Sediment yield exceeds sediment production in arid region drainage basins

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ABSTRACT

We use ^{10}Be and ^{26}Al to determine long-term sediment generation rates, identify significant sediment sources, and test for landscape steady state in Nahal Yael, an extensively studied, hyperarid drainage basin in southern Israel. Comparing a 33 yr sediment budget with 33 paired ^{10}Be and ^{26}Al analyses indicates that short-term sediment yield (113–138 $t \cdot km^{-2} \cdot yr^{-1}$) exceeds long-term sediment production (74 ± 16 $t \cdot km^{-2} \cdot yr^{-1}$) by 53%–86%. The difference suggests that the basin is not in steady state, but is currently evacuating sediment accumulated during periods of more rapid sediment generation and lower sediment yield. Nuclide data indicate that (1) sediment leaving the basin is derived primarily from hillslope colluvium, (2) bedrock weathers more rapidly beneath a cover of colluvium than when exposed, and (3) long-term erosion rates of granite, schist, and amphibolite are similar.

Keywords: ^{10}Be, ^{26}Al, Nahal Yael, cosmogenic, erosion rates, sediment generation rates.

INTRODUCTION

Quantifying the rate at which rock erodes and sediment is produced is fundamental to understanding Earth as a system. Rates of sediment production (rock erosion) are typically inferred from estimates of sediment yield either measured as a flux of sediment past a gauging station or determined by measuring the accumulation of sediment in a reservoir (Schumm, 1963; Judson and Ritter, 1964; Meade, 1969; Trimble, 1977; Saunders and Young, 1983; Schick and Lekach, 1993). Equating sediment yield and sediment production implies steady-state behavior and assumes no change in the volume of sediment stored within a basin, an assumption repeatedly questioned (Meade, 1969; Trimble, 1977, 1999; Walling, 1983; Bull, 1991).

We compare 33 yr of sediment yield data from Nahal Yael to long-term, time-integrated rates of sediment generation determined by measuring in situ produced cosmogenic ^{10}Be and ^{26}Al. Significant differences between rates of sediment generation and sediment yield indicate that Nahal Yael, an intensively instrumented, hyperarid basin in southern Israel (Schick and Lekach, 1993), is currently exporting more sediment than is being generated by the weathering of bedrock. These data and others (Trimble, 1977; Brown et al., 1995; Clapp et al., 1997) suggest that over human time scales, balanced sediment production and yield may be the exception rather than the rule.

BACKGROUND

Nahal Yael occupies a small (0.6 km^2), mountainous drainage basin in the Negev Desert, Israel (Figs. 1 and 2). The basin is underlain by Precambrian rock (Shimron, 1974; Schick and Lekach, 1993), gneissic granite in the north, schist in the middle, and amphibolite to the south (Fig. 2). In the northern (granite) and middle (schist) sections, exposed bedrock dominates the uplands; significant colluvial cover is limited to bedrock hollows and the lowermost parts of hillslopes (Fig. 1). Sediment storage within these sections is confined to isolated colluvial deposits and alluvial terraces (generally <3 m thick) along the narrow valley bottom (Fig. A[1]). In contrast, hillslopes in the southern section (amphibolite) have bedrock exposed on the top 10–20 m and substantial colluvial cover over the lower hillslopes.

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[1]GSA Data Repository item 2000104, Figure A, Figure B, Appendix A, and Table A, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2000.htm.

Figure 1. Upstream view of Nahal Yael drainage basin from near sample site NY7 (see Fig. 2). Field of view is 600 m.

Data Repository item 2000104 contains additional material related to this article.

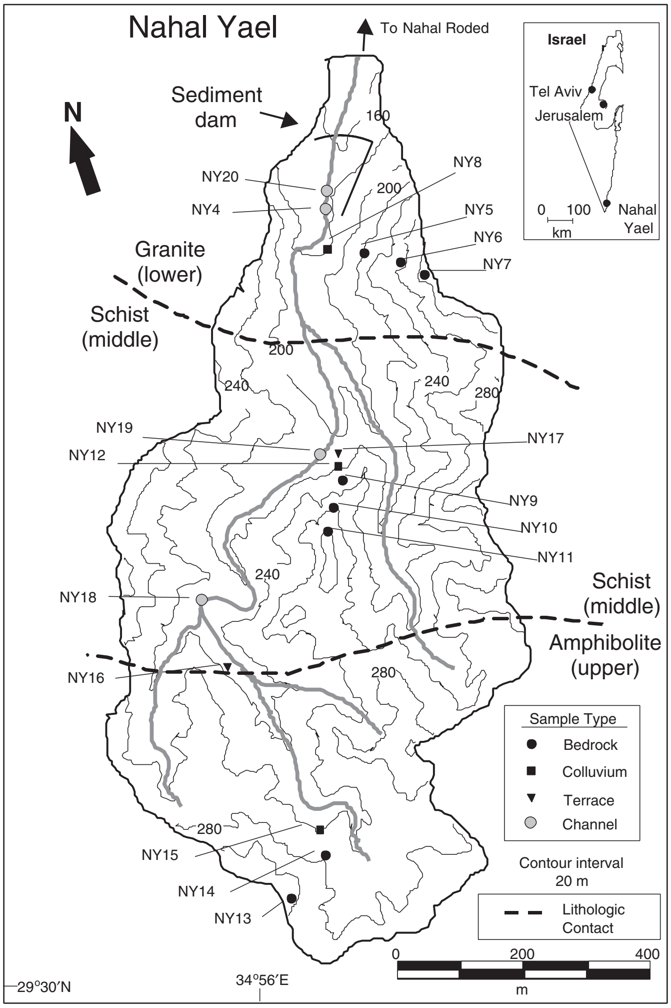

Figure 2. Map of Nahal Yael and site location (inset). Sample locations are shown for bedrock, hillslope colluvium, alluvial terraces, and channel sediment. Gray lines are channels. Topography is adapted from Schick and Lekach (1993); lithology is from Shimron (1974).

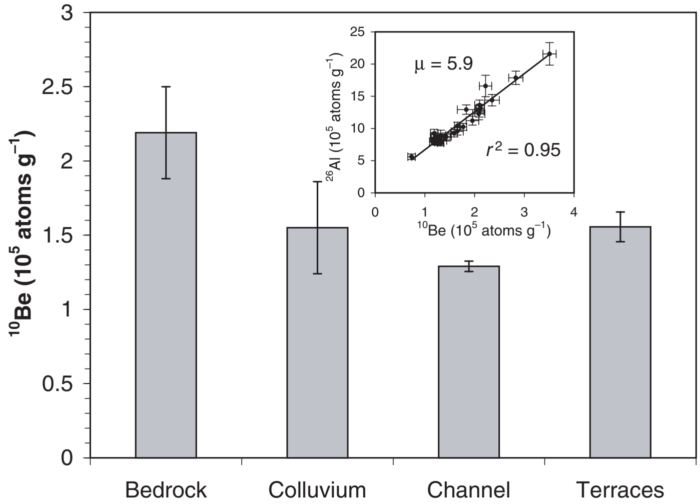

Figure 3. Average ^{10}Be concentrations measured in samples from geomorphic features (bedrock outcrops, colluvium, channel sediment, and terraces) of Nahal Yael. Error bars represent 1 standard error of means. Average bedrock nuclide activity is significantly greater (90% confidence) than averages of other features. Inset shows ^{10}Be vs. ^{26}Al for samples collected in Nahal Yael.

In 1967, Hebrew University researchers (Bull and Schick, 1979; Schick and Lekach, 1993) began constructing a sediment budget for Nahal Yael using automatically collected hydrologic and suspended-sediment data, estimates of bedload yield from scour chains and pebble tracing, and surveys of sediment deposition behind an earthen dam constructed in 1977 to trap and monitor sediment yields with nearly 100% efficiency (Schick and Lekach, 1993). Over the 33 yr monitoring history, 14 yr had no flow and 8 yr had events during which flow did not exit the basin (Schick and Lekach, 1993). In October 1997, a storm with an estimated recurrence interval >50 yr delivered >460 t of sediment to the mouth of the basin. The 33 yr record, including the large storm of 1997 and the 14 yr without flow, results in an integrated sediment yield of $138 \pm 19\ \mathrm{t \cdot km^{-2} \cdot yr^{-1}}$. The average sediment yield excluding the large storm of 1997 is $113 \pm 16\ \mathrm{t \cdot km^{-2} \cdot yr^{-1}}$.

We measured ^{10}Be and ^{26}Al in quartz to determine the maximum limiting, long-term rate at which sediment is generated and to identify areas where sediment is generated and stored. The assumptions and limitations of such measurements and their interpretations were discussed by Lal (1991), Bierman and Steig (1996), Bierman and Turner (1995), Brown et al. (1995), Granger et al. (1996), Clapp et al. (1997, 1998), and Small et al. (1999).

SAMPLING LOCATIONS AND METHODS

We measured nuclide concentrations in bedrock outcrops, hillslope colluvium, alluvial terraces, and channel alluvium (Figs. 2 and 3; Table A—see footnote 1). Laboratory methods are described in Appendix A (see footnote 1). Individual nuclide measurements discussed in the text include an analytical error of 1 σ.

We sampled channel alluvium at four locations along Nahal Yael (Fig. 2), using the channel as an integrator of different sediment sources and associated ^{10}Be and ^{26}Al from throughout the drainage basin. As flow within the channel travels down the basin, sediment from terraces and tributaries along the channel's length is entrained and mixed. As the channel cuts through alluvial deposits, it temporally integrates sediment deposited by many different depositional events.

Bedrock outcrops were sampled in three lithologically distinct transects (Fig. 2). Within the granitic terrain, where quartz is uniformly distributed throughout the bedrock, three samples were collected from a single hillslope at evenly spaced, 20 m elevation intervals. Within the schist terrain, where quartz is concentrated in crosscutting veins that are no more or less resistant to weathering than the surrounding rock, we collected three samples from the quartz veins, keeping as close to 20 m elevation spacing as possible. In the amphibolite terrain, quartz is also concentrated in veins; however, shorter hillslopes and fewer quartz veins limited us to only two samples ~20 m apart in elevation.

Three composite samples of hillslope colluvium, each composed of samples taken at ~1 m intervals across the base of the slope but above any channel-derived sediment, were collected from hillslopes below the three bedrock transects (Fig. 2). Two composite samples of alluvial terrace sediment were collected by mixing subsamples collected at evenly spaced depth increments (~10 cm) in the alluvium exposed by channel incision. Each sediment sample was divided into three grain-size fractions; we find no relationship between nuclide concentration and sediment grain size (Fig. B; see footnote 1).

Measured ^{26}Al/^{10}Be ratios ($\mu = 5.9 \pm 0.48$) (Fig. 3, inset) are consistent with the currently accepted production ratio of ~ 6:1 (Nishiizumi et al., 1989), indicating that the sediment and bedrock we sampled do not have long-term (>100 k.y.), complex histories of burial and exhumation. Because the two isotopes are well correlated ($r^2 = 0.95$), we present primarily the ^{10}Be measurements; however, the ^{26}Al measurements are used in all calculations (Table 1).

RESULTS AND DISCUSSION

Bedrock Erosion and Sediment Generation

We use nuclide concentrations in geomorphic features to identify significant sources of sediment to the channel and compare relative rates of

TABLE 1. SEDIMENT GENERATION AND EQUIVALENT ROCK EROSION RATES FOR NAHAL YAEL AND OTHER SITES

Location	Reference	Sediment generation rate		Sediment yield	Rock erosion rate			Site average	Annual precipitation	Lithology
		^{10}Be ($t\ km^{-2}\ yr^{-1}$)	^{26}Al ($t\ km^{-2}\ yr^{-1}$)	Sediment budget ($t\ km^{-2}\ yr^{-1}$)	^{10}Be ($m\ m.y.^{-1}$)	^{26}Al ($m\ m.y.^{-1}$)	Sediment budget ($m\ m.y.^{-1}$)	(m)	($mm\ yr^{-1}$)	
Nahal Yael†, Israel	This paper	78 ± 16	70 ± 16	113 to 138	29 ± 6	26 ± 6	42 to 51	240	30	Granite, schist, amphibolite
Yuma Wash, Arizona	Clapp et al. (1998)	81 ± 5	81 ± 8	N.D.	30 ± 2	30 ± 3	N.D.	220	91	Rhyolite, granite
Arroyo Chavez, New Mexico	Clapp et al. (1997)	273 ± 62	281 ± 73	394 ± 68	101 ± 23	104 ± 27	146 ± 25	2000	377	Sandstone
Fort Sage Mts., California	Granger et al. (1996)	162* ± 38		157 ± 38	60* ± 14		58 ± 14	1300	>370	Granodiorite
Wind River Range, Wyoming	Small et al. (1999)	39 ± 11	35 ± 11	N.D.	14 ± 4	13 ± 4	N.D.	3600	>285	Gneiss
Luquillo Forest, Puerto Rico	Brown et al. (1995)	116 ± 41	N.D.	202	43 ± 15	N.D.	75	700	4000	Quartz-diorite

Note: N.D. = No data.

*Published rate is average of ^{10}Be and ^{26}Al rates.

† Sediment generation and rock erosion rates calculated from sample NY20 (located closest to basin outlet) using formulation of Bierman and Steig (1996) and production rates of Nishiizumi et al. (1989) scaled for latitude and elevation according to Lal (1991) and assuming no muon production. Conversion between erosion and sediment generation rates based on densities of 2.7 ($g\ cm^{-3}$) for bedrock and 1.6 ($g\ cm^{-3}$) for sediment.

processes shaping desert environments. Average ^{10}Be concentrations in bedrock outcrops ($2.18 \pm 0.31 \times 10^5$ atoms · g^{-1}, $n = 8$) are higher than those in hillslope colluvium ($1.54 \pm 0.30 \times 10^5$ atoms · g^{-1}, $n = 3$), suggesting that exposed bedrock weathers more slowly (more nuclide accumulation) than bedrock beneath a colluvial cover (Fig. 3). These observations are consistent with previous cosmogenic measurements (Bierman, 1994; Clapp et al., 1997, 1998; Small et al., 1999).

Lower average nuclide concentrations in colluvium could result from cosmic-ray shielding (less exposure) by material now eroded. However, the 6.3×10^4 atoms · g^{-1} difference between exposed bedrock and colluvium would require shielding by colluvium deeper than 50 cm, far thicker than we observed on the steep slopes of Nahal Yael. Most likely, the nuclide abundance difference can be attributed to shielding beneath shallow (centimeters to decimeters) colluvium coupled with associated increases in both physical and chemical weathering, the result of increased water retention and moisture-bedrock contact time beneath a cover of colluvium (Bull, 1991; Small et al., 1999).

Nuclide concentrations, and thus erosion rates, are not statistically discernible between the three lithologies (Fig. 4). Nuclide concentrations measured in the granitic transect, where quartz is uniformly distributed, imply a positive relationship between elevation above the stream channel and nuclide concentration (Fig. 4, inset), perhaps reflecting a period of time when the lower granitic hillslopes held a cover of colluvium consistent with suggestions of a late Pleistocene–early Holocene stripping of hillslope colluvium (Bull and Schick, 1979; Bull, 1991). Schist and amphibolite transects show no significant relationship between nuclide abundance and elevation.

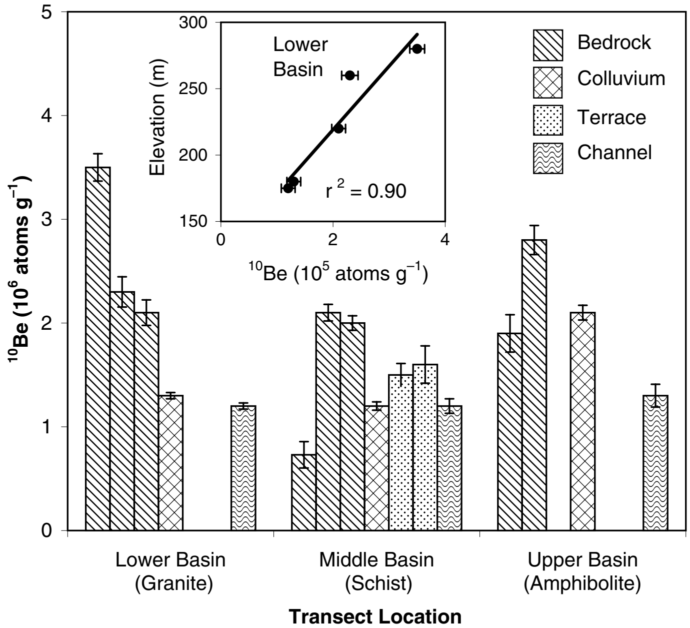

Figure 4. ^{10}Be concentrations measured at three transects in Nahal Yael. Nuclide concentrations are shown for bedrock, hillslope colluvium, terrace alluvium, and channel alluvium (waved stripes). Error bars represent one standard error of means. Inset shows positive linear relationship between ^{10}Be and elevation in granite transect. Points represent nuclide concentrations and elevations of three bedrock, one colluvium, and one stream channel sample.

Dynamics of Sediment Production and Transport

Nuclide data allow us to fingerprint sediment sources and suggest that most sediment in Nahal Yael is supplied by the middle and lower parts of the basin; the upper part of the Nahal Yael basin has more stable colluvial cover and contributes less sediment to the channel. The most important sediment source is colluvium stored in hollows and at the bottom of the slopes. Other sediment sources (exposed bedrock and terraces) contribute significantly less sediment.

Upper Basin. In the upper amphibolitic basin, nuclide concentrations in widespread hillslope colluvium ($2.16 \pm 0.06 \times 10^5$ atoms · g^{-1}, NY15) are higher than those measured in colluvium of the lower (granite and schist) parts of the basin (1.21 ± 0.02 to $1.28 \pm 0.02 \times 10^5$ atoms · g^{-1}, NY12 and NY8, respectively; Fig. 4). Average nuclide concentrations from the upper basin bedrock ($2.33 \pm 0.50 \times 10^5$ atoms · g^{-1}, NY13 and NY14) are only slightly greater than in the upper basin colluvium ($2.16 \pm 0.06 \times 10^5$ atoms · g^{-1}, NY15), indicating that exposed bedrock may be a significant source of sediment to the upper basin hillslopes. The nuclide concentration ($1.42 \pm 0.09 \times 10^5$ atoms · g^{-1}), measured in channel alluvium exiting the upper part of the basin (NY18), is greater than concentrations measured lower in the basin (1.22 ± 0.04 to $1.32 \pm 0.02 \times 10^5$ atoms · g^{-1}, NY20 and NY4, respectively), consistent with longer colluvial residence time in the upper basin.

Middle Basin. In the middle basin, sediment is currently stored along the valley bottom and to a lesser degree on the lower hillslopes in discontinuous alluvial terraces shown to be Pleistocene in age by optically stimulated luminescence dating (Lekach et al., 1999). Consistent with these observations, nuclide data (Fig. 4) suggest that there is some storage of sediment in alluvial terraces, because nuclide concentrations in these terraces (1.45 ± 0.11 and $1.66 \pm 0.06 \times 10^5$ atoms · g^{-1}, NY16 and NY17, respectively) are slightly greater than in samples from the sediment-supplying hillslopes above ($1.21 \pm 0.02 \times 10^5$ atoms · g^{-1}, NY12). The difference between NY17 (terrace) and NY12 (colluvium) is significant at the 2 σ level, and the difference between NY16 (terrace) and NY12 (colluvium) is significant at 1 σ but not 2 σ. The nuclide concentration of the channel alluvium ($1.24 \pm 0.04 \times 10^5$ atoms · g^{-1}, NY19) is similar to the hillslope samples, but less than terrace samples, suggesting that hillslopes supply more sediment to the channel than alluvial terraces.

The difference in concentrations between the colluvium and the terrace sediment (~3.0×10^4 atoms $\cdot$ g^{-1}) may reflect cosmic-ray dosing of terrace alluvium either prior to or following deposition. If we assume that the terraces were deposited rapidly at some point in the past, and integrate nuclide production (5.77 atoms of $^{10}Be \cdot g^{-1} \cdot yr^{-1}$) over the average terrace depth (~2 m), assuming sediment density of 1.6 $g \cdot cm^{-3}$, we calculate rapid deposition of alluvial terraces ca. 11 ka, consistent with the hypothesized late Pleistocene–early Holocene stripping of hillslopes in response to climate change (Bull and Schick, 1979; Bull, 1991). Alternatively, the alluvial terraces could have been deposited steadily, during which time nuclide accumulation continually occurred (Clapp et al., 1997). Steady-state deposition at ~125 $m \cdot m.y.^{-1}$ over ~16 k.y. would account for the additional ~3.0×10^4 atoms $\cdot$ g^{-1} measured in the ~2 m of alluvium.

Lower Basin. In the lower basin, colluvium resides only in hollows and isolated, thin deposits at the base of the slopes, suggesting minimal storage and short residence time. Consistent with short, near-surface residence, the average nuclide concentration of the hillslope colluvium in the lower basin (Fig. 4) is low ($1.28 \pm 0.02 \times 10^5$ atoms $\cdot$ g^{-1}, NY8). Channel alluvium ($1.25 \pm 0.03 \times 10^5$ atoms $\cdot$ g^{-1}, average of NY4 and NY20) and hillslope colluvium (NY8) nuclide concentrations are similar, suggesting that in the lower basin hillslopes supply most sediment to the channel of Nahal Yael.

Sediment Production Versus Sediment Yield

From nuclide concentrations measured in the channel sediment at the outlet of Nahal Yael (NY4 and NY20), we estimate (using Bierman and Steig [1996] and nuclide production rate estimates of Nishiizumi et al., 1989) a maximum, limiting, basin-wide sediment generation rate of 74 ± 16 $t \cdot km^{-2} \cdot yr^{-1}$, consistent with rates determined for other regions using similar methods (Table 1). This is likely an overestimate, because recent work suggests that long-term production rates of ^{10}Be and ^{26}Al are 10%–15% lower (Clark et al., 1995).

Sediment yield from Nahal Yael (113–138 $t \cdot km^{-2} \cdot yr^{-1}$), calculated from the sediment budget, is at least 53%–86% greater than the long-term rate of sediment generation estimated using ^{10}Be and ^{26}Al (Table 1). The difference between sediment yield and generation rates, along with the isotopic data, suggest that sediment is being mined from colluvium stored during a period when sediment generation outpaced sediment yield. Two of three similar studies elsewhere (Table 1) also suggest that current sediment yields exceed long-term rates of sediment generation (Brown et al., 1995; Granger et al., 1996; Clapp et al., 1997). These data show that the assumption of short-term landscape steady state is likely invalid. Episodic periods of sediment aggradation are followed by downcutting and sediment evacuation, possibly resulting from changes in climate or land use (Bull and Schick, 1979; Bull, 1991).

The measured differences between rates of sediment generation and sediment yield illustrate the danger of using short-term sediment yields to estimate long-term, basin-wide rates of bedrock erosion. Cosmogenic nuclides can provide direct estimates of long-term, basin-scale sediment generation rates and fingerprint significant sediment storage and source areas within drainage basins. These nuclides are invaluable in quantitatively addressing fundamental questions in arid-region geomorphology and may be used to identify temporal changes in sediment generation.

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