Third and Final Draft, 25 January 2015

*REPORT on NSF-SPONSORED WORKSHOP*

# Optimizing the next generation of AMS for measuring $^{10}$Be and $^{26}$Al

*November 14 and 15, 2014 University of California, Irvine*

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## 1.0 Executive Summary

The application of the cosmogenic nuclides $^{10}$Be and $^{26}$Al has expanded exponentially over the past two decades; yet, despite significant advances in the design of Accelerator Mass Spectrometry (AMS) systems needed to measure these nuclides, no new instruments optimized for measuring $^{10}$Be and $^{26}$Al have been commissioned in the United States in more than 25 years.

This report summarizes the findings of a 2-day workshop held at the Keck Carbon Cycle facility (University of California, Irvine), the purpose of which was to evaluate the potential of a new, compact, automated, low voltage AMS system for making important and useful isotopic measurements in support of Earth Science research in the United States with emphasis on better understanding surface processes and climate history. The workshop brought together twelve experts in the field of AMS and the application of $^{10}$Be and $^{26}$Al. Based on discussions at the workshop, this document provides a blueprint both for a next generation United States AMS instrument and the research and research-training facility that could be realized with this instrument at its core.

Next-generation AMS instruments offer simplicity of operation, a small footprint, extensive automation, and thus the potential to significantly decrease cost while increasing sample throughput. The ability to make numerous measurements at lower cost than at present will catalyze science that cannot be done today. Examples include high-resolution analyses of ice core $^{10}$Be, deciphering complex exposure/erosion histories of moraine boulders by creating probability density functions of boulder age, global erosion rate and deglacial age mapping, and building long time series records of surface processes related to climate change through $^{10}$Be preserved in lake and marine cores.

Advances in AMS instrumentation over the last decade, including increased source ionization efficiency, the use of He as a stripper gas, the optimization of beam-line geometry, and development of ion detectors with better discrimination capability, offer dramatic performance improvements. Smaller, lower-voltage AMS systems now approach the performance of larger, far more complex systems when analyzing any but the lowest-ratio samples. The time is ripe to create a new American AMS facility with a low-voltage, automated instrument at its core.

## 2.0 Statement of the need for the workshop

In the past several decades, the use of the cosmogenic nuclides $^{10}$Be and $^{26}$Al to approach fundamental and applied research questions in Earth, atmospheric and ocean sciences has grown exponentially (e.g., Balco et al., 2011; Elements Magazine, October 2014). Such nuclides provide quantitative control on the rates of Earth processes, allow dating of materials critical to interpreting past environmental change, and are used to quantify changes in the atmosphere over time, including both climate response and climate forcing (Granger et al., 2013). On the sample processing side, several dozen small to moderate-throughput labs, and four large labs (Washington, Lamont, Purdue, and Vermont) have been set up in the United States to produce samples so that isotopic ratios of $^{10}$Be and $^{26}$Al can be analyzed using accelerator mass spectrometry (AMS). AMS is the only technique currently capable of effectively measuring the extremely low concentrations of these nuclides that are typical of most terrestrial samples (Synal, 2013, and references therein).

In the United States, measurement of $^{10}$Be and $^{26}$Al is done almost exclusively at two facilities – PRIME lab at Purdue University and the Center for Accelerator Mass Spectrometry (CAMS) at Lawrence Livermore National Laboratory (LLNL). At the core of both of these facilities are large, high-voltage (10 million volts) accelerators that were originally designed for basic nuclear physics research, but which have been repurposed for AMS. These are large, complicated spectrometers requiring a many-person team to operate and maintain. They have some automation, but usually require operators in attendance either for safety reasons or because they require frequent re-tuning to maintain optimal performance.

These large systems have the advantage of high transmission of high charge state ions, and therefore very high sensitivity for the low-level analyses needed to date low-ratio samples (e.g., very young samples or samples from high erosion rate environments). Such instruments are critical for measuring low-ratio samples. These existing instruments also have a wide tolerance for less-than-optimally prepared samples. They are, however, difficult and expensive to maintain, resulting in AMS costs for $^{10}$Be and $^{26}$Al that have risen even as the demand for AMS analyses has increased several fold in the last decade. Much of the cost of such instruments resides in the personnel required to maintain and operate them.

In the last decade, AMS instruments have evolved, with the development of smaller-footprint systems based on accelerators operating at only 0.2-1.0 million volts (Christl et al., 2013). These stable, highly automated systems are far less costly to purchase, maintain, and run, and have been extremely successful in providing high-throughput and low-cost radiocarbon analyses (Suter et al., 2010).

Until recently, the new, smaller systems had limitations in terms of efficiency and sensitivity when used to measure $^{10}$Be and $^{26}$Al, isotopes of particular interest to much of the Earth Science community. Four innovations in the last three years, three emanating from the AMS laboratory at ETH Zurich and one resulting from collaboration spurred by this workshop, have radically altered this situation.

First, the use of helium as stripper gas in the high-voltage terminal of the accelerator leads to much-enhanced stripping and transmission of low charge state positive ions through the accelerator (Vockenhuber et al., 2013) and hence efficiency for detection of the rare isotope (e.g., $^{10}$Be and $^{26}$Al).

Second, the addition of another magnet in combination with a silicon nitride degrader foil in the high-energy analysis system effectively eliminates the troublesome backgrounds that plagued earlier attempts to measure $^{10}$Be on these small machines (Müller et al., 2010a). This has resulted in a substantial gain in sensitivity to the point that it now approaches that of the larger accelerators (Christl et al., 2013). The $^{10}$Be and $^{10}$B ions lose different amounts of energy in the degrader foil, and hence can be largely separated by a subsequent energy analysis. In this way, the counting rate of $^{10}$B that must be handled by the detector is reduced from several million per second to ~1000 per second. Modern detectors (see below) can handle the latter rate, but are completely overwhelmed by the former.

Third, there have been significant improvements to the gas-ionization detectors that count the $^{10}$Be and $^{26}$Al ions (Müller et al., 2010b). These detectors are now capable of resolving $^{10}$Be ions from the residual post-analysis $^{10}$B ions at counting rates up to several thousand per second. In addition, a gas-absorber cell with ultra-uniform silicon nitride windows may be added in front of the detector. This is used for $^{26}$Al measurements to absorb preferentially the very high count rate of $^{13}C^{+}$ ions that inevitably accompany the $^{26}Al^{2+}$ ions, while allowing the $^{26}$Al to pass through into the detector. This allows the very high yield of $^{26}Al^{2+}$ ions from helium gas stripping (60%) to be exploited, resulting in substantially higher efficiency than if $^{26}Al^{1+}$ ions were used (Lachner et al., 2014). The same authors also report encouraging results using the absorber method for $^{10}$Be. If this can be refined sufficiently for routine operation, it would avoid the need for the degrader foil and the attendant losses in the post-foil analysis system, and again enhance efficiency.

Lastly, experiments performed by J. Southon on the 0.5 MV NEC AMS at UC Irvine and by D. Rood at SUERC demonstrate alterations to the standard NEC ion source and the use of non-copper cathodes designed differently than those provided by NEC can significantly increase both beam currents and ionization efficiency. Generating more ions from the source allows more ions to be counted and thus increases the efficiency of isotopic ratio measurements. More information about experiments done as part of this effort are included in the last section of this white paper.

Taken together, these four developments have improved the capabilities of the smaller systems to the point that it is now possible to construct an optimized design for routine, high-throughput, and high-sensitivity analyses of $^{10}$Be and $^{26}$Al. Such an optimized system does not presently exist (although the 0.5 MV system at ETH Zurich is now used routinely for $^{10}$Be and $^{26}$Al analyses), but all the components of a successful design have been demonstrated. Hence the time is ripe for the United States to promote the design, construction, and operation of what would become a world-leading facility.

The new instrument will be able to routinely measure both $^{10}$Be and $^{26}$Al. These are, in many cases, complementary isotopes because they are both extracted from the same quartz aliquot for measurement of *in situ* produced nuclides and because the ratio of the two isotopes provides important information about sample exposure and burial history. Calculations we have done based on the literature and tests we made on the Irvine AMS system suggest that measurement of $^{10}$Be in samples having $^{10}$Be/$^{9}$Be and $^{26}$Al/$^{27}$Al ratios $> 5*10^{-14}$ will be routine at useful precisions ($<5\%$ $1\sigma$) with extended counting times (see section 3 of this document). In addition, the new AMS will have the capability for high-precision radiocarbon measurements for dating and tracing applications. Although not part of the principal motivation for the instrument - because several radiocarbon-capable AMS systems are already installed in the United States - this radiocarbon capability will be produce much broader scientific and educational impacts, in particular enhancing undergraduate student interaction opportunities that utilize the facility to understand isotope systematics and do applied isotope geochemistry.

## 3.0 Workshop Structure

A workshop for the purpose of scoping a new American AMS instrument and facility was held on November 14 and 15, 2014 on the campus of the University of California, Irvine where participant Southon runs the W. M. Keck Carbon Cycle Accelerator Mass Spectrometry Laboratory (http://www.ess.uci.edu/researchgrp/ams/). This laboratory houses an earlier version of an AMS instrument similar to that the workshop was intended to optimize.

The workshop was divided into three sessions (see Table 1, workshop schedule)

a. During the first session on Friday morning, participants discussed the current state of science research and research training that they, and the broader community, conduct with $^{10}$Be and $^{26}$Al, and how that science could be enhanced by a new instrument dedicated to projects that require either large numbers of measurements at moderate precision or fewer numbers of measurements at high accuracy.

**TABLE 1. Workshop Schedule**

*Friday, November 14, 2014*

<u>Morning - science plan for instrument</u>
9:00 - 11:00 Discussion and identification of projects that could benefit from large numbers of moderate precision analyses at lower than current costs (see attached list from proposal as prompt).

- Identification of best projects for white paper
- Identification of references for white paper
- Identify who will write which half page summaries

11:00 – 12:00 Participants write summary drafts including references
12:00 – 1:30 Tour of AMS and Lunch break (catered at Irvine)

<u>Afternoon – budget and operation plan for facility</u>
1:30 – 3:00 Discussion of operation and budget plan for facility

- sample throughput
- user community requirements
- per sample/per day costing
- payment model
- staffing model

3:00 – 3:30 Break
3:30 – 5:00 Drafting of operation and budget plan as group including cost structure and estimated costs
5:00 – 6:30 Break
6:30 – Group dinner

*Saturday November 15, 2014*

<u>All day – Instrument design and optimized facility</u>
9:00 – 11:00 Discussion - Optimizing $^{10}$Be performance in low voltage AMS

- Consideration of recent design advances and what to incorporate
- Source configuration and number
- Isotopes
- Cathode preparation requirements
- Carbon-14 in minerals/rocks?

11:00 – 12:00 Participants write summary of discussion for white paper including references
12:00 – 1:30 Lunch break (walking) at Tender Greens in the University Center
1:30 – 5:00 Draft specifications for instrument
6:00 Group Dinner

b. During Friday afternoon, workshop participants defined a science plan for a new AMS facility that seamlessly integrates research and research training as well as sample collection, preparation, and analysis to ensure both the quality of the results and the depth of training offered to student and post-doctoral participants. Considering the high degree of automation of modern AMS systems, we discussed a budget model for such a system that allows significant reduction in end-user costs so that projects with the need for large numbers of analyses become financially feasible without on-going facility support costs from NSF.

c. During the third session (all day Saturday) participants compiled a list of optimal specifications and design ideas for an automated, moderate cost, low accelerating voltage, next generation AMS system optimized for the measurement of $^{10}$Be and $^{26}$Al and capable of measuring $^{14}$C. Using the UC Irvine system as a model, we closely examined beam line geometry and modifications (particularly ion source and extraction) made by Southon to improve AMS performance and stability. This discussion led to several experiments that we performed after the workshop to test hypotheses advanced by participants.

## 4.0 Workshop Findings

Below, we consider workshop findings in the context of the foci presented above, first defining the uses of AMS for research and research training, then considering the science plan and budget model for a new facility, and concluding with a plan for instrument optimization to make high quality, low cost AMS measurements while training the next generation of geoscientists.

### *4.1 Current state of the research and research training that would benefit from large numbers of moderate precision, lower cost AMS measurements of $^{10}Be$ and $^{26}Al$*

AMS has been used since the mid 1980s to solve problems in Earth Sciences, including measuring the age of landforms, deciphering the climate history of our planet, tracing the movement of sediment across Earth's surface, and determining the recurrence interval of major earthquakes. While some research projects require only a handful of samples, many projects of interest today require tens to hundreds of samples to address questions where the variability of natural systems often exceeds the measurement precision of AMS instruments. Below, we provide example applications of cosmogenic nuclides where the ability to measure large numbers of samples, currently a challenge because of the AMS costing structure, could catalyze transformative scientific advances.

In addition to making precise measurements, understanding both the accuracy and long-term reproducibility of isotope ratio and isotope concentration measurements is critical. Quantifying and testing for both precision and accuracy requires large number of standard measurements used for normalization and to monitor system performance, and also a large number of QA/QC geologic and laboratory replicates to ensure reproducibility of sampling and sample preparations. These measurements take significant proportions of beam time, and for most facilities where beam time is expensive, it is not cost-effective to dedicate time to these measurements. The budget model for any new facility should allow for time to make QC measurements. Workshop participants concluded that extensive QA/QC is a fundamental but often overlooked quality requirement of AMS that should be a central tenet of the facility's science and training mission – the AMS radiocarbon community provides an excellent example.

4.1.1 Ice core science: high resolution records of $^{10}$Be deposition

Ice cores from the polar regions preserve a high-resolution archive of $^{10}$Be variations over tens to hundreds of thousands of years. Measuring cosmogenic $^{10}$Be in large numbers of ice core samples is key for estimating solar variability (and thus solar forcing of climate change) prior to the modern era (Beer et al., 1988; Steig et al, 1996; Bard et al., 2006) and $^{10}$Be provides the *only* data for determining solar variability prior to 1612 CE (Galileo's discovery of sunspots). Longer term measurements of $^{10}$Be have been used to infer changes in geomagnetic field strength (Wagner et al., 2000). $^{10}$Be is a good tracer of short-term variability because it (unlike $^{14}$C) has a short atmosphere residence time, just 1 to 2 years. Yet most estimates of solar variability -- a critical part of the climate forcing calculations used with general circulation models (e.g., Schmidt et al., 2011) – rely on $^{10}$Be data from a single record (at South Pole). The deposition of $^{10}$Be to an ice core location depends both on the $^{10}$Be production rate and on atmospheric processes that are moderated by climate. The local deposition of $^{10}$Be (at a given ice core site) can vary independently of the production rate if atmospheric circulation changes. To separate the production rate and climate influences, multiple high-quality records in different climatic environments are needed (e.g., Muscheler et al,. 2007; Steinhilber et al., 2012). Developments in the last decade of very high resolution ice core chemistry measurements provide strong constraints on snow accumulation rates and deposition; yet, $^{10}$Be records have not been obtained at comparable resolution due primarily to cost of making the AMS measurements. Existing records are incomplete, at low resolution only, or otherwise problematic (Bard et al., 2007). Obtaining high resolution (yearly) records of $^{10}$Be in ice cores from multiple locations that include the most recent few decades would allow the ice core community to take advantage of overlap with the modern climate record that is most reliable during the satellite era (1979 onwards). Such records would be used in concert with state-of-the-art climate models, several of which now include $^{10}$Be production, transport and deposition physics (e.g. Heikkilä et al., 2009; Heikkilä and Smith, 2013; Field et al., 2006; 2009; Field and Schmidt, 2009). *$^{10}$Be analysis of ice cores were pioneered by American scientists (Finkel and Nishiizumi, 1997), but more* *recently this important part of ice core science has moved overseas. With the new AMS facility scoped here, there is high potential for American institutions to again be important players in this field and, in turn, to restart United States' leadership in the basic question how critical solar variations have been, are, and will be in past, present and future climate change. Understanding and interpreting the $^{10}Be$ concentration in ice cores requires the analyses of many thousands to tens of thousands of ice core samples by AMS. This work would be practical on an automated AMS system where per sample costs could be much less than those available today.*

#### 4.1.2 Dating ancient Antarctic landforms

Antarctica hosts one of the oldest landscapes on Earth (Putkonen et al., 2008) and preserves a surficial record of former ice extent and surface processes extending back through the Miocene and potentially into the Oligocene (Schaefer et al., 2000; Marchant et al., 1993). The long-term history of this ice sheet has uniquely important implications for global climate, ocean circulation, and sea level. With a small number of exceptions (e.g., Nishiizumi et al., 1991; Ivy Ochs et al., 1995), cosmogenic isotope chronologies have been measured for mostly the youngest part of this time range, from the last glacial maximum to present (e.g., Bromley et al., 2010, 2012; Hall et al., 2013; Todd et al., 2010; Stone et al., 2003) leaving the older deposits with only a few dates (Brook et al., 1995) mostly based on noble gas measurements (e.g., Bruno et al., 1997; Schaefer et al., 1999 and 2000). Pliocene-aged and younger pre-LGM deposits (i.e., deposits datable with $^{10}Be$) are widespread, well-preserved, and useful for addressing a variety of questions, such as behavior of Antarctic ice masses through a range of climatic and orbital conditions. However, due to geomorphic variability and isotopic inheritance from prior exposure periods, large numbers of samples must be analyzed to reliably constrain the age of any given landform. *Long-exposed, well-preserved samples from older glaciations in the Antarctic contain high concentrations of cosmogenic nuclides and are thus easily and rapidly measured at high precision on a low-voltage AMS system such as that scoped here.*

#### 4.1.3 Dating and understanding ice sheet history

As Earth's climate system changes, ice sheets, in particular their response to past and present climate changes, are becoming the focus of both scientists and society alike because of the role melting terrestrial ice has in global sea level rise (IPCC, 2007), their location in hotspots of accelerated warming (Graversen et al., 2008), and their connectivity with Earth systems at lower latitudes (e.g., Church et al, 2013; Kelly et al., 2014, Blard et al., 2007). *In situ* produced cosmogenic nuclides have been used for 25 years to date glacial deposits including moraines (Phillips et al., 1990) and bedrock outcrops (Nishiizumi et al., 1991). Cosmogenic nuclide dating provided a new and revolutionary way to decipher the climate information held by these archives and transformational progress has been achieved over the last two decades (Balco, 2011).

The power of this dating system is that organic material is not needed (in comparison to $^{14}C$) and if a variety of assumption are met (no erosion, inheritance or cover by till and snow) ages can be measured stretching back tens and even hundreds of thousands of years although erosion often limits accurate dating the last glacial cycle or perhaps the last two (Kaplan et al., 2007).

For example, $^{10}Be$ has been used to define the history of continental ice sheet margins (Balco and Schaefer, 2006; Balco et al., 2002), and to understand (using the dipstick method) the thickness of now vanished ice (e.g., Stone et al., 2003; Corbett et al., 2013). Combining dipsticks with marginal retreat rates in response to past climate changes (Briner et al., 2009; Corbett et al., 2011, 2013; Young et al., 2011, Hughes et al., 2012) has the potential to allow 3-D definition of paleo-ice sheet geometry over time.

Nuclides including $^{10}Be$ have been widely applied to alpine glacial systems. For example, $^{10}Be$ has been used to test whether the advance and retreat of alpine glaciers is synchronous or asynchronous (Laabs et al., 2009; Schaefer et al., 2009) and related to major climate events (Gosse et al., 1995). Measurements have been made across climate zones including the tropics allowing workers to assess whether climate changes are similar at different latitudes and in different hemispheres (e.g., Kelley et al., 2014; Stroup et al., 2014; Blard et al., 2007) and to create an inter-hemispheric map of mountain glacier fluctuations from pole-to-pole and from the last glacial cycle through the last termination into the Holocene (Laabs et al., 2009; Schaefer et al., 2009; Kaplan et al., 2010; Putnam et al., 2012, 2013a; Schimmelpfennig et al., 2012, 2014). Such global mapping of alpine glacial behavior will address important climate questions such as inter-hemispheric phasing of major climate events including the Last Glacial Maximum and the transition to the Holocene warm period. *Measuring samples exposed since the end of the last glaciation is easily within reach of the next generation of AMS. Lower cost AMS analyses will enable more boulders and bedrock samples to be dated and the resulting increased spatial resolution of geochronologic data will improve our understanding of paleo-glacial response to climate change.*

#### 4.1.4 Deciphering climate history where glaciers have been cold-based and non-erosive

Cold-based ice, frozen to the bed and non erosive, covers most of Antarctica and much of the high Arctic. The result is extensive preservation of relic landscapes. Such landscapes produce erratic boulders and display bedrock surfaces that often carry large inventories of inherited nuclides (Bierman et al., 1999; Briner et al., 2005, 2006; Corbett et al., 2014). Isotope inheritance from prior periods of exposure is both a hindrance and an opportunity for research. Inheritance, when studied with multiple cosmogenic nuclides (such as paired $^{10}Be/^{26}Al$ analyses), provides an opportunity to "see" how polar landscapes evolve through time and thus suggests new conceptual models of ice sheet history and polar landscape evolution (Bierman et al., 1999; Nishiizumi et al., 1991; Corbett et al., 2013). Such inheritance from prior periods of exposure and burial confounds simple exposure age dating and requires the measurement of large numbers of samples to screen for inheritance and to understand the apparent age structure of moraine boulder populations

(Briner et al., 2006) - a costly and thus rare approach that when applied has provided important insights into long-term polar ice sheet history in the past two decades. Although the study of landscapes covered by cold-based ice has challenges (Briner et al., 2005), it is important to refine the methods required to tackle these geologically complex areas because they are archives of valuable climatic and glacial information and because the world's glaciers and ice sheets are likely to undergo significant changes in the face of anthropogenic climate forcing (IPCC, 2013). Much of the planet's ice mass is concentrated in the high-latitudes where the presence of cold-based ice makes study more challenging, including Greenland (Håkansson et al., 2008), Antarctica (Sugden et al., 2005), and Arctic Canada (Briner et al., 2006). These landscapes can provide insight about episodes of rapid ice margin retreat (Briner et al., 2009; Corbett et al., 2013; Hughes et al., 2012), the long-term stability of continental ice sheets (Bierman et al., 2014), and the response of these ice sheets to prior periods of climate warmth (Funder et al., 1985). Because these landscapes preserve such long histories, they are valuable to study because they provide insight about long-term glacial patterns rather than just behavior since the LGM. *Lowering the cost of AMS for multiple nuclide analyses (paired $^{10}$Be/$^{26}$Al measurements) would transform the approach to studying complex, high-latitude landscapes that have been subjected to alternate periods of exposure and burial with limited erosion. Such work, which is currently cost-prohibitive, is easily doable with a low voltage AMS because nuclide concentrations in areas with cold-based ice are usually very high.*

#### 4.1.5 The global timing and pattern of the Last Glacial Maximum and Holocene transition

The Last Glacial Maximum and its transition to the ongoing interglacial represents the most dramatic climate and environmental transition in recent geological history (Lisiecki and Raymo, 2005; Taylor et al., 1993). Climate records from this time period, if they could be well deciphered, hold important information about the fundamental mechanisms driving Earth's climate system in the past and thus perhaps in the present and future (Shakun et al., 2012). Glacial advances and subsequent retreats during this key interval are recorded in moraines and other glacially derived sediment and glacially modified bedrock surfaces. Indeed, two recent reviews of the Last Glacial Maximum have relied heavily on cosmogenic age estimates (Clark et al., 2009; Denton et al., 2010). Extracting the deposition age of a moraine by dating surface materials is not usually straightforward both because of isotopes inherited from prior periods of exposure and because of moraine degradation over time. Until now, reliable moraine chronologies are mostly limited to moraines in ideal settings (only the most stable landforms with many large, erosion-resistant boulders). The few case studies based on comprehensive $^{10}$Be surveys of moraines (e.g. Schaefer et al., 2006; Applegate et al., 2012; Putnam et al., 2013a,b) make the case that a high density of samples from moraine boulders or other glacier sediment records is essential to retrieve all the climate information available because moraines are subjected to multiple geomorphic processes which create spatial variability in apparent exposure ages. This strategy, of using large numbers of samples to define the age of glacial features, is transformative because it could provide the statistical footing on which to base an inter-hemispheric understanding of climate and glacier processes during and shortly after the LGM. *Such a detailed inter-hemispheric investigation of LGM and Termination 1 glacier fluctuations requires thousands of AMS analyses and until now, the overall costs of such a global LGM glacier survey has been a limiting factor*.

#### 4.1.6 Meteoric $^{10}Be$ for quantifying surface process rates

Meteoric $^{10}Be$ was used extensively several decades ago to quantify surface process rates and date landforms (e.g., Pavich et al., 1986; Brown et al., 1988; McKean et al., 1993) but its use declined as *in situ*-produced $^{10}Be$ became the nuclide of choice for such studies. In recent years, however, meteoric $^{10}Be$ has seen a resurgence of use (e.g., Reusser and Bierman, 2010; Graly et al., 2010; Willenbring and von Blanckenburg, 2010; Bierman et al., 2014). Meteoric $^{10}Be$ offers several advantages, including ease of chemical preparation, the ability to work with fine-grained material lacking quartz, and high $^{10}Be/^{9}Be$ ratios. Examples of research areas that could grow with the ability to conduct studies with large sample sizes include: calibration of meteoric $^{10}Be$ delivery rates to soil (Reusser et al., 2010; Ouimet et al., 2015); the ability to couple $^{10}Be$ and $^{9}Be$ measurements to infer information regarding both denudation and weathering intensity (Bacon et al., 2012; von Blanckenburg et al., 2012); and quantification of rates of regolith production and residence times (West et al., 2014, 2015). *Due to the high isotope ratios, a next generation automated AMS is ideally suited for meteoric $^{10}Be$ measurements in soil and sediment. The ability to provide cost-effective, large sample studies will enable transformative research on Earth surface processes.*

#### 4.1.7 Sediment budgeting

Understanding the source, residence time, and movement of sediment across Earth's surface is a critical problem both for basic research and applied geoscience (e.g., Reid and Dunne, 1984). Sediment budgets, where sources and sinks of sediment are accounted for explicitly, provide a framework for understanding Earth as a system (Dietrich and Dunne, 1978). Understanding long term rates of sediment generation was a challenge to building such budgets, a challenge answered by the application of $^{10}Be$ (Nichols et al., 2005a) which provided integrated estimates not only of sediment generation rates (Portenga and Bierman, 2011) but of sediment transport times and fluxes (Nichols et al., 2005b) as well as a tracer for the movement of sediment from localized erosion hotspots (Reusser and Bierman, 2010). Reusser et al. (2015) show direct regulatory benefits of measuring $^{10}Be$ in stream sediment for setting limits on sediment loading that are consistent with natural, background rates of sediment production and transport. There are important applications of $^{10}Be$-based sediment budgeting to natural resource management including evaluation background rates of sediment input to World Heritage sites such as the Great Barrier Reef (Nichols et al., 2014). Recently, Nelson et al. (2013) took a similar approach in the Arctic, using $^{10}Be$ to demonstrate that most sediment leaving

Greenland in today's interglacial is derived from the ice itself, not the deglaciated landscape around the Greenland's margin. *Understanding sediment budgets requires a large number of moderate precision $^{10}$Be measurements to determine nuclide concentrations in a river network, i.e., up and downstream of tributary junctions and across gradients in landscape parameters, particularly average basin slope (Portenga et al., 2014; Savi et al., 2014). A next generation automated AMS can provide a cost-effective means for tracking sediment through the environment.*

4.1.8 Rates and dates of tectonic activity

In situ produced cosmogenic isotopes have become an important tool in active tectonics and paleo-seismology providing age control for previously undatable features (e.g., bedrock scarps, Mitchell et al., 2001), in areas where organic materials for radiocarbon are scarce (such as deserts, Chevalier et al., 2005), and for deposits older than ~45 ky, the effective limit of radiocarbon dating. Surface exposure studies allow investigation of neotectonics and related processes without the need for excavating deep trenches. Fault slip-rate studies often rely on the dating of alluvial fans (Bierman et al., 1995; Zehfuss et al., 2001; Behr et al., 2010; Rood et al. 2011). Such deposits have complicated depositional histories; in order to best estimate depositional age (differentiate inheritance and/or erosion), tens of samples per surface are necessary (e.g., Behr et al., 2010; Matmon et al., 2006). Also, multiple depth profiles (each containing at least half a dozen samples) can reveal patterns and timing of fan deposition and post-depositional processes that erode fan surfaces through stripping and deflation (Clapp et al., 2001). Combined with numerical models (Hidy et al. 2010), such profiles can yield high resolution ages. Profiles of cosmogenic nuclides on fragile geologic features, such as precariously balanced rocks (Balco et al., 2011), can be used to test earthquake hazard models. Each of these features requires multiple samples, and multiple features per site need to be dated in order to have confidence in the results. Paleoseismology studies that directly date bedrock fault scarps in moderate to low slip rate environments (e.g., Mitchell et al., 2001; Benedetti et al., 2002), require dozens of densely spaced samples to obtain robust information about the timing, frequency, and slip per event for earthquake ruptures; data critical to improved understanding of fault behavior. Furthermore, to understand fault segmentation and rupture dynamics at a fault system scale requires multiple sites per fault. Dating of paleo-earthquakes using cosmogenic nuclide ages of rock fall deposits (Rinat et al., 2014; Mackey and Quigley, 2014) requires large numbers of samples so as to be able to image multiple events in poly-genetic deposits with confidence. Detection of blind faults and fault-bend induced uplift is possible using $^{10}$Be to measure localized increases in drainage basin erosion rates (Wobus et al., 2005; Gudmundsdottir et al., 2013). Such studies may detect unmapped faults, which represent significant geological hazards to mountain communities. There are intriguing but so far untested applications of cosmogenic nuclides for neotectonics including isochron burial dating of Plio-Pleistocene strata for fault slip and uplift rates (Rockwell et al., 1988), particularly for slow-slip rate faults (i.e., low hazard) but high risk areas (near nuclear sites). In situ

$^{14}C/^{10}Be$ burial dating also has potential for paleoseismology in trenches with no organic material. *For all of these studies, it is the scatter in the data or the distribution of concentrations that are important, not the error on any individual age, so we learn more with large numbers of ages at moderate precision than fewer ages at higher precision, the perfect application multiple isotope measurements made at low cost by automated, low-voltage AMS.*

4.1.9 The power of clast by clast analysis in understanding landscape evolution

Most of what we know about landscape-scale erosion through measurements of $^{10}Be$ has been learned by measuring amalgamated detrital samples, i.e., bags of river sand and hillslope soil (Portenga and Bierman, 2011). Yet, this approach, because of the averaging involved, throws away important data about clast to clast variance (e.g., Repka et al. 1997) and thus the dependence of erosion on slope and elevation. Only a few pioneering studies have made clast by clast analyses of cosmogenic nuclides and thereby created probability density functions of nuclide concentration. For example, Codilean et al. (2008) measured $^{21}Ne$ in 32 clasts collected from the Gaub River in Namibia to partition erosion by elevation. More recently, McPhillips et al. (2014) measured $^{10}Be$ in large populations of clasts (n = 68) from a modern day river and a Pleistocene terrace and compared the shapes of the distributions along with landscape evolution models to conclude that earthquakes rather than climate change triggered hillslope erosion by debris flows. *If a sufficient number of clasts could be analyzed then variations in clast history (erosion rate) could be tied to specific source lithologies (and thus to regions of a watershed) answering fundamental questions about both spatial and lithologic variations in erosion rate. Only with lower cost, higher throughput AMS will this transformative research become possible.*

4.1.10 The relationship between climate, tectonics, and erosion

Fundamental to understanding both Earth as a system and the system response to climatic forcing that changes over time is the interaction between climate, tectonics, and the rate of erosion (Raymo and Ruddiman, 1992). Cosmogenic nuclides, particularly those measured in both contemporary and old river sediments have provided important data to establish the linkages between climate, erosion, and tectonics over time (Schaller et al., 2004; Cox et al., 2009; Portenga and Bierman, 2011). Currently the geomorphology community has abundant data on how erosion rates vary over space during the integration time of these nuclides (thousands to tens of thousands of years), but lacks information about how climatic or tectonic changes force these rates over geologic time scales. One approach to answering these questions is measuring $^{10}Be$ and $^{26}Al$ in river terrace and foreland basin that are "repositories" of river sediment through time (McPhillips et al., 2013; Cox et al., 2009; Bierman et al., 2005; Charreau et al., 2011). Ideally, such time series would be measured at a high sample density comparable to the time-resolution of the paleomagnetic time-scale (< 100 kyr in some parts of the Plio-Pleistocene). Such an approach can also be used for clastic sediment from marine cores (Bierman et al., 2014). *Because of the spatial and temporal variance inherent in landscape-scale systems, this approach to understanding climatic and tectonic influences on erosion rates now and in the past will benefit from numerous measurements made at moderate precision such as by a low voltage AMS.*

4.1.11 Understanding soil formation rates

Quantifying soil formation rates is key for addressing high-priority research initiatives in Earth surface processes such as predicting how Earth's surface will change during the Anthropocene (NRC, 2010). The majority of Earth's surface is mantled in soil and soils play a key role in regulating critical zone processes (e.g., Anderson et al., 2007). Cosmogenic nuclides revolutionized the study of soil dynamics by providing the ability to determine the rate that rock is transformed into soil (Heimsath et al., 1997). Yet our understanding of the rate that soil is produced from underlying parent materials is limited to less than a dozen sites globally (e.g., Heimsath et al., 2012). The current lack of soil production measurements that cover a wide range of landscapes and ecosystems limits our ability to understand and generate predictive models on the role that broad-scale controls—mean annual precipitation, biota, lithology and others—play in governing soil production and rock weathering rates. Soil production rate studies are often limited to a few tens of analyses (e.g., Heimsath et al., 1997), which can require amalgamation of samples (e.g., Jungers et al., 2009; Norton and von Blanckenburg, 2010), with potential loss of key information regarding site-specific variability in processes. *The ability to increase the number of soil production rate measurements via more efficient and lower cost AMS analyses would open new avenues for soil and hillslope-scale studies, such as landscape response to climate change and the sustainability of agricultural practices.*

4.1.12 Global erosion rate mapping

Determining erosion and weathering fluxes at the scale of entire continents (including cratons and mountain ranges) is a key research area worldwide. Cosmogenic nuclides provide the ability to measure rates of Earth surface change on timescales relevant to the evolution of topography (e.g., Lal, 1991), and are hence an ideal tool for solving major challenges in Earth surface science. Quantifying the flux of sediment from continents to the oceans is key for constraining global-scale geological and biogeochemical cycles (Bierman and Nichols, 2004). Mountains are thought to play a key role in regulating the geological carbon cycle via links among rock uplift, erosion, and weathering (Chamberlin, 1899; Raymo and Ruddiman, 1992) because mountains are the dominant locus of erosion and weathering on Earth's surface (Larsen et al., 2014). However, cosmogenic nuclide denudation rate data exist for only 2.3% of Earth's land area (Portenga and Bierman, 2011), requiring significant extrapolation to predict erosion and weathering budgets for Earth's un-measured surface (Willenbring et al., 2013; Larsen et al., 2014). Studies seeking to disentangle climate and tectonic controls on denudation rates are often limited to a few tens of samples (e.g., Bookhagen and Strecker, 2012; Scherler et al., 2014). Global-scale estimates of sediment delivery to oceans exist, but these are based on short-term river gauging records that, do not integrate over geomorphically relevant timescales and are severely impacted by landuse and dam construction (Milliman and Farnsworth, 2011). Without long-term estimates of denudation rates at large spatial scales, it is not possible to determine the roles that infrequent, high magnitude erosion events (Kirchner et al., 2001; Covault et al., 2013) or anthropogenic modification of surface processes play in dictating the transport of material from land to oceans. *The ability to generate large sample size cosmogenic nuclide datasets derived from measurements of fluvial sediments would enable—for the first time—the ability to quantify material budgets for entire mountain ranges or continents on time scales relevant to landscape evolution and biogeochemical cycling. Only moderate precision is required for these analyses because there is significant temporal and spatial variance in the cosmogenic nuclide concentration in sediment (Lupker et al., 2012); thus such analyses are well matched to a low voltage, automated AMS system.*

#### 4.1.13 Dating of buried Pleistocene and Pliocene sediments

The 2X relative difference in the half lives of $^{10}$Be and $^{26}$Al provides the opportunity for using the pair of nuclides as a chronometer in situations where a sample is exposed at the surface and then buried (Granger and Muzikar, 2001; Granger, 2006). Such an approach can also consider three nuclides (Balco and Shuster, 2009). This approach has been used for years in a few situations that are described as simple burial (primarily deeply buried samples from caves, e.g., Stock et al., 2005) to deduced the rate of river incision (Granger et al., 1997; Granger et al., 2001; Haeuselmann et al., 2007) and landscape evolution (Kong et al., 2009; Davis et al., 2012), to date glacial tills in polar regions (Hidy et al., 2013), and to calculate the age of artifacts and fossils (Shen et al., 2009; Mercader et al., 2012). Recently, Balco and Rovey (2008) and Erlanger et al. (2012) proposed a different approach to burial dating that has greatly increased the diversity of samples that can be successfully used to establish the age of previously undatable Pleistocene and Pliocene strata (Balco and Rovey, 2010). This isochron burial dating method requires dual isotope analysis of at least 4 and preferably 8 or more samples (each with both nuclides, $^{10}$Be and $^{26}$Al) per isochron. It has the distinct advantage of not requiring assumptions regarding post-burial nuclide production; however, because is so expensive (at current rates, AMS analysis costs alone for a single robust isochron are many thousands of dollars), it remains underutilized as a dating tool although it is widely applicable in many geomorphic settings from the poles to the equator. The power of isochron fitting through multiple data points means that the precision of each data point is less important than the number of samples and the range of isotopic concentrations represented in the isochron. *Because a single isochron can require 10 to 20 individual AMS analyses, the cost advantage of a low voltage AMS becomes exceptionally important. Low voltage AMS has sufficient sensitivity to provide isotopic data for many isochron projects where sediment was originally derived from moderately to slowly eroding terrains. Cost savings resulting from a next generation AMS will catalyze much wider use of this important dating method and greatly expand chronologic knowledge of Pleistocene and Pliocene strata.*

### *4.2 Science plan and budget model for the new facility*

In response to the scientific utility of nuclides such as $^{10}$Be and $^{26}$Al, numerous sample processing laboratories, large and small, have been established across the United States (Figure 1). These laboratories are staffed by faculty, technicians, and students, who as part of their degrees, are being trained in research techniques including sample collection and sample preparation. Because there are only two AMS facilities in the United States routinely measuring $^{10}$Be and $^{26}$Al and one of these (Livermore) is in a secure, government facility, many of those doing sample preparation have not had the opportunity to learn the principles of AMS, the technique used to measure their samples. This is of particular concern given that optimal analytical conditions can only be achieved with well-prepared samples, whose preparation requires an understanding of how the AMS instrument works and how it effects the quality of the data produced. A new AMS facility should be open to the broader community and provide extensive opportunities for training and community involvement.

#### <u>4.2.1 Users of the new facility</u>

We anticipate that a new AMS facility will measure samples processed in a wide range of laboratories. American sample processing facilities for $^{10}$Be that we know of are currently located at locations shown on Figure 1. Most of these laboratories are running below their capacity, at least in part because the cost of AMS limits the number of samples prepared. Lowering the cost of AMS will not only more fully utilize existing sample preparation laboratories, but will spawn the creation of new labs: some of these new preparation labs will likely be dedicated to the processing of $^{10}$Be in ice cores while others will be created by the new generation of practitioners, including students trained in many of the existing sample preparation laboratories mentioned above. A high-throughput, next generation AMS will be the facility with capacity to handle the samples produced not only by today's graduate students, but tomorrow's faculty, a significant broader impact for the next generation.

Workshop participants agreed that the effective cap on the total number of samples analyzed is set by the funds that NSF and other agencies allocate for AMS analyses. The experience with $^{14}$C shows that as more AMS facilities came on line, the cost of each measurement decreased making analyses more affordable; thus, more samples were

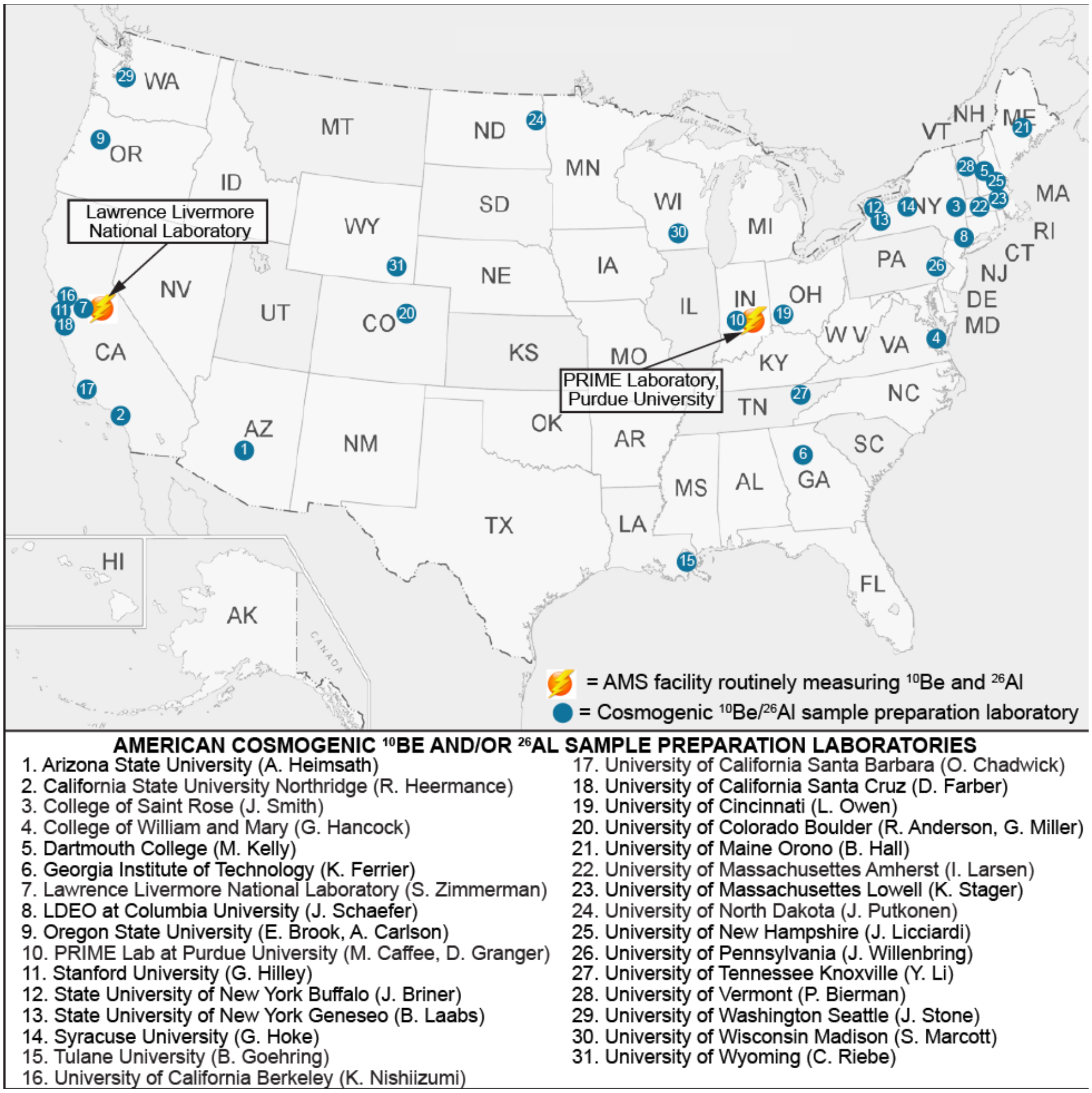


*Figure 1. Map of United States showing cosmogenic sample preparation facilities for $^{10}$Be and $^{26}$A and AMS facilities that routinely analyze $^{10}$Be and $^{26}$Al.*

generated by the community, more scientists used $^{14}$C to solve an increasing number of research problems, and the broader impacts of the facilities increased. For example, when the Irvine facility came on line for $^{14}$C a decade ago, it did not put other labs out of business, but led to an increased number of $^{14}$C sample analyses.

<u>4.2.2 Budget model for new AMS facility</u>

The new AMS system we scope in white paper is optimized for efficient, automated operation during measurement of $^{10}$Be and $^{26}$Al; although not a target isotope, $^{14}$C can also be measured precisely. The source and beam line are designed to maximize transmission and efficiency while minimizing downtime. Because this is fundamentally an "off the shelf" AMS, with a mature core technology incorporating recent innovations, the instrument can be managed and maintained by two people who know how to service it as long as a machine shop and electronics technician are available on an "as needed" basis to remedy unusual problems. The data collection, data reduction, and maintenance must be simple enough and well designed to facilitate high throughput – the catalyst for reducing AMS cost and increasing accessibility to measurements.

Workshop participants considered the costs and staffing of current AMS facilities with which they were familiar and concluded that a next generation AMS system will be much less staff intensive than current AMS facilities because of two factors. First, extensive automation is now the norm for new AMS instruments. Second, the comparatively simple design of a low-voltage AMS reduces the complexity of the instrument, increasing the stability of the system and reducing the number of parts that could fail. We conclude that operating a new AMS facility would require two staff:

1. A full time, senior technical person whose responsibilities would be to keep the AMS running. This person would have extensive prior experience in "hands on" AMS and would be able to troubleshot systems issues, clean and rebuild the ion source, repair electrical and mechanical components, and conduct routine measurements including loading wheels with samples and reducing data. It is likely that this person would have a doctoral degree (although extensive experience might allow the substitution of an MS degree). While this staff person would be encouraged to publish papers detailing the operation of the facility and new knowledge gained in the course of their work, they would not be expected or encouraged to have an independent research career; rather, their focus would be facility operation. For costing estimates, we assume 12 months of salary for the senior technical staff at a rate of $5000/month plus benefits.

2. A tenured Earth Science faculty member with extensive experience in cosmogenic isotopes and AMS analysis needs to be the public face of the laboratory, interacting with other geoscientists on collaborative projects. Participants agreed that the faculty member could not teach a full course load and still lead what will be a national and international facility. They considered that a half time association with the AMS facility and modified course load (base budget funded) would be appropriate for the long-term. For costing estimates, we assume 6 months of salary for the lab director at a rate of $8500/month.

In addition to these staff, it is important to have a high quality machine shop available to make repairs and modifications to the instrument as well as electronics technicians available to solve problems that were beyond the expertise of the laboratory staff.

4.2.3. Facility start up costs

There will be one-time costs at facility start up. These include faculty and staff time during facility design, instrument installation, and commissioning as well as one-time costs for equipping the facility. For the 6 months before and a year after delivery of the instrument, it is likely that the entire effort of both staff members will be directed toward instrument start up and that there would be no income for the facility during this time period to offset salary costs.

We suggest that any budget and timeline for starting up the new AMS facility include a substantial period (6 months to a year) for instrument optimization including support for graduate students to become deeply involved in the optimization process. Possible applied research foci could include: 1. Testing the effect of sample geometry, cathode material, and sample binder composition on ionization/total system efficiency; 2. Altering source geometry and ionizer selection to maximize ionization efficiency; 3. Optimizing measurement, standardization, and data reduction strategy to improve both accuracy and throughput while realistically defining instrument performance limits.

Workshop participants suggested the following list of tools would be needed to set up a new AMS facility so that the instrument could be efficiently operated and maintained. Their estimated costs are included parenthetically. A full mechanical tool kit and Dremel tool ($1500), a full electronics toolkit including multimeter, oscilloscope, electrometer, and current source ($15,000), glovebox for packing cathodes and handling beryllium ($5000), contained sandblaster for source cleaning ($2000), cathode packing equipment for standards ($2000), radiation safety equipment including a microrem meter and Geiger counter ($2000), flammables cabinet ($500), microscope for cathode inspection ($1000), He leak detector ($20,000), computers and printers for data analysis and recordkeeping ($3000).

### 4.2.4 Facility Layout

The AMS will require about ~1500 ft$^2$ of space including a space for the AMS itself with controlled temperature and humidity (as per specifications from the manufacturer) as well as filtered and conditioned air. Over-pressuring the room will ensure cleanliness. A separate control room and office is beneficial as it reduces exposure to noise for operators. A small separate room is optimal for assembling wheels and preparing standards. Given the cost and sensitivity of the instrument, key card security would be appropriate.

Utilities include low conductivity, re-circulated cooling water chilled to 20 $^{\circ}$C and sufficient to handle the cooling load as well as a single power feed for the instrument. The $SF_6$ gas handling system uses 3-phase 208V power. There is usually little need for concern about radioactivity. The instrument is not powerful enough to produce neutrons although a few x-rays may be generated by the ion source. Back up power is preferred and dry compressed air is required. Tanked argon is used and requires proper wall holders for safety. Cabinetry for storing spares and equipment as well as chairs and desks for operators need to be provided to fit out the laboratory.

4.2.5 Spares

To properly maintain the instrument and minimize downtime, the workshop recommended a full spares kit be acquired as part of instrument acquisition. Such a kit should include all internal parts for the ion source, a spare turbo pump, a spare roughing pump, ion gauge heads, sample wheels, detector windows, power supplies, and preamplifiers.

4.2.6 Per year sample loading and costing

Prior experience of workshop participants suggests that it will be possible to run at least one 134 sample wheel of $^{10}$Be each week using only several days of beam time, leaving the rest of the week for maintenance, data reduction, and method development. Wheels of $^{26}$Al are likely to take longer because beam currents are lower and wheels of $^{14}$C are likely to take less time because beam currents and isotope ratios are higher. Each wheel would contain about 100 billable unknowns (the other cathodes are standards, replicates, and blanks that cannot be charged) suggesting a steady state throughput of 4000 to 4500 cathodes per year is reasonable accounting for several holiday weeks as well as down time for preventive maintenance and repairs.

Staff salary (a fixed cost) accounts for most of the expense of AMS analysis; thus increasing throughput on a largely automated instrument will reduce per sample costs. However, samples require different amounts of beam time to measure and thus have different real costs. For example, samples with high $^{10}$Be/$^{9}$Be ratios will require less beam time than samples with low ratios and the desired precision of analyses as well as the quality of cathodes, as indicated by the beam currents they produce, will also affect the time it takes to make a measurement and thus its cost.

There are various ways to approach costing samples with the realization that most sample analysis costs will be paid from grants that require *a priori* estimates of costs. One can employ an average cost model, charging the same for each analysis, an approach that favors low-ratio and difficult to measure samples. On the other hand, one could bill by beam time, which more realistically apportions cost but is difficult to manage because sample ratios and performance are impossible to know *a priori*.

Workshop participants agreed that a predictable rate structure was important as was a structure that encouraged efficiency and mirrored the true cost of making analyses. The goal is to reflect the cost of sample analysis and to encourage projects that are currently not practical given the current cost of AMS analysis. Participants suggested the following:

- That a single rate be established for "average cathodes" that were run for a specified time on the AMS (for $^{10}Be$, nominally 20 minutes in 10 measurement cycles). This would result in variable precisions depending on sample $^{10}Be/^{9}Be$ ratio and cathode performance (a function of sample size and purity both of which are dependent on the preparing laboratory). Since $^{26}Al$ sample would run longer, because of lower beam currents, the price would like be higher.
- That a lower beam day/collaborative rate be established for very large projects that would use a significant portion of the facilities capabilities (for example, running thousands of samples from an ice core). Such funding would likely pay the salaries of staff directly for a period of time. Method development proposals could also be costed in this way.
- That a higher rate be established for cathodes needing longer that average run times either because they required better than nominal precision or had very low ratios.
- That an initial price structure be put in place at start up and then evaluated after a year or two of operation to see if it correctly reflected the costs of making analyses.

4.2.7 Per sample cost estimate

Yearly costs of running the new AMS facility include staff salaries with benefits, equipment maintenance, and consumables. Consumables include the costs for standards, cathodes for standards, and computer supplies.

Participants in the workshop suggested that a robust database with a user-friendly interface is key to reducing staff workloads, as is allowing credit card payment for those submitting small numbers of samples; automated data download for users will free staff time and reduce costs. See a description of such a database below.

Full time technical staff member with benefits @ 45% = $88,000
Half time faculty member with benefits @ 45% = $85,000
Consumables = $15,000
Equipment maintenance = $20,000

**Total Yearly fixed costs = $208,000**

Costs for AMS measurement assuming 2000 unknown cathodes/year = ~ $100/cathode
Costs of AMS measurement assuming 4000 unknown cathodes/year = ~ $50/cathode

Depending on the costing structure of the University hosting the facility there are likely to be indirect costs or space charges that will increase the actual cost per analysis but even at a nominal indirect cost rate of 50%, these prices are less than half of those charged by the other AMS facilities in the United States and include no subsidy beyond of the original purchase price of the instrument.

### 4.2.8 Data Management and QA/QC Plan

Streamlining sample submission, sample tracking, billing, and data reporting are key efficiencies that will keep costs down and allow laboratory personnel to focus on science and making excellent measurements. To that end, we discussed creating a SQL database that would be used to organize, query, and conduct meta-analysis on archived data for both unknowns and QA/QC samples. The database would allow automated user access to data for samples they have provided for analysis and would be used for tracking accounts and costs. Such a database would be designed specifically to accept software output files (e.g. from NEC, DMAN, and ABC files), synchronize the AMS data with all the chemical and field data provided by submitters if they chose, and then pipe all the data into the CRONUS calculator (Balco and Stone, 2008) if so desired by users. The database would export data to a report template, invoice template, and book keeping/accounting sub-database would maximize efficiency and minimize time spent on administration by AMS personnel. Although this database set up represents an up-front cost at facility startup, creating the database should be a simple task for an experienced programmer, and should be set up in such a way that AMS personnel can easily use and modify the system. The database would allow all users to track QA/QC data over time (such as internal standards) run by the AMS.

Designing a flexible and responsive data management system is critical for efficient, cost-effective operation of the AMS facility and should be scoped, designed, and created alongside the instrument so that it is ready for testing and operation when the instrument is commissioned. Such a database and the automation it provides will lower long-term costs and increase data accessibility. It should be developed by a professional but there is great opportunity for graduate students in computer science to participate in the work, thus providing a broader impact.

A well considered plan to ensure the quality of analytical results generated by the new facility is critical and will rely on a smoothly functioning database. At a minimum, the isotopic ratios and beam currents of primary and secondary standards run with all unknowns need to be followed over time and the results disseminated on the web to assure the community that AMS performance actually meets stated specifications. The primary and secondary standards would be loaded by the AMS lab to diagnose machine performance and normalize analyses; however, based on the variance above and beyond counting statistics shown by repeated analysis of the CRONUS cosmogenic standards (Jull et al., 2014) by different laboratories, there is clearly a need to consider quality control more broadly in order to develop a realistic error budget as well as quantify accuracy and precision of the isotopic measurements made at the new AMS facility.

The radiocarbon community provides a useful example. Sample preparation laboratories collaborating with AMS facilities normally process both blanks and standards along with unknowns and submit all of these cathodes together for analysis. Such an approach more robustly quantifies reproducibility and the ability of the AMS system to make accurate measurements of samples prepared using different chemistries and packed into cathodes by different people. By requesting that all submitting labs provide process blanks, CRONUS standards, and processed dilutions of existing AMS standards, a new facility could move the broader cosmogenic community toward a greater awareness of variances between labs and improve the quality of data for all involved.

#### 4.2.9 Relationship to existing AMS facilities and existing American analytic capacity

The United States leads the world in low-level AMS analytical capability (Granger et al., 2014; Rood et al., 2010), but compared to Europe, Australia, New Zealand, and elsewhere, we are without a high-throughput/low sample cost AMS facility. For example, the two existing US AMS laboratories that routinely make $^{10}$Be and $^{26}$Al analyses, Livermore and PRIME, average ~ 2000 $^{10}$Be and hundreds of $^{26}$Al analyses per year (more $^{26}$Al at PRIME than LLNL). In contrast, the new, automated ASTER-CEREGE facility (France) measured around 5000 $^{10}$Be and several hundred $^{26}$Al cathodes (including standards) for each of the last three years.

Progress in the application of cosmogenic nuclides to many different fields of Earth Science has been explosive over the last decade, and researchers overseas have made key innovations, increasing the efficiency of AMS analytical hardware. Now is the time for the United States to integrate these novel technologies with the existing American leadership in applied Earth Science. A new, high-throughput, high-efficiency AMS will catalyze science and science training that matters in such important fields as polar science, climate change, Earth Surface Processes, and Earth system dynamics.

The new facility considered by this white paper would not replace the existing AMS facilities in the United States but would complement them. The automation and resulting efficiency would allow investigators to tackle projects that require large numbers of moderate precision measurements, projects that are currently untenable because of costs. Thus, we expect total demand for $^{10}$Be and $^{26}$Al analyses to grow in response to a reduction in analytical cost.

The broader impacts of a new AMS facility will be significant, changing the face of American research and research training related to the application of cosmogenic nuclides for the next several decades. The new instrument will have an impact across numerous disciplines – climate science, polar geology, geomorphology, tectonics, atmospheric science, soil science, and land management. Implementing next generation/21$^{st}$ century AMS technology combined with substantially lower per sample costs will open up new and important avenues for discovery for example, time series involving hundreds of measurements will become routine as will characterizing the probability distribution of isotope concentrations on landforms such as moraines, global mapping of erosion rates, and the application of isochron burial dating.

Just as important, a new University-based facility will become another nucleus for educating the next generation of American scientists in a variety of disciplines that including mass spectrometry, ice core science, paleoclimatology, and earth surface process. Placing the facility in the eastern United States would complement existing facilities in the west (LLNL) and mid-continent (PRIME) and makes particular sense for student training given the number of colleges and universities in eastern North America as well as the number of processing laboratories in the eastern United States (Figure 1). The new facility should not only enrich the student experience but also improve the quality of science. It will achieve this by enabling the deep involvement of the geoscientists with cosmogenically-oriented projects all the way from initiation to completion by encouraging visitation with an open-door policy where people come to learn and participate in AMS measurements. We envision the new facility as a scientific community hub that will bring together users including faculty and students while catalyzing international and industry-government-academic partnerships.

### *4.3 Schematic design of the next generation AMS instrument*

The next American AMS facility, as envisioned by workshop participants, builds on recently published technical advances demonstrated by others as well as on recent experiments we have conducted on existing instruments to assist with design optimization specifically for $^{10}$Be and $^{26}$Al. We emphasize that the envisaged system is not intended to compete with the larger, higher voltage AMS facilities (PRIME and CAMS), which will retain significant advantages for the measurement of very young samples or samples that require the highest precision for low ratio analyses. Rather, the new system will complement those facilities by allowing larger sample suites and thus the reduction of geomorphic uncertainties while at the same time cutting costs because of automation.

We view development of the next American AMS facility as a low-risk, high-return endeavor because the core technologies have been proven. Over the last few years, a number of low voltage AMS instruments have been installed around the world. Next generation, low voltage AMS systems have reliably and reproducibly measured $^{10}$Be and $^{26}$Al (Christl et al., 2013). Low accelerating voltage AMS instruments have been developed and installed at ETH in Zurich (Muller et al. 2010b), New Zealand, and China (Muller et al., 2013) and 1 MV systems are operating in Seville, Bucharest, and Aarhus. The next instruments of this type are being installed in India and Australia in 2015. While all of these instruments can measure $^{10}$Be and $^{26}$Al, none are optimized specifically for these nuclides. Rather, they are instruments that were designed for measuring $^{14}$C and have been adapted for $^{10}$Be and $^{26}$Al. Here we schematically design the first AMS optimized for the analysis of $^{10}$Be and $^{26}$Al, a prelude to installing such an instrument in the United States.

We approached schematic design of a next generation AMS instruments with the goal of optimizing analysis quality (precision and accuracy) by maximizing total system efficiency and stability. The core instrument is a proven, mature design produced routinely by NEC and known as the XCAMS design. It is a 0.5 MV instrument.

### 4.3.1 New data collected to optimize design and operation of new instrument

During the second day of the workshop, participants discussed simple experiments that could help guide design of an optimized low voltage AMS. Because others have recently demonstrated the importance of changes to the high-energy (post accelerator) part of the beamline (Müller et al., 2010a) and detector (Lachner et al., 2014), we focused our experiments on the ion source in an attempt to maximize the efficiency with which negative ions are generated, extracted, and transported before being injected into the accelerator. We did two experiments.

*Experiment 1*. To understand the effect of cathode materials on the ionization efficiency of a standard NEC SNICS cesium sputter source at SUERC, we replaced the copper cathodes usually used for $^{10}$Be measurements with stainless steel cathodes. We measured ionization and total system efficiencies for $^{10}$Be using the methods described in Rood et al. (2010). Both cathode types were of the NEC design geometry and packed with material containing the same amount of BeO (~1 mg) and 1:1 molar mixture of BeO:Nb.

*Experiment 2*. To estimate the ionization efficiency of an NEC SNICS ion source modified to use a different ionizer, different cathode design, and different extraction and low energy beamline than the SUERC AMS, we measured beam currents for $^{9}$Be$^{16}$O$^{-}$ on the UC Irvine NEC low-voltage AMS. To do this experiment, we used different amounts of $^{10}$Be standard material (BeO:Nb same 1:1 molar ratio) in aluminum cathodes of the Roberts design used at NOSAMS (Woods Hole, $^{14}$C AMS laboratory). Although the Irvine instrument is dedicated to radiocarbon and does not analyze other cosmogenic nuclides, Southon retuned the AMS so as to be able to measure the BeO- currents as a function of time.

Our investigation was prompted by a comparison of total system efficiency for $^{10}$Be on the SUERC AMS (5 MV, NEC) and the LLNL FN tandem (Rood et al., 2014). Although there is only a two to three-fold difference in initial $^{9}$Be ion current (8-10 μA SUERC vs. 24-30 μA LLNL), there is a 10X difference in total system efficiency (0.1 vs ~1%) between these systems (Rood et al., 2010; Rood et al., 2014).

The first experiment showed that by replacing copper cathodes with stainless cathodes (the material used for $^{10}$Be cathodes at both PRIME and LLNL), ionization efficiency on the NEC SNICS ion source is significantly improved at SUERC. We found that:

- There was negligible $^{10}$Be background coming from stainless cathode material.
- Stainless cathodes produced up to 14.5 µA of BeO- and produced >10 µA for the first ~40 min of sputtering (they still had 4.5 µA after two hours of sputtering). This is a significant increase over currents produced from BeO packed in copper cathodes (Figure 2).
- Using stainless cathodes generated a nearly 3-fold improvement in ionization efficiency (~0.3% to ~0.8%) -- likewise a doubling of total system efficiency (~0.1% to ~0.2%) and thus significantly improved theoretical counting-statistics precision (i.e., doubled the number of counts reaching the detector).

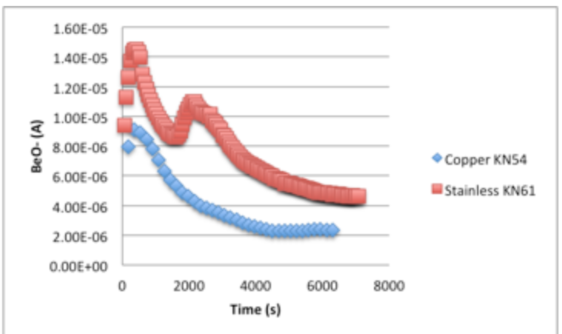


*Figure 2. Beam current over time for stainless (red) cathode packed with $^{10}$Be standard material and copper cathode (blue) packed with standard material. Data collected on SUERC 5MV NEC AMS using standard NEC SNICS source.*

The second experiment clearly showed that modifications to the standard NEC SNICS source done at UC Irvine dramatically increase the ionization efficiency and source output (Figure 3). Beam currents over the first 1000 seconds (the nominal run time of samples at LLNL) for some cathodes are above 20 µA, performance approaching that of the LLNL source. We found that packing more sample material into the cathode increases the initial beam current, which is likely a sample height effect, c.f. Hunt et al. (2006). The initial beam current of the cathode loaded with the most BeO is higher than that of the other cathodes; this is significant, considering that the ionization efficiency we estimate for the larger sample is roughly the same as for the smaller samples. The higher current from the more fully packed cathode tells us optimizing the depth of the sample surface below the top of the cathode hole will help get the most beam out in the shortest period of time. This optimization should be done during the final design of the back-packed cathodes. Not only will such experiments increase the efficiency of AMS analysis, they will ensure that the same target geometry is always presented to the ion source for all unknowns and for the standards used for normalization. Ensuring a reproducible target geometry makes the source easier and faster to set up after a cleaning, and will make the beam emittance of the cathodes more constant, which will increase precision and accuracy of the normalized measurements.

Using these data, we calculated an BeO- ionization efficiency of 3% for the modified

NEC source used at UC Irvine, similar to that calculated for the LLNL source by Rood et al. (2010), and an order of magnitude higher than that calculated for standard NEC source used at SUERC (Rood et al., 2014).

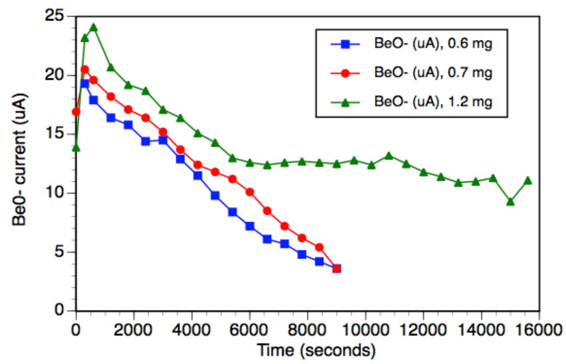


*Figure 3. Beam current over time for three cathodes packed with differing amounts of $^{10}Be$ standard material. Data collected on Irvine 1MV NEC AMS using modified NEC source and aluminum cathodes.*

The differences in total system efficiency between LLNL and SUERC are well illustrated by the results found for very low-level samples measured by Bierman and Rood at both the SUERC and LLNL AMS units and published in Nelson et al., (2014). For samples of similar $^{10}Be/^{9}Be$ ratio (all in the $10^{-14}$ range), the reported uncertainty of the measured isotope ratio at SUERC is a factor of 2 to 3 times higher than for samples have a similar ratio and measured at LLNL. This offset is well explained by the 10X difference in ionization efficiency between the different AMS facilities and demonstrates the importance of optimizing the ion source so that ions of BeO- are generated as efficiently as possible.

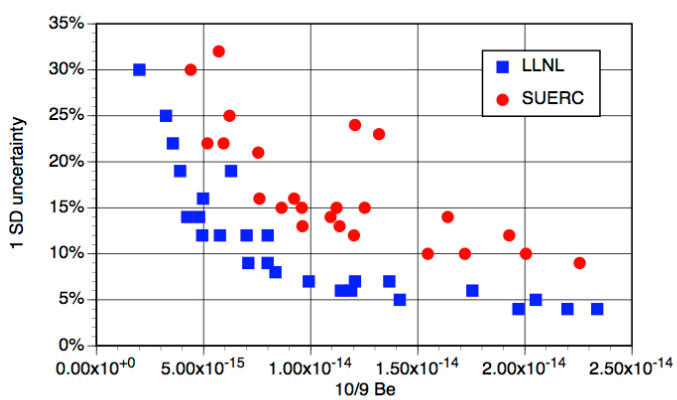


*Figure 4. Precision versus ratio for samples from Greenlandic rivers (Nelson et al., 2014) measured at SUERC and LLNL. Offset of 2 to 3X in precision is consistent with 10X difference in ionization efficiency considering that precision scales with square root of $^{10}Be$ counts in the detector.*

### 4.3.2 Anticipated performance of low voltage AMS system

Using findings published by other labs and the experimental data reported above, workshop participants concluded that an optimized next-generation, low-voltage AMS system would have a sensitivity for $^{10}Be$ measurement within the range of the two larger AMS systems with which participants were most familiar and for which published data exist (LLNL and SUERC; Rood et al., 2010, 2013, 2014). Our findings (calculations shown in Table 2) for Be measurements are based on using non-copper cathodes (experiment 1), observing a 3% BeO- ionization efficiency for the NEC SNICS source as modified for use at UC Irvine (experiment 2), and published transport efficiencies for the low energy TANDY system using He stripping at ETH in Zurich and data from the NEC XCAMS system at GNS Science in New Zealand (Müller et al., 2010a; Lachner et al., 2014; A. Zondervan, pers. comm.).

**TABLE 2. Calculations of total system efficiency for low voltage AMS**

| | *Ion Source / Extraction* | | *Stripper (He gas)* | | *High Energy* | | *Detector* |
|---|---|---|---|---|---|---|---|
| *Nuclide* | *Ion* | *Ionization efficiency* | *Charge State* | *Charge Exchange Efficiency* | *Charge State* | *Transport Efficiency* | *Total system efficiency* |
| Be-10 | BeO- | 3% | 1+ | 60% | 2+ | 18% | 0.3% |
| Al-26 | Al- | 0.1% | 2+ | 56% | 2+ | 57% | 0.03% |

*Calculations based on charge exchange efficiencies from Lachner et al., 2014. Transport efficiencies for Be based on data from the NEC XCAMS system at GNS Science in New Zealand (A. Zondervan, pers. comm.), which is similar to values reported by Lachner et al. (2014) and Müller et al. (2010a) for the TANDY system at ETH Zurich. Transport efficiencies for Al based on Lachner et al. (2014) for TANDY system using He stripping.*

For an optimized low-voltage system, which we schematically design here, the predicted $^{10}Be$ total system efficiency is at least 0.3%; this is 30 to 50% of the efficiency reported for the FN-based system at LLNL (Rood et al., 2010) and several times higher than that calculated for the NEC 5 MV AMS at SUERC (Rood et al., 2014). The high total system efficiency for the low voltage AMS results because:

1. Roughly the same number of negative BeO ions are produced (ionization efficiency) by the modified NEC and LLNL sources (experiment 2) and the stripping yield using He gas (low voltage AMS) is higher for $Be^{1+}$ ions (charge exchange efficiency; Lachner et al., 2014) than for foil stripping (LLNL; Rood et al., 2010).
2. But, transport efficiency is lower in the low voltage system because $^{10}Be$ ions are lost in the degrader foil, which is necessary to eliminate isobaric $^{10}B$ in low voltage systems (Lachner et al., 2014; Müller et al., 2010a). The use of the degrader foil results in 2-3X fewer $^{10}Be$ counts in the detector (total system efficiency).

What does this difference in total system efficiency mean in practice? Because the statistical uncertainty of an AMS measurement is generally limited by and scales with the square root of the number of rare isotope counts reaching the detector (Poisson counting statistics), a 2 to 3X difference in the number of counts translates to only a 1.4 ($\sqrt{2}$) to 1.7 ($\sqrt{3}$) loss of precision presuming a similar counting time; however, most cathodes are not sample limited; that is, for all but the lowest ratio samples, AMS analysis stops because a desired precision has been reached rather than the cathode running out of material. For a low voltage system, most samples can simply be run longer to achieve a level of precision matching that available on higher voltage systems. The high level of automation and the stability provided by gas stripping allow new, low-voltage AMS systems to be run unattended overnight and on weekends, so the time needed to run a sample is much less of a consideration than at the existing facilities, where beam time is divided among many nuclides and operation is usually attended by at least one operator.

Similar thinking suggests that use of He stripper gas and measuring $2^+$ ions for Al will allow for a $^{26}Al$ detection limit and total system efficiency consistent with those achieved on other AMS systems (excepting those like PRIME which use a gas filled magnet; Granger et al., 2014). Indeed, automation (and the ease with which samples can be run for hours with little additional cost) may tip the scales in favor of low-voltage AMS for routine $^{26}Al$ samples, where larger amounts of sample (nominally >2 mg and often up to 4 mg) can be loaded into cathodes pressed from the back. At SUERC, these back-packed cathodes have run for hours while still maintaining beam currents >50% of their initial value.

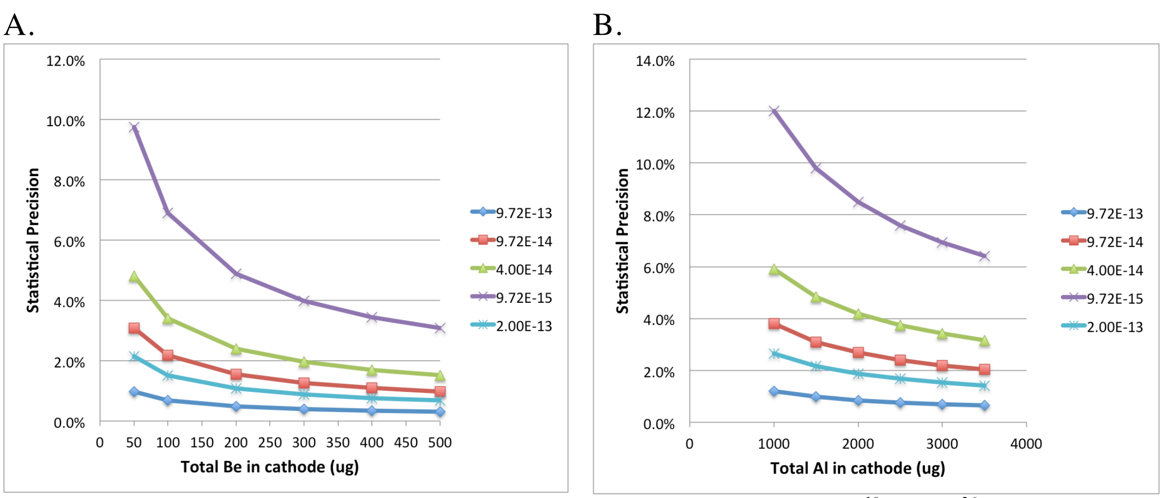


*Figure 5. Prediction of achievable precision on optimized low-voltage AMS for $^{10}Be$ and $^{26}Al$ based on calculations presented in Table 2. These precisions are based on the estimated efficiencies presented in Table 2 using the method of Rood et al. (2010).*

Calculations based on the performance of existing low-voltage systems (including our experiments, the assumptions presented in this report, and advances reported in the literature) clearly indicate that an optimized next generation, low voltage AMS system would be capable of measuring 1000s of samples annually with several percent $1\sigma$ precision for $^{10}Be/^{9}Be$ and $^{26}Al/^{27}Al$ down to mid $10^{-14}$ and backgrounds in the $10^{-15}$ range. Figure 5 shows the predicted achievable statistical precision for samples run on such an optimized low voltage AMS with differing isotopic ratios and sample amounts for Be and Al, respectively.

4.3.3 Specific modifications of the NEC XCAMS system to optimize $^{10}Be$ and $^{26}Al$ performance

Based on the results of experiments described above, advances demonstrated at other AMS facilities, and their knowledge of AMS, workshop participants suggested the following changes be made to the standard NEC XCAMS design in order to optimize $^{10}$Be and $^{26}$Al performance. For simplicity, the following narrative follows the sample (ion beam) down the beam line from the source to the detector.

*4.3.3.1 The ion source.*

Generating negative ions as efficiently as possible is key to successful analysis of $^{10}$Be and $^{26}$Al on a low voltage AMS. On the basis of the experiments we conducted (Figures 2 and 3) and the experiences of workshop participants we believe that the SNICS ion source, supplied by NEC, could be modified to significantly increase the efficiency of ion generation for at least $^{10}$Be and likely $^{26}$Al (as Southon has done on the NEC AMS at Irvine) by making the following changes.

- Use a large 134 sample wheel so that longer, more efficient sample runs are the norm and so that large numbers of primary and secondary standards can be used to ensure analysis quality.
- Replace the standard NEC 134 sample wheel with the "Roberts design" as used at NOSAMS, so that it can accommodate larger Irvine-style stainless steel cathodes, packed from the back. We have demonstrated a two fold increase in ionization efficiency and total system efficiency using stainless rather than copper cathodes for Be measurements on the SUERC AMS (Figure 2). Packing samples from the back (a modification to the UC Irvine design but one that is standard for NEC cathodes) will present a uniform sample geometry to the cesium beam, matching sample and standard geometry even if sample sizes vary and likely increase beam current (at least for Al where fully packed cathodes give much higher current as shown by Hunt et al., 2007, their Figure 1).
- Have on hand a complete second set of internal parts for the ion source and extractor to allow quick (<1 day) servicing while doing source cleaning "offline". This will allow the use of a clean, optimally performing ion source at all times.
- Modify the extractor/lens assembly so that it is of the Southon design and can be removed from the source end for rapid maintenance.
- Add adjustment rods to the source so that sample position can be changed while the source is running to optimize source output and the ablation geometry of material packed into the cathodes.
- Add an additional turbo pump and backing pump (an Edwards scroll pump) on the source so as to more rapidly bring source to high vacuum and to improve performance during runs by reducing the pressure in the low energy beam line.
- Use a Heatwave ionizer (as used at Livermore) to improve ionization efficiency. The importance of this modification has been demonstrated for carbon already by Southon, Roberts, and at CAMS and now by our workshop for BeO- (Figure 3).

*4.3.3.2. Low energy beam line*

- Add a second Einzel lens in the injection beam line after pump 2 and before the first magnet to reduce the beam size at object and image points, and hence ultimately at the gas stripper. This increases the beam divergence.
- Open up the pole gaps in the first magnet to accommodate the increased divergence, and thus increase beam transmission and total system efficiency. Add a shield in vacuum box at right angles to stop the $^{18}$O, Fe, Ag, and Nb beams thus protecting the vacuum box from erosion and decreasing maintenance.
- Add the ability to monitor Be and Al ion currents on the low energy side so that transmission can be optimized during tuning.

*4.3.3.3. Accelerator*

- Use helium as a stripping gas to generate for higher yields of the selected charge state and to improve transmission due to lower scattering losses (Lachner et al., 2014).
- Redesign the stripper canal to accommodate helium stripping and optimize transmission. The new design would be based on that at UC Irvine (including differential pumping provided by three turbo pumps), tailored to the size and divergence of the beam, but also taking into account the higher flow rates required for helium.

*4.3.3.4. High energy beam line*

- Add an electrostatic quadrupole triplet lens immediately after the accelerator to allow all beams ($Be^+$, $Al^{2+}$, $C^+$) to be focused at the object point of the analyzing magnet. This ensures that the subsequent beam optics is the same for all three beams. It has the added advantage of providing adequate space for the inclusion of a 130° second magnet after the ESA. The system we envision has the lens (~1 m long) focusing the beam to a waist ~ 1.5 m downstream of the quadrupole. That waist serves as the object point for the magnet, which is another 1.5 m or so down the beam line. This is the way large AMS systems get the HE magnet well clear of any problems with poor vacuum due to stripper gas coming out of the accelerator. We anticipate that this will add ~4 m to the post-accelerator beam line.
- In addition to the (moveable) off-axis Faraday cups for $^{13}$C and $^{12}$C, one of which would double as the $^{9}$Be cup, add a third cup on the other side for $^{27}$Al.
- Add ladder for degrader foils so that foil replacement is straightforward and so that foil thickness can be easily optimized.
- Open up the gap in ESA (from 40 mm to 50 mm) to accommodate a wider range of scattering angles after the degrader foil. A wider gap in the 130° magnet would also be advantageous and likely increase transmission.
- Change the final magnet to 130 degrees to achieve true point-to-point focusing within the limited space available. This ESA/magnet system is also achromatic, which relaxes the demand on the size of the final detector and optimizes ion

detection. The gap in the magnet should be as large as practical to accommodate scattering from the degrader foil.

*4.3.3.5 Detector*

- Either copy the Zurich-style detector or purchase one from Zurich capable of discriminating $^{10}$Be from the residual $^{10}$B at rates up to several kHz. With the addition of an absorber cell, this should also be capable of measuring $^{26}$Al as the $2^+$ ion. CoolFet preamps from Amptek are required to minimize electronic noise.

*4.3.3.6 Beam profile monitors*

- Additional beam profile monitors should be added so that beam optics can be tuned using lenses and magnet settings for optimal ion transmission. Monitors need to be placed close to the waists at the object points of the injection and analyzing magnets and at the image point of the analyzing magnet as well as in front of the $2^{nd}$ magnet or the electrostatic quad to measure beam divergences.

*4.3.3.7 Gas handling system*

- AMS should include a large system that pumps more rapidly and captures all $SF_6$ rather than discarding some each time tank is opened; this reduces downtime and prevents venting a greenhouse gas.

## 5.0 Implications of establishing a new American AMS facility

A new, state of the art, automated AMS facility would have many positive broader impacts both on science and on education. Such a facility and the lower cost analyses it would provide meanss that more and potentially better science could be done to address a wide variety of basic research issues, many of which are directly relevant to society such as climate change, earthquake hazards, and erosion monitoring. Installing the first low-voltage AMS system, specifically optimized for $^{10}$Be and $^{26}$Al, would solidify the United States as a leader in cosmogenic nuclide science and support a broad range of applications used to do cutting edge Earth Science for which America is well known.

A new AMS facility, especially one located in the eastern United States where there is a high concentration of geoscience departments, would be a catalyst for graduate and undergraduate education. For graduate students using cosmogenic nuclides, it will open up the black box as they will be able to travel to the AMS and participate in measurements of their samples. For graduate students in physics and chemistry, the AMS will provide a platform for research focused on improving sample analysis. For undergraduates, the presence of a AMS could transform the way geochronology is learned. For example, with weekly runs of $^{10}$Be and a geoscience-dedicated instrument like the one considered here, it would be possible to collect a sample, clean the quartz, separate Be, and do the AMS measurement all within one semester. Radiocarbon could be done even more quickly. Imagine a class collecting a lake core or opening a trench in a river terrace and collecting organic material during a field lab. The next week, the material could be prepared and graphitized, and the following week, $^{14}$C measured on the AMS. The new AMS would make it possible to teach cosmogenic nuclides and geochronology, with a significant hands-on component.

AMS and its primary application, measurement of cosmogenic nuclides applied to problems at and near Earth's surface, have come a long way since the AMS systems now operating in the United States were designed over two decades ago. Overseas, the installation of modern, next generation AMS systems proceeds apace. Novel, small, and efficient AMS systems have increased throughput due to a high level of automation; their simplicity of operation and lower maintenance requirements greatly reduces the need for technical support personnel, allowing analyses to be made at much lower costs. The design and implementation of an AMS facility run, used, and dedicated to Earth Scientists as envisaged here is a paradigm change. Establishing such a facility and pairing it with an instrument designed with the goal of optimizing throughput and accuracy while at the same time lowering the cost of making isotopic measurements, marks a maturation in the field of cosmogenic nuclide applications.

## 6.0 References Cited

Anderson, S.P., von Blanckenburg, F., and White, A.F., 2007, Physical and chemical controls on the critical zone: Elements, v. 3, no. 5, p. 315-319.

Applegate, P.J., Urban, N.M., Keller, K., Lowell, T.V., Laabs, B.J.C., Kelly, M.A., and Alley, R.B., 2012, Improved moraine age interpretations through explicit matching of geomorphic process models to cosmogenic nuclide measurements from single landforms: Quaternary Research, v. 77, p. 293-304.

Bacon, A.R., Bierman, P.R., and Rood, D.H., 2012, Coupling meteoric $^{10}$Be with pedogenic losses of $^{9}$Be to improve soil residence time estimates on an ancient North American interfluve: Geology, v. 40, no. 9, p. 847-850.

Balco, G., 2011, Contributions and unrealized potential contributions of cosmogenic-nuclide exposure dating to glacier chronology, 1990-2010: Quaternary Science Reviews, v. 30, p. 3-27.

Balco, G., Purvance, M.D., and Rood, D.H., 2011, Exposure dating of precariously balanced rocks: Quaternary Geochronology, v. 6, no. 3-4, p. 295-303.

Balco, G., and Rovey, C.W., 2008, An Isochron Method for Cosmogenic-nuclide Dating of Buried Soils and Sediments: American Journal of Science, v. 308, p. 1083-1114.

Balco, G., and Rovey, C.W., 2010, Absolute chronology for major Pleistocene advances of the Laurentide Ice Sheet: Geology, v. 38, no. 9, p. 795-798.

Balco, G., and Schaefer, J.M., 2006, Cosmogenic-nuclide and varve chronologies for the deglaciation of southern New England: Quaternary Geochronology, v. 1, no. 1, p. 15-28.

Balco, G., and Shuster, D.L., 2009, $^{26}$Al–$^{10}$Be–$^{21}$Ne burial dating: Earth and Planetary Science Letters, v. 286, p. 570-575.

Balco, G., and Stone, J.O.H., 2008, A simple, internally consistent, and easily accessible means of calculating surface exposure ages and erosion rates from Be-10 and Al-26 measurements: Quaternary Geochronology, v. 3, p. 174-195.

Balco, G., Stone, J.O., Porter, S.C., Caffee, M.W., 2002. Cosmogenic-nuclide ages for New England coastal moraines, Martha's Vineyard and Cape Cod, Massachusetts, USA: Quaternary Science Reviews, v. 21, p. 2127-2135.

Bard, E., and Frank, M., 2006, Climate change and solar variability: What's new under the sun?: Earth and Planetary Science Letters, v. 248, p. 1-14.
Bard, E., Raisbeck, G.M., Yiou, F., Jouzel, J., 2007, Comment on "Solar activity during the last 1000 yr inferred from radionuclide records" by Muscheler et al. (2007): Quaternary Science Reviews, v. 26, p. 2301-2304.

Beer, J., Siegenthaler, U., Bonani, G., Finkel, R.C., Oeschger, H., Suter, M., and Woelfli, W., 1988, Information on past solar activity and geomagnetism from $^{10}$Be in the Camp Century ice core: Nature, v. 331, p. 675-679.

Behr, W.M., Rood, D.H., Fletcher, K.E., Guzman, N., Finkel, R., Hanks, T.C., Hudnut, K.W., Kendrick, K.J., Platt, J.P., Sharp, W.D., Weldon, R.J., and Yule, J.D., 2010, Uncertainties in slip rate estimates for the Mission Creek strand of the southern San Andreas fault at Biskra Palms Oasis, southern California: Geological Society of America Bulletin, v. 122, no. 9-10, p. 1360-1377.

Benedetti, L., Finkel, R., Papanastassiou, D., King, G., Armijo, R., Ryerson, F., Farber, D., and Flerit, F., 2002, Post-glacial slip history of the Sparta fault (Greece) determined by $^{36}$Cl cosmogenic dating: evidence for non-periodic earthquakes: Geophysical Research Letters, v. 29, no. 8, p. 87-1–87-4.

Bierman, P.R., Corbett, L.B., Graly, J., Neumann, T, Lini, A., Crosby, B., and Rood, D., 2014, Preservation of a pre-glacial landscape under the center of the Greenland Ice Sheet: Science, v. 344, p. 402-405.

Bierman, P., Gillespie, A., Caffee, M., 1995, Cosmogenic ages for earthquake recurrence intervals and debris-flow fan deposition, Owens Valley, CA: Science, v. 270, p. 447-450.

Bierman, P., Marsella, K., Patterson, C., Davis, P., Caffee, M., 1999, Mid-Pleistocene cosmogenic minimum-age limits for pre-Wisconsinan glacial surfaces in southwestern Minnesota and southern Baffin Island: a multiple nuclide approach: Geomorphology, v. 27, p. 25-39.

Bierman, P.R. and Nichols, K.K., 2004, Rock to sediment - Slope to sea with $^{10}$Be - Rates of landscape change: Annual Review of Earth Science. v. 32. p. 215–255.

Bierman, P.R., Reuter, J.M., Pavich, M., Gellis, A. Caffee, M.W. and Larsen, J., 2005, Using cosmogenic nuclides to contrast rates and scales of sediment production and sediment yield in the semi-arid, arroyo-dominated landscape of the Rio Puerco Basin, New Mexico: Earth Surface Processes and Landforms, v. 30, no. 8, p. 935-953.

Bierman, P., and Shakun, J., 2013, In situ produced $^{10}$Be in marine sediment records 7 million years of Greenland ice sheet erosion in response to changing climate: Geological Society of America Abstracts with Programs, v. 45, no. 7, p. 260.

Blard P.H., Lavé, J., Pik, R., Wagnon, P., and Bourlès, D., 2007, Persistence of full glacial conditions in the central Pacific until 15,000 years ago: Nature, v. 449, p. 591-594.

Bookhagen, B., and Strecker, M.R., 2012, Spatiotemporal trends in erosion rates across a pronounced rainfall gradient: Examples from the southern Central Andes: Earth and Planetary Science Letters, v. 327, p. 97-110.

Briner, J.P., Bini, A.C., and Anderson, R.S., 2009, Rapid early Holocene retreat of a Laurentide outlet glacier through an Arctic fjord: Nature Geoscience, v. 2, p. 496-499.

Briner, J.P., Miller G.H., Davis, P. T., and Finkel R.C., 2005, Cosmogenic exposure dating in arctic glacial landscapes: implications for the glacial history of northeastern Baffin Island, Arctic Canada: Canadian Journal of Earth Sciences, v. 42, p. 67-84.

Briner, J.P., Miller, G.H., Davis, P.T., and Finkel, R.C., 2006, Cosmogenic radionuclides from fiord landscapes support differential erosion by overriding ice sheets: Geological Society of America Bulletin, v. 118, no. 3-4, p. 406-420.

Bromley, G.R.M., Hall, B., Stone, J., Conway, H., and Todd, C., 2010, Late Cenozoic deposits at Reedy Glacier, Transantarctic Mountains: implications for former thickness of the West Antarctic Ice Sheet: Quaternary Science Reviews, v. 29, p. 384-398.

Bromley, G.R.M., Hall, B.L., Stone, J.O., and Conway, H., 2012, Late Pleistocene evolution of Scott Glacier, southern Transantarctic Mountains: Implications for the Antarctic contribution to deglacial sea level: Quaternary Science Reviews, v. 50, p. 1-13.

Brook, E.J., Brown, E.T., Kurz, M.D., Ackert, R.P., Raisbeck, G.M., and Yiou, F., 1995, Constraints on age, erosion, and uplift of Neogene glacial deposits in the Transantarctic Mountains determined from in situ cosmogenic $^{10}$Be and $^{26}$Al: Geology, v. 23, no. 12, p. 1063-1066.

Brown, L., Pavich, M.J., Hickman, R.E., Klein, J., and Middleton, R., 1988, Erosion of the eastern United States observed with $^{10}$Be: Earth Surface Processes and Landforms, v. 13, no. 5, p. 441-457.

Bruno, L.A., Baur, H., Graf, T., Schlüchter, C., Signer, P., and Wieler, R., 1997, Dating of Sirius Group tillites in the Antarctic Dry Valleys with cosmogenic $^{3}$He and $^{21}$Ne: Earth and Planetary Science Letters, v. 147, no. 1-4, p. 37-54.

Chamberlin, T.C., 1899, An attempt to frame a working hypothesis of the cause of glacial periods on an atmospheric basis: Journal of Geology, v. 7, no. 6, p. 545-584.

Charreau, J., Blard, P.-H., Puchol, N., Avouac, J.-P., Lallier-Vergès, E., Bourlès, D., Braucher, R., Gallaud, A., Finkel, R., Jolivet, M., Chen, Y., and Roy, P., 2011, Paleo-erosion rates in Central Asia since 9Ma: A transient increase at the onset of Quaternary glaciations?: Earth and Planetary Science Letters, v. 304, no. 1-2, p. 85-92.

Chevalier, M.L., Ryerson, F.J., Tapponnier, P., Finkel, R.C., Van Der Woerd, J., Haibing, L., and Qing, L., 2005, Slip-rate measurements on the Karakorum fault may imply secular variations in fault motion: Science, v. 307, p. 411-414.

Christl, M., Vockenhuber, C., Kubik, P.W., Wacker, L., Lachner, J., Alfimov, V., and Synal, H.-A., 2013, The ETH Zurich AMS facilities: Performance parameters and reference materials: Nuclear Instruments and Methods in Physics Research B, v. 294, p. 29-38.

Church, J.A., Clark, P.U., Cazenave, A., Gregory, J.M., Jevrejeva. S., Levermann, A., Merrifield, M.A., Milne, G.A., Nerem, R.S., Nunn, P.D., Payne, A.J., Pfeffer, W.T., Stammer, D., and Unnikrishnan, A.S., 2013, Sea Level Change, *in* Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P.M., eds., Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change: Cambridge UK, Cambridge University Press.

Clapp, E., Bierman, P.R., Pavich, M., and Caffee, M., 2001, Rates of sediment supply to arroyos from uplands determined using in situ produced cosmogenic $^{10}Be$ and $^{26}Al$ in sediments: Quaternary Research, v. 55, no. 2, p. 235-245.

Clark, P.U., Dyke, A.S., Shakun, J.D., Carlson, A.E., Clark, J., Wohlfarth, B., Mitrovica, J.X., Hostetler, S.W., and McCabe, A.M., 2009, The Last Glacial Maximum: Science, v. 325, no. 5941, p. 710-714.

Codilean, A.T., Bishop, P., Stuart, F.M., Hoey, T.B., Fabel, D., and Freeman, S.P.H.T., 2008, Single-grain cosmogenic $^{21}Ne$ concentrations in fluvial sediments reveal spatially variable erosion rates: Geology, v. 36, no. 2, p. 159-162.

Corbett, L.B., Bierman, P.R., Graly, J., Neumann, T., and Rood, D., 2013, Constraining landscape history and glacial erosivity using paired cosmogenic nuclides in Upernavik, northwest Greenland: Geological Society of America Bulletin, v. 125, no. 9-10, p. 1539-1553.

Corbett, L.B., Bierman, P.R., Lasher, G.E., and Rood, D.H., 2015, Landscape chronology and glacial history in Thule, northwest Greenland: Quaternary Science Reviews, v. 109, p. 57-67.

Corbett, L.B., Young, N.E., Bierman, P.R., Briner, J.P., Neumann, T.A., Graly, J.A., and Rood, D.H., 2011, Paired bedrock and boulder $^{10}Be$ concentrations resulting from early Holocene ice retreat near Jakobshavn Isfjord, western Greenland: Quaternary Science Reviews, v. 30, p. 1739–1749.

Covault, J.A., Craddock, W.H., Romans, B.W., Fildani, A., and Gosai, M., 2013, Spatial and temporal variations in landscape evolution: Historic and longer-term sediment flux through global catchments: Journal of Geology, v. 121, no. 1, p. 35-56.

Cox, R., Bierman, P., Jungers, M., and Rakotondrazafy, M., 2009, Erosion rates and sediment sources in Madagascar inferred from $^{10}Be$ analysis of lavaka, slope, and river sediment: Journal of Geology, v. 117, p. 363–376.

Davis, M., Matmon, A., Rood, D.H., and Avnaim-Katav, S., 2012, Constant cosmogenic nuclide concentrations in sand supplied by the Nile River over the last 2.5 Ma: Geology, v. 40, no. 4, p. 359–362.

Denton, G.H., Anderson, R.F., Toggweiler, R.R., Edwards, R.L., Schaefer, J.M., and Putnam, A.E., 2010, The last glacial termination: Science, v. 328, p. 1652-1656.

Dietrich, W.E., and Dunne, T., 1978, Sediment budget for a small catchment in mountainous terrain, *in* Slaymaker, O., ed., Fluvial Geomorphology: New York, Routledge, p. 31-48.

Erlanger, E.D., Granger, D.E., and Gibbon, R.J., 2012, Rock uplift rates in South Africa from isochron burial dating of fluvial and marine terraces: Geology, v. 40, p. 1019-1022.

Field, C.V., and Schmidt, G.A., 2009, Model-based constraints on interpreting 20th century trends in ice core $^{10}Be$: Journal of Geophysical Research, v. 114, p. D12110.

Field, C.V., Schmidt, G.A., Koch, D., Salyk, C., 2006, Modeling production and climate-related impacts on $^{10}Be$ concentration in ice cores: Journal of Geophysical Research, v. 111, p. D15107.

Field, C.V., Schmidt, G.A., Shindell, D.T., 2009, Interpreting $^{10}Be$ changes during the Maunder Minimum: Journal of Geophysical Research, v. 114, p. D02113.

Finkel, R.C., and Nishiizumi, K., 1997, Beryllium-10 concentrations in the Greenland Ice Sheet Project 2 ice core from 3-40 ka: Journal of Geophysical Research, v. 102, p. 26699-26706.

Funder, S., Abrahamsen, N., Bennike, O., and Feyling-Hanssen, R.W., 1985, Forested Arctic: Evidence from North Greenland: Geology, v. 13, p. 542-546.
Gosse, J.C., Evenson, E.B., Klein, J., Lawn, B., and Middleton, R., 1995, Precise cosmogenic $^{10}$Be measurements in western North America; support for a global Younger Dryas cooling event: Geology, v. 23, no. 10, p. 877-880.

Graly, J.A., Bierman, P.R., Reusser, L.J., and Pavich, M.J., 2010, Meteoric $^{10}$Be in soil profiles– A global meta-analysis: Geochimica et Cosmochimica Acta, v. 74, no. 23, p. 6814-6829.

Granger, D.E., 2006, A review of burial dating methods using $^{26}$Al and $^{10}$Be: Geological Society of America Special Paper 415, v. 415, p. 1-16.

Granger, D. E., Caffee, M.W., and Woodruff, T.E., 2014, A tenfold increase in $^{26}$Al currents at PRIME lab: revisiting old ideas and exploring new possibilities with a gas-filled-magnet: Geological Society of America Abstracts with Programs, v. 46, no. 6, p. 240.

Granger, D.E., Fabel, D., and Palmer, A.N., 2001, Pliocene-Pleistocene incision of the Green River, Kentucky, determined from radioactive decay of cosmogenic $^{26}$Al and $^{10}$Be in Mammoth Cave sediments: Geological Society of America Bulletin, v. 113, no. 7, p. 825-836.

Granger, D.E., Kirchner, J.W., and Finkel, R.C., 1997, Quaternary downcutting rate of the New River, Virginia, measured from differential decay of cosmogenic $^{26}$Al and $^{10}$Be in cave-deposited alluvium: Geology, v. 25, no. 2, p. 107-110.

Granger, D.E., Lifton, N.A., and Willenbring, J.K., 2013, A cosmic trip: 25 years of cosmogenic nuclides in geology: Geological Society of America Bulletin, v. 125, no. 9-10, p. 1379-1402.

Granger, D.E., and Muzikar, P.F., 2001, Dating sediment burial with in situ-produced cosmogenic nuclides; theory, techniques, and limitations: Earth and Planetary Science Letters, v. 188, no. 1-2, p. 269-281.

Graversen, R.G., Mauritsen**,** T., Tjernstrom, M., Kallen, E., and Svensson, G., 2008, Vertical structure of recent Arctic warming: Nature, v., 541, p. 53-56.

Gudmundsdottir, M., Blisniuk, K., Ebert, Y., Levine, N.M., Rood, D.H., Wilson, A., and Hilley, G.E., 2013, Restraining bend tectonics in the Santa Cruz mountains, CA, imaged using $^{10}$Be concentrations in river sands: Geology, v. 41, no. 8, p. 843–846.

Haeuselmann, P., Granger, D.E., Jeannin, P.-Y., and Lauritzen, S.-E., 2007, Abrupt glacial valley incision at 0.8 Ma dated from cave deposits in Switzerland: Geology, v. 35, no. 2, p. 143-146.

Hakansson, L., Alexanderson, H., Hjort, C., Moller, P., Briner, J.P., Aldahan, A., and Possnert, G., 2008, Late Pleistocene glacial history of Jameson Land, central East Greenland, derived from cosmogenic $^{10}$Be and $^{26}$Al exposure dating: Boreas, v. 38, no. 2, p. 244-260.

Hall, B., Denton, G., Stone, J., and Conway, H., 2013. History of the grounded ice sheet in the Ross Sea sector of Antarctica during the last glacial maximum and the last termination: Geological Society of London Special Publications, v. 381, p. 167-181.

Heikkilä, U., Beer, J., and Feichter, J., 2009, Meridional transport and deposition of atmospheric $^{10}$Be: Atmospheric Chemistry and Physics, v. 9, p. 515-527.

Heikkilä, U., and Smith, A.M., 2013, Production rate and climate influences on the variability of $^{10}$Be deposition simulated by ECHAM5-HAM: Globally, in Greenland, and in Antarctica: Journal of Geophysical Research, v. 118, p. 2506-2520.

Heimsath A.M., 2012, Quantifying processes governing soil-mantled hillslope evolution, *in* Lin, H., ed., Hydropedology: Synergistic Integration of Soil Science and Hydrology: Waltham MA, Academy Press, p. 205-242.

Heimsath, A.M., Dietrich, W.E., Nishiizumi, K., and Finkel, R.C., 1997, The soil production function and landscape equilibrium: Nature, v., 388, p. 358-361.

Heyman, J., Stroevena, A.P., Harborb, J.M., and Caffee, M.W., 2011, Too young or too old: Evaluating cosmogenic exposure dating based on an analysis of compiled boulder exposure ages: Earth and Planetary Science Letters, v. 302, p. 71–80.

Hidy, A.J., Froese, D.G., Gosse, J.C., Bond, J.D., and Rood, D.H., 2013, A late Pliocene age for the earliest and most extensive Cordilleran Ice Sheet in northwestern Canada: Quaternary Science Reviews, v. 61, p. 77-84.

Hidy, A.J., Gosse, J.C., Pederson, J.L., Mattern, J.P., and Finkel, R.C., 2010, A geologically constrained Monte Carlo approach to modeling exposure ages from profiles of cosmogenic nuclides: An example from Lees Ferry, Arizona: Geochemistry Geophysics Geosystems, v. 11, no. 9, p. Q0AA10.

Hughes, A., Rainsley, E., Murray, T., Fogwill, C., Schnabel, C., and Xu, S., 2012, Rapid response of Helheim Glacier, southeast Greenland, to early Holocene climate warming: Geology, v. 40, no. 5, p. 427–430.

Hunt, A.L., Petrucci, G.A., Bierman, P.R. and Finkel, R.C., 2006, Metal matrices to optimize anion beam currents for accelerator mass spectrometry: Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, v. 243, no. 1, p. 216-222.

(IPCC) Intergovernmental Panel on Climate Change, 2013, Climate Change 2013: The Physical Science Basis: Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change: Cambridge UK, Cambridge University Press.

Ivy-Ochs, S., Schluchter, C., Kubik, P.W., Dittrich-Hannen, B., and Beer, J., 1995, Minimum $^{10}$Be exposure ages of early Pliocene for the Table Mountain plateau and the Sirius Group at Mount Fleming, Dry Valleys, Antarctica: Geology, v. 23, no. 11, p. 1007-1010.

Jungers, M.C., Bierman, P.R., Matmon, A., Nichols, K., Larsen, J., and Finkel, R., 2009, Tracing hillslope sediment production and transport with in situ and meteoric $^{10}$Be: Journal of Geophysical Research: Earth Surface, v. 114, p. F04020.

Kaplan, M.R., Coronato, A., Hulton, N.R.J., Rabassa, J.O., Kubik, P.W., and Freeman, S.P.H.T., 2007, Cosmogenic nuclide measurements in southernmost South America and implications for landscape change: Geomorphology, v. 87, p. 284-301.

Kaplan, M.R., Schaefer, J.M., Denton, G.H., Barrell, D.J.A., Chinn, T.J.H., Putnam, A.E., Andersen, B.G., Finkel, R.C., Schwartz, R., and Doughty, A., 2010, Glacier retreat in New Zealand during the Younger Dryas stadial: Nature, v. 467, p. 194–197.

Kelly, M.A., Russell, J.M., Baber, M.B., Howley, J.A., Loomis, S.E., Zimmerman, S.R., Nakileza, B., and Lukaye, J., 2014. Expanded glaciers during a dry and cold Last Glacial Maximum in equatorial East Africa: Geology, v. 42, no. 6, p. 519-522.

Kirchner, J.W., Finkel, R.C., Riebe, C.S., Granger, D.E., Clayton, J.L., King, J.G., and Megahan, W.F., 2001, Mountain erosion over 10 yr, 10 ky, and 10 my time scales: Geology, v. 29, no. 7, p. 591-594.

Kong, P., Granger, D.E., Wu, F.-Y., Caffee, M.W., Wang, Y.-J., Zhao, X.-T., and Zheng, Y., 2009, Cosmogenic nuclide burial ages and provenance of the Xigeda paleo-lake:

Implications for evolution of the Middle Yangtze River: Earth and Planetary Science Letters, v. 278, no. 1-2, p. 131-141.

Lal, D., 1991, Cosmic ray labeling of erosion surfaces; in situ nuclide production rates and erosion models: Earth and Planetary Science Letters, v. 104, no. 2-4, p. 424-439.

Lal, D., and Peters, B., 1967, Cosmic rays produced radioactivity on the Earth. Handbuk der Physik, v. 46, p. 551-612.
Laabs, B.J.C., Refsnider, K.A., Munroe, J.S., Mickelson, D.M., Applegate, P.J., Singer, B.S., and Caffee, M.W., 2009, Latest Pleistocene glacial chronology of the Uinta Mountains: support for moisture-driven asynchrony of the last deglaciation: Quaternary Science Reviews, v. 28, p. 1171-1187.

Lachner, J., Christl, C., Müller, A.M., Suter, M., and Synal, H.A., 2014, $^{10}$Be and $^{26}$Al low-energy AMS using He-stripping and background suppression via an absorber: Nuclear Instruments and Methods in Physics Research B., v. 331, p. 209-214.

Larsen, I.J., Montgomery, D.R., and Greenberg, H.M, 2014, The contribution of mountains to global denudation: Geology, v. 42, no. 6, p. 527-530.

Lisiecki, L., and Raymo, M., 2005, A Pliocene-Pleistocene stack of 57 globally distributed benthic d$^{18}$O records: Paleoceanography, v. 20, p. PA1003-1020.

Lupker, M., Blard, P.-H., Lavé, J., France-Lanord, C., Leanni, L., Puchol, N., Charreau, J., and Bourlès, D., 2012, $^{10}$Be-derived Himalayan denudation rates and sediment budgets in the Ganga basin: Earth and Planetary Science Letters, v. 333, p. 146-156.

Mackey, B.H., and Quigley, M.C., 2014, Strong proximal earthquakes revealed by cosmogenic $^{3}$He dating of prehistoric rockfalls, Christchurch, New Zealand: Geology, v. 42, no. 11, p. 975-978.

Matmon, A., Nichols, K.K., and Finkel, R., 2006, Isotopic insights into smoothening of abandoned fan surfaces, southern California: Quaternary Research, v. 66, p. 109-118.

Marchant, D.R., Denton, G.H. and Swisher, C.C. III, 1993, Miocene-Pliocene-Pleistocene glacial history of Arena Valley, Quartermain Mountains, Antarctica: Geografiska Annaler, v. 75, no. 4, 269-302.

McPhillips, D., Bierman, P.R., and Rood, D.R., 2013, Landscape response to Pleistocene-Holocene precipitation changes in the Western Cordillera, Peru: $^{10}$Be concentrations in modern and terrace sediments: Journal of Geophysical Research Earth Surface, v. 118, no. 4, p. 2488–2499.

McPhillips, D., Bierman, P.R., and Rood, D.R., 2014, Millennial-scale record of landslides in the Andes consistent with earthquake trigger: Nature Geoscience, v. 7, p. 925-930.

Mercader, J., Gosse, J.C., Bennett, T., Hidy, A.J., and Rood, D.H., 2012, Cosmogenic nuclide constraints on final Middle Stone Age lithics from Niassa, Mozambique: Quaternary Science Reviews, v. 47, p. 116-130.

Milliman, D., and Farnsworth, K.L. 2011. River discharge to the coastal ocean: New York, Cambridge University Press, 384 p.

Mitchell, S.G., Matmon, A.S., Bierman, P.R., Enzel, Y., Caffee, M., and Rizzo, D., 2001, Displacement history of a limestone normal fault scarp northern Israel from cosmogenic $^{36}$Cl: Journal of Geophysical Research, v. 106, p. 4247-4265.

Müller, A.M., Christl, M., Döbeli, M., Kubik, P.W., Suter, M., and Synal, H.-A., 2010a, Boron suppression with a gas ionization chamber at very low energies (E < 1 MeV): Nuclear Instruments and Methods B, v. 268, p. 843-846.

Müller, A.M., Christl, M., Lachner, J., Suter, M., and Synal, H.-A., 2010b, Competitive $^{10}$Be measurements below 1 MeV with the upgraded ETH-TANDY AMS facility: Nuclear Instruments and Methods B, v. 268, p. 2801-2807.

Müller, A.M., Suter, M., Fu, D., Ding, X., Liu, K., Synal, H-A, Zhou, L., 2013, A simple way to upgrade a compact radiocarbon AMS facility for $^{10}$Be: Radiocarbon, v. 55, no. 2-3, p. 231-236.

Muscheler, R., Joos, F., Beer, J., Muller, S.A., Vonmoos, M., and Snowball, I., 2007, Solar activity during the last 1000 yr inferred from radionuclide records: Quaternary Science Reviews, v. 26, p. 82-97.

(NRC) National Research Council, 2010, Landscapes on the edge: New horizons for research on Earth's surface: Washington DC, National Academies Press, 163 p.

Nelson, A.H., Bierman, P.R., Shakun, J.D., and Rood, D.H., 2014, Using in situ cosmogenic $^{10}$Be to identify the source of sediment leaving Greenland: Earth Surface Processes and Landforms, v. 39, no. 8, p. 1087-1100.

Nichols, K.K., Bierman, P.R., Caffee, M., Finkel, R., and Larsen, J., 2005a, Cosmogenically enabled sediment budgeting: Geology, v. 33, no. 2, p. 133-136.

Nichols, K.K., Bierman, P.R., Eppes, M.C., Caffee, M., Finkel, R., and Larsen, J., 2005b, Late Quaternary history of the Chemehuevi Mountain piedmont, Mojave Desert, deciphered using $^{10}$Be and $^{26}$Al: American Journal of Science, v. 305, no. 5, p. 345-368.

Nichols, K.K., Bierman, P.R., and Rood, D.H., 2014, $^{10}$Be constrains the sediment sources and sediment yields to the Great Barrier Reef from the tropical Barron River catchment, Queensland, Australia: Geomorphology, v. 224, p. 102-110.

Nishiizumi, K., Kohl, C.P., Arnold, J.R., Klein, J., Fink, D., and Middleton, R., 1991, Cosmic ray produced $^{10}$Be and $^{26}$Al in Antarctic rocks; exposure and erosion history: Earth and Planetary Science Letters, v. 104, no. 2-4, p. 440-454.

Norton, K.P., and von Blanckenburg, F., 2010, Silicate weathering of soil-mantled slopes in an active Alpine landscape: Geochimica et Cosmochimica Acta, v. 74, p. 5243-5258.

Ouimet, W., Dethier, D., Bierman, P., Wyshnytsky, C., Shea, N. and Rood, D., 2015, Spatial and temporal variations in meteoric $^{10}$Be inventories and long term deposition rates, Colorado Front Range: Quaternary Science Reviews, v. 109, p. 1-12.

Pavich, M.J., Brown, L., Harden, J., Klein, J., and Middleton, R., 1986, $^{10}$Be distribution in soils from Merced River terraces, California: Geochimica et Cosmochimica Acta, v. 50, no. 8, p. 1727-1735.

Phillips, F.M., Zreda, M.G., Smith, S.S., Elmore, D., Kubik, P.W., and Sharma, P., 1990, Cosmogenic chlorine-36 chronology for glacial deposits at Bloody Canyon, eastern Sierra Nevada: Science, v. 248, no. 4962, p. 1529-1532.

Portenga, E.W., and Bierman, P.R., 2011, Understanding Earth's eroding surface with $^{10}$Be: GSA Today, v. 21, no. 8, p. 4-10.

Portenga, E., Bierman, P.R., Duncan, C., Corbett, L., Kehrwald, N.M., and Rood, D., 2014, Erosion rates of the Bhutanese Himalaya determined using in situ-produced $^{10}$Be: Geomorphology, doi 10.1016/j.geomorph.2014.09.027 (in press).

Putkonen J., Balco G., and Morgan D., 2008, Slow regolith degradation without creep determined by cosmogenic nuclide measurements in Arena Valley, Antarctica: Quaternary Research, v. 69, p. 242-249.

Putkonen, J., and Swanson, T., 2013, Accuracy of cosmogenic ages for moraines: Quaternary Research, v. 59, p. 255-261.

Putnam, A.E., Schaefer, J.M., Denton, G.H., Barrell, D.J.A., Birkel, S.D., Kaplan, M.R., Andersen, B.G., Finkel, R.C., Schwartz, R., and Doughty, A.M., 2013a, The last glacial maximum at 44°S documented by a $^{10}$Be moraine chronology at Lake Ohau, Southern Alps of New Zealand: Quaternary Science Reviews, v. 62, p. 114-141.

Putnam, A.E., Schaefer, J.M., Denton, G.H., Barrell, D.J.A., Andersen, B.G., Koffman, T.N.B.K., Rowan, A.V., Finkel, R.C., Rood, D.H., Schwartz, R., Vandergoes, M.J., Plummer, M.A., Brocklehurst, S.H., Kelley, S.E., and Ladig, K.L., 2013b. Warming and glacier recession in the Rakaia valley, Southern Alps of New Zealand, during Heinrich Stadial 1: Earth and Planetary Science Letters, v. 382, p. 98-110.

Putnam, A.E., Schaefer, J.M., Denton, G.H., Barrell, D.J.A., Andersen, B.G., Schwartz, R., Chinn, T.J.H., and Doughty, A.M., 2012, Regional climate control of glaciers in New Zealand and Europe during the pre-industrial Holocene: Nature Geoscience, v. 5, p. 627-630.

Raymo, M.E., and Ruddiman, W.F., 1992, Tectonic forcing of late Cenozoic climate: Nature, v. 359, p. 117-122.

Reid, L.M., and Dunne, T., 1984, Sediment production from forest road surfaces: Water Resources Research, v. 20, p. 1753-1762.

Repka, J.L., Anderson, R.S., and Finkel, R.C., 1997, Cosmogenic dating of fluvial terraces, Fremont River, Utah: Earth and Planetary Science Letters, v. 152, no. 1-4, p. 59-73.

Reusser, L.J., and Bierman, P.R., 2010, Using meteoric $^{10}$Be to track fluvial sand through the Waipaoa River basin, New Zealand: Geology, v. 38, no. 1, p. 47-50.

Reusser, L., Bierman, P.R., and Rood, D., 2015, Quantifying human impacts on rates of erosion and sediment transport at a landscape scale: Geology, doi 10.1130/G36272.1 (in press).

Reusser, L., Graly, J., Bierman, P., and Rood, D., 2010, Calibrating a long□term meteoric $^{10}$Be accumulation rate in soil: Geophysical Research Letters, v. 37, no. 19, p. L19403.

Rinat, Y., Matmon, A., Arnold, M., Aumaître, G., Bourlès, D., and Keddadouche, K., 2014, Holocene rockfalls in the southern Negev Desert, Israel and their relation to Dead Sea fault earthquakes: Quaternary Research, v. 81, no. 2, p. 260-273.

Rockwell, T.K., Keller, E.A., and Dembroff, G.R., 1988, Quaternary rate of folding of the Ventura Avenue anticline, western Transverse Ranges, southern California: Geological Society of America Bulletin, v. 100, p. 850–858.

Rood, D.H., Burbank, D.W., and Finkel, R.C., 2011, Spatiotemporal patterns of fault slip rates across the central Sierra Nevada Frontal Fault Zone: Earth and Planetary Science Letters, v. 301, p. 457-468.

Rood, D.H., Hall, S., Guilderson, T.P., Finkel, R.C., and Brown, T.A., 2010, Challenges and opportunities in high-precision Be-10 measurements at CAMS: Nuclear Instruments and Methods B: Beam Interactions with Materials and Atoms, v. 268, no. 7-8, p. 730-732.

Savi, S., Norton, K., Picotti, V., Brardinoni, F., Akçar, N., Kubik, P.W., Delunel, R., and Schlunegger, F., 2014, Effects of sediment mixing on $^{10}$Be concentrations in the Zielbach catchment, central-eastern Italian Alps, Quaternary Geochronology, v. 19, p. 148-162.

Schaefer, J.M., Akçar, N., Koffman, T., Ivy-Ochs, S., Schwartz, R., Finkel, R.C., Zimmerman, S., Schlüchter, C., 2014, A chronology of Holocene and Little Ice Age glacier culminations of the Steingletscher, Central Alps, Switzerland, based on high-sensitivity beryllium-10 moraine dating: Earth and Planetary Science Letters, v. 393, p. 220-230.

Schaefer, J.M., Baur, H., Denton, G.H., Ivy-Ochs, S., Marchant, D.R., Schluchter, C., and Wieler, R., 2000, The oldest ice on Earth in Beacon Valley, Antarctica: new evidence from surface exposure dating: Earth and Planetary Science Letters, v. 179, p. 91-99.

Schaefer, J.M., Denton, G.H., Barrell, D.J.A., Ivy-Ochs, S., Kubik, P.W., Andersen, B.G., Phillips, F.M., Lowell, T.V., and Schlüchter, C, 2006, Near-Synchronous Interhemispheric Termination of the Last Glacial Maximum in Mid-Latitudes: Science, v. 312, no. 5779, p. 1510-1513.

Schaefer, J.M., Denton, G.H., Kaplan, M., Putnam, A., Finkel, R.C., Barrell, D.J.A., Anderson, B.G., Schwartz, R., Mackintosh, A., Chinn, T., and Schluchter, C., 2009, High-Frequency Holocene Glacier Fluctuations in New Zealand Differ from the Northern Signature: Science, v. 324, p. 622-625.

Schafer, J., Ivy-Ochs, S., Wieler, R., Leya, I., Baur, H., Denton, G.H., and Schluechter, C., 1999, Cosmogenic noble gas studies in the oldest landscape on Earth: surface exposure ages of the Dry Valleys, Antarctica: Earth and Planetary Science Letters, v. 167, no. 3-4, p. 215-226.

Schaller, M., von Blanckenburg, F., Hovius, N., Veldkamp, A., van den Berg, M.W., and Kubik, P.W., 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, v. 112, no. 2, p. 127-144.

Scherler, D., Bookhagen, B., and Strecker, M.R., 2014, Tectonic control on $^{10}$Be□derived erosion rates in the Garhwal Himalaya, India: Journal of Geophysical Research Earth Surface, v. 119, no. 2, p. 83-105.

Schimmelpfennig, I., Schaefer, J.M., Akçar, N., Ivy-Ochs, S., Finkel, R.C., and Schlüchter, C., 2012, Holocene glacier culminations in the Western Alps and their hemispheric relevance: Geology, v. 40, no. 10, 891-894.

Schmidt, G.A., Jungclaus, J.H., Ammann, C.M., Bard, E., Braconnot, P., Crowley, T.J., Delaygue, G., Joos, F., Krivova, N.A., Muscheler, R., Otto-Bliesner, B., Pongratz, J., Shindell, D.T., Solanki, S.K., Steinhilber, F., and Vieira, L.E.A., 2011, Climate forcing reconstructions for use in PMIP simulations of the last millennium (v1.0): Geoscientific Model Development, v. 4, p. 33-45.

Schmidt, S.R.H., Kuhlmann, J., Mingorance, F., and Ramos, V.A., 2011, A note of caution on the use of boulders for exposure dating of depositional surfaces: Earth and Planetary Science Letters, v. 302, p. 60–70.

Shakun, J.D., Clark, P.U., He, F., Marcott, S.A., Mix, A.C., Liu, Z., Otto-Bliesner, B., Schmittner, A., and Bard, E., 2012, Global warming preceded by increasing carbon dioxide concentrations during the last deglaciation: Nature, v. 484, p. 49–54.

Shen, G., Gao, X., Gao, B., and Granger, D.E., 2009, Age of Zhoukoudian Homo erectus determined with $^{26}$Al/$^{10}$Be burial dating: Nature, v. 458, p. 198-200.

Steig, E.J., Polissar, P.J., Stuiver, M., Grootes, P.M., and Finkel, R.C., 1996, Large amplitude solar modulation cycles of $^{10}$Be in Antarctica: Implications for atmospheric mixing processes and interpretation of the ice core record: Geophysical Research Letters, v. 23, p. 523-526.

Steinhilber, F., Abreu, J.A., Beer, J., Brunner, I., Christl, M., Fischer, H., Heikkilä, U., Kubik, P.W., Mann, M., McCracken, K.G., Miller, H., Miyahara, H., Oerter, H., and Wilhelms, F., 2012, 9,400 years of cosmic radiation and solar activity from ice cores and tree rings: Proceedings of the National Academy of Sciences, v. 109, p. 5967-5971.

Stock, G.M., Granger, D.E., Sasowsky, I.D., Anderson, R.S., and Finkel, R.C., 2005, Comparison of U-Th, paleomagnetism, and cosmogenic burial methods for dating caves: Implications for landscape evolution studies: Earth and Planetary Science Letters, v. 236, no. 1-2, p. 388-403.

Stone J.O., Balco G., Sugden D.E., Caffee M.W., Sass L.C. III, Cowdery S.G. and Siddoway C., 2003, Holocene deglaciation of Marie Byrd Land, West Antarctica: Science, v. 299, p. 99-102.

Stroup, J.S., Kelly, M.A., Lowell, T.V., Applegate, P.J., and Howley, J.A., 2014, Little Ice Age fluctuations of Qori Kalis outlet glacier, Quelccaya Ice Cap, Peruvian Andes: Geology, v. 42, no. 4, p. 347-350.

Sugden, D.E., Balco, G., Cowdery, S.G., Stone, J.O., and Sass, L.C., 2005, Selective glacial erosion and weathering zones in the coastal mountains of Marie Byrd Land, Antarctica: Geomorphology, v. 67, p. 317-334.
Suter, M., Müller, A.M., Alfimov, V., Christl, M., Schulze-König, T., Kubik, P.W., Synal, H.-A., Vockenhuber, C., and Wacker, L., 2010, Are compact AMS facilities a competitive alternative to larger tandem accelerators?: Radiocarbon, v. 52, no. 2-3, p. 319-330.

Synal, H.A., 2013, Developments in accelerator mass spectrometry: International Journal of Mass Spectrometry, v. 349-350, p. 192-202.

Taylor, K.C., Lamorey, G.W., Doyle, G.A., Alley, R.B., Grootes, P.M., Mayewski, P.A., White, J.W.C., and Barlow, L.K., 1993, The flickering switch of late Pleistocene climate change: Nature, v. 361, p. 432–436.

Todd, C., Stone, J., Conway, H., Hall, B., and Bromley, G., 2010, Late Quaternary evolution of Reedy Glacier, Antarctica: Quaternary Science Reviews, v. 29, p. 1328-1341.

Vockenhuber, C., Alfimov, V., Christl, M., Lachner, J., Schulze-König, T., Suter, M., and Synal, H.A., 2013, The potential of He stripping in heavy ion AMS: Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, v. 294, p. 382-386.

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

Wagner, G., Masarik, J., Beer, J., Baumgartner, S., Imboden, D., Kubik, P.W., Synal, H.A., and Suter, M., 2000, Reconstruction of the geomagnetic field between 20 and 60 kyr BP from cosmogenic radionuclides in the GRIP ice core: Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, v. 172, no. 1-4, p. 597-604.

West, N., Kirby, E., Bierman, P., and Clarke, B.A., 2014, Aspect-dependent variations in regolith creep revealed by meteoric $^{10}$Be: Geology, v. 42, no. 6, p. 507-510.

West, N., Kirby, E., Bierman, P., Slingerland, R., Ma, L., Brantley, S., and Rood, D., 2013, Regolith production and transport at the Susquehanna Shale Hills Critical Zone Observatory, Part 2: Insights from meteoric $^{10}$Be: Journal of Geophysical Research Earth Surface, v. 118, no. 3, p. 1877-1896.

Willenbring, J. K., and von Blanckenburg, F., 2010, Meteoric cosmogenic Beryllium-10 adsorbed to river sediment and soil: Applications for Earth-surface dynamics: Earth-Science Reviews, v. 98, no. 1, p. 105-122.

Willenbring, J.K., Codilean, A.T., and McElroy, B., 2013, Earth is (mostly) flat: Apportionment of the flux of continental sediment over millennial time scales: Geology, v. 41, no. 3, p. 343-346.

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

Young, N., Briner, J., Stewart, H., Axford, Y., Csatho, B., Rood, D., and Finkel, R., 2011, Response of Jakobshavn Isbrae, Greenland, to Holocene climate change: Geology, v. 39, no. 2, p. 131–134.

Zehfuss, P.H., Bierman, P.R., Gillespie, A.R., Burke, R.M., and Caffee, M.W., 2001, Slip rates on the Fish Springs fault, Owens Valley, California deduced from cosmogenic $^{10}$Be and $^{26}$Al and relative weathering of fan surfaces: Geological Society of America Bulletin, v. 113, no. 2, p. 241-255.