Erosion rates & patterns inferred from cosmogenic ^{10}Be in the Susquehanna River Basin

Joanna M. Reuter

Thesis Defense

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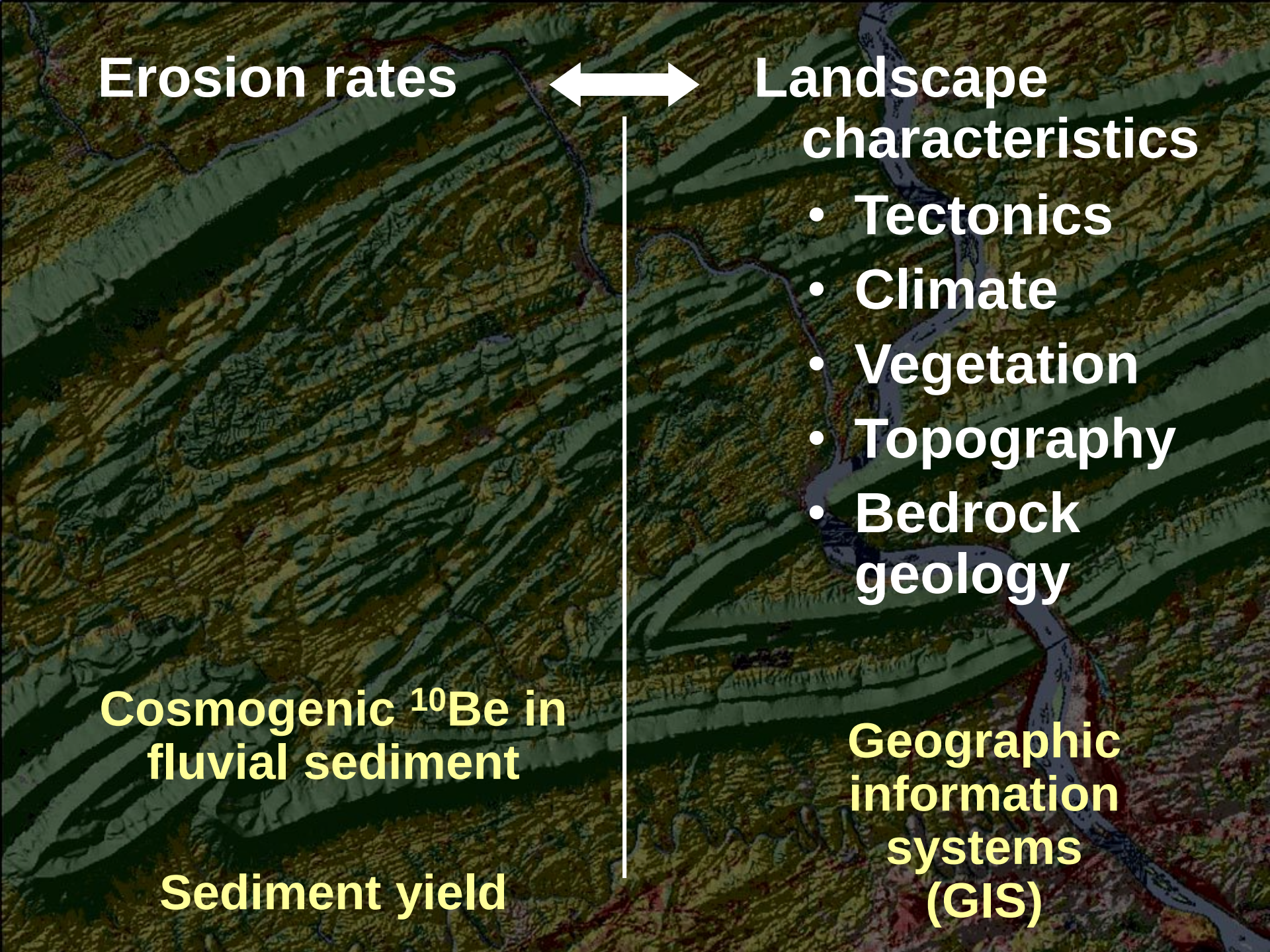
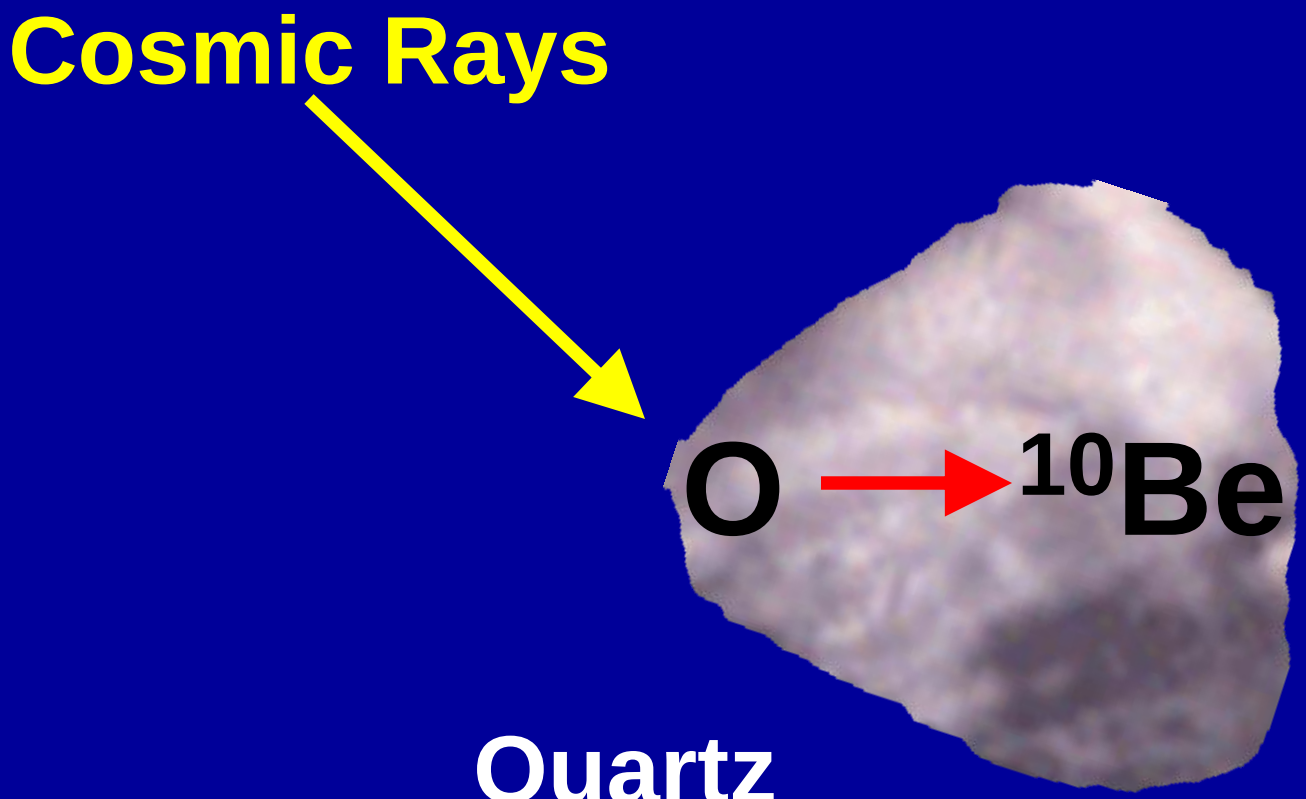
Paul Bierman, advisor

Motivation:

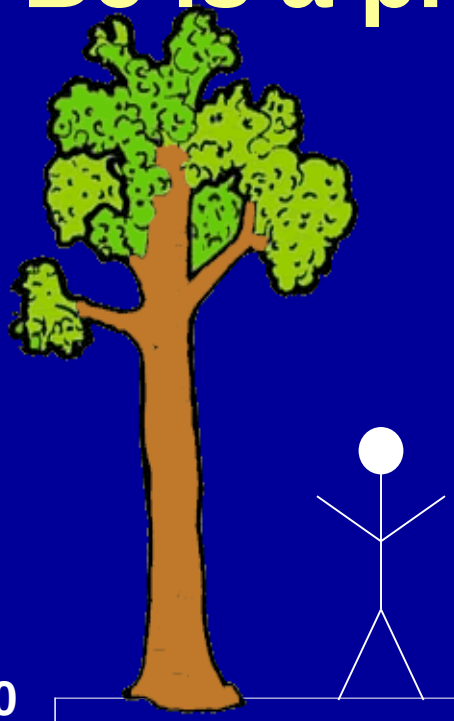
- Applied questions
  - Chesapeake Bay sedimentation
- Basic science questions
  - Topographic change over time
  - Relationships between erosion rate and landscape characteristics


Erosion rates
Landscape characteristics
• Tectonics
• Climate
• Vegetation
• Topography
• Bedrock geology
Cosmogenic ^{10}Be in fluvial sediment
Sediment yield
Geographic information systems (GIS)

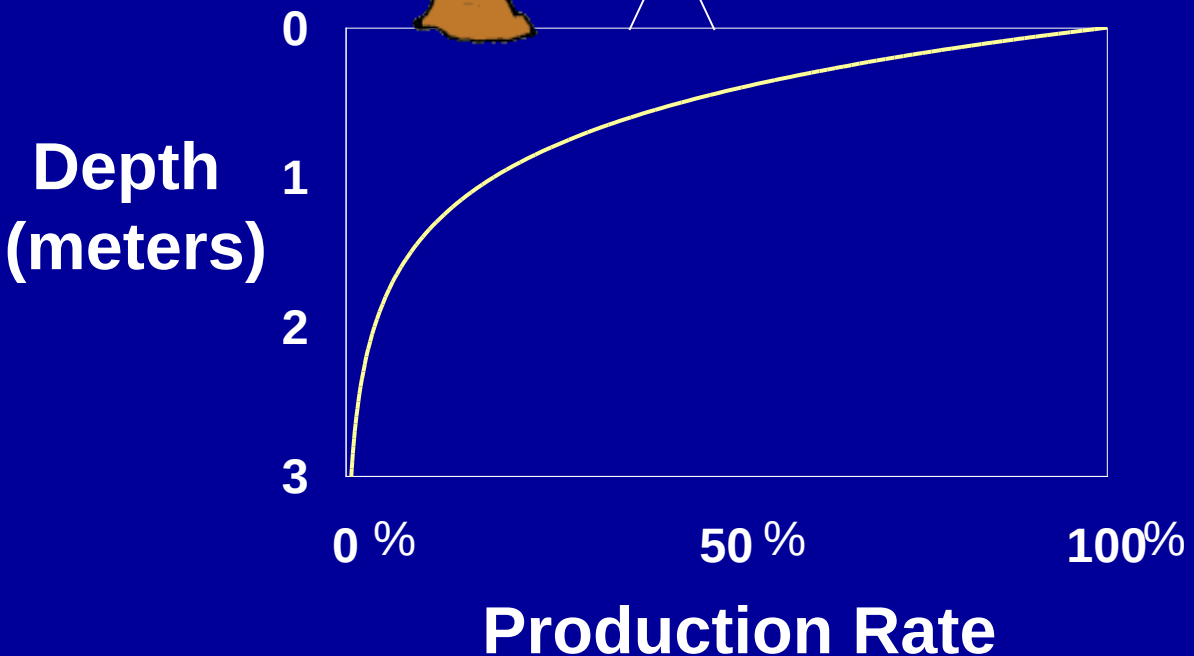
Cosmic ray bombardment produces ^{10}Be in quartz.



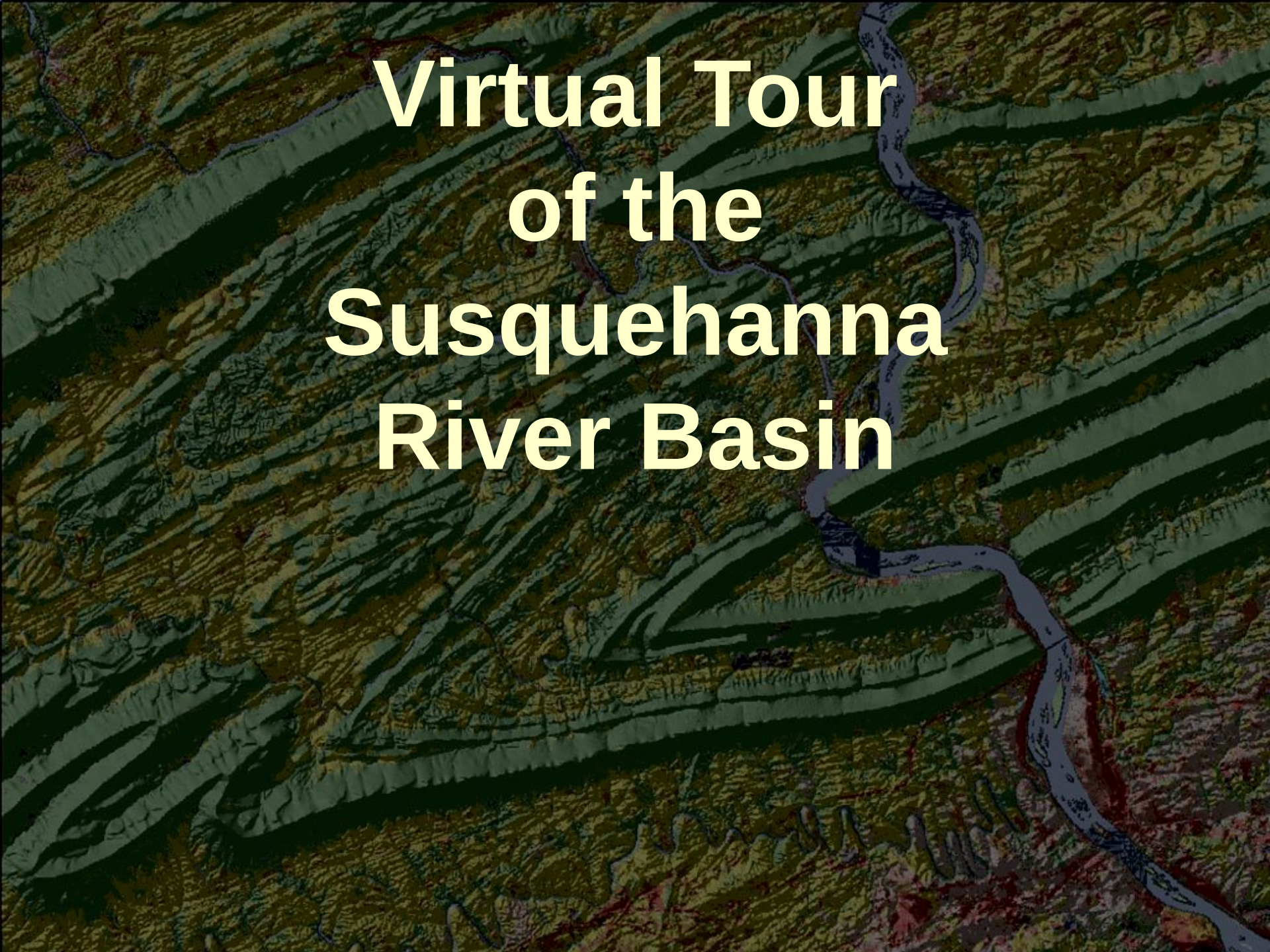
^{10}Be is a proxy for erosion rate.

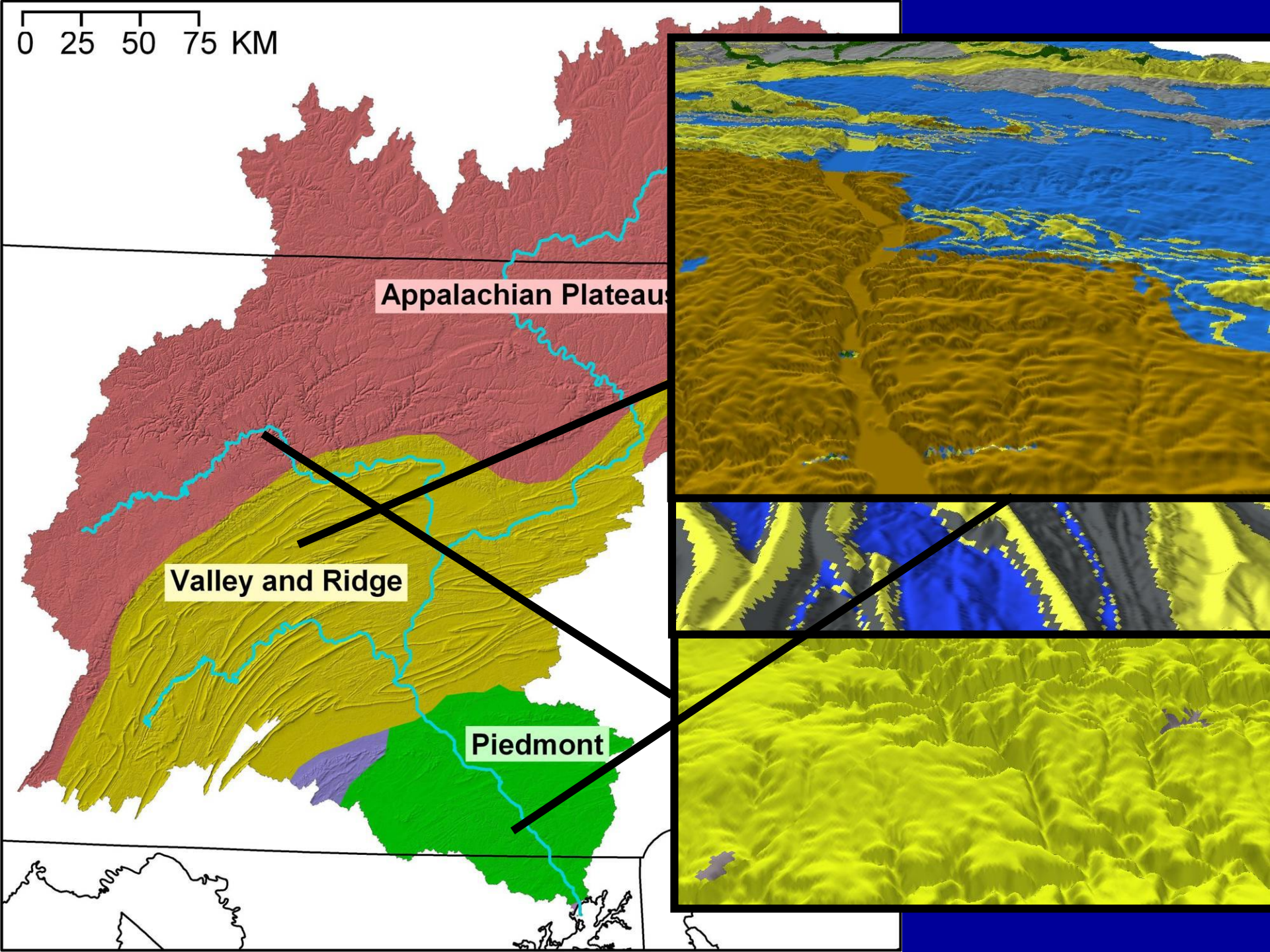


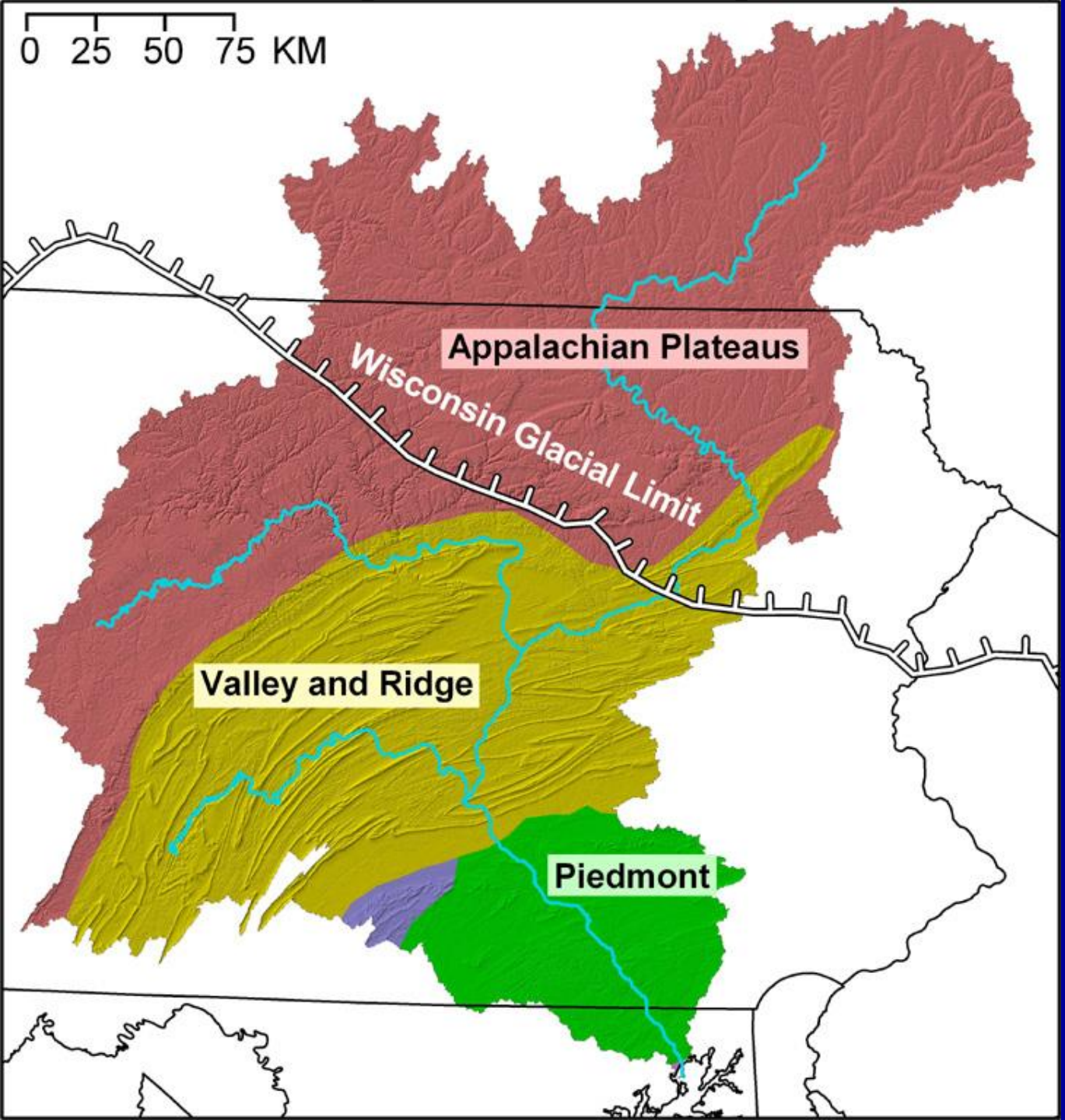
Time scale:
10^4-10^5 years

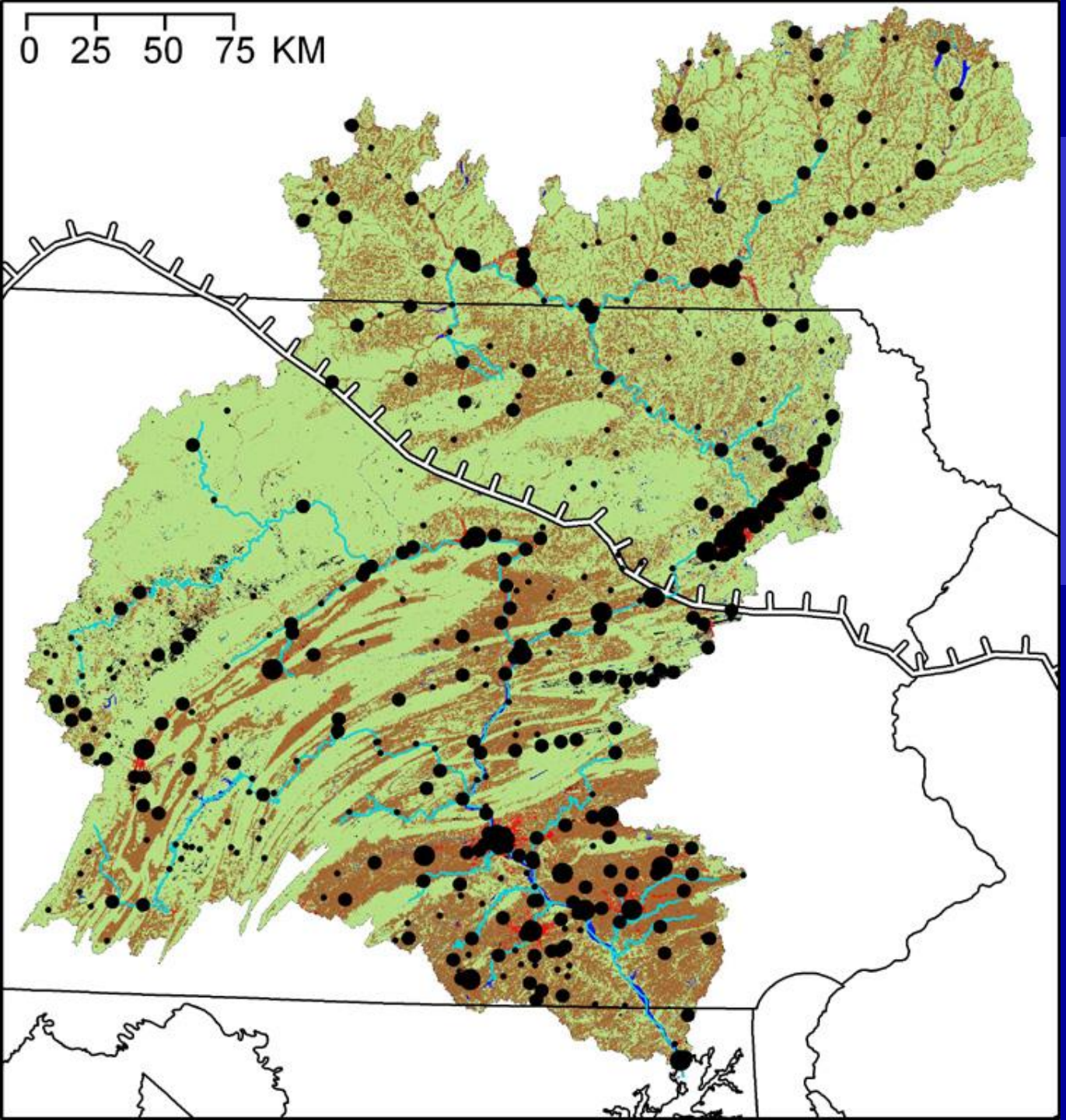


Virtual Tour of the Susquehanna River Basin



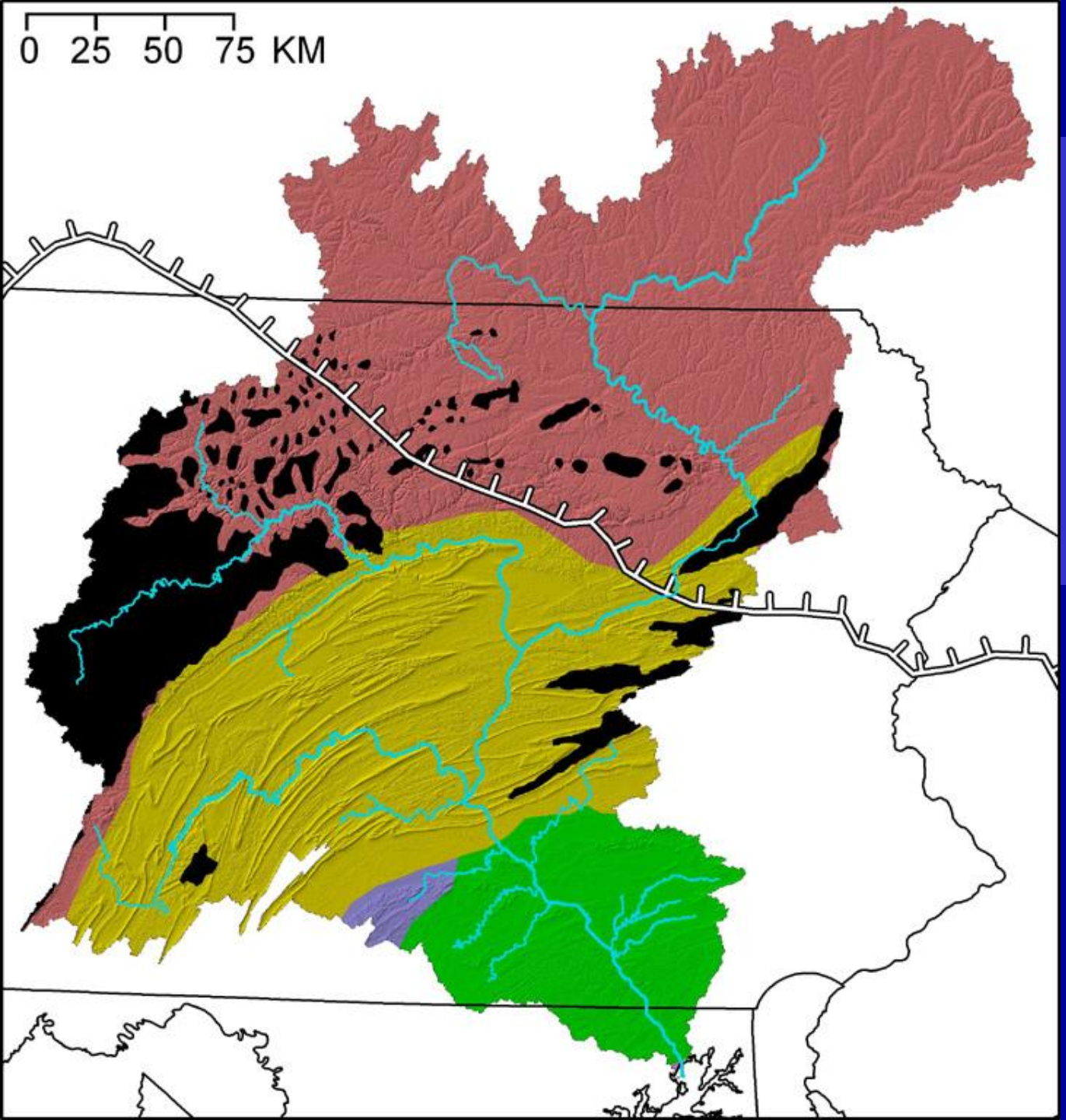

0 25 50 75 KM
Appalachian Plateaus
Valley and Ridge
Piedmont


0 25 50 75 KM
Appalachian Plateaus
Wisconsin Glacial Limit
Valley and Ridge
Piedmont



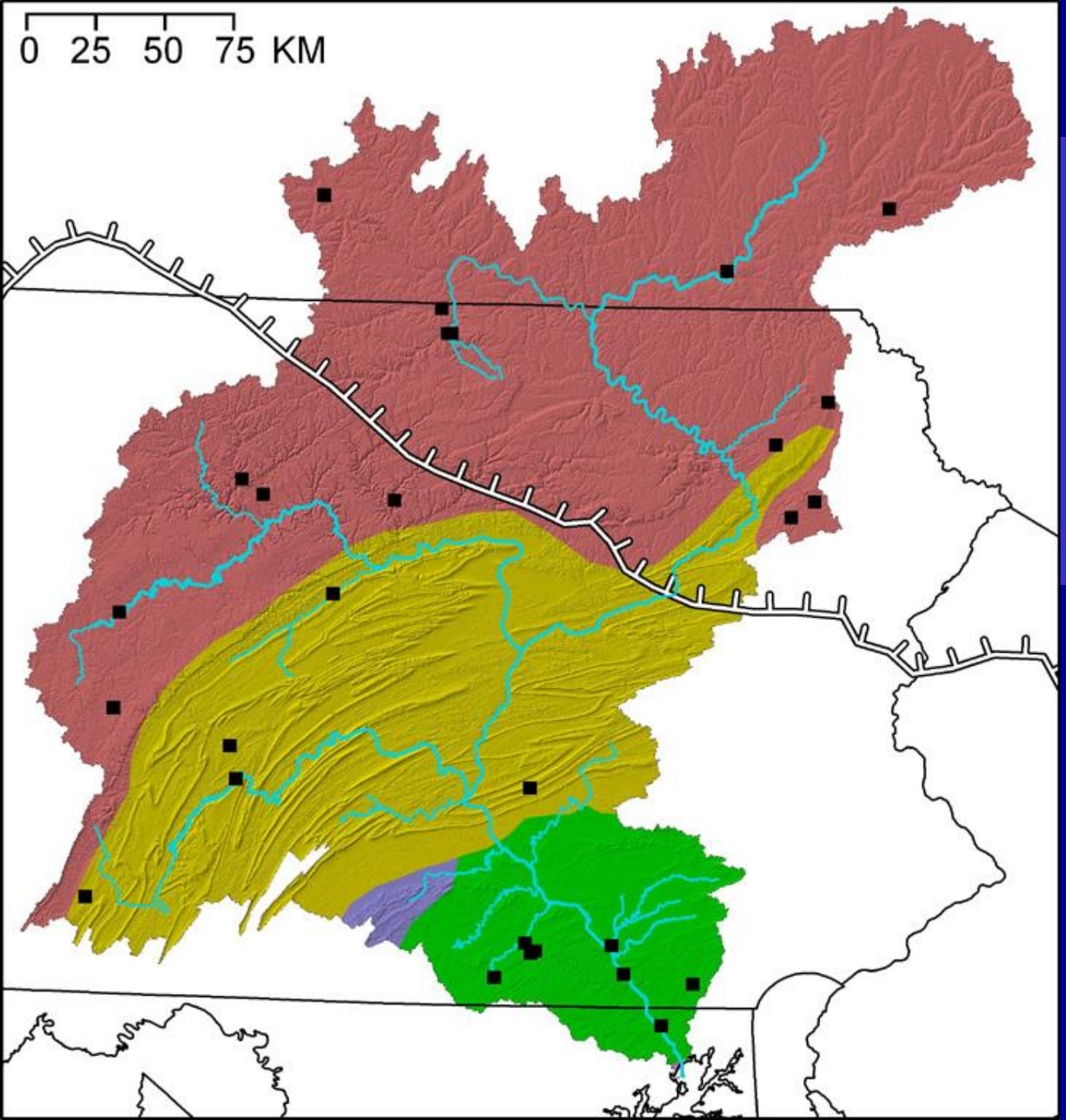
EXPLANATION

- Cities & towns



EXPLANATION

Coal fields

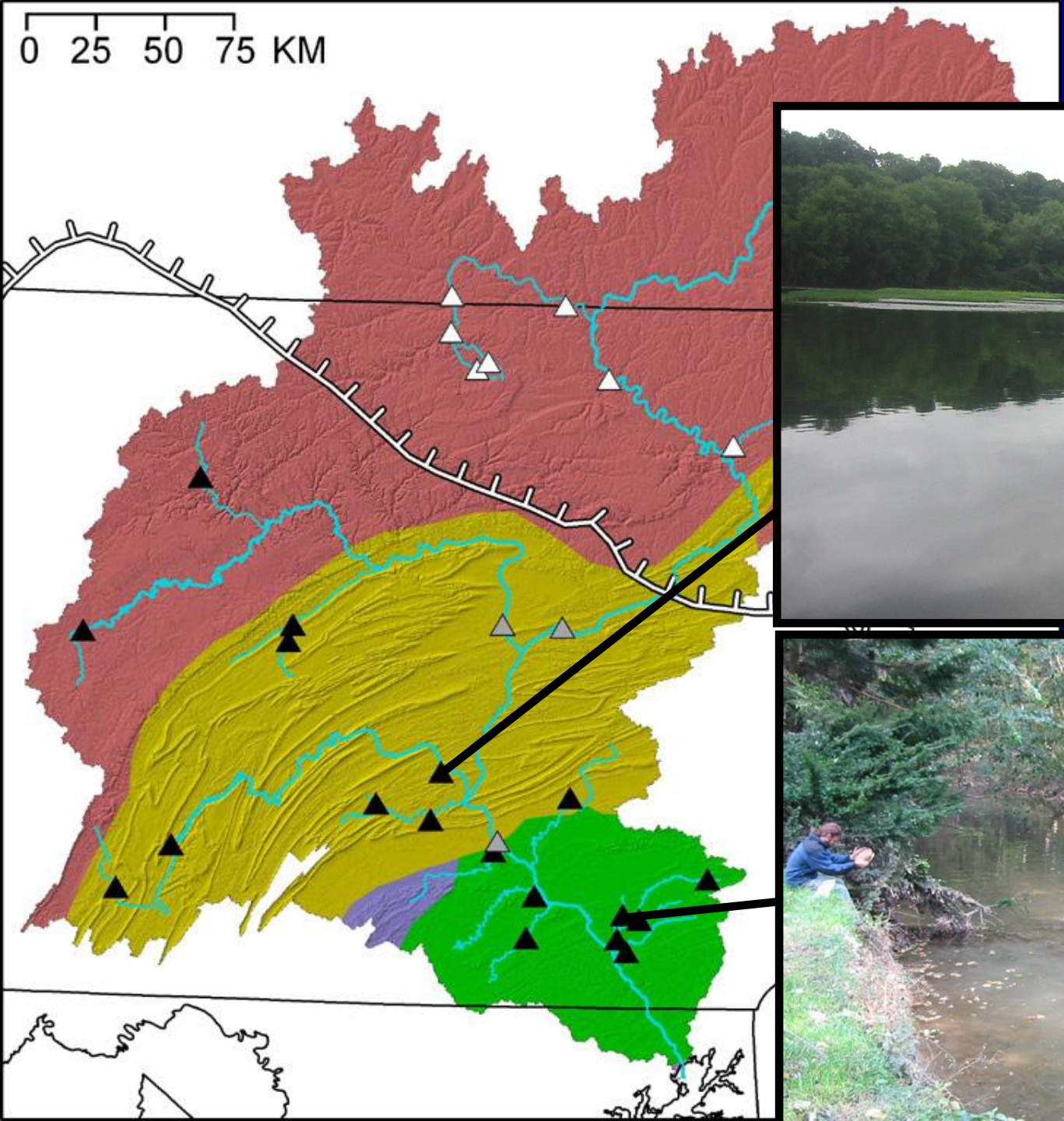


EXPLANATION

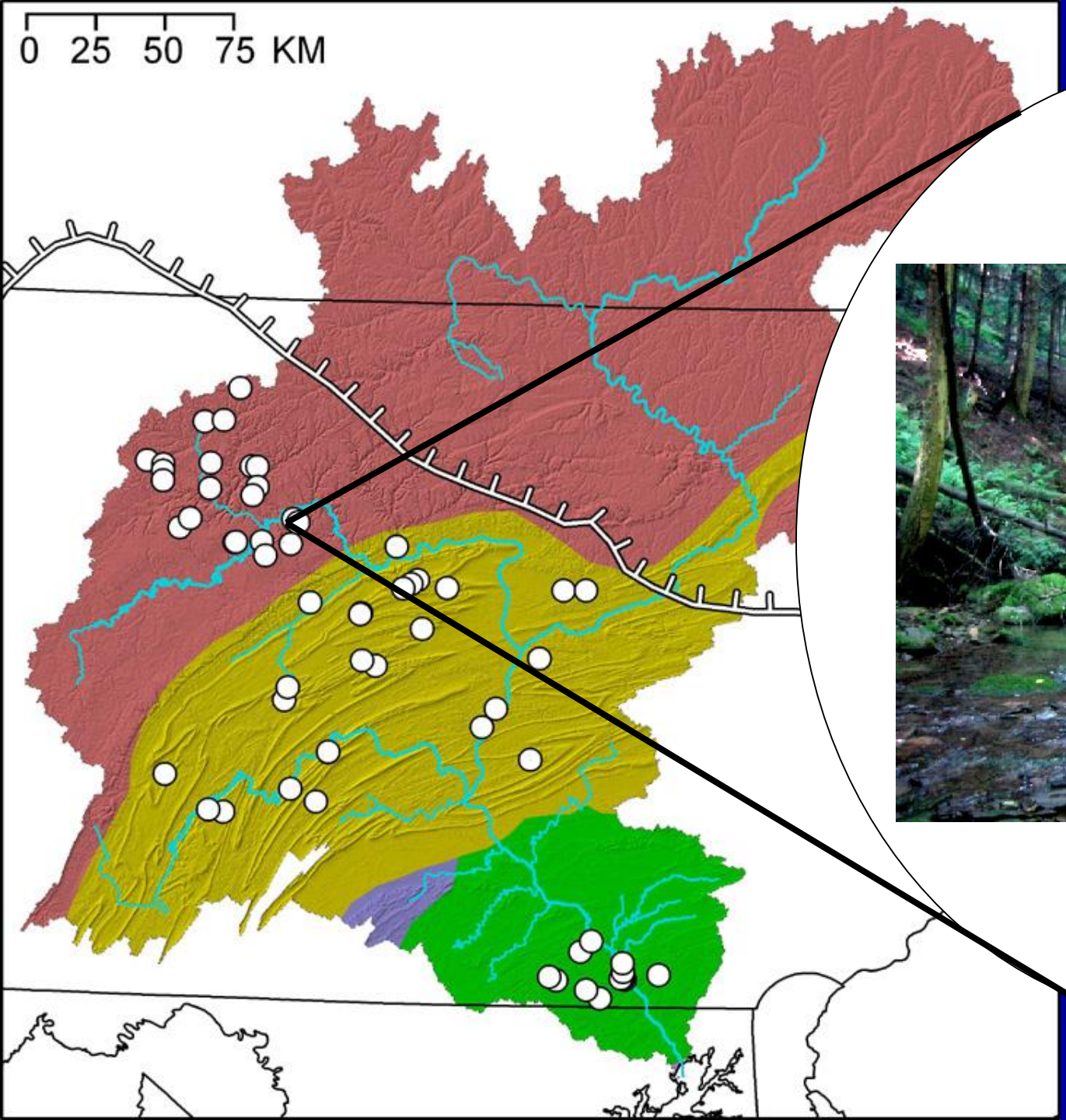
- Major dams


Basin Selection
and
Sampling Approach

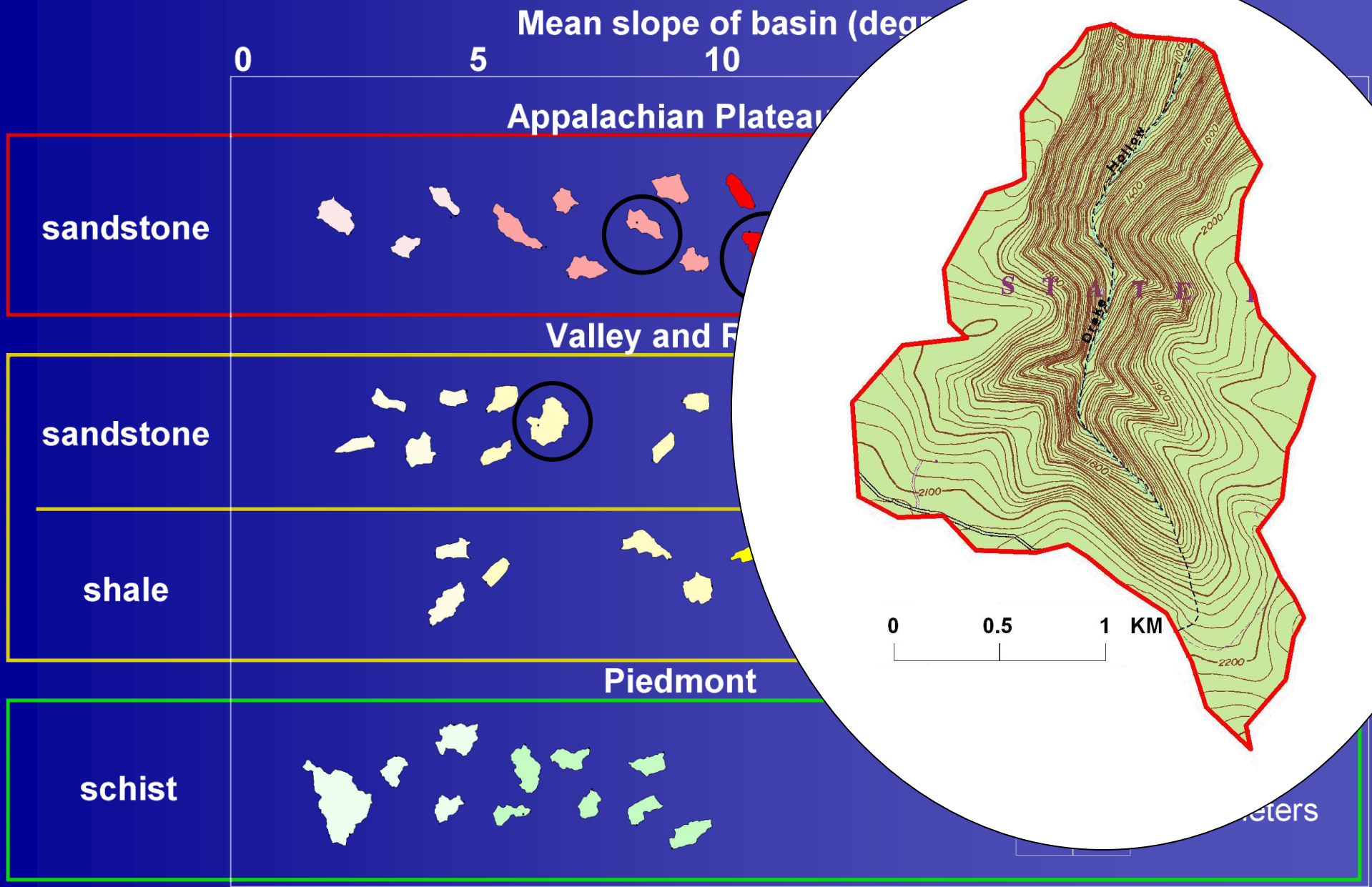
USGS Basins



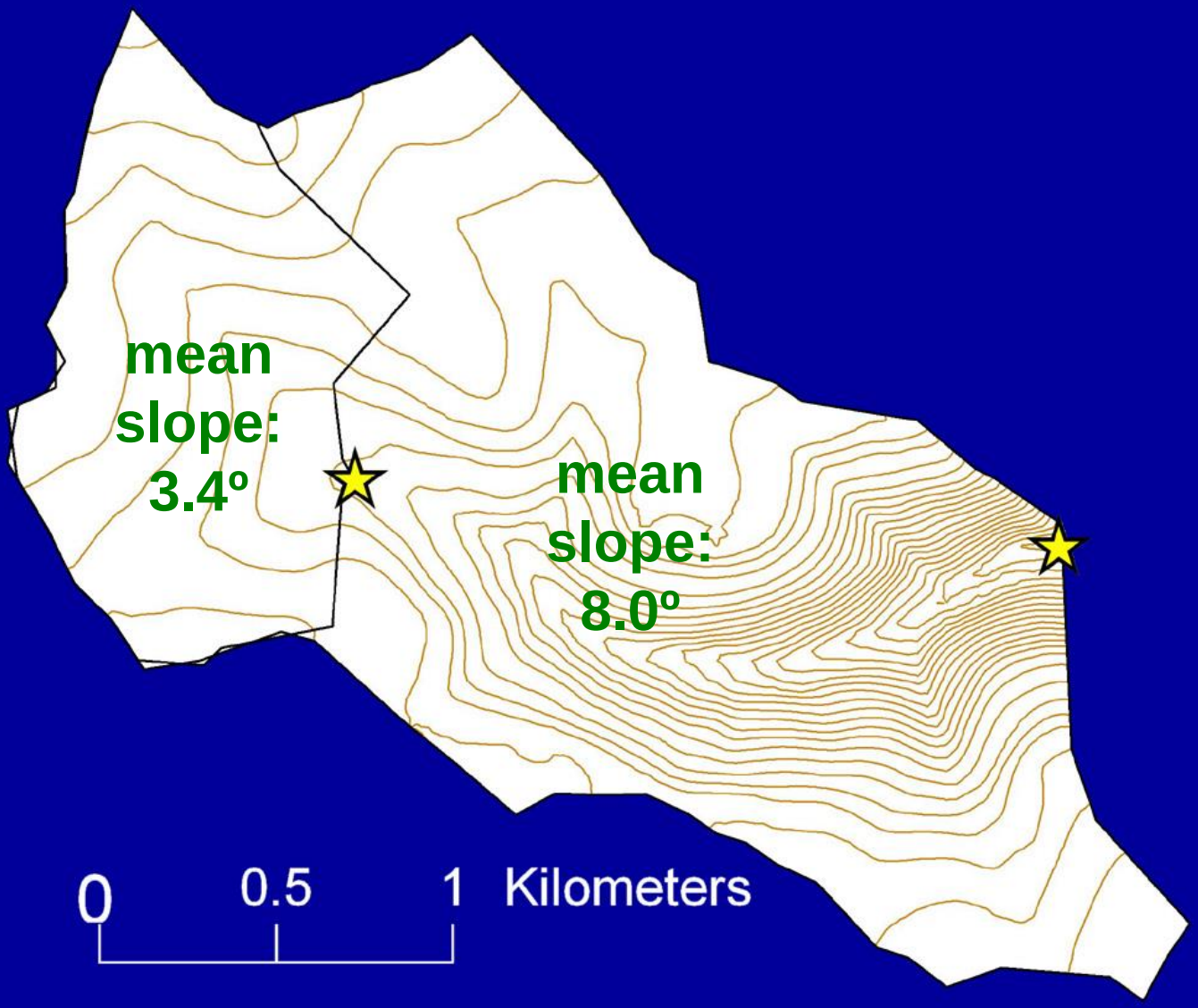
GIS-selected



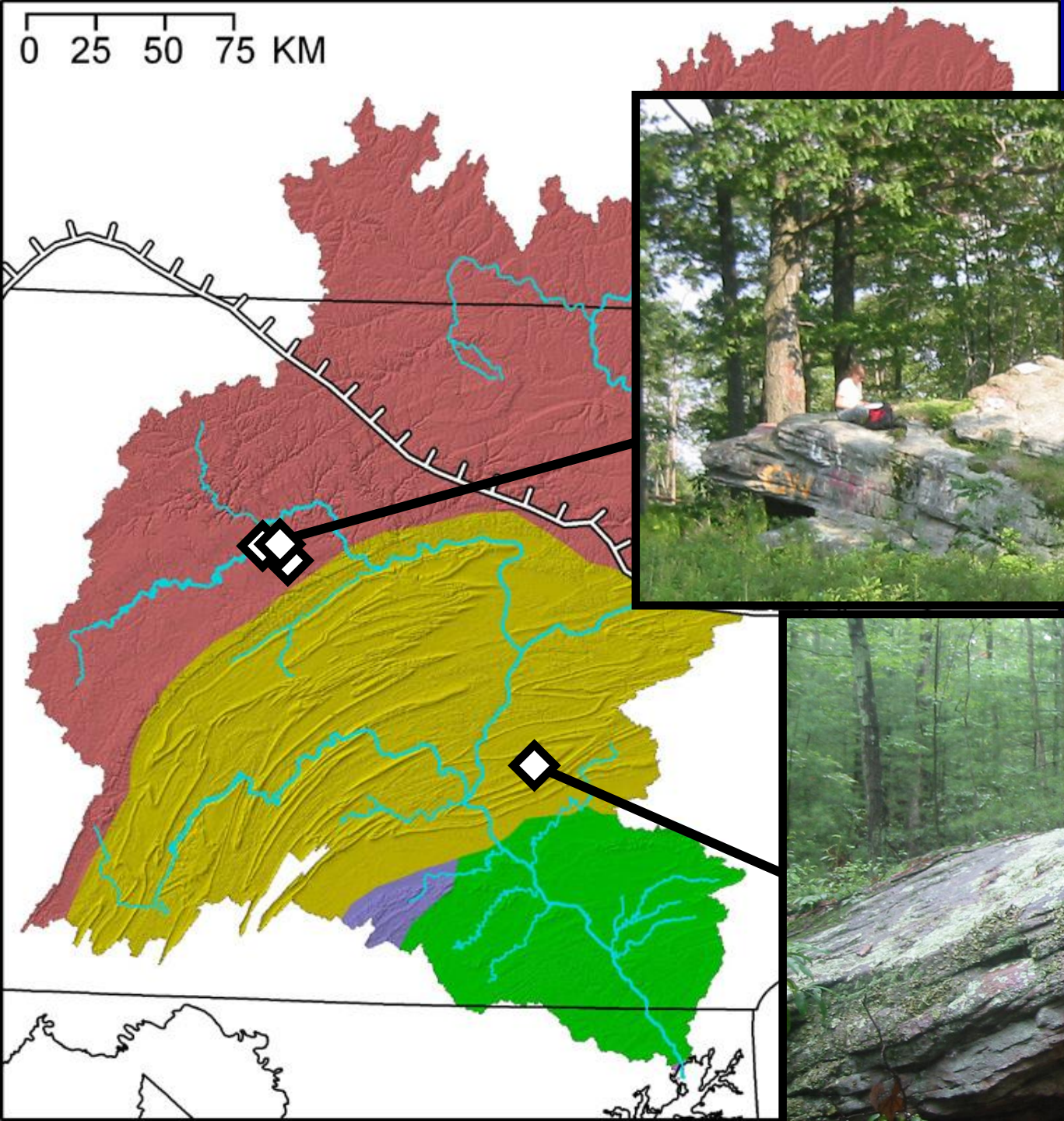
GIS-selected Basins



GIS-selected Basins: Nested Basins

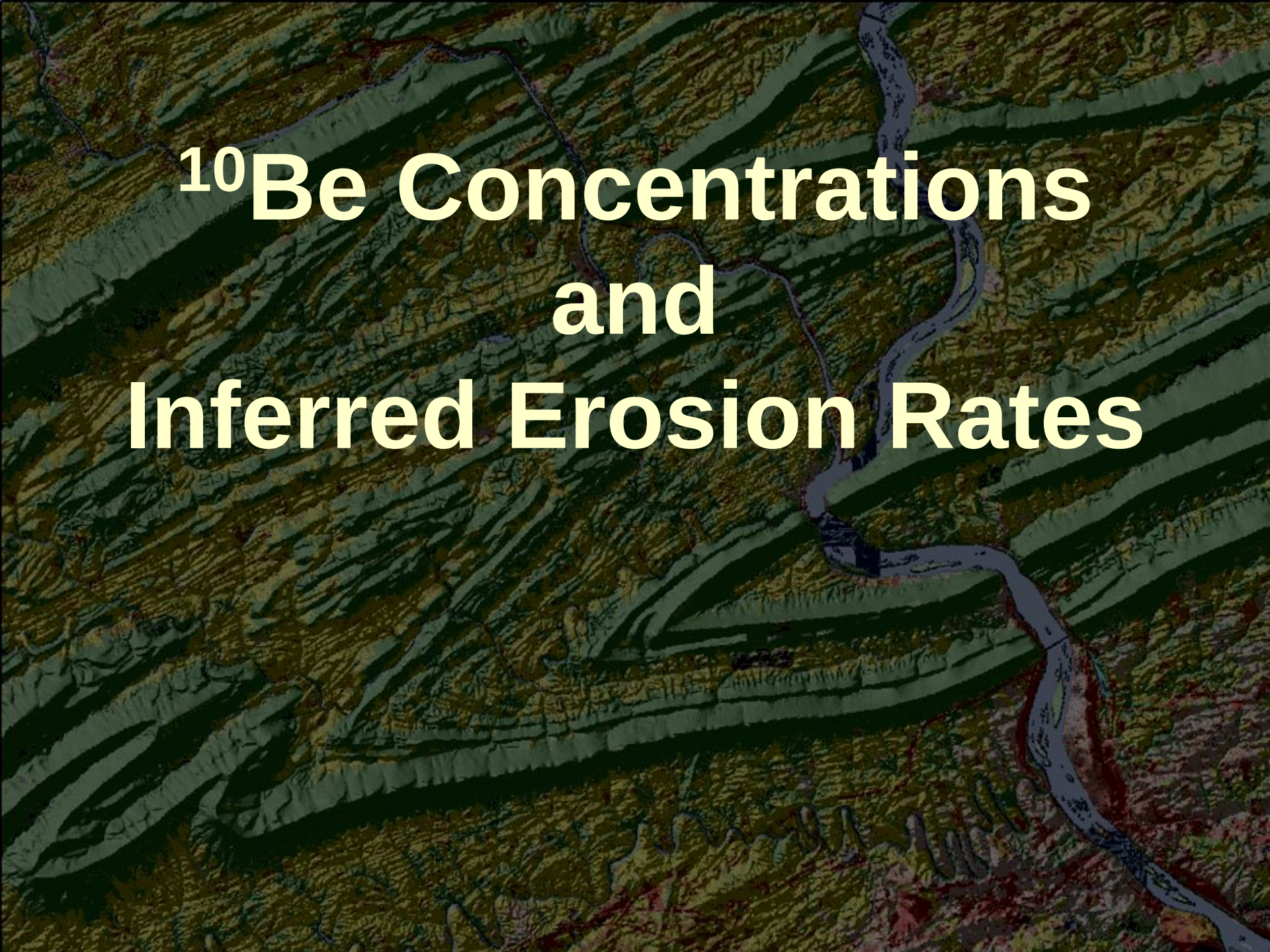


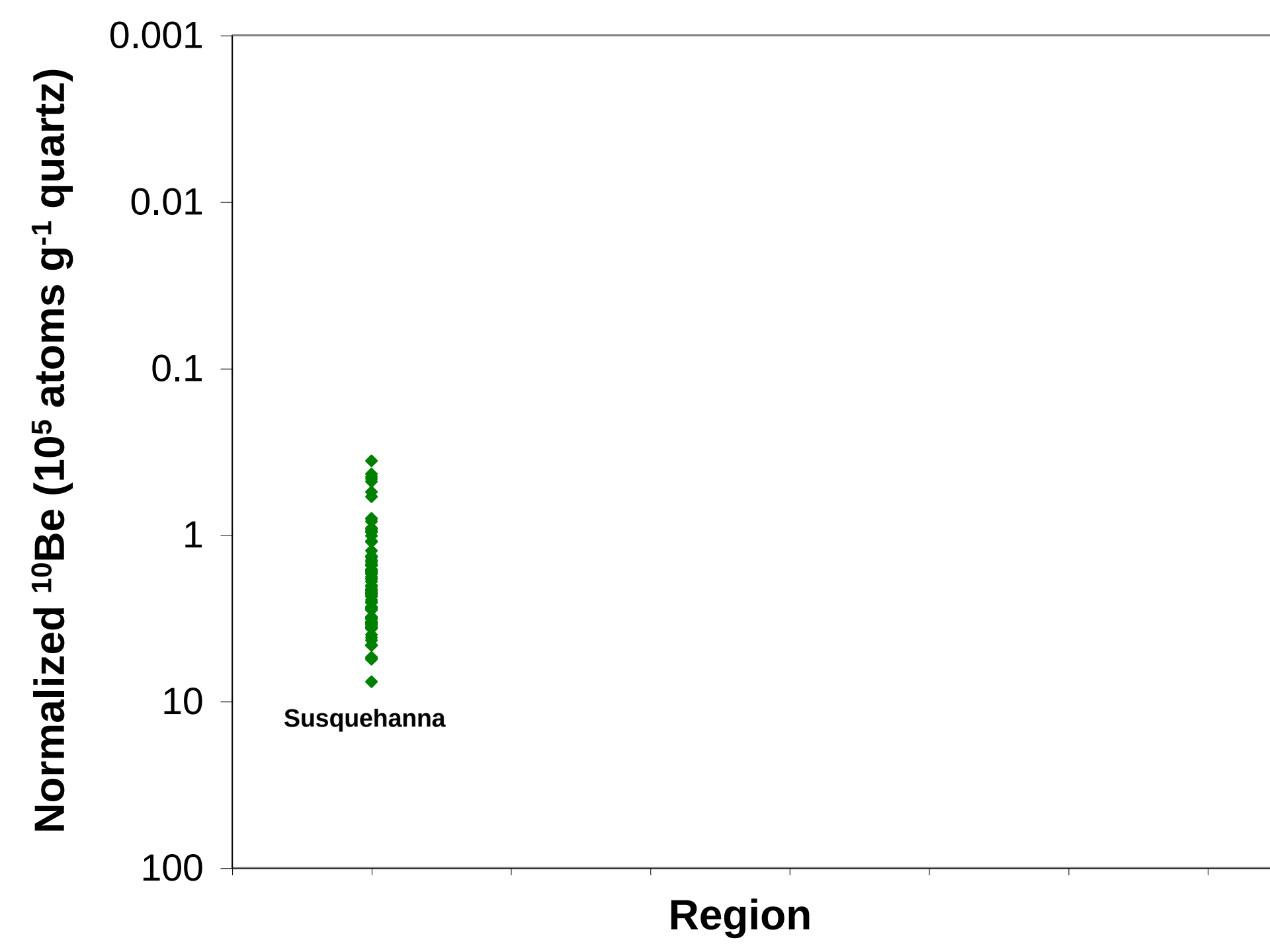
Bedrock Samples



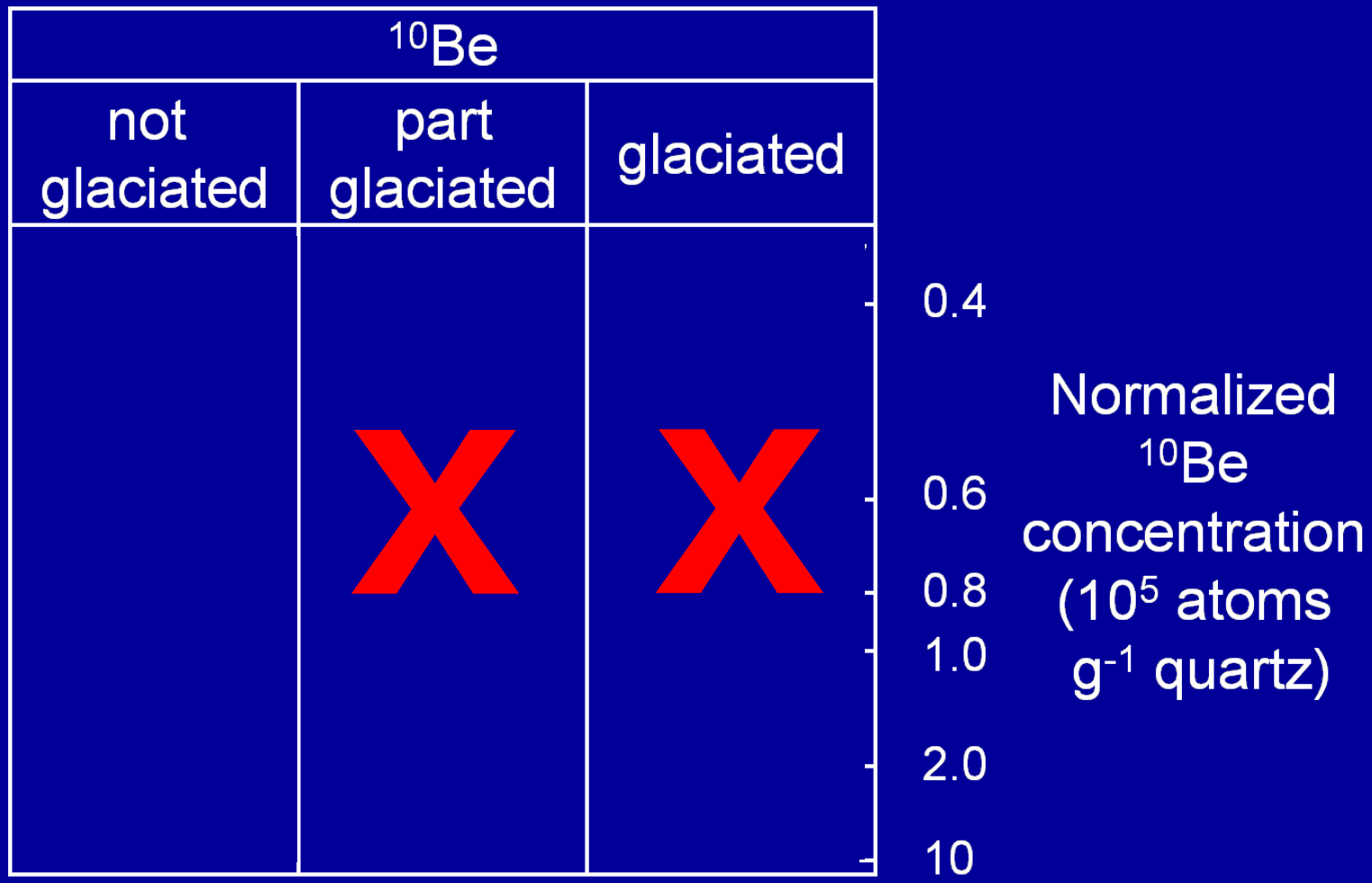
Summary of Groups of Samples

- **USGS Basins**
  - **mostly large, complex**
- **GIS-selected Basins**
  - **small, simple**
- **Bedrock Samples**

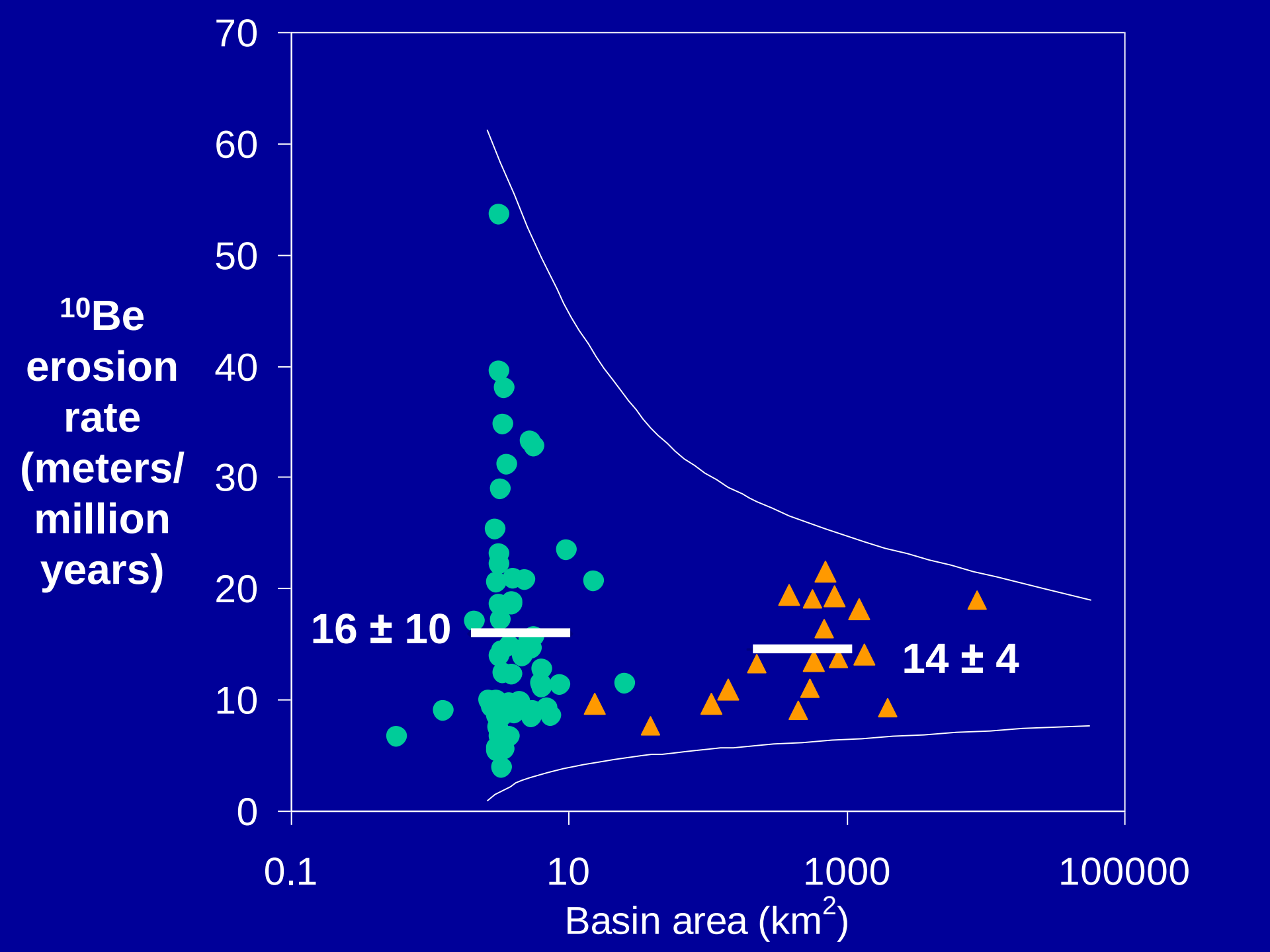

^{10}Be Concentrations
and
Inferred Erosion Rates

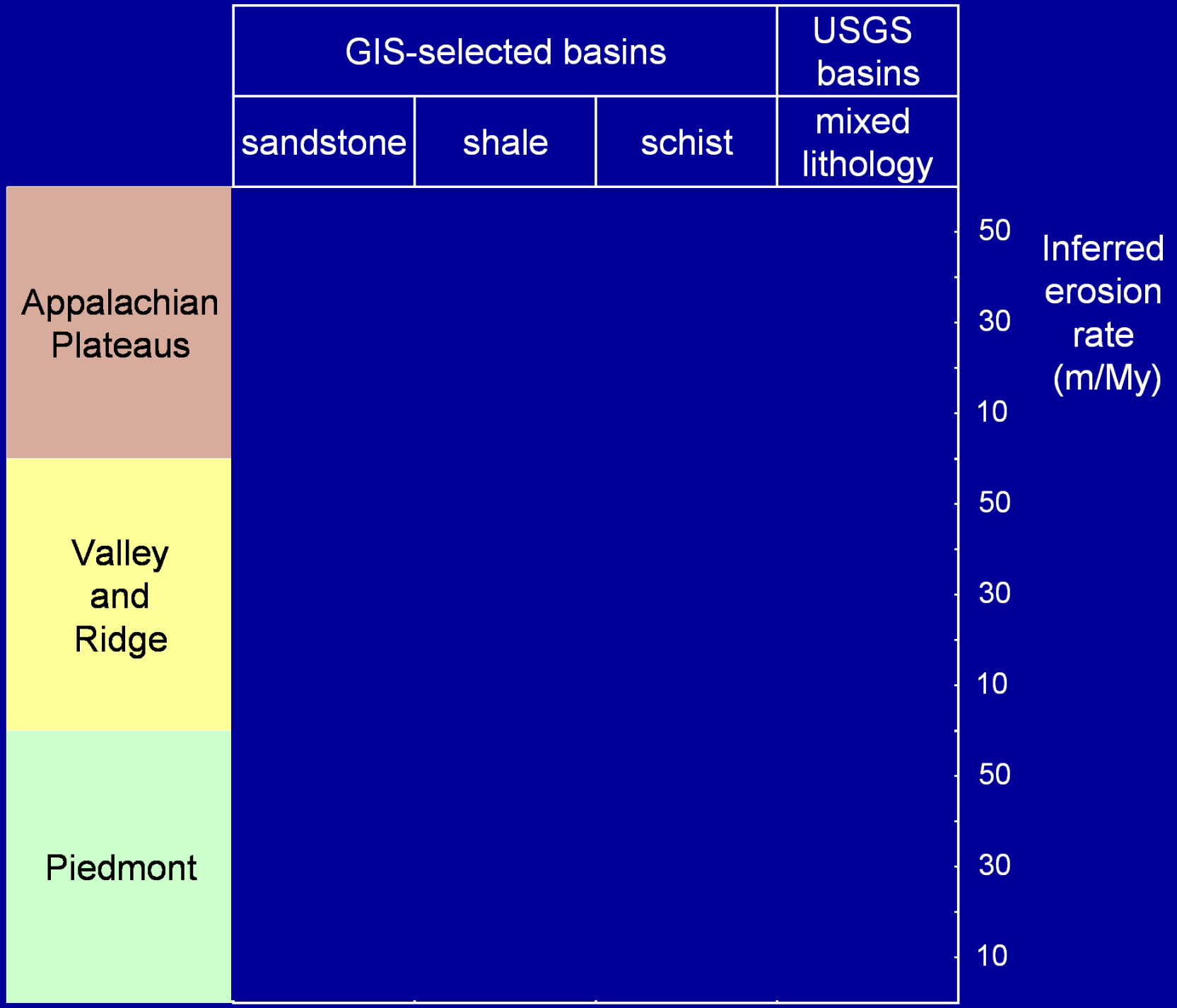

0.001
0.01
0.1
1
10
100
Normalized ^{10}Be (10^5 atoms g^{-1} quartz)
Susquehanna
Region

Results for USGS Basins

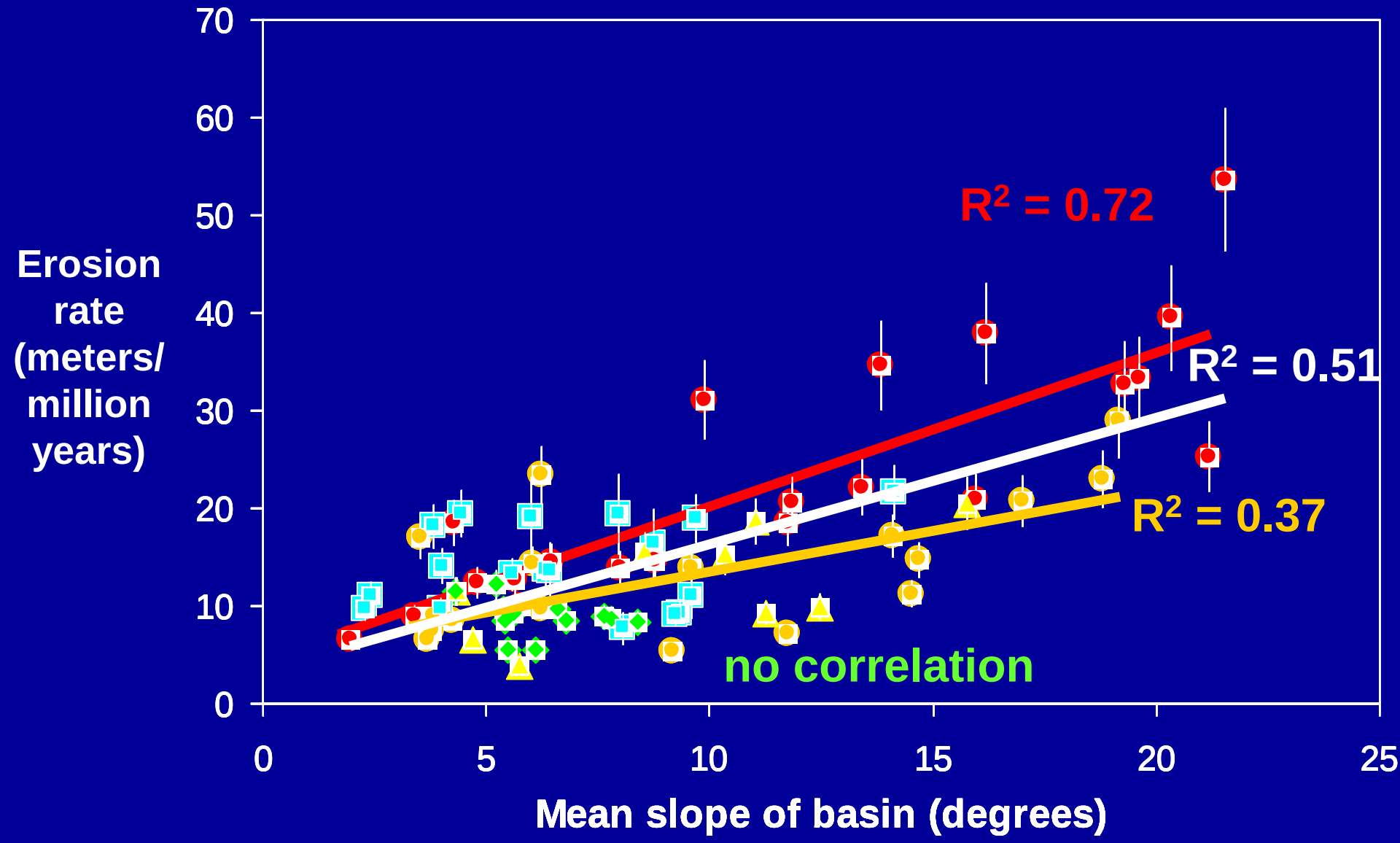


if assumptions have been met

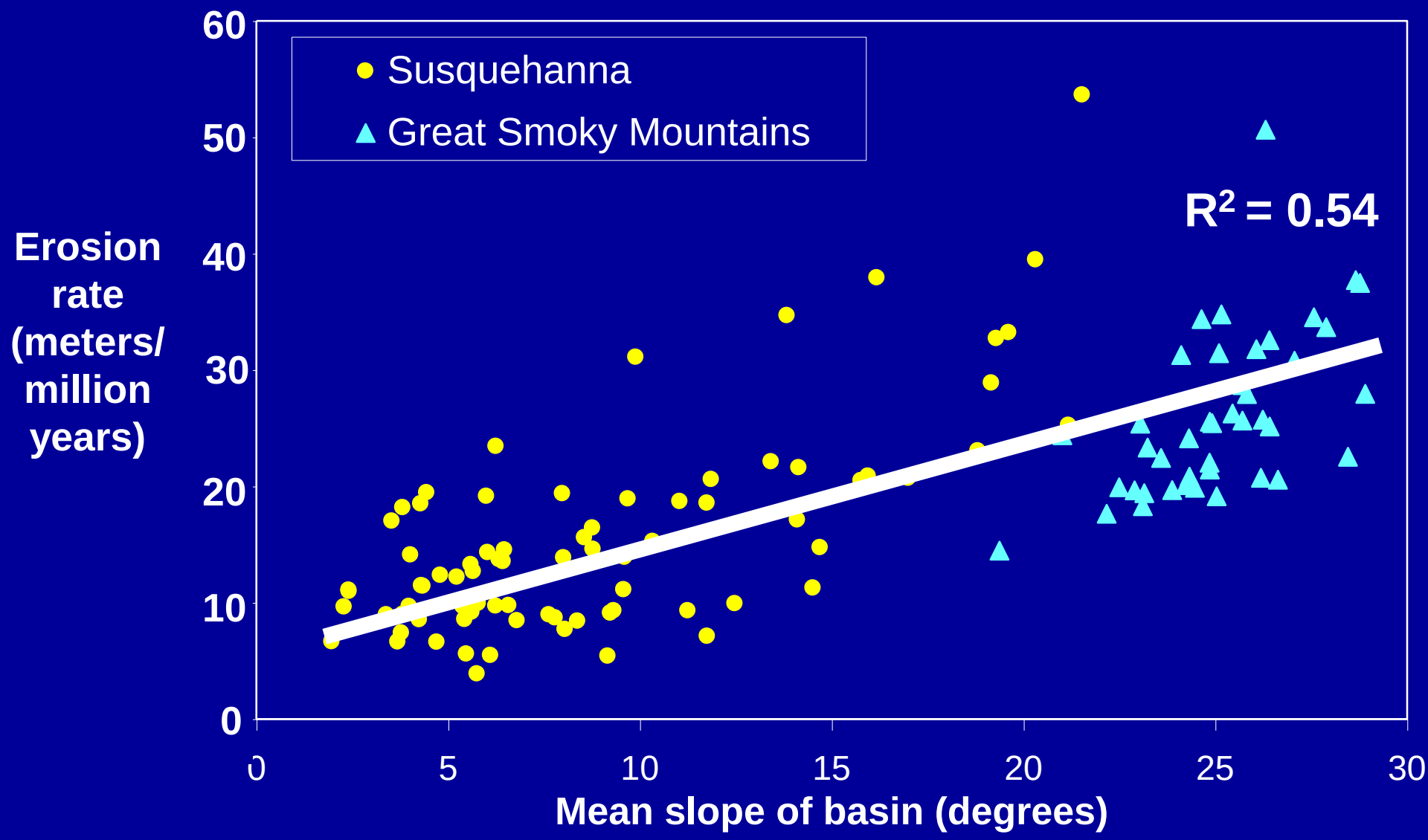

70
60
50
40
30
20
10
0
^{10}Be erosion rate (meters/ million years)
16 ± 10
14 ± 4
0.1
10
1000
100000
Basin area (km^2)


GIS-selected basins
USGS basins
sandstone
shale
schist
mixed lithology
Appalachian Plateaus
Valley and Ridge
Piedmont
50
30
10
50
30
10
50
30
10
Inferred erosion rate (m/My)

Slope

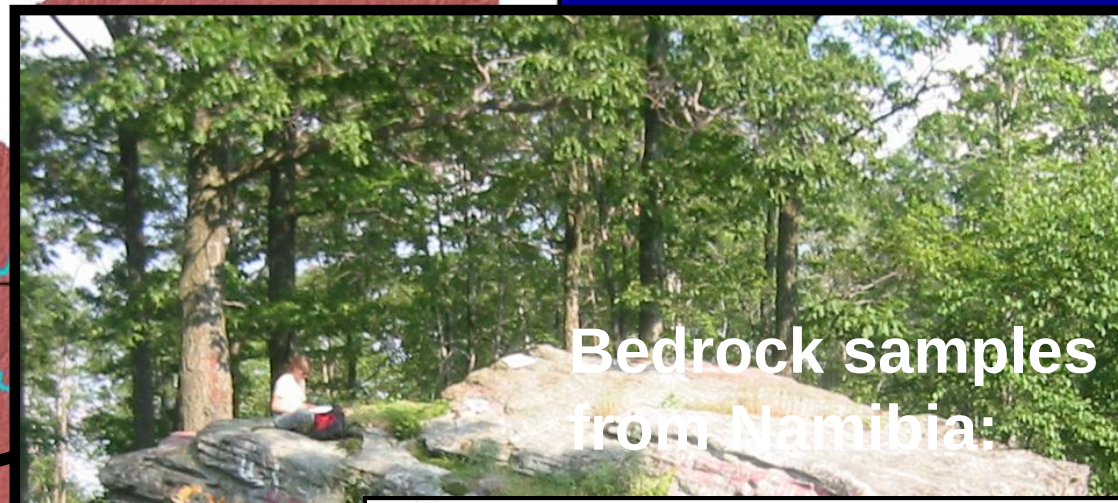

Erosion rate (meters/ million years)
70
60
50
40
30
20
10
0
0
5
10
15
20
25
Mean slope of basin (degrees)
R² = 0.72
R² = 0.51
R² = 0.37
no correlation

^{10}Be Erosion of the Appalachians



Smokies data from Matmon et al., 2003

Bedrock Samples

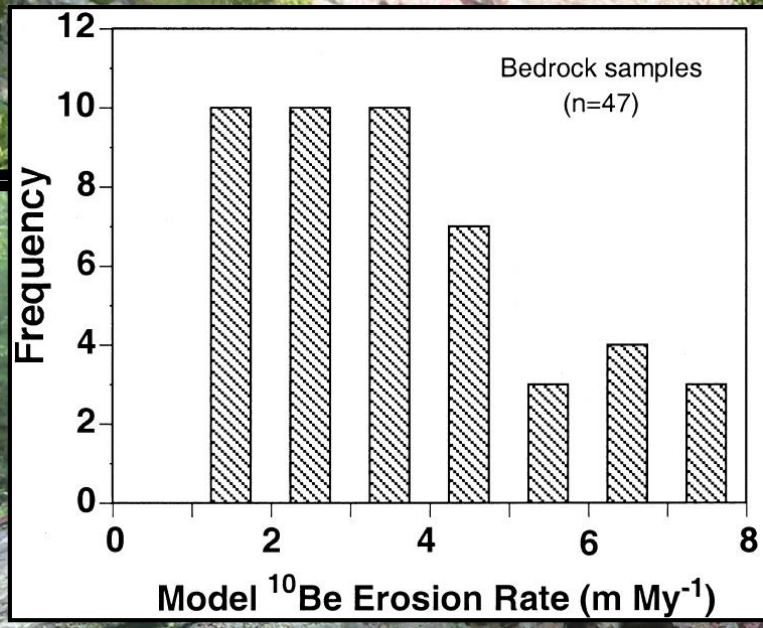


4.9 m/My

4.0

4.0

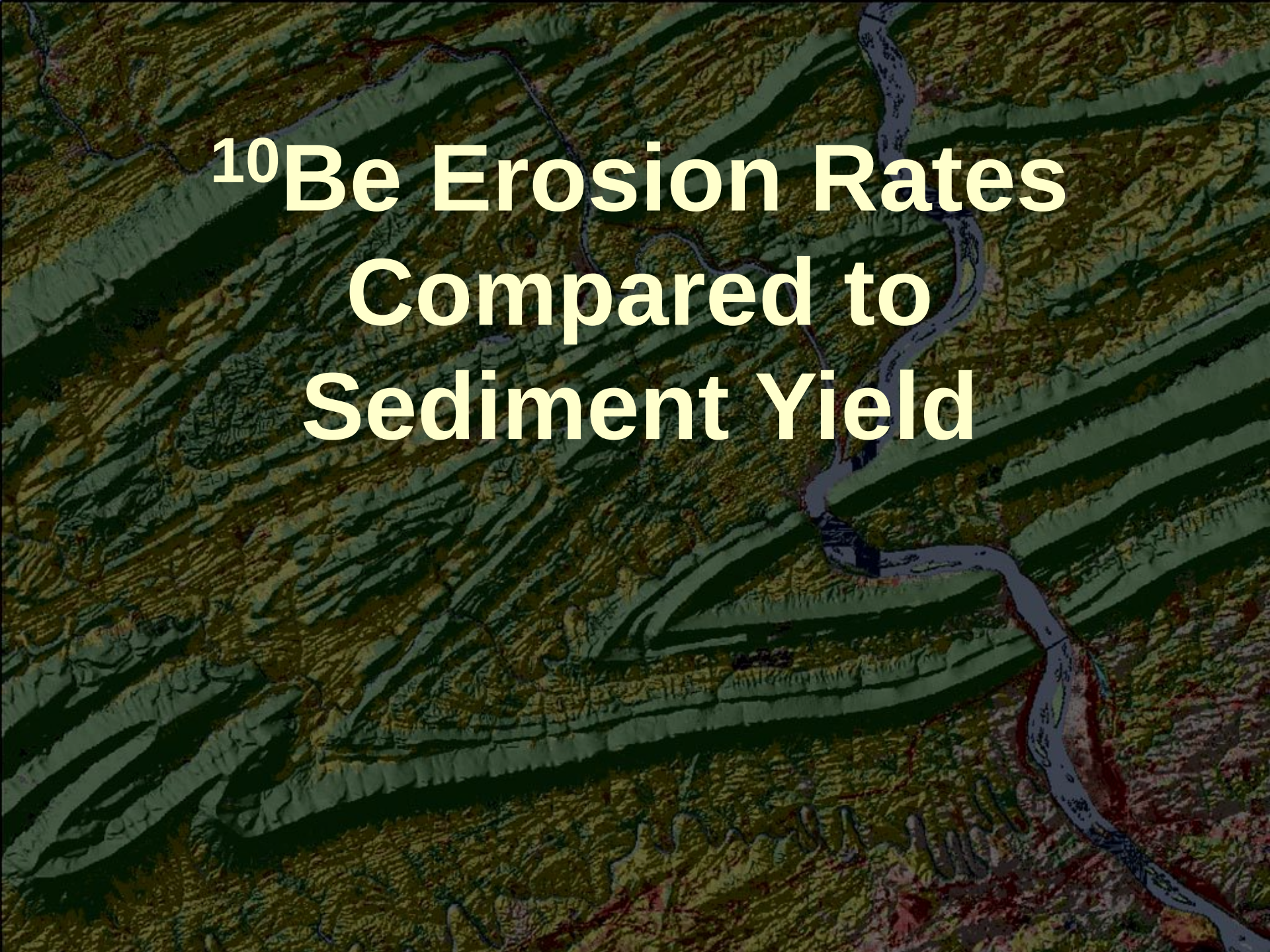
2.5 m/My



Source:
Bierman and Caffee, 2001

Summary of Results

- Erosion rate correlates positively with basin slope
- No discernible relationship exists between lithology and erosion rate
- Results for non-glaciated USGS basins are robust
- For basins impacted by glaciation, ^{10}Be results cannot be directly interpreted as erosion rates
- Bedrock outcrops are eroding slowly


^{10}Be Erosion Rates
Compared to
Sediment Yield

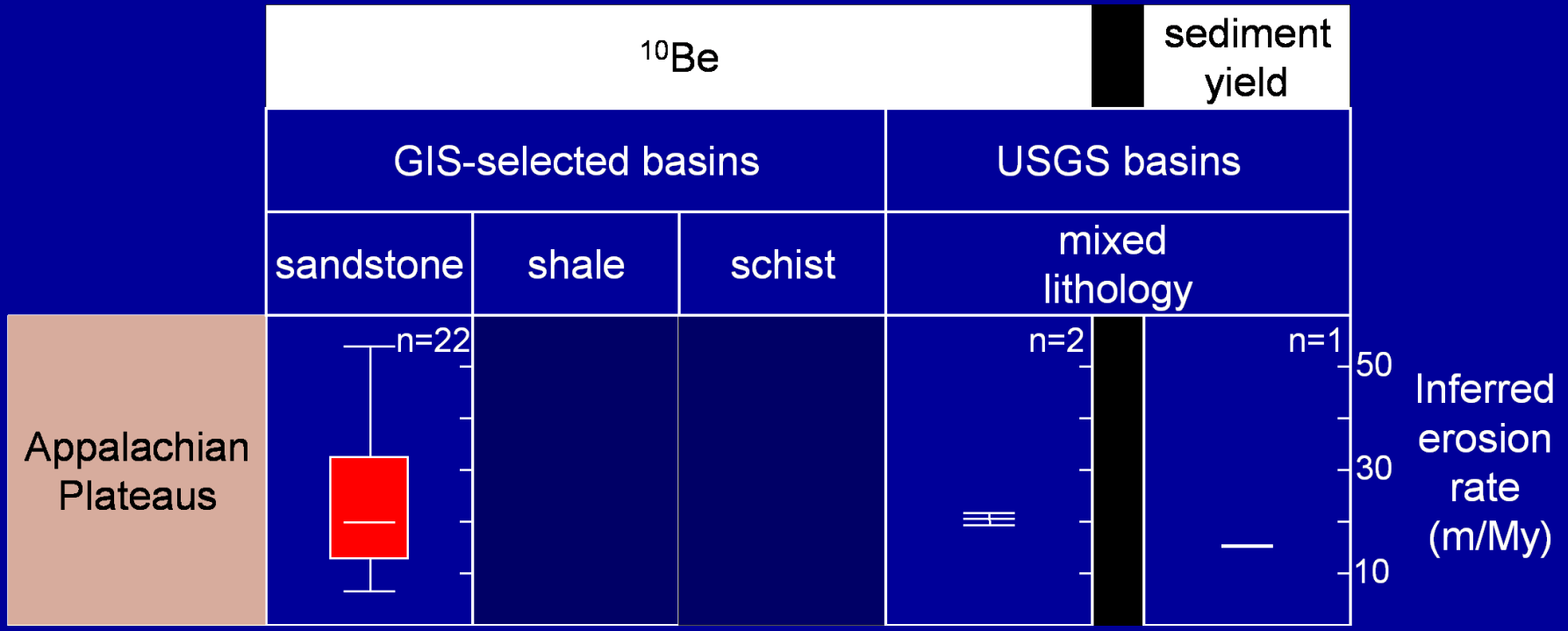
^{10}Be vs. Sediment Yield

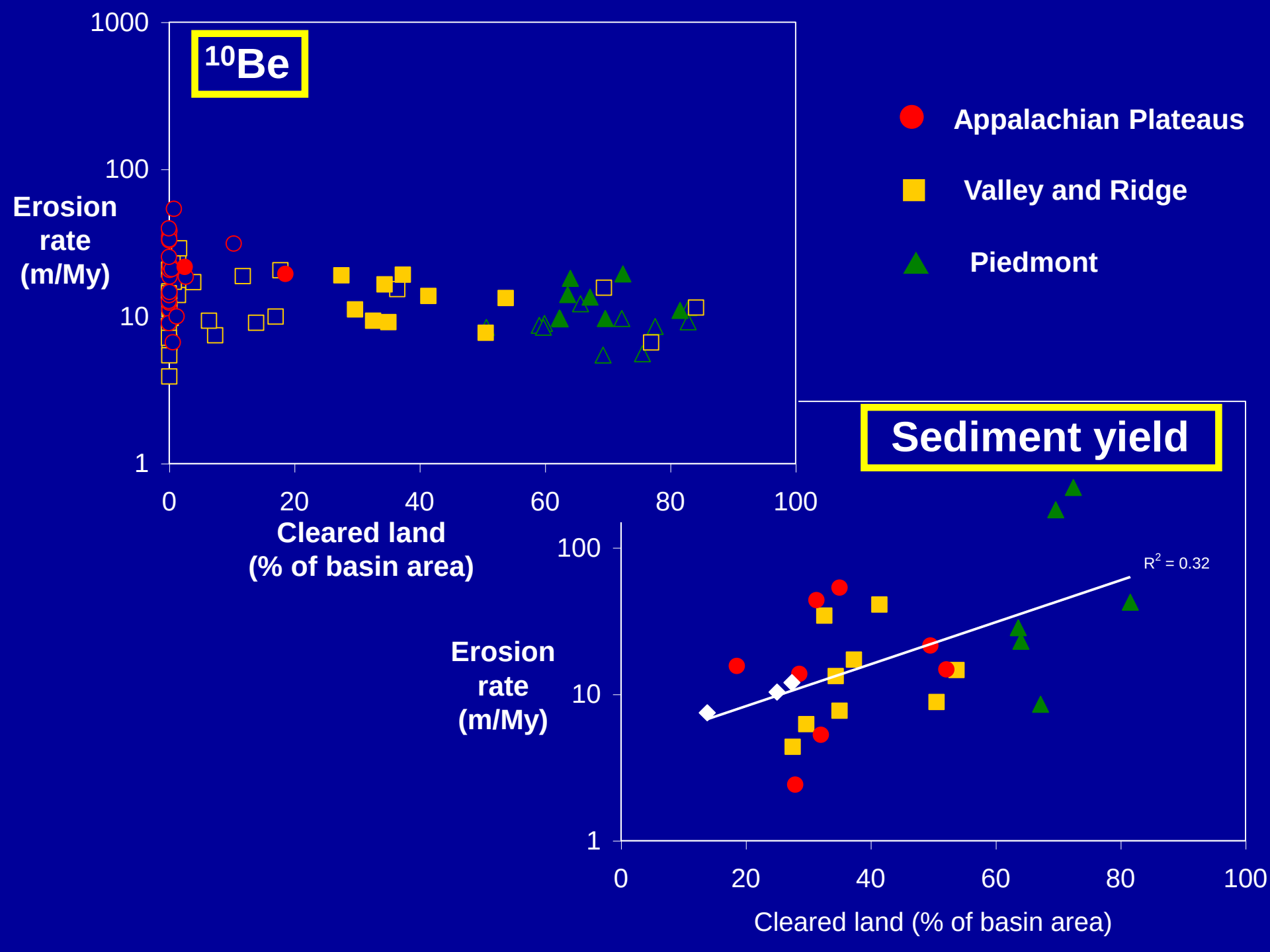
- Sediment generation
- Time scale: 10^4-10^5 years
- Representative of full rock erosion

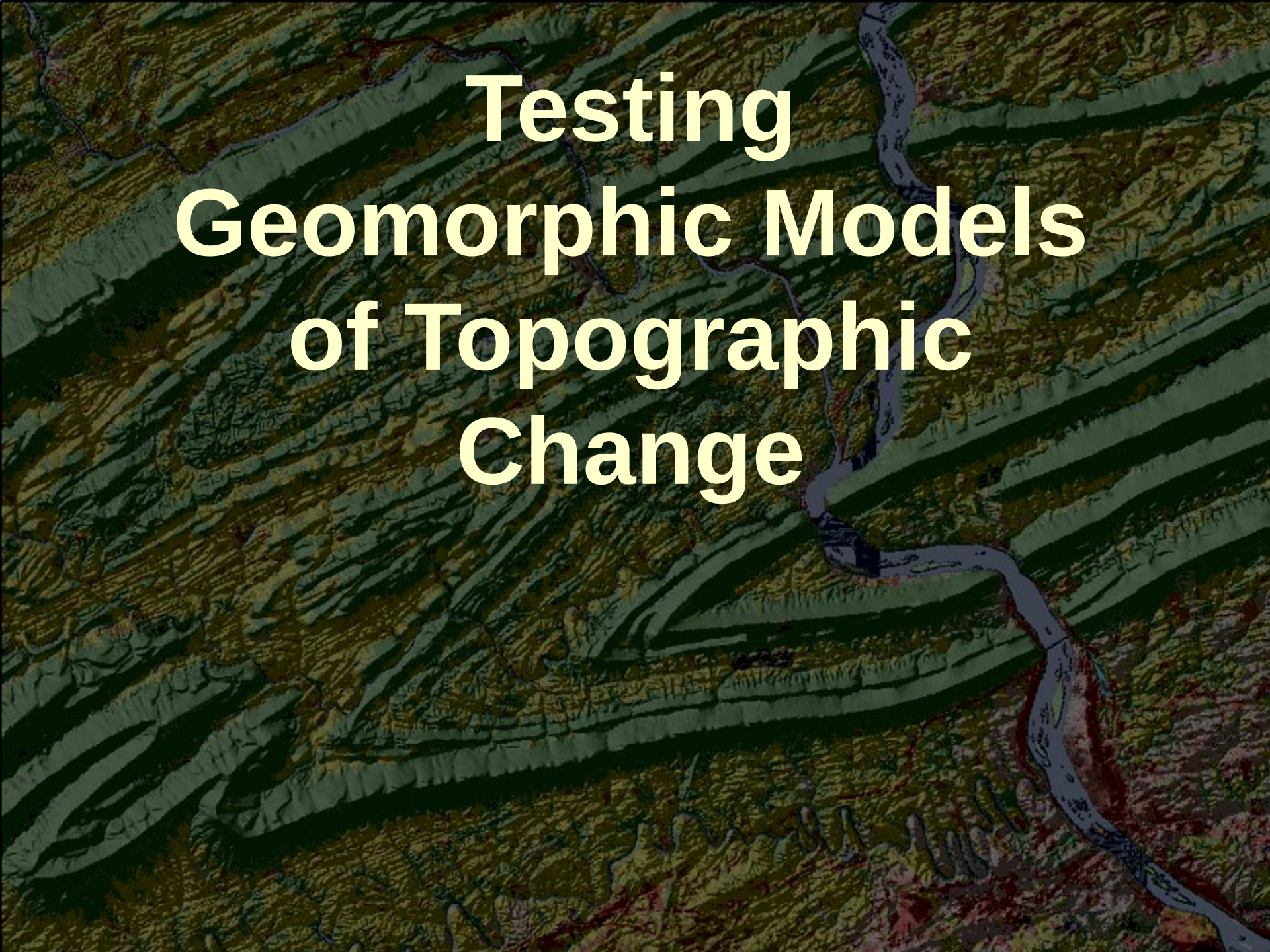
- Export of sediment from the basin
- Period of record, 2 to 29 years
- Suspended load only; does not include dissolved load or bedload

For comparison, present both as erosion rates (m/My)

Source of sediment yield data:
Gellis et al. (2005), Williams and Reed (1972), and unpublished data from A. Gellis

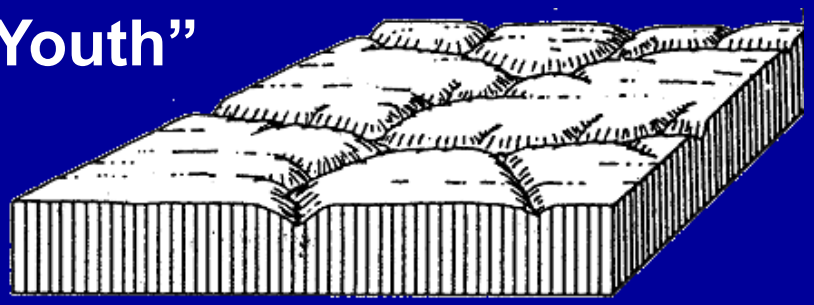

^{10}Be
sediment yield
GIS-selected basins
USGS basins
sandstone
shale
schist
mixed lithology
Appalachian Plateaus
n=22
n=2
n=1
50
30
10
Inferred erosion rate (m/My)


^{10}Be
1000
100
10
1
Erosion rate (m/My)
0
20
40
60
80
100
Cleared land (% of basin area)
Appalachian Plateaus
Valley and Ridge
Piedmont
Sediment yield
100
10
1
Erosion rate (m/My)
R^2 = 0.32
0
20
40
60
80
100
Cleared land (% of basin area)


Testing
Geomorphic Models
of Topographic
Change

Geographical Cycle (Davis)

“Youth”



“Maturity”

“Old Age”

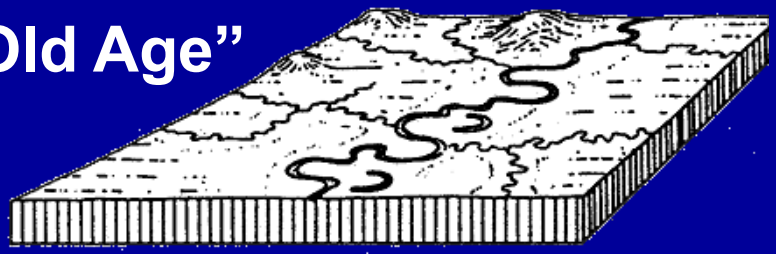
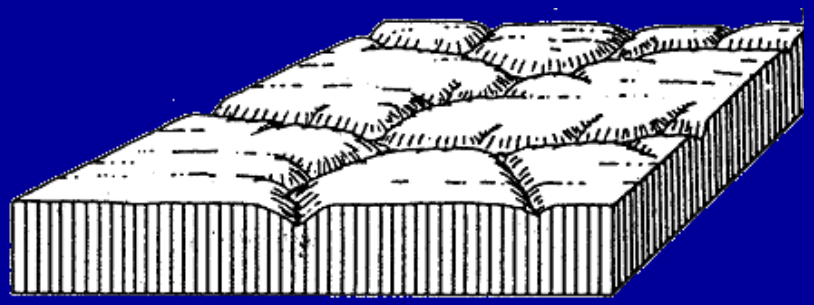


Image sources:
http://www.staff.amu.edu.pl/~sgp/gw/wmd/wmd.html
http://epswww.unm.edu/facstaff/gmeyer/eps481/481tectclimateveg_files/frame.htm#slide0032.htm

Dynamic Equilibrium (Hack)



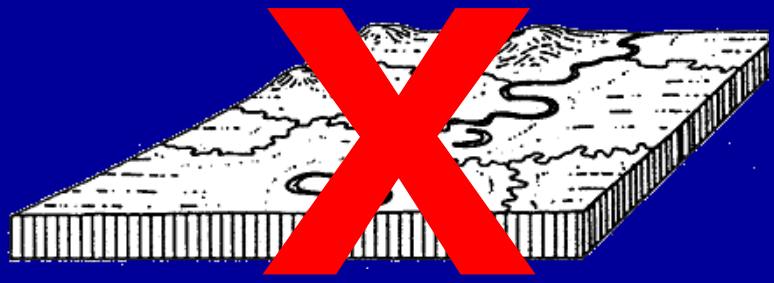
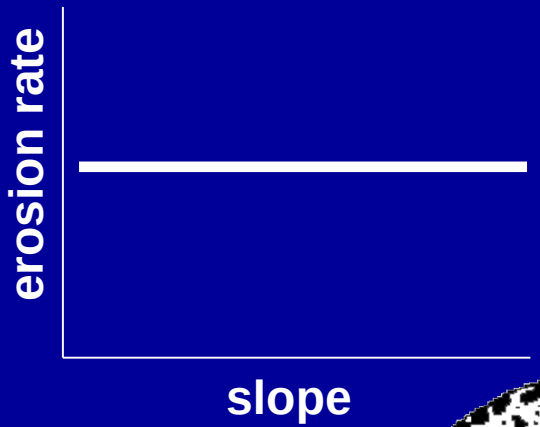
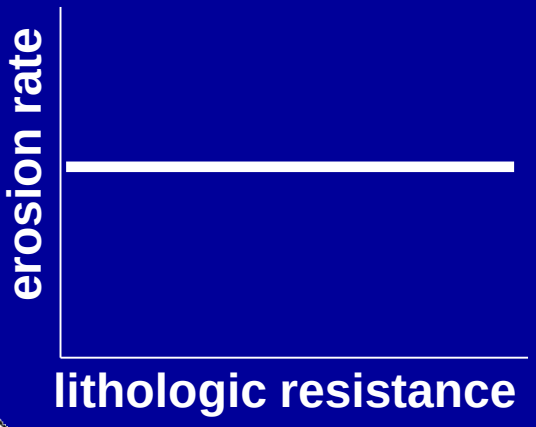


Image source:
http://epswww.unm.edu/facstaff/gmeyer/eps481/481tectclimateveg_files/frame.htm#slide0032.htm

Dynamic Equilibrium (Hack)

"It is assumed that within a single erosional system all elements of the topography are mutually adjusted so that they are downwasting at the same rate."





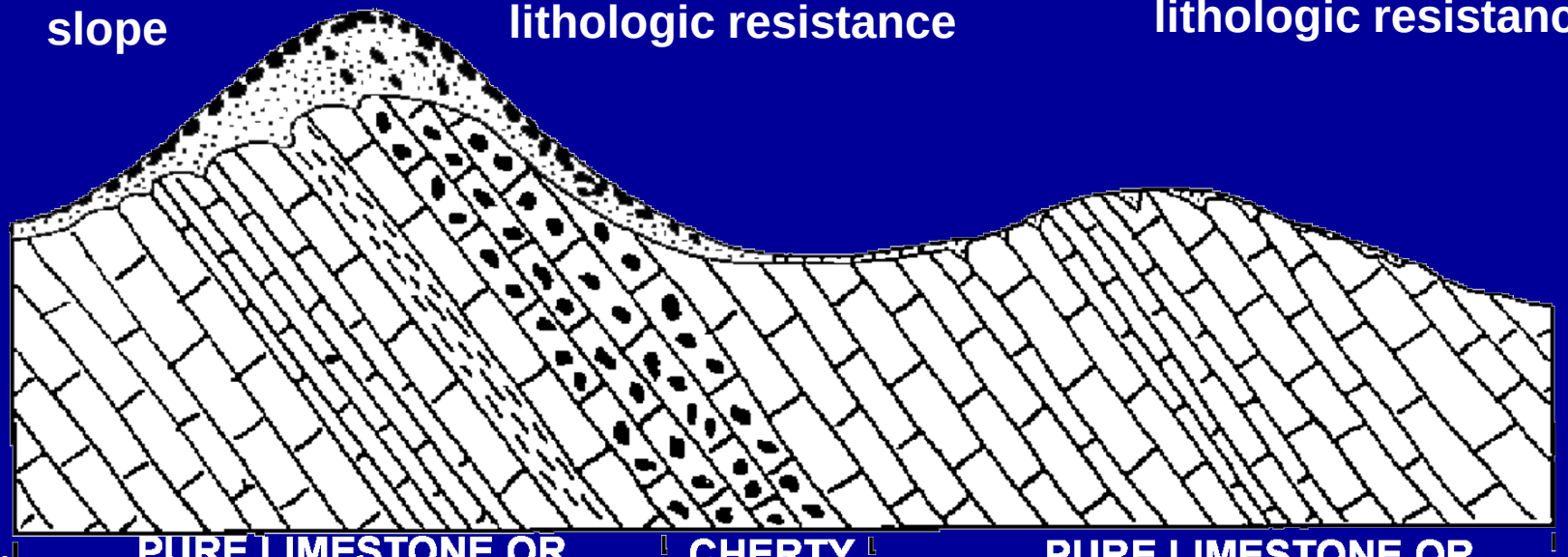
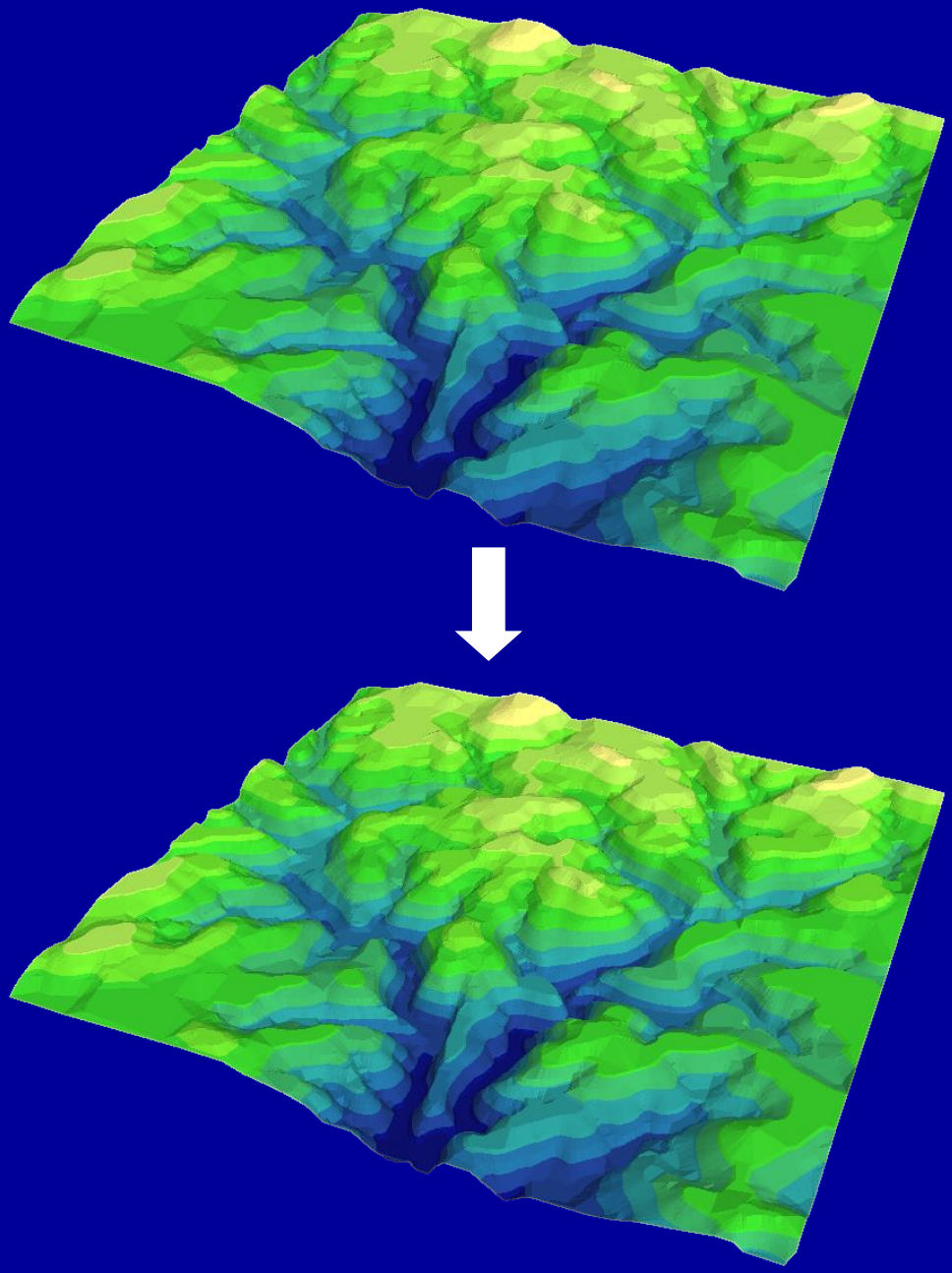
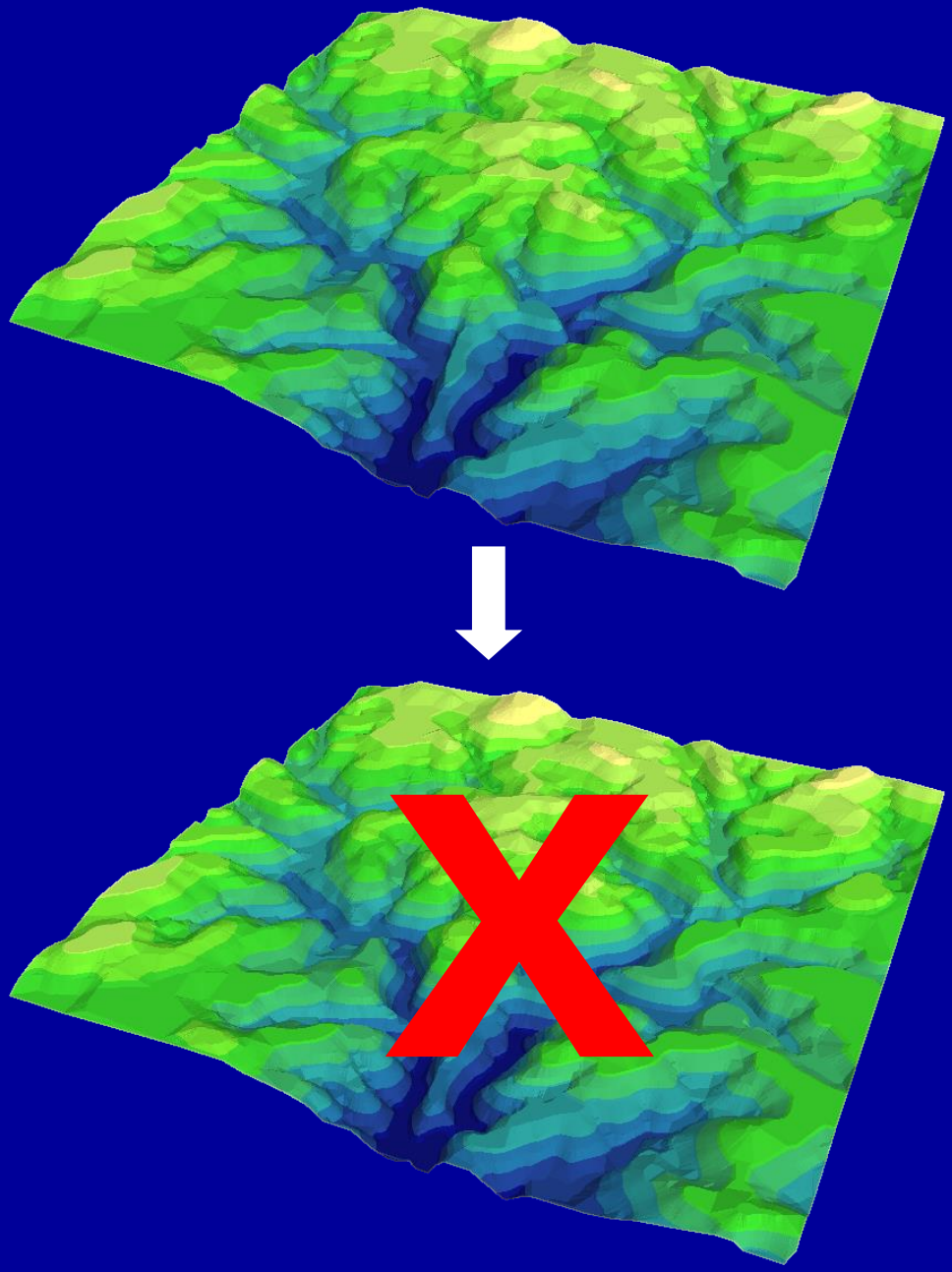


Image source:
Hack (1960)

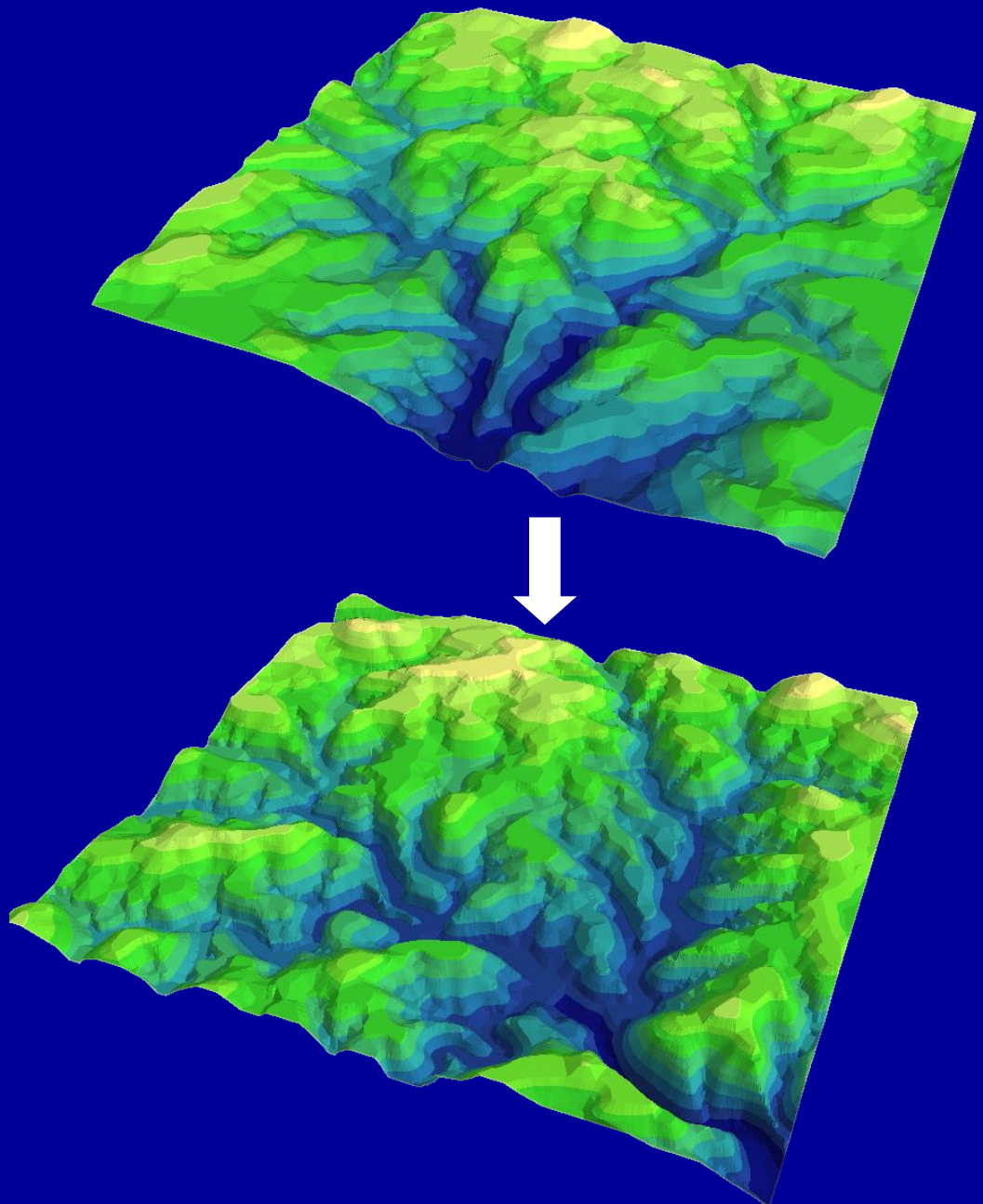
Dynamic Equilibrium (Hack)



Statistical Steady State

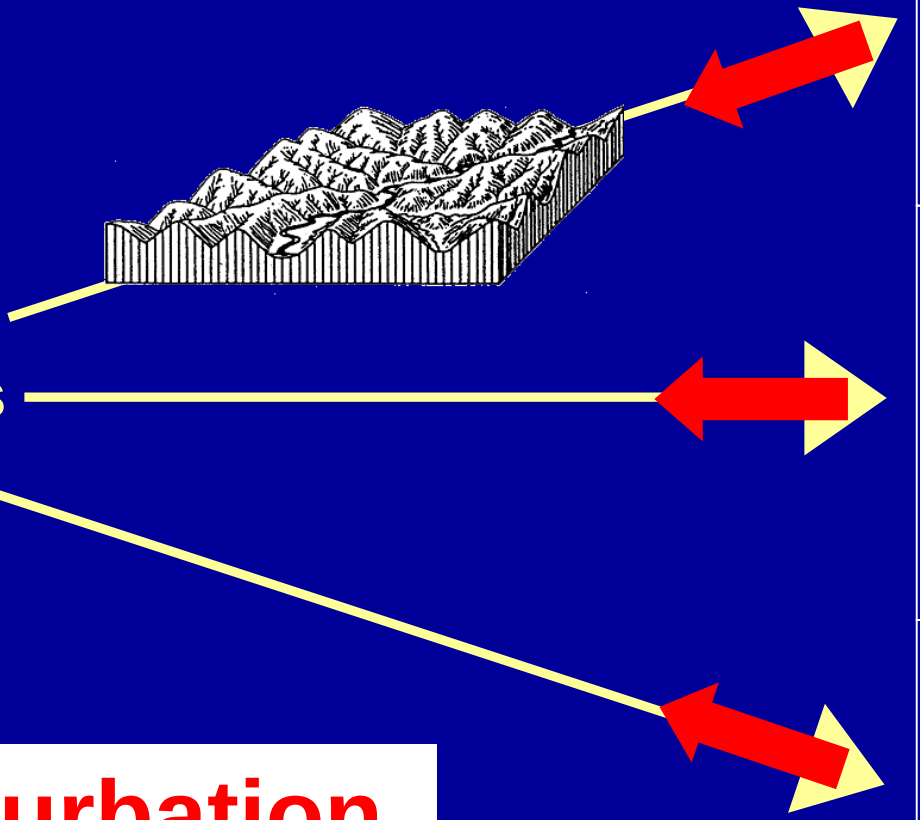


Statistical Steady State



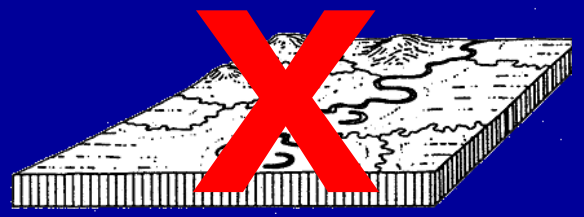
Less stable ⟷ More stable

Mountains



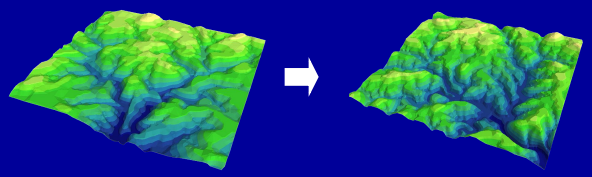
Perturbation

Geographical Cycle
Peneplain

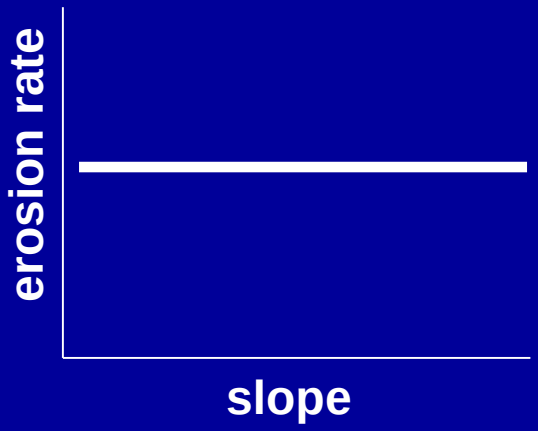


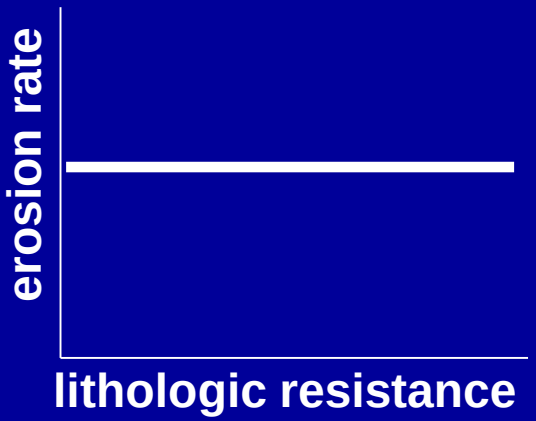
Dynamic Equilibrium
Uniformly eroding topography

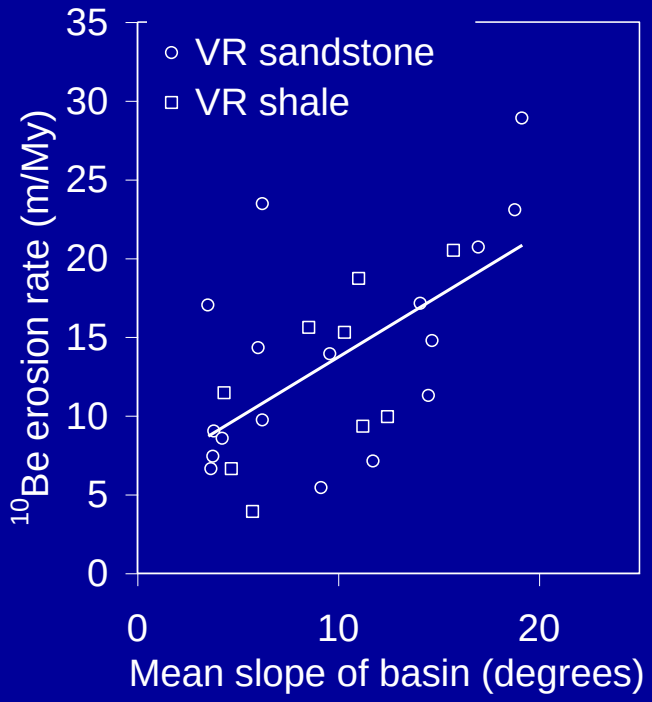
Statistical Steady State
Changing topography, constant relief

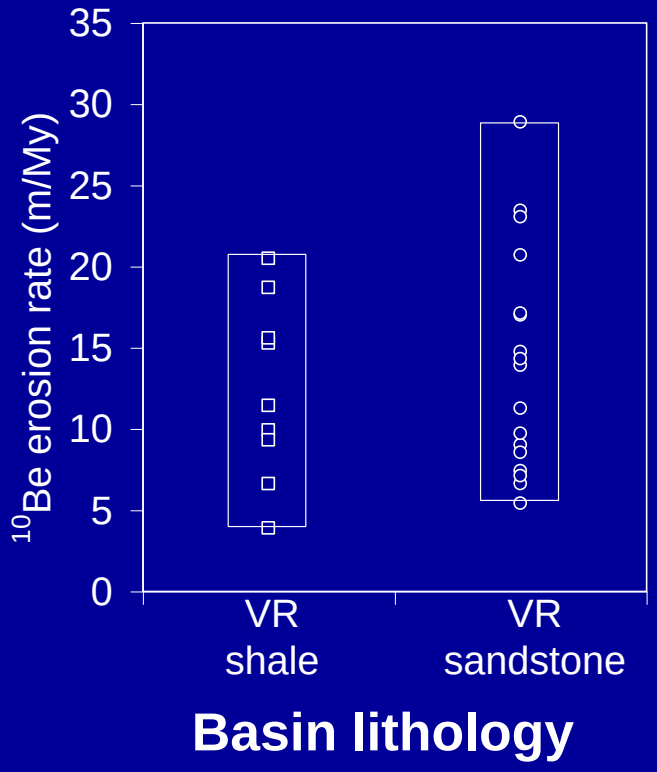


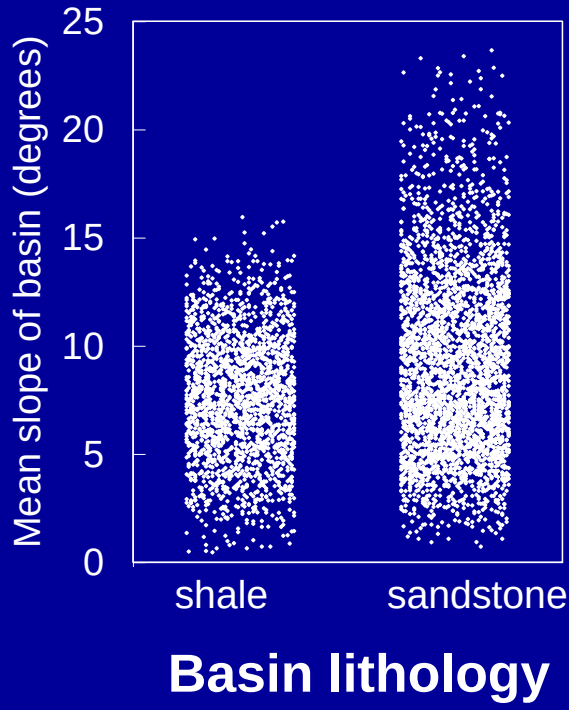
Hack's Equilibrium?





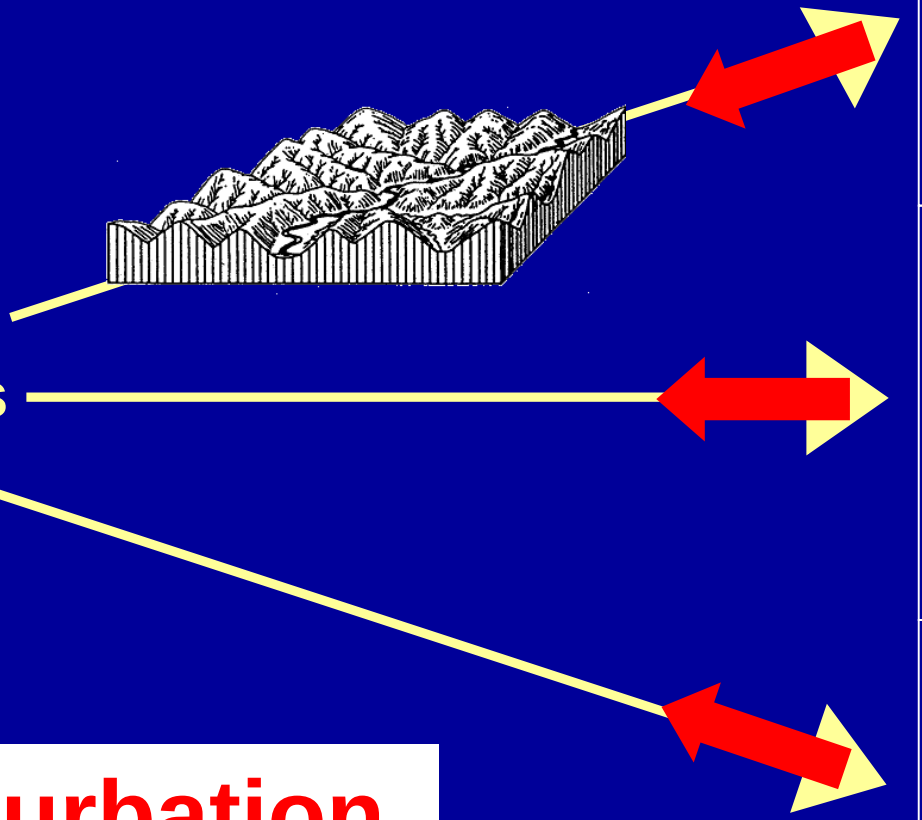






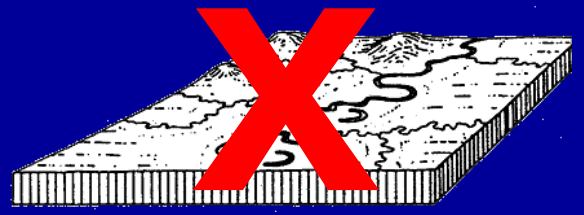
Less stable ⟷ More stable

Mountains



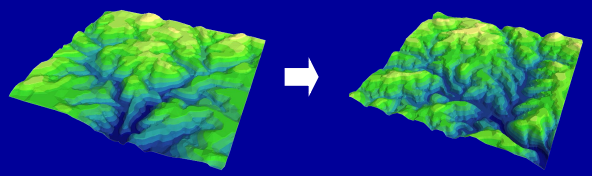
Perturbation

Geographical Cycle
Peneplain



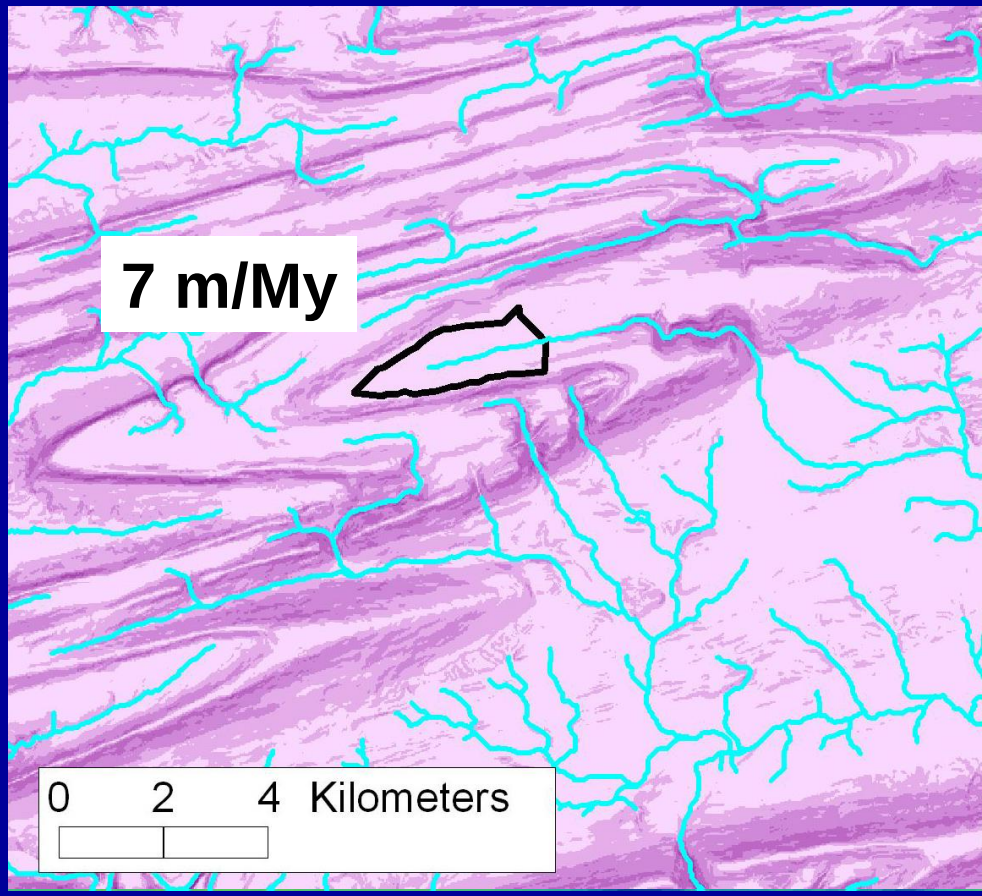
Dynamic Equilibrium
Uniformly eroding topography

Statistical Steady State
Changing topography, constant relief

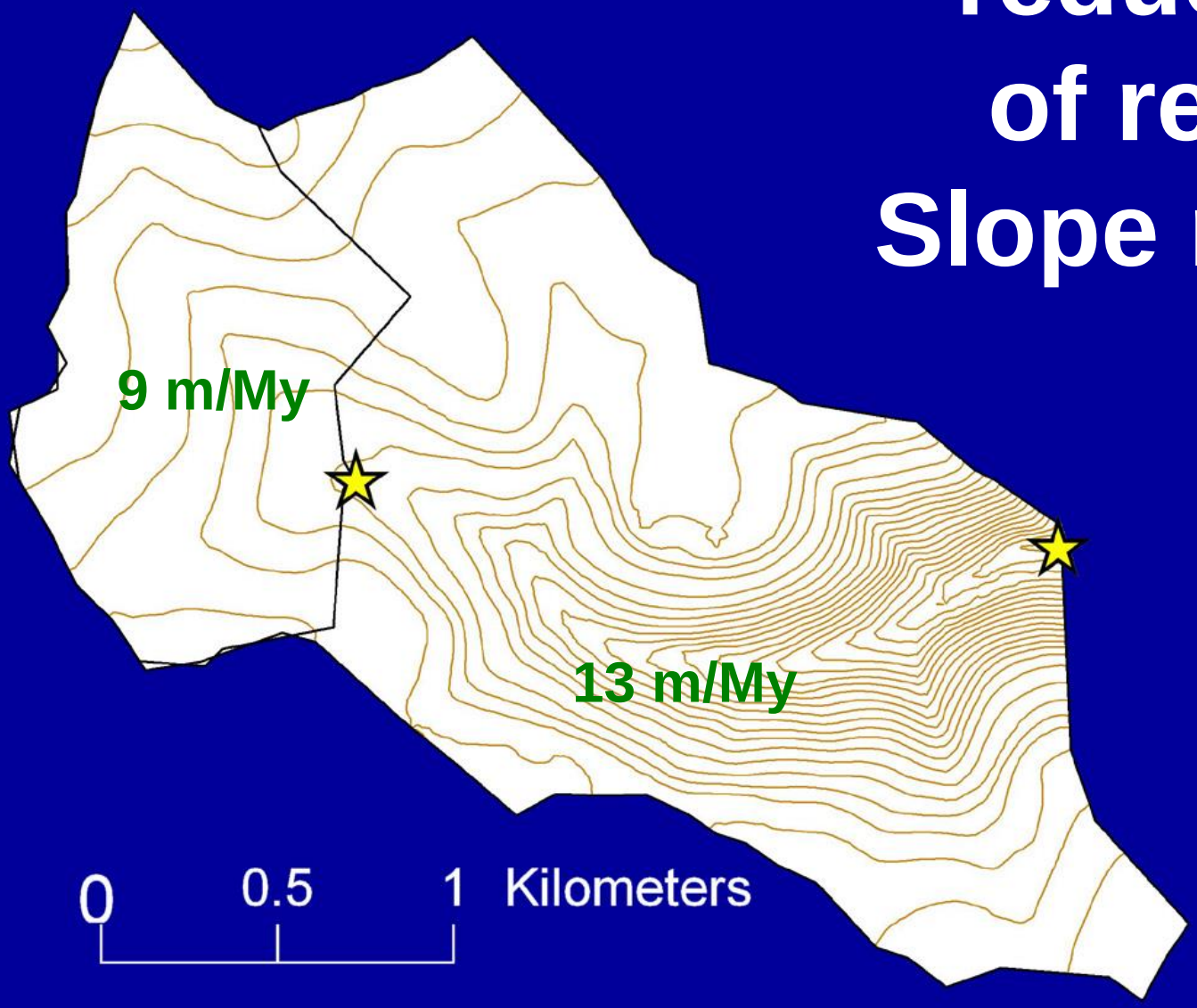


Is Relief Changing?

- Slow erosion of ridges:
  - Bedrock samples
  - High elevation, low slope sandstone basins
- Capacity for rapid stream incision:
  - Holtwood Gorge



Mechanism for reduction of relief: Slope retreat



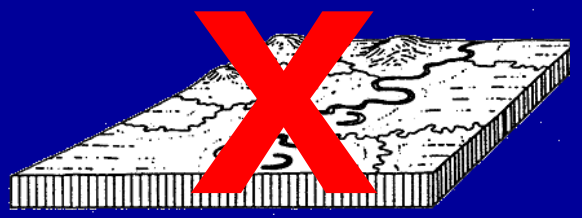
Less stable

More stable

Mountains

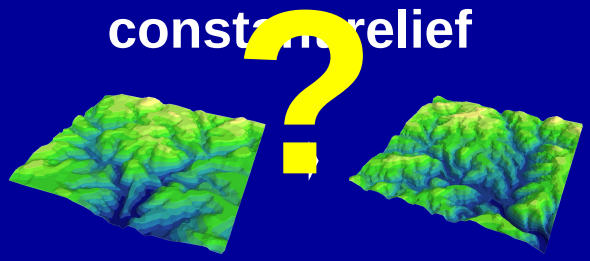
Perturbation

Geographical Cycle
Peneplain



Dynamic Equilibrium
Uniformly eroding topography

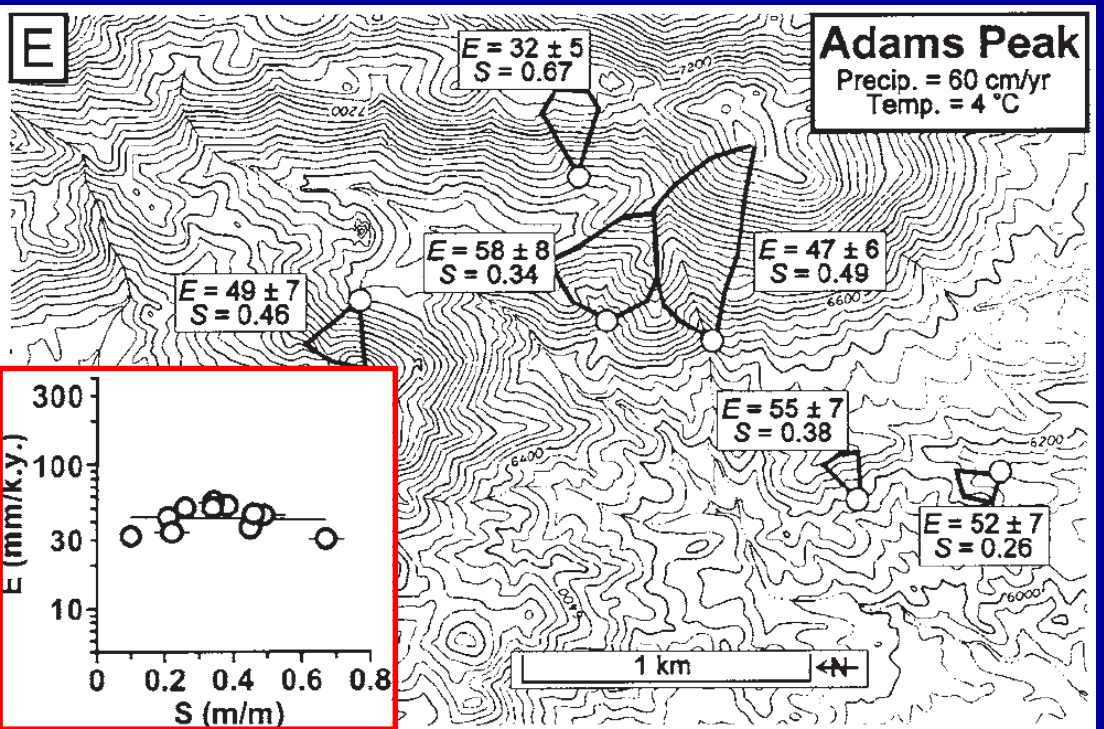
Statistical Steady State
Changing topography, constant relief



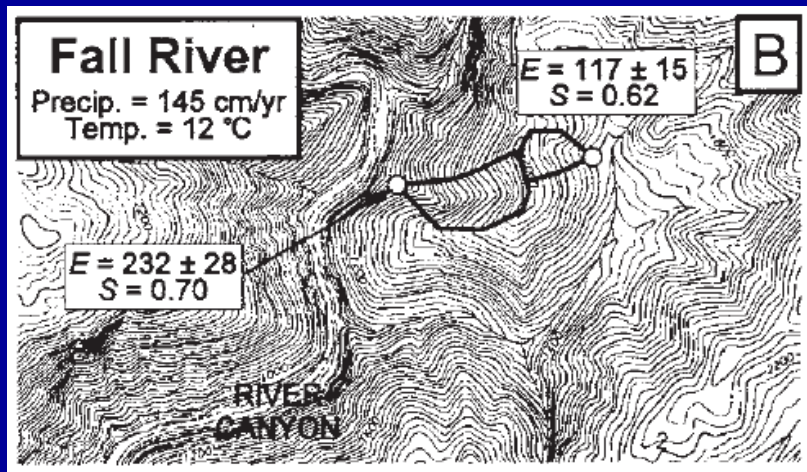
Perturbation?

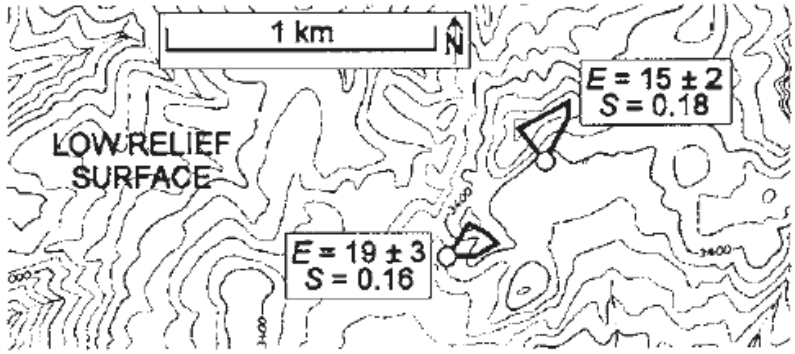
Background:
^{10}Be data from the Sierra Nevada
Riebe et al. (2001)

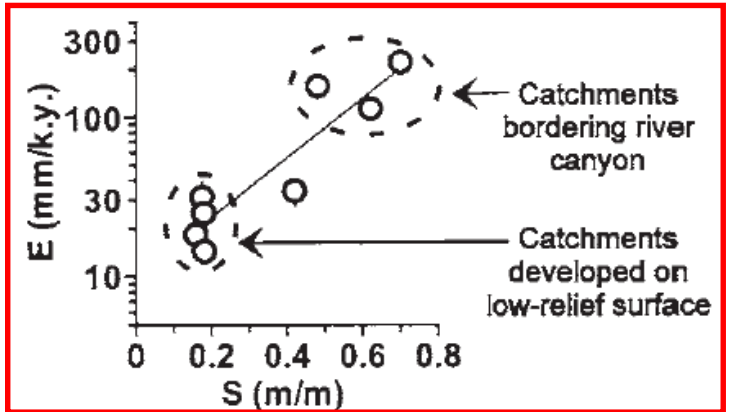
No base level fall,
no correlation with slope:

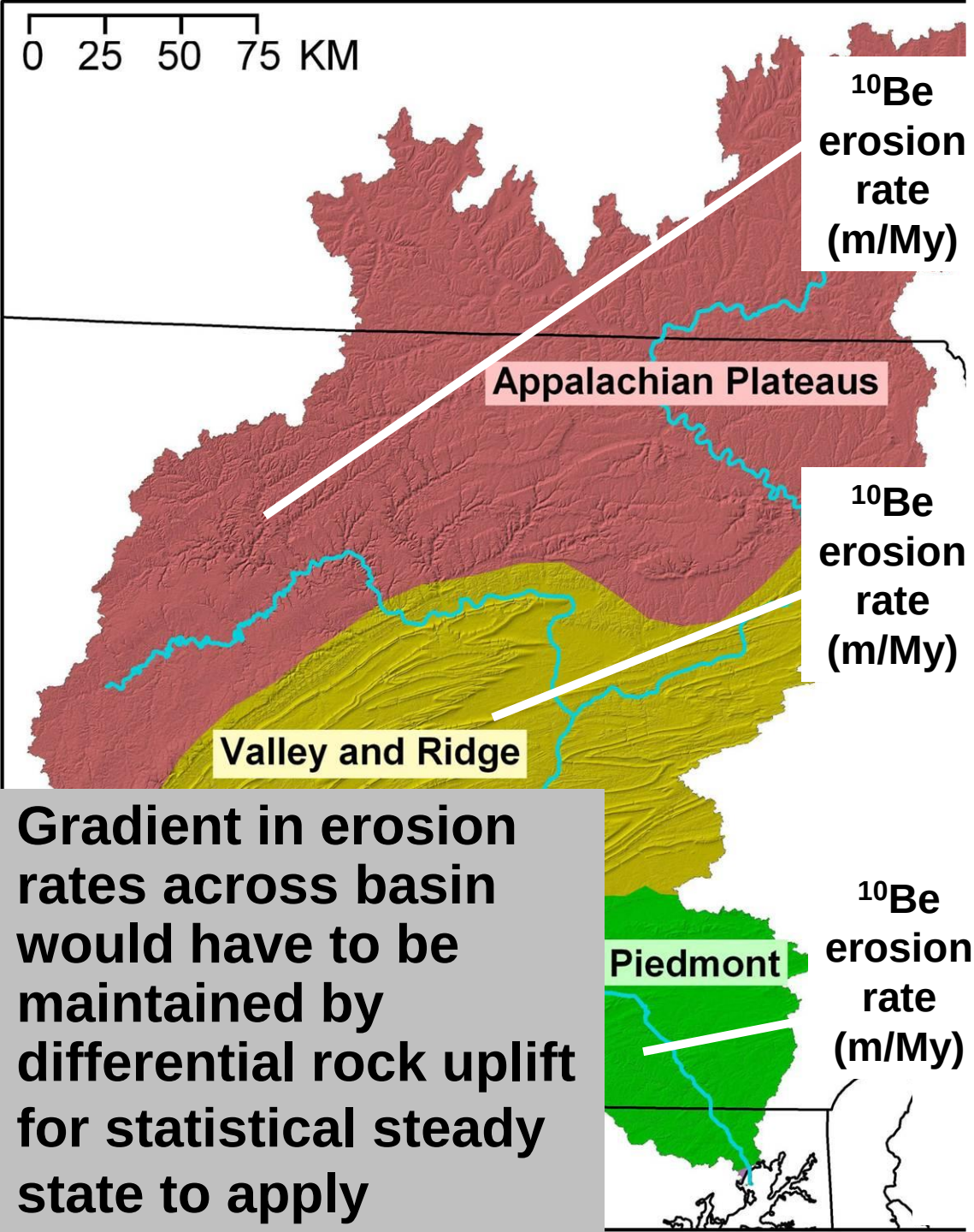


Base level fall,
correlation with slope:

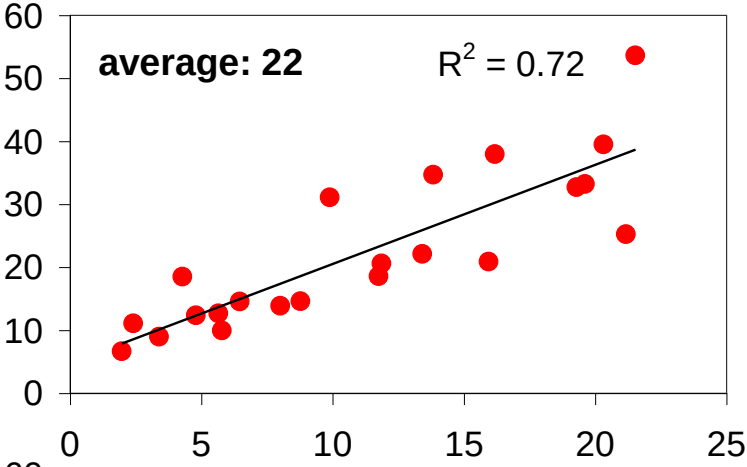


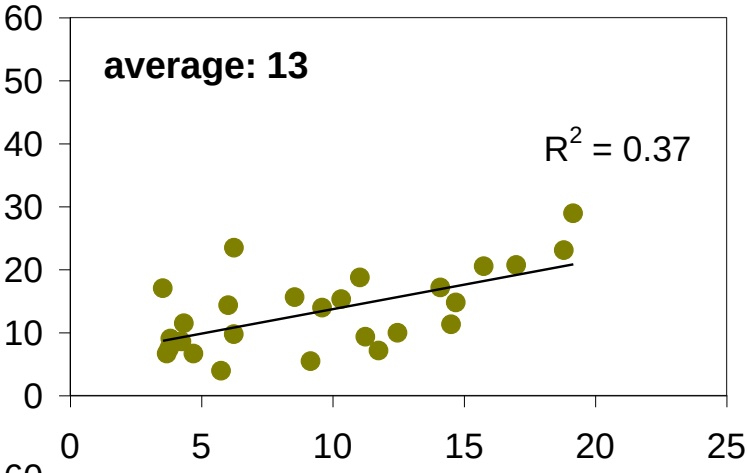


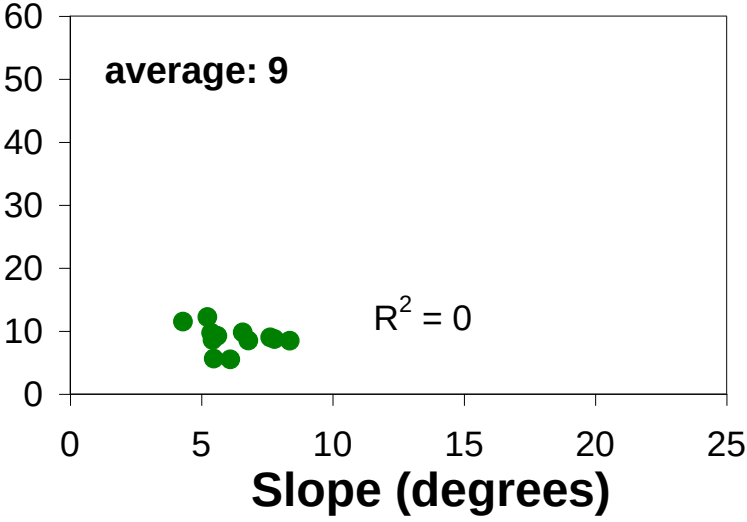




Gradient in erosion rates across basin would have to be maintained by differential rock uplift for statistical steady state to apply







Less stable

More stable

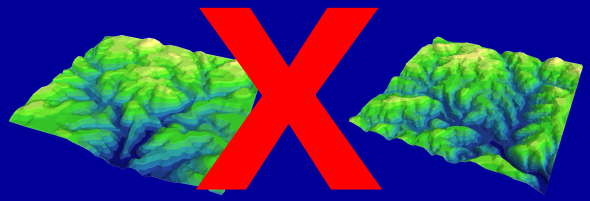
Mountains

Perturbation

Geographical Cycle
Peneplain

Dynamic Equilibrium
Uniformly eroding topography

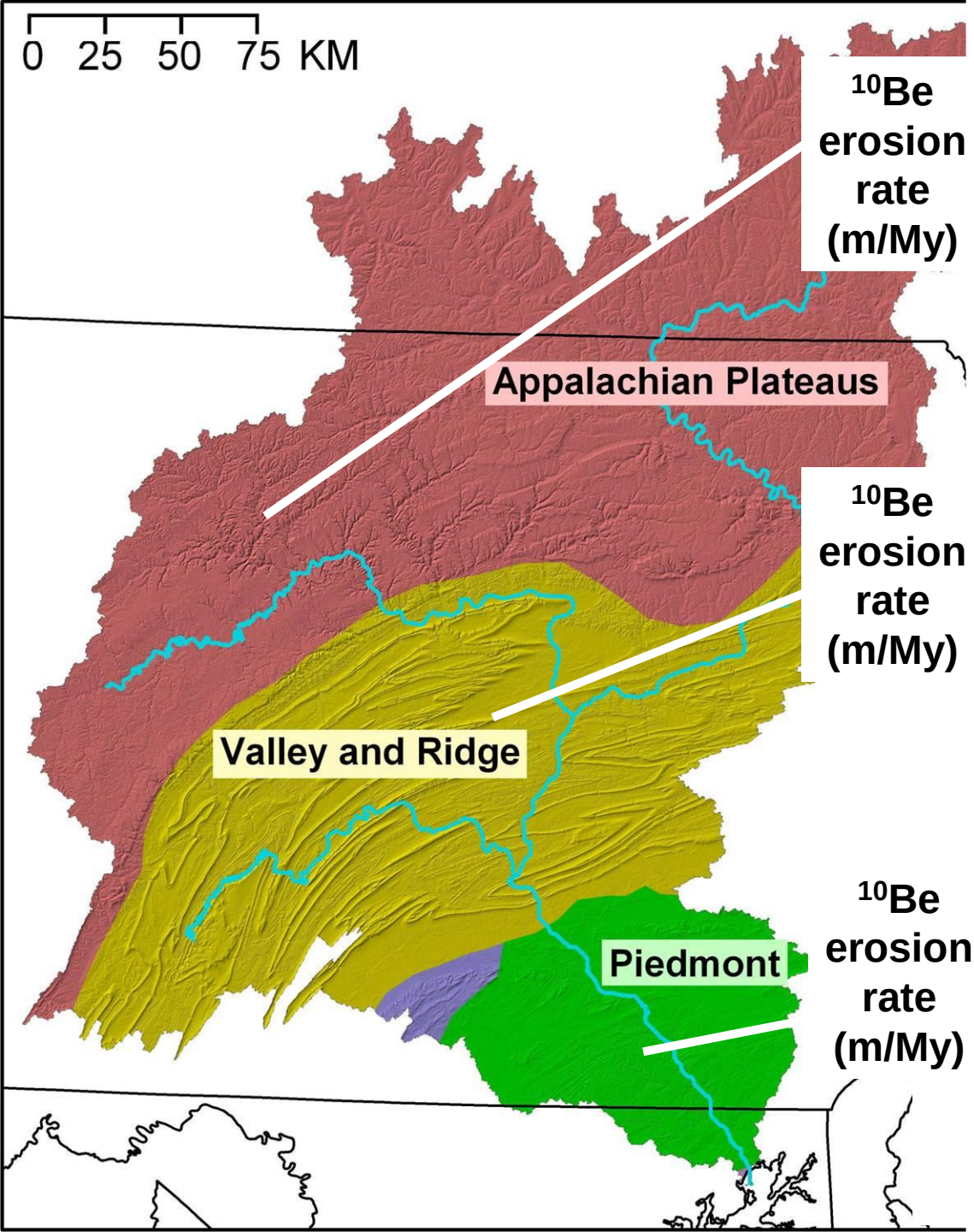
Statistical Steady State
Changing topography, constant relief

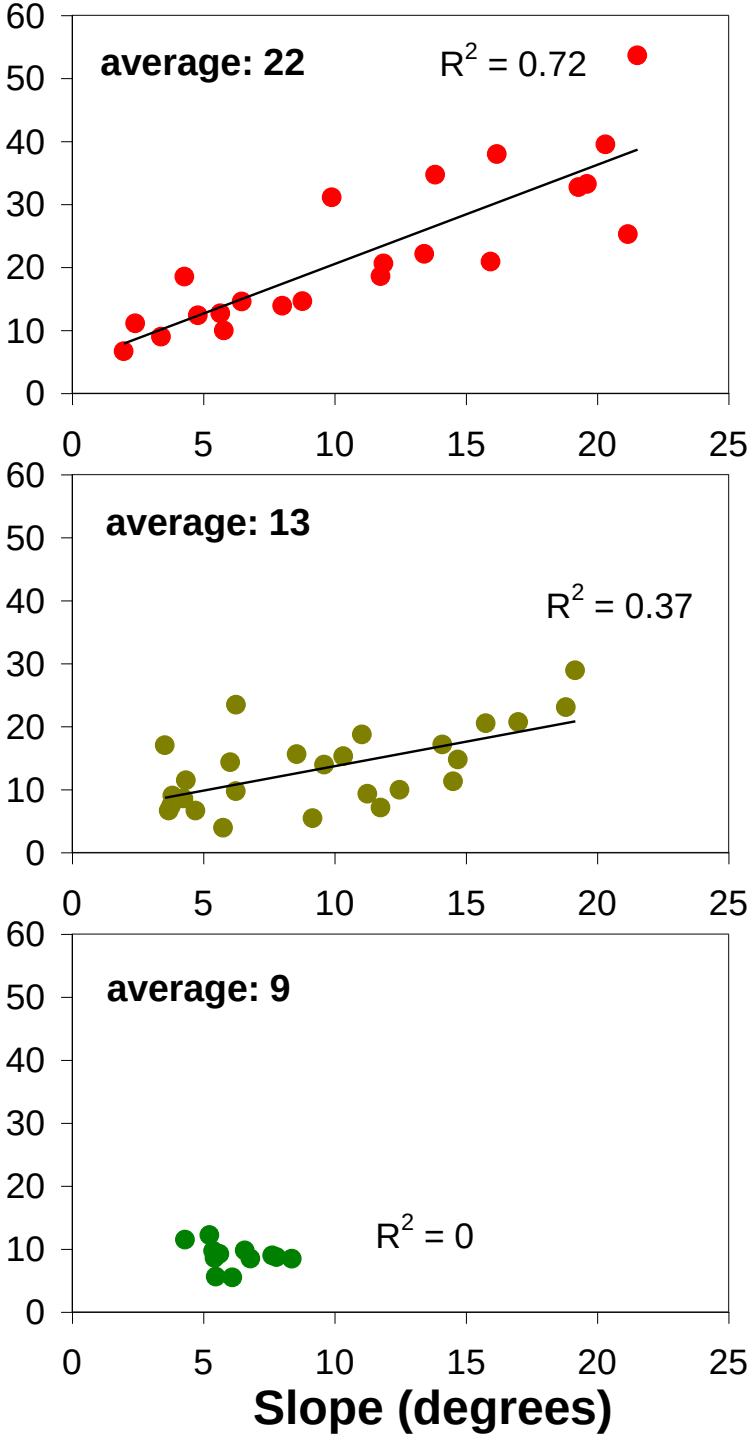


Evidence for a Miocene Perturbation

- Offshore sedimentary record: increased sediment delivery (Poag and Sevon, 1989; Pazzaglia and Brandon, 1996)
- Fission track: period of rapid exhumation beginning in the Miocene (Blackmer et al., 2001)
- Detrital chert and detrital fission track data suggest stream capture and drainage reorganization in the central Appalachians (Naeser et al., 2004)

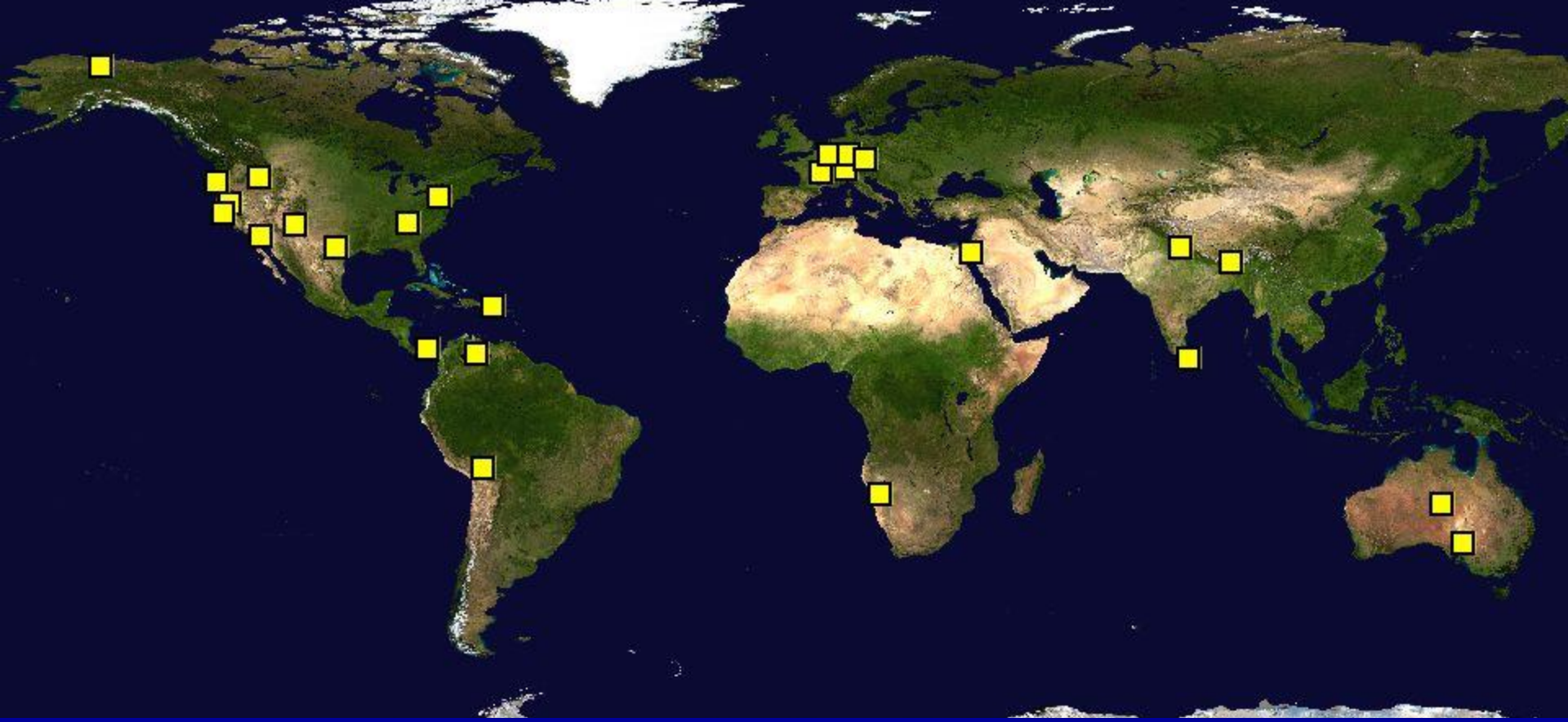
Rates and patterns of erosion in the Susquehanna River Basin may reflect ongoing adjustment to Miocene stream capture and base-level fall.


0 25 50 75 KM
^{10}Be erosion rate (m/My)
Appalachian Plateaus
^{10}Be erosion rate (m/My)
Valley and Ridge
^{10}Be erosion rate (m/My)
Piedmont


average: 22
R^2 = 0.72
average: 13
R^2 = 0.37
average: 9
R^2 = 0
0 5 10 15 20 25
0 10 20 30 40 50 60
Slope (degrees)

Global Compilation of ^{10}Be Data from Fluvial Sediment:

A Brief Overview



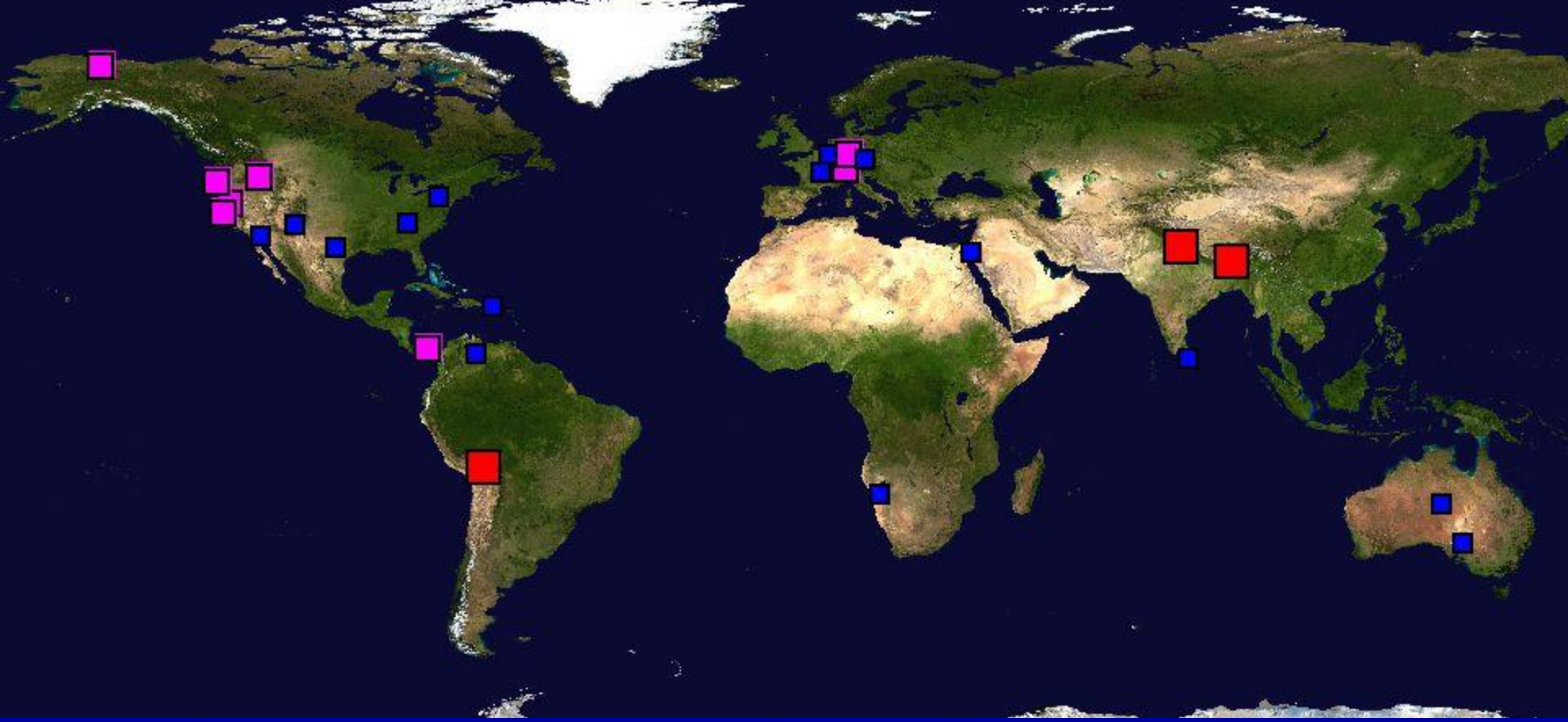
Regions with ^{10}Be erosion rate data from sediment

Published data from:

Bierman and Caffee, 2001; Brown et al., 1995; Brown et al., 1998; Clapp et al., 2000; Clapp et al., 2002; Granger et al., 1996; Heimsath et al., 1997; Heimsath et al., 2001; Hewawasam et al., 2003; Kirchner et al., 2001; Matmon et al., 2003; Morel et al., 2003; Riebe et al., 2000; Riebe et al., 2003; Schaller et al., 2001; Vance et al., 2003

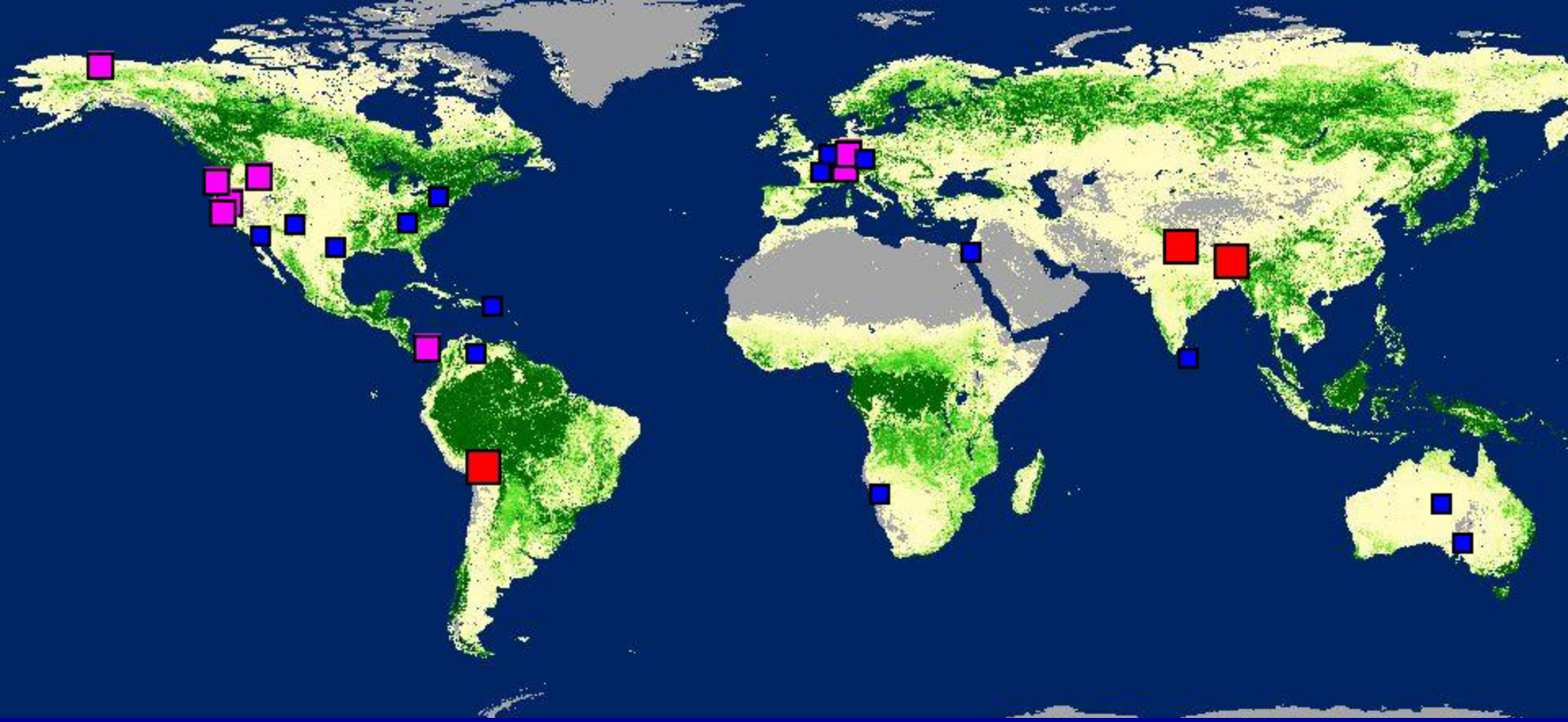
In press, in preparation, and unpublished data from:

Bierman, Duncan, Johnsson, Nichols, Reuter, Safran



Erosion rate, in meters/million years, for largest sampled basin in region

- < 50
- 50 - 150
- > 500

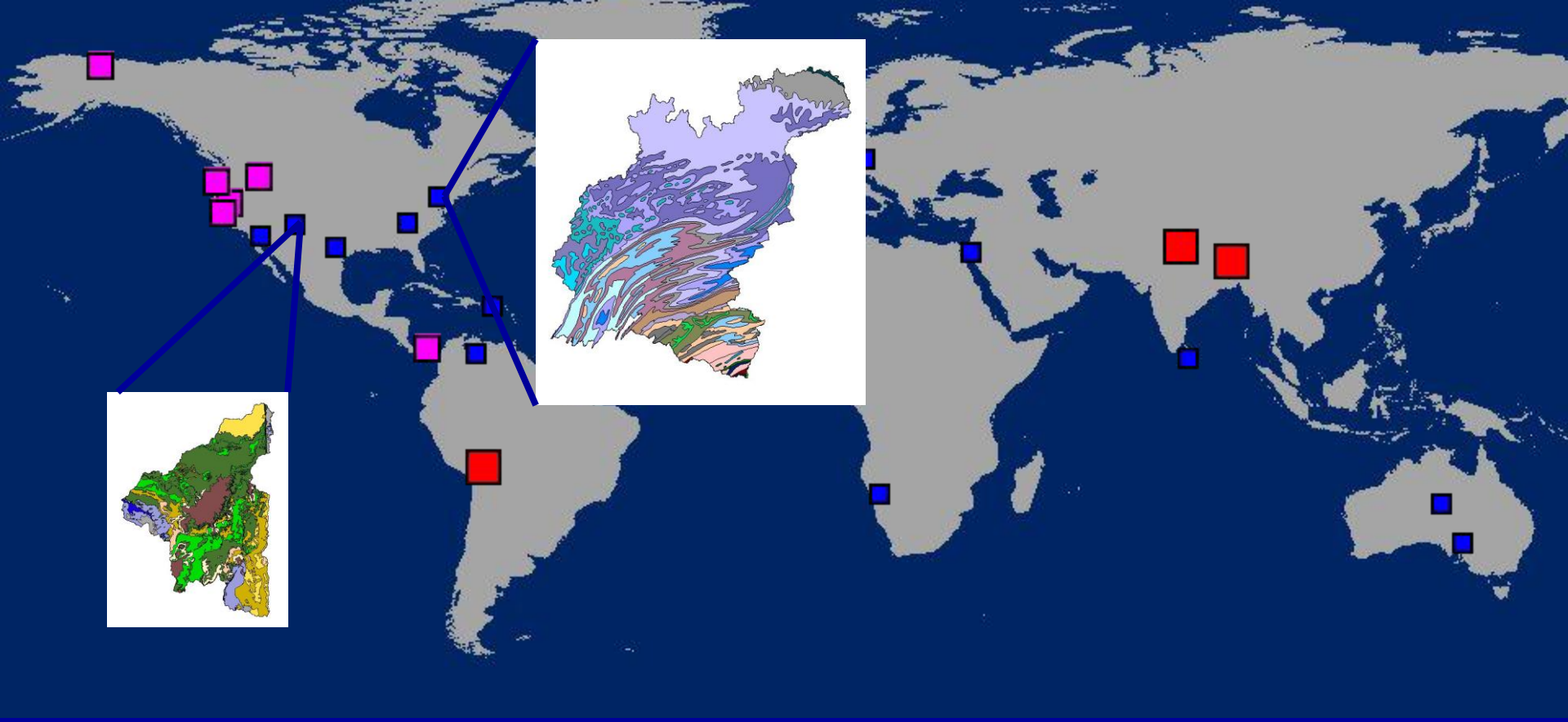


Topography

Tectonics

Climate

Vegetation



Topography

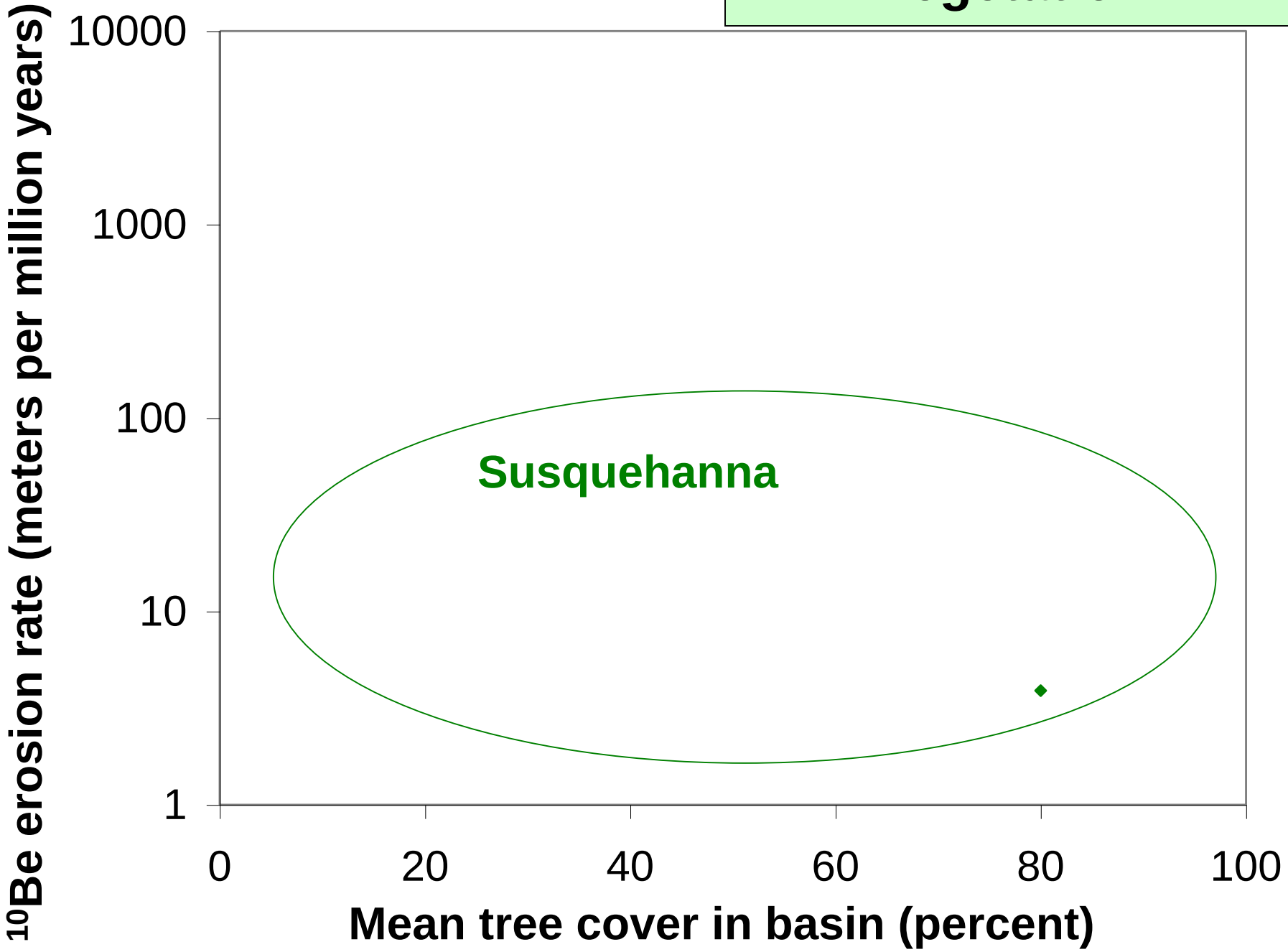
Tectonics

Climate

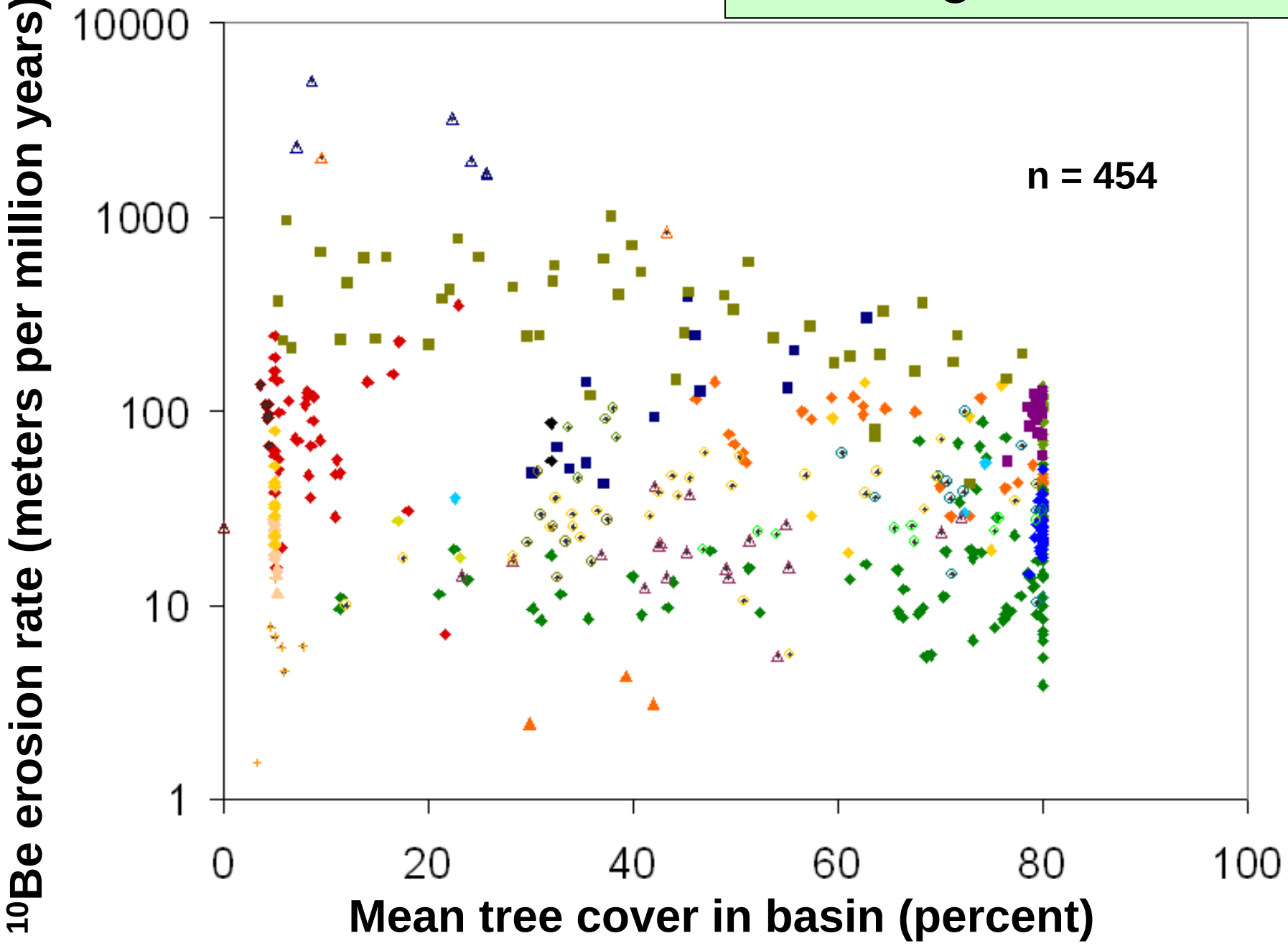
Vegetation

Lithology

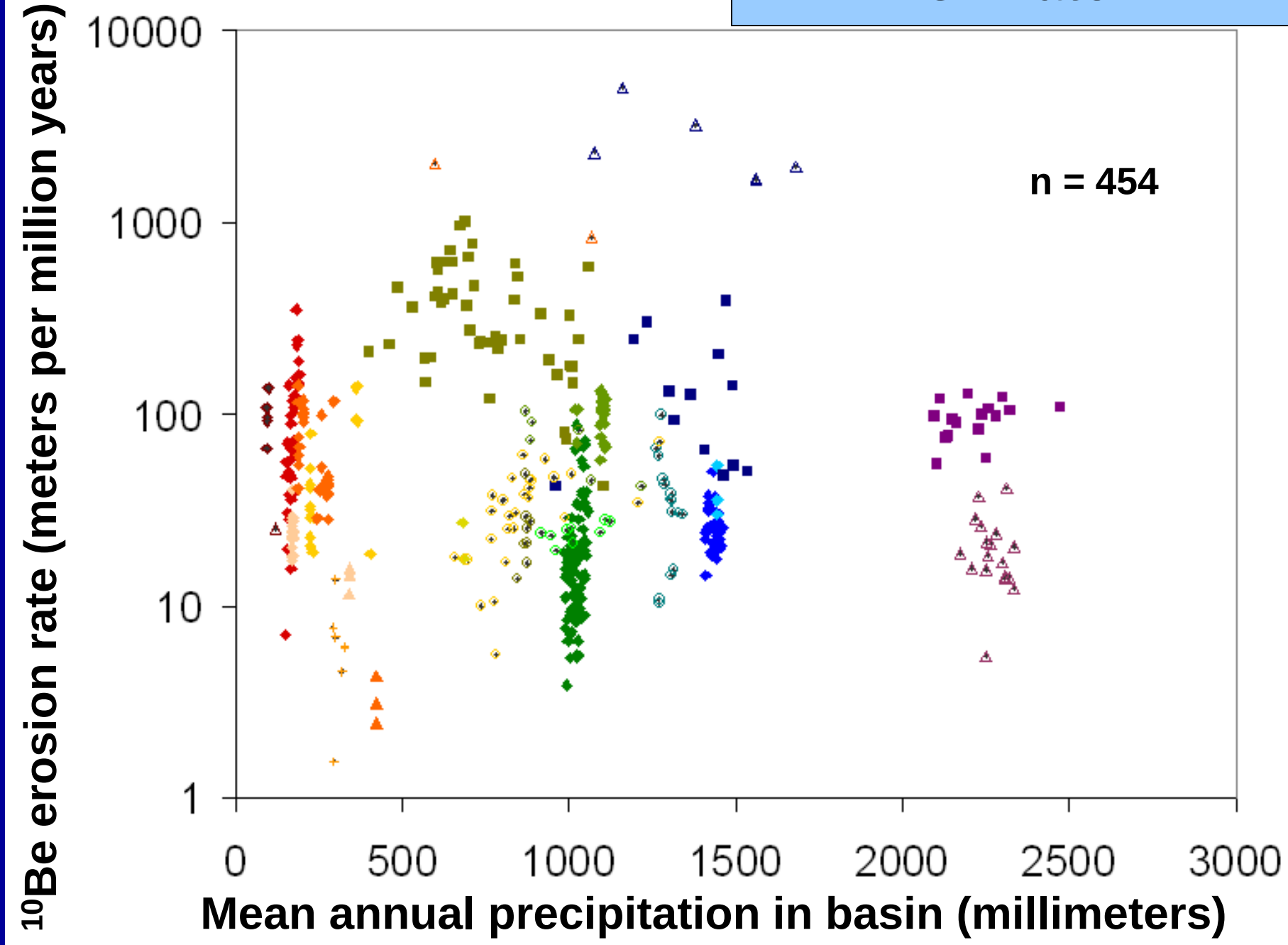
Vegetation


10000
1000
100
10
1
0
20
40
60
80
100
Susquehanna
^{10}Be erosion rate (meters per million years)
Mean tree cover in basin (percent)

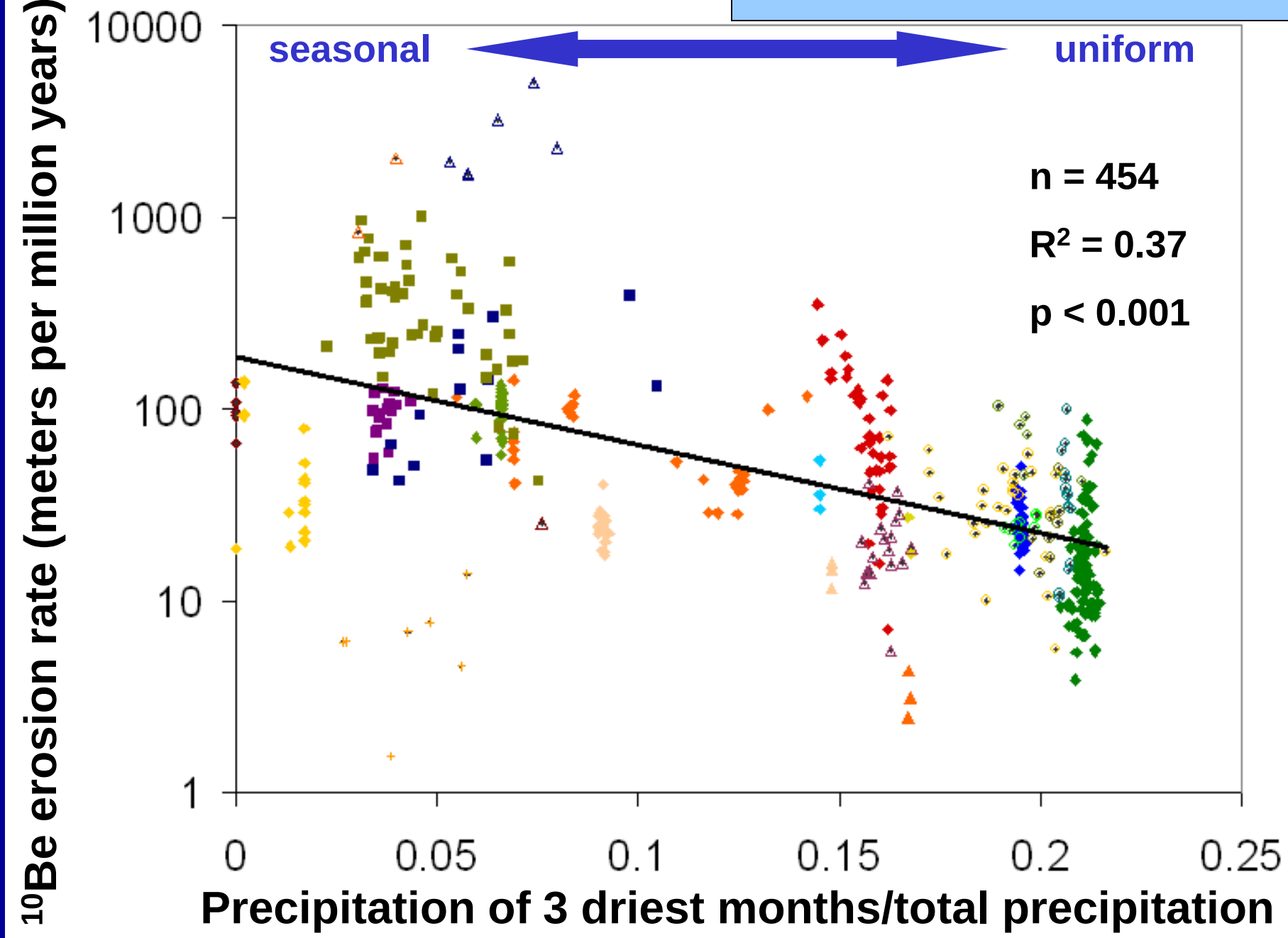
Vegetation


10000
1000
100
10
1
0
20
40
60
80
100
n = 454
^{10}Be erosion rate (meters per million years)
Mean tree cover in basin (percent)

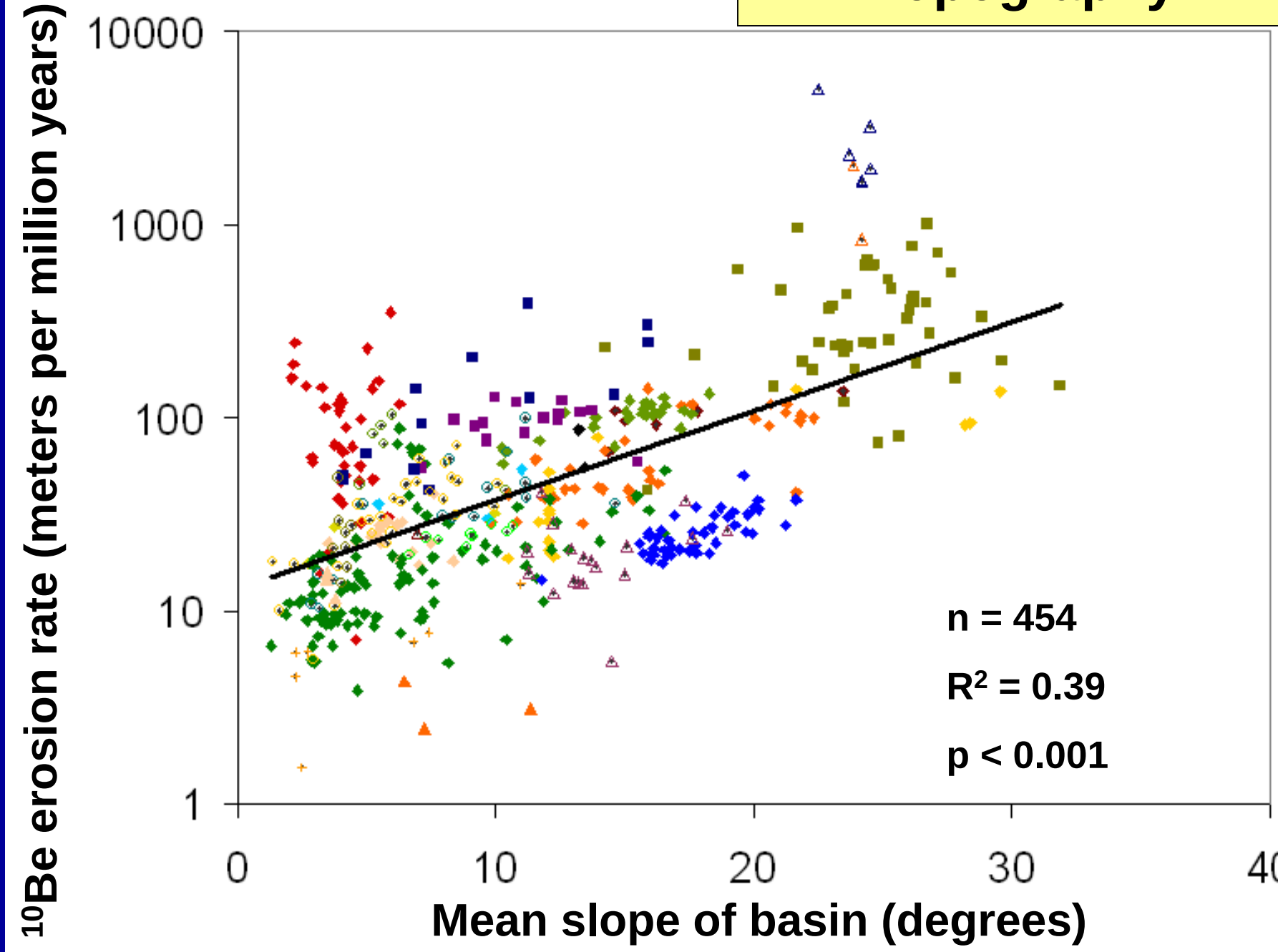
Climate


10000
1000
100
10
1
0
500
1000
1500
2000
2500
3000
n = 454
^{10}Be erosion rate (meters per million years)
Mean annual precipitation in basin (millimeters)

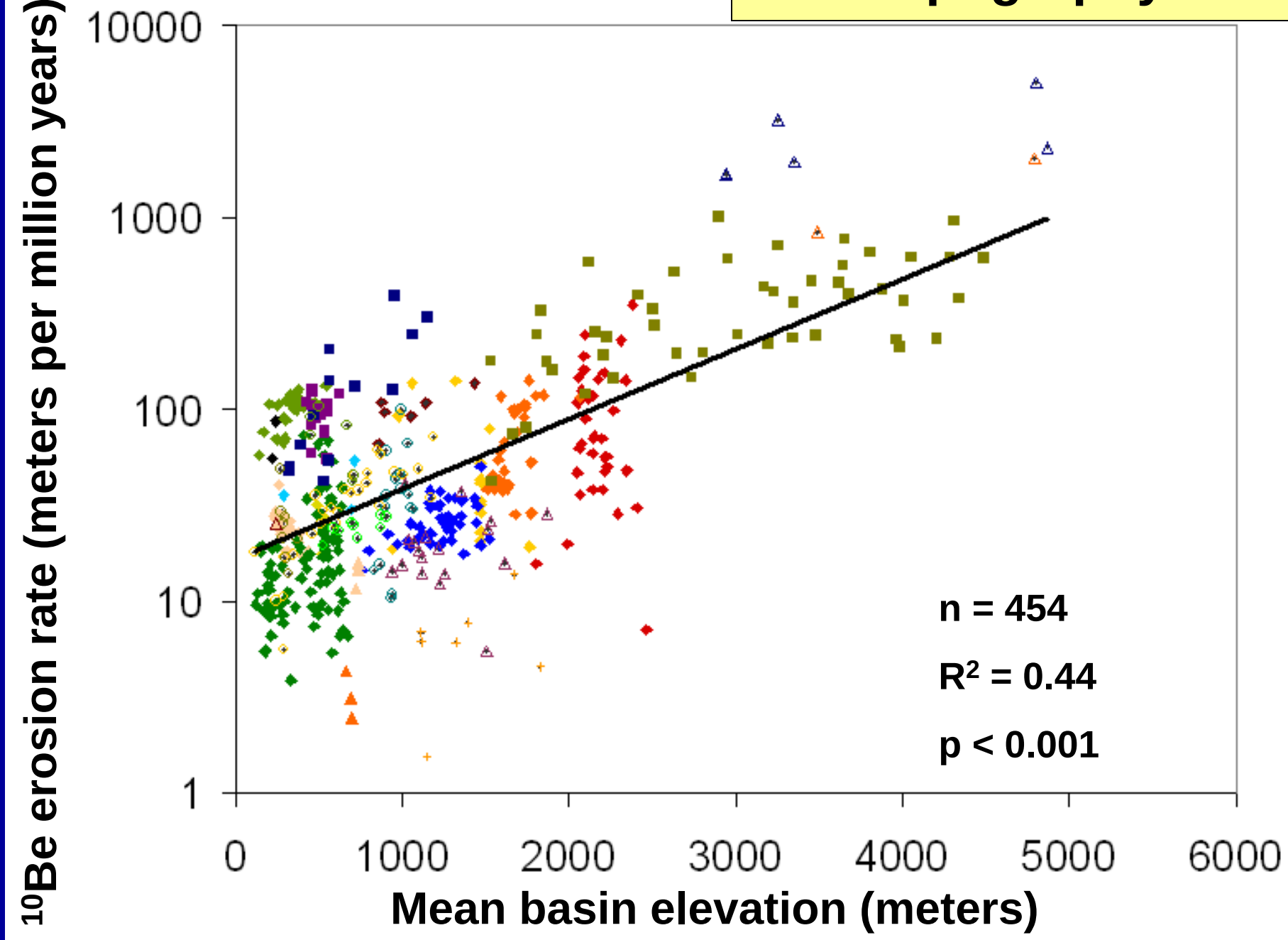
Climate


seasonal
uniform
n = 454
R² = 0.37
p < 0.001
10000
1000
100
10
1
0
0.05
0.1
0.15
0.2
0.25
¹⁰Be erosion rate (meters per million years)
Precipitation of 3 driest months/total precipitation

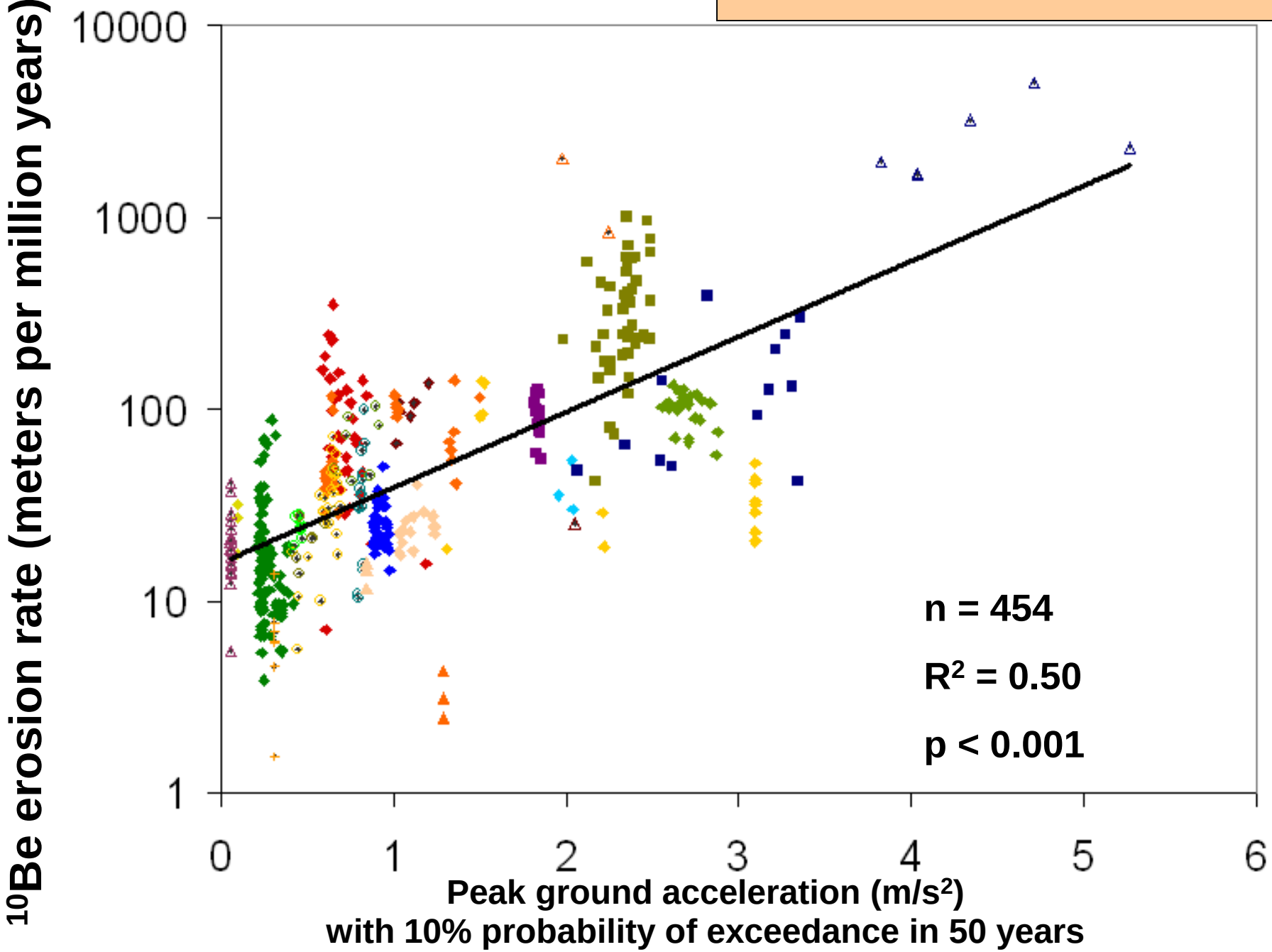
Topography


10000
1000
100
10
1
0
10
20
30
40
^{10}Be erosion rate (meters per million years)
Mean slope of basin (degrees)
n = 454
R^2 = 0.39
p < 0.001

Topography


10000
1000
100
10
1
0
1000
2000
3000
4000
5000
6000
^{10}Be erosion rate (meters per million years)
Mean basin elevation (meters)
n = 454
R^2 = 0.44
p < 0.001

Tectonics


10000
1000
100
10
1
0
1
2
3
4
5
6
^{10}Be erosion rate (meters per million years)
Peak ground acceleration (m/s^2)
with 10% probability of exceedance in 50 years
n = 454
R^2 = 0.50
p < 0.001

Conclusions

- **Tectonics**
  - **Susquehanna River Basin erosion rates are relatively low and similar to other passive margin and tectonically quiescent settings**
- **Topography**
  - **Slope matters**
  - **Elevation and erosion rate are not correlated within the region**
- **Climate**
  - **Relatively uniform intra-annual distribution of precipitation, and correspondingly low erosion rates**
  - **Glaciation disrupts isotopic steady state and precludes simple interpretation of erosion rates from ^{10}Be**

Conclusions

- **Vegetation and land use**
  - **^{10}Be results are robust to land use impacts**
  - **Contemporary sediment yields for the Piedmont are high relative to background ^{10}Be sediment generation rates**
- **Lithology**
  - **No clear impact of lithology on erosion rate in the Susquehanna River Basin**
- **History**
  - **Rates and patterns of erosion may reflect ongoing adjustment to Miocene stream capture and base-level fall**

Acknowledgments

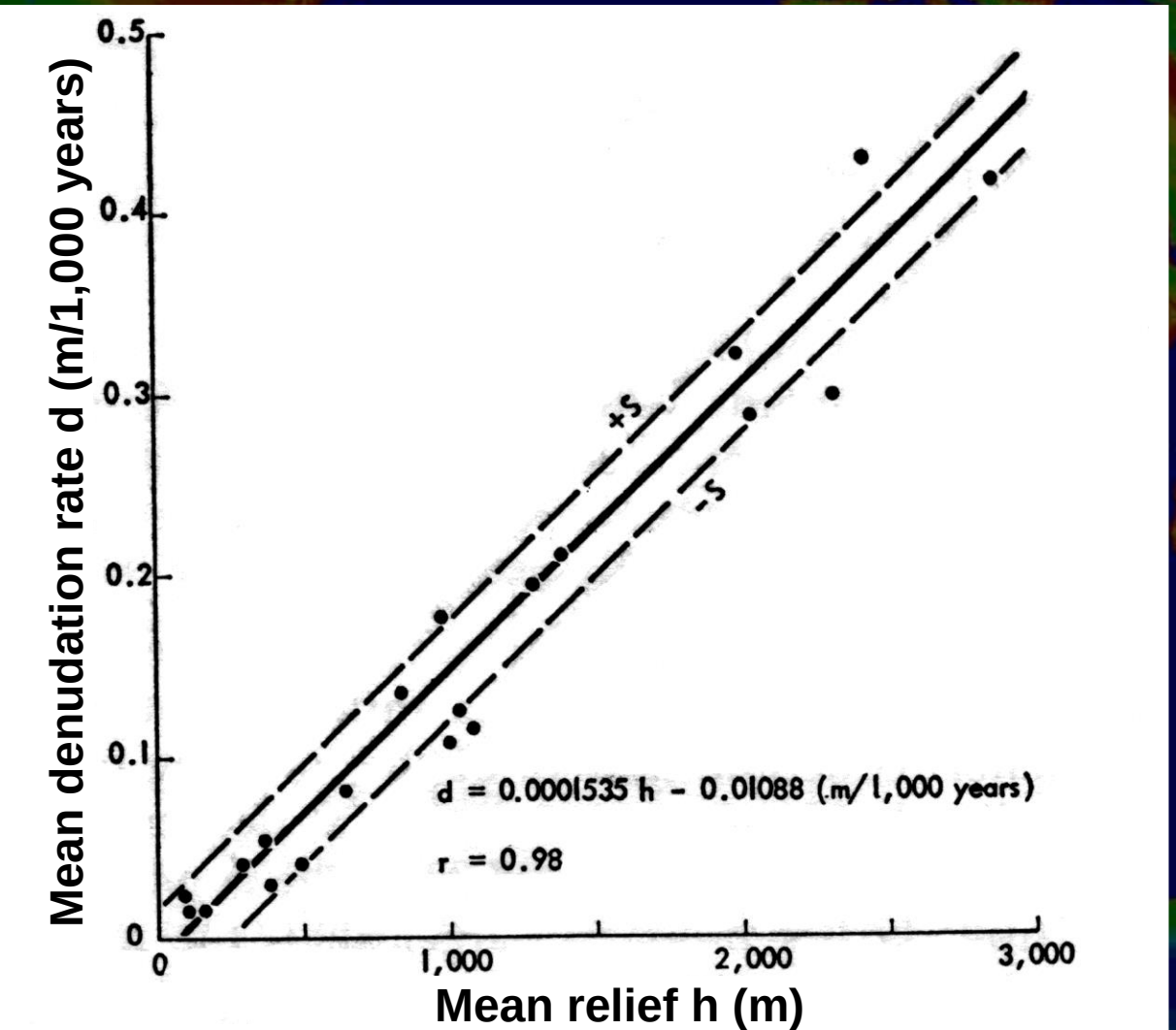
- Funding: NSF, USGS, UVM
- Paul Bierman
- Jen Larsen, Megan McGee, Bob Finkel
- Milan Pavich, Allen Gellis
- Donna Rizzo, Beverley Wemple, Cully Hession
- Luke Reusser, Matt Jungers, and all the other Geo grads, faculty, & staff
- Eric Butler


JSQ 117
JSQ 120

For example:

Erosion rates ⟷ **Landscape characteristics**

– **Sediment yield**



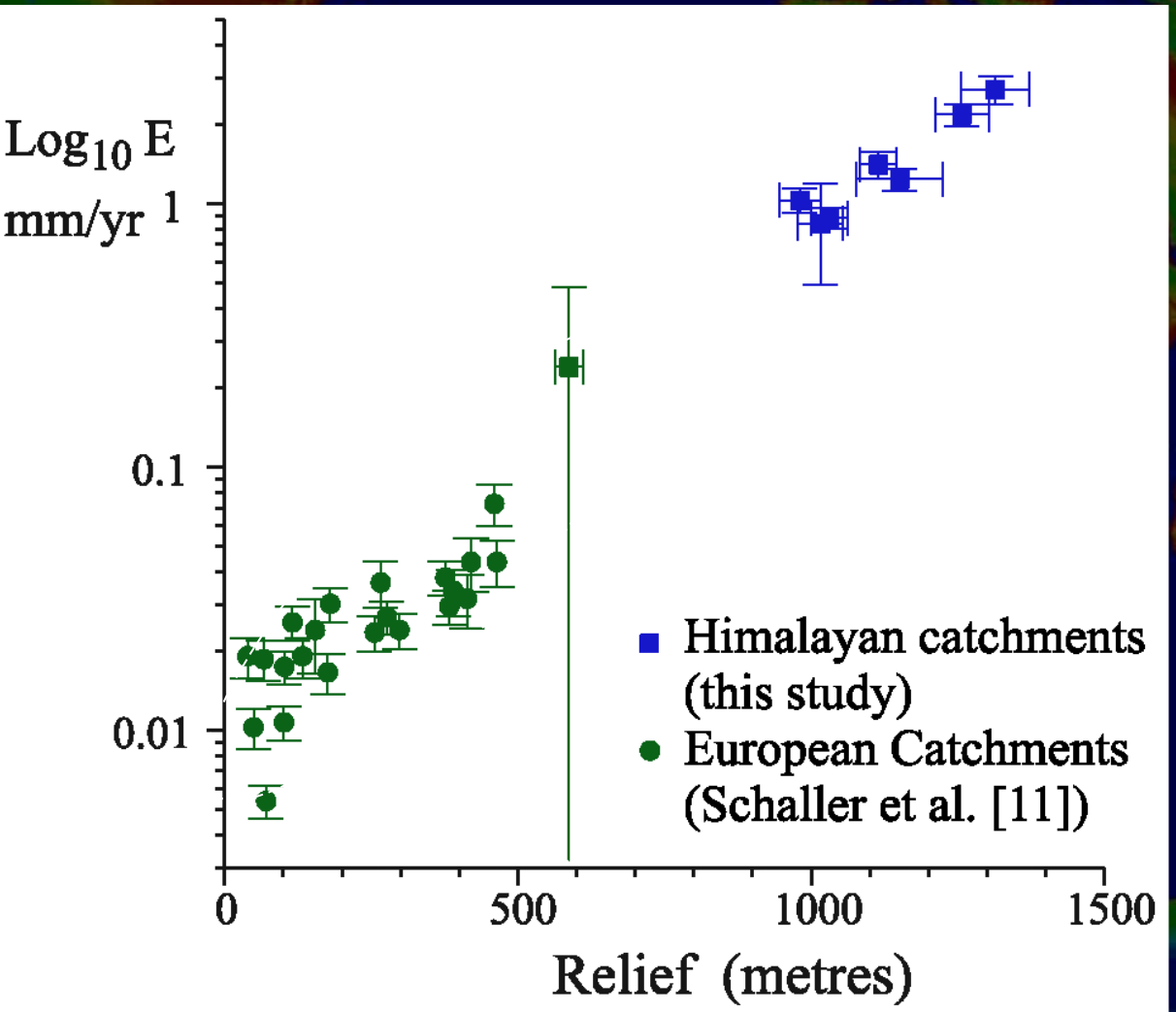
- **Topography**
  - **Relief**

from Ahnert, 1970

For example:

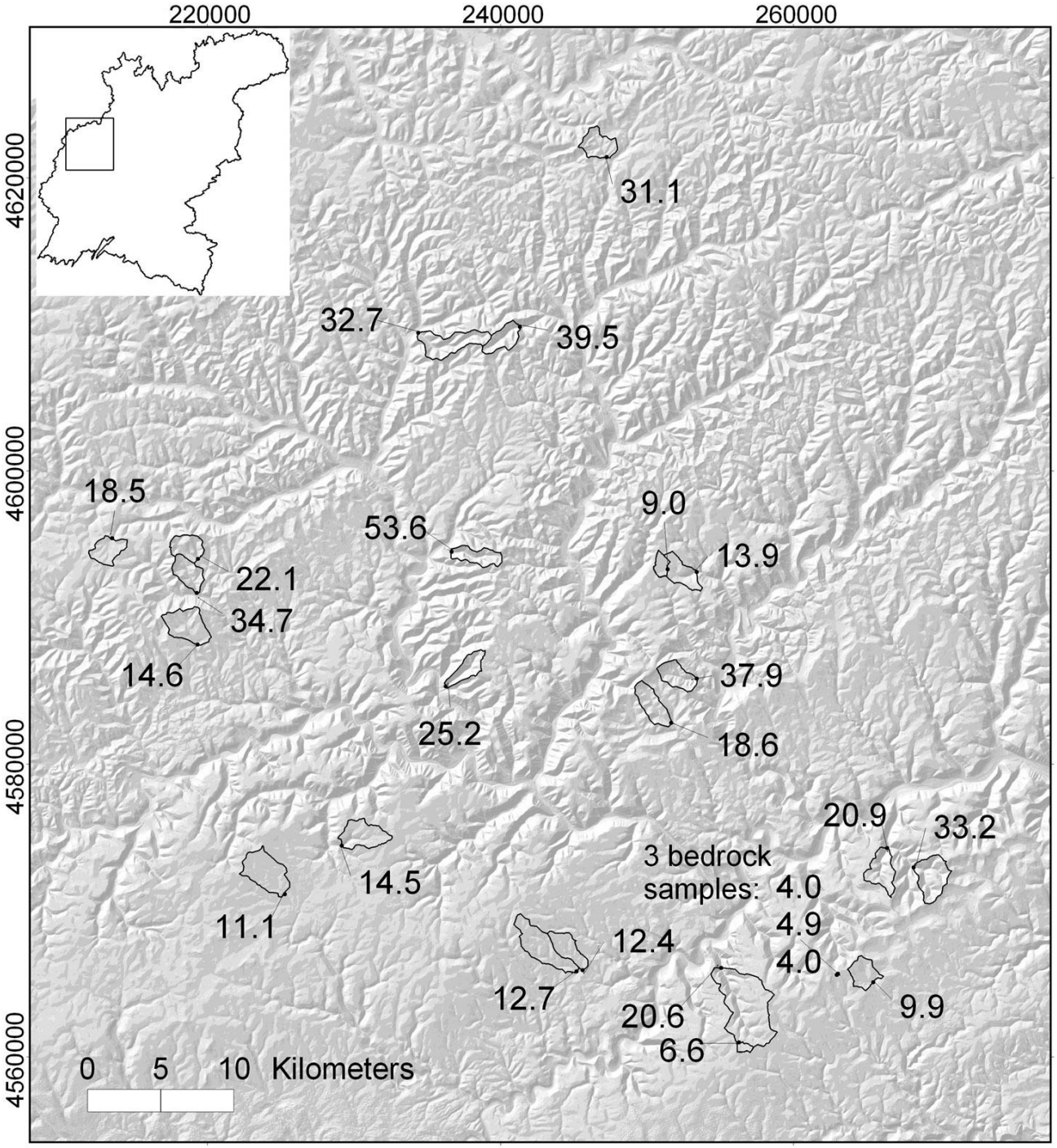
Erosion rates ⟷ Landscape characteristics

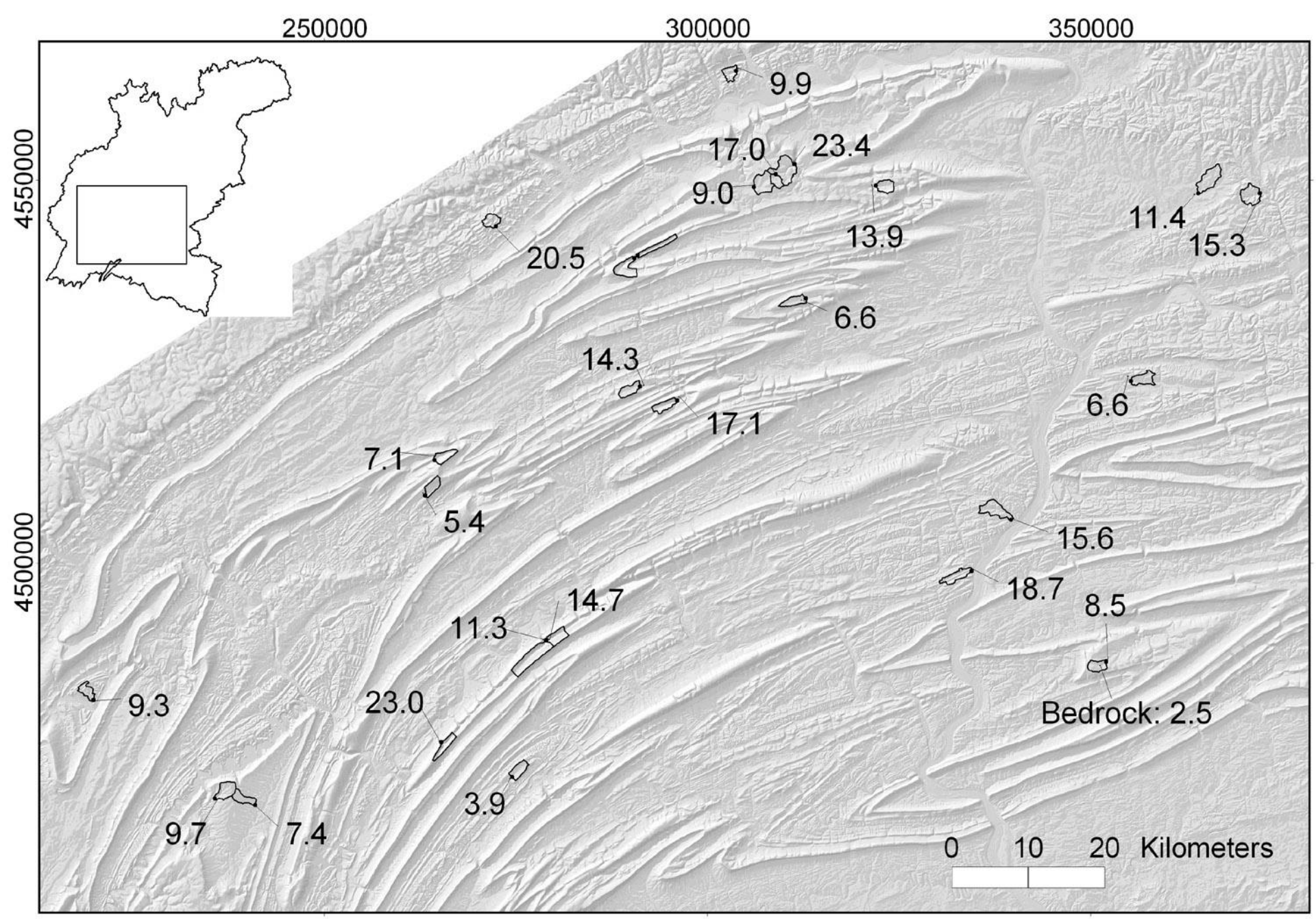
– ^{10}Be in fluvial sediment

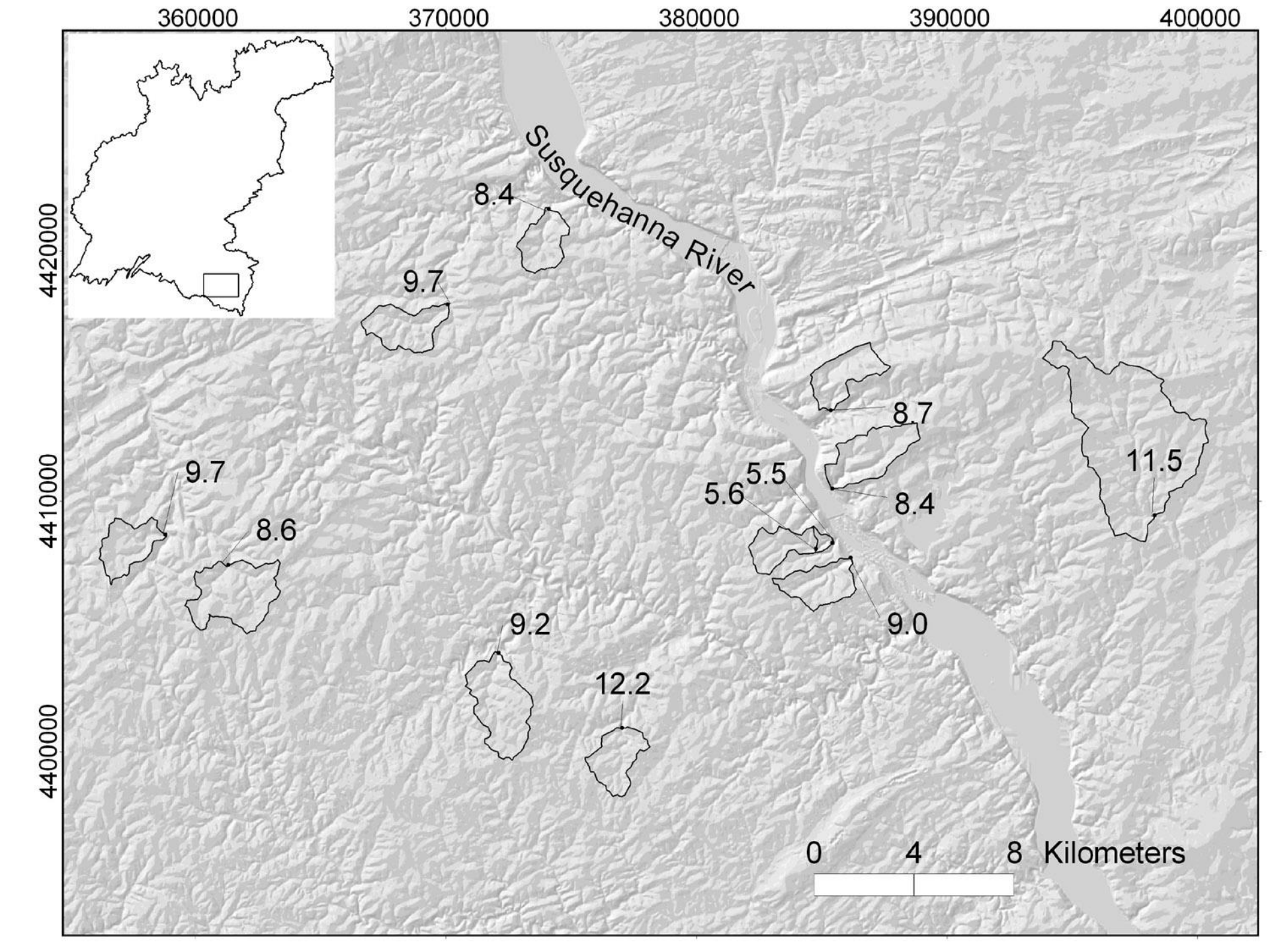


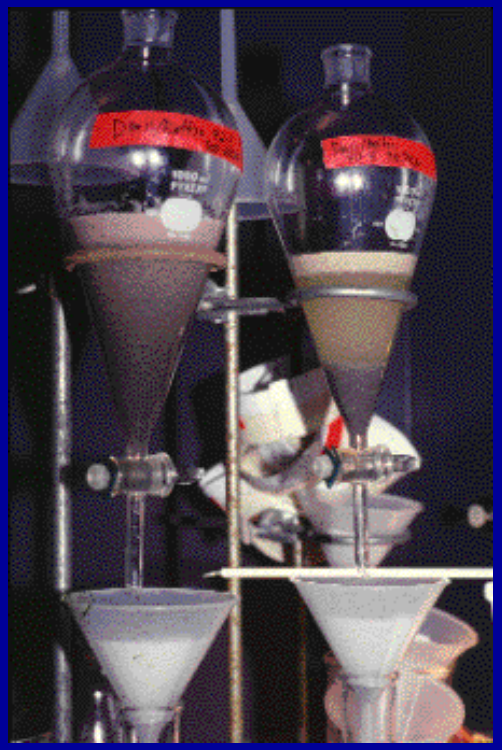
- Topography
  - Relief

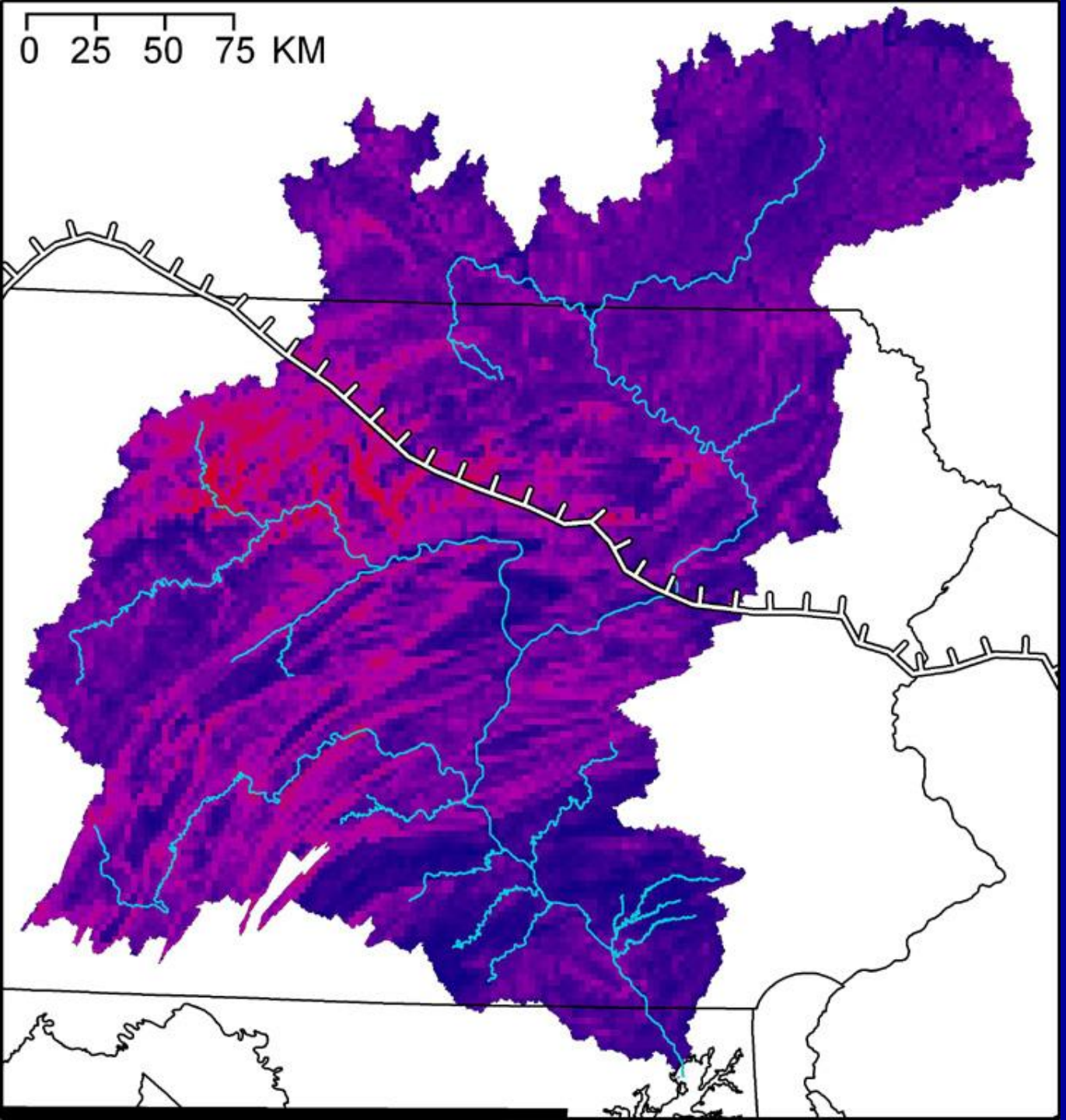
from Vance et al., 2003

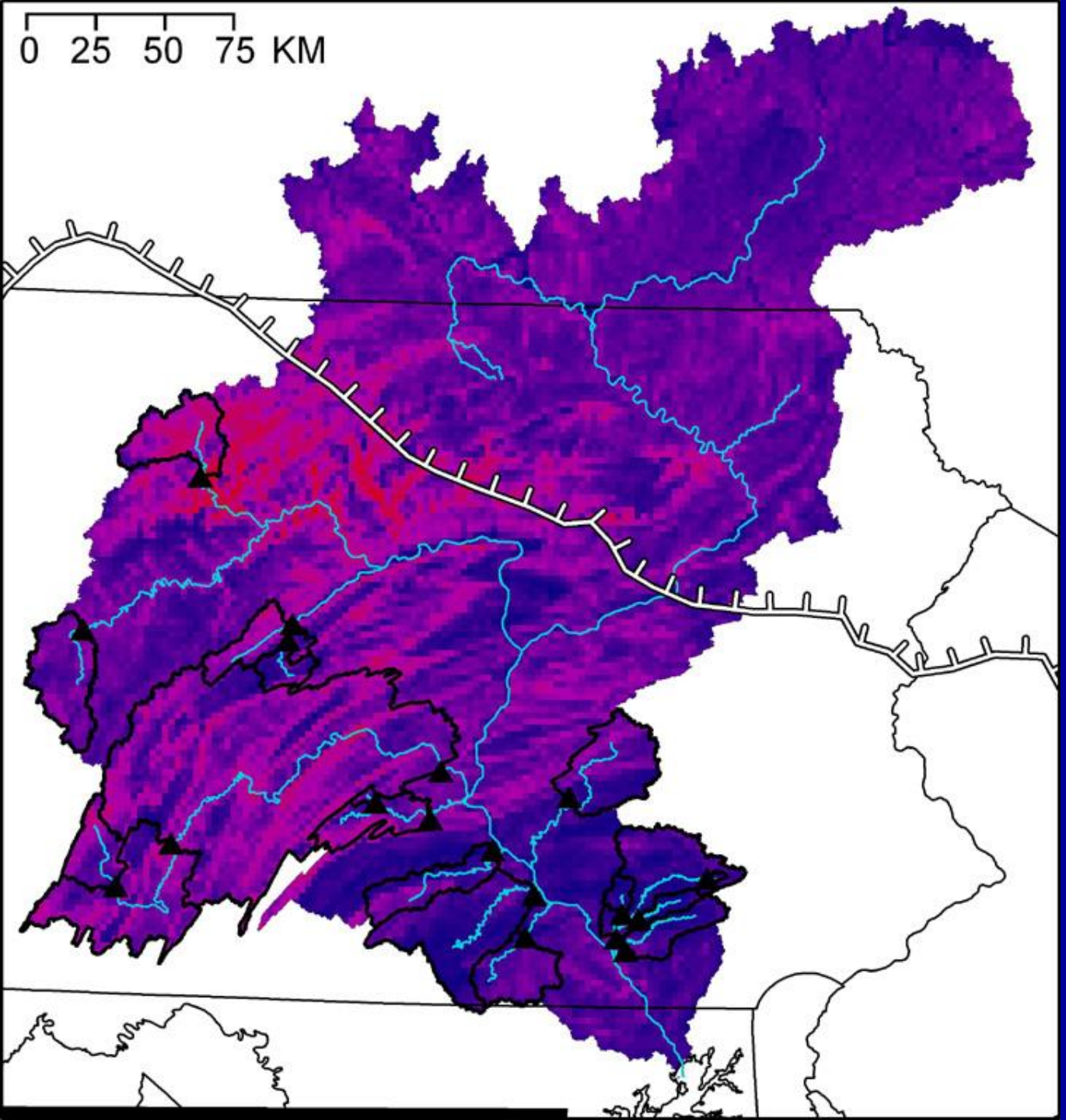

220000
240000
260000
4620000
4600000
4580000
4560000
31.1
32.7
39.5
18.5
53.6
9.0
13.9
22.1
34.7
14.6
25.2
37.9
18.6
20.9
33.2
3 bedrock
samples: 4.0
4.9
4.0
14.5
11.1
12.4
12.7
20.6
6.6
9.9
0 5 10 Kilometers


250000
300000
350000
4550000
4500000
9.9
17.0
23.4
9.0
13.9
20.5
11.4
15.3
6.6
14.3
17.1
6.6
7.1
5.4
15.6
18.7
14.7
11.3
8.5
9.3
23.0
Bedrock: 2.5
3.9
9.7
7.4
0
10
20
Kilometers


360000
370000
380000
390000
400000
4420000
4410000
4400000
Susquehanna River
8.4
9.7
9.7
8.6
8.7
8.4
5.6
5.5
9.0
11.5
9.2
12.2
0
4
8 Kilometers

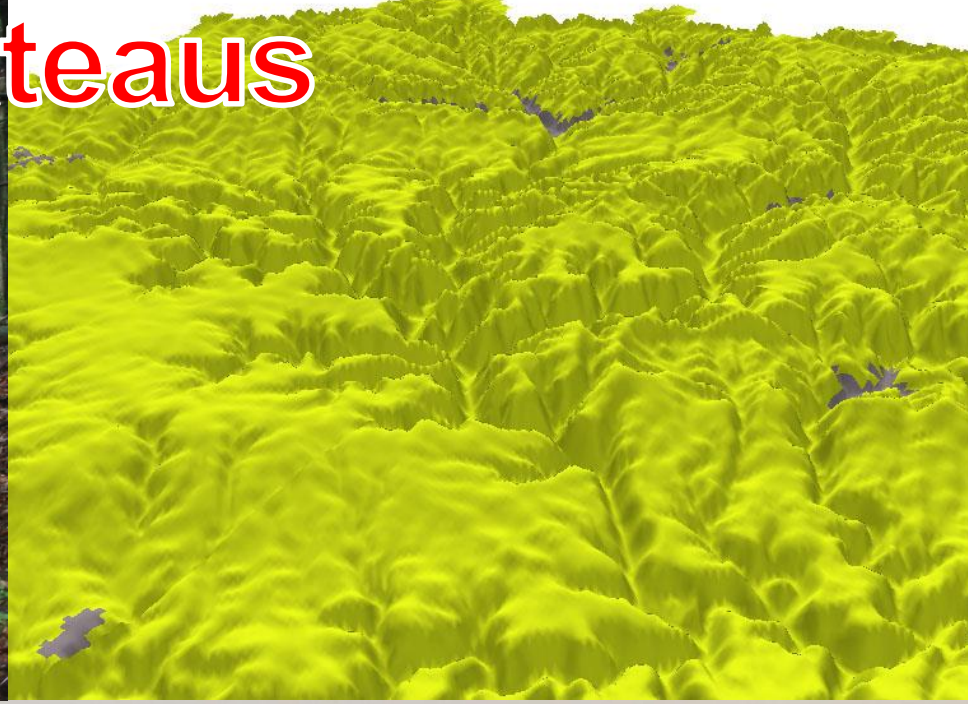


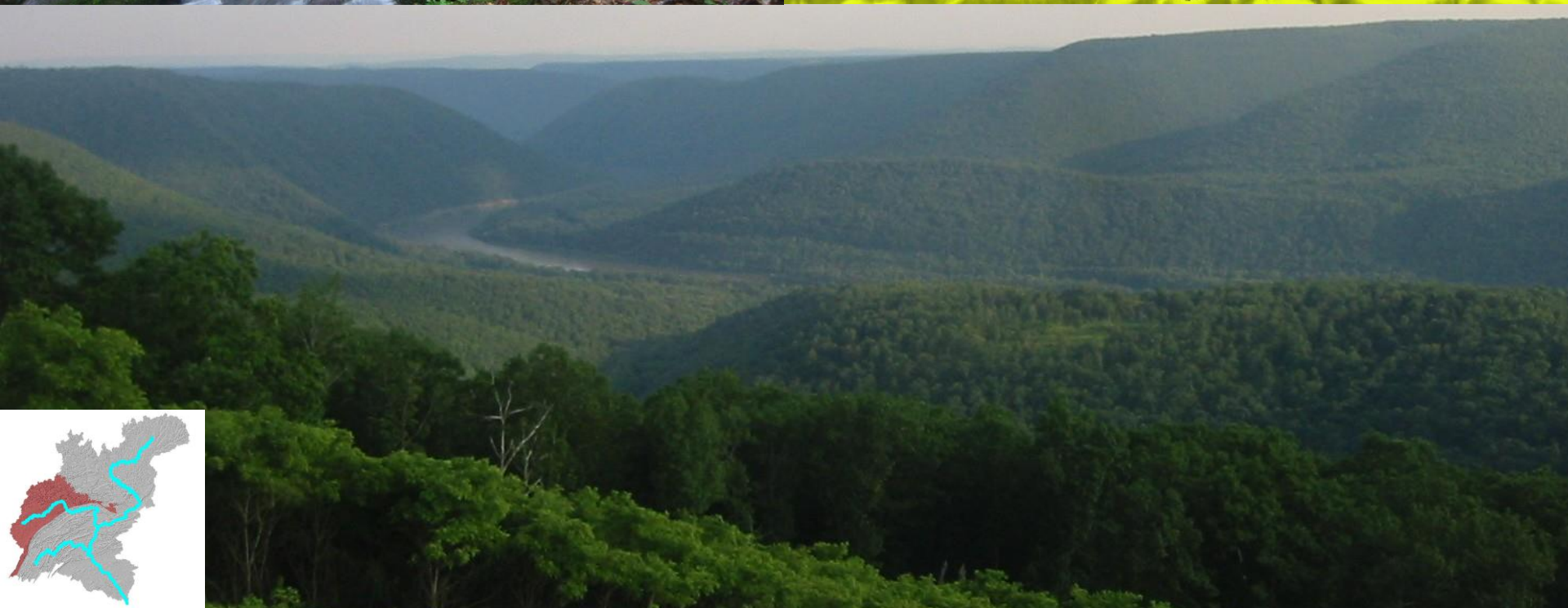

0 25 50 75 KM



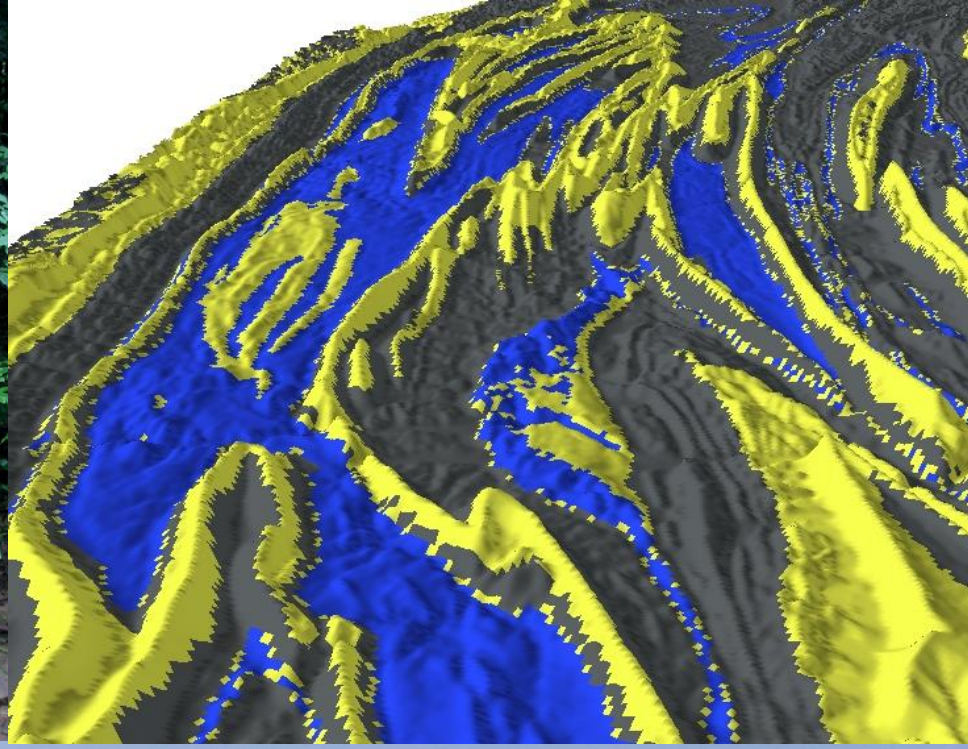
Results for non-glaciated USGS basins are robust within a factor of 2

Appalachian Plateaus

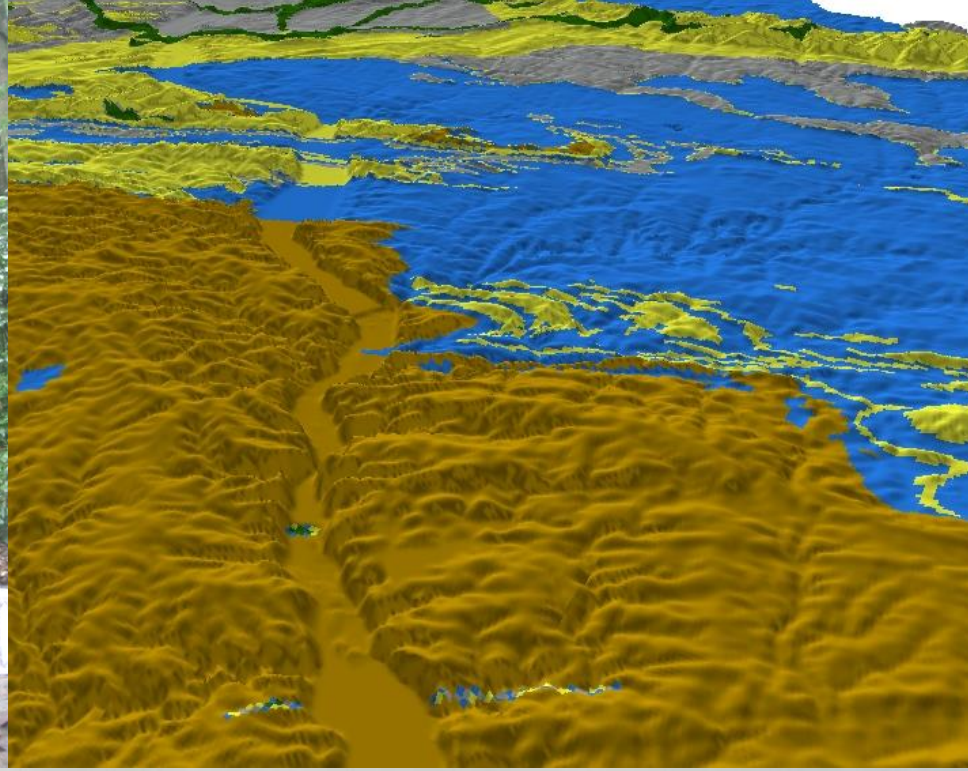


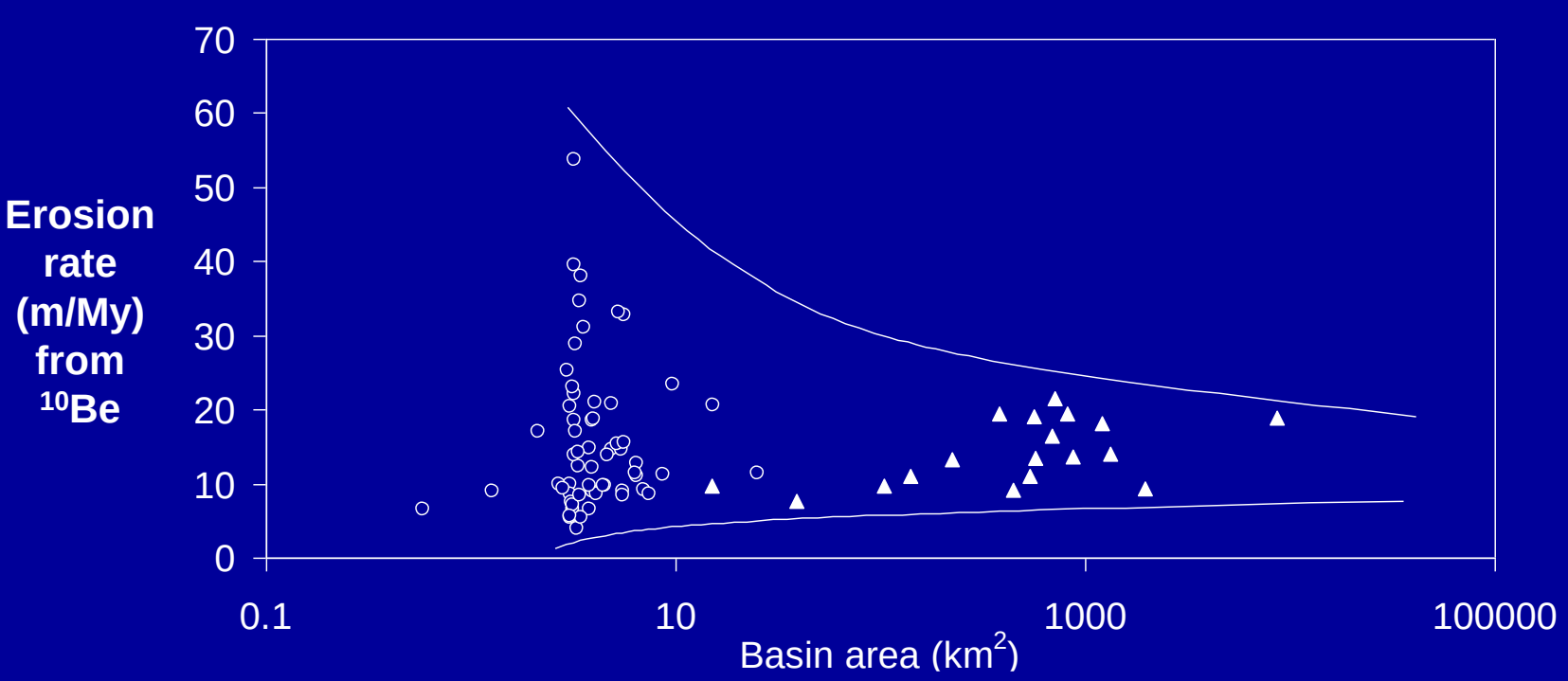


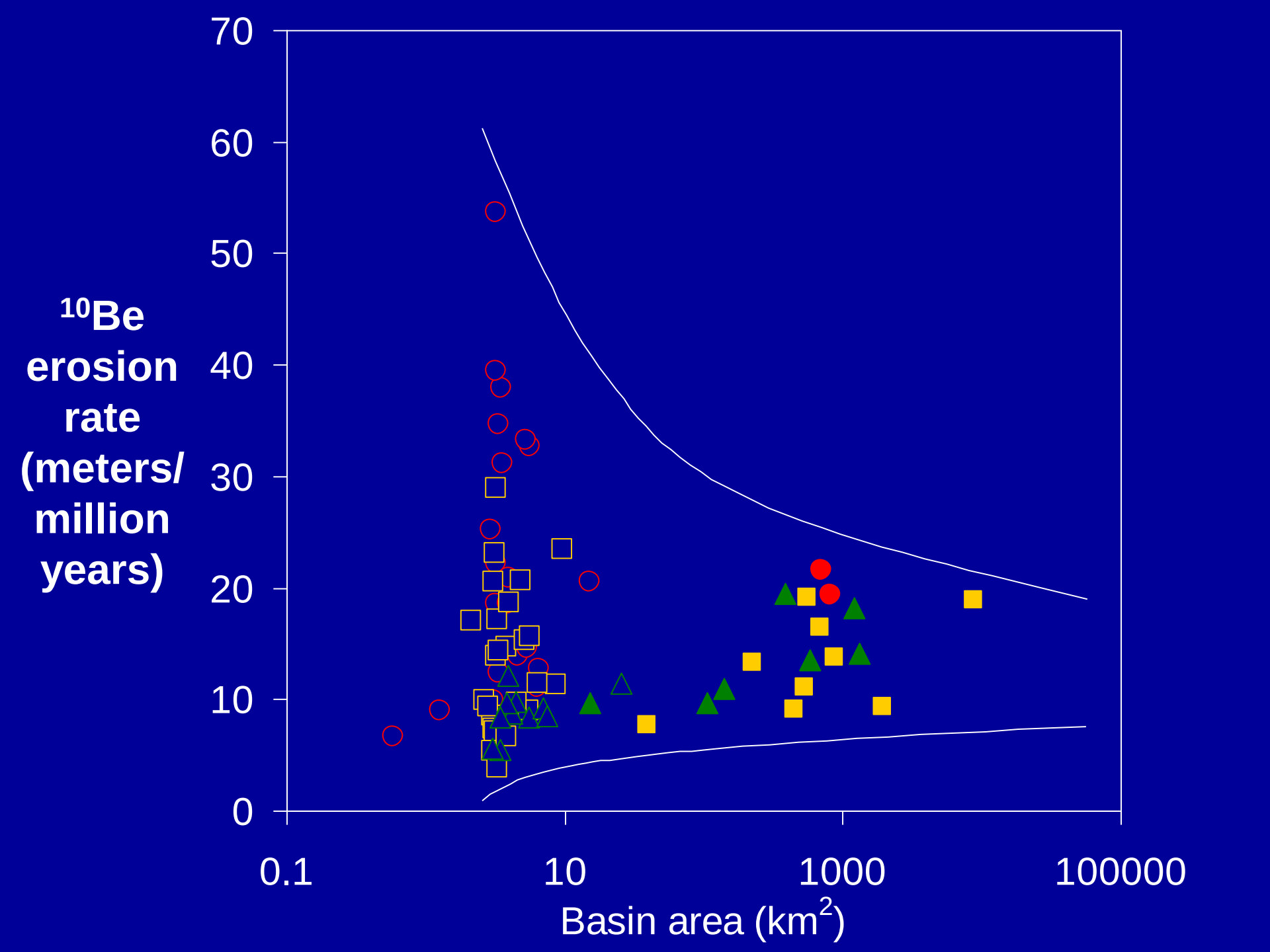
Valley & Ridge



Piedmont



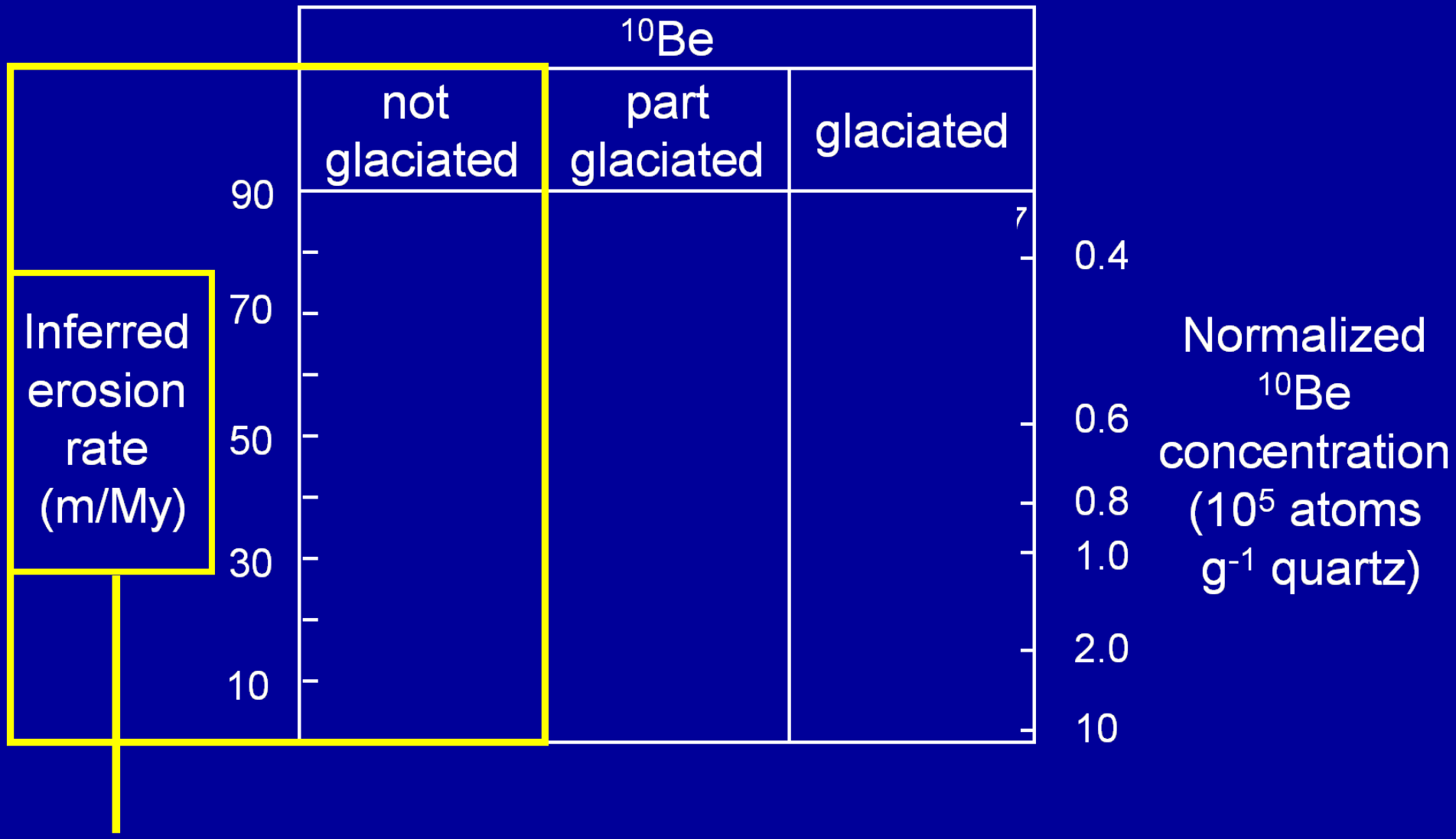

Erosion rate (m/My) from ^{10}Be
70
60
50
40
30
20
10
0
0.1
10
1000
100000
Basin area (km^2)


^{10}Be erosion rate (meters/ million years)
70
60
50
40
30
20
10
0
0.1
10
1000
100000
Basin area (km^2)

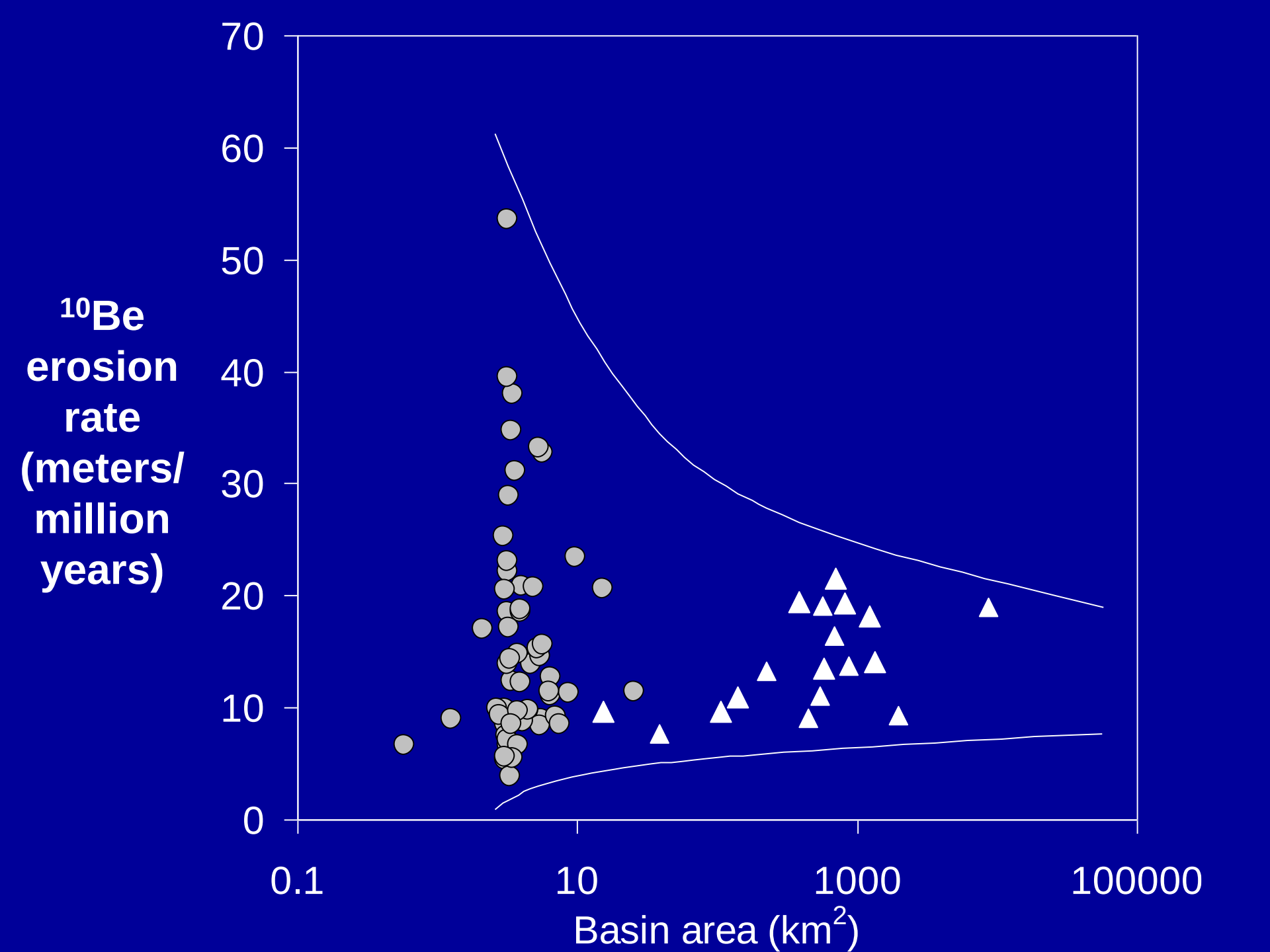
Factors of possible importance for understanding sediment dynamics and/or interpreting ^{10}Be data

- Multiple lithologies, varying quartz content
- Glaciation
- Human impact
  - Agriculture
  - Logging
  - Development
  - Coal mining
  - Dams

Results for USGS Basins

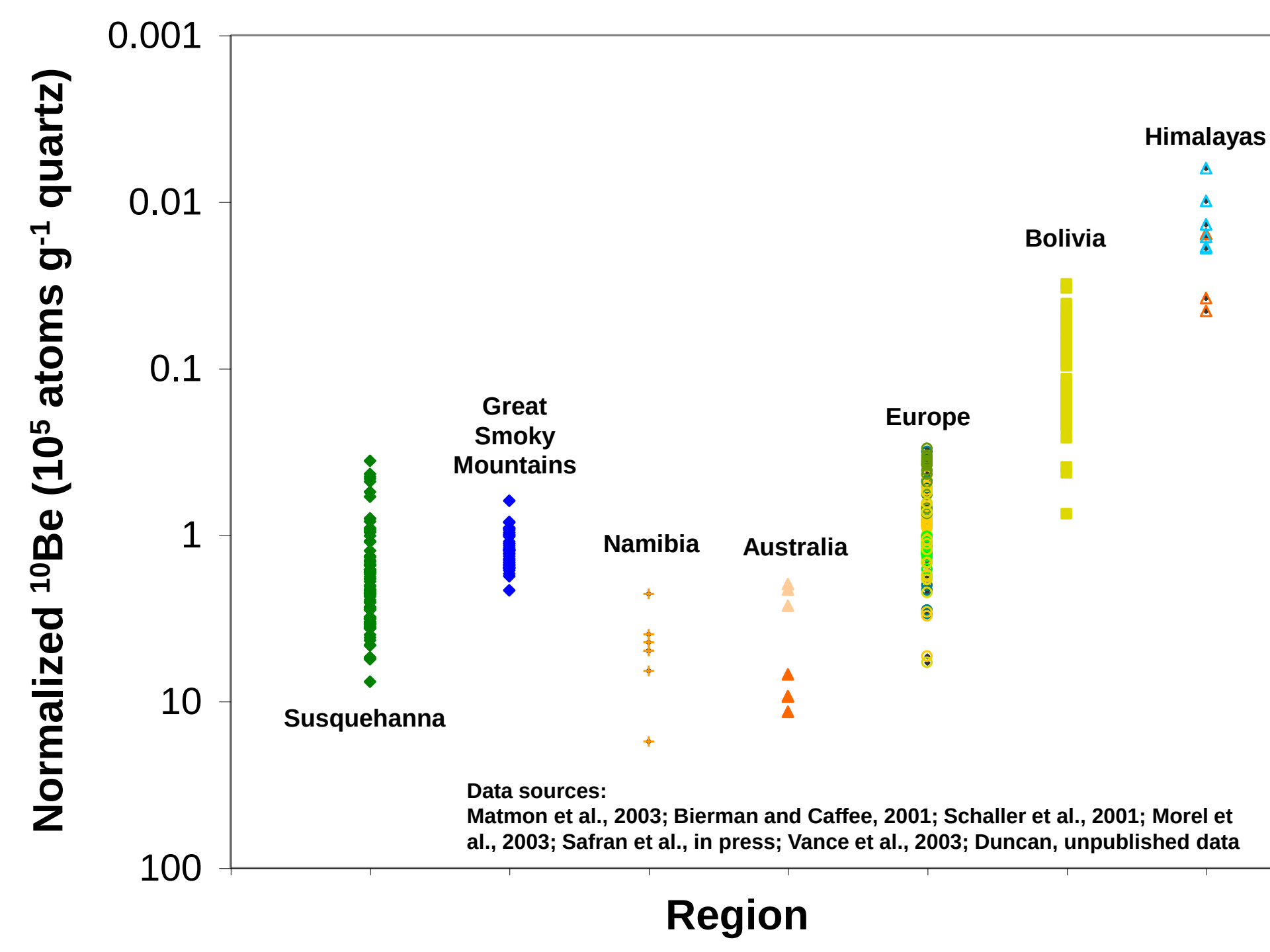


if assumptions have been met


^{10}Be erosion rate (meters/ million years)
70
60
50
40
30
20
10
0
0.1
10
1000
100000
Basin area (km^2)

Summary

Landscape characteristic	Metric	Relates to ^{10}Be erosion rate?
Lithology	Rock Type (Susquehanna)	No
	Erodibility metric (Rio Puerco)	Yes


0.001
0.01
0.1
1
10
100
Normalized ^{10}Be (10^5 atoms g^{-1} quartz)
Region
Susquehanna
Great Smoky Mountains
Namibia
Australia
Europe
Bolivia
Himalayas
Data sources:
Matmon et al., 2003; Bierman and Caffee, 2001; Schaller et al., 2001; Morel et al., 2003; Safran et al., in press; Vance et al., 2003; Duncan, unpublished data

Summary: ^{10}Be and Sediment Yield

- Sediment yield is out of equilibrium with ^{10}Be in the Piedmont