Quantifying Human Impacts on Natural Rates Of Erosion Along Continental Margins

A dissertation presented
By
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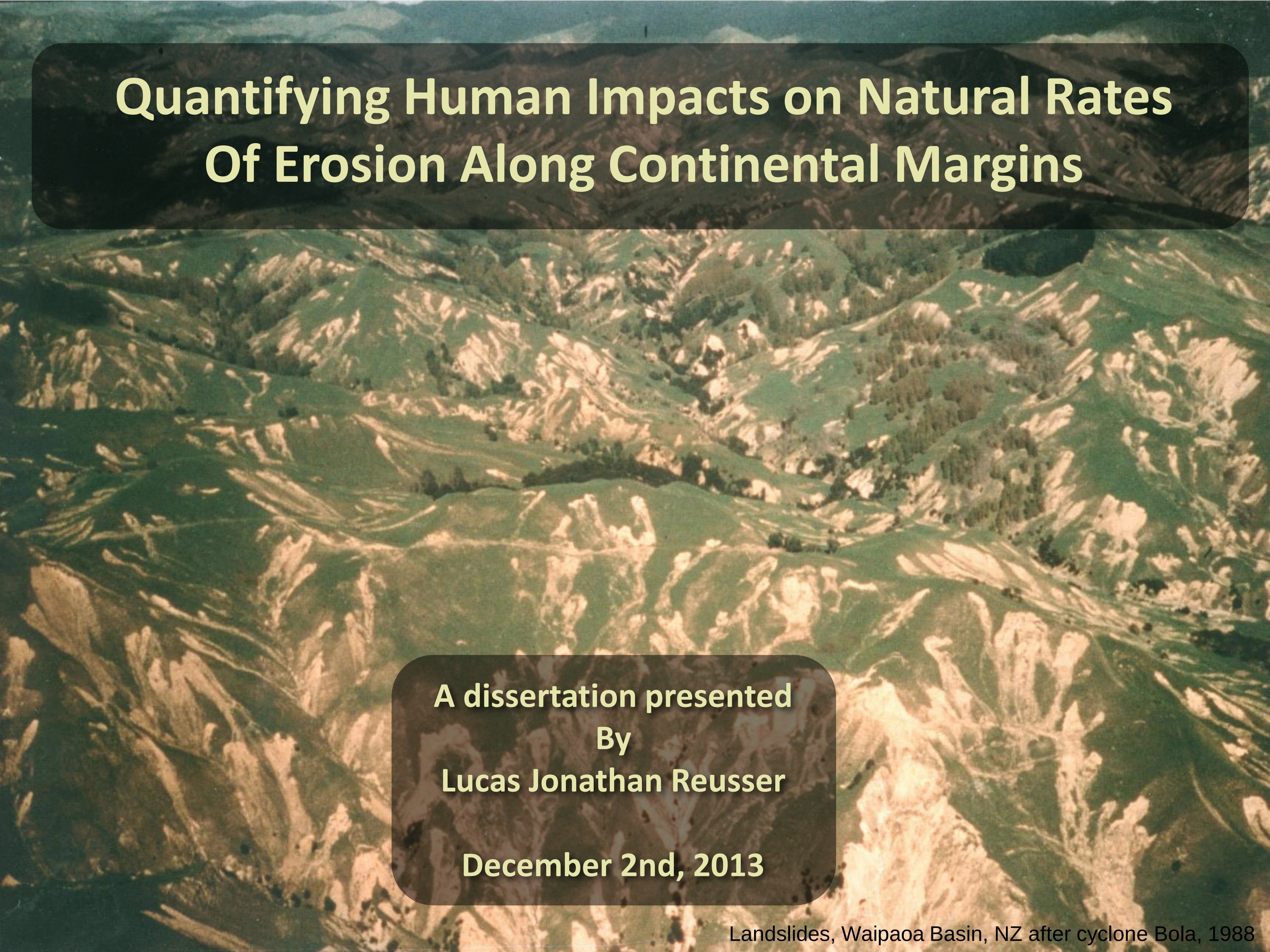
December 2nd, 2013

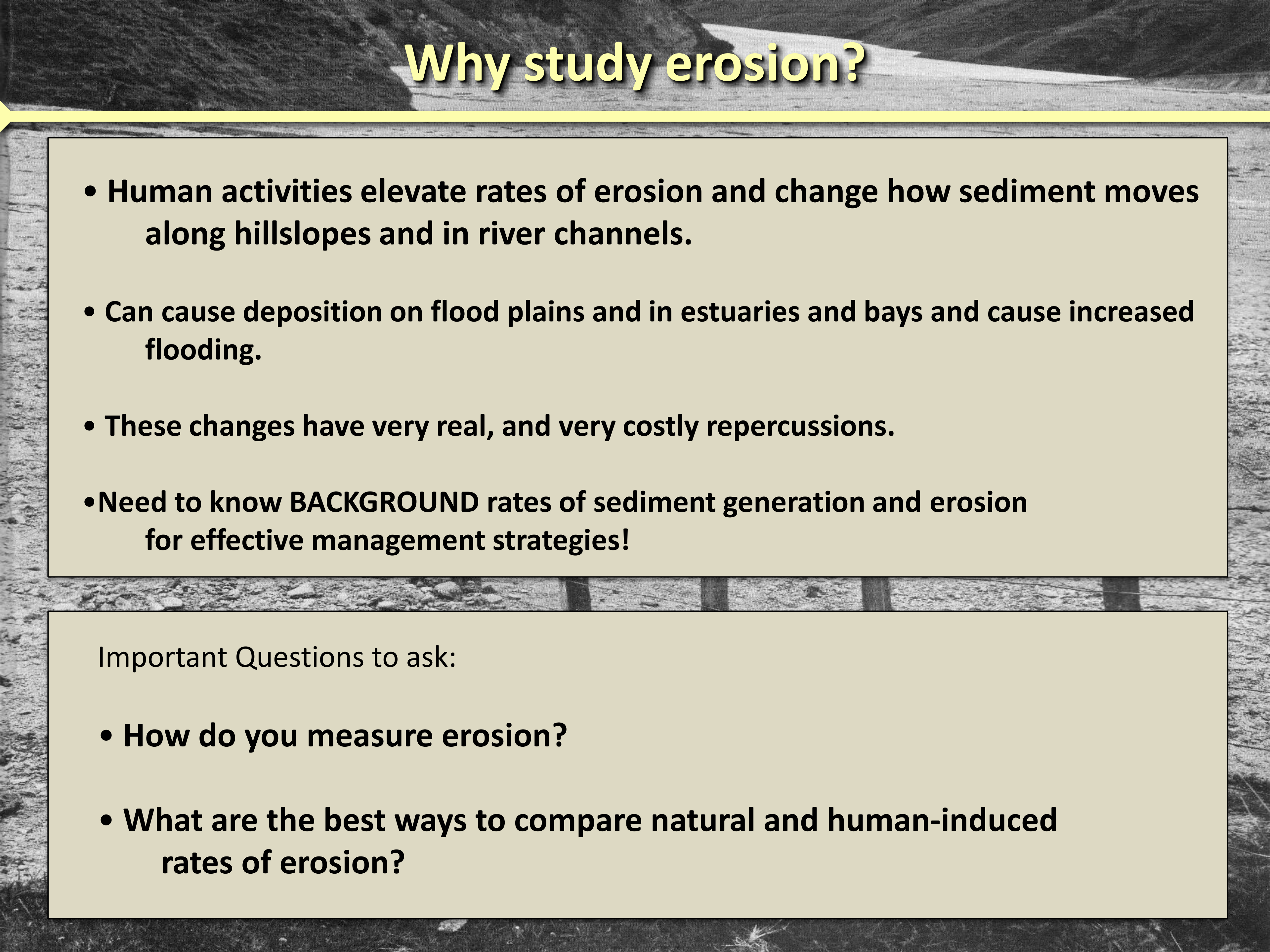


Landslides, Waipaoa Basin, NZ after cyclone Bola, 1988

Seminar outline

- **Overview of Research**
    - Landscape erosion – natural and human-induced
    - Methods of measurement
    - Background rates with ^{10}Be vs. Short-term rates
    - Introduction to Study Sites
- **Primary Objectives**
- ***In situ* and meteoric ^{10}Be systematics**
- **Background erosion and erosion prediction along the southern Appalachian Piedmont, Atlantic Passive Margin**
- **Sediment mixing and background erosion in the active and non-uniformly eroding Waipaoa Basin, North Island, New Zealand**
- **Summary and conclusions**

Why study erosion?



- Human activities elevate rates of erosion and change how sediment moves along hillslopes and in river channels.

- Can cause deposition on flood plains and in estuaries and bays and cause increased flooding.

- These changes have very real, and very costly repercussions.

- Need to know BACKGROUND rates of sediment generation and erosion for effective management strategies!

Important Questions to ask:

- **How do you measure erosion?**

- **What are the best ways to compare natural and human-induced rates of erosion?**

Methods of measuring erosion:

Short-term:

(years to decades)

- Reservoir Infilling Rates
- Water body infilling rates
- Sediment Yields (Delivery) from Rivers

Limitations:

- Very short integration periods (episodic delivery)
- Extreme sensitivity to landuse history

Intermediate Time Frame:

(Typically thousands to tens of thousands)

Cosmogenic Isotopes such as ^{10}Be

- Erosion at discrete points

-or-

- Spatially and Temporally Averaged Drainage Basin-Scale Erosion Rates

- **Good for comparing natural and human-induced rates**

Long-term:

(millions to hunderds of millions)

- Thermochronometry
  - Fission Track
  - (U-Th)/He
- Offshore Sedimentation Rates

Limitations:

- Long integration time.
- Records reflect periods of vastly different climatic and potentially tectonic conditions

Study regions:

- Broad geographic regions along several well-characterized continental margins

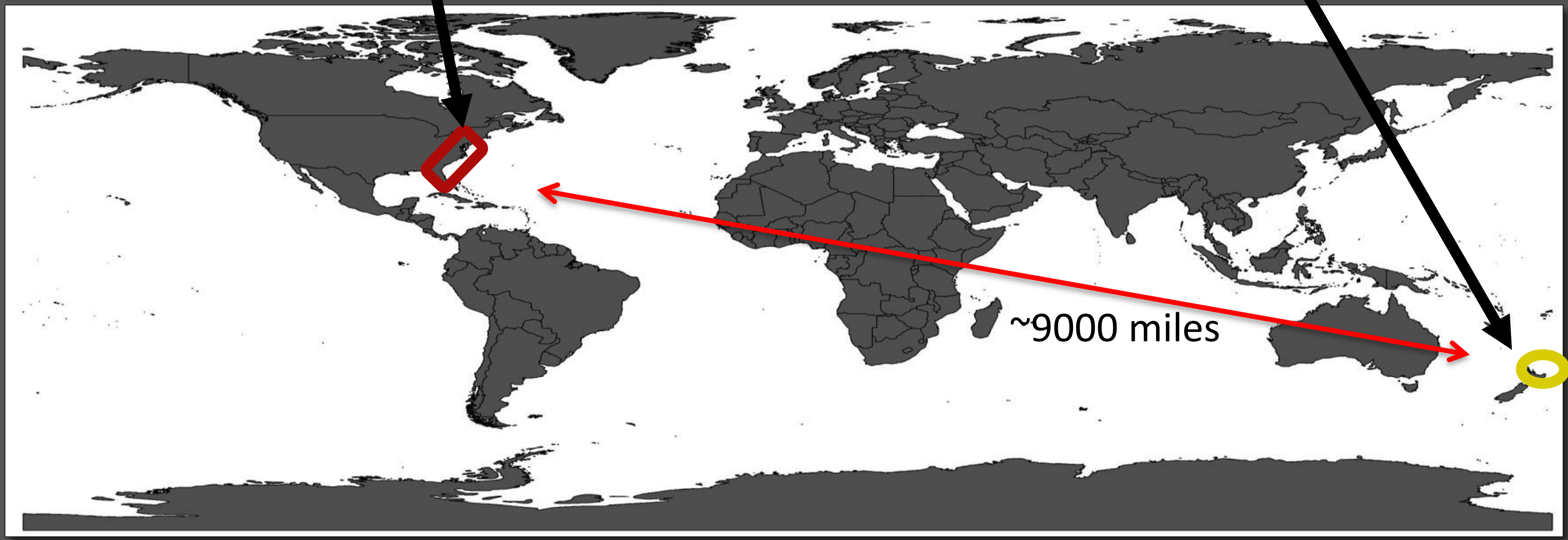
- Widely differing tectonic and climate gradients, But share similar landuse histories (agricultural)

Southern Appalachian Piedmont

- Passive Margin Environment
- Intense agricultural disturbance Between 1700 and ~1920

Waipaoa River Basin North Island, NZ

- Active subduction margin
- Widespread agricultural land-Clearance. Modern afforestation Efforts.



Primary Objectives of Research:

1. **Comparison of natural long-term (*in situ* ^{10}Be), and modern-day, human-induced (sediment yield derived) rates of erosion.**
    - Potential implications for resource management.

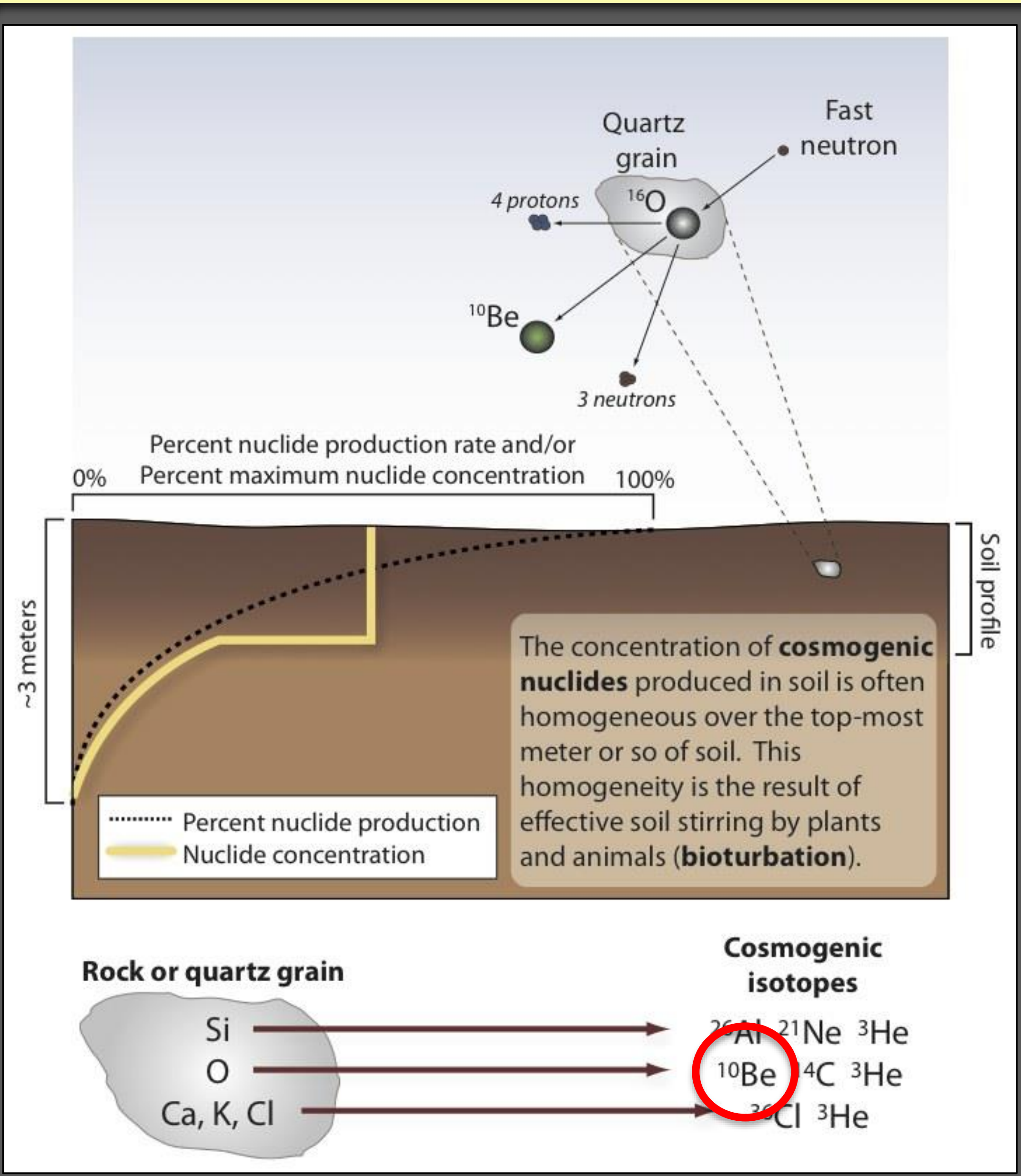
2. **Investigate the sourcing and mixing of sediment in disturbed landscapes with meteoric ^{10}Be.**
    - Primarily in the Waipaoa River Basin, NZ where quartz is scarce.
    - Apportion the relative contribution of sediment from different regions across a landscape.

1. **Explore relationships between tectonics, climate, and land-use history with one of the largest coherent ^{10}Be datasets collected to date.**
    - Provide ^{10}Be erosion rates in previously untestable environments
    - Compare and contrast ^{10}Be findings to other measures of landscape change.
    - Further develop relationships between erosion and physical landscape characteristics.

Production and accumulation of

- *In situ* ^{10}Be
- Meteoric ^{10}Be

In situ production of ^{10}Be:



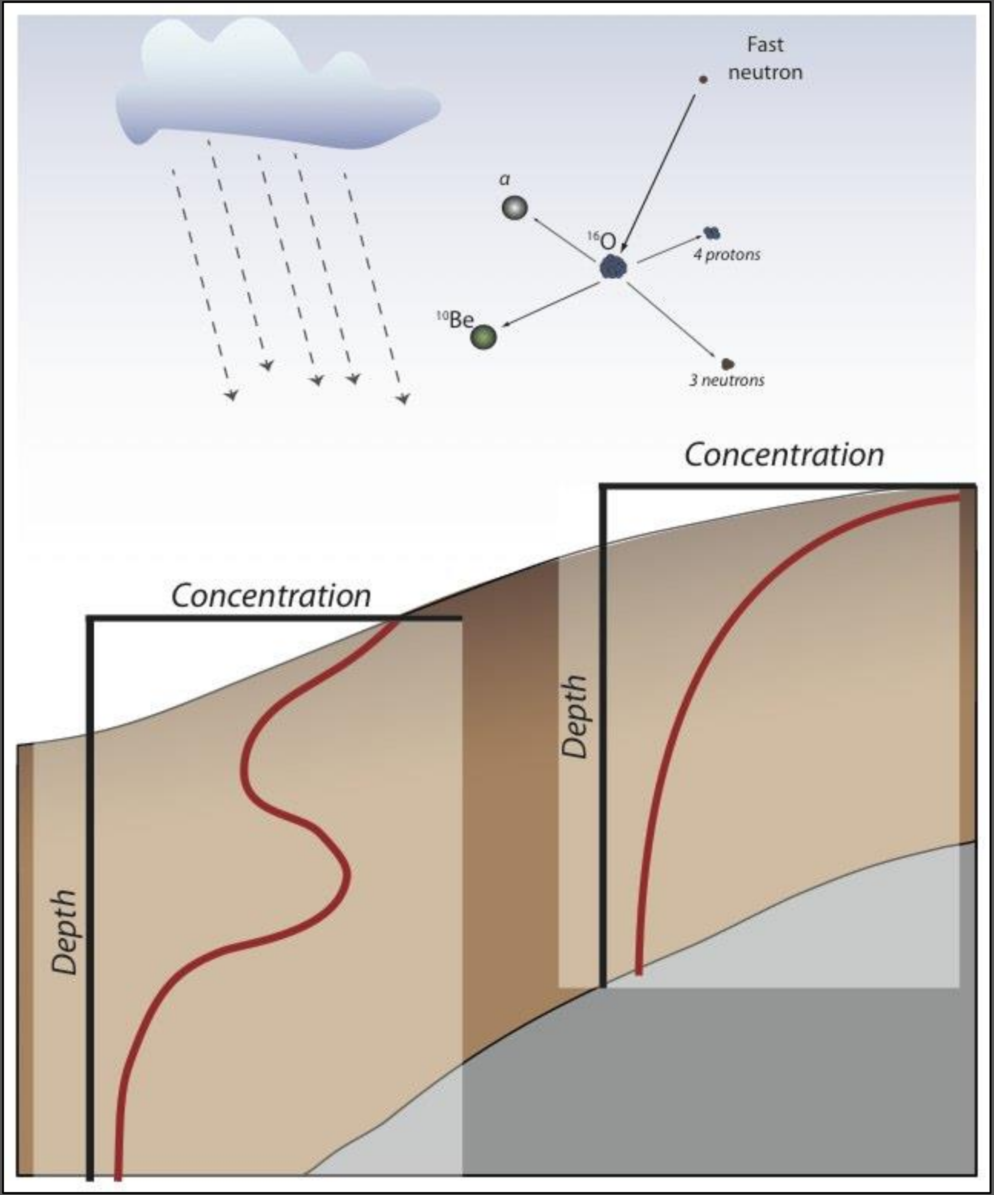
The concentration of **cosmogenic nuclides** produced in soil is often homogeneous over the top-most meter or so of soil. This homogeneity is the result of effective soil stirring by plants and animals (**bioturbation**).

- Produced in upper several meters of rocks and sediment exposed at Earth’s Surface.

- Production rate: ~**5.2** atoms per gram of quartz per year - **measurable with AMS.**

- Half-life of ~**1.36** millions years – residence time of near surface materials much shorter meaning ^{10}Be behaves as a **stable nuclide** over period of measurement.

Accumulation of meteoric ^{10}Be in soils:



- Produced in the **atmosphere** by the same processes as *in situ* ^{10}Be

- **Delivered** to soils across landscapes in rain, and to a lesser extent in NZ in dust.

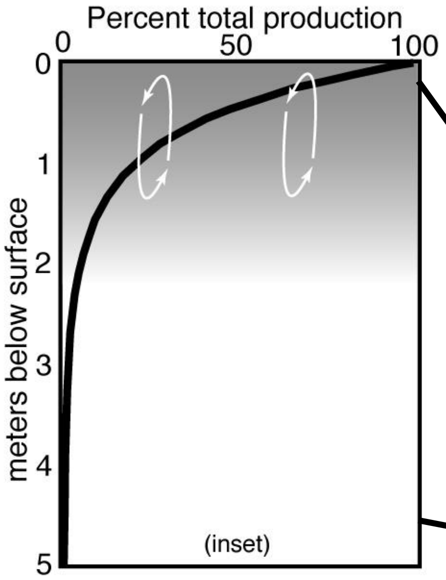
- Accumulates over time in hillslope materials that eventually make their way to river channels.

- Accumulation rate: **~1.7 x 10^{6}** atoms per cm^{2} annually – easily **measurable with AMS.**

- Half-life of ~**1.38** millions years – residence time of near surface materials much shorter meaning ^{10}Be behaves as a **stable nuclide** over period of measurement.

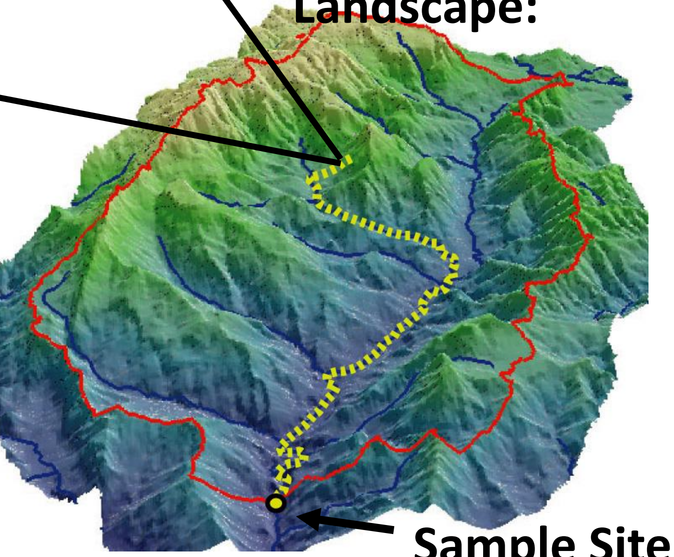
Drainage basin-scale erosion rates with *in situ* ^{10}Be And sediment sourcing meteoric ^{10}Be:

Production at Surface:



- Exponential decay with depth
- Production limited to upper several meters - **Isolates near-surface process rates**
- Thorough mixing homogenizes ^{10}Be inventory - **relatively insensitive to Human Landuse Practices**

Steadily Eroding Landscape:



Sample Site

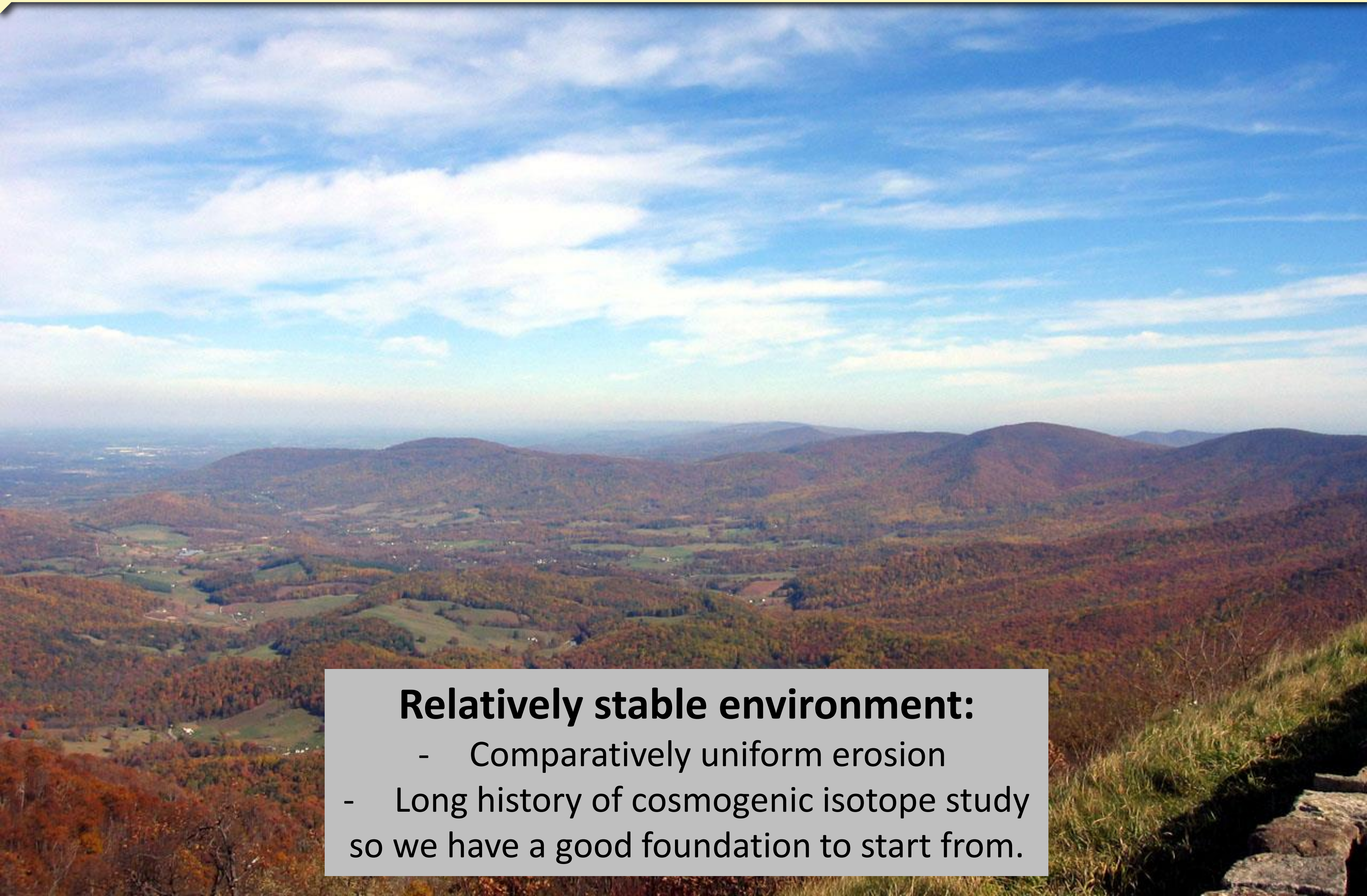
Sediment Sample:

- Rivers Mix millions Of sediment grains
- Each grain has unique history of Exhumation Erosion and Transportation To sample site
- Represents the spatially averaged history of erosion within a drainage basin

Erosion Along Continental Margins:

1. Southern Appalachian Piedmont and Blue Ridge, draining the North American Atlantic passive margin.
2. Waipaoa River Basin along the tectonically active eastern margin of New Zealand’s North Island.

1. Southern Appalachian Piedmont, USA



Relatively stable environment:

- Comparatively uniform erosion
- Long history of cosmogenic isotope study

so we have a good foundation to start from.

Appalachian Mountain Chain

Stretches more than 2500 km from Newfoundland, CAN to Alabama, USA

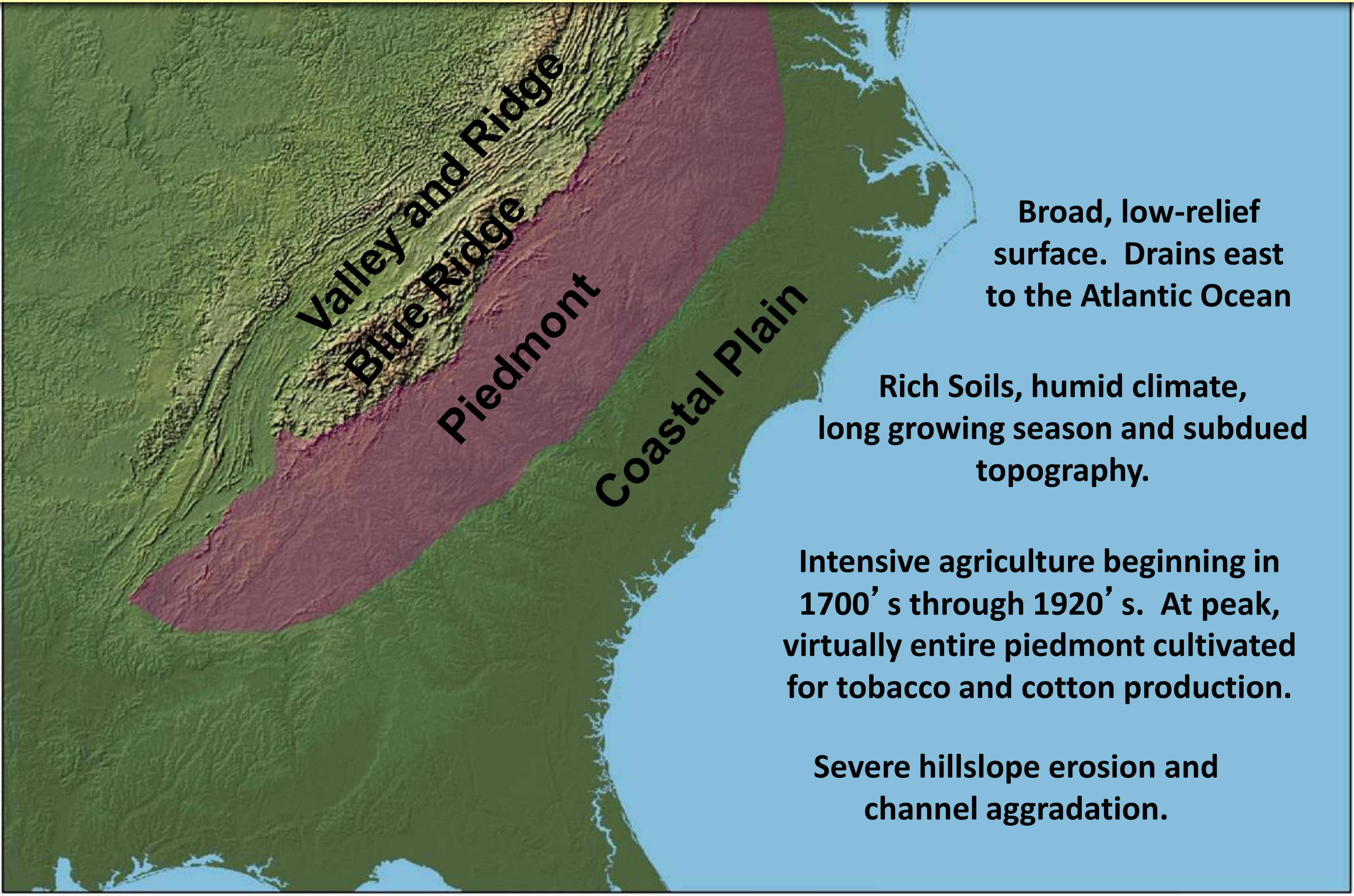
Largely stable environments. Tectonically quiescent for >200 My

Uplift driven by erosion - isostacy

Inspired more than a century of research into:

- The growth and decay of landscapes.
- The persistence of topography.
- The erosional consequences of human-landscape interactions.
- Modern different than background

Southern Appalachian Piedmont



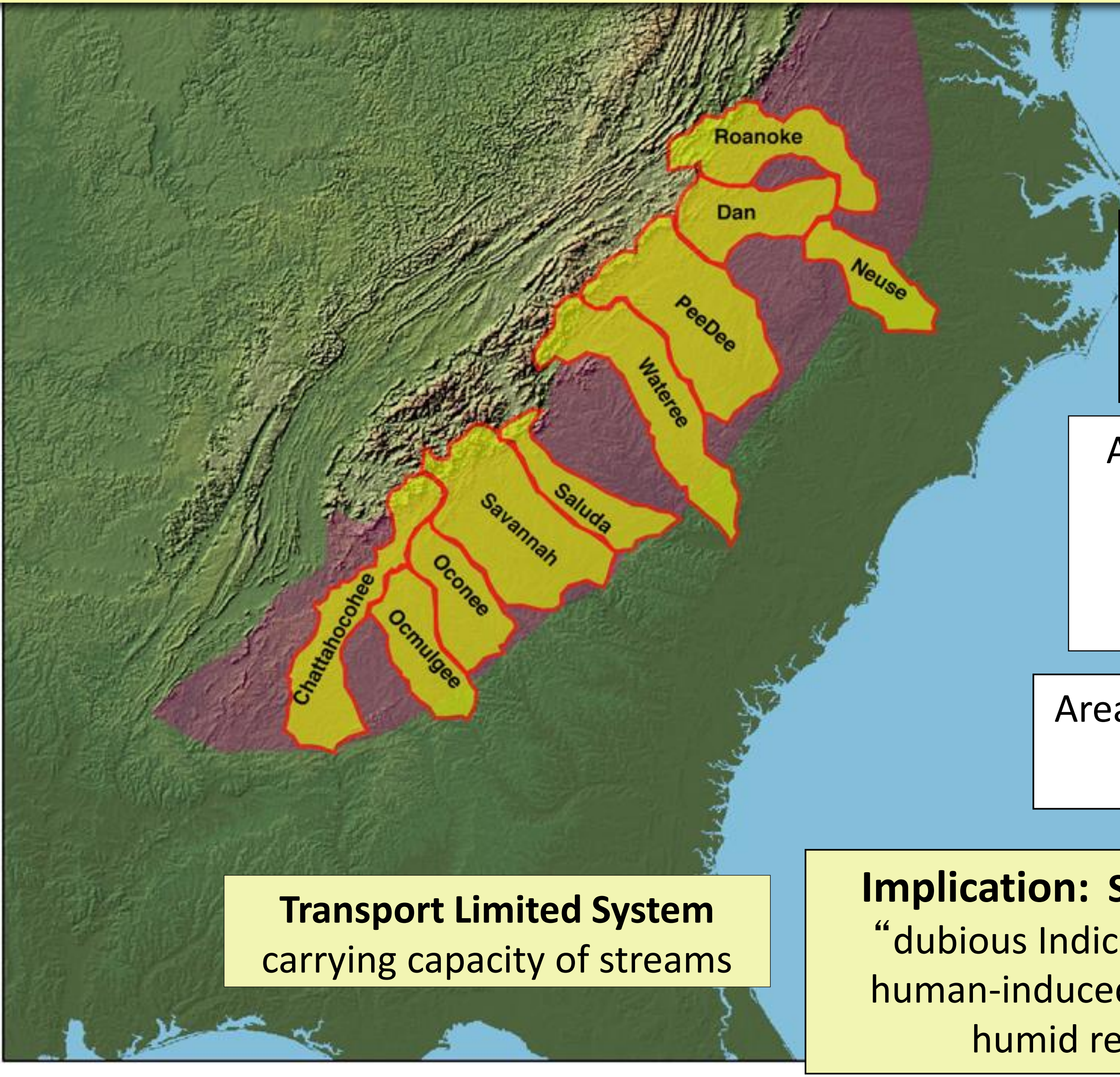
Broad, low-relief
surface. Drains east
to the Atlantic Ocean

Rich Soils, humid climate,
long growing season and subdued
topography.

Intensive agriculture beginning in 1700's through 1920's. At peak, virtually entire piedmont cultivated for tobacco and cotton production.

Severe hillslope erosion and channel aggradation.

"Un-equilibrium streams" - Trimble, 1977



Area-averaged upland erosion rate

~950 m/My

Area-averaged erosion rates inferred from sediment yield data

50 m/My

Area-averaged delivery ratio

~ 5 %

Transport Limited System
carrying capacity of streams

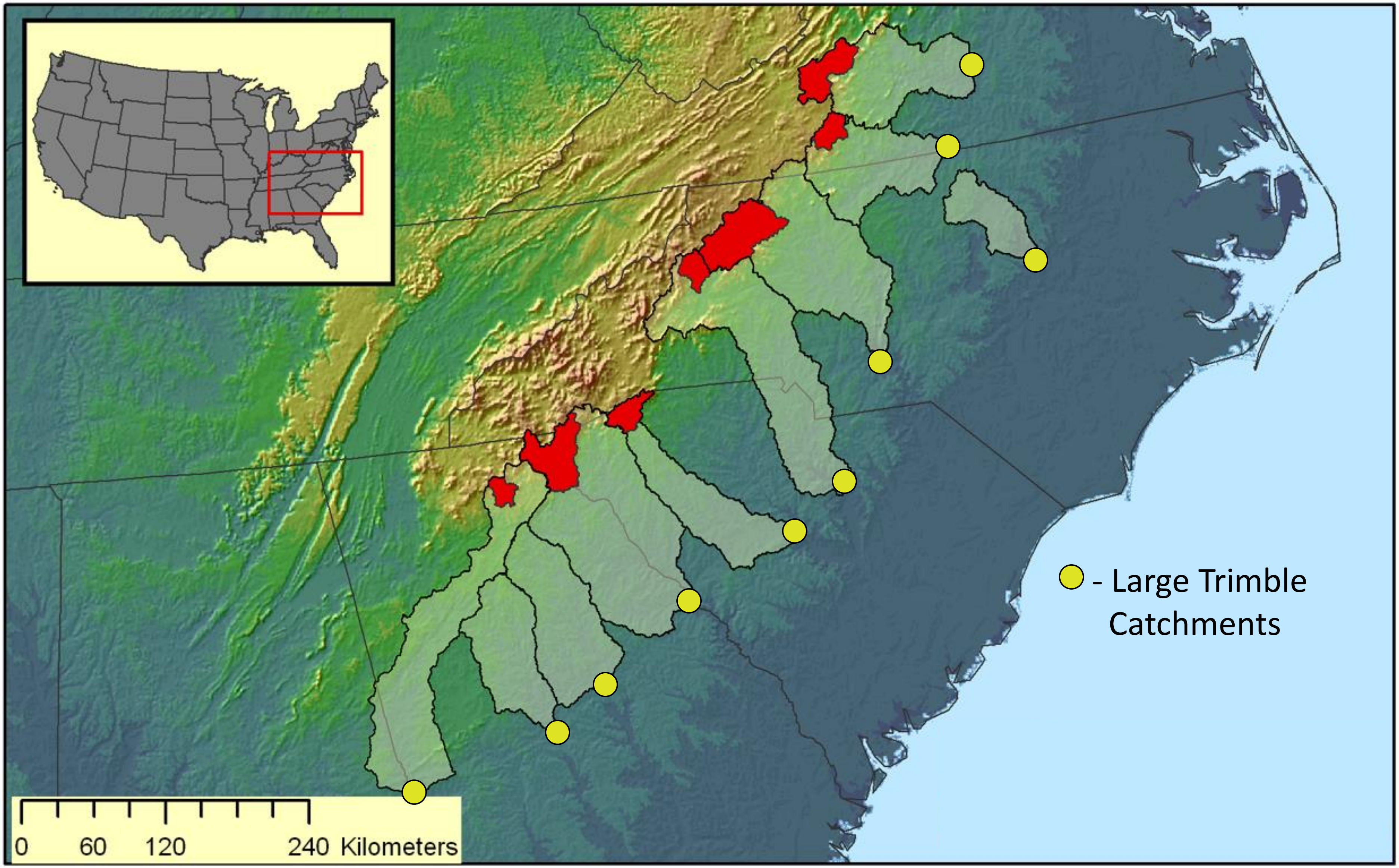
Implication: Sediment yield data are "dubious Indicators" of backgroud or human-induced **erosion rates** in large humid region catchments

Frist testable hypothesis with ^{10}Be:

Frist testable hypothesis with *in situ* ^{10}Be:

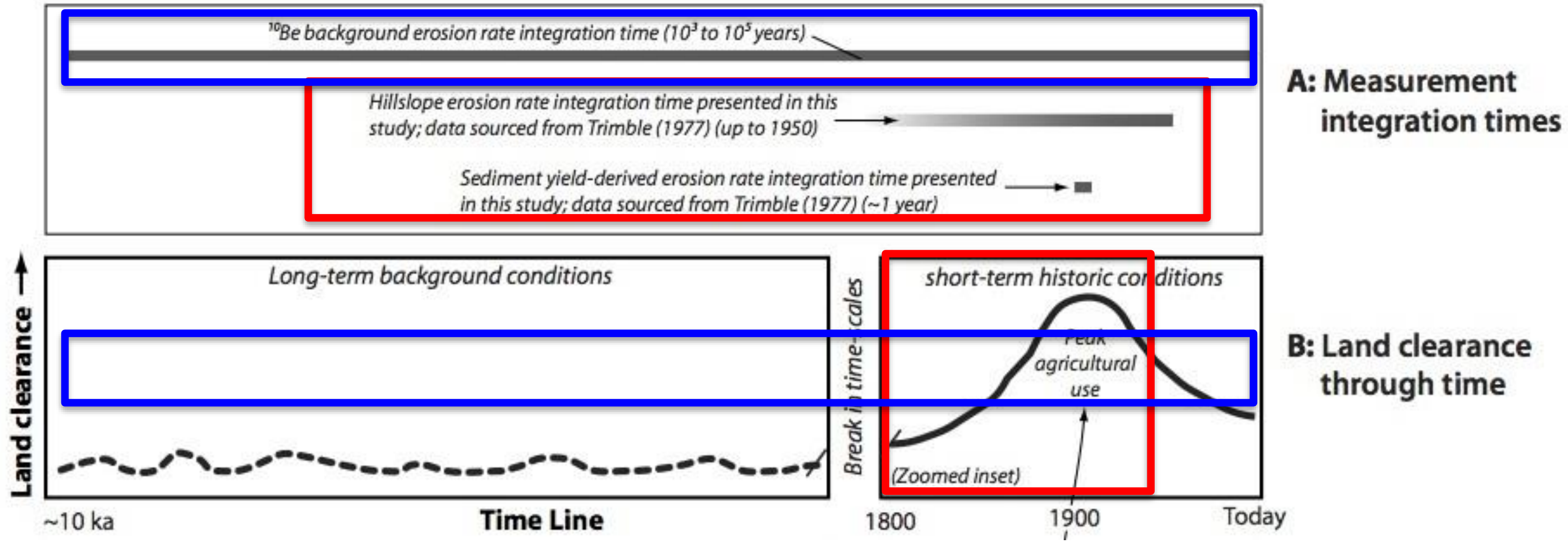
- **Background ^{10}Be** erosion rates from **large** Piedmont basins are lower than human-induced hillslope or sediment yield rates.

Sampling strategies – large basins



● - Large Trimble Catchments

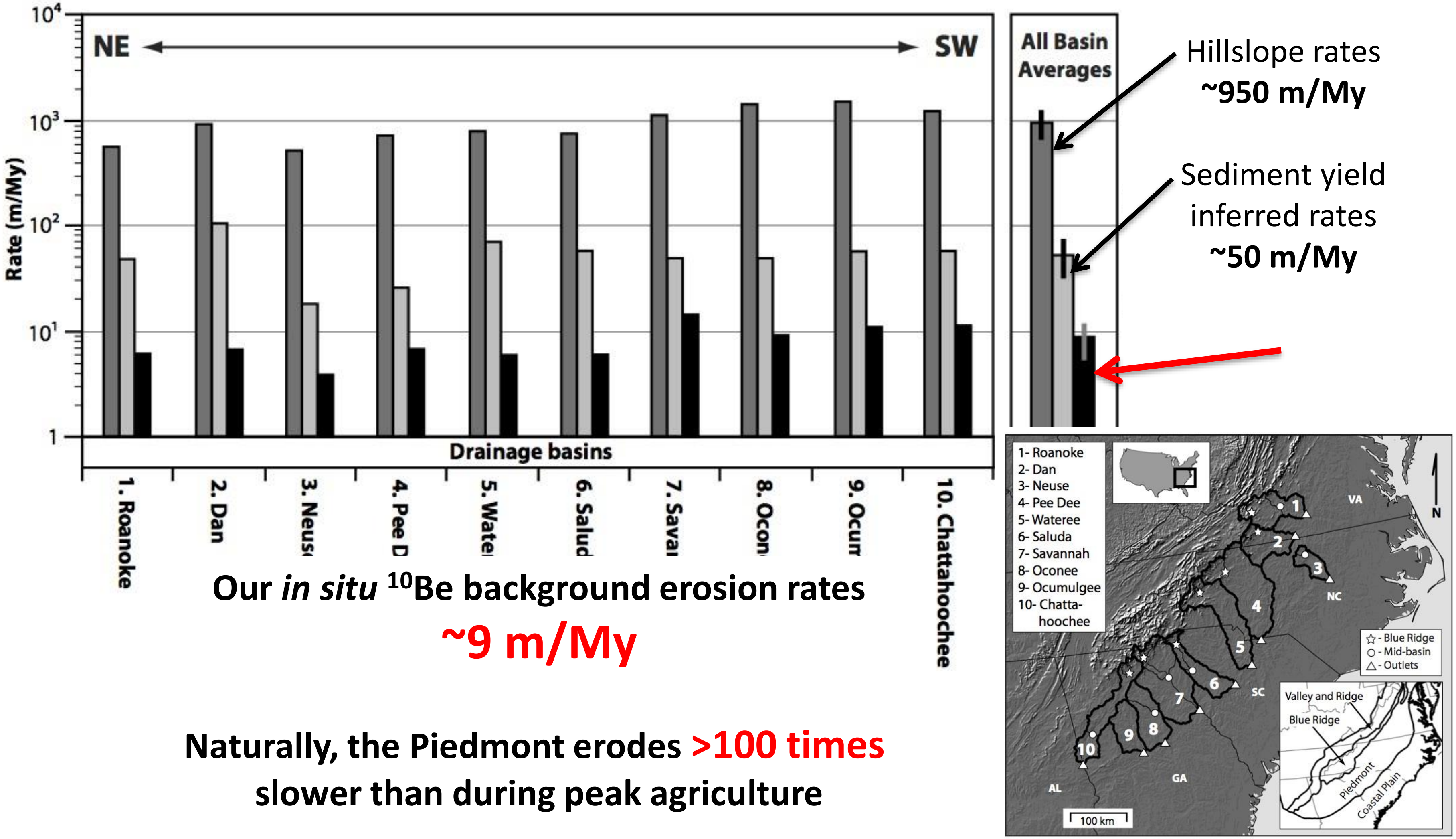
Conceptual models of long- vs. short-term erosion:



- Rates of hillslope erosion integrated from 1700 - ~1950.
- Sediment yield inferred rates ~1 year (1909)

- *In situ* $_{10}$Be rates provide much longer-term averaged background rates.

In situ ^{10}Be results from this study compared to hillslope erosion rate and sediment yield-derived erosion rates from Trimble, (1977).



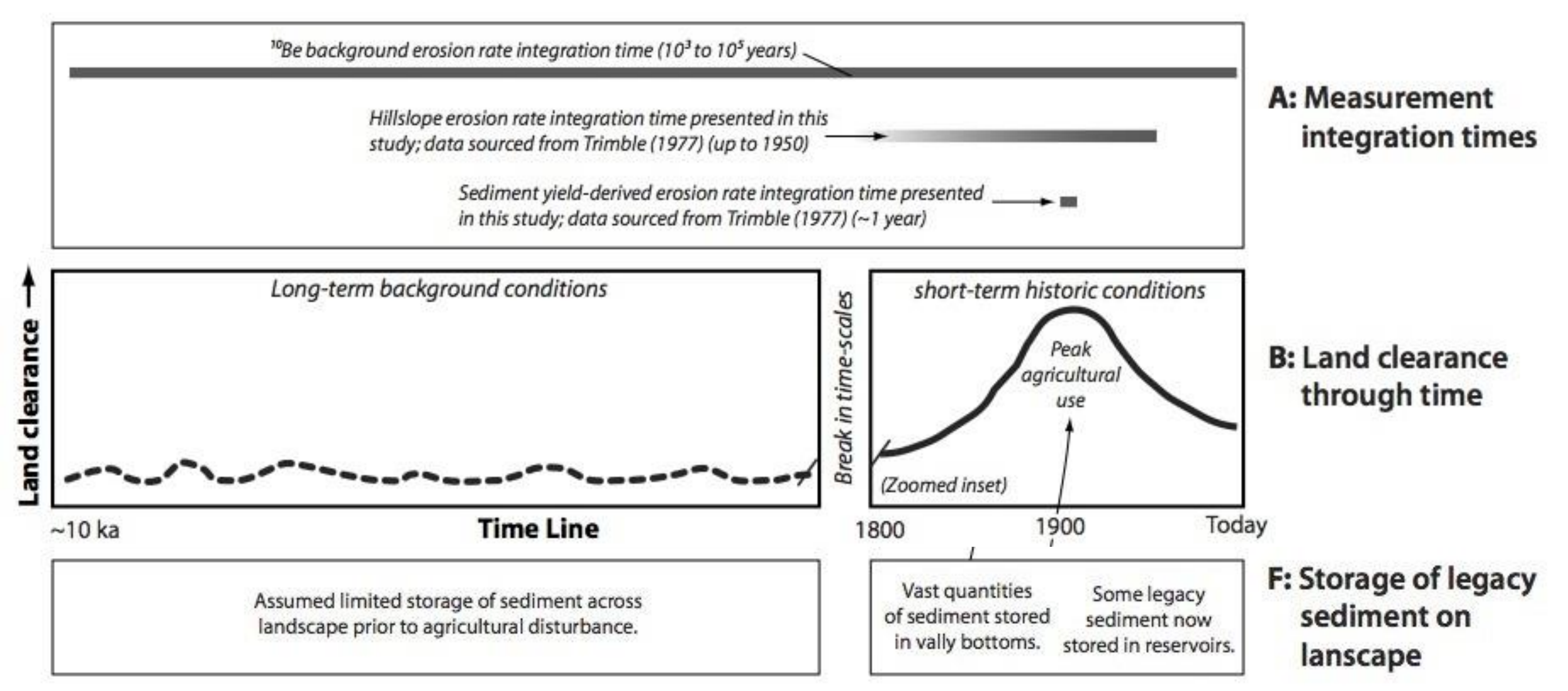
Hillslope rates
~950 m/My

Sediment yield
inferred rates
~50 m/My

Our *in situ* ^{10}Be background erosion rates
~9 m/My

Naturally, the Piedmont erodes >100 times slower than during peak agriculture

Where is all the sediment now?
Recovery from past landuse disturbances:



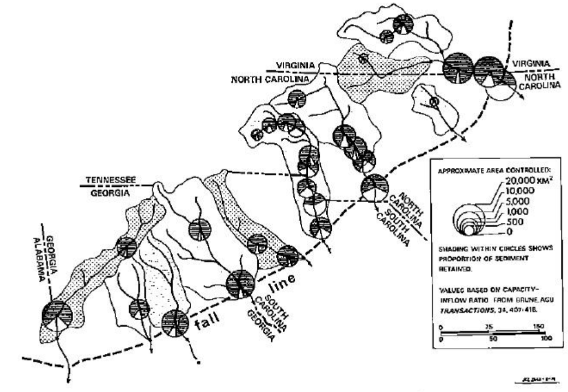
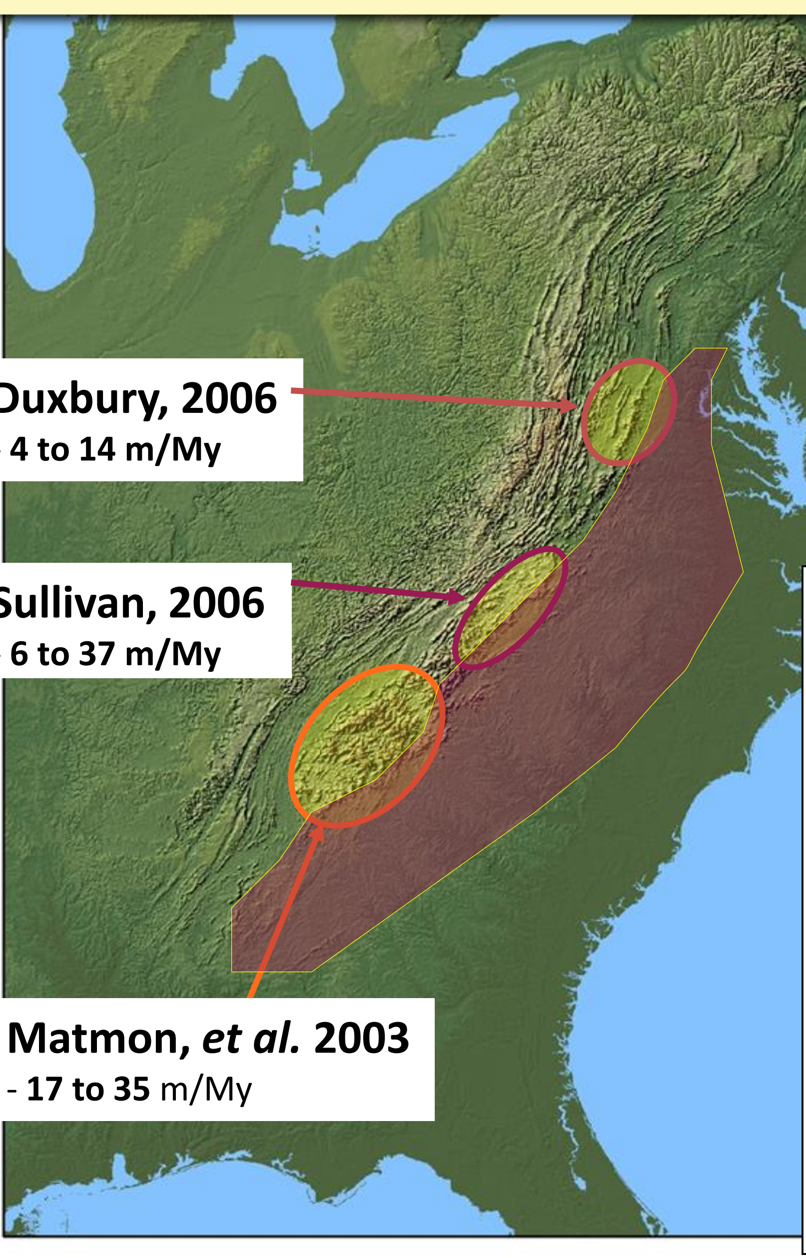


Fig. 3. Trap efficiency of Piedmont reservoirs.

Testable hypotheses with ^{10}Be for small basins:

- Background rates of erosion in small sub-basins are related to their **average basin slopes**.
- The relationship between average basin slope and background *in situ* ^{10}Be erosion rates can be used to **predict** rates in drainage basins **without ^{10}Be data.**

Previous Appalachian ^{10}Be research



Duxbury, 2006
- **4 to 14 m/My**

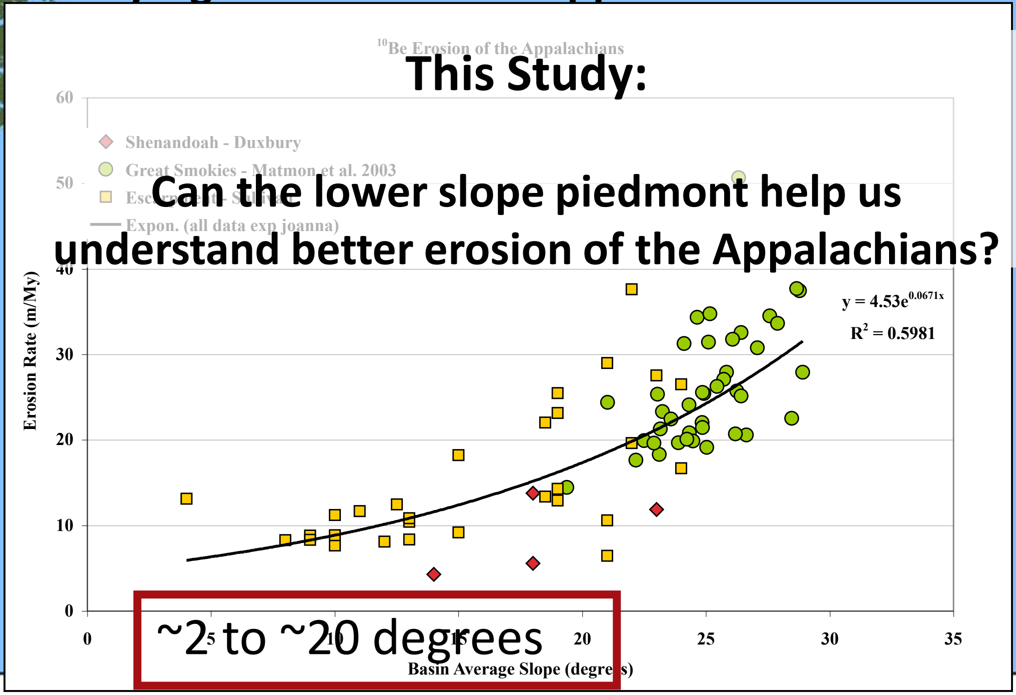
Sullivan, 2006
- **6 to 37 m/My**

Matmon, *et al.* 2003
- **17 to 35** m/My

Potential controlling variables of erosion Rate tested in higher slope Appalachian terrain:

- Physiographic province
- Mean elevation
- Land cover and land use
- Mean basin slope

Only significant variable appears to be SLOPE

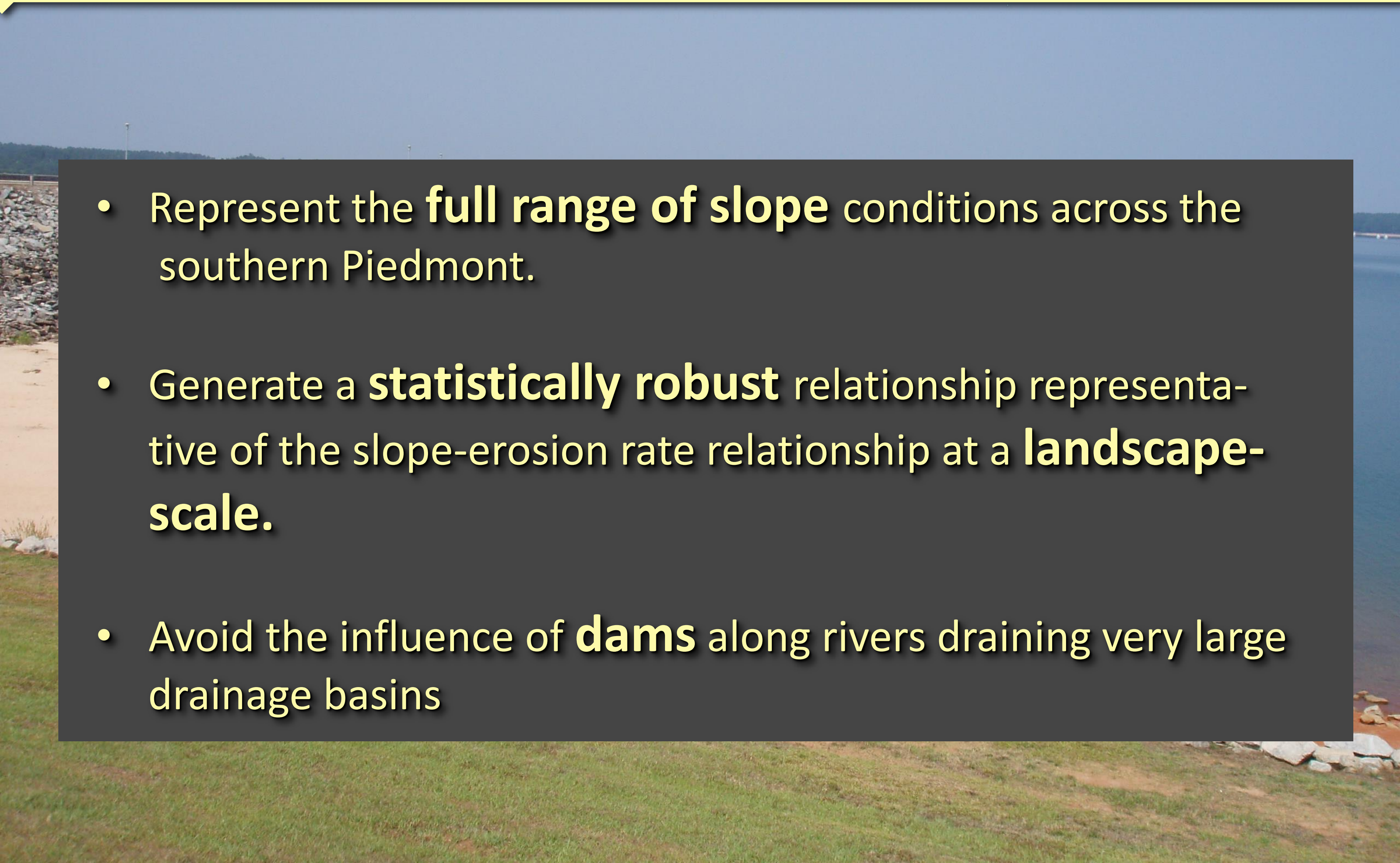


This Study:

Can the lower slope piedmont help us understand better erosion of the Appalachians?

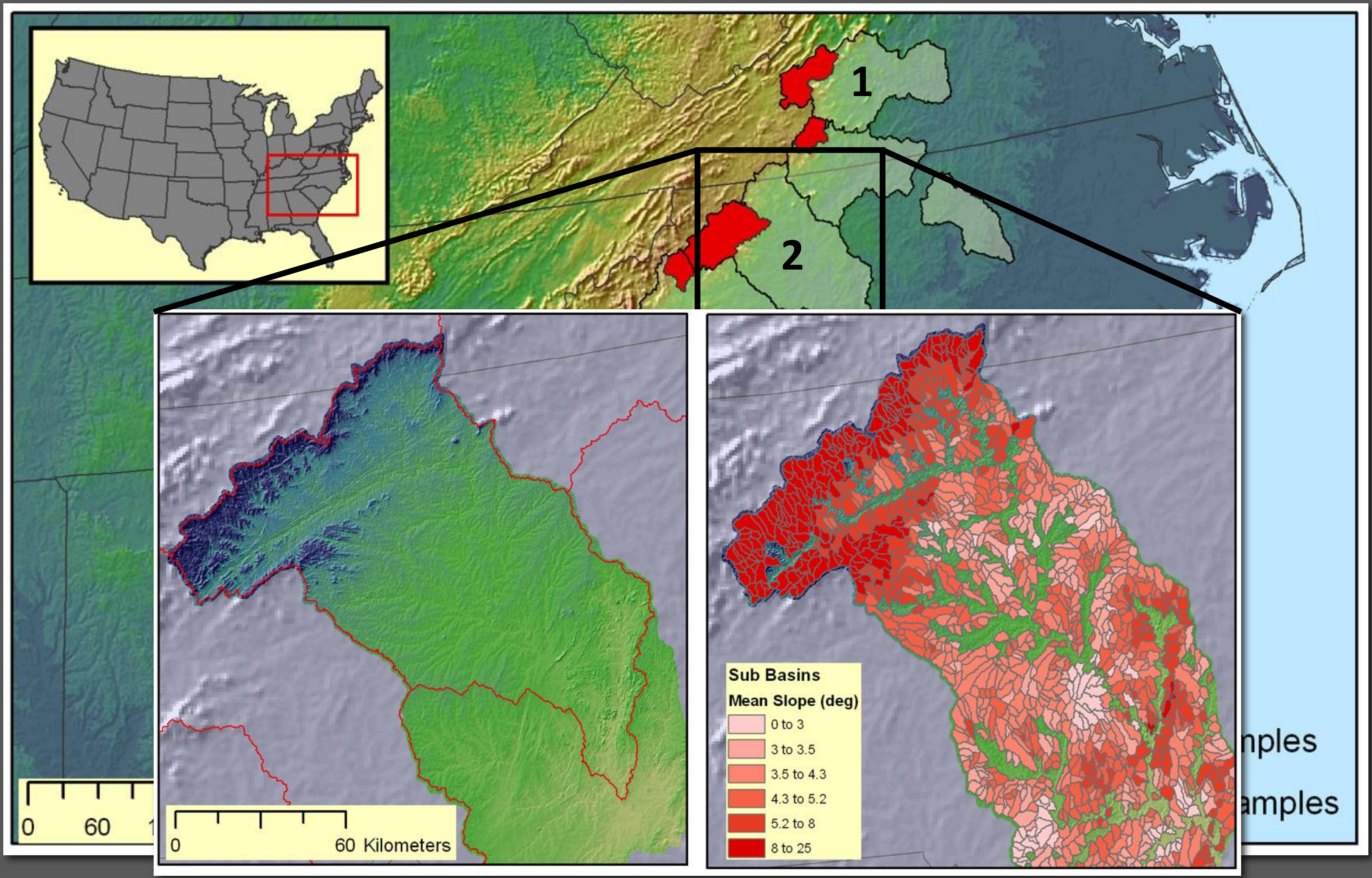
~2 to ~20 degrees

Rationales' for testing slope-dependence At small-basin scales:

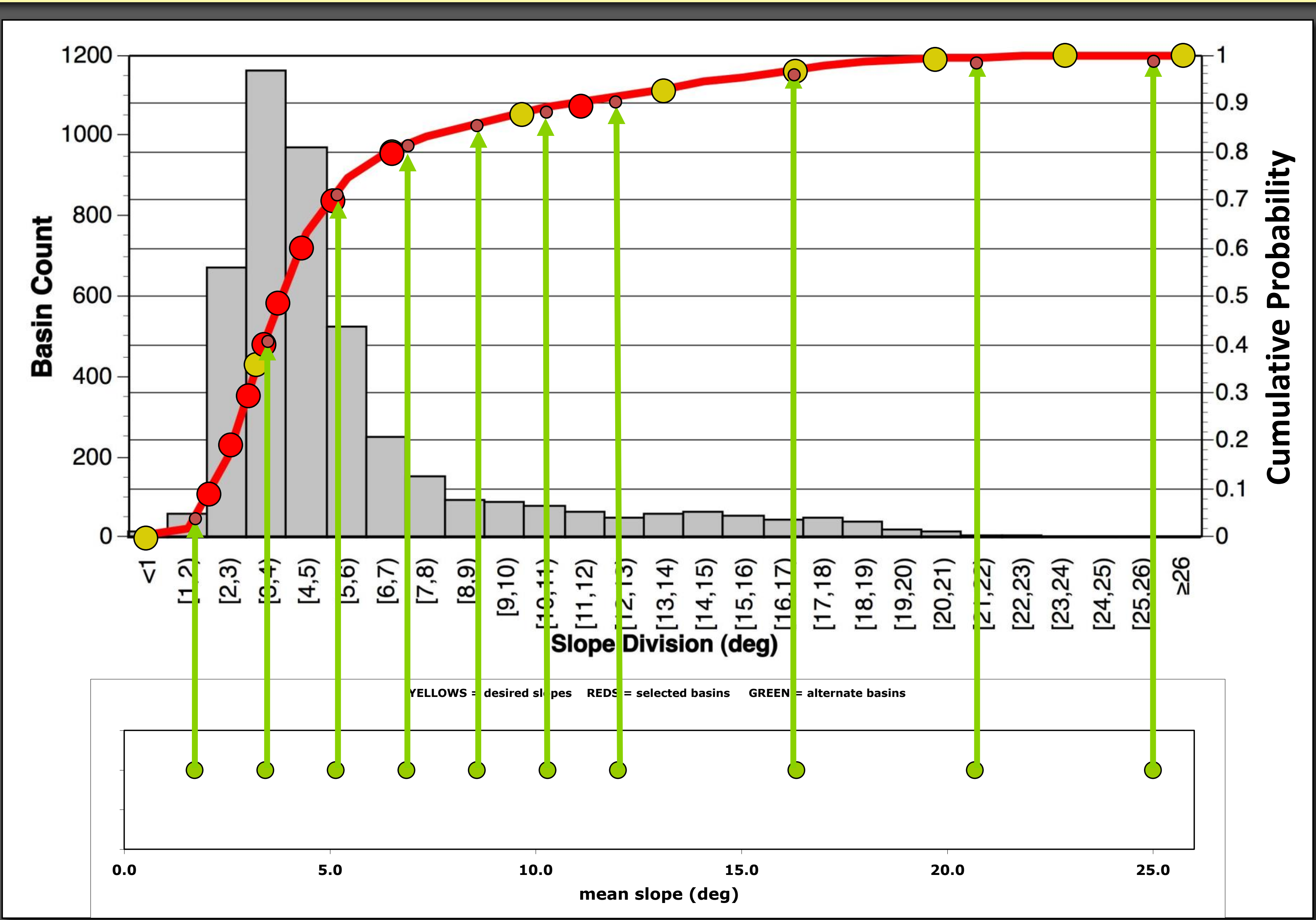


- Represent the **full range of slope** conditions across the southern Piedmont.
- Generate a **statistically robust** relationship representative of the slope-erosion rate relationship at a **landscape-scale.**
- Avoid the influence of **dams** along rivers draining very large drainage basins

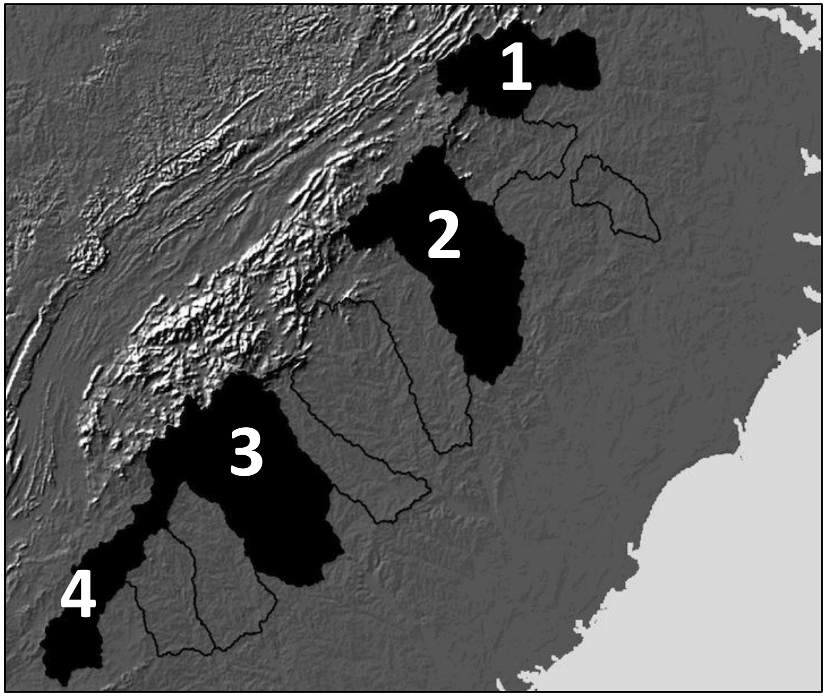
Sampling strategies - small slope basins

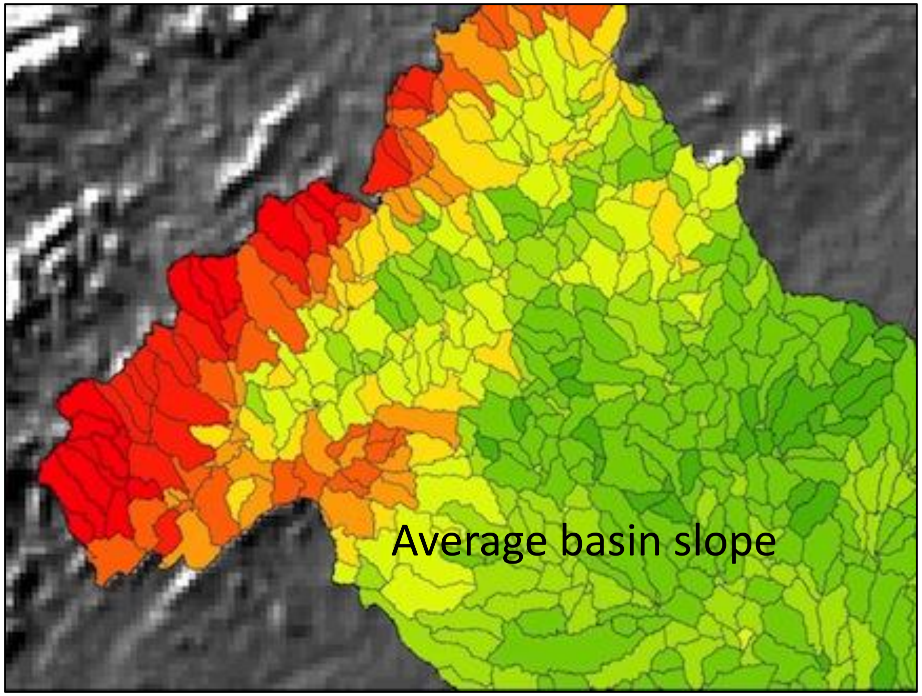


Slope distribution of potential sample basins



What we find for the 37 small slope-test basins:

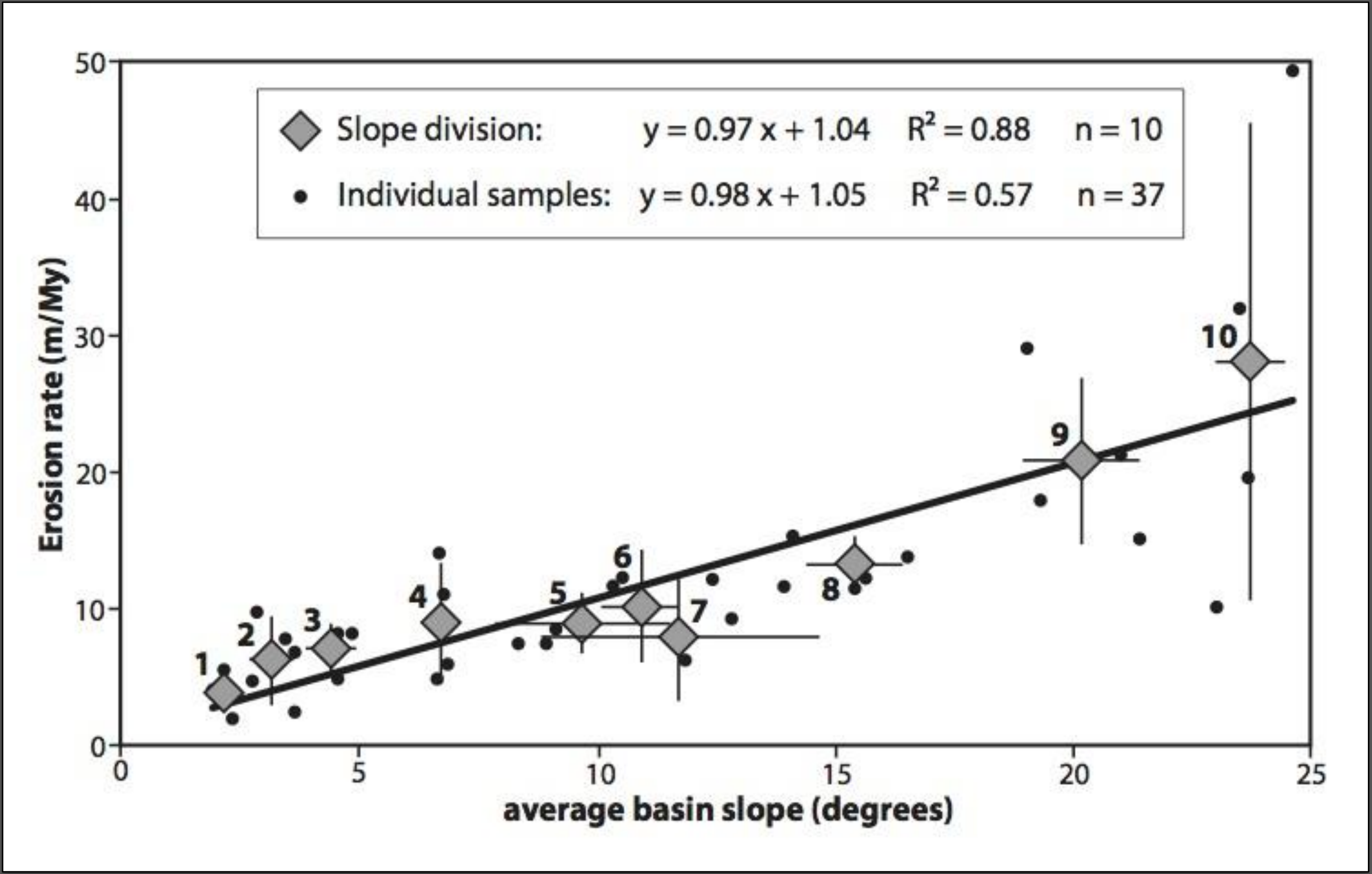




-Roanoke, Pee Dee, Savannah, and Chatahoochee basins
-Represent the NE to SW range across the entire study area

~3050 potential sample basins **~20 km^2** in size

What we find for the 37 small slope-test basins:



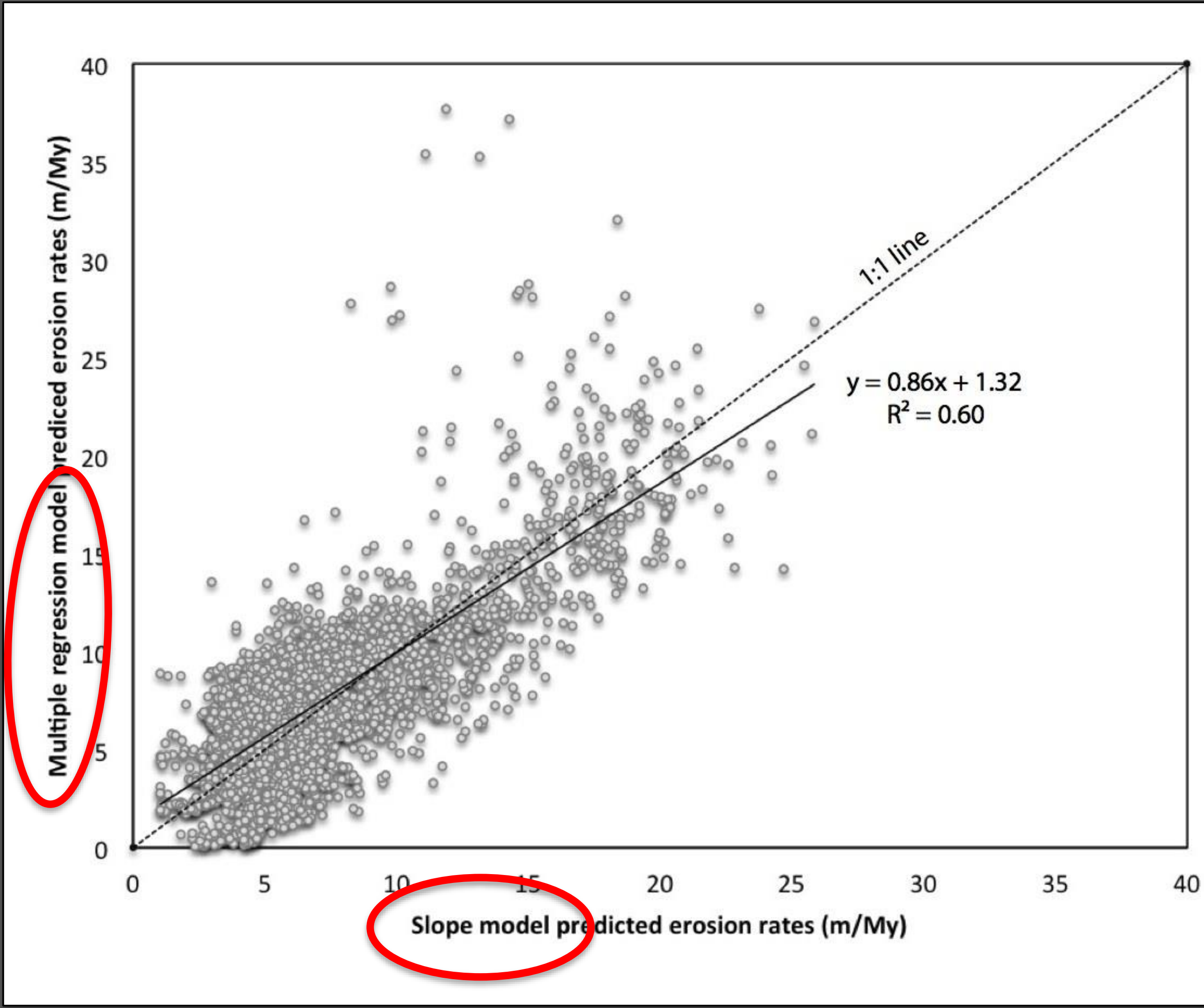
Also generated a stepwise multiple regression model using these 37 small basin-test results:

Significant variables included in the model:

- Average basin elevation
- Basin relief
- Average basin slope
- MAP
- MAT

Adj. $R^2 = 0.63$
$p<0.0001$

Predicted small-basin erosion rates made with both models:



Predicted erosion rates
for all

5100

small basins

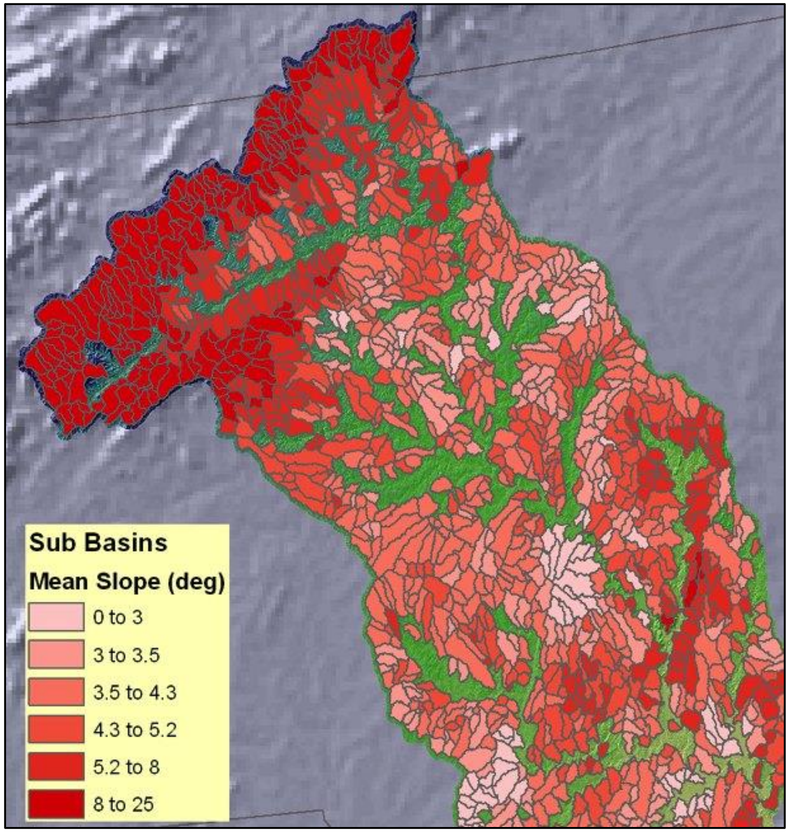
within the

10

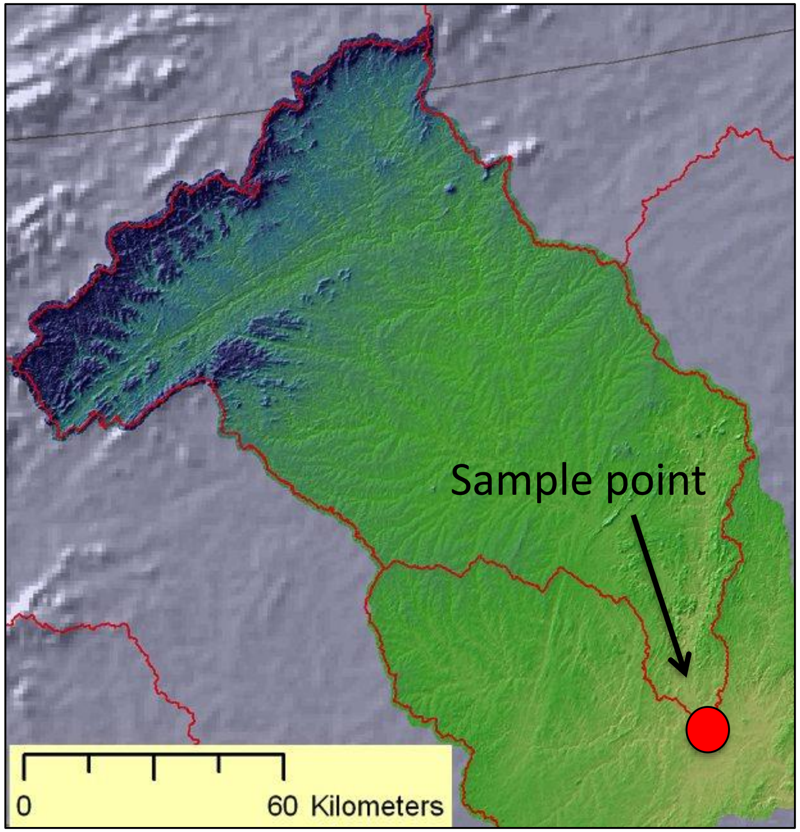
large Piedmont
drainage basins

Scaling up:
Predicting large basin erosion rates from models:

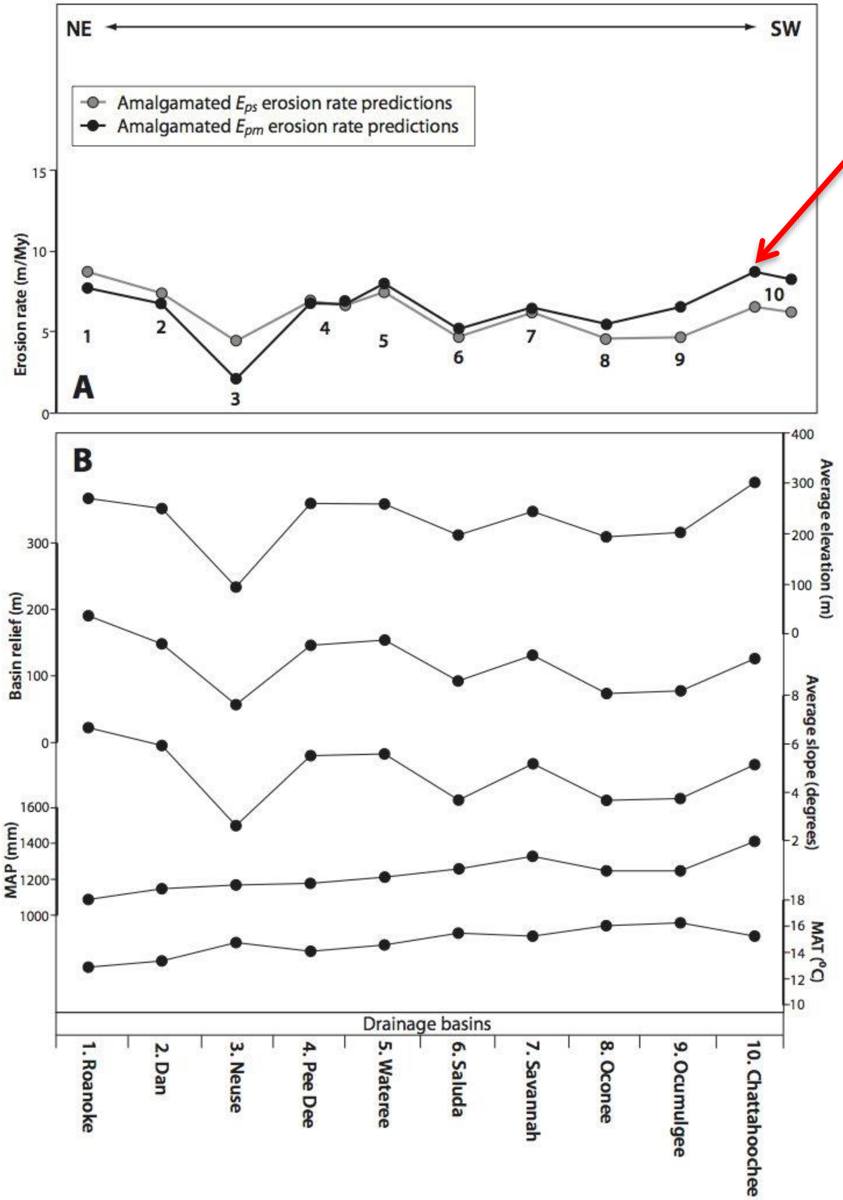
Using lots of erosion rate predictions for small basins made with both models…



To predict an area-weighted amalgamated erosion for a large basin (E_{ps} and E_{pm}).



Does it work?

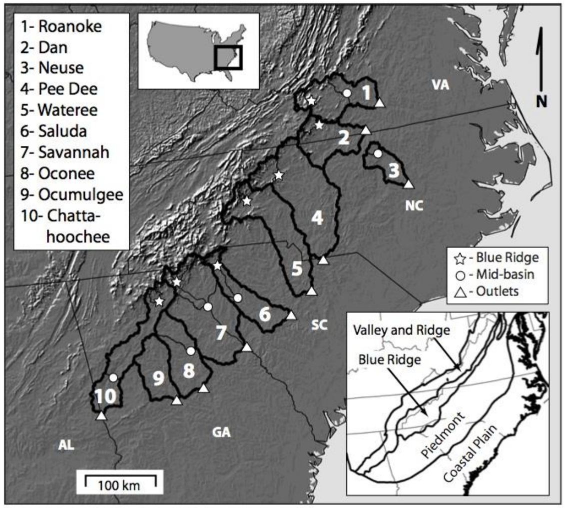


Multiple regression model tracks the rends of all variables included well.

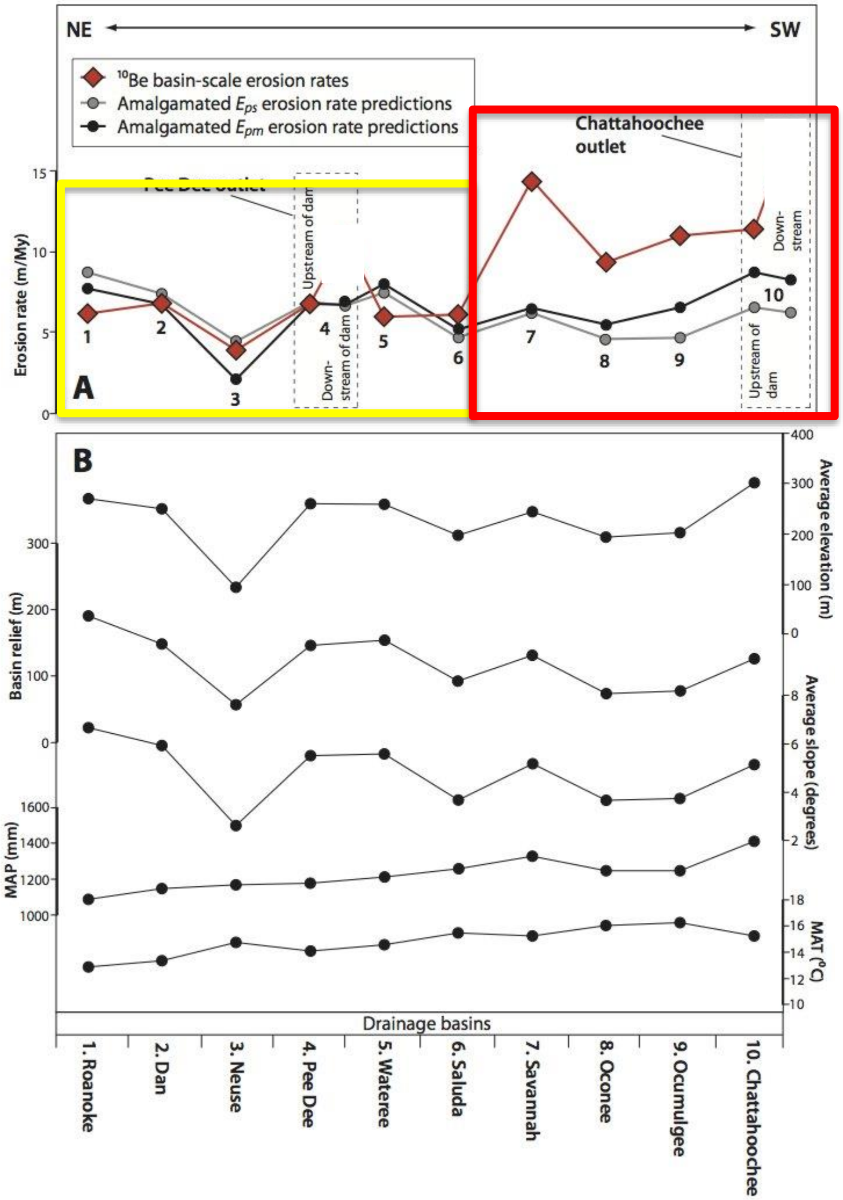
Amalgamated erosion rate predictions made with both models match each other well.

Implication:

Average basin slope alone Is a powerful and robust predictor of erosion rates.

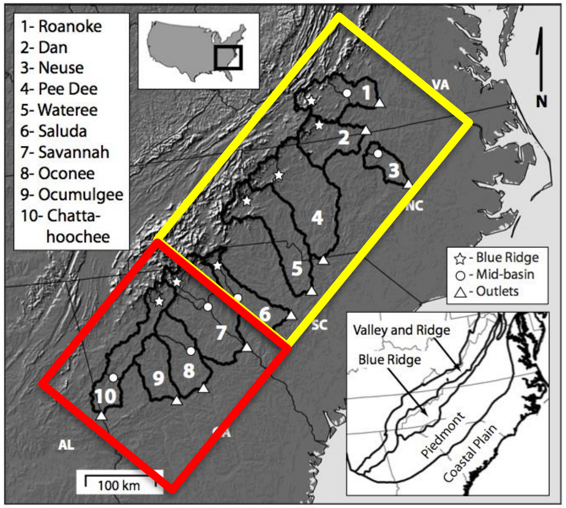


How do predictions compare to ^{10}Be data for outlets?

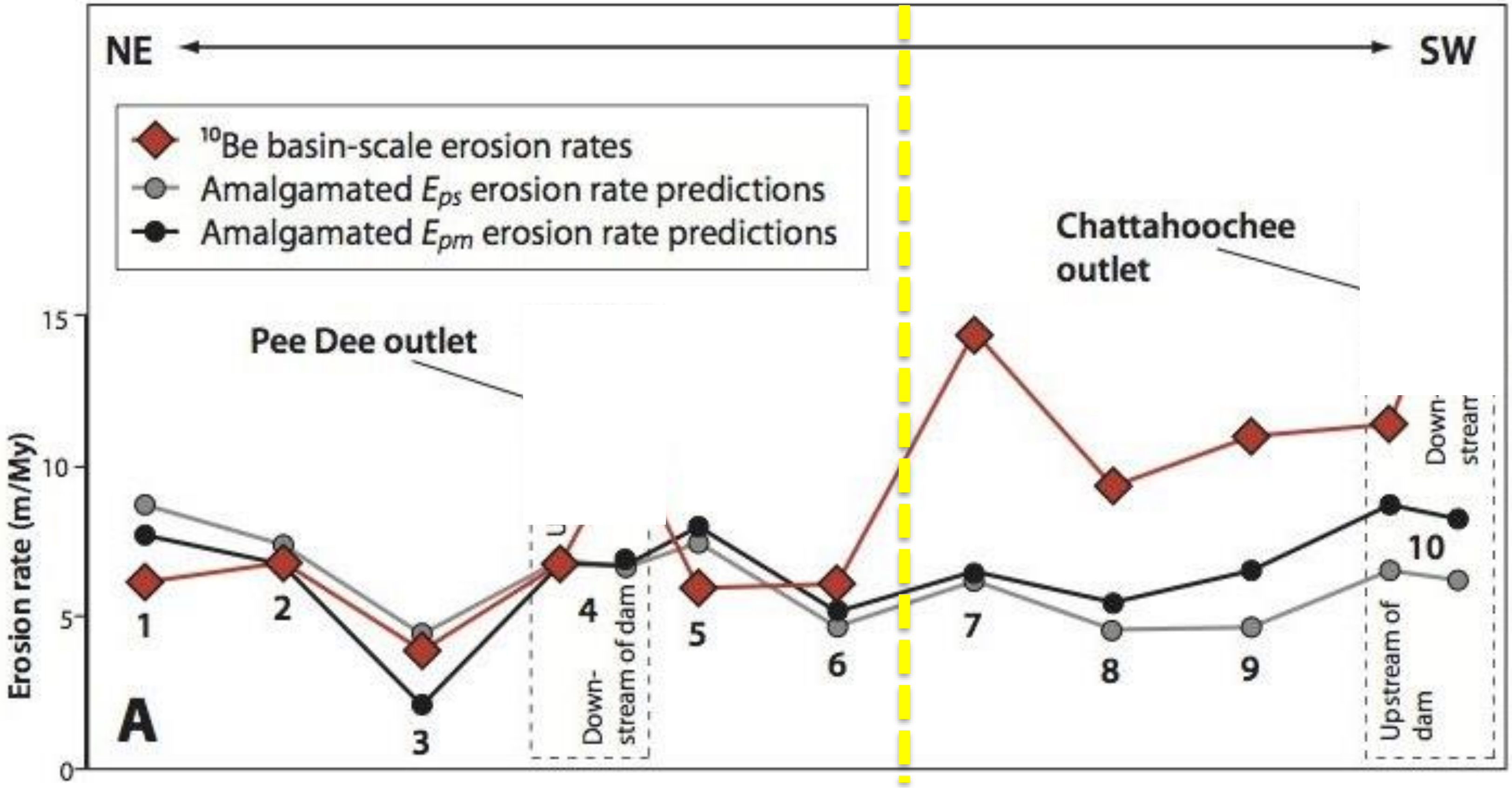


Predicted and measured rates agree well in the northeastern basins

But not so well for the southwestern basins

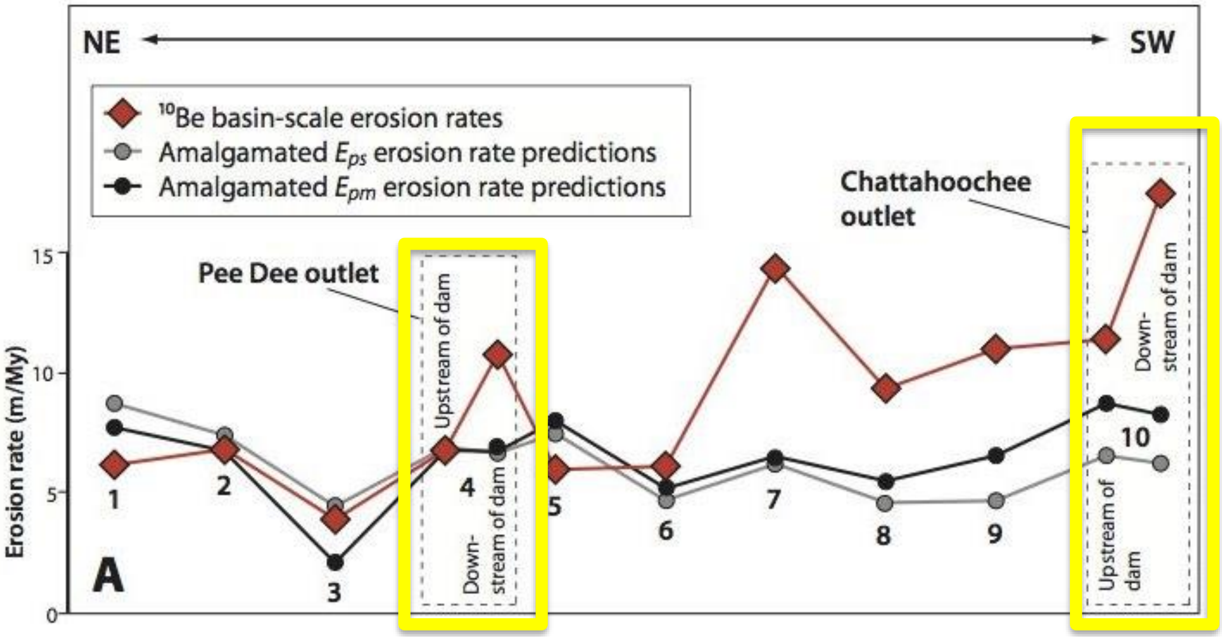


Potential explanation for N vs. S differences:



No discernable differences in geology climate, or landuse history, BUT…

Damn dams – (dam-pair sampling):



Dams impede flow of
water AND
river sediment

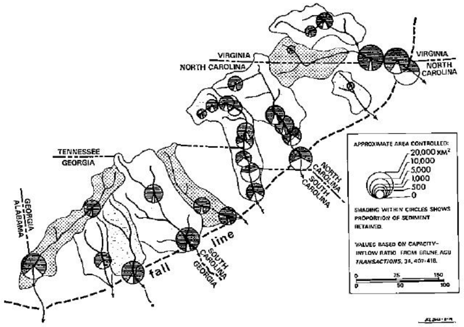
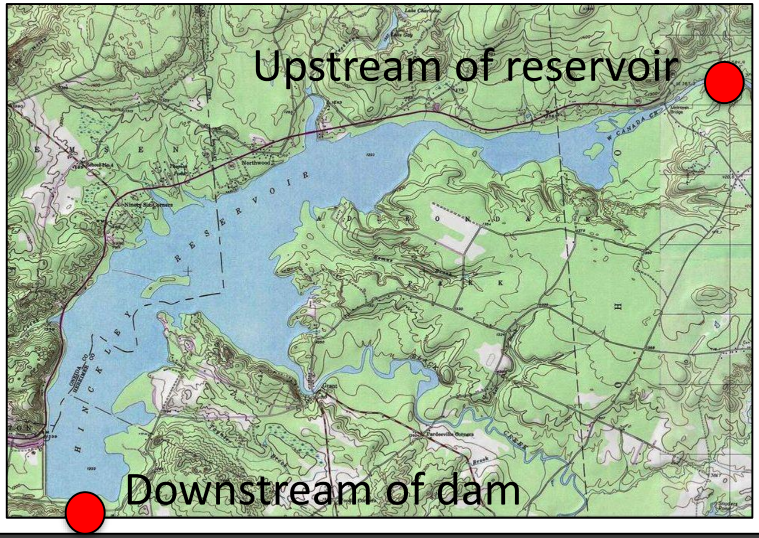


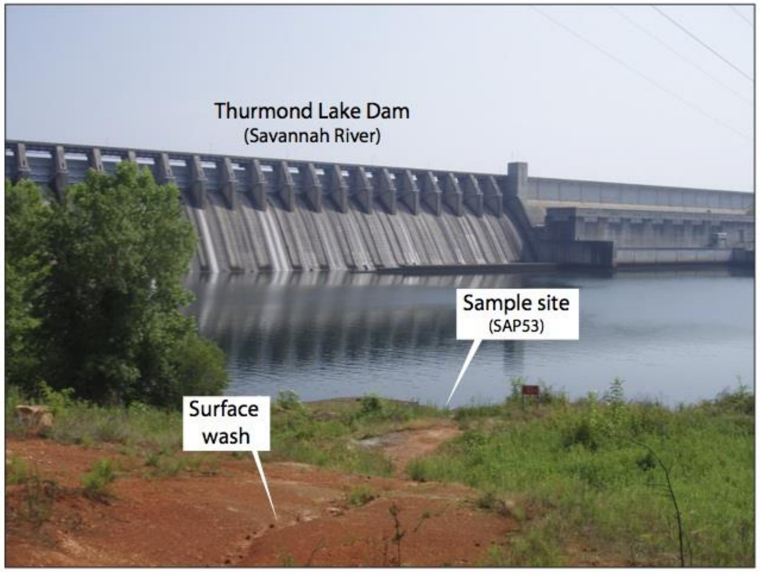
Fig. 3. Trap efficiency of Piedmont reservoirs.

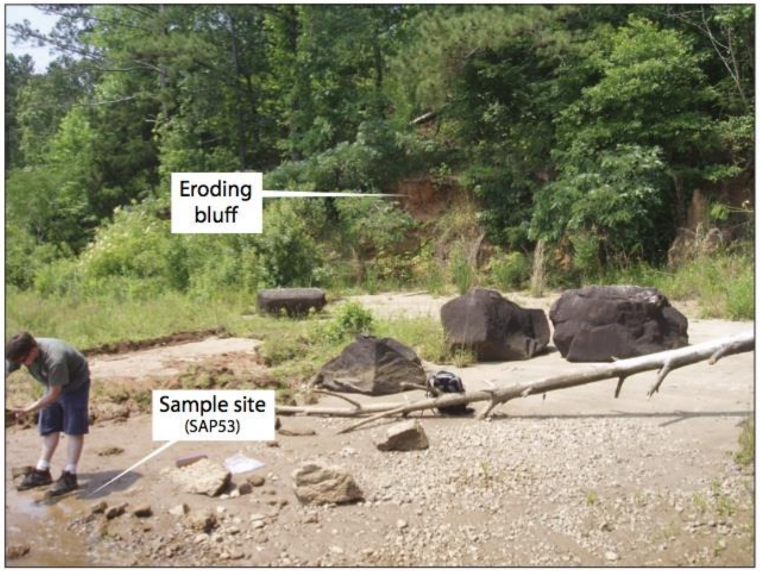


I collected samples up and downstream of dams
All southern rivers sampled below dams

Implication:
Samples collected downstream may reflect locally sourced material
Thus
Don't represent basin-scale erosion

Never before tested assumption:



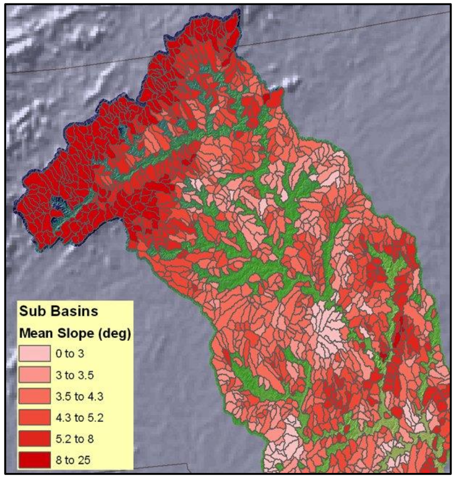


Very real implication for interpreting drainage basin background erosion rates made with *in situ* ^{10}Be in large river basins.

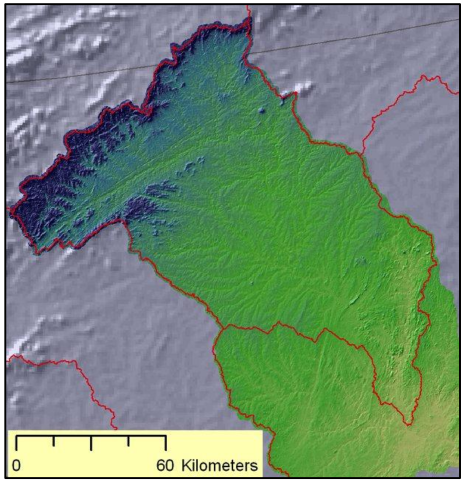
Our small-basin *in situ* ^{10}Be-derived amalgamated erosion rates may be more reliable estimates of background erosion rates.

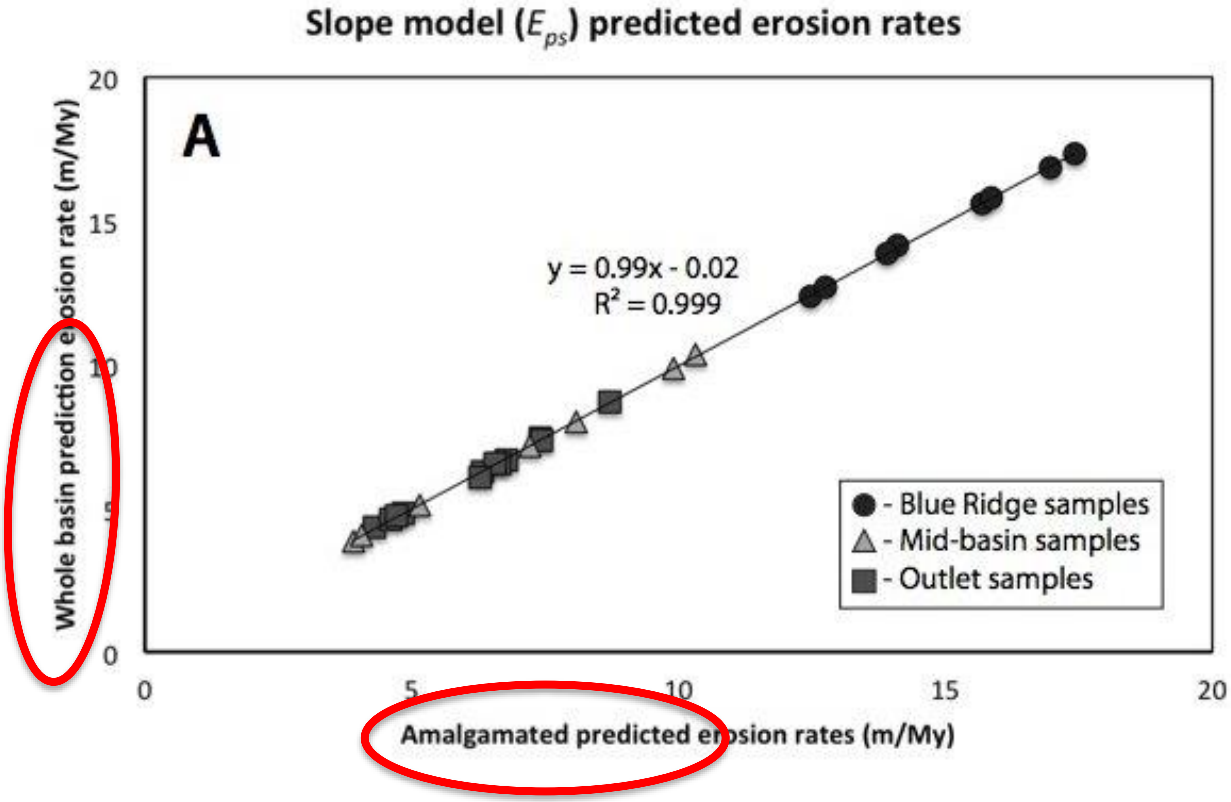
Scalability of small-basin slope-based model:

Amalgamated small basin approach



Whole-basin average slope





Simple slope model is fully scalable

Implication:

Potentially, we can predict a background Erosion rate at any point along a river network.

Summary of finding from the southern Piedmont:

- Human landuse practices on the Piedmont increased rates of hillslope erosion by more than 100-fold above background.
- Much of the sediment is still stored on the landscape and trapped in dam reservoirs.
- We can predict background erosion rates with simple statistical models.
- The influence of dams must be considered with using *in situ* ^{10}Be to infer background erosion in LARGE basins.

Real-world implications:

- Using the simple, and scalable average basin slope – based model we can predict erosion rates and mass fluxes of sediment at any point along a river network on the southern Piedmont.

- Could be used to establish realistic TMDL levels of sediment and associated pollutants.

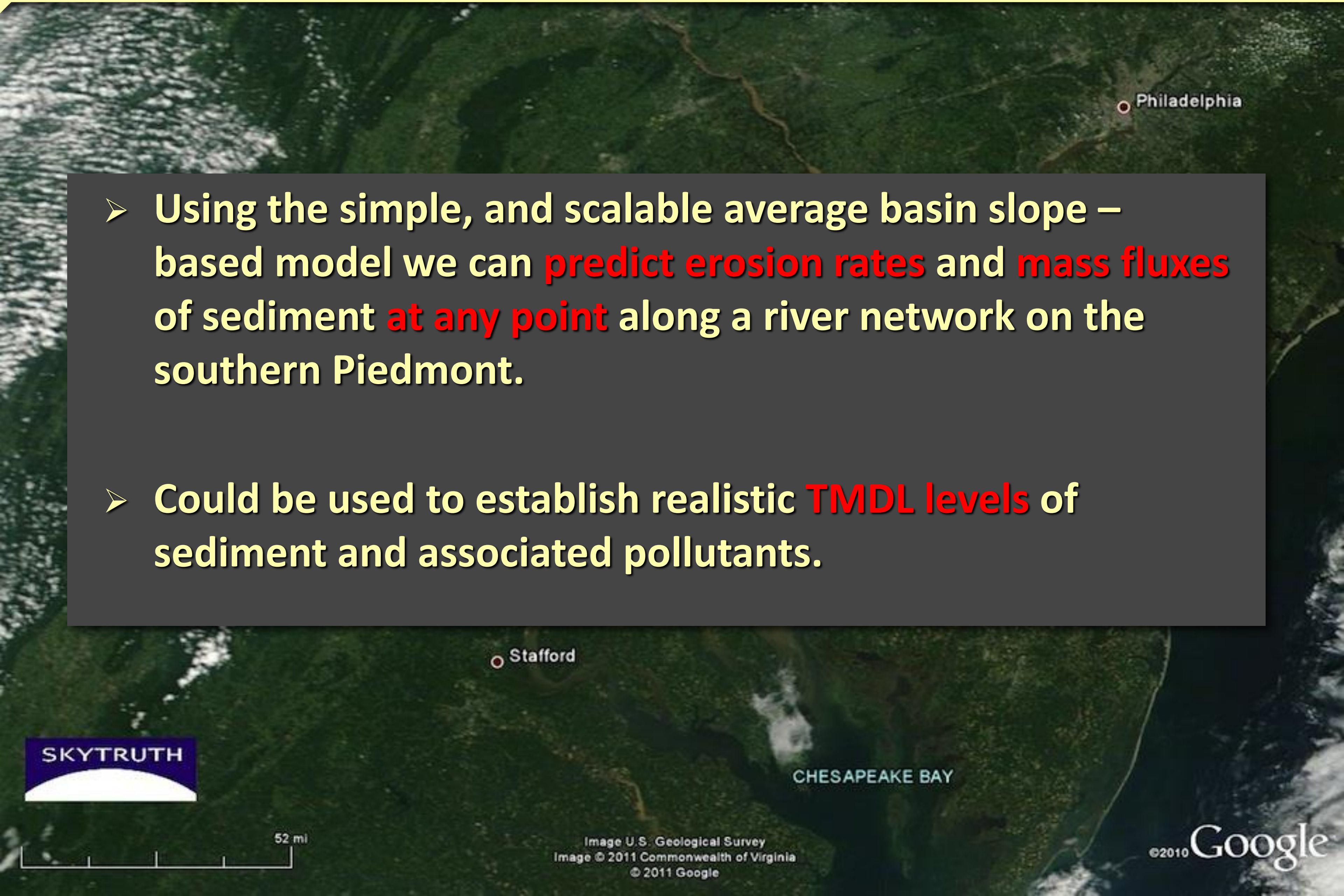


Image U.S. Geological Survey
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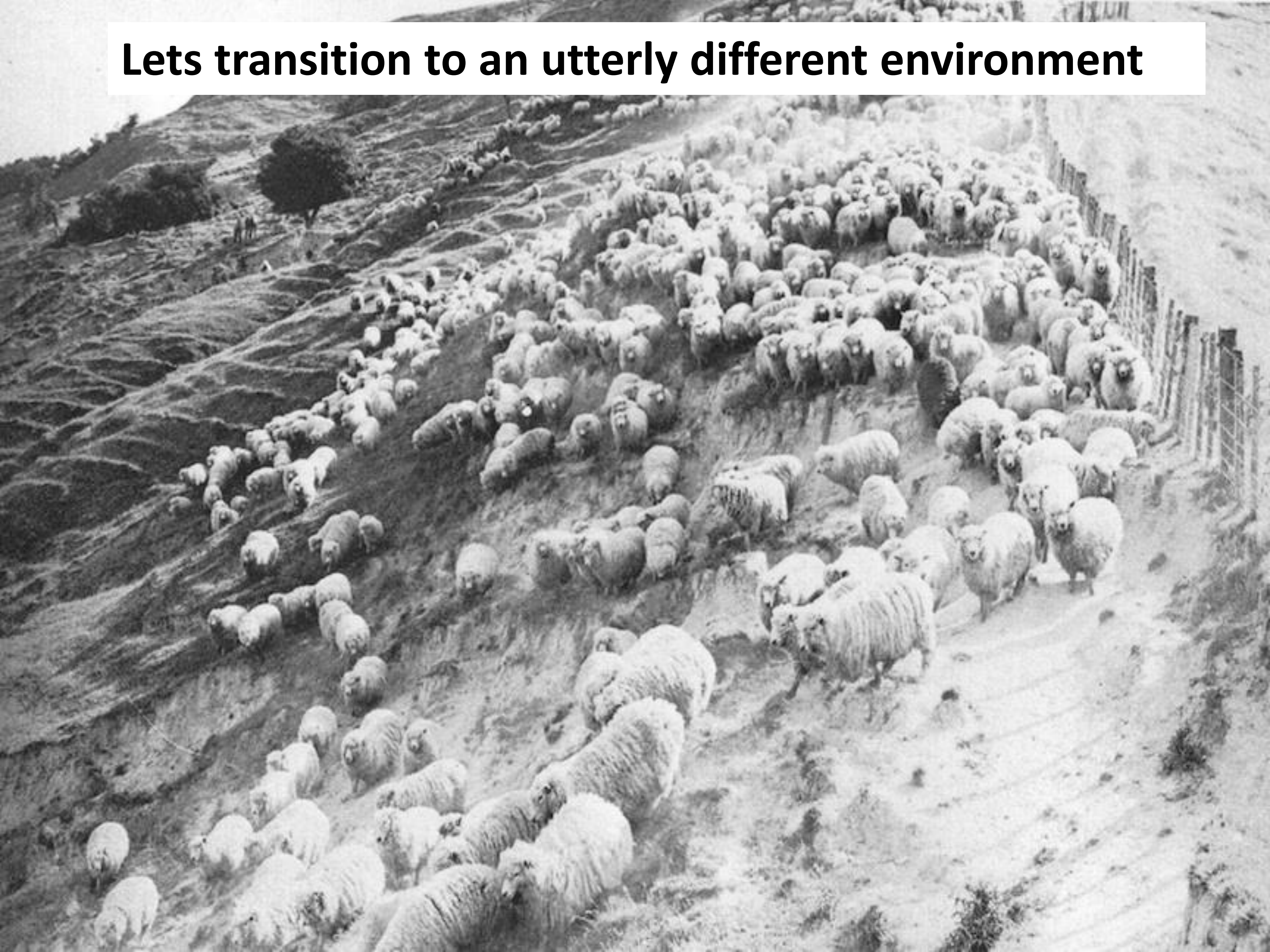
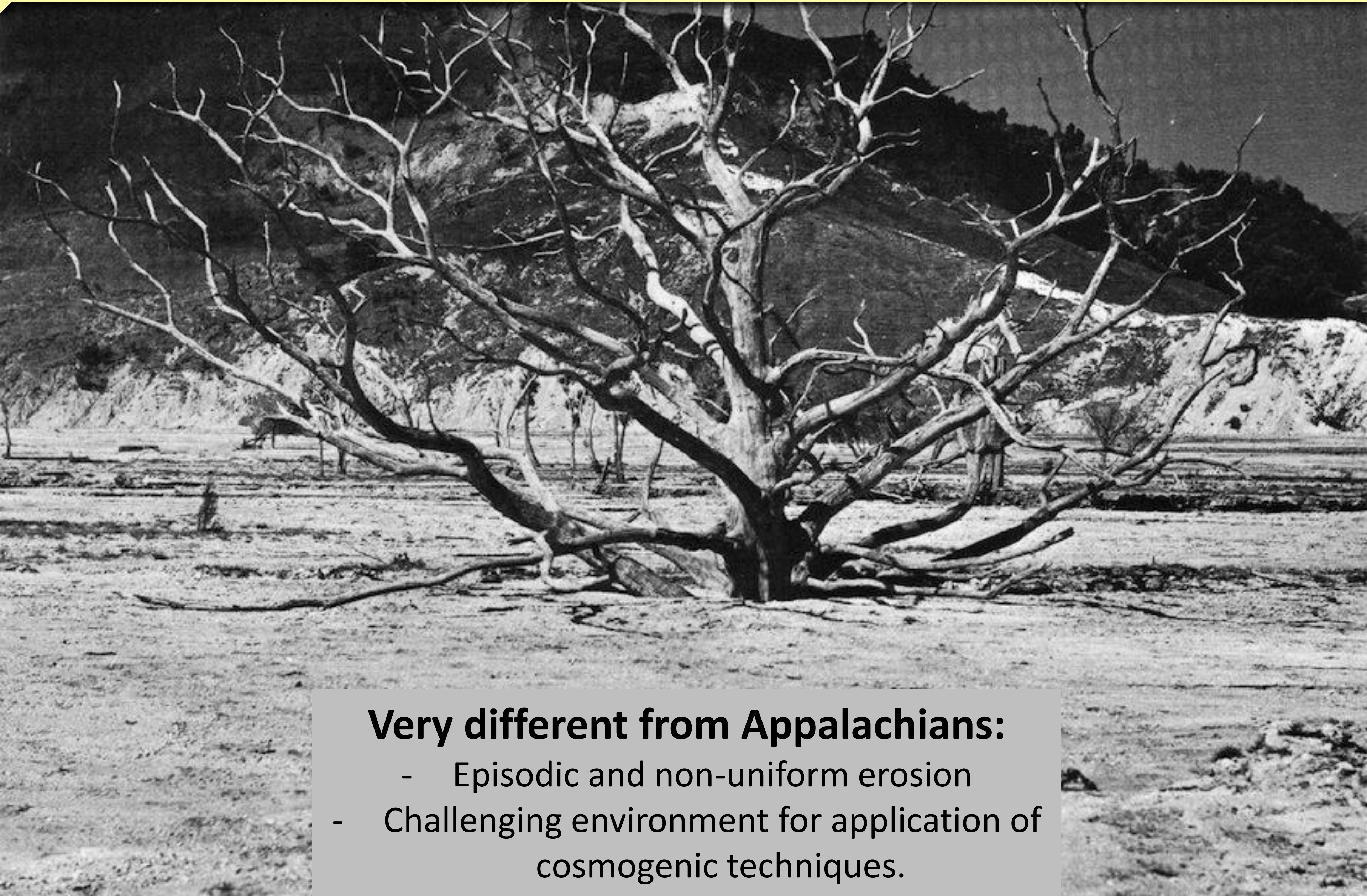
Lets transition to an utterly different environment



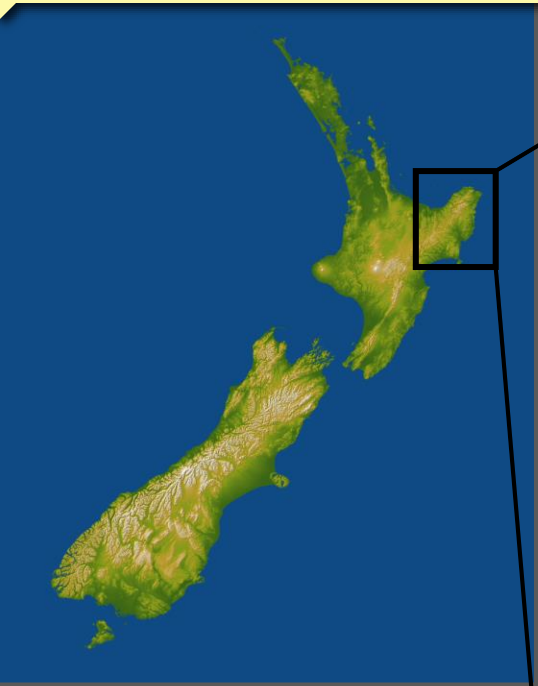
2. Waipaoa Basin, North Island, NZ

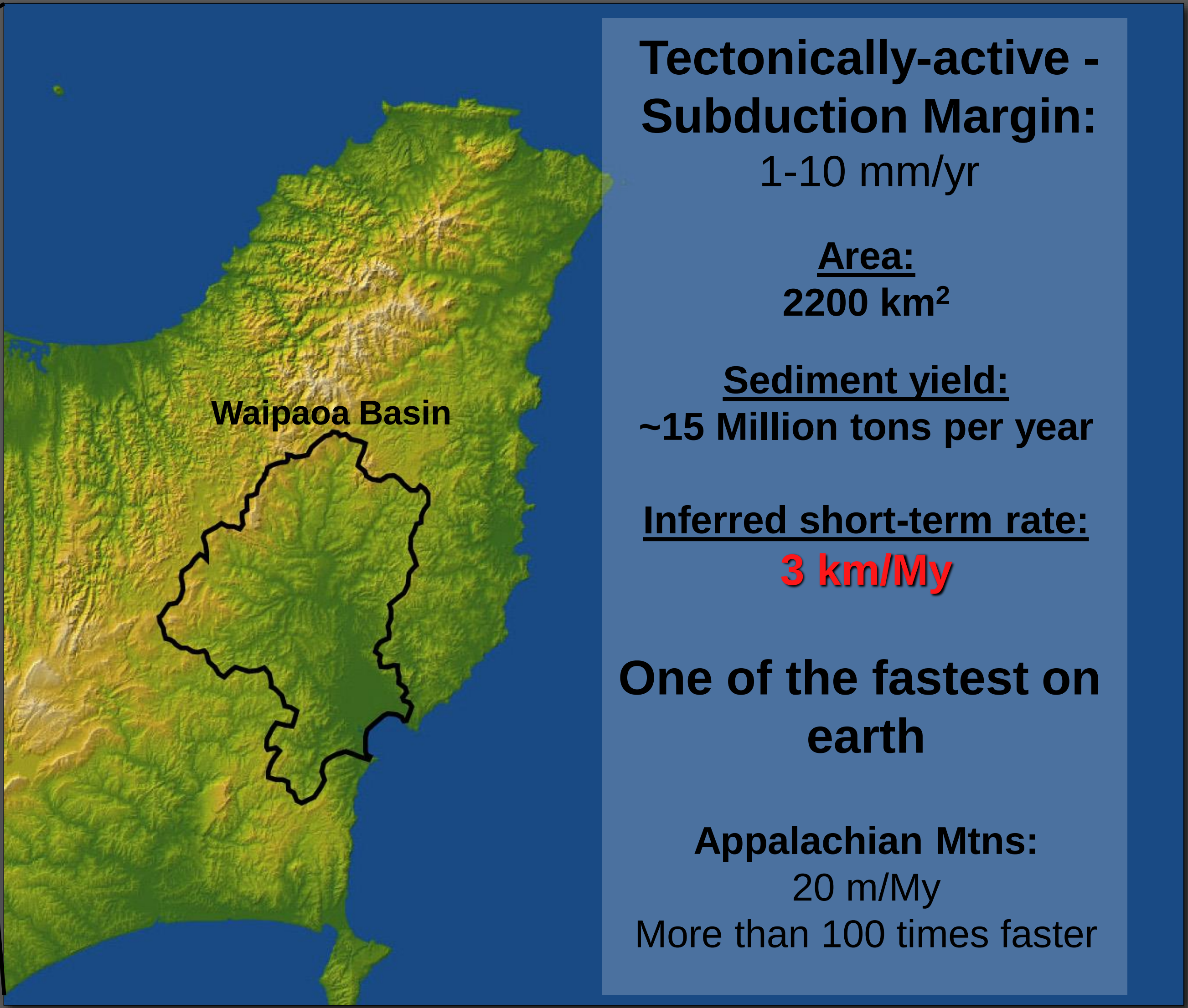


Very different from Appalachians:

- Episodic and non-uniform erosion
- Challenging environment for application of cosmogenic techniques.

Erosion in the Waipaoa Basin:





Tectonically-active - Subduction Margin:
1-10 mm/yr

Area:
2200 km^2

Sediment yield:
~15 Million tons per year

Inferred short-term rate:
3 km/My

One of the fastest on earth

Appalachian Mtns:
20 m/My
More than 100 times faster

Erosion in the Waipaoa Basin:

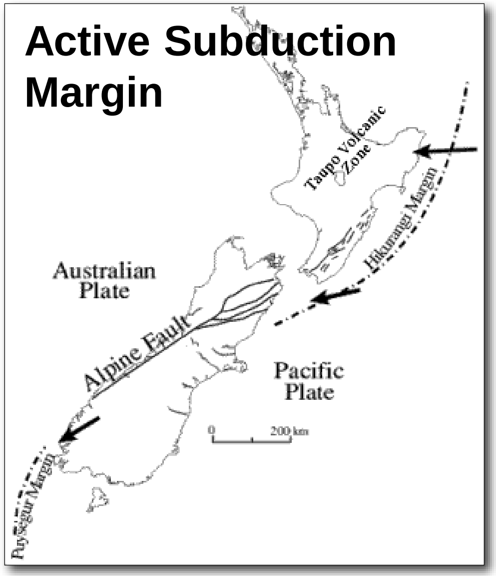
- Waipaoa Basin displays some of the most dramatic erosional features found anywhere in the world

- Has attracted researchers from around the globe over the past several decades

- Complex story of natural erodibility, extensive landclearance for agriculture, and subsequent reforestation efforts.

Natural Causes for Erosion:

Active Subduction Margin



Temperate Maritime Climate:

-highly seasonal precipitation (1.3 to 2.5 m/yr)
-periodic cyclonic activity (ENSO related)
-frequent intense rainfall events
(29% chance every year, 99% every ten)
-hydrologically triggered mass movements (landslides)

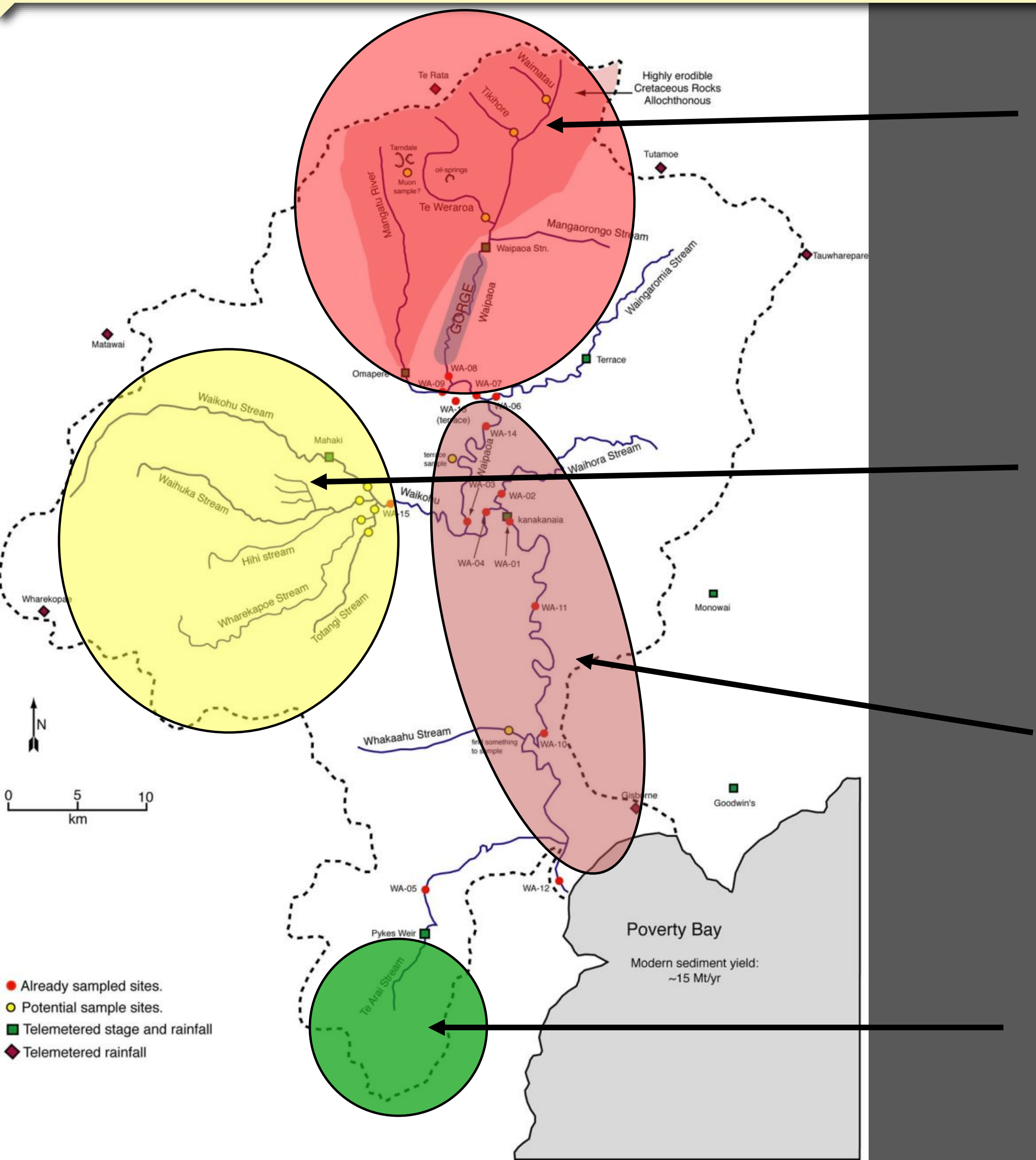
Region Primed For Erosion:

No More Trees!

Deforestation = massive erosion in the Waipaoa

- Mauri settlement ~700 yr BP.
- Commenced in early 1800’s with European settlement of NZ
- By 1880, downstream portions of basin cleared
- By 1920, upstream portions cleared
- Today, only 3% of basin remains covered in native vegetation

Variable response to land clearance:



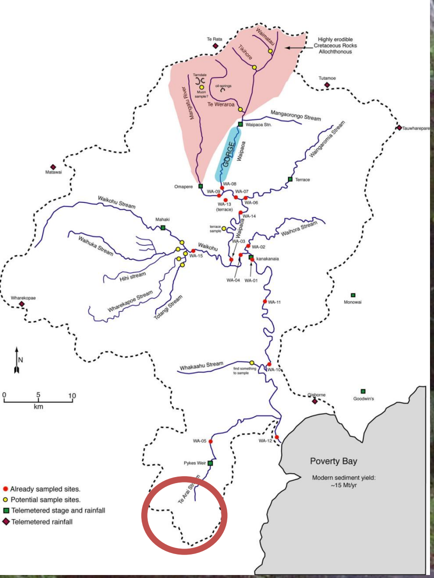
Severe Gullying:
weak rocks, faulted, fractured

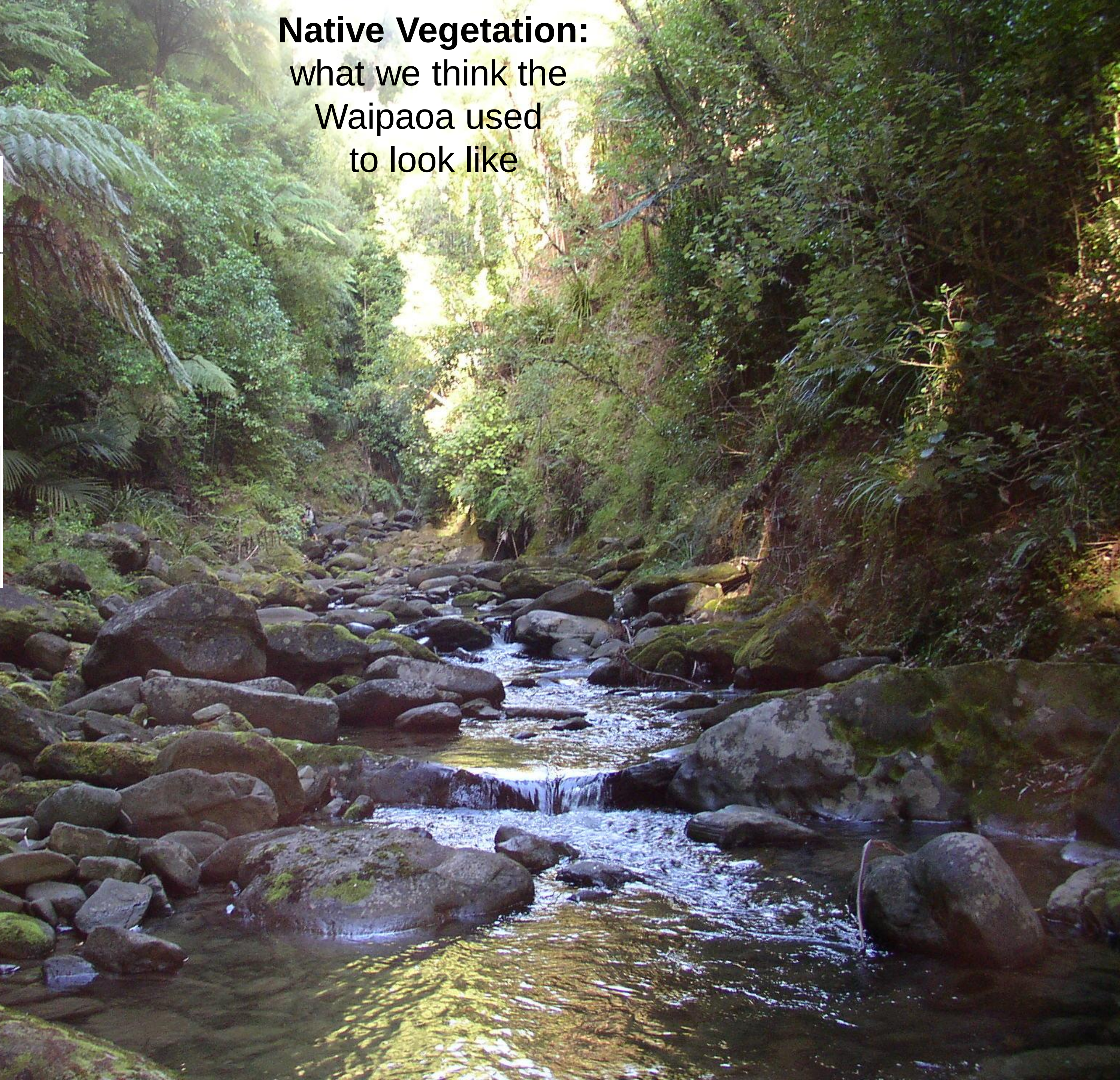
Widespread Landsliding:

Channel Aggradation:
deposition of upstream sediment

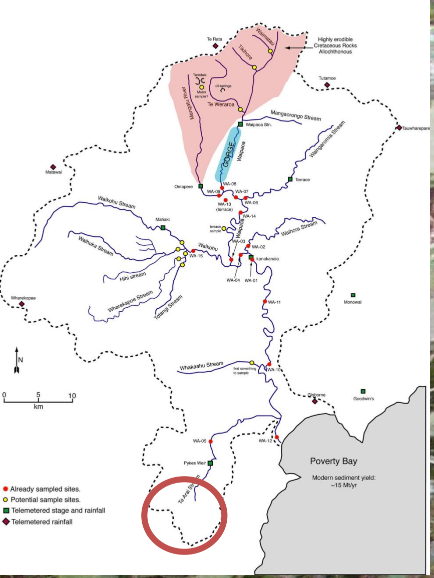
Only remaining Native Vegetation

Native Vegetation: what we think the Waipaoa used to look like

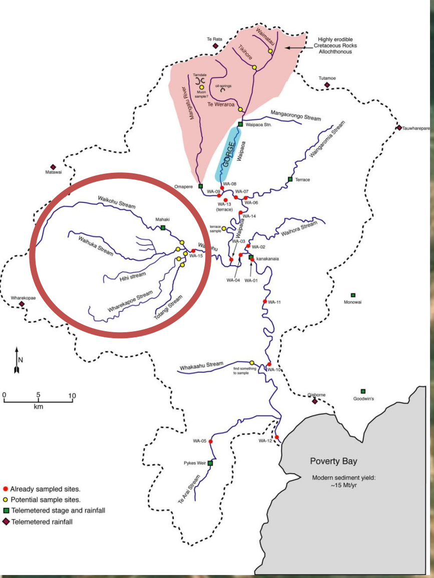




Native Vegetation: what we think the Waipaoa used to look like



By 1910, the erosional effects of clearance were widespread



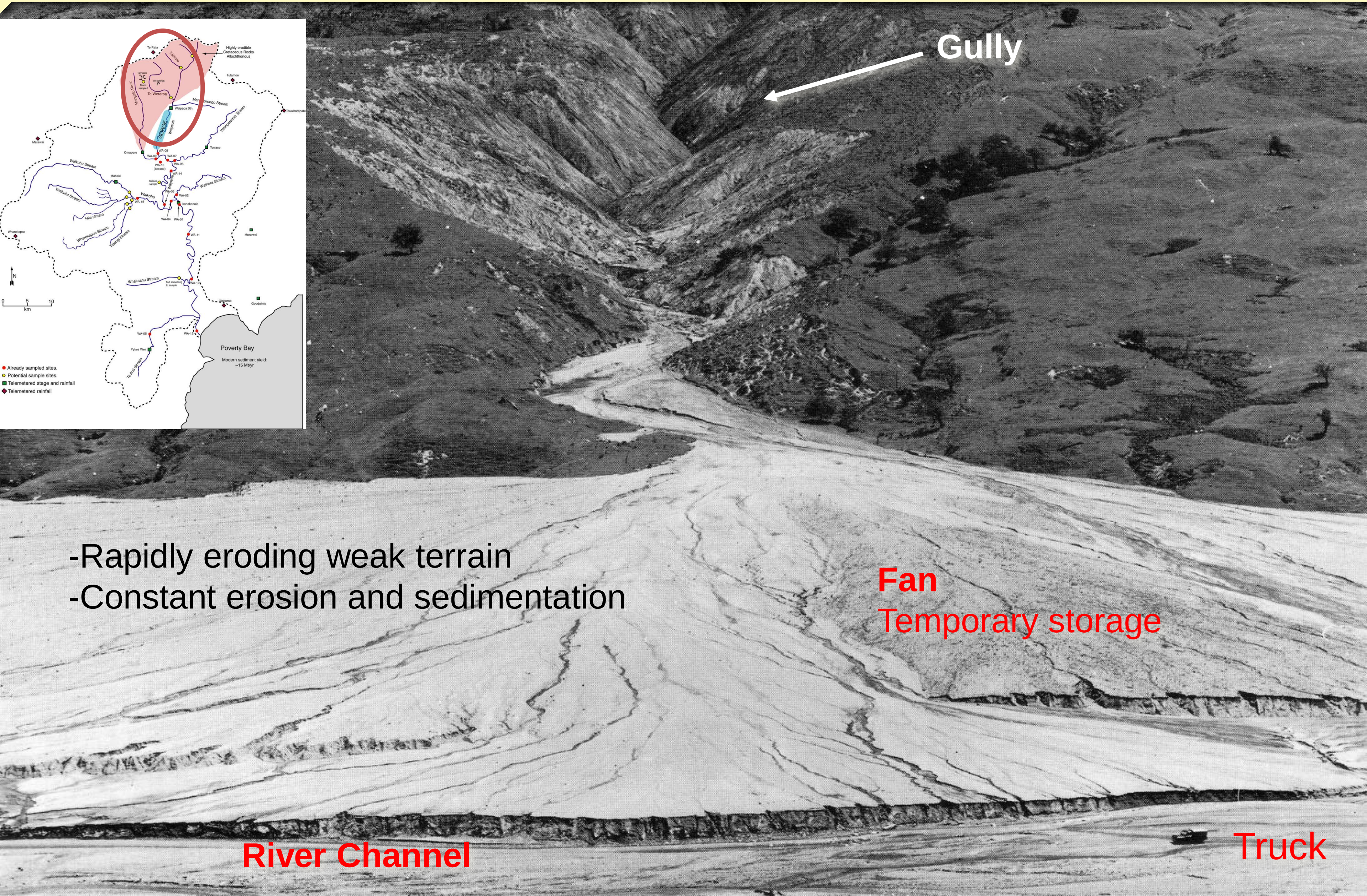
Pervasive landsliding

-Hydrologically triggered

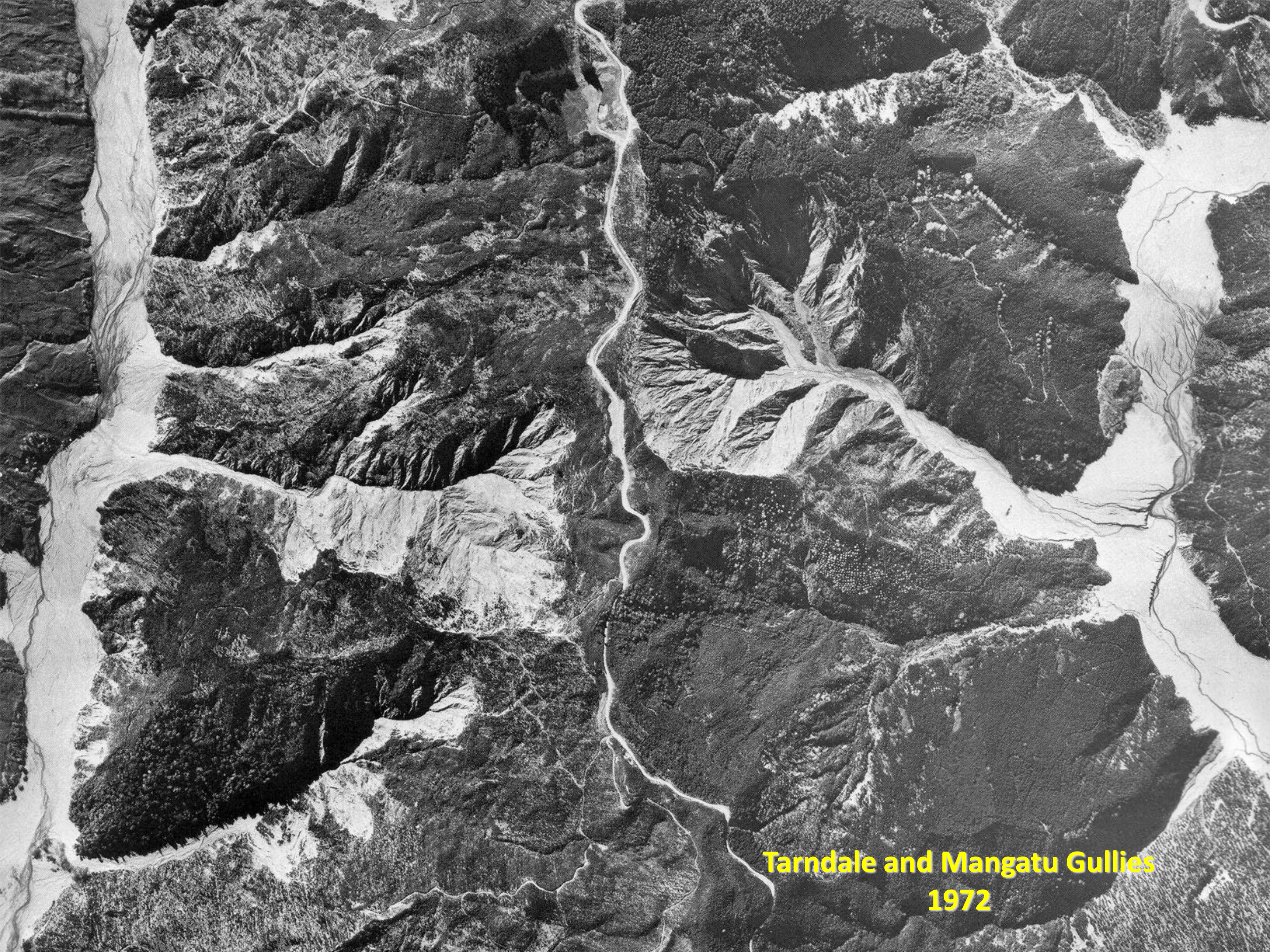
-Extreme rainfall events

-No trees to anchor hillslopes

By 1910, the erosional effects of clearance were widespread



-Rapidly eroding weak terrain
-Constant erosion and sedimentation



Tarndale and Mangatu Gullies
1972

Today, gully-derived sediment overwhelms material in the Waipaoa mainstem channel

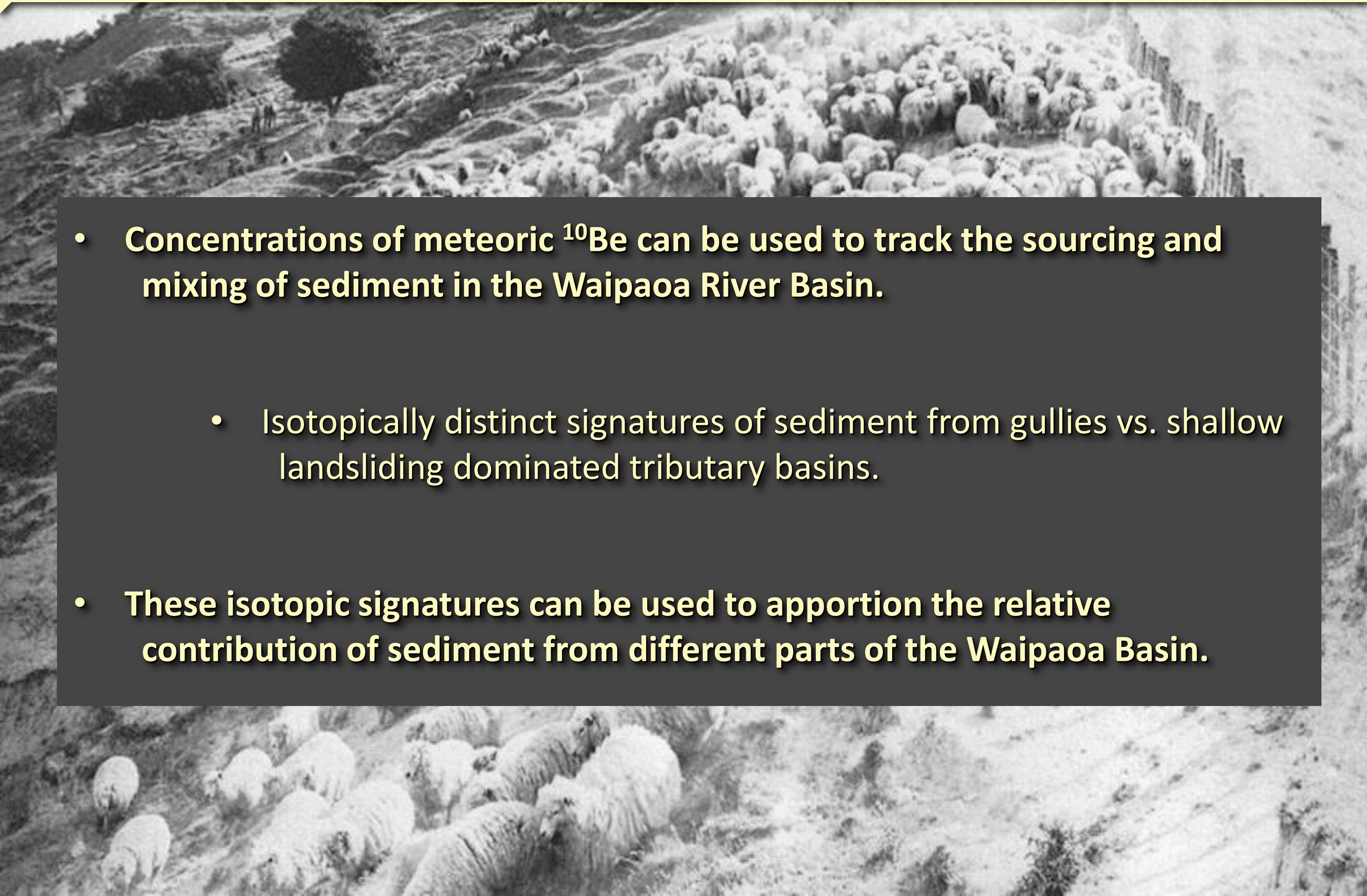
Channel aggradation 1994
Rip Bridge

Channel aggradation late nineties
Rip Bridge

Channel aggradation 2002
No more bridge

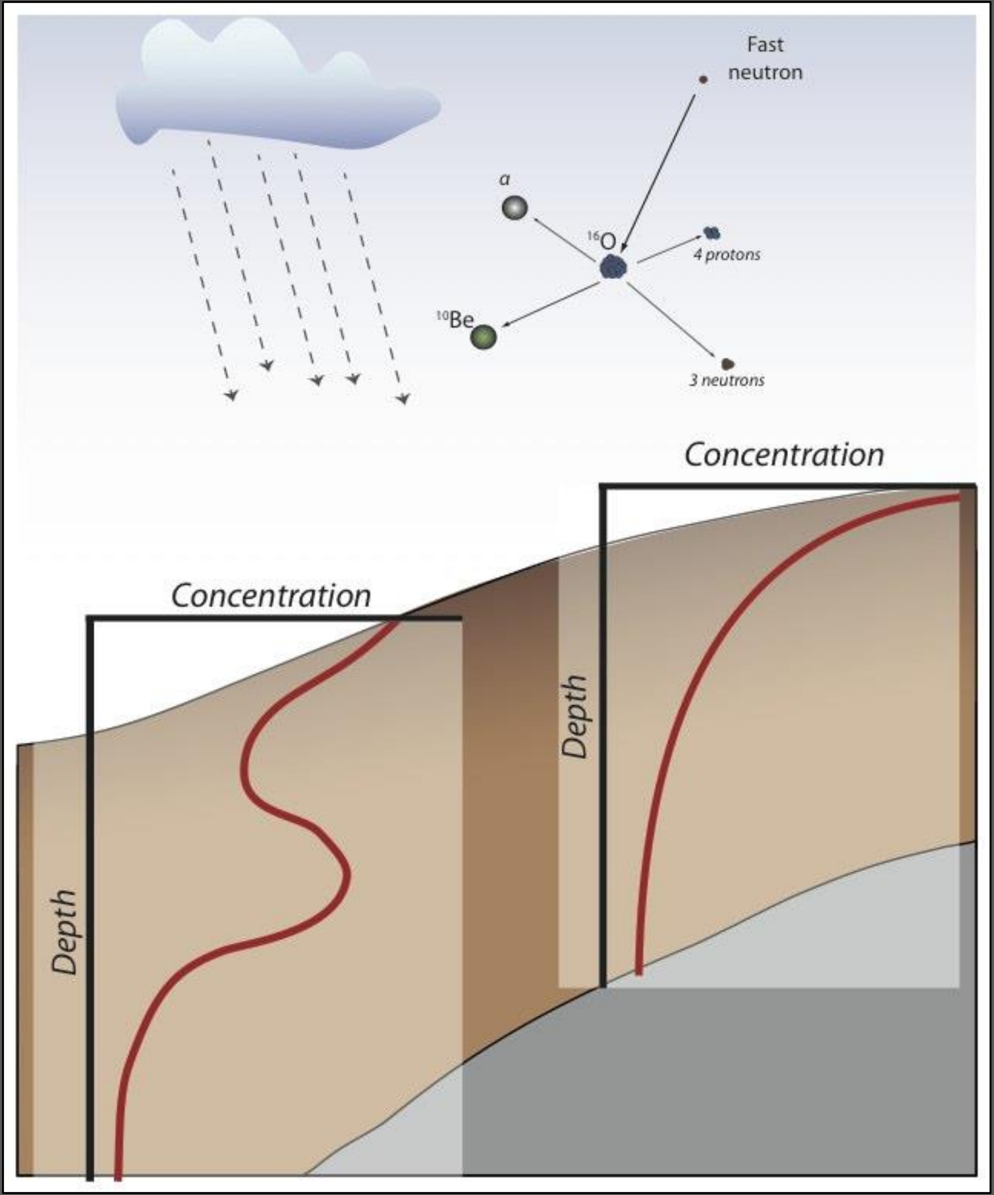
Continual flood plain deposition of sediment increased rates of flooding in regions downstream (Poverty Bay Flats):

Testable hypothesis with meteoric ^{10}Be:



- **Concentrations of meteoric ^{10}Be can be used to track the sourcing and mixing of sediment in the Waipaoa River Basin.**
    - Isotopically distinct signatures of sediment from gullies vs. shallow landsliding dominated tributary basins.
- **These isotopic signatures can be used to apportion the relative contribution of sediment from different parts of the Waipaoa Basin.**

Accumulation of meteoric ^{10}Be in soils:



- Produced in the **atmosphere** by the same processes as *in situ* ^{10}Be

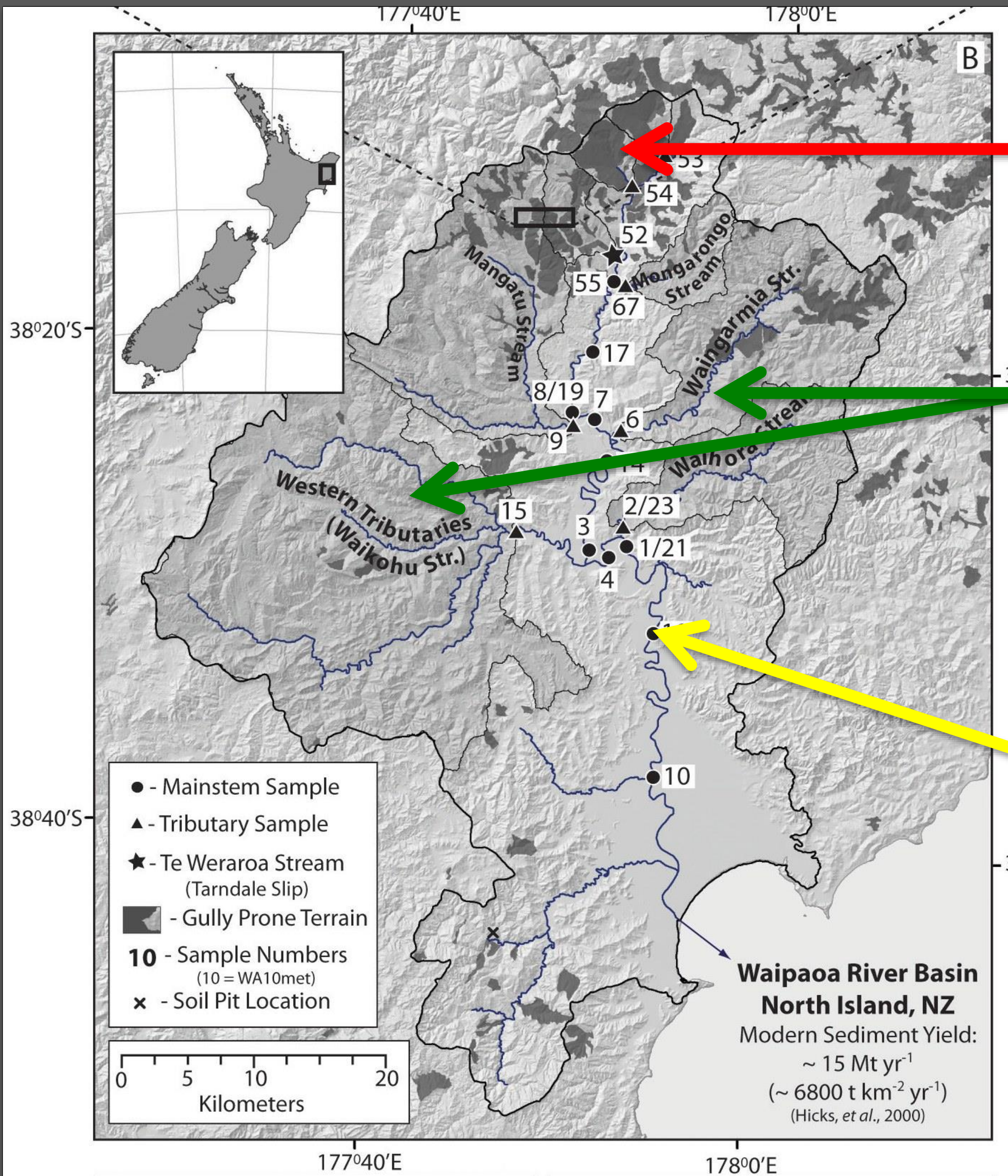
- **Delivered** to soils across landscapes in rain, and to a lesser extent in NZ in dust.

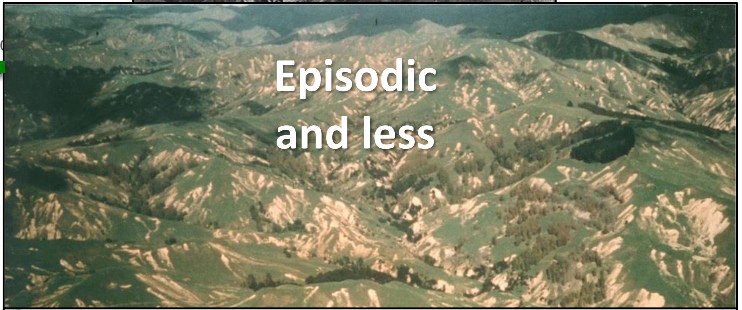
- Accumulates over time in hillslope materials that eventually make their way to river channels.

- Accumulation rate: **~1.7 x 10^6** atoms per cm^2 annually – easily **measurable with AMS.**

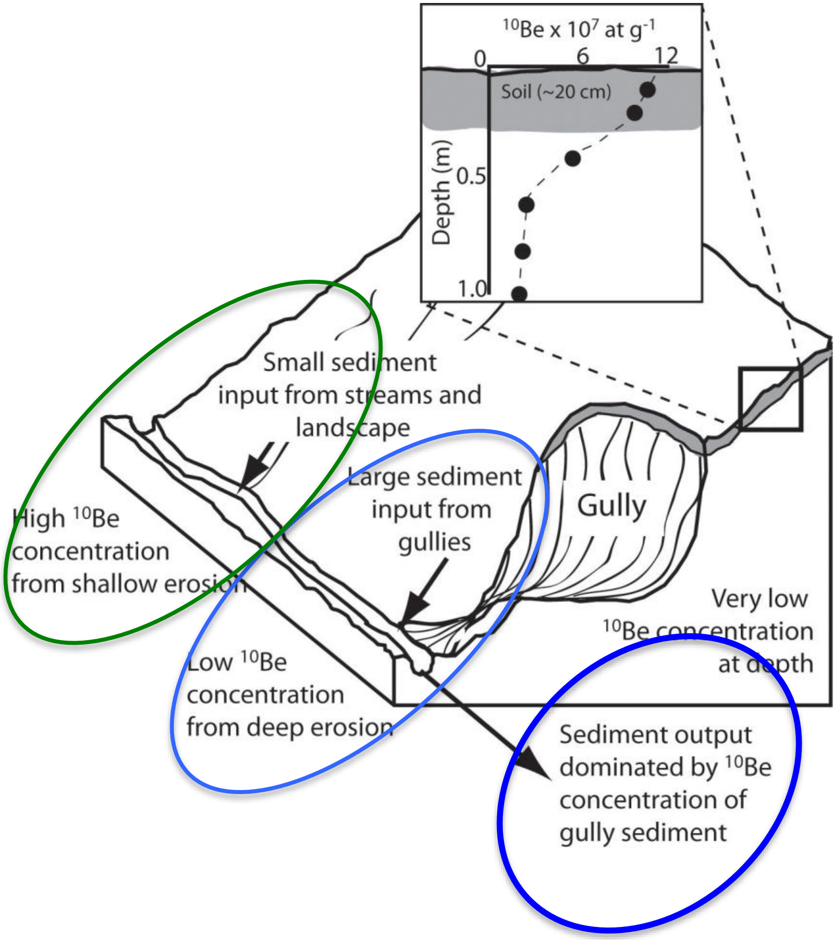
- Half-life of ~**1.38** millions years – residence time of near surface materials much shorter meaning ^{10}Be behaves as a **stable nuclide** over period of measurement.

Chasing sediment in the Waipaoa Basin:

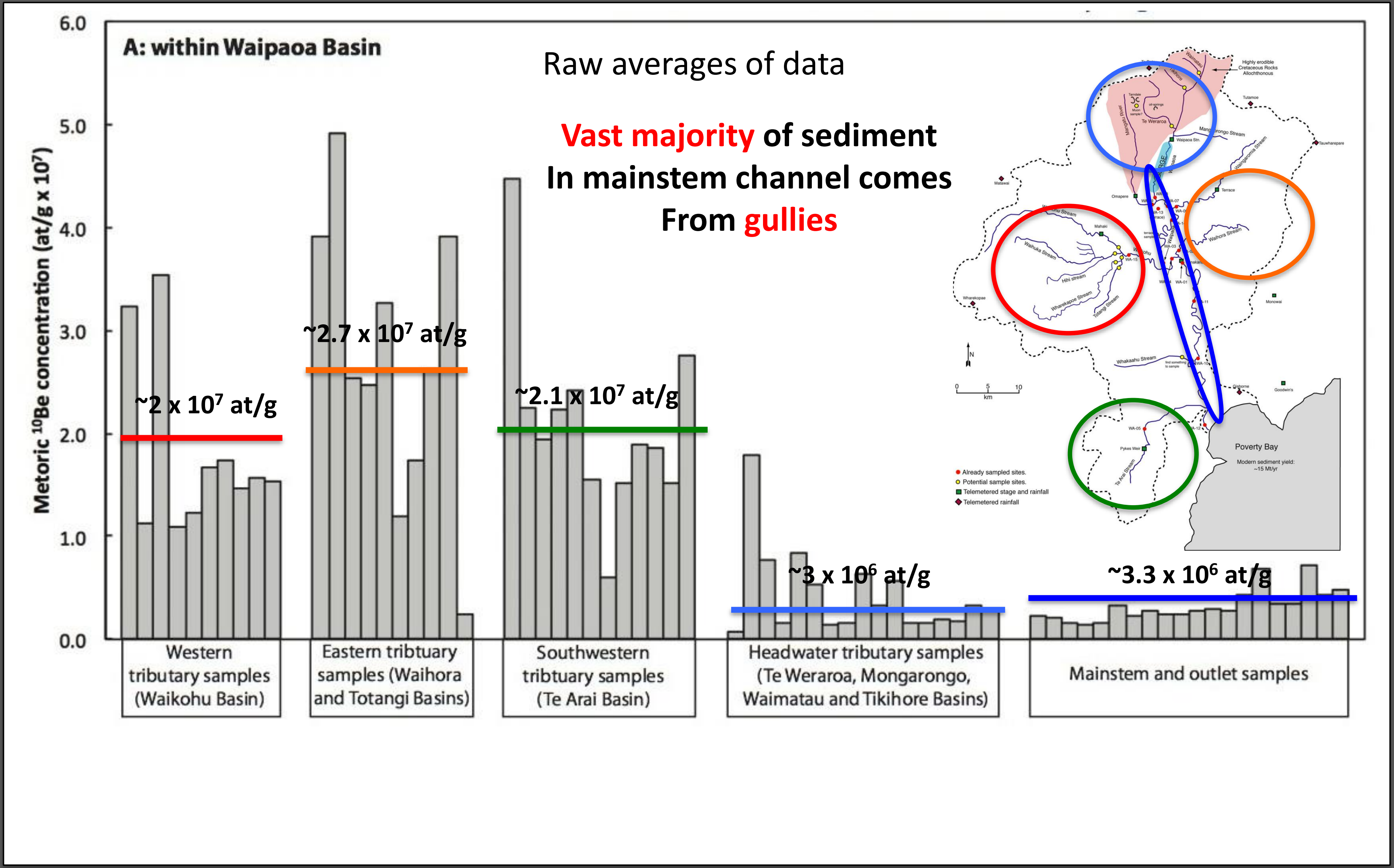




Isotopic signatures of sediment:



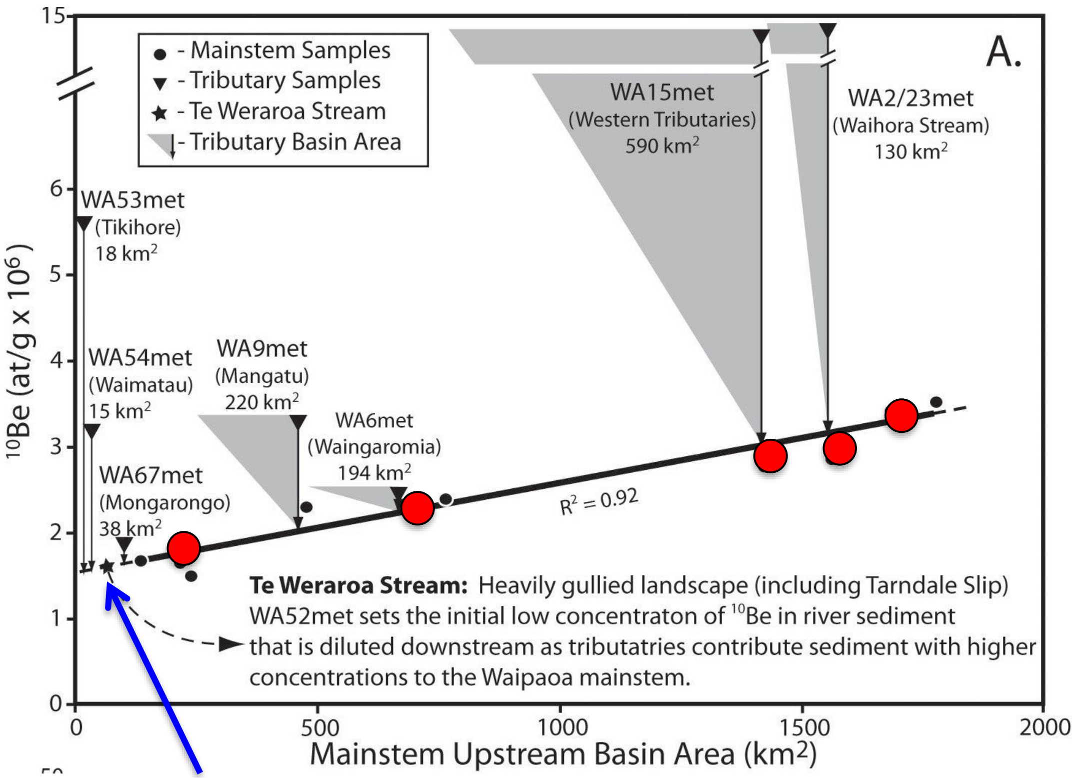
Spatial distribution of meteoric ^{10}Be concentrations:



Raw averages of data

Vast majority of sediment In mainstem channel comes From gullies

Mixing of sediment with different isotopic signatures:



Te Weraroa Stream: Heavily gullied landscape (including Tarndale Slip) WA52met sets the initial low concentraton of ^{10}Be in river sediment that is diluted downstream as tributatries contribute sediment with higher concentrations to the Waipaoa mainstem.

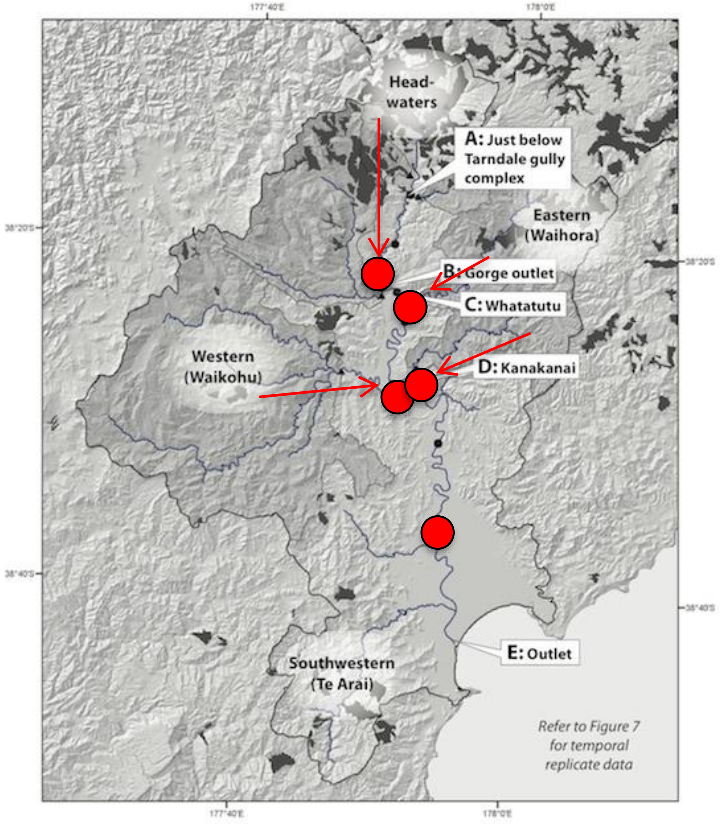
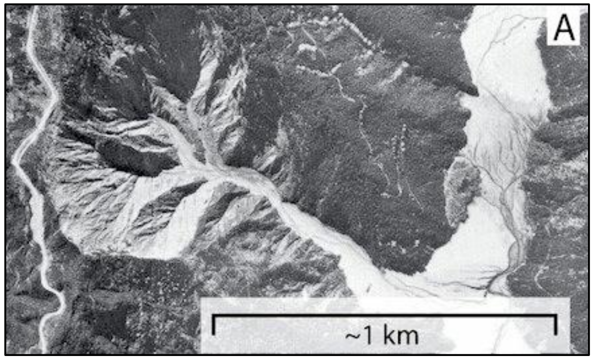


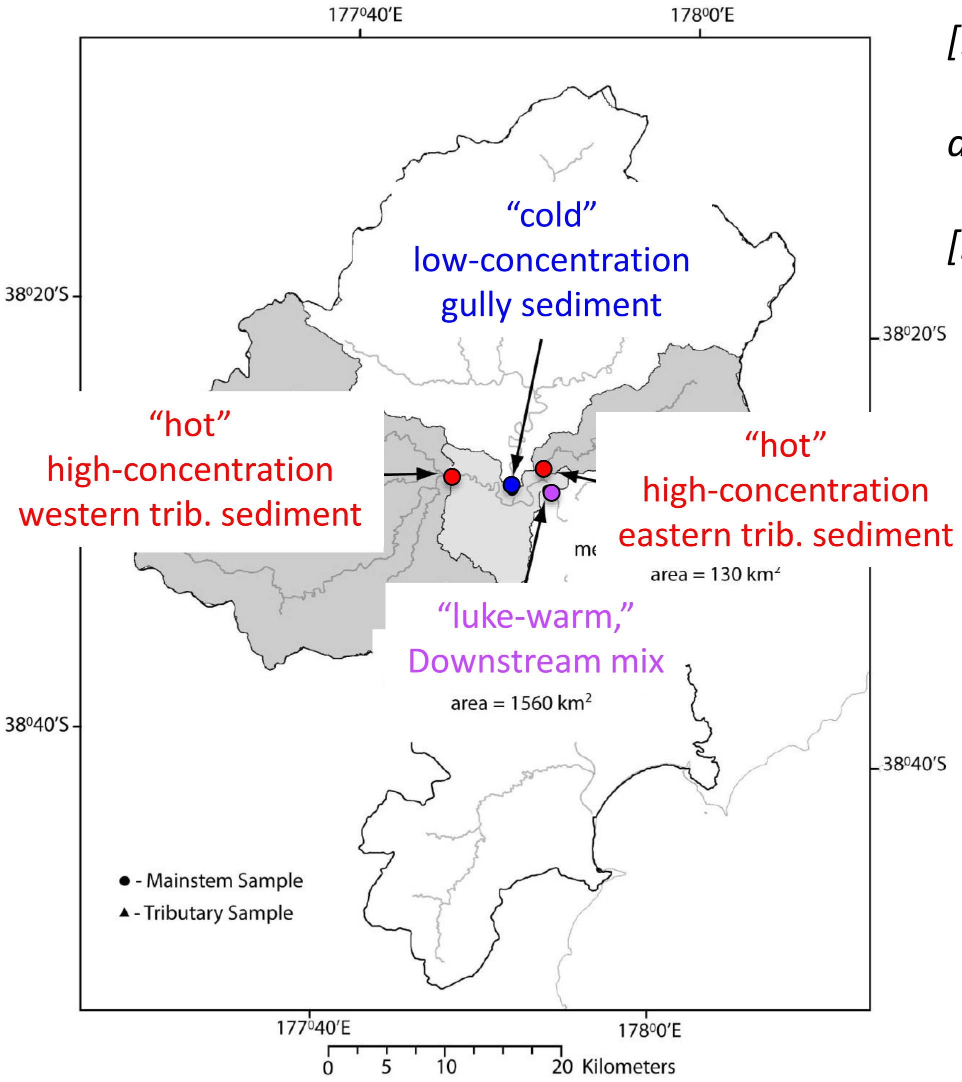
Figure 8:



Tarndale gully is the starting **isotopic signature**

Tarndale signal is **augmented** with **higher concentration** sediment from incoming tributaries.

Mixing model – apportioning relative contribution:



"cold"
low-concentration
gully sediment

"hot"
high-concentration
western trib. sediment

"hot"
high-concentration
eastern trib. sediment

"luke-warm,"
Downstream mix

$$[N_{up}][m_{up}] + [N_{trib}][m_{trib}] = [N_{down}][m_{up} + m_{trib}]$$

and

$$[m_{up}] + [m_{trib}] = 100\ \%$$

Areas of the headwaters and the eastern and western tribs. combined are roughly equal

Gullied headwaters produce sediment at a rate

20 times

that of the east and west

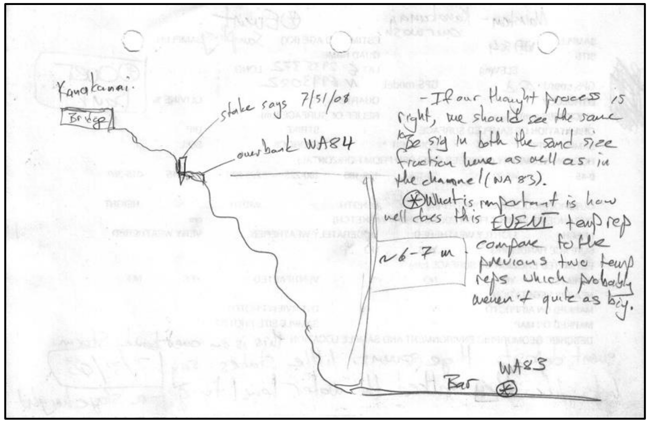
Testable hypotheses with meteoric ^{10}Be:

- **We can track temporal changes in meteoric ^{10}Be concentration by resampling the same sites at different times.**

- **We can infer how source area change through time, and at different flow conditions.**

1. May 2004 – fluvial sediment
2. March 2005 – fluvial sediment
3. August 2008 – fluvial sediment
4. August 2008 – overbank flood deposit (event deposit)

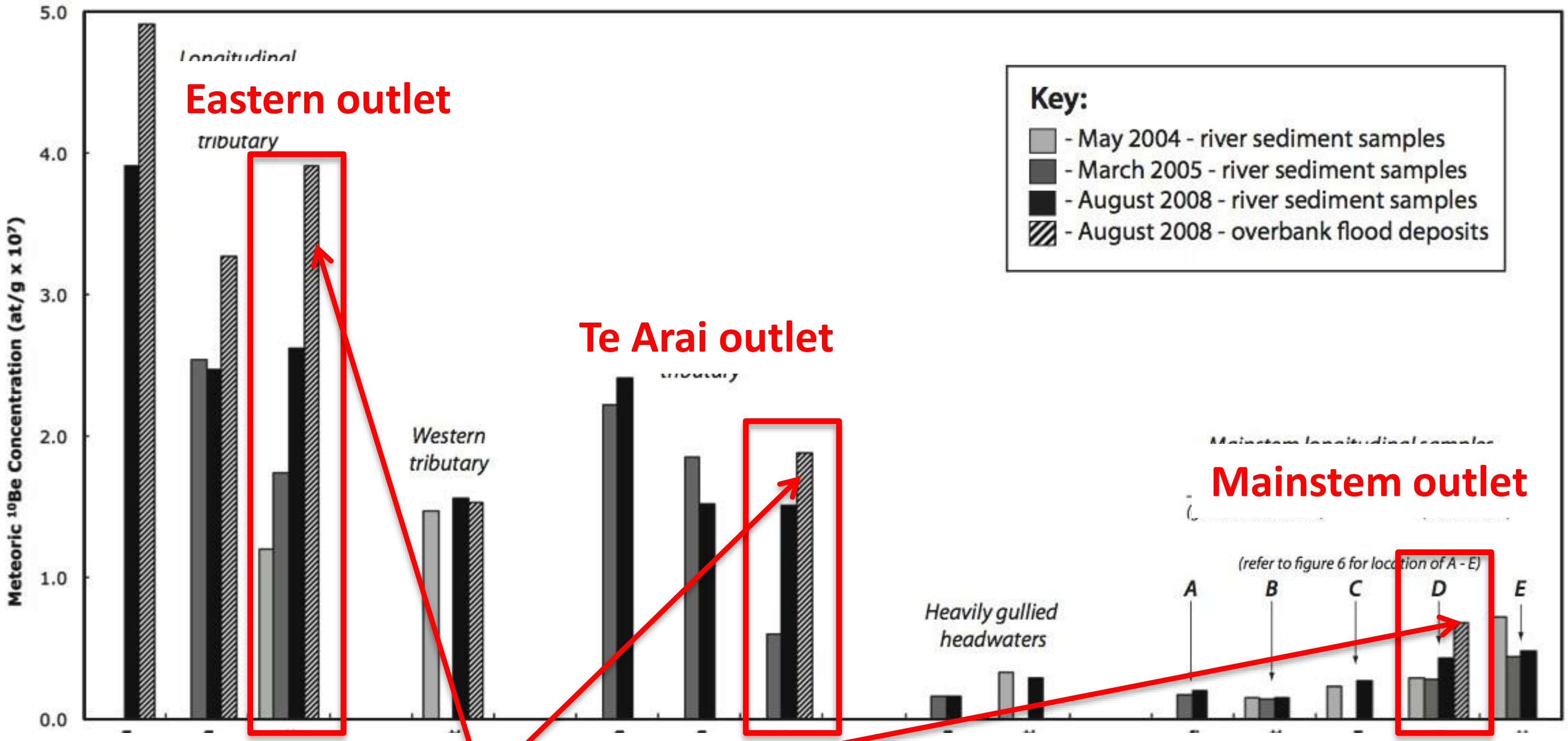
Basin-wide deposit



-If our thought process is right, we should see the same to be sig in both the sand size fraction here as well as in the channel (WA 83).

⊛ What is important is how well does this EVENT temp rep compare to the previous two temp reps which probably weren't quite as big.

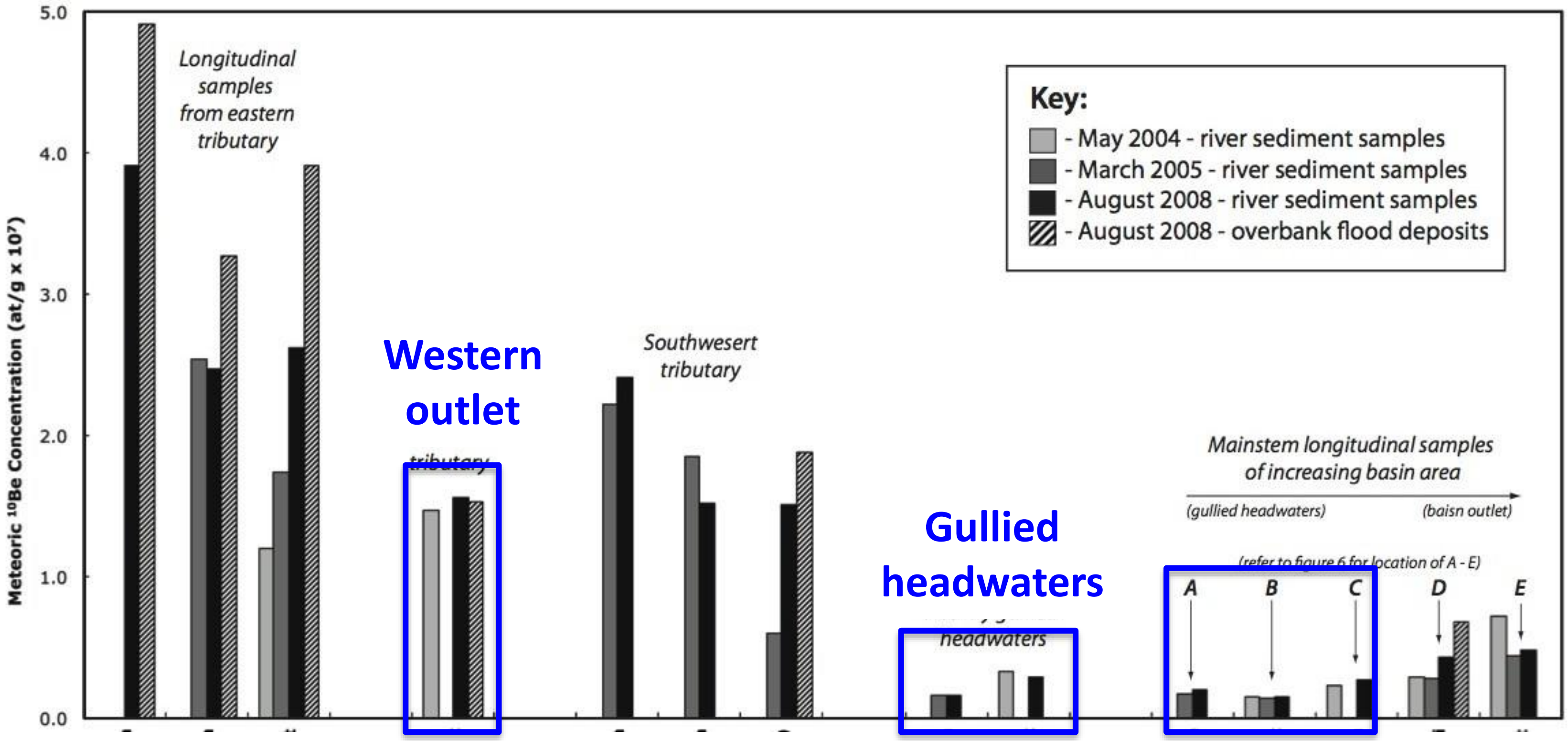
Temporal variable in meteoric ^{10}Be:



Not exactly sure why concentration are increasing through time in fluvial sediments?

Flood deposit likely reflects episodic input of shallow sediment with higher concentration landslide sediment from 7/31/2008 event.

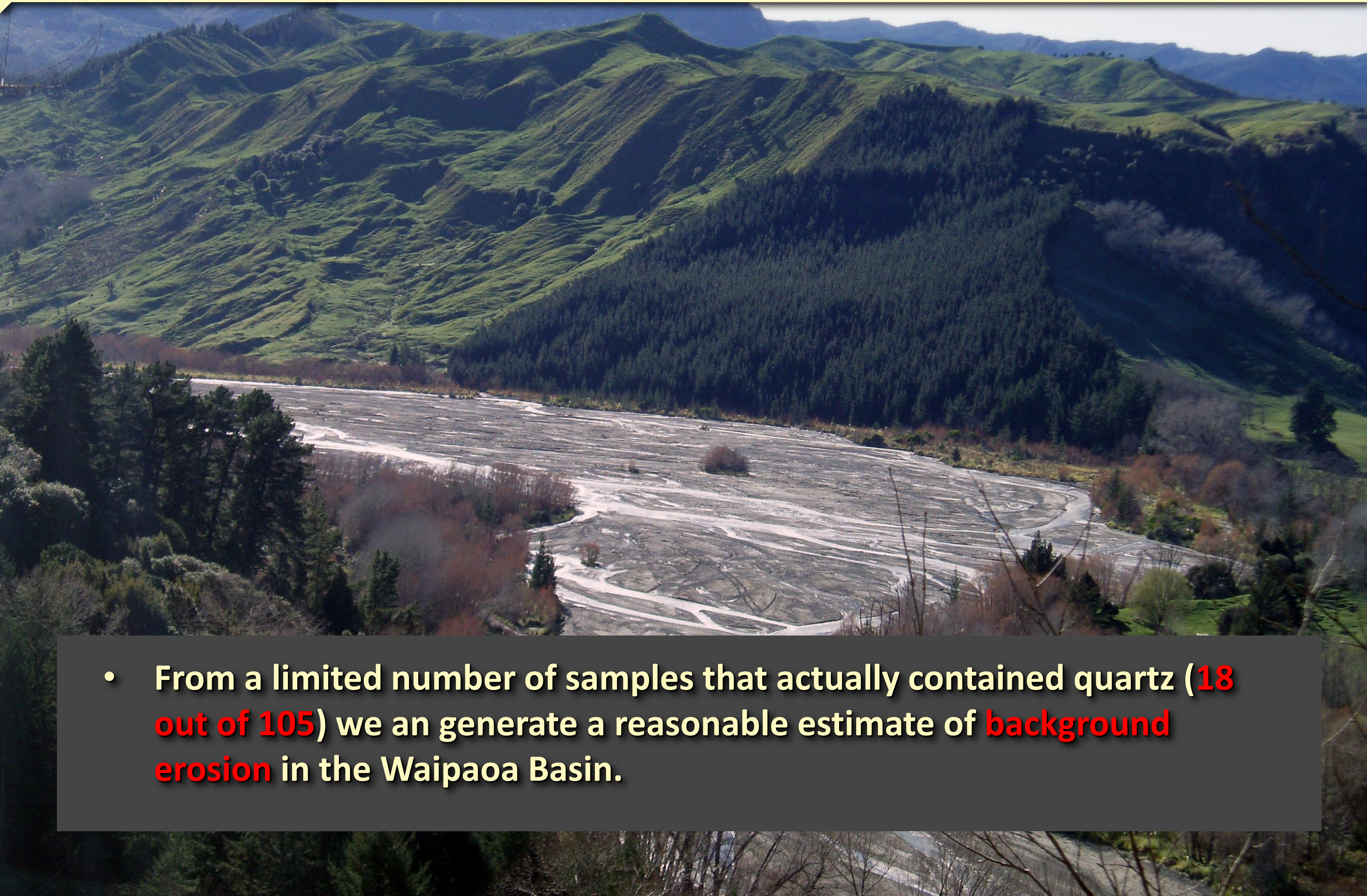
Temporal variable in meteoric ^{10}Be:



Don't see distinct temporal variability in the headwaters or gully dominate points along the mainstem channel.

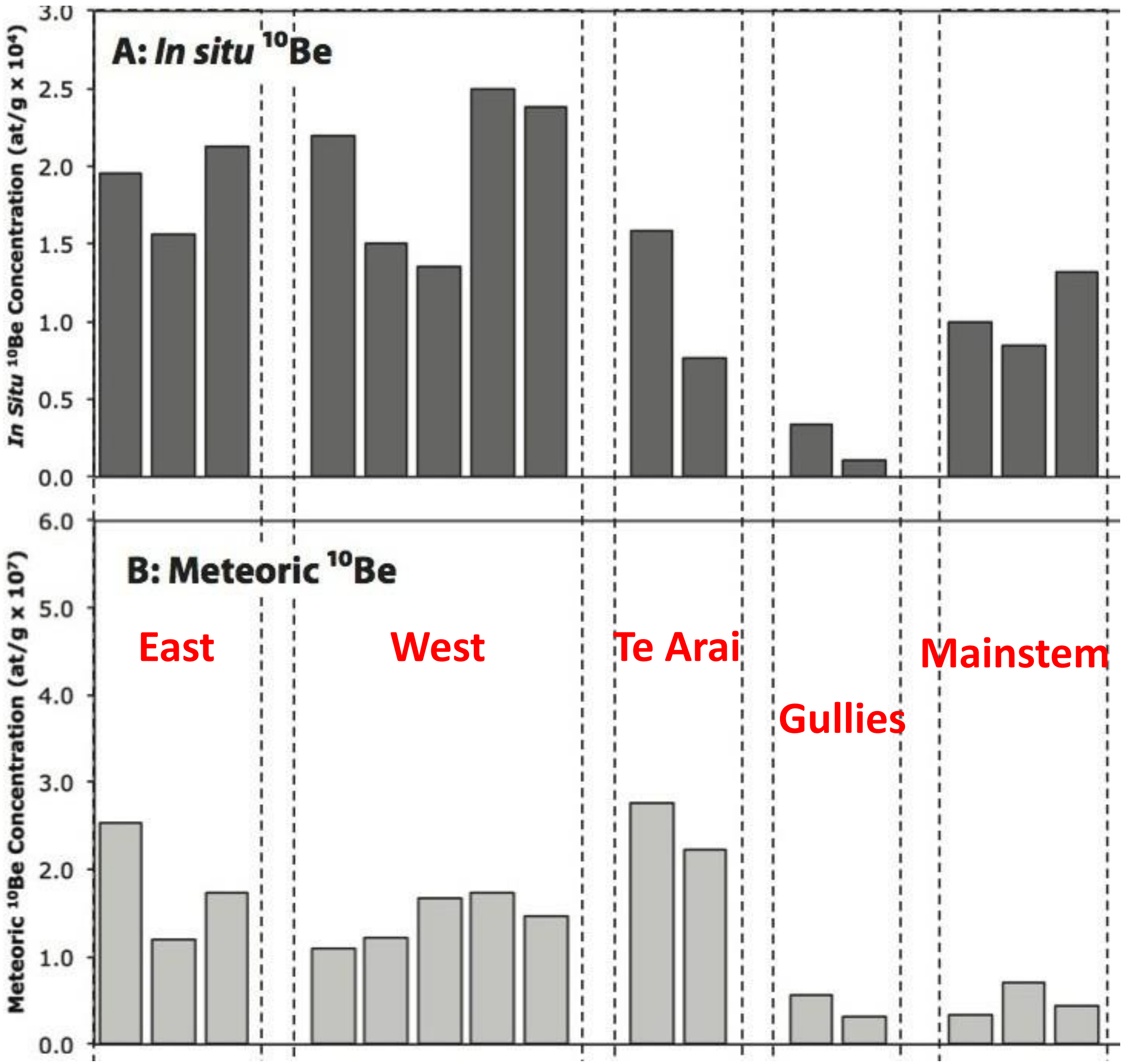
Gullies continuously feed deeply-sourced, low concentration sediment to channels. These regions aren't as sensitive to stochastic weather events like landslide-dominated basins.

Testable hypothesis with *in situ* ^{10}Be:



- From a limited number of samples that actually contained quartz (18 out of 105) we an generate a reasonable estimate of background erosion in the Waipaoa Basin.

In situ and meteoric ^{10}Be comparison samples:

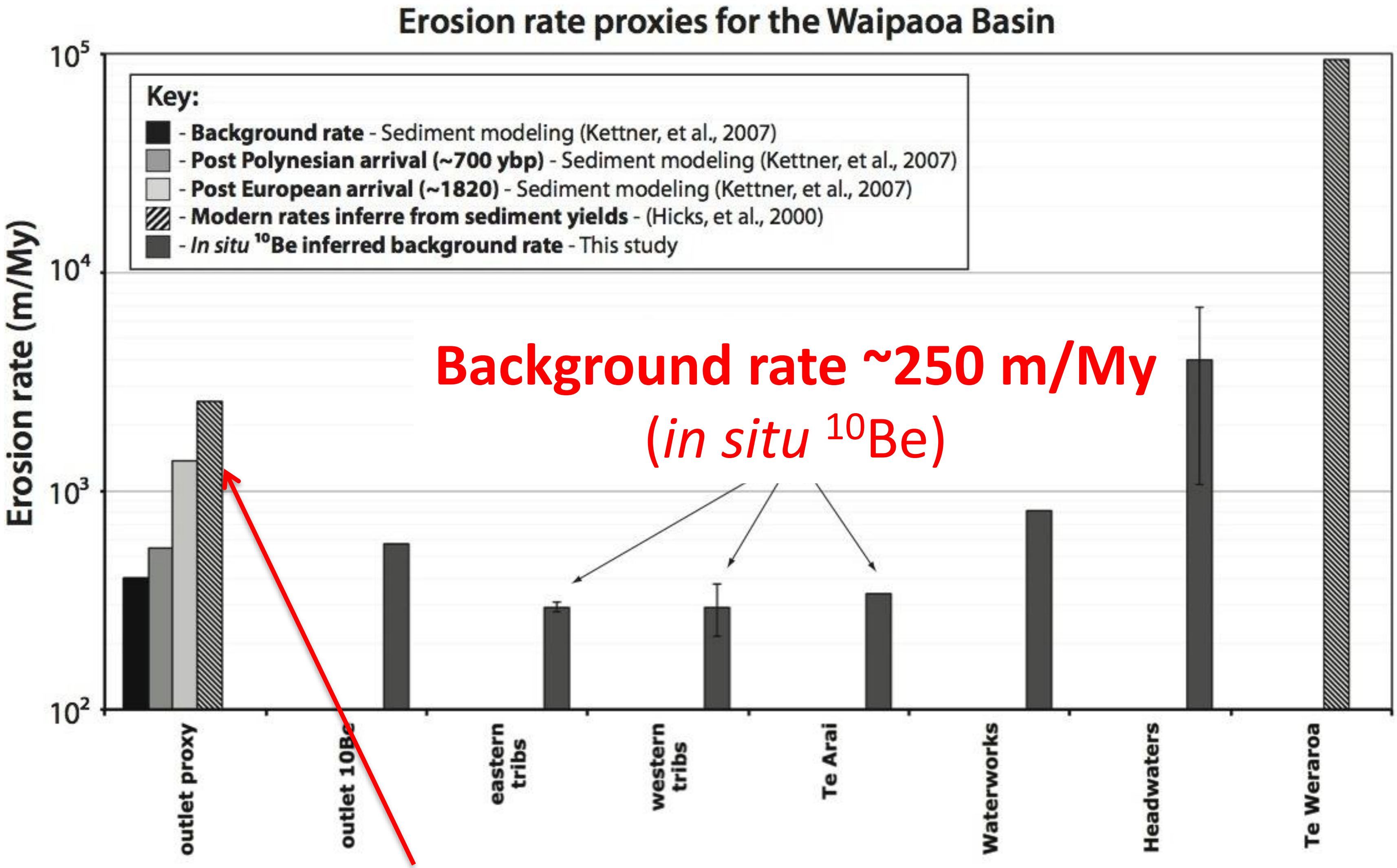


Quartz only:

Only reflects the exposure
History of lithologies
That contain quartz.

Bulk sample:
theoretically reflects
entire drainage basin.

Reasonable estimate of background erosion:



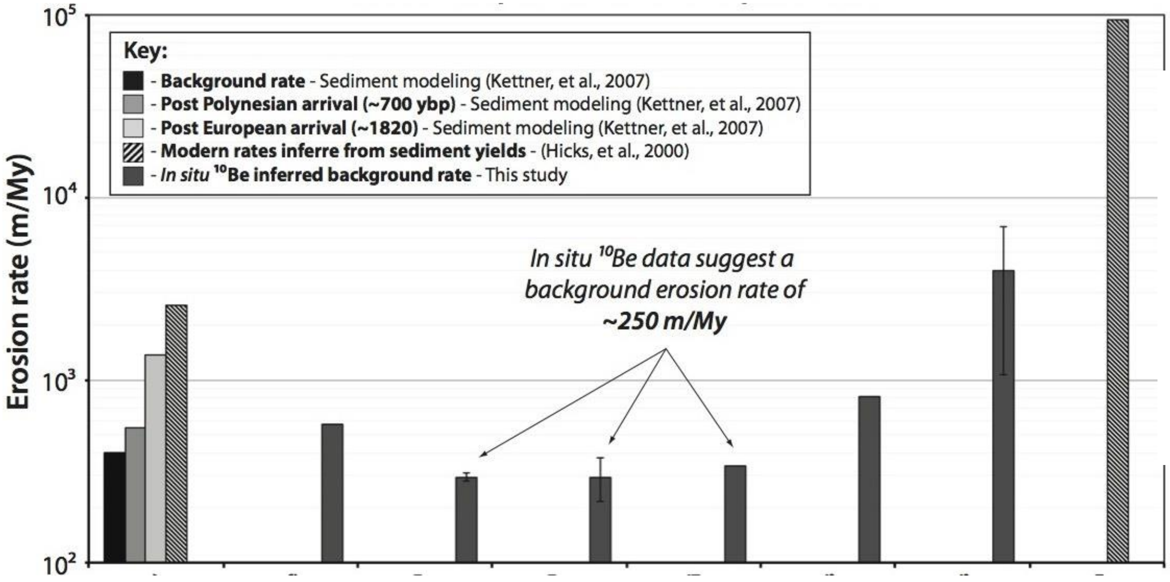
Background rate ~250 m/My

(*in situ* ^{10}Be)

Just about 100 times slower than contemporary sediment-yield-inferred

Erosion rate reflecting agricultural disturbance

Brings us full circle back to the Appalachians:



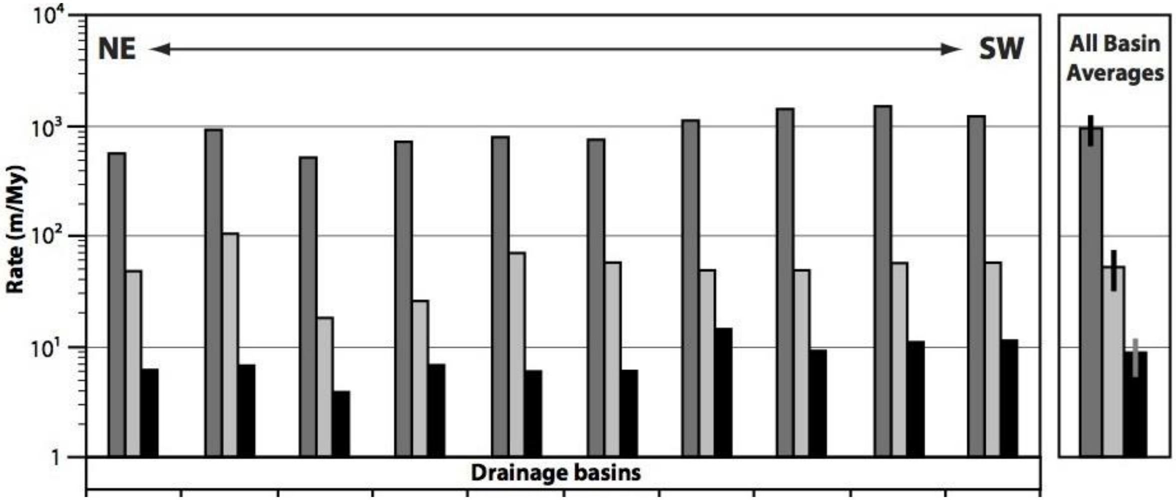
-Tectonically active

-Non-uniform erosion

-Event driven (cyclones)

-Intense human disturbance

-Human ~100 > Background rates



-Largely passive

-Relatively uniform erosion

-Humid temperate climate.

-Intense human disturbance

-Human ~100 > Background rates

Summary and conclusions of research:

For the southern Appalachian Piedmont:

1. Background in situ 10Be rates are ~100 times slower than agricultural rates of hillslope erosion.

2. At peak disturbance, streams were incapable of transporting the majority of sediment fed to them. Even today, most of it is stored across the landscape in valley bottoms, toe-slopes and impounded in dam reservoirs.

3. Generated a statistically robust dataset and predictive model from the slope-erosion rate relationship for small-basins.

4. Model is scalable and can be used to predict erosion at any point along a river network in the southern Piedmont.

Summary and conclusions of research:

For the Waipaoa River Basin, NZ:

1. Proof of concept: Meteoric 10Be can be used to track fluvial sand within a tectonically active river network, severely disturbed by past human landuse practices
2. Simple mixing models allow us to assess the relative contribution of sediment from different regions within a watershed.
3. Temporal replicates demonstrate how source areas, and erosion style change through time and as a function of flow conditions.
4. As for the southern Piedmont, human landuse practices appear to have increased inferred erosion rates by 100 times above background.

Implications for land management:

For the southern Appalachian Piedmont:

- **With the scalable slope-based model, we can predict a background erosion rate at any point along the southern Piedmont.**
  - These predictions could be used to inform TMDL levels for sediment and associated pollutants in waterways and water bodies.

For the Waipaoa River basin, New Zealand:

- **Can apportion the relative contribution of sediment from different tributary basins within a watershed using a simple mixing model.**
  - Gully-sourced sediment in the Waipaoa systems is visibly obvious, but a similar approach could be used in other, less disturbed basins where the contribution from various regions is less obvious.

Acknowledgments:

- **Funding sources: NSF, DEPSCoR, U.S. Geological Survey**

- **My Committee:** Paul Bierman, Donna Rizzo, Austin Troy, and Beverley Wemple.

- **UVM Folks:**
  - All my fellow Geology Grads
  - Cosmo Crew
  - Geology faculty

- **Family and Friends for all their support along the way!**

And special thanks go to……..

Matt Jungers for endless help in the field at so many location around the globe

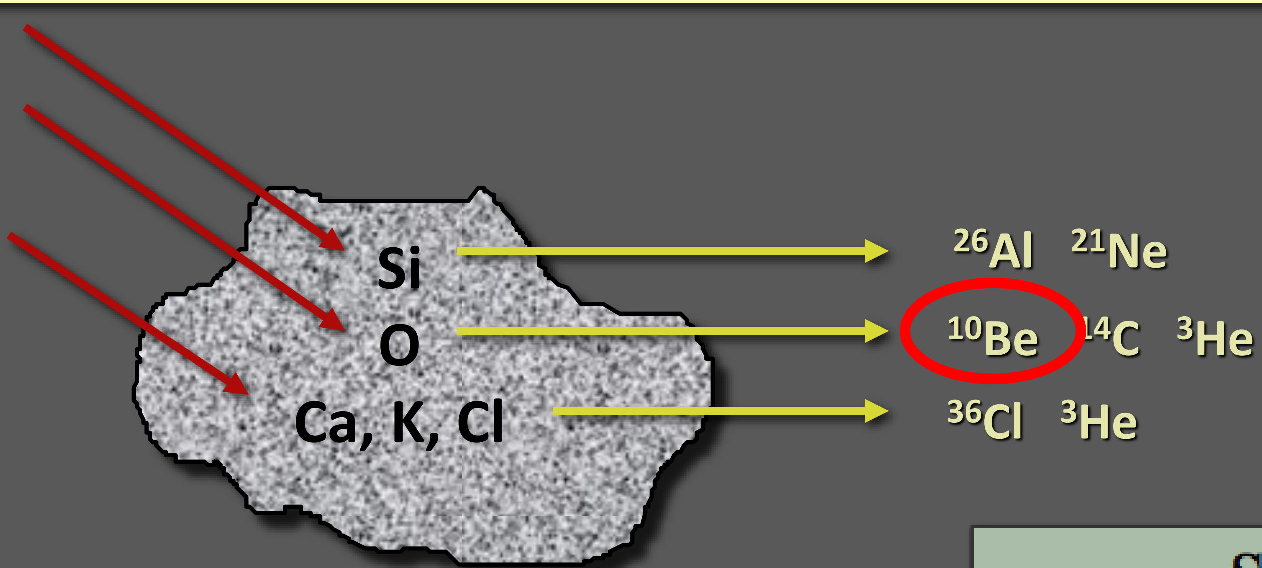
Will Hacket for countless hours of driving through the Appalachian Mountains.

And for tallying the number of Waffle Houses by region

And of course Paul Bierman for providing endless help and guidance over many many years!!

Questions?

In situ production of ^{10}Be:



Si → ^{26}Al ^{21}Ne

O → ^{10}Be ^{14}C ^{3}He

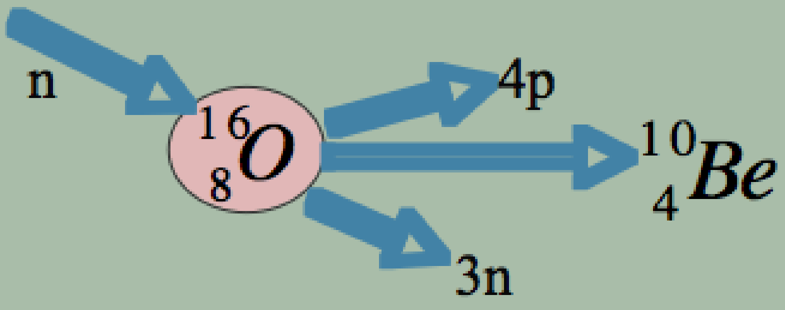
Ca, K, Cl → ^{36}Cl ^{3}He

- Produced in upper several meters of rocks and sediment exposed at Earth’s Surface.

- Production rate: **5.2** atoms per gram of quartz per year - **measurable with AMS**

- Half-life of **1.5** millions years - residence time of near surface materials much shorter meaning ^{10}Be behaves as a **stable nuclide** over period of measurement.

Spallation



$$^{16}O(n,4p3n)^{10}Be$$

$$^{28}Si(n,p2n)^{26}Al$$

Equilibrium Stream Concept

Primary motivation for this project:

"There is a balance between the material transported by the stream and that produced on the hillslopes" (Judson and Ritter, 1964)

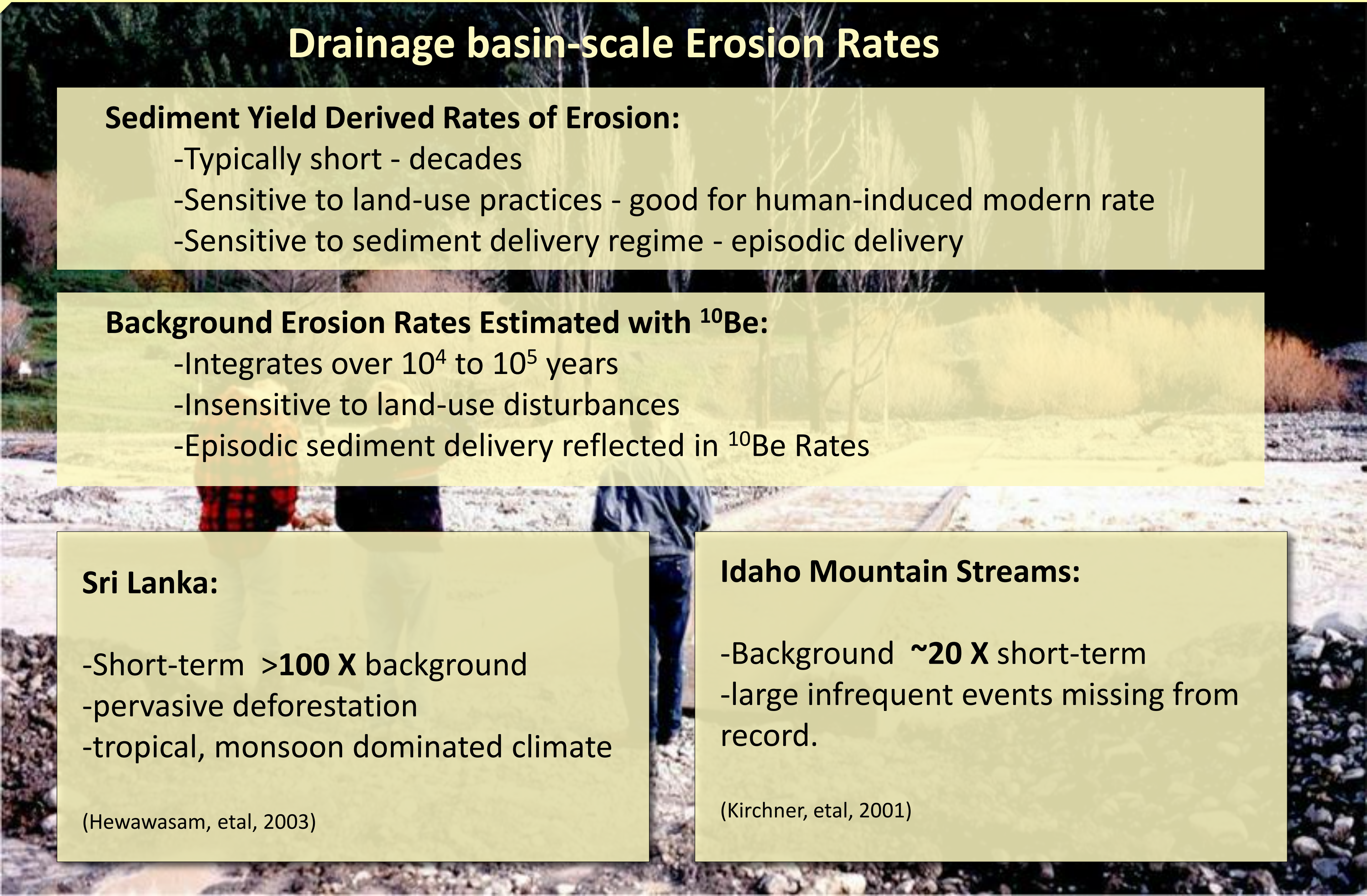
- Steady-state between hillslope erosion and sediment leaving a catchment
- Essential requirement when modeling denudation rates from sediment yields

SELDOM TRUE TODAY…Especially when humans get involved!

Stream "Un" Equilibrium Along the Southern Pidemont (Trimble, 1977)

- Ten large catchments draining the majority of the southern Piedmont (2,000 - 20,000 km^2)
- Sediment yield data reflecting peak agricultural disturbance.
- Sediment yield vs. hillslope erosion vs. rates of denudation.
- Does Stream Equilibrium hold??

Background (^{10}Be) vs. short-term (sed. yields)



Drainage basin-scale Erosion Rates

Sediment Yield Derived Rates of Erosion:

- -Typically short - decades
- -Sensitive to land-use practices - good for human-induced modern rate
- -Sensitive to sediment delivery regime - episodic delivery

Background Erosion Rates Estimated with ^{10}Be:

- -Integrates over 10^4 to 10^5 years
- -Insensitive to land-use disturbances
- -Episodic sediment delivery reflected in ^{10}Be Rates

Sri Lanka:

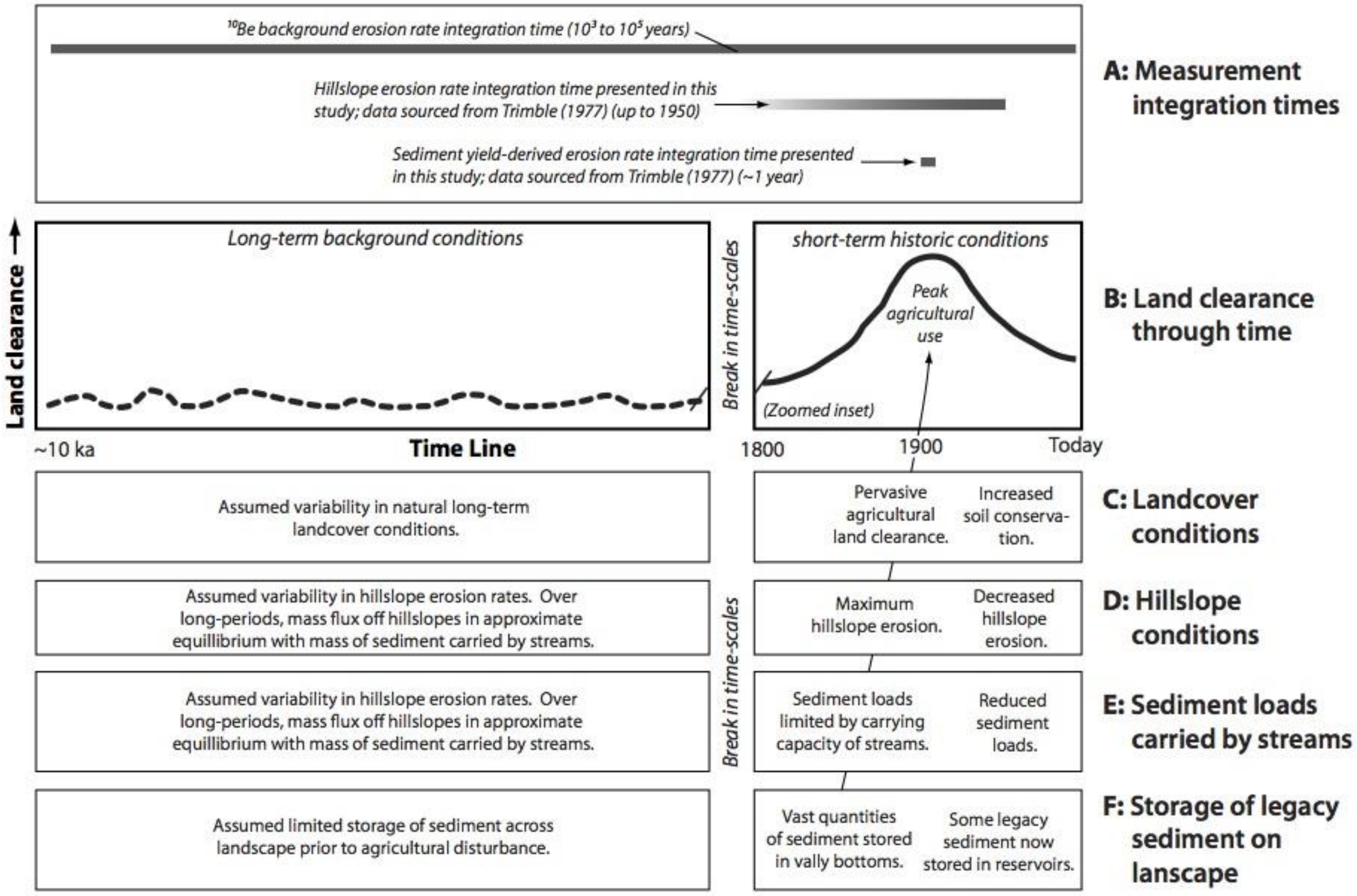
-Short-term >**100 X** background
-pervasive deforestation
-tropical, monsoon dominated climate

(Hewawasam, etal, 2003)

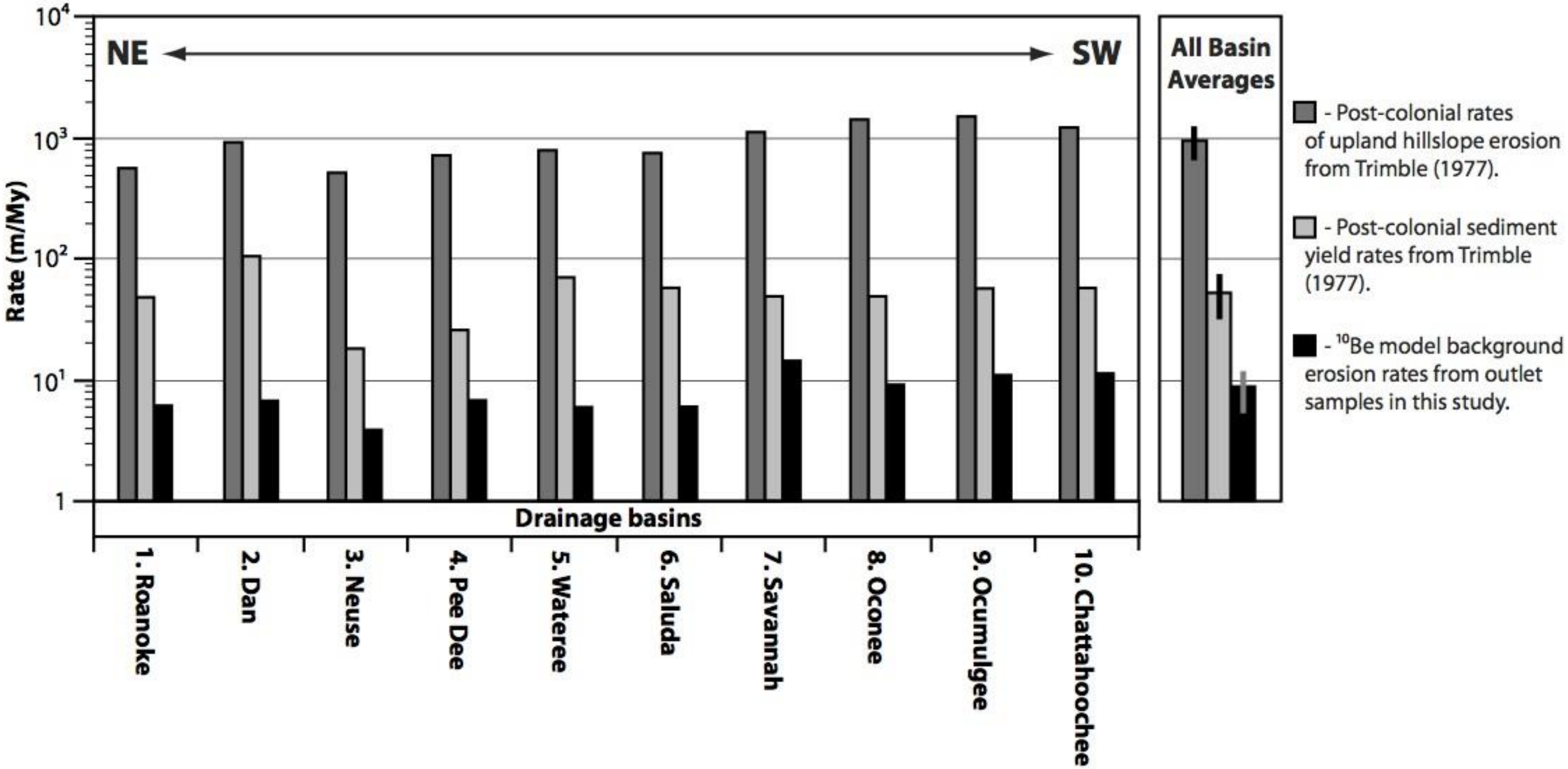
Idaho Mountain Streams:

-Background **~20 X** short-term
-large infrequent events missing from record.

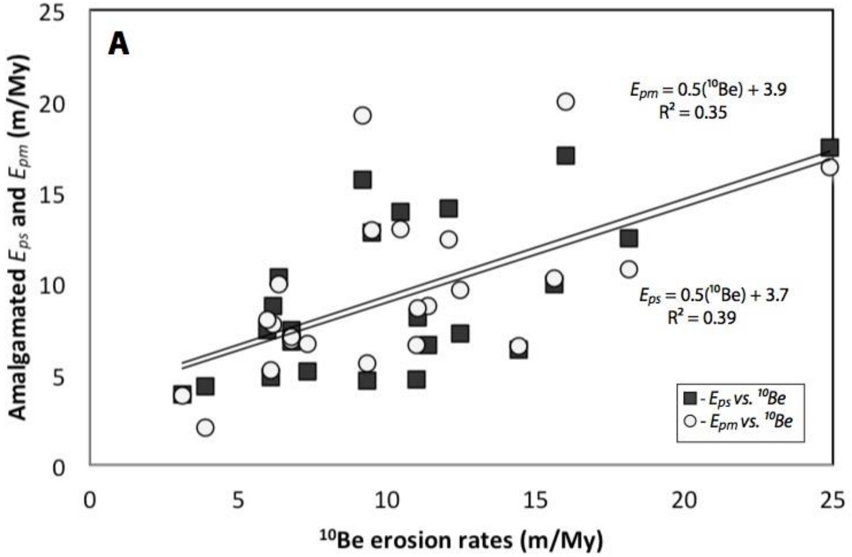
(Kirchner, etal, 2001)



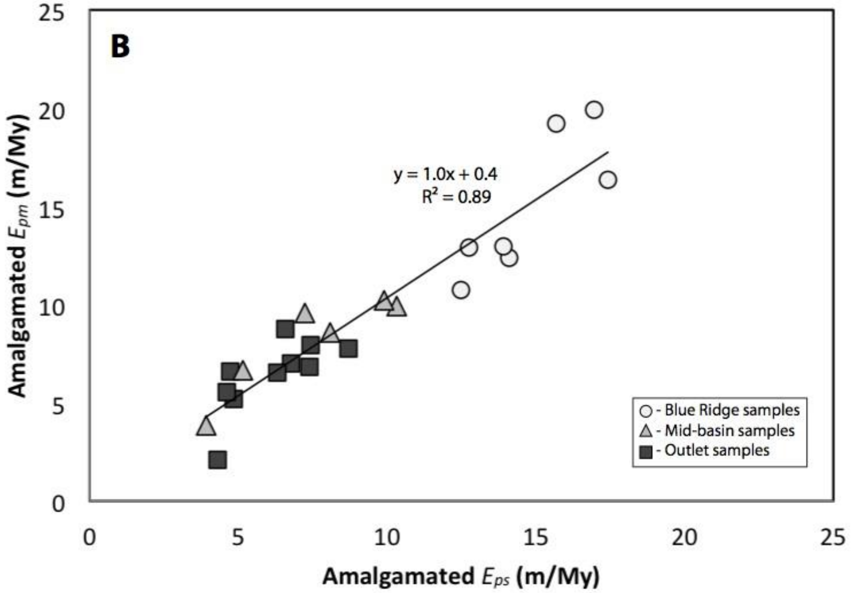
Assumed variability in natural long-term landcover conditions.	Pervasive agricultural land clearance.	Increased soil conservation.	**C: Landcover conditions**
Assumed variability in hillslope erosion rates. Over long-periods, mass flux off hillslopes in approximate equillibrium with mass of sediment carried by streams.	Maximum hillslope erosion.	Decreased hillslope erosion.	**D: Hillslope conditions**
Assumed variability in hillslope erosion rates. Over long-periods, mass flux off hillslopes in approximate equillibrium with mass of sediment carried by streams.	Sediment loads limited by carrying capacity of streams.	Reduced sediment loads.	**E: Sediment loads carried by streams**
Assumed limited storage of sediment across landscape prior to agricultural disturbance.	Vast quantities of sediment stored in vally bottoms.	Some legacy sediment now stored in reservoirs.	**F: Storage of legacy sediment on lanscape**

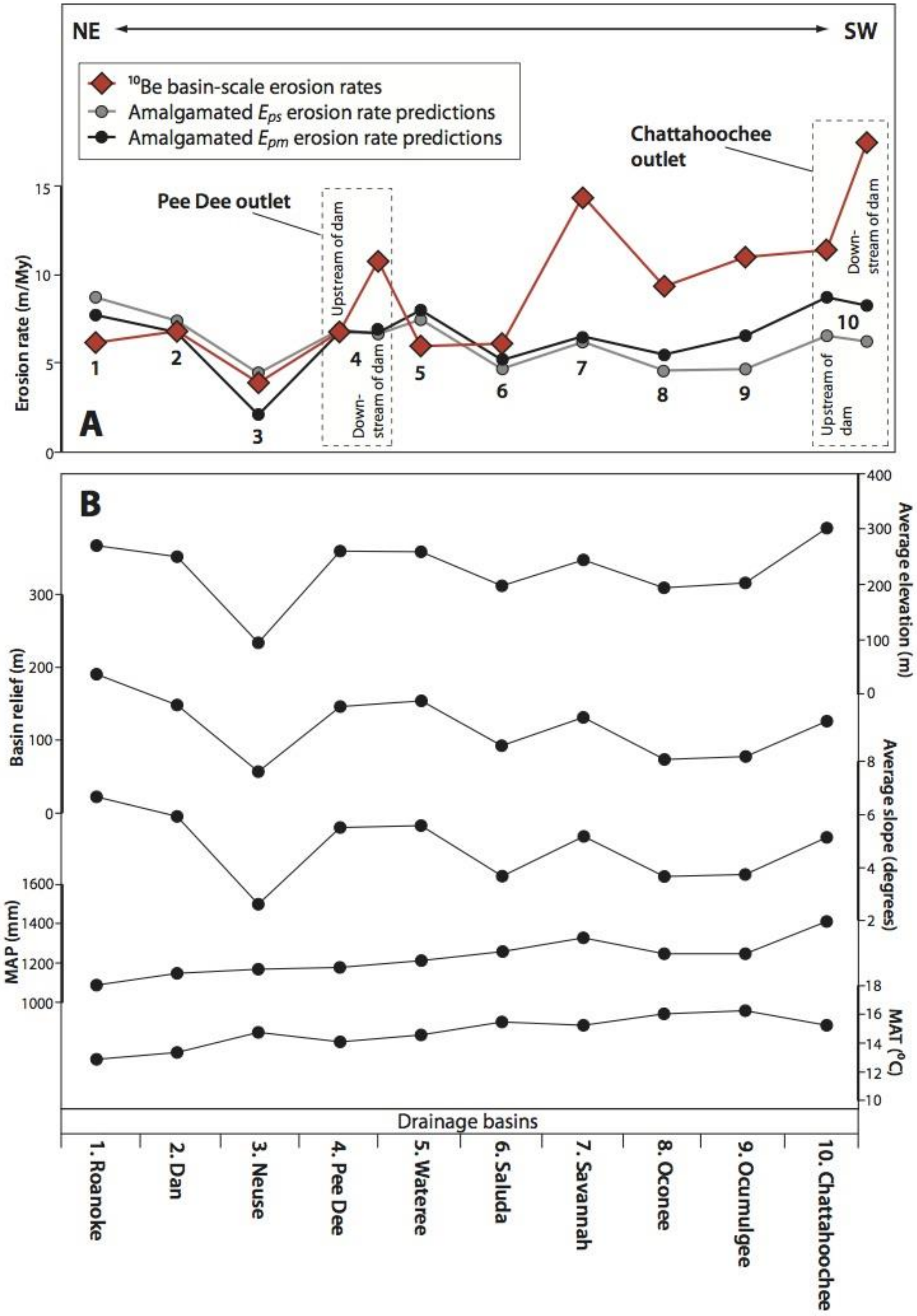

10^4
10^3
10^2
10^1
1
Rate (m/My)
NE
SW
All Basin Averages
Drainage basins
1. Roanoke
2. Dan
3. Neuse
4. Pee Dee
5. Wateree
6. Saluda
7. Savannah
8. Oconee
9. Ocumulgee
10. Chattahoochee
▨ - Post-colonial rates of upland hillslope erosion from Trimble (1977).
☐ - Post-colonial sediment yield rates from Trimble (1977).
■ - ¹⁰Be model background erosion rates from outlet samples in this study.

Amalgamated predictions (E_{ps} *vs.* E_{pm}) vs. ^{10}Be rates for large basins

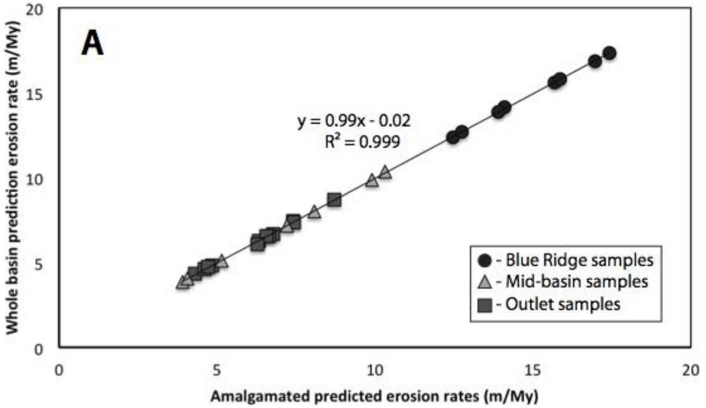


Amalgamated predictions (E_{ps} *vs.* E_{pm}) for large basins

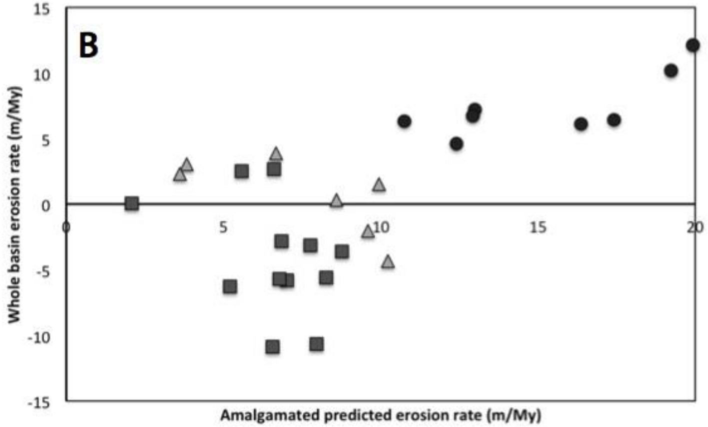



NE
SW
^{10}Be basin-scale erosion rates
Amalgamated E_{ps} erosion rate predictions
Amalgamated E_{pm} erosion rate predictions
Chattahoochee outlet
Pee Dee outlet
Upstream of dam
Down-stream of dam
Down-stream of dam
Upstream of dam
Erosion rate (m/My)
0
5
10
15
1
2
3
4
5
6
7
8
9
10
A
B
Basin relief (m)
0
100
200
300
Average elevation (m)
0
100
200
300
400
Average slope (degrees)
2
4
6
8
MAP (mm)
1000
1200
1400
1600
MAT (°C)
10
12
14
16
18
Drainage basins
1. Roanoke
2. Dan
3. Neuse
4. Pee Dee
5. Wateree
6. Saluda
7. Savannah
8. Oconee
9. Ocumulgee
10. Chattahoochee

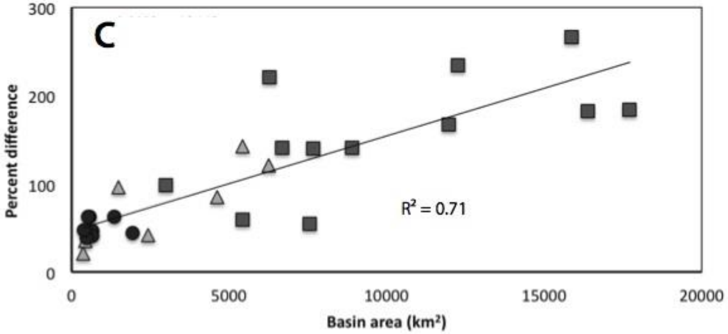
Slope model (E_{ps}) predicted erosion rates



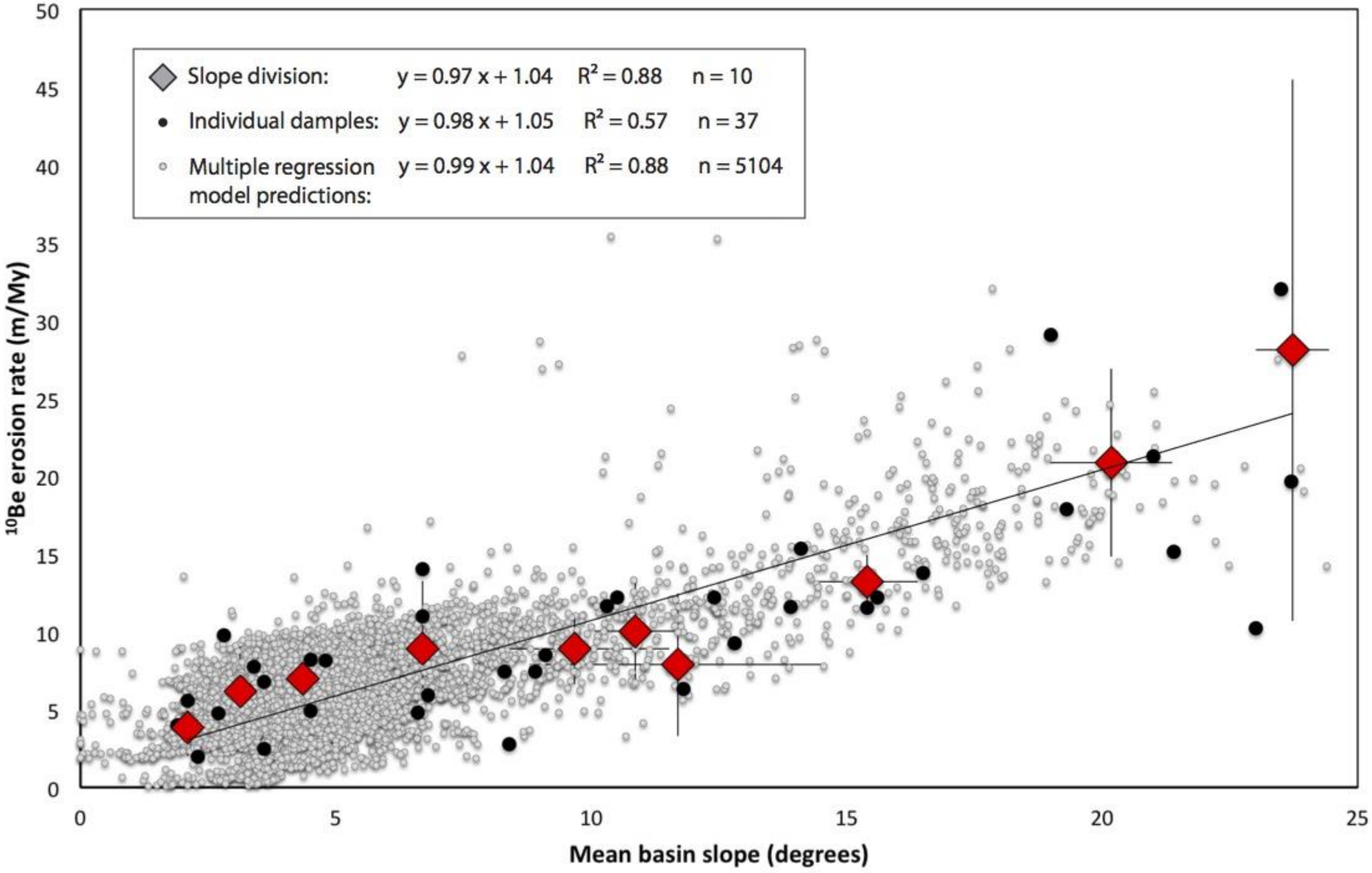
Multiple regression model (E_{pm}) predicted erosion rates



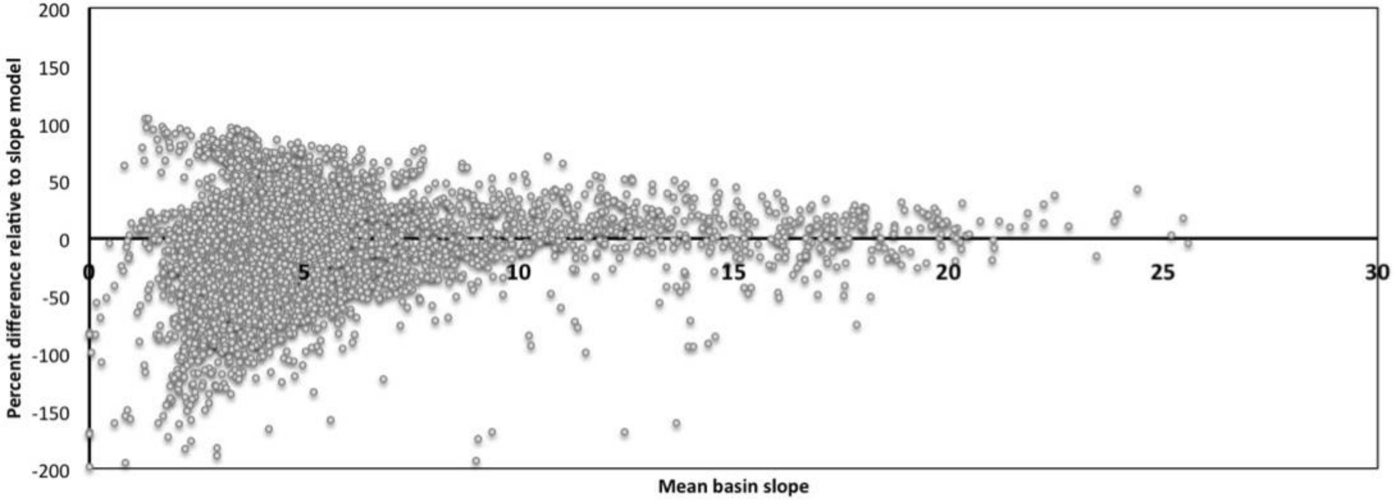
Percent difference between amalgamated and whole-basin predictions (relative to amalgamated) as a function of basin area

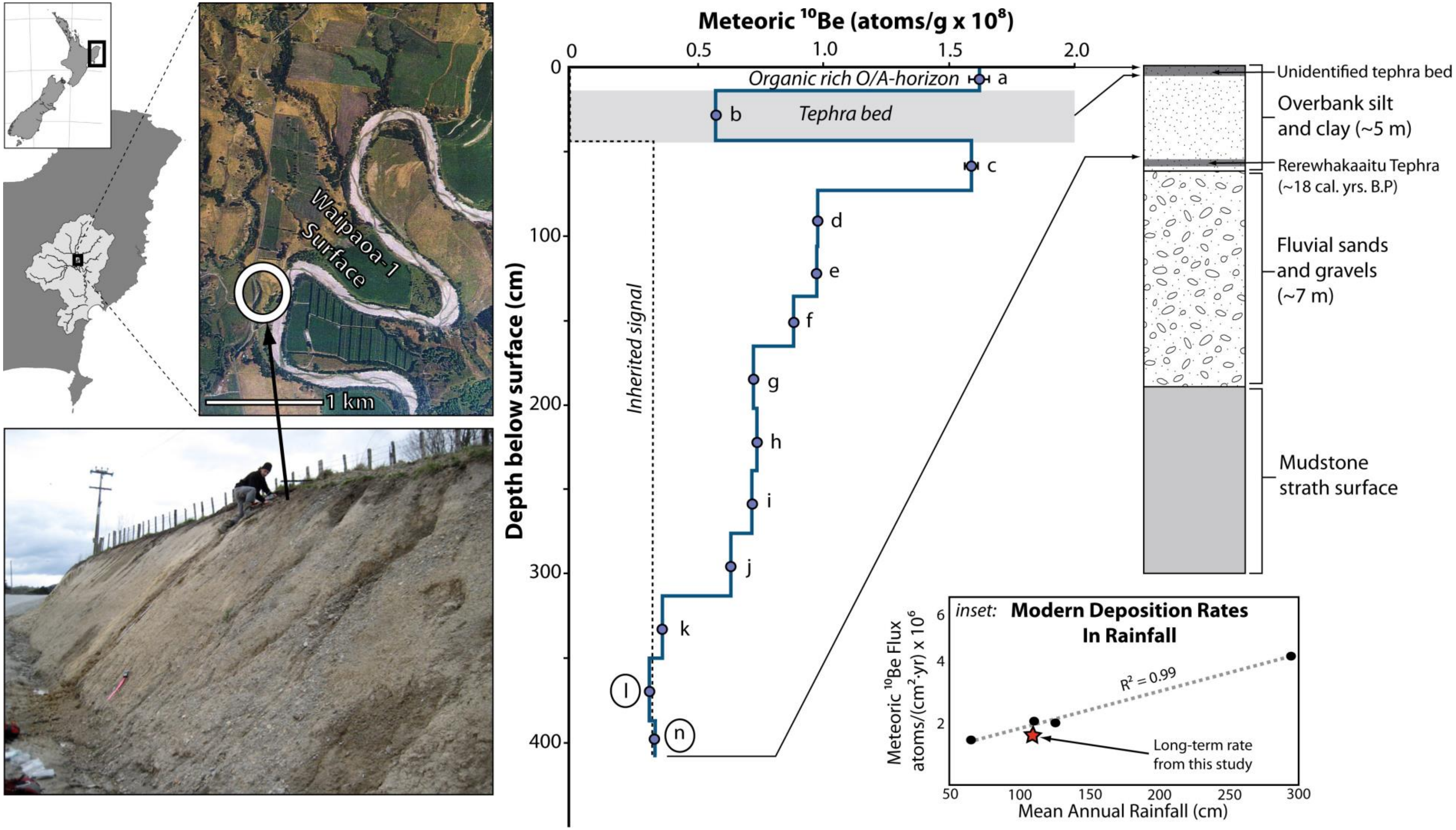


Multiple regression model erosion rate predictions for all 5104 sub-basin along the southern Applachain Piedmont displayed over the 37 sample used to generate the slope model.



Percent difference between erosion rates predicted with the simple slope model and the multiple regression model for all sub-basins along the southern Appalachian Piedmont




Waipaoa-1 Surface
1 km
Meteoric ^{10}Be (atoms/g x 10^{8})
0
0.5
1.0
1.5
2.0
Depth below surface (cm)
0
100
200
300
400
Organic rich O/A-horizon
Tephra bed
Inherited signal
a
b
c
d
e
f
g
h
i
j
k
l
n
Unidentified tephra bed
Overbank silt and clay (~5 m)
Rerewhakaaitu Tephra (~18 cal. yrs. B.P)
Fluvial sands and gravels (~7 m)
Mudstone strath surface
inset: Modern Deposition Rates In Rainfall
Meteoric ^{10}Be Flux atoms/(cm^{2}·yr) x 10^{6}
2
4
6
$R^2 = 0.99$
Long-term rate from this study
50
100
150
200
250
300
Mean Annual Rainfall (cm)

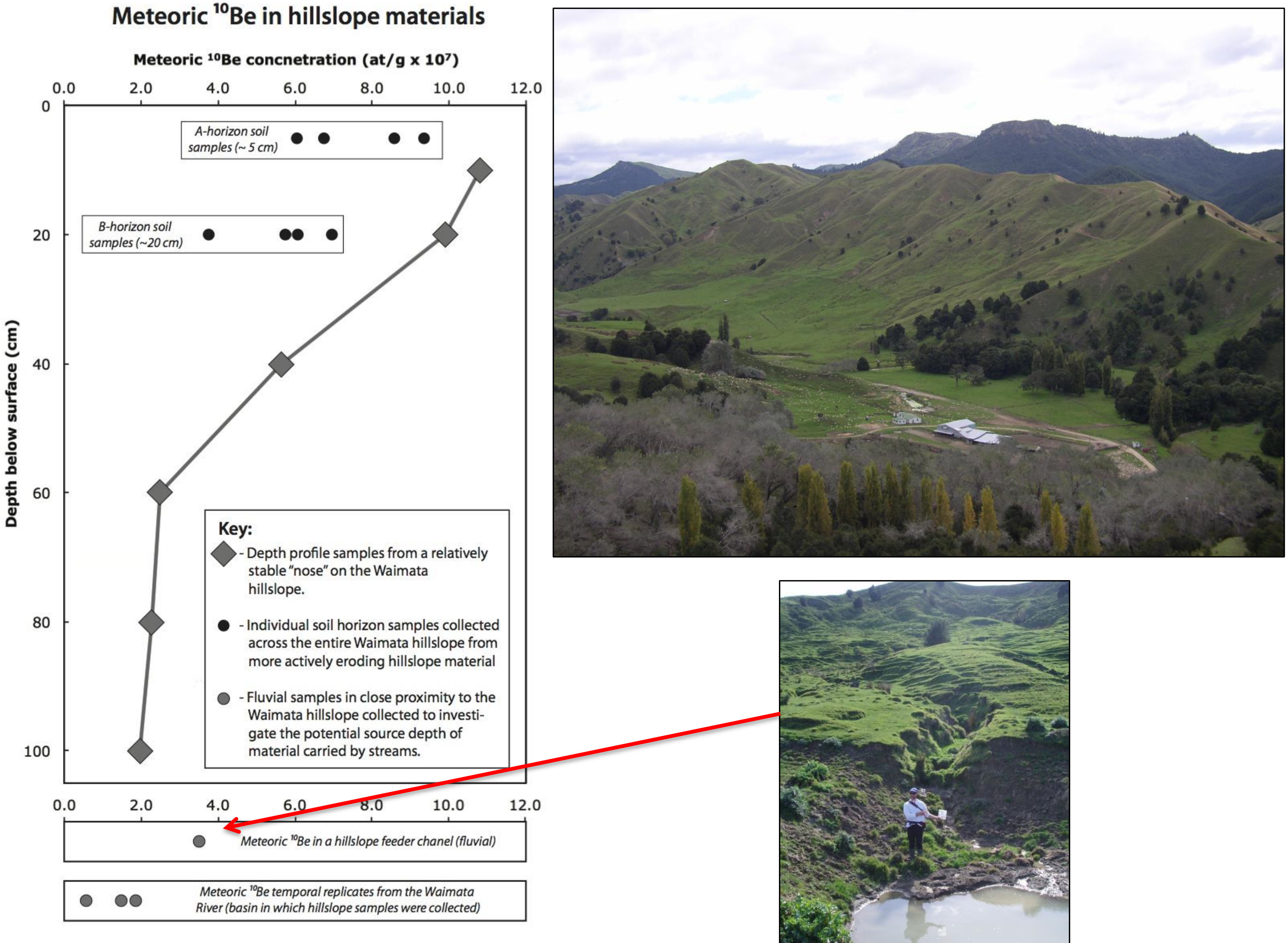

Meteoric ^{10}Be in hillslope materials
Meteoric ^{10}Be concnetration (at/g x 10^7)
0.0
2.0
4.0
6.0
8.0
10.0
12.0
Depth below surface (cm)
0
20
40
60
80
100
A-horizon soil samples (~ 5 cm)
B-horizon soil samples (~20 cm)
Key:
- Depth profile samples from a relatively stable "nose" on the Waimata hillslope.
- Individual soil horizon samples collected across the entire Waimata hillslope from more actively eroding hillslope material
- Fluvial samples in close proximity to the Waimata hillslope collected to investigate the potential source depth of material carried by streams.
Meteoric ^{10}Be in a hillslope feeder chanel (fluvial)
Meteoric ^{10}Be temporal replicates from the Waimata River (basin in which hillslope samples were collected)

Figure 10:

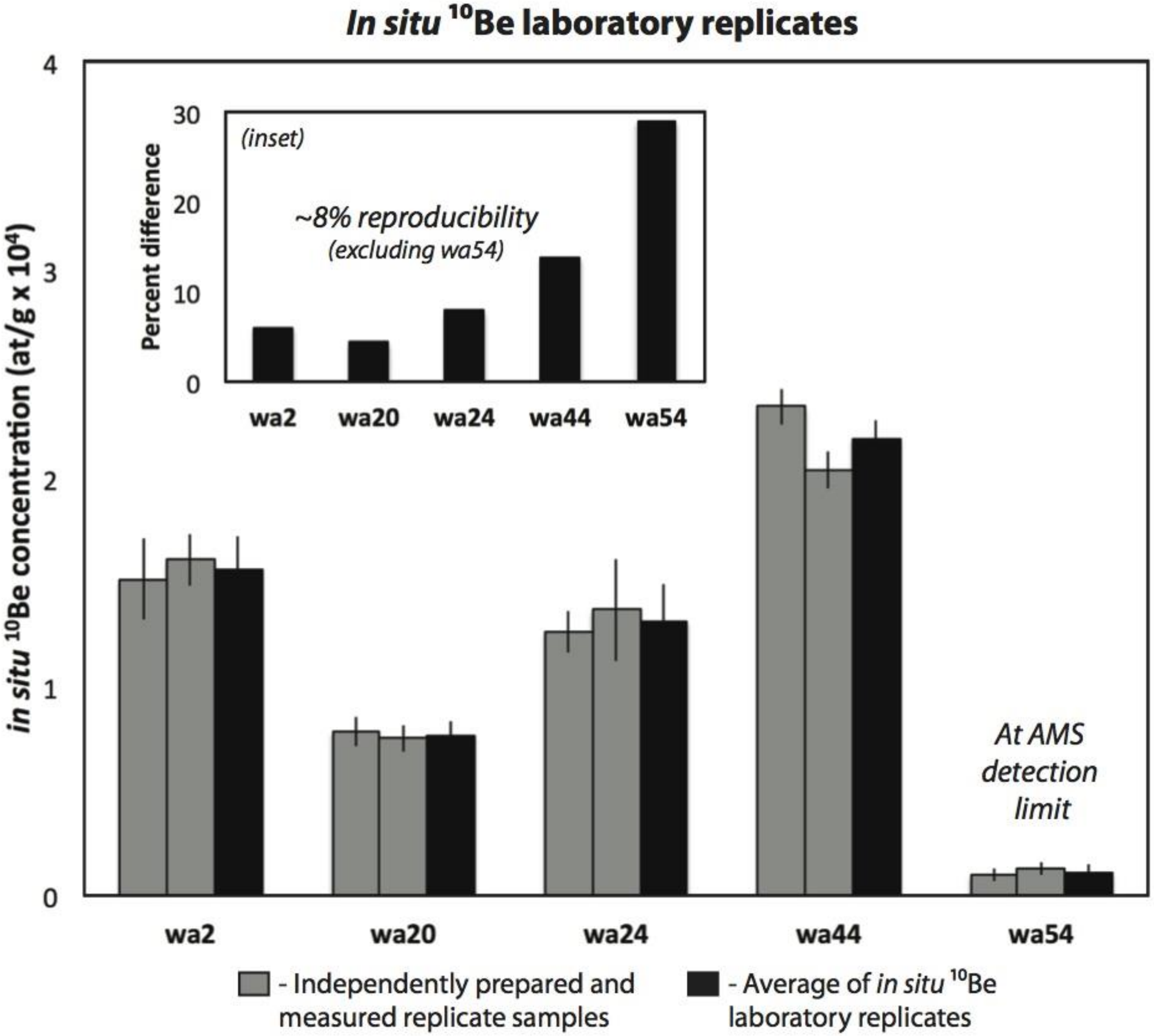

In situ ^{10}Be laboratory replicates
in situ ^{10}Be concentration (at/g x 10^4)
0
1
2
3
4
(inset)
Percent difference
0
10
20
30
~8% reproducibility
(excluding wa54)
wa2
wa20
wa24
wa44
wa54
At AMS detection limit
wa2
wa20
wa24
wa44
wa54
- Independently prepared and measured replicate samples
- Average of *in situ* ^{10}Be laboratory replicates

Figure 2:

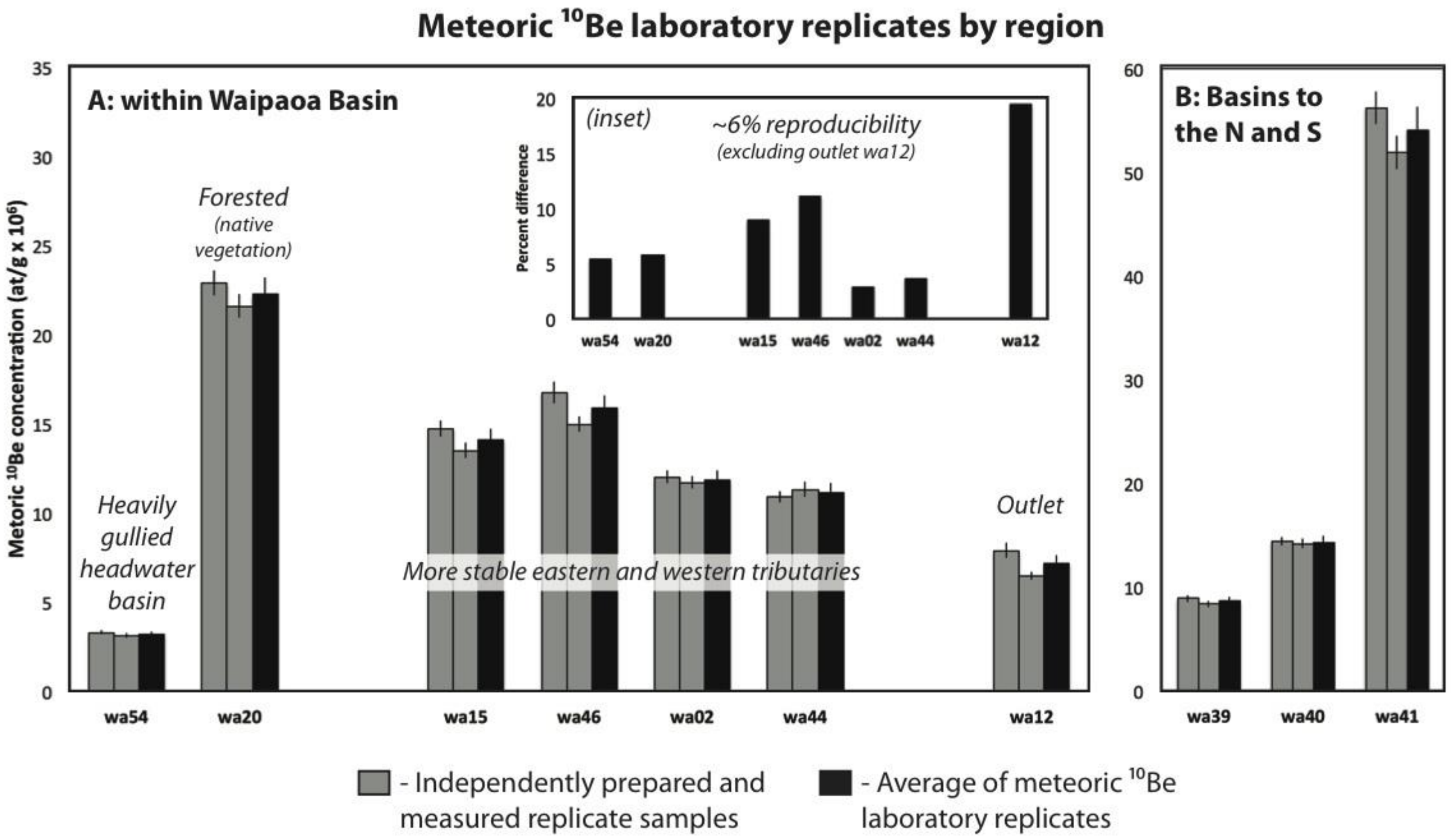

Meteoric ^{10}Be laboratory replicates by region
A: within Waipaoa Basin
Metoric ^{10}Be concentration (at/g x 10^6)
35
30
25
20
15
10
5
0
Heavily gullied headwater basin
Forested (native vegetation)
More stable eastern and western tributaries
Outlet
wa54
wa20
wa15
wa46
wa02
wa44
wa12
(inset)
~6% reproducibility
(excluding outlet wa12)
Percent difference
20
15
10
5
0
wa54
wa20
wa15
wa46
wa02
wa44
wa12
B: Basins to the N and S
60
50
40
30
20
10
0
wa39
wa40
wa41
- Independently prepared and measured replicate samples
- Average of meteoric ^{10}Be laboratory replicates

Figure 3:

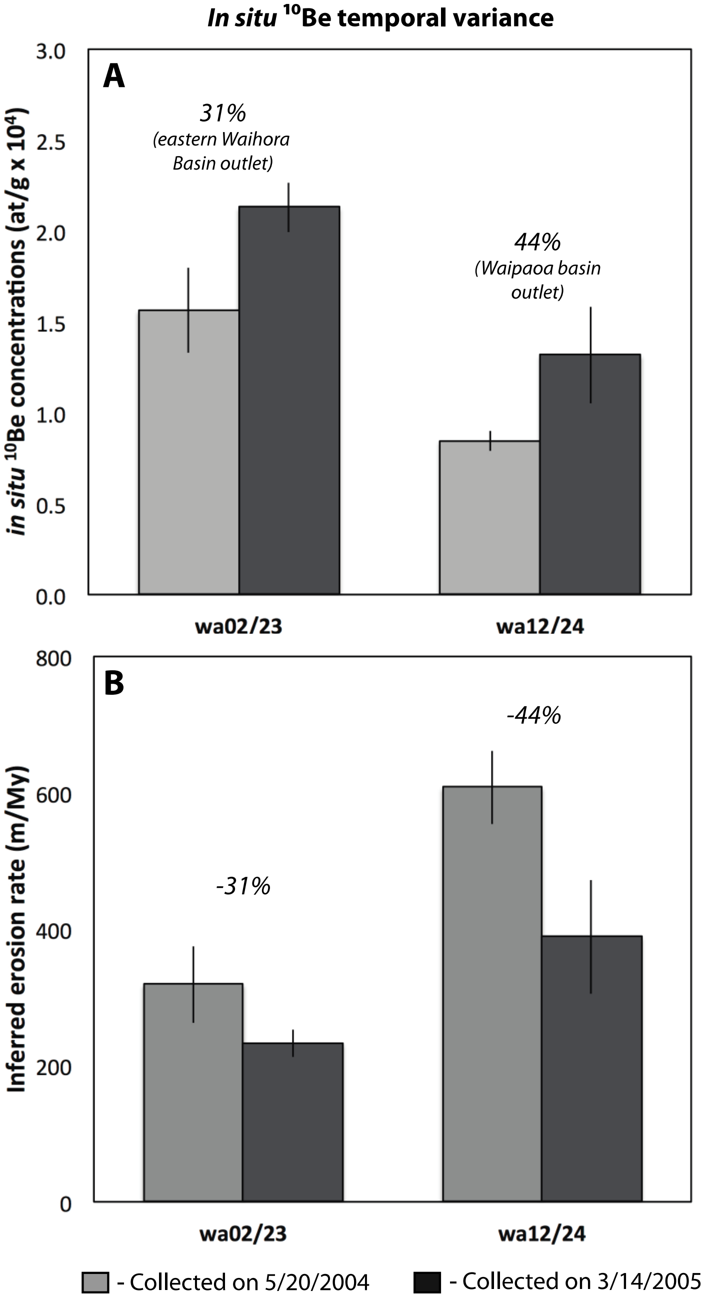

In situ ¹⁰Be temporal variance
A
in situ ¹⁰Be concentrations (at/g x 10⁴)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
31%
(eastern Waihora Basin outlet)
44%
(Waipaoa basin outlet)
wa02/23
wa12/24
B
Inferred erosion rate (m/My)
800
600
400
200
0
-31%
-44%
wa02/23
wa12/24
- Collected on 5/20/2004
- Collected on 3/14/2005

Figure 6:

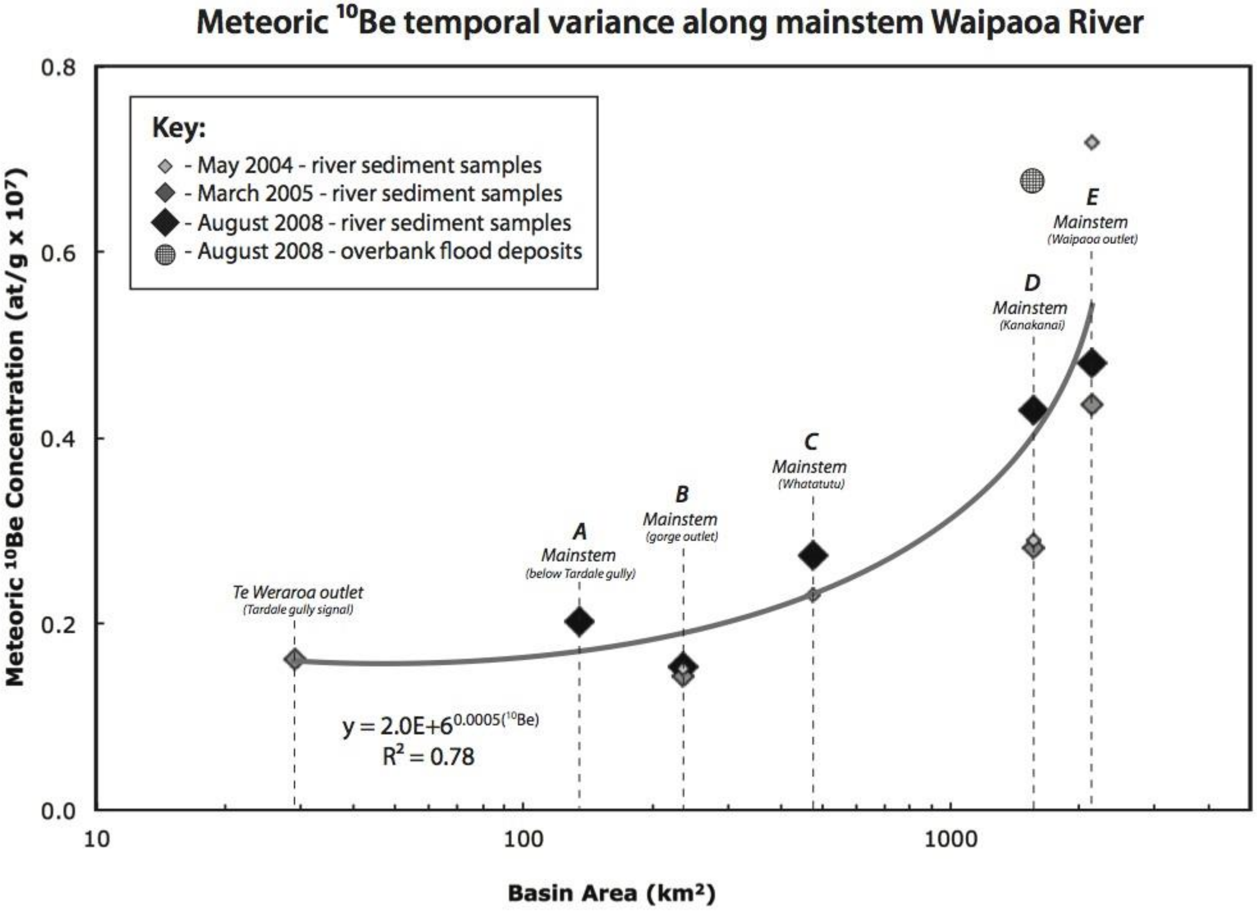

Meteoric ^{10}Be temporal variance along mainstem Waipaoa River
Key:
◆ - May 2004 - river sediment samples
◆ - March 2005 - river sediment samples
◆ - August 2008 - river sediment samples
▦ - August 2008 - overbank flood deposits
Te Weraroa outlet
(Tardale gully signal)
A
Mainstem
(below Tardale gully)
B
Mainstem
(gorge outlet)
C
Mainstem
(Whatatutu)
D
Mainstem
(Kanakanai)
E
Mainstem
(Waipaoa outlet)
$y = 2.0E+6^{0.0005(^{10}Be)}$
$R^2 = 0.78$
Meteoric ^{10}Be Concentration (at/g x 10^7)
0.0
0.2
0.4
0.6
0.8
10
100
1000
Basin Area (km²)

Figure 9:

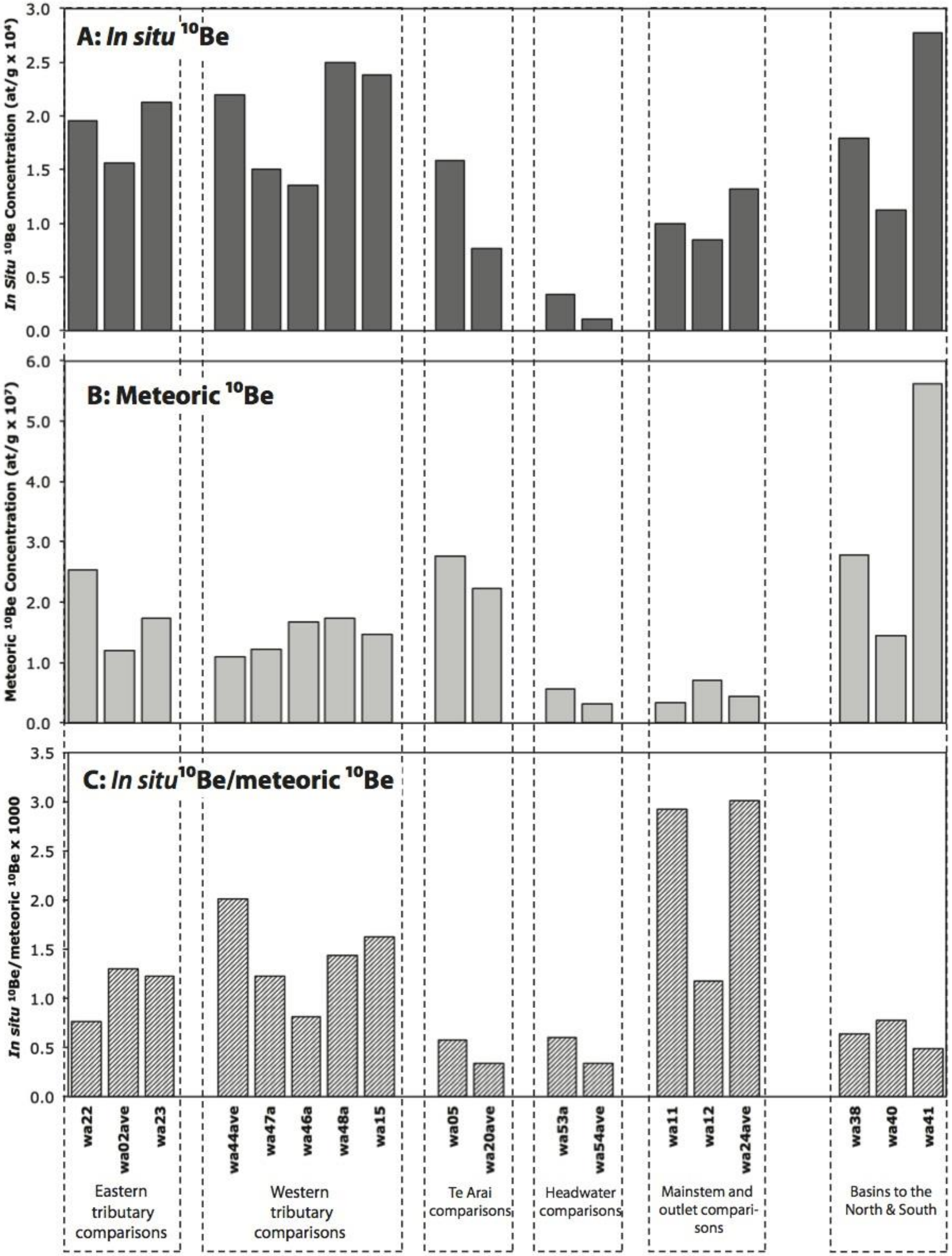

A: In situ ^{10}Be
In Situ ^{10}Be Concentration (at/g x 10^4)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
B: Meteoric ^{10}Be
Meteoric ^{10}Be Concentration (at/g x 10^7)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
C: In situ ^{10}Be/meteoric ^{10}Be
In situ ^{10}Be/meteoric ^{10}Be x 1000
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
wa22
wa02ave
wa23
wa44ave
wa47a
wa46a
wa48a
wa15
wa05
wa20ave
wa53a
wa54ave
wa11
wa12
wa24ave
wa38
wa40
wa41
Eastern tributary comparisons
Western tributary comparisons
Te Arai comparisons
Headwater comparisons
Mainstem and outlet comparisons
Basins to the North & South

Figure 11:

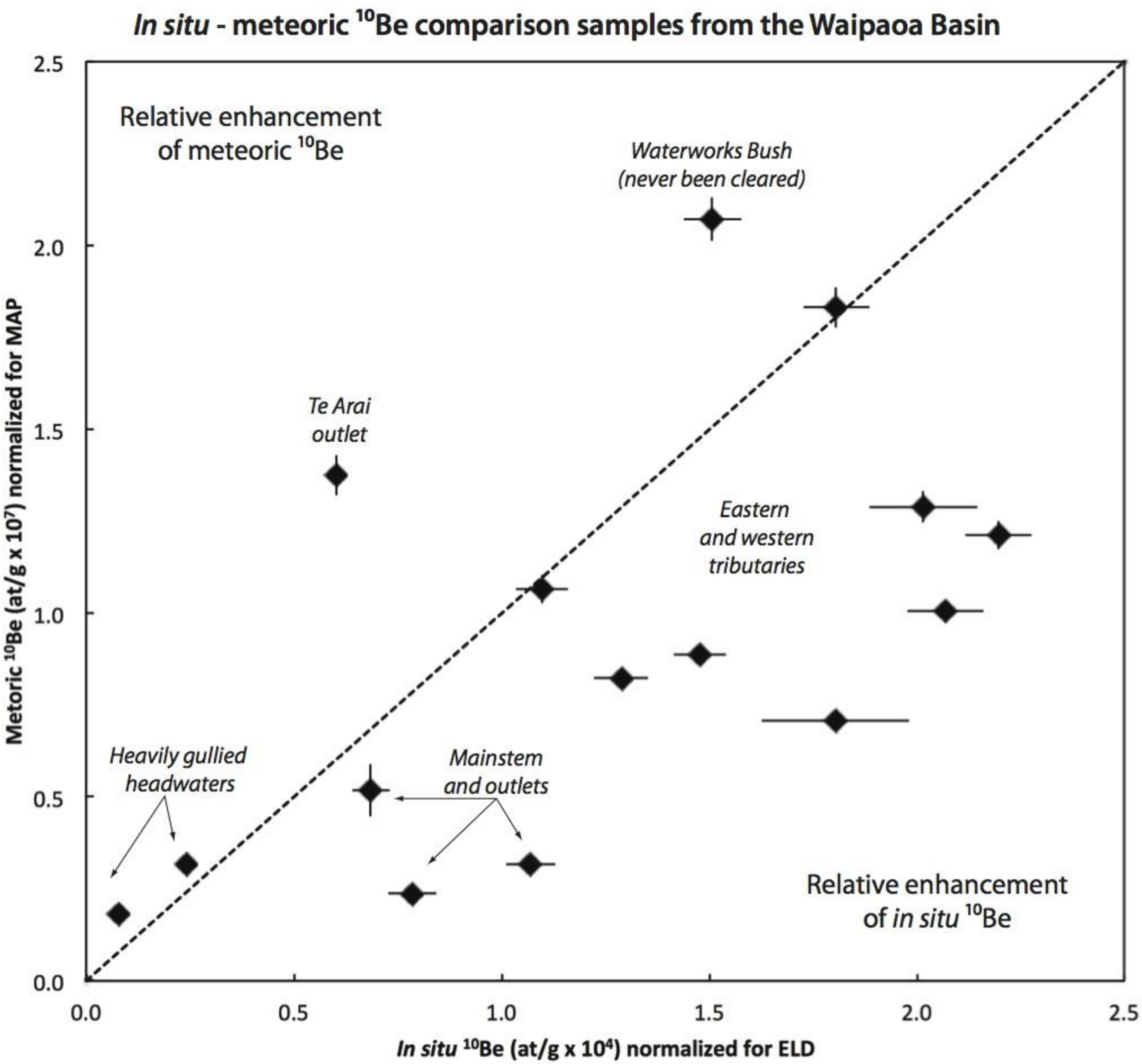
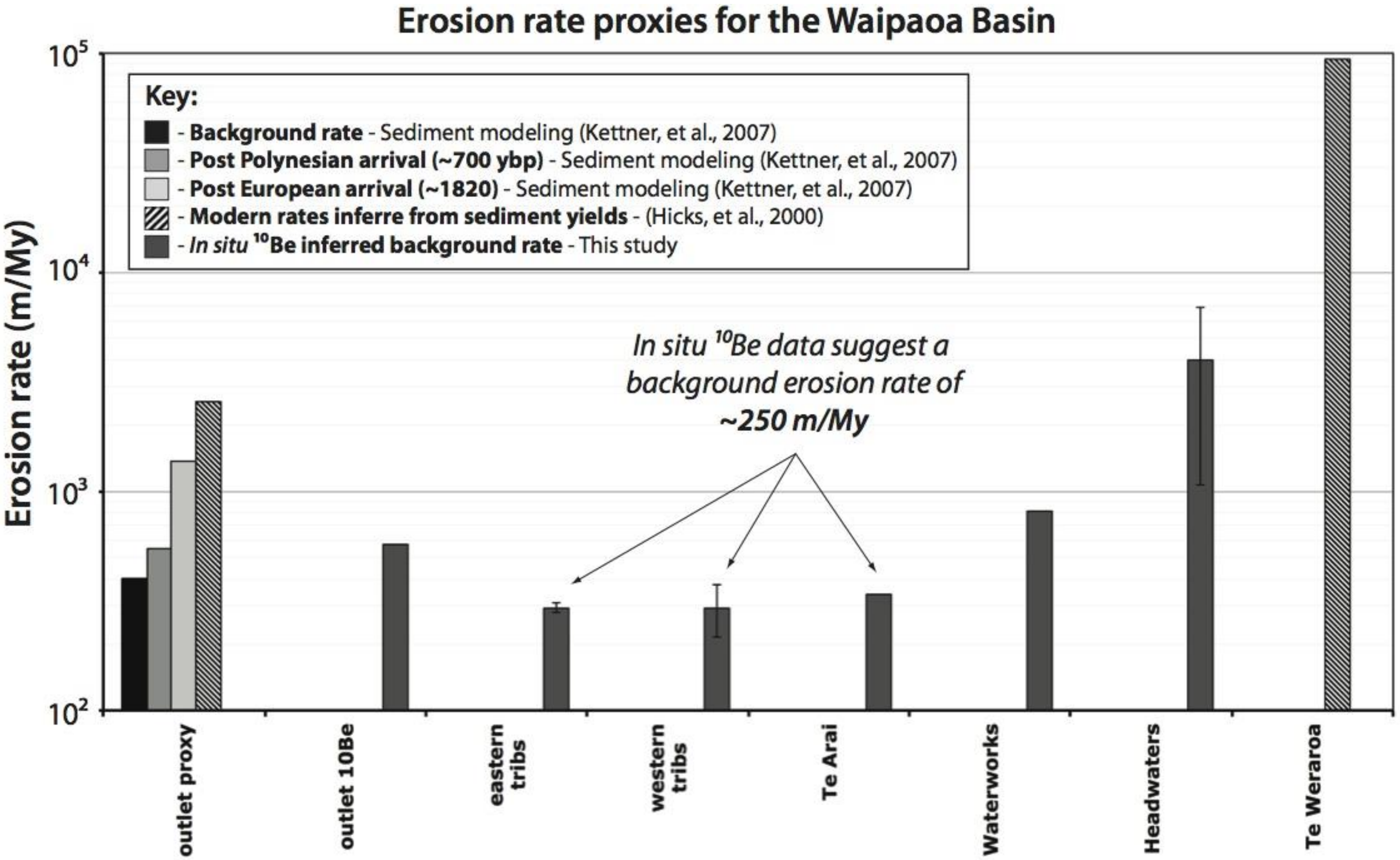

In situ - meteoric ^{10}Be comparison samples from the Waipaoa Basin
Relative enhancement of meteoric ^{10}Be
Waterworks Bush (never been cleared)
Te Arai outlet
Eastern and western tributaries
Heavily gullied headwaters
Mainstem and outlets
Relative enhancement of *in situ* ^{10}Be
Metoric ^{10}Be (at/g x 10^7) normalized for MAP
In situ ^{10}Be (at/g x 10^4) normalized for ELD
0.0
0.5
1.0
1.5
2.0
2.5
0.0
0.5
1.0
1.5
2.0
2.5

Figure 12:



Erosion rate proxies for the Waipaoa Basin
Erosion rate (m/My)
10^5
10^4
10^3
10^2
Key:
- Background rate - Sediment modeling (Kettner, et al., 2007)
- Post Polynesian arrival (~700 ybp) - Sediment modeling (Kettner, et al., 2007)
- Post European arrival (~1820) - Sediment modeling (Kettner, et al., 2007)
- Modern rates inferre from sediment yields - (Hicks, et al., 2000)
- In situ ^{10}Be inferred background rate - This study
In situ ^{10}Be data suggest a background erosion rate of ~250 m/My
outlet proxy
outlet 10Be
eastern tribs
western tribs
Te Arai
Waterworks
Headwaters
Te Weraroa

Figure 13:

Template

Template 2:

Template