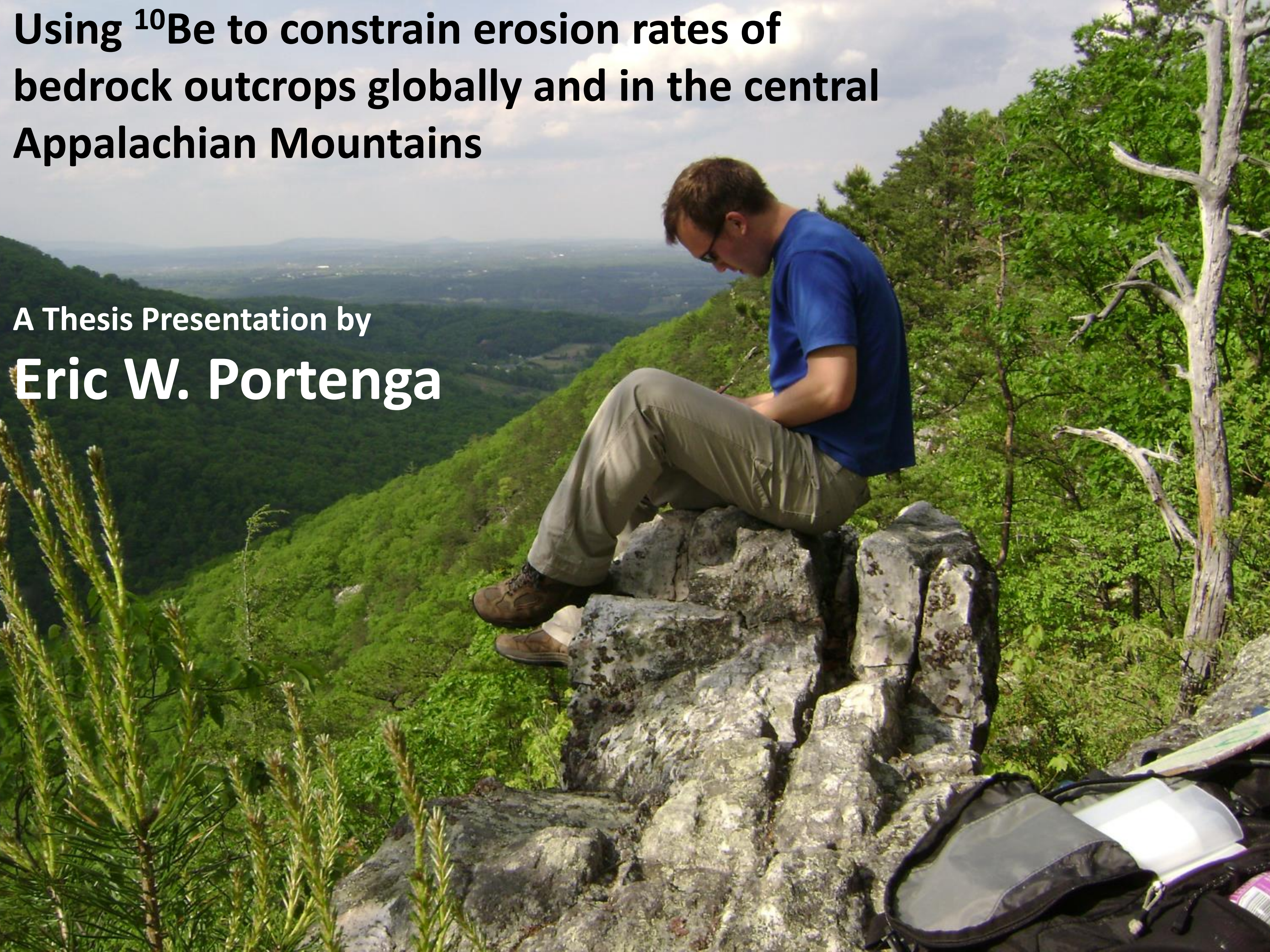
# Using $^{10}Be$ to constrain erosion rates of bedrock outcrops globally and in the central Appalachian Mountains

A Thesis Presentation by


## Eric W. Portenga

# Outline of Talk

- Thesis Objectives
- $^{10}Be$ Background
- Appalachian Outcrop Study
- Global Erosion Rate Compilations
- Appalachians and Global Comparison
- Conclusions

# Thesis Objectives

- Measure erosion rates of bedrock outcrops along ridgelines in the central Appalachian Mountains
- Create global database of erosion rates to create a context to which central Appalachian rates can be compared
- Determine what factors exert control over erosion rates
- Compare outcrop erosion rates to rates determined through other methods

# The “Why?” Factor – Outcrop Erosion

Backbones of mountain ranges and dominant landscape features

Little is known about outcrop erosion rates; data is under-represented in literature

One of the many sources from which sediment is produced

Sets the pace of pre-human landscape change to evaluate our impacts on environment

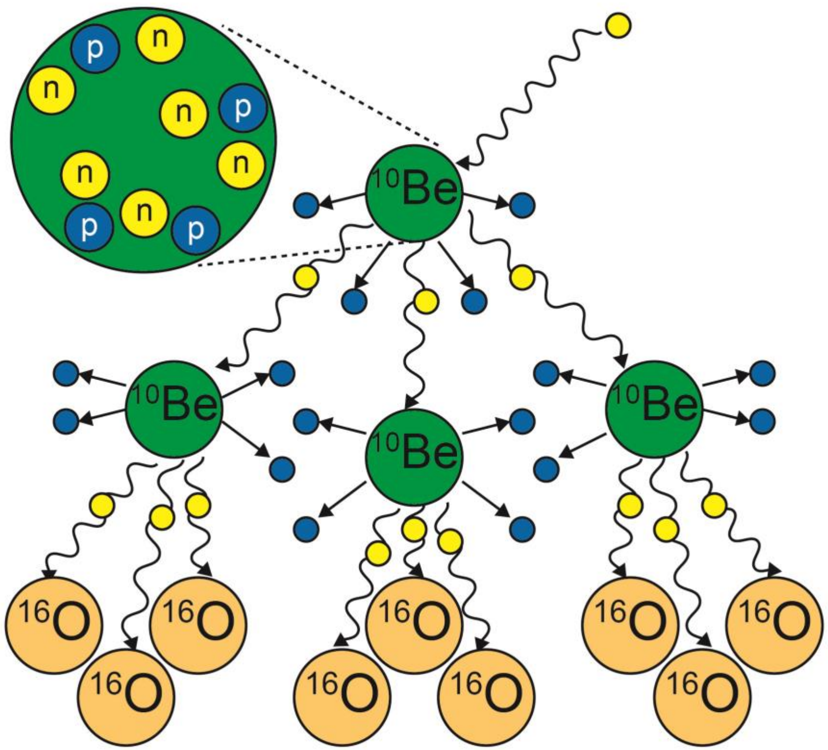
Weathering of silicates acts as a sink in the carbon cycle – climate change implications

# Why Use $^{10}$Be?

- Other methods of measuring erosion rates incorporate often-violated assumptions
  - Sediment Yield: Short-term measurements are indicative of long-term rates
    **Kirchner et al., 2001**
  - Humans have little impact on the modern sedimentation rate
    **Trimble, 1977**
- Long-term denudation methods are not appropriate for more recent timescales
  - Fission-track thermochronology
  - (U-Th)/He methods

# $^{10}Be$ Production

- Cosmic ray bombardment by fast neutrons
- Nuclear spallation reactions
- Occurs naturally
  - Atmosphere (meteoric)
  - Minerals (*in situ*)
- Quartz
  - Ubiquitous
  - Simple chemical formula ($SiO_2$)
  - Meteoric $^{10}Be$ is easily removed
  - Resistant to acid etching

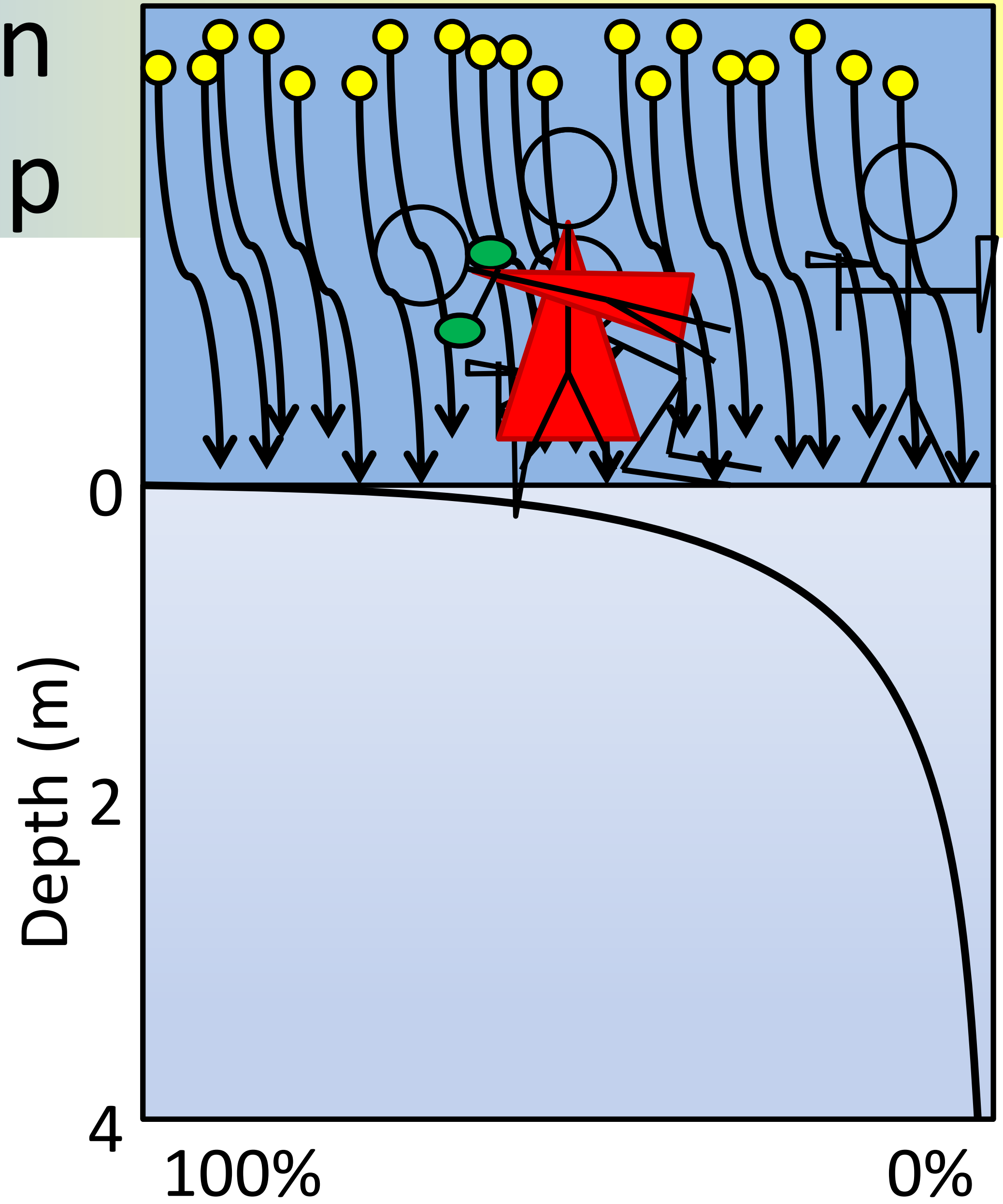


# $^{10}$Be Production in a Bedrock Outcrop

- Assumptions
  - Constant Bombardment
  - Continuous exposure
  - No Erosion

$$P_x = P_0 e^{(-\frac{x\rho}{\Lambda})}$$

$P$ = Production Rate
$x$ = Depth
$\rho$ = Density
$\Lambda$ = Attenuation Depth




(Adapted from Bierman and Nichols, 2004)

# Erosion Rates from $^{10}$Be Concentrations

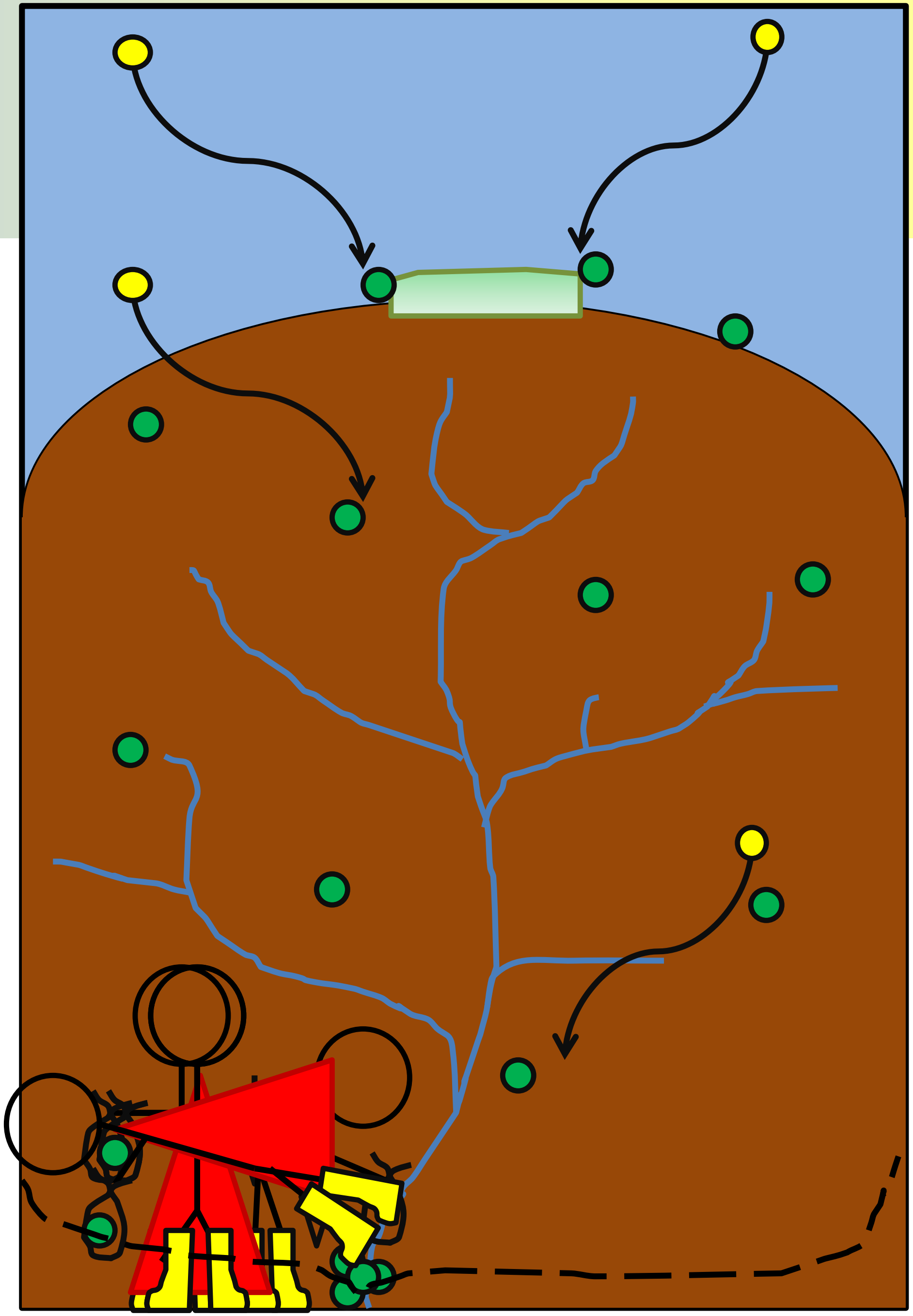
- $^{10}$Be concentration integrates production as its depth from the surface decreases
  - Constant Erosion Rate
  - Simple Exposure History
  - Granular disintegration

$$N = \frac{P}{(\frac{\rho\varepsilon}{\Lambda} + \lambda)} e^{(\frac{x\rho}{\Lambda})}$$

$N$ = Nuclide Concentration
$P$ = Production Rate
$\varepsilon$ = Erosion Rate
$\lambda$ = Half-life
$x$ = Depth
$\rho$ = Density
$\Lambda$ = Attenuation Depth

# $^{10}$Be in River Sediment

- Constant erosion of bedrock produces sediment
- Quartz grains in sediment come from all points within a basin
- River systems naturally mix sediment so it is representative of entire basin



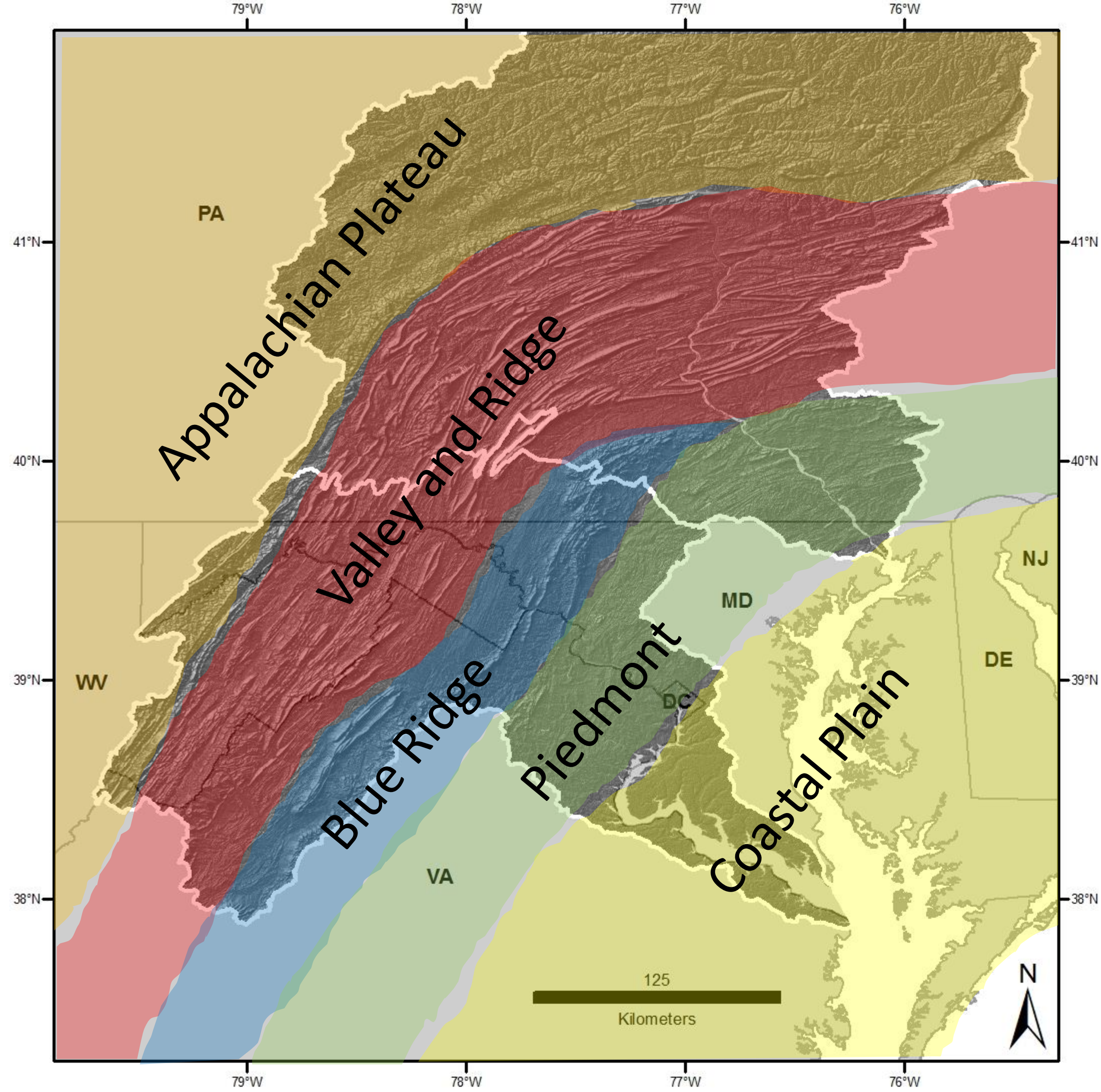
# Erosion Rates in the Central Appalachian Mountains using $^{10}Be$

- Measure erosion rates from bedrock outcrops
- Determine factors controlling erosion rates
- Numerous basin-averaged erosion rates come from this region

# History of Central Appalachian Mountains

- Devonian sediments
  - Sandstones, arenites, limestones, shales
- Permian mountain building – Alleghenian Orogeny
  - Deforms sedimentary units into plunging anticlines and synclines
  - Metamorphoses siliclastic rocks into hard quartzites
- Triassic rifting
  - Regional uplift

# Physiographic Provinces



# Methods Used to Measure Landscape Change in the Central Appalachians

**Fission-track Thermochron.**

**16 – 33 m $My^{-1}$**

(Naeser et al., 2001, 2004, 2005; Blackmer et al., 1994; Roden, 1991)

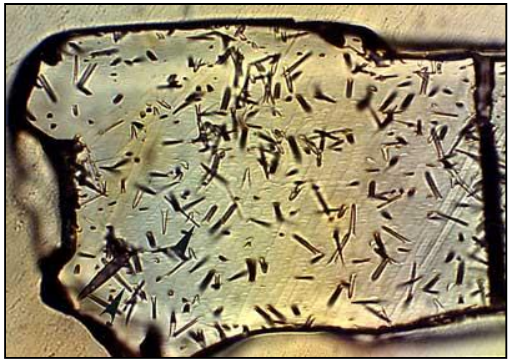


Photo: pangea.stanford.edu

**(U – Th)/He Thermochron.**

**7 – 25 m $My^{-1}$**

(Reed et al., 2005; Spotila et al., 2003)

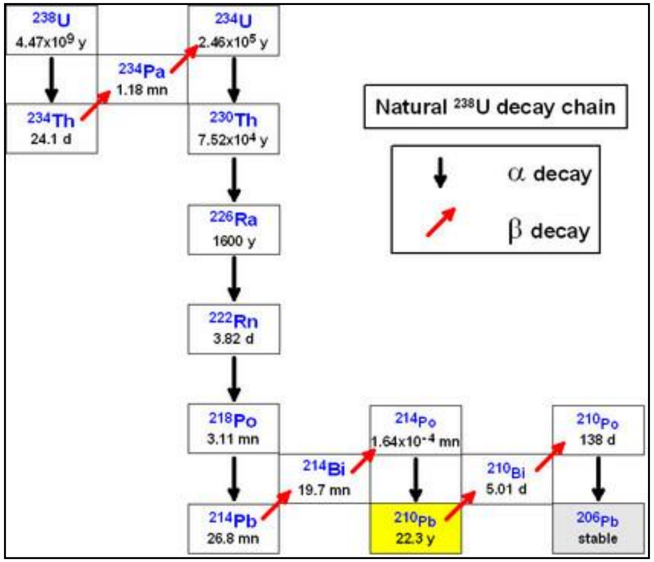



Photo: oliviermegand.com

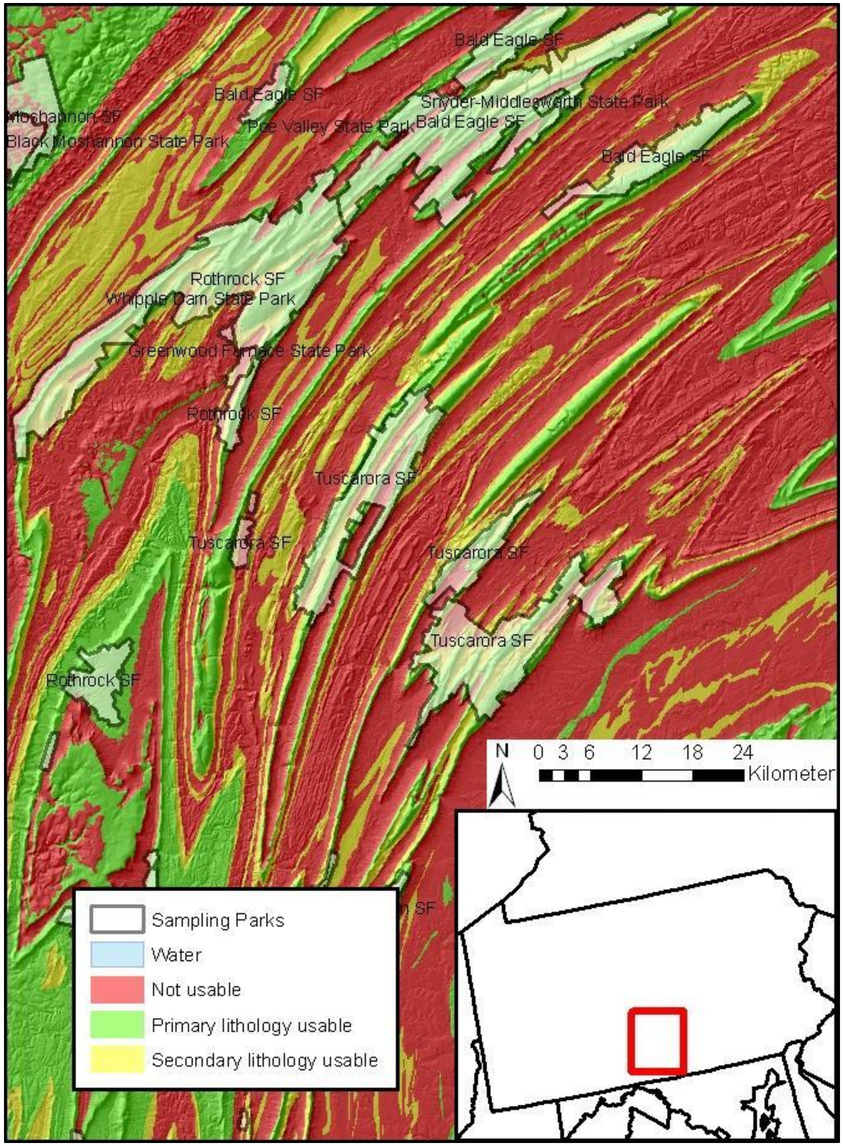
**$^{10}Be$ Basin and Cave Methods**

**10 – 27 m $My^{-1}$**

(Granger et al., 1997; Reuter, 2005; Duxbury, 2009; Trodick et al., 2010)

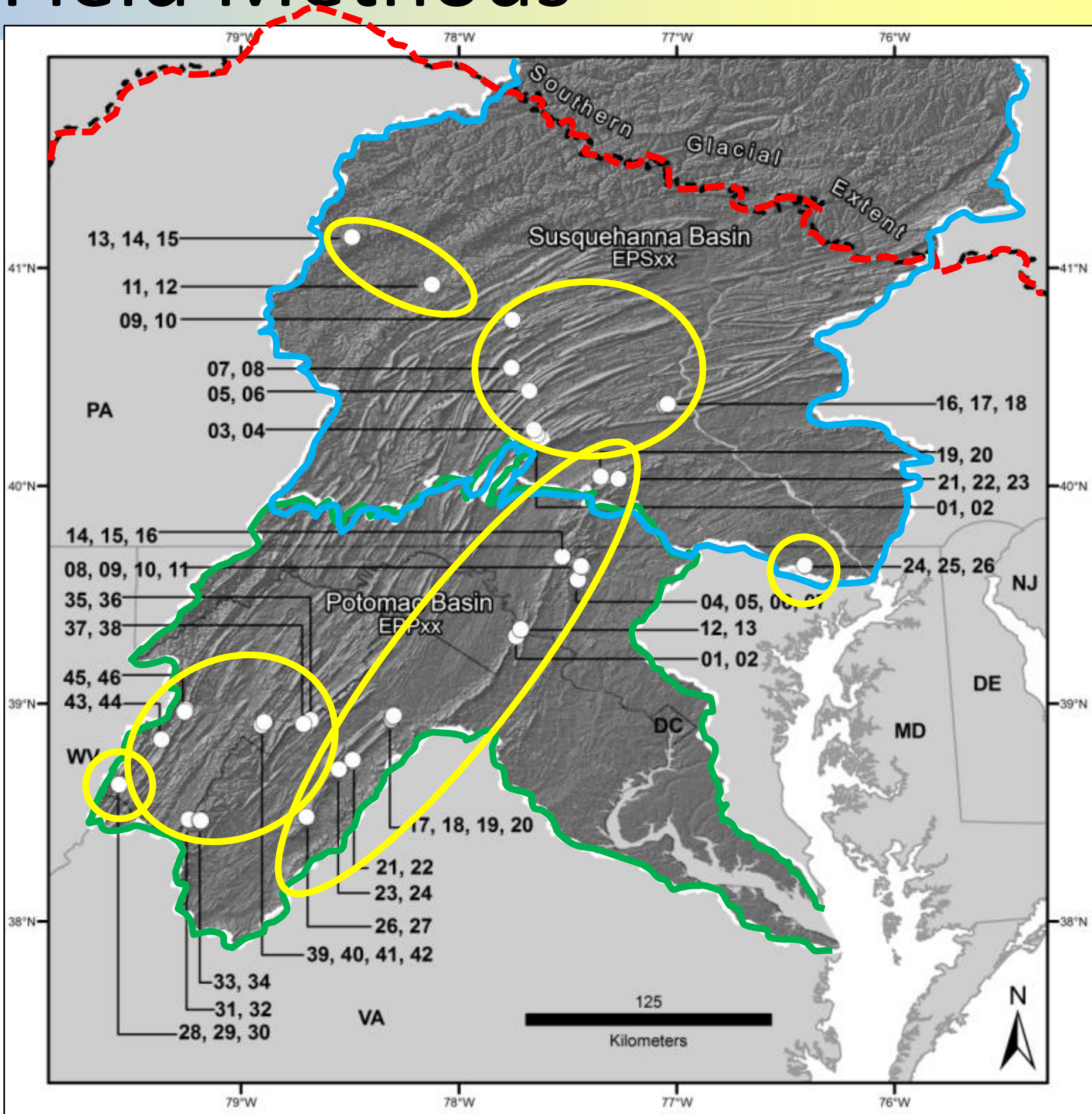
# Sampling Strategy

- Optimization of time in field requires knowledge of sampling sites beforehand
- ArcGIS
  - Topography
  - Lithology
  - Ease of Access
- Google Earth and internet image search verification



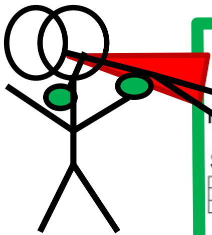
# Field Methods

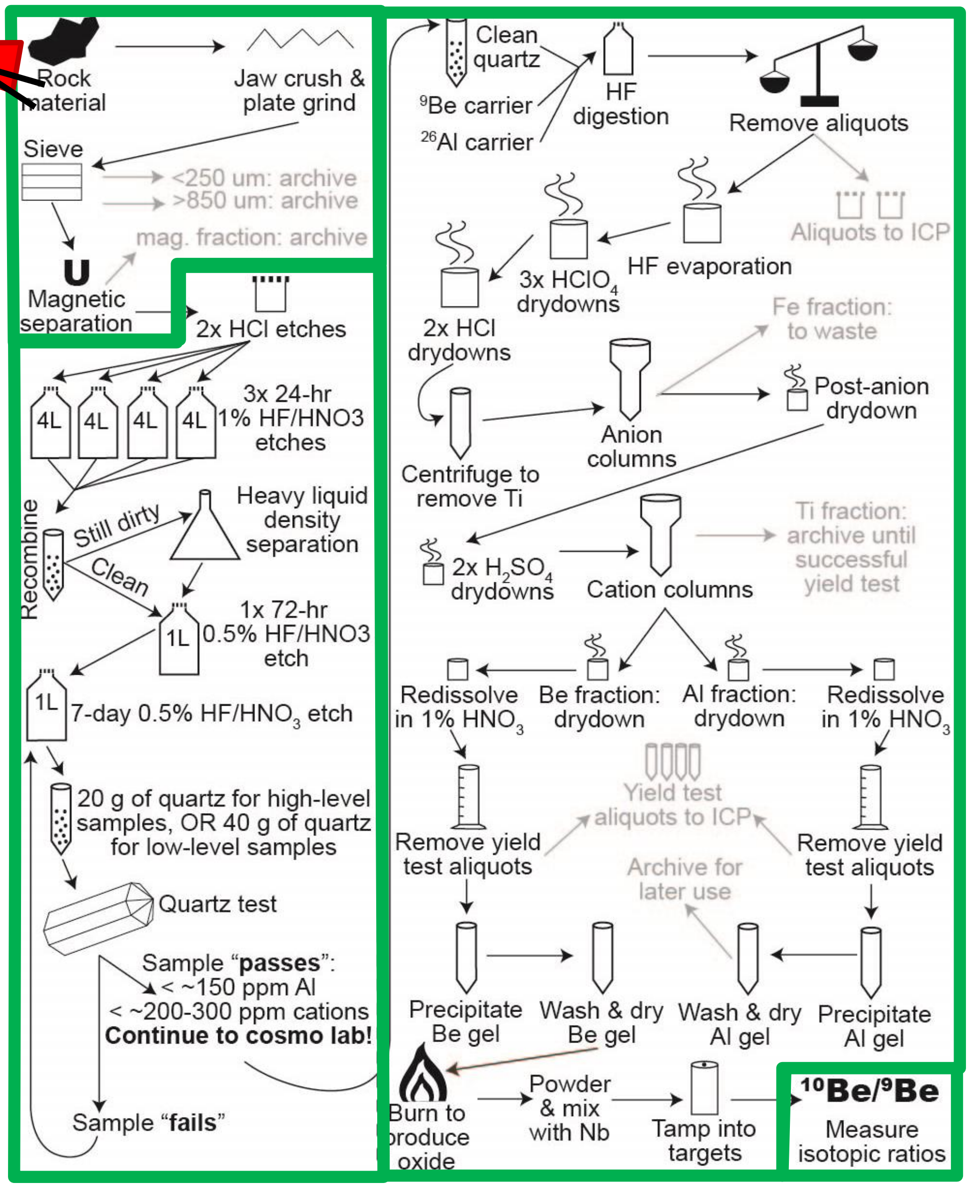
- South of Glacial Extent
- $n_{total} = 72$
  - $n_{Pot} = 46$
  - $n_{Sus} = 26$
- Sample Types
  - Main Ridge
  - Spur Ridge
  - Near Cliff
- 4 Regions
  - App. Plateau
  - Valley & Ridge
  - Blue Ridge
  - Piedmont



# Field Methods

# Laboratory Methods

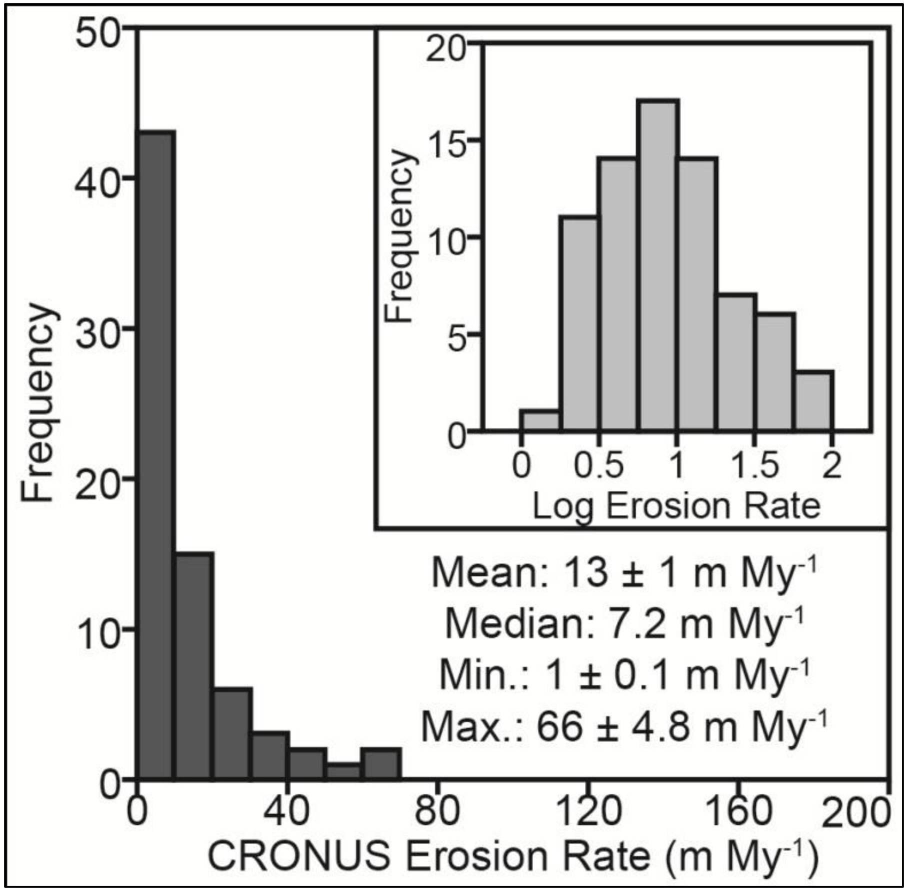





Source: Lee Corbett

- 4 Processes
  - Rock Room
  - MinSep Lab
  - Cosmo Lab
  - AMS (LLNL)

# New Appalachian Erosion Data




- Skewed distribution requires log-transform

# Outcrop Erosion Rates from Each Basin

**Potomac River**

- Mean

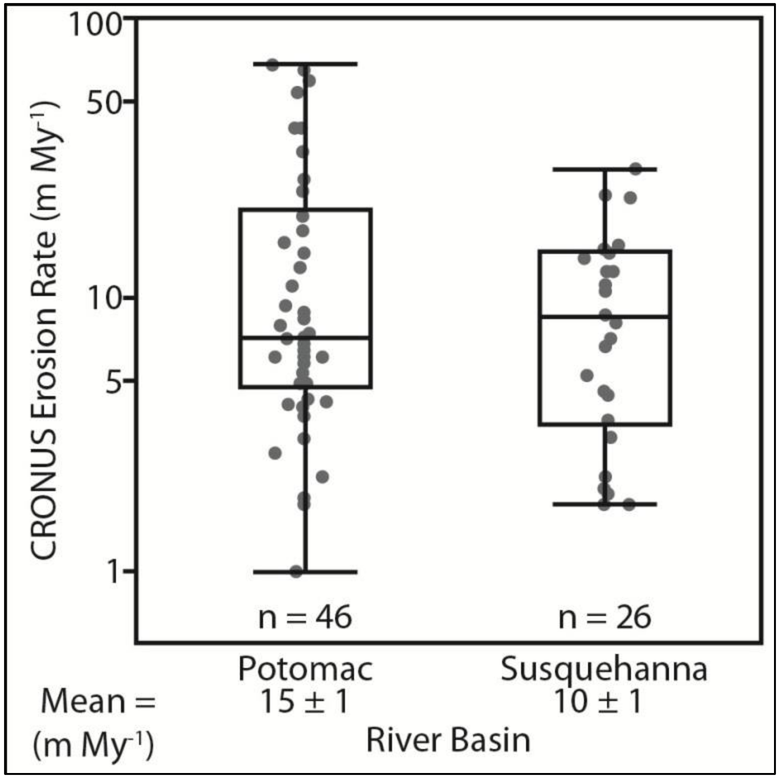
  15 ± 1 m $My^{-1}$

- Median

  7.1 m $My^{-1}$

- Range

  1.0 – 66 m $My^{-1}$




Means from basins are inseparable at the 95% confidence interval ($p$ = 0.32)

**Susquehanna River**

- Mean

  10 ± 1 m $My^{-1}$

- Median

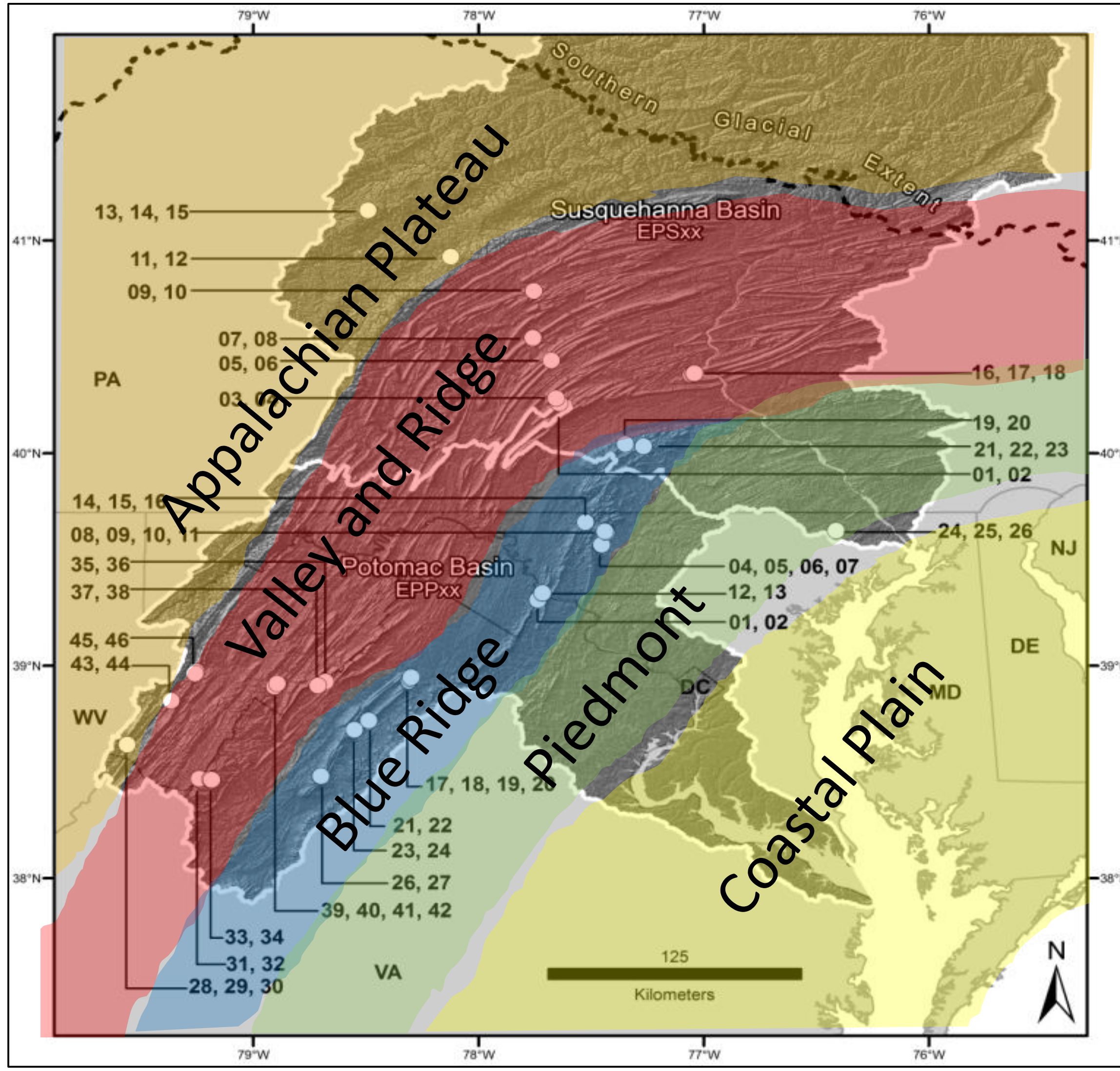
  8.3 m $My^{-1}$

- Range

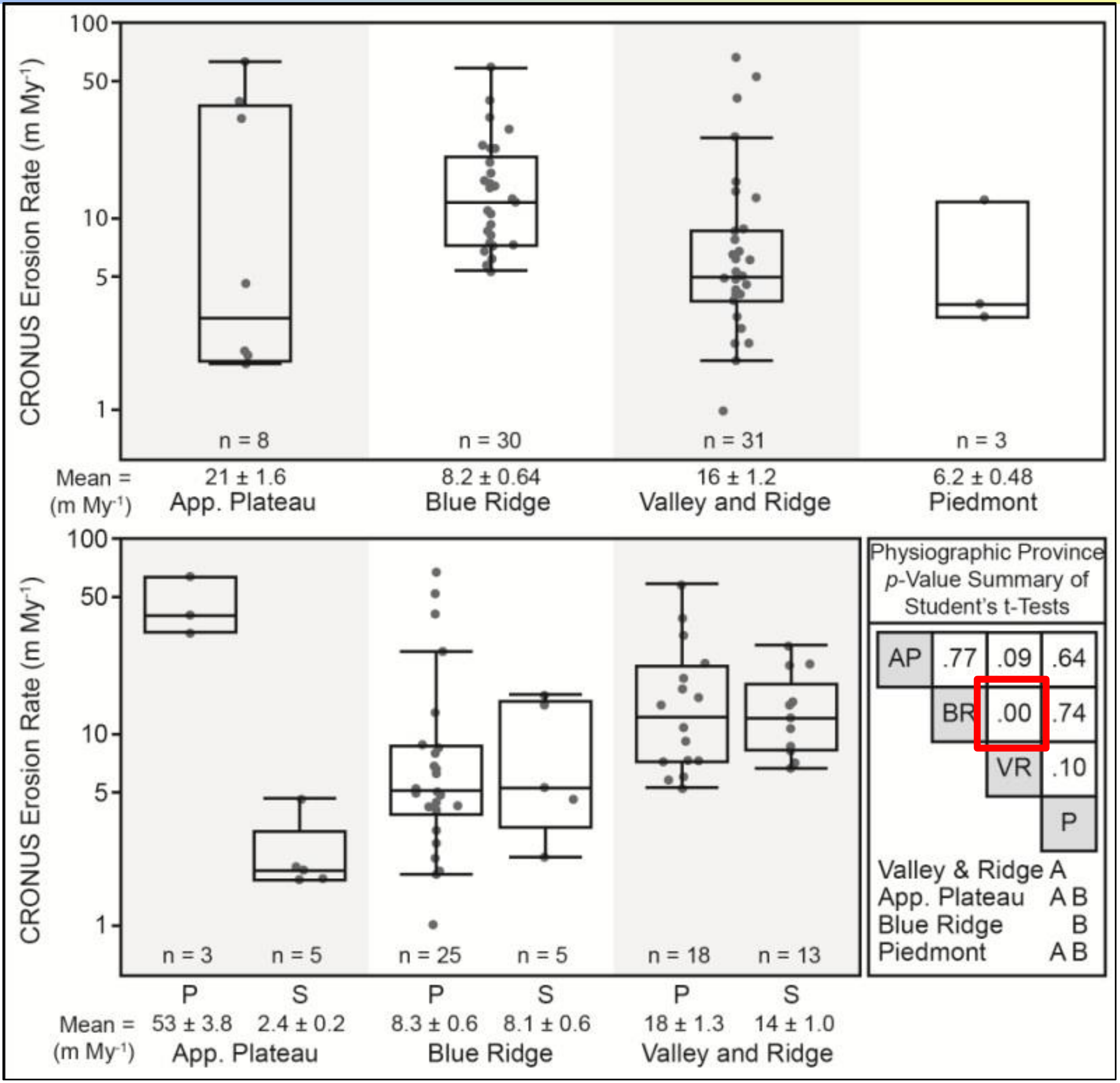
  1.8 – 28 m $My^{-1}$

# Mean Provincial Outcrop Erosion Rates

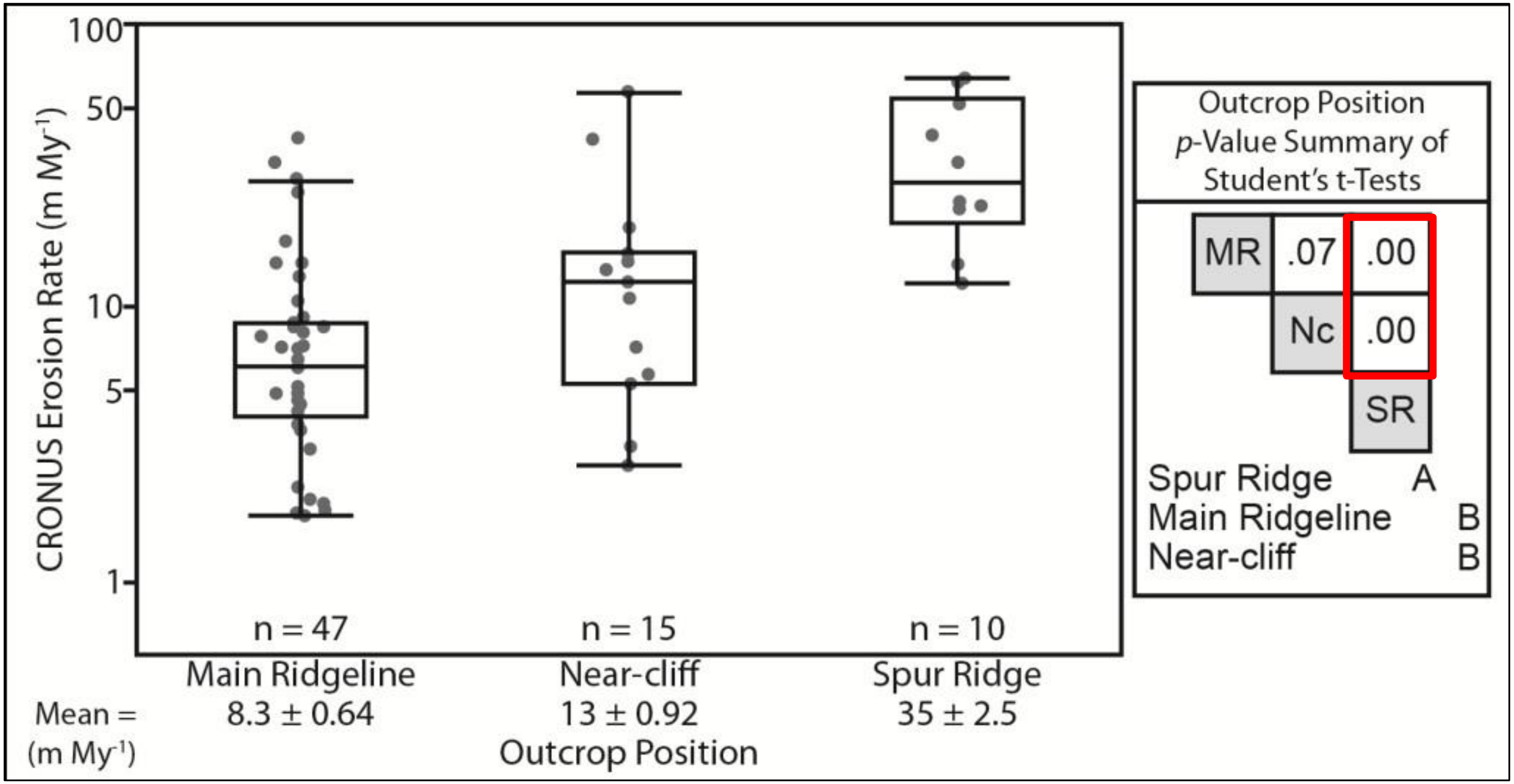
- Piedmont
  6.2 m $My^{-1}$
- Blue Ridge
  8 m $My^{-1}$
- Valley & Ridge
  16 m $My^{-1}$
- App. Plateau
  Pot. = 53 m $My^{-1}$
  Sus. = 2.4 m $My^{-1}$



# Mean Provincial Outcrop Erosion Rates

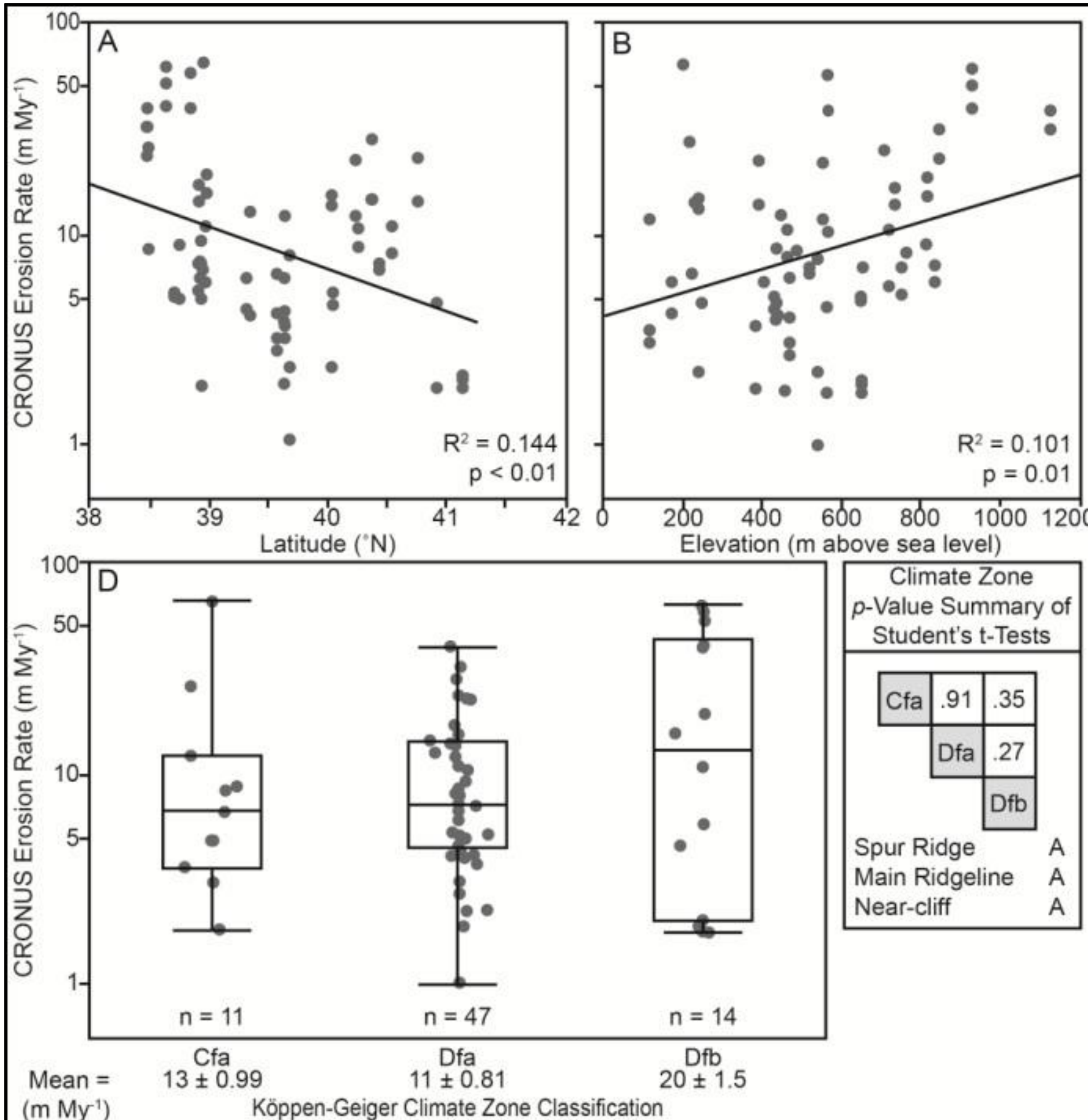


# Mean Positional Erosion Rates



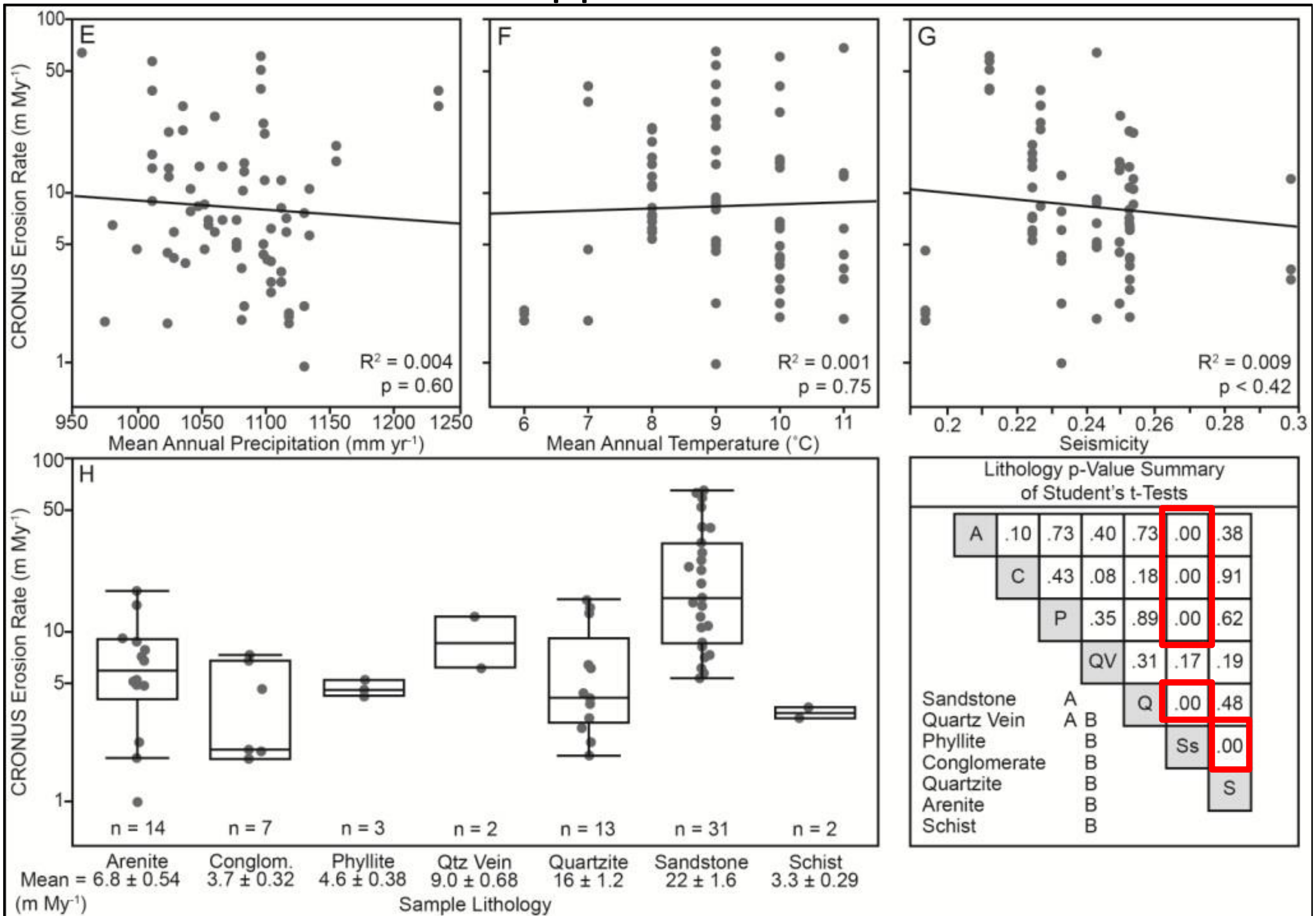

- Spur-ridges erode faster than other types ($p < 0.001$)
- Ridge-line and near-cliff samples erode similarly ($p = 0.07$)

# Statistical Relations between Outcrop Erosion Rates and Environmental Parameters in Central Appalachians




- Cfa = Temperate: hot summer without a dry season
- Dfa = Cold: hot summer without a dry season
- Dfb = Cold: warm summer without a dry season
- Temperate
  - $T_{hot}>10$; $0<T_{cold}<18$
- Cold
  - $T_{hot}>10$; $T_{cold}\leq 0$

# Statistical Relations between Outcrop Erosion Rates and Environmental Parameters in Central Appalachians

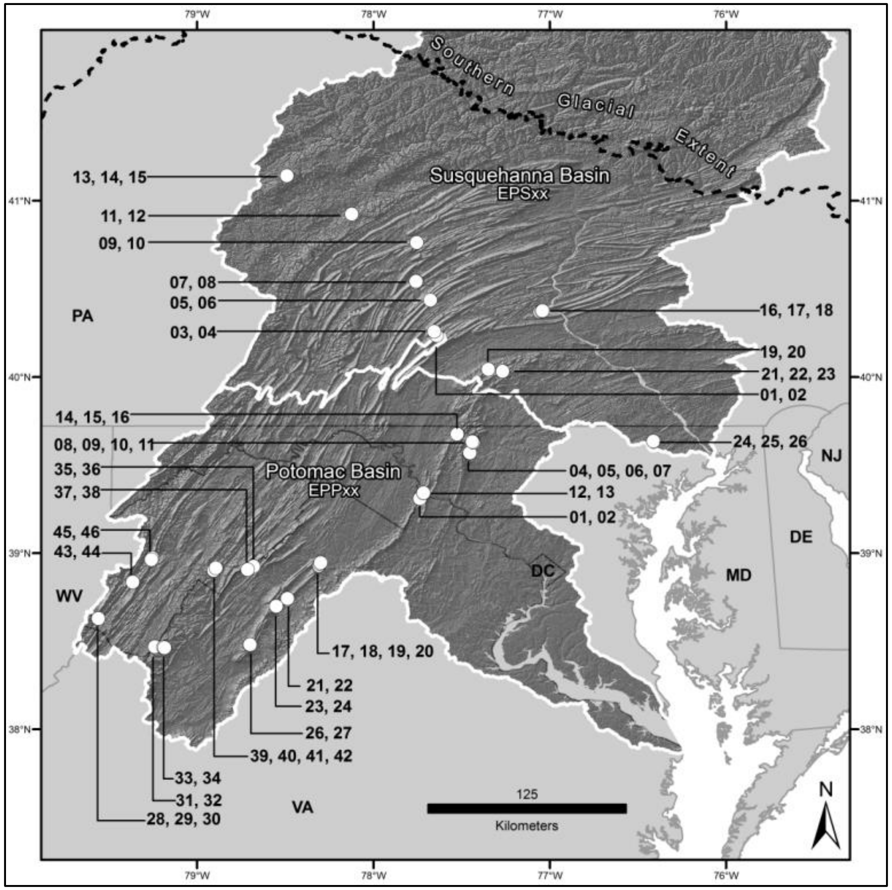


# Principle Component Analysis

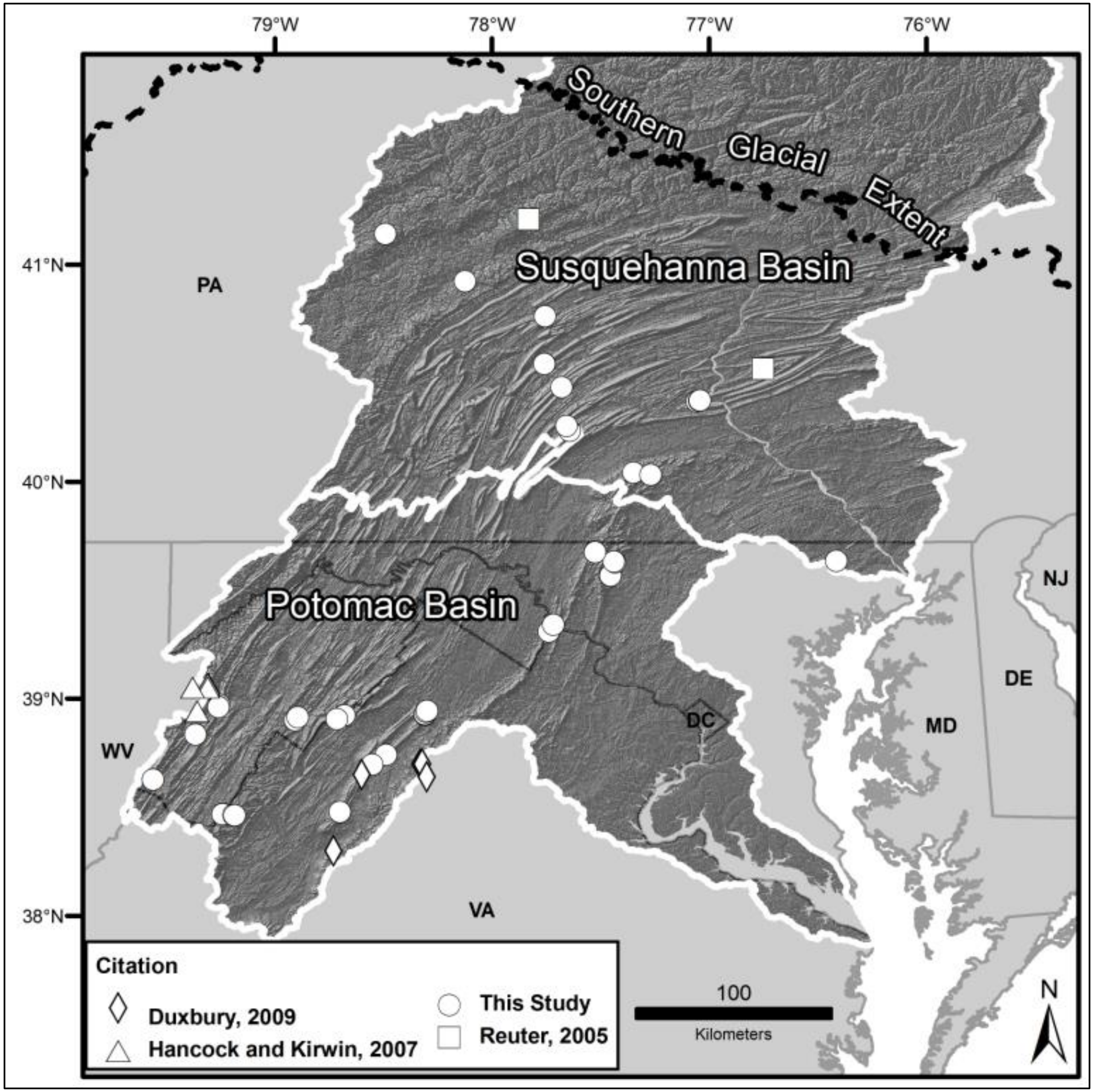
- Variables may be correlated to one another and are thus not independent of each other
- PCA removes these dependencies by creating three new variables
  - Seismic-physiography
  - Latitude-Temperature
  - Precipitation
- Multivariate regression of PCA variables explains 25% of erosion rates in the study area

# Relative Standard Deviations at Each Site

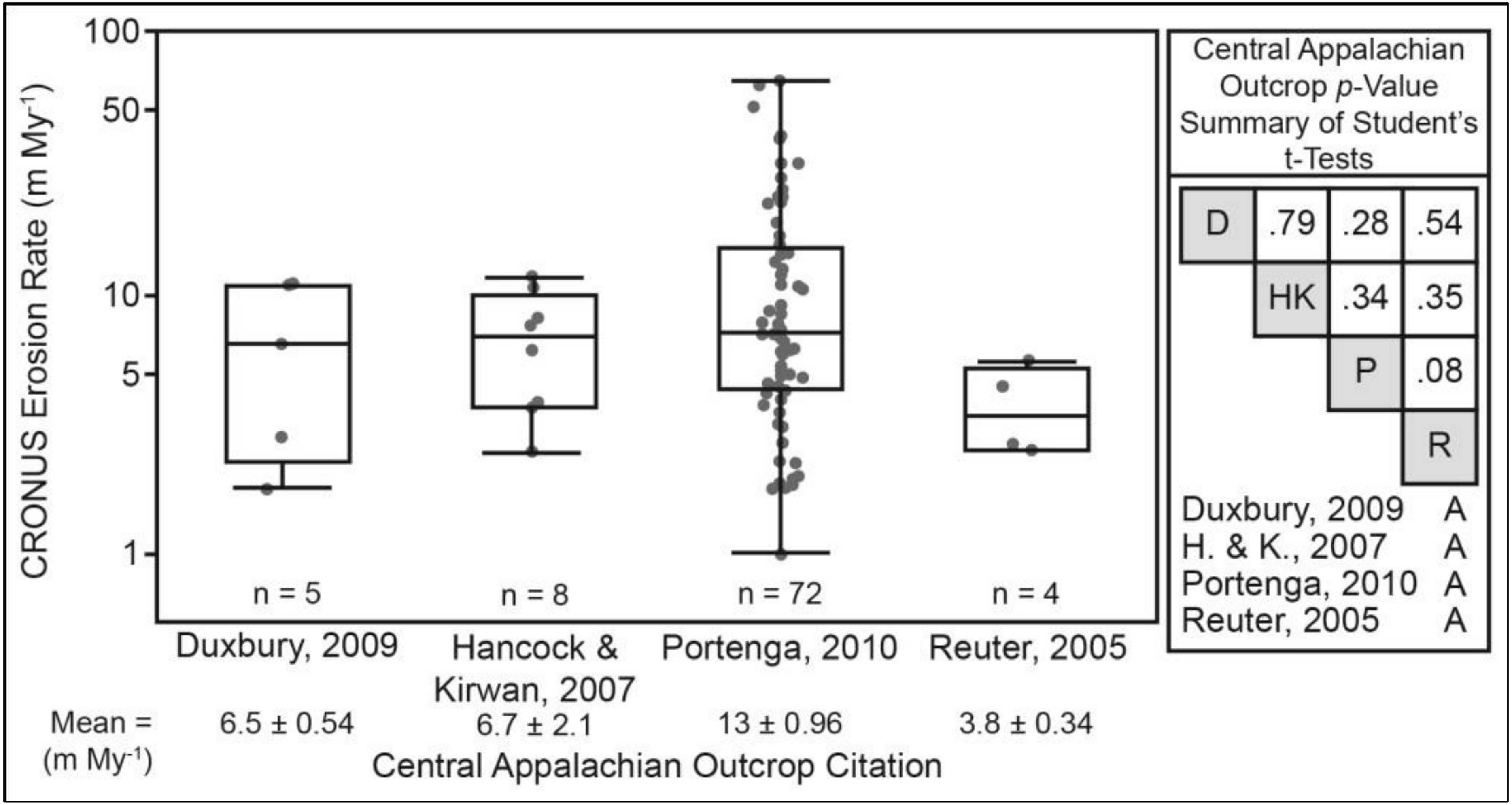
- Relative Standard Deviations for each site
  - Avg.: 0.39
  - Range: 0.03 – 0.98
  - Sites with RSD > 0.50 may include samples which violate cosmogenic method assumptions



# Other Regional Outcrop Erosion Rates

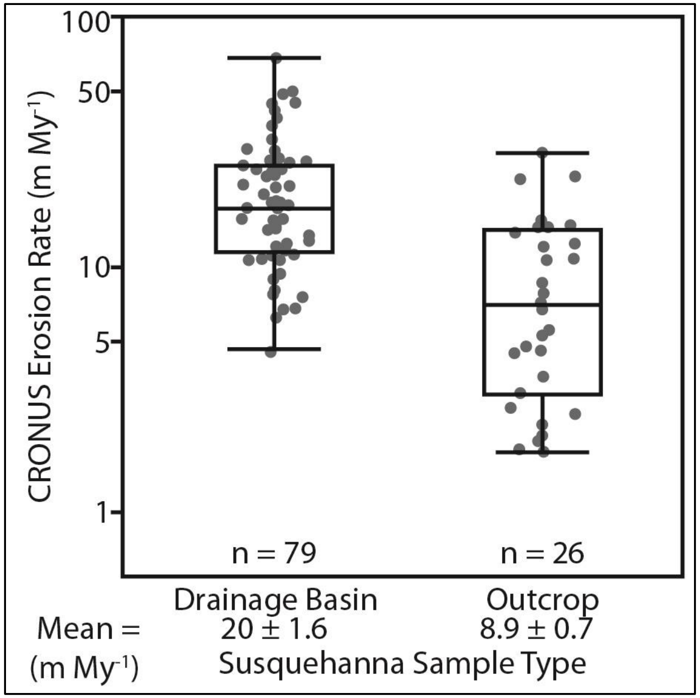


# Other Regional Outcrop Erosion Rates



# Higher Basin Erosion Rates in the Susquehanna River Basin

| Susquehanna | Susquehanna |
|---|---|
| **Basins** (n = 79) | **Outcrops** (n = 26) |
| Mean = 20 ± 1.6 m $My^{-1}$ | Mean = 8.9 ± 0.7 m $My^{-1}$ |
| Median = 17 m $My^{-1}$ | Median = 8 m $My^{-1}$ |




Means are not similar at the 95% confidence interval (*p* = 1)

# Similar Basin and Outcrop Erosion Rates in the Potomac River Basin

Potomac **Basins** (n = 62)

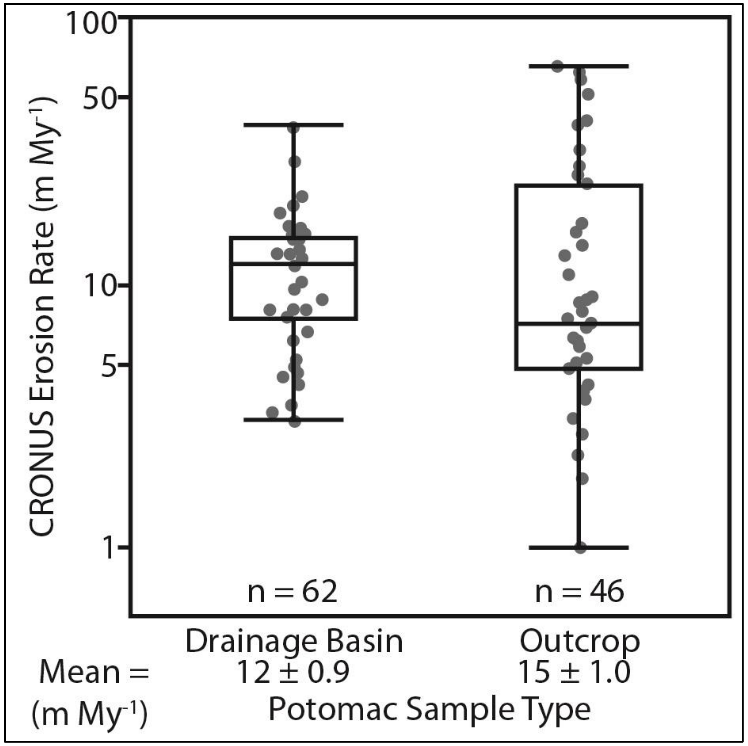
Mean = 12 ± 0.9 m $My^{-1}$

Median = 12 m $My^{-1}$

Potomac **Outcrops** (n = 46)

Mean = 15 ± 1 m $My^{-1}$

Median = 7.1 m $My^{-1}$




Means for outcrops and basins are inseparable at the 95% confidence interval ($p$ = 0.40)

# Putting Erosion Rates into Global Context

- Cosmogenic erosion rates are similar to erosion rates determined from other studies, which introduces a question:

Is 13 m $My^{-1}$ fast or slow?

- We now need a global context to compare these erosion rates

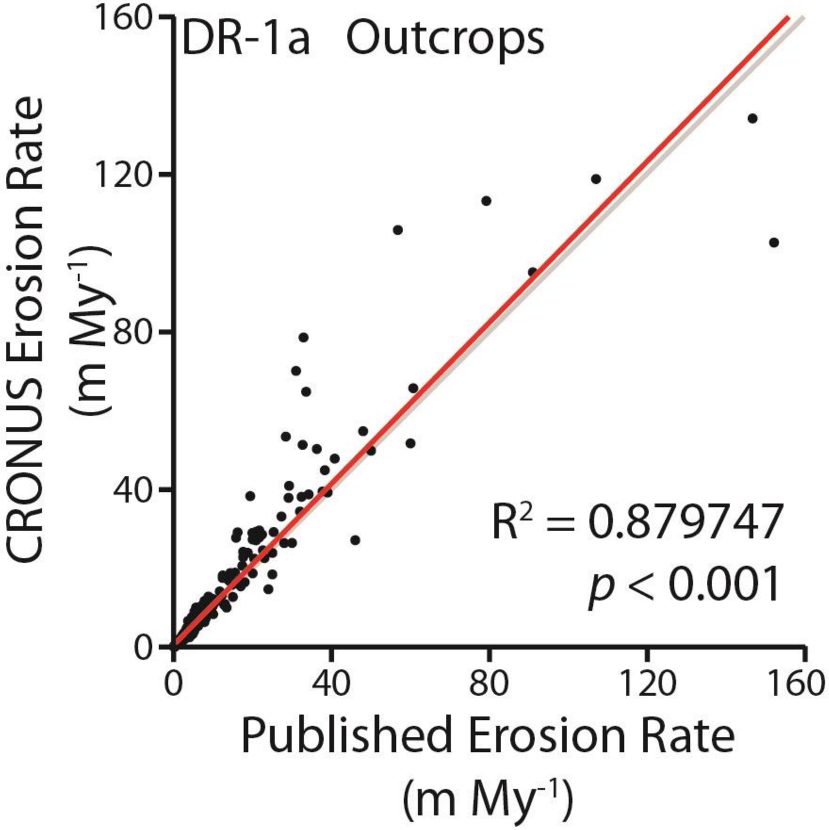
# A Global Compilation of $^{10}$Be Erosion Rates

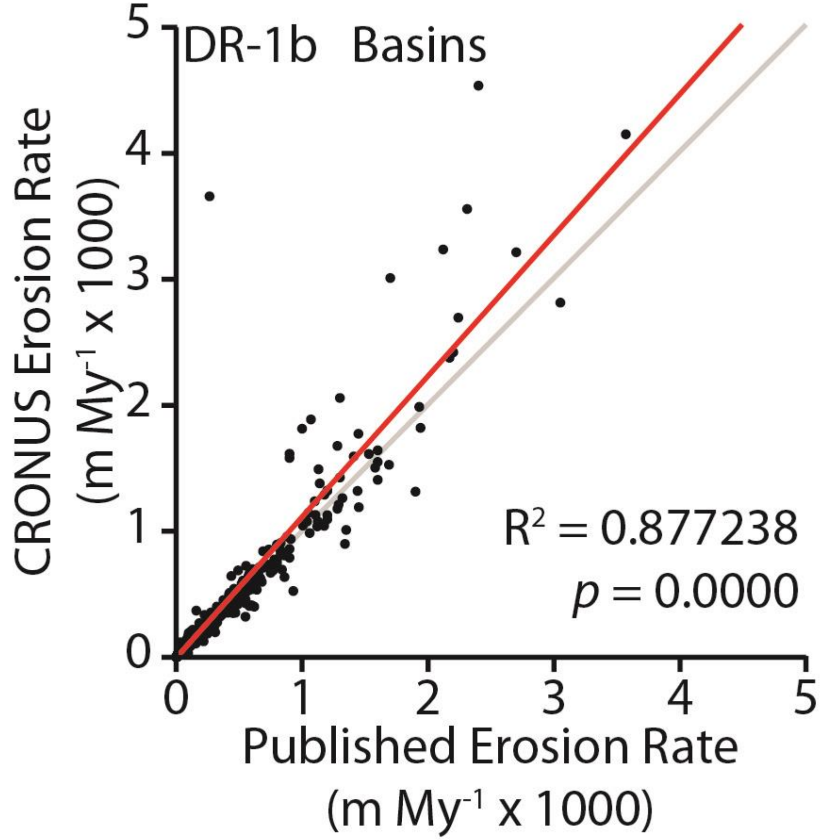
- What?
  1. Create a global context in which regional studies can be set
  2. Analyze relationship between bedrock outcrop and drainage basin erosion rates
  3. Understand relationship between erosion rates and metrics quantifying environmental parameters
- How?
  1. Compile all publically available erosion rate data
  2. Summarize behavior of erosion rates in various climatic, tectonic, and physical settings
  3. Use statistics to analyze relationships between erosion rates and environmental parameters
- Why?
  1. Most studies are small, geographically, and this allows trends in similar environments to be observed on a much larger scale
  2. Reveals whether method observations are consistent in numerous study sites
  3. Different parameters may exert varying amounts of control over erosion rates

# Compilation Methods

- Gather publically available $^{10}$Be data
  - Original $^{10}$Be concentrations
  - Production rates, scaling schemes, corrections
  - $^{10}$Be Analysis standard material
  - Published erosion rates
- Recalculate erosion rates from published $^{10}$Be concentrations – CRONUS on-line Calculator
  - First true normalization of erosion rates between studies
    - Outcrops
      - Determine actual sampling sites
    - Drainage Basins
      - Determine where sample was taken
      - Redelineate watershed boundaries

# Published v. CRONUS Erosion Rates




n = 418

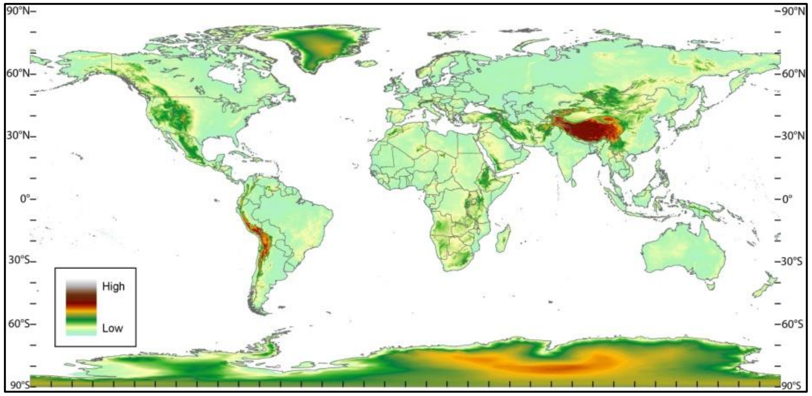
n = 1110

# Compilation Methods

- Assign physical and environmental parameter values from global datasets
  - Elevation/Relief/Slope → Digital Elevation Models (DEMs)
  - Mean Annual Precipitation/Temperature → WorldClim Global Acquisition
  - Seismicity → Global Seismic Hazard Assessment Map
  - Vegetation → Percentage tree cover map
  - Climate Zone → Köppen-Geiger Classification System
  - Lithology → publication references

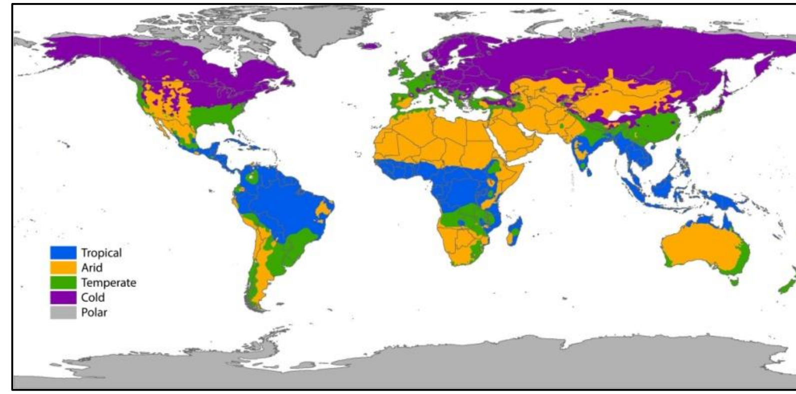
# Data Coverages

Elevation



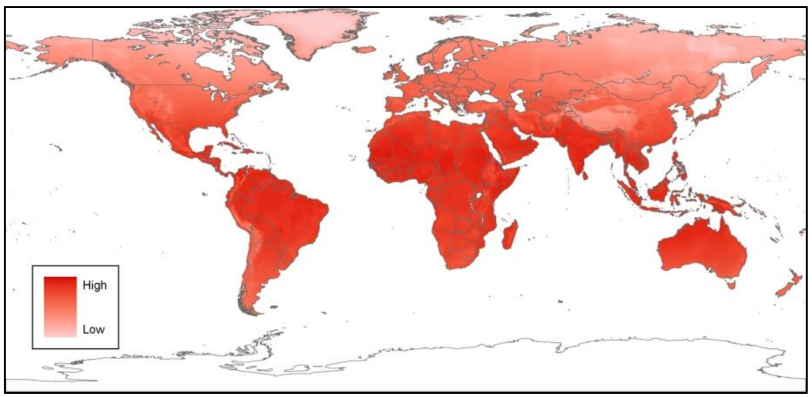

US Geol. Survey

Climate Zone



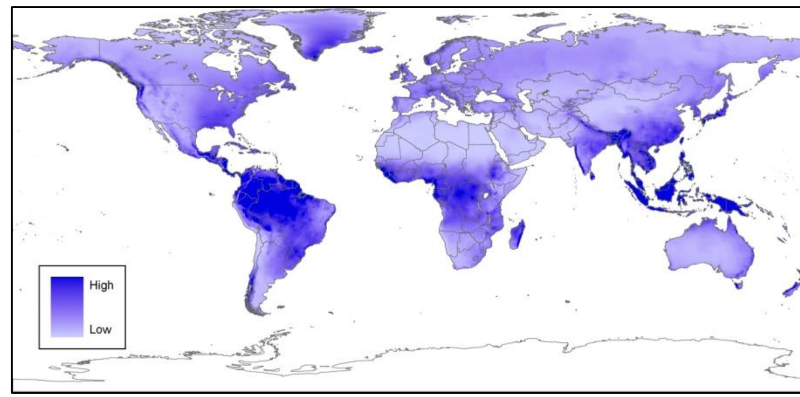

Peel et al., 2007

M.A. Temp.



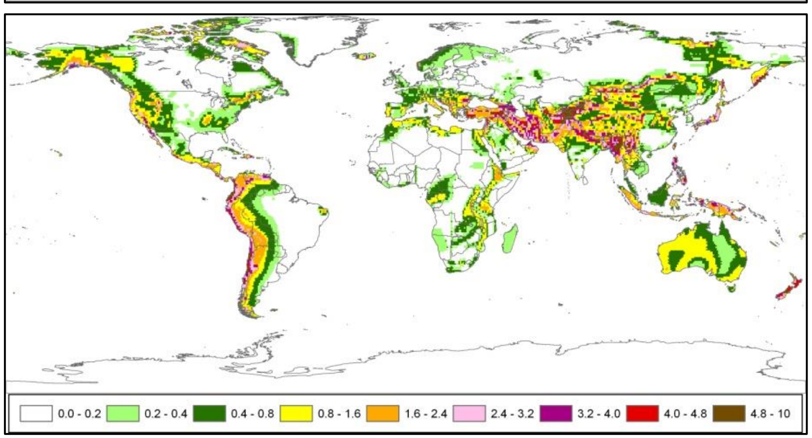

Hijmans et al., 2005

M.A. Precip.



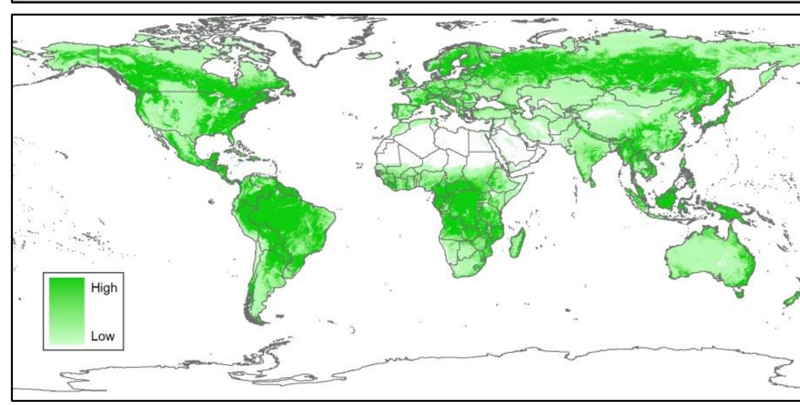

Hijmans et al., 2005

Seismicity




Giardini et al., 1999

Vegetation

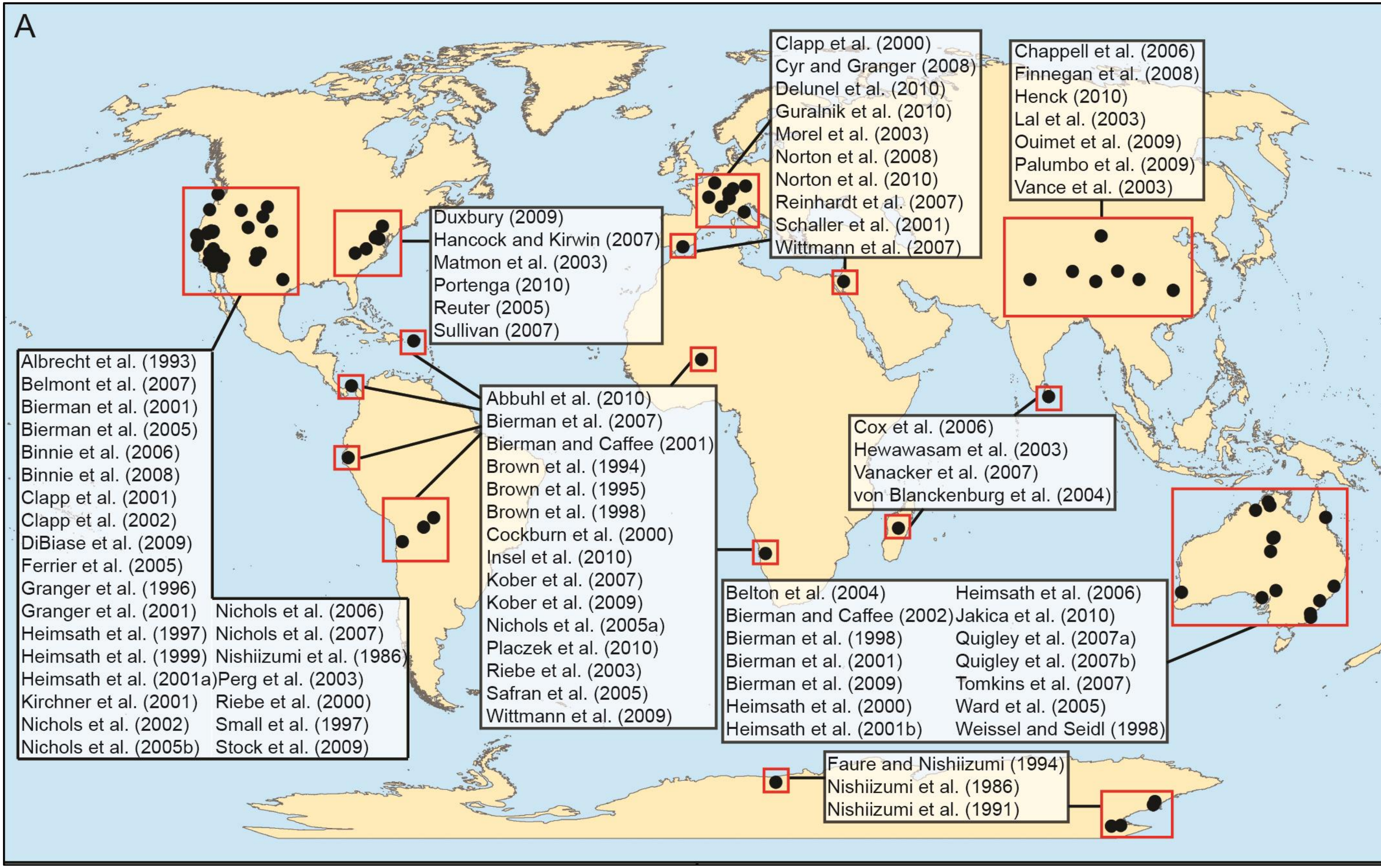



Defries et al., 2000

# Compilation Methods

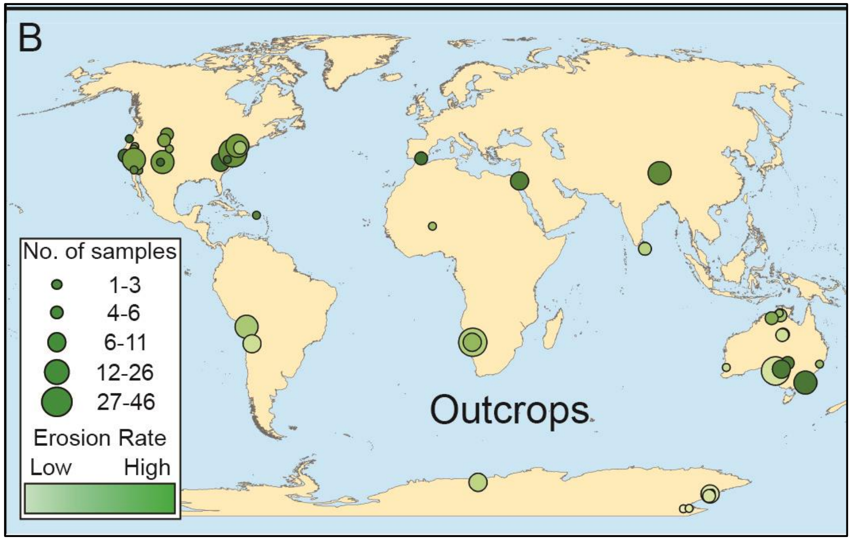
- Statistical Analyses
  - Bivariate relationships
    - Simple linear regressions
    - ANOVA
  - Multivariate relationships – forward stepwise regressions
    - Significant parameters entered into regression  one at a time
    - Parameters which significantly strengthen the regression remain in the analysis; those that do not are ejected

# Erosion Rate Sample Locations

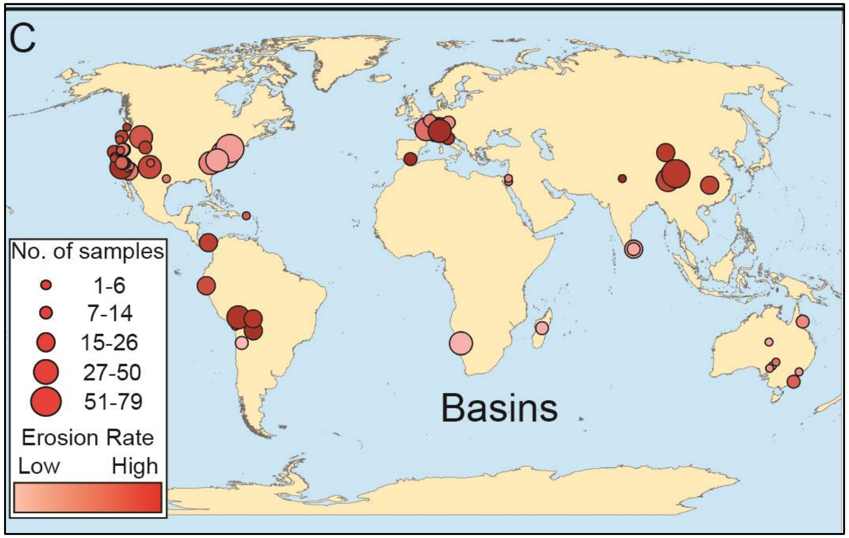


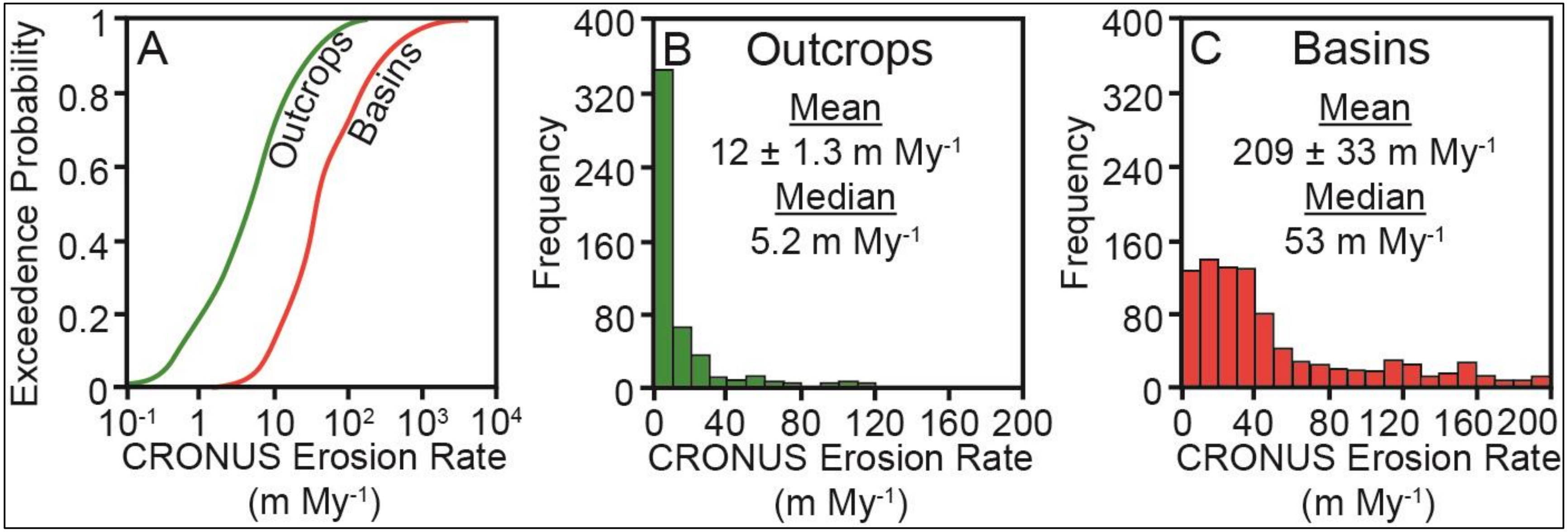
# Distribution of Sample Types

## Outcrops

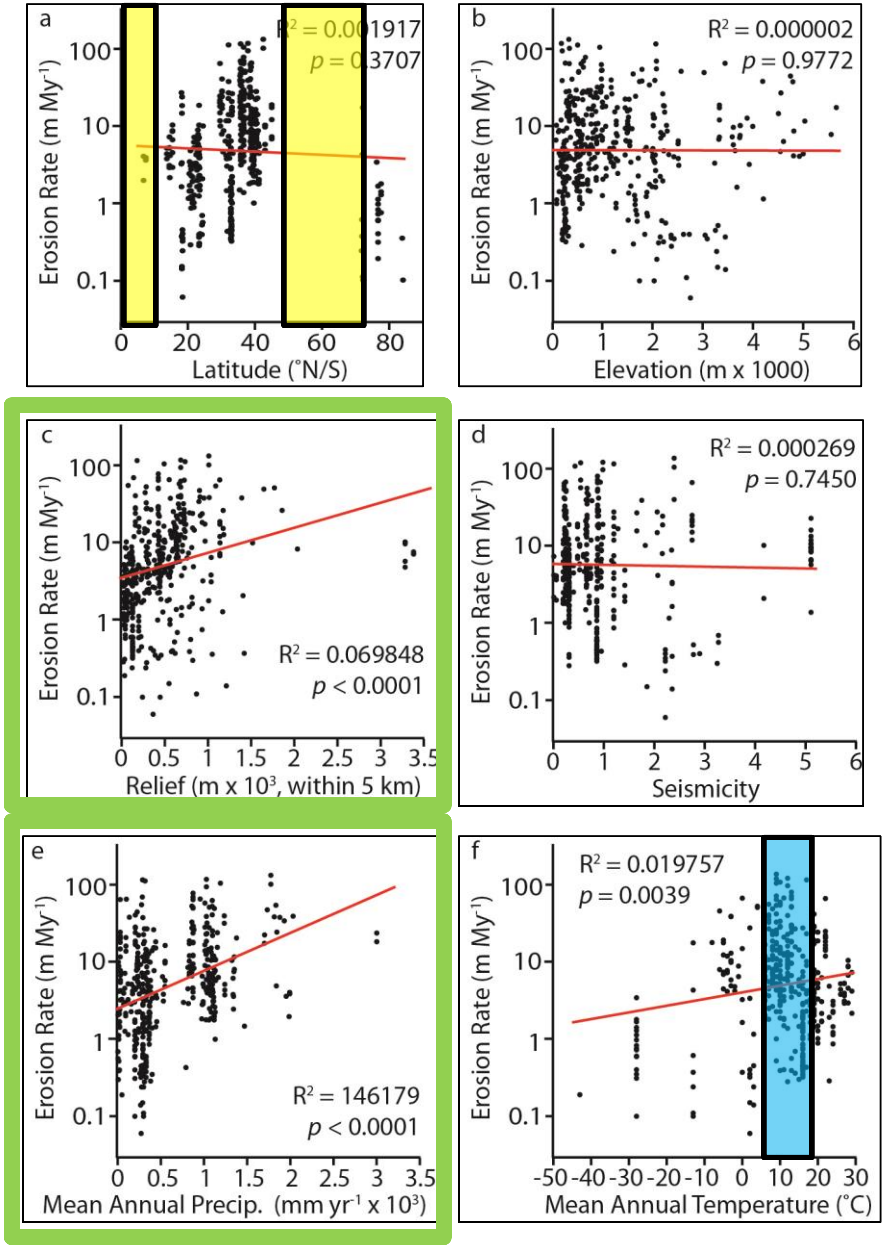



## Drainage Basins



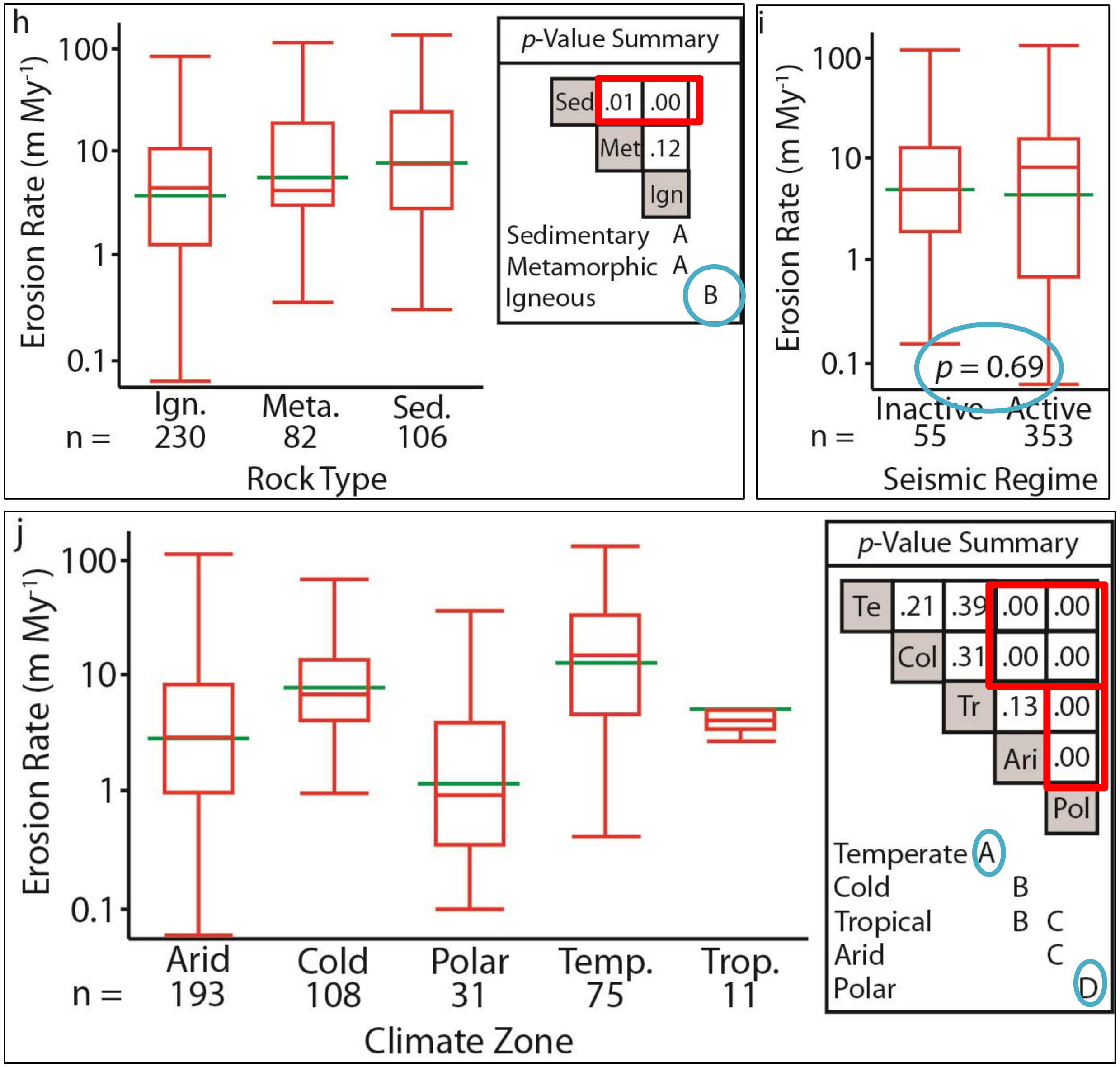



# Outcrop Bivariate Analyses



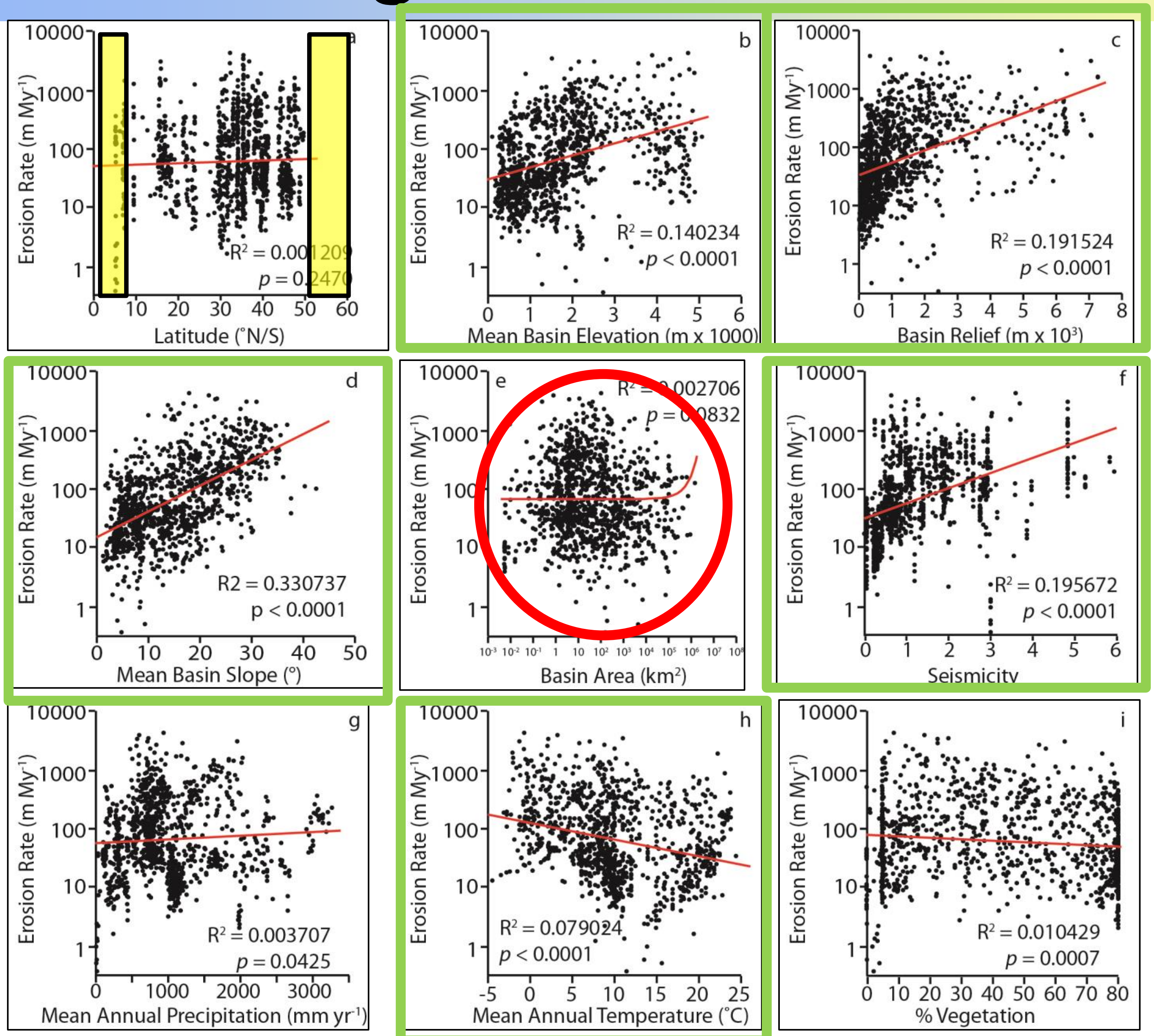

- Geographic Sampling Gaps between 0-10 and 50-70° Latitude
  - Ice Cover
  - Southern Ocean
- MAP and Relief produce strongest relationships with outcrop erosion rate
- Erosion peaks with a MAT of ~10°C

# Outcrop Bivariate Analyses



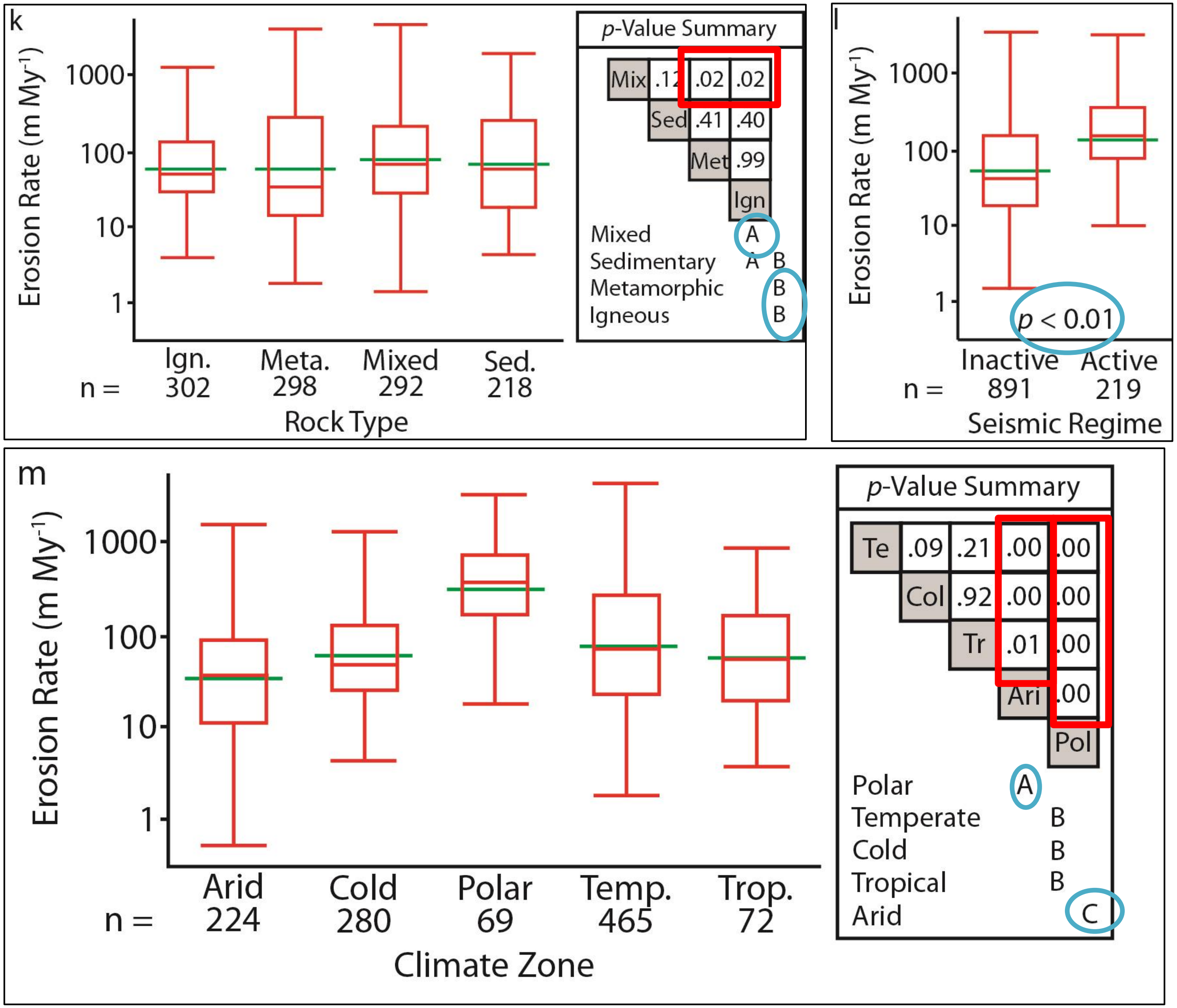

- Igneous rocks erode more slowly than any other rock type
- Erosion rates are similar in active and inactive seismic settings
- Outcrops in temperate climates erode the fastest; polar outcrops erode the slowest

# Drainage Basin Bivariate Analyses



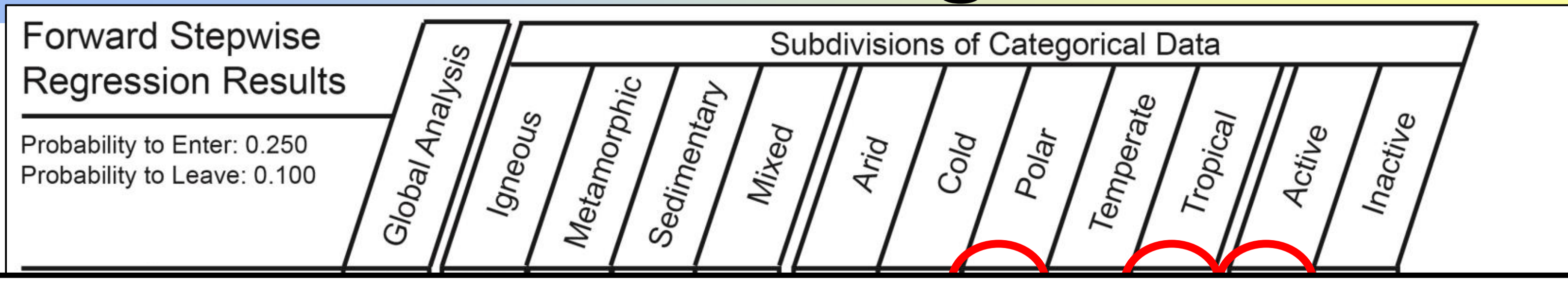

- Sampling gaps also observed at high and low latitudes
- More parameters yield strong relationships with drainage basins than outcrops
- No relation with basin area means cosmogenic erosion rates are not affected by the sediment delivery ratio

# Drainage Basin Bivariate Analyses




- Basins underlain by mixed lithologies erode faster than those underlain by all metamorphic or igneous lithologies
- Basins in seismically active settings erode faster than those in inactive settings
- Basins in polar climates erode the fastest while those in arid climates erode the slowest

# Multivariate Regressions




- 56% of Basin Erosion Rate variability is explained by 8 parameters
- Explainable erosion rates for other subdivisions are high, even if the sample population is large
- Average Basin Slope is the consistently the most relevant regressor for the global and nearly all sub-categories; those which is it not the most relevant, it is still high
- All other parameters are highly variable in terms of their relevance

- 33% of Outcrop Erosion Rate variability is explained by 5 parameters
- Explainable erosion rate variability for other subdivisions is inconsistent
  - Subdivisions with high $R^2$ values also have smaller sample populations
- Latitude is not always a relevant regressor, but it is the most frequent dominant regressor
- Elevation, Relief, Mean Annual Precipitation, Mean Annual Temperature, and Seismicity are significant at times, but their level of significance is greatly variable

# Multivariate Regressions

Forward Stepwise Regression Results

Probability to Enter: 0.250
Probability to Leave: 0.100

Outcrops

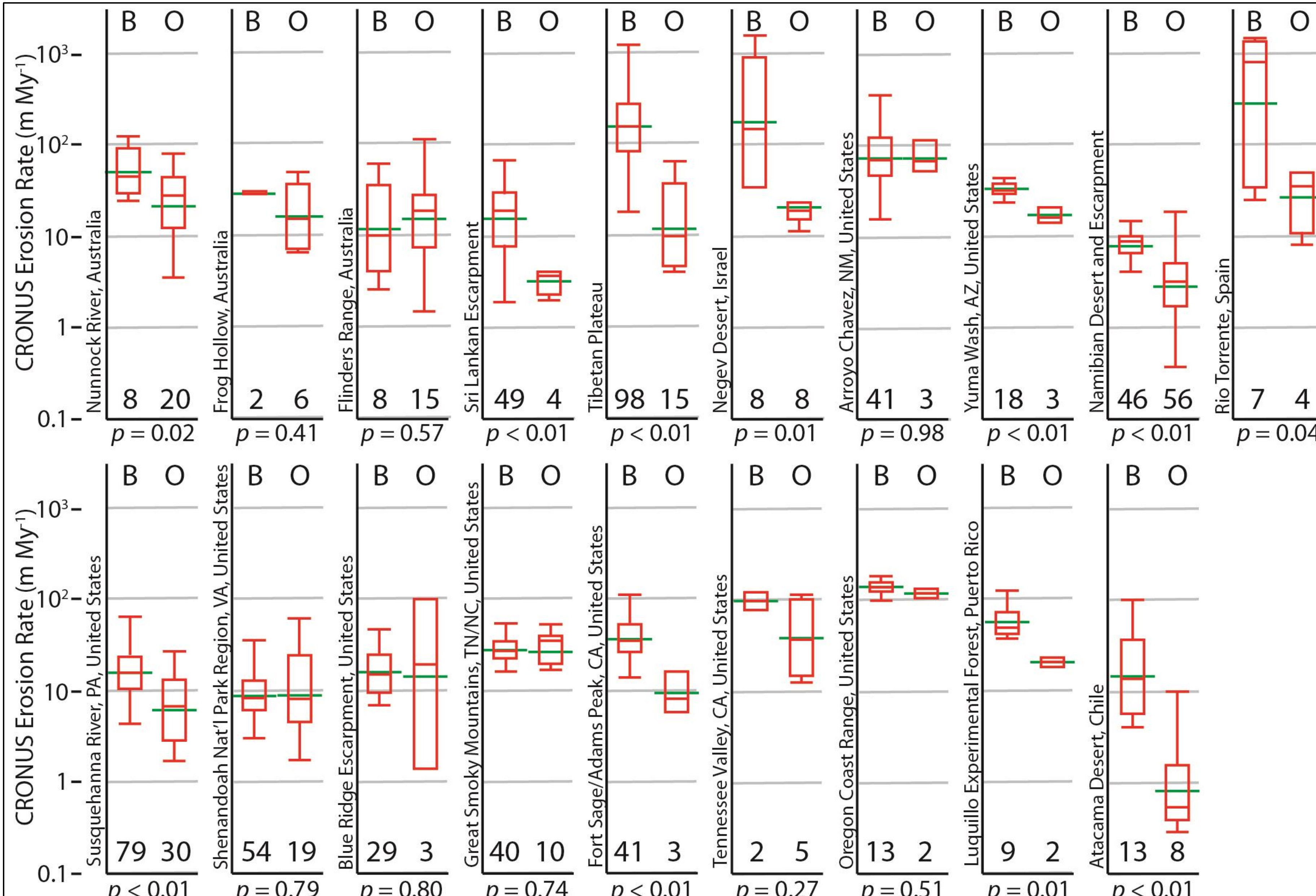
| | Global Analysis | Igneous | Metamorphic | Sedimentary | Mixed | Arid | Cold | Polar | Temperate | Tropical | Active | Inactive |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Subdivisions of Categorical Data | | | | | | | | | | |
| n = | 418 | 230 | 82 | 106 | N/A | 193 | 108 | 31 | 75 | 11 | 55 | 363 |
| Mean (m $My^{-1}$) = | 12 | 9 | 13 | 19 | N/A | 8 | 13 | 4 | 26 | 7 | 14 | 12 |
| Median (m $My^{-1}$) = | 5 | 4 | 4 | 8 | N/A | 3 | 7 | 1 | 14 | 4 | 8 | 5 |
| Latitude (°N/S) | .147 | .139 | | | N/A | .046 | | .484 | .071 | | .379 | .031 |

- Means for Drainage Basins are almost always at least ~1 order of magnitude higher than the mean for Outcrops
- Medians for Drainage Basins in the global analysis and subdivisions are also at least ~1 order of magnitude her than medians of Outcrops

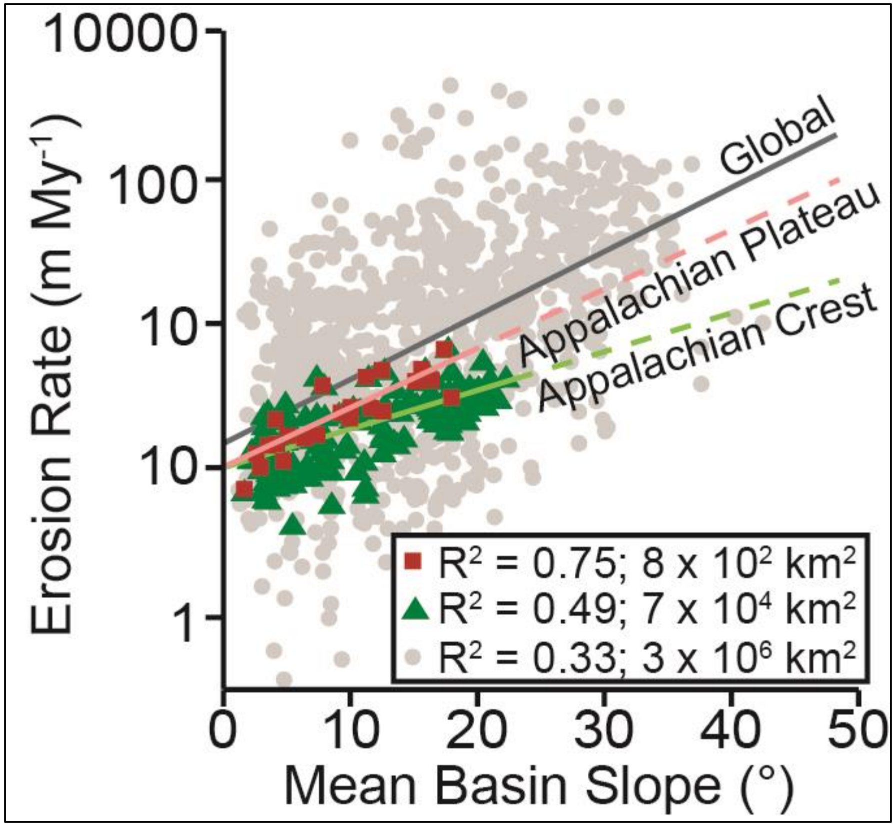
| | Global Analysis | Igneous | Metamorphic | Sedimentary | Mixed | Arid | Cold | Polar | Temperate | Tropical | Active | Inactive |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| n = | 1110 | 302 | 298 | 218 | 292 | 224 | 280 | 69 | 465 | 72 | 219 | 891 |
| Mean (m $My^{-1}$) = | 209 | 148 | 288 | 163 | 226 | 103 | 158 | 550 | 254 | 120 | 364 | 171 |
| Median (m $My^{-1}$) = | 53 | 52 | 35 | 60 | 73 | 37 | 49 | 380 | 73 | 54 | 154 | 42 |
| Parameters: Latitude (°N/S) | .043 | .036 | .077 | .022 | .072 | .207 | .001 | | | | .089 | .045 |
| Elevation (m) | | | .005 | .047 | .009 | .002 | | | .003 | .087 | | .004 |
| Basin Relief (m) | .102 | | .088 | .009 | .138 | .013 | .471 | .035 | .158 | .091 | .152 | .052 |
| MAP (mm $yr^{-1}$) | .011 | .075 | | | .008 | .186 | .010 | .006 | | .006 | .008 | .013 |
| MAT (°C) | .001 | .006 | .002 | .006 | .013 | .003 | | .087 | .013 | .058 | | .004 |
| Seismicity | .047 | .043 | .024 | .072 | .013 | .016 | .008 | | .457 | .548 | .009 | .324 |
| Slope (°) | .342 | .450 | .481 | .355 | .349 | .298 | .172 | .664 | .045 | .032 | .377 | .119 |
| % Vegetation | .011 | | .140 | | .027 | .024 | .077 | | .034 | .011 | .007 | .023 |
| Basin Area ($km^2$) | .002 | | .013 | | .003 | | .010 | .005 | .002 | .017 | | .006 |
| $R^2$ = | .557 | .610 | .831 | .512 | .631 | .747 | .749 | .796 | .712 | .849 | .642 | .588 |

Relevance: High … Low

# Outcrop vs. Drainage Basins



# Geographic Scale Dependency



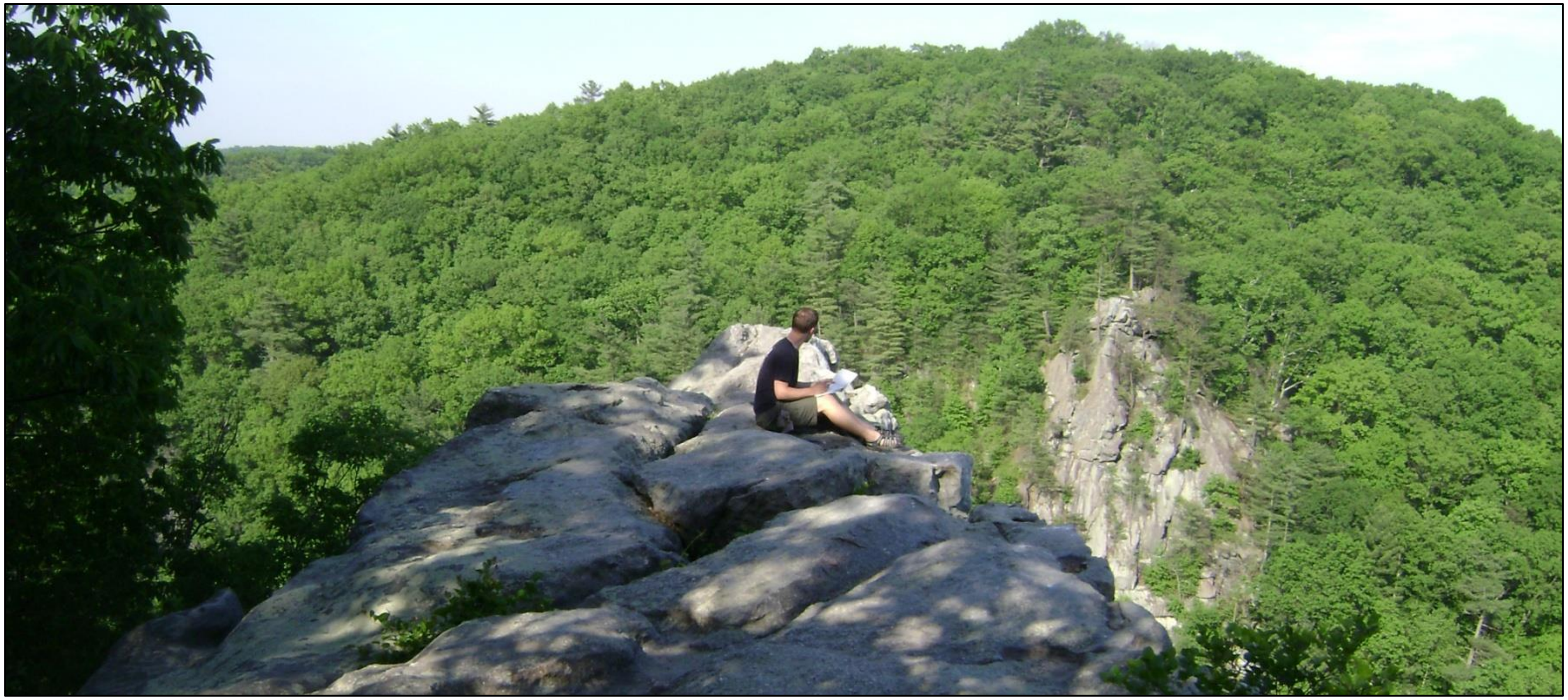

- Smaller study areas provide stronger relationships with parameters
- Parameters important at a local scale may be unimportant at a larger scale
- Multivariate methods are required for larger scales as more parameters are introduced

# Summary of Global Compilations

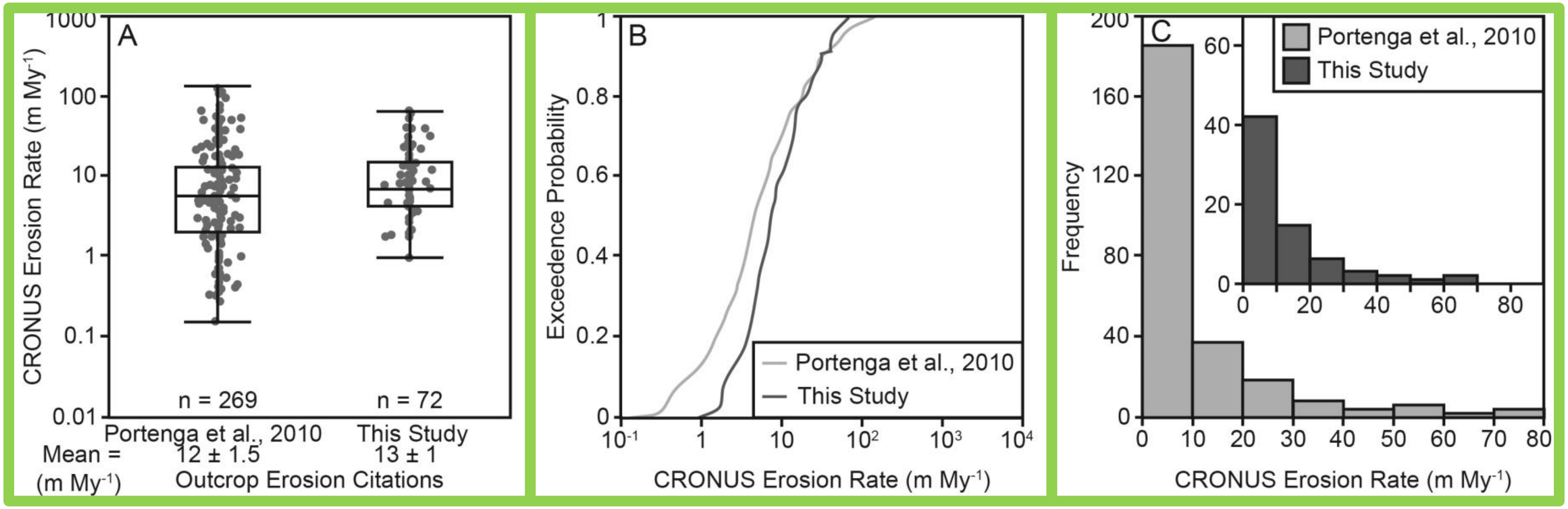
- Global erosion rates are slow (<140 m $My^{-1}$)
- Large geographic sampling gaps exist
  - Easily accessible locations
  - Not all regions are quartz dominated
- Basins erode more quickly than outcrops
  - True for both means and medians
- Observations made at a local scale may not be the same on the global scale. Inverse, also.
- More than one factor controls erosion rates; thus, multivariate methods are more appropriate than bivariate methods

# “Where do I fit in?” says the Appalachians

- With a sufficient summary of how outcrops erode globally, rates of outcrop erosion in the central Appalachians can now be compared

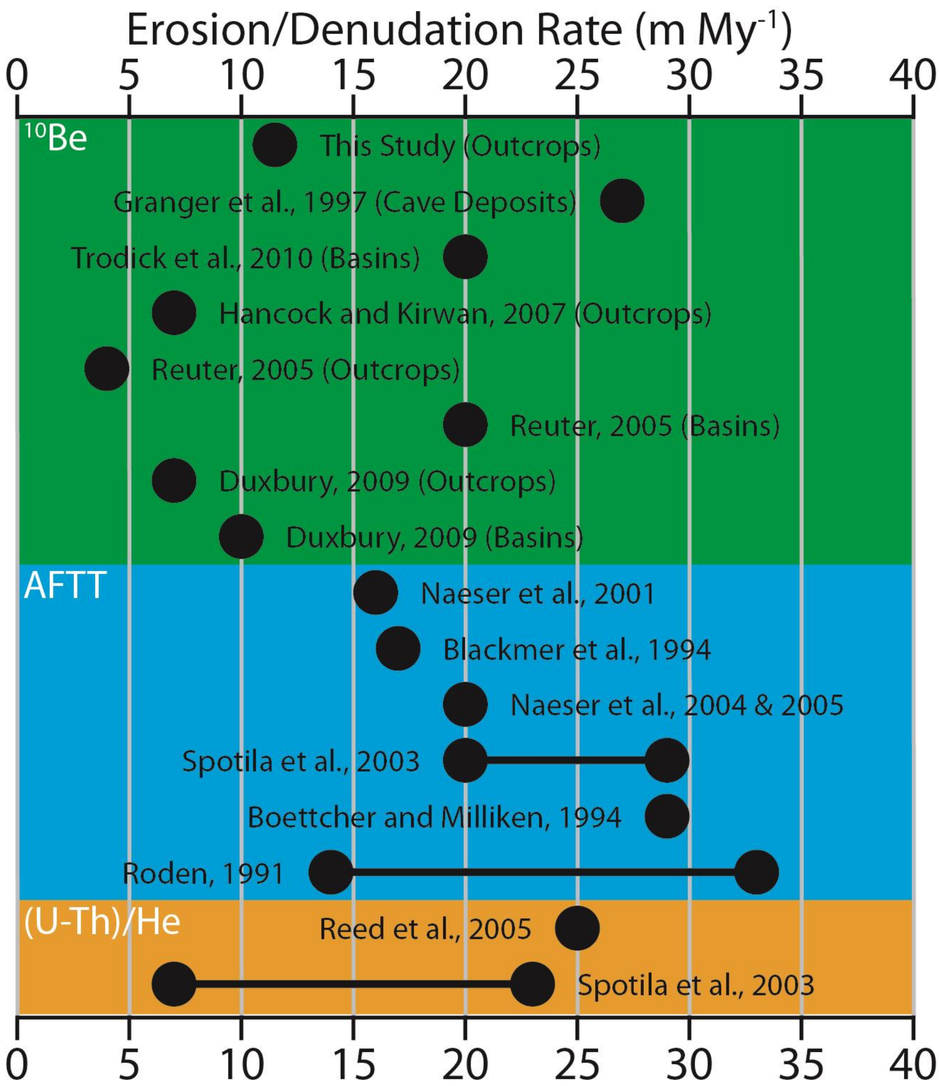


# Appalachian Erosion in the Global Context




- Appalachian outcrops erode significantly faster than global outcrops from similar settings ($p < 0.01$), but are still **low**
- Narrower distribution of erosion rates in the central Appalachian Mountains
- Distributions are skewed similarly toward low erosion rates

# Regional History of Central Appalachian Landscape Evolution




- Avg. outcrop erosion rates are similar to basin erosion rates
- Avg. outcrop erosion rates are lower than AFT Thermochron.
- Avg. outcrop erosion rates within range of (U-Th)/He dating

- Similar thermochronologic denudation and cosmogenic erosion rates confirm a slow denudational history of the central Appalachian Mountains since post-Alleghenian rifting

# Conclusions

- Erosion rates of bedrock outcrops in the central Appalachian Mountains are slow (13 m $My^{-1}$)
- Independent environmental and physical parameters explain 25% of outcrop erosion variability
- Outcrops from this study erode neither faster nor slower than other outcrops in the region measured using the same methods
- The Potomac River Basin is generally lowering at an even rate, preserving landscape features
- Relief is increasing in the Susquehanna River Basin
- Outcrops in the central Appalachian Mountains erode slightly faster than global outcrops

# Conclusions

- 418 bedrock outcrop and 1110 drainage basin erosion rates show outcrops erode more slowly than the basins in which they are situated
- 33% of Outcrop and 56% of Drainage Basin erosion rate variability is explained through multivariate statistics – the rest is held up in factors and processes left unmeasured or not well understood
- Parameters exerting control over erosion rates on small scales do not always exert similar control on large scales

# Conclusions

- Erosion rates in the Central Appalachian Mountains on millennial timescales are similar to denudation rates on longer timescales (>$10^6$ yrs)
- The region shows consistently low rates of exhumation since post-Alleghenian rifting of Pangea in the early Triassic (<30 m $My^{-1}$)

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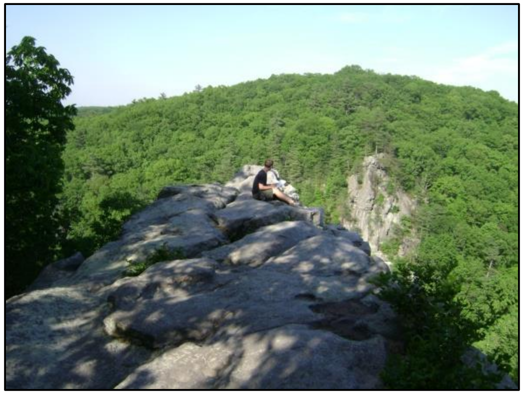
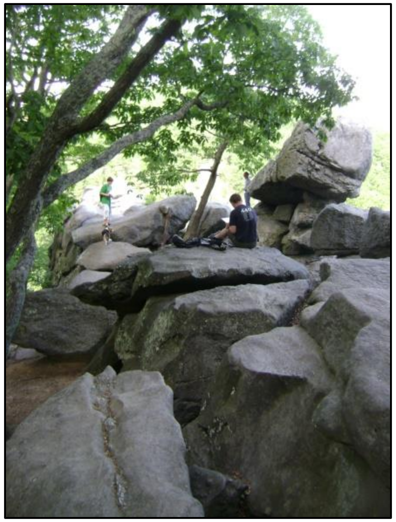


# Questions?