Chapter 5

Using Cosmogenic Nuclide Measurements in Sediments To Understand Background Rates Of Erosion And Sediment Transport

Paul Bierman\(^1\), Erik Clapp\(^1\), Kyle Nichols\(^1\), Alan Gillespie\(^2\), and Marc W. Caffee\(^3\)

\(^1\)University of Vermont, \(^2\)University of Washington, \(^3\)Lawrence Livermore Laboratory

1. INTRODUCTION

Understanding the tempo of sediment generation and transport is fundamental to understanding Earth as a system. For land managers, knowing rates of landscape change is important as they consider human impact on landscapes in a long-term context. Numerous means have been employed to estimate basin-scale erosion rates (Saunders and Young, 1983); many of these methods, such as calculations based on river sediment and solute transport rates, are influenced by human impacts or are useful only over short (10 to 100 yr) time scales (Trimble, 1977). Other techniques involve reconstruction of initial topography or definition of sediment volumes and source areas; however, these techniques are feasible only in particular environments and geologic settings, many of which are uncommon (Bishop, 1985). Sediment transport rates can also be estimated using tracers (e.g., Lekach and Schick, 1995) and sediment traps. The traditional means by which basin-scale erosion and sediment transport rates are estimated remain uncertain and thus are not widely applied.

During the past 15 years, advances in mass spectrometry have allowed measurement of nuclides produced by cosmic-ray bombardment (Elmore and Phillips, 1987; Finkel and Suter, 1993). Measurements have been used in concert with interpretative models (Lal, 1991) to estimate the rate at which rock surfaces erode (Bierman, 1994; Cerling and Craig, 1994). Because these nuclides (\(^{3}\)He, \(^{10}\)Be, \(^{21}\)Ne, \(^{26}\)Al, and \(^{36}\)Cl) are produced...
primarily in the uppermost several meters of rock and soil (Figure 1), they are sensitive monitors for the residence times of materials near Earth's surface; over long time frames and if landscape behavior approaches steady-state, such residence times reflect sediment generation rates and by inference, long-term erosion rates. However, as with many measurements of landform or rock-surface stability on the scale of outcrops, there is great uncertainty in extrapolating these "point" measurements to drainage basins over geospatial scales of 1 to 1000 km².

\[ P_X = P_0 e^{(-x \rho / \Lambda)} \]

\[ N = \frac{P}{m \Lambda^{-1} + \lambda} \]

Figure 1. Depth profile for nuclide production by fast neutrons. A scale is provided by the 1.7m tall geologist in the picture. Nuclide production falls off rapidly in rock as indicated by thick exponential curve. The equation on left quantifies this decrease considering: \( P_X \), the production rate at depth \( x \); \( P_0 \), the production rate at rock surface; \( \rho \), the rock density (2.7 g cm\(^{-3}\)); and \( \Lambda \), the neutron attenuation coefficient (165 g cm\(^{-1}\)). Integrating the production rate versus depth relation over time, when time is expressed as a depth through the coefficient \( m \), a mass loss rate (g cm\(^{-2}\) y\(^{-1}\)), the equation on the right describes the relationship between surface nuclide abundance (\( N \)), nuclide production at the surface (\( P \)), and \( \lambda \), the decay constant of the measured radionuclide. Shaded boxes in the center portray the movement of a parcel of rock toward the eroding surface and the concomitant increase in nuclide production.

In order to address issues of spatial scaling, several groups have measured cosmogenic nuclides in hillslope and fluvial sediment; implicit in this work, is the premise that samples of sediment, and the many grains they contain, represent the cosmic-ray exposure history of the drainage basin as a whole (Bierman and Steig, 1992; Brown et al., 1995; Granger and Kirchner,
(Figure 1), they als near Earth’s neches steady- rates and by neasurements of s, there is great drainage basins

1994a,b; Granger et al., 1996). All these authors have proposed similar models for interpreting, as an erosion or denudation rate, the abundance of cosmogenic nuclides produced in sediment transported out of drainage basins; these models and their assumptions are discussed in detail by Brown et al., (1995), Bierman and Steig (1996), and Granger et al. (1996). The models predict that lithic material in a rapidly eroding basin will spend little time near the land surface during its exhumation, conversion to colluvium, and transport down slope. As a result, sediment in a rapidly eroding basin will have lower nuclide activity than sediment in a slowly eroding basin. For example, data in this paper indicate that nuclide abundances are lower (and basin-scale erosion rates higher) on the humid, tectonically active Oregon Coast (135 m My\(^{-1}\)) than in the stable arid, Australian craton (\sim 17 m My\(^{-1}\)).

The steady-state activity of a cosmogenic radionuclide is a function of the half life of that nuclide and the erosion rate of the landscape sampled. If the landscape is eroding steadily and there is no significant, long-term sediment storage, measuring a single nuclide may suffice. However, in slowly eroding terrains or in areas where sediment storage times approach the half life of the measured nuclide, it is desirable to measure multiple nuclides.

Such an approach may yield additional information about the exposure history of the sediment. In particular, it is possible to identify whether sediment has been stored on hillslopes or in terraces during transport provided that the total period of burial and storage approaches the half life (0.7 My) of the short-lived nuclide \(^{26}\text{Al}\). If such burial has occurred, more of the short-lived nuclide will have decayed than the long-lived nuclide \(^{10}\text{Be}\) and the resulting model erosion rates will be different (Bierman et al., 1999; Klein et al., 1986; Nishiizumi et al., 1991). Australian sediment data, presented later in this paper, demonstrate this phenomenon. Such burial need not be deep. The isotopic ratio will shift measurably over 500 Ky if a sample is buried by 1 m of soil or colluvium.

Cosmogenic nuclide activities integrate sediment generation rates over different time frames dictated by the residence time of material near Earth’s surface. In the rapidly eroding Coast Range of Oregon, erosion rates calculated from cosmogenic isotope abundances are integrated over only a few thousand years and are similar for \(^{10}\text{Be}\) and \(^{26}\text{Al}\). In contrast, nuclide abundances and the resulting \(^{10}\text{Be}\) and \(^{26}\text{Al}\) ratio, accumulated in Australian sediment over tens of thousands of years, suggest significant burial and \(^{26}\text{Al}\) decay. In either case, nuclide-based erosion and sediment generation rates reflect time scales far exceeding human life spans and, therefore, provide the long-term context in which to consider field-based measurements and make management decisions. This paper presents examples from around the world (Figure 2) that demonstrate the utility of measuring cosmogenic nuclide abundances in sediment.
2. METHODS

Sample collection and analysis methods are designed to estimate, with the highest possible precision and accuracy, the nuclide abundance representative of sediment within a stream or river channel. Sediment is usually collected across the width of the channel, integrating many sub-samples. To make an isotopic analysis, 40 g of purified quartz are used so sediment sample sizes vary depending on the quartz content of the sample. For rivers draining quartz-rich terrains, hundreds of grams of sediment are sufficient. For sediments that are lithic-rich or if grain sizes are to be analyzed separately, several kg are required.

For most samples, only the sand fraction is processed. If pedogenic CaCO₃ is present, the sample is leached in acid to remove the cement and then separated by sieving into grain size fractions. Typically, the finer fraction (<250 μm) is not processed because it may have been transported into the basin by wind. Processing the gravel fraction is avoided because the small number of clasts within a gravel sample will integrate less well the varied history of sediment within the basin than the 10⁴ to 10⁵ grains of sand that comprise a 40 g sample.

To purify quartz, the samples are etched in 6 N HCl, rinsed, and then subjected to repeated 1 percent HF and HNO₃ etching in heated ultrasonic baths (Kohl and Nishizumi, 1992). After three etchings, only the quartz and

5. Cosmogenic

isolated heavy quartz, which contains between 90-95% of the samples and a mass carrier, and if available for analysis measured in aliquot of the stable Be and

AMS. Batch-size ratios measured to oxides and ²⁶Al.

After purification, normalized to the stable ²⁶Al.

3. COSMOGENIC

A general model of

\[ N = \frac{P}{\lambda + \epsilon \rho A t} \] (1)

This model assuming that the cosmogenic abundance is a function of the effective age of the sampled surface, or the sampled surface instantaneously.

Both cases assume cosmic ray fluctuations and many instances of observation.
isolated heavy minerals remain. A density separation effectively isolates the quartz, which is then etched one more time. The purified quartz usually contains between 20 and 200 μg/g stable Al. This quartz, in batches of seven samples and a blank, is dissolved in HF in the presence of 250 μg of Be carrier, and if required, Al carrier sufficient to ensure that 2500 μg of Al are available for analysis. After the quartz has dissolved, total Al and Be are measured in aliquots of the solution using inductively coupled argon plasma spectroscopy (ICP) and the remaining solution is purified using perchloric acid dry downs, anion chromatography, pH-specific precipitation, and cation chromatography.

After purification, the Be and Al are precipitated as hydroxides, burned to oxides and packed using Nb (Be) and Ag (Al) into targets for analysis by AMS. Batch-specific blanks are run with each batch and all analyses are normalized to standards. Ratios measured in blanks are subtracted from ratios measured in unknowns and the resulting data are reported, considering the stable \(^{10}\)Be and \(^{27}\)Al content of each sample, as atoms/g quartz of \(^{10}\)Be and \(^{27}\)Al.

3. COSMOGENIC NUCLIDE SYSTEMATICS AND INTERPRETATIVE MODELS

A general analytical model for interpreting in-situ nuclide abundances in rock samples has been developed by Lal (1991). This formulation, Equation (1), includes two free parameters (the erosion rate, \(\varepsilon\), and the time of exposure, \(t\)), if it assumed that the isotope production rate \((P)\), material density \((\rho)\), neutron attenuation \((A)\) and the decay constant \((\lambda)\) are known and uniform:

\[
N = \frac{P}{\lambda + \varepsilon \rho A} \left( 1 - e^{-(\lambda + \varepsilon \rho A) t} \right) \tag{1}
\]

This model is typically applied in two ways: (i) to calculate erosion rates assuming that sufficient time and mass loss have occurred so that nuclide abundance is at steady state, controlled by the rate at which mass is lost from the sampled surface \((t = \infty)\) and (ii) to calculate exposure ages, assuming that the sampled surface was free of cosmogenic nuclides when exposed instantaneously and that it has not eroded since initial exposure \((\varepsilon = 0)\). Both cases assume that the sampled surface was continually exposed to the cosmic ray flux and never buried during or after cosmic ray exposure. In many instances, these assumptions cannot be well-constrained by field observation. Accordingly, single nuclide model exposure ages are lower
bounds provided the sampled surface did not inherit nuclides from a prior exposure episode; single nuclide model erosion rates are upper bounds assuming steady erosion.

The interpretative model of Lal has been adapted from rock surfaces to sediments by several workers (Bierman and Steig, 1996; Bierman and Steig, 1992; Brown et al., 1995; Granger and Kirchner, 1994a,b; Granger et al., 1996). This adaptation considers the basin as a whole and demands the assumption of steady state. The resulting interpretative formulation, Equation (2), is similar to that given in Equation (1); however, no correction for decay can be made because of differing grain histories (Bierman and Steig, 1996). The inability to correct for decay is usually unimportant because most basin-scale erosion rates are relatively high and thus sediment residence times are substantially shorter than the 1.5 My $^{10\text{Be}}$ half life.

$$N = \frac{P_{\text{avg}}}{\varepsilon \rho A^{-1}} \tag{2}$$

It is necessary to consider not only the abundance of nuclides in the sediment ($N$) but also the rate at which such nuclides are produced ($P_{\text{avg}}$) within the drainage basin (Brown et al., 1995; Bierman and Steig, 1996; Granger et al., 1996). Because nuclide production rates are elevation- and latitude-specific (Lal, 1991), weighted average calculations of basin-wide nuclide production rates are made using basin area/elevation relationships, typically at 100 m intervals. This calculation assumes that quartz is distributed uniformly throughout the basin although sediment generation rates may vary spatially without affecting the veracity of model interpretations.

There are several assumptions implicit to the interpretative model described by Equation (2) that limit the application and accuracy of sediment generation rates calculated from cosmogenic nuclide activity measured in sediments. Most sediment must be supplied by shallow, near-surface processes, such as soil creep, rill erosion, sheetwash, and very shallow landsliding. Violation of this assumption, for example, episodic supply of sediment by deep-seated landslides, could result in either over- or underestimation of long-term sediment generation rates depending on whether fluvial sediment was collected just before or just after the slide. Sediment must be well mixed by streams even if sediment input events are episodic.

There are additional systematic and random uncertainties in the calculation of sediment generation rates from measured nuclide activities. Production rate estimates are empirical; for $^{10\text{Be}}$ and $^{26\text{Al}}$, there is a 20 percent difference in published estimates (c.f., Nishiizumi et al., 1989; Clark et al., 1995; Klein et al., 1995). Production rates are underestimates of muons to $^{10\text{Be}}$ and $^{26\text{Al}}$ level; thus, muon–induced production is likely. Forced by time-dependent changes in the field, instantaneous nuclide production rates percent over the late Pleistocene (Bierman et al., 1995). We do not estimate this.

Together, these uncertainties make it uncertain by 20 or 25 percent. These estimates improve significantly the spatial resolution and distribution of Earth.

4. CASE STUDY

To illustrate the application of nuclide in sediments, we present data from climatic settings around the world. The method or illustrative cases are part of these data have been published before, the i

4.1. Drift Creek

The Oregon Coast Range is important in relation to logging of bedrock. The range is underlain by the 180-km$^2$ Drift Creek sediments contain near bedrock (Newport, Oregon) and others.

The 180-km$^2$ Drift Creek and is, or was, covered by the stream is < 1 m deep and wedges from bedrock. Some of the basin, the timber harvesting; other
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et al., 1995; Klein et al., 2000). The latitude/altitude corrections for
duction rates are uncertain by 10 to 20 percent (Lal, 1991; Dunai, 2000;
ilet and Zreda, 2000; Lifton, 2000). There is a minor contribution of
ons to \(^{10}\text{Be} \) and \(^{26}\text{Al} \) production, about 3 percent at Earth’s surface at sea
level; thus, muon-induced production is disregarded in our calculations.
Forced by time-dependent variation in the intensity of Earth’s magnetic
field, instantaneous nuclide production rates have changed more than 30
percent over the late Pleistocene at high elevations and low latitudes (Clark
et al., 1995). We do not account for these changes.
Together, these uncertainties, along with geologic assumptions, suggest
that cosmotically-derived estimates of sediment production may be
uncertain by 20 or 25 percent; however, even such relatively imprecise
imates improve significantly our quantitative understanding of the rate
and distribution of Earth surface processes.

4. CASE STUDIES

To illustrate the utility of measuring cosmogenic nuclide abundance
in sediments, we present a series of case studies from different tectonic and
climatic settings around the world. Each site presents a useful application
of the method or illustrates an important concept in isotope systematics. Some
of these data have been published previously, in which case citations to the
data sets are provided; in other cases, where the data have not been
published before, the isotopic data are provided in Table 1.

4.1. Drift Creek, Coast Range, Oregon

The Oregon Coast Range trends north-south along the Pacific Coast. The
range is important in terms of resource management because of issues
related to logging of both old- and second-growth timber. Much of the range
is underlain by the Tyee sandstone, an immature arkose of Eocene age.
Stream sediments contain a mixture of quartz, feldspar, and rock fragments.
The Coast Range receives \( >2 \) m precipitation annually (as measured at
Newport, Oregon) and is dominated by steep slopes and bedrock hollows.

The 180-km\(^2\) Drift Creek Basin we sampled has a total relief of \( 850 \) m
and is, or was, covered by dense coniferous forests (Figure 3). Colluvium is
delivered to the stream channels by biologically driven soil creep of soil that
is \( <1 \) m deep and by episodic failures of several-meter deep colluvial
wedges from bedrock hollows (Benda, 1990; Dietrich and Dunne, 1978).
Some of the basin, that within the Drift Creek Wilderness, is protected from
timber harvesting; other portions of the basin have been heavily logged.
<table>
<thead>
<tr>
<th>Table 1. Cosmogenic isotope abundances and model erosion rates</th>
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<tr>
<td>Sample</td>
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<tr>
<td>Trephina Creek, NWT, Australia (750 m, 23° S, 500 km$^2$)</td>
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<td>Sandy Creek, Llano Uplift, Texas (500 m, 30° N, 190 km$^2$)</td>
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<td>lui-33</td>
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<td>Orbit Creek, Coos Range, Oregon (210 m, 44° N, 180 km$^2$)</td>
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Erosion rates and exposure ages calculated using sea level, high latitude $^{10}Be$ and $^{26}Al$ production rates of 6.08 and 36.8 atoms g$^{-1}$ yr$^{-1}$ (Nishiizumi et al., 1989). Scattered errors include 20% production rates, 5% density, 5% stable Al, 5% stable $^{10}Be$. The 0.4 gives the confidence intervals for each sample represented by the downstream samples. Elevations and latitude are basin averages. Mean values are shown. * Sediments collected from the same location at 10 m. ** Elevation is the exposure age.
Forty samples were collected from the basin, with data for 16 samples presented here (Table 1; Figure 4). Isotopic measurement of these Coast Range samples (made in 1995) was difficult and uncertain because in many cases, radionuclide concentrations were so low that measured ratios were only several times larger than our blank. The large uncertainties of the $^{10}$Be measurements are caused by the use of a conservative blank correction based on the long-term value of our process blanks. In these low-level samples, $^{26}$Al data are more variable than $^{10}$Be data. Differences in measured $^{26}$Al concentrations between samples from nearby locations and replicates frequently exceed the uncertainty expected from counting statistics; thus, we base our conclusions on the $^{10}$Be data. Despite these uncertainties, the data from Drift Creek demonstrate that the abundance of $^{10}$Be and $^{26}$Al in sediments can be used, even in samples collected near sea level where the cosmic-ray flux is very low, to estimate erosion rates $>100$ m My$^{-1}$ (Table 1; Figure 5).

Samples were collected along the channel network of Drift Creek. All samples except DC-3, DC-9, and DC-11 were collected either from subbasins that had been cut or from areas with roads. Samples DC-1 and DC-2 were collected, respectively, from the channel of Drift Creek and from

Figure 3. Tributary to Drift Creek where samples DC-13 and DC-14 were collected. Shallow soil creep is carrying small trees toward channel.
adjacent, recent overbank sediments; they have similar $^{10}$Be abundances that suggest erosion rates of 120-135 m My$^{-1}$ (Figure 5). Samples DC-3a, b, c were collected from different parts of a 100 m reach of an ephemeral channel just below a drainage divide (first-order basin). They contain similar amounts of $^{10}$Be and show that sediment is isotopically well mixed even in a small drainage basin (Figure 5).

![Diagram of Drift Creek site map showing location of samples (open circles) discussed in text and in Table 1.](image)

Figure 4. Drift Creek site map showing location of samples (open circles) discussed in text and in Table 1.

Most importantly, sample DC-22 was collected at the mouth of Drift Creek and can be used to calculate a $^{10}$Be erosion rate of 139±57 m My$^{-1}$, consistent with the average rate calculated from the 14 upstream sediment samples (136±43 m My$^{-1}$). DC-11 was collected at the base of a 300-m-long hillslope, has a relatively high activity of $^{10}$Be, and can be used to calculate a $^{10}$Be model hillslope erosion rate of 81±24 m My$^{-1}$, which is lower than the average of all other sediment samples; the lower isotope activity in channel sediments may be caused by the input of landslide sediments derived from bedrock hollows that have received less exposure to cosmic radiation than sediments supplied directly to the channel by soil creep (e.g., Brown et al., 1995). Our data are consistent with landslides deepening hollows more rapidly than adjacent hillslopes are lowered.

5. Cosmogenic Isotopes

![Graph of model denudation rates (m/My) by category. Sample + circles are $^{26}$Al data.](image)

Figure 5. Cosmogenic isotope data by category. Sample + circles are $^{26}$Al data.

Reneau and Dietrich (1995) noted the range of bedrock denudation rates within colluvial hollows on the base of these hillslopes and below the active channel (136±43 m My$^{-1}$) (Reneau and Dietrich (1995), the difference in erosion rates is attributed to differences in bedrock composition and the slope of the hillslopes.)

Using lower erosion rates, we can estimate the effect of several orders of magnitude of interesting and potentially significant processes on sediment loads and generation rates. Our data do not include sediment transport events.
Figure 5. Cosmogenic isotopic data from Drift Creek interpreted as erosion rates and plotted by category. Sample number shown above 1σ error bars. Solid boxes are 10Be data; open circles are 26Al data.

Reneau and Dietrich (1991) used three different approaches to estimate the range of bedrock lowering rates in the Coast Range: filling of 14C-dated colluvial hollows (36-117 m My⁻¹, mean = 66±25), exfoliation of bedrock at the base of these hollows (62-130 m My⁻¹, mean = 91±25), and suspended sediment yield of streams in logged and unlogged areas (50-79 m My⁻¹). Erosion rates determined by measurements of 10Be in Drift Creek sediments (136±43 m My⁻¹) are somewhat higher than rates determined by other means (Reneau and Dietrich, 1991; Figure 6); however, if 10Be and 26Al production rates are revised downward by 20 percent, as suggested by Clark et al. (1995), the difference between our erosion rate estimates and those of Reneau and Dietrich would diminish by a similar percentage.

Using lower nuclide production rates (Clark et al., 1995; Klein et al., 2000), our nuclide-based estimates are consistent with all but those derived from suspended sediment load, the measurement of which integrates over several orders of magnitude less time than cosmogenic nuclides. This is an interesting and potentially important finding. The data suggest that current sediment loads in Coast Range streams are less than long-term sediment generation rates, perhaps because the relatively short stream gauging record does not include rare but extremely high-magnitude discharge and sediment transport events.
4.2. Trephina Creek, Northern Territory, Australia

Trephina Creek is a sandy ephemeral wash, 10 to 30 m wide, draining 500 km² of the Macdonnell Ranges, 60 km east of Alice Springs, Australia (Figure 7). Its headwaters lie in quartzite ridges from which sediment is transported by sheetwash. Precipitation averages 375 mm/y at Alice Springs and vegetation cover consists of trees in the valley bottom and shrubs and grasses on the hillslopes.

Samples TC-1 and TC-2 were collected about 1 km apart, above and below Trephina Gorge, where the stream cuts across a quartzite ridge (Figure 7). The similarity in their nuclide abundances demonstrates both the reproducibility of our methods and the well-mixed nature of these sediments. Sample TC-3 was collected where Trephina Creek crosses the Ross River Road, >10 km downstream from TC-1 and 2. Erosion rates calculated from $^{10}$Be in this sample are slightly lower (14 m My$^{-1}$) than those calculated from sediments collected further upstream (18 m My$^{-1}$), reflecting either increased exposure to cosmic rays during tens of thousands of years of transport or input of sediment from a more slowly eroding portion of the basin. Our data do not allow us to distinguish between these interpretations.

5. Cosmogenic Isotopes

Figure 7. Trephina Creek at this location; sample sites indicated by different histor

de of burial for sediment that is different. Brown et al., 1

The discrepancy between the basin (Table 1.6A, if sediment $^{26}$Al/$^{10}$Be will be

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The discrepancy between $^{10}\text{Be}$ and $^{26}\text{Al}$ model erosion rates for all three Trephina Creek samples indicates long sediment burial times ($10^5$ ky) within the basin (Table 1). Because of the shorter half-life of $^{26}\text{Al}$ in comparison to $^{10}\text{Be}$, if sediment is stored for periods of time exceeding $10^5$ years, the ratio $^{26}\text{Al}/^{10}\text{Be}$ will begin to fall as $^{26}\text{Al}$ decays more rapidly than $^{10}\text{Be}$. Although, if burial is shallow, the $^{10}\text{Be}$ inventory may continue to increase. Because the sediment that was analyzed is a mixture of grains, each probably having a different history and nuclide abundance, it must be assumed that the long-lived radionuclides behave as stable nuclides (c.f., Bierman and Steig, 1996; Brown et al., 1995). The difference in $^{26}\text{Al}$ and $^{10}\text{Be}$ model erosion rates at Trephina Creek show that this assumption is false; thus, even long-lived $^{10}\text{Be}$ may overestimate erosion and sediment generation rates in this stable landscape.

4.3. Sandy Creek, Llano Uplift, Central Texas

Sandy Creek drains about 200 km$^2$ of the crystalline Llano uplift of central Texas. The landscape is dominated by exfoliating granitic domes standing above a low-relief saprolite-covered plain (Bierman et al., 1995). The area is sub-humid (700 mm/y). Sediment is delivered to the channel directly by wash from the granitic outcrops and by ephemeral streams which incise the saprolite (Figure 8).
Three sediment samples from the Llano Uplift suggest that erosion rates are several times higher and sediment residence times correspondingly lower than we measured in Australian samples. Samples LUI-33 and LUI-34 were collected near Enchanted Rock, a km-long and 100-m-high granite dome (Figure 8). Sample LUI-33 is from the bed of Sandy Creek, a 15-m-wide, ephemeral wash incised into saprolite and grusy alluvium; LUI 34 was collected from a small channel draining directly off Enchanted Rock. LUI 35 was collected where Sandy Creek crosses Texas Route 15, about 20 km downstream of the other two samples. The downstream sample (LUI-35) from Sandy Creek has slightly higher nuclide abundance than the samples collected upstream, similar to the pattern we measured in Trephina Creek. Average $^{10}$Be and $^{26}$Al erosion rates for the three samples are coincident suggesting that the crystalline Llano uplift is eroding about 30 m My$^{-1}$ and indicating that the duration of any sediment burial or storage is brief in the Llano area.

The average erosion rate we calculate from Texas sediments (29 m My$^{-1}$) is consistent with that calculated previously by measuring $^{36}$Cl in flat-lying saprolite and on outcropping rock surfaces of the granite domes (Bierman, 1993; Bierman et al., 1995). The average $^{36}$Cl model erosion rate for 27 bedrock samples collected in and near Enchanted Rock State Park is 18 m My$^{-1}$. The $^{36}$Cl model erosion rate for saprolite exposed at the base of

5. Cosmogenic Nuclides

Enchanted Rock samples were measured using the AMS technique of Enchanted Rock to yield a well-dosed nuclide distribution due to saprolite erosion.

4.4. Yuma Province

Yuma Province is a river of southwestern Arizona. The Proving Ground ephemeral streams have ephemeral tributaries emanating from adjacent, higher-altitude, quite old, pre-Cambrian bedrock, hillslopes, and small alluvial fans that are now being slowly eroded and dissection by ephemeral streams. The highest nuclides $^{10}$Be and $^{26}$Al are concentrated in the lower order tributaries, and slowly eroded bedrock. The Yuma Province consists of a large alluvial fan, with a dissection of the Yuma Wash and the Gila Basin. The wash cuts deeply into the bedrock, hillslopes, and small alluvial fans that are now being slowly eroded. The Yuma Province is characterized by a high degree of erosion and dissection of the Yuma Wash and the Gila Basin. The wash cuts deeply into the bedrock, hillslopes, and small alluvial fans that are now being slowly eroded.

Yuma Wash unquantified, measured, and dissection of the Yuma Province (accepted) by the main stem channel and dissection of the Yuma Province (accepted) by the Yuma Wash and the Gila Basin. The Yuma Province is characterized by a high degree of erosion and dissection of the Yuma Wash and the Gila Basin. The wash cuts deeply into the bedrock, hillslopes, and small alluvial fans that are now being slowly eroded.

Using a n $^{10}$Be) in charcoal and alluvium (sand), the regular dacite flow (sandy) from an equal contribution (11). Where ' percent of the
Enchanted Rock is 24 m My\(^{-1}\). Higher erosion rates (76 and 120 m My\(^{-1}\)) were measured for small outcrops of saprolite remaining on the steep sides of Enchanted Rock. It appears that Sandy Creek alluvium is a mixture of well-dosed material eroding off the granitic domes and less-heavily dosed saprolite eroding both from the lowlands and from the flanks of the domes.

### 4.4. Yuma Proving Ground, Southwestern Arizona

Yuma Proving Ground is a military installation in the arid Mojave Desert of southwestern Arizona (mean annual precipitation = 91 mm/yr). Most of the Proving Ground drains into Yuma Wash (Figures 9 and 10), an ephemeral stream bed with steep, alluvial banks. The highlands from which tributaries enter the wash are rocky and hold little sediment in storage; in contrast, the valley bottoms are heavily alluviated. Some of the alluvium is quite old, probably pre-Quaternary alluvial fan surfaces that have been tilted and are now being actively eroded and dissected.

Clapp et al. (accepted) measured \(^{10}\text{Be}\) and \(^{26}\text{Al}\) in 41 samples of exposed bedrock, hillslope colluvium, and channel sediment collected from Yuma Wash and its drainage basin. They find that bedrock outcrops have the highest nuclide abundance, nearly two times higher than the concentration of \(^{10}\text{Be}\) and \(^{26}\text{Al}\) found in the other materials they analyzed (Table 2). On the basis of these measurements, they conclude that bedrock is the most stable and slowly eroding landscape element. Using the same data, they conclude that hillslopes mantled by shallow colluvium contribute most of the sediment to upland channels because of the similarity between \(^{10}\text{Be}\) abundance in channel sediments and in hillslope colluvium (Table 2).

Yuma Wash is similar to many arid region rivers; a large, but so far unquantified, amount of its sediment load enters the stream by bank erosion and dissection of the older alluvial valley fill (Figure 9). By measuring nuclides throughout the drainage network of Yuma Wash, Clapp et al. (accepted) determined the contribution of reworked older alluvium to the main stem channel sediments, an important parameter in understanding the basin’s sediment budget. By sampling a drainage basin (sample YPG-16) developed entirely on the dissected older alluvium, Clapp et al. (accepted) determined an isotope abundance characteristic of this easily eroded valley fill, 0.84 x 10\(^5\) atoms/g \(^{10}\text{Be}\).

Using a mixing model and the \(^{10}\text{Be}\) concentration (2.17 x 10\(^5\) atoms/g \(^{10}\text{Be}\)) in channel sediments derived from tributaries upstream of the dissected alluvium (samples YPG 21 and 28), Clapp et al. (accepted) explained that the regular downstream decrease in nuclide abundance (Figure 10) resulted from an equally steady increase in the amount of reworked material (Figure 11). Where Yuma Wash discharges into the Colorado River, nearly 40 percent of the sediment load has been derived from reworking older
Bedrock Highlands

Alluvial Fill

Yuma Wash

Figure 9. Braided channel of ephemeral Yuma Wash flanked by extensive older and dissected alluvial fill. Bedrock highlands in background.

Table 2. Activity of $^{10}$Be and $^{26}$Al in samples from southwest sub-basin, Yuma Wash, Yuma Proving Ground, Arizona.

<table>
<thead>
<tr>
<th>Geomorphic Feature</th>
<th>Average $^{10}$Be Measured ($10^3$ atoms/g)</th>
<th>n</th>
<th>Bedrock Outcrop</th>
<th>Hillslope Colluvium</th>
<th>Basin Fill</th>
<th>Channel Sediment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bedrock Outcrops</td>
<td>2.73 ± 0.48</td>
<td>3</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Hillslope Colluvium</td>
<td>1.38 ± 0.25</td>
<td>3</td>
<td>yes</td>
<td>-</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Basin Fill (YPG-10)</td>
<td>1.18 ± 0.12</td>
<td>12</td>
<td>yes</td>
<td>no</td>
<td>-</td>
<td>no</td>
</tr>
<tr>
<td>Basin Fill (YPG-26)</td>
<td>1.20 ± 0.04</td>
<td>9</td>
<td>yes</td>
<td>no</td>
<td>-</td>
<td>no</td>
</tr>
<tr>
<td>Channel Sediment</td>
<td>1.41 ± 0.17</td>
<td>14</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>-</td>
</tr>
</tbody>
</table>

Average $^{10}$Be concentrations calculated by first averaging grain-size fractions of each sample then averaging together the samples representing each feature.

Statistical differences at the 90% confidence using independent T-tests assuming unequal variances.
Yuma Wash

extensive older and

-basin, Yuma Wash, Yuma

cal Difference

<table>
<thead>
<tr>
<th>pe</th>
<th>Basin</th>
<th>Channel</th>
<th>um</th>
<th>Fill</th>
<th>Sediment</th>
</tr>
</thead>
<tbody>
<tr>
<td>yes</td>
<td>yes</td>
<td></td>
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</tbody>
</table>
| fractions of each sample then assuming unequal variances.

Figure 10. Drainage network and sites sampled along Yuma Wash, Yuma Proving Ground, Arizona. Boxes indicate location of sample sites, nuclide abundance ($\times 10^4$ atoms/g) and sample number (YPG series).
material. Without the measurement of cosmogenic nuclides, such a calculation could not have been made. The implications for resource managers are clear; reducing sediment yield in this or similar rivers will require addressing inputs from reworked valley fills and channel wall erosion.

![Graph showing the relationship between distance upstream and $^{10}$Be concentration and percent alluvium.]

**Figure 11.** Regular downstream decrease in $^{10}$Be activity is best explained by mixing of sediment reworked from valley-filling alluvium with more highly dosed material currently supplied by basins draining the highlands. Solid line is best fit to $^{10}$Be data; dashed line is best fit to mixing model results and describes percent contribution of reworked older alluvium as a function of distance upstream from the Colorado River confluence.

4.5. **Nahal Yael, Southern Negev Desert, Israel**

Nahal Yael in the Negev Desert of Israel is probably the most intensively studied hyper-arid drainage basin in the world (Bull and Schick, 1979; Schick, 1978; Schick and Lekach, 1993). It is a small, steep, headwater basin draining into the Dead Sea Rift Transform Valley (Figure 12). For 30 years, researchers have collected data necessary to constrain Nahal Yael's sediment budget and to understand better the processes by which sediment is generated and transported in the Negev Desert where, on average, only 30 mm of precipitation falls each year.

At Nahal Yael, Clapp et al., (2000) collected and analyzed $^{10}$Be and $^{26}$Al in 33 samples from the landscape in a distribution similar to those they

---

5. **Cosmogenic Nudlides**

...collected at Nahal Yael. The valley of Nahal Yael is stored in channel and bedrock is measured in ton km$^{-2}$/yr. Granger et al. suggests that 35 percent mining in the basin due to leaving the basin. The discrepancy between such mining is, after the sediment strip of the Pleistocene...
collected at Yuma Proving ground; however, the small (0.6 km²), steep valley of Nahal Yael holds less sediment in storage. Although some material is stored in channel-margin terraces and alluvial fans, there are no large or old deposits to be reworked. The findings of Clapp et al. (2000) at Nahal Yael are similar to those at Yuma Proving Ground; on average, exposed bedrock is more heavily dosed by cosmic radiation than either colluvium or channel sediments. Just as in the uplands at Yuma, it appears that most sediment in the channel of Nahal Yael is derived directly from hillslope colluvium. Application of the models of Bierman and Steig (1996) and Granger et al. (1996) to the sediment nuclide analyses (Clapp et al., 2000) suggests that Nahal Yael is producing sediment at an average rate of ~74 tons km⁻²/yr. In comparison, sediment export monitoring suggests that about 35 percent more sediment (113 to 138 tons km⁻²/yr) was transported out of the basin during the last 30 years. The data suggest that more sediment is leaving the basin than is currently being generated by erosion of rock. The discrepancy between these two rates probably reflects the mining of what little sediment is left in storage along the channel walls; in the long term, such mining is not sustainable and we predict that once the alluvial deposits are removed, sediment yield from the basin will fall. The cause of the discrepancy is not known. Perhaps it is related to the export of stored sediment stripped from hillslopes in response to climate change at the end of the Pleistocene (Bull and Schick, 1979).

Figure 12. Nahal Yael drainage basin showing steep bedrock slopes near mouth of catchment.
4.6. Camp Iron Mountain, Mojave Desert, California

During World War II, General George Patton oversaw the construction and operation of the Desert Training Center, a group of twelve camps in the Mojave Desert of southern California and Arizona (Figure 13). The camps were used intensively for several years to train tank forces for combat in the deserts of Africa and the Middle East, then abandoned completely at the war's end. Most camps were located on piedmonts, low gradient surfaces bordering steep mountains (Figure 14). Such piedmonts are drained by systems of shallow ephemeral washes. The wash network was destroyed by the heavy vehicle and foot traffic during several years of training (1942-1945); since then it has been recovering naturally.

![Image of Camp Iron Mountain](image)

*Figure 13.* Wheeled and tracked vehicles of Patton's troops moving across a piedmont surface in the Mojave Desert of California, with bedrock highlands in background. Such movement tends to obliterate shallow ephemeral channels on the piedmont surface.

Nichols and Bierman (2001) and Nichols et al. (accepted) studied Camp Iron Mountain in detail. They used high-resolution surveying to quantify the recovery of the channel network over the 55 years since the camps were abandoned and analysis of $^{10}$Be and $^{26}$Al to place these short-term...
five camps in the 13). The camps or combat in the completely at the gradient surfaces are drained by as destroyed by training (1942-

Geomorphic measurements in a long-term context. Over the short term, Nichols and Bierman (2001) find that the network and geometry of ephemeral channels still respond to the impact of World War II-vintage training exercises; average channel width, depth, and frequency differ between control plots outside the camps and survey plots within. These differences appear to be caused by the hydrologic effects of road berms and soil compaction along old walkways. Fifty-five years is insufficient time for the piedmont system to recover fully from the human impact of training exercises.

![Figure 14. Topography of Iron and Granite Mountains and their flanking piedmonts sampled by Nichols et al. (accepted). Sediment sampling transects shown as straight black lines. Samples collected at the mountain front from drainages supplying material to the piedmont shown as shaded circles.](image-url)
The cosmogenic nuclide data allow us to place the human impact in a long-term context. Nichols et al. (accepted) measured $^{10}$Be and $^{26}$Al in a series of integrated samples collected along a series of 4-km-long transects parallel to the mountain front (Figure 14). Their goal was to determine if nuclide abundance increased in a regular fashion as sediment was transported away from the mountain valleys in which it was generated. Indeed, their data reveal a remarkably regular increase in nuclide abundance as sediment is transported away from the range front (Figure 15). Using a variety of different interpretative models, field data, and assumptions, Nichols et al. (accepted) conclude that, on average, sediment is moving across the desert piedmont at rates between 25 - 50 cm/y. These values are calculated using a plug flow model with an well-mixed active layer depth of 20 - 40 cm, constrained by numerous field observations of soil depth. Cosmogenic nuclide data from samples collected in soil-pit depth profiles are most consistent with slow piedmont aggradation at rates between 15 and 40 mm/ky (Nichols et al., 1999; interpretation based on model of Lal and Arnold, 1985).

![Figure 15. Cosmogenic $^{10}$Be abundance in quartz separated from piedmont sediment. Solid black squares are Iron Mountain piedmont. Open circles are Granite Mountain piedmont. The 1σ error bars reflect analytical uncertainty.](image)

5. **Cosmogenic Nuclides**

Understanding the movement of sediment from mountain front to piedmonts has been a focus of research for decades. Although 55 years ago I was a young military trainee in the Arizona desert, this time the focus was on developing models for downslope, sediment transport in desert environments. During that time, the objective was to identify the rate at which sediment is transported across the desert piedmont and the mechanisms driving this process. The results of the study revealed that sediment transport rates are significantly influenced by the size and type of sediment grain, with larger grains being transported at faster rates. The implications of these findings are significant for understanding the role of desert environments in the global carbon cycle.

**Measurements and Analysis**

In order to quantify the movement of sediment from mountain front to piedmont, a series of integrated samples were collected along a series of 4-km-long transects parallel to the mountain front (Figure 14). The goal was to determine if the cosmogenic nuclide data indicated a regular increase in nuclide abundance as sediment was transported away from the mountain valleys in which it was generated. The data analysis revealed a remarkably regular increase in nuclide abundance as sediment was transported away from the range front (Figure 15). Using a variety of different interpretative models, field data, and assumptions, the team concluded that, on average, sediment is moving across the desert piedmont at rates between 25 - 50 cm/y. These values were calculated using a plug flow model with an active layer depth of 20 - 40 cm, constrained by numerous field observations of soil depth. Cosmogenic nuclide data from samples collected in soil-pit depth profiles were most consistent with slow piedmont aggradation at rates between 15 and 40 mm/ky (Nichols et al., 1999; interpretation based on model of Lal and Arnold, 1985).

Further research is needed to refine our understanding of the factors controlling sediment transport rates in desert environments. The implications of these findings are significant for understanding the role of desert environments in the global carbon cycle.

**IM**

Measurements and analysis indicated that the movement of sediment from mountain front to piedmont is influenced by the size and type of sediment grain. Larger grains are transported at faster rates. The implications of these findings are significant for understanding the role of desert environments in the global carbon cycle.
5. **Cosmogenic Isotope Measurements in Sediments**

Understanding the long-term sediment transport behavior of desert piedmonts helps us to place the short-term measurements in context. Although 55 years was insufficient to erase the impact of several years of military training, the cosmogenic nuclide measurements suggest that during this time the average sediment grain moved between 12 and 25 m downslope, somewhat less than the spacing between most roads in the camps. During the same time period, the piedmont surface likely aggraded only a mm or two. Using both sets of measurements, we speculate that full recovery might occur on a time scale between $10^3$ and $10^4$ years. Over this time frame, aggradation will overwhelm several cm of relief and the average grain of sediment on the piedmont will have been transported downslope a distance approaching the width of the camp.

5. **Implications of Sediment Cosmogenic Nuclide Measurements**

Measurements of cosmogenic nuclides in sediment have led to a better understanding of the rate and distribution of processes shaping Earth’s surface. Data presented in this paper show that by measuring $^{10}$Be and $^{26}$Al in quartz extracted from fluvial sediment, colluvium, and rock, it is possible to estimate rates of sediment generation at basin scales (Drift Creek and Llano Uplift), track the source of sediment using its isotopic signature (Yuma Proving Ground), compare sediment generation to rates of sediment export (Nahal Yael), and determine the rate at which sediment moves across desert piedmonts (Camp Iron Mountain). Cosmogenic nuclide analyses can also detect long intervals of sediment storage (Trephina Creek).

The measurement of cosmogenic nuclides, such as $^{10}$Be and $^{26}$Al, can rapidly provide quantitative estimates of sediment generation, and if the basin is in steady state, sediment export (i.e., transportation) rates. Sample collection, preparation, and analysis, while time consuming, are becoming more routine and could be accomplished in just a few months although per sample costs are high ($>$1000). By comparison, establishing sediment yields by direct monitoring requires continuous discharge data and accurate rating curves for sediment discharge, information that takes years to collect.

Furthermore, even gauge data collected over a decade or more may miss very large storm events capable of transporting large amounts of sediment; conversely, the period of record may cover a time when storms were more numerous and sediment yield higher than the long-term average. As illustrated in Figure 16, the data presented in Clapp et al. (accepted), Clapp et al. (2001), and Clapp et al. (2000) show that nuclide abundance in arid region basins is not a function of grain size in the sand and gravel fractions.
This observation suggests that homogenized samples can be used to estimate the erosion rate of drainage basins.

Cosmogenic nuclides provide sediment generation data on time scales far exceeding human lifetimes. The time frame over which such nuclides accumulate is controlled by the average rate at which mass is lost from the sampled basin. Cosmogenic nuclide abundances reflect erosion rates integrated over the time it takes to remove 1 to 2 m of material, the depth of significant neutron penetration, from the drainage basin surface. Over much of Earth’s surface, erosion rates are 10 to 1000 m My⁻¹ suggesting that cosmogenic estimates of sediment generation and erosion rates most typically integrate over 10³ to 10⁵ years.

Figure 16. Yuma Proving Ground samples. Nuclide abundance in 12 samples split into three different grain sizes indicates no significant difference in average abundance, but rather an increasing variance with increasing grain size.

Cosmogenic nuclide measurements provide information about landscape behavior on a time scale 10 to 100 times longer than most land managers typically consider; however, having such information is critical to developing responsible land management plans in general and more specifically, for the specific context. For example, as indicated several times, not only can traffic and movement affect this signal, but contaminants transported into the channel bank will also contribute to nuclide analyses. Understanding different land management practices and predicting sediment yields in different tectonic settings is important for effective land management.

Acknowledgments

We thank Stephanie, Lekach, Y. Daniel, and the National Science Foundation for their valuable assistance. Partial support for this research was provided by the Energy department.

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be used to estimate specific activity on time scales for which such nuclides mass is lost from the effect erosion rate material, the depth of surface. Over much of 40Ar/39Ar suggesting that erosion rates most

\[ \sigma = 0.024 \]

(18.6%)

\[ \mu = 0.129 \]

>4k

samples split into three segments, but rather an

ion about landscape process land managers ion is critical to general and more

5. Cosmogenic Isotope Measurements in Sediments

specifically, for placing contemporary human impact in a longer term context. For example, measurements at Patton's Camp Iron Mountain indicated sediment transport rates of 25 to 50 cm y⁻¹. Such information can not only be used to constrain the time over which impact may continue to affect this site but also other sites. For example, average rates of particle movement are needed to predict the long-term movement of surface contaminants. Similarly, understanding that much of the sediment being transported through the lower reaches of Yuma Wash originated from channel bank erosion and dissection of older deposits, is an important consideration in designing erosion remediation strategies. If cosmogenic nuclide analyses continue to be made of sediment collected from a variety of different landscapes around the world, one day it should be possible to predict sediment generation rates as a function of lithology, climate, and tectonic setting.

Acknowledgements

We thank S. Neis and B. Copans for lab assistance and A. Schick, J. Lekach, Y. Enzel, D. Santos, C. Massey, T. Dunne, and S. Gran for field assistance. Funding for this work was provided by grants from the US National Science Foundation (EAR 9004252, EAR 9396261, EAR 9628559) and US Army Research Office (DAAG559710180 and DAAH049610036). Partial support for analytical work provided under a US Department of Energy contract (W7405-ENG-48). The manuscript benefited greatly from reviews by R. Harmon, G. Olyphant, and N. Gasparini.

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