Quaternary downcutting rate of the New River, Virginia, measured from differential decay of cosmogenic ^{26}Al and ^{10}Be in cave-deposited alluvium

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ABSTRACT

The concentrations of the cosmogenic radionuclides ^{26}Al and ^{10}Be in quartz can be used to date sediment burial. Here we use ^{26}Al and ^{10}Be in cave-deposited river sediment to infer the time of sediment emplacement. Sediment burial dates from a vertical sequence of caves along the New River constrain its Quaternary downcutting rate to 27.3 ± 4.5 m/m.y. and may provide evidence of regional tectonic tilt.

INTRODUCTION

River downcutting rates are important for understanding rates of erosion, landform evolution, and tectonic uplift. Measurements of river downcutting rates provide first-order estimates of landscape lowering rates (e.g., Young and McDougall, 1993). Moreover, because large rivers tend to preserve characteristic longitudinal profiles, the spatial pattern of uplift along a river's course can be inferred from variations in downcutting rates along the river's profile (e.g., Burbank et al., 1996; Pazzaglia and Gardner, 1994).

River downcutting rates are usually measured by dating strath or alluvial terraces formed by the river in the past and preserved above its banks as it has incised. However, dating river terraces is often problematic, because easily datable materials are rarely available. Cosmogenic nuclide methods have provided new techniques for dating river terraces, by estimating the exposure time of bare bedrock straths (Burbank et al., 1996) or alluvial gravels (Anderson et al., 1996) to cosmic rays near the ground surface. However, cosmogenic nuclide exposure dating cannot be straightforwardly applied where terrace material may have been buried, eroded, or reworked since the terrace was originally formed.

Measuring river downcutting rates from terraces is particularly problematic in karst terrain, where terraces may be degraded by carbonate dissolution and doline collapse. However, riverside caves can record river levels, either as repositories of river sediment, or through calcite formations which form only above the water table. Speleothems may be dated by ^{14}C or U-series methods to infer water table lowering rates (Ford et al., 1981; Williams, 1982; Gascoyne et al., 1983), and alluvium preserved in riverside caves can sometimes be dated by sediment magnetostratigraphy to infer river downcutting rates (Schmidt, 1982; Sasowsky et al., 1995; Farrant et al., 1995; Springer et al., 1996).

BURIAL DATING WITH ^{26}Al AND ^{10}Be

Here we present a technique for dating sediment burial by the decay of the cosmogenic radionuclides ^{26}Al and ^{10}Be. Quartz grains are exposed to cosmic rays and acquire ^{26}Al and ^{10}Be during exhumation from hillslopes and transport through river networks. After these quartz grains are subsequently buried and shielded from cosmic radiation (for example by deposition in a cave), their ^{26}Al (radioactive meanlife τ_{26} = 1.02 ± 0.04 m.y. [Norris et al., 1983]) and ^{10}Be (τ_{10} = 2.18 ± 0.09 m.y. [Hofmann et al., 1987]) will decay at different rates. The ^{26}Al/^{10}Be ratio will therefore lower through time, recording the time since burial. Following Lal (1991), we calculate that the ^{26}Al/^{10}Be ratio $(N_{26}/N_{10})_0$ in a steadily eroding outcrop will change with erosion rate (E) as follows:

$$\left(\frac{N_{26}}{N_{10}}\right)_0 = \frac{P_{26}\left(\frac{1}{\tau_{10}} + \frac{E}{\Lambda}\right)}{P_{10}\left(\frac{1}{\tau_{26}} + \frac{E}{\Lambda}\right)} \qquad (1)$$

where N_{26}, N_{10}, P_{26}, and P_{10} are the concentrations and production rates of ^{26}Al and ^{10}Be, respectively, and Λ is the cosmic ray penetration depth ($\Lambda \approx 60$ cm in rock of density 2.6 g cm^{-3}). For erosion rates much faster than Λ/τ_{26}, the ^{26}Al/^{10}Be ratio approaches $(N_{26}/N_{10})_0 = P_{26}/P_{10}$ = 6.04 ± 0.54 (Nishiizumi et al., 1989); for erosion rates much slower than Λ/τ_{10}, it approaches $P_{26}\tau_{26}/P_{10}\tau_{10} \approx 2.7$ (Fig. 1).

If minerals accumulate ^{26}Al and ^{10}Be while exposed near the surface, and are subsequently shielded from cosmic radiation (e.g., by deposition deep within a cave), then cosmogenic radionuclide production will cease, and ^{26}Al and ^{10}Be will decay according to:

$$N_{26} = \left(N_{26}\right)_0 e^{-t_{\text{burial}}/\tau_{26}} \text{ and}$$
$$N_{10} = \left(N_{10}\right)_0 e^{-t_{\text{burial}}/\tau_{10}} \qquad (2)$$

where t_{burial} is the time since burial and and represent initial ^{26}Al and ^{10}Be concentrations. Because ^{26}Al decays faster than ^{10}Be, the ratio N_{26}/N_{10} decreases exponentially over time (Fig. 2):

$$\frac{N_{26}}{N_{10}} = \left(\frac{N_{26}}{N_{10}}\right)_0 e^{-t_{\text{burial}}\left(1/\tau_{26} - 1/\tau_{10}\right)}. \qquad (3)$$

Equations 1–3 can be solved iteratively. Starting with an initial guess of the erosion rate E, equation 1 can be solved for the initial ^{26}Al/^{10}Be ratio, $(N_{26}/N_{10})_0$, then equation 3 can be solved for the burial age t_{burial}, then equation 2 can be solved for a new estimate of the erosion rate, followed by iteration to equation 1. Convergence is normally achieved after a few iteration loops.

Equations 1–3 can be used to estimate burial times and preburial erosion rates from buried sediment, provided that the sediment (1) had initial ^{26}Al and ^{10}Be concentrations that were unaffected by previous episodes of burial, (2) was buried quickly (with respect to both radioactive decay and the total time spent buried), and (3) was buried deep enough that it has remained shielded from cosmic radiation (Lal and Arnold, 1985). How deep is deep enough? Both neutron spallation and negative muon capture can produce cosmogenic nuclides in buried sediment, and thus alter its ^{26}Al/^{10}Be ratio from that predicted by equation 3. Neutron spallation reactions produce most of these cosmogenic radionuclides at shallow depths, with a minor addition

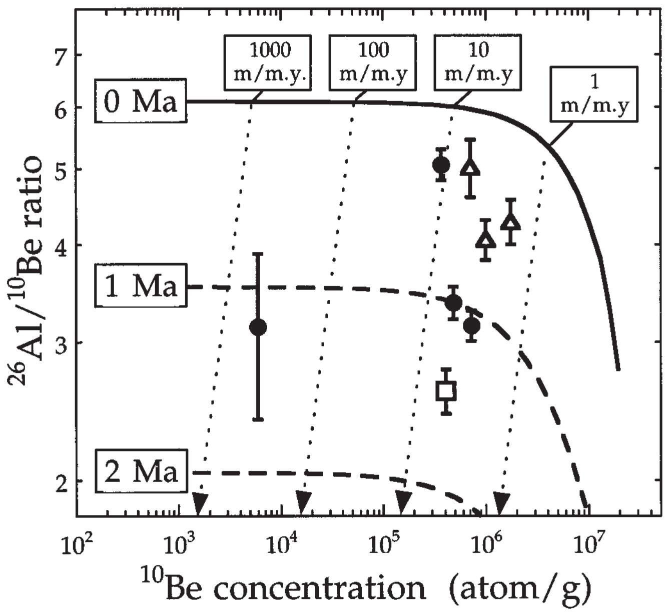

Figure 1. $^{26}Al/^{10}Be$ ratio plotted against ^{10}Be concentration can be used to infer sediment burial ages (after Lal, 1991). Solid line labeled "0 Ma" represents $^{26}Al/^{10}Be$ ratio in steadily eroding rock, as determined by equation 1 (see text). Erosion rates are shown from 1 m/m.y. to 1000 m/m.y., calculated for ^{10}Be production rate of 8.8 atoms g^{-1} yr^{-1} (as in Table 1). When rock is shielded from cosmic radiation, radioactive decay causes $^{26}Al/^{10}Be$ ratio to decline parallel to straight dotted lines, according to equation 3 (see text). 1 Ma and 2 Ma isochrons are shown as dashed lines. ^{26}Al and ^{10}Be data (Table 1) are plotted for five cave sediment samples (circles are Pearisburg caves, square is Eggleston cave) and four modern river sediment samples (triangles). Cave sediment burial times range from 0.29 ± 0.18 Ma to 1.47 ± 0.22 Ma. Preburial erosion rates may be calculated by backtracking $^{26}Al/^{10}Be$ ratios parallel to dotted decay lines to intercept on solid "0 Ma" exposure line, and range from 2.1 ± 0.5 m/m.y. to 451 ± 153 m/m.y.

from negative muon capture (~2% at our New River site). However, because neutrons are more rapidly attenuated than muons, nuclide production by negative muon capture dominates below ~3 m depth. In rock of density 2.85 g cm^{-3}, neutron spallation rates decrease by a factor of 10 for every 1.3 m depth below the surface, whereas muogenic nuclide production decreases to 10% of its surface value at ~11 m and 1% of its surface value at ~31 m (muogenic production calculated from Strack et al., 1994). Postburial nuclide production distorts the calculated burial age by an amount that increases with burial time t_{burial}, increases with preburial erosion rate E, and decreases with burial depth. For example, sediment eroded from bedrock at 10 m/m.y. and then buried for 1 m.y. would need to be buried >3.25 m deep (in rock of density 2.6 g cm^{-3}) to prevent postburial nuclide production from distorting its calculated burial age by more than 10%; achieving this accuracy with sediment buried for 4 m.y. requires burial >26 m deep.

The range of datable burial ages is constrained to about 0.3–5 Ma. Buried sediments must have $^{26}Al/^{10}Be$ ratios <~5 (and thus burial ages >~0.3 Ma) to be accurately dated, given the uncertainties in ^{26}Al and ^{10}Be analyses (5%–10%) and in the P_{26}/P_{10} ratio (~9%). Conversely, sediments buried for more than ~5 m.y. will rarely contain enough ^{26}Al to be datable.

Quartz river sediment deposited in caves is ideal for burial dating with ^{26}Al and ^{10}Be. Alluvium deposited deep within caves is well shielded from cosmic rays, so equation 3 can be used to date sediment emplacement. Because cave-deposited river sediments remain fixed relative to bedrock while the river incises, the emplacement times of ancient river sediments in caves, now high above the modern river, can be used to infer river downcutting rates.

NEW RIVER STUDY AREA

The New River drains the crystalline Blue Ridge and cuts across the Valley and Ridge province of Virginia (Fig. 2). As the river flows across cave-forming dolomites (Schultz et al., 1986) in the Valley and Ridge province, its bedload spills into caves which open onto the riverbed beneath the water surface (E. Lancaster, personal commun.). River incision leaves these caves abandoned high in riverside cliffs.

One of us (Granger) explored every known cave along the New River in the Valley and Ridge (more than 50 caves in all), and found 5 caves with emplaced river sediment, as much as 35 m above the modern river. The cave deposits are distinguished by well-rounded gravels and cobbles in a well-sorted, clast-supported fabric, and extend ~10 m to >100 m into the cave entrances. Because the sampled caves are located in high riverside cliffs, and sediment was collected from at least 10 m within the caves, sediment within the caves has been shielded by tens of metres of solid rock since its emplacement; cosmogenic nuclide production (by both neutrons and muons) inside the caves is therefore negligible. We measured ^{26}Al and ^{10}Be concentrations in distinctive clasts of vein quartz gravels derived from the New River's headwaters in the metamorphic Blue Ridge, more than 75 km upstream (Hack, 1973).

About 20 individual vein quartz clasts from each cave and from four modern river samples were crushed and amalgamated into large samples (~200 g each), then purified by selective chemical dissolution (Kohl and Nishiizumi, 1992). A reference ~0.5 mg Be spike was added to each sample, and natural background Al concentrations were measured by flame atomic absorption spectrophotometry. $^{10}Be/^{9}Be$ and $^{26}Al/^{27}Al$ ratios were measured by accelerator mass spectrometry at Lawrence Livermore National Laboratory (Davis et al., 1990).

RESULTS

Results from ^{26}Al and ^{10}Be analyses of the five cave samples are shown in Table 1 and Figure 1. Sediment emplacement times inferred from equations 1–3 range from 0.29 ± 0.18 Ma for a cave 12 ± 2 m above the modern river, to 1.47 ± 0.22 Ma for a cave 29 ± 2 m above the river. Regressing the elevation of caves above the modern river by the age of sediment emplacement shows that the New River's downcutting rate is 27.3 ± 4.5 m/m.y. (Fig. 3).

Figure 3 shows that a single river downcutting rate regressed through the data deviates from three of the five data points by >1.5 standard errors, implying that either (1) we have underestimated our uncertainties, or (2) a single regression line does not fully explain the data. To examine the second possibility, we divided the sampled caves into two groups and analyzed each group separately. Four of the sampled caves are clustered together near the town of Pearisburg, while one cave is located ~10 km to the southeast, near the town of Eggleston (Fig. 2). Inferred river downcutting rates are slightly different at the two locations: the river is incising at 30.2 ± 5.5 m/m.y. at Pearisburg, and more slowly, 19.7 ± 3.2 m/m.y., at Eggleston. Although only a single sample exists to constrain the Eggleston downcutting rate, the difference between the two rates (10.5 ± 3.5 m/m.y.) suggests regional tectonic tilt, in a direction consistent with inferred motion of an active seismic zone beneath the study area (Fig. 2) (Bollinger and Wheeler, 1983; Mills, 1986; Bollinger and Wheeler, 1988). (Uncertainty in the inferred tilt rate is calculated only from analytical uncertainties, because systematic uncertainties have little effect on the difference between the two incision rates.) The inferred tilt rate (1.05 ± 0.35 nanoradians/yr) would be difficult to detect by other methods.

Erosion rates inferred from equation 3 range from 3.7 ± 0.9 m/m.y. to 12.0 ± 2.8 m/m.y., with a single outlier at 451 ± 153 m/m.y. (Table 1). Despite large differences in inferred erosion rates, the four Pearisburg samples yield burial ages consistent with a constant river downcutting rate. This illustrates an important point: because the burial dating technique is based on the ratio of ^{26}Al to ^{10}Be, and not their absolute concentrations, it is not sensitive to the rate of erosion. The very high inferred erosion rate for one sample might result from a catastrophic storm or

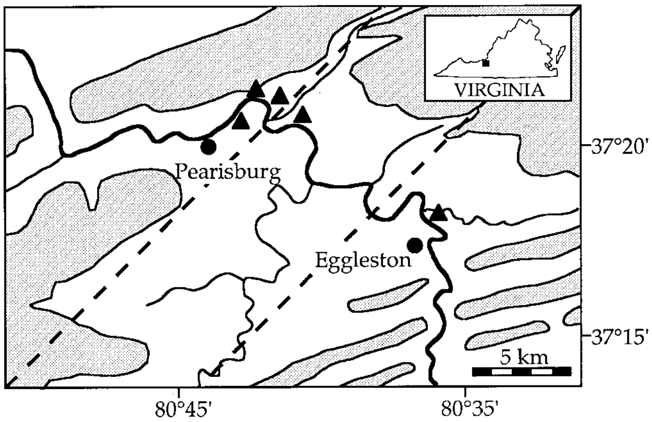

Figure 2. Location map of sampled caves (triangles) along New River in Valley and Ridge province of Virginia. Shaded areas represent mountains. Giles County seismic zone lies in crystalline basement beneath study area, between dashed lines (Bollinger and Wheeler, 1988). River downcutting rate inferred from caves near Pearisburg exceeds that inferred from cave near Eggleston, suggesting possible tectonic tilt associated with Giles County seismic zone over late Quaternary.

landslide that carried cobbles from quartz veins in the Blue Ridge to caves in the Valley and Ridge in a single event.

DISCUSSION

A major uncertainty in our burial dating technique is the assumption that the river's sediment remained unburied prior to cave deposition. If the sediment were buried for times comparable to τ_{26} and τ_{10}, then the initial ratio of ^{26}Al to ^{10}Be in the cave sediment would be less than predicted by equation 1, and equation 3 would overestimate the sediment's burial time in the cave. To test for an inherited burial signal, we measured ^{26}Al and ^{10}Be concentrations in modern river sediment.

Table 1 shows that four samples collected from the modern river have burial ages from 0.26 ± 0.22 m.y. to 0.61 ± 0.19 m.y., suggesting that this material may have spent significant time shielded from cosmic radiation. However, we suspect that this is a recent anomaly. A dam constructed in 1939 has prevented sediment from the Blue Ridge from reaching the study area; thus our modern river sediment samples may be mostly derived from river terraces downstream of the dam, which are being eroded by agriculture and urban construction (see Bartholomew and Mills, 1991, for a map of river terraces). Quartz cobbles collected 2.1 m and 4.3 m below the surface of a terrace, ~55 m above the modern river, have ^{26}Al/^{10}Be ratios of 2.60 ± 0.27 and 2.03 ± 0.22, respectively, yielding inferred burial ages of 1.50 ± 0.27 m.y. and 2.00 ± 0.29 m.y.; 25%–50% of such material in modern river sediment could produce the observed burial signatures. On average, sediment burial times during river transport must be short, because the volume of material stored in alluvial deposits is typically much smaller than the volume of material created by eroding $\Lambda \approx 60$ cm from the entire catchment. Furthermore, extrapolating the burial ages of the four Pearisburg cave sediments to modern river level (i.e., assuming a constant river downcutting rate) yields an expected burial age for active river sediment of –0.09 ± 0.17 m.y., indistinguishable from zero. For these reasons, we believe that the cave sediment was emplaced with little history of burial, and that the burial signal present in modern alluvium is anomalous. This hypothesis could be tested by sampling modern river sediment from upstream of the dam.

Previous attempts to measure the New River's downcutting rate have been hampered by a lack of datable material and by poor preservation of river terraces. Houser (1981) estimated the New River's downcutting rate at 40 m/m.y., based on the modern sediment load of the nearby South Fork of the Shenandoah River (Hack, 1965). Bartholomew and Mills (1991) considered a range of estimates, from 40 m/m.y. (long-term [~100 m.y.] erosion rates in Hack, 1979), to 55 m/m.y. (the downcutting rate of the Green River, Kentucky, inferred from cave sediment magnetostratigraphy [Schmidt, 1982]), to 100 m/m.y. (the downcutting rate of the Ohio River, inferred from glacial deposits above the river dated by Swadley [1980]). Mills (1986) had previously estimated the New River's downcutting rate as 286 m/m.y. by assigning a Wisconsinan (70 ka) age, based on the degree of mineral weathering, to river gravels preserved 20 m above the river. Because no datable materials could be found on the river terraces, none of these disparate estimates could previously be checked. Mills (1986) also attempted to measure tectonic tilt rates by correlating the maximum elevation of river gravels on degraded terraces high above the New River. However, there are no clear age estimates for these gravels, and little

TABLE 1. BURIAL AGES AND EROSION RATES FROM ^{26}Al AND ^{10}Be IN CAVE AND RIVER SEDIMENT

Sample	Height above river (m)	^{26}Al (10^6 atoms/g)	^{10}Be (10^5 atoms/g)	Burial age (m.y.)	Erosion rate (m/m.y.)
Pearisburg caves					
Virginian Cliff #1	12 ± 2	1.86 ± 0.07	3.68 ± 0.11	0.29 ± 0.18(0.08)	12.0 ± 2.8(0.6)
Quartz Cobble	27 ± 2	1.63 ± 0.07	4.84 ± 0.10	1.02 ± 0.19(0.09)	6.0 ± 1.4(0.3)
Virginian Cliff #3	31 ± 2	0.019 ± 0.002	0.059 ± 0.013	1.25 ± 0.50(0.46)	451 ± 153(112)
Klotz Quarry	35 ± 2	2.29 ± 0.09	7.27 ± 0.15	1.09 ± 0.19(0.08)	3.7 ± 0.9(0.2)
Eggleston cave					
Benton Williams #1	29 ± 2	1.43 ± 0.09	5.48 ± 0.11	1.47 ± 0.22(0.12)	4.0 ± 1.0(0.3)
Modern river sediment					
Ripplemead	---	3.57 ± 0.22	7.11 ± 0.41	0.26 ± 0.22(0.15)	6.2± 1.5(0.5)
Shanklin Creek	---	3.23 ± 0.24	6.41 ± 0.28	0.26 ± 0.22(0.16)	6.9 ± 1.7(0.6)
Curve Point Bar	---	4.06 ± 0.23	1.00 ± 0.21	0.61 ± 0.19(0.10)	3.5 ± 0.8(0.2)
Peppers Ferry	---	7.54 ± 0.47	1.76 ± 0.03	0.42 ± 0.19(0.11)	2.1 ± 0.5(0.1)

Note: Cave locations and descriptions are available in Douglas (1964) and Holsinger (1975) except for Quartz Cobble Cave (37°21'03"N, 80°43'03" E), which was previously unexplored. Burial ages and exposure times are calculated as described in text, assuming ^{26}Al and ^{10}Be production rates of 53.2 ± 10.6 and 8.8 ± 1.8 atoms g^{-1} a^{-1}, estimated from Nishiizumi et al. (1989) and corrected for latitude (37°) and elevation (550 m) as in Lal (1991), and production rate ratio P_{26}/P_{10} of 6.04 ± 0.54. Uncertainties are stated as ±1 standard error, and are shown as both random uncertainty (in parentheses, based on analytical uncertainties), and total uncertainty (including uncertainty in production rates, production rate ratio, penetration depth, and radioactive meanlife).

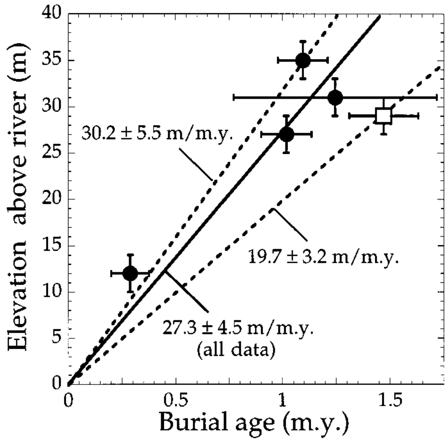

Figure 3. Downcutting rates inferred from emplacement times of river gravels in caves high above New River. Regressing all data together indicates downcutting rate of 27.3 ± 4.5 m/m.y. Separating data by cave location reveals that four caves near Pearisburg (circles) record downcutting rate of 30.2 ± 5.5 m/m.y., while single cave near Eggleston (open square) records downcutting rate of 19.7 ± 3.2 m/m.y. Difference between downcutting rates suggests regional tectonic tilt rate of 1.05 ± 0.35 m km^{-1} $m.y.^{-1}$ near Giles County seismic zone over late Quaternary. Downcutting rates are constrained to pass through origin. Error bars represent analytical uncertainty. Data regressed by method of York (1966).

reason to believe that they were deposited synchronously. $^{26}Al/^{10}Be$ burial dating provides better-constrained estimates of both New River incision and tectonic tilt rates.

Burial dating with ^{26}Al and ^{10}Be opens a new window into dating sediments and measuring geomorphic process rates, because its useful time scale, 0.3–5 Ma, is beyond the limits of U-Th dating, and because the technique can be used to infer both burial dates and erosion rates. Furthermore, because $^{26}Al/^{10}Be$ burial dating requires only quartz, this technique may be used where other datable materials are unavailable. Burial dating with ^{26}Al and ^{10}Be can also be applied to other sedimentary deposits (such as basin fills, alluvial fans, or river terraces) provided that sediment is buried tens of metres below the ground surface, beyond the influence of cosmic ray neutrons and muons. This study provides the first radiometric estimate of the New River's downcutting rate, thus demonstrating the utility of $^{26}Al/^{10}Be$ burial dating for tectonic and geomorphic research.

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