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“Difference Dating”: A novel approach towards dating alpine glacial moraines

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1 "Difference Dating": a novel approach towards excluding inaccurate
2 boulder exposure ages at alpine moraines

3
4 February 21, 2017

5 Rachel D. Valletta, Jane K. Willenbring, Adam R. Lewis

6 **ABSTRACT**

7 The East Antarctic Ice Sheet responds sluggishly to shifts in climate. To capture subtle changes in Antarctic
8 climate, researchers have focused instead on smaller alpine and cirque glaciers that fringe the ice sheet
9 throughout the McMurdo Dry Valleys. The exposure ages of glacial moraine boulders scatter widely and often
10 incorporate large amounts of inheritance, prohibiting the construction of a regional deglaciation chronology.
11 We present a new sampling technique that takes advantage of ubiquitous desert pavements and allows for the
12 detection of inheritance in overlying glacial moraine boulders. Our approach requires a large sample set, but
13 offers increased confidence in modeling moraine age, an acceptable trade-off considering the need for more
14 refined Antarctic paleoclimate reconstructions. Using the beryllium-10 system in sandstone quartz, we show
15 that single exposure ages collected from moraine boulder tops are frequently inaccurate, and consistently
16 over- and underestimate moraine age. Difference dating offers a new approach to dating alpine glacial
17 moraines independent from traditional boulder exposure age dating.

18 Keywords: cosmogenic radionuclides, exposure dating, inheritance, Dry Valleys

1 Introduction

Since its inception over three decades ago, cosmogenic radionuclide dating has become the glacial geomorphologist's hallmark tool for constructing deglaciation chronologies. A variety of geologic features are targeted to help unravel the timing and duration of glacier ice coverage and range from bedrock to glacial erratics. Perhaps the most common application of exposure dating in periglacial environments is that of moraine boulders, first applied by Phillips *et al.* (1990). Because of the boulders' positioning on terminal and lateral moraines, exposure ages correspond to the timing of glacier retreat and, in turn, mark a mass balance adjustment as a result of some transition in climate (e.g., Gosse *et al.*, 1995).

Exposure dating is widely applied throughout the Antarctic continent. Of great interest is understanding the response of the East Antarctic Ice Sheet to climatic forcing, particularly within the context of its potential contribution to global sea level rise. Such studies have focused on the ice sheet's outlet glaciers feeding into the McMurdo Dry Valleys (Brook *et al.*, 1993; Marchant *et al.*, 1994; Staiger *et al.*, 2006; Swanger *et al.*, 2010). Overall, moraine boulder exposure ages indicate that outlet glaciers have retreated since the Pliocene, with minor fluctuations observed during both global glacials and interglacials (Brook *et al.*, 1993; Brown *et al.*, 1991; Swanger *et al.*, 2011). A sensitive climatic record may exist in high elevation alpine glacier deposits, but these locations have remained largely underutilized because of observed scatter in moraine boulder exposure ages which produce dubious deglaciation chronologies. With this limitation, a new approach to dating glacial moraines is necessary.

We present first results from a novel sampling method that offers an independent moraine dating tool. The "difference dating" technique uses exposure age dating of both moraine boulders and underlying desert pavement clasts. We apply this sampling technique to two moraines in the Leibert Cirque, Olympus Range and demonstrate that only one of four boulders sampled is likely representative of moraine age. This application will prove useful throughout the Dry Valleys where moraine boulders lie atop intact desert pavements. Finally, we suggest future improvements to the technique.

1.1 Regional setting

Leibert Cirque lies perched at 1400 masl on the north wall of Wright Valley in the Olympus Range. To the south lies the Labyrinth (Lewis *et al.*, 2006) and to the west Lower Wright Glacier, an outlet glacier draining Taylor Dome of the East Antarctic Ice Sheet. Local bedrock and cirque headwalls are dominantly comprised

of Taylor Group sandstones and Ferrar Dolerite of the Devonian-age Beacon Supergroup (*Turnbull et al.*, 1994). Much of the high elevation Olympus Range exists in the stable upland zone of the Dry Valleys, where extreme aridity and cold temperatures dominate. Precipitation is limited and glacier mass accumulation comes mostly from snow blown off the Polar Plateau (*Marchant and Head*, 2007).

VandenHeuvel (2002) referred to Leibert Cirque as ‘Cirque E’ and described three prominent alpine moraines within: moraines 1, 2 and 3, referring to distal, intermediate, and most proximal to the headwall in position (1820 m, 1690 m, 1400 m, respectively) (see Fig. 1). For ease of comparison, we will adopt this nomenclature. The same moraine sequence was noted in adjacent Dean and Dipboye Cirque. We have sampled moraines 1 and 2. Moraines 1 and 2 are arcuate in plan view and parallel to one another; they vary in length (892 m, 922 m) and reach a maximum width in their western portion (3.0, 4.2 m) where they abut patchy exposures of Circe Till (*Lewis et al.*, 2007). Each moraine is dominantly composed of sandstone boulders and <5% dolerite boulders. Corrugated sandstone bedrock outcrops beyond the extent of outer moraine 1. *VandenHeuvel* (2002) attributes moraine formation to the expansion of an alpine glacier at the cirque headwall and invokes the preservation of a desert pavement beneath moraine till as evidence that alpine glaciation was cold-based and non-erosive. Today, all alpine glaciers in the Dry Valleys stable upland zone are cold-based and in equilibrium with the modern climate (*Fountain et al.*, 2016).

1.2 Boulder scatter

Moraine boulders sampled for exposure ages produce widely scattered results in the Olympus Range. For example, in Dean and Dipboye Cirques, *VandenHeuvel* (2002) and *Swanger et al.* (2014) measured ^3He in dolerite boulders from two moraines and together produced mean apparent exposure ages ranging 99-946 ky and 325-1450 ky, $\sim 142\%$ to $>130\%$ different, respectively. We may expect high scatter in ^3He datasets because the nuclide is stable, which captures longer exposure histories and thus a higher probability of inheritance. But, high scatter is also observed in ^{10}Be exposure ages from two alpine moraines on Mount Jason, ~ 12 km to the east of Leibert Cirque, where exposure ages ranging 251-527 ky and 1195-2171 ky are as much as $\sim 70\%$ and $\sim 60\%$ different, respectively (*Valletta*, unpublished data). For comparison, a review from temperate glaciers in low latitude regions showed much less skew of only 38% (*Putkonen and Swanson*, 2003). These same data produce reduced chi-square statistics ($\chi_R^2 \gg 1$), implying data scatter resulting from sources other than measurement error alone (*Balco*, 2011), including inheritance.

Cold-based glacial conditions found in the Olympus Range promote the accumulation of nuclide inheritance.

In temperate glacial settings, basal ice above the pressure-melting point slides atop and erodes underlying bedrock, depositing boulders in terminal moraines and exposing them to cosmic radiation for the first time. Conversely, cold-based glaciers are weak erosive agents (*Cuffey et al.*, 2000) because they are largely frozen to underlying bedrock where stress (and basal shearing) reduces to zero; the ice-rock interface remains below the pressure melting point and overlying ice moves via internal plastic deformation only (*Hooke*, 2005). Boulders originate in surrounding cliffs, reach the glacier via rockfall, and travel to the terminal moraine supraglacially, receiving cosmic radiation throughout their entire transport history. This phenomenon is often noted throughout the Dry Valleys (e.g., *Swanger et al.*, 2011) and the Transantarctic Mountains (e.g. *Hein et al.*, 2014) as the primary driver for observed boulder exposure age scatter.

In regions where inheritance is thought to dominate boulder exposure age scatter, researchers may select the youngest age as most representative. Recent modeling efforts indicate that this practice is often better at estimating the moraine age than the population’s median or mean, but that it is not always precise (*Applegate et al.*, 2012).

1.3 Desert pavement exposure histories

As an alternative moraine dating technique, we turn to the underlying desert pavement that stretches continuously between and beneath moraines 1 and 2. Desert pavements are armored stone surfaces that create interlocking stone mosaics and lie atop matrices of finer grained sands (*Cooke*, 1970); they are ubiquitous throughout the Dry Valleys. As many as five mechanisms are recognized for pavement formation and include removal of fines via deflation or overland flow, upward migration of clasts via freeze/thaw, inflation via dust deposition, or degradation via physical and/or chemical weathering (*Bockheim*, 2010).

We assess the exposure histories of the Leibert Cirque pavement in two locations: 1) buried, beneath moraine boulders and 2) exposed, surrounding moraine boulders. We assume these two locations would undergo identical exposure histories were the moraine till never deposited. The boulder’s exposure age -if accurate- should account for the difference in pavements’ accumulated nuclide inventories. Assuming we can accurately constrain the production rate at each sampled pavement site, we can 1) identify which boulders best reflect true moraine age (if any) and 2) independently estimate moraine age.

In addition, we can use pavement histories to inform on the duration of cold-based glaciation. The lack of post-formational reworking of the Leibert Cirque lag pavement indicates that overriding glacial ice remained cold-based and protected, rather than obliterated, this delicate feature. This has been observed numerous

time elsewhere (e.g., *Davis et al.*, 2006; *Kleman and Glasser*, 2007). Thus, we can interpret the apparent exposure age of exposed pavement clasts as the minimum amount of time since cold-based glaciation has dominated.

2 Material and Methods

2.1 Experimental methods

Four boulder and 44 pavement samples were collected during the austral summer of 2011 for ^{10}Be and ^{26}Al analysis. Each sample's physical characteristics - including luster, iron oxide staining, ventification and quartzification - were qualitatively recorded. All radioisotopes were measured in clean quartz aliquots prepared at the University of Pennsylvania Cosmogenic Isotope Lab. We extracted clean quartz from rock using a series of strong acid leaches adapted from established procedures (*Kohl and Nishiizumi*, 1992), including two overnight leaches in 5% HNO_3 and 5% HF on a roller and one overnight treatment in 1% HNO_3 and 1% HF in a heated sonicator bath. Clean quartz aliquots were subjected to a pure HF etch and Aqua Regia cleansing. Samples were spiked with 250 μl ^9Be carrier (Scharlau Be carrier, $^{10}\text{Be}/^9\text{Be} \approx 2 \times 10^{-15}$), dissolved in pure, heated HF , dried, and converted to chlorinated form via addition of 6 M HCl . 250 μl aliquots were removed from each sample and measured on the in-house ICP-OES for total Al ($[^{27}\text{Al}]$). Chlorinated samples were passed through an anion exchange resin (Bio-rad AG1x8 100-200 mesh) to separate Be and Al, dried, then treated with 0.4 M Oxalic Acid. Be aliquots were passed through a second cation exchange resin once (Bio-rad AG50-X8 200-400 mesh) and Al aliquots and chemical blank (SPEX Al Carrier, $^{26}\text{Al}/^{27}\text{Al} \approx 5 \times 10^{-14}$) were passed through a second cation exchange resin twice (Bio-rad AG1-X8 100-200 mesh). All aliquots were precipitated in 1:1 superpure NH_4OH :Milli-Q H_2O , dried in quartz crucibles and oxidized over open flame ($>1000^\circ\text{C}$). BeO and Al_2O_3 precipitates were homogenized in a 1:3 ratio with Nb and Ag powders (respectively) and packed into clean cathodes for $^{10}\text{Be}/^9\text{Be}$ and $^{26}\text{Al}/^{27}\text{Al}$ measurement at the Purdue PRIME Lab Accelerator Mass Spectrometer (AMS). ^{10}Be , ^{26}Al concentrations are normalized to 07KNSTD (*Nishiizumi et al.*, 2007) and KNSTD (*Nishiizumi*, 2004) isotope ratio standards, respectively.

2.2 Numerical methods

Cosmogenic radionuclides accumulate in eroding geologic surfaces via the following relationship:

$$N(z, t) = N_{inh}(z)e^{-\lambda t} + \frac{P_{sp}(z)}{\lambda + \rho\epsilon/\Lambda_{sp}} \left[1 - e^{-(\lambda + \rho\epsilon/\Lambda_{sp})t} \right] + \int_0^t P_{mu}(z + \epsilon\tau) d\tau \quad (1)$$

where N is a measured concentration of cosmogenic radionuclide (atoms g^{-1}), N_{inh} is the inherited nuclide concentration, λ is the nuclide decay constant (y^{-1}), ρ is density (g cm^{-3}), ϵ is erosion rate (cm y^{-1}), Λ_{sp} is attenuation length (g cm^{-2}), t is time of exposure (y), and P_{sp} and P_{mu} are production rates (atoms g^{-1}) into the subsurface, depth z (cm). We ignore the final term for muogenic production because $P_{mu} \ll P_{sp}$ and $\rho\epsilon/\Lambda_{sp} \ll \lambda$.

We report the exposure ages of boulders based on measured nuclide inventories using the updated CRONUS calculator (Marrero *et al.*, 2016) with the 'Sa' scaling scheme and a long term erosion rate of $\epsilon=10 \text{ cm My}^{-1}$ based on locally-derived erosion rates (Schäfer *et al.*, 1999; Summerfield *et al.*, 1999; Nishiizumi *et al.*, 1991; Ivy-Ochs *et al.*, 1995).

As an independent check on the boulder's exposure age, we use desert pavement clasts collected from two locations with unique production rates. This sampling scheme is grounded in the reasoning that, assuming no loss to erosion or decay, the difference in nuclide inventories between two pavement clasts (atoms g^{-1}) is simply the difference in their production rates (atoms $\text{g}^{-1} \text{ y}^{-1}$) multiplied by the moraines age (y). We target pavement clasts that are exposed at the surface (N_{exp}) and buried beneath a moraine boulder (N_{bur}):

$$N_{exp}(t) = N_{inh}(0)e^{-\lambda t} + \frac{P_{sp}(0)}{\lambda + \rho\epsilon/\Lambda_{sp}} (1 - e^{-(\lambda + \rho\epsilon/\Lambda_{sp})t}) \quad (2)$$

$$N_{bur}(t) = N_{inh}(0)e^{-\lambda t} + \frac{fP_{sp}(0)}{\lambda} (1 - e^{-\lambda t}) \quad (3)$$

where $P_{sp}(0)$ is the production rate at the surface of the pavement. Note that N_{exp} is actively undergoing erosion, but N_{bur} is not. Also note that production at N_{bur} is reduced by a factor of f , the geometric shielding factor imposed by the boulder ($0 \leq f \leq 1$) (see Section 2.2.1). To be clear, the inheritance term N_{inh} here refers to nuclide inheritance in each pavement clast (not the boulder). Next, using Eqs. 2 and 3, we solve for the difference in nuclide inventories, ΔN :

$$\Delta N = \frac{P_{sp}(0)}{\lambda + \rho\epsilon/\Lambda_{sp}} (1 - e^{-(\lambda + \rho\epsilon/\Lambda_{sp})t}) - \frac{fP_{sp}(0)}{\lambda} (1 - e^{-\lambda t}) \quad (4)$$

In solving for ΔN , N_{inh} drops out and we can solve for a unique moraine age, t . We will refer to this t value as the “difference date.” The following terms have associated uncertainties which we assume take a Gaussian distribution: P_{sp} , f (see Section 2.2.1) and ΔN . To incorporate these uncertainties into our solution, we use a 5000-run Monte Carlo simulation, similar to that presented in *Balco et al.* (2005). Each run uses a randomly selected value from these Gaussian distributions and solves for a unique value of difference date¹. To satisfy Eq. 4 we use the following values: $\Lambda=140 \text{ g cm}^{-2}$ (*Borchers et al.*, 2016), λ is 4.99×10^{-7} for ^{10}Be and 9.83×10^{-7} for ^{26}Al (*Korschinek et al.*, 2010; *Chmeleff et al.*, 2010), and unique $P_{sp}(0)$ values at each sample site using elevation scaling factors calculated with the LSD method (*Lifton et al.*, 2014). We again assign a value of $\epsilon=10 \text{ cm My}^{-1}$; including an uncertainty with ϵ does not alter model results.

If boulder exposure ages accurately depict the timing of moraine formation, then boulder exposure ages should equal difference dates. If not, one of three scenarios is possible: 1) the boulder has underestimated the age of the moraine, 2) the boulder has overestimated the age of the moraine, or 3) the difference date is quantified incorrectly, perhaps due to the inclusion of outliers.

To corroborate these modeling steps, we measure burial ages on a single clast beneath each boulder and on a single exposed clast using Al-Be burial ages (*Granger*, 2006). Burial dating is made possible by the differential rates of decay of two nuclides with non-equal half-lives. To find a unique burial age for each clast, we manipulate Eq. 1 to include both 1) erosion before burial and 2) post-burial production in the absence of erosion:

$$N_j = \frac{P_{sp,j}(0)}{\lambda + \rho\epsilon/\Lambda_{sp}} e^{-(\lambda + \rho\epsilon/\Lambda_{sp})t_b} + \frac{fP_{sp,j}(0)}{\lambda} (1 - e^{-\lambda t_b}) \quad (5)$$

where N is the measured concentration of nuclide j (^{26}Al or ^{10}Be) and t_b is burial time. We now have two equations to solve for two unknowns (ϵ , t_b). We solve Eq. 5 using the same Monte Carlo scheme described above.

2.2.1 Calculating shielding factors

Central to the aforementioned modeling efforts is the proper calculation of f , the geometric shielding factor. To calculate f we use Balco’s (2014) MATLAB code for calculating cosmic ray shielding. The code uses

¹To ensure 5000 runs is sufficient, we plot the standard deviation after each successive run and observe that it converges after ~ 2000 runs.

Monte Carlo integration to calculate the flux of cosmic radiation received at a near-surface site shielded by geologic obstructions. Individual ray paths incident on the buried pavement sites are partially or completely attenuated as they travel through obstructions (overlying moraine boulders). The mass thickness through which the rays are attenuated is a function of both the obstruction’s density and its linear thickness. The former is measured as the distance through which a ray path traveling at a certain angle must traverse to reach the buried sampling site. The code produces a shielding factor, f , the ratio of the production rate at a shielded site to that at an identically located non-shielded site.

To simulate obstructions, Balco used 360° field photographs and photogrammetric software to generate three-dimensional enclosed spaces termed “shape models.” Here, we take advantage of a fortuitously sampled dataset, but one not initially designed with digital shape models in mind. In the absence of 360° photographs of our sampling sites, we develop shape models manually using Meshlab (<http://meshlab.sourceforge.net/>), a freely available graphics software package. We use a combination of available field photographs and boulder measurements to create a shape model for each sampled boulder and calculate f beneath each boulder’s center. The basic mesh of each boulder is an icosphere, a spherical mesh made via the subdivision of icosahedron faces, which is then deformed to fit measured dimensions. Though this approach smooths out fine-scale features on the boulder face, we are most concerned with properly rendering the maximum vertical height of each boulder because the maximum intensity of incident radiation is strongly concentrated near the vertical (*Gosse and Phillips*, 2001). Changing the overall shape of the boulder does not significantly affect f so long as the maximum vertical scale is maintained. However, f is very sensitive to the maximum vertical height for boulders ~ 1 m tall. We run the script three times on each shape model and average the resulting f values. Each buried location is associated with a single f . Note that boulder OLY-38 was too large to overturn and buried sites OLY-36 and OLY-37 were collected from smaller boulders immediately adjacent to OLY-38; see Fig. 2. Based on these boulders’ orientation, we assume that all boulders were deposited simultaneously.

Because we do not use an automated, digitally-derived shapefile, we must incorporate some human-induced uncertainty associated with measuring boulder heights in the field and via photographs. We assign a conservative error of ± 10 cm in boulder height measurements. For boulders ≤ 70 cm tall, this error corresponds to $< 10\%$ of f and for larger boulders ≥ 100 cm tall this error increases to $\leq 30\%$. This is to be expected as f increases exponentially with increasing shielding thickness (see Balco, 2014, his Fig. 4).

3 Results

3.1 Radionuclide measurements

3.1.1 ^{10}Be

We measured ^{10}Be in 48 samples (4 sandstone boulder surfaces and 44 pavement clasts) in 5 total batches; see Table 1. Chemical blanks processed with each batch registered 2.91 ± 0.86 , 3.18 ± 1.59 , 8.77 ± 1.58 , 33.2 ± 4.60 , and $32.0 \pm 5.75 \times 10^4$ ^{10}Be atoms g^{-1} . Despite relatively high blank measurements, near-saturated sample concentrations ensure low overall contributions of blank contamination to sample ^{10}Be . Most blank concentrations represent $\ll 1\%$ of sample concentration. In three samples (OLY-26-P3, OLY-31-DP3, and OLY-33-DP7) the blank concentration represented $>2\%$ of total ^{10}Be atoms (2.72%, 2.04%, and 3.67%, respectively). All OLY-26 clasts are discarded as outliers; see Section 3.1.3. Samples OLY-31-DP3 and OLY-33-DP7 fall within error of their site’s sample populations and are deemed acceptable. A single sample, OLY-36-DP4 registered a low ^9Be beam count on the AMS. It is included in Table 1 for reference, but is excluded from analysis.

We note that those clasts with lower-than-average $[^{10}\text{Be}]$ exhibit retention of fine surface topographies and lack well-developed iron oxide staining and greasy luster siliceous crusts. This is true of all samples collected at site OLY-26 and boulder surfaces. Samples with more physical evidence of ventifaction and quartzification register greater $[^{10}\text{Be}]$, an observation also made on dolerite clasts (*Staiger et al.*, 2006; *Swanger et al.*, 2011); see Fig. 3.

3.1.2 ^{26}Al

We measured ^{26}Al in 5 samples, 4 of which were buried beneath moraine boulders. The chemical blank returned a ratio of $0.00 \pm 1.18 \times 10^{-13}$ $^{26}\text{Al}/^{27}\text{Al}$ indicating negligible contributions of ^{26}Al during lab processing.

3.1.3 Outlier exclusion

Properly identifying outliers in this scattered dataset is crucial to our approach. Ideally, a robust statistical criteria could be used to reject outliers, e.g. Chauvenet’s criterion (*Rinterknecht et al.*, 2006). However,

the logistics of our sampling method limit us to a rather small dataset collected at each site; there are only so many pavement clasts that lie beneath each overturned boulder. Accordingly, we are limited to a quasi-quantitative approach to identify and reject outliers. For a discussion on outlier treatment, we refer the reader to *Balco* (2011).

We use simple methods to help visualize the spread in the dataset, the first of which are kernel density estimates (also referred to as “camelplots”). In this type of plot, we represent each measurement by a single PDF using a Gaussian distribution normalized by the total number of samples. All sample PDFs are summed together, forming the kernel density estimate which peaks in a region near some “true” value; see Fig. 4. Most typically, exposure ages are used to construct PDFs, but here we represent each PDF with a mean, $\mu=^{10}\text{Be}$ measurement, and a standard error, $\sigma=^{10}\text{Be}$ measurement error. Kernel density estimates clearly show the clustering of pavement clasts between 30-38 Matoms g^{-1} . Two samples register >40 Matoms g^{-1} and most other scattered samples fall between 15-30 Matoms g^{-1} ; these samples may represent improperly sampled moraine material. They are removed from analysis. Seven samples register <10 Matoms ^{10}Be and are of the same order as overlying boulders [^{10}Be]. As such, these samples are interpreted as spalled boulder chunks and removed from analysis. Plotting the cumulative distribution function of all pavement clasts at each moraine provides an additional method for visualizing the identified outliers and confirms our selection; see Fig. 5.

3.2 Exposure ages and model results

^{10}Be measured on exposed clasts produce minimum exposure ages that range 2.6 to 5 My, and average 4.2 My. Several clasts register saturated concentrations, likely reflecting production at higher elevations before delivery to the cirque floor.

Each moraine boulders shielding factor (f) and apparent exposure age is listed alongside the underlying pavements difference date and Al-Be burial age in Table 2. At each site, we first removed outliers from the measurement datasets before solving for the difference date. [For all sites, $N_{exp}=35.52\pm1.97$ Matoms g^{-1} , the mean concentration of exposed pavement clasts ($n=9$). N_{bur} is unique to each buried site.] See Fig. 6 for a comparison of all difference dates with boulder top exposure ages.

3.3 Moraine 1

At outer moraine 1, site I, the boulder's apparent exposure age is 416 ± 9.5 (75) ky. All pavement samples beneath the site I boulder are discarded as outliers and we cannot test the validity of this exposure age.

At moraine 1, site II, the boulder's apparent exposure age is 288 ± 4.5 (48) ky. The corresponding difference date is 318 ± 64 ky, comparable to its Al-Be burial age of 362 ± 316 ky. The agreement amongst the site II boulder exposure age, difference date, and burial age leads us to the conclusion that moraine 1 is likely closer to its difference date of 318 ± 64 ky. We select the difference date, rather than the boulder exposure age, because it is better constrained with multiple buried ($n=4$) and exposed ($n=9$) pavement clasts, compared to the boulder's single measurement. This conclusion supports the notion that the site I boulder overestimates the age of moraine 1 and likely contains inheritance. Simultaneously, this conclusion supports the notion that the site II boulder may slightly underestimate the age of moraine 1, perhaps due to boulder spalling events.

3.4 Moraine 2

At inner moraine 2, site III, the boulder's exposure age is 393 ± 8 (67) ky, older than its corresponding difference date of 366 ± 90 ky. This discrepancy is likely due to inheritance in the site III boulder. We did not measure an Al-Be burial age at this site.

At inner moraine 2, site IV, the boulder top exposure age is 93 ± 1.5 (15) ky, significantly less than its two corresponding difference dates of 149 ± 46 ky and 164 ± 42 . The slight disagreement between the two difference dates at site IV may be the result of an inaccurate estimation of f . Two Al-Be measurements register 85 ± 334 and 189 ± 253 ky of total burial, in broad agreement with the difference dates.

Assuming the pavement formed in a spatially uniform manner, difference dates measured at both sites III and IV should match, but they do not. We attribute this to site III data, where all pavement clasts except one are excluded as outliers. This single clast (OLY-33-DP10) registers $N_{bur} = 32.4 \pm 1.0$ Matoms g^{-1} , a value that is lower than other moraine 2 buried sites OLY-36 ($N_{bur} = 34.31 \pm 0.25$ Matoms g^{-1}) ($n=7$) and OLY-37 ($N_{bur} = 33.72 \pm 0.28$ Matoms g^{-1}) ($n=5$). Lower N_{bur} values have the overall effect of increasing the calculated difference date and likely results in an erroneous age.

Based on the mean difference dates at site IV, we conclude the inner moraine 2 is ~ 157 ky. Similar to

moraine 1, we find that the difference dating exercise at moraine 2 indicates moraine boulder exposure ages can both over- and underestimate moraine age.

3.4.1 Additional Al/Be results

Despite large uncertainties, sites II and IV Al-Be burial ages agree with their corresponding difference dates. More precise burial ages may be obtained using burial isochron dating on larger datasets, especially when incorporating Bayesian treatments (Muzikar, 2011).

The Al/Be isotope ratios contain further information; see Fig. 7. First, note that all samples cluster near saturation except OLY-26-DP4, giving us more confidence that this sample is likely an outlier and that excluding it and samples of similar concentration from analysis was appropriate. Secondly, we note that the single exposed sample, OLY-32-DP5, is saturated with respect to Al and very near saturation with respect to Be. All other buried samples plot near to and below OLY-32-DP5 in the burial zone. This suggests that buried samples traveled along the constant-exposure line towards saturation (much like OLY-32-DP5) until they were buried by moraine till. Thus, a single stage exposure-burial history is sufficient to explain buried clasts' location on the erosion-island plot. Finally, we calculate a steady-state erosion rate from the single exposed pavement sample of $4 \pm 3 \text{ cm My}^{-1}$, a value in excellent agreement with published regional erosion rates.

4 Discussion

4.1 Difference dating: future directions

Moraine difference dates indicate that only a single moraine boulder of the four sampled may represent true moraine age. We posit that Leibert Cirque moraines 1 and 2 are $\sim 318 \text{ ky}$ and $\sim 157 \text{ ky}$, respectively. We observe that when boulders do not explain pavement exposure histories, they can either over- or underestimate moraine age. While the literature is rich with instances of moraine boulder inheritance producing ages that are too old, the occurrence of ages that are too young is not as frequently observed in the Dry Valleys [save instances of diffusive loss of ^3He from pyroxene (*Brook et al.*, 1993)]. We regard it as most likely that sandstone boulders are subject to random spalling events, resulting from thermal fracturing and freeze/thaw processes, which shed exterior boulder surfaces containing high radionuclide concentrations. This argument

is also invoked to explain boulder scatter in Taylor Glacier deposits (*Swanger et al.*, 2011). The observation of pavement clasts containing $[^{10}\text{Be}]$ concentrations of the same magnitude as boulder tops supports this hypothesis.

Our initial difference dating results are encouraging and, with future improvements, the technique could essentially replace boulder exposure age dating in appropriate settings. The primary goal of future applications should be to incorporate multi-nuclide systems so as to minimize age uncertainty. In this study, the relative share of uncertainty alters slightly between sample sets, but is consistently dominated by nuclide measurement uncertainties. For all locations, the largest source of uncertainty is $\sigma\Delta N$ (ranging from 42% to as much as 83%), followed by σf (ranging 10% to 34%), and finally by σP (ranging 7% to 28%). Reducing $\sigma\Delta N$ will result from larger sample sets (though this may not always be possible), precise laboratory processing (though our average process blank result is acceptable at $\sim 0.8\%$ total ^{10}Be atoms, it can be improved), and application to more tightly constrained nuclide systems (e.g., ^3He). Negligible contributions from σf can be achieved simply by using automated shapefile creation. Reduction in σP is more challenging, but may be possible if difference dating is applied near production rate calibration sites, such as the exposed bedrock features in Arena Valley (*Balco and Shuster*, 2009).

Like boulder exposure age dating, the difference dating technique is suitable to a range of target minerals/isotope systems. The method requires greater physical disturbance of moraine deposits and more challenging sampling efforts, but offers a moraine age estimate unaffected by potentially overwhelming inheritance issues. Difference dating can be validated in future studies using isochron burial dating in the buried pavement clasts, provided production rates can be properly constrained at each buried and exposed location. Quartz sands underlying the pavement clasts may represent an additional target for difference dating.

4.2 Paleoclimatic inferences

The average exposure age of the desert pavement indicates that cold-based glaciation has endured for >4.2 My. This is in agreement with regional climatic records that place the onset of hyperaridity and cold-based glaciation well before that at ~ 14 My (e.g., *Lewis et al.*, 2007, 2006; *Valletta et al.*, 2015).

Difference dates indicate glacial advance during marine isotope stages 6 and 9. Evidence for concurrent glacial advance during both stages is found throughout the Dry Valleys (*Higgins et al.*, 2000; *Swanger et al.*, 2011; *Brook et al.*, 1993; *Brown et al.*, 1991). Though, correlating distant glacial deposits which

may reflect valley-wide climatic signals is likely precluded by the complex nature of glacial behavior here, which is strongly controlled by localized wind patterns and solar radiation (*Hoffman et al.*, 2016). Ideally, comparative difference dates could be collected from the Wright Valley cirques conjoining Leibert, and others throughout the Olympus Range. While our outermost moraine 1 age seems to agree with *VandenHeuvel* (2002)’s minimum exposure age collected on a correlated moraine sequence in Dean Cirque (325 ± 15 ky), our moraine 2 age exceeds his youngest corresponding age (99 ± 12 ky). In DipBoye Cirque, the youngest ages from moraines 1 and 2 both exceed our moraine ages (421 ± 6 ky and 386 ± 5 ky, respectively) (*Swanger et al.*, 2014). This mismatch again highlights that moraine boulder exposure ages are highly unlikely to reflect true moraine age in high elevation alpine deposits, that moraine boulders may both over- or underestimate true moraine age, and the need for an alternative moraine dating method is great.

5 Conclusions

We present a method for confirming the exposure age of moraine boulders that lie atop intact desert pavement surfaces. In the field, sampling logistics may be complicated by physical limitations; boulders must be small enough to overturn. Extreme care must be made while sampling so as to not incorporate moraine lag. This is not always possible because pavement clasts may exceed the age at which quartz rinds and ventifaction become well-developed. In this case, samples must be rejected as outliers following isotope measurement, a relatively straight-forward procedure. The difference dating technique would lend itself well to paired isotope systems in which isochron burial dating is possible.

Ongoing work looks to improve our method and expand the deglaciation chronology recorded in high-altitude cirque glacier deposits. Recent fieldwork has sampled the corresponding moraine sequence in DipBoye Cirque with the intention of implementing the difference dating technique. Accordingly, proper field photographs were taken to produce automated shapefiles, a more reliable approach to calculating shielding factors at each site.

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Figure 1: Sampling location. A: Overview of Wright Valley region (Landsat 8). B: Inset of box A. Sequence of five cirques on the northern wall of Wright Valley. C: Sequence of moraines 1-3 in Leibert Cirque (E) (WorldView).

Figure 2: Example of sampling site. Pictured: OLY-36, -37, and -38. Note sub-vertical cliffs composed of Beacon Supergroup sandstone in the background. Moraine boulders are likely sourced from these cliffs during rockfall events. In the foreground, note boulder OLY-38 (maximum height: 125 cm tall) which has fractured in place and overlies an intact desert pavement. Site OLY-37 (not visible) lies beneath the fractured, 90 cm tall segment of OLY-38. The foremost, smaller boulder (maximum height: 30 cm) has been rolled away to reveal site OLY-36.

Figure 3: Samples representing progressive stages of ventifaction and quartzification. A: OLY-26-P5. Pavement clasts collected from site OLY-26 retain granular surficial grooves and lack a greasy surface luster and quartz rind. Red-orange stains are patchy. B: OLY-33-DP6. Granular appearance is replaced by a thin <0.1 cm thick quartz rind, no clear ventifacted facets are apparent yet. Red-orange staining covers entire clast. C: OLY-31-DP5. The surface of most exposed pavement clasts are strongly ventifacted and characterized by a greasy surface luster, red-orange staining, and impermeable rinds up to ≤ 0.5 cm thick. All images are digitally brightened.

Figure 4: Kernel density estimates buried beneath moraine 1 (panel A) and moraine 2 (panel B), and exposed between the moraines (panel C). Each clast ^{10}Be measurement (μ) and uncertainty (σ) are plotted as Gaussian distributions and summed to form a kernel density estimate normalized to one (bold line).

Figure 5: The cumulative distribution function for all pavement clasts, buried (circles) and exposed (diamonds). Outliers are identified via kernel density estimate plots and are plotted here in red.

Figure 6: Histograms depicting results of the Monte Carlo simulation carried out at sampling sites II, III and IV. Measured exposure ages of each boulder are plotted as vertical lines with experimental (black) and overall (gray) uncertainties.

Figure 7: Al/Be erosion-island plot. The exposed sample, OLY-32-DP5, corresponds to a steady-state erosion rate of $4 \pm 3 \text{ cm My}^{-1}$. The position of OLY-26-DP4 relative to other buried samples confirms it is an outlier. All other buried samples plot near to and below a single exposed sample OLY-32-DP5, supporting our interpretation of the pavement's exposure history. That is, constant exposure until emplacement of glacial moraines.

Location	Field ID	Sample type ^a	Nuclide	Quartz mass (g)	Thickness (cm)	Concentration (10 ⁶ atoms g ⁻¹)	
<i>Inner moraine</i>							
Site I (-77.5094, 160.9412) 1406 masl	OLY-27-B	boulder	¹⁰ Be	20.18	3.0	6.53	± 0.13
	OLY-28-DP	exposed	¹⁰ Be	30.83	5.0	21.13	± 0.34
	OLY-26-DP3	buried	¹⁰ Be	19.68	1.9	3.22	± 0.07
	OLY-26-DP4	buried	¹⁰ Be	22.12	2.5	6.14	± 0.10
			²⁶ Al			30.52	± 1.71
	OLY-26-DP5	buried	¹⁰ Be	22.73	1.9	5.54	± 0.07
Site II (-77.5095, 160.9395) 1397 masl	OLY-30-B	boulder	¹⁰ Be	19.10	3.0	4.83	± 0.07
	OLY-29-DP	exposed	¹⁰ Be	24.34	5.0	27.37	± 0.34
	OLY-31-DP1	buried	¹⁰ Be	26.88	3.5	33.56	± 0.52
	OLY-31-DP2	buried	¹⁰ Be	29.04	1.3	15.43	± 0.27
	OLY-31-DP3	buried	¹⁰ Be	10.22	1.6	16.29	± 0.38
	OLY-31-DP4	buried	¹⁰ Be	18.89	1.3	30.97	± 0.65
			²⁶ Al			108.40	± 6.02
	OLY-31-DP5	buried	¹⁰ Be	25.08	1.9	32.50	± 0.68
	OLY-31-DP6	buried	¹⁰ Be	12.79	2.3	33.13	± 0.49
<i>Outer moraine</i>							
Site III (-77.5076, 160.9571) 1426 masl	OLY-34-B	boulder	¹⁰ Be	23.18	1.7	6.52	± 0.12
	OLY-32-DP1	exposed	¹⁰ Be	19.89	3.8	43.70	± 0.70
	OLY-32-DP2	exposed	¹⁰ Be	27.17	3.0	34.94	± 0.83
	OLY-32-DP3	exposed	¹⁰ Be	20.91	3.2	40.71	± 0.69
	OLY-32-DP4	exposed	¹⁰ Be	29.26	6.4	33.60	± 0.67
	OLY-32-DP5	exposed	¹⁰ Be	23.40	2.5	36.65	± 0.49
			²⁶ Al			138.6	± 7.73
	OLY-32-DP6	exposed	¹⁰ Be	30.93	4.7	35.6	± 0.4
	OLY-33-DP1	buried	¹⁰ Be	24.99	7.0	9.25	± 0.15
	OLY-33-DP6	buried	¹⁰ Be	18.41	2.3	23.32	± 0.32
	OLY-33-DP7	buried	¹⁰ Be	24.76	3.2	8.73	± 0.19
	OLY-33-DP8	buried	¹⁰ Be	29.76	2.5	26.51	± 0.48
	OLY-33-DP9	buried	¹⁰ Be	16.48	1.9	27.45	± 0.68
	OLY-33-DP10	buried	¹⁰ Be	9.97	3.1	32.4	± 1.0
Site IV (-77.5077, 160.9564) 1426 masl	OLY-38-B	boulder	¹⁰ Be	24.87	2.0	1.65	± 0.03
	OLY-35-DP1	exposed	¹⁰ Be	29.76	1.9	31.29	± 0.41
	OLY-35-DP2	exposed	¹⁰ Be	33.78	2.5	34.96	± 0.70
	OLY-35-DP3	exposed	¹⁰ Be	28.41	1.3	35.05	± 0.62
	OLY-35-DP4	exposed	¹⁰ Be	30.95	1.9	28.06	± 0.54
	OLY-35-DP5	exposed	¹⁰ Be	30.41	1.9	35.74	± 0.93
	OLY-35-DP6	exposed	¹⁰ Be	32.09	1.3	35.98	± 0.57
	OLY-35-DP7	exposed	¹⁰ Be	32.69	3.2	37.13	± 0.49
	OLY-36-DP1	buried	¹⁰ Be	30.30	3.8	35.70	± 0.78
	OLY-36-DP2	buried	¹⁰ Be	31.50	3.8	33.4	± 0.5
			²⁶ Al			110.50	± 6.13
	OLY-36-DP3	buried	¹⁰ Be	31.49	3.8	34.81	± 0.58
	OLY-36-DP4	buried	¹⁰ Be	30.82	3.2	17.58	± 3.69
	OLY-36-DP5	buried	¹⁰ Be	31.93	5.1	35.46	± 0.53
	OLY-36-DP6	buried	¹⁰ Be	29.46	1.9	32.15	± 0.78
	OLY-36-DP7	buried	¹⁰ Be	23.94	1.9	32.68	± 0.85
	OLY-36-DP8	buried	¹⁰ Be	29.89	2.5	35.97	± 0.50
	OLY-37-DP1	buried	¹⁰ Be	27.54	1.3	34.95	± 0.51
	OLY-37-DP2	buried	¹⁰ Be	29.85	2.0	32.83	± 0.75
	OLY-37-DP3	buried	¹⁰ Be	31.03	3.5	32.41	± 0.44
	OLY-37-DP4	buried	¹⁰ Be	28.44	1.3	34.77	± 0.52
			²⁶ Al			105.20	± 5.95
	OLY-37-DP6	buried	¹⁰ Be	29.21	2.5	28.87	± 0.44
	OLY-37-DP7	buried	¹⁰ Be	16.94	2.0	33.62	± 0.78

Table 1: Cosmogenic nuclide data

^aDesert pavement clasts are designated as 'buried' (beneath that site's corresponding boulder) or 'exposed.'

Location	Field ID	Shielding factor, f			Boulder top exposure age (ky) ¹			Difference date (ky)			Al-Be burial age (ky)		
Site II	OLY-31	0.35	±	0.06	288	±	4.5 (48)	318	±	64	362	±	316
Site III	OLY-33	0.41	±	0.05	393	±	8.1 (68)	366	±	90	-		
Site IV	OLY-36	0.48	±	0.02	93	±	1.5 (15)	149	±	46	85	±	334
	OLY-37	0.29	±	0.08	93	±	1.5 (15)	164	±	42	189	±	253

¹ internal (external) uncertainty

Table 2: Model results

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