for submission to GEOLOGY

January 28, 2002

TEMPORALLY AND SPATIALLY UNIFORM RATES OF EROSION IN THE SOUTHERN APPALACHIAN GREAT SMOKY MOUNTAINS

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ABSTRACT

Cosmogenic nuclide, fission track, long term sediment budget, and sediment yield data indicate that the Great Smoky Mountains and the southern Appalachians are eroding and generating sediment at a similar rate, about 30 m My^{-1}, over both time and space. In this study, we measured ^{10}Be in fluvial sediment samples (n=25) from eight Great Smoky Mountain drainages (1 to 190 km^2). Results suggest spatially homogeneous sediment generation (on the 10^4 to 10^5 year time scale and >100 km^2 spatial scale) at 73±13 tons km^{-2} yr^{-1}, equivalent to bedrock erosion at 27±5 m My^{-1}. At these scales, the cosmogenic nuclide data support Hack's classic model of Appalachian dynamic equilibrium. ^{10}Be-modeled rates of erosion are similar to Mesozoic and Cenozoic erosion rates estimated by other methods (10 to 60 m My^{-1}). In contrast, unroofing rates during the Paleozoic orogenic events that formed the Appalachian Mountains imply higher integrated erosion rates ($\geq 10^2$ m My^{-1}) consistent with rates reported from other active mountain belts. These results suggest that mountain belts erode rapidly during and immediately after orogenesis. However, erosion rates decrease significantly after termination of tectonically driven uplift, enabling the survival of ancient mountain belts, such as the Appalachians, as topographic features in the contemporary landscape.

INTRODUCTION

The Appalachian Mountains, one of the largest and most studied ancient orogenic belts, were built by a series of collisional events in the Paleozoic and an extensional event in the Late Triassic (Blackmer et al., 1994; Boettcher and Milliken, 1994; Friedman and Sanders, 1982; Pazzaglia and Brandon, 1996). While the constructional history, structure, and lithology of the range are fairly well understood, the pattern and tempo by which the Appalachians have and are being eroded is not well known despite a variety of geomorphic studies, the first of which was completed over 100 years ago (Davis, 1899).

The longevity of the Appalachian range is striking. To understand the survival of these mountains, one needs to quantify the rate at which they erode through time and space. Over the past 40 years, the rate at which the Appalachians have and are losing mass has been estimated quantitatively by a variety of methods that integrate different temporal and spatial scales (e.g. Judson, 1968; Moore, 1974; Hack, 1979; Gordon, 1979; Pavich, 1985; Zen, 1991; Bierman et al., 1995; Huvler, 1996; Naeser et al., 1999, 2001; Granger et al., 1997, 2001). The wide range of denudation rates suggested in these studies (4 to > 200 m My^{-1}) is a result of spatial and temporal scaling issues as well as the uncertainty of the various parameters used in the different methods (Milliman and Meade, 1983).

To estimate the rate and pattern by which the Great Smoky Mountains, a well studied part of the southern Appalachians, are eroding, we measured ^{10}Be in fluvial sediment (Brown et al., 1995; Granger et al., 1996; Bierman and Steig, 1996; Clapp et al., 2000, 2001; Schaller et al., 2001; Bierman et al., 2001). The Great Smoky Mountains (Fig. 1), built of metamorphosed sedimentary rocks of Neoproterozoic to early Cambrian age with isolated areas of Mesoproterozoic gneiss (King et al., 1968), rise >1500 m above adjacent valleys. Relief over most of the range is significant with steep slopes feeding sediment into deeply incised river valleys. Mean annual rainfall ranges from 165 to 250 cm, depending on elevation (http://www.nps.gov/grsm/gsmsite/natureinfo.html; 11/01).

Slopes and mountain crests are mostly soil covered and heavily vegetated. Only minor gullying and storm-related landslide scars are evident. Diffusive processes, including tree throw, appear to move most colluvium down slope. Weathered rock (saprolite) below the soil is thick; in some places over ten meters deep.

METHODS

We sampled alluvial sand from 8 large drainage systems that transport sediment out of the Smoky Mountains; these systems drain 56% of the range's area (Fig. 2). ^{10}Be was measured by accelerator mass spectrometry at Livermore National Laboratory in quartz separated from the 250-850 μm fraction using procedures outlined in Bierman and Caffee (2001). In order to interpret nuclide data for each basin, we calculated basin-integrated nuclide production rates convolving basin hypsometery, the altitude production-rate function (Lal, 1991; Erosion rate calculation[1]), and the sea-level high-latitude production rates estimate of Bierman et al. (1996) for ^{10}Be (5.17 atoms g^{-1} y^{-1}).

Because most Great Smoky Mountain river valleys are steep and narrow, there is no significant long-term storage of sediment in the mountainous drainage basins, which lack terraces, large gravel bars, flood plains, and large alluvial fan deposits. As a result, straightforward calculation of sediment generation rates from the ^{10}Be activities in the sampled sediments (Bierman and Steig, 1996) is possible. Quartz, the mineral from which ^{10}Be was extracted, is homogeneously distributed in the drainage basins.

Sample GSCO-1 was taken immediately below the confluence of two large drainage basins and their respective outlet samples, GSCO-2 and GSRF-12, to test the efficiency of fluvial mixing (Fig. 3). Indeed, our nuclide data show that sediment from these different sources is well and rapidly mixed below the junction (Evidence for

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[1] GSA Data Repository item XXX, Table 1, Erosion rate calculation, Evidence for thorough mixing, Table 2, Additional references, is available on request from Document Secretary, GSA, P.O.Box 9140, Boulder, CO 80301-9140, editing@geosociety.org or at www.geosociety.org/pubs/ftXXXX.htm.

thorough mixing; see footnote 1), allowing for the unbiased calculation of drainage-basin average sediment generation rates and, by inference, erosion rates. Sample GSBC-2 was taken 1.6 km upstream from GSBC-1 as a replicate. Both samples yielded similar ^{10}Be activities verifying our laboratory methods and sampling strategy.

RESULTS

Sediment samples collected from the Great Smoky Mountain drainage systems (n=25) yielded ^{10}Be activities between 0.20×10^{6} and 0.46×10^{6} atoms g^{-1} quartz (Table 1; see footnote 1). Using the interpretive model of Bierman and Steig (1996), these activities are consistent with sediment generation rates between 46 and 95 tons km^{-2} yr^{-1}, the equivalent of model erosion rates between 17 and 35 m My^{-1} (Figs. 2, 3, and 4). Erosion rates in headwater tributary basins of the Raven Fork and of the Oconaluftee River (for which there are no upstream samples; n=12) range from 17 to 35 m My^{-1} with an average of 27±5 mMy^{-1}. Basin scale erosion rates inferred from analysis of sediments collected from the outlet rivers (n=8) that transport most of the sediment from the Great Smoky Mountains range from 22 to 34 m My^{-1} with an average of 27±5 m My^{-1}. The largest river (basin area, 330 km^{2}) draining the Great Smoky Mountains has a basin average erosion rate of 28±6 m My^{-1} (Table 2; see footnote 1) similar to that of the headwater tributaries and the outlet rivers. Our data show no correlation between drainage basin area and inferred erosion rates nor do ^{10}Be activities increase downstream, confirming the field observation of insignificant alluvial storage and suggesting that most measured ^{10}Be is produced by cosmic-ray dosing on hill slopes rather than during fluvial transport. However, there is a distinct inverse relationship between the scatter in erosion rates, i.e., variance, and drainage basin area above the sample site (Fig. 4).

DISCUSSION

Spatial homogeneity

Our results suggest spatially homogeneous erosion of the Great Smoky Mountains on the 10^4 to 10^5 year time scale, the time it takes the upper several meters of rock, which accumulate cosmogenic nuclides, to erode (Lal, 1991). The two-fold variance of erosion rates in low-order drainage basins reflects local variability in small basin characteristics and behavior over space and time (Fig. 4). The rapid and efficient mixing of sediments from the different tributaries is expressed by the diminishing variance in model erosion rates as basin size increases and by mass balance calculations (Evidence for thorough mixing; see footnote 1). When analyzed at a spatial scale of >100 km^2, rates of sediment production and erosion across the range are uniform.

Erosion over time

Short term sediment yields (~10^2 yr)

Sediment load data collected by the U.S. Geological Survey for some rivers in the Great Smoky Mountain area (http://webserver.cr.usgs.gov/sediment/plsql/stateanchor; 6/01) indicate that historic sediment yields are similar to sediment generation rates calculated from cosmogenic nuclide activities in alluvial sediments. Sediment load measurements (1935 to 1938) made in the Tuckasegee River at Bryson City (1700 km^2; Fig. 2) suggest an average sediment yield of 320,000 Mg yr^{-1}, equivalent to a sediment generation rate of 188 tons yr^{-1} km^{-2} and an average rock surface lowering rate (assuming steady state) of about 65 m My^{-1} (ρ=2.7 g cm^{-3}). Sediment load measurements (1934 to 1935) in the Little River basin (~490 km^2; Fig. 2) suggest an average sediment yield of 28,000 Mg yr^{-1}, equivalent to a sediment generation rate of 57 tons yr^{-1} km^{-2} (rock surface lowering rate of about 21 m My^{-1}). Calculated rates of erosion in other parts of the Appalachian Mountains, based on the assumption that contemporary sediment yield reflects sediment generation, range between 5 and 50 m My^{-1} (Hack, 1979; Menard, 1961; Judson, 1968; Judson and Ritter, 1964; Gilluly, 1964; Gordon, 1979; Fig. 5).

Cenozoic and Mesozoic denudation rates (~10^7 yr)

Fission track analysis of zircons and apatites sampled from rocks of the Great Smoky Mountains indicate slow rock uplift through the annealing zone of apatite (60-110°C) during the Triassic to Lower Cretaceous (Naeser et al., 1999, 2001). Fission track data imply an average Great Smoky Mountain denudation rate for the Cretaceous (160-95 Ma) of 20-25 m My^{-1} and ~20 m My^{-1} from the late Triassic to recent times. Fission track data from other parts of the Appalachian Mountains indicate similar rates of erosion (Zimmerman, 1979; Doherty and Lyons, 1980; Fig. 5). Mesozoic and Cenozoic rates of erosion in the Appalachians that range between 10 and 60 m My^{-1} are also calculated using sediment budgets and the emplacement depths of presently exposed igneous intrusions (Zen, 1991; Menard, 1961; Fig. 5).

Paleozoic denudation rates

In contrast to relatively slow rates of rock erosion during the Mesozoic and Cenozoic (<60 m My^{-1}), rates of unroofing in the Paleozoic, when the Appalachian mountains were constructed by orogenic events, were ≥100 m My^{-1} (Huvler, 1996; Zen, 1991; Pavich, 1985; Sutter, et al., 1985; Fig. 5). Similarly high rates of mass loss are typical in active Cenozoic mountain belts (Summerfield and Hulton, 1994; Hovius, 1998; Summerfield, 2000 and references therein). The contrast between the high Paleozoic rates of mass loss and low rates in the Mesozoic and Cenozoic suggests that rates of mountain erosion decrease rapidly soon after the termination of tectonic activity, and then remain relatively constant, enabling the landscape to approach a steady state in terms of mass loss over time when considered on time scales longer than 10^5 to 10^6 (Pazzaglia and Brandon, 2001; Whipple, 2001).

IMPLICATIONS

^{10}Be activity in river sediment suggests that the Great Smoky Mountains as a whole are eroding between 25 and 30 m My^{-1}. If drainage basins greater than several tens of km^2 are considered, erosion is spatially homogeneous supporting Hack's 1960 concept of dynamic equilibrium which postulates that in the southern Appalachians, "…all elements of topography are mutually adjusted so that they are downwasting at the same rate." However, the variability of erosion rates that we measured among low-order drainages implies dynamic equilibrium is not an appropriate description of the slope/erosion rate relationship at the headwater scale. Considering drainage by drainage erosion rate variation, together with the antiquity of the mountain range, suggests that Hack's dynamic equilibrium might never be achieved at the scale of headwater streams.

Coupling erosion rates estimated by activities of cosmogenic nuclides with fission track, sediment yield, and Appalachian sediment budget data suggests that erosion rates of the Great Smoky Mountains have been similar over the 10^2 to 10^7 year time scales. The spatial and temporal uniformity of erosion rates suggests a balance between erosion and rock uplift. Such temporal similarity implies that the Great Smoky Mountains may be a steady-state landscape, the result of Hack's dynamic equilibrium persisting over 10^7 years on the spatial scale of a mountain range.

Some models of mountain belt erosion predict that initial elevation and relief are reduced by 90% in as little as 60 million years (Ahnert, 1970) or that complete erosion of a continent to sea level would occur within 100 to 300 My (Harrison, 1994). The results of this study are in contrast to these models and suggest the longevity of mountain belts. Despite erosion at rates of about 30 m My^{-1} for the last 180 My, the southern Appalachian Mountains have prominent topographic expression and significant relief. The combination of relatively low rates of erosion and a relatively thick crust (40-50 km; Hutchinson et al., 1983; Iverson and Smithson, 1983) has enabled the isostatic response to erosional unloading to maintain the topographic expression of the southern

Appalachians for hundreds of millions of years. This combination of low erosion rates and thick crust might also explain the topographic persistence of other Paleozoic mountain belts.

ACKNOWLEDGMENTS

Matmon supported by USGS. Analysis supported by USGS and NSF grant EAR-9628599.

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FIGURE CAPTIONS

Figure 1 - Location map. Great Smoky Mountains (GSM) located at the southern end of the Appalachian Mountains are marked by a black box. DEM source - http://fermi.jhuapl.edu/states/us/us_map.html.

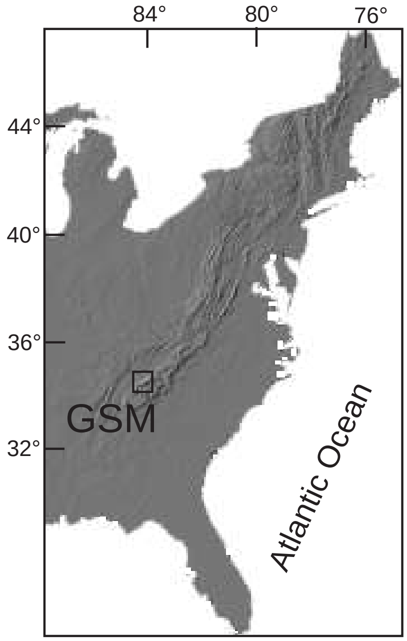
Figure 2 - Drainage system of the Great Smoky Mountain National Park with sampling locations marked by solid circles. Numbers below sample names are model rates of erosion (m My^{-1}). Samples were collected at or near the Great Smoky Mountain National Park boundary to ensure that drainage basins are not disturbed by contemporary land-use practices and to avoid sampling low-relief areas where sediment might be stored for considerable periods of time. Within the two shaded drainage systems (the Raven Fork and Oconaluftee River), we sampled the larger tributaries feeding the main channel (Fig. 3). Sediment was sampled from within

the channels or from sandbars. Little River gaging station is located outside the limits of the figure, about 20 km northwest of X. G – Gatlingburg, TN. BC – Bryson City, NC. OB – Oconaluftee River basin. RFB – Raven Fork basin. 10 km grid is in UTM.

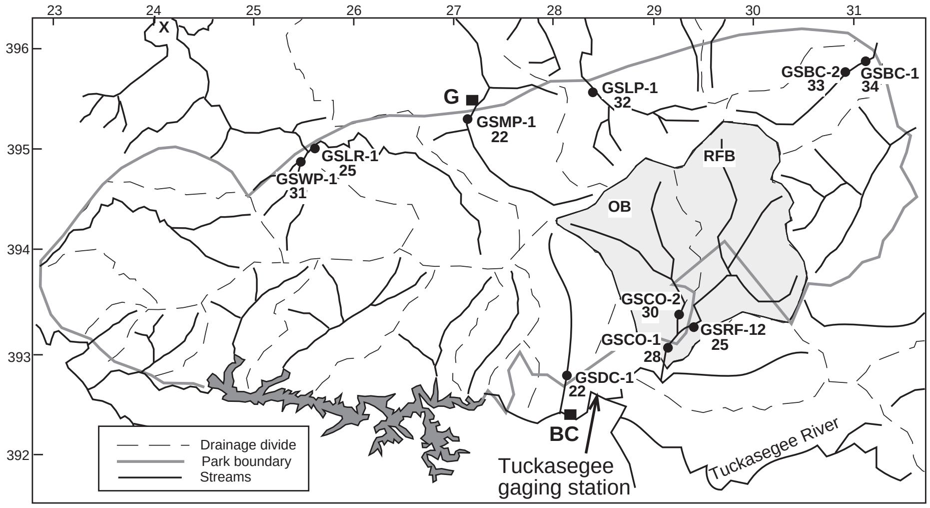
Figure 3 - Detailed map of the Oconaluftee River and Raven Fork basins. Solid lines mark streams. Dashed lines mark drainage divides. Sample locations are marked with solid circles. Numbers below sample names are model rates of erosion in m My^{-1}. ^{10}Be activities do not increase downstream suggesting insignificant storage. 10 km UTM grid.

Figure 4 – Although there is no correlation between erosion rates and drainage basin area, variance in erosion rates decreases as drainage basin area increases. The mean erosion rate calculated from tributary samples is similar to that of the outlet basins indicating thorough and rapid mixing of sediment from the various tributaries. Replicate samples are circled.

Figure 5 – Rates of mass loss in the Appalachian Mountains measured by different methods for different time spans. A. From the Paleozoic to present. High rates of denudation prevail in the Paleozoic during the Taconian, Acadian, and Alleghanian orogenies. Rates decrease after termination of tectonic activity. B. Rates of denudation in the Appalachian Mountains during the Mesozoic and Cenozoic. Sediment budgets calculated by measuring the volume of sediment deposited over a time interval and assuming the source area that supplied the sediment. Shaded areas indicate measurements related directly to the Great Smoky Mountains. Unshaded areas relate to measurements in other parts of the Appalachians. SY 1 – Sediment yield from the Tuckasegee River. SY 2 - Sediment yield from the Little River.



Matmon et al., Fig. 1



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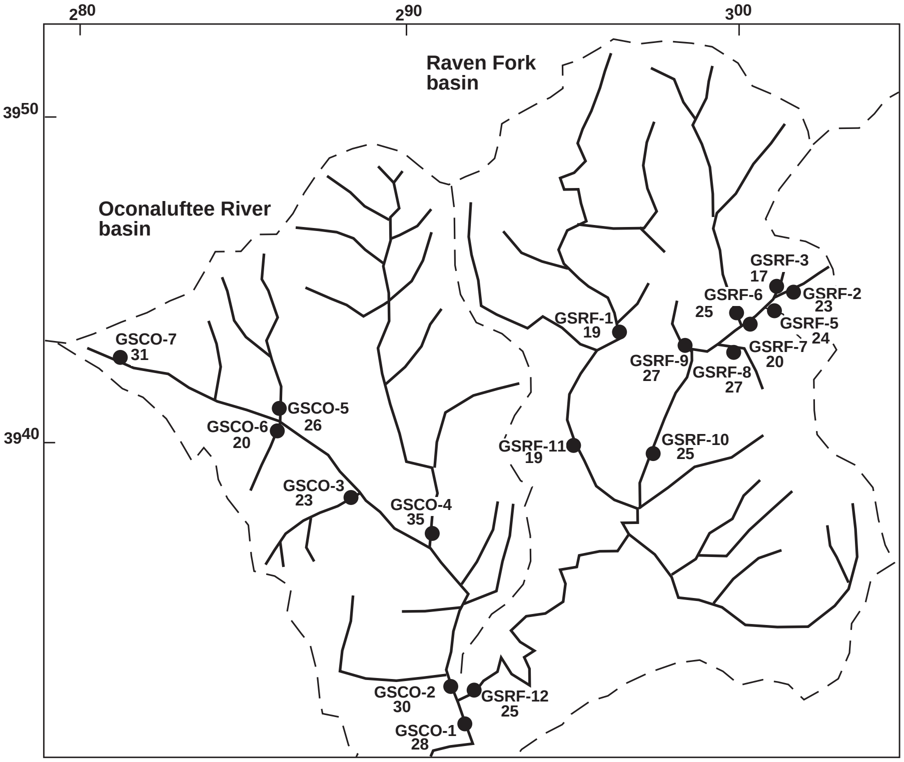

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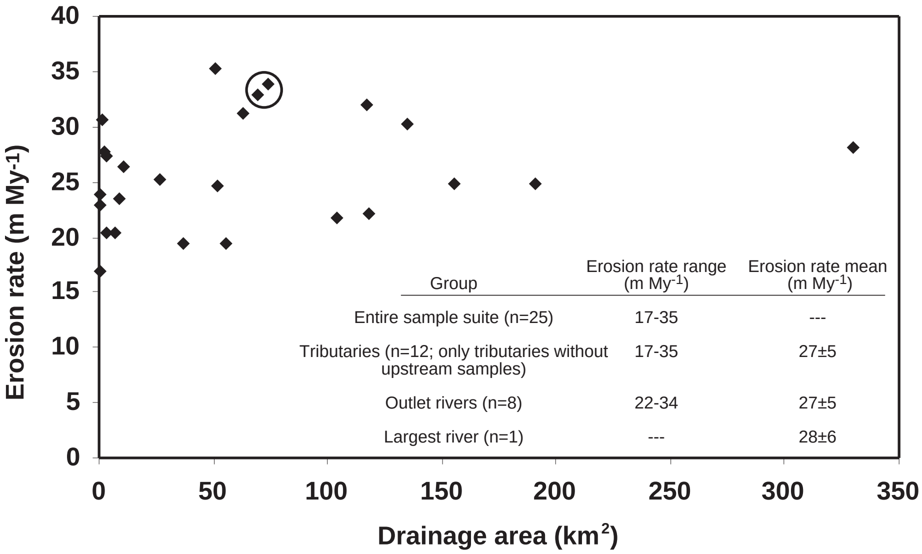
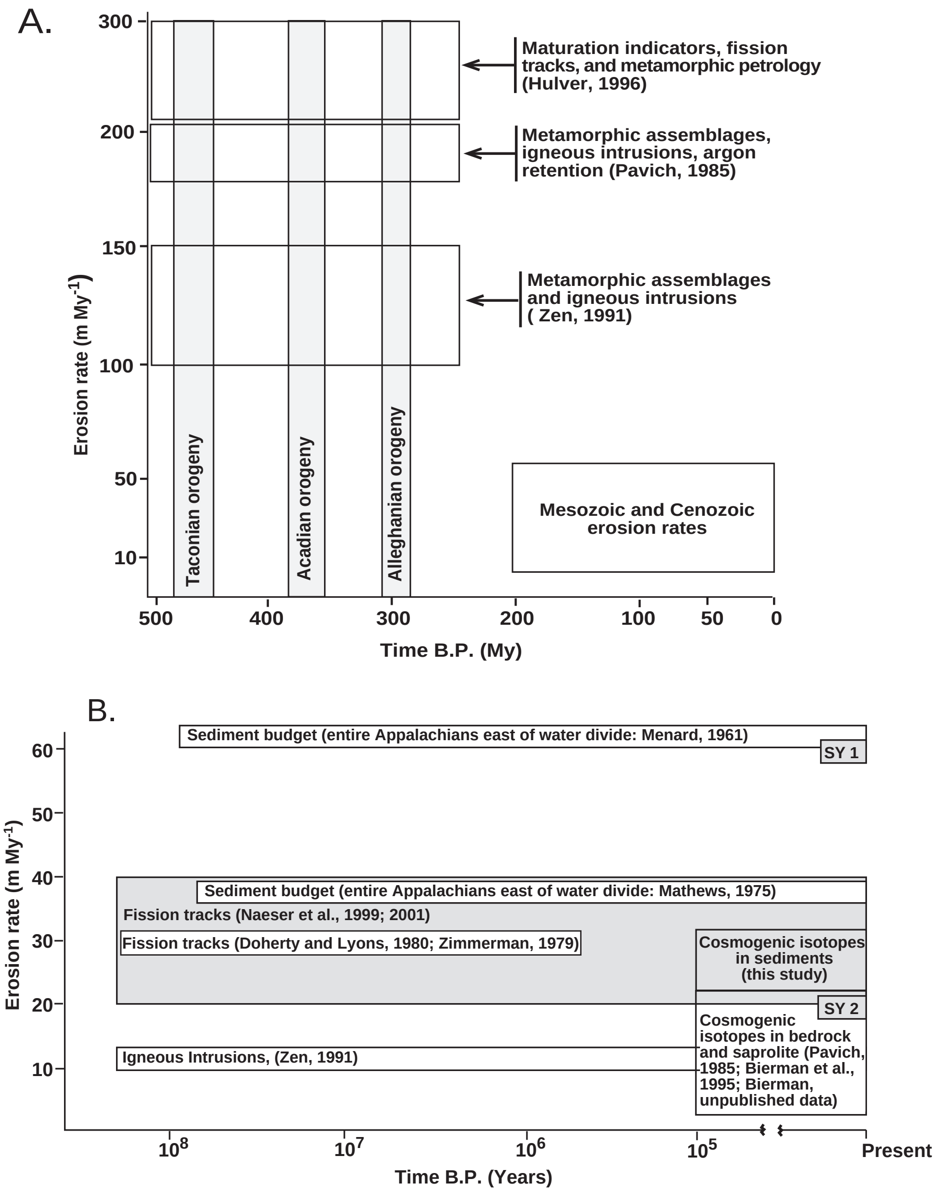


Group	Erosion rate range (m My^{-1})	Erosion rate mean (m My^{-1})
Entire sample suite (n=25)	17-35	---
Tributaries (n=12; only tributaries without upstream samples)	17-35	27±5
Outlet rivers (n=8)	22-34	27±5
Largest river (n=1)	---	28±6

Matmon et al., Figure 4



Matmon et al., Figure 5

Data Repository 1 – Matmon et al.

TABLE 1. COSMOGENIC RESULTS FOR GREAT SMOKY MOUNTAIN SAMPLES

Sample name	Measured ^{10}Be (10^6 atoms g^{-1})	^{10}Be model ε (m My^{-1})	Drainage area (km^2)	^{10}Be production factor
GSRF-1 (T)	0.434±0.011	19.3±4.2	36.9	2.69
GSRF-2 (T)	0.335±0.009	22.7±4.9	1.4	2.44
GSRF-3 (T)	0.461±0.012	16.9±3.7	1.0	2.51
GSRF-5 (T)	0.322±0.009	23.7±5.1	1.0	2.45
GSRF-6 (T)	0.341±0.009	25.0±5.4	27.3	2.74
*GSRF-7 (T)	0.376±0.011	20.4±4.4	7.7	2.46
GSRF-8 (T)	0.297±0.009	27.2±5.9	3.6	2.58
GSRF-9 (T)	0.274±0.008	27.4±5.9	2.9	2.40
*GSRF-10 (T)	0.325±0.009	24.6±5.3	51.9	2.56
*GSRF-11 (T)	0.452±0.011	19.3±4.2	55.7	2.80
GSRF-12 (B)	0.310±0.009	24.8±5.4	191.5	2.46
†GSCO-1 (B)	0.264±0.010	28.0±6.1	330.2	2.37
GSCO-2 (B)	0.234±0.007	30.1±6.5	134.9	2.25
GSCO-3 (T)	0.312±0.008	23.3±5.0	9.4	2.33
GSCO-4 (T)	0.200±0.006	35.1±7.6	51.4	2.25
GSCO-5 (T)	0.317±0.008	26.2±5.7	11.6	2.67
GSCO-6 (T)	0.361±0.012	20.2±4.4	3.3	2.34
GSCO-7 (T)	0.278±0.007	30.5±6.6	2.3	2.71
GSBC-1 (B)	0.234±0.006	33.7±7.3	74.8	2.52
§GSBC-2 (B)	0.247±0.008	33.0±7.1	65.7	2.60
GSDC-1 (B)	0.316±0.008	21.6±4.7	104.9	2.19
GSLP-1 (B)	0.225±0.007	31.8±6.9	117.3	2.28
GSLR-1 (B)	0.264±0.007	24.8±5.4	155.8	2.10
GSMP-1 (B)	0.267±0.007	22.0±3.4	118.3	1.88
GSWP-1 (B)	0.242±0.006	31.0±6.7	63.6	2.40

Note: (B) Outlet rivers of the Great Smoky Mountains. (T) Tributary of Oconaluftee River (GSCO), and Raven Fork (GSRF). Model erosion rates calculated using sea-level, high-latitude ^{10}Be production rate of 5.17 atoms g^{-1} yr^{-1} supported by data from Bierman et al. (1996), Stone (2000), and Gosse and Stone (2001), and normalized for latitude and elevation using nucleon only scaling of Lal (1991). Uncertainties in measured ^{10}Be are analytical errors. ^{10}Be model ε are calculated propagating 20% uncertainty in production rates and scaling factors. ^{10}Be production factor expresses the integrated surface production in each basin relative to sea-level, high-latitude production.

*Tributary samples that include upstream samples.

†Below the confluence of GSRF-12 and GSCO-2. This site was sampled to verify sediment mixing and sampling strategy.

§Replicate of sample GSBC-1

Erosion rate calculation

In order to interpret nuclide data for each basin, we calculated basin-integrated nuclide production rates by combining basin hypsometery and the altitude production-rate function of Lal (1991) in 100 meter bins (Bierman and Steig, 1996). For large basins (>60 km^2), we determined basin hypsometery using DEMs. For small basins (<60 km^2), we digitized topographic maps.

Erosion rates were calculated using the approach of Bierman and Steig (1996):

$$N = \{P/(\varepsilon\rho\Lambda^{-1}) \quad (1)$$

Sediment generation rates were calculated using:

$$N = \{P/(m\Lambda^{-1}) \quad (2)$$

where N= measured activity (atoms ^{10}Be g^{-1} quartz), P = basin integrated production rate (atoms ^{10}Be g^{-1} quartz yr^{-1}), ε = erosion rate (cm yr^{-1}), m = sediment generation rate (g yr^{1}cm^{-2}), ρ = density (g cm^{-3}), and Λ = attenuation depth (g cm^{-2}). This approach has been successfully tested in several studies using drainage basins of different sizes (Brown et al., 1995; Granger et al., 1996; Clapp et al., 2000, 2001; Bierman et al., 2001; Schaller et al., 2001).

Evidence for thorough mixing

Thorough mixing of sediment from different tributaries can be tested by a mass balance calculation. For example, the sediment generation rate at sample location GSCO-1 (Figs. 2 and 3) is $7.32*10^{-3}$ (g yr^{-1} cm^{-2}) using the area weighted average of GSCO-2 and GSRF-12 and $7.69*10^{-3}$ (g yr^{-1} cm^{-2}) using ^{10}Be activity in sample GSCO-1 (Fig. 3). The difference between the two calculations is ~5% indicating the agreement between expected and measured sediment generation rates and verifying the assumption of thorough mixing.

TABLE 2. CALCULATION OF AVERAGE EROSION RATES IN THE GREAT SMOKY MOUNTAINS

Group	Sample name	Basin area km^2	^{10}Be ε m My^{-1}	ε * Basin area 10^6 m^3 My^{-1}
Tributaries (with no upstream samples; n=12)				
	GSRF-1	36.9	19.3±4.2	712.6
	GSRF-2	1.4	22.7±4.9	31.8
	GSRF-3	1.0	16.9±3.7	16.6
	GSRF-5	1.0	23.7±5.1	23.2
	GSRF-6	27.3	25.1±5.4	683.4
	GSRF-8	3.6	27.2±5.9	98.5
	GSRF-9	2.9	27.4±5.8	78.5
	GSCO-3	9.4	23.3±5.0	218.5
	GSCO 4	51.4	35.1±7.6	1804.3
	GSCO-5	11.6	26.2±5.7	303.3
	GSCO-6	3.3	20.2±4.4	66.3
	GSCO-7	2.3	30.5±6.6	68.7
	Total basin area=	151.9		4015.7
		Weighted ε=	27.0±5.0	
Outlet rivers (n=8)				
	GSRF-12	191.5	24.8±5.4	4750.2
	GSCO-2	134.9	30.1±6.5	4063.9
	GSDC-1	104.9	21.6±4.7	2262.3
	GSLP-1	117.3	31.8±6.9	3733.7
	GSMP-1	118.3	22.0±3.4	2599.7
	GSWP-1	63.6	31.0±6.7	1974.1
	GSLR-1	155.8	24.8±5.4	3862.8
	GSBC-1	74.8	33.7±7.1	2522.4
	Total basin area=	961.2		25769.1
		Weighted ε=	26.8±4.7	
Rivers >100 km^2 (n=6)				
	GSRF-12	191.5	24.8±5.4	4750.2
	GSCO-2	134.9	30.1±6.5	4063.9
	GSDC-1	104.9	21.6±4.7	2262.3
	GSLP-1	117.3	31.8±6.9	3733.7
	GSMP-1	118.3	22.0±3.4	2599.7
	GSLR-1	155.8	24.8±5.4	3862.8
	Total basin area=	822.8		21272.9
		Weighted ε=	25.9±4.2	
Largest river (n=1)				
	GSCO -1	330.2	28.0±6.1	9239.8

Notes:

1. Weighted erosion rate of each basin is calculated by multiplying basin area with the ^{10}Be modeled erosion rate for that basin.
2. Average erosion rate of the group is calculated by dividing the total mass production (Basin area *ε) by the total area of all the basins in the group.

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