Dating Disappearing Ice with Cosmogenic Nuclides

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Crescentic gouges formed by the impact of rocks embedded at the base of a glacier as it moves over bedrock, Gotthard Pass, Switzerland. The ^{10}Be age of the rock surface is about 15,000 years (Hippe et al. 2014). Ice flow was from bottom left to top right. Photo: K. Hippe

Cosmogenic nuclides are remarkably well suited to dating glacial landforms. Exposure dating of boulders on moraines and of glacially sculpted bedrock allows the determination of the ages of former ice margins, from which past glaciations can be temporally constrained. Where moraines are lacking or are poorly preserved, outwash is dated with depth-profile dating. Two-nuclide methods can be used to determine the ages of buried till. Multinuclide measurements of bedrock ages also provide insights into periods of non-erosive ice coverage and can be used to identify regions with selective linear erosion. Of particular interest is the use of cosmogenic nuclides to assess rates of glacier retreat and glacial erosion.

Keywords: surface exposure dating, moraine, glacially modified bedrock, deglaciation age, ^{10}Be

INTRODUCTION

The Quaternary period, the last 2.58 million years of Earth history, is characterized by extremes in climate. These extremes are vividly indicated in the geologic record by the evidence for repeated advances and retreats of glaciers: the large ice sheets that occur in the higher latitudes and the alpine glaciers of mountainous regions. These glaciers change volume, and thus thickness and length, in response to changes in temperature and precipitation (Oerlemans 2005). In this way, their former extents record past changes in climate. Many studies use marine sediments and ice cores to reconstruct past climate variations. Neither of these types of records, however, provides information on the locations or specific extents of glaciers on continents, nor how patterns of ice distribution have varied spatially with time.

Glaciers erode the underlying bedrock, carry sediment from the accumulation area, and eventually deposit this material in the ablation area along their margins as moraines (Fig. 1). After the glacier retreats, the moraines and associated landforms, such as outwash fans and terraces, mark its former extent. Mapping of past ice margins based on such evidence and the reconstruction of paleoglaciers provide a glimpse into past climates. However, because of the difficulty in establishing absolute rather than relative chronologies, the glacier record is difficult to fit into a chronological framework of past climate change based on marine sediments and ice cores. This inability to directly date glacial landforms was eliminated when surface exposure dating with cosmogenic nuclides was developed (Gosse and Phillips 2001). Because of this geochemical advance, scientists can now understand global and regional patterns of ice advance and decay. A focus of these studies, for example, is the patterns that resulted from the Last Glacial Maximum (LGM) about 22,000 years ago. Scientists can also explore in detail whether glacier changes were synchronous between the Northern and Southern hemispheres (Schaefer et al. 2006; Clark et al. 2009). At individual sites, the fine details of timing of ice-volume variations allow us to explore their relationship with past atmospheric patterns (e.g. Akçar et al. 2014).

DATING PAST ICE MARGINS: GLACIAL AND RELATED DEPOSITS

Cosmogenic Nuclide Exposure Dating of Glacial Sediments: Principles

Cosmogenic nuclides (^{3}He, ^{10}Be, ^{14}C, ^{21}Ne, ^{26}Al, ^{36}Cl) accumulate predictably in minerals exposed at the Earth surface due to nuclear reactions induced by cosmic ray particles (see Dunai and Lifton 2014 this issue). By measuring cosmogenic nuclide concentrations in rocks or sediment, the period of exposure can be calculated. Surface exposure dating with cosmogenic nuclides is especially well suited to the dating of glacial landforms (Fig. 1). The boulders transported by a glacier originate from collapsed rock walls in the accumulation area and from rocks plucked from beneath the glacier's base. Both processes usually produce fresh, never-before-exposed rock surfaces. These boulders are transported by the glacier and finally deposited in moraines. As the glacier melts back from the moraine, deposition ceases, the cosmogenic clock begins to record time, and cosmogenic nuclides build up in the boulders and sediment of the moraines and outwash. Therefore, exposure dating of a boulder on the moraine crest can well approximate the time since the glacier last contributed sediments to the moraine (Fig. 2).

Detailed information about past glacier activity may be gleaned if the moraine architecture is well preserved. The fact that a glacier may fluctuate about the terminal moraine for centuries to millennia may also allow study of the period of glacier occupation. Dating of boulders on the most distal ridges constructed during a glacier advance

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provides information about the timing of maximum ice extent and the onset of active retreat (Gosse et al. 1995). In addition, dating of the innermost moraine gives the onset of glacier downwasting at the end of the advance period. In some cases, terminal moraines may be poorly preserved or completely lacking as a result of strong fluvial modification during deglaciation. Lateral moraines are often good targets for dating, but sometimes they can be complex because they can have a composite architecture that reflects repeated occupation. Detailed field mapping of the landforms to be dated is a prerequisite for judicious sampling.

Exposure ages from boulders on a moraine do not necessarily cluster around a single age. This is related to several processes acting on the landscape. The presence of a non-zero nuclide concentration (called "inherited" nuclides, or simply "inheritance") in the rock surface at the beginning of exposure leads to overestimates of age (Fig. 3). Several studies compiling ages from sites across the globe suggest that marked inheritance in moraine boulders is rare (Heyman et al. 2011). More common is a boulder exposure age that is younger than the true age of deposition. This is because moraines degrade as they age and boulders may be exhumed or toppled. Exhumed boulders that were covered by sediment for part of their exposure period yield exposure ages that are younger than the true time of deposition. Such effects may be reduced by sampling large (>1.5 m high), broad boulders that are well embedded in relatively stable moraine crests. Nevertheless, when the age estimates show significant scatter, a detailed scrutiny of the landforms and morphostratigraphic relationships is required. In some cases, the oldest age may prove to be geomorphologically the most reasonable. Taking a mean of all ages is not necessarily the best choice (Ivy-Ochs et al. 2007).

Exposure Dating of Boulders

Robust results have been obtained by dating boulders on Last Glacial Maximum and younger moraines. Schimmelpfennig et al. (2012) studied Holocene lateral moraines deposited by the Tsidjiore Nouve Glacier in the Valais Alps (Switzerland) (Fig. 4). The outer lateral moraines had ^{10}Be ages that indicated their formation during the earliest Holocene, in good agreement with moraines in similar positions at other sites in the Alps (cf Ivy-Ochs et al. 2009). Boulders along the composite Little Ice Age moraine (the Little Ice Age is a cold period lasting from 1350 to 1860 AD when glaciers expanded) yielded ages that fall into two groups: (1) several hundred years and (2) 3800 to 3200 years old. These data suggest that the glacier reoccupied the lateral moraine at least twice during the late Holocene. Indeed, most of the volume of these lateral moraines was built up before the Little Ice Age. As shown by the Schimmelpfennig et al. study, windows into older deposits along moraine crests and complicated inset lateral moraine structures allow dating of periods of repeated occupation and provide an excellent opportunity to reconstruct glacier changes during pre–Little Ice Age, late Holocene advances.

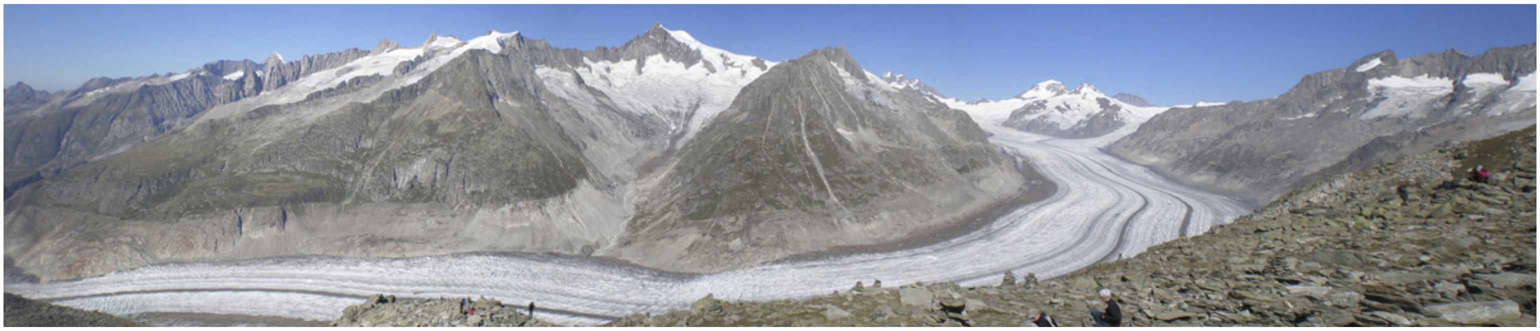
Approaches to Dating Degraded Moraines

Exposure ages of boulders on older, degraded moraines (>200,000 years) commonly show marked scatter, with most if not all ages being too young (Heyman et al. 2011 and references therein). Alternate approaches to dating such ice margins with cosmogenic nuclides have been sought.

Schaller et al. (2009) tested the use of cosmogenic nuclide depth-profile dating methods in a study of the Pinedale (LGM) and Bull Lake (pre-LGM) moraines at the Fremont Lake site in the Wind River Range (Wyoming, USA). Depth-profile dating is based on the fact that the rate of nuclide production decreases exponentially with depth in rock or sediment (see Dunai and Lifton 2014 this issue). Schaller et al. (2009) collected sand samples every 10–20 cm to a depth of more than 2 m from the surface of the moraine crests. For the moraine that formed during the Pinedale glaciation, the age that was determined from the depth profile (Schaller et al. 2009) agreed within errors with the exposure ages of boulders (21 ka) dated by Gosse et al. (1995). For the Bull Lake moraine, which was deposited at about 140 ka (Gosse et al. 1995), depth-profile dating yielded an age about half that obtained by surface exposure dating of boulders (Schaller et al. 2009). This raises the point that successful depth-profile dating benefits from a relatively flat and stable upper surface of the landform. The Schaller et al. results show that moraines often do not satisfy these requirements. The code for calculations of ages based on depth-profile data is given in a recent paper by Hidy et al. (2010).

To determine the age of the advance of a glacier whose moraines bear few intact boulders, Hein et al. (2009) dated individual cobbles from the outwash connected to moraines in the Lago Pueyrredon valley (Argentina). Coarse gravels are deposited in the forefield of an advancing glacier by meltwater streams. During glacier downwasting, meltwater often incises into the outwash deposits, creating terraces. Dating the time of abandonment of the terrace surfaces pinpoints the onset of glacier retreat. The flat upper surface of the outwash deposit increases the stability of this portion of the landscape compared to moraine slopes and thus is better suited for depth-profile dating. Hein et al. (2009) incrementally collected tens of cobbles down to a depth of 150 cm, and obtained an age of 260 ka. They also showed that in arid settings, where little post-depositional modification has occurred, the age of the oldest clasts on the terrace surface dates the glacier advance associated with the outwash.

Figure 1 The Great Aletsch Glacier, Switzerland. The color change on the far valley wall (vegetation occurs higher up) delineates the location of the lateral moraine formed along the right-hand side of the glacier during the Little Ice Age. Photo: L. Grämiger



Buried Glacial Deposits

Buried glacial deposits, such as those recognized in sediment cores, are difficult to date, especially where volcanic ash marker beds with known age are absent. To find out when deeply buried glacial sediments were deposited, and thus date the glacier advance, cosmogenic nuclide burial dating is used. This method is based on the difference in the half-lives of ^{10}Be and ^{26}Al (see von Blanckenburg and Willenbring 2014 this issue). Balco et al. (2005) used ^{26}Al /^{10}Be burial dating to determine how long the glacial sediment in a core taken in central Missouri, USA, had been buried. After deposition, this sediment was exposed subaerially and the ^{26}Al and ^{10}Be nuclides accumulated. In the next glacier advance, the till and associated paleosol were buried and shielded from cosmic rays. After that point, the ratio between ^{26}Al and ^{10}Be changed only due to decay. As ^{26}Al decays twice as fast as ^{10}Be, the measured ratio reveals how long the two nuclides have been decaying, in other words the amount of time elapsed since they were last exposed to cosmic rays. This tells us how long the till has been buried. The buried till studied by Balco et al. was found to be deposited by the Laurentide Ice Sheet when it extended as far south as central Missouri more than 2 million years ago.

DATING PAST ICE MARGINS: BEDROCK

Cosmogenic Nuclide Exposure Dating of Glacial Bedrock: Principles and Examples

Glacially sculpted bedrock offers alternative surfaces for cosmogenic nuclide exposure dating. Determining the age of bedrock surfaces opens many more possibilities for constraining the timing of past glaciation events than estimating the ages of glacial landforms using only moraines. During ice retreat, newly exposed surfaces begin accumulating cosmogenic nuclides for the first time if a sufficient amount of glacial erosion occurred during the glacier-overriding event. During some of the first applications of cosmogenic nuclide dating, however, it was discovered that glacial erosion of less than ~3 meters can lead to incomplete removal of cosmogenic nuclides that accumulated in glacial surfaces during prior periods of exposure (Nishiizumi et al. 1989). Although this may in some cases hamper dating, several early investigators recognized the inheritance issue (also see Benedetti and Van der Woerd 2014 this issue) and took advantage of it by inverting inherited concentrations into glacial erosion rates when combined with independent information about glacier history (Briner and Swanson 1998; Fabel et al. 2002).

Chronologies based on cosmogenic nuclide exposures have been produced from bedrock since some of the very first applications and from a variety of topographic settings (Fig. 2; Nishiizumi et al. 1989). Because bedrock in alpine valleys is deeply eroded by ice, outcrops here are often inheritance-free and yield reliable exposure ages. An elegant application of cosmogenic nuclide exposure dating of alpine valley bedrock was by Guido et al. (2007), who determined the rate of glacier retreat in the San Juan Mountains (Colorado, USA) by calculating exposure ages from samples collected from a transect along the valley bottom. In a similar type of study, Hippe et al. (2014) combined ice-flow direction indicators and ^{10}Be exposure dating to track the northward movement of the ice divide at Gotthard Pass (Switzerland) during the last deglaciation. Despite the abundance of bedrock lining valley bottoms in mountain ranges around the globe and the detailed glacier histories archived within them, surprisingly few studies have utilized this information.

In ice sheet settings, the spatial pattern of landscapes with or without inheritance can be more complex. Ice sheets can be fickle eroders, as described by Sugden (1978), who classified landscapes in terms of the intensity of glacial erosion. In locations of "selective linear erosion," ice sheets typically erode the bottom of glacial troughs very effectively. For example, the results from cosmogenic nuclide exposure dating along the strait between Greenland and

Figure 2 Ideal sampling sites for cosmogenic nuclide exposure dating. (**A**) and (**B**) Deeply ice-scoured bedrock surfaces in a landscape of aerial scouring near Jakobshavn Isbræ, western Greenland. (**C**) Stable boulder resting directly on bedrock in southwestern Norway. (**D**) Stable erratic boulder with minor weathering deposited on a severely weathered bedrock tor suspected to contain inheritance, Baffin Island, Canadian Arctic.

Arctic Canada (Nares Strait), partly from bedrock surfaces, confirmed that the Innuitian and Greenland ice sheets converged during the LGM (Zreda et al. 1999). However, due to the selective nature of ice sheet erosion, surfaces of landscapes between glacial troughs contain abundant inheritance. Landscapes here have been unmodified or only slightly modified by overriding ice sheets, and the boundary between landscape zones with inheritance and without can be extremely sharp (Briner et al. 2006; Harbor et al. 2006). In broad areas that have been heavily eroded, classified as landscapes of aerial scouring (Sugden 1978), reliable exposure dating chronologies have led to important advances in our understanding of ice sheet history. For example, recent studies from lowlands in western Greenland that rely on the exposure dating of bedrock have shown that outlet glaciers of the Greenland Ice Sheet responded sensitively to centennial-scale climate perturbations in the early Holocene (Young et al. 2013). Although paired bedrock–boulder tests have confirmed the lack of inheritance in these landscape types, inheritance continues to be encountered even in glacially sculpted bedrock. Thus, the dating of bedrock surfaces could be combined with the dating of moraines or perched erratics (Fig. 2), just as the dating of moraines could be paired with the dating of other sample types.

At high latitudes, the presence of cold-based, non-erosive ice has led to the widespread preservation of inheritance in many areas. Abundant inheritance inhibits exposure dating chronologies, especially in some ice sheet interiors where ice was minimally erosive, leading to insignificant glacial erosion (Fabel et al. 2002). Several approaches can help provide chronologies of the last deglaciation even in these difficult areas, such as limiting samples to valley bottoms that focused glacier flow and led to sufficient erosion, or using isotopes with such short half-lives (^{14}C) that the "cosmogenic clock" is reset by isotope decay during prolonged ice cover (Miller et al. 2006).

One additional benefit of using cosmogenic nuclide exposure dating in bedrock landscapes involves the dating of erratic cobbles and boulders perched directly on bedrock surfaces. For well-chosen erratics perched on bedrock, the post-depositional degradation complication that can plague the dating of moraine boulders can be ruled out. This strategy has been adopted to avoid not only moraine-degradation problems but also to date bedrock where inheritance is suspected. For example, in the inter-trough portions of landscapes of selective linear erosion, upland bedrock contains inherited nuclides and is not a reliable sample type for dating deglaciation. Erratics perched on bedrock in these landscapes, however, are typically far traveled and devoid of inheritance, yielding reliable exposure ages for deglaciation. This strategy has been adopted in Antarctica to determine the thinning rates of ice sheets during the Holocene (Stone et al. 2003), much like valley-bottom bedrock has been used to calculate retreat rates. Other investigators have focused on questions about the presence or absence of nunataks (peaks never covered by ice) during the Last Glacial Maximum. By dating erratics from inter-trough upland surfaces, it has become apparent that many high-elevation sites previously thought to have remained ice free were in fact likely occupied by ice sheets during the Last Glacial Maximum (Staiger et al. 2005).

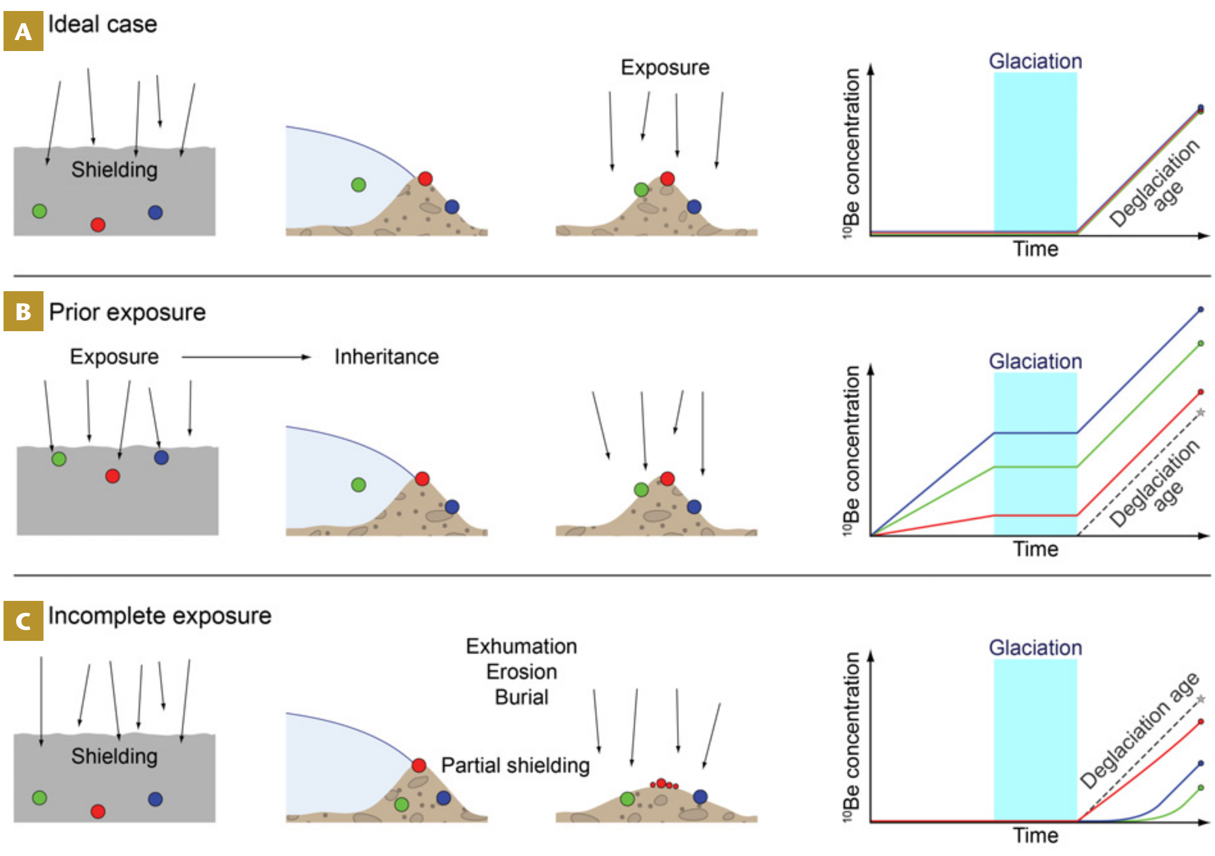


Figure 3 Schematic of three possible relationships between the exposure ages of boulders and the true depositional age of moraines (modified from Heyman et al. 2011): (**A**) exposure age same as "true" age, (**B**) exposure age "too old," and (**C**) exposure age "too young." On the right-hand side, the buildup of cosmogenic nuclides (in this case ^{10}Be) with time in the respective boulder surfaces (green, red, blue circles) is shown. In (B), inherited nuclides (accumulated before deposition on the moraine) are present; the ages are older than the age of the moraine. In (C), the boulders disintegrated or were exhumed some time after moraine deposition; the ages are younger than the moraine.

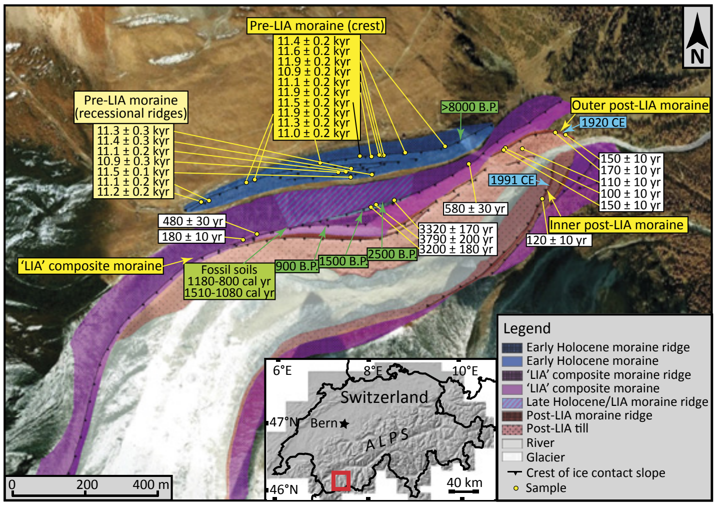


FIGURE 4 Geomorphological sketch map and ^{10}Be exposure ages of boulders on Holocene moraines of the Tsidjiore Nouve Glacier in the Valais Alps, Switzerland (modified from Schimmelpfennig et al. 2012). Results show that the outer, left-side lateral moraine (violet) formed during the early Holocene, about 11,000 years ago. For the Little Ice Age moraine (fuchsia), exposure dates of several thousand and several hundred years for different portions of the moraine suggest repeated glacier advances during the latest Holocene. LIA = Little Ice Age.

MULTIPLE ISOTOPE APPROACHES

Many investigators have taken advantage of the inheritance archived in uneroded ice sheet landscapes by measuring multiple isotopes with varying half-lives to constrain the history of ice occupation. In a novel application at the time, Bierman et al. (1999) used ^{10}Be and ^{26}Al in upland surfaces on Baffin Island, Arctic Canada, to determine that these landscapes have been periodically overridden by the Laurentide Ice Sheet throughout the Quaternary Period. Numerous more recent investigations have exploited inheritance to achieve long-term histories of ice occupation versus ice-free conditions in Antarctica, Arctic Canada, Greenland, the United Kingdom, and Scandinavia. One remaining problem with this approach is not being able to constrain how many episodes of burial and exposure took place or when they occurred. Commonly, investigators rely on independent information about glacial–interglacial cycles, such as δ^{18}O records of global ice volume from marine sediments, to guide interpretations about past ice-cover histories. This limitation, combined with the inability of the common isotopes ^{10}Be and ^{26}Al to resolve recent (<100 ka) episodes of burial (due to their relatively long half-lives and current analytical limitations), makes it not feasible to use this approach to evaluate ice cover during the LGM in landscapes of cold-based ice. Combining the radionuclides with stable cosmogenic ^{21}Ne provides another dimension in the study of patterns of glacial erosion, especially in regions with very long exposures, such as Antarctica (Sugden et al. 2014).

IN SITU ^{14}C

Using in situ ^{14}C in areas of prolonged cold-based ice cover during the last glaciation is a valuable approach for addressing questions about LGM ice thickness and the presence or absence of nunataks. Yet, thus far it has not been used widely, which mainly stems from difficult and time-consuming analytical procedures (Lifton et al. 2001). Despite its current under-utilization, there are growing numbers of applications for using in situ ^{14}C in dating. For example, Goehring et al. (2011) combined in situ ^{14}C with high-precision ^{10}Be analysis to decipher both glacial abrasion rates and the history of ice occupation of the Rhone Glacier, in the Swiss Alps. The paired-isotope technique holds tremendous promise for greatly expanding empirical data sets of glacial abrasion rates and for constraining times during the Holocene with smaller-than-present glacier extents; both of these parameters have been historically elusive to scientists.

A second application of in situ ^{14}C similarly targets Holocene glacier history—but in this case not of alpine glaciers, but rather of non-erosive ice caps. In situ ^{14}C concentrations in bedrock recently exposed at receding ice margins should be lower than in bedrock surfaces that lie beyond the reach of Holocene glaciation. The ^{14}C concentration in this case is lower not due to bedrock removal via glacial erosion but rather to decay during the Holocene ice burial event(s) (Fig. 5). Given the relatively short half-life of ^{14}C (5730 years), burial by ice for thousands or even hundreds of years can be detected. In the first application of this kind, Anderson et al. (2008) constrained the duration of ice cap presence on the uplands of north-central Baffin Island. One caveat of this approach is that the deviation of the ^{14}C concentrations in formerly ice-covered sites from those in non-ice-covered sites can only be attributed to the cumulative burial duration, even if the burial occurred during multiple phases.

SUMMARY AND OUTLOOK

The study of glacial sediment and landforms not only allows the reconstruction of past glacier extent but also provides insight into paleoglacier dynamics. But the significance of this lies in assigning ages to the information gleaned. Before the advent of cosmogenic nuclide dating methods, moraines were difficult to date and glacially modified bedrock was impossible to date. The dating of boulders on moraines to date disappearing ice is one of the most common uses of cosmogenic nuclides. Depth-profile dating of glacial outwash sediments and burial dating of buried glacial tills are further methods for dating past ice extents. Cosmogenic nuclide results from the dating of ice-marginal deposits are increasingly being used to derive climatic forcings based on glaciological models (e.g. Dühnforth and Anderson 2011). Profound improvements in our understanding of the timing of past glaciations have also resulted from dating bedrock. For example, chronologies from long

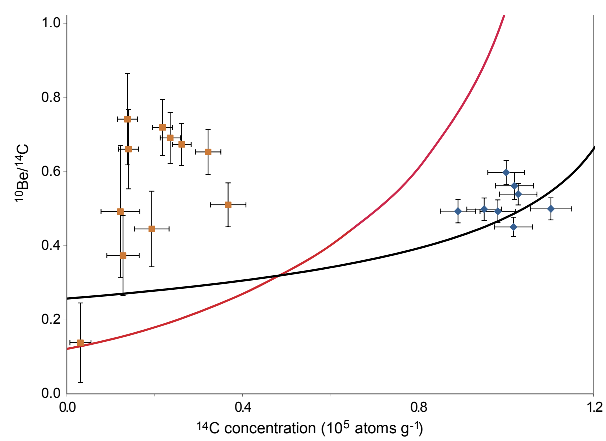


FIGURE 5 ^{10}Be/^{14}C versus ^{14}C two-isotope or erosion-island plot. The black line shows the evolution of the nuclide concentrations during continuous exposure. The red line is the steady-state erosion line connecting all points for rocks in saturation with respect to erosion for both ^{14}C and ^{10}Be (see Hippe et al. 2014 for details). Data from the Gotthard Pass bedrock (blue points; Hippe et al. 2014) display continuous exposure, while data from the Rhone Glacier bedrock (orange points; Goehring et al. 2011) suggest burial (by the Rhone Glacier) for at least several thousand years (see also Goehring et al. 2011).

transects of bedrock samples and boulders on bedrock have provided rates of glacier and ice sheet retreat that are relevant for current glacier changes in a warming world. In places where moraines are absent or where moraine degradation inhibits moraine boulder dating, dating bedrock and boulders up-valley from moraines has constrained the timing of moraine abandonment. Finally, major gaps in our understanding of high-latitude ice sheet history could not have been filled without measuring cosmogenic nuclides in bedrock surfaces. The inventories of cosmogenic nuclides with varying half-lives (and stable noble gases) archived in bedrock surfaces have recorded a history of past glacier occupation, and our exploitation of this information is just beginning. In sum, the measurement of cosmogenic nuclides in moraine boulders and glacial bedrock surfaces has become a critical component of the toolbox used to date disappearing ice.

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REFERENCES

Akçar N and 6 coauthors (2014) Glacier response to the change in atmospheric circulation in the eastern Mediterranean during the Last Glacial Maximum. Quaternary Geochronology 19: 27-41

Anderson RK, Miller GH, Briner JP, Lifton NA, DeVogel SB (2008) A millennial perspective on Arctic warming from ^{14}C in quartz and plants emerging from beneath ice caps. Geophysical Research Letters 35: doi: 10.1029/2007GL032057

Balco G, Rovey CW II, Stone JOH (2005) The first glacial maximum in North America. Science 307: 222

Benedetti L, Van der Woerd J (2014) Cosmogenic nuclide dating of earthquakes, faults, and toppled blocks. Elements 10: 357-361

Bierman PR, Marsella KA, Patterson C, Davis PT, 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 27: 25-39

Briner JP, Swanson TW (1998) Using inherited cosmogenic ^{36}Cl to constrain glacial erosion rates of the Cordilleran ice sheet. Geology 26: 3-6

Briner JP, Miller GH, Davis PT, Finkel RC (2006) Cosmogenic radionuclides from fjord landscapes support differential erosion by overriding ice sheets. GSA Bulletin 118: 406-420

Clark PU and 8 coauthors (2009) The Last Glacial Maximum. Science 325: 710-714

Dühnforth M, Anderson RS (2011) Reconstructing the glacial history of Green Lakes Valley, North Boulder Creek, Colorado Front Range. Arctic, Antarctic, and Alpine Research 43: 527-542

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

Fabel D, Stroeven AP, Harbor J, Kleman J, Elmore D, Fink D (2002) Landscape preservation under Fennoscandian ice sheets determined from in situ produced ^{10}Be and ^{26}Al. Earth and Planetary Science Letters 201: 397-406

Goehring BM and 7 coauthors (2011) The Rhone Glacier was smaller than today for most of the Holocene. Geology 39: 679-682

Gosse JC, Phillips FM (2001) Terrestrial in situ cosmogenic nuclides: theory and application. Quaternary Science Reviews 20: 1475-1560.

Gosse JC, Klein J, Evenson EB, Lawn B, Middleton R (1995) Beryllium-10 dating of the duration and retreat of the last Pinedale glacial sequence. Science 268: 1329-1333

Guido ZS, Ward DJ, Anderson RS (2007) Pacing the post-Last Glacial Maximum demise of the Animas Valley glacier and the San Juan Mountain ice cap, Colorado. Geology 35: 739-742

Harbor J and 7 coauthors (2006) Cosmogenic nuclide evidence for minimal erosion across two subglacial sliding boundaries of the late glacial Fennoscandian ice sheet. Geomorphology 75: 90-99

Hein AS and 6 coauthors (2009) Middle Pleistocene glaciation in Patagonia dated by cosmogenic-nuclide measurements on outwash gravels. Earth and Planetary Science Letters 286: 184-197

Heyman J, Stroeven AP, Harbor JM, Caffee MW (2011) Too young or too old: Evaluating cosmogenic exposure dating based on an analysis of compiled boulder exposure ages. Earth and Planetary Science Letters 302: 71-80

Hidy AJ, Gosse JC, Pederson JL, Mattern JP, Finkel RC (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 11: doi: 10.1029/2010GC003084

Hippe K and 7 coauthors (2014) Chronology of Lateglacial ice flow reorganization and deglaciation in the Gotthard Pass area, Central Swiss Alps, based on cosmogenic ^{10}Be and *in situ* ^{14}C. Quaternary Geochronology 19: 14-26

Ivy-Ochs S, Kerschner H, Schlüchter C (2007) Cosmogenic nuclides and the dating of Lateglacial and Early Holocene glacier variations: The Alpine perspective. Quaternary International 164-165: 53-63

Ivy-Ochs S, Kerschner H, Maisch M, Christl M, Kubik PW, Schlüchter C (2009) Latest Pleistocene and Holocene glacier variations in the European Alps. Quaternary Science Reviews 28: 2137-2149

Lifton NA, Jull AJT, Quade J (2001) A new extraction technique and production rate estimate for in situ cosmogenic ^{14}C in quartz. Geochimica et Cosmochimica Acta 65: 1953-1969

Miller GH, Briner JP, Lifton NA, Finkel RC (2006) Limited ice-sheet erosion and complex exposure histories derived from in situ cosmogenic ^{10}Be, ^{26}Al, and ^{14}C on Baffin Island, Arctic Canada. Quaternary Geochronology 1: 74-85

Nishiizumi K and 6 coauthors (1989) Cosmic ray production rates of ^{10}Be and ^{26}Al in quartz from glacially polished rocks. Journal of Geophysical Research: Solid Earth 94: 17907-17915

Oerlemans J (2005) Extracting a climate signal from 169 glacier records. Science 308: 675-677

Schaefer JM and 8 coauthors (2006) Near-synchronous interhemispheric termination of the Last Glacial Maximum in mid-latitudes. Science 312: 1510-1513

Schaller M, Ehlers TA, Blum JD, Kallenberg MA (2009) Quantifying glacial moraine age, denudation, and soil mixing with cosmogenic nuclide depth profiles. Journal of Geophysical Research: Earth Surface 114: doi: 10.1029/2007JF000921

Schimmelpfennig I, Schaefer JM, Akçar N, Ivy-Ochs S, Finkel RC, Schlüchter C (2012) Holocene glacier culminations in the Western Alps and their hemispheric relevance. Geology 40: 891-894

Staiger JKW and 7 coauthors (2005) Quaternary relief generation by polythermal glacier ice. Earth Surface Processes and Landforms 30: 1145-1159

Stone J and 6 coauthors (2003) Holocene deglaciation of Marie Byrd Land, West Antarctica. Science 299: 99-102

Sugden DE (1978) Glacial erosion by the Laurentide Ice Sheet. Journal of Glaciology 83: 367-391

Sugden DE, Fogwill CJ, Hein AS, Stuart FM, Kerr AR, Kubik PW (2014) Emergence of the Shackleton Range from beneath the Antarctic Ice Sheet due to glacial erosion. Geomorphology 208: 190-199

von Blanckenburg F, Willenbring JK (2014) Cosmogenic nuclides: Dates and rates of Earth-surface change. Elements 10: 341-346

Young NE, Briner JP, Rood DH, Finkel RC, Corbett LB, Bierman PR (2013) Age of the Fjord Stade moraines in the Disko Bugt region, western Greenland, and the 9.3 and 8.2 ka cooling events. Quaternary Science Reviews 60: 76-90

Zreda M, England J, Phillips F, Elmore D, Sharma P (1999) Unblocking of the Nares Strait by Greenland and Ellesmere ice-sheet retreat 10,000 years ago. Nature 398: 139-142