Cosmogenic Nuclides and Erosion at the Watershed Scale

Darryl E. Granger[1] and Mirjam Schaller[2]

1811-5209/14/0010-369$2.50 DOI: 10.2113/gselements.10.5.369

Cosmogenic nuclides in sand from an active river bed (here in the Pamir Mountains) disclose the modern erosion rate of an entire watershed. Sediment from river terraces (like those seen beneath the village) provides the "paleo–erosion rate": the erosion rate prevailing at the time of sediment deposition. Photo courtesy of Elena Grin

Landscapes are sculpted by a variety of processes that weather and erode bedrock, converting it into soils and sediments that are moved downslope. Quantifying erosion rates provides important insights into a wide range of questions in disciplines from tectonics and landscape evolution to the impacts of land use. Cosmogenic nuclides contained in quartz sediment provide a robust tool for determining spatially averaged erosion rates across scales ranging from single hillslopes to continental river basins and are providing fundamental clues to how landscapes evolve. Cosmogenic nuclides in buried sediments contain unique information about paleo–erosion rates up to millions of years in the past. This article explores some of the basic ideas behind various methods used to infer catchment-wide erosion rates and highlights recent examples related to problems in tectonics, climate, and land use.

Keywords: cosmogenic nuclide, erosion, paleoerosion, river sediment

INTRODUCTION

At the grandest scale, Earth's topography represents an accumulation of potential energy from mantle convection and tectonics, balanced by decay from chemical weathering and physical erosion. Over timescales of 10^3–10^6 years, hillslope erosion, soil formation, and sediment accumulation define the distribution and fertility of soil upon which our societies depend. There is a critical need to understand how soil erosion from land use is depleting this natural resource and how modern rates compare with those from the past. Climate change also affects erosional processes in complicated ways, which can be difficult to discern without accurate measurements of erosion rates over various timescales.

Curiously, the problem is that the rate of erosion is a tricky thing to measure. It is a measure of something that isn't there anymore, and of how quickly it went away. What is needed is a sensitive way to measure how much material was once at a given place and the rate at which that material was lost to dissolution, erosion, and sediment transport. There have been a number of traditional approaches to the problem. For example, over long timescales (millions of years), one can use thermochronology to infer the rate of rock cooling due to exhumation by erosion from kilometers below the surface (Reiners and Shuster 2009). Over very short timescales of years to decades, sediment and solute fluxes from a watershed can be monitored, but these measurements are difficult to make with accuracy and may not capture important but infrequent events. A better approach over timescales from decades to millennia is to measure sediment accumulation in lakes and reservoirs or in datable sedimentary deposits, such as alluvial fans. Unfortunately, these measurements require special circumstances and can be subject to considerable uncertainty due to spatial variations in sedimentation rate and in sediment-trapping efficiency.

There is an important middle ground over timescales of 10^3–10^5 years in which rocks weather and soils form, climate changes from glacial to interglacial, rivers incise or aggrade, and civilizations rise and fall. This is the timescale that belongs to cosmogenic nuclides. Over the past two decades, cosmogenic nuclides have emerged as the method of choice for inferring erosion rates over spatial scales that can be as small as a single outcrop to as large as watersheds spanning a continent.

DETERMINING EROSION RATES

Theory and Methods

Cosmogenic nuclides such as ^{10}Be (half-life, $t_{1/2}$, = 1.39 My) and ^{26}Al ($t_{1/2}$ = 0.702 My) are produced in minerals such as quartz by reactions with secondary cosmic ray neutrons, protons, and muons (for details see Dunai and Lifton 2014 this issue). These nuclides can be used to infer erosion rates because their production rates within a mineral grain depend on their proximity to the Earth's surface. Production rates decrease exponentially with depth in rock or soil (with a mean cosmic ray penetration length of ~60 cm in rock of density 2.6 g cm^{-3}). For an eroding surface, this means that the cosmogenic nuclide concentration integrates the history of a grain's approach toward the surface. In other words, the cosmogenic nuclide concentration contained in a mineral grain today reflects how quickly the overlying mass went away.

Mathematically, it can be shown that the cosmogenic nuclide concentration in an eroding rock is inversely proportional to erosion rate (Lal 1991). Erosion, as used

1 Department of Earth, Atmospheric, and Planetary Sciences
Purdue University, West Lafayette, IN 47907-2051, USA
E-mail: dgranger@purdue.edu

2 Department of Geosciences, University of Tübingen
72074 Tübingen, Germany
E-mail: mirjam.schaller@uni-tuebingen.de

here, refers to the combination of physical erosion and chemical weathering that removes mass near the surface. Early in the development of cosmogenic nuclide applications, it was recognized that bedrock outcrops can be used to determine the denudation history of that particular rock. However, in the mid-1990s researchers realized that cosmogenic nuclides in detrital sediment grains can also be used to determine erosion rates [for reviews see Bierman and Nichols (2004) and Granger and Riebe (2013)].

Two key realizations led to interpreting cosmogenic nuclides in sediment. The first was that for a well-mixed soil eroding at steady state (and in the absence of a high degree of chemical weathering within the soil), the average concentration of cosmogenic nuclides in the soil is the same at all soil depths. This concentration is equal to the concentration contained in the surface of a rock outcrop eroding at the same rate. In other words, for a given erosion rate, a sample of well-mixed soil has exactly the same concentration as exposed bedrock. The effects of chemical weathering are somewhat more complex, as they vary with depth, and an entire research field has emerged dedicated to interpreting weathering rates with cosmogenic nuclides (e.g. Dixon and Riebe 2014 this issue).

The second key to interpreting cosmogenic nuclides in sediment is that for well-mixed stream sediment, the average concentration in the sediment yields the average erosion rate in the watershed (Fig. 1). This relies on the assumptions that sediment is supplied at a rate that is proportional to the erosion rate, that the mineral being analyzed (i.e. quartz) is evenly distributed throughout the entire catchment, and that the cosmogenic nuclide in question was absent before the rock approached the surface.

It is worth examining these assumptions in detail. We begin with the idea that detrital sediment from well-mixed soil on a hillslope has a cosmogenic nuclide concentration that is inversely proportional to the hillslope erosion rate. For a watershed that is eroding homogeneously (i.e. everywhere at the same rate), then the concentration in stream sediment is equal to that of the soils on the hillslopes and the stream sediment yields the erosion rate. In most cases we can ignore sediment storage and transport time in the stream system, which occurs much faster than the timescale of erosion rates, that is, the time to erode the landscape by 60 cm. For a watershed that is eroding heterogeneously, a surprisingly simple solution emerges if we consider the flux-averaged cosmogenic nuclide concentration. That is, areas of the landscape that are eroding quickly provide a large fraction of the quartz but have a low cosmogenic nuclide concentration; conversely, areas eroding slowly provide less quartz but have a high cosmogenic nuclide concentration. In this case, the average cosmogenic nuclide concentration in the sediment reflects the spatially averaged erosion rate from the entire watershed. Remarkably, the equation to determine the erosion rate from an entire watershed is functionally identical to the equation used to determine the erosion rate from a single eroding outcrop. For example, the cosmogenic nuclides contained in a single sample of sand can yield the spatially averaged erosion rate of a watershed ranging in size from the catchment of a small upland creek to the entire Amazon River basin (Fig. 2; Wittmann et al. 2011).

While the assumption of well-mixed and representative stream sediment may hold approximately true, landslides or other such episodic events may deliver an overwhelming load of sediment that temporarily biases the average. If the preponderance of a sample comes from just one landslide, then the inferred erosion rate will reflect primarily only that area. Moreover, if the landslide incorporates fresh bedrock or saprolite, then the cosmogenic nuclide concentration will be lowered and the inferred erosion rate will be faster than the long-term average. On the other hand, if landsliding dominates sediment delivery in the watershed, then it is important to sample that material or the inferred erosion rate will be too slow. The best solution is to sample a sufficiently large catchment with enough landslides so that any single event does not significantly influence the average cosmogenic nuclide concentration (e.g. Yanites et al. 2009).

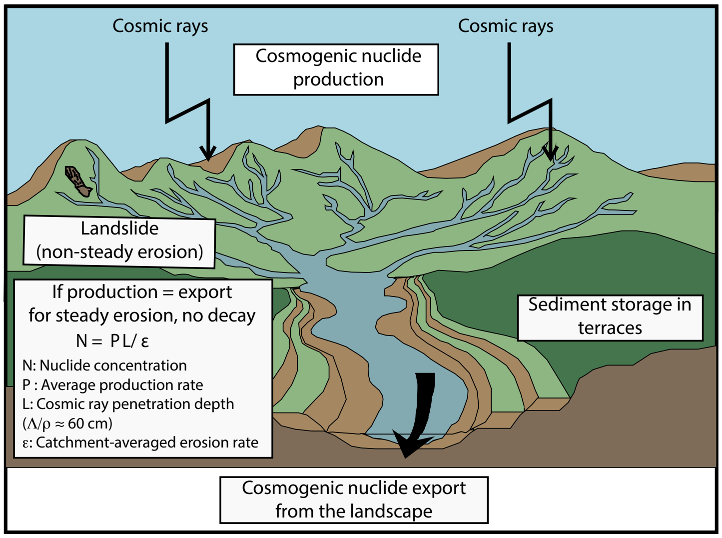

Figure 1 An eroding landscape provides sediment that can be analyzed to determine its erosion rate. Because cosmogenic nuclide concentrations are inversely proportional to erosion rates, the flux-weighted ^{10}Be concentration reflects the spatially averaged erosion rate. Care must be taken to avoid the influence of landslides, which can temporarily bias the sediment budget, and to avoid catchments with extensive sediment storage. Sediment in archives such as terraces can be used to determine paleo–erosion rates at the time of sediment deposition. Penetration length $\Lambda = 160$ g cm^{-2}; density $\rho = 2.6$ g cm^{-3}.

Figure 2 Sampling river sand for cosmogenic nuclide determination in the Qilian Shan, northern China. A single sample of 10–100 g of quartz can yield the spatially averaged erosion rate of the sediment-contributing area upstream. Photo courtesy of Kai Hu

Timescale of Erosion

The timescale over which in situ–produced cosmogenic nuclides measure erosion rates is one of the major strengths of the method, but this also limits the sorts of problems

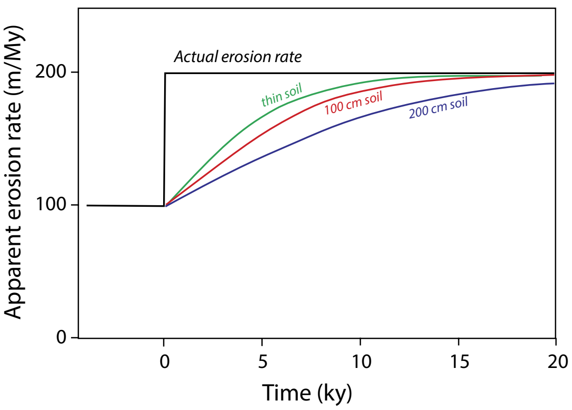

Figure 3 The apparent erosion rate inferred from cosmogenic nuclides can take thousands of years to respond to an actual change in surface erosion rates. The response time, or the time it takes for the apparent erosion rate to match the real erosion rate, depends on both the erosion rate and the soil thickness. The graph shows the apparent erosion rate in response to a step change in erosion rate from 100 to 200 m/My, for soil thicknesses of 0, 100, and 200 cm, calculated for typical rock density of 2.6 g cm^{-3} and soil density of 1.5 g cm^{-3}. For thin soils the apparent erosion rate has increased by 90% of the actual change within ~9 ky, while for 200 cm thick soils the same increase in apparent erosion rates takes over 15 ky.

to which cosmogenic nuclides can be applied. Because cosmogenic nuclides integrate the history of production rates and because production rates fall off exponentially with depth, for a steady erosion rate the concentration is equivalent to the mineral residence time within the top 160 g cm^{-2} (~60 cm in rock of density 2.6 g cm^{-3}, or ~1 m in soil of density 1.6 g cm^{-3}). In other words, the timescale of bedrock erosion is equal to the time it takes to lower the landscape by ~60 cm, roughly equivalent to the timescale of soil formation in many landscapes. This timescale implies that cosmogenic nuclides effectively dampen rapid changes in erosion rate. If erosion rates change suddenly—for example, due to recent land use or climate change—then the cosmogenic nuclide concentration in the soil will change only slowly, with a response time determined by both the soil mixing depth and the time taken to erode ~60 cm of rock (Fig. 3). The damped response time means that the cosmogenic nuclide concentration measured in soils today represents the long-term average erosion rate, which is usually independent of recent changes in land use and soil degradation.

Examples of Catchment-Wide Erosion Rates

Over the past 20 years, erosion rates have been estimated by measuring the cosmogenic nuclides contained in thousands of river-sediment samples from virtually every climatic and tectonic environment in the world (e.g. Portenga and Bierman 2011; Covault et al. 2013 and references therein). Generally, these erosion rates are based on the measurement of ^{10}Be produced in situ in quartz. Several persistent themes have emerged from the data.

One surprising conclusion from these cosmogenic nuclide–based erosion rates is that climate is less important for regulating erosion rates than previously assumed. While erosion rates certainly vary strongly under conditions of climatic extremes where erosional processes are fundamentally different (for example, erosion is slow in hyperarid deserts with little biological activity and fast in glacial and periglacial environments), climate generally plays a secondary role in determining erosion rates over most of the planet. Climate strongly affects the degree of soil weathering (Dixon and Riebe 2014), but the total erosion rate is more commonly determined by factors such as river and hillslope gradients that are adjusted to balance local uplift. Thus, erosion rates on low-relief continental shields are generally slow regardless of climate (~1–10 m/My), while they are much faster (~10^3–10^4 m/My) on rapidly uplifting mountain ranges.

The conclusion that landscape erosion rates are ultimately set by tectonics driving river incision and hillslope erosion rather than by climate has a number of implications. Perhaps the most important is that cosmogenic nuclide–based erosion rates can be used as a proxy for local river incision and uplift rates (e.g. Wobus et al. 2005). This is a powerful notion for landscapes at dynamic equilibrium because it suggests that a handful of sand can provide the local incision and uplift rates (Kirby and Whipple 2012).

The numerous cosmogenic nuclide measurements now available allow comparison of erosion rates over different timescales. Catchment-averaged erosion rates from cosmogenic nuclides can be compared to short-term suspended- and dissolved-sediment loads in rivers (e.g. Wittmann et al. 2011; Covault et al. 2013). Interestingly, Covault et al. (2013) found that the vast majority of cosmogenic nuclide–based erosion rates are faster than those inferred from monitored sediment yield. This tendency was first noticed by Kirchner et al. (2001), who invoked the importance of large but infrequent events in sediment delivery. While the abundances of cosmogenic nuclides average such variability, stream-gauging methods are likely to miss the largest and most important events that may happen only once in a decade or a century. In addition, sediment storage in floodplains tends to buffer rapid changes in sediment supply due to land use (Wittmann et al. 2011). Only in the most highly modified landscapes or in landscapes with very low sediment storage capacity do modern erosion rates consistently exceed cosmogenic nuclide–based erosion rates (e.g. Hewawasam et al. 2003).

PALEO–EROSION RATES

If modern-day river sediment contains information about the erosion rate of its source area, then sedimentary deposits should be able to tell us about paleo–erosion rates and how erosion rates have varied through time in response to changes in climate or tectonics.

Estimates of paleo–erosion rates provide powerful insights into the behavior of ancient landscapes. It must be recognized, however, that the cosmogenic nuclides that are generally useful for determining erosion rates, such as ^{10}Be and ^{26}Al in quartz, are radioactive. Also, cosmogenic nuclide production does not fully stop even after several meters of burial. Thus, accurate paleo–erosion rate determinations require correcting for loss due to radioactive decay as well as continued production by deeply penetrating muons. The slower the paleo–erosion rate and the more deeply buried the sediment, the further back in time one can infer paleo–erosion rates—generally up to 5–10 million years.

Of course, accurate paleo–erosion rate determinations require knowing the depositional age of the sediment. But what if the age is not known independently? The beauty of cosmogenic nuclides is that it is possible to date the sediment directly using "burial dating." Measuring at least two nuclides in the same mineral grains (such as ^{10}Be, ^{26}Al, and/or ^{21}Ne in quartz; Balco and Shuster 2009) allows one to solve for the burial age and the paleo–erosion rate simultaneously.

Examples of Paleo–erosion Rates

A good example of how paleo–erosion rates can be estimated over glacial/interglacial timescales comes from the pioneering work of Schaller et al. (2002). In their study of sediments in terraces of European rivers, they found that erosion rates were roughly twice as fast during the Last Glacial Maximum (LGM) as they are today. Estimates show that the ~80 m/My determined for the LGM became much slower, to ~30–40 m/My, through the Holocene to the present. The faster rates may be due to frost-cracking and/or periglacial processes that accelerated erosion and soil transport during the LGM (e.g. Delunel et al. 2010).

Paleo–erosion rates can also be determined from buried sediment over much longer timescales of millions of years to decipher how landscapes have responded to climate change and tectonic uplift (Schaller et al. 2004). Paleo–erosion rates (and burial dates) allow one to explore how erosion rates and valley-incision rates have varied at the same site over millions of years, and thus to quantify how landscapes have responded to long-term climate change and uplift. For example, a compilation of paleo–erosion rate determinations that span million-year timescales (Fig. 4) records the varied responses of landscapes to the expansion of Northern Hemisphere glaciation near 2.5 My ago. Together these types of studies provide an opportunity to examine the influence of long-term climate change on hillslope erosion rates.

Measurements of cosmogenic nuclides also show that erosion rates have increased in many glaciated or partially glaciated watersheds, even during interglacials. This is true in the northern Swiss Alps (Haeuselmann et al. 2007), the Sierra Nevada of California, USA (Stock et al. 2004), and the Tian Shan in China (Charreau et al. 2011) (Fig. 4). Erosion rates have increased in some unglaciated watersheds as well, particularly in areas subject to a periglacial climate. Schaller et al. (2004) found increased erosion in the Meuse River, the Netherlands, likely due to both climate change and uplift of the Ardennes Mountains. A dramatic increase in erosion rate is documented in an unglaciated valley in the Sangre de Cristo Range, Colorado, USA (Refsnider 2010). Anthony and Granger (2007) studied sediment in caves along the Cumberland Plateau in the unglaciated southeastern United States and showed that paleo–erosion rates systematically increase in the Pleistocene hundreds of kilometers south of the Laurentide ice sheet margin. Interestingly, data from Mammoth Cave in central Kentucky (Granger et al. 2001) do not show any change in paleo–erosion rates across this same climatic transition, even though the site is closer to the ice margin.

DEVELOPING TRENDS: METEORIC ^{10}BE

While the discussion thus far has focused on ^{10}Be produced in situ within mineral grains, there is another, much larger, inventory of meteoric ^{10}Be in soil. ^{10}Be is produced in the atmosphere and delivered to the surface by wet and dry deposition (e.g. Dunai and Lifton 2014). As a fallout radionuclide, meteoric ^{10}Be is incorporated into a variety of archives, including snow and ice; lacustrine, estuarine, and marine sediment; manganese nodules on the sea floor; and soil. Measurements of meteoric ^{10}Be have been used to address a wide range of geologic problems, from snow and ice accumulation to sediment recycling in subduction zones. We focus here on the specific use of meteoric ^{10}Be for determining erosion rates. For recent reviews, see Willenbring and von Blanckenburg (2010), Graly et al. (2010), and Granger et al. (2013).

Meteoric ^{10}Be is a particle-reactive species that adsorbs strongly to mineral grains, particularly clays, for soil pH greater than about 6. Unlike in situ–produced ^{10}Be, the meteoric variety migrates within the soil profile, to a depth determined largely by soil pH, soil texture, and grain size. More recently, the ^{10}Be/^{9}Be ratio of beryllium adsorbed to sediment has been used to simultaneously determine the erosion rate and the degree of chemical weathering of bedrock within a watershed. The ^{10}Be is derived from meteoric fallout while the ^{9}Be comes from the chemical weathering of bedrock (von Blanckenburg et al. 2012). Advantages of the meteoric technique are that only ~1 gram of fine-grained material is required and that the ^{10}Be/^{9}Be ratio is nearly independent of lithology.

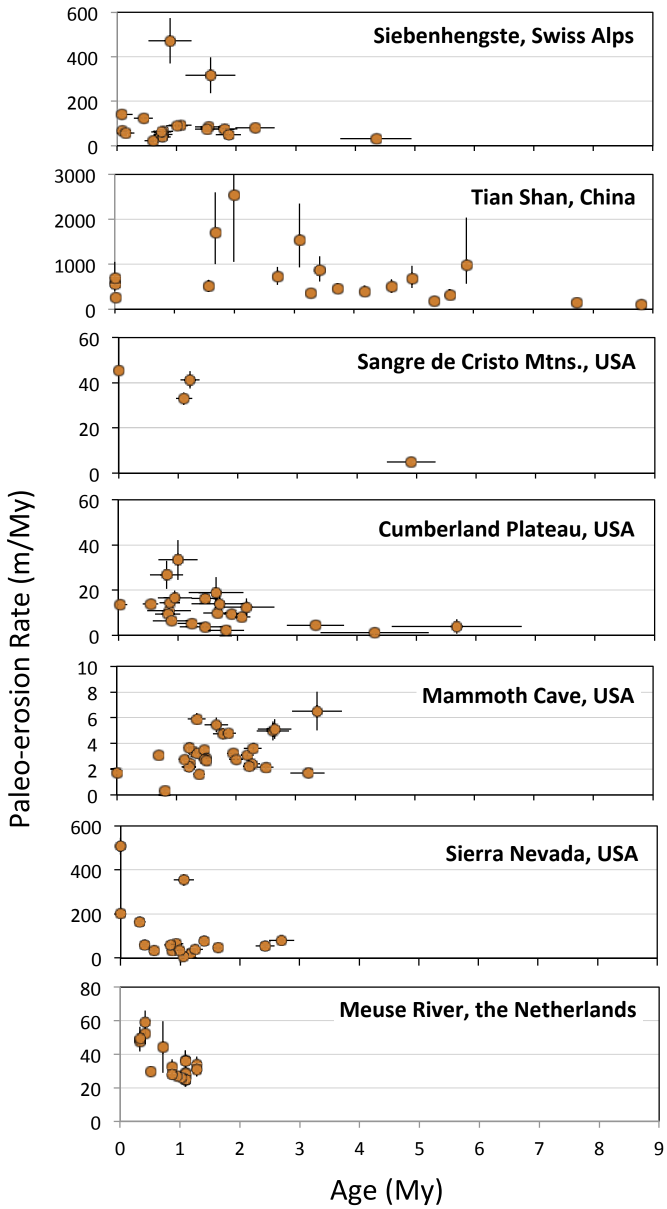

Figure 4 Paleo–erosion rates from ancient sediment as a function of time for seven northern-latitude sites that span at least 1 million years. All but one show increasing erosion rates and/or erosional variability, whether for slowly eroding landscapes such as the Cumberland Plateau, USA, or the Meuse River in the Netherlands where maximum erosion rates are 60 m/My or for high mountains such as the Swiss Alps or the Tian Shan, China, eroding more than 10 times faster. All ages and erosion rates are plotted as originally reported by the authors (cited in the text) and have not been adjusted to a uniform ^{10}Be production rate and half-life, which would result in minor changes.

During the early years of cosmogenic nuclide applications, meteoric ^{10}Be was widely used for exploring surface processes because of its relatively high atmospheric concentrations. This approach, however, was largely eclipsed by measurements of the in situ–produced variety in the early 1990s as methods were developed for determining ^{10}Be contained in quartz. Recent years have seen a resurgence in the meteoric variety's popularity, but one must recognize that beryllium mobility in the environment can be complex and is still poorly understood. Meteoric ^{10}Be holds great promise for exploring erosion rates and sediment transport, as well as changing environmental conditions.

SUMMARY

Cosmogenic nuclides are now the "gold standard" for determining erosion rates of rocks and watersheds. The method is rooted in the physics of energetic-particle attenuation, which allows geologists to query a rock about the material that used to be on top of it and the rate at which the material was lost. A handful of sand from a riverbed can tell us about the average erosion rate upstream. Sedimentary archives offer a unique record of how erosion rates have changed through time. Cosmogenic nuclides are finally allowing geologists to answer age-old questions about how the landscapes and soils around us reflect their combined legacy of climate, tectonics, and land use.

ACKOWLEDGMENTS

We would like to acknowledge the helpful comments by the guest editors as well as reviews by P. Belmont, B. Bookhagen, and V. Godard.

REFERENCES

Anthony DM, Granger DE (2007) A new chronology for the age of Appalachian erosional surfaces determined by cosmogenic nuclides in cave sediments. Earth Surface Processes and Landforms 32: 874-887

Balco G, Shuster DL (2009) ^{26}Al–^{10}Be–^{21}Ne burial dating. Earth and Planetary Science Letters 286: 570-575

Bierman PR, Nichols KK (2004) Rock to sediment—slope to sea with ^{10}Be—rates of landscape change. Annual Review of Earth and Planetary Sciences 32: 215-255

Charreau J and 11 coauthors (2011) Paleo-erosion rates in Central Asia since 9 Ma: A transient increase at the onset of Quaternary glaciations? Earth and Planetary Science Letters 304: 85-92

Covault JA, Craddock WH, Romans BW, Fildani A, Gosai M (2013) Spatial and temporal variations in landscape evolution: Historic and longer-term sediment flux through global catchments. Journal of Geology 121: 35-56

Delunel R, van der Beek PA, Carcaillet J, Bourlès DL, Valla PG (2010) Frost-cracking control on catchment denudation rates: Insights from *in situ* produced ^{10}Be concentrations in stream sediments (Ecrins–Pelvoux massif, French Western Alps). Earth and Planetary Science Letters 293: 72-83

Dixon JL, Riebe CS (2014) Tracing and pacing soil across slopes. Elements 10: 363-368

Dunai TJ, Lifton NA (2014) The nuts and bolts of cosmogenic nuclide production. Elements 10: 347-350

Graly JA, Bierman PR, Reusser LJ, Pavich MJ (2010) Meteoric ^{10}Be in soil profiles – A global meta-analysis. Geochimica and Cosmochimica Acta 74: 6814-6829

Granger DE, Riebe CS (2013) Cosmogenic nuclides in weathering and erosion. In: Drever JI (ed) Surface and Groundwater, Weathering and Soils. Treatise on Geochemistry 5, Elsevier, 36 pp, doi:10.1016/B978-0-08-095975-7.00514-3

Granger DE, Fabel D, Palmer AN (2001) Pliocene–Pleistocene incision of the Green River, Kentucky, determined from radioactive decay of cosmogenic ^{26}Al and ^{10}Be in Mammoth Cave sediments. GSA Bulletin 113: 825-836

Granger DE, Lifton NA, Willenbring JK (2013) A cosmic trip: 25 years of cosmogenic nuclides in geology. GSA Bulletin 125: 1379-1402

Haeuselmann P, Granger DE, Jeannin P-Y, Lauritzen S-E (2007) Abrupt glacial valley incision at 0.8 Ma dated from cave deposits in Switzerland. Geology 35: 143-146

Hewawasam T, von Blanckenburg F, Schaller M, Kubik P (2003) Increase of human over natural erosion rates in tropical highlands constrained by cosmogenic nuclides. Geology 31: 597-600

Kirby E, Whipple KX (2012) Expression of active tectonics in erosional landscapes. Journal of Structural Geology 44: 54-78

Kirchner JW and 6 coauthors (2001) Mountain erosion over 10 yr, 10 k.y., and 10 m.y. time scales. Geology 29: 591-594

Lal D (1991) Cosmic ray labeling of erosion surfaces: *in situ* nuclide production rates and erosion models. Earth and Planetary Science Letters 104: 424-439

Portenga EW, Bierman PR (2011) Understanding Earth's eroding surface with ^{10}Be. GSA Today 21(8): 4-10

Refsnider KA (2010) Dramatic increase in late Cenozoic alpine erosion rates recorded by cave sediment in the southern Rocky Mountains. Earth and Planetary Science Letters 297: 505-511

Reiners PW, Shuster DL (2009) Thermochronology and landscape evolution. Physics Today 62: 31-36

Schaller M, von Blanckenburg F, Veldkamp A, Tebbens LA, Hovius N, Kubik PW (2002) A 30 000 yr record of erosion rates from cosmogenic ^{10}Be in Middle European river terraces. Earth and Planetary Science Letters 204: 307-320

Schaller M, von Blanckenburg F, Hovius N, Veldkamp A, van den Berg MW, Kubik PW (2004) Paleoerosion rates from cosmogenic ^{10}Be in a 1.3 Ma terrace sequence: Response of the River Meuse to changes in climate and rock uplift. Journal of Geology 117: 127-144

Stock GM, Anderson RS, Finkel RC (2004) Pace of landscape evolution in the Sierra Nevada, California, revealed by cosmogenic dating of cave sediments. Geology 32: 193-196

von Blanckenburg F, Bouchez J, Wittmann H (2012) Earth surface erosion and weathering from the ^{10}Be (meteoric)/^{9}Be ratio. Earth and Planetary Science Letters 351-352: 295-305

Willenbring JK, von Blanckenburg F (2010) Meteoric cosmogenic Beryllium-10 adsorbed to river sediment and soil: Applications for Earth-surface dynamics. Earth-Science Reviews 98: 105-122

Wittmann H, von Blanckenburg F, Maurice L, Guyot J-L, Filizola N, Kubik PW (2011) Sediment production and delivery in the Amazon River basin quantified by in situ-produced cosmogenic nuclides and recent river loads. GSA Bulletin 123: 934-950

Wobus C, Heimsath A, Whipple K, Hodges K (2005) Active out-of-sequence thrust faulting in the central Nepalese Himalaya. Nature 434: 1008-1011

Yanites BJ, Tucker GE, Anderson RS (2009) Numerical and analytical models of cosmogenic radionuclide dynamics in landslide-dominated drainage basins. Journal of Geophysical Research Earth Surface 114: doi: 10.1029/2008JF001088

ICP Sample Introduction Solutions for Geochemistry

▸ from the leader in fluoropolymer manufacturing

> **"Geochemistry would not be where it is today if it were not for Savillex Corporation."**
>
> *– Dr. Mike Cheatham, Syracuse University*

Savillex Corporation has been proudly serving the geochemistry community for over 35 years.

Our fluoropolymer labware products are used throughout the world for sample digestion, separations, storage and many other applications. We understand the unique needs of geochemists and now our new line up of ICP-OES and ICP-MS sample introduction products combine the highest performance and the lowest metal background with the ruggedness and reproducibility required for routine analysis.

All of our ICP sample introduction products are designed, molded and tested in house, using only the highest purity grade PFA resins.

Nebulizers – C-Flow

- C-Flow microconcentric PFA nebulizer range with the narrowest uptake rate specification
- New C-Flow 35 with uptake rate of 35uL/min +/-7uL/min
- C-Flow range for desolvators – standard fitment on the CETAC Aridus II
- C-Flow 700d with removable uptake line for high solids applica-tions – up to 25% TDS
- All C-Flows can be backflushed without tools

Inert Kits

- PFA kits with Scott type chamber
- True double pass design gives lower RSDs
- O-ring free end cap
- Platinum or sapphire injectors
- Available for Agilent 7500/7700/8800 and Thermo Element 2/Neptune

NEW!

Purillex™ FEP and PFA Bottles

- Lowest metal background
- Highest seal integrity

For technical notes, videos and to find your local Savillex distributor, visit **www.savillex.com**.

Savillex Corporation
Phone: 952.935.4100 | Fax: 952.936.2292
Email: info@Savillex.com | www.savillex.com