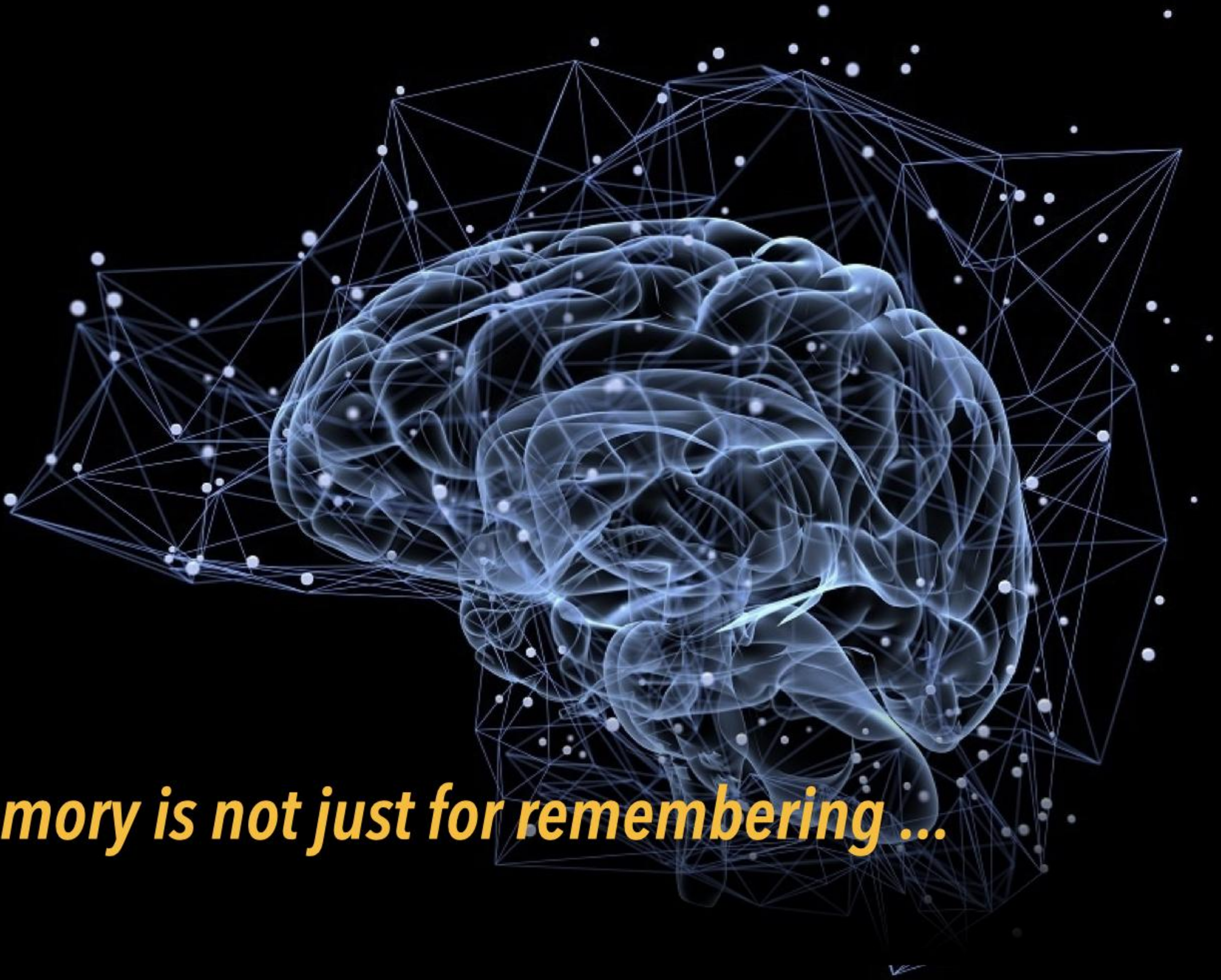
LANDSCAPE MEMORY

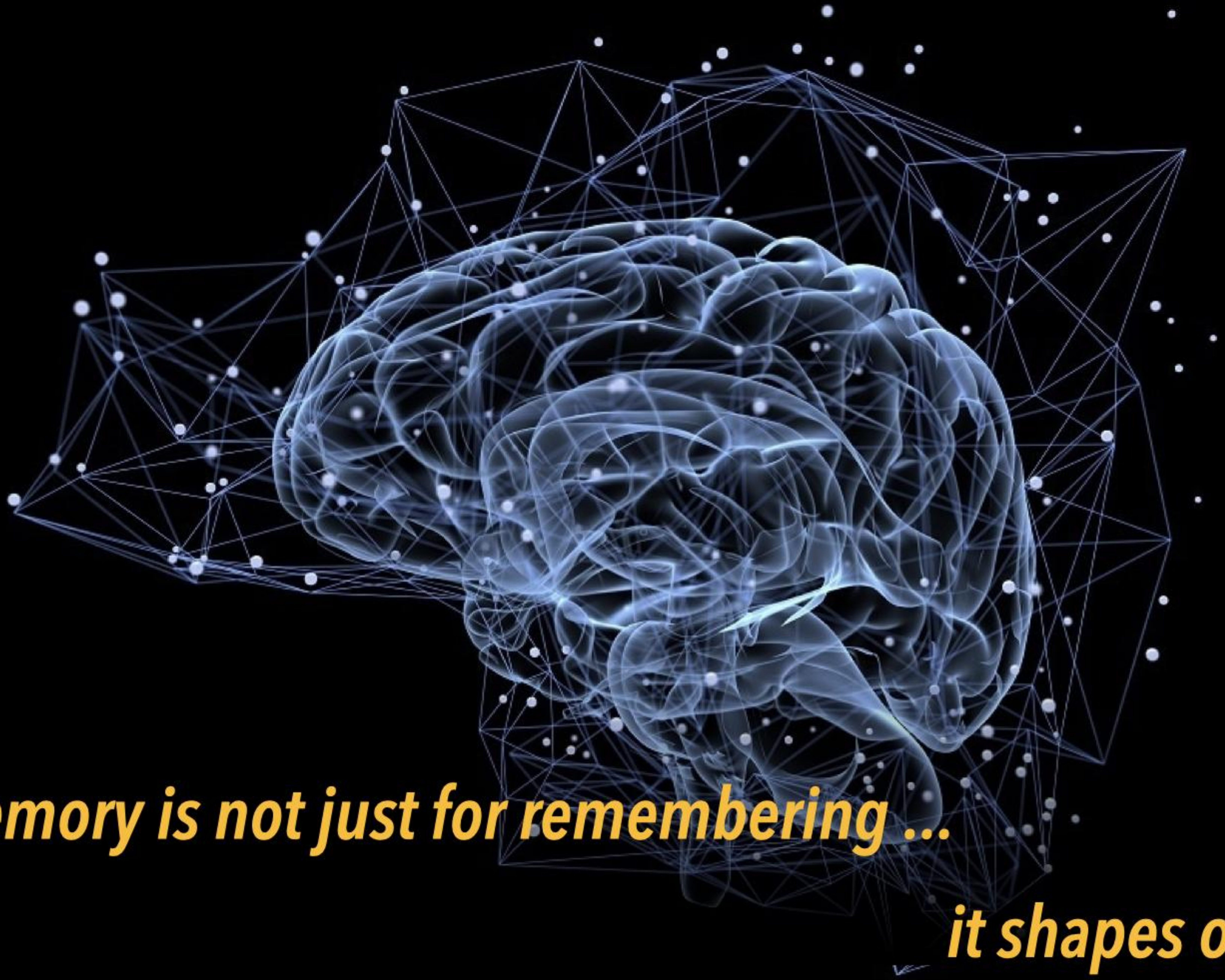
HOW EVENTS OF THE PAST DETERMINE FUTURE OUTCOMES

"View Along the Allegheny Near Aspinwall, PA"
by William Coventry Wall (1867)

Benjamin R. Hayes
Bucknell University



Memory is not just for remembering ...



Memory is not just for remembering ...

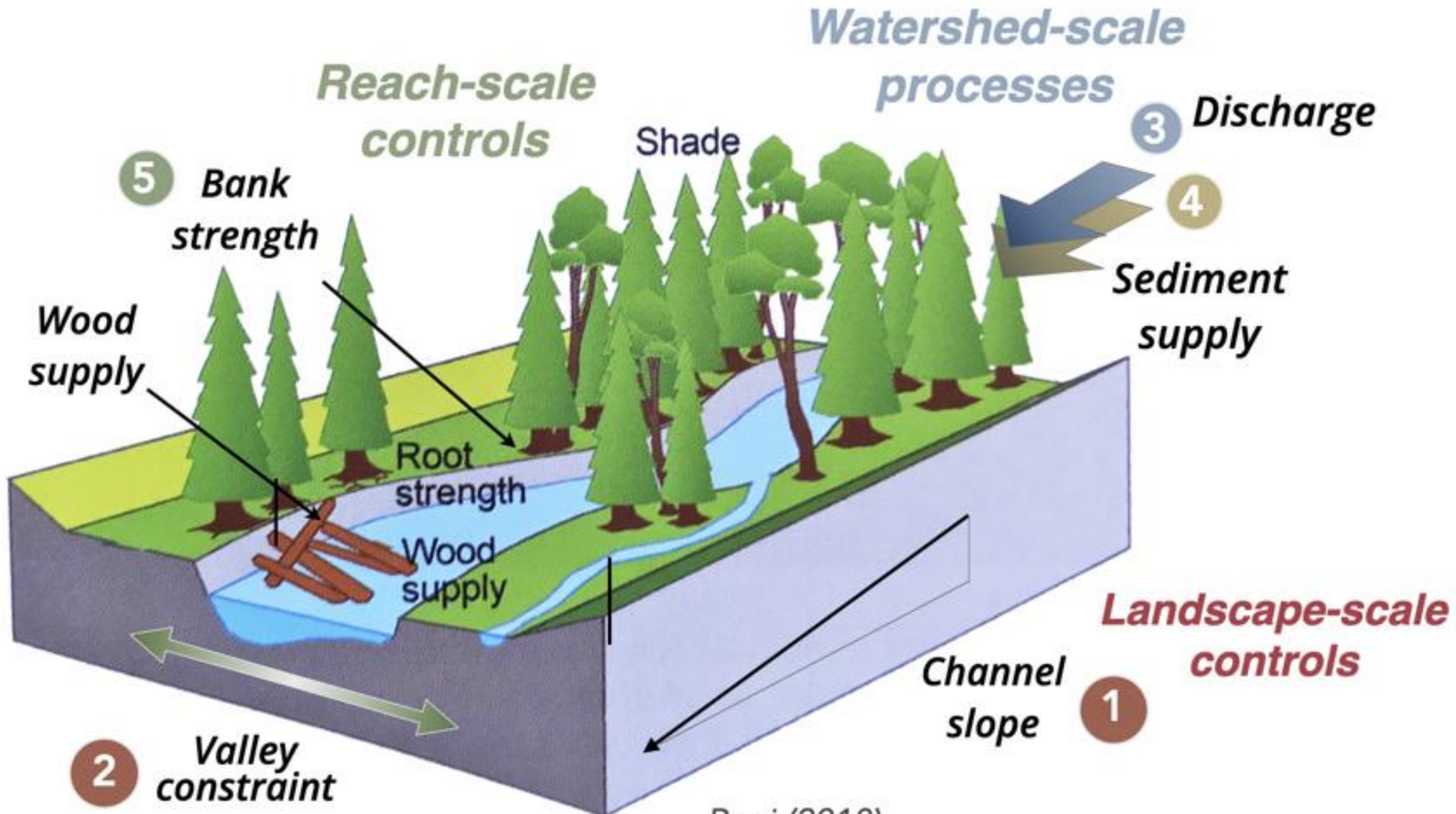
it shapes our future.

FOOD FOR THOUGHT .....

1. Both social and fluvial-ecological systems are far from being in **equilibrium**.
2. They are characterized by **thresholds**, **multiple states**, and **surprising phenomena**.
3. Because of the connection between ecological and societal systems, cross-scale **interactions happen**. These interactions must be recognized and anticipated.
4. We should be aware of **slowly evolving conditions**.
5. **Short-term measures can not resolve persistent, chronic problems,** nor can they deal with **continuous change**.

KEY CONCEPTS

- Behavior - how and why systems respond to perturbations
- Process linkages and inherited disfunction (cascading effects)
- Episodic memory - its affect on possible outcomes in the future



Roni (2018)

Episodic Memory #1 (Deep Geologic Time)

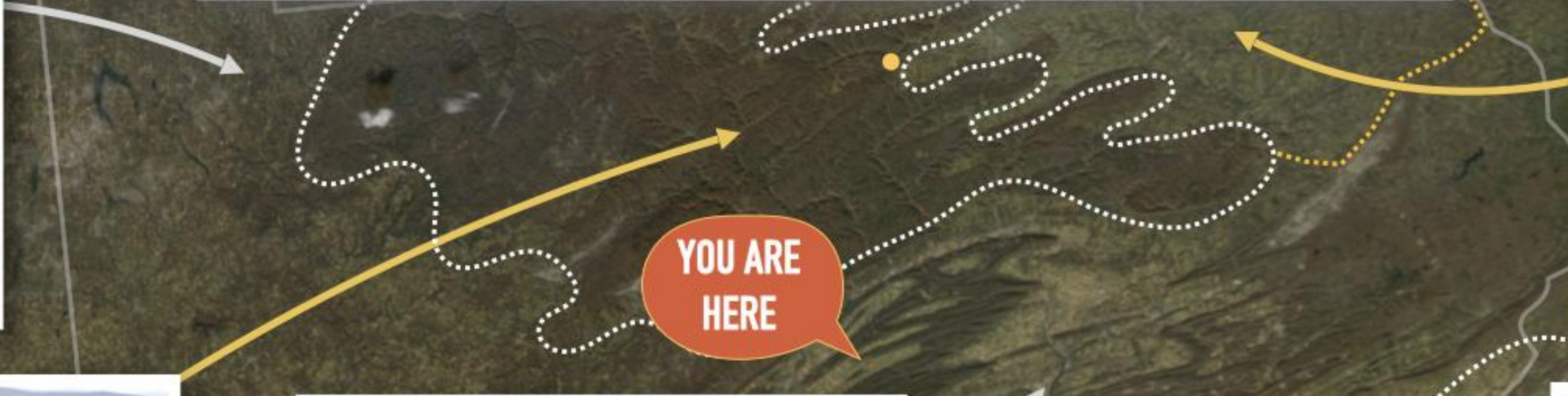
- ***Paleozoic, Mesozoic, and Cenozoic eras***

High Plateau Section

(Warren, Clarion, Forest, McKeen, Elk, Cameron counties)
Flat-lying sedimentary rocks, with lower relief, broad hillslopes and narrow valley floors

Glaciated Plateaus

(Bradford, Tioga, Sullivan and Lycoming counties)
Gravel-bed rivers, complex assemblage of alluvium, till, valley-train outwash, and underlying ice-contact deposits



Deep Valley Section

(Clinton, Potter, Tioga, Lycoming, and Sullivan counties)
Gravel-bed streams flowing through narrow canyons carved in flat-lying sedimentary rocks, with steep hillslopes, high relief, and narrow valley floors

Ridge & Valley Province

(Centre, Union,Northumberland, Snyder, Columbia, Montour, Luzerne, Mifflin, & Juniata counties)
Broad limestone valleys, shale hillslopes and meandering streams with suspended sediment loads

Piedmont Province

(Franklin, Perry, Cumberland, York, Lancaster, York, Berks, Chester, Leighigh, and Bucks counties)
Rolling hills and valleys, low relief, meandering streams with suspended sediment loads

1 *Key Concept*

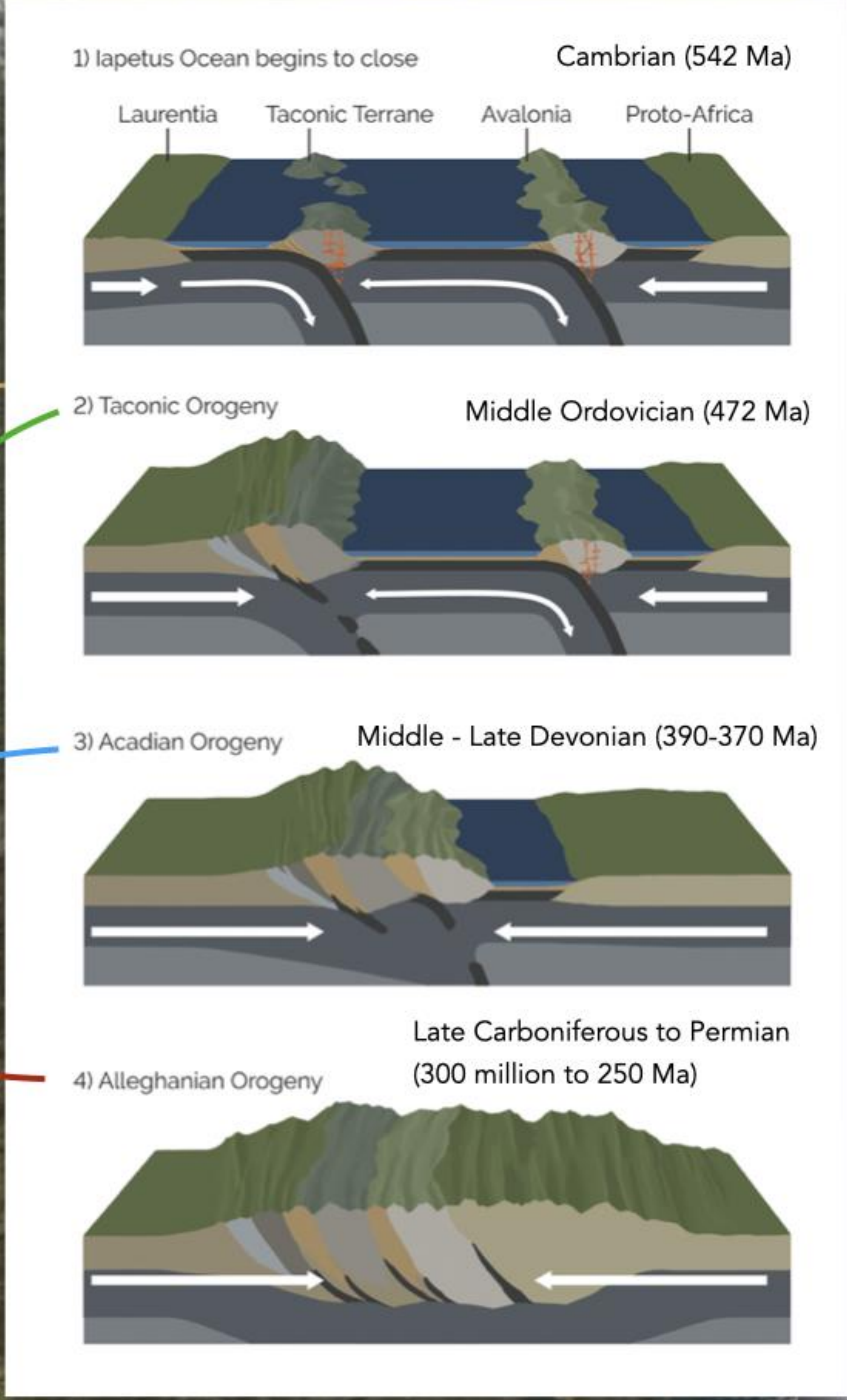
Drainage Network Development and Landscape Fabric

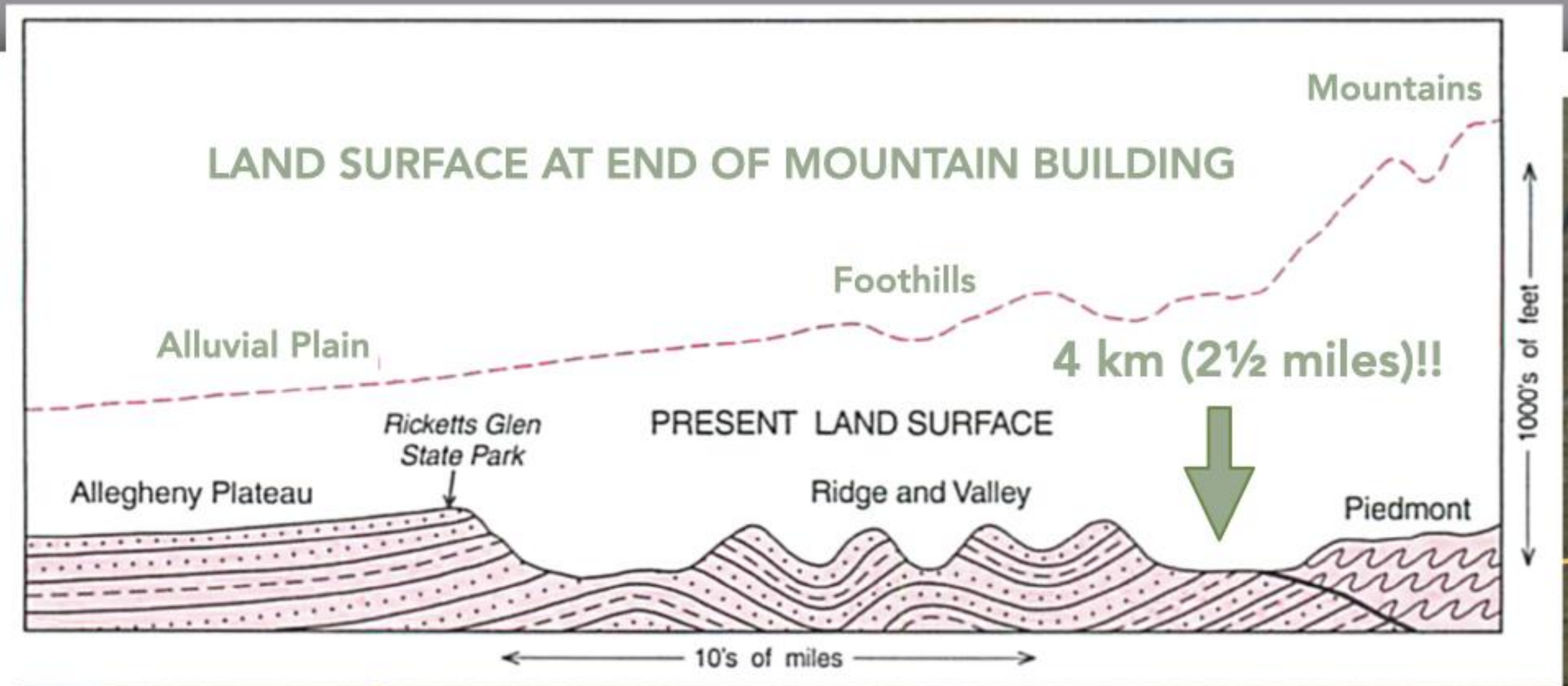
Baselevel change; landscape erosion, and drainage network development

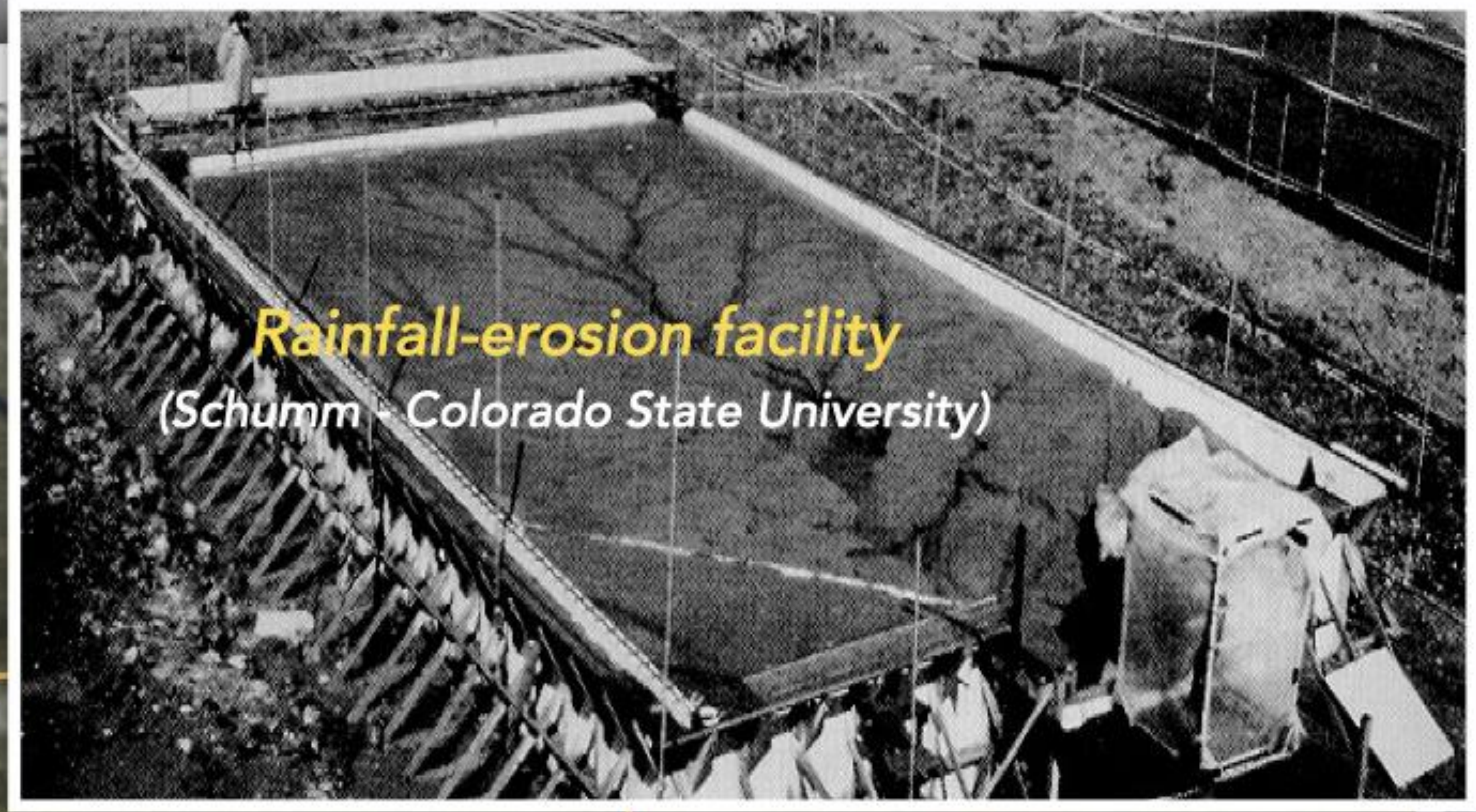
Episodic Memory #1:

- ***Ancient depositional environments***
- ***Compression, heat, fracturing during tectonic orogenic events***

YEARS AGO	ERA OR EON	PERIOD	ACTIVITY AFFECTING PENNSYLVANIA
0 to 1.8 million	CENOZOIC ERA	QUATERNARY	Glaciation; periglacial erosion and deposition
1.8 million to 66 million		TERTIARY	Weathering and erosion; creation of present landscape
66 million to 146 million	MESOZOIC ERA	CRETACEOUS	Erosion and weathering
146 million to 200 million		JURASSIC	Diabase intrusions; opening of Atlantic Ocean
200 million to 251million		TRIASSIC	Separation of North America from Africa; sedimentation in rift valley
251 million to 299 million	PALEOZOIC ERA	PERMIAN	ALLEGHANIAN OROGENY: Collision of Africa and North America, mountain building, thrust faulting, and folding; much erosion
299 million to 359 million		PENNSYLVANIAN AND MISSISSIPPIAN (Carboniferous)	Alluvial deposition; eastward advance of shoreline followed by development of low, flat alluvial plain
359 million to 416 million		DEVONIAN	ACADIAN OROGENY: Collision of Avalonia, Europe, and North America; formation of Catskill Delta
416 million to 444 million		SILURIAN	Erosion of mountains; deposition of sand and mud
444 million to 488 million		ORDOVICIAN	TACONIC OROGENY: Thrusting of volcanic arc; development of Appalachian basin
488 million to 542 million		CAMBRIAN	Transgression of the sea; carbonate deposition







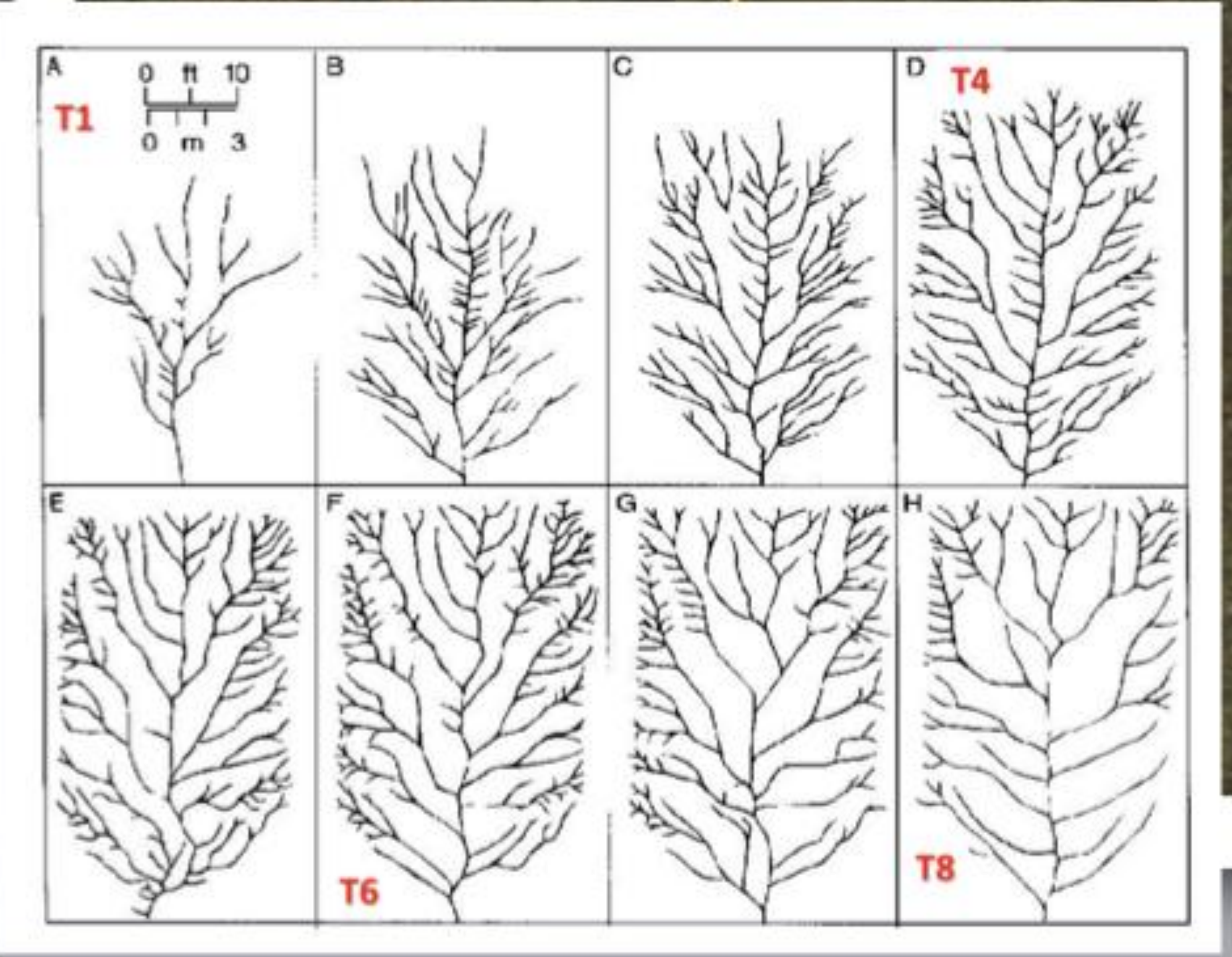
Denudation Rates

23-31 m / m.y. - Cenozoic

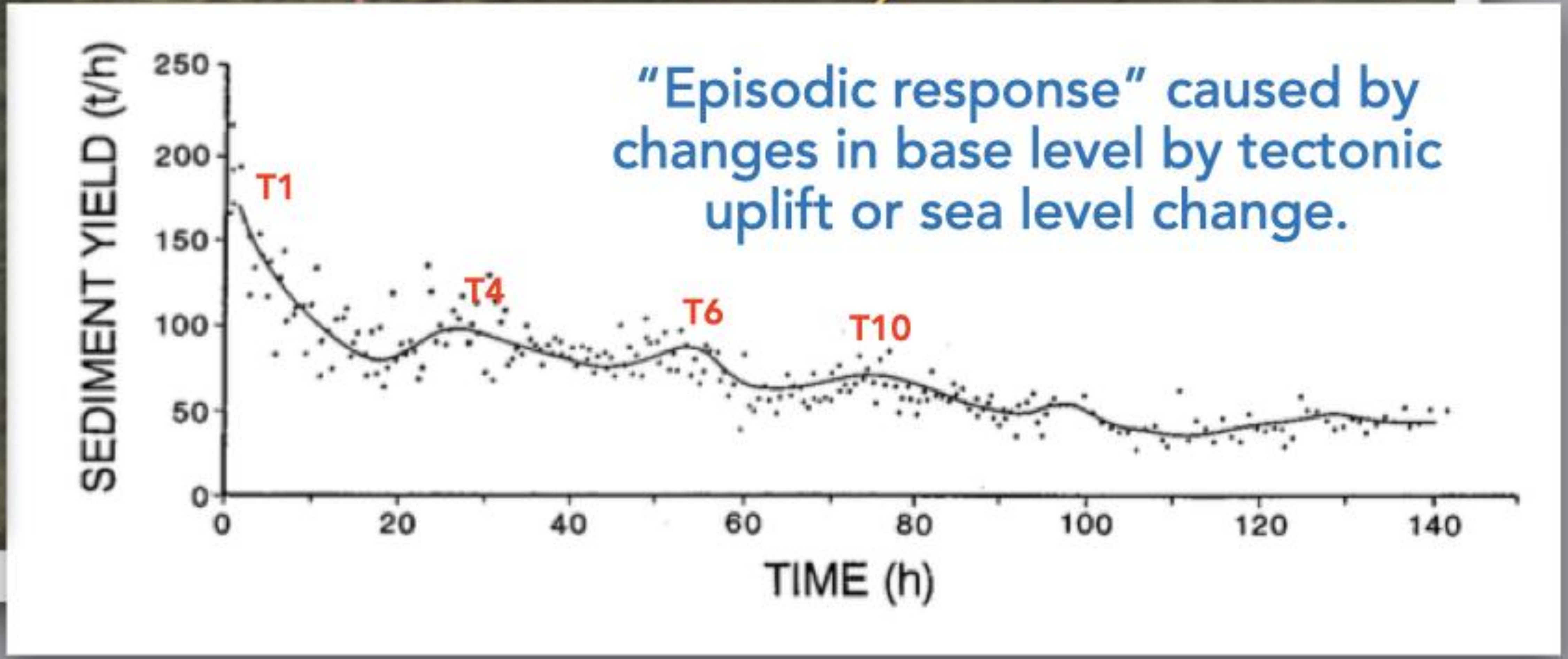
100-300 m / m.y. - Paleozoic

- Appalachians were uplifted to heights of 4,500m (Rockies or Andes)
- Over the past 240 million years the landscape has been gradually lowered (denuded) by intense weathering and erosion.
- Landscape-scale elements (regional provinces, watersheds, aquifers, soil catenas, etc.)

1 *Key Concept*



- *Episodes of tectonic uplight & base-level change*
- *Long periods of erosion, transport, and deposition*
- *Evolution of drainage network*



Episodic Memory #1:

- ***Ancient depositional environments***
- ***Compression, heat, fracturing during tectonic orogenic events***

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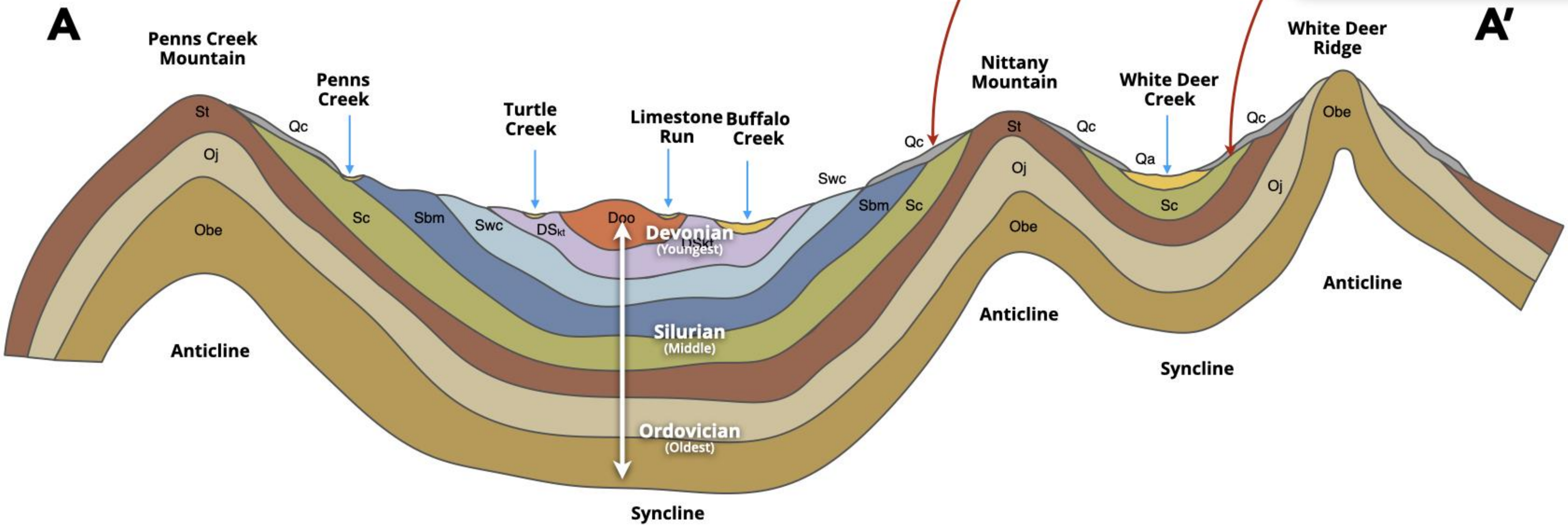
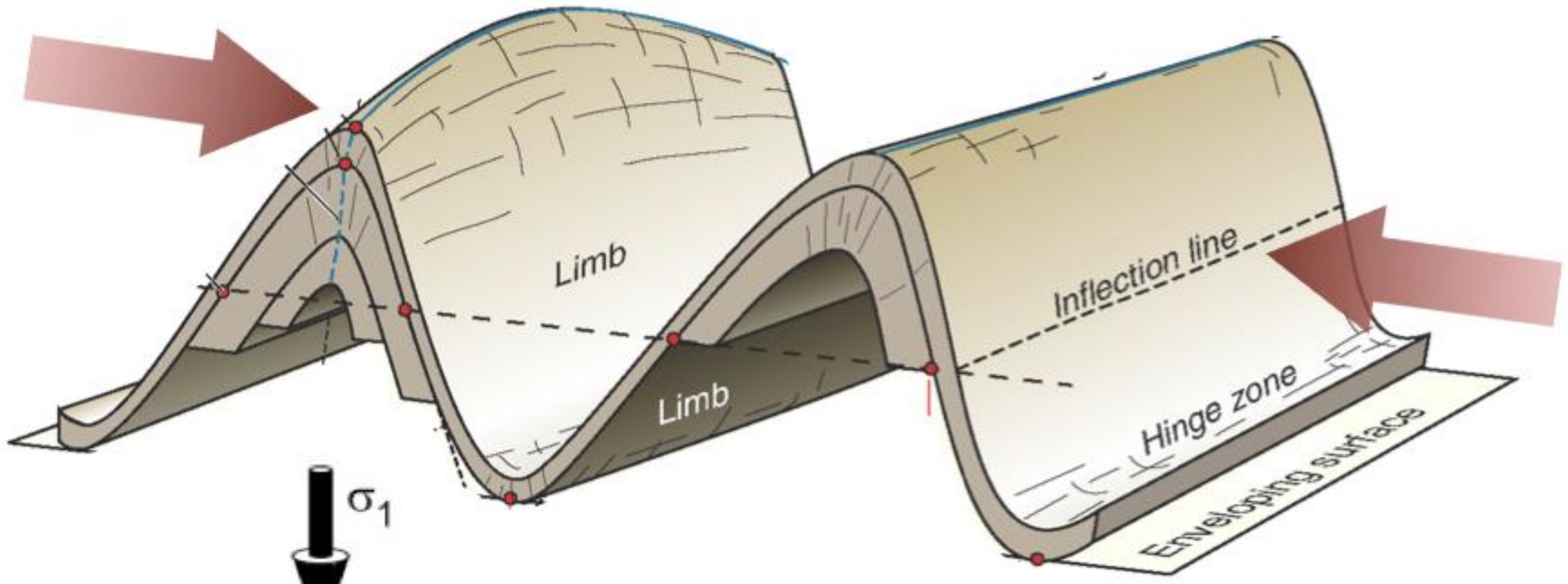
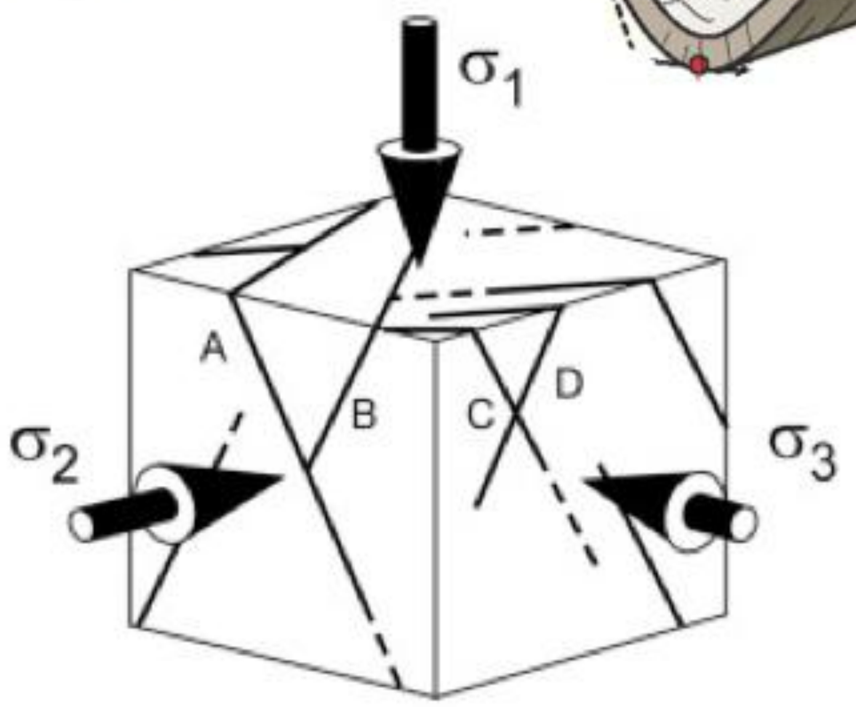
Geologic Cross-Section

(Not to scale)



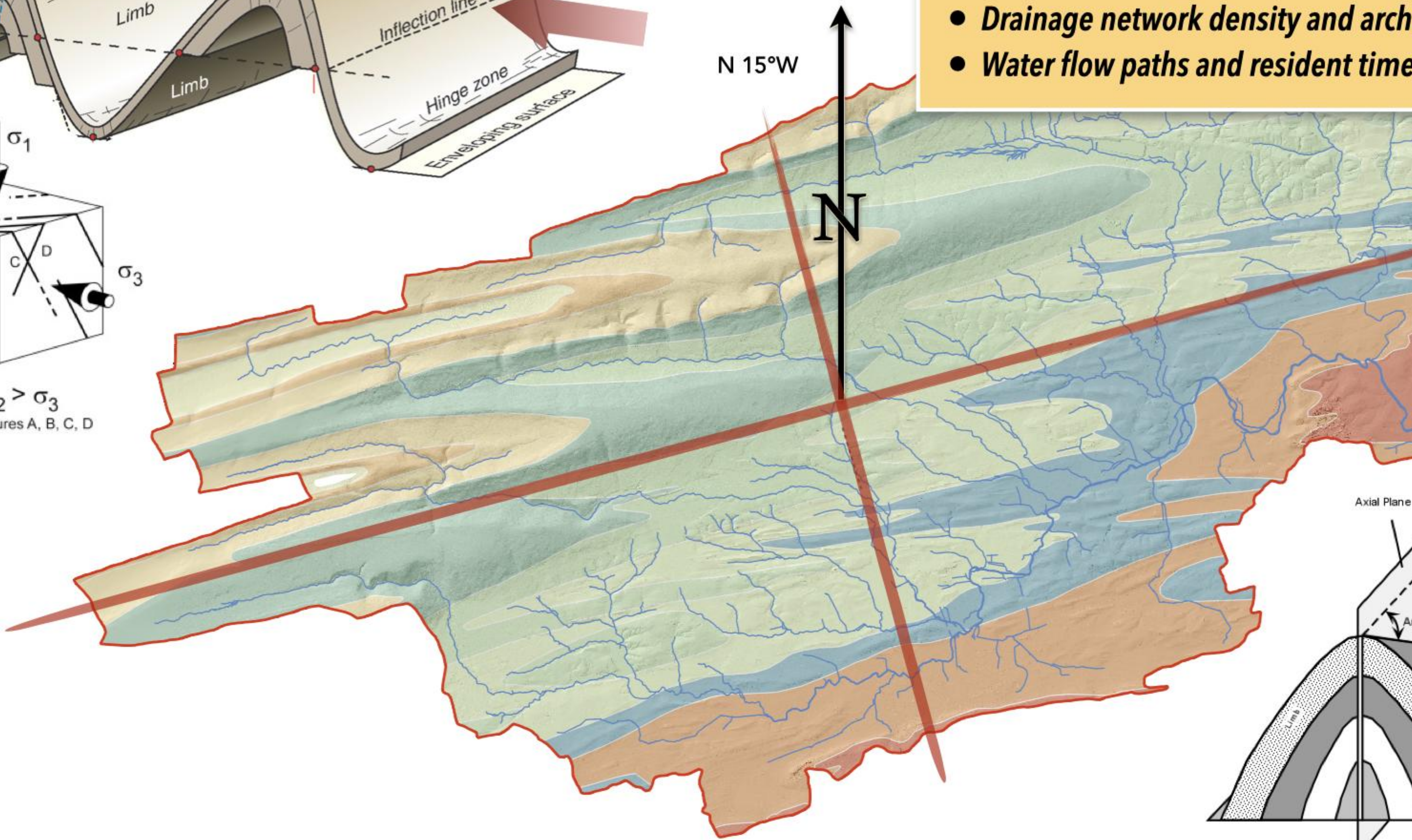


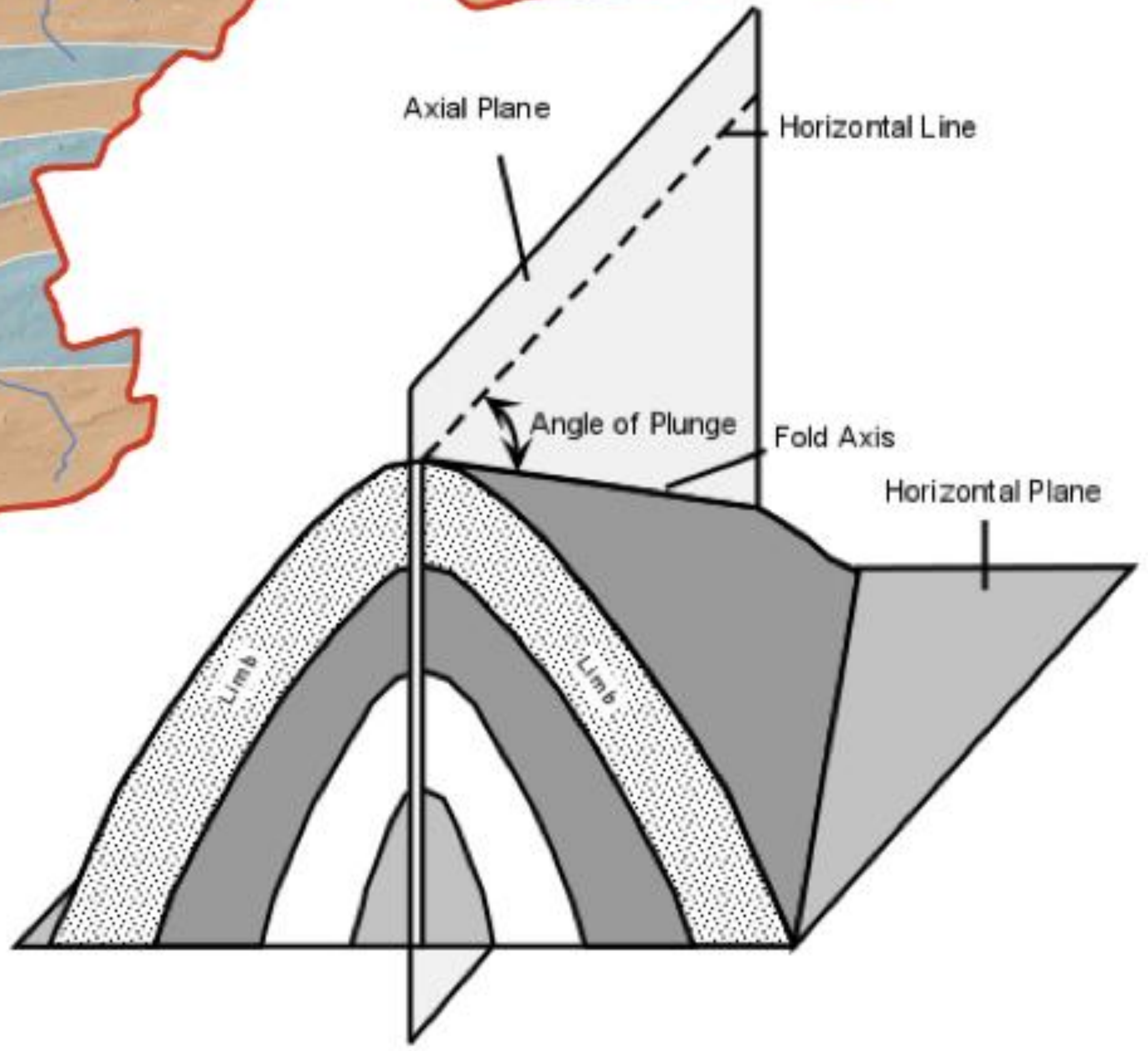


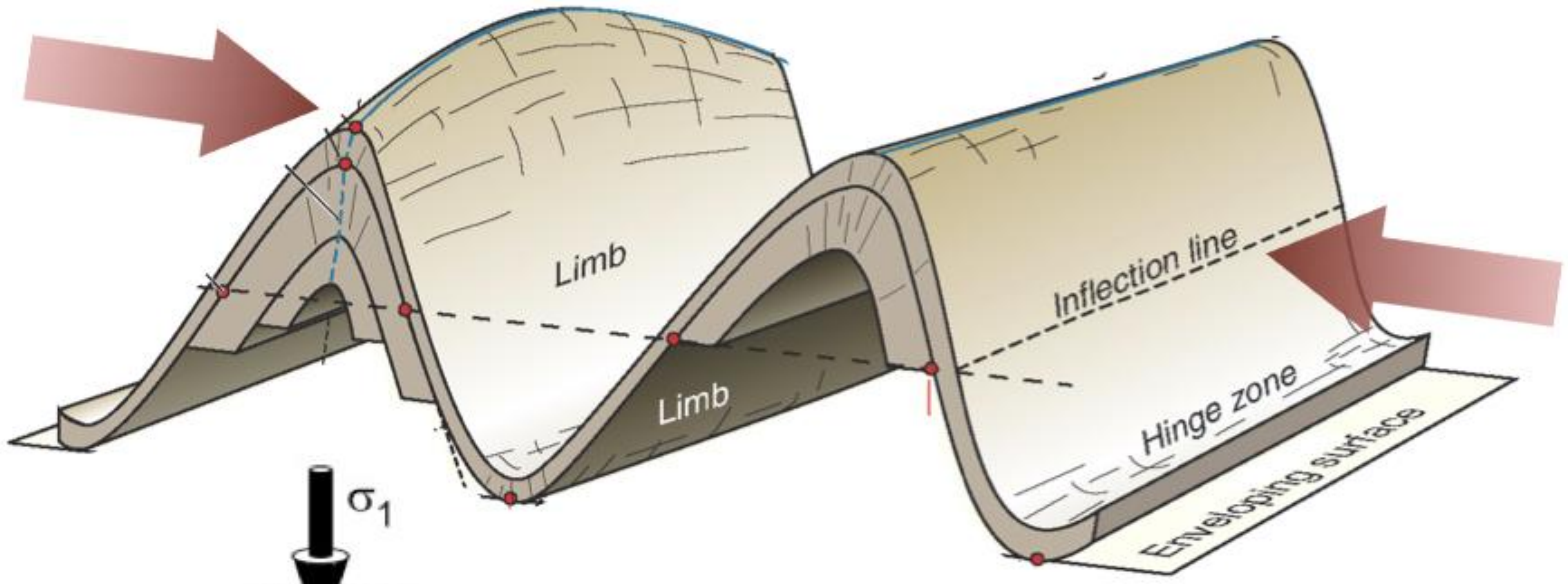
$\sigma_1 > \sigma_2 > \sigma_3$
Polymodal fractures A, B, C, D

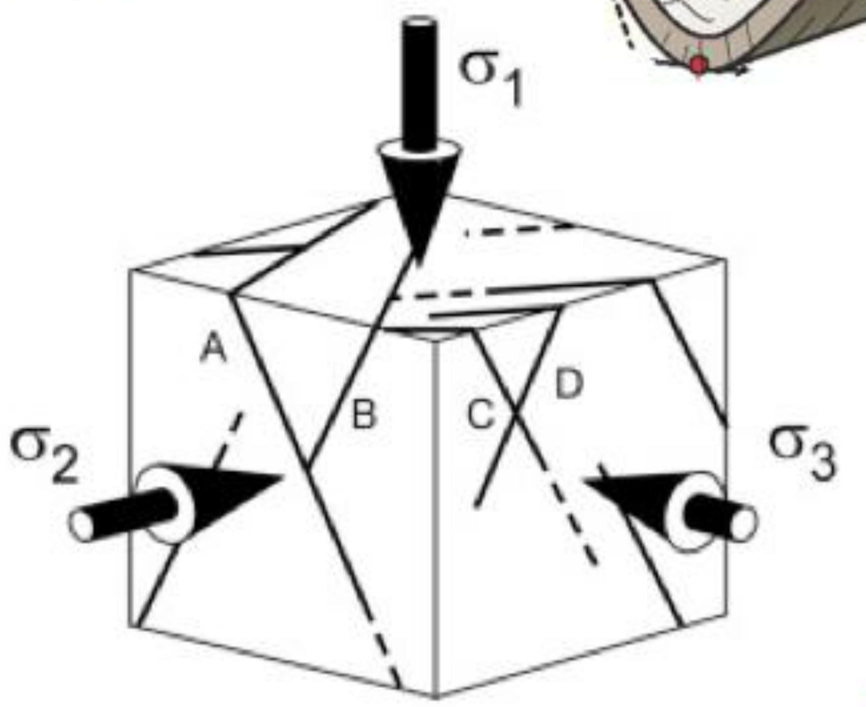
Episodic Memory #1

- ***Bedrock lithology & structural fabric***
- ***Drainage network density and architecture***
- ***Water flow paths and resident times***









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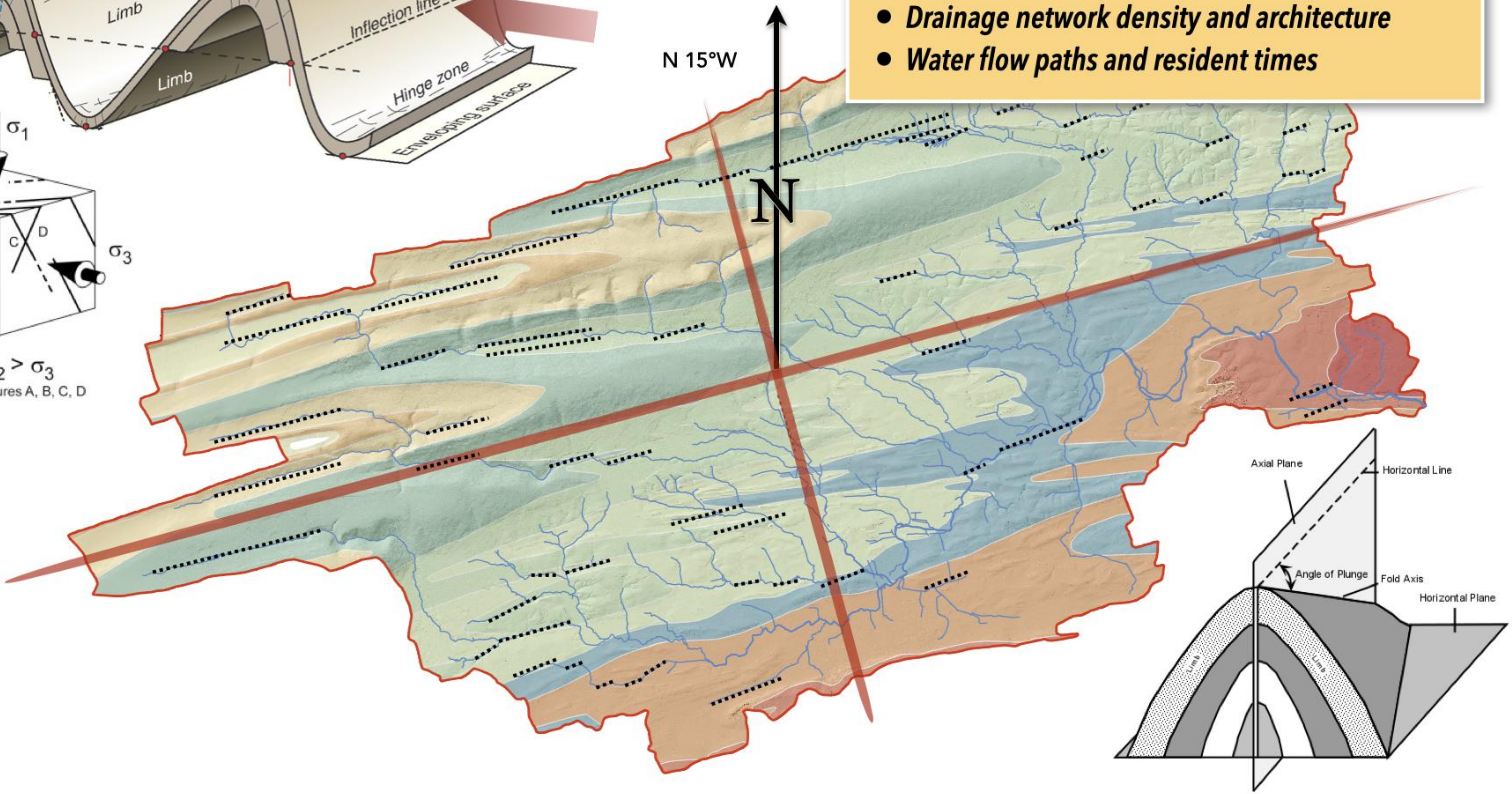

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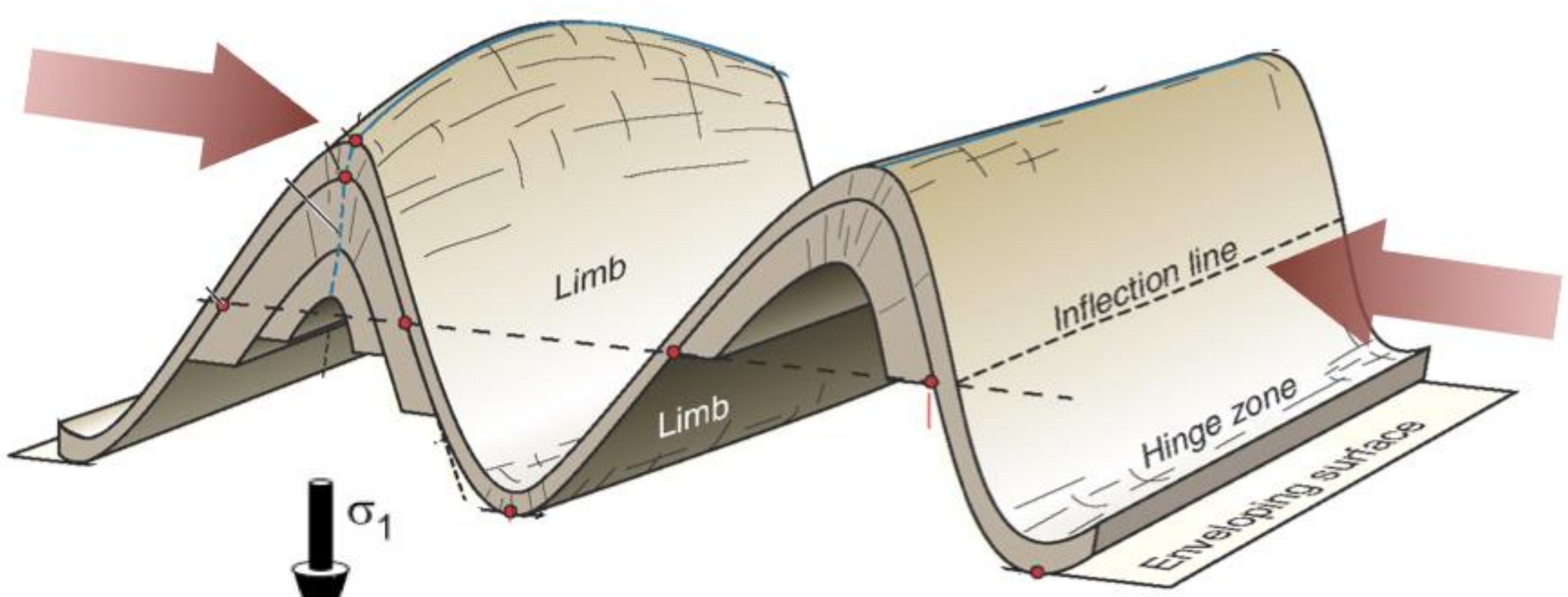

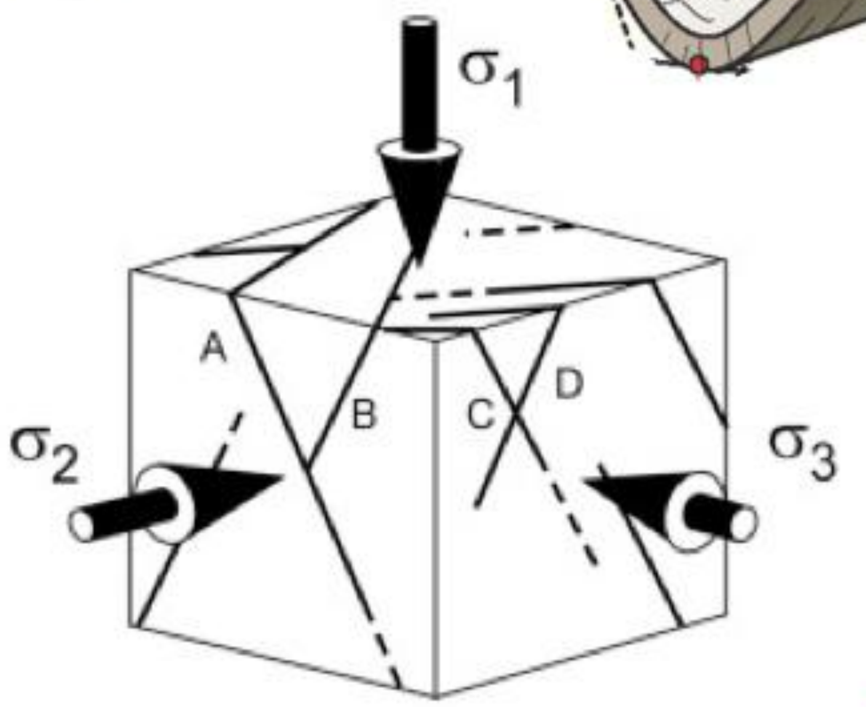

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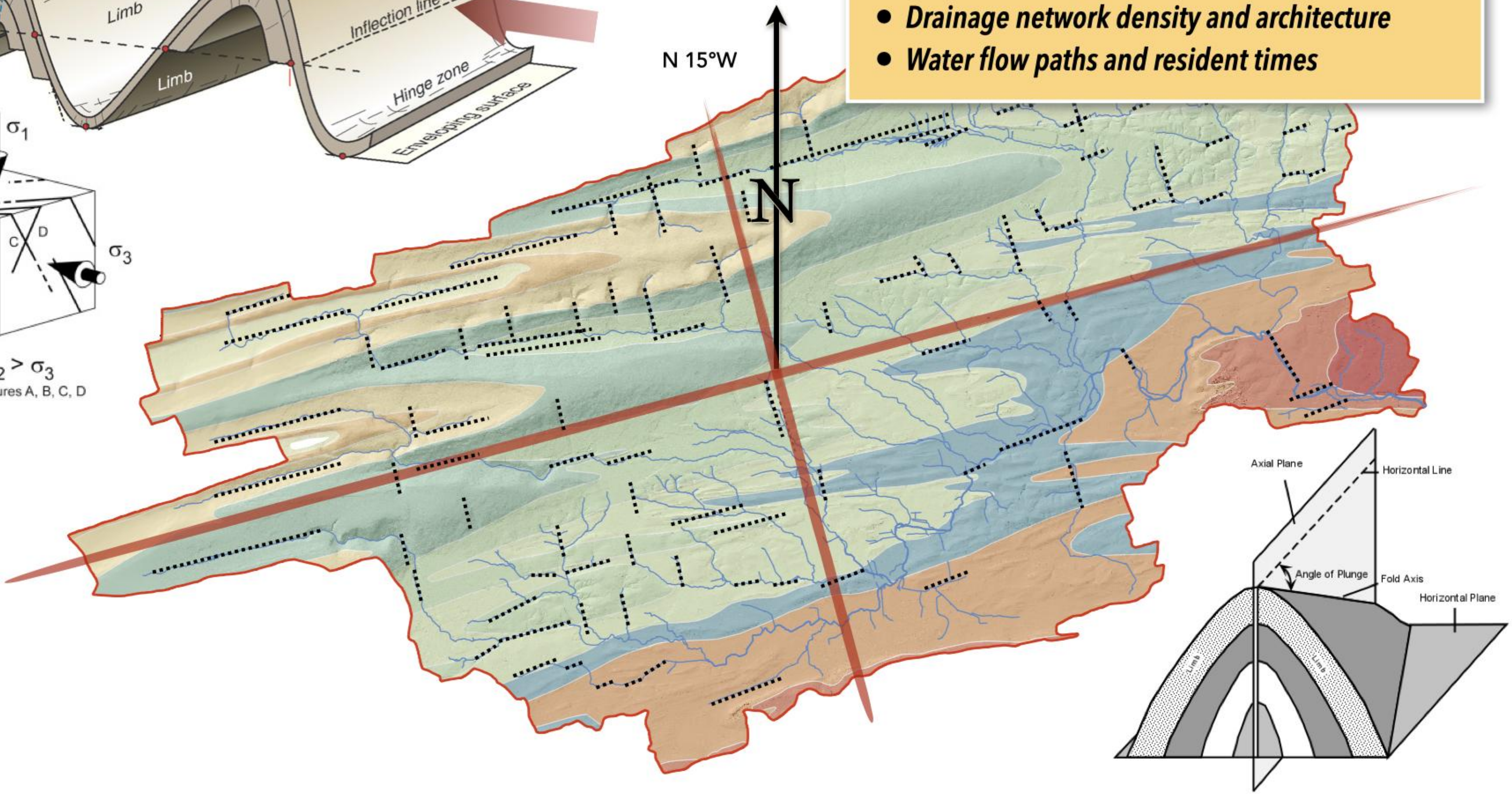
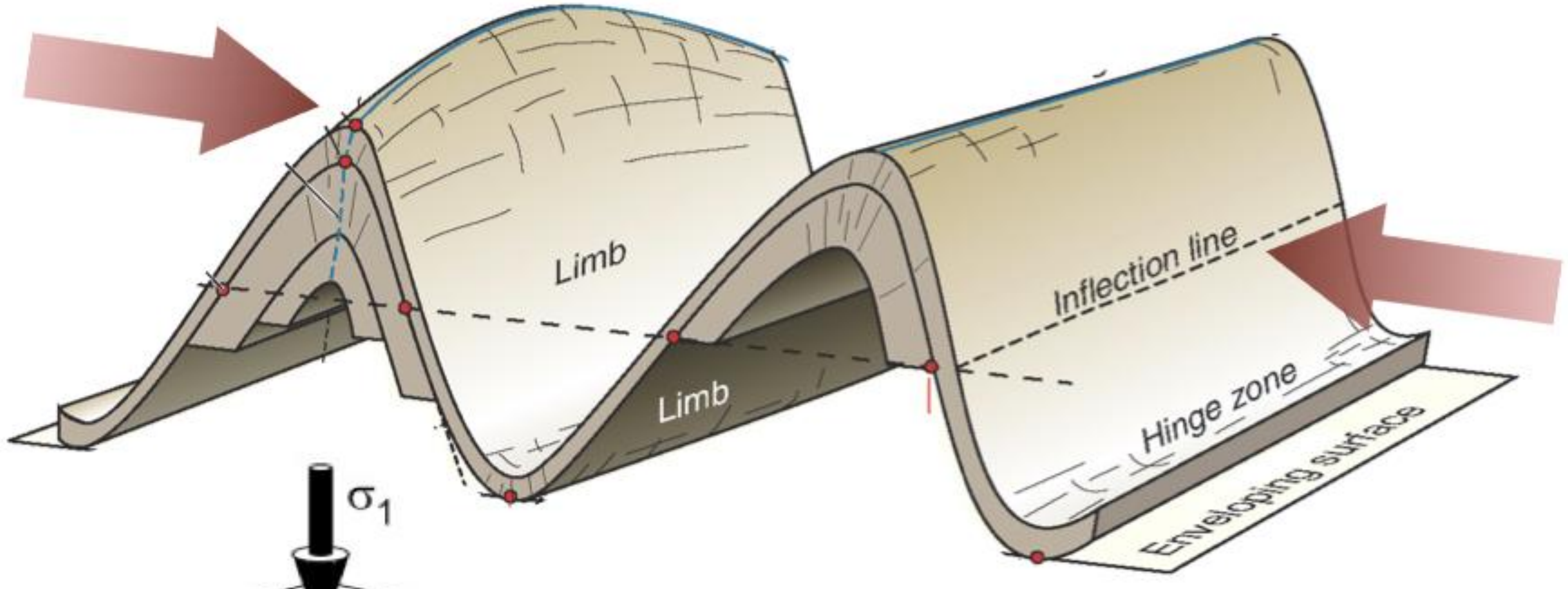
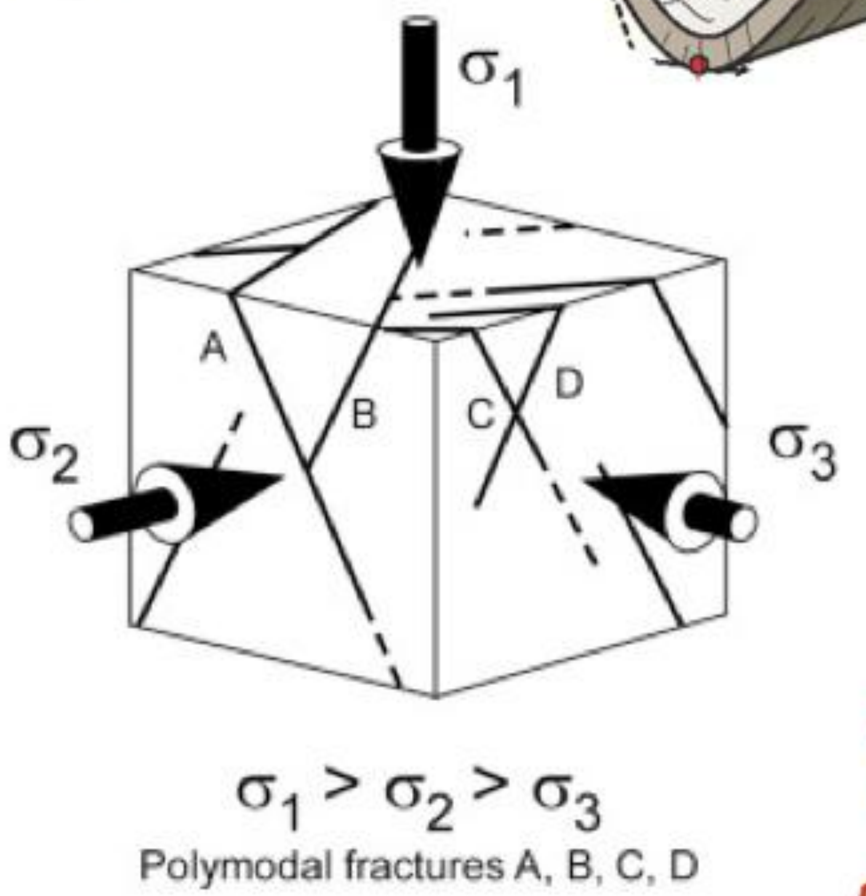
Polymodal fractures A, B, C, D







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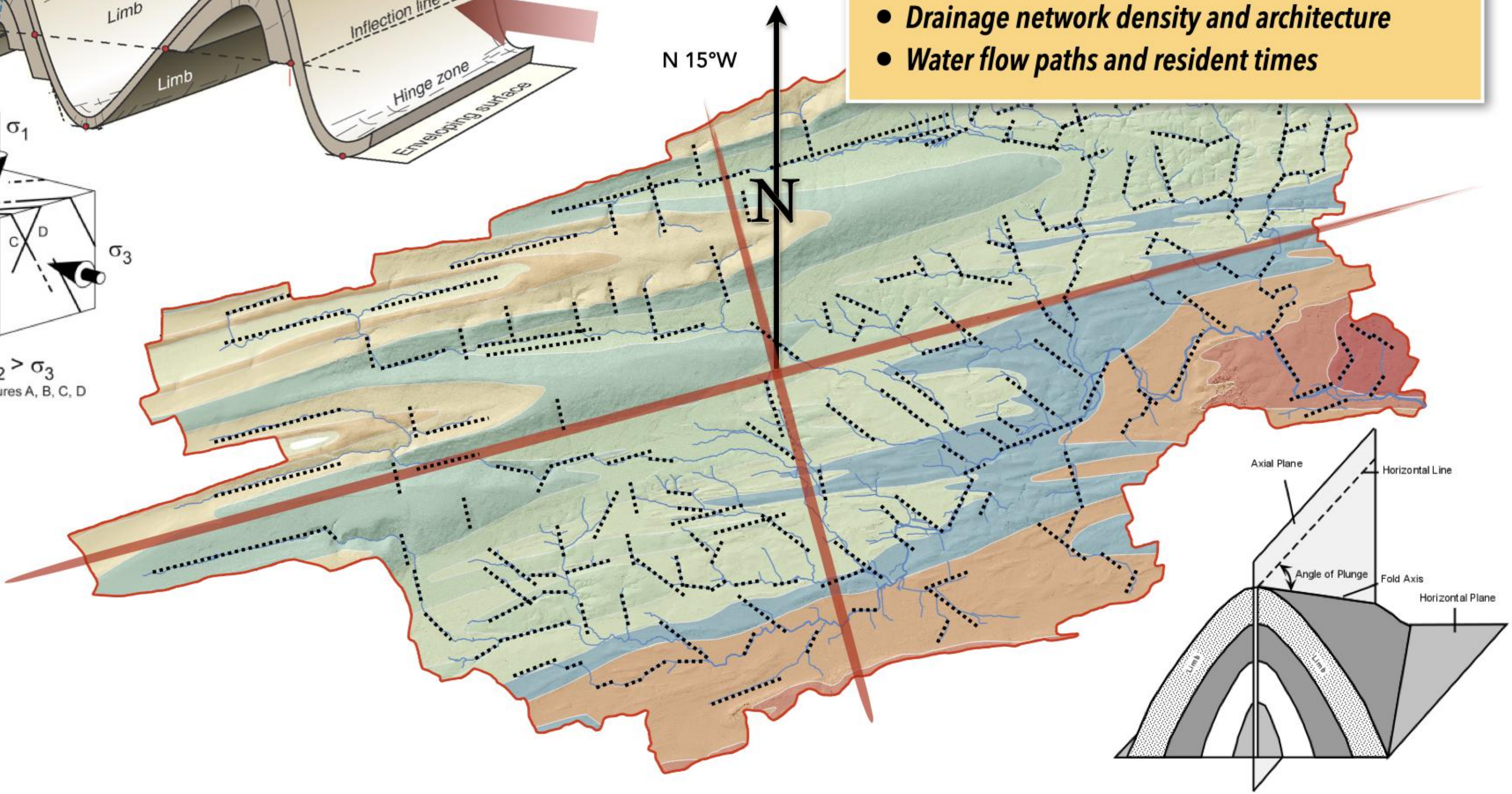
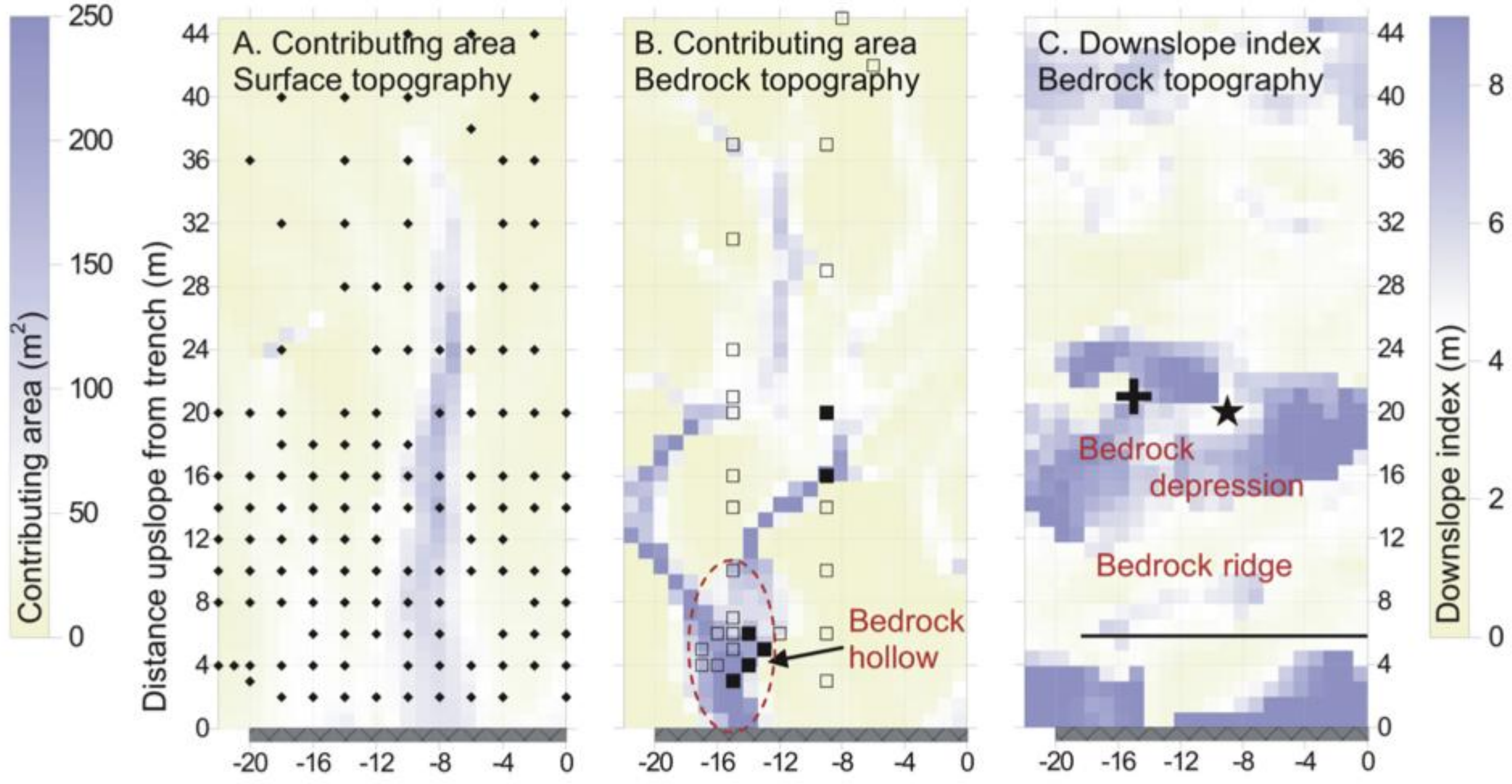
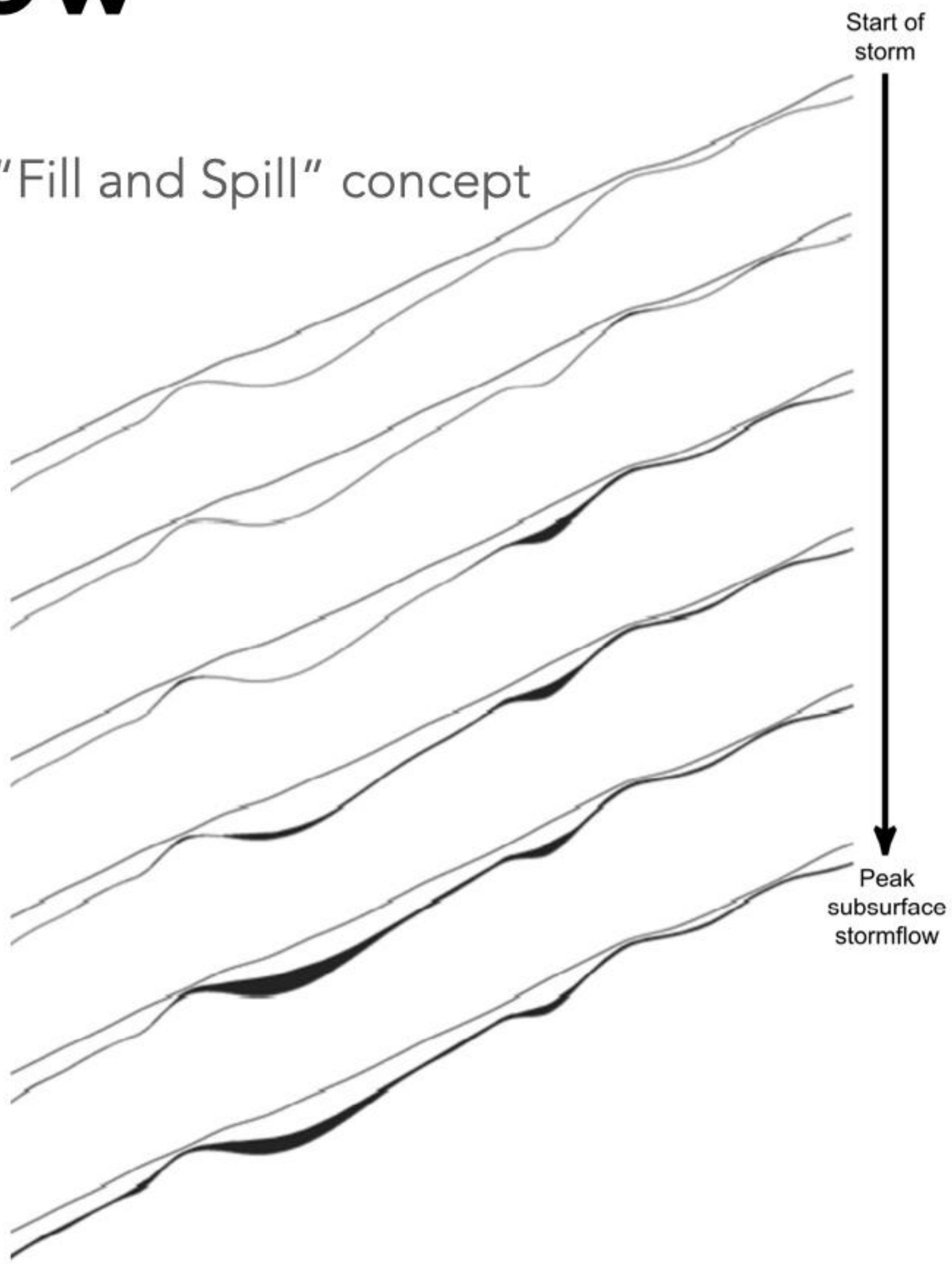


THRESHOLDS IN SUBSURFACE FLOW



"Fill and Spill" concept

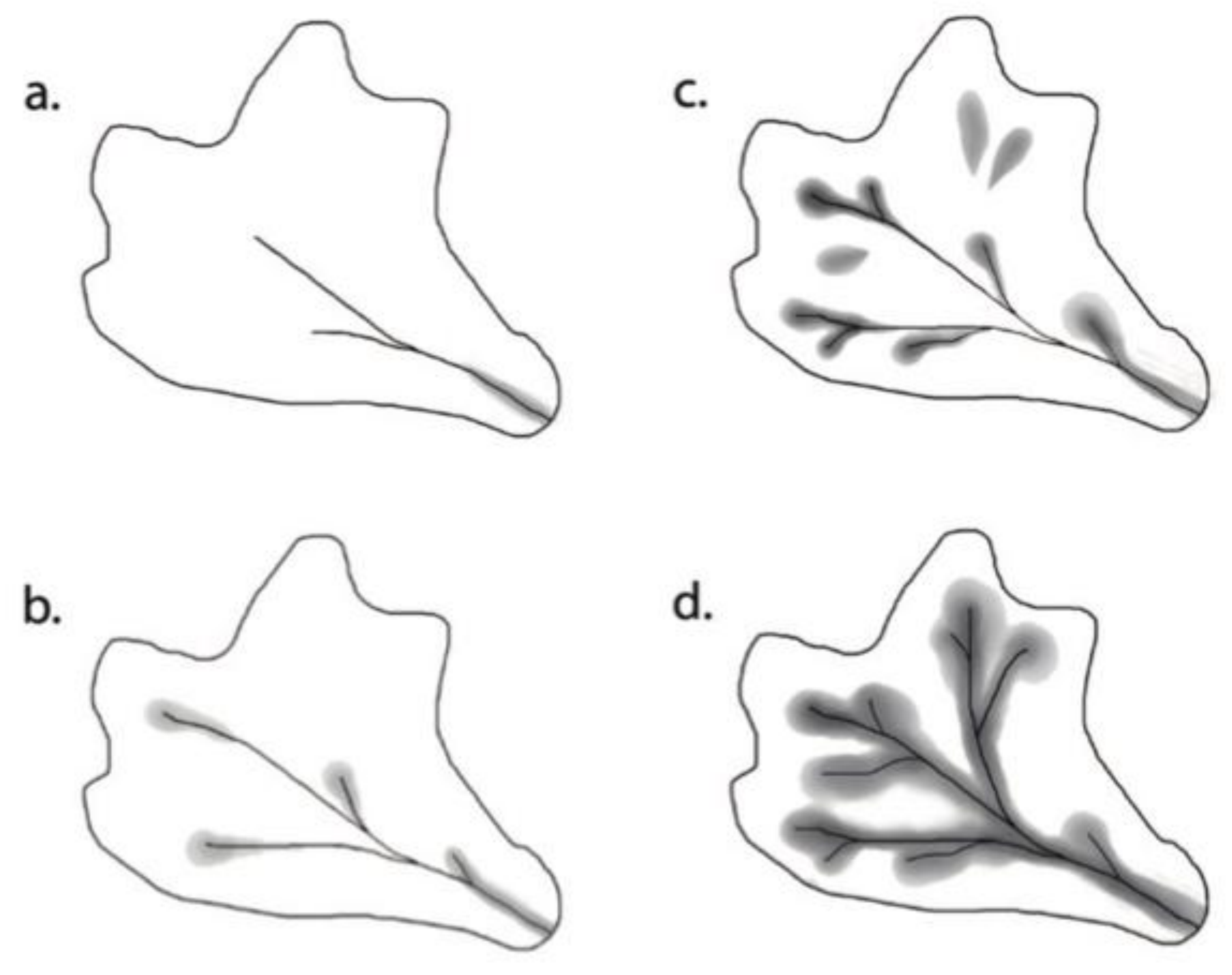


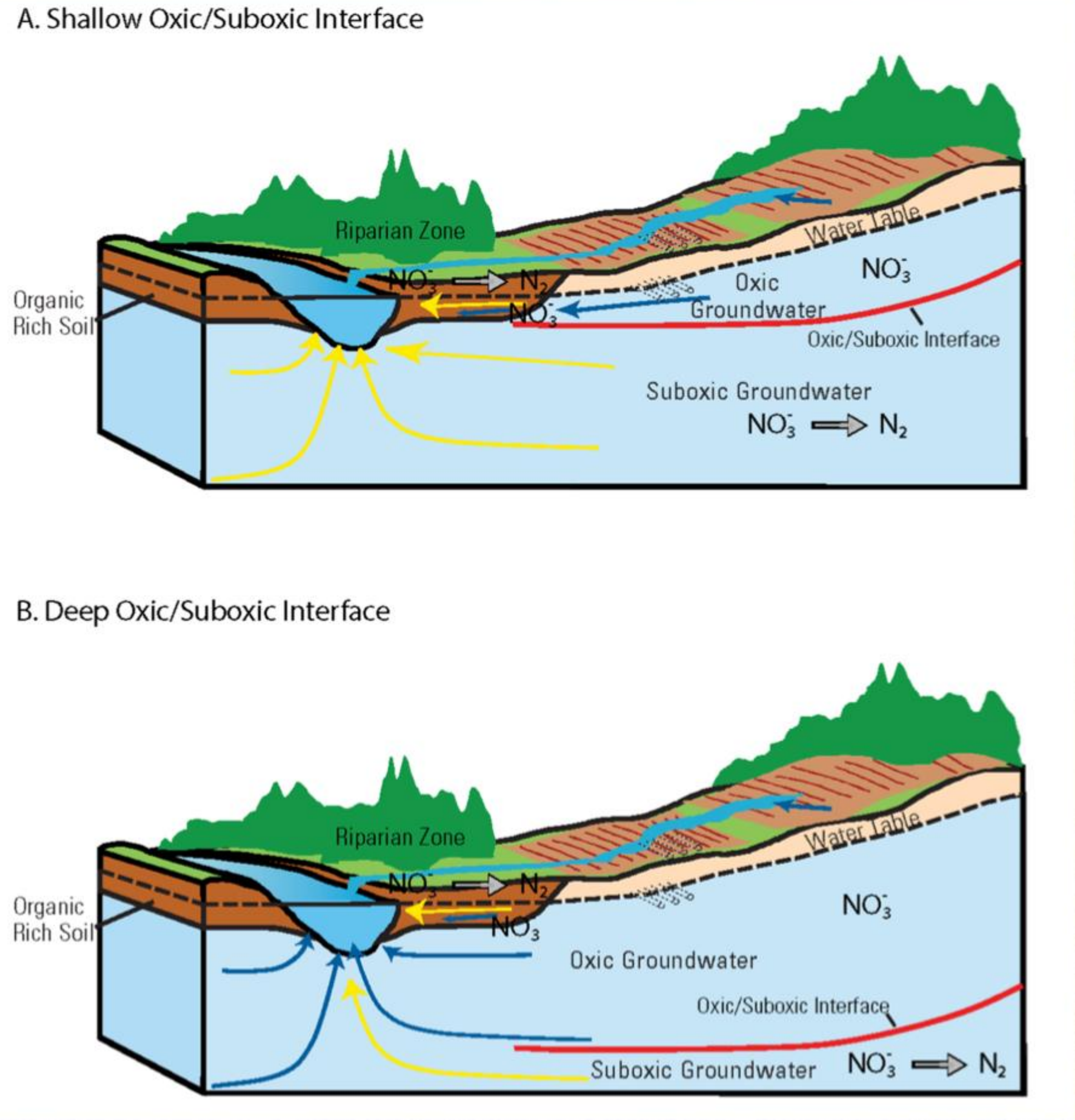
From: Tromp-van Meerveld and McDonnell (2006)


A "STREAM" EXTENDS FAR BEYOND ITS CHANNEL BANKS

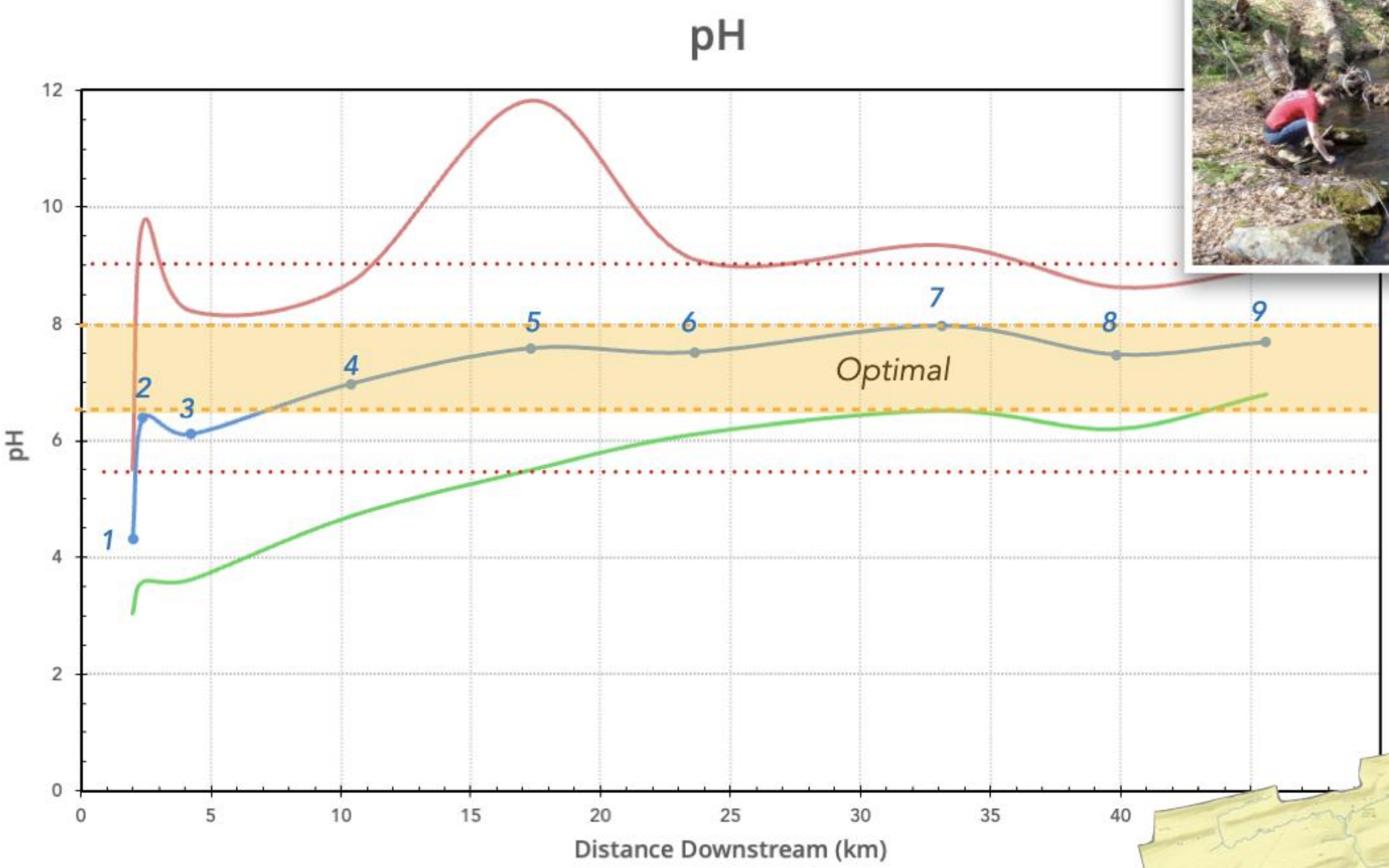

Variable Source Area Concept
a.
b.
c.
d.
A "STREAM" EXTENDS FAR BEYOND ITS CHANNEL BANKS

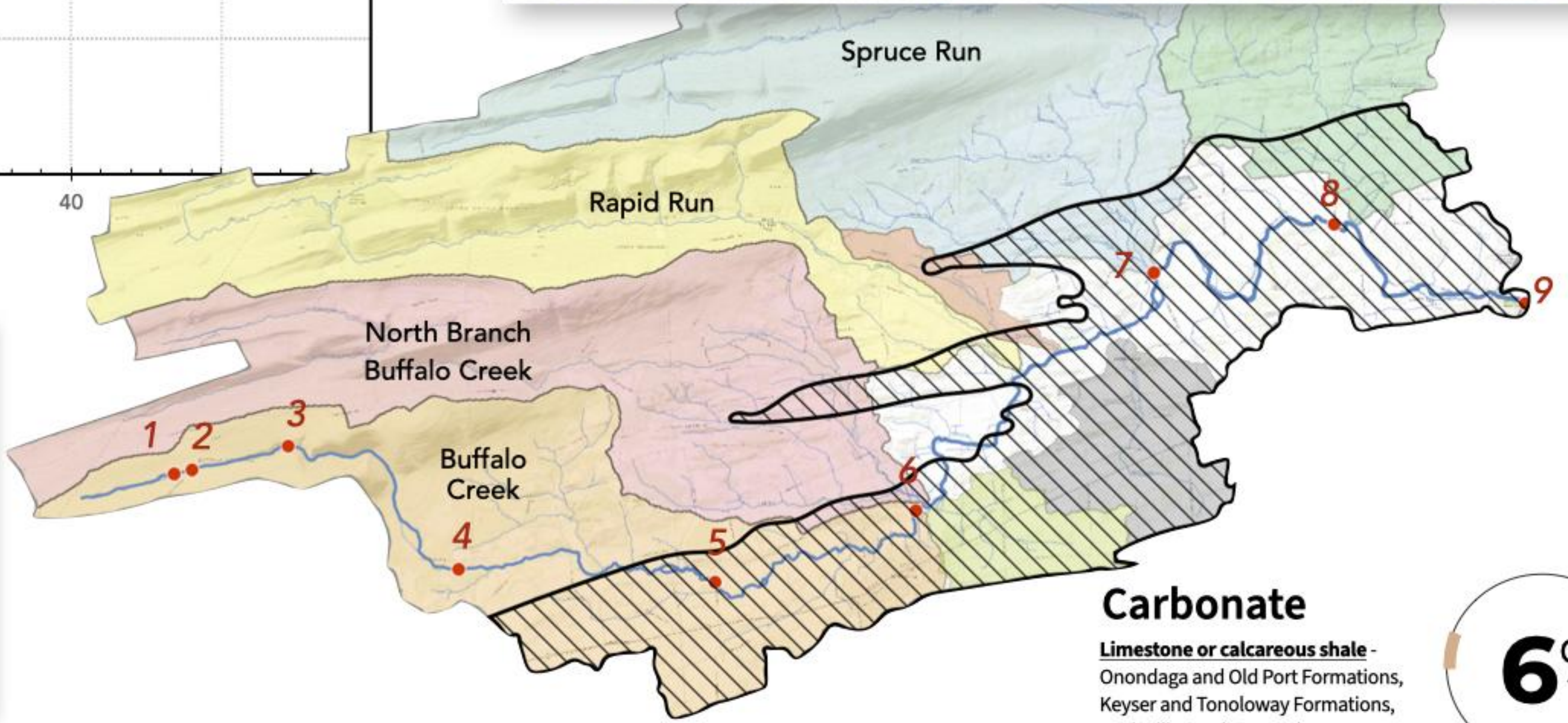
Variable Source Area Concept





Wherry et. al. (2021) Factors Affecting Nitrate Concentrations in Stream Base Flow, *Environ. Sci. Technol.* **55**: 902–911.





Episodic Memory #1

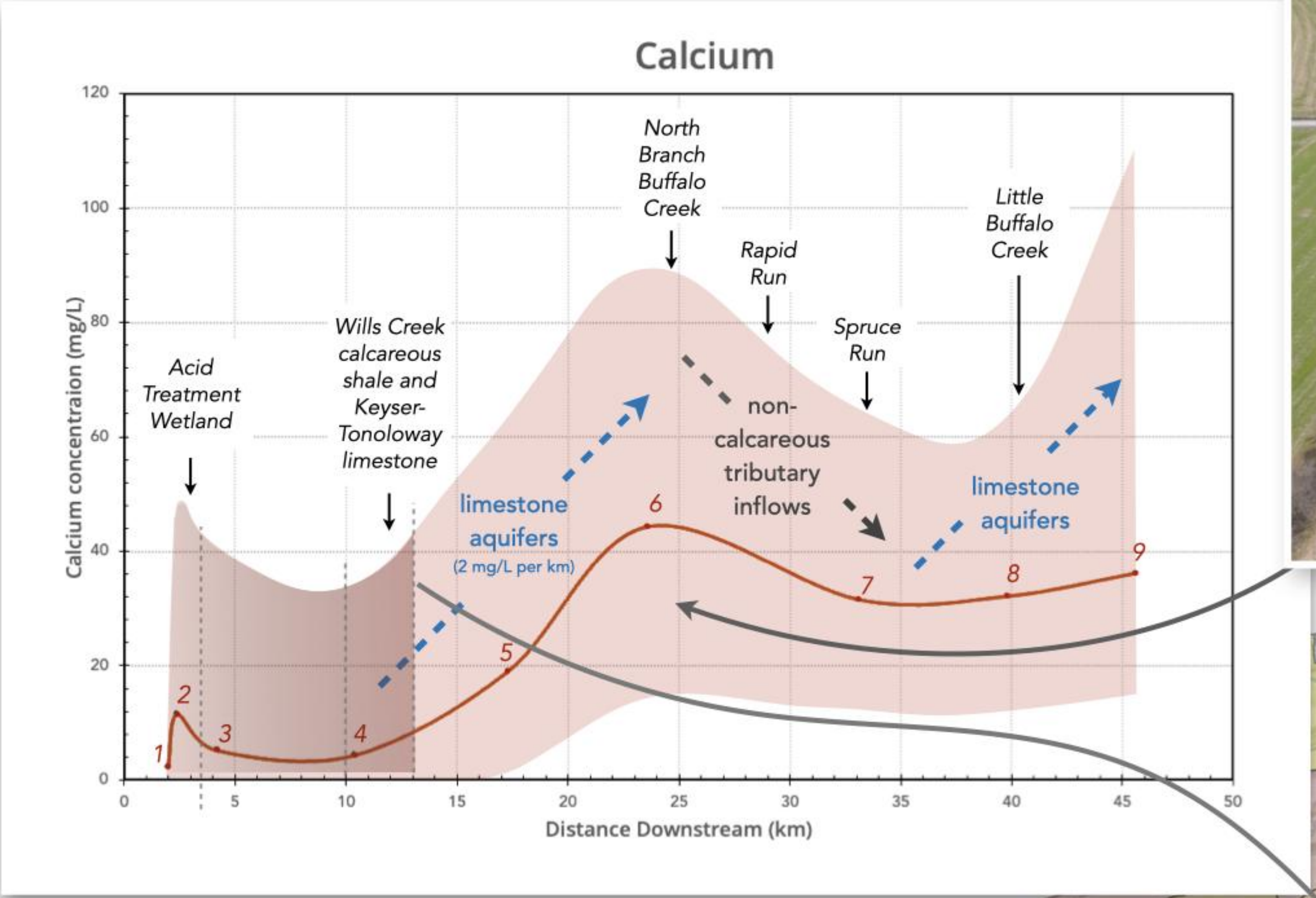
- ***Long periods of weathering; development of residual soils and catena profiles***
- ***Depositional materials (alluvial fans, drift & tills)***

Carbonate

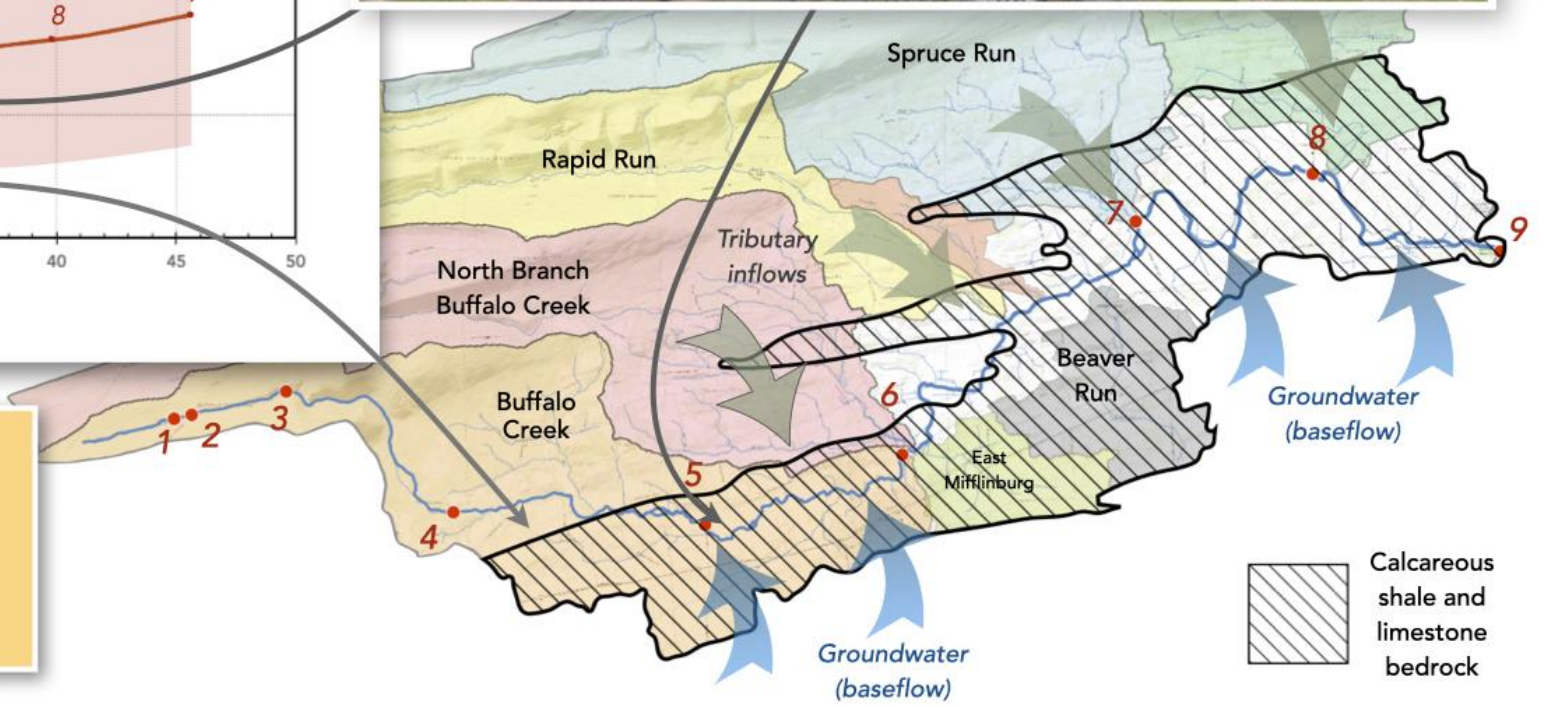
Limestone or calcareous shale - Onondaga and Old Port Formations, Keyser and Tonoloway Formations, and Wills Creek Formation

6%

STREAM'S BASELINE CHEMISTRY



Buffalo Creek as it flows under the Hayes Covered Bridge on Hoover Road (site #5)

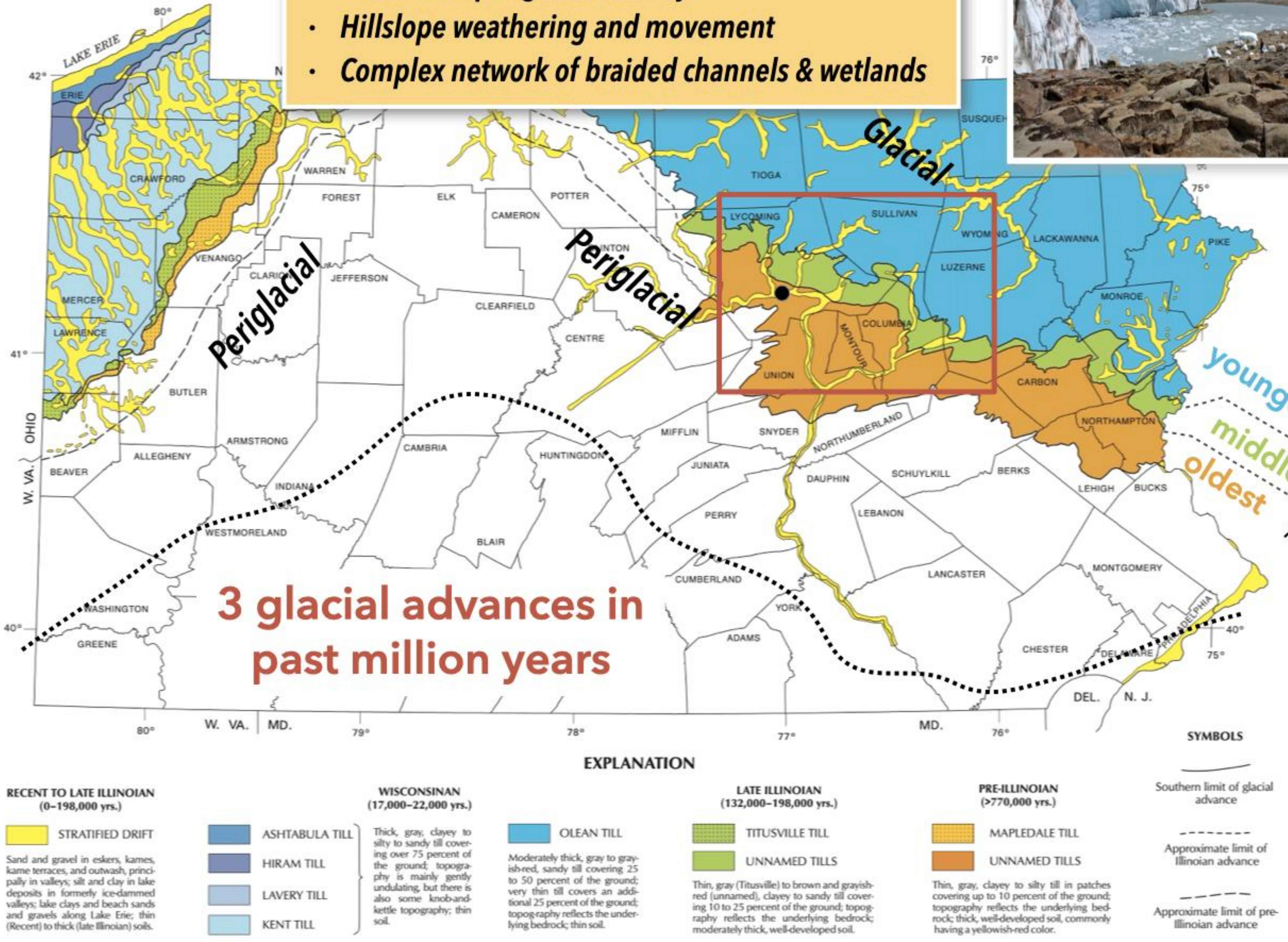


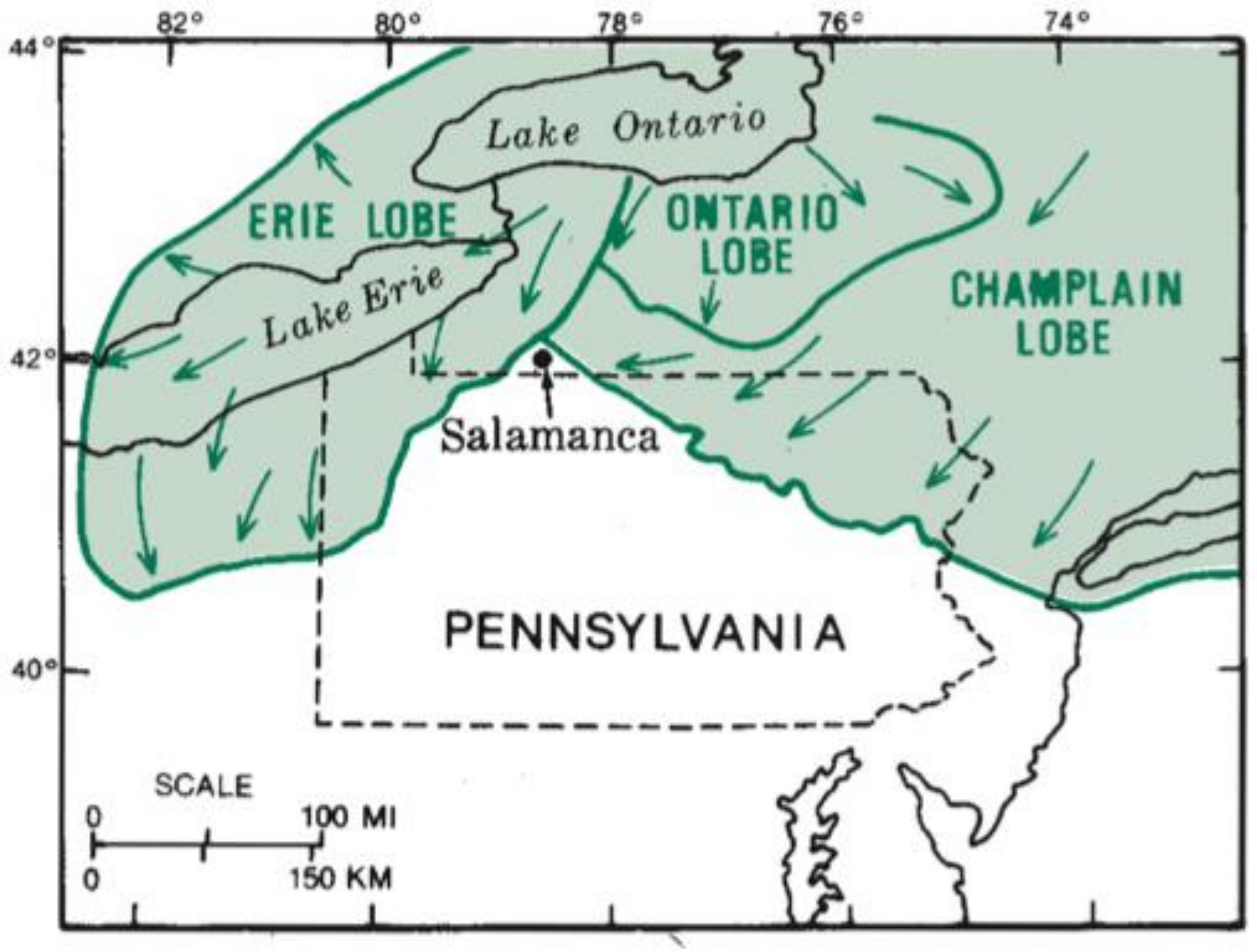
Episodic Memory #1

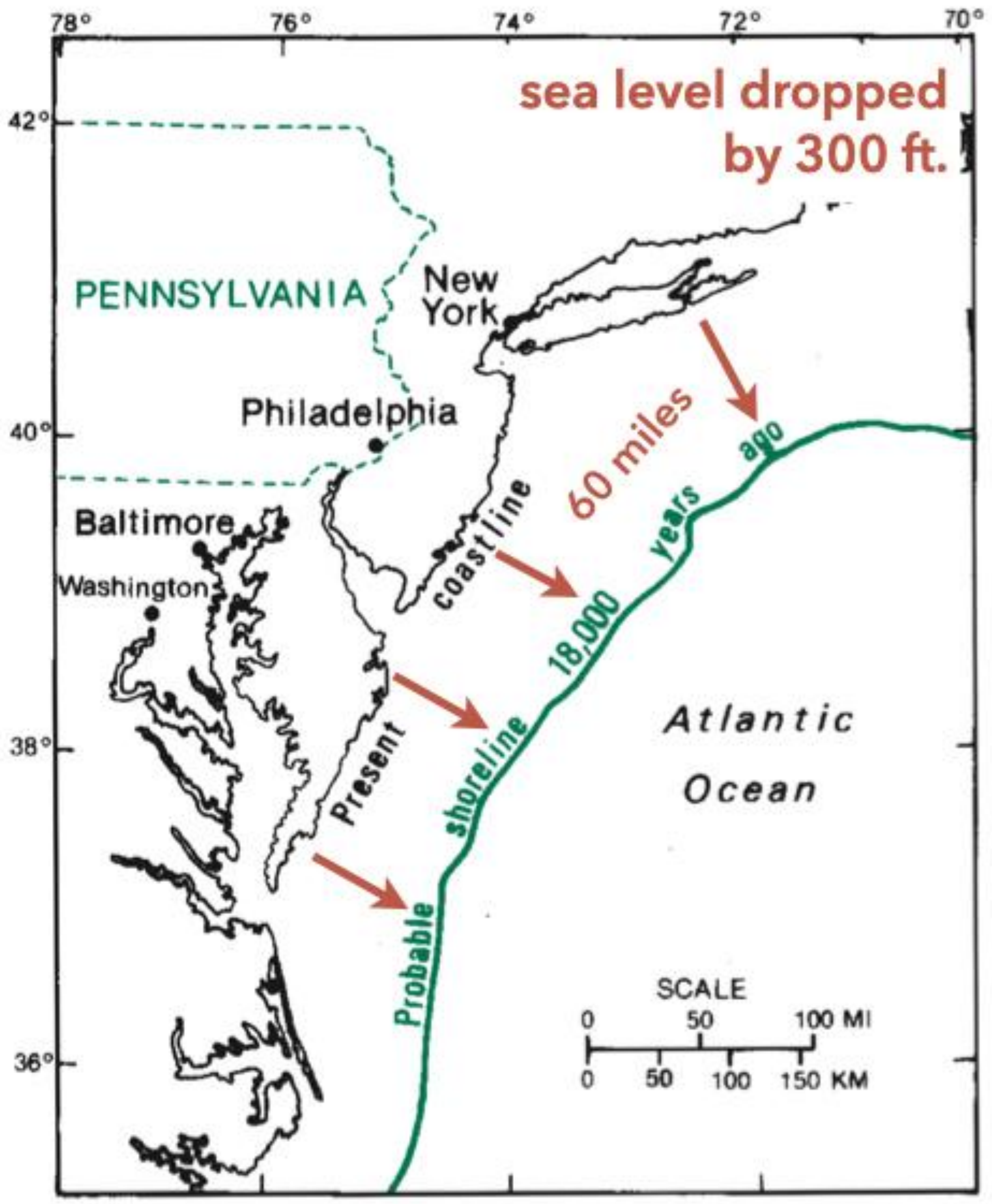
- ***Baseline chemistry of valley streams***
- ***Effect of tributary hydrogeology***

Episodic Memory #2 (Pleistocene)

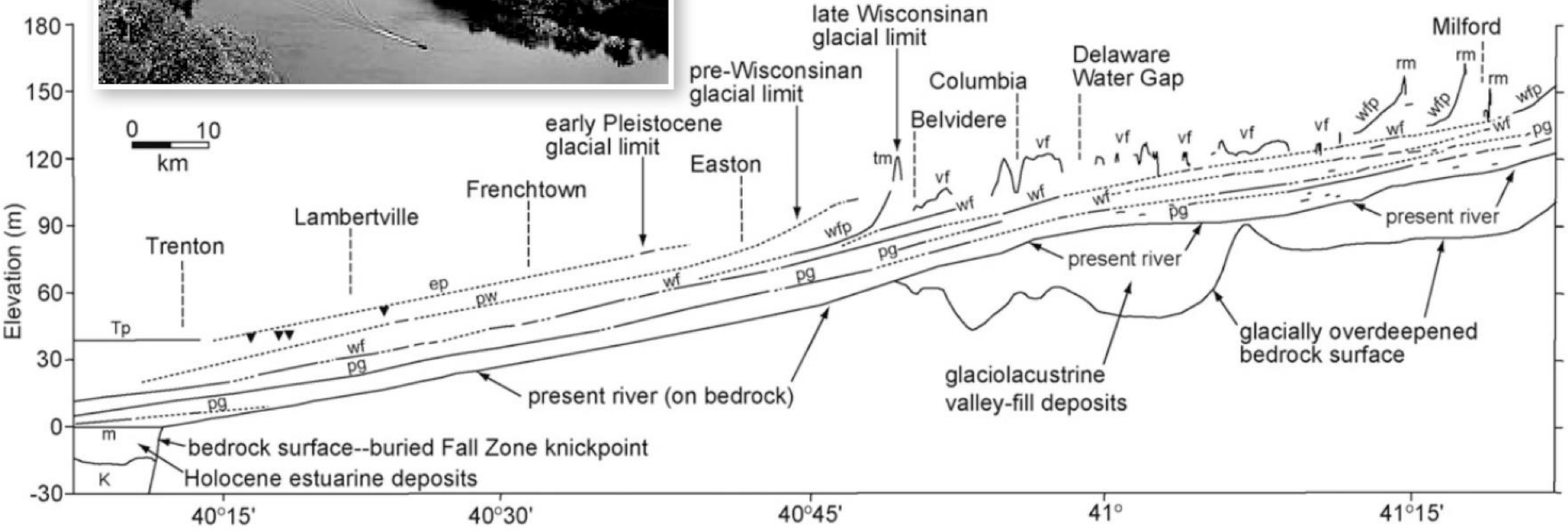
- *Glacial and periglacial activity*
- *Hillslope weathering and movement*
- *Complex network of braided channels & wetlands*



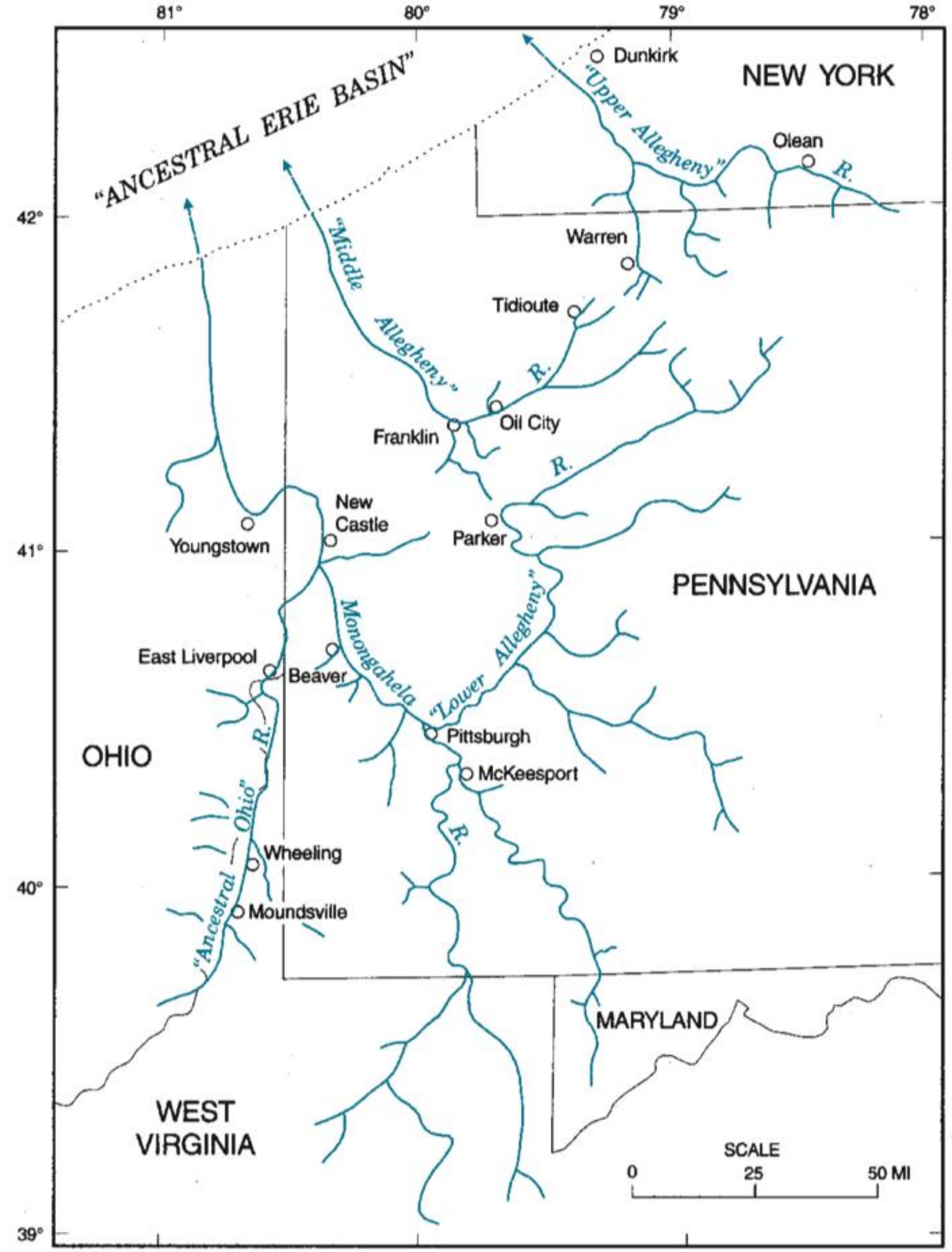




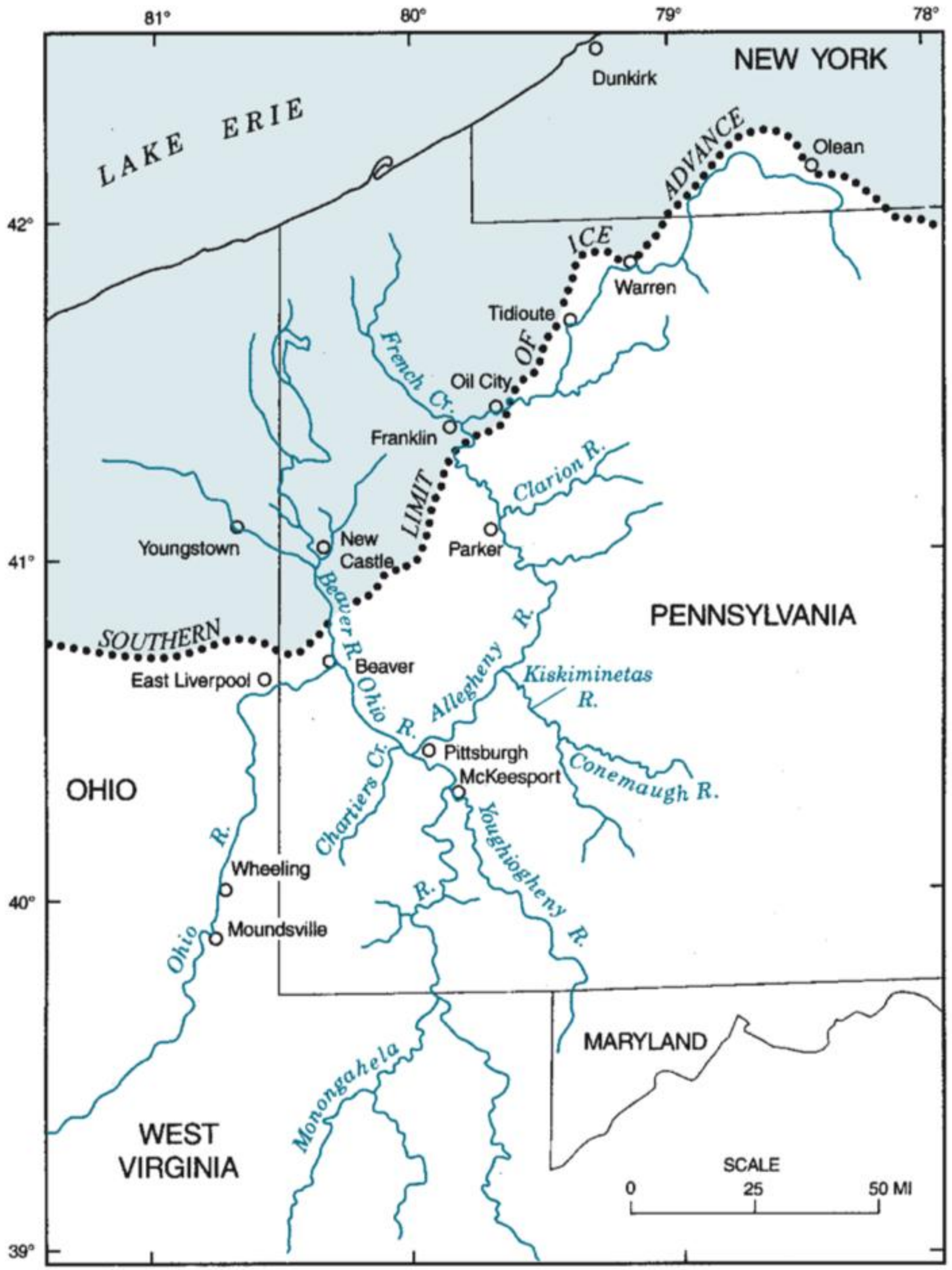
DELAWARE RIVER TERRACES

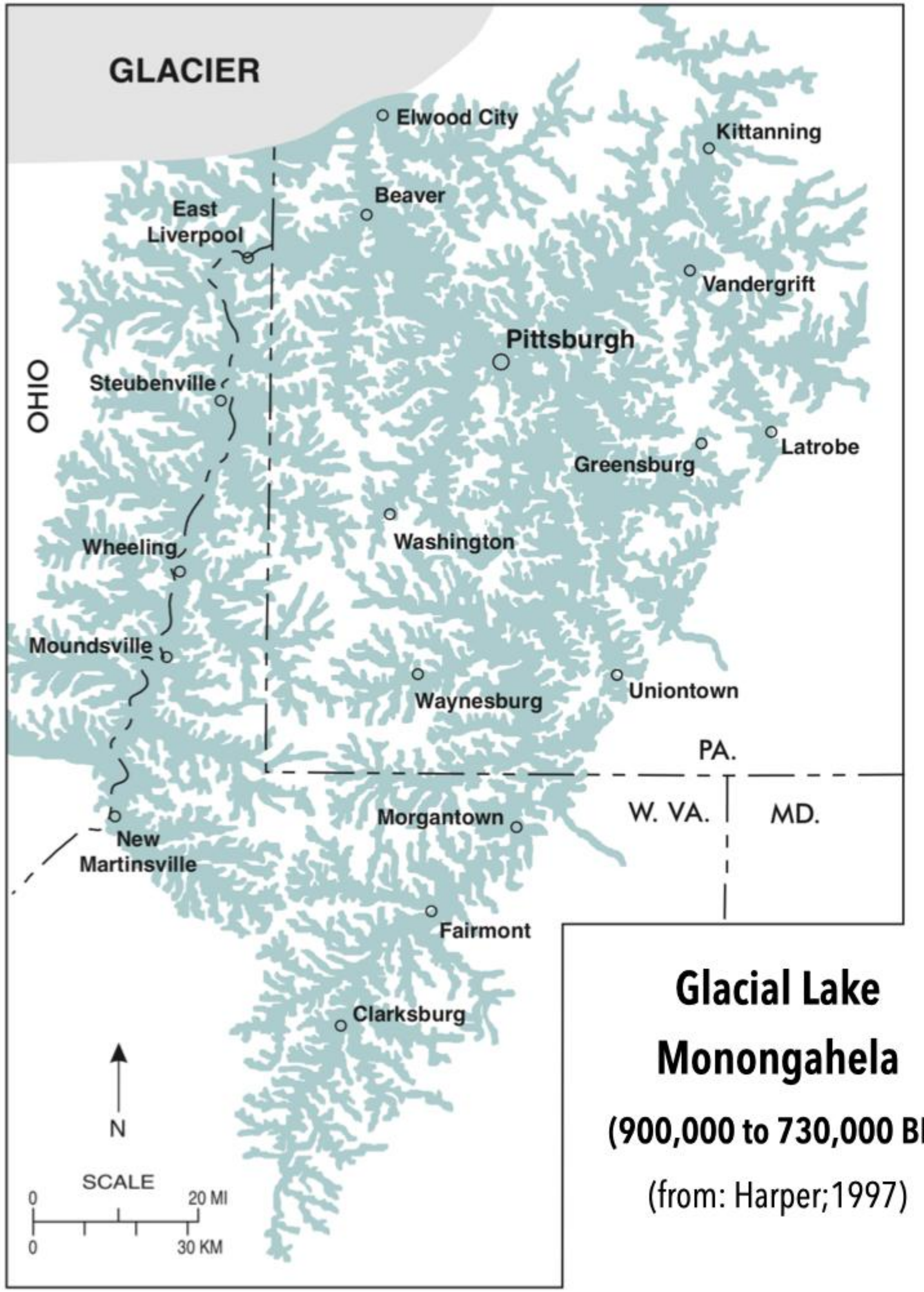


Pre-glacial drainages



Drainage Pattern Today

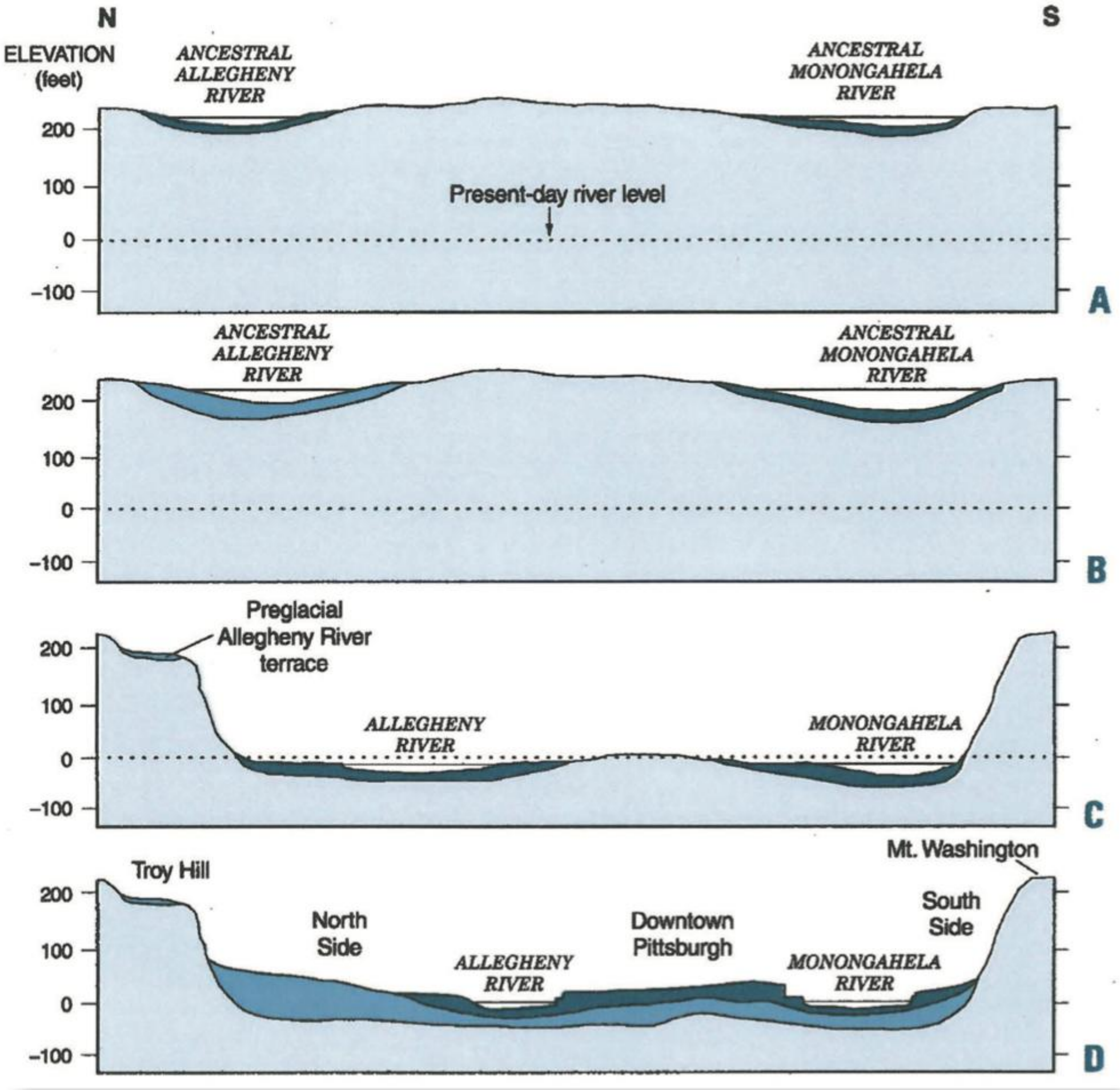


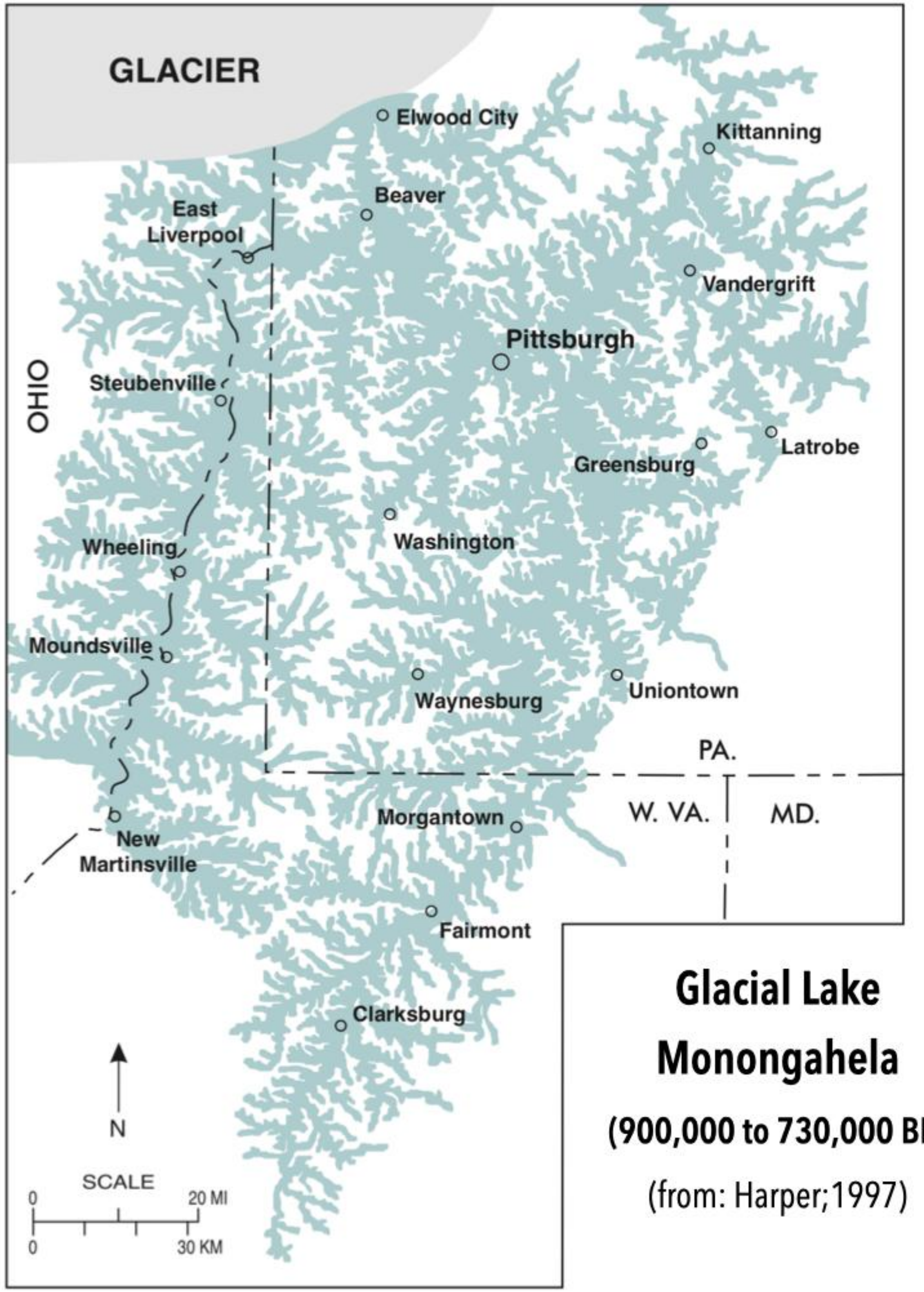


Glacial Lake Monongahela

(900,000 to 730,000 BP)

(from: Harper;1997)





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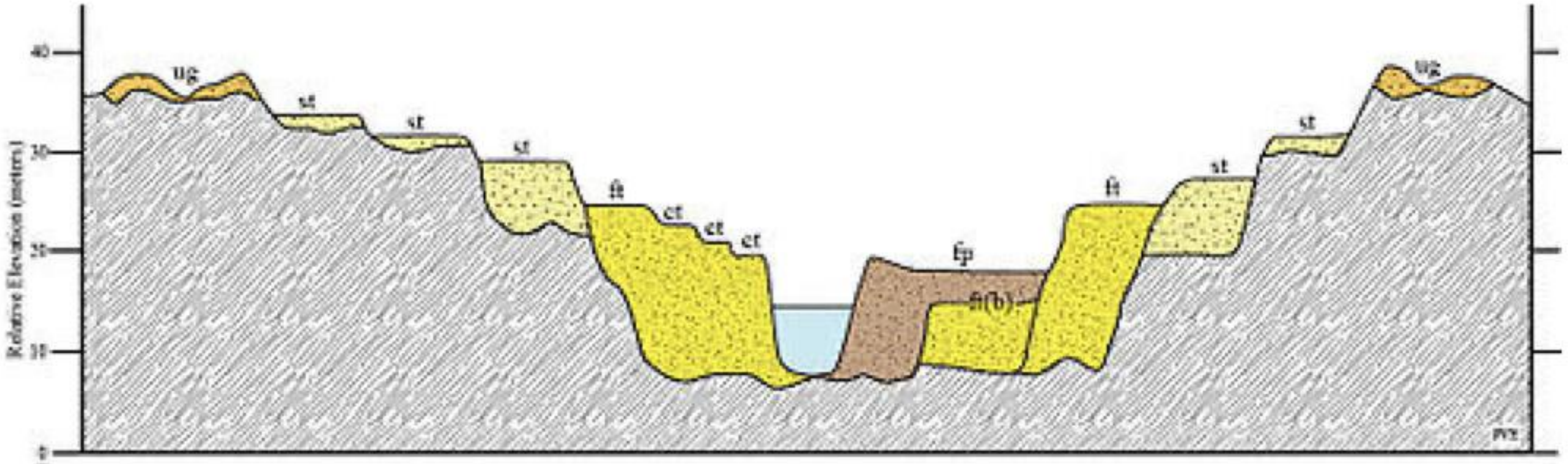
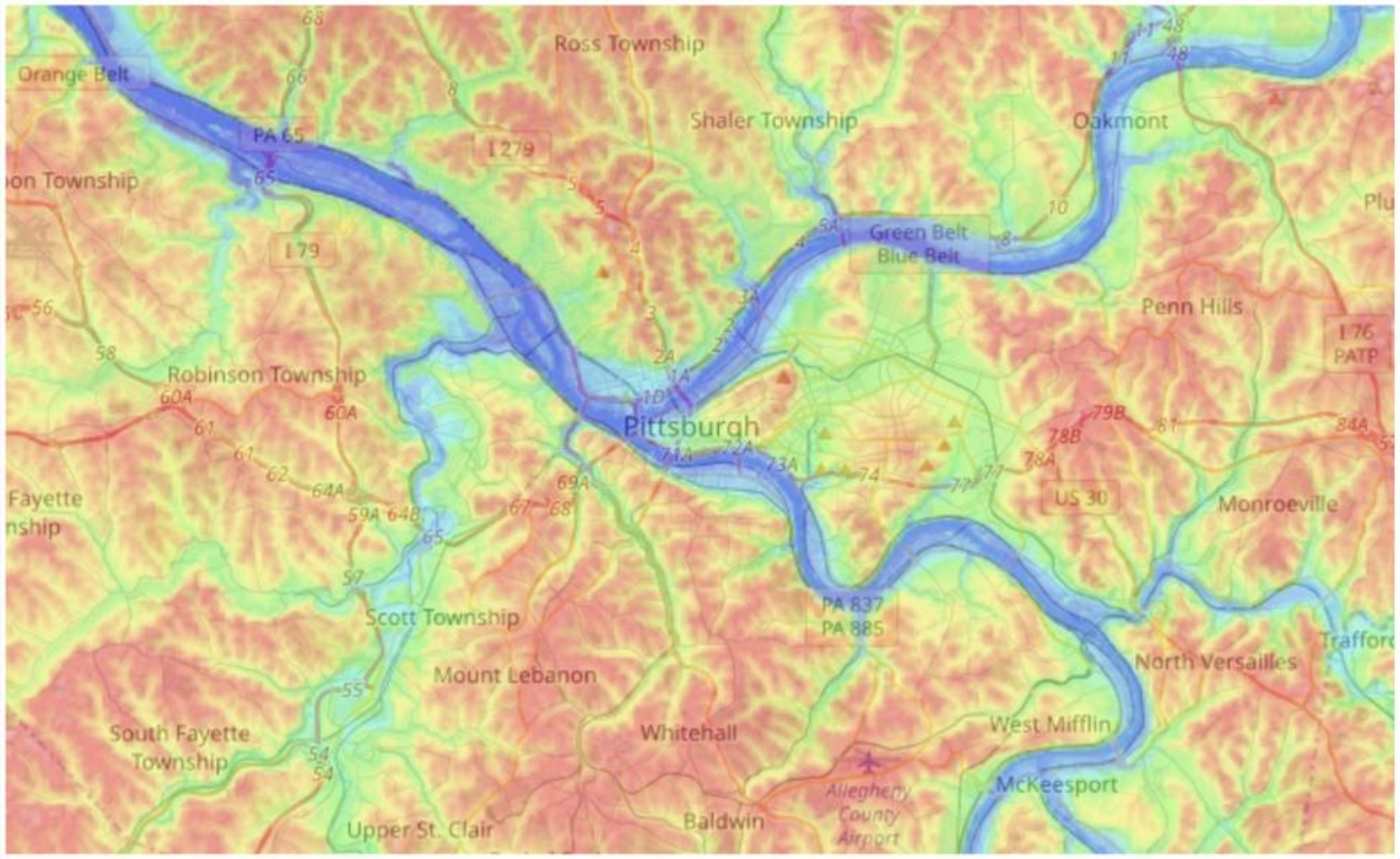
Pleistocene Terraces

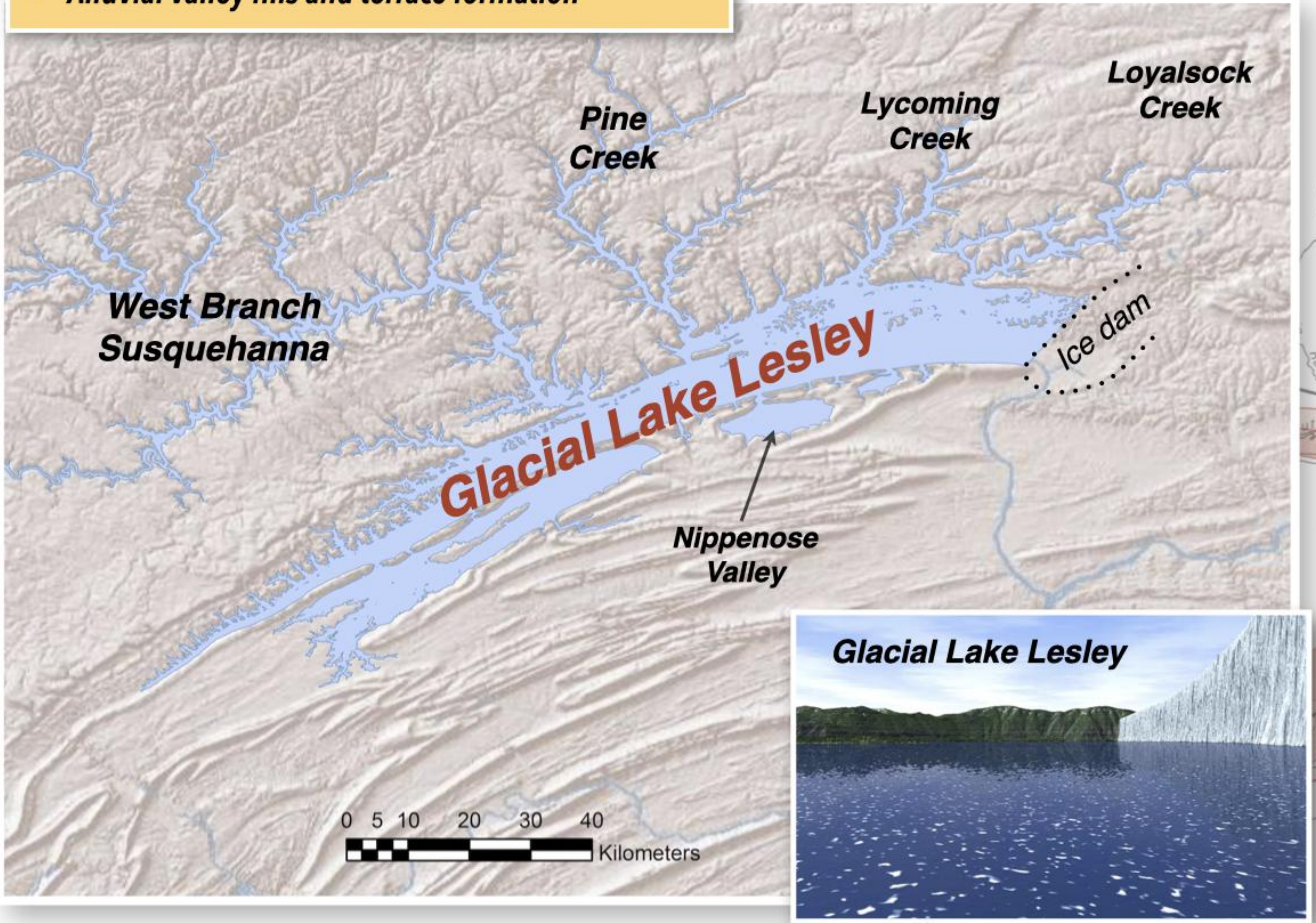


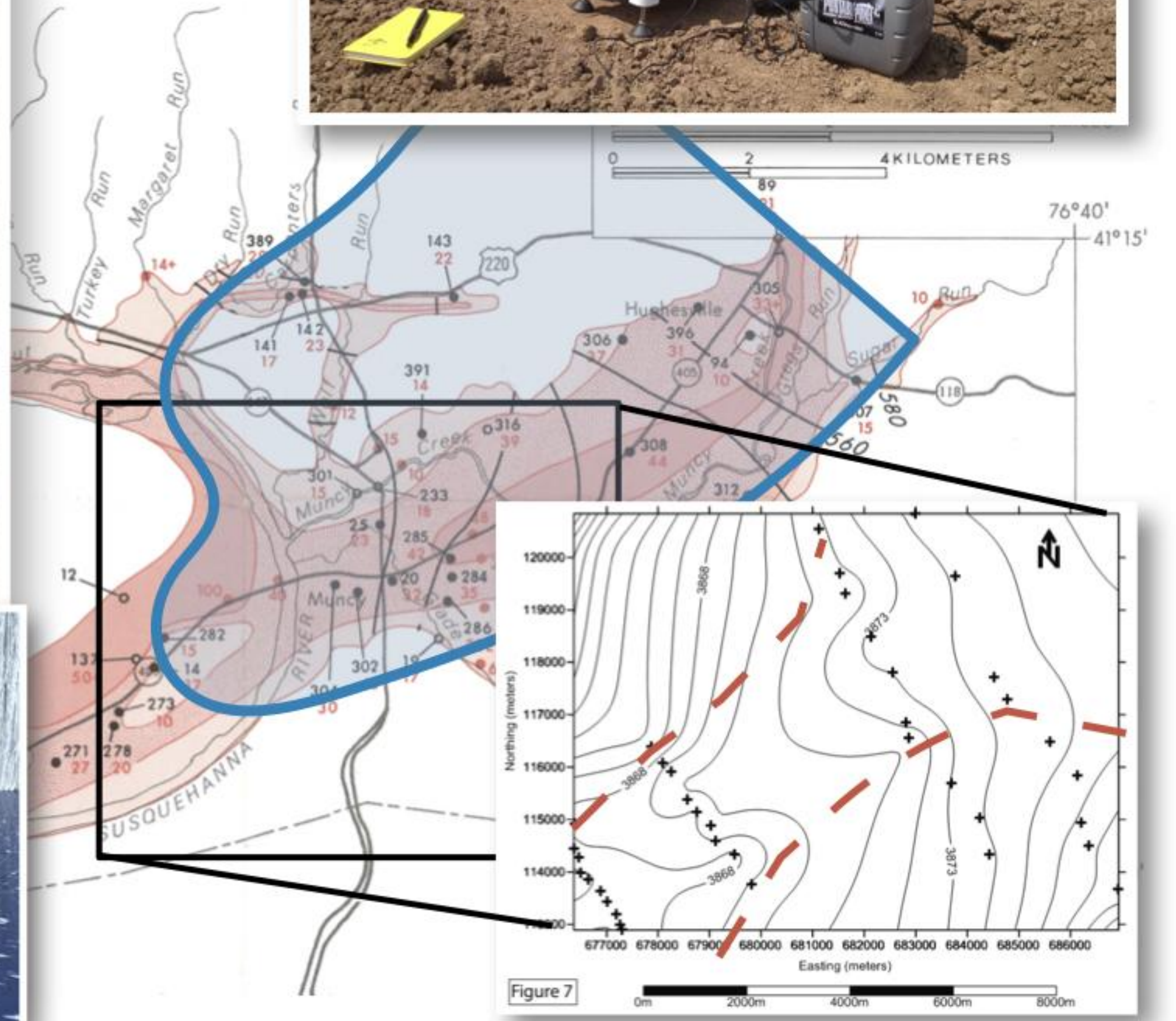


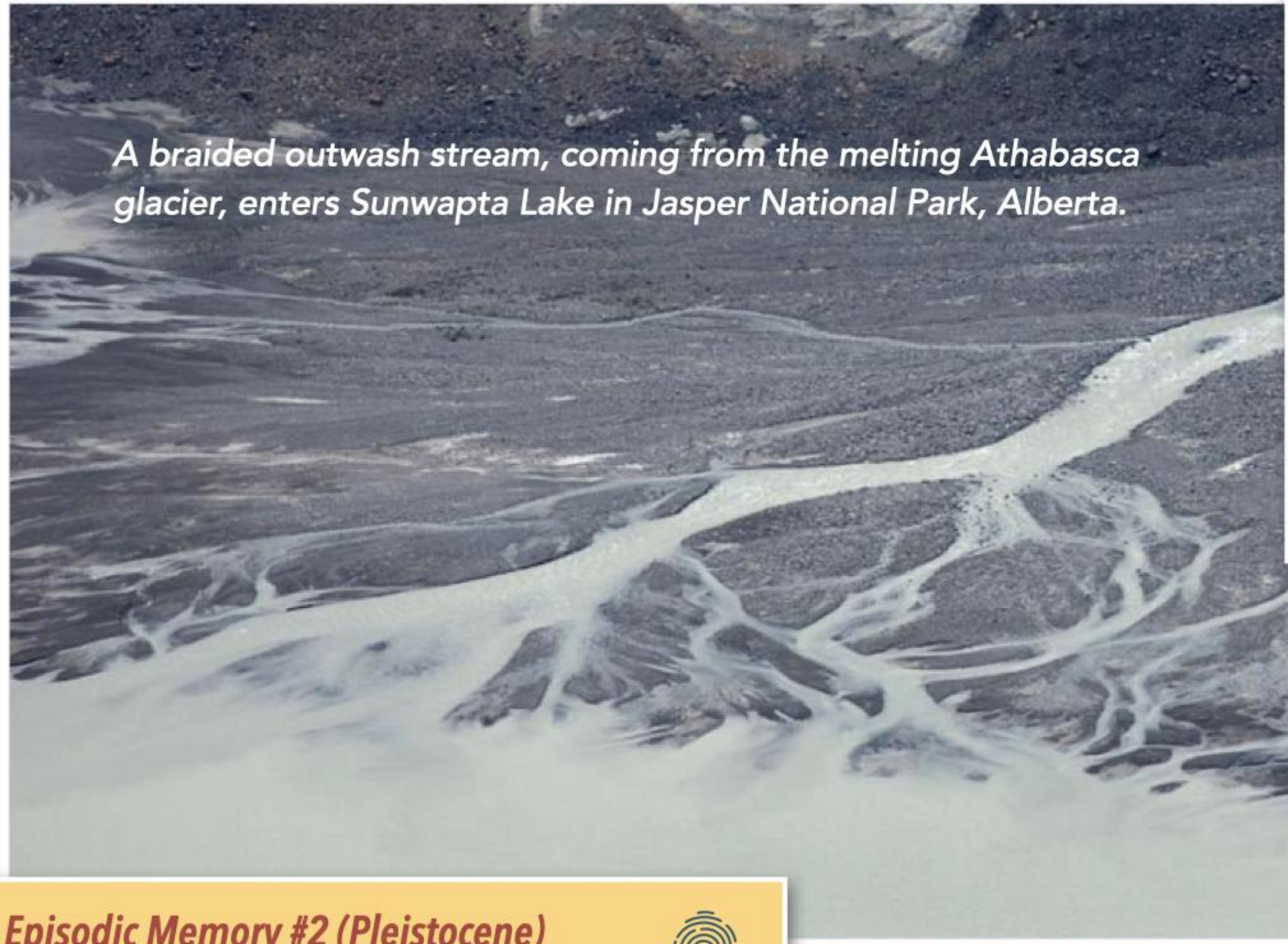
Episodic Memory #2 (Pleistocene)

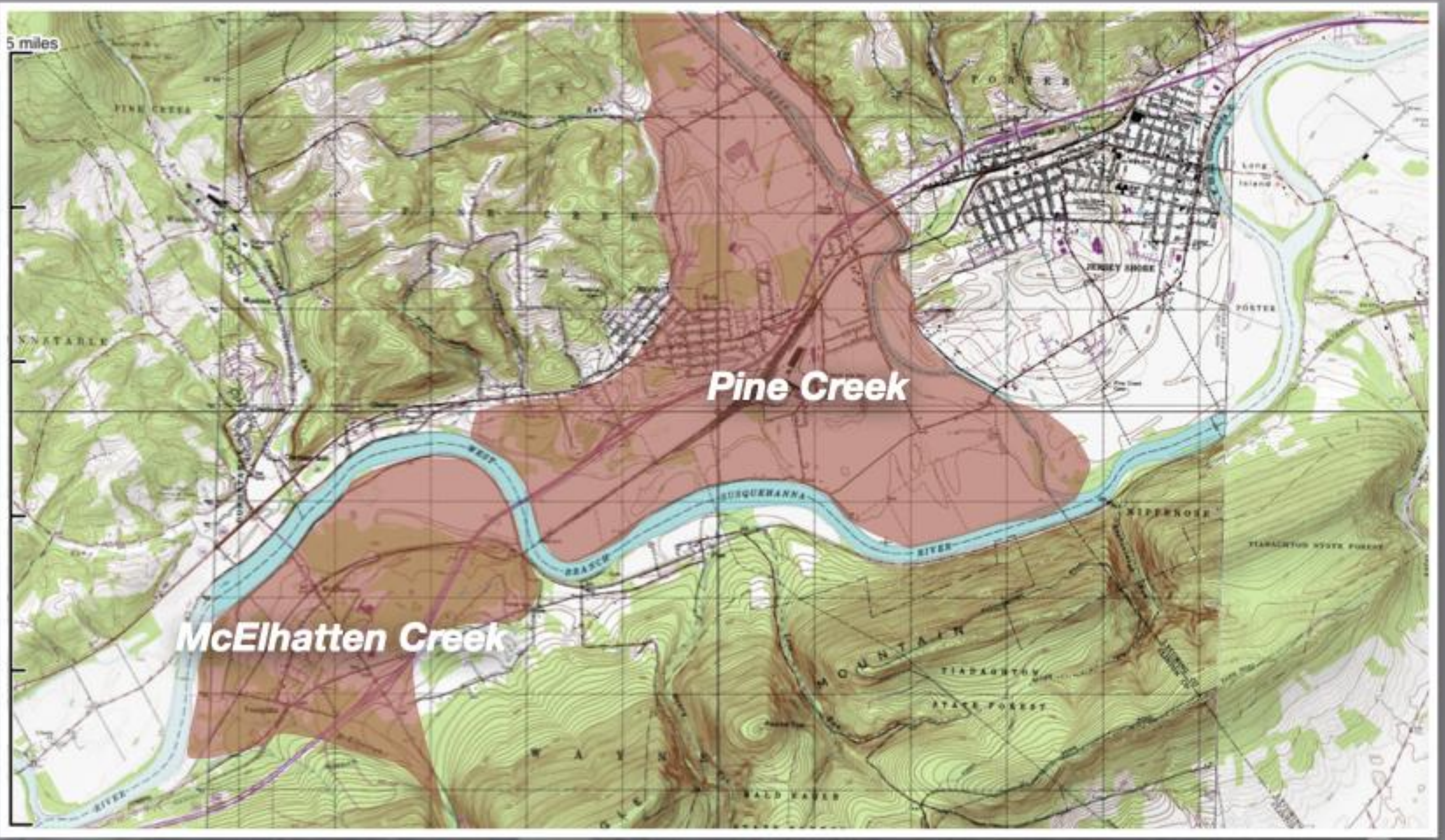
- *Ice dams and glacial lakes*
- *Catastrophic outburst floods (jokullaups)*
- *Alluvial valley fills and terrace formation*

Micro-variations in Earth's gravitational field (μGals) reflect density differences in underlying alluvium and bedrock







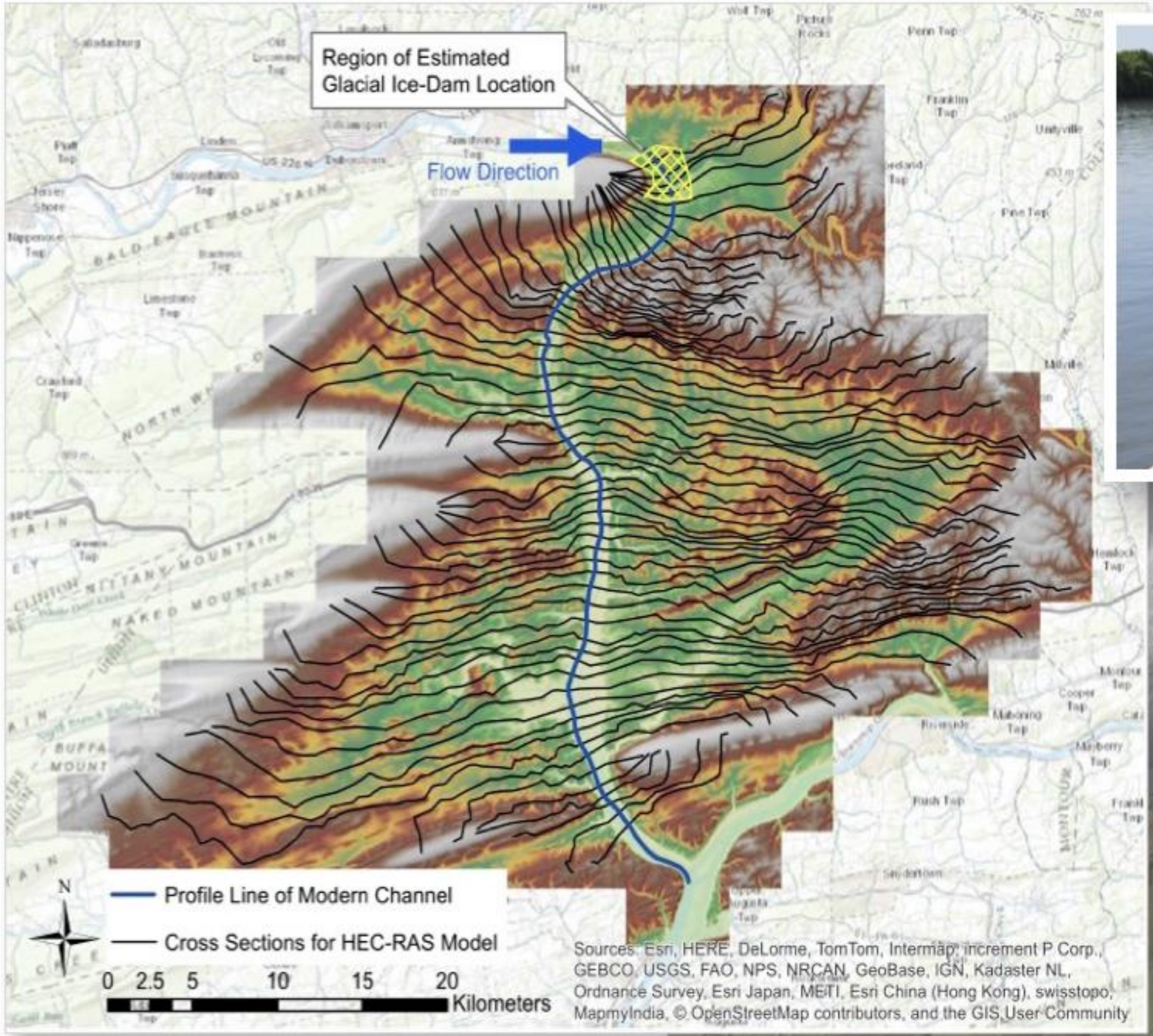


Episodic Memory #2 (Pleistocene)

- ***Ice dams and glacial lakes***
- ***Accelerated hillslope weather and erosion***
- ***Alluvial valley fills and alluvial fans***

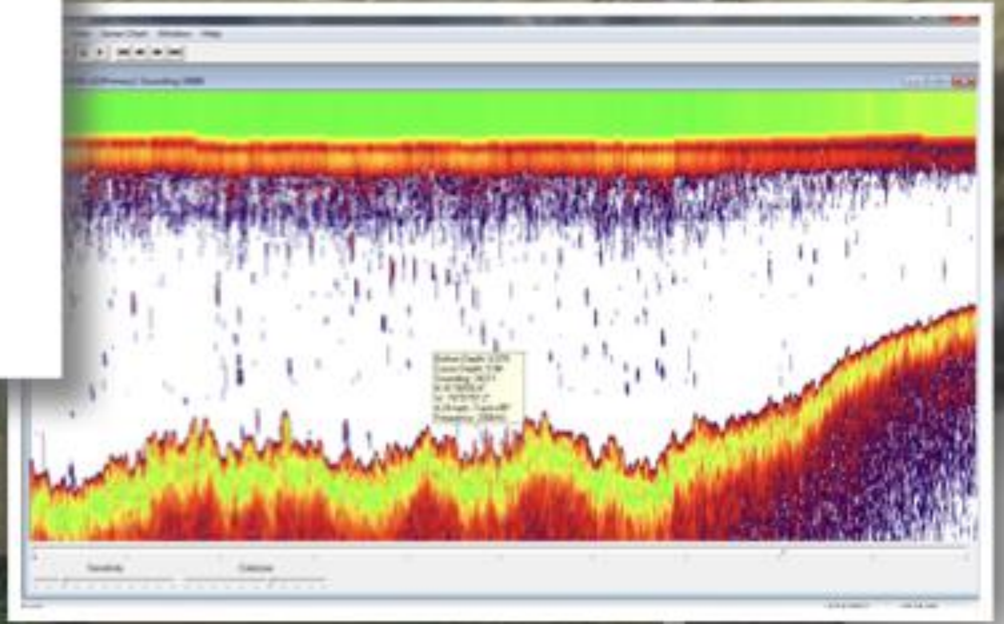
Glacio-fluvial Fan Deltas in West Branch Valley

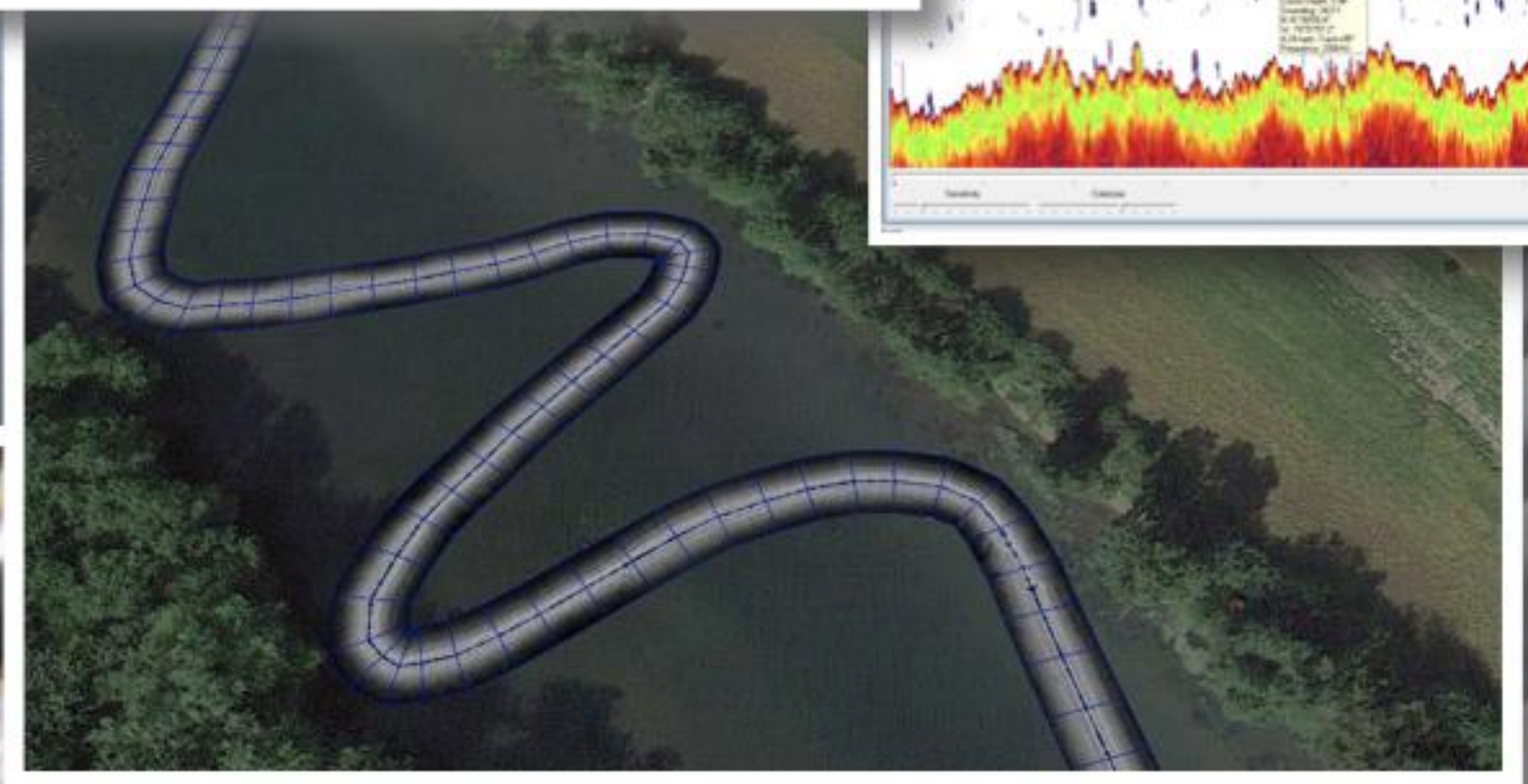
McElhatten and Pine Creek Fans "push" the Susquehanna across the valley



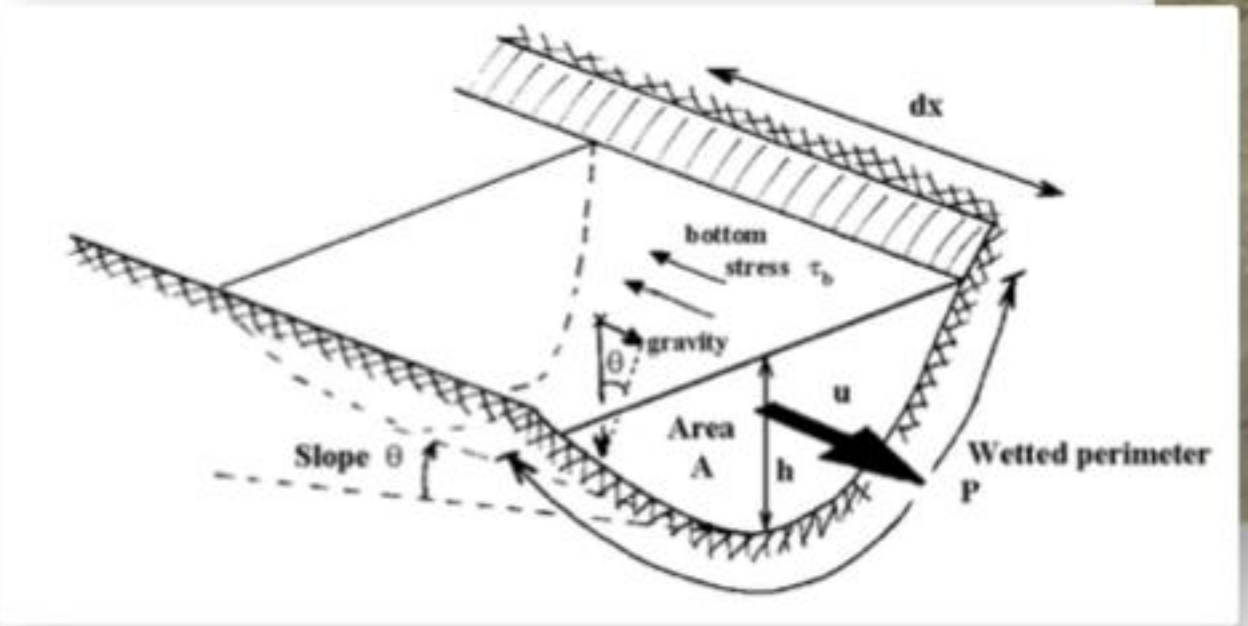
River Bathymetric Surveys

Vertical and Side-scan sonar data were collected in a zig-zag pattern with a cross sectional spacing of 5-10 m.





Island/bars downstream of bedrock outcrops. Expansion/depositional reach with elongated mid-channel bars and dissected floodplain. [Location: Montgomery; 15.5 km. View north, looking up river.]

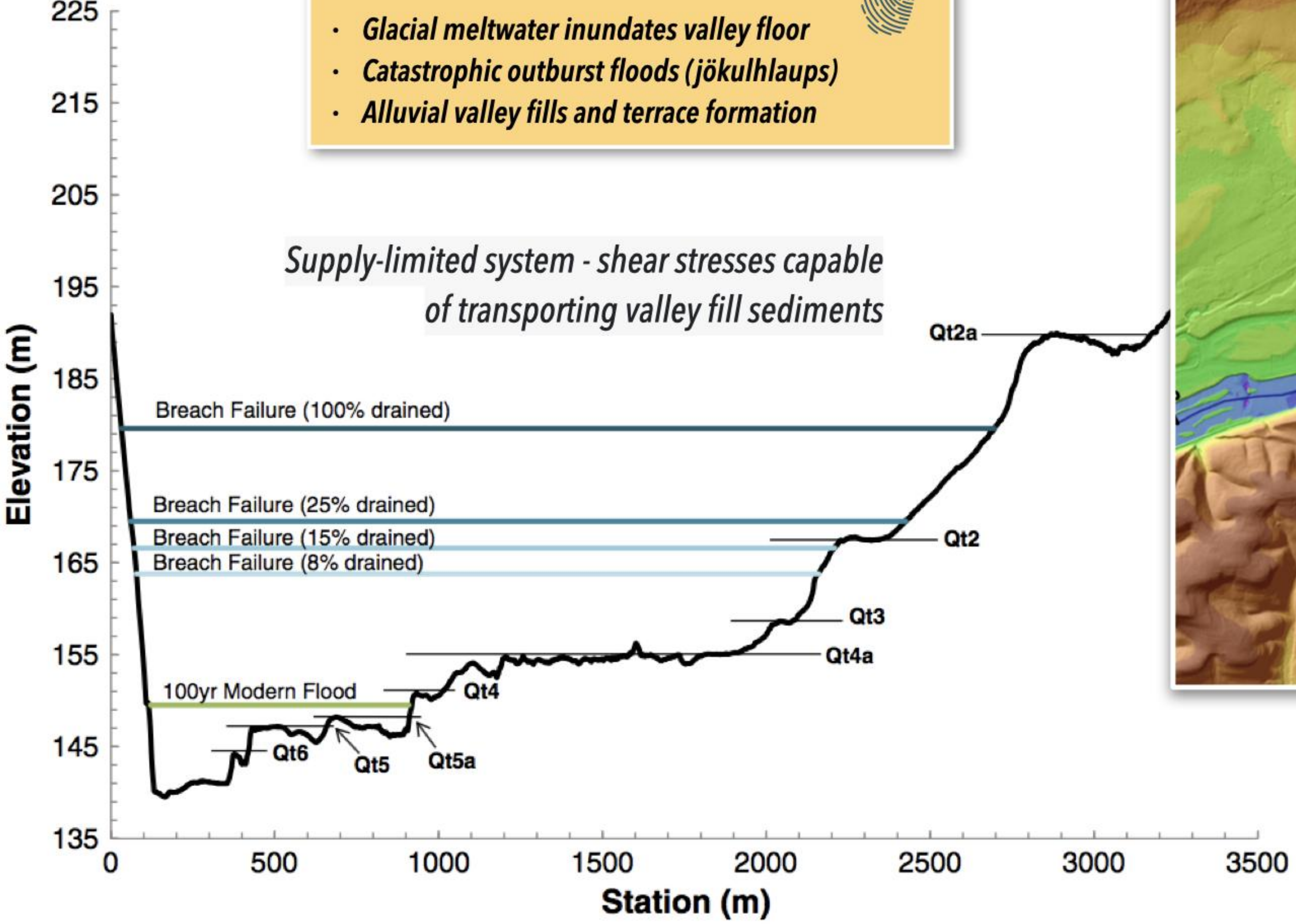


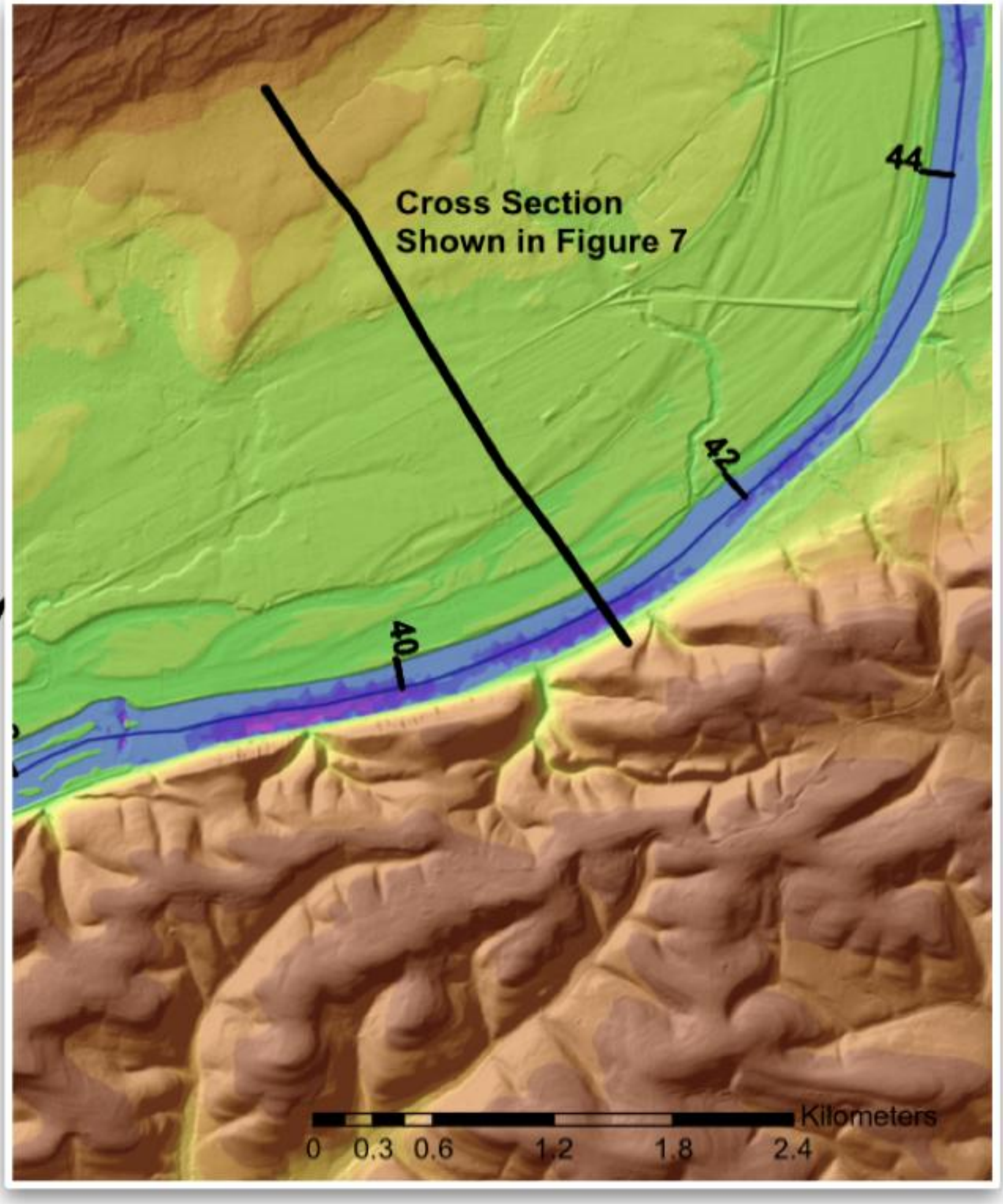
$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} = -g\frac{\partial h}{\partial x} + gS - C_D\frac{u^2}{h}$$

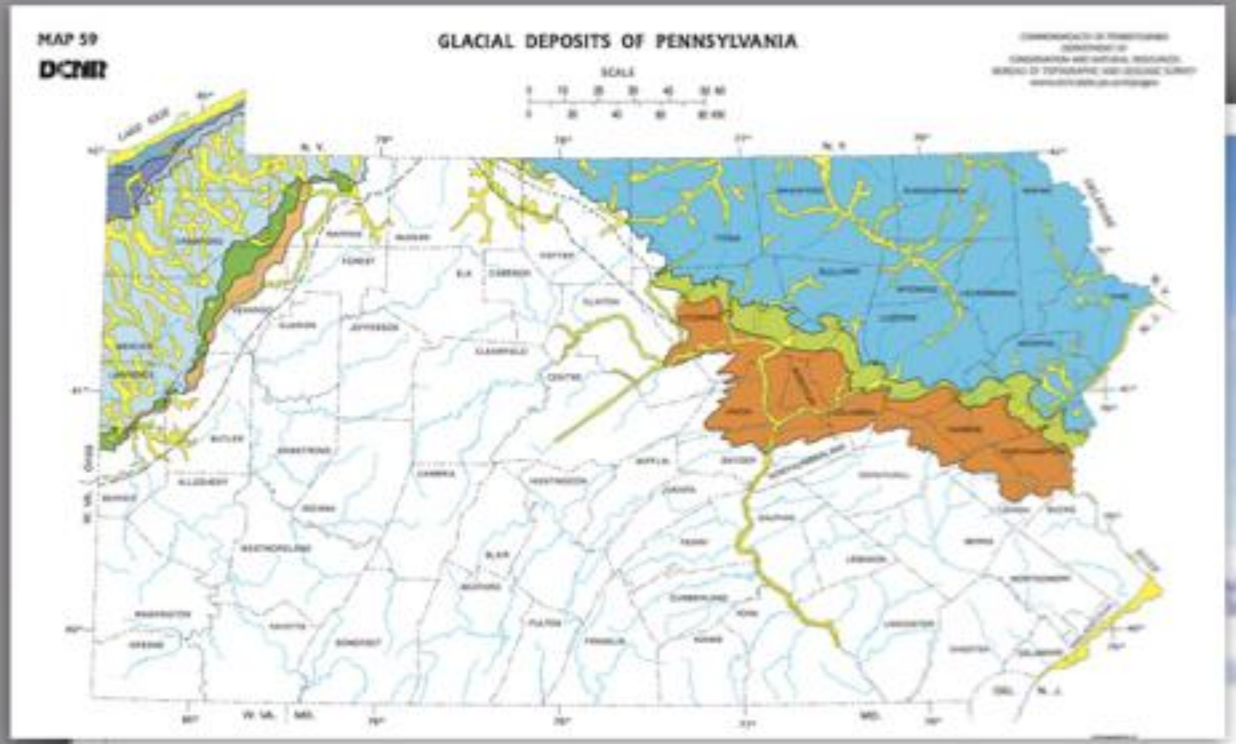
Episodic Memory #2

- *Glacial meltwater inundates valley floor*
- *Catastrophic outburst floods (jökulhlaups)*
- *Alluvial valley fills and terrace formation*

Supply-limited system - shear stresses capable of transporting valley fill sediments

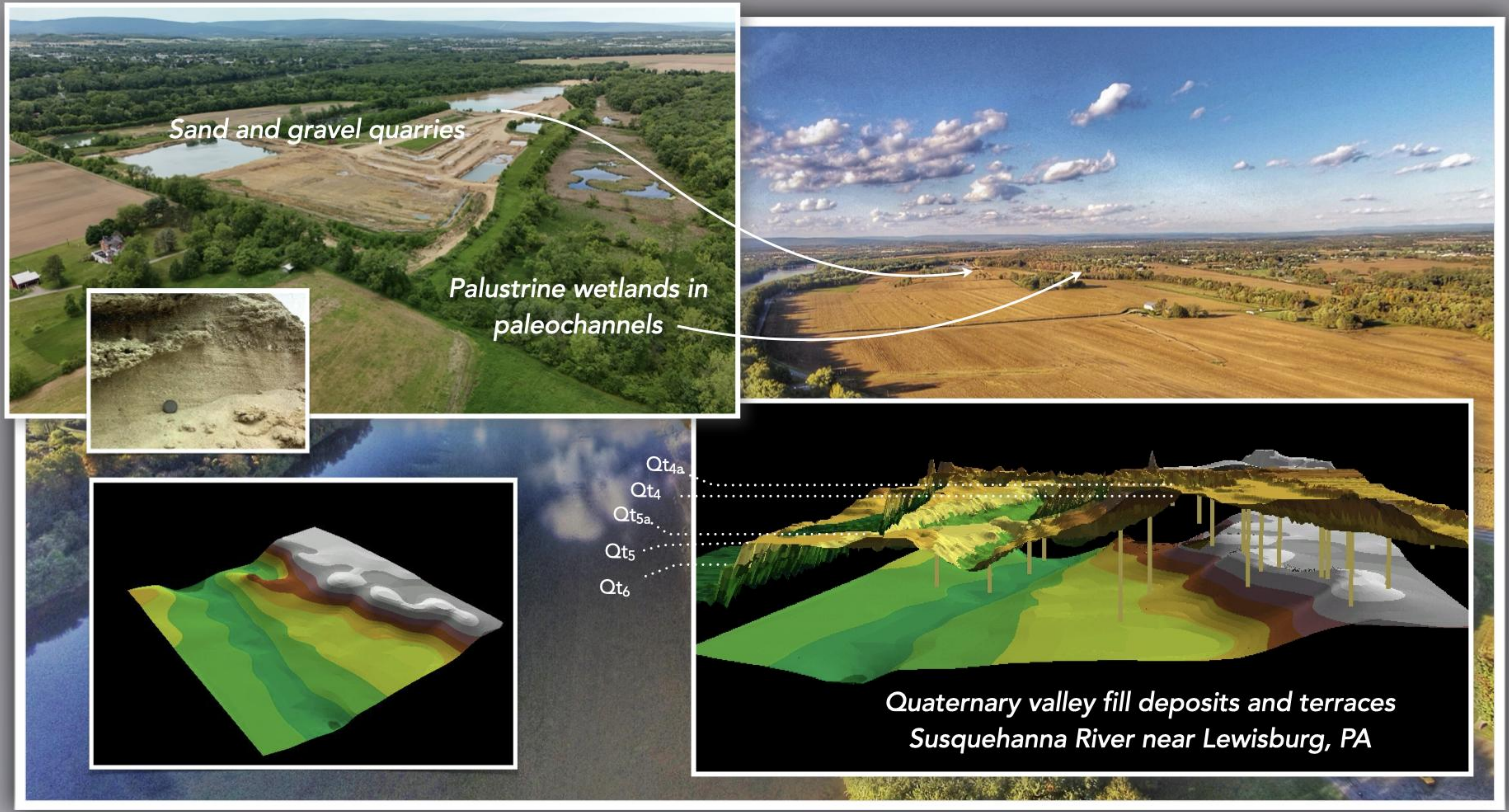


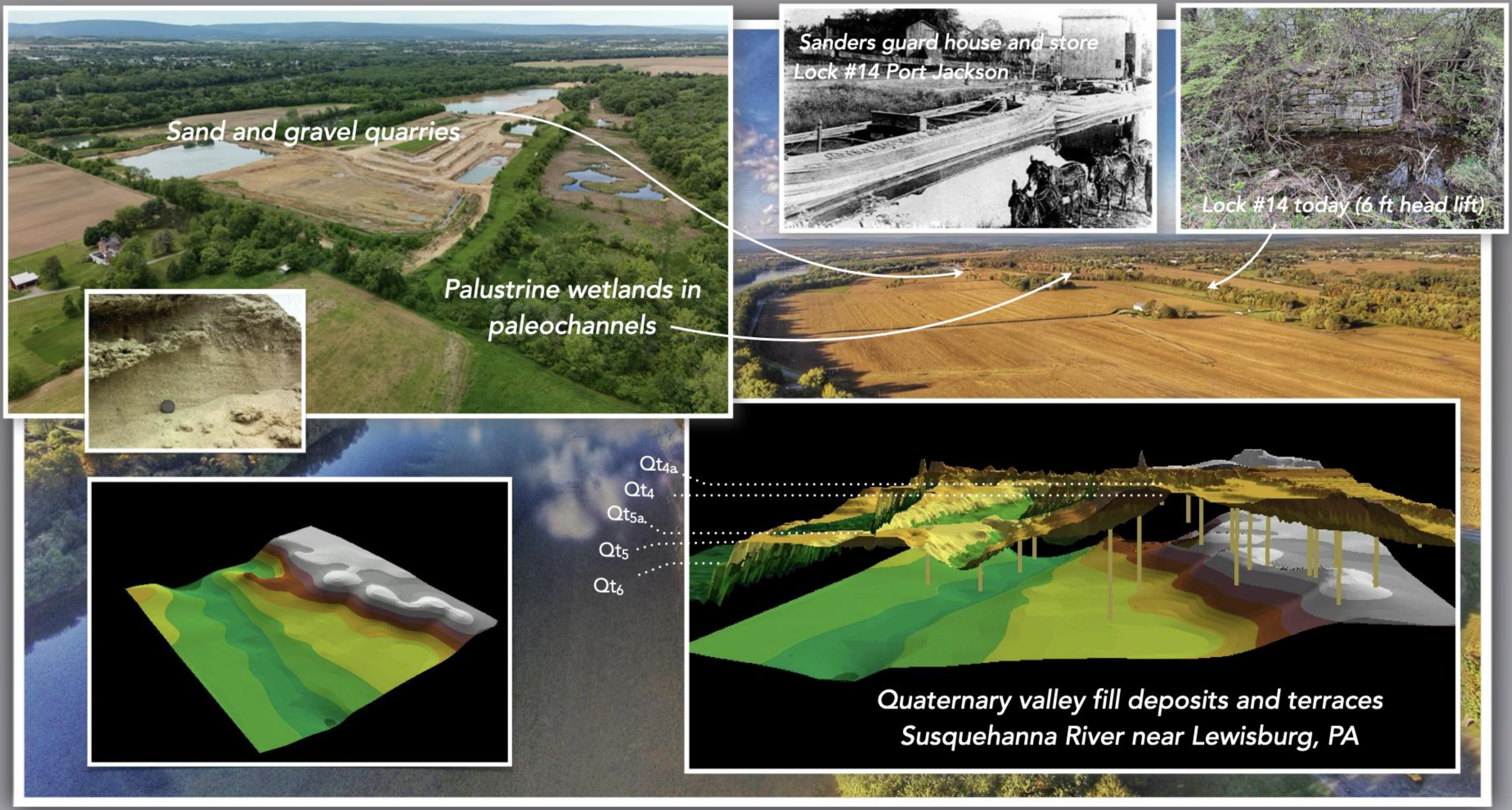




Episodic Memory #2 (Pleistocene glaciation)

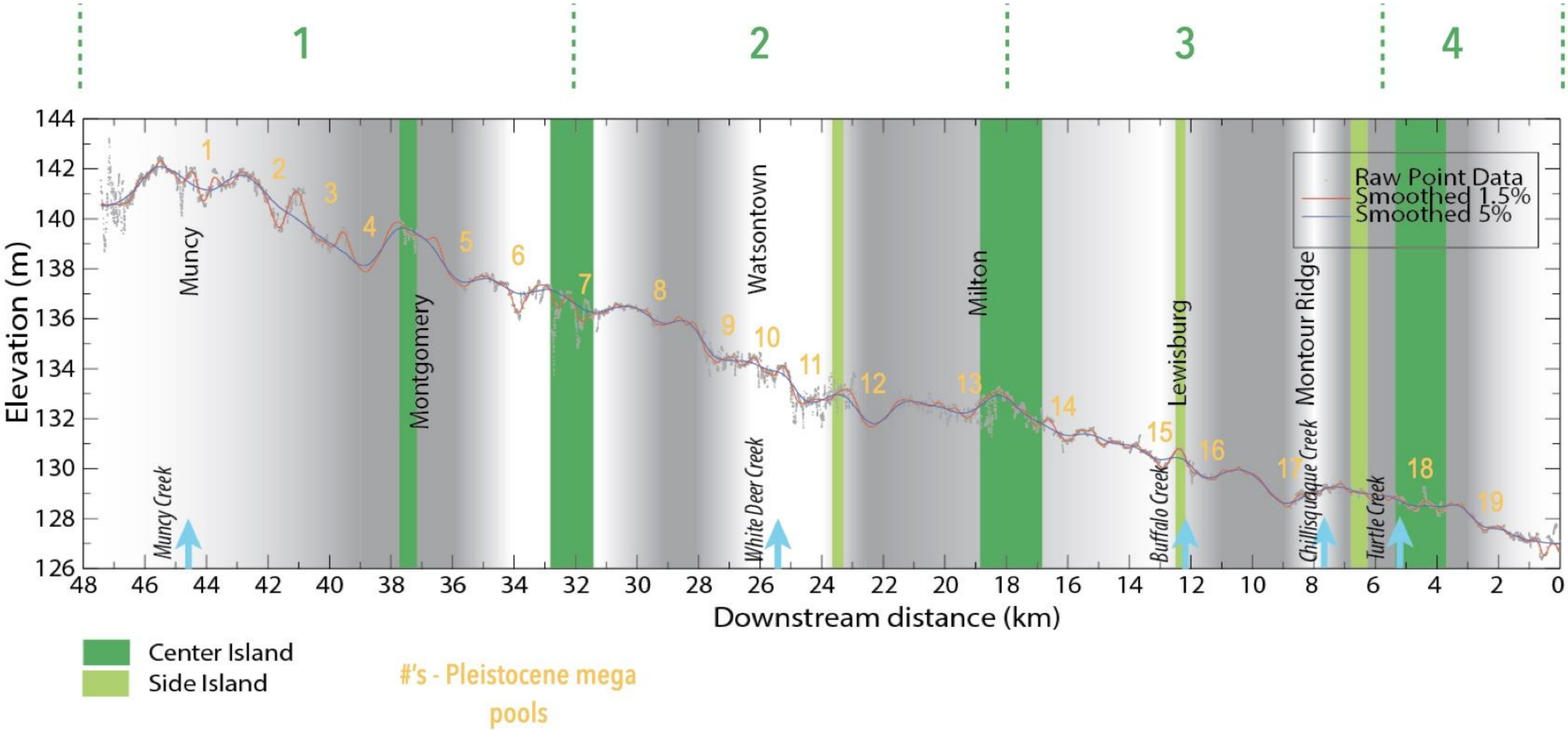
- ***Episodes of baselevel change and terrace formation***
- ***Glaciofluvial outwash and valley fill***
- ***Complex valley network of braided paleochannels***
- ***Riverine and palustrine wetland complexes***


Sand and gravel quarries
Palustrine wetlands in paleochannels
Qt4a
Qt4
Qt5a
Qt5
Qt6
Quaternary valley fill deposits and terraces
Susquehanna River near Lewisburg, PA



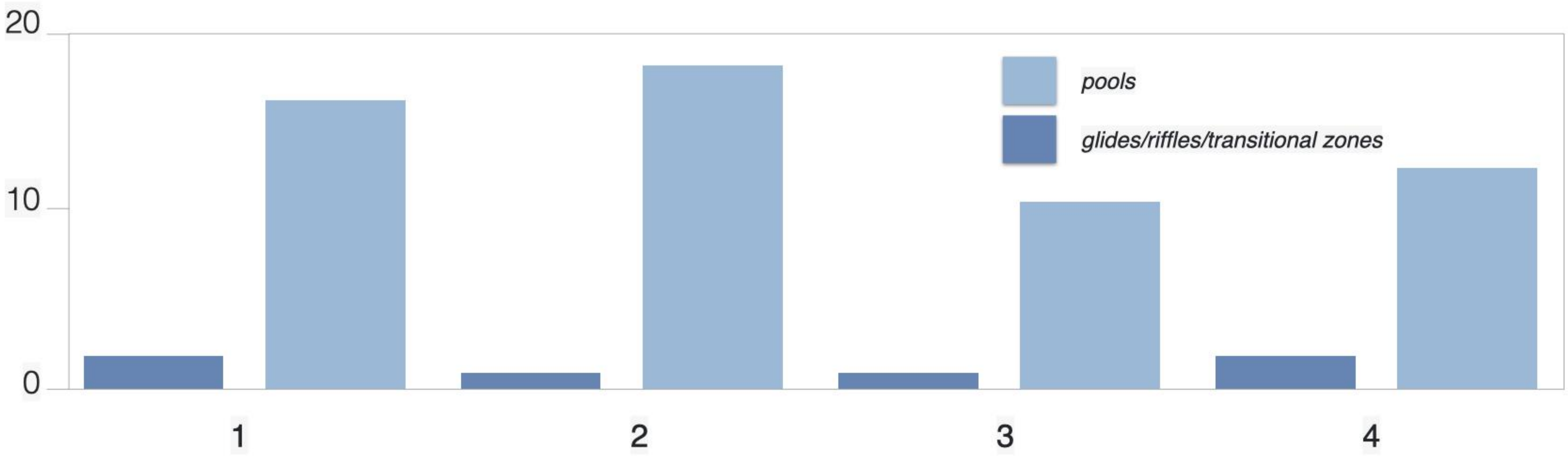
Sand and gravel quarries
Palustrine wetlands in paleochannels
Sanders guard house and store
Lock #14 Port Jackson
Lock #14 today (6 ft head lift)
Qt4a
Qt4
Qt5a
Qt5
Qt6
Quaternary valley fill deposits and terraces
Susquehanna River near Lewisburg, PA

Paleoflood features persist in present day channel and define large-scale river aquatic ecotones



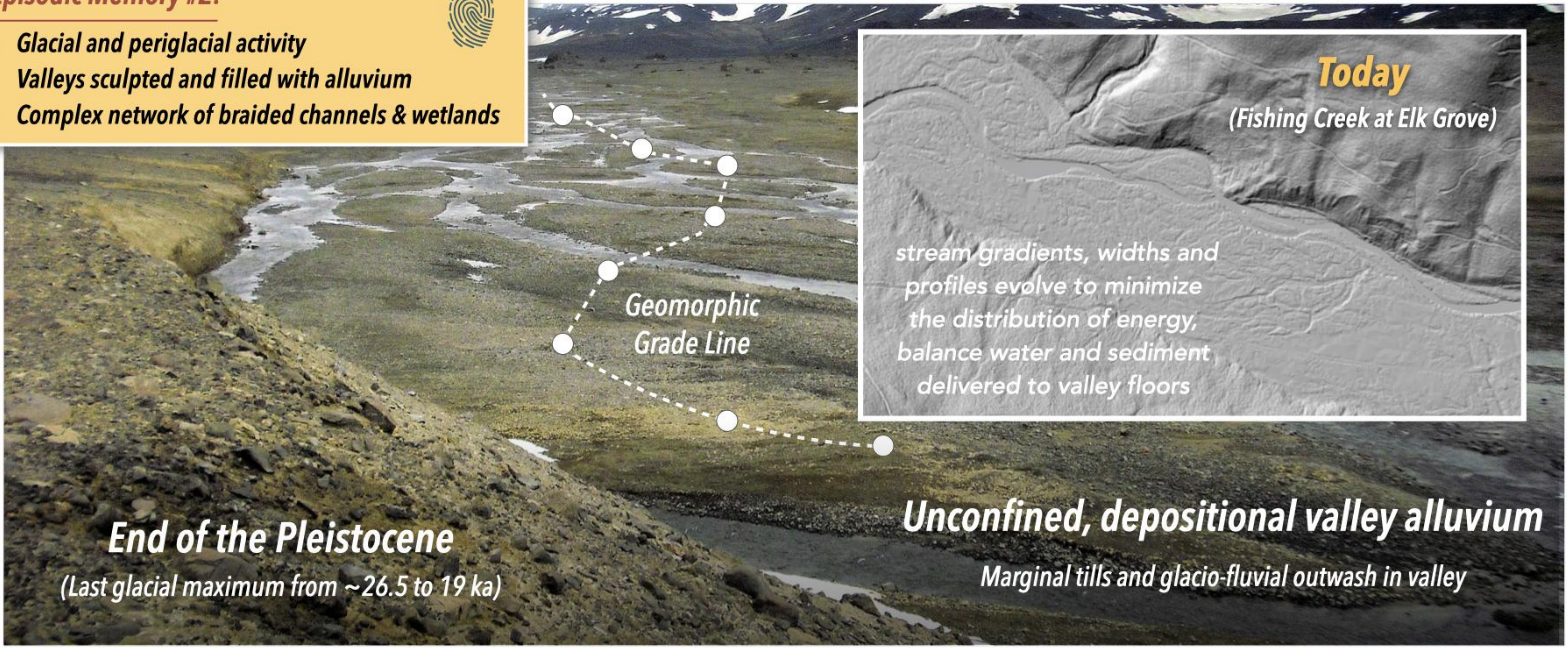
Fish Habitat

Muskellunge Surveys



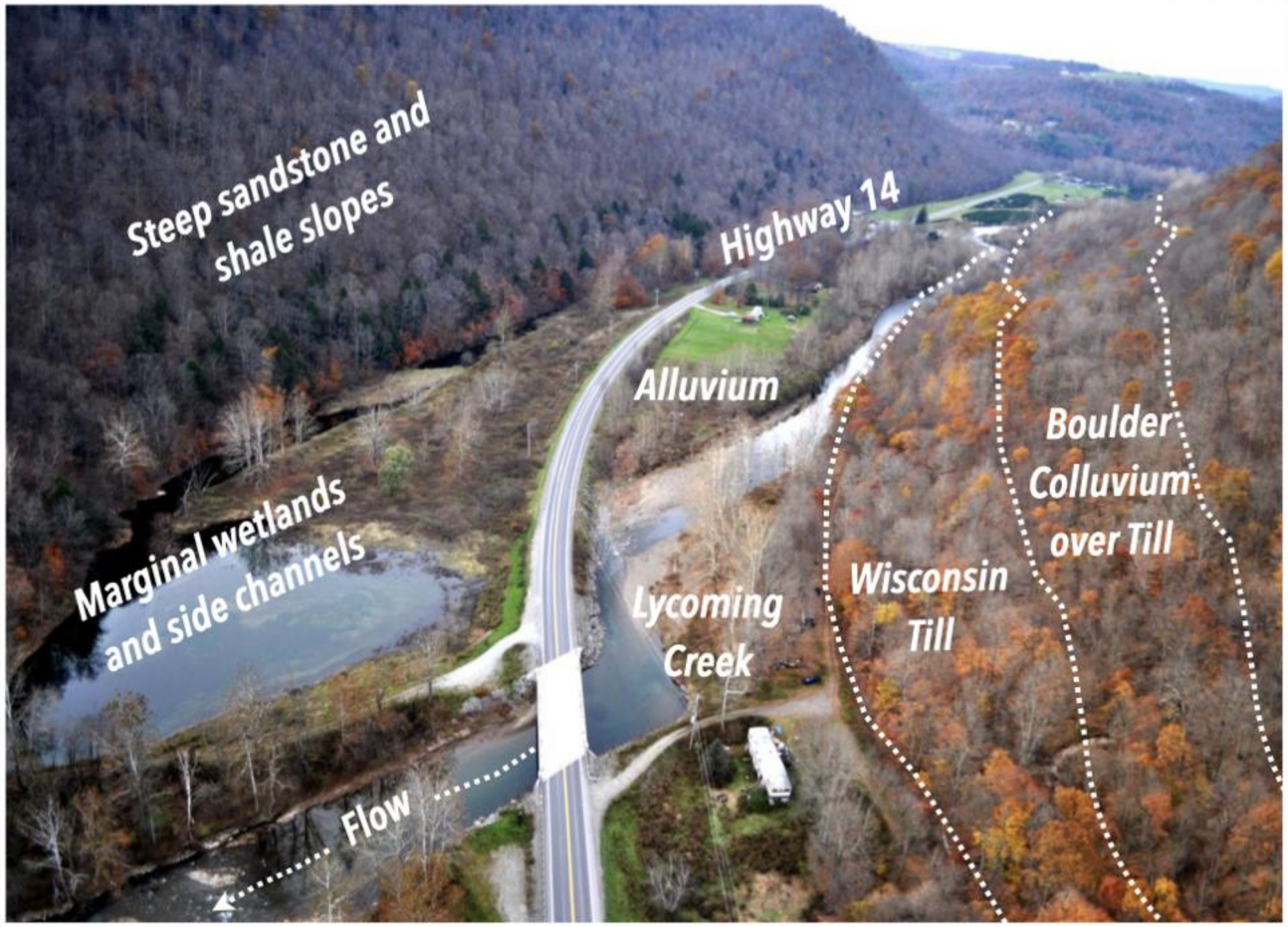
Episodic Memory #2:

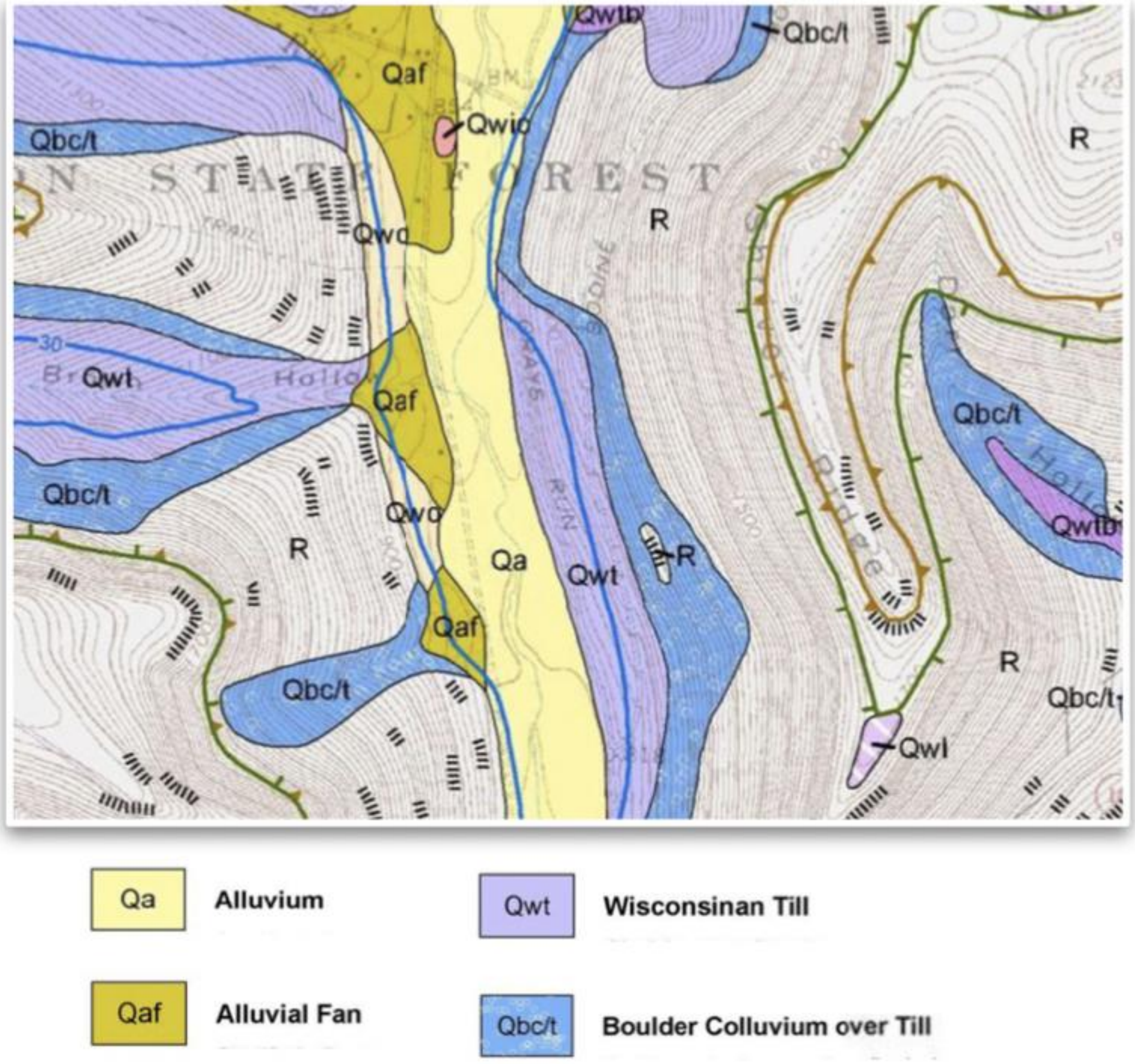
- *Glacial and periglacial activity*
- *Valleys sculpted and filled with alluvium*
- *Complex network of braided channels & wetlands*



Recent geologic episodes - glacial and periglacial processes

Hillslopes (colluvium + alluvial fans), multiple channel-wetlands,



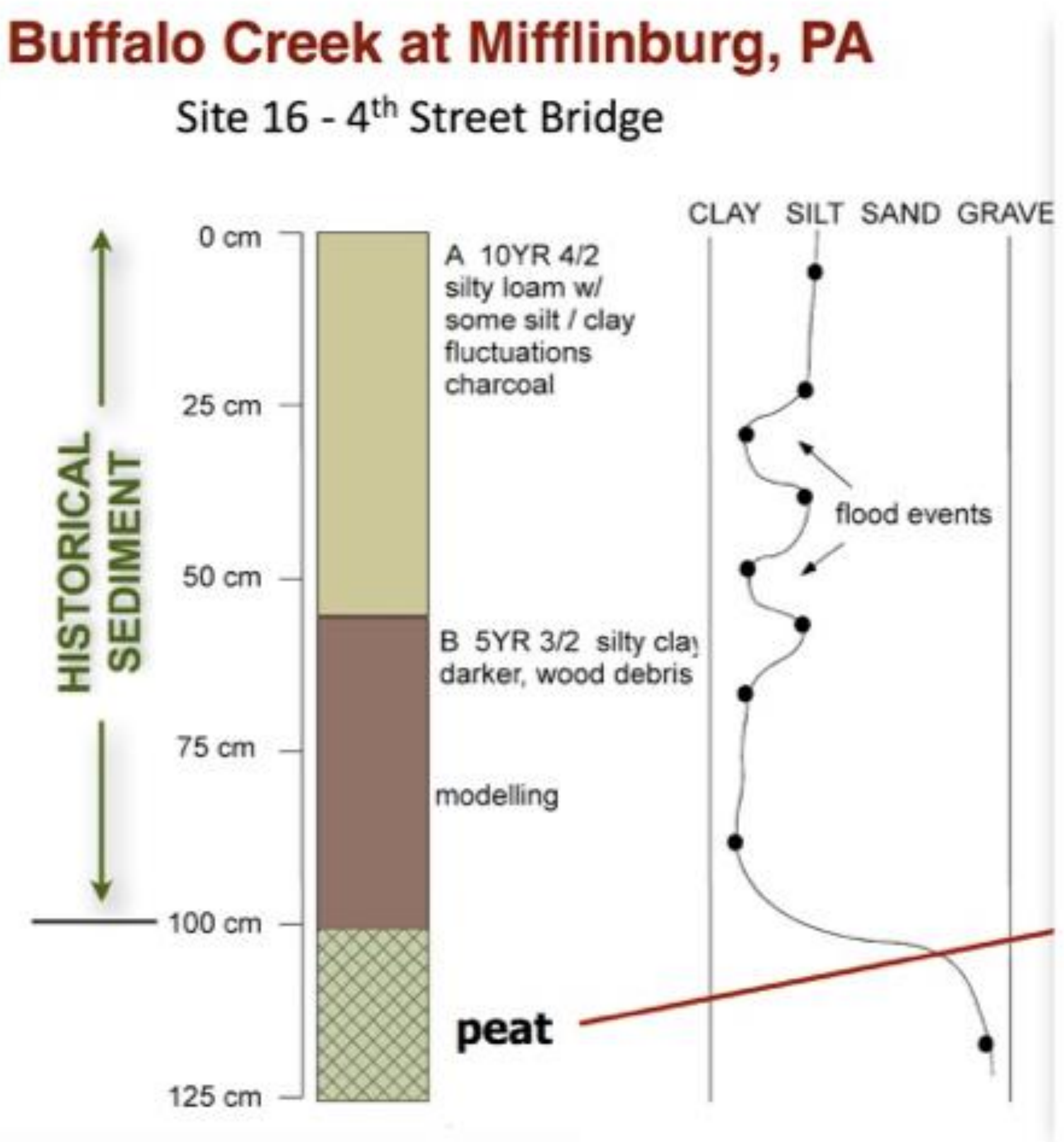


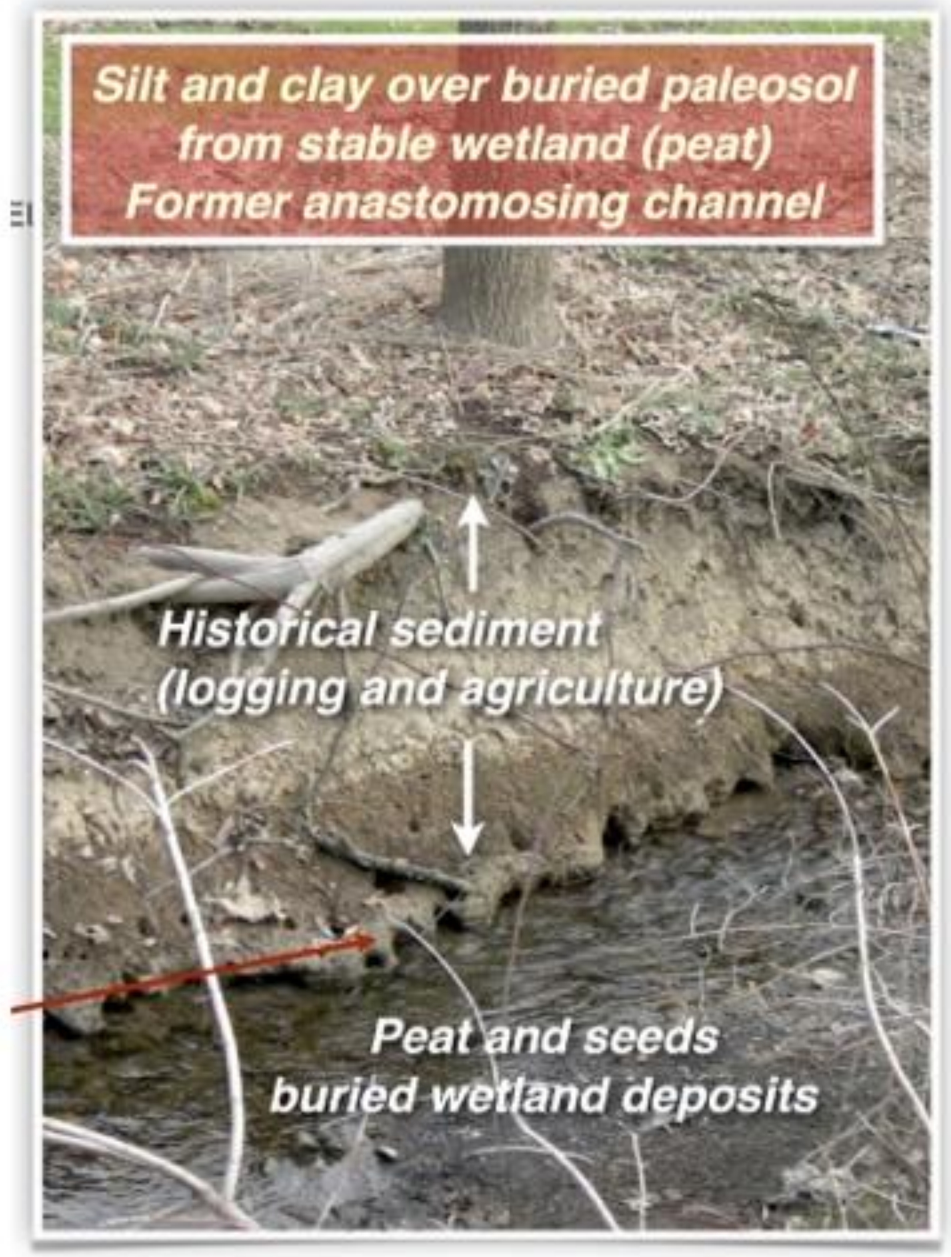
Valley architecture and sediment source areas

(1) alluvium in valley bottom; (2) colluvium; (3) alluvial fans; (4) glacial till

Key Concept 2

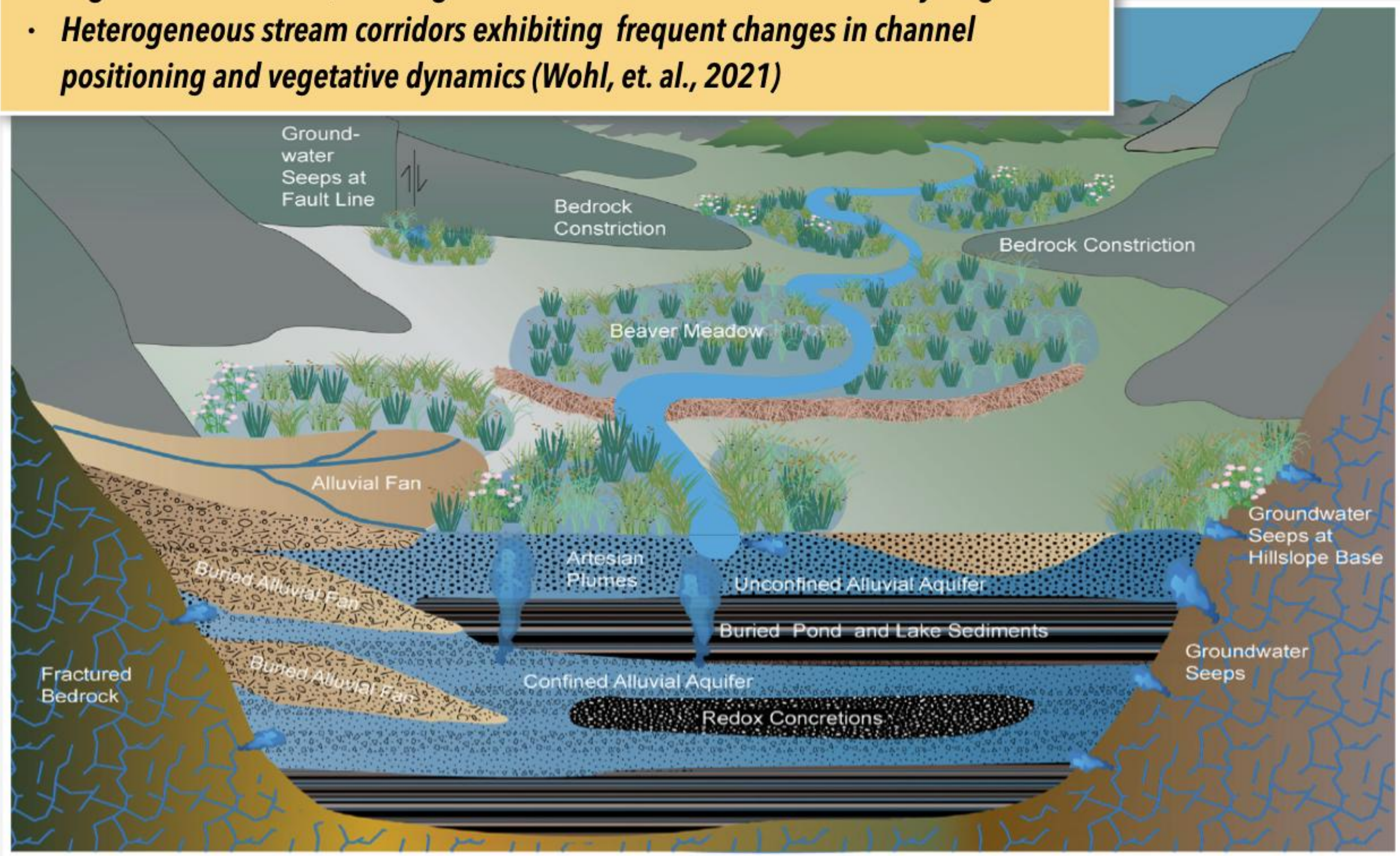
BURIED LANDSCAPES

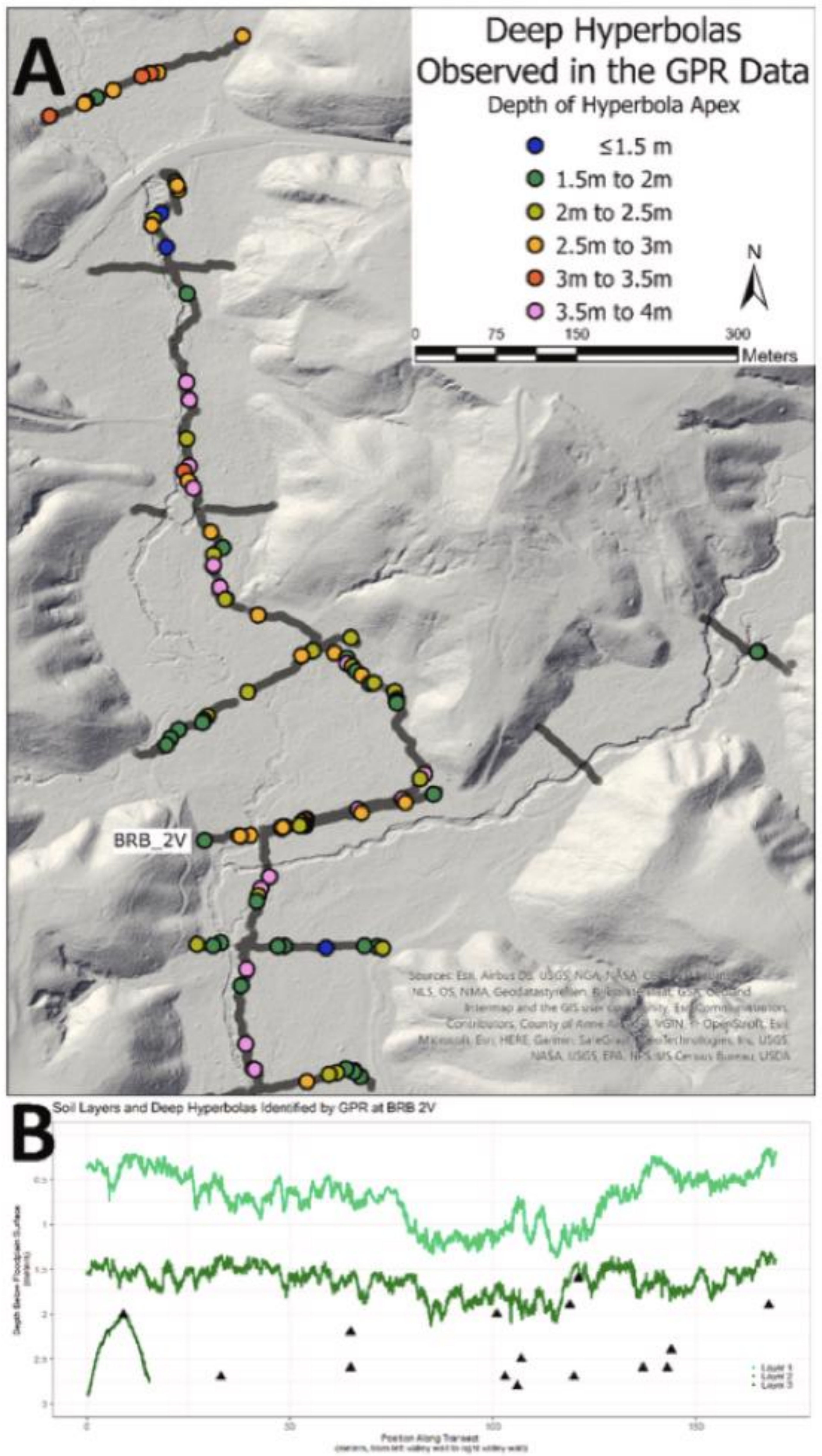




Episodic Memory #3 (Holocene)

- ***Tens of thousands of years of wet, marshy valley bottoms***
- ***Kaliedoscope streams - patch mosaic of different geomorphic forms and vegetative succession, with high water and sediment retention and cycling***
- ***Heterogeneous stream corridors exhibiting frequent changes in channel positioning and vegetative dynamics (Wohl, et. al., 2021)***



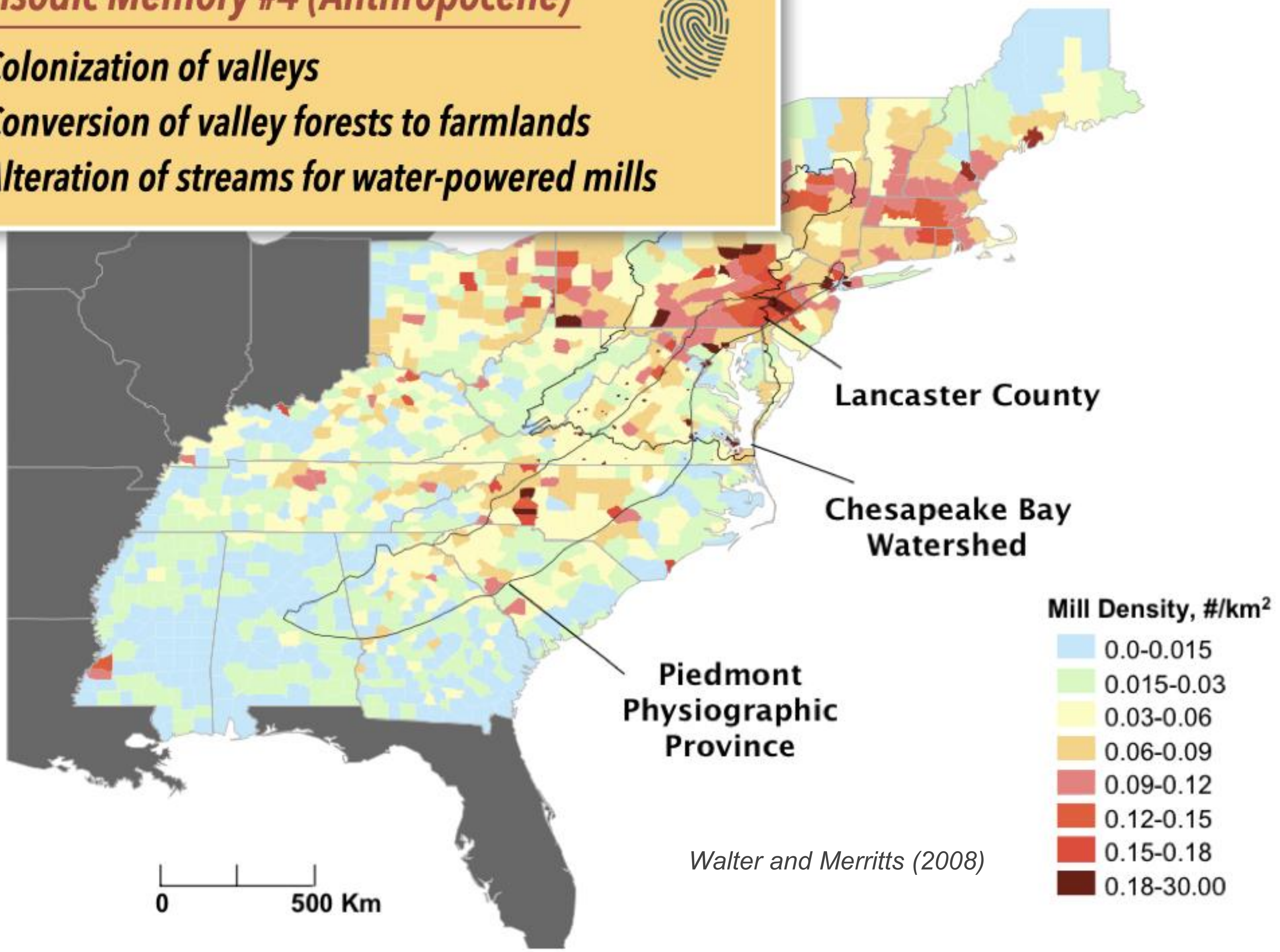


Pollock, MM and Norman, LM (2025). "Wet meadow regeneration through restoration of biophysical feedbacks," Front. Environ. Sci. 13:1592036. doi: 10.3389/fenvs.2025.1592036

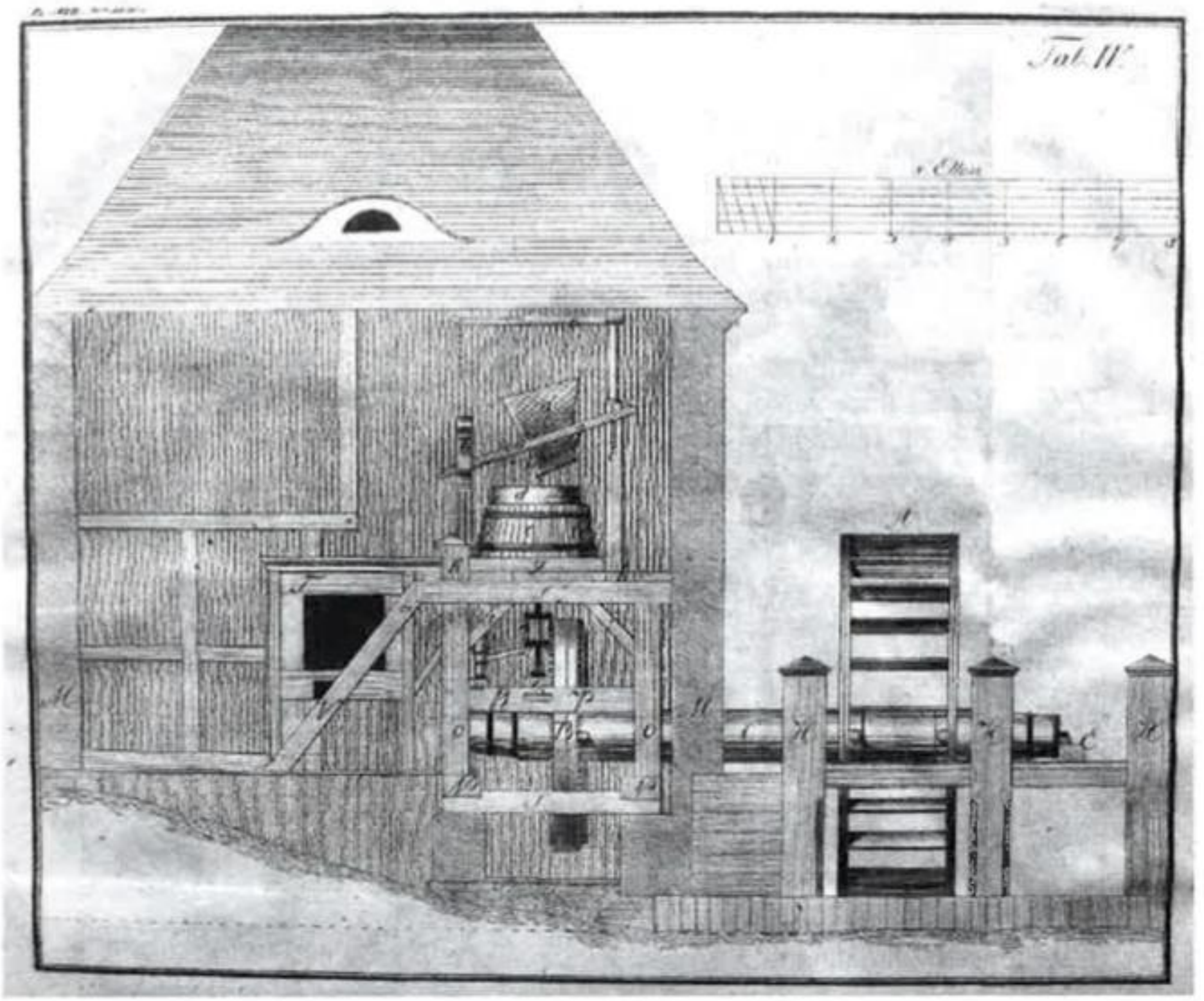
Cashman, M., et. al. (2025). "Hidden legacies: Investigating buried pre-colonial stream corridors in the Mid-Atlantic Coastal Plain, Maryland, USA" Ecological Engineering, https://doi.org/10.1016/j.ecoleng.2025.107771

Episodic Memory #4 (Anthropocene)

- *Colonization of valleys*
- *Conversion of valley forests to farmlands*
- *Alteration of streams for water-powered mills*



Walter and Merritts (2008)



Water-powered mills in the United States

~60,000 mills in 1840 census

2 *Key Concept*

Present-day channel adjustments date back to watershed changes associated with early settlement

WATER-POWERED MILLS

Episodic Memory #4 (Anthropocene)

- *Fingerprint of legacy sediments behind historic water-powered mills clearly remembered in the landscape today*
- *Unless removed, system has very low likelihood of hydro-ecological uplift.*

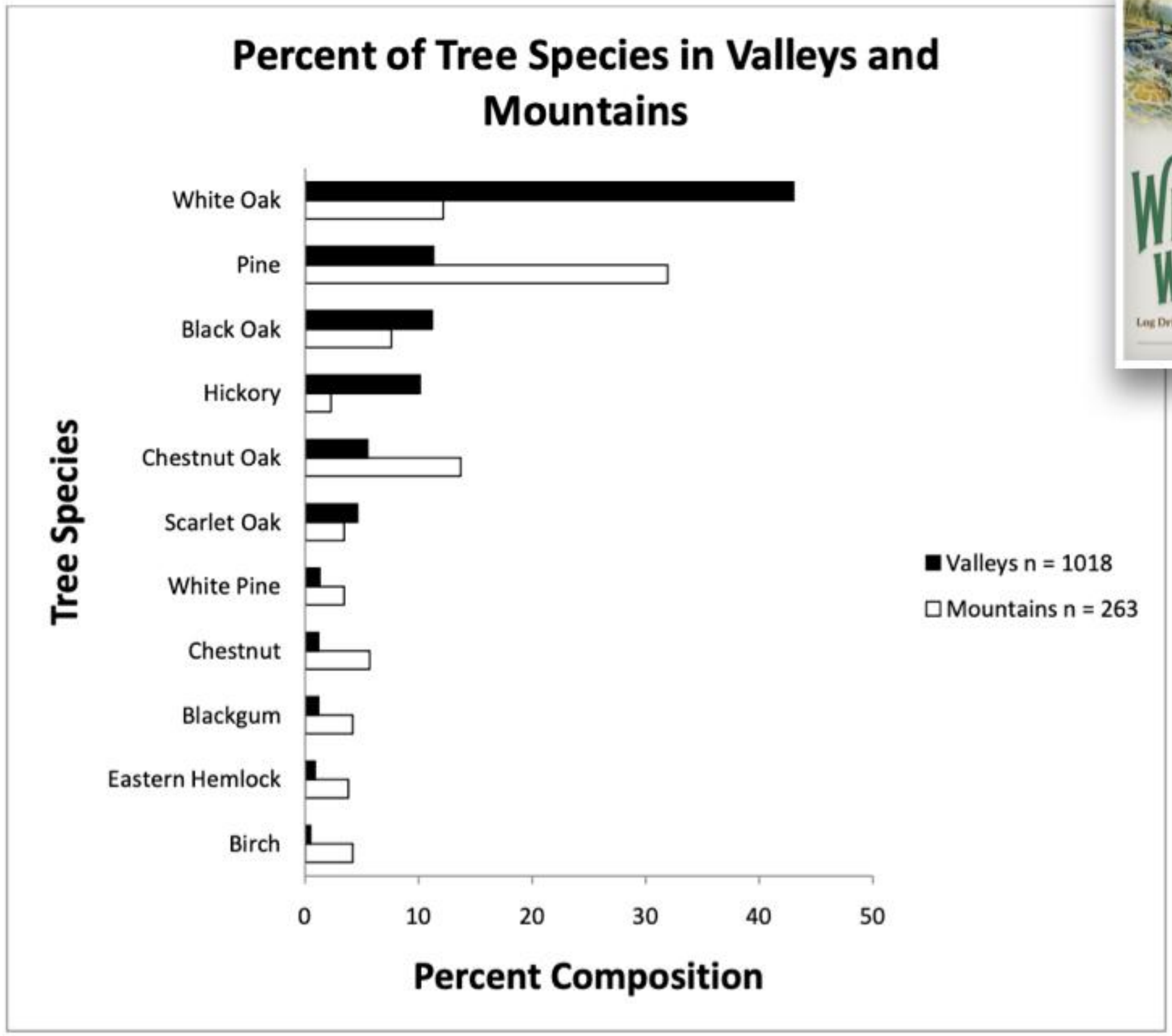
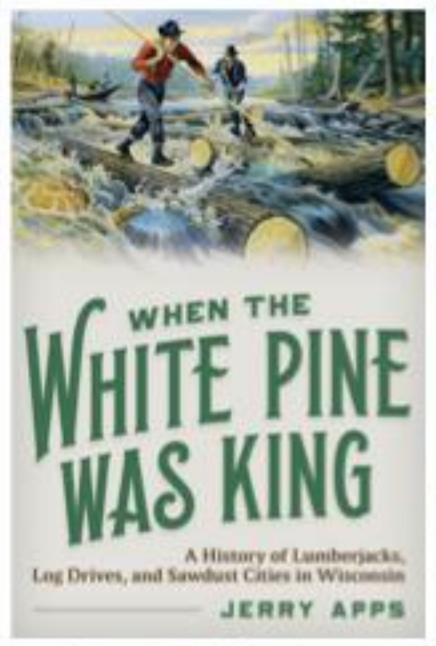
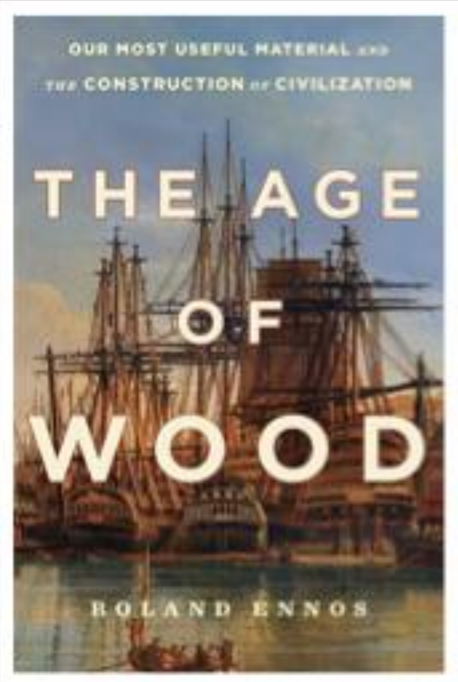


Figure 7. The frequency of tree species in the valleys and in the mountains of Union County based on land survey data from 1755 to 1855.

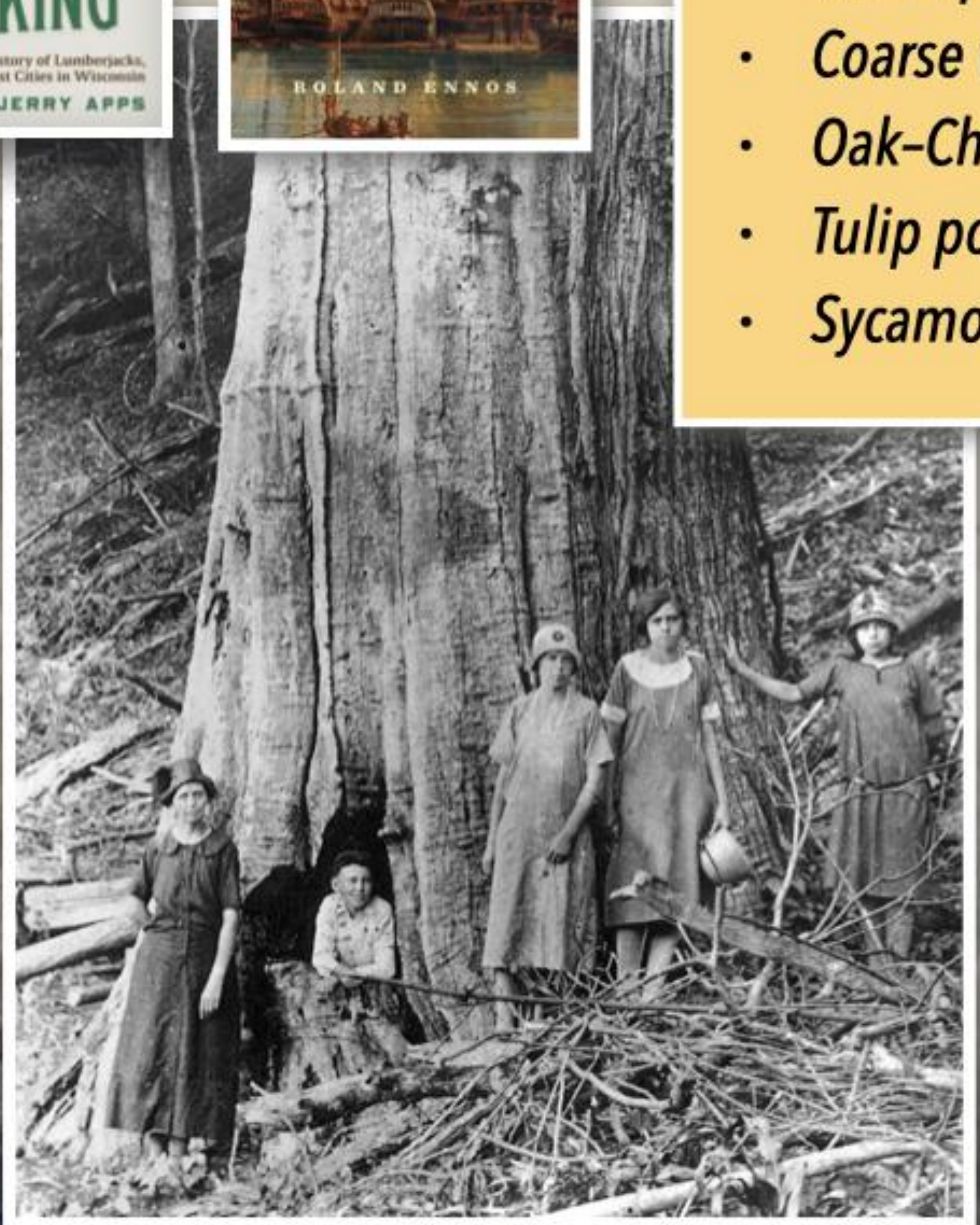
From: Gonsalves (2011)





Episodic Memory #5 (Holocene forests)

- *Ecologically stable at large scales, yet dynamic locally*
- *Trees 300–500+ years old were common in many regions.*
- *White pines reportedly reached 200+ feet tall.*
- *Coarse woody debris and standing snags were abundant.*
- *Oak-Chestnut-Hickory woodlands on dry ridges*
- *Tulip poplar-oak-ash forests in Great Valley limestone soils*
- *Sycamore-elm-ash floodplain forests*

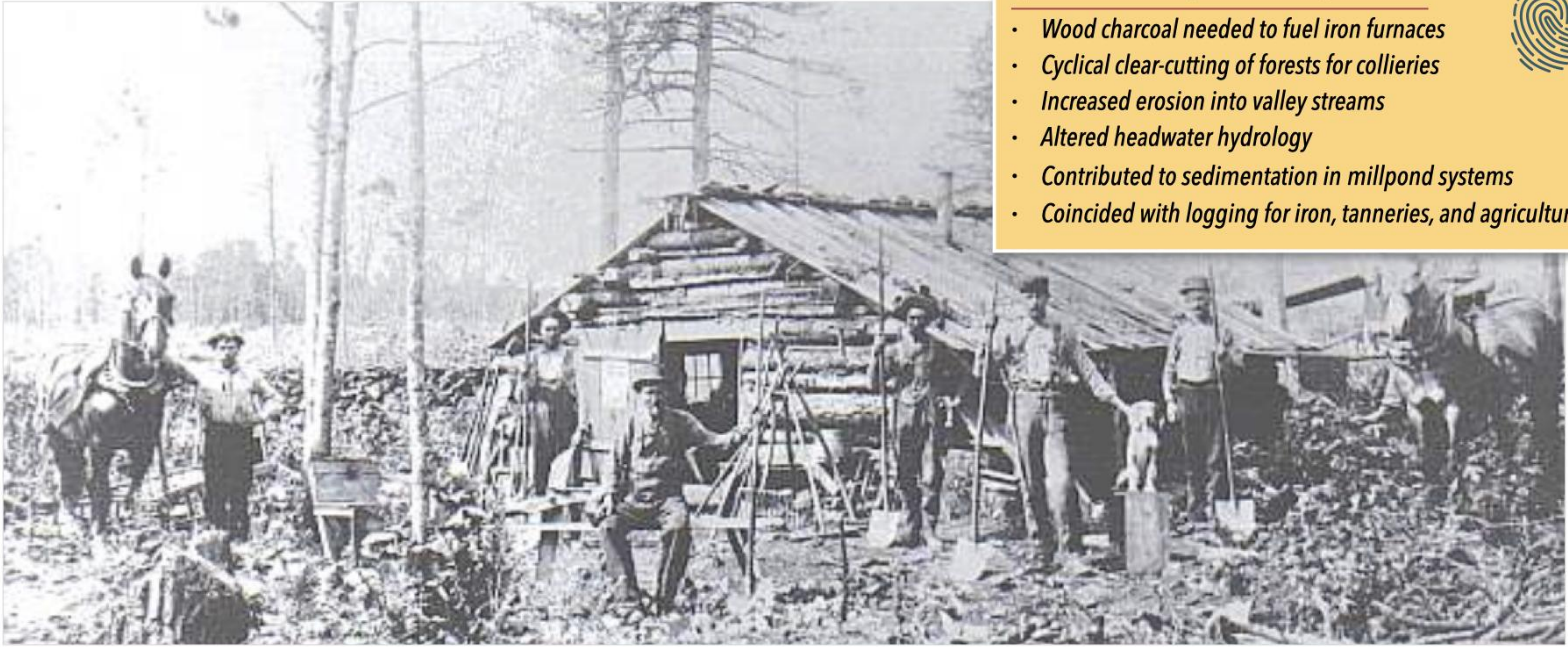


Pre-colonial valley and mountain forests

Over 90% of landscape was covered by forests; Structurally complex and regionally distinct

Episodic Memory #8 (Anthropocene)

- *Wood charcoal needed to fuel iron furnaces*
- *Cyclical clear-cutting of forests for collieries*
- *Increased erosion into valley streams*
- *Altered headwater hydrology*
- *Contributed to sedimentation in millpond systems*
- *Coincided with logging for iron, tanneries, and agriculture*



Widespread clearcutting for charcoal production

Selective harvesting of oak, chestnut, hickory, and other hardwoods packed into slow-burning charcoal kilns

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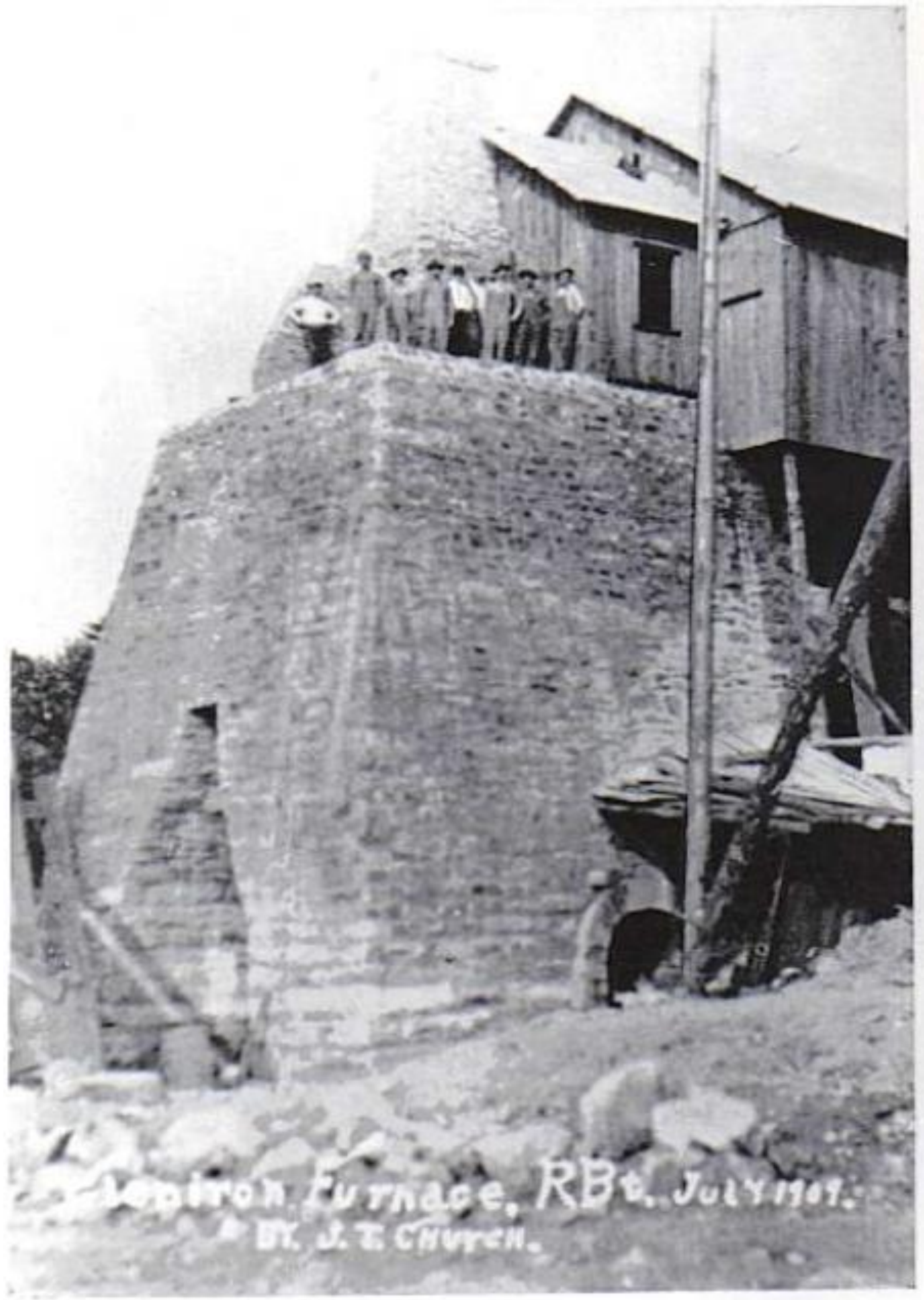
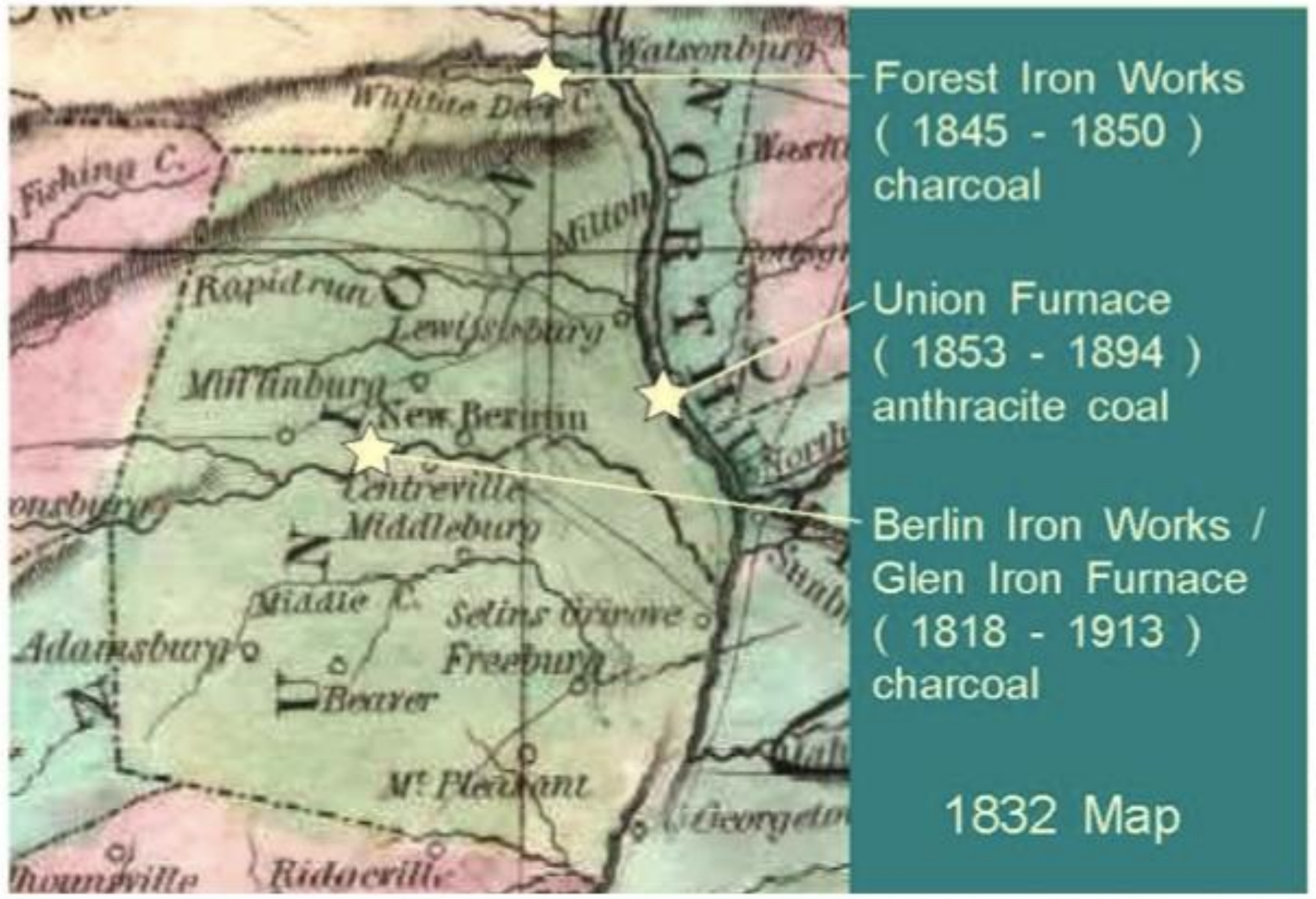


The Glen Iron Furnace

Recorded 1908

One Charge:	Charcoal – 20 bushels ~150 pounds
	Iron Ore – 400 to 600 pounds
	Limestone – 75 to 100 pounds
Number of Charges per Day:	35 to 45
Daily Production of Pig Iron:	3 to 5 tons



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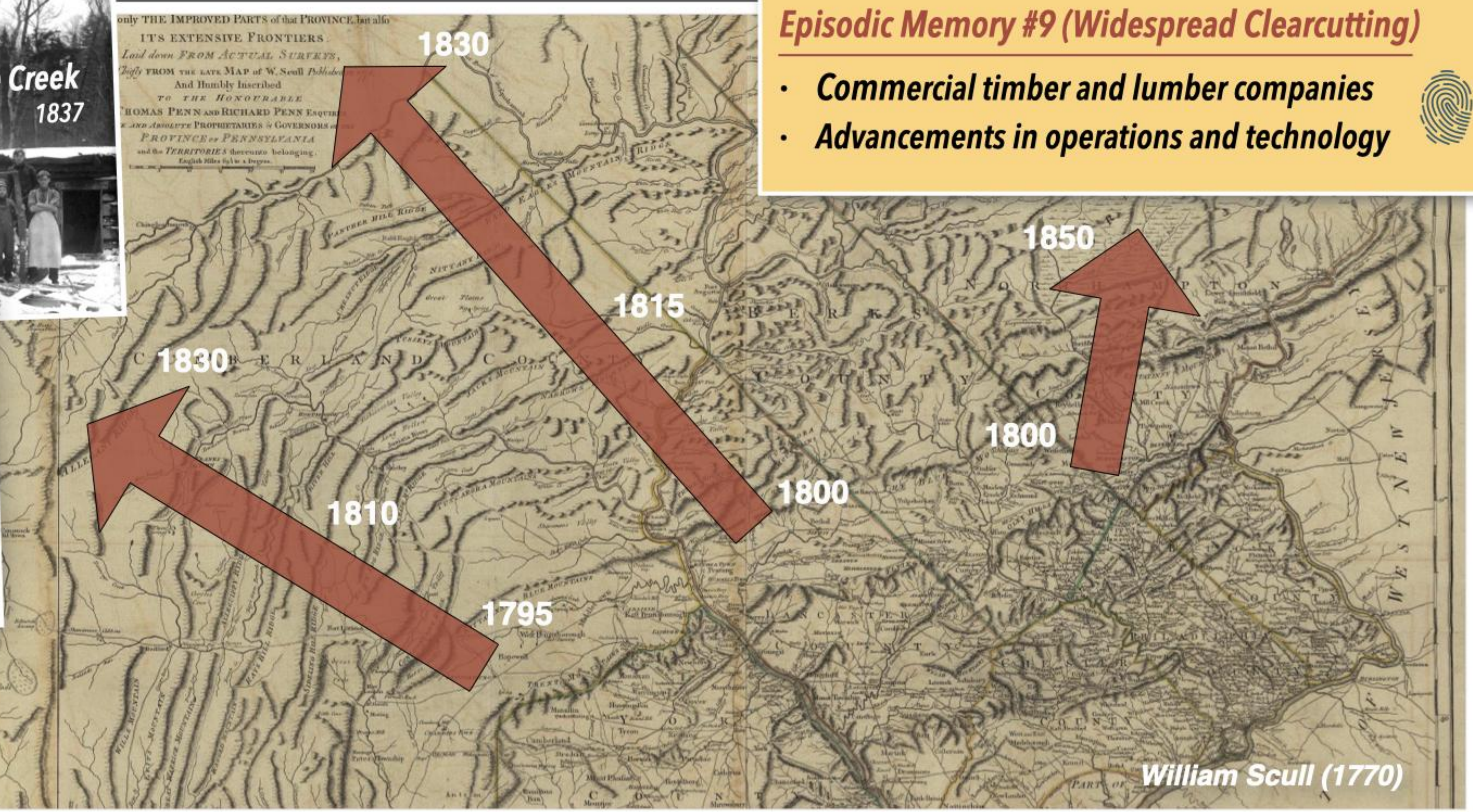
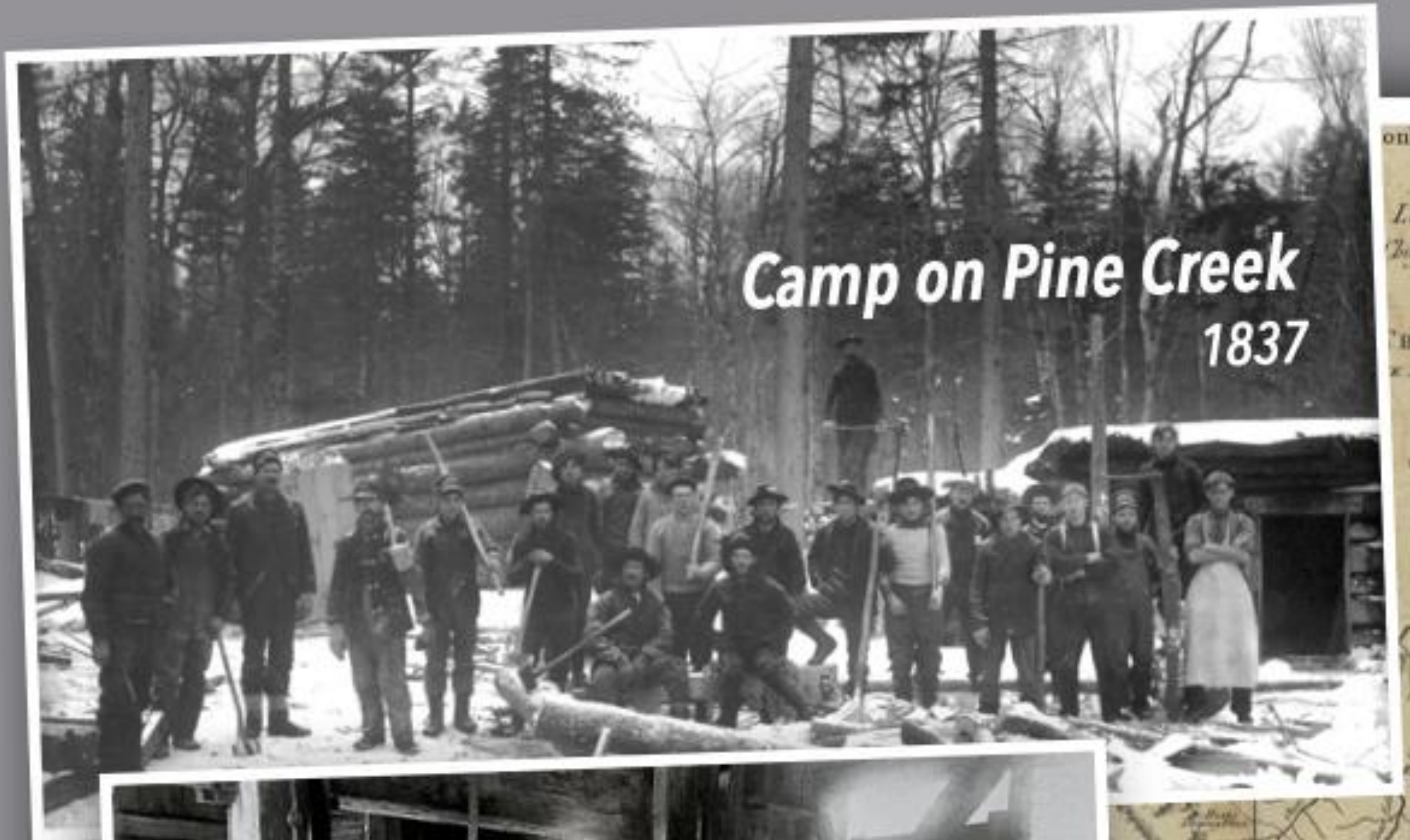
Widespread clearcutting for charcoal production

Selective harvesting of oak, chestnut, hickory, and other hardwoods packed into slow-burning charcoal kilns

Episodic Memory #9 (Widespread Clearcutting)

- Commercial timber and lumber companies
- Advancements in operations and technology



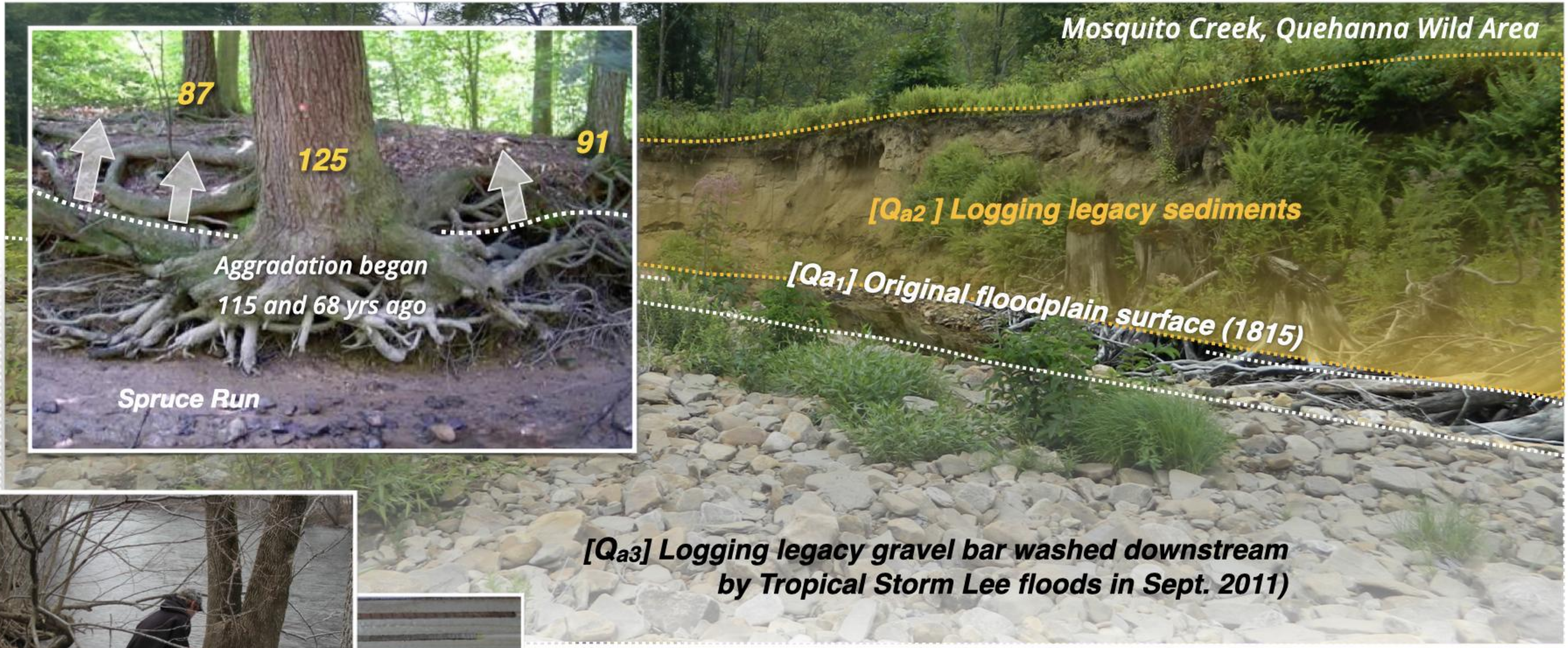


Episode 6: 19th century timber harvesting

Log drives, splash dams, rafts, and arks prior to 1880 | narrow-gauge railroads until 1915.

Episodic Memory #9

- Channel modification - dredging, straightening, berming, wood removal
- Oversimplification of fluvial network into a single, straightened channel
- 1000-fold loss of wetland and side channel habitat (refugia and spawning areas)

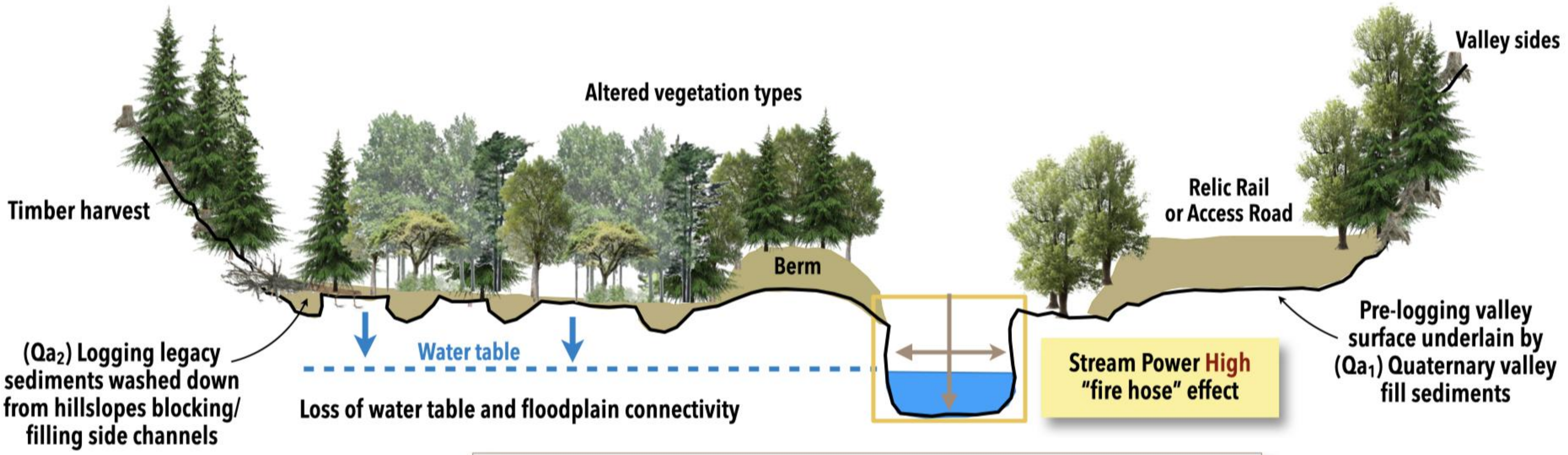


Logging legacy sediments

Sediment storage and metastable condition

Present-day Condition

Oversimplified and Disconnected Fluvial System - Low Resiliency and Redundancy

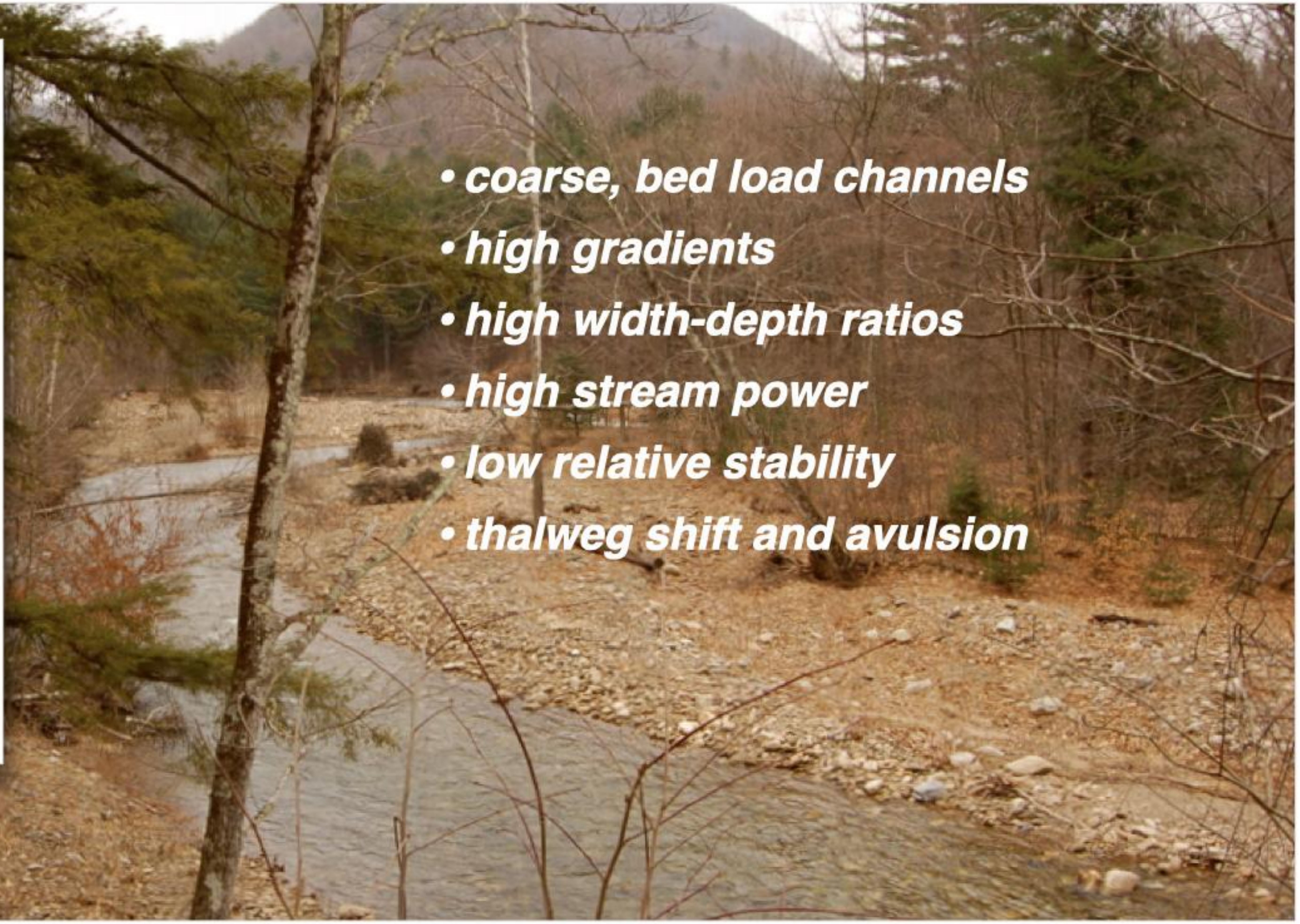


Channel INCISION and WIDENING

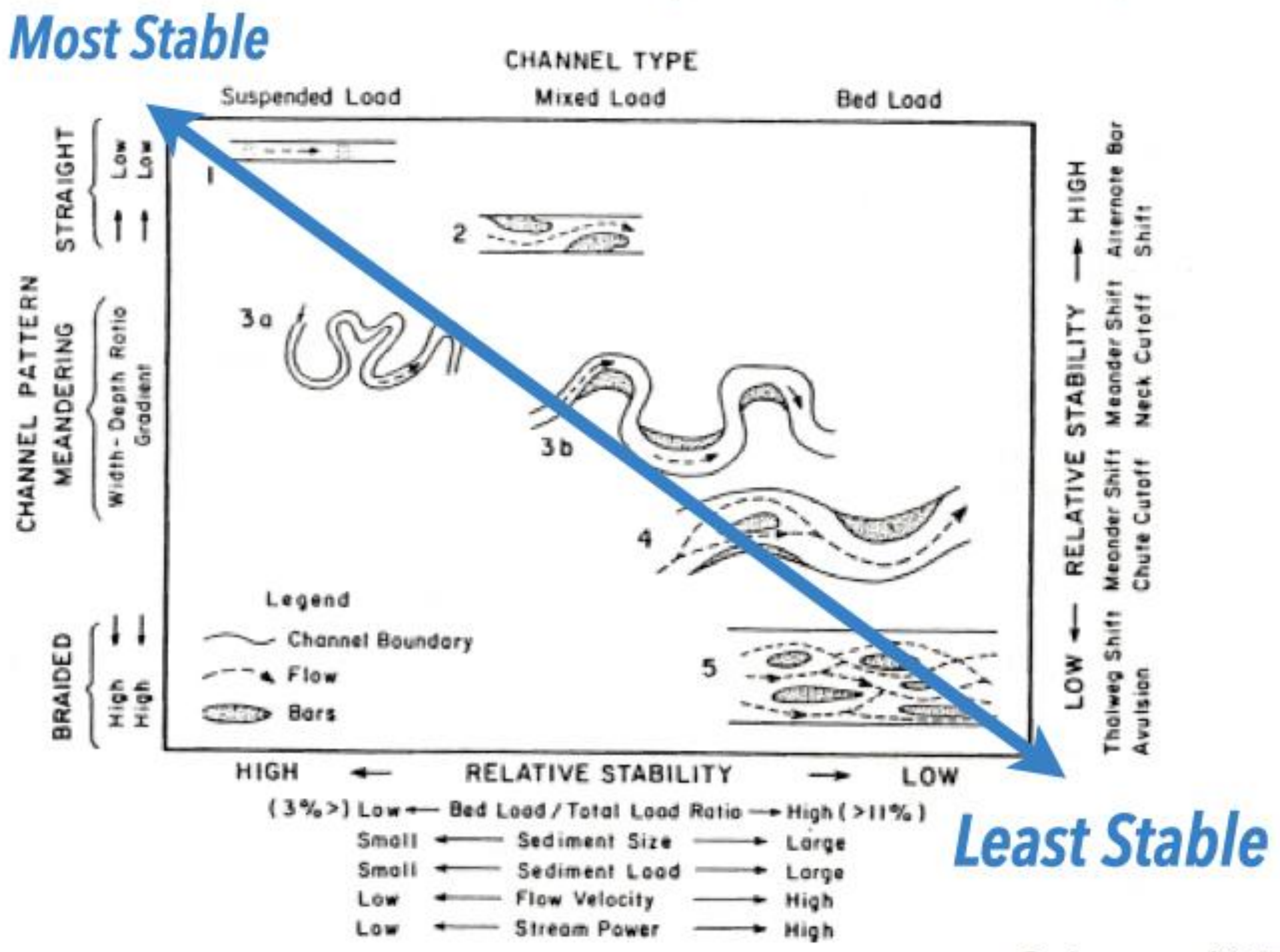
HIGH stream power (from deposition to transport)

MINIMAL to NO large wood debris and habitat complexity

ARMORED bed substrate - POOR spawning conditions



Form-Stability Relationships



Schumm (1977)

- ***coarse, bed load channels***
- ***high gradients***
- ***high width-depth ratios***
- ***high stream power***
- ***low relative stability***
- ***thalweg shift and avulsion***

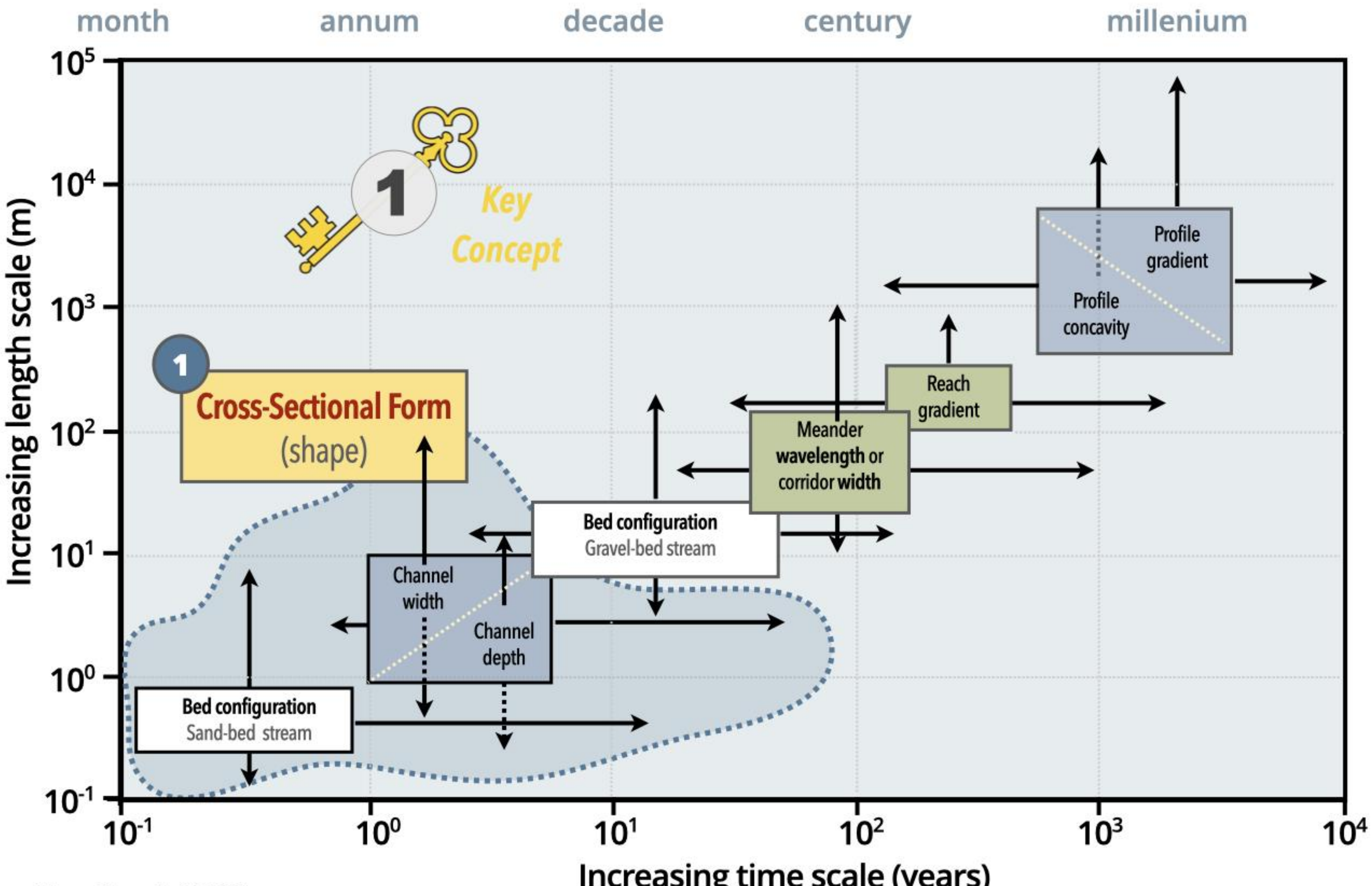
Big Bear Creek
Lycoming County, PA

1 **Key Concept**

Alluvial channels **self-adjust**

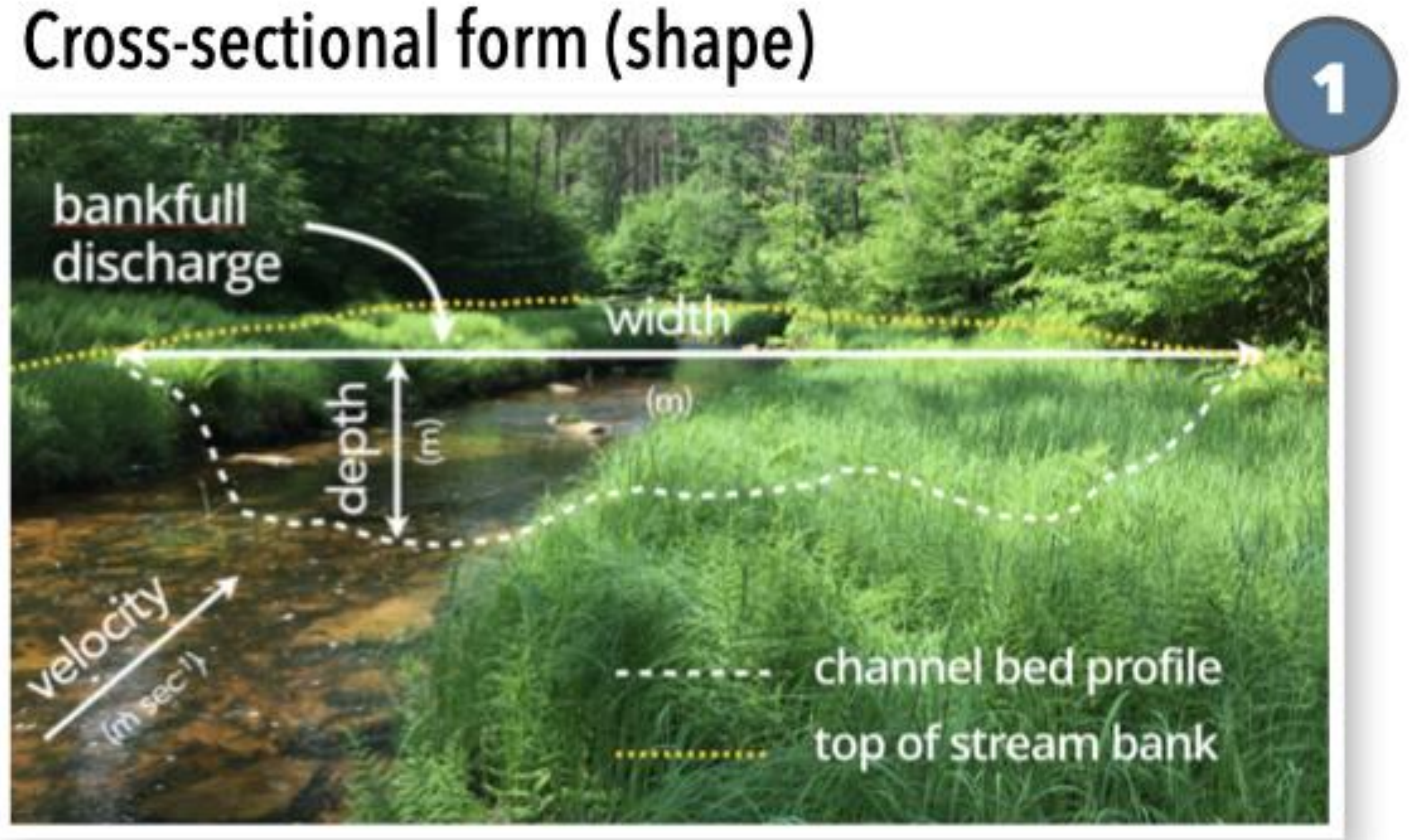
Stream morphology = f (Q, Q_s, S, W/D, sediment size, bank material, vegetation, ...)

SCALES OF FLUVIAL ADJUSTMENT



After Church (1998)

Cross-sectional form (shape)



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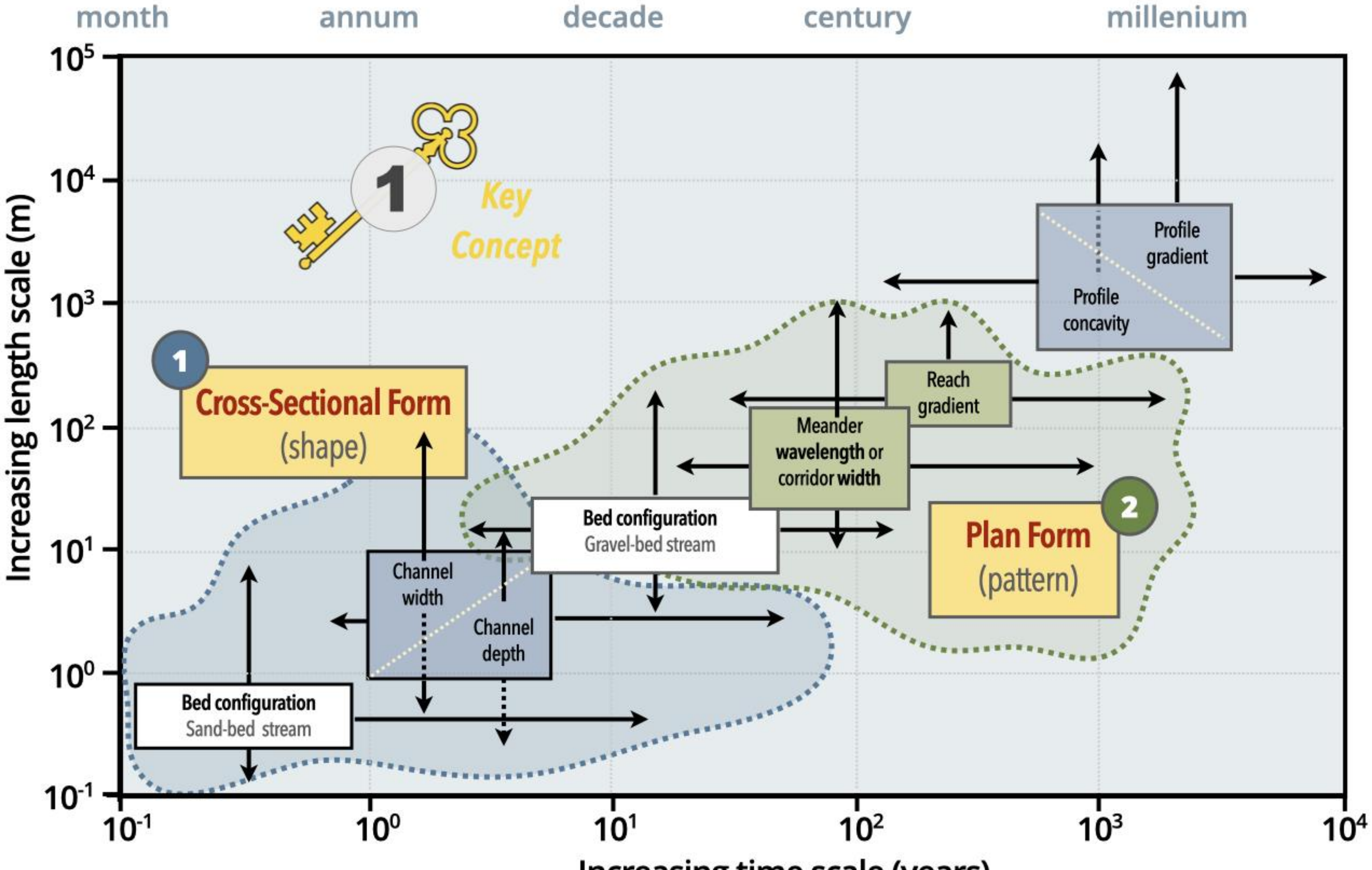

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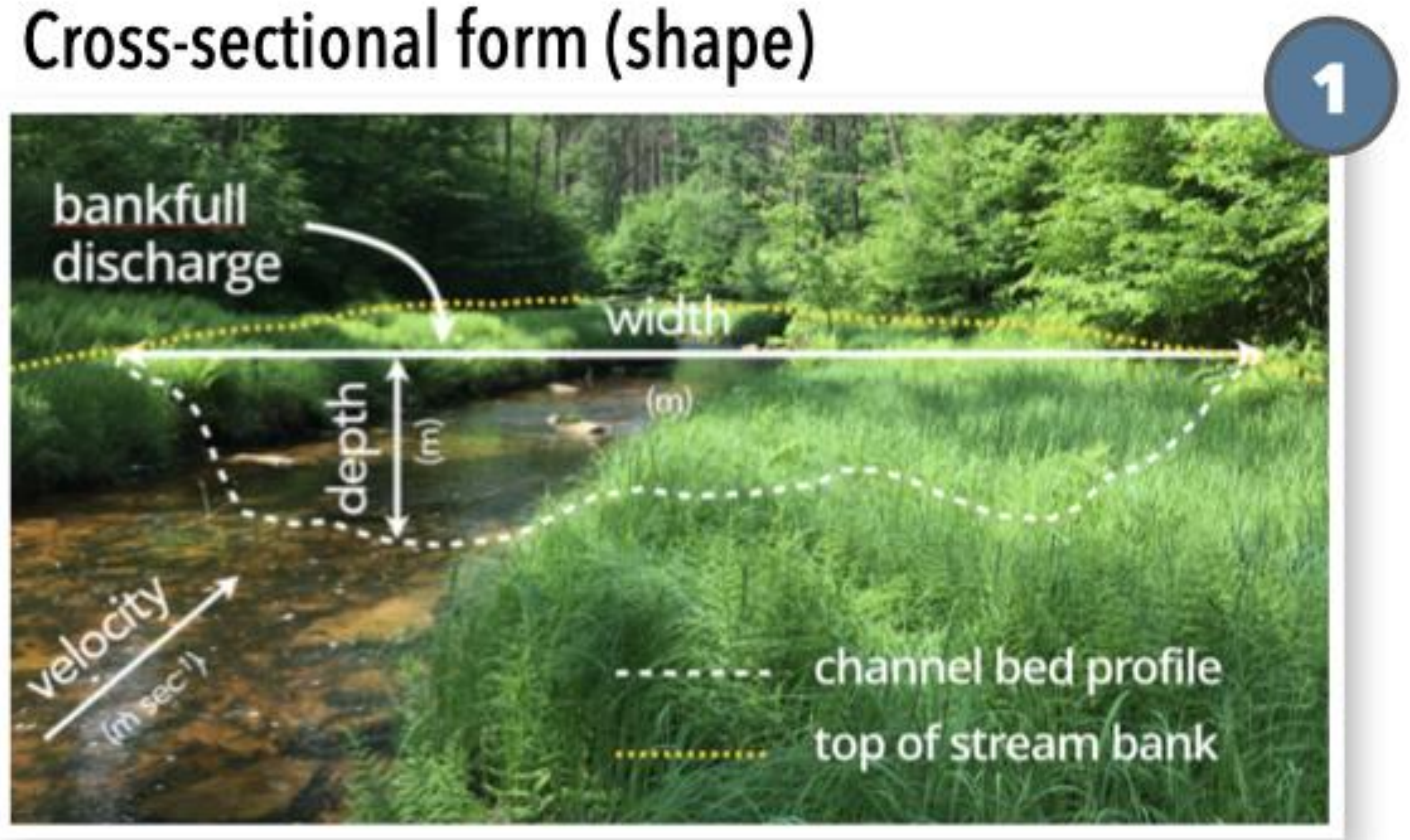
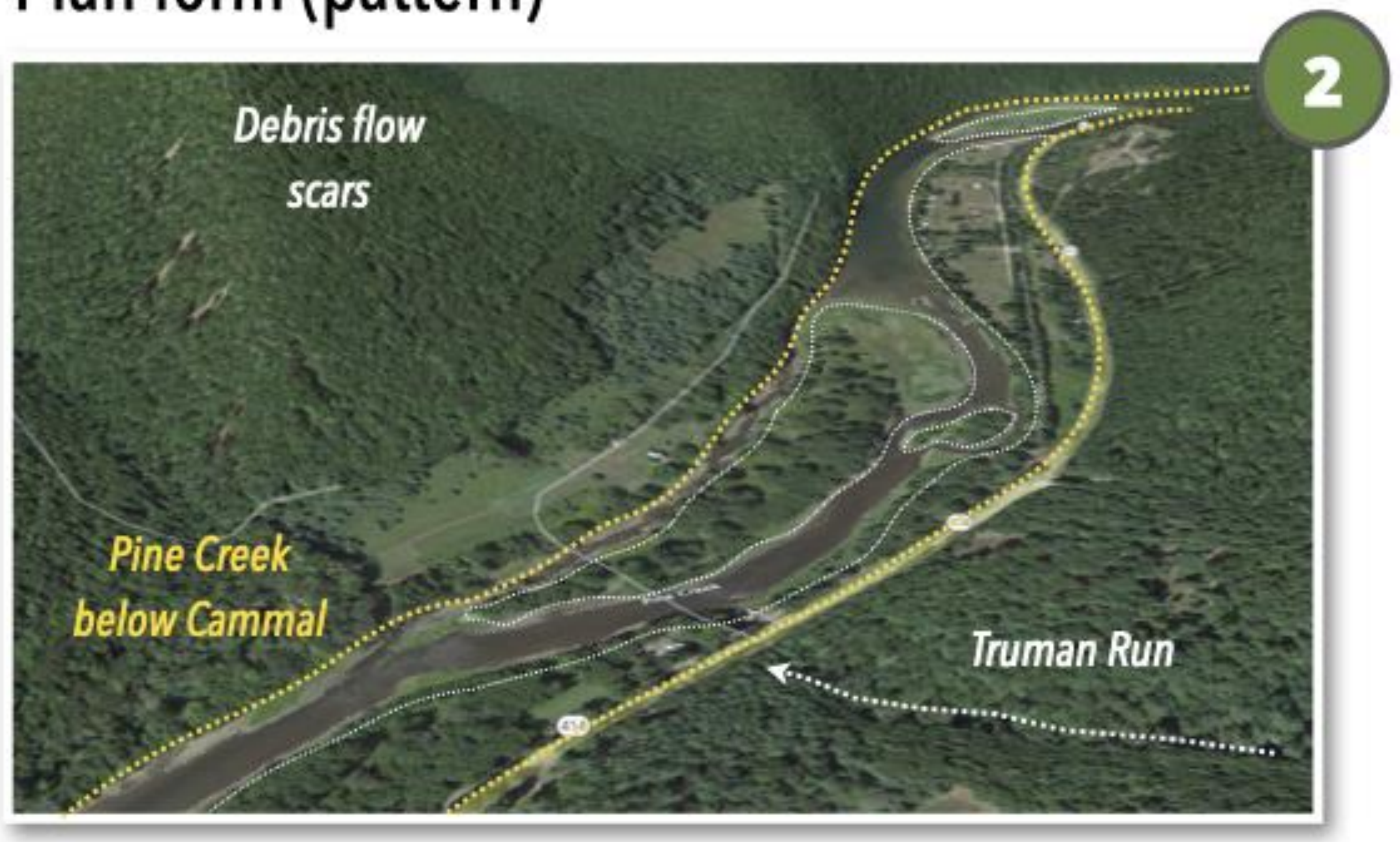
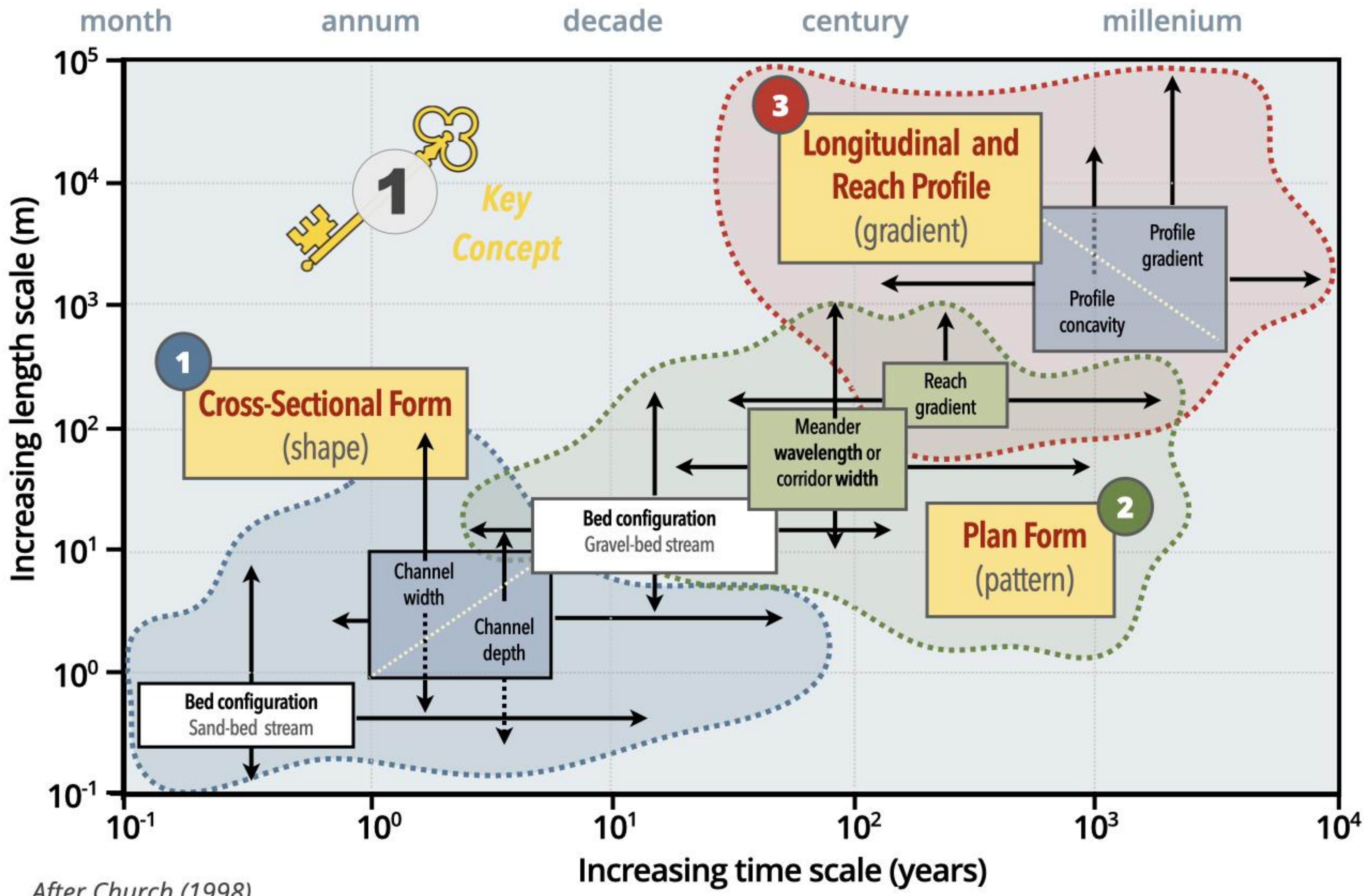


Plan form (pattern)



SCALES OF FLUVIAL ADJUSTMENT



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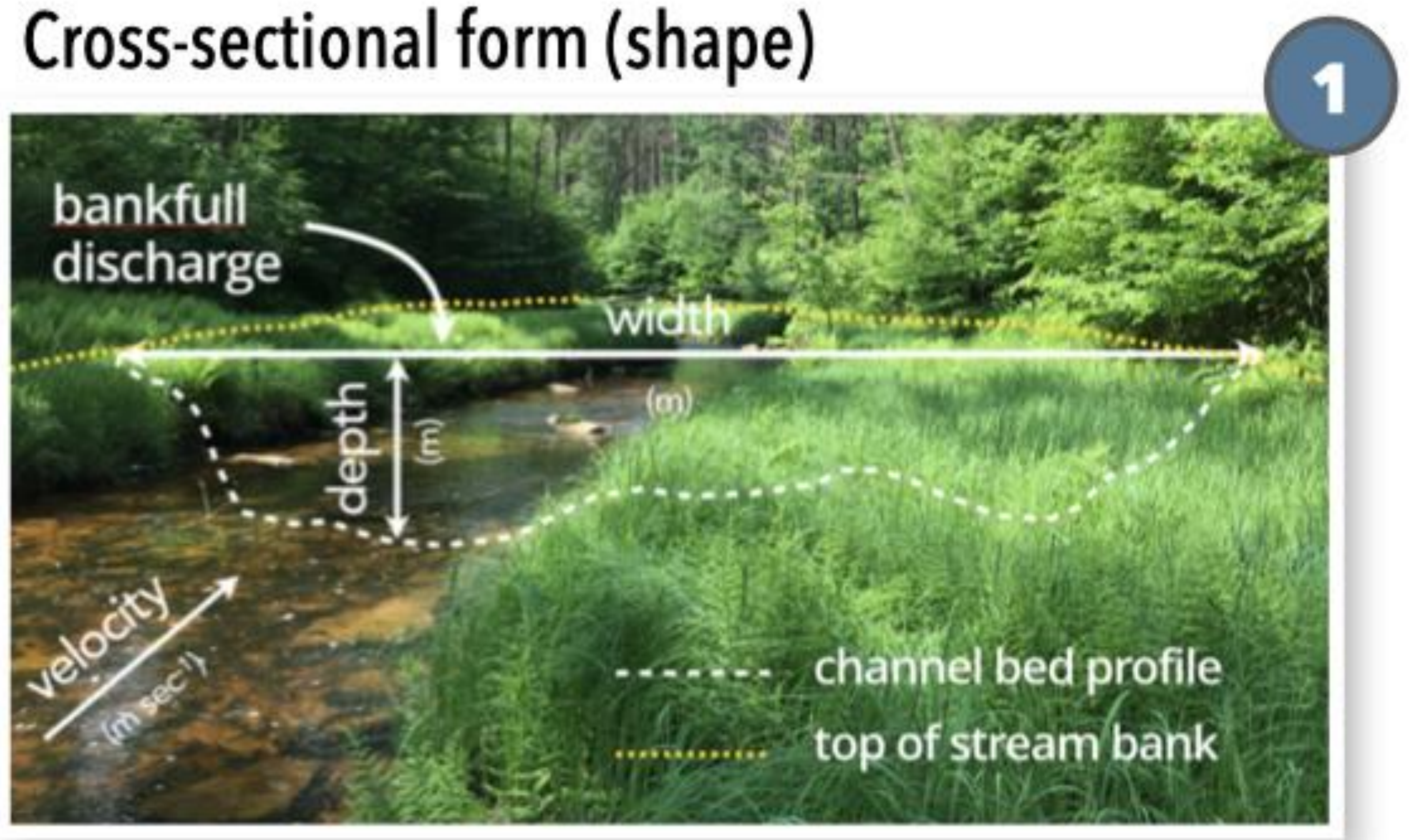
Cross-sectional form (shape)



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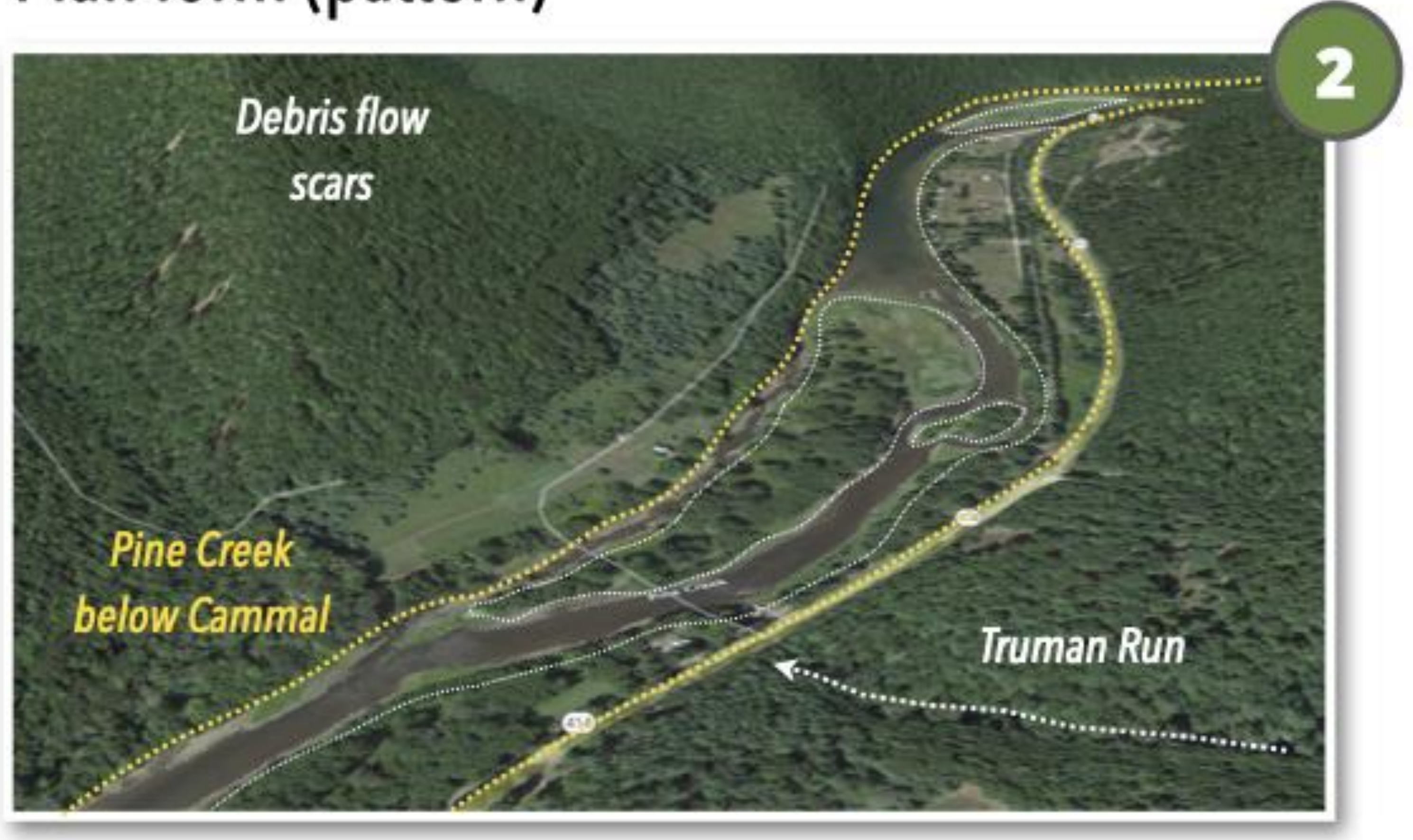
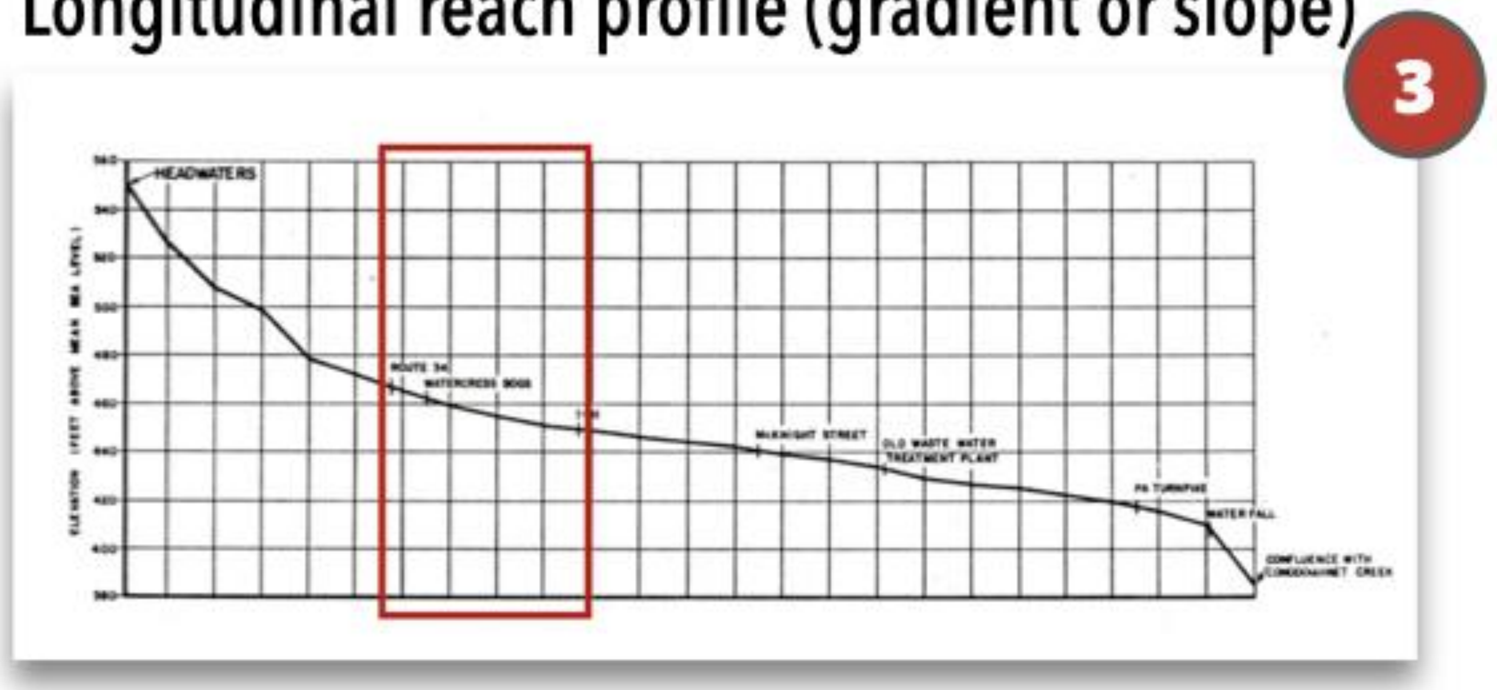


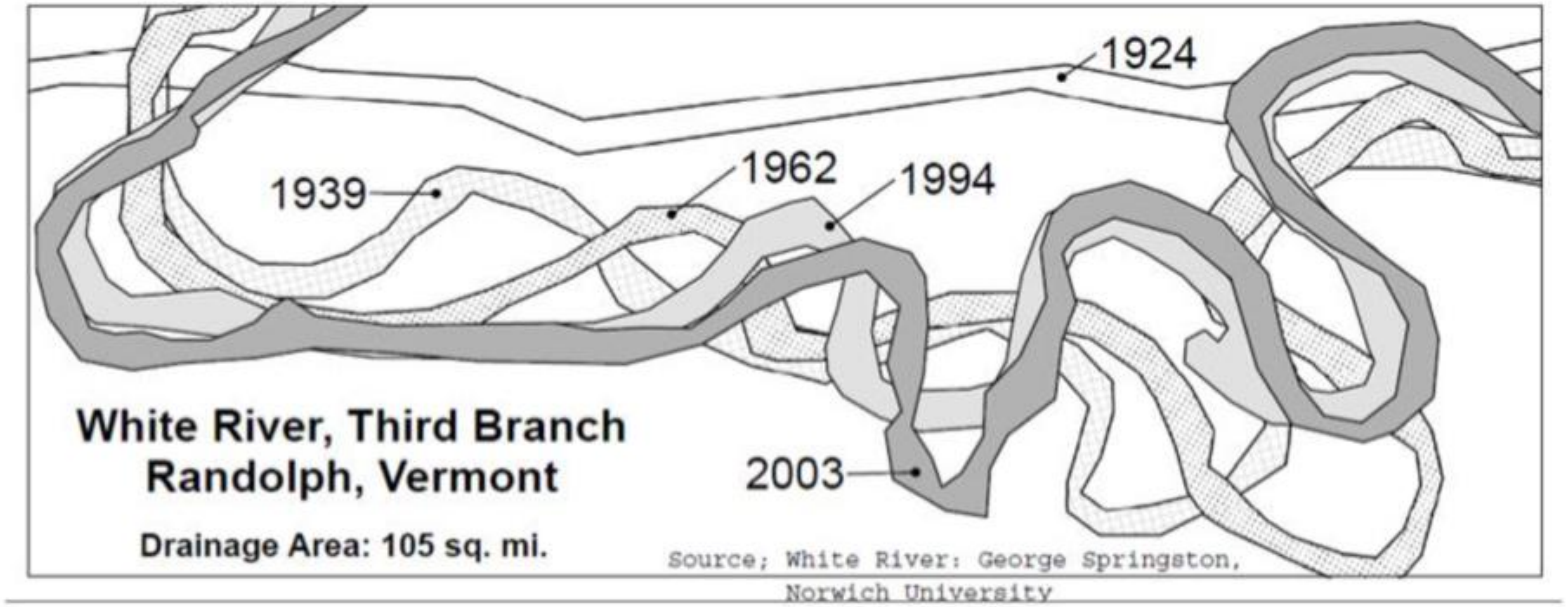
Longitudinal reach profile (gradient or slope)



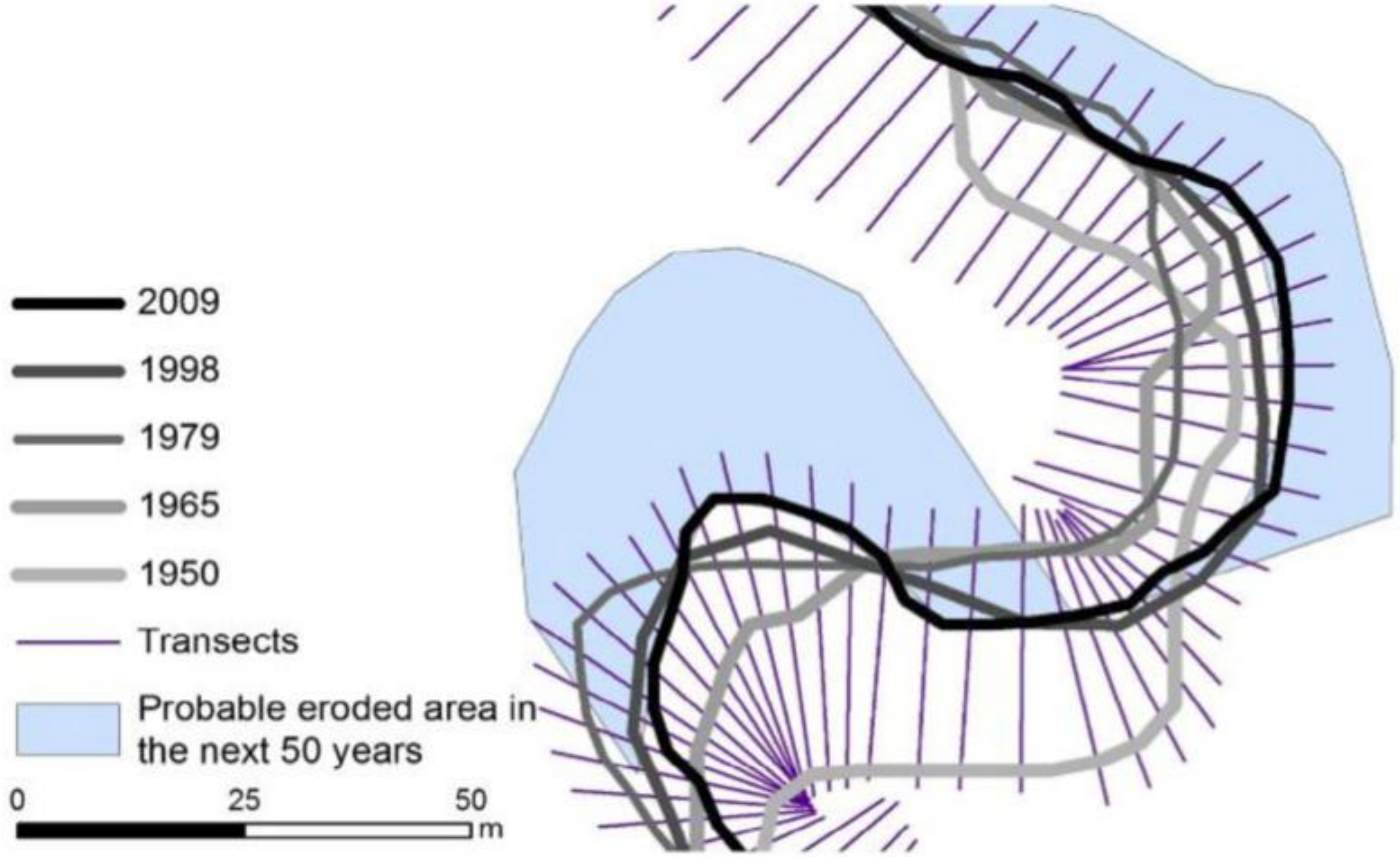
- **Freedom Space** (Espace d' Liberte)
- Room for the River (Ruimte voor de Rivier) Process Domain
- **Functional Process Zone**
- Erodible Corridor
- **Channel Migration Zone**

Variables to ALWAYS consider

- **Space**
- Time
- Energy
- Material



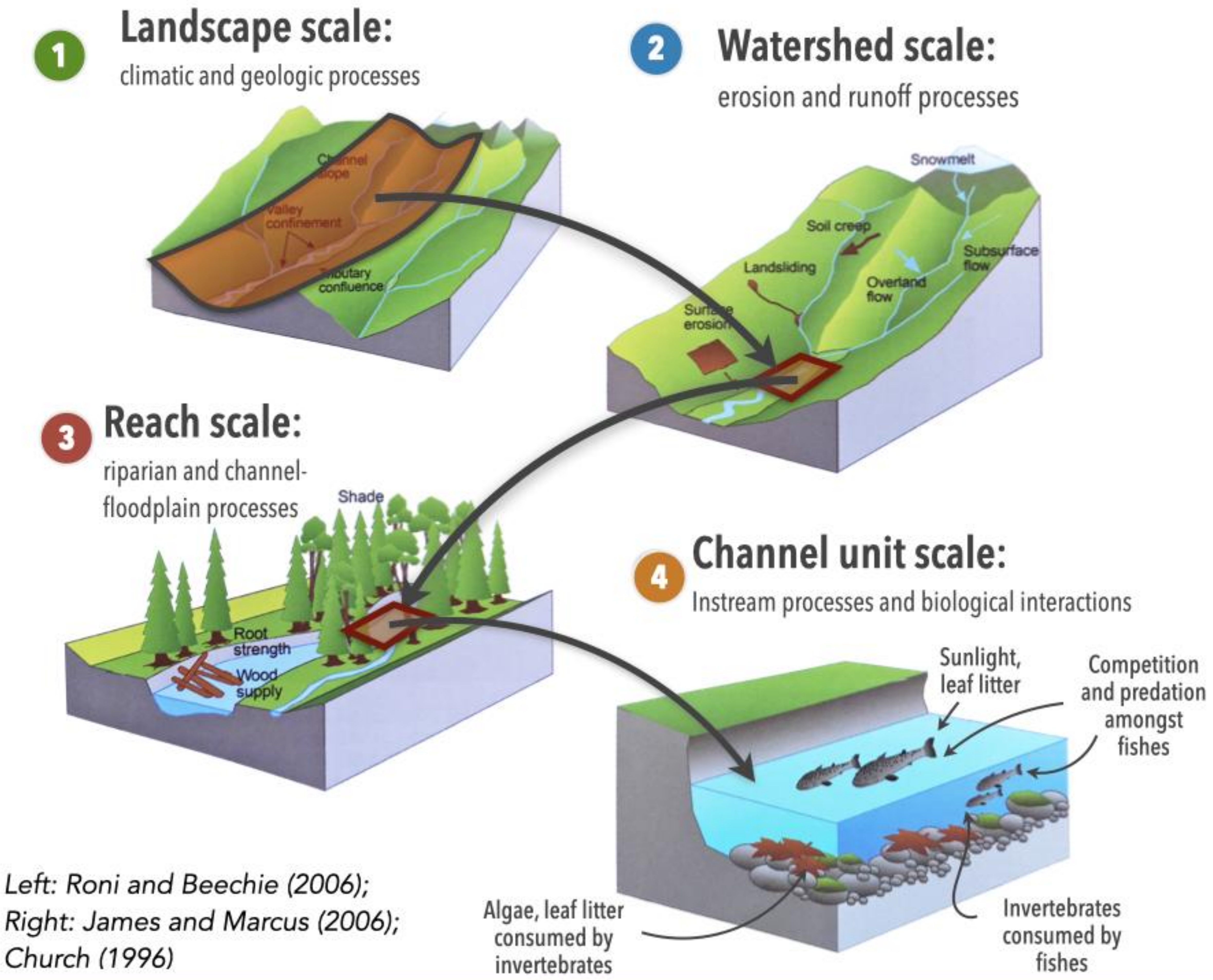
Straightened 1924 river channel regains natural sinuosity and meander migration pattern in subsequent decades.

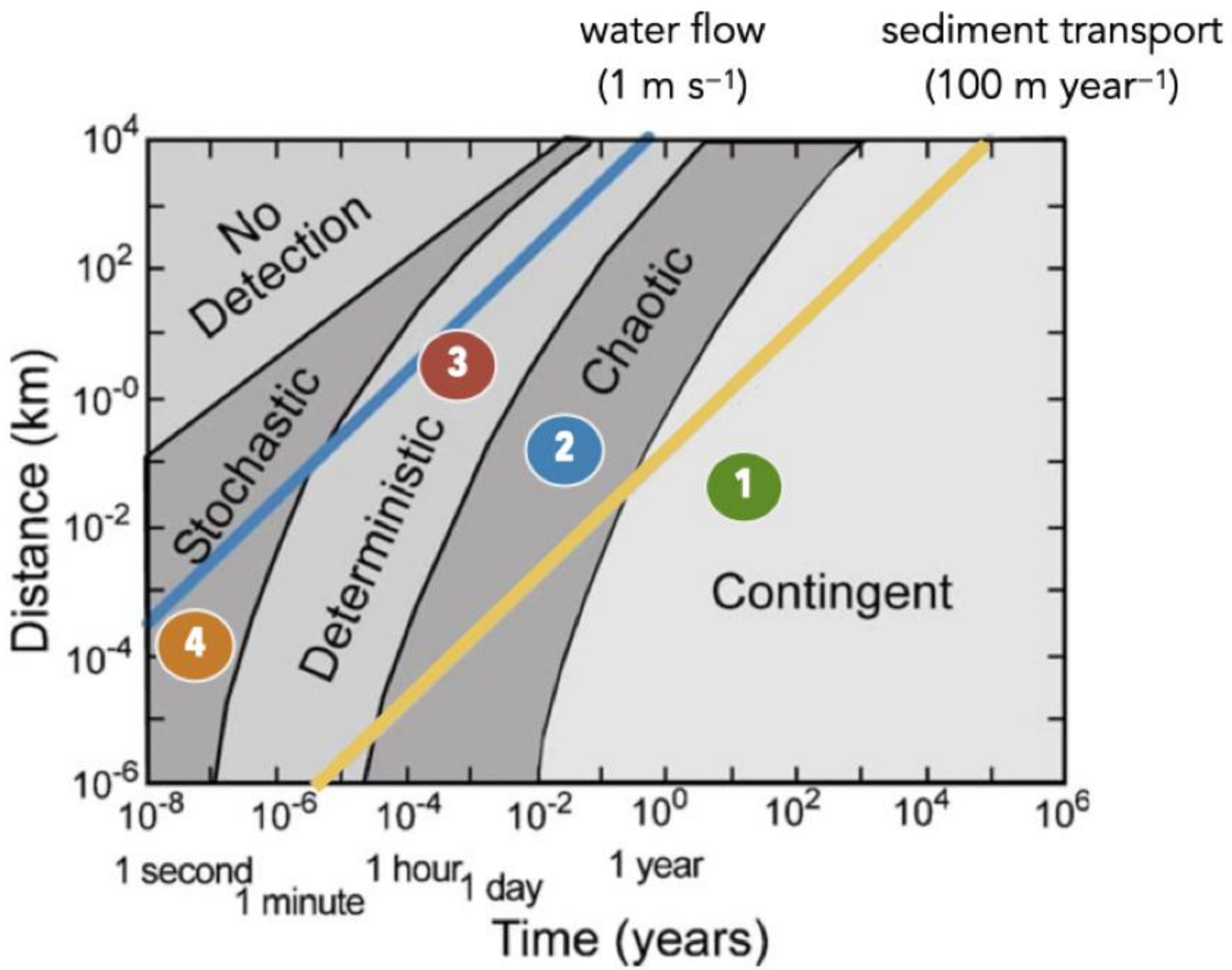


2 Key Concept

Space is **essential** for fluvial adjustment

Shift restoration goals from "bank stabilization" to enabling "functional process"



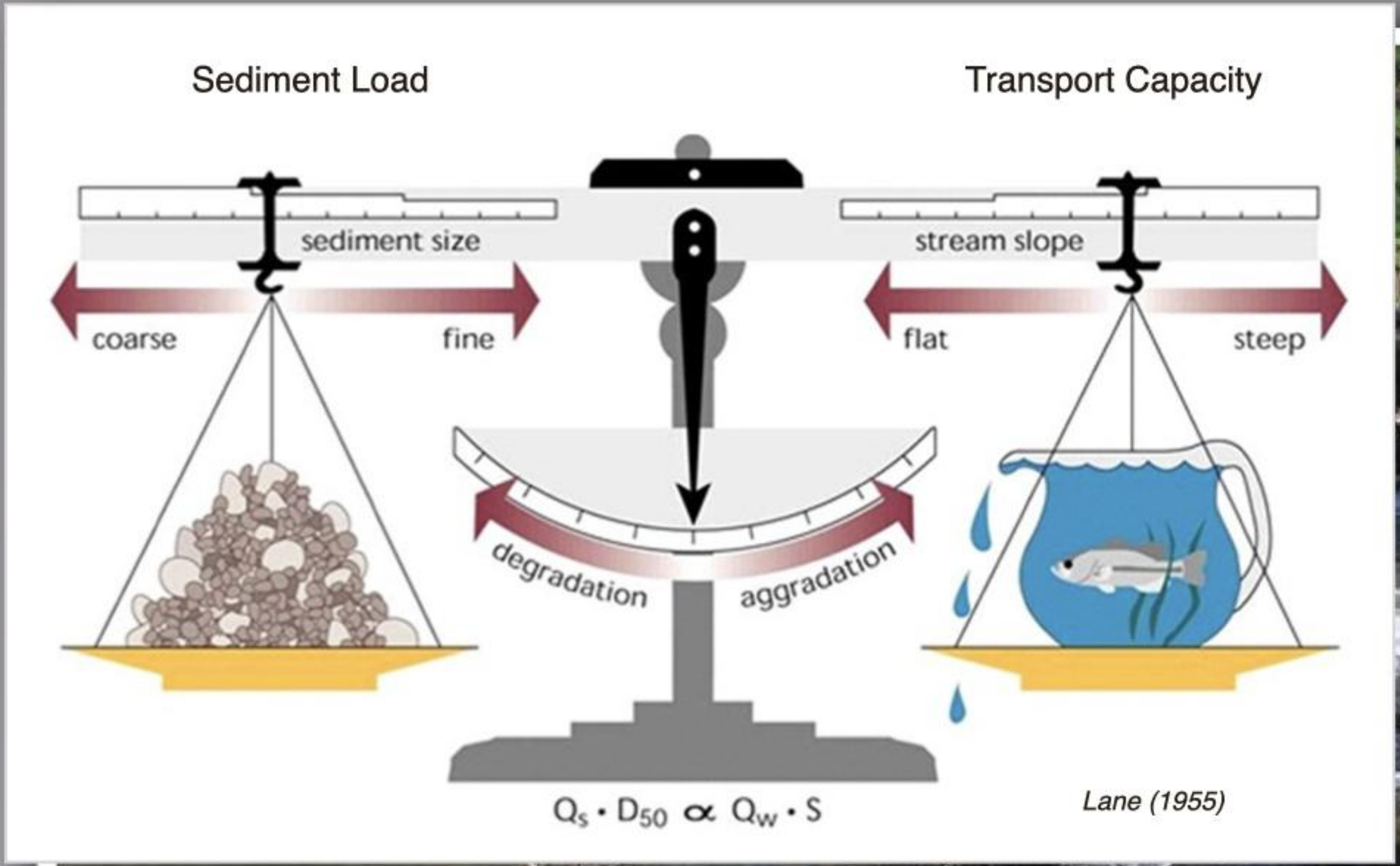


Left: Roni and Beechie (2006);
Right: James and Marcus (2006);
Church (1996)

3 *Key Concept*

Scale dependency of causality

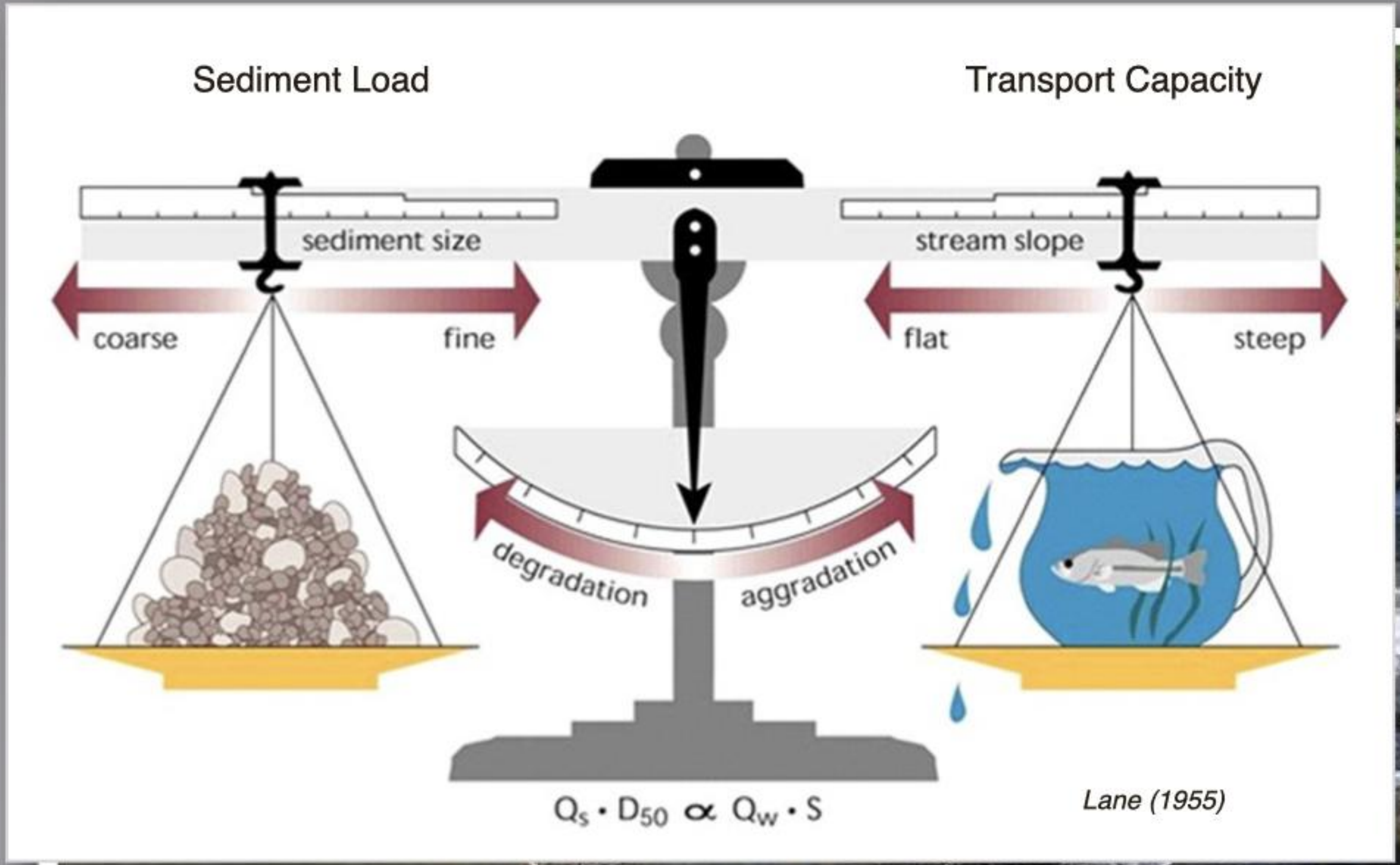
Monitoring, assessment, explanation, valuation, and management

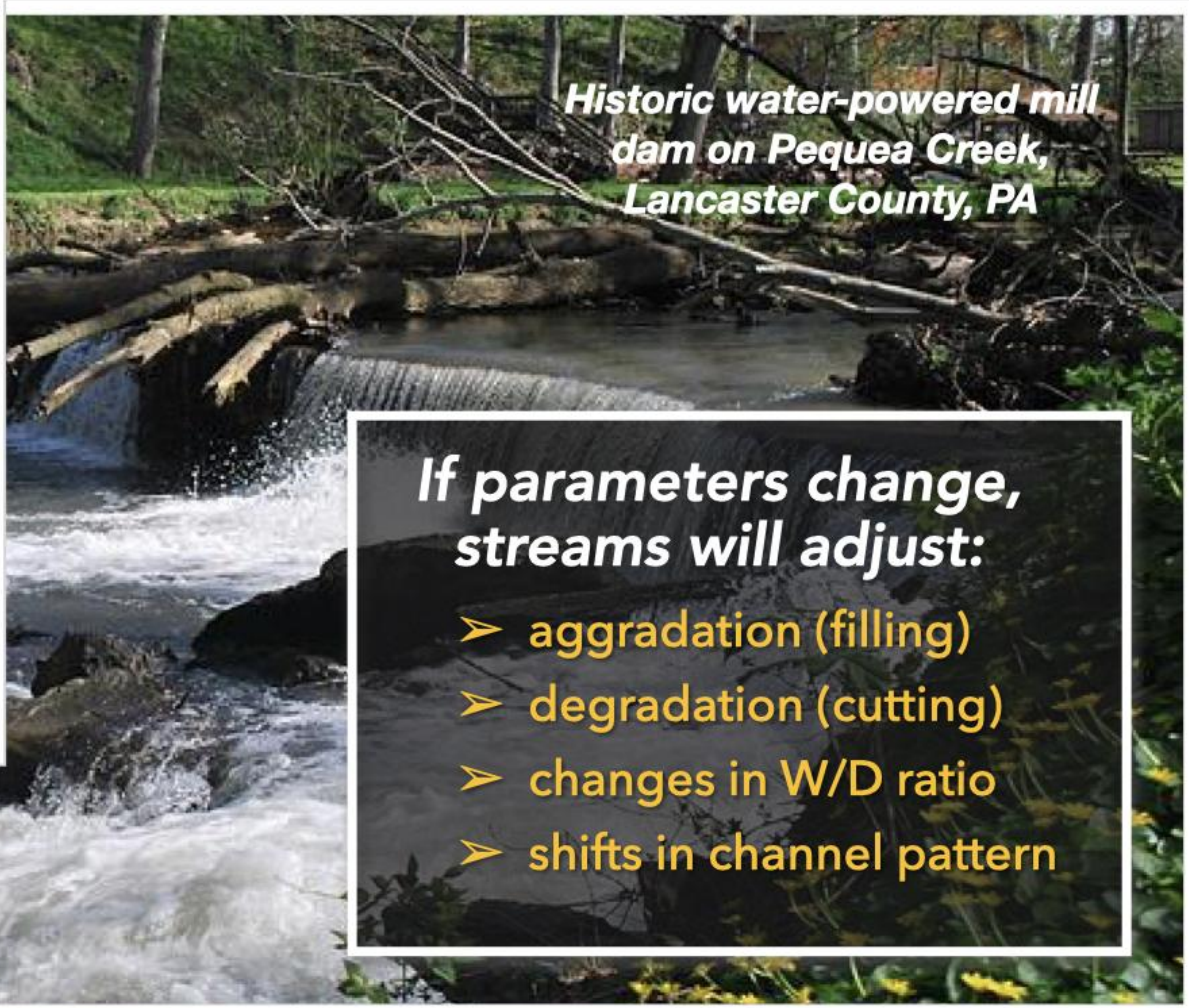


4 Key Concept

Streams work towards a state of equilibrium

Stable rivers are in “balance” with their watershed inputs (water and sediment)





4 *Key Concept*

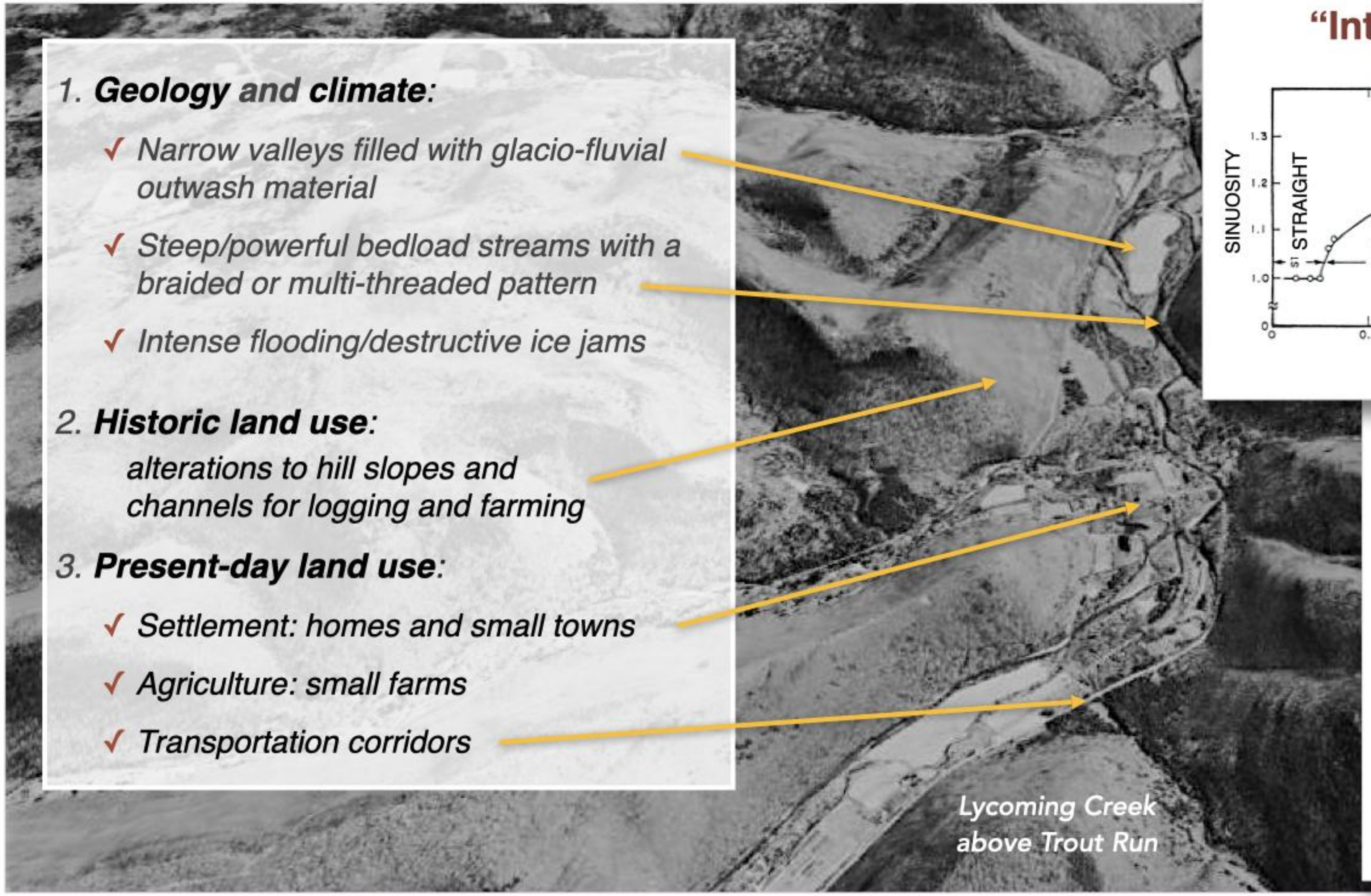
Streams work towards a state of equilibrium

Stable rivers are in “balance” with their watershed inputs (water and sediment)

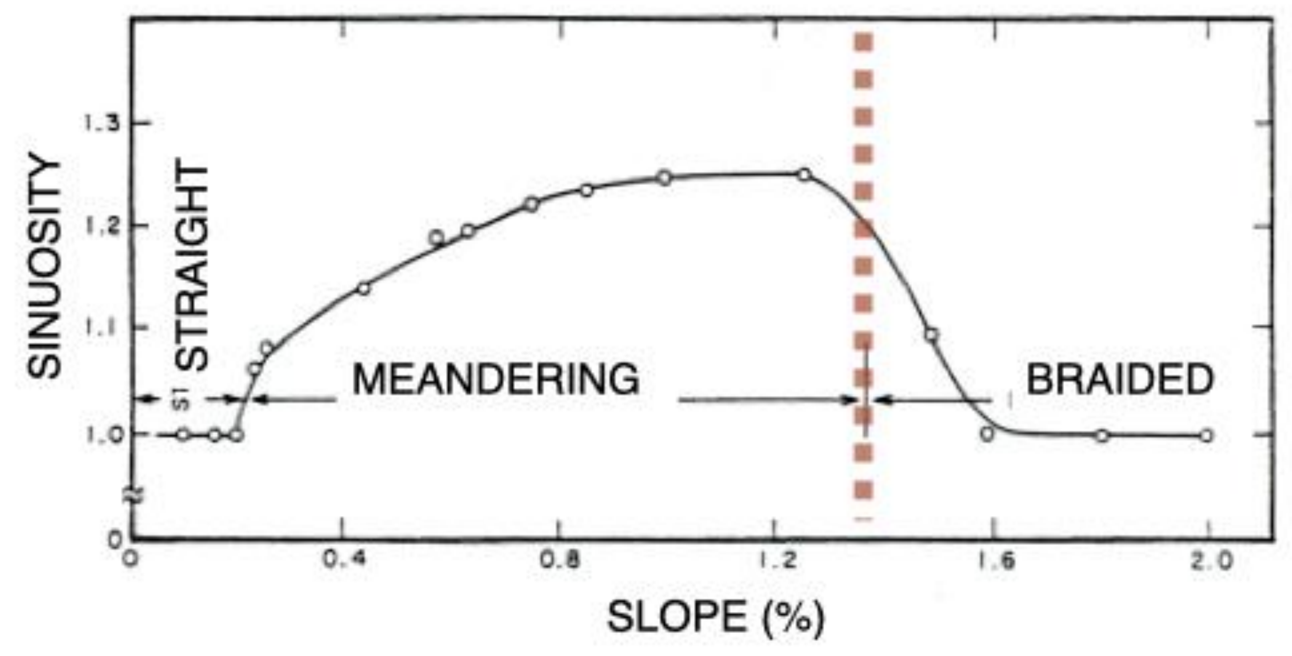
1. ***Geology* and *climate*:**
   - ✓ *Narrow valleys filled with glacio-fluvial outwash material*
   - ✓ *Steep/powerful bedload streams with a braided or multi-threaded pattern*
   - ✓ *Intense flooding/destructive ice jams*

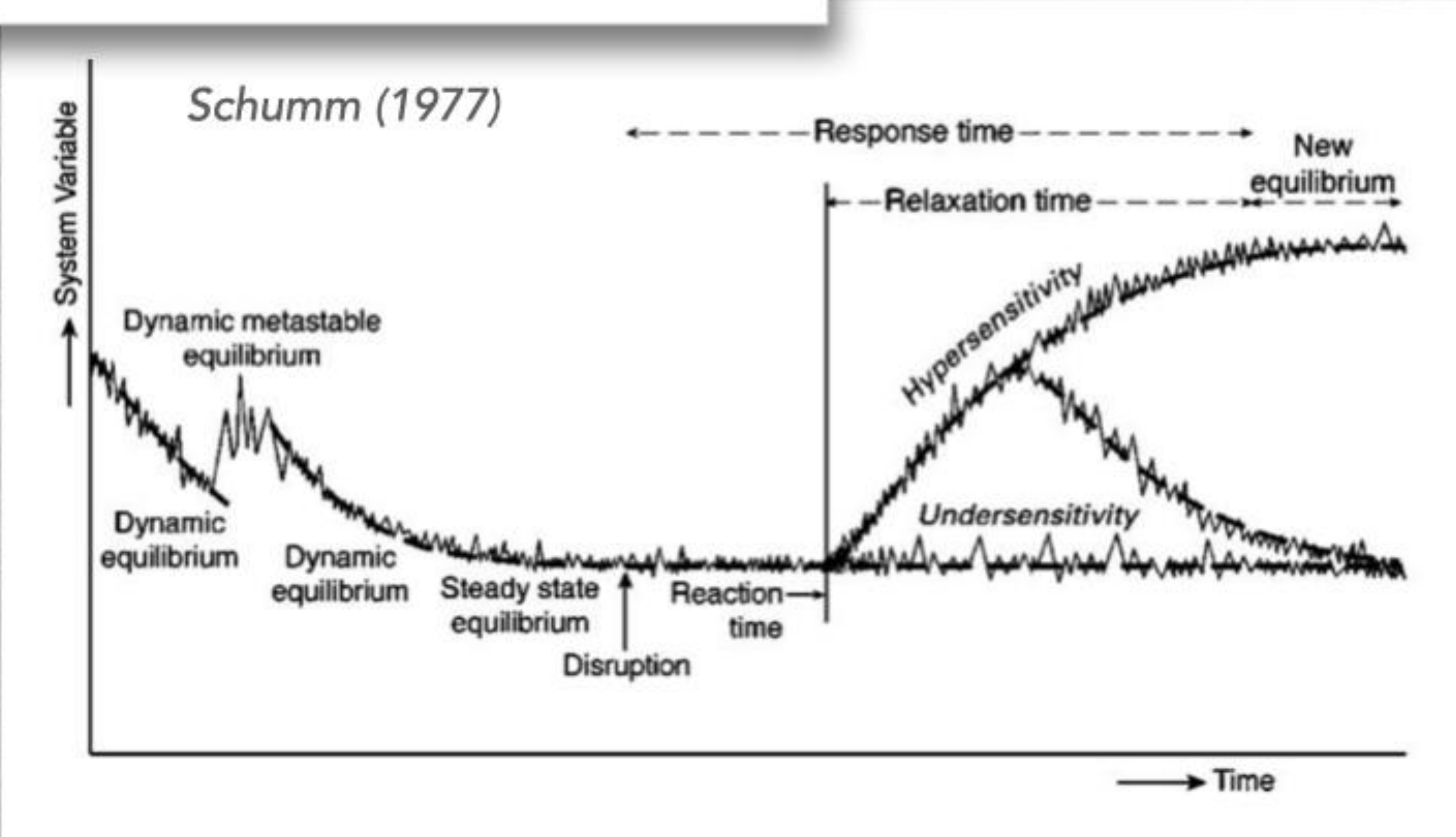
2. ***Historic land use*:**
   alterations to hill slopes and channels for logging and farming

3. ***Present-day land use*:**
   - ✓ *Settlement: homes and small towns*
   - ✓ *Agriculture: small farms*
   - ✓ *Transportation corridors*



"Intrinsic" thresholds

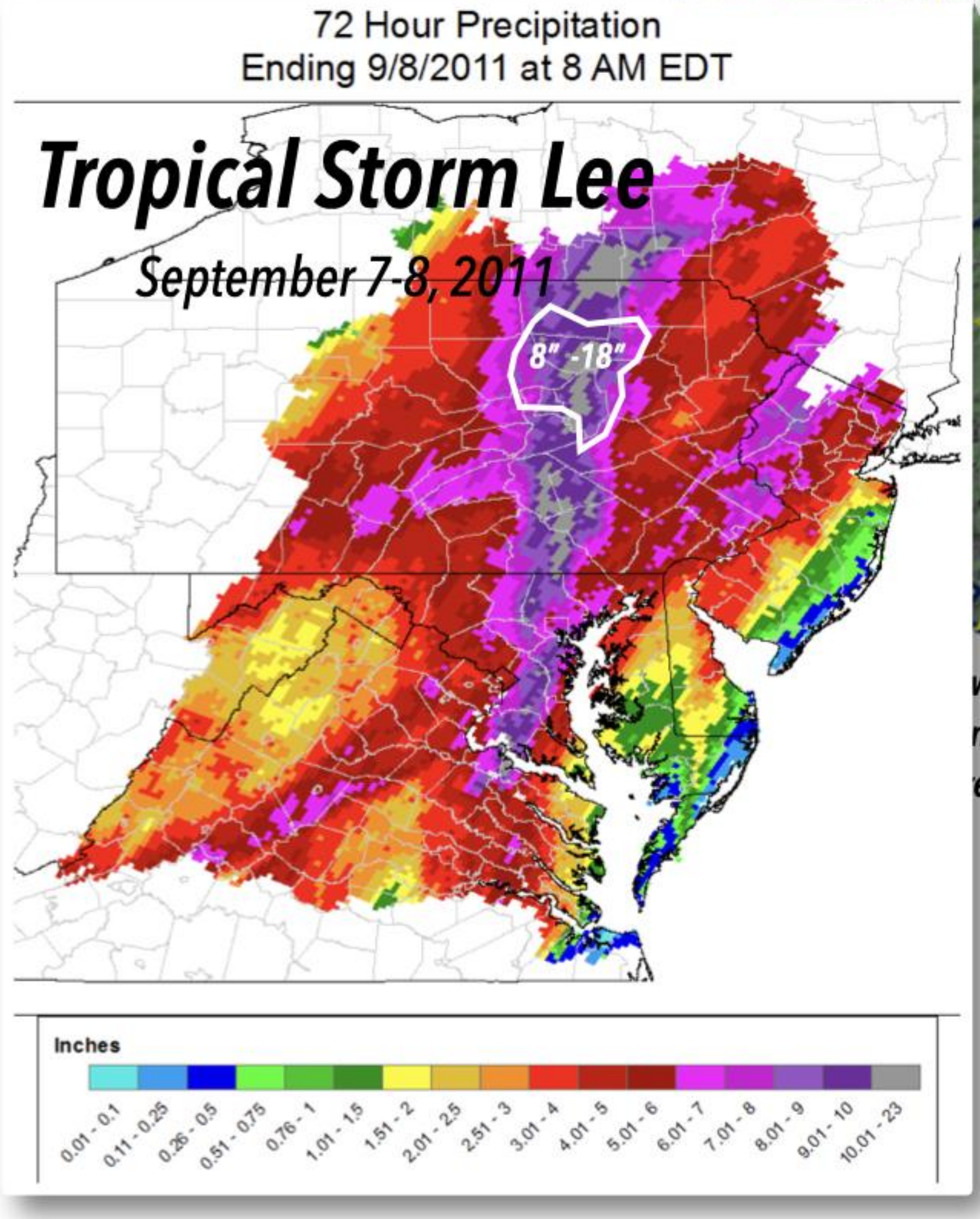


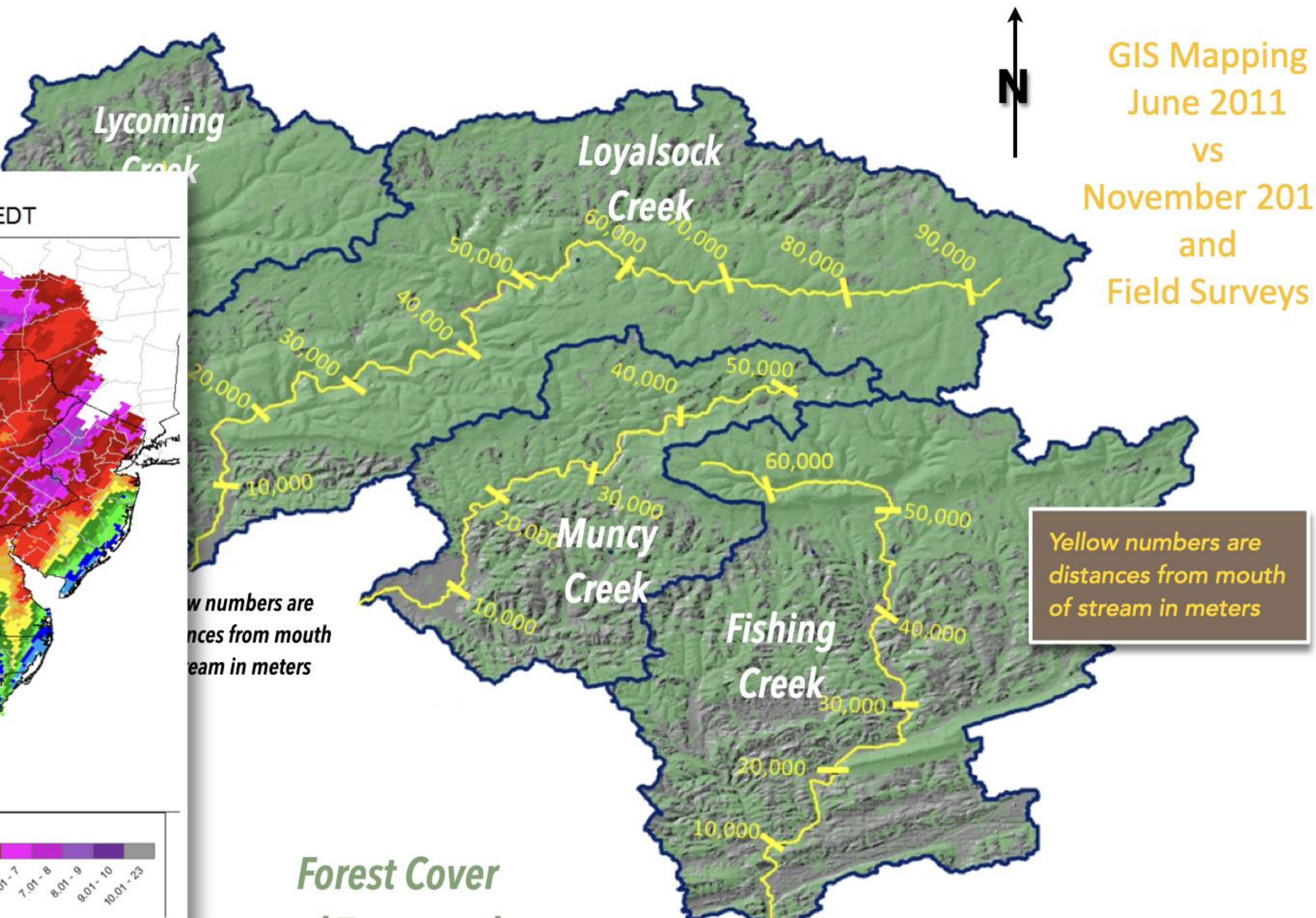


System thresholds and Dynamic Equilibrium

5 Key Concept

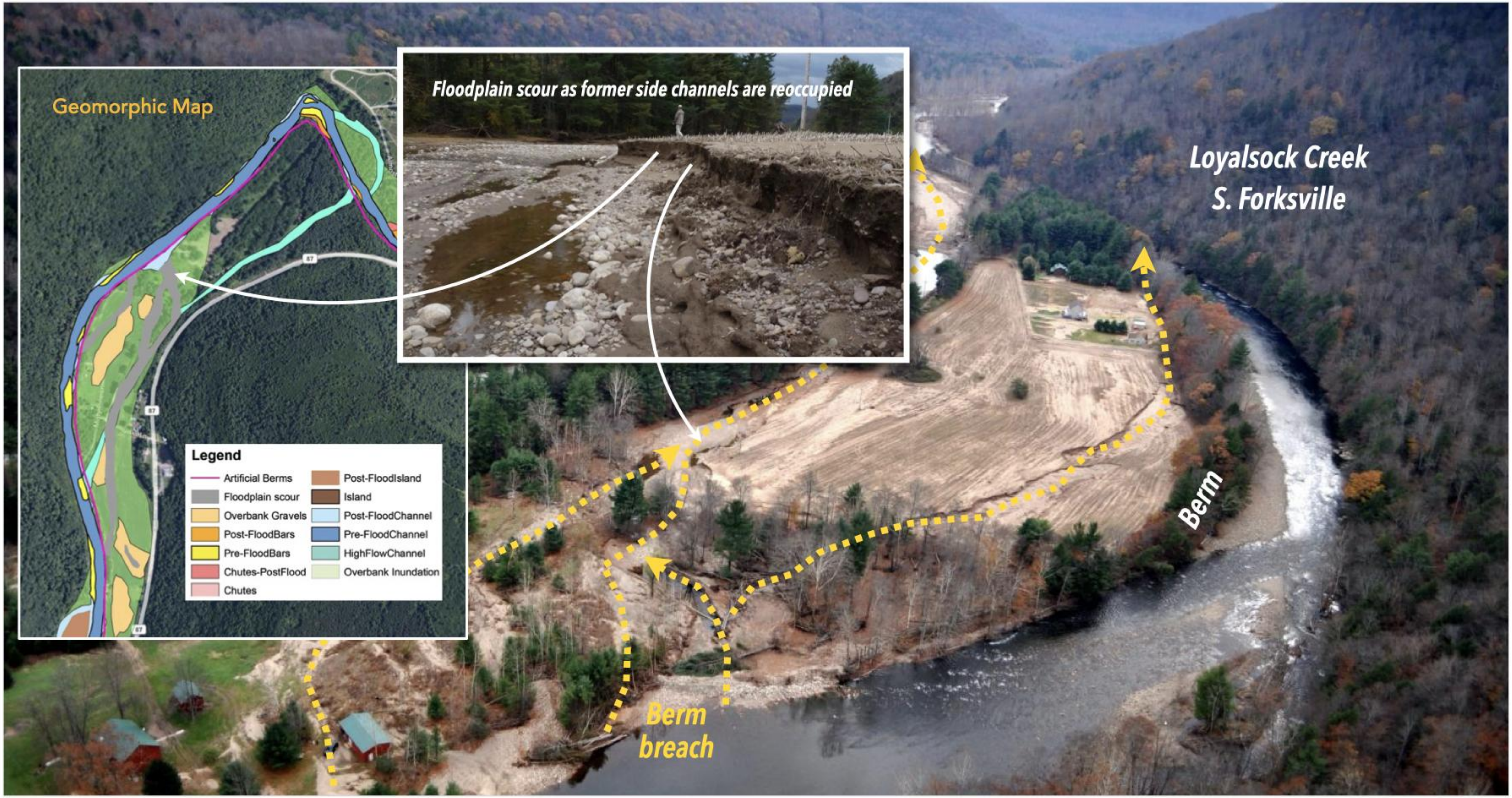
Study Area > 250 km
4 watersheds

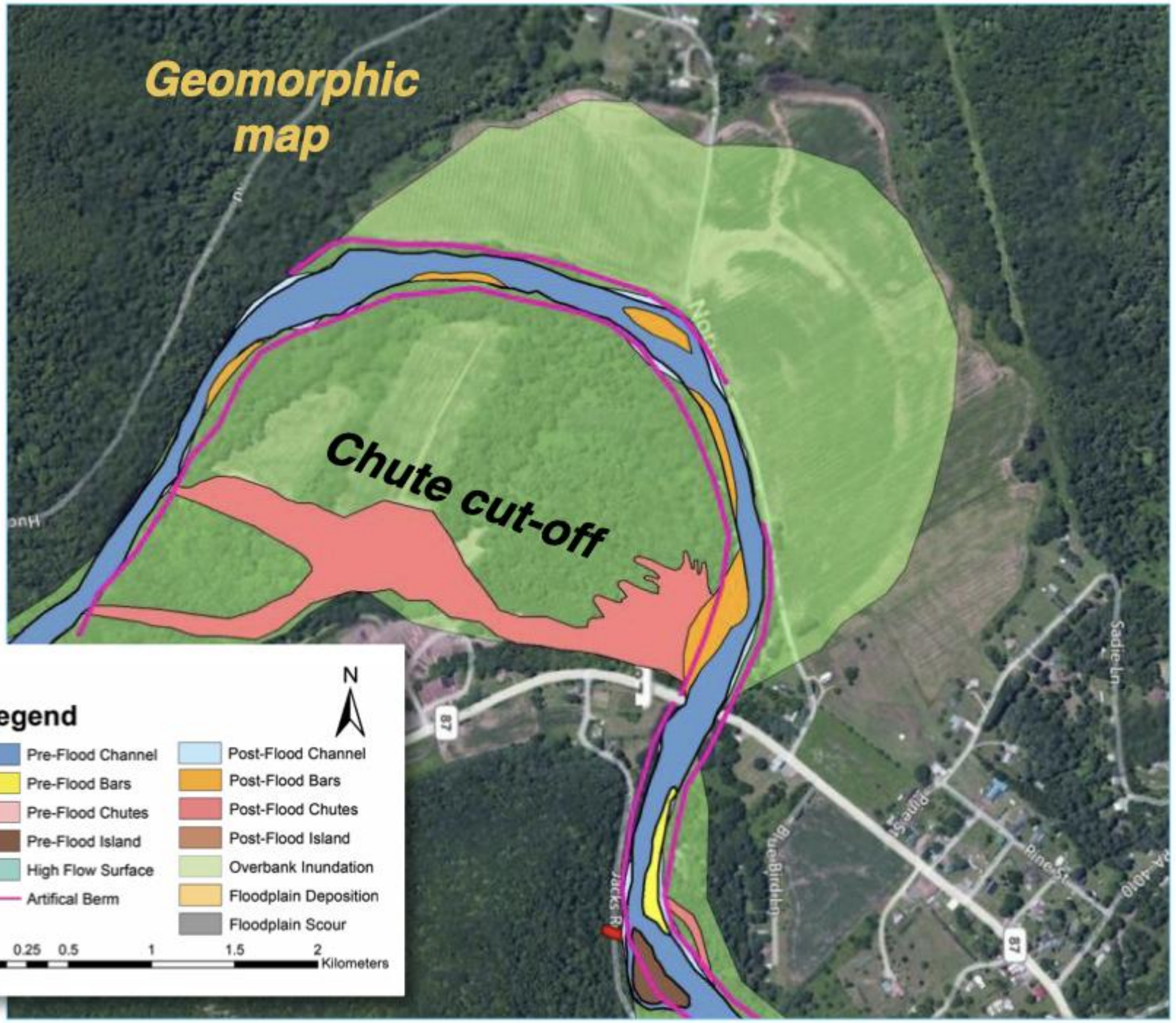




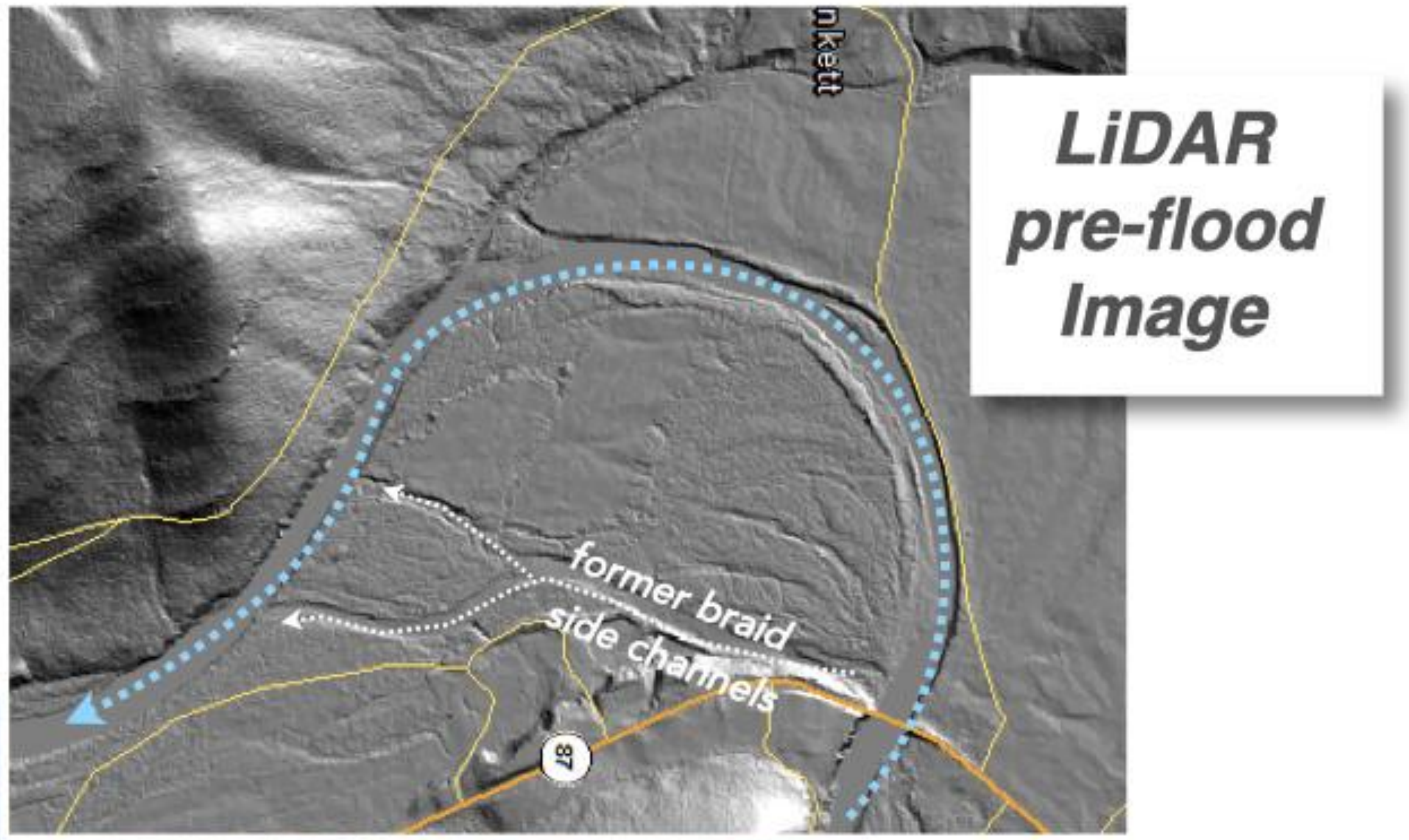
GIS Mapping
June 2011
vs
November 2011
and
Field Surveys

Forest Cover and Topography


Geomorphic Map
Floodplain scour as former side channels are reoccupied
Loyalsock Creek
S. Forksville
Legend
Artificial Berms
Floodplain scour
Overbank Gravels
Post-FloodBars
Pre-FloodBars
Chutes-PostFlood
Chutes
Post-FloodIsland
Island
Post-FloodChannel
Pre-FloodChannel
HighFlowChannel
Overbank Inundation
87
Berm
Berm breach



Loyalsock Creek near Hillsgrove

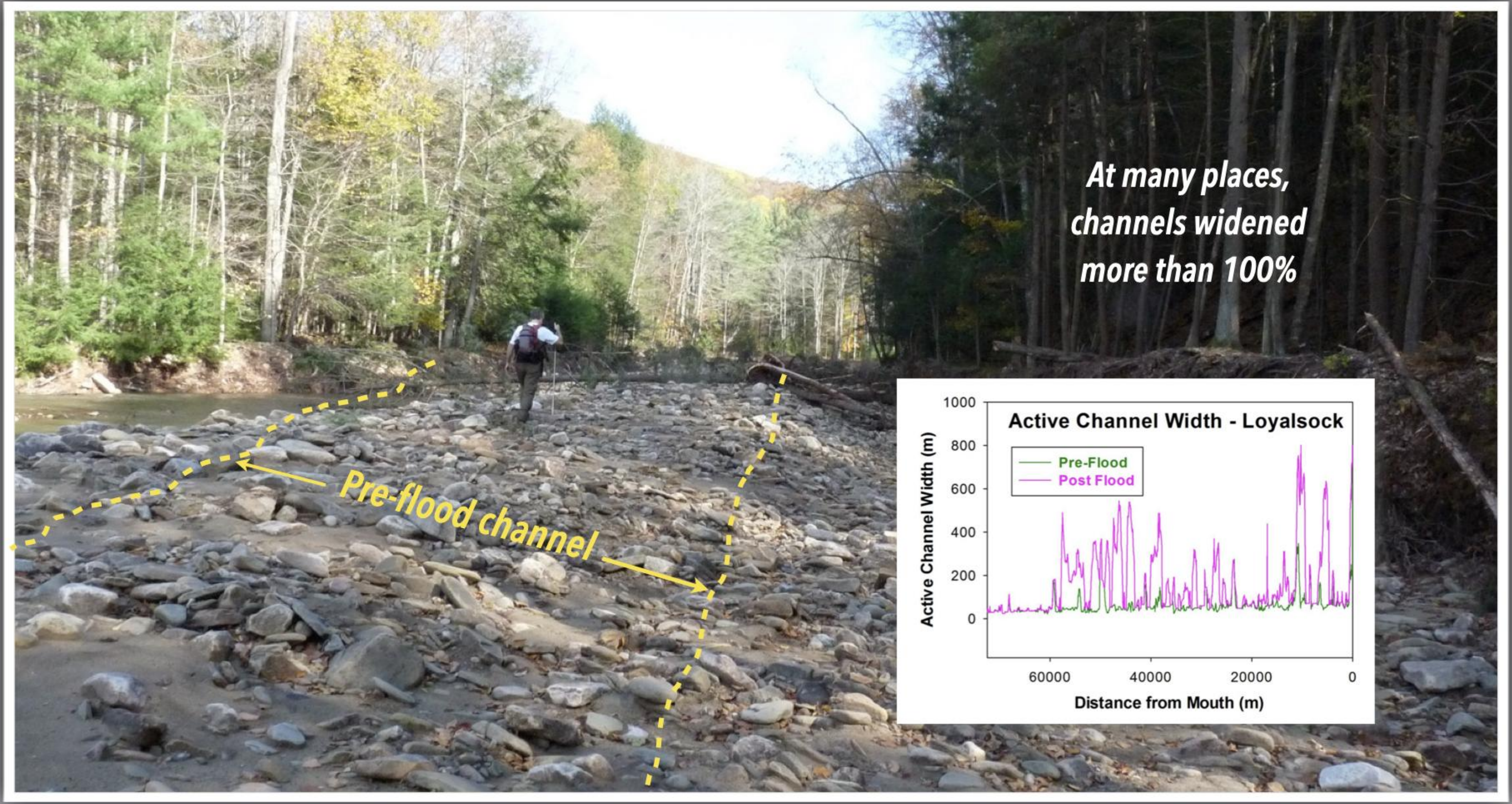


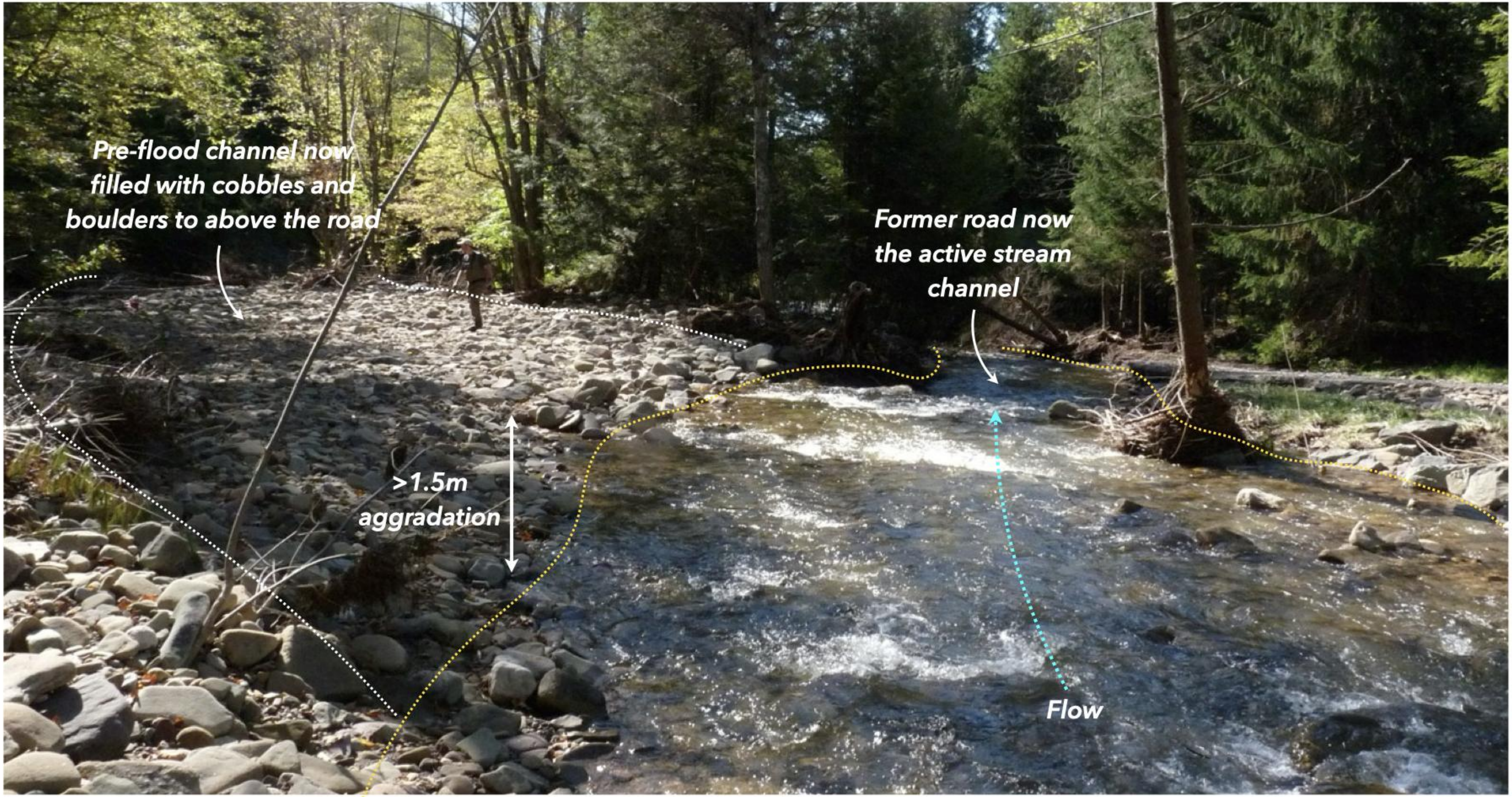
From: Kochel, Hayes, and others (2016)

Chute cut-offs on inside of large meanders

Re-occupying former braid side channels on the inside of large meander bends

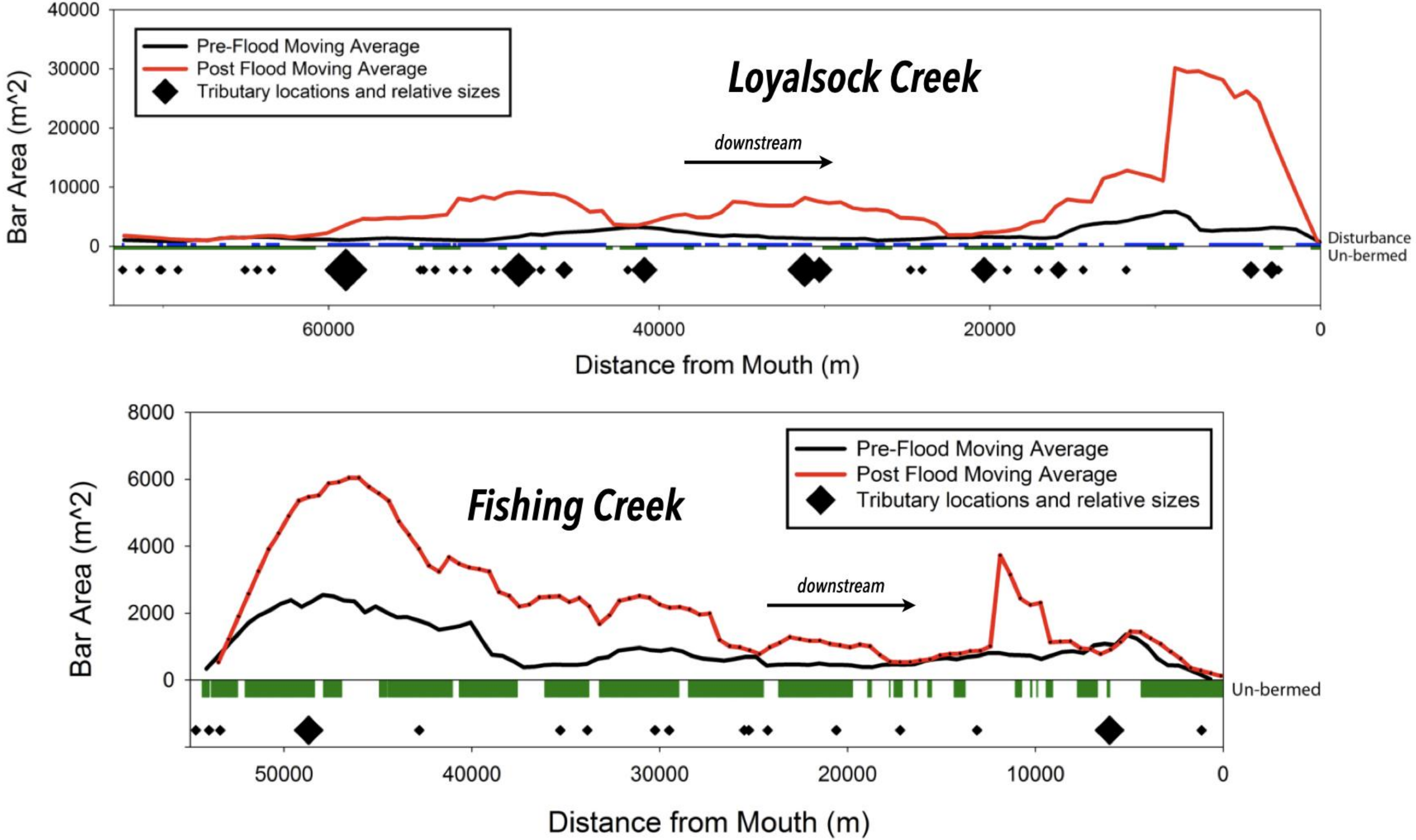

At many places, channels widened more than 100%
Pre-flood channel


At many places, channels widened more than 100%
Pre-flood channel
Active Channel Width - Loyalsock
Pre-Flood
Post Flood
Active Channel Width (m)
1000
800
600
400
200
0
60000
40000
20000
0
Distance from Mouth (m)


Pre-flood channel now
filled with cobbles and
boulders to above the road
Former road now
the active stream
channel
>1.5m
aggradation
Flow


Alluvial Fan Formation
(Fishing Creek above Elk Grove, PA)
Sept 2018

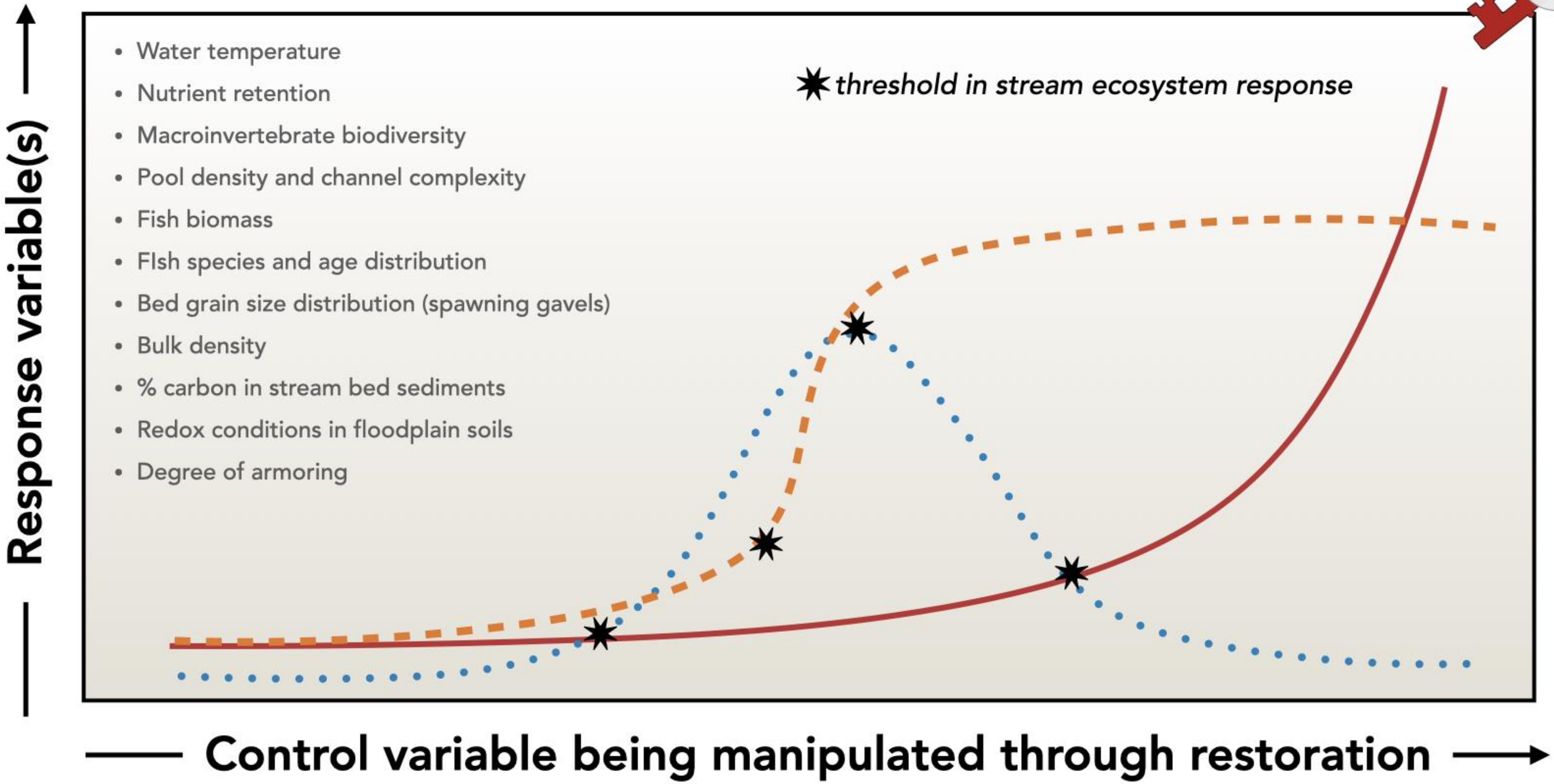

Forest Burial by Debris Flows
(Fishing Creek above Elk Grove, PA)
Sept 2018



Loyalsock Creek
Pre-Flood Moving Average
Post Flood Moving Average
Tributary locations and relative sizes
downstream
Bar Area (m^2)
40000
30000
20000
10000
0
Disturbance
Un-bermed
60000
40000
20000
0
Distance from Mouth (m)
Fishing Creek
Pre-Flood Moving Average
Post Flood Moving Average
Tributary locations and relative sizes
downstream
Bar Area (m^2)
8000
6000
4000
2000
0
Un-bermed
50000
40000
30000
20000
10000
0
Distance from Mouth (m)

DISRUPTION - RESPONSE (BEHAVIOR)

Key 5 Concept



- flow regime
- sediment regime
- extent of riparian zone
- connectivity with the floodplain
- backwater habitat
- connectivity with the hyporheic zone

After Wohl et. al. (2015).

Assessing restoration structures on stream in Bradford County, PA