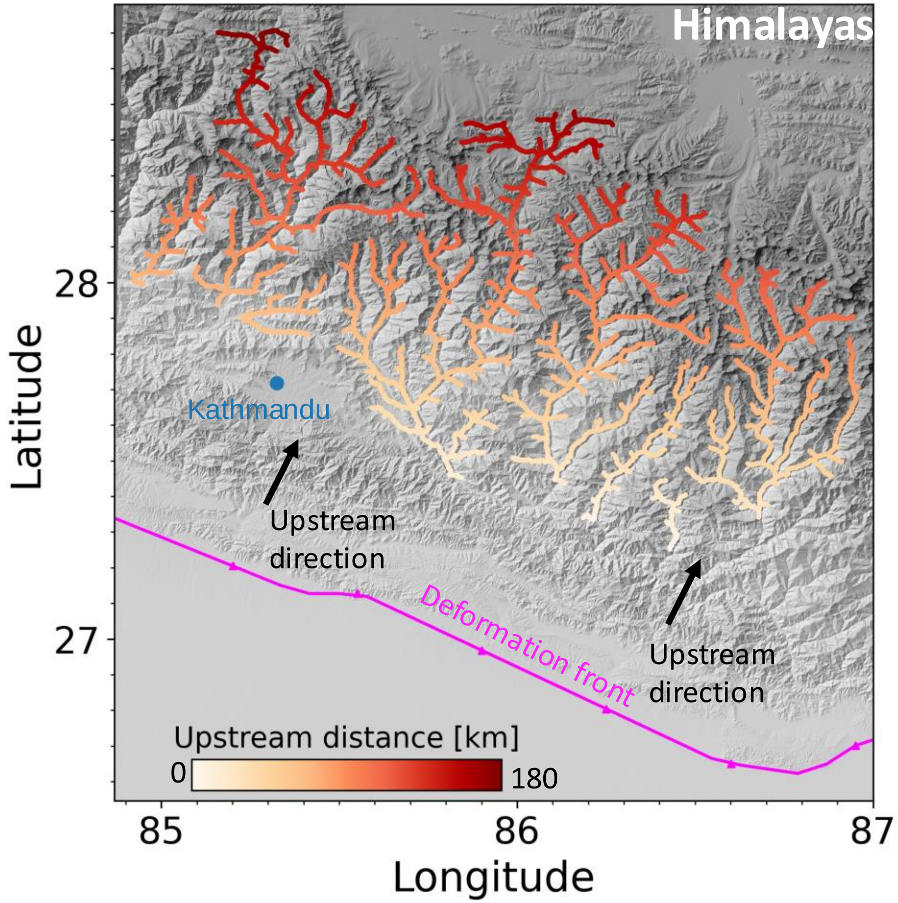
Oryan et al., in review

INVERTING HIMALAYAS USING $\chi_{u,k}$ TRANSFORMATION

1. Download a DEM and compute drainage area corrected for climate.
2. Map the spatial distribution of major lithological sections for piecewise rock erodibility values.
3. Describe 2D uplift surface using interpolating B-spline functions extending across the river network.







Oryan et al., in review

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1. Download a DEM and compute drainage area corrected for climate.
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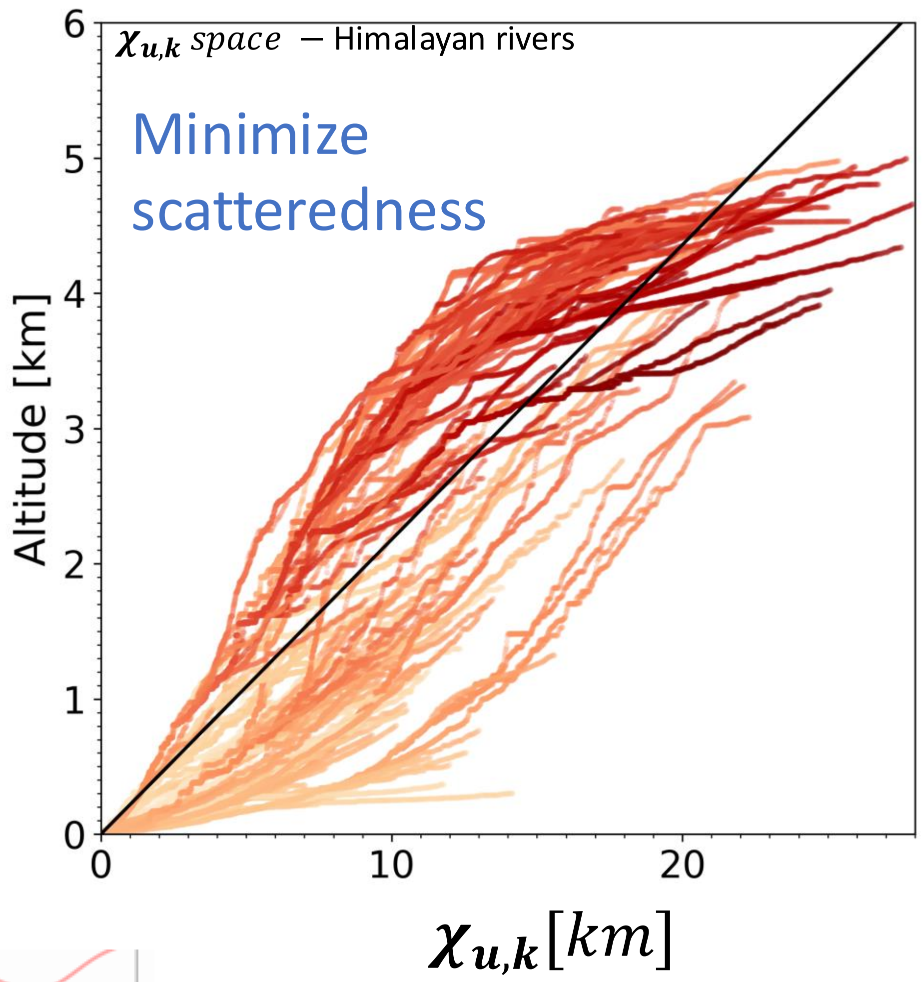
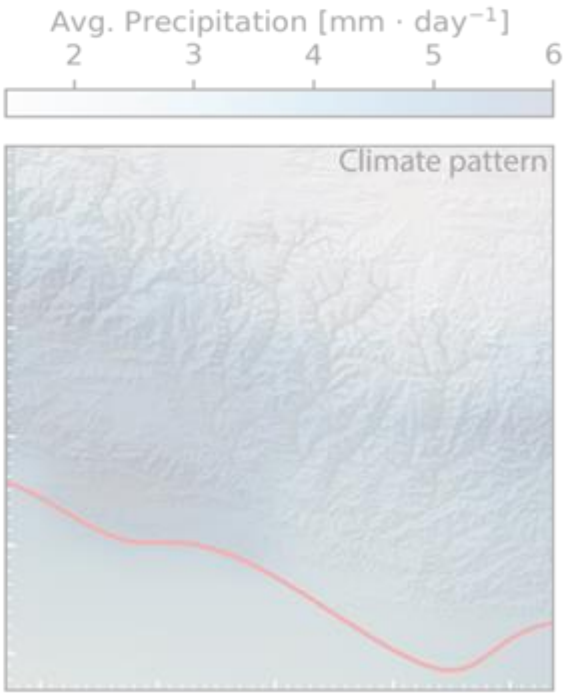
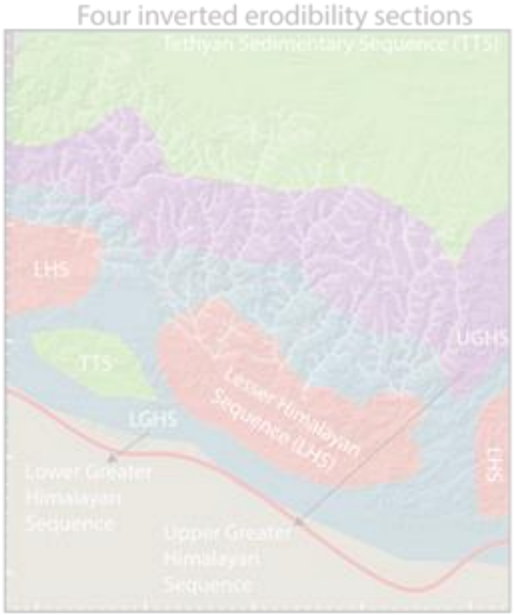
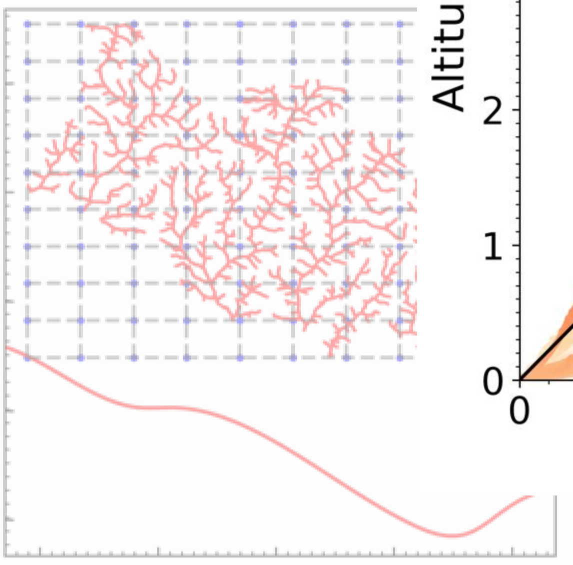
3. Describe 2D uplift surface using interpolating B-spline functions extending across the river network.
4. Invert for uplift and erodibility values minimizing $\chi_{u,k}$.







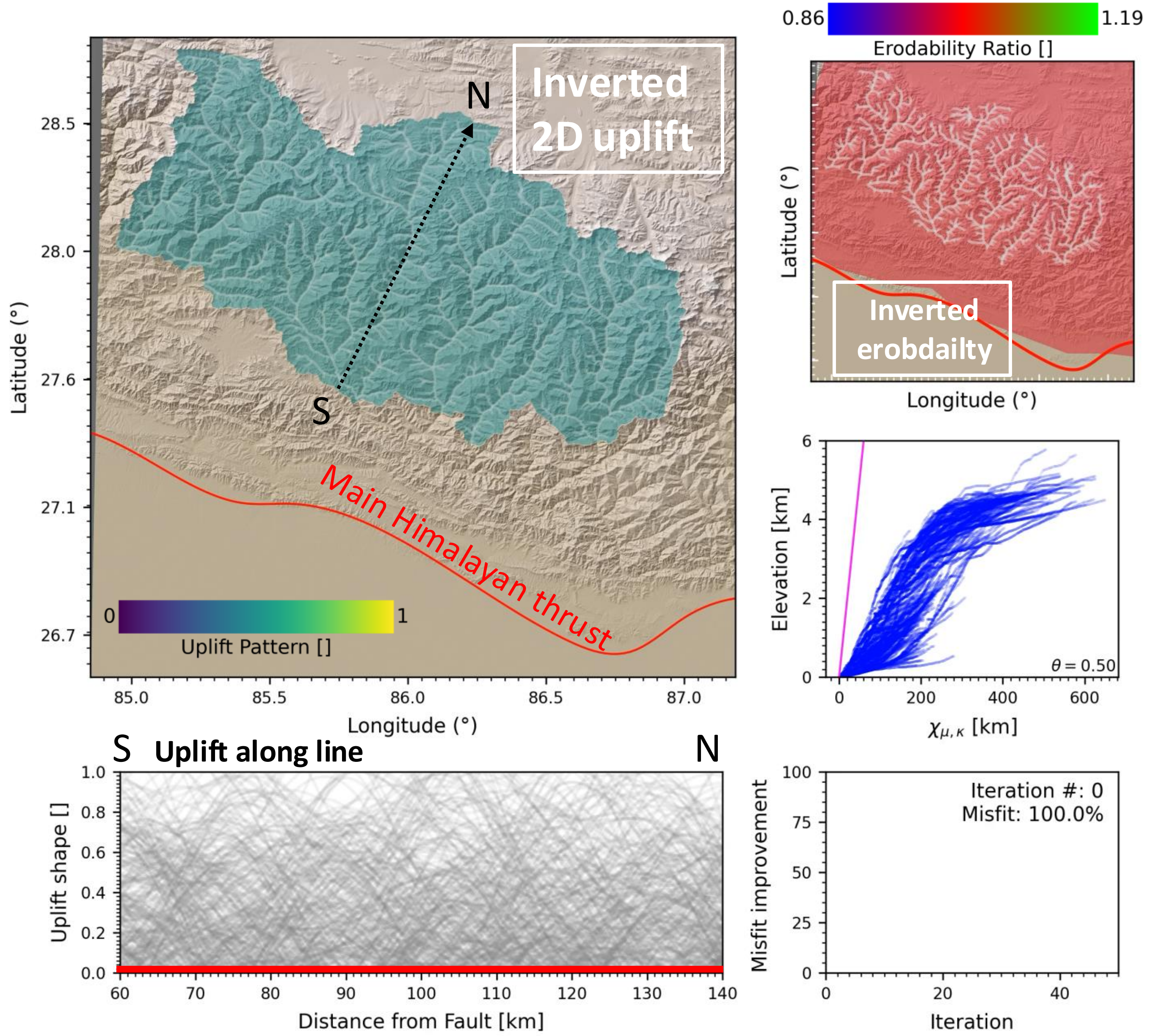


Oryan et al., in review

INVERTING HIMALAYAS USING $\chi_{u,k}$ TRANSFORMATION

- Inversion of 120,000 river nodes spanning 18,000km^2 using Bayesian Quasi-Newton inversion method.
- Inverting for 144 parameters describing the uplift pattern and 4 erodibility values that best linearizes river profiles in $\chi_{u,k}$ space.

Mean solution	
Posterior sample	



Oryan et al., in review

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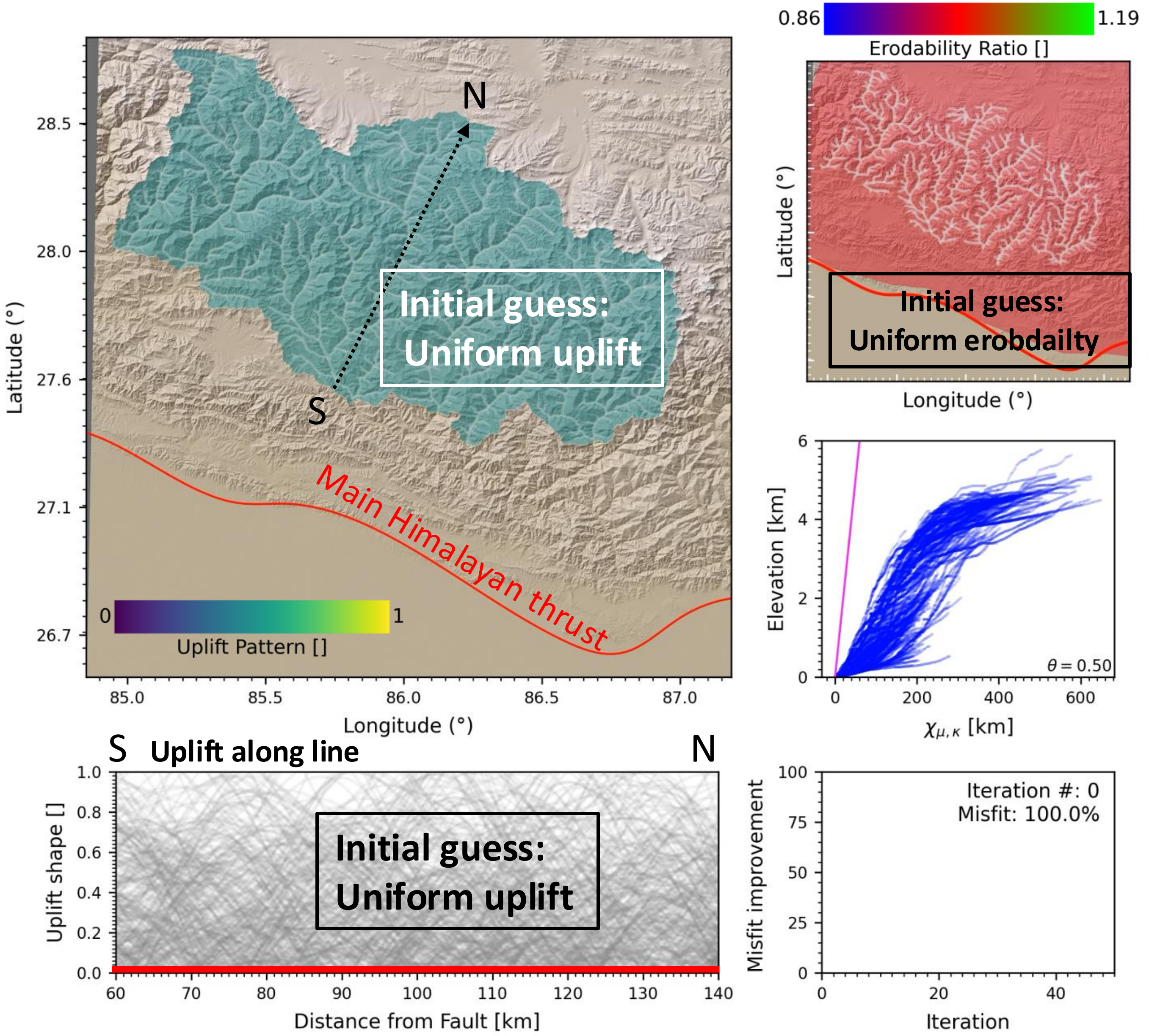

Mean solution

Posterior sample

Oryan et al., in review

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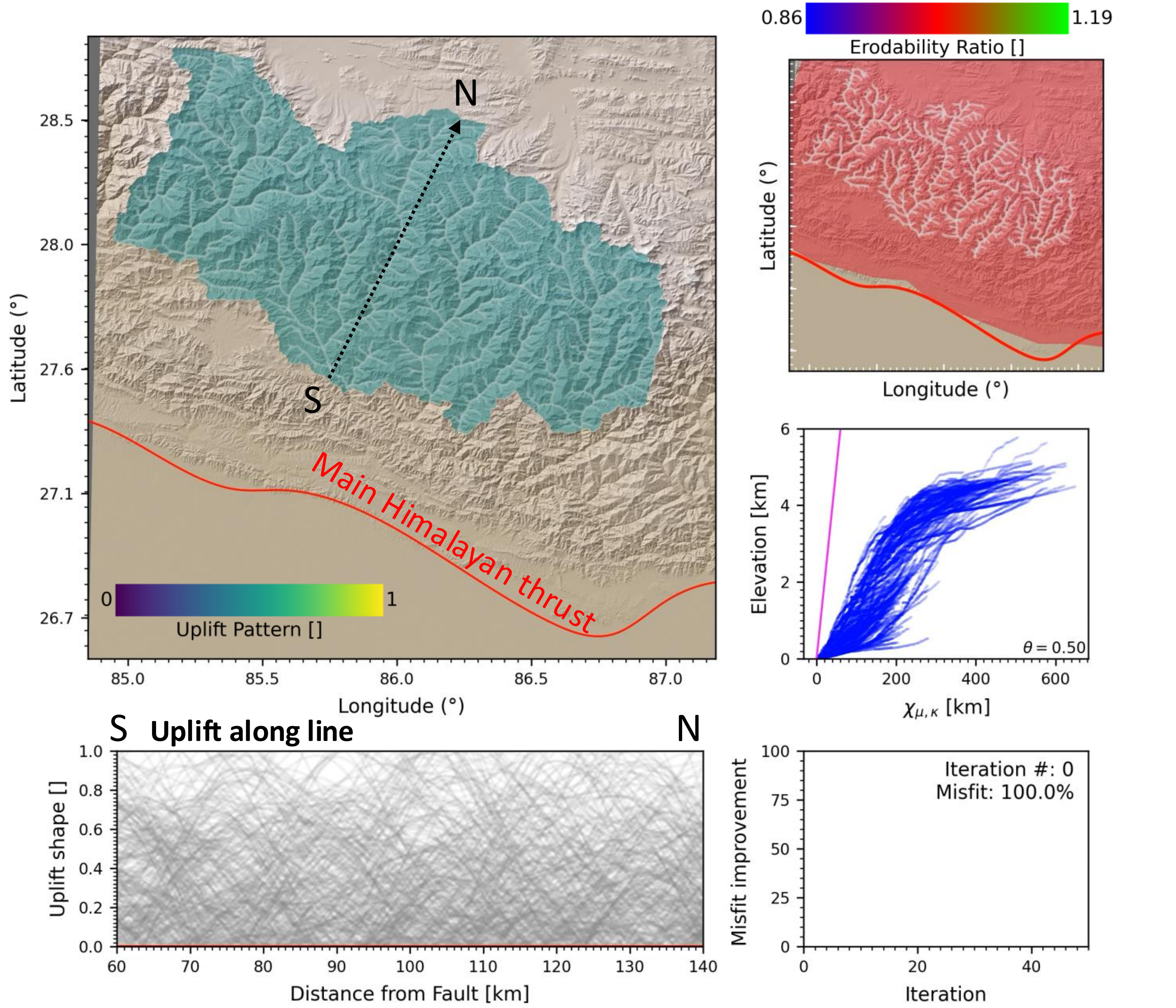
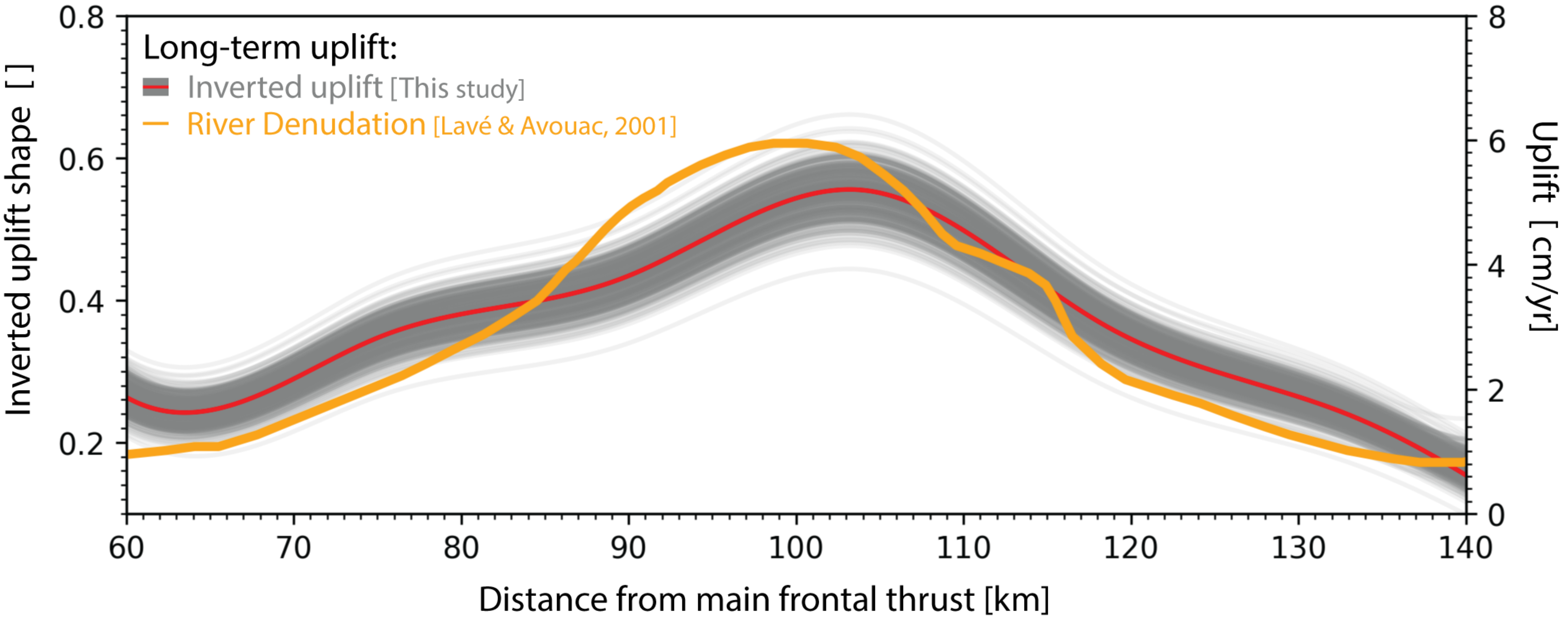


Mean solution	red line
Posterior sample	grey line

Oryan et al., in review

RETRIEVED UPLIFT PATTERN RESEMBLE PREVIOUS ESTIMATES

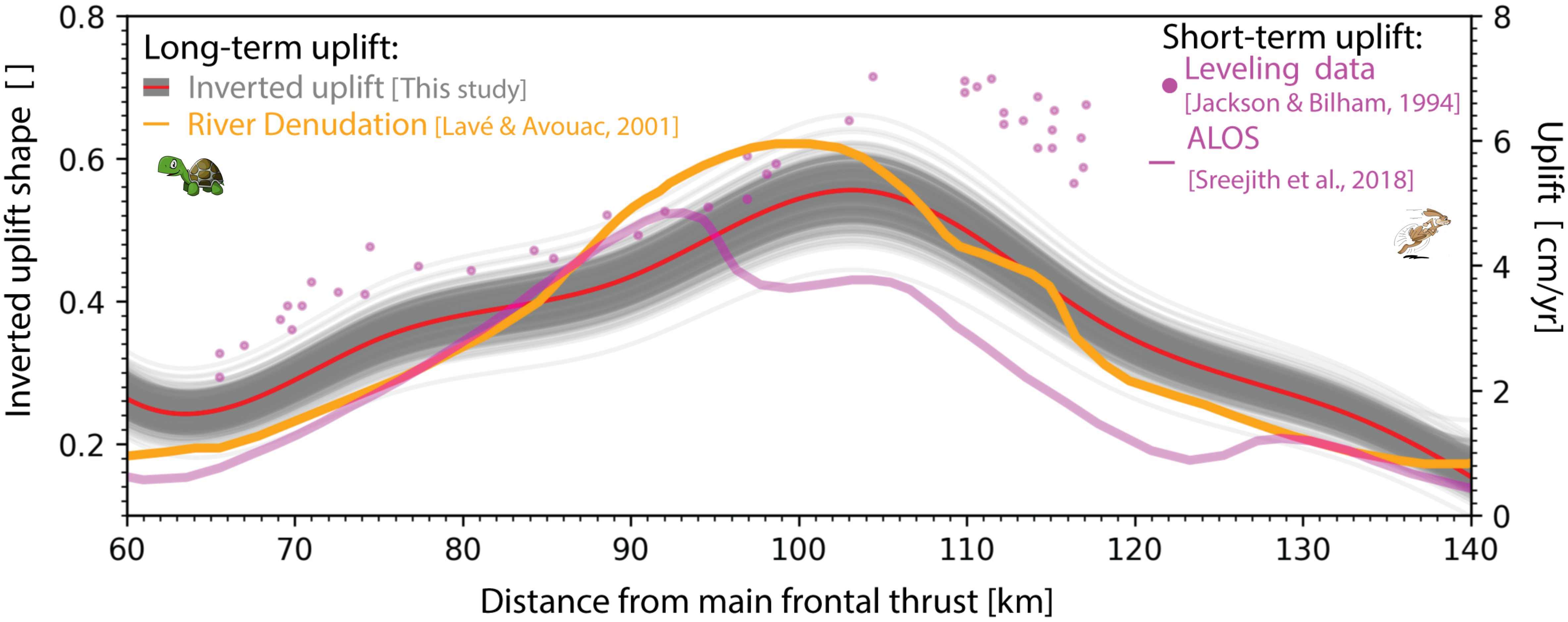
- Inferred long-term uplift matches denudation rates.



Oryan et al., in review

RETRIEVED UPLIFT PATTERN RESEMBLE PREVIOUS ESTIMATES

- Inferred long-term uplift matches denudation rates.
- Uplift shape is comparable with shape of short term interseismic uplift.



Oryan et al., in review

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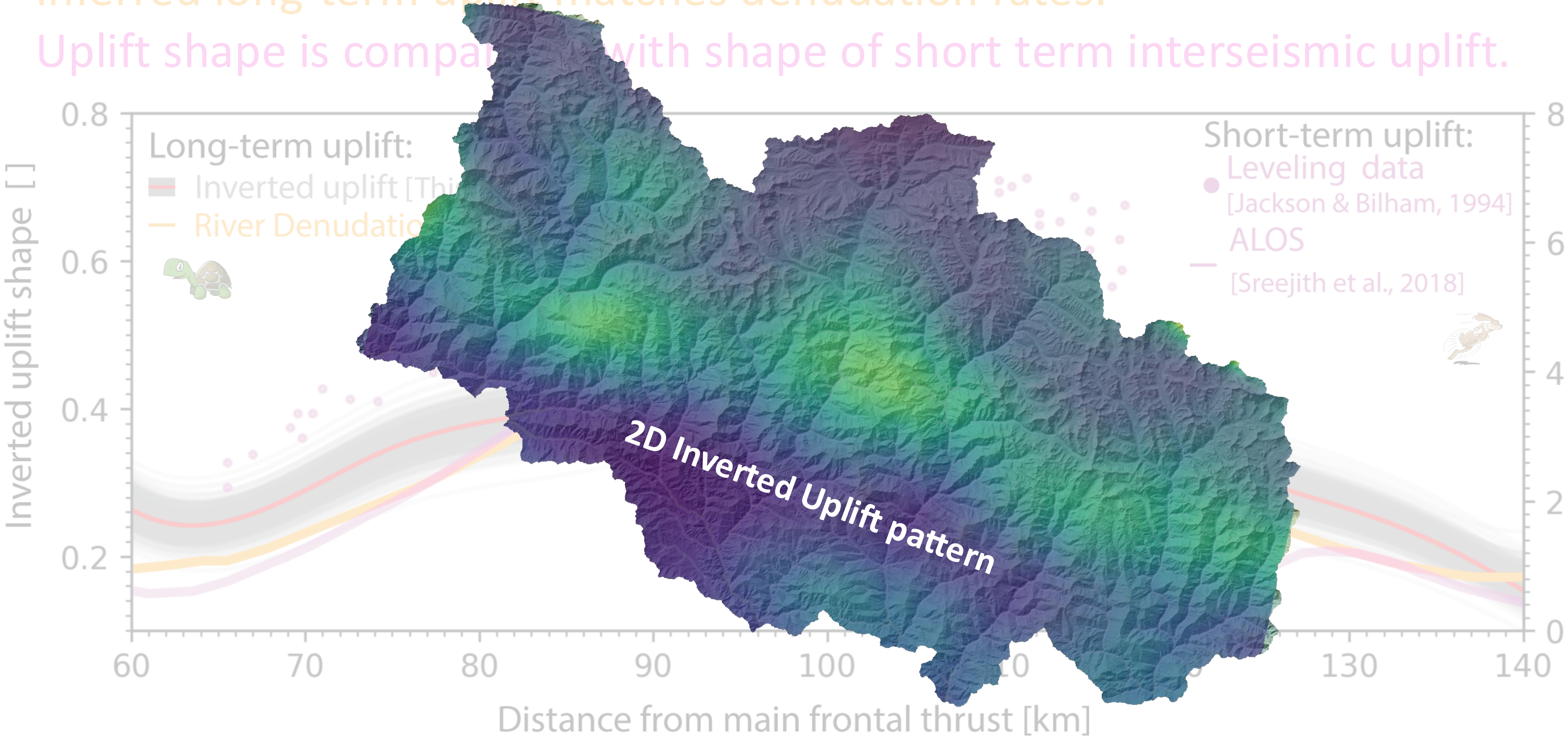
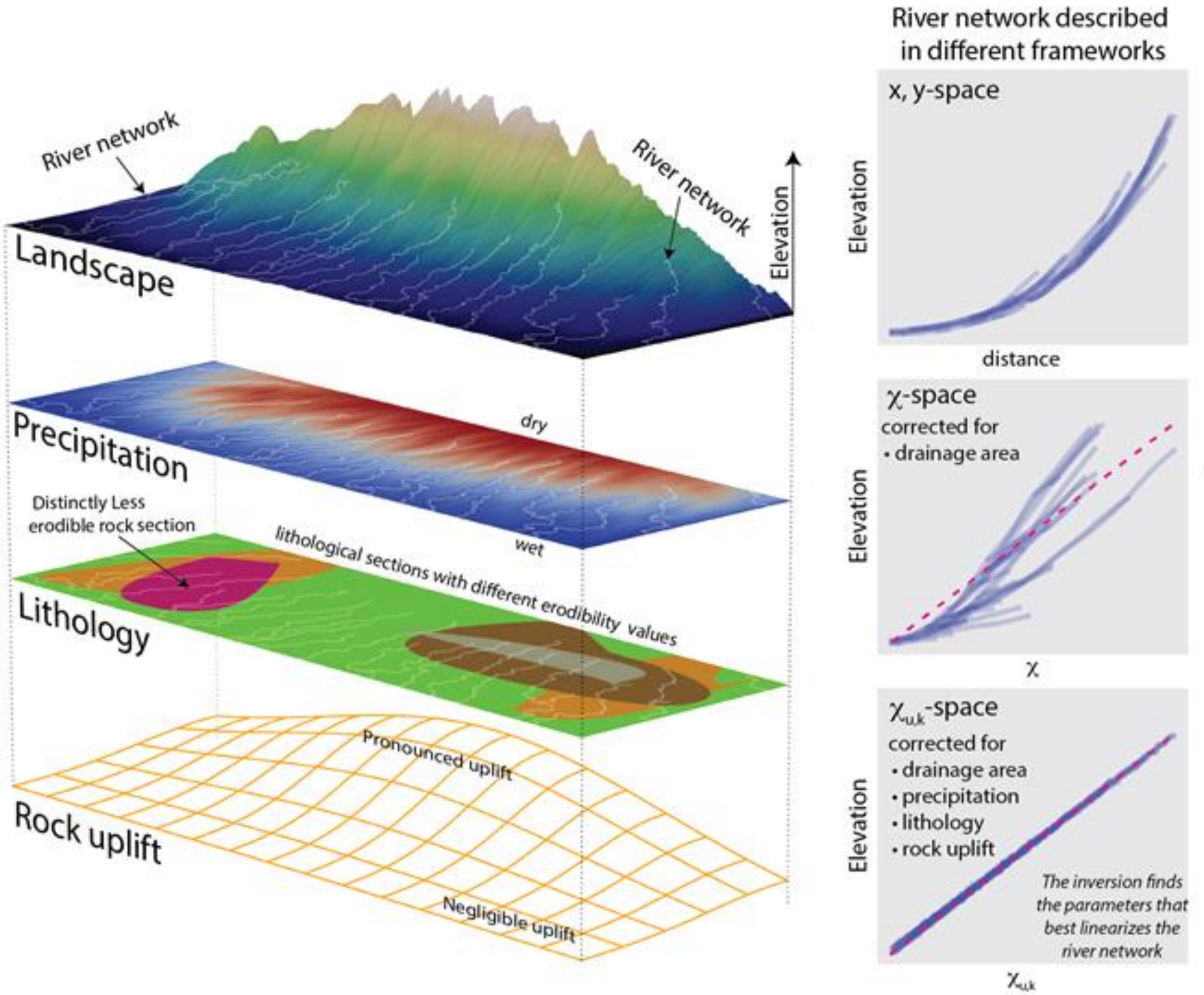


Oryan et al., in review

KEY POINTS SO FAR

- Inversion in $\chi_{u,k}$ space can disentangle the contributions of tectonics, climate and erodibility from landscapes.
- This approach opens the door to leveraging time-averaged signals preserved in landscapes to infer crustal deformation resulting from earthquake cycles.

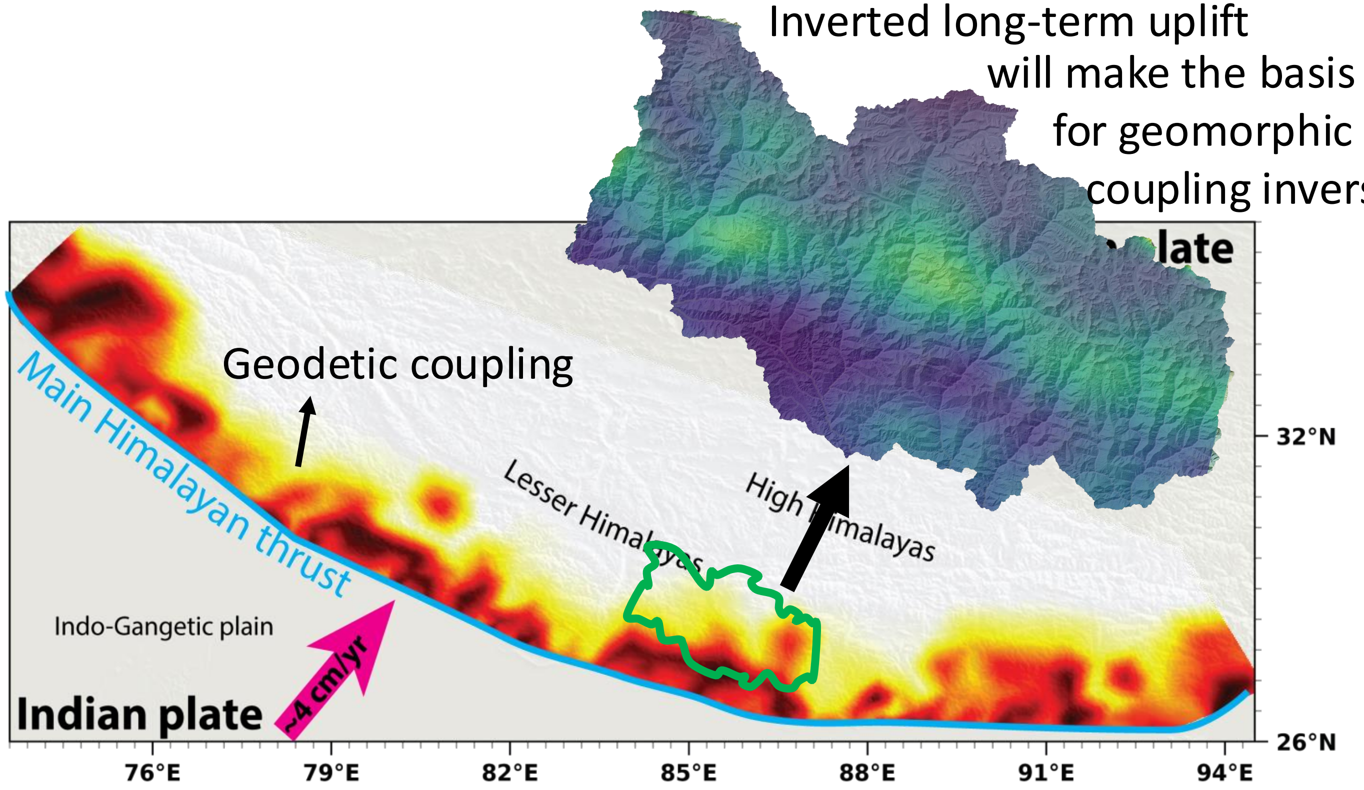


Section 4 – Research Program at Dartmouth

INVERTING LANDSCAPES FOR PERSISTENT PLATE LOCKING

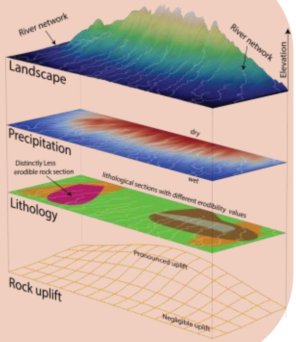
- My group will use the frameworks described in sections 2 and 3 to **invert forearc landscapes for long-term megathrust coupling.**

Inverted long-term uplift will make the basis for geomorphic coupling inversions



Observational data

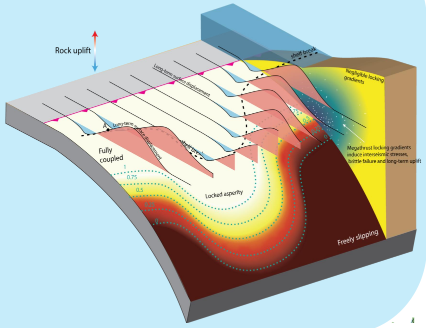
Inferring Long-Term Tectonic Uplift from Bayesian Inversion of Landscapes [Oryan et al. in review]



Landscape ⇨ Long-term Uplift

Forward model

Fingerprints of Megathrust Locking in Subduction Landscapes [Oryan et al.,2024]



Coupling ⇨ Long-term Uplift

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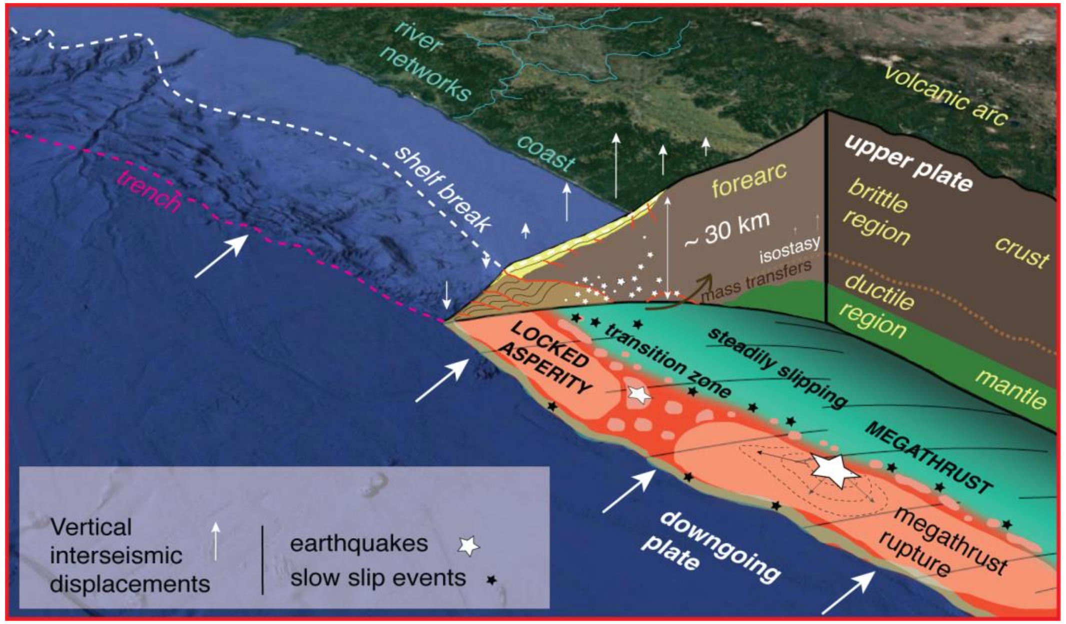

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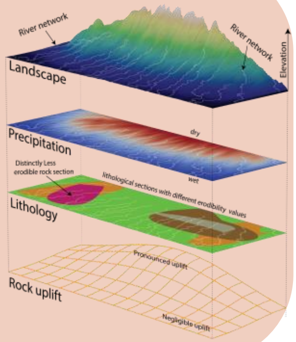

Landscape ⟹ **Long-term Uplift**

Forward model

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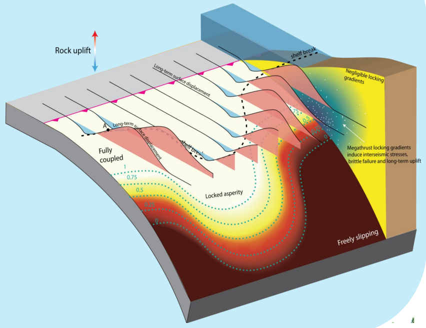
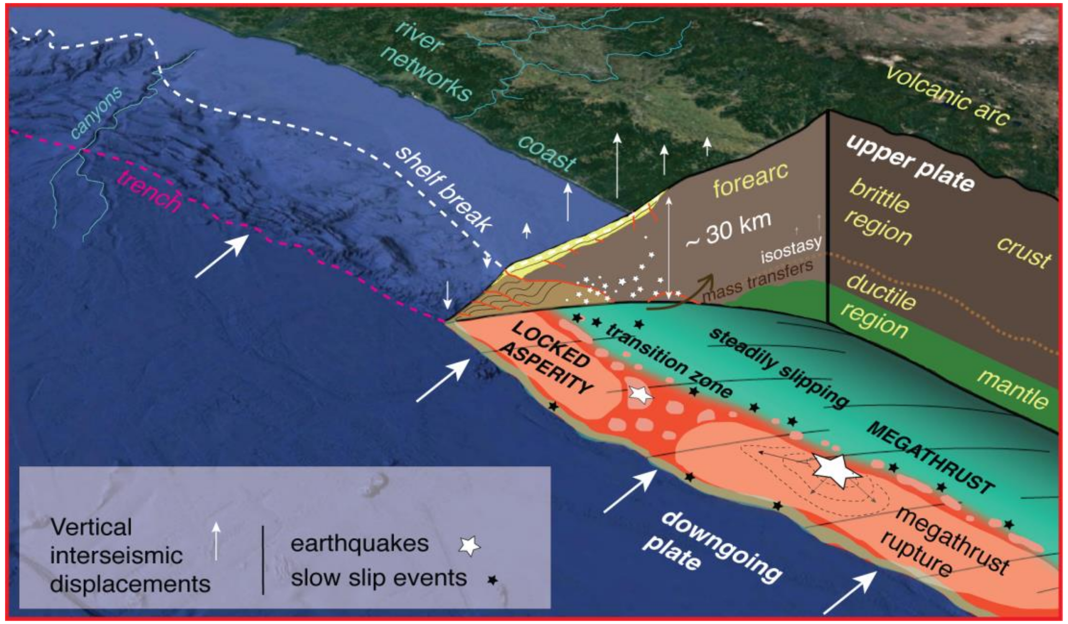


Coupling ⟹ **Long-term Uplift**

INVERTING LANDSCAPES FOR PERSISTENT PLATE LOCKING

- My group will use the frameworks described in sections 2 and 3 to **invert forearc landscapes for long-term megathrust coupling.**
- We will strive to expand our observational record and use **submarine canyons**.



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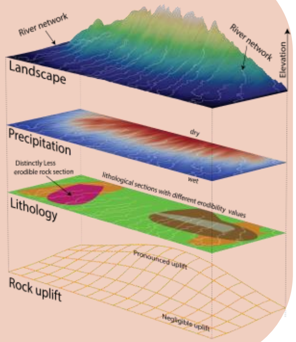

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Forward model

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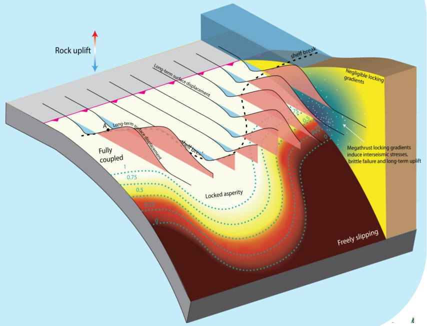
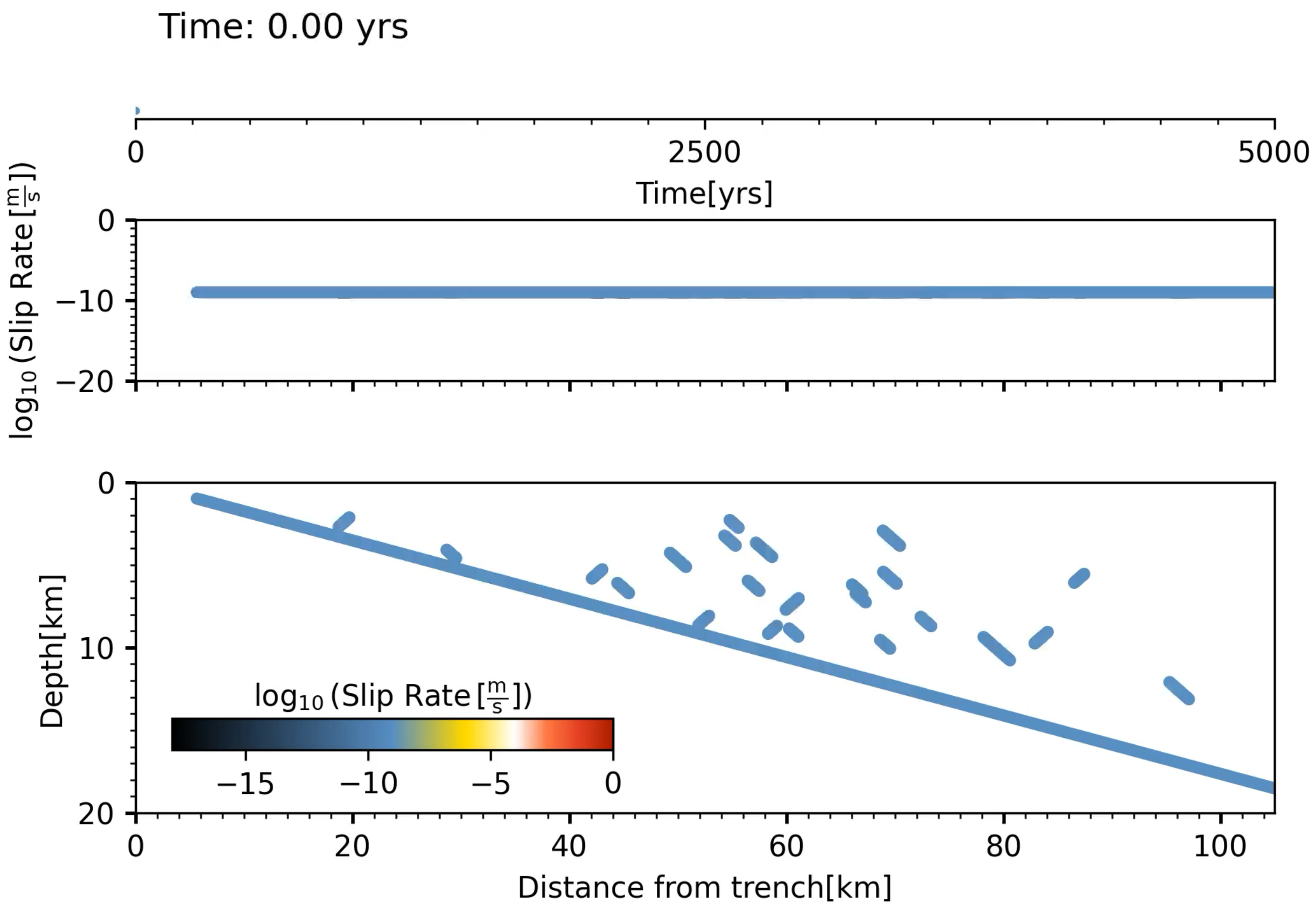


Coupling ⟹ **Long-term Uplift**

THE ENERGY BUGDET OF EARTHQUAKE CYCLES

- **Unraveling Energy Distribution in Subduction Zones:** We will study the rheological properties that govern the balance between elastic deformation (fueling earthquakes) and inelastic strain (shaping subduction zone landscapes).



Oryan et al., in prep.

THE ENERGY BUGDET OF EARTHQUAKE CYCLES

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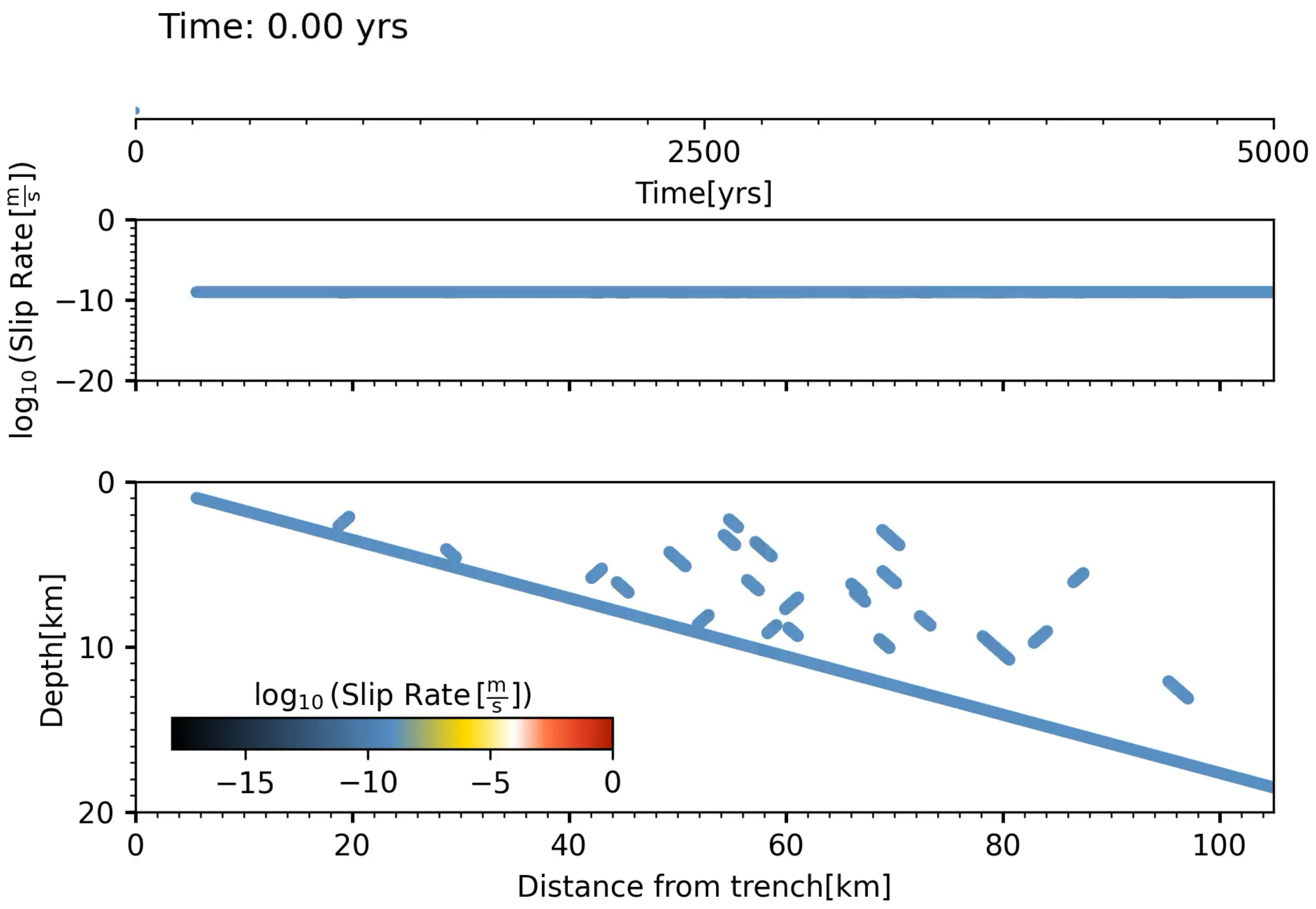
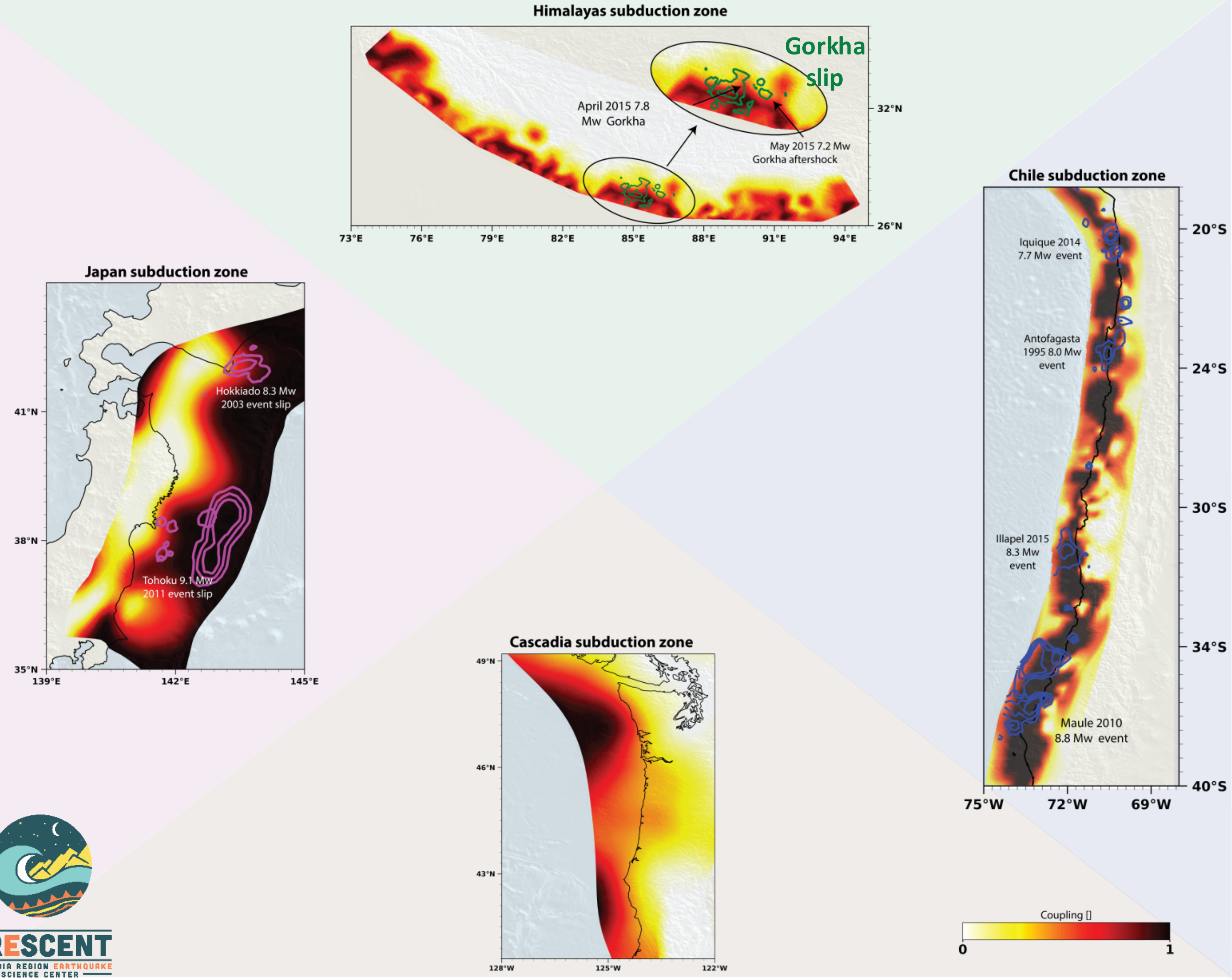
- **Investigating Seismic Cycle Dynamics:** Using SEAS simulations, my group will explore how non-recoverable strain accumulation in the overriding plate impacts earthquake dynamics and the coseismic period.



Oryan et al., in prep.

UNIFYING MEGATHRUSTS FAULTS USING OPTIMAL TRANSPORT AND MACHINE LEARNING TOOLS

- Seismo-geodetic observations span **decades at each subduction zone.**



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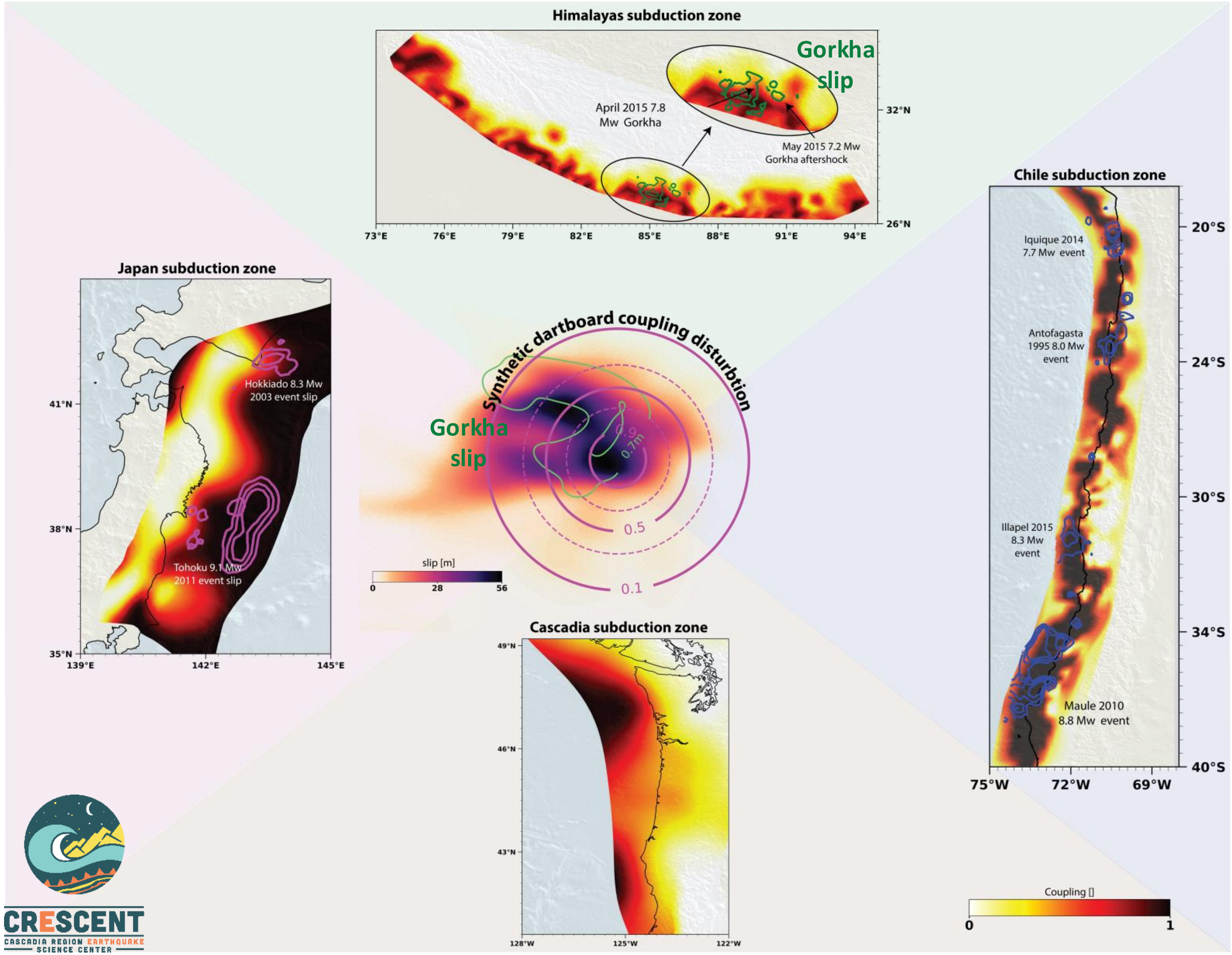

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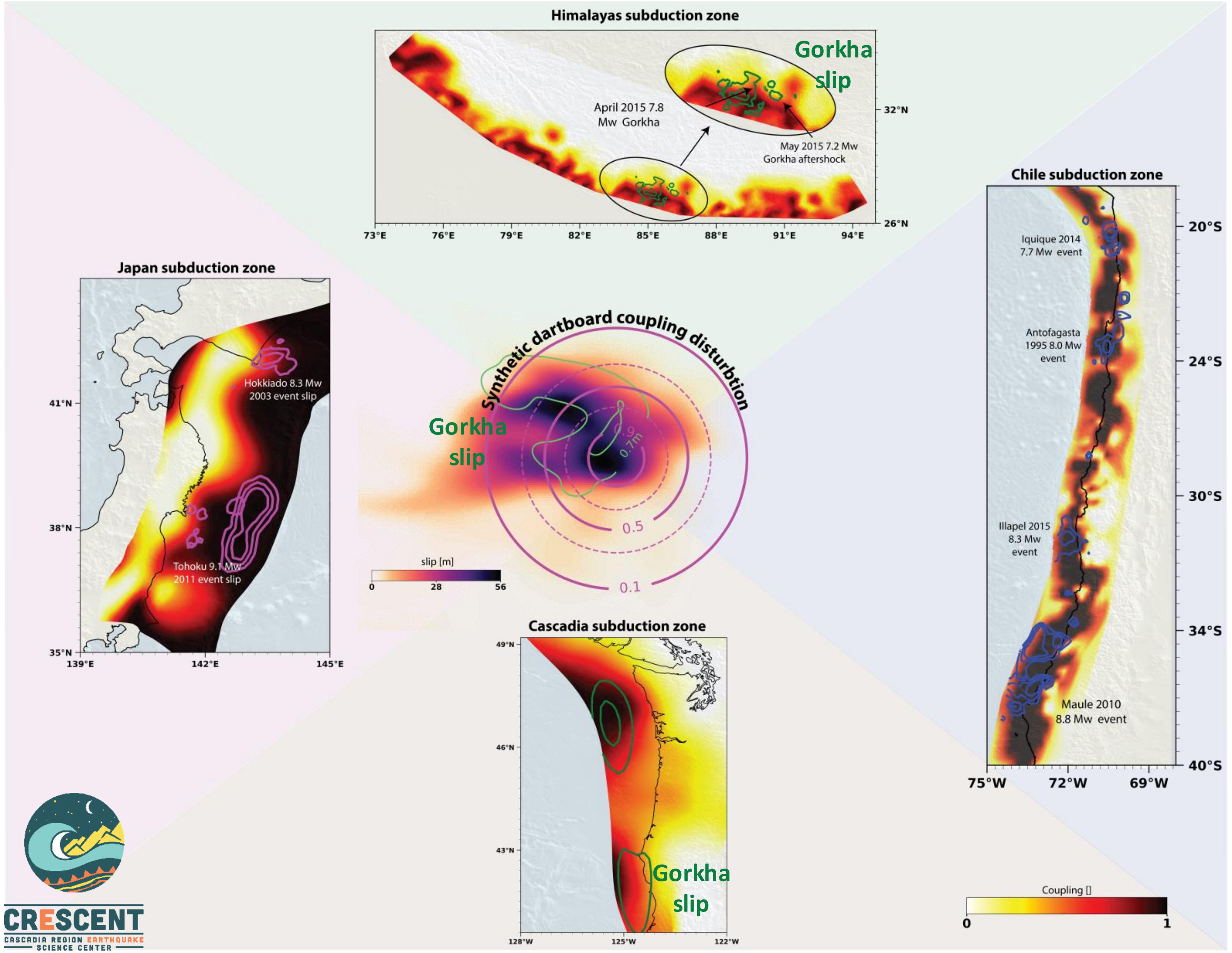
- Seismo-geodetic observations span **decades at each subduction zone.**
- My group will use machine learning and optimal transport tools to compute geodetically and physically consistent **geometric mappings between megathrusts**.
- This approach will **extend our seismo-geodetic observational** record several-fold and allow us to assess seismic hazard more robustly.



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UC San Diego

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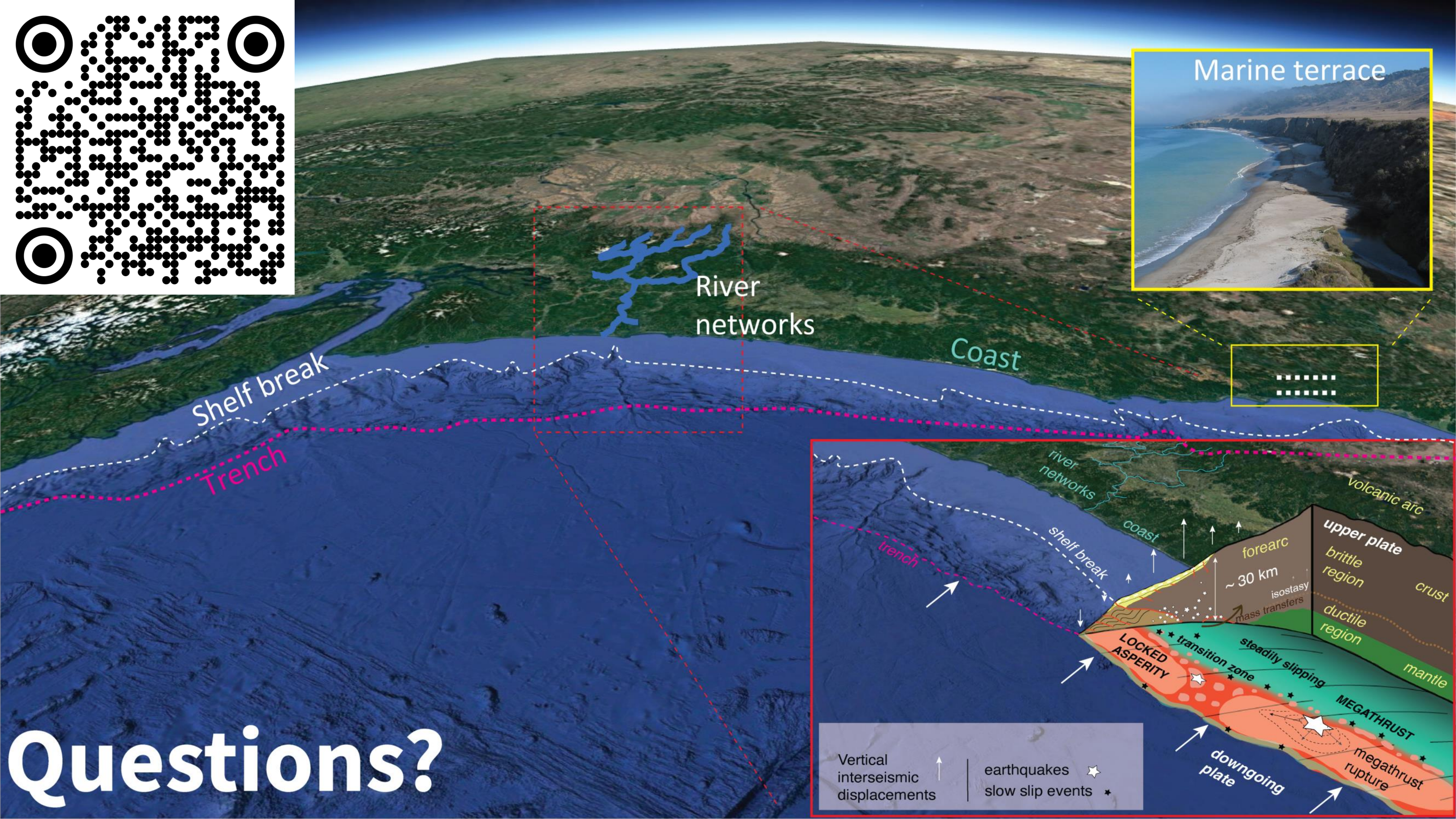
CASCADIA REGION EARTHQUAKE SCIENCE CENTER

Questions?



Marine terrace
River
networks
Coast
Shelf break
Trench
river
networks
volcanic arc
trench
shelf break
coast
forearc
upper plate
brittle
region
crust
~ 30 km
isostasy
mass transfers
ductile
region
mantle
LOCKED
ASPERITY
transition zone
steadily slipping
MEGATHRUST
megathrust
rupture
downgoing
plate
Vertical
interseismic
displacements
earthquakes
slow slip events