USING ^{10}Be TO CONSTRAIN EROSION RATES OF BEDROCK OUTCROPS, GLOBALLY AND IN THE CENTRAL APPALACHIAN MOUNTIANS

A Thesis Proposal Presented

by

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The following members of the Thesis Committee have read and approved this document before it was circulated to the faculty.

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Abstract

Bedrock erosion rates are difficult to constrain over 10^3-10^6 year timescales. My initial compilation and preliminary analysis of published ^{10}Be bedrock outcrop erosion rates shows no clear relationship between the rate at which bedrock erodes and any one landscape or climate parameter (e.g. mean annual precipitation, temperature, elevation, latitude, etc.). Small numbers of data from many different study sites around the world, however, suggest that exposed bedrock outcrops, particularly those along ridgelines, erode more slowly than the drainage basins in which they are located. In order to test the hypothesis that exposed bedrock erodes more slowly than drainage basins and thus helps to shape the large scale geomorphology of some landscapes, I will collect samples (n≈40) of exposed bedrock from ridgelines in the central Appalachian Mountains. My samples will come from three study areas where UVM students have or are estimating basin-scale rates so that I can make meaningful comparisons. Upon completion of this study, numerous data will be added to the bedrock erosion and landscape denudation literature. My work will thus further the understanding of how quickly exposed bedrock surfaces erode and through comparison with basin-scale erosion rate data, suggest how landscapes in ancient mountain belts evolve through time.

Introduction

Many regions around the world are typified by the presence of bedrock outcrops. Yet, as common as exposed bedrock may be, the rates at which it erode are poorly constrained (Saunders, 1983). It is important to understand how bedrock outcrops erode not only because they are the backbones of mountain ranges, but because they are one source from which sediment is generated and may control how landscapes evolve with time.

Prior to the past twenty years, bedrock erosion rate estimates were made in various ways, each of which incorporated different assumptions and resulted in different errors. One method involves measuring the depth of text incision and sharpness of edges on exposed tombstones in New England cemeteries (Matthias, 1967). Rahn (1971) did not measure erosion rates from tombstones; rather, he used the relative erodability of various lithologies of tombstones and suggested that bare rock on the landscape followed the same trend.

More recently, methods such as apatite fission track thermochronology (AFTT) and (U-Th)/He dating have been used to estimate denudation rates of mountain ranges on the $>10^6$ year timescale (Ehlers and Farley, 2002; Reiners and Brandon, 2006). Over the past twenty years, advancements in accelerator mass spectrometry (AMS) allowed cosmogenic radionuclides such as ^{10}Be, ^{26}Al, and ^{36}Cl to be used for bedrock and basin-wide erosion studies on 10^3-10^6 year timescales (e.g. Elmore and Phillips, 1987; Bierman and Nichols, 2004; Gosse and Phillips, 2001).

Many cosmogenic radionuclide erosion rate studies focus on basin-wide erosion rates and include few, if any, bedrock samples (Table 1). Globally, exposed bedrock erosion rates (measured in rock samples collected from single outcrops) are usually less than basin-wide erosion rates (measured in fluvial sediments). However, in all but two studies (Namibia: Bierman et al., 2007; Great Smoky Mountains: Matmon et al., 2003b) number of bedrock data points is very small compared to the number of basin-wide data points and the significance of the conclusions is uncertain.

In the central and southern Appalachian Mountains, three studies with very small numbers of exposed bedrock samples (Duxbury et al., 2006, n=5; Sullivan et al., 2007, n=3; Jungers et al., 2006, n=2) suggest that outcrops erode more slowly than the basins in which they are located. One Appalachian study (Matmon et al., 2003b) suggests that exposed bedrock and basin-scale erosion rates are similar. Understanding the difference between exposed bedrock and basin-scale erosion rates is important because it may explain the apparent contradiction between similar basin-scale erosion rates for sandstone and shale in the Valley and Ridge province where sandstone holds up the high ridges and shale underlies the low valleys (Figure 1, Reuter et al., 2004).

My compilation of existing cosmogenic estimates of exposed bedrock erosion rates indicates significant geographical gaps in the global distribution of study sites. Along with the uncertainty of how and why exposed bedrock and basin-scale erosion rates differ, the lack of data hampers a more complete understanding of how landscapes evolve through time under the control of regional parameters (e.g. climate, elevation). Therefore, collecting and adding more exposed bedrock erosion data to the literature will make for a more robust analysis of parameters controlling erosion and will allow several more significant comparisons between basin-scale and outcrop-scale rates of erosion. My data will also allow for a more detailed conceptualization of landscape evolution along the Appalachian Mountains.

Literature Review

Physics of Cosmogenic Nuclides

Beryllium-10 is produced multiple ways as summarized by Bierman (1994) and Lal (1991). For bedrock outcrop erosion studies, ^{10}Be, produced through spallation by cosmic rays, is the most useful (Nishiizumi et al., 1986). Cosmic rays, primarily protons, interact with particles in the atmosphere creating secondary neutrons which then strike Earth; their interactions with O atoms produce ^{10}Be. These spallation interactions are more common at Earth's surface and decrease exponentially with depth according to the equation by Lal (1991):

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

The production rate (P_x) at a depth (x) is determined by the production rate at the surface (P_0), the density of the material (ρ), and the absorption mean free path (Λ), which has a value of 165 g cm^{-2} and accounts for the absorption of 80% of cosmic rays at a depth of ~1 m in rock. Surface production rates are low, ~5 atoms g^{-1} yr^{-1}, and describe how quickly cosmogenic nuclides are created, but do not take into account the nuclide's half-life (λ=1.5 My for ^{10}Be). With this factor taken into account, the equation below is used to estimate bedrock erosion rates from measured isotope concentrations (Lal, 1991):

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

where N is the nuclide concentration and ε is the erosion rate.

Latitude and altitude control the cosmic ray flux and thus the production rate of cosmogenic nuclides. Correction factors for latitude and elevation have been determined by Lal and Peters (1967) and must be applied to raw ^{10}Be concentrations before model erosion rates can be determined.

The advancement of technologies such as AMS allows erosion rates to be measured directly through the analysis of cosmogenic nuclides – ^{10}Be being the most common for bedrock studies (Elmore and Phillips, 1987; Nishiizumi et al., 1986). AMS is the most appropriate method of measurement for cosmogenic radionuclide concentrations because it has a low detection limit for these nuclides (Granger and Riebe, 2007; Lal, 1988; Lal and Peters, 1967). Any mineral containing ^{10}Be can be used for erosion studies as long as absorbed atmospheric ^{10}Be can be removed (Nishiizumi et al., 1986, 1990; Ivy-Ochs et al., 1998). Quartz quickly emerged as the optimal mineral phase to use in bedrock studies because of its prevalence, resistance to atmospheric ^{10}Be absorption, low Al content, and measurable quantities of cosmogenic ^{10}Be (Bierman, 1994).

Bedrock Erosion Rates – Applications of Cosmogenic Radionuclides

The use of cosmogenic radionuclides in determining erosion rates has grown considerably since the late 1980s (e.g. Nishiizumi et al., 1991; Brown et al, 1995; Small et al., 1997; Clapp et al., 2000; Nichols et al., 2006). Many studies have involved either obtaining basin-wide erosion rates using stream sediments or determining how bedrock weathers under a mantle of sediment or soil (e.g. Brown et al., 1995; Clapp et al., 2001; Granger et al., 2001; Heimsath et al., 2006); many fewer studies present the erosion rates of exposed bedrock (e.g. Nishiizumi et al., 1991; Cockburn et al., 2000; Hancock and Kirwin, 2007).

This shortage of cosmogenic data from bedrock outcrops limits our understanding of how landforms change through time in different geographic settings and prevents rigorous comparison to results from other methods such as AFTT and (U-Th)/He dating, although such comparisons have been made (von Blanckenburg et al., 2004; Cockburn et al., 2000; Granger et al., 2001). Studies in which bedrock outcrop erosion is not the primary focus (Table 1) have compared basin-wide erosion rates to various environmental parameters such as mean annual precipitation (Matmon et al., 2003b), elevation (Heimsath et al., 2006), and stream power (Vanacker et al., 2007) with varied success. With a few exceptions, correlations have not been explored in studies focusing solely on exposed bedrock (Bierman and Caffee, 2001, 2002). All existing studies (Table 1) were made on local or regional scales; no global compilation of cosmogenic ^{10}Be bedrock outcrop erosion data exists.

Many studies in which exposed bedrock erosion rates were compared to basin-wide erosion rates show bedrock eroding more slowly than the basin as a whole (Figure 2). Outcrop samples taken in the Luquillo Experimental Forest, Puerto Rico, for example, yield model erosion rates of ~20 m My^{-1} compared to basin-scale erosion rates of ~43 m My^{-1} (Brown et al., 1995). The island of Sri Lanka has outcrop erosion rates of ~4.2 m My^{-1} compared to the basin-wide average of ~20 m My^{-1} (von Blanckenburg et al., 2004). In contrast, in the Great Smoky Mountains, Matmon (2003b) found a landscape where the average erosion rates of outcrops were indistinguishable from the basin-wide average erosion rates (~25 m My^{-1} and ~27 m My^{-1}, respectively; Figure 2).

Outcrop erosion rates have also been used in studies comparing exposed bedrock erosion to that of covered bedrock, whether it be by boulders (Granger et al., 2001), soil (Heimsath et al., 1997), or sand (Clapp et al., 2001). Bare rock in the American Sierra Nevada erodes at ~8.5 m My^{-1} whereas bedrock covered by boulders and colluvium erodes at ~35 m My^{-1} (Granger et al., 2001). In northern California, Heimsath et al. (1997) found the highest bedrock erosion rates of ~45 m My^{-1} under a thin mantle of soil cover whereas exposed bedrock is eroding at ~38 m My^{-1}. Similar results were found in basins along the southeastern Australian escarpment (Heimsath et al., 2006, 2000). In Arizona and New Mexico, slopes covered by sand and colluvium were also found to have higher erosion rates than those of exposed bedrock in the same basin (Clapp et al., 2001, 2002). The higher erosion rates of shielded bedrock has been attributed to the ability of colluvium, soil, and sand to retain moisture which facilitates chemical weathering whereas most water runs off exposed bedrock (Granger et al., 2001; Clapp et al., 2001, 2002).

Nearly all studies focusing only on bedrock outcrop erosion rates have been done on passive margins in arid environments (Table 1). Samples taken from inselbergs on Australia's Eyre Peninsula exhibit slow erosion rates (~4 m My^{-1} on average, but as low as ~40 cm My^{-1}) suggesting that these landforms have changed little throughout the Cenozoic (Bierman and Caffee, 2002). Along the Namibian Escarpment, erosion rates of ~6.5 m My^{-1} (Cockburn et al., 2000) and ~3 m My^{-1} (Bierman and Caffee, 2001) were gathered from inselbergs and outcrops along the escarpment. Other arid environments not on passive margins also show erosion rates as low as ~10 m My^{-1} (Nichols et al., 2006; Clapp et al., 2000). Antarctic outcrops produce some of the lowest erosion rates with an average of ~1.2 m My^{-1} and a low of 12 cm My^{-1} (Nishiizumi et al., 1986, 1991).

Bedrock summits in many western United States mountain ranges are eroding at rates only slightly higher than rock in arid environments: ~8.7 m My^{-1} in the Wind River Range, WY; ~13.2 m My^{-1} in the Beartooth Mountains, MT; ~9.2 m My^{-1} in the Front Range, CO; and ~4 m My^{-1} in the Sierra Nevada, CA (Small et al., 1997). Summit erosion rates in the passive margin Appalachian Mountains are within the range of their western counterparts (~6.5 m My^{-1}) even though they are in a much older and less tectonically active environment (Hancock and Kirwin, 2007).

Exposed bedrock erosion rate data from the Appalachian Mountains are limited to a few exposures primarily within basin-wide studies (Table 1). Exposed bedrock erosion rates range from ~2.5 – 50 m My^{-1}, with an average of 26.79±2.98 m My^{-1} (n=29; Hancock and Kirwin, 2007; Duxbury et al., 2006; Jungers et al., 2006; Matmon et al., 2003b; Sullivan et al., 2007).

Objectives

My study will further the knowledge of how quickly exposed bedrock erodes and landscapes change. Specific objectives include the following:

- Determine erosion rates (using cosmogenic ^{10}Be analysis) from bedrock samples collected at three sites in the Appalachian Mountains. These samples (n ≈ 40) will come from the Susquehanna River basin, Shenandoah National Park, and the Potomac River basin - areas previously or currently studied using the basin-scale approach (Reuter et al., 2004; Duxbury et al., 2006).

- Compare cosmogenically derived bare bedrock erosion rates with other rates previously determined by other methods for the Appalachians including non-cosmogenic denudation estimates (AFTT and/or (U-Th)/He) and basin-scale erosion rate estimates.
- Compile cosmogenic ^{10}Be concentrations measured in previous bedrock erosion studies as well as add a significant amount of bedrock data to the current literature in order to identify physical attributes of the sample location that may, alone or in groups, control bedrock erosion rates. This work was begun in preparation for my proposal.

Methods

Work Completed

Throughout the fall of 2008, I compiled raw ^{10}Be concentration data from every bedrock sample in as many published studies as I was able to find (Table 1). I have created a spreadsheet with these data and included key information such as sample elevation above sea level, latitude and longitude, mean annual precipitation, mean annual air temperature, and the samples' geometry in regards to horizon shielding. Before any global-scale correlations were made, I normalized raw ^{10}Be data for latitude and altitude according to methods of Lal (1991).

Current Work

Currently, I am incorporating geological map and topographical data into ArcGIS for the purposes of finding suitable sample collection locations. These sites will lie within or near previously studied regions of the Appalachians (Duxbury et al., 2006; Reuter et al., 2004) so that I can compare bedrock erosion rates to basin- scale erosion rates.

Upcoming Work

I will visit my study area in May to collect samples by rock hammer and chisel from bedrock outcrops – the general locations of which are found using a GIS analysis (Figure 3). The following summer months and fall of 2009 will be spent in the laboratory preparing my samples for cosmogenic nuclide analysis. Preparing my samples is essential to isolate purified quartz that only incorporates *in situ*-produced ^{10}Be, and is done according to the methods described in Kohl and Nishiizumi (1992). After ^{10}Be is fully extracted from rock samples, I will take the samples to Lawrence Livermore National Laboratory in Livermore, California for AMS analysis. Methods of sample preparation are available on the University of Vermont's Cosmogenic Nuclide Laboratory website (http://www.uvm.edu/cosmolab/).

When all samples have been measured by AMS, I will use that data to estimate bedrock erosion rates from my field area and begin writing my Masters Thesis in the form of publications. I will attend conferences to share my findings. I plan to defend my Masters Thesis at the end of the Spring Term, 2010.

Initial Results

Data from the literature (Table 1) supports the idea that exposed bedrock erosion rates are not controlled by any single physical parameter. On a global scale, there is no correspondence between exposed bedrock erosion rate and elevation (Figure 4). The highest erosion rates are found in mid northern latitudes (Figure 5); however, this could reflect the distribution of study locations since much of the continental landmass is north of the equator.

Understanding the role climate plays in controlling erosion rates is crucial to put better constraints on erosion models (Riebe et al., 2001). Only a few studies have compared climate controls with exposed bedrock erosion rates (Bierman and Caffee, 2002, 2001). Positive correlations between mean annual precipitation and the lowest measured model erosion rates on bedrock surfaces have been found in Australia (Bierman and Caffee, 2002; Figure 6a) and the Namibian Great Escarpment (Bierman and Caffee, 2001; Figure 6b); however, there is no global relation between mean annual precipitation and exposed bedrock erosion rates. Exposed bedrock erosion rates appear to peak at a mean annual air temperature of 10°C (Figure 7).

Lithology may play some role in setting erosion rates (Figure 8). Pure quartz outcrops have the lowest mean and median erosion rates. Metamorphic and igneous rocks appear to erode from outcrops at similar rates whereas sedimentary rocks have the greatest variability in erosion rates.

Tables

Table 1. Summary of studies used in global exposed bedrock erosion rate assessment.

Bedrock Outcrop Erosion Summary Table				
Study No.	Study Location	No. of Samples	Focus*	Reference
1	Namib Desert and Escarpment, Namibia	48	O	Bierman and Caffee (2001)
2	Eyre Peninsula, Australia	75	O	Bierman and Caffee (2002)
	Northern Territory, Australia	18		
3	Cumberland Peninsula, Baffin Island, Canada	7	O	Bierman et al. (1999)
4	Luquillo Experimental Forest, Puerto Rico	2	B	Brown et al. (1995)
5	Negev Desert, Israel	8	B	Clapp et al. (2000)
6	Arroyo Chavez Basin, NM, USA	3	S	Clapp et al. (2001)
7	Yuma Wash, AZ, USA	3	S	Clapp et al. (2002)
8	Namib Desert, Namibia	20	O	Cockburn (2000)
9	Shenandoah National Park, VA, USA	5	B	Duxbury et al. (2006)
10	Diamond Mountains Batholith, CA, USA	3	S	Granger et al. (2001)
11	Dolly Sods, WV, USA	9	O	Hancock and Kirwin (2007)
12	Tennessee Valley, CA, USA	5	S	Heimsath et al. (1997)
13	Southeast Australian Escarpment, Australia	6	S	Heimsath et al. (2000)
14	Frog Hollow, Southeast Australia	7	B	Heimsath et al. (2001)
15	Coos Bay Region, Oregon, USA	4	S	Heimsath et al. (2001)
16	Southeast Australian Escarpment, Australia	18	S	Heimsath et al. (2006)
17	Laurely Fork, PA, USA	2	B	Jungers et al. (2006)
18	Great Smoky Mountains, TN & NC, USA	10	B	Matmon et al. (2003b)
19	Alabama Hills, CA, USA	20	O	Nichols et al. (2006)
20	Allan Hills, Antarctica	1	O	Nishiizumi et al. (1986)
	Anza Borrego, CA, USA	2		
21	Haleakala Volcano, HI, USA	1	O	Nishiizumi et al. (1990)
22	Allan Hills, Antarctica	9	O	Nishiizumi et al. (1991)
	Reckling Peak, Antarctica	2		
	Sör Rondane, Antarctica	8		
	Tillite Glacier, Antarctica	4		
	Wright Valley, Antarctica	4		
23	Torrente Catchment, Sierra Nevada, Spain	8	B	Reinhardt et al. (2007)
24	Wind River Range, WY, USA	7	O	Small et al. (1997)
	Beartooth Mountains, MT, USA	5		
	Front Range, CO, USA	4		
	Sierra Nevada, CA, USA	3		
25	Blue Ridge Escarpment, USA	3	B	Sullivan et al. (2007)
26	Sri Lanka	4	B	Von Blanckenburg et al. (2004)
27	Baker's Creek, southeastern Australia	1	B	Weissel and Seidl (1998)

*O=Bedrock Outcrops, B=Basin-wide, S=Sediment, Soil or Boulder shielding

Figures

Figure 1. Basin-scale erosion rates (estimated from ^{10}Be content of fluvial sediment) in the Valley and Ridge province of the Susquehanna River Basin show no difference between weak (shale) and resistant (sandstone) lithologies. Taken from Reuter et al. (2004).

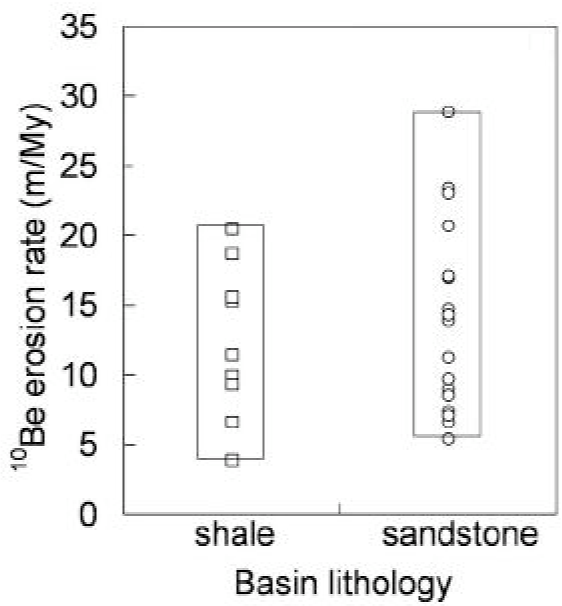


Figure 2. Exposed bedrock erosion rates taken from catchments in which basin-wide averaged erosion rates were also taken. Numbers in the bar represent the total number of samples analyzed in each study. Error bars represent the range of errors in erosion rate estimates. Studies selected from Table 1.

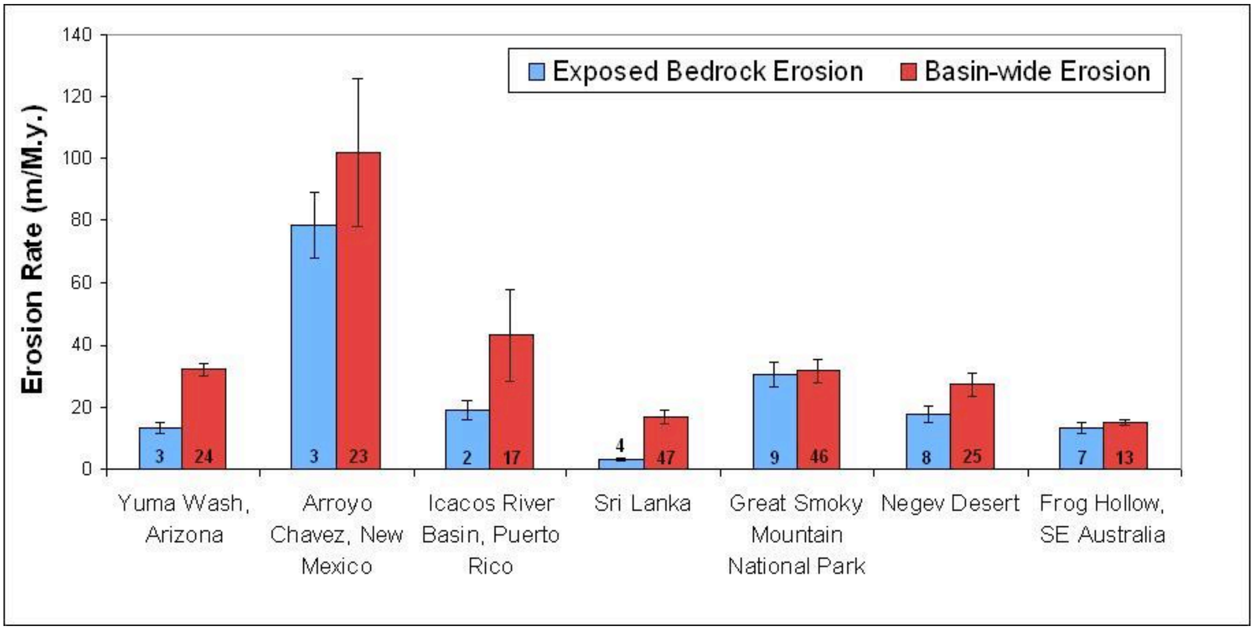


Figure 3. Example of GIS analysis that I am using to select locations where exposed bedrock has been measured. Green polygons are units in which the dominant lithology type is quartz-rich. Yellow polygons are units in which the secondary lithology is quartz-rich. Red polygons are quartz poor. Faded polygons are Pennsylvania State Parks and the turquoise line running through the map area is the Appalachian Trail. Purple dots are sites at which either strike/dip or lineation measurements have been taken by other geologists, meaning bedrock is exposed at that point.

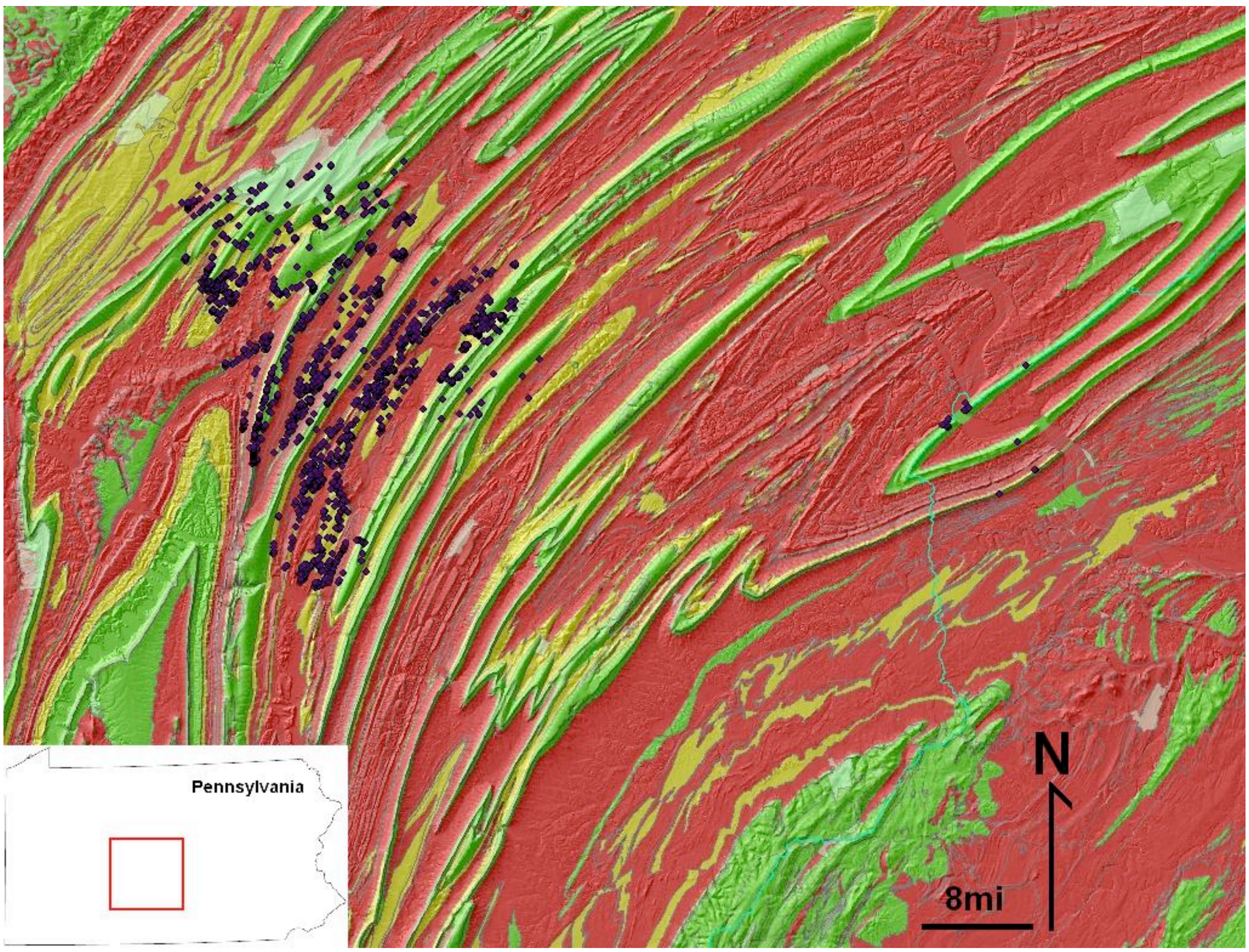


Figure 4. On a global scale, erosion rates of bedrock outcrops do not vary systematically with elevation. Data from studies in Table 1.

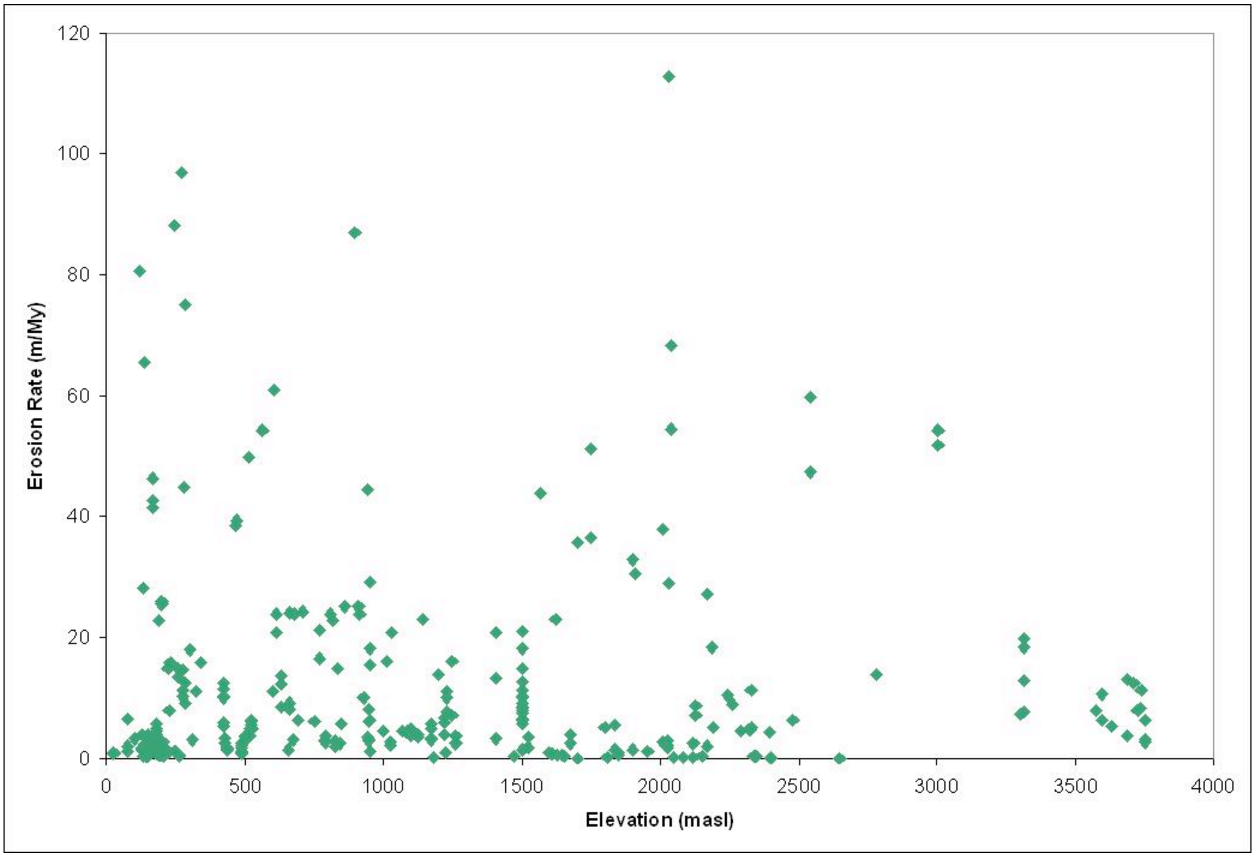


Figure 5. Global erosion rates by latitude. Data from studies in Table 1. Green line represents the area of continental landmass at each latitude, adapted from Kempe (1979).

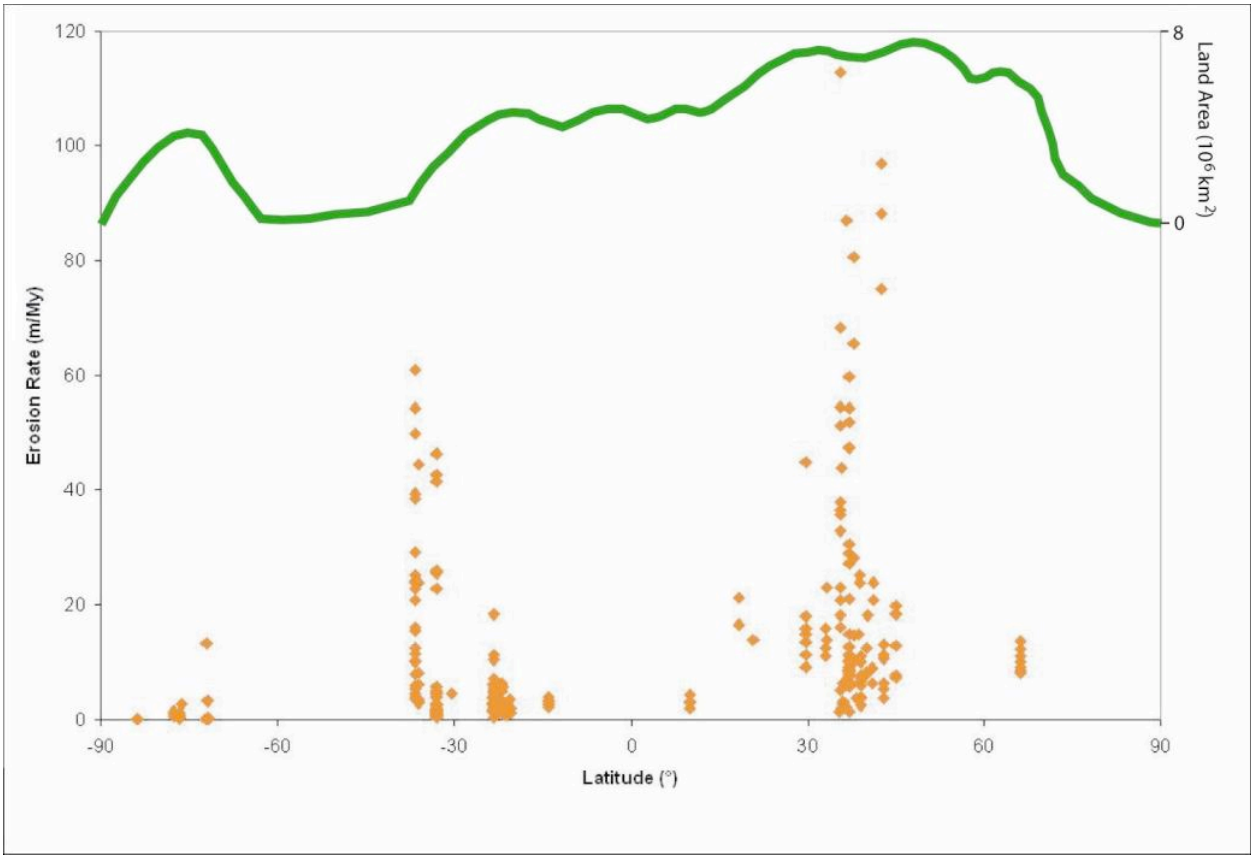


Figure 6. Lowest bedrock erosion rate at each sampling area correlate with mean annual precipitation in (A) Australia (Bierman and Caffee, 2002) and (B) Namibia (Bierman and Caffee, 2001).

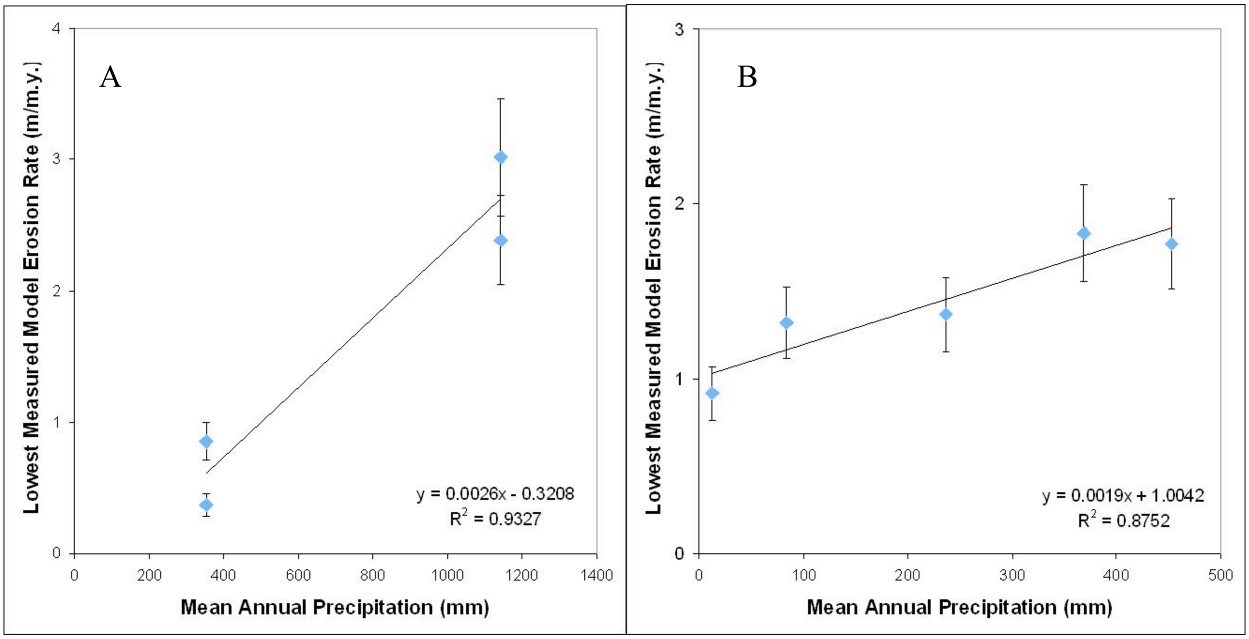


Figure 7. Erosion rates from bedrock outcrops are not related to mean annual precipitation. Data from studies in Table 1.

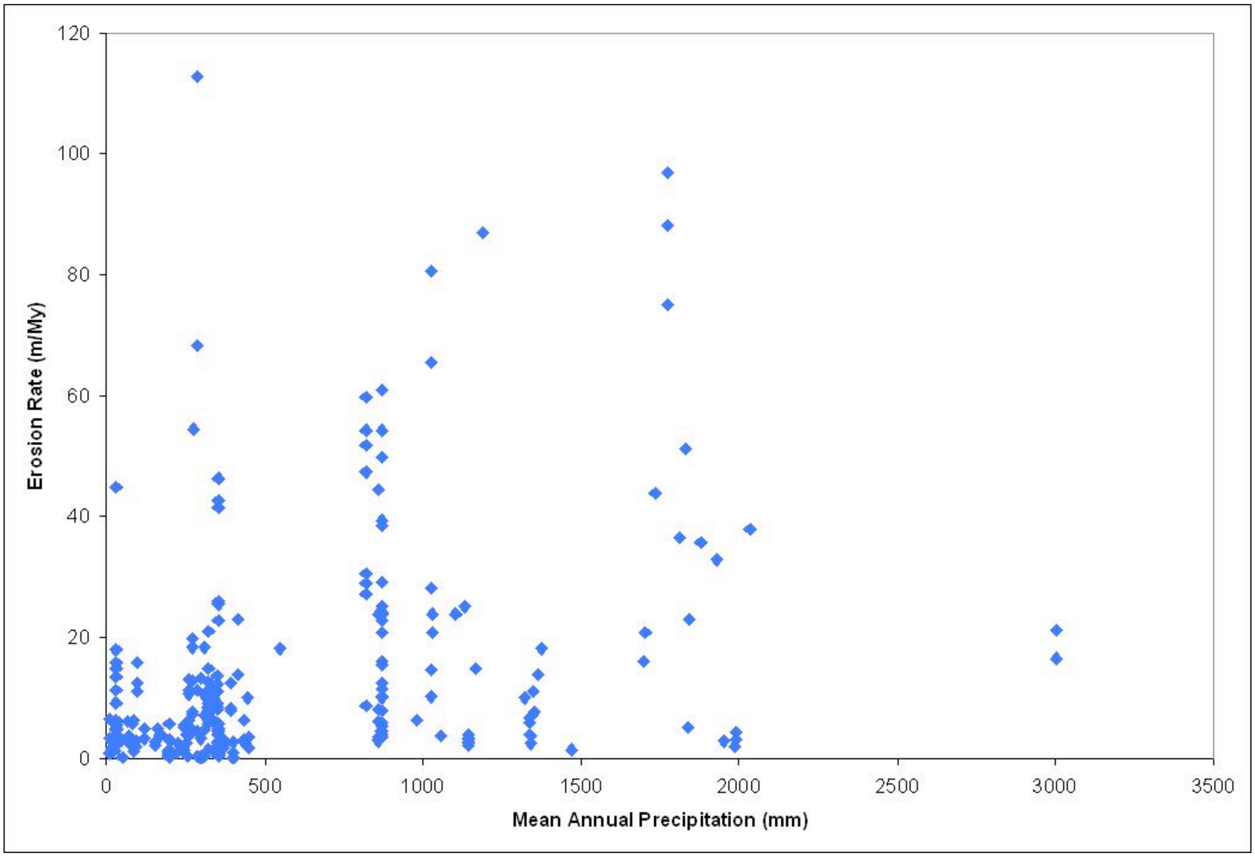


Figure 8. Erosion rates of exposed bedrock are highest at a mean annual air temperature of about 10°C. Data from studies in Table 1.

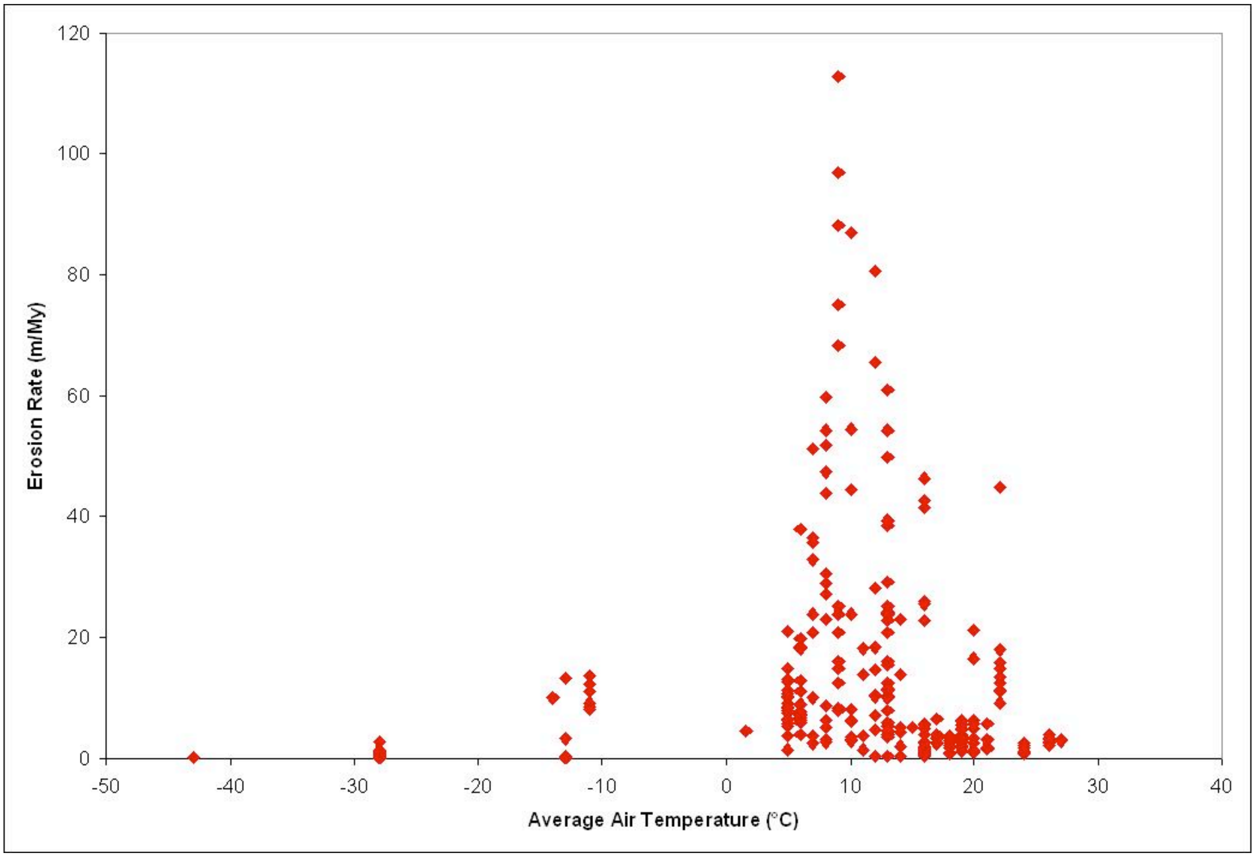
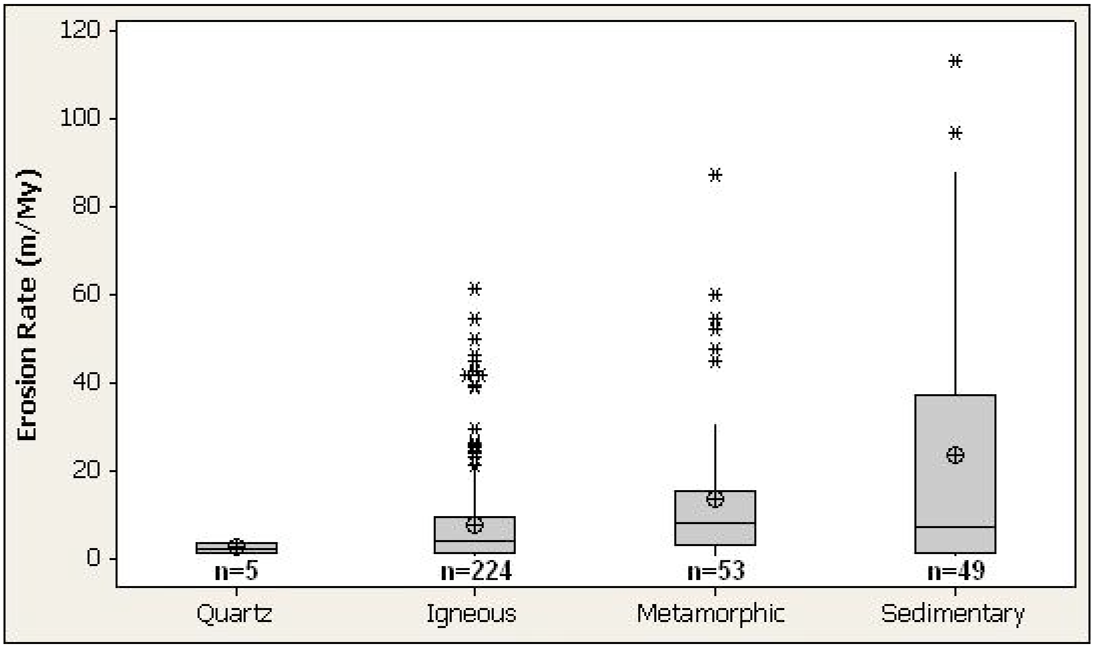


Figure 9. Box and whisker plot of exposed bedrock erosion rates by lithology. Upper and lower limits of boxes indicate 75th and 25th quartiles, respectively; the bar in the box represents the median erosion rate; crosshairs indicate the average erosion rate; whiskers show maximum and minimum erosion rates; and stars are statistical outliers. Data are from studies in Table 1.



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