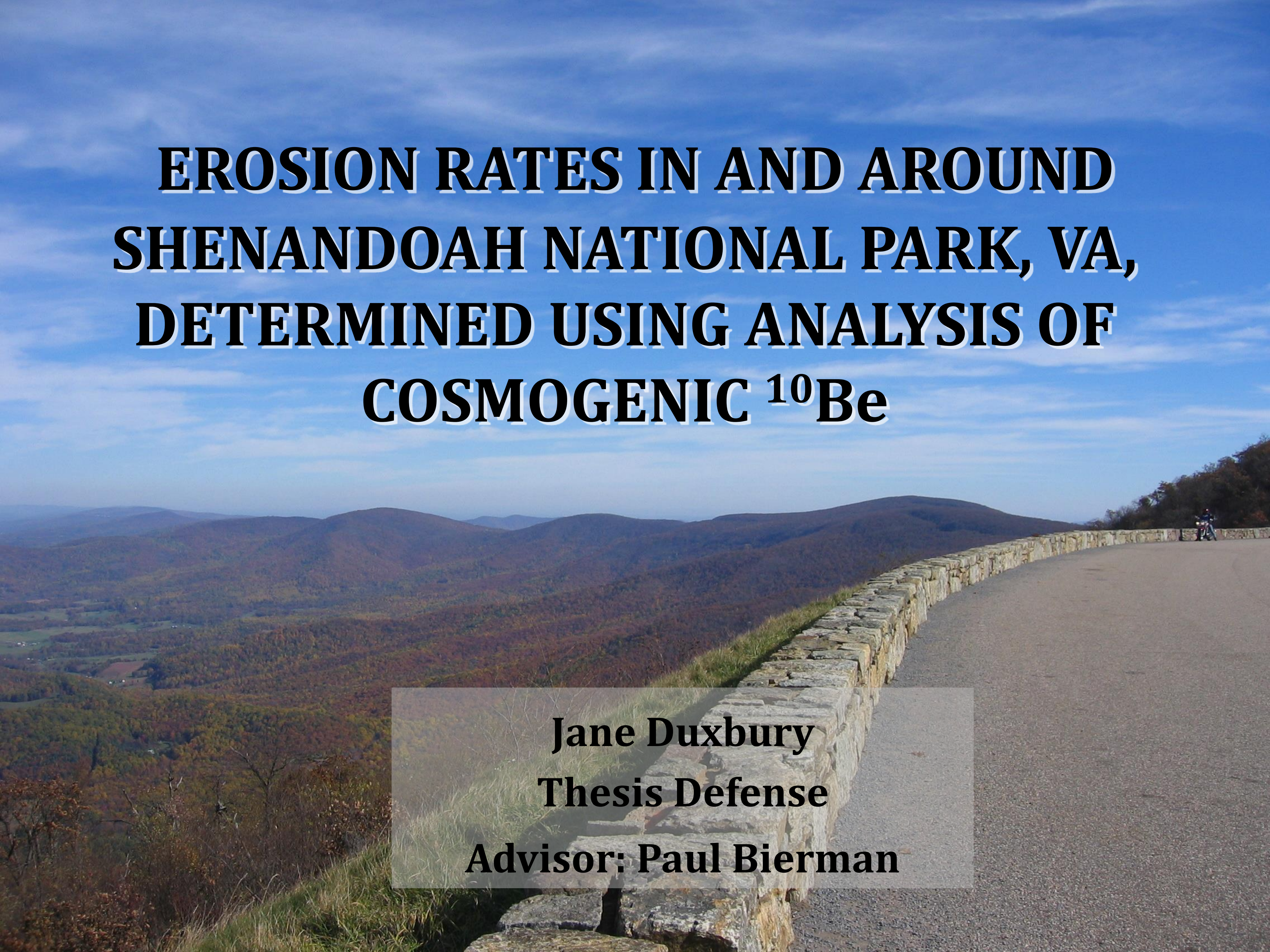
EROSION RATES IN AND AROUND SHENANDOAH NATIONAL PARK, VA, DETERMINED USING ANALYSIS OF COSMOGENIC ^{10}Be
Jane Duxbury
Thesis Defense
Advisor: Paul Bierman






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Outline

- Objectives
- Introduction to the project
- Cosmogenic Isotopes
- Methods
- Data & Results
- Discussion
- Future work

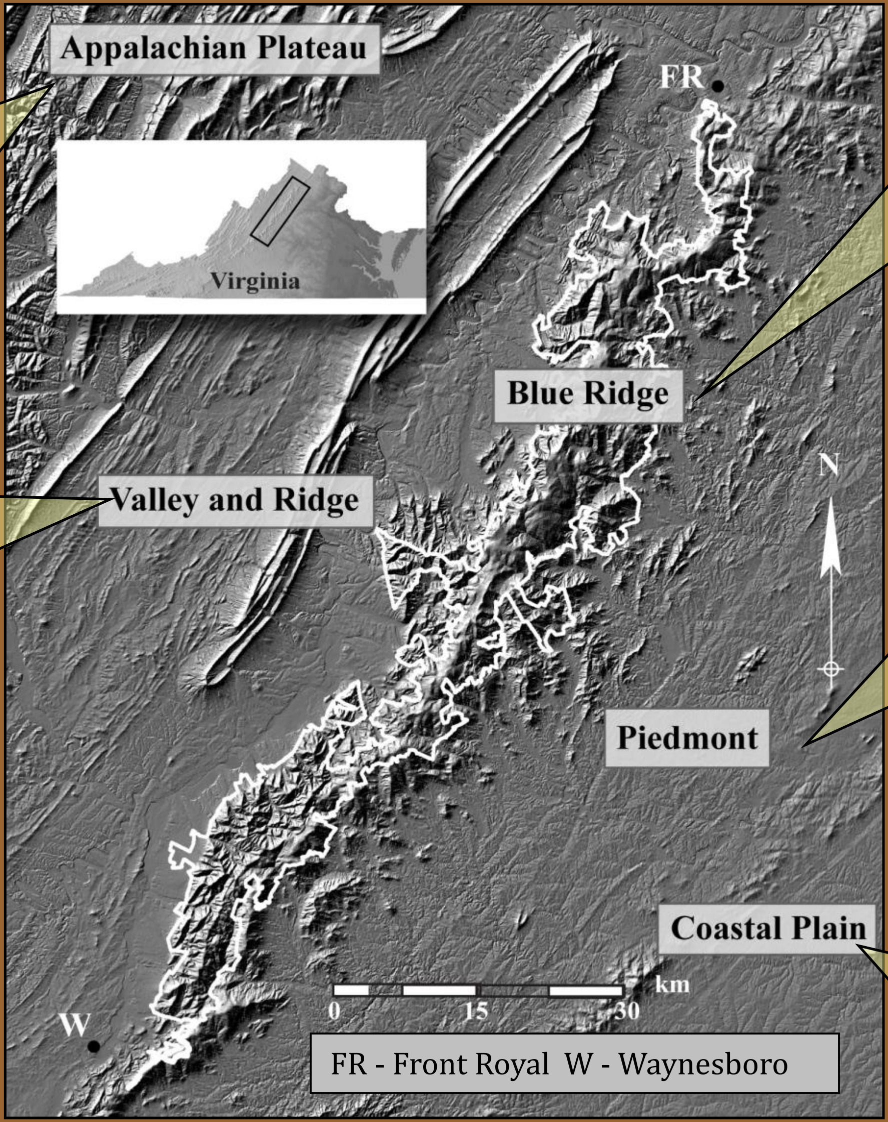
Objectives

- Appalachian Mountains paradox
- Determine erosion rates in and around the Park on a 10^3 to 10^5 year timescale
- To determine whether average erosion rates differ between the four lithologies cropping out in the Blue Ridge province within the Shenandoah National Park.
- To test Hack's (1960) model of *dynamic equilibrium* and steady state behavior.
- To compare the relationships between ^{10}Be-based erosion rates and slope, basin area and lithology with other Appalachian Mountain range studies such as Matmon et al. (2003a, 2003b); Reuter et al. (2005); and Sullivan et al. (accepted).
- To examine the relationship between ^{10}Be concentration and grain size in the context of previous research by Matmon et al. (2003b), Brown et al. (1995), Clapp et al. (1997, 1998, 2001, 2002), and Sullivan et al. (accepted).

Introduction - Physical Setting

low-amplitude folds and flat lying, gently folded strata

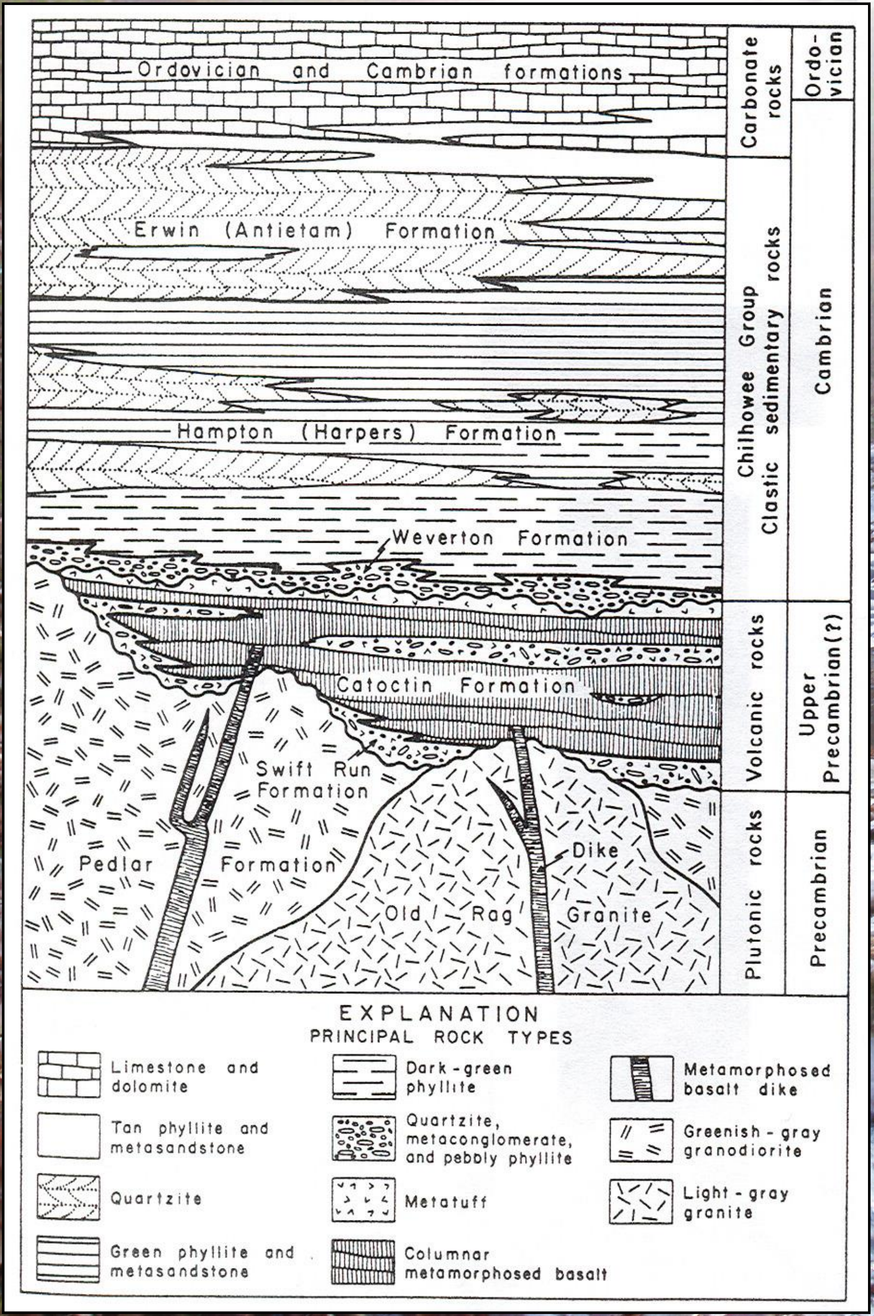
linear, parallel ridges and valleys



anticlinorium with a core of crystalline and metamorphosed sedimentary and volcanic rocks

low-relief area with deeply weathered and saprolitized bedrock

Cretaceous and Tertiary sediments



Principle Rock Types

Granite - Old Rag Granite and Pedlar Formation (Granodiorite)

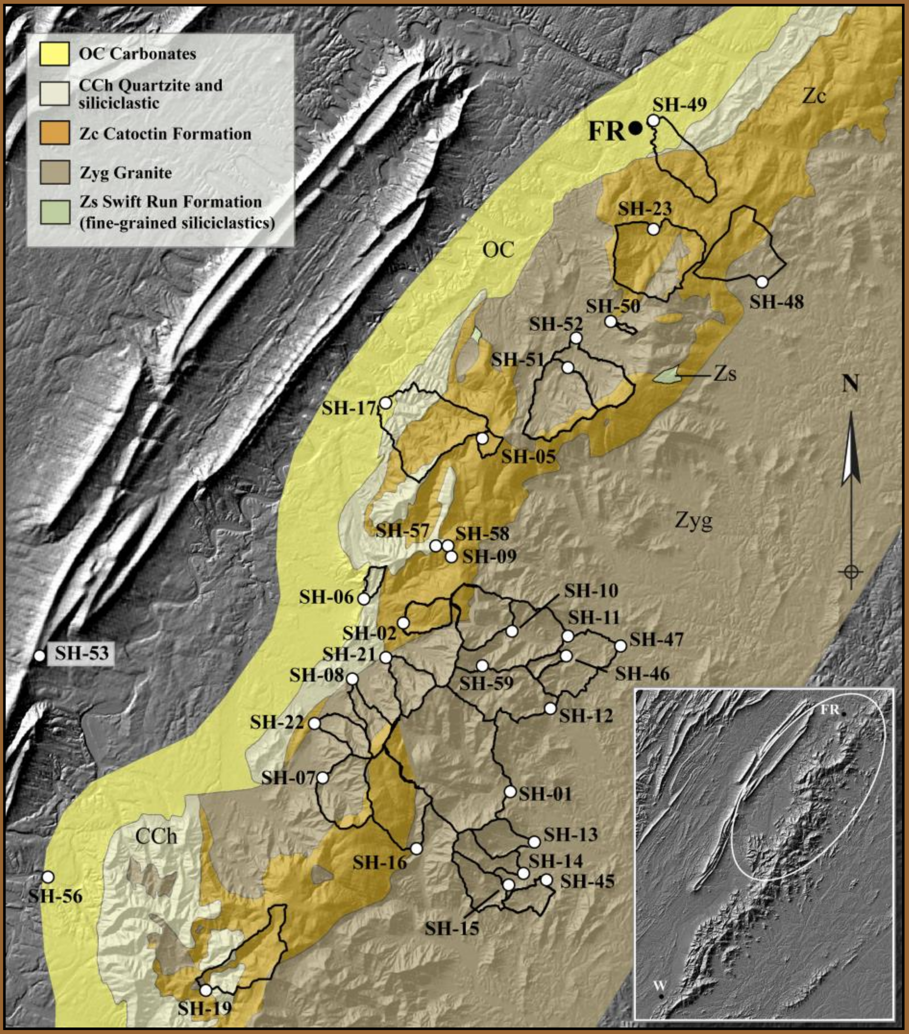
Quartzite - Erwin and Swift Run formations

Metabasalt - Catoctin Formation

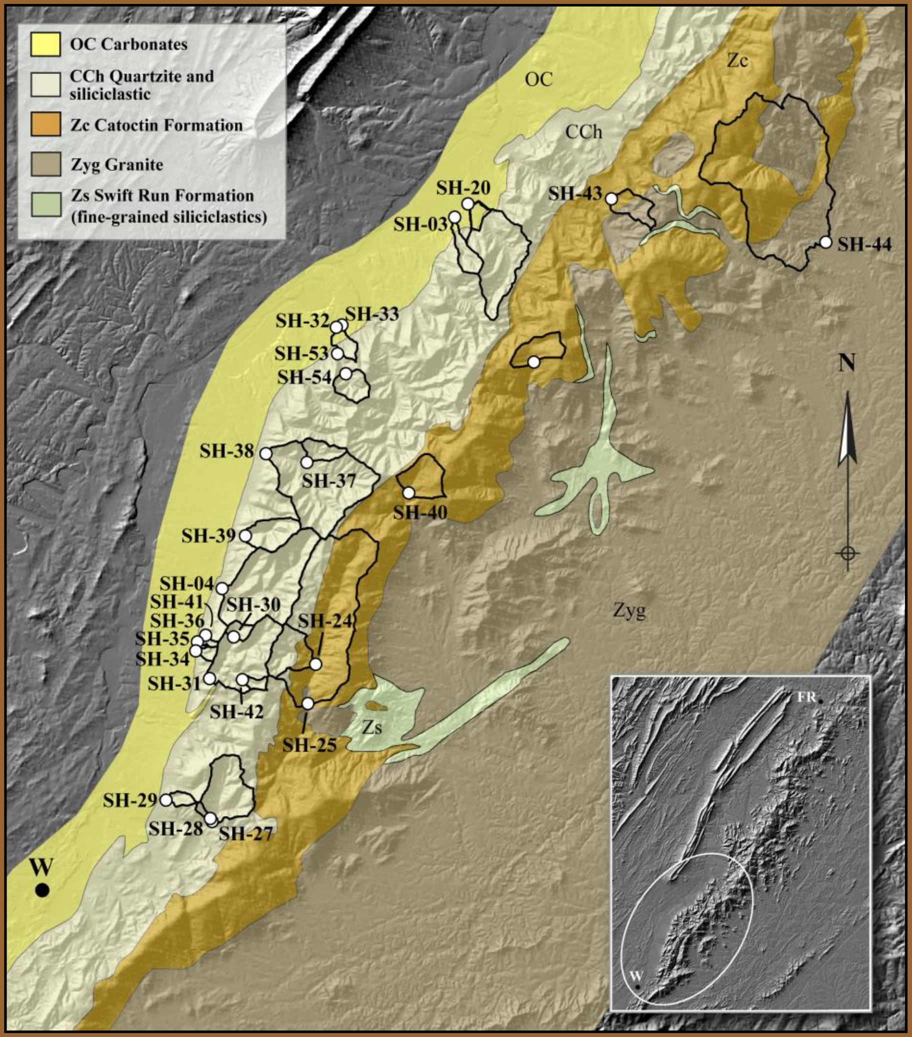
Siliciclastic Rocks - Weverton and Hampton Formations

Introduction - Physical Setting

Northern Section



Southern Section



Techniques for Estimating Erosion Rates

- **Sediment Yields - years to decades timescale**

- **Cosmogenic Isotopes - 10^3 - 10^5 years**

- **Thermochronology**
  - $^{40}Ar/^{39}Ar$
  - (U-Th)/He
  - Fission-track

  10^5 - 10^7 years timescale

The Use of ^{10}Be to Monitor Erosion Rates

Why use ^{10}Be?

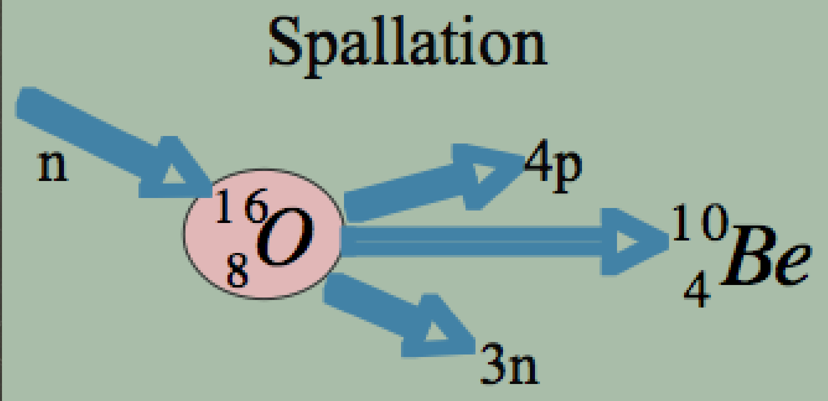
- ❖ It provides erosion rates over intermediate timescales (10^3 - 10^5 years)
- ❖ It is the longest-lived of the unstable cosmogenic isotopes (1.5×10^6 years)
- ❖ Easily measured in quartz
- ❖ Widely distributed on Earth's surface
- ❖ Easily separated from other minerals

Cosmogenic Isotopes

Cosmic Rays

- In Situ Cosmogenic Nuclides:

  ^{3}He, ^{10}Be, ^{21}Ne, ^{26}Al, ^{36}Cl
- 10^3 - 10^5 yrs timescale



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

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

Production Rate Curve

$$P_{\chi} = P_{o}e^{-(\rho(\chi)/\Lambda)}$$

Where:

$P\chi$ = nuclide production rate at depth x (atoms g^{-1} yr^{-1})

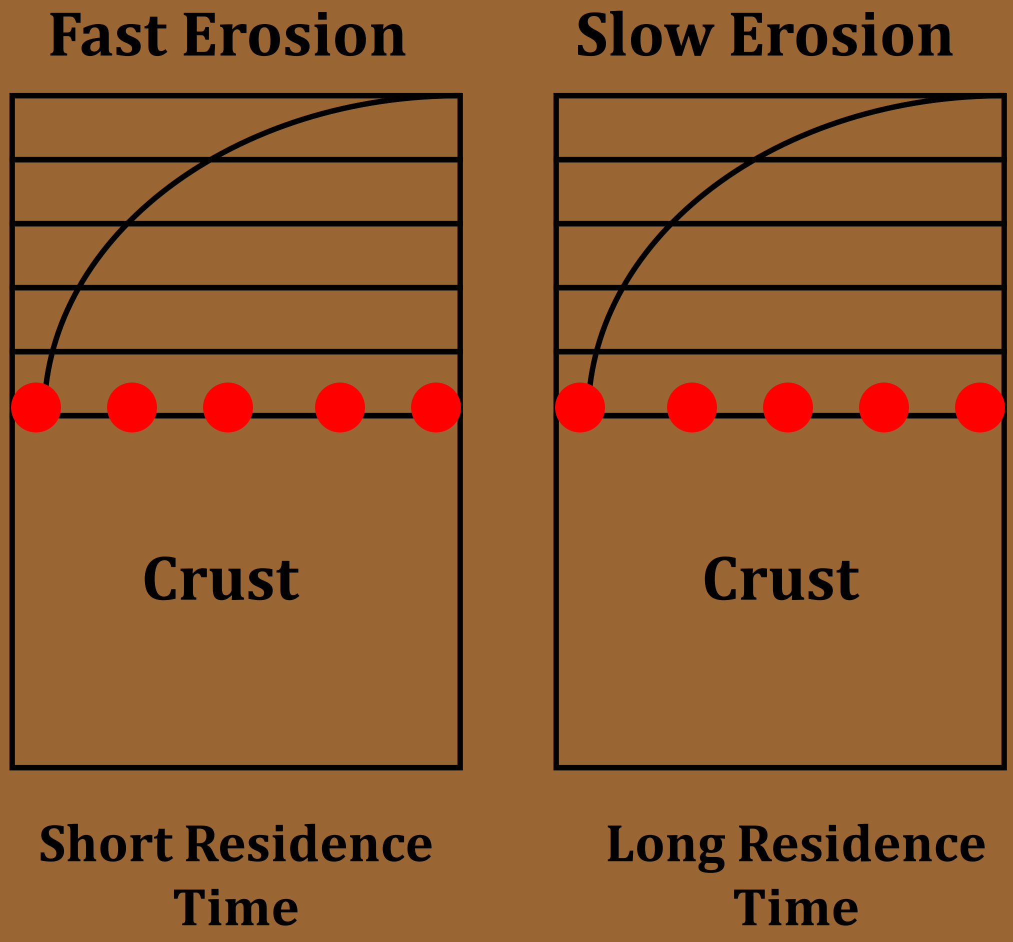
P_o = sediment production rate (5.17 atoms g^{-1} yr^{-1})

ρ = density of material (2.7 g cm^{-3} for rock)

Λ = attenuation factor 165 cm g^{-2}

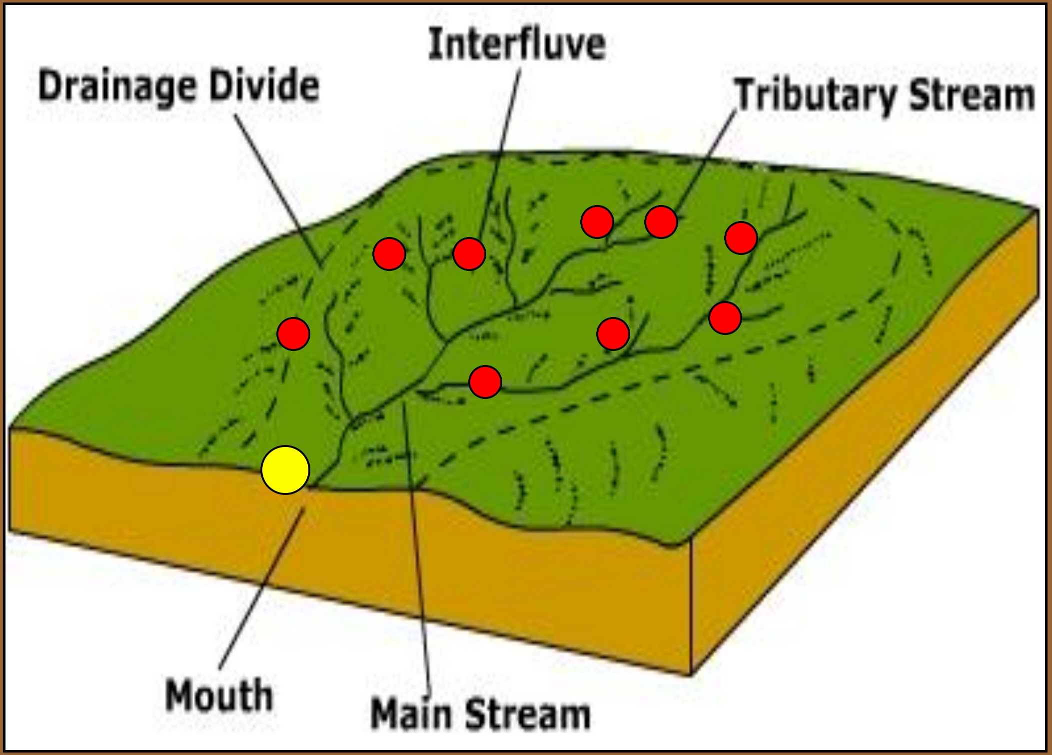
Inferring Basin Scale Erosion Rates

- ^{10}Be accumulation increases near the surface
- ^{10}Be concentration is high in slowly eroding basins



Inferring Basin Scale Erosion Rates

- ❖ Rivers transport sediments from basins, therefore, concentration of ^{10}Be in stream sediment indicates sediment production rate



- ❖ Corrections are applied to account for basin altitude and latitude
- ❖ Time Scale of erosion rates = 10,000-100,000 years

Assumptions

- Steady state erosion e.g. erosion is constant and continuous - rate of uplift and erosion remain unchanged over time.
- Isotopic concentration of all sediment being generated and transported out of a basin is constant over time - tested by Matmon in the Great Smoky Mountains.
- For both sediment and bedrock it is assumed that the cosmic ray flux is constant over time, that there has been no ephemeral shielding from soil, snow, or sediments, and that the nuclide production rate is known.
- For sediment, additional assumptions include constant or minimal sediment storage in the sampled basin, steady rates of erosion, adequate mixing of sediment, and homogenous quartz distribution.

Methods

- GIS analysis
- Sample collection
- Laboratory methods
- Calculation of erosion rates from ^{10}Be concentrations

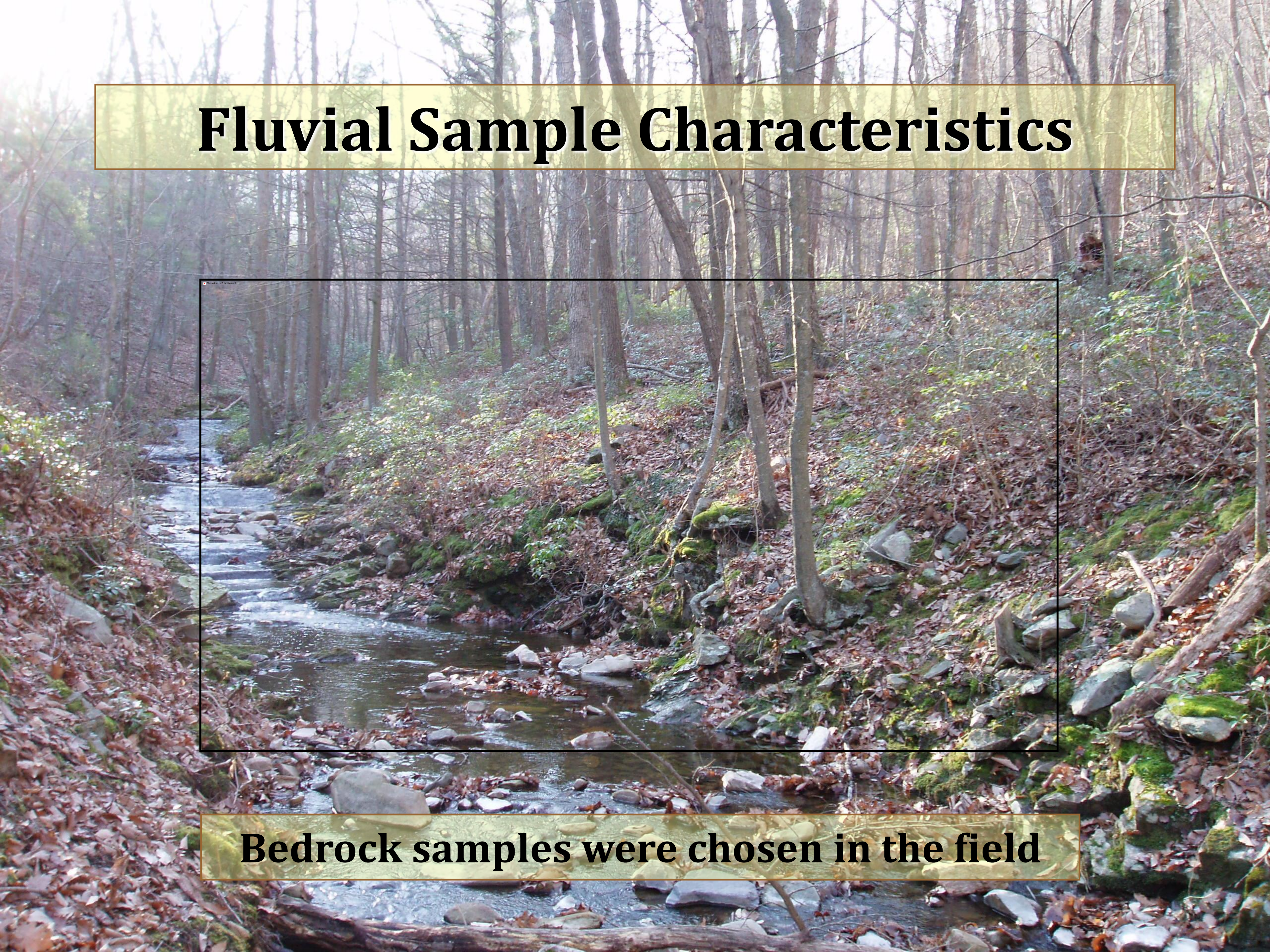
GIS Analysis

- Delineation of drainage basins, using USGS 10m DEM's (Digital Elevation Models) along with bedrock geology and National Hydrography Datasets (NHD) provided the stream layer.
- Database from which to define basins of appropriate size.
- Sampling sites chosen according to specific criteria including basin size, mean slope and lithology.

Sampling Strategy – Basin Selection

- To test the effect of lithology on erosion rates using the four major lithologies within the Park - granite, metabasalt, quartzite, and siliciclastic rocks, and original parameters.
- Sediment was sampled from 41 single-lithology basins (including two temporal replications), 11 multilithology basins, and 5 bedrock outcrops.
- Four initial sample sites, one for each lithology, were collected in the following grain-size splits At these first four sample sites grain-size splits, (0.25 – 0.85 mm, 0.85 – 2 mm, 2 – 10 mm, and >10 mm) in order to test the relationship between ^{10}Be concentrations and grain size.

Fluvial Sample Characteristics



Bedrock samples were chosen in the field

Sample Collection

- 54 samples from active river or stream channels (0.5 - 1 kg of sediment)
- All samples sieved to the 0.25 - 0.85 mm size fraction
- 5 bedrock samples (~ 1 kg)

Laboratory Methods

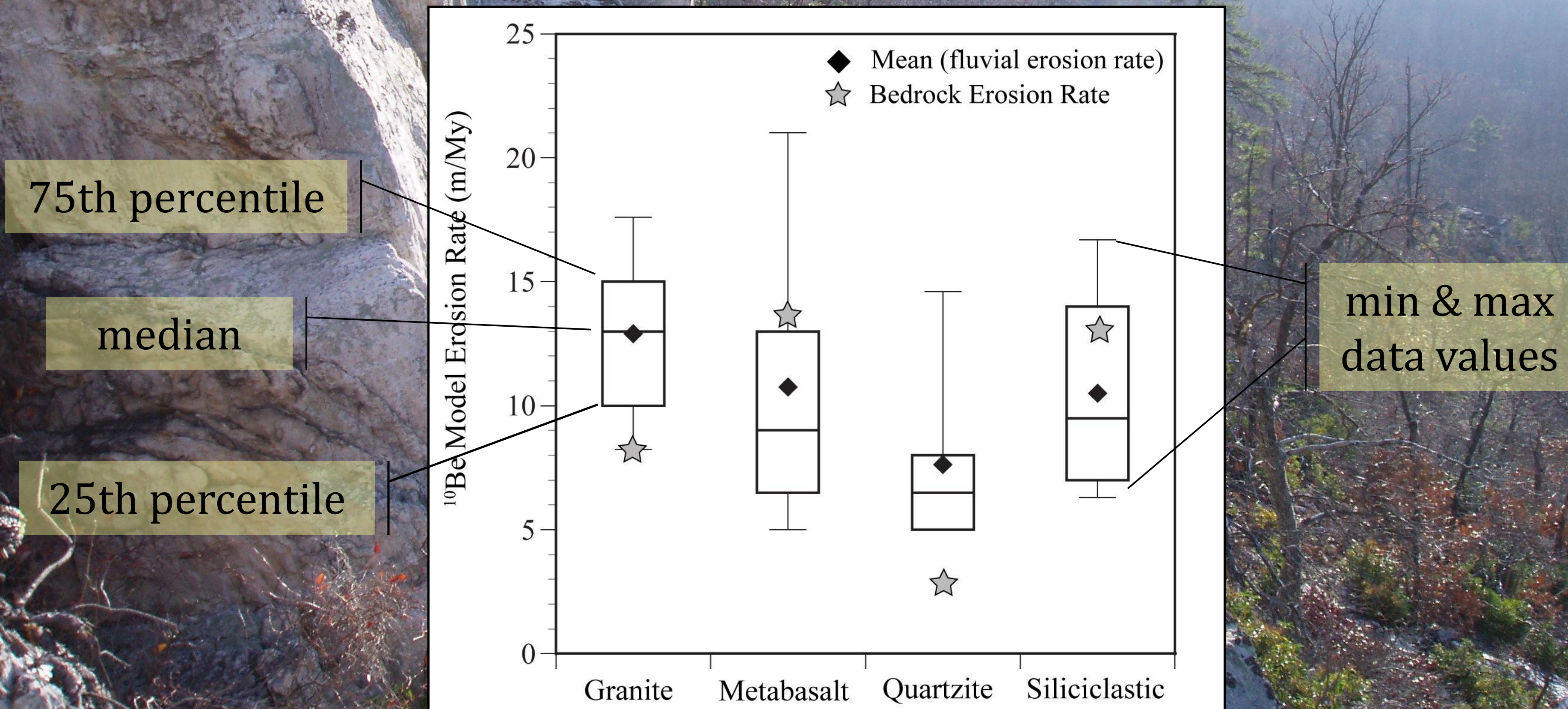
- Quartz was purified in the UVM Mineral Separation Lab:
  - Two 24-hour ultrasonic etches of samples in hot 6N HCl.
  - Three 24-hour ultrasonic etches in dilute HF/HNO_3.
  - Density separation to remove heavy minerals such as magnetite and ilmenite.
  - 48-hour etch in dilute HF/HNO_3.
- ^{10}Be was isolated in the UVM Cosmogenic Laboratory (grain-size splits).
- The ^{10}Be isolated from the grain-size splits was measured using accelerator mass spectrometry (AMS) at the Lawrence Livermore Laboratory.
- The remaining samples were processed to isolate ^{10}Be at the GU-SUERC Cosmogenic Nuclide Laboratory (CNL) at the Scottish Universities Environmental Research Centre in East Kilbride, Scotland.

Calculation of Erosion Rates from ^{10}Be Concentrations

- ^{10}Be concentrations of the initial four samples with grain-size splits were normalized using standards developed by Nishiizumi at LLNL assuming a ^{10}Be half-life of 1.5 My.
- The remaining samples analyzed at CNL using the standard NIST (SRM4325) (National Institute of Standards and Technology.
- ^{10}Be concentrations of all the samples were then corrected for latitude-altitude based on the polynomials of Lal (1988) for neutrons only.
- Basin scale erosion rates were modeled using the interpretive model of Bierman and Steig (1996) with a normalized sea level, high latitude ^{10}Be production rate of 5.2 atoms g^{-1} quartz yr^{-1}, an attenuation depth of 165 g cm^{-2}, and assuming a rock density of 2.7 g cm^{-3}.

Data - Bedrock Samples

- ❖ **Erosion rates for these samples range from 2.4-13.0 m/My**

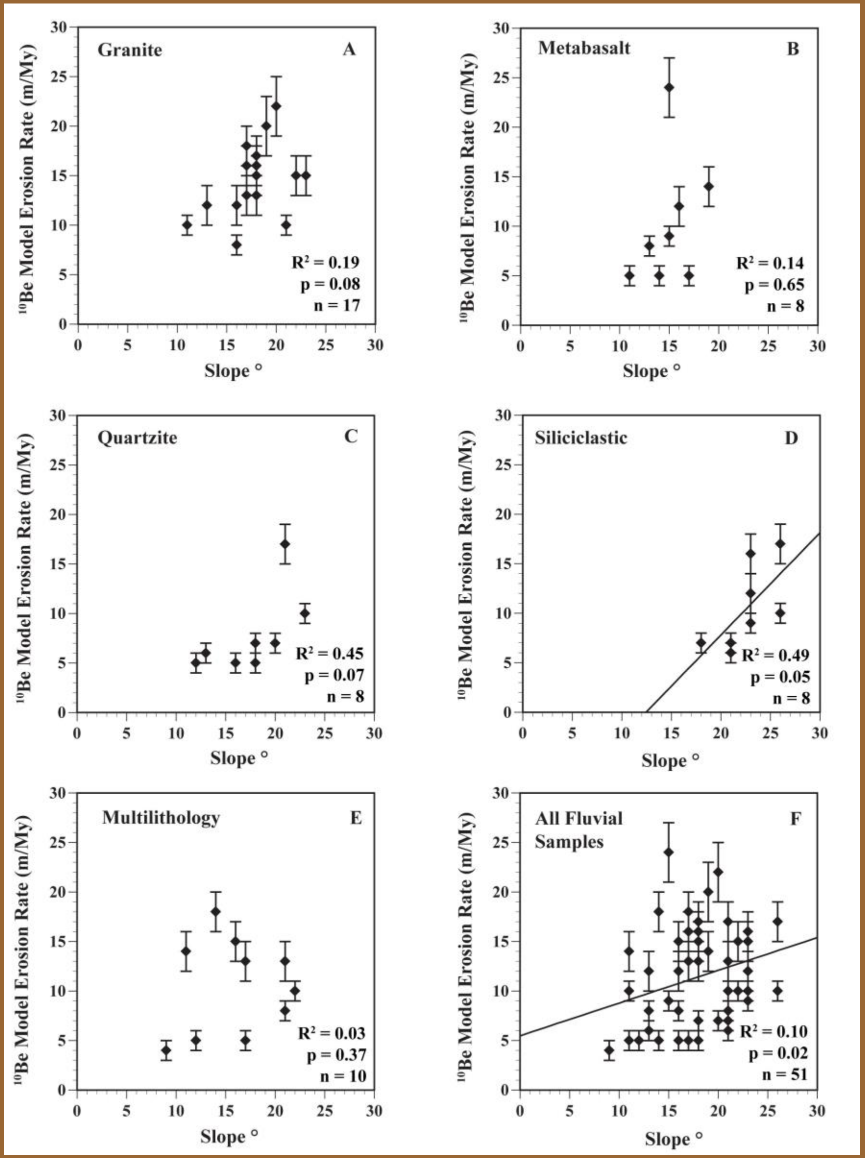


Data - Fluvial Samples

- Inferred erosion rates for the basins range from 3.8 ± 0.5 - 23.6 ± 3.0 m/My for all lithologies.
- The mean erosion rate for single-lithology basins is 11.3 ± 4.8 m/My (n = 43).
- The erosion rate ranges by lithology are:
  - granite, 7.9–21.8 m/My;
  - metabasalt 4.8– 23.6 m/My;
  - quartzite 4.7–16.8 m/My;
  - siliciclastic rocks 6.2–16.7 m/My.
- The mean erosion rate for multilithology basins (n = 11) is 10.2 ± 4.6 m/My, with a range of 3.8-17.6 m/My.
- Erosion rates for the Shenandoah and Rappahannock Rivers are 7.3 ± 0.9 m/My and 13.8 ± 1.8 m/My, respectively.

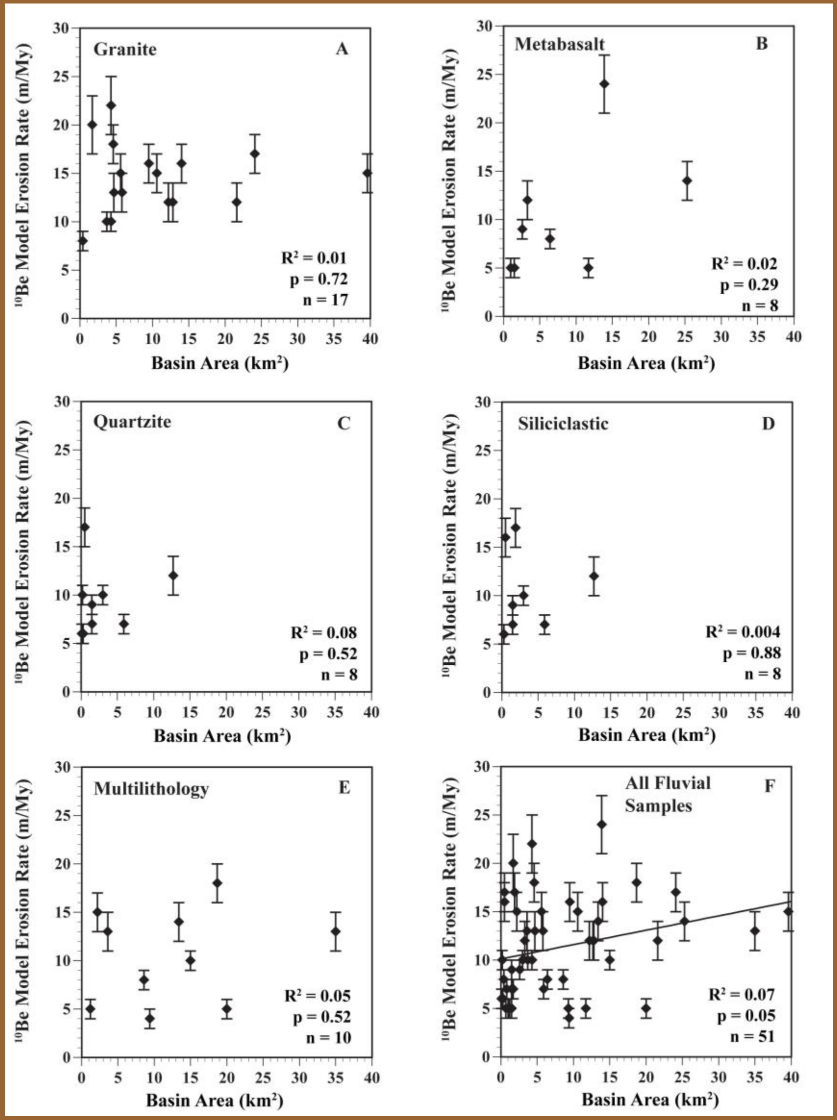
Data - Fluvial Samples By Lithology

^{10}Be modeled erosion rate (m/My)vs. slope (°)



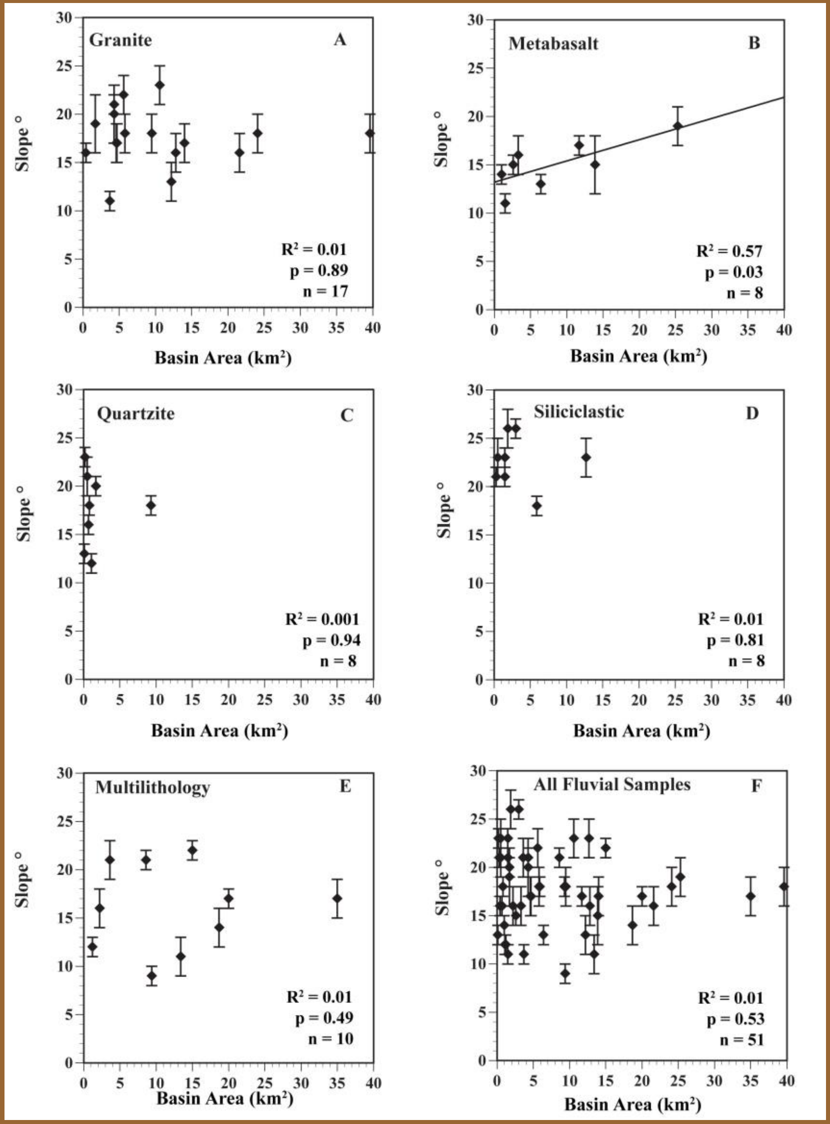
Data - Fluvial Samples By Lithology

^{10}Be modeled erosion rate (m/My) vs. basin area (km^2)



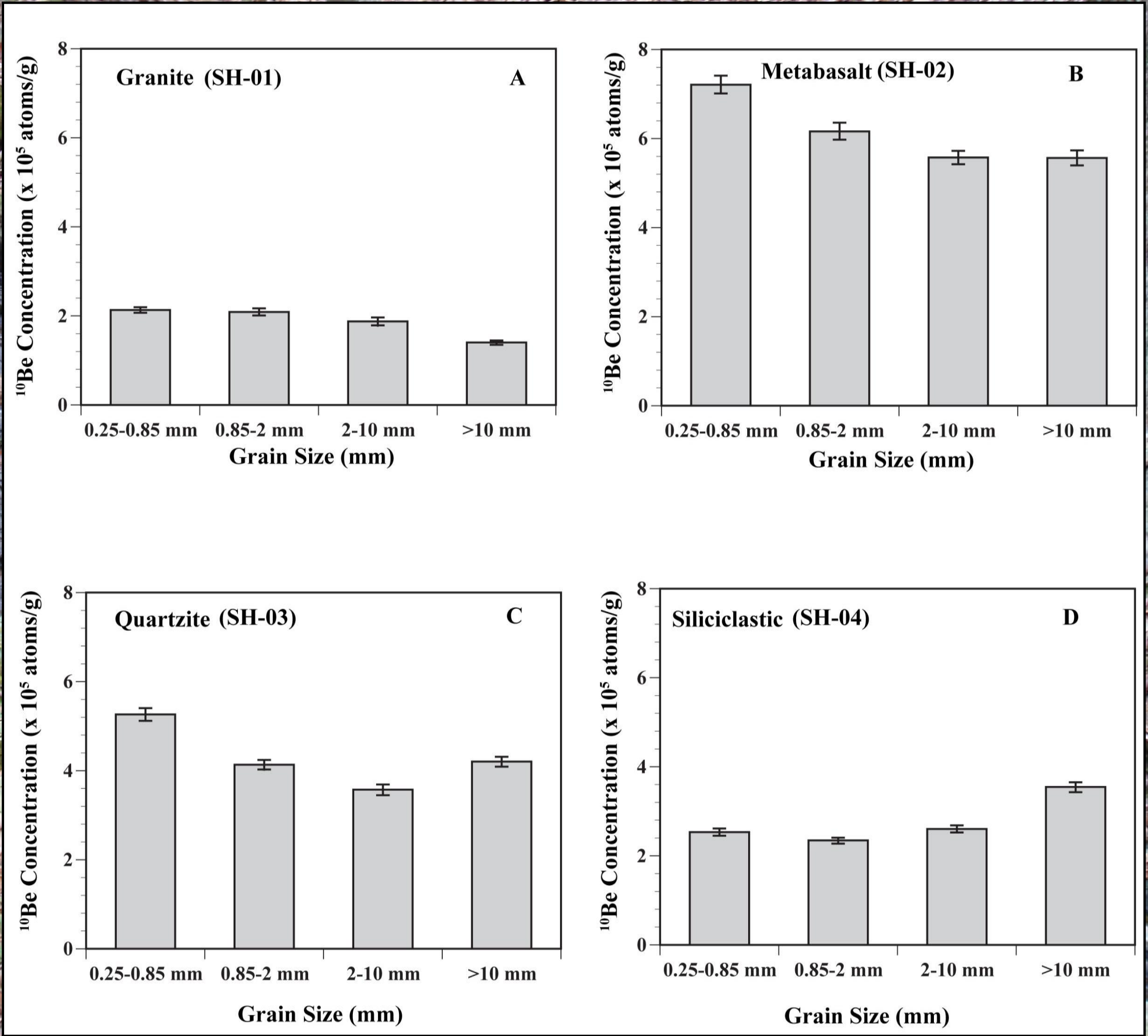
Data - Fluvial Samples By Lithology

Slope (° 0) vs. basin area (km²)



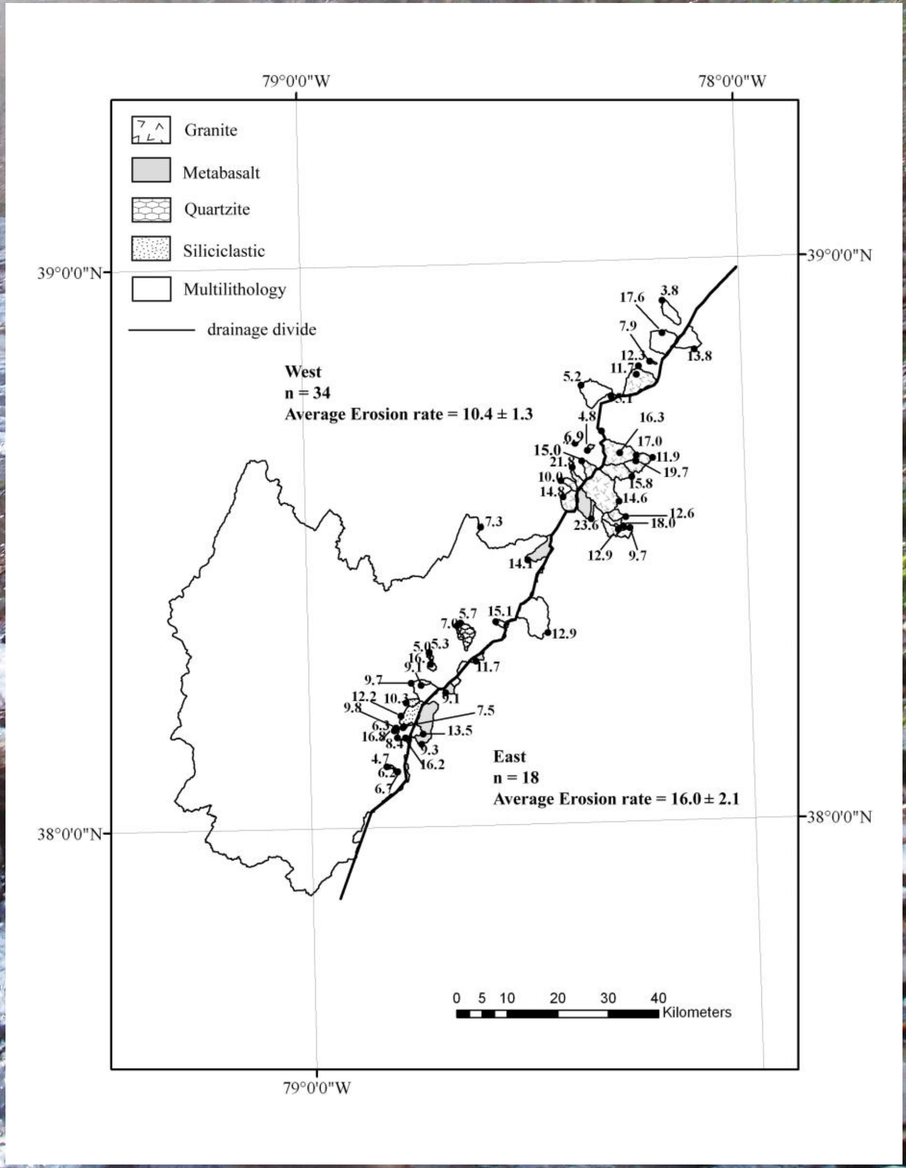
Data - Grain-Size Analysis

- Grain-size specific ^{10}Be analysis of four samples showed a monotonic decrease in ^{10}Be concentration with grain-size in 2 of the 4 samples.



Data - Fluvial Samples By Aspect

- Erosion rates on the eastern side of the divide are faster than on the west.
  - East = ~16 m/My
  - West = ~10 m/My

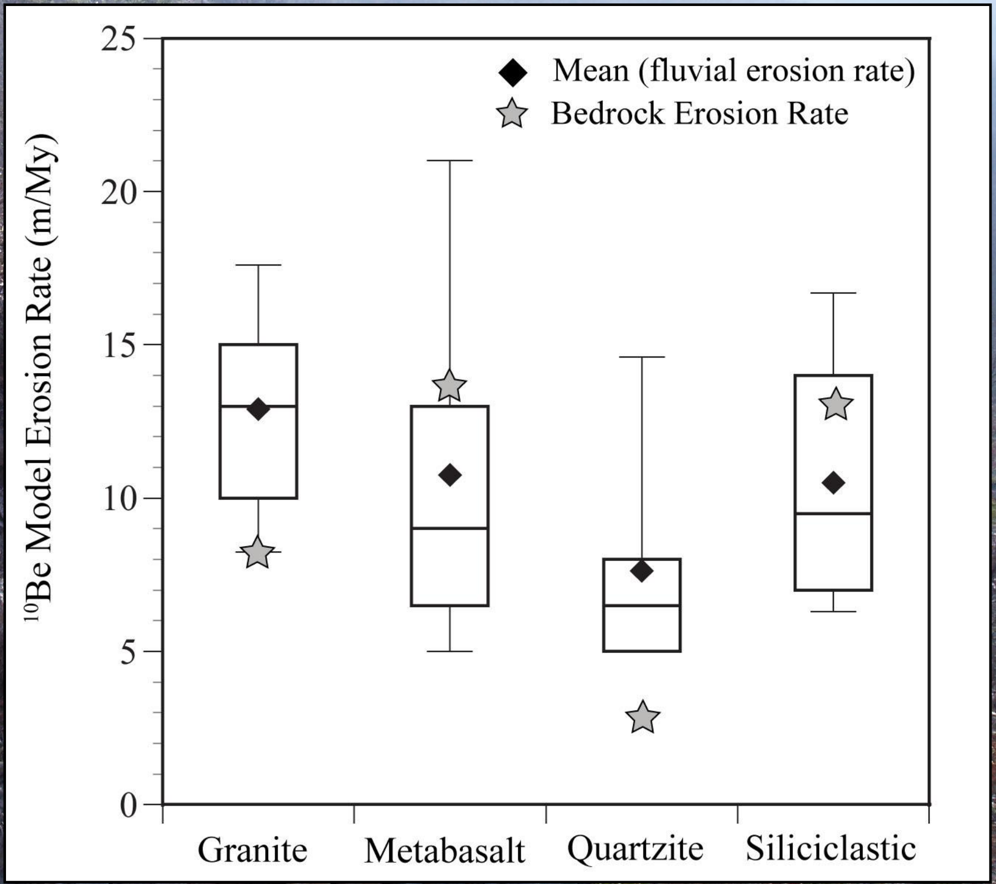


Objectives - Discussion

To determine whether average erosion rates differ between the four lithologies cropping out in the Blue Ridge province within the Shenandoah National Park, and to compare the relationships between ^{10}Be-based erosion rates and slope, basin area

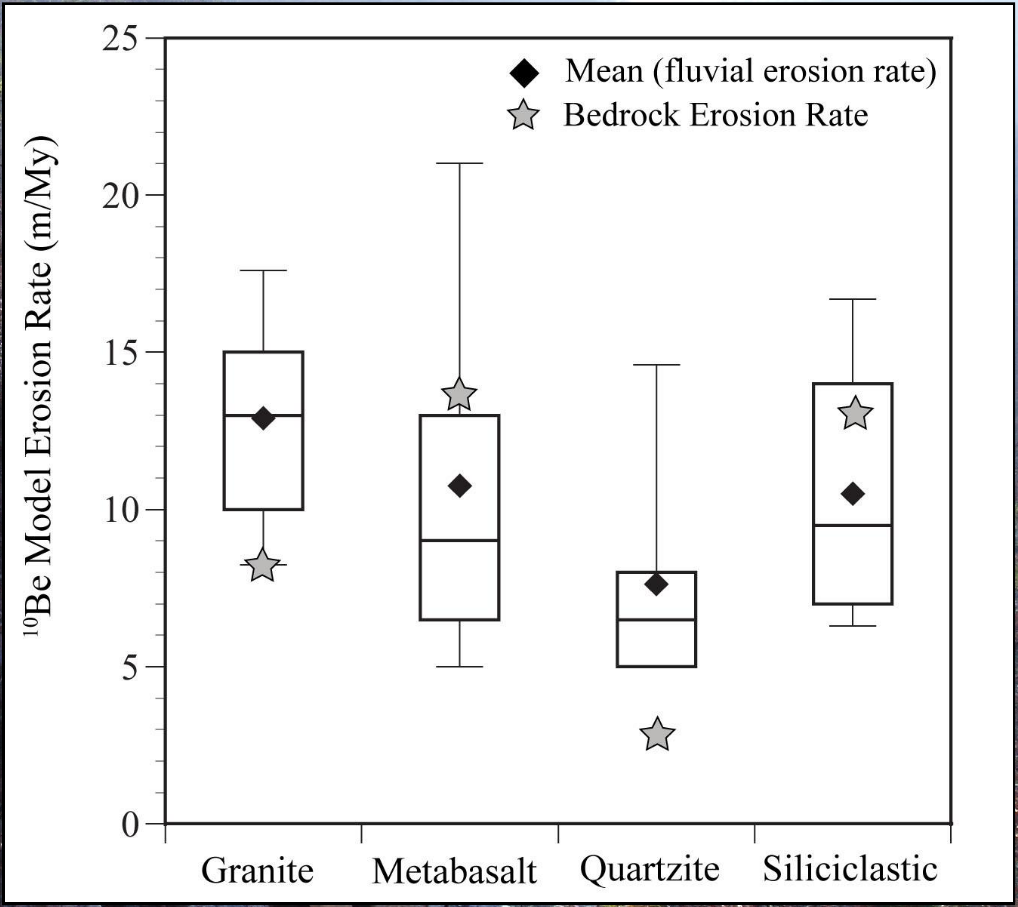
Discussion: Comparing Erosion Rates - Bedrock

- The range of bedrock (2.4-13 m/My, n = 5) and single-lithology, basin-scale erosion rates (4.7 to 24 m/My, n = 42) overlap.
- Bedrock outcrops are eroding more slowly on average (μ = 7.9 ± 5.0 m/My, n = 5, p = 0.001) than single-lithology drainage basins (μ = 11.6 ± 4.8 m/My, n = 42).
- This discrepancy between bedrock and fluvial erosion rates has been noted elsewhere (Bierman and Caffee, 2001; Clapp and others,2001; Clapp and others, 2002; Reuter, 2005).



Discussion : Comparing Erosion Rates - Lithology

- **In the Shenandoah National Park area, there are few statistically significant relationships between landscape-scale metrics and fluvial erosion rates.**
- **Only quartzite was significantly different from granite when comparing erosion rates (p =0.001)**

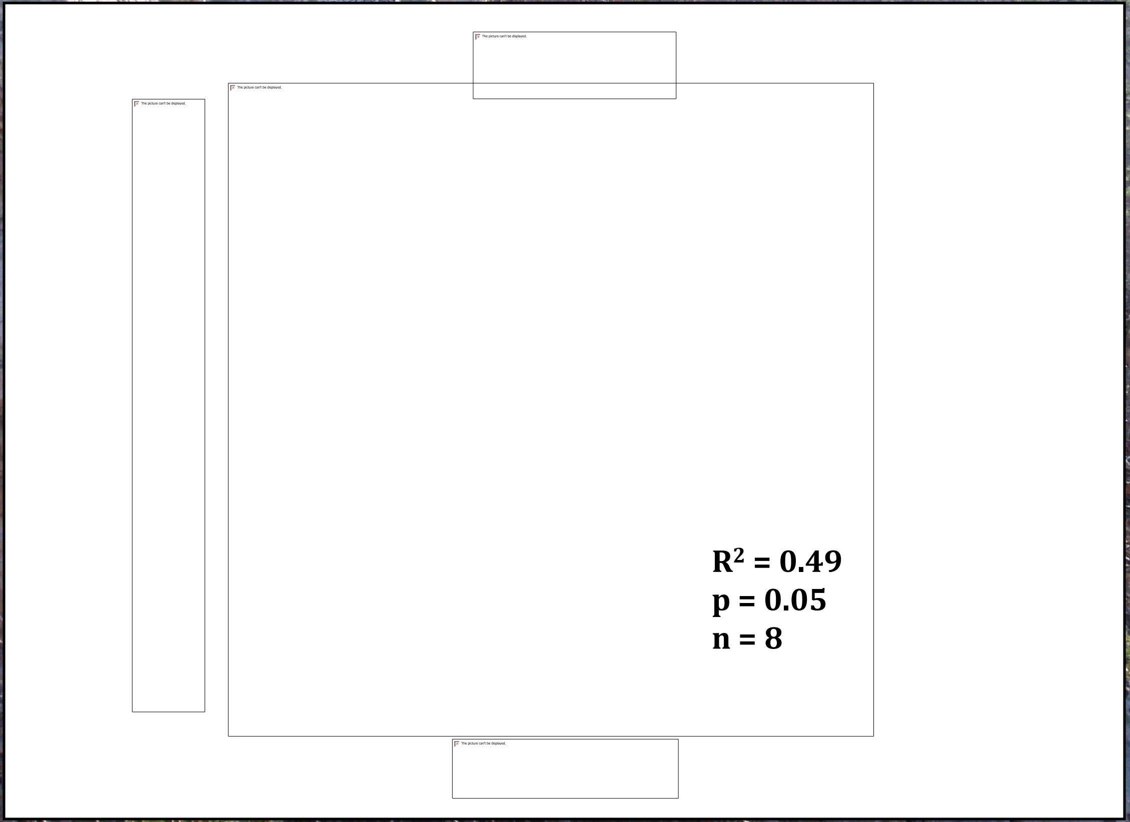


Discussion: Comparing Erosion Rates - Lithology

- The lack of a definitive relationship between basin-scale erosion rates and lithology echoes previous work in the Great Smoky Mountains (Matmon and others, 2003a; Matmon et al., 2003b), the Susquehanna River Basin (Reuter, 2005), and Namibia (Bierman and Caffee, 2001).

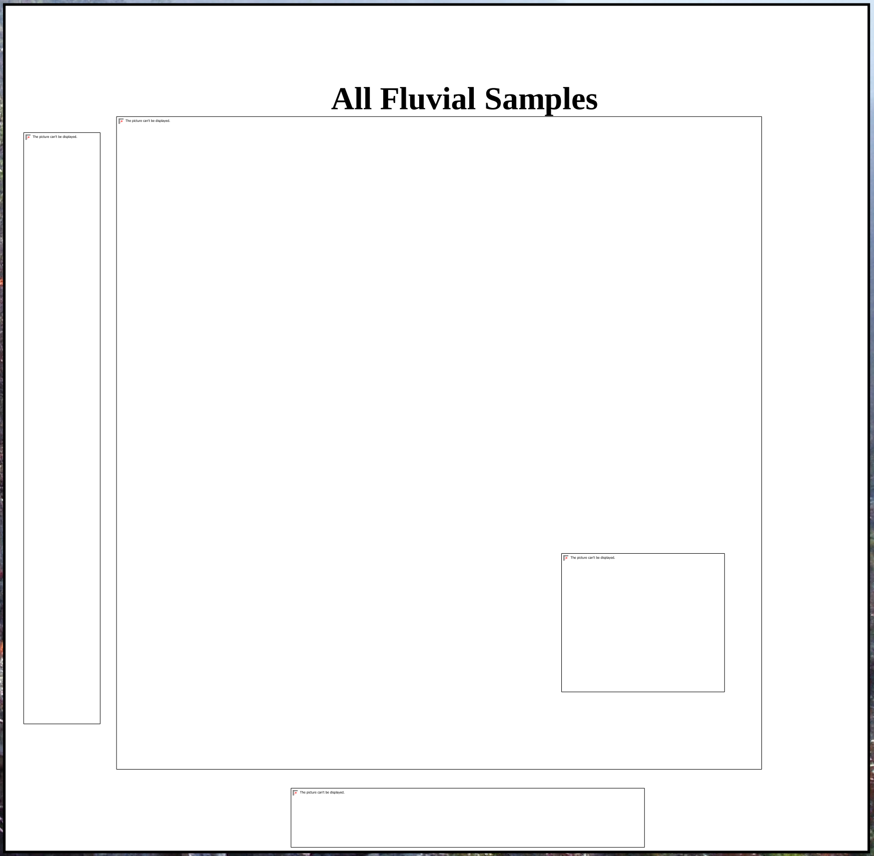
Discussion: Comparing Erosion Rates - Lithology

- ❖ **Siliciclastic rocks are the only lithology for which there is a significant correlation between erosion rate and slope ($p = 0.05$, $R^2 = 0.49$).**



Discussion: Comparing Erosion Rates - Lithology

- There is a significant relationship between cosmogenically-estimated erosion rates and basin area for all samples, but the relationship is very weak (R^2 = 0.07).
- The variability of erosion rates appears to decrease with increasing basin area, similar to results elsewhere in the Appalachian Mountains and consistent with fluvial mixing downstream (Matmon et al., 2003a; Matmon et al., 2003b; Reuter, 2005; Sullivan et al., accepted).



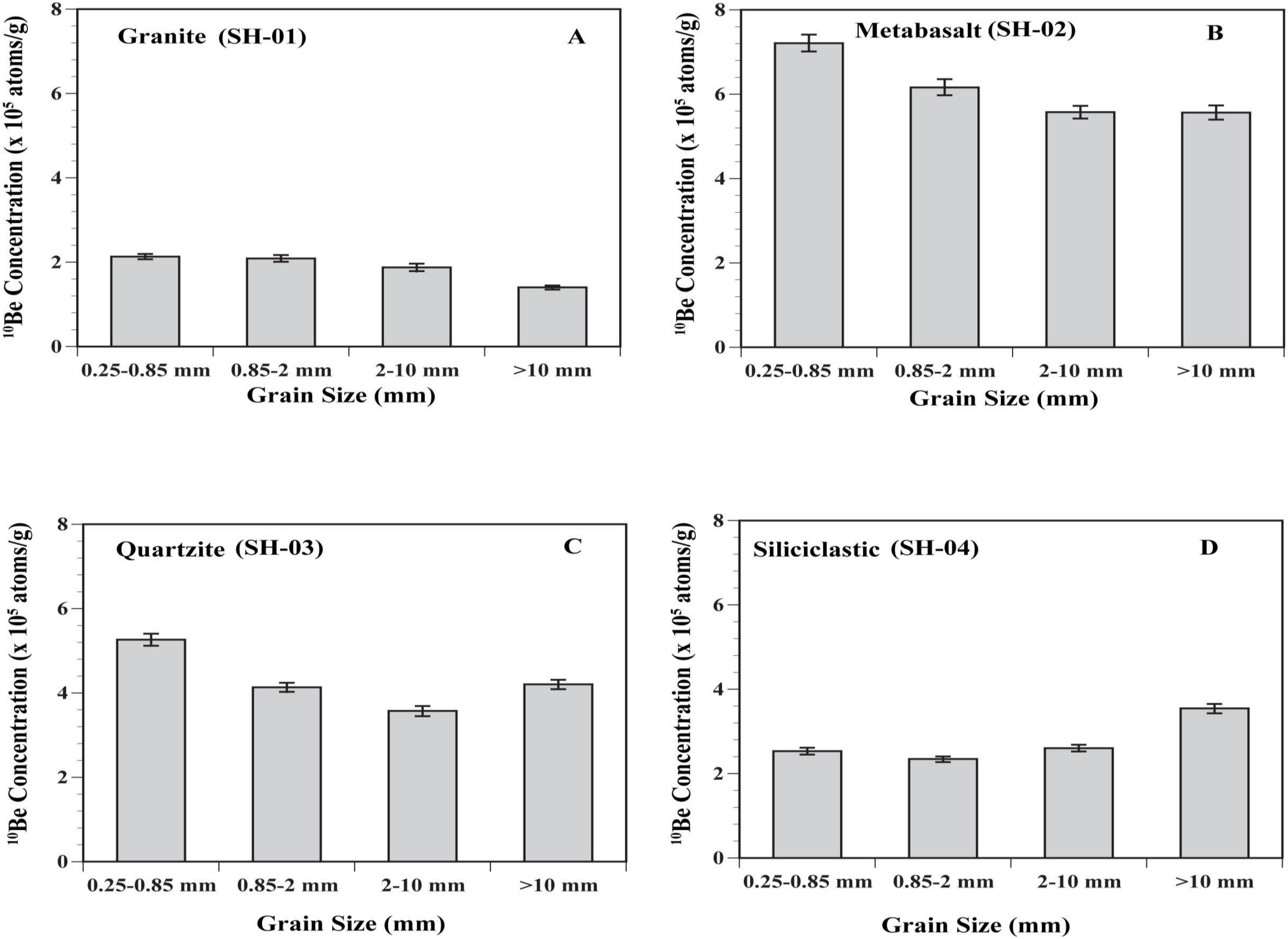
Objectives - Data

To examine the relationship between ^{10}Be concentration and grain size in the context of previous research by Matmon et al. (2003b), Brown et al. (1995), Clapp et al. (1997, 1998, 2001, 2002), and Sullivan et al. (accepted).

Discussion: Comparing Erosion Rates - Grain-Size Analysis

Objective - to determine whether grain-size influences ^{10}Be concentration in fluvial sediment.

- Brown et al. (1995) suggested that lower ^{10}Be concentrations in larger grain sizes could result from mass wasting events that excavate and carry previously shielded coarse material rapidly down slope.
- Matmon et al. (2003) suggested that the systematic difference in ^{10}Be concentrations between small and large grains in the Great Smoky Mountains results from source area elevation and clast transport distance.



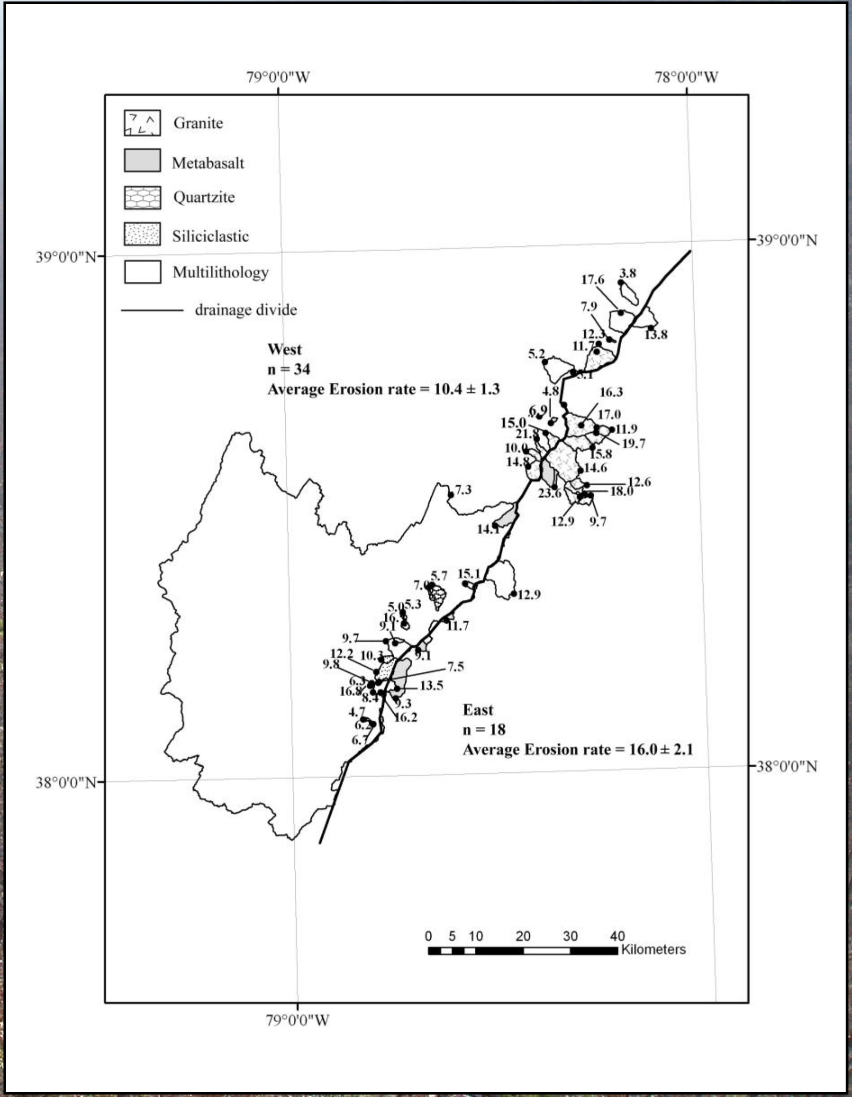
Granite (SH-01)
A
Metabasalt (SH-02)
B
Quartzite (SH-03)
C
Siliciclastic (SH-04)
D
^{10}Be Concentration (x 10^5 atoms/g)
0
2
4
6
8
0.25-0.85 mm
0.85-2 mm
2-10 mm
>10 mm
Grain Size (mm)

Discussion : Comparing Erosion Rates - Grain-Size Analysis

- Grain-size specific cosmogenic analysis of four sediment samples showed no consistent trend of concentration and indicate ~26 to 34 % differences on average between the sand-fraction (250-850 mm) analyzed and larger grain sizes.
- Differences may account for the variability in calculated erosion rates observed between basins and may reflect different source areas or processes delivering different grain sizes to the channels.

Discussion: Comparing Erosion Rates - East/West Divide

- Basin erosion rates on the eastern side of the divide are faster (μ = 16.0 ± 2.1 m/My) than those on the west (μ = 10.4 ± 1.3 m/My) (p = 0.001)
- East-west variations are mirrored by the erosion rates obtained from two of the major rivers draining the Park, the Rappahannock River to the east (13.8 m/My) and the Shenandoah River to the west (7.3 m/My)
- East-west dichotomy may be:
  - a function of rock type
  - pre-Miocene drainage migration
  - Miocene drainage capture



Objectives

To compare the relationships between ^{10}Be-based erosion rates and slope, basin area and lithology with other Appalachian Mountain range studies such as Matmon et al. (2003a, 2003b); Reuter et al. (2005); and Sullivan et al. (accepted).

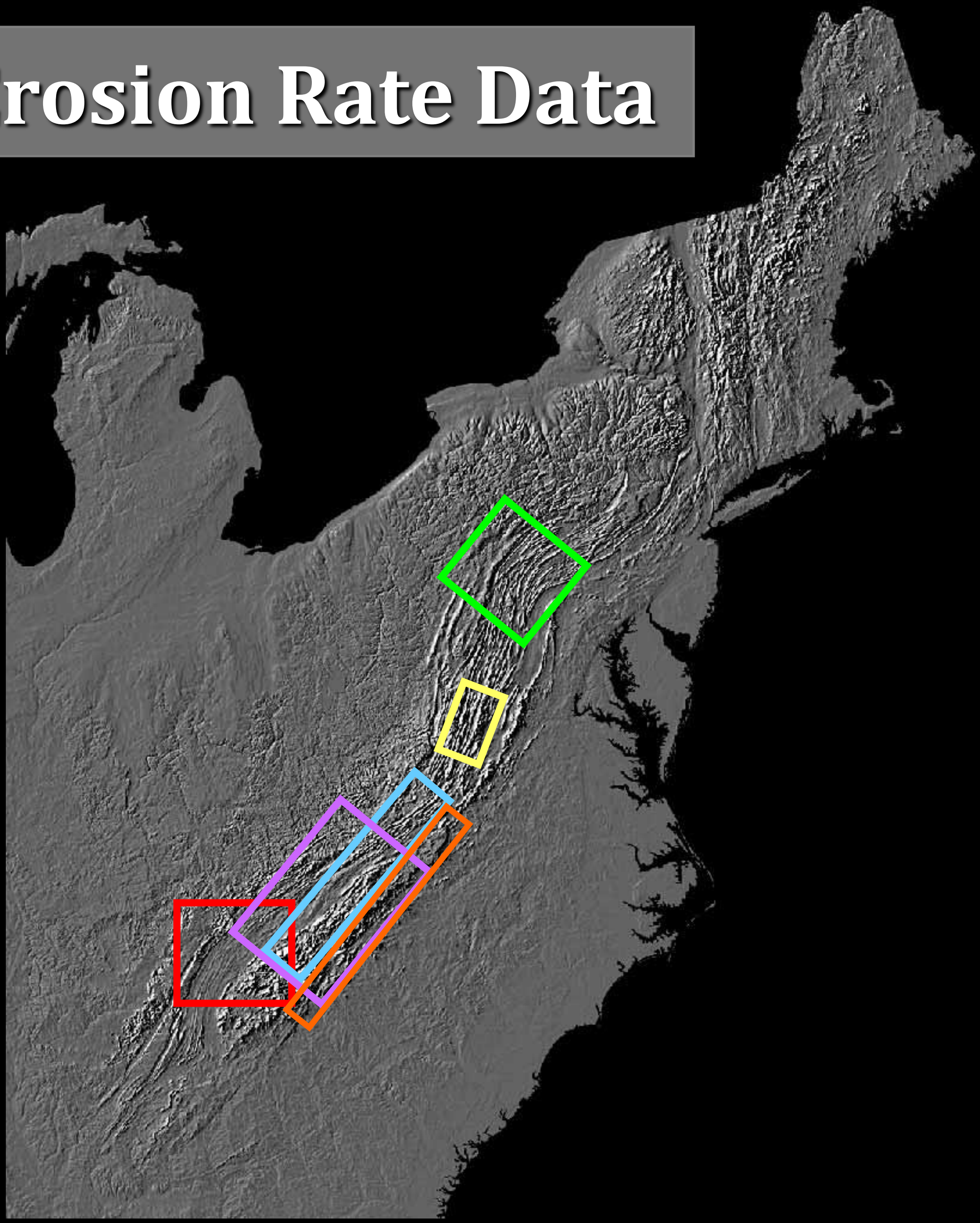
Placing Shenandoah Region Erosion Rates in Context

- **Cosmogenically determined bedrock and basin-scale erosion rates for the Shenandoah National Park region (~11 m/My) are in general consistent with those estimated elsewhere in the Appalachian Mountains: in schist and gneiss (12.5 m/My) for the Blue Ridge just above the Blue Ridge Escarpment (Sullivan et al., accepted), ~300 km to the south; and are similar to those in the Valley and Ridge of the Susquehanna River (13 m/My; Reuter et al., 2005).**
- **Rates do vary in other areas of the Southern Appalachians: in the Great Smoky Mountains (27 ± 6 m/My); Matmon et al., 2003a; Matmon et al., 2003b).**
- **The average bedrock erosion rates around Shenandoah (7.9 ± 5.0 m/My) are similar to the sandstone on the Appalachian Plateau at Dolly Sods, West Virginia (5.7 m/My) (Hancock and Kirwan, 2007), and of the granite of Panola Mountain in the Georgia Piedmont (7 m/My; Bierman, 1993).**

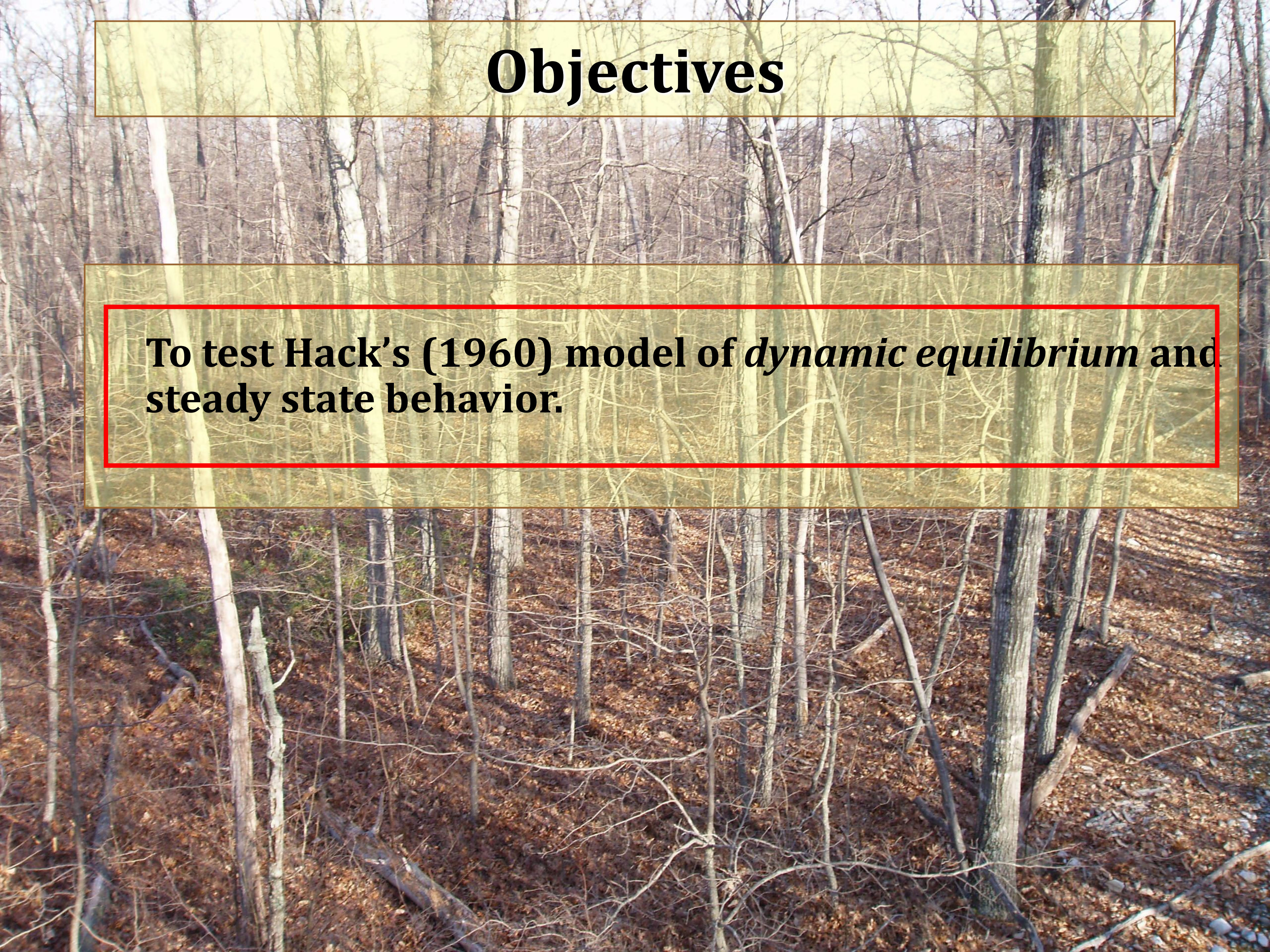
Appalachian Erosion Rate Data

Erosion rates in the context of other research:

- Matmon et al. (2003)
  25 - 30 m/My
- Reuter et al. (2004)
  4 - 54 m/My
- Spotila et al. (2004)
  10 - 20 m/My
- Naeser et al. (2005)
  20 m/My
- Sullivan et al. (2007)
  12.5 m/My
- This study
  11 m/My



Objectives



To test Hack's (1960) model of *dynamic equilibrium* and steady state behavior.

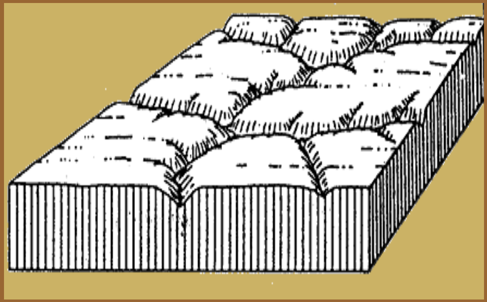
Hack's *Dynamic Equilibrium*

Why does the Blue Ridge of the Shenandoah National Park area look the way it does?

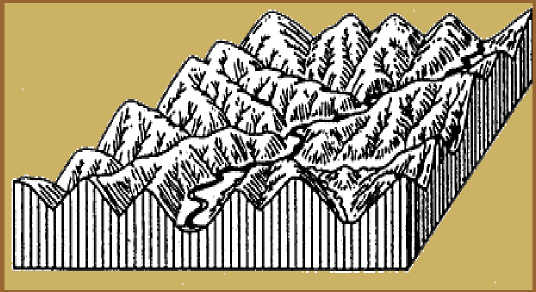
- Cosmogenic data suggests that there is no correlation between erosion rate and basin average slope in the Park.
- This is in contrast to elsewhere in the Southern Appalachians such as the Great Smoky Mountains, the Blue Ridge Escarpment, and the Susquehanna Drainage Basin where erosion rate and slope are positively and significantly correlated.
- We can explore this independence of erosion rate from slope, lithology, and basin area via Hack's (1960) model of *dynamic equilibrium.*

Hack's *Dynamic Equilibrium*

Uniformly eroding topography



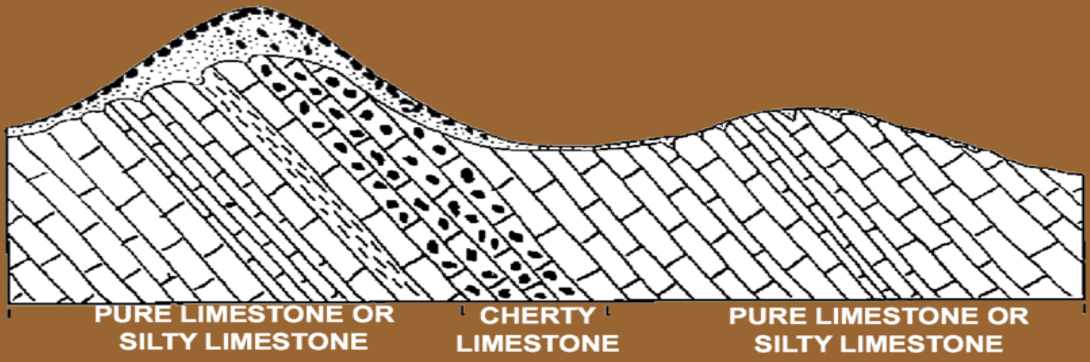
"Youth"



"Maturity"

"Old Age"

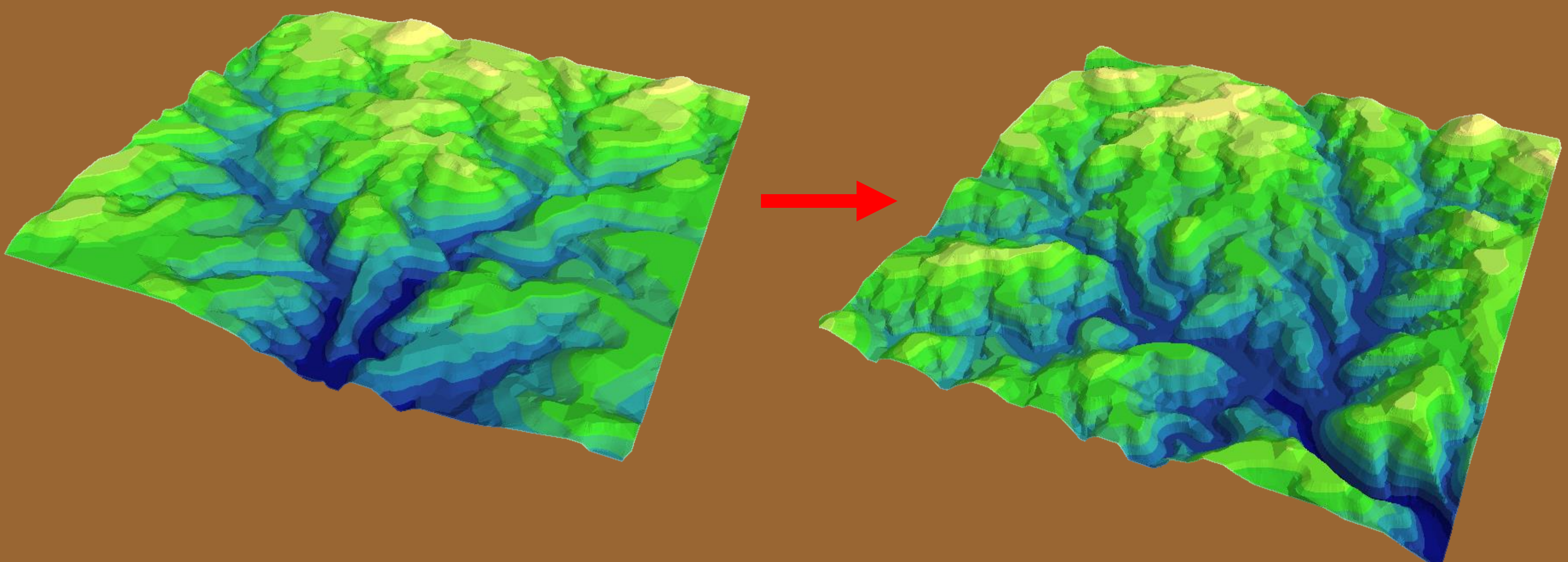
Differences in erosional resistance or rock strength are compensated for by slope



"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."

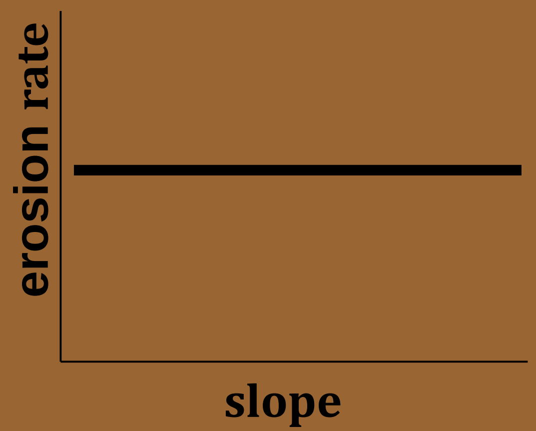
Hack's model of steady state behavior

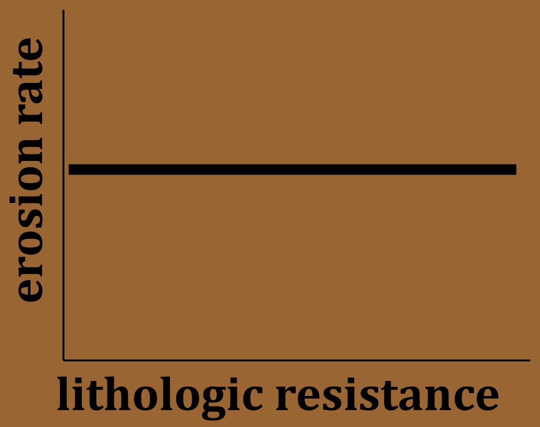
Changing topography, constant relief



Hack's Dynamic Equilibrium

The independence of erosion rate from slope, lithology, and basin area in the Shenandoah region dataset supports Hack's model of *dynamic equilibrium*





Summary of Findings

- In general average erosion rates do not differ between lithologies.
- The lack of significant lithologic and slope relationships with basin-scale erosion rates supports Hack's (1960) model of *dynamic equilibrium* where landscape morphology is adjusted to the erosional resistance of the underlying rock over the long-term.
- The erosion rates (~11 m/My) in this study's region are similar to those found in other parts of the Appalachians, e.g. Blue Ridge Escarpment (12.5 M/My); Susquehanna River Valley (13 m/My).
- Grain size does not affect ^{10}Be concentration.
- The landscape of the Blue Ridge Province is a product of slow erosion, with millennial scale erosion rates averaging ~11 m/My, similar to post-orogenic denudation rates integrated over times periods 1 to 2 orders of magnitude longer.
- Steady erosion over time suggests that the region's landscape may well have remained grossly similar for millions of years.

Future Work

- Lower erosion rates of quartzite rocks and the presence of less resistant rocks on the ridgeline:

  including a deeper integration of ongoing structural studies
- Further bedrock sampling to aid understanding of rock resistance and the importance of local variations in rock
- A collaborative study integrating cosmogenic and themochronologic data

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- Dash Duxbury


Questions?