Quaternary Research 74 (2010) 63–72

Contents lists available at ScienceDirect

Quaternary Research

journal homepage: www.elsevier.com/locate/yqres

Moraine chronosequence of the Donnelly Dome region, Alaska

A. Matmon [a,*], J.P. Briner [b], G. Carver [c], P. Bierman [d], R.C. Finkel [e,f]

[a] Institute of Earth Sciences, Hebrew University of Jerusalem, Jerusalem 91904, Israel
[b] Department of Geology, University at Buffalo, Buffalo, NY 14260, USA
[c] CARVER GEOLOGIC Inc., PO Box 52, 12021 Middle Bay Drive, Kodiak, AK 99615, USA
[d] Department of Geology and School of Natural Resources, University of Vermont, Burlington, VT 05405, USA
[e] Earth and Planetary Science Department, University of California, Berkeley, CA 94720, USA
[f] Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, CA 94550, USA

ARTICLE INFO

Article history:
Received 24 November 2009
Available online 26 May 2010

Keywords:
Cosmogenic exposure ages
Moraines
Alaska
Delta
Donnelly

ABSTRACT

We present ^{10}Be exposure ages from moraines in the Delta River Valley, a reference locality for Pleistocene glaciation in the northern Alaska Range. The ages are from material deposited during the Delta and Donnelly glaciations, which have been correlated with MIS 6 and 2, respectively. ^{10}Be chronology indicates that at least part of the Delta moraine stabilized during MIS 4/3, and that the Donnelly moraine stabilized ~17 ka. These ages correlate with other dates from the Alaska Range and other regions in Alaska, suggesting synchronicity across Beringia during pulses of late Pleistocene glaciation. Several sample types were collected: boulders, single clasts, and gravel samples (amalgamated small clasts) from around boulders as well as from surfaces devoid of boulders. Comparing ^{10}Be ages of these sample types reveals the influence of pre/post-depositional processes, including boulder erosion, boulder exhumation, and moraine surface lowering. These processes occur continuously but seem to accelerate during and immediately after successive glacial episodes. The result is a multi-peak age distribution indicating that once a moraine persists through subsequent glaciations the chronological significance of cosmogenic ages derived from samples collected on that moraine diminishes significantly. The absence of Holocene ages implies relatively minor exhumation and/or weathering since 12 ka.

Introduction

Deposition of moraine sequences by valley glaciers offers the opportunity to study climatic patterns at a temporal scale of 10^3–10^5 yr. Moraine morphology changes over time because of surface processes; generally, sharp crests and unweathered boulders characterize young moraines and subdued relief, well-developed soils, and weathered boulders characterize old moraines (Benn and Evans, 1997; Putkonen and Swanson, 2003). The relative changes in these parameters combined with morphostratigraphic relationships provide guidelines that enable the qualitative temporal ordering of moraines and the reconstruction of glacial advance and retreat events (e.g. Sharp and Birman, 1963; Sharp, 1969, 1972). However, spatial relations between moraines are not always simple. Major glaciations remove moraines previously deposited during less extensive ice advances, and therefore erase part of the glacial record. Thus, it is important to date moraines accurately in order to establish the correct stratigraphy and chronology.

Improvements in dating technologies have significantly increased geologists' ability to refine glacial patterns (e.g. Narama et al., 2007; Lakeman et al., 2008; Thackray et al., 2008; Davis et al., 2009; Owen et al., 2009a). Specifically, the use of cosmogenic exposure dating has enabled researchers to date glacial features that otherwise could not be dated (Phillips et al., 1990; Gosse and Phillips, 2001; Bierman, 2007) and moraine chronologies based on exposure dating now exist from many mountainous locations around the world (e.g. Phillips et al., 1990; Owen et al., 2002, 2006, 2009b; Putkonen and Swanson, 2003; Benson et al., 2004; Smith et al., 2005, 2008; Matmon et al., 2006; Fabel et al., 2006; Schäfer et al., 2006; Meriaux et al., 2009). In the right settings, cosmogenic exposure ages constrain the timing of glacier retreat and the subsequent stabilization of the moraine (e.g., Phillips et al., 1990; Zreda et al., 1994; Gosse et al., 1995; Gosse and Phillips, 2001; Briner et al., 2005; Gillespie et al., 2008). The time gap between deposition and stabilization of the moraine is the result of surface processes, such as boulder erosion and exhumation and moraine-crest flattening, that operate on the moraine after ice retreat. The duration of this period is not well-constrained. However, it may last several thousands of years. Thus, in the absence of isotope inheritance, moraine ages based on cosmogenic exposure dating are thought to provide minimum constraints on the age of deposition.

* Corresponding author.
E-mail address: arimatmon@cc.huji.ac.il (A. Matmon).

0033-5894/$ – see front matter © 2010 University of Washington. Published by Elsevier Inc. All rights reserved.
doi:10.1016/j.yqres.2010.04.007

Despite its advantages, the use of cosmogenic isotopes in glacial geochronology involves the understanding and consideration of pre- and post-deposition processes that influence cosmogenic exposure ages. For example, the inclusion of sediment that was exposed prior to its deposition in the moraine can yield exposure ages older than the actual age of the moraine complicating the interpretation of moraine age (e.g. Marsella et al., 2000; Balco et al., 2002; Owen et al., 2006; Dortch et al., 2010). A more common complication results from post-depositional processes. Freeze and thaw cycles and chemical weathering lead to alteration of surface boulders, loss of cosmogenically dosed material, and yield exposure ages younger than the age of the moraine. Similarly, degradation of moraine crests leads to exhumation of new material at the moraine surface, which yields exposure ages younger than the age of moraine deposition (Hallet and Putkonen, 1994). The rate of surface modification depends on several factors of which climate is an important one. Thus, climatic cycles are followed by changes in the rate of weathering and erosion of moraines. Several studies deal with such influences and provide possible solutions (e.g. Briner et al., 2002; Putkonen and Swanson, 2003; Benson et al., 2004; Putkonen et al., 2008; Briner, 2009; Meriaux et al., 2009).

As a glacial period comes to an end, relative warming and sea-level rise are followed by more frequent freeze–thaw cycles, increased rainfall, and partial melting of permafrost. These processes generate more sediment and enable faster and more efficient transport of material off moraines. These processes operate on all exposed moraines, including those deposited by preceding glaciations. Increased bioturbation that follows these climatic changes enhances the production of sediment (Zazula et al., 2007). Thus, we hypothesize that increased erosion and exhumation of moraines, and by inference, partial resetting of exposure ages, are expected to occur in a moraine at the waning stages of glacial periods, and perhaps into interglacial periods.

Alaska is one of few accessible locations in the Arctic that was not covered by a continental ice sheet during Pleistocene glaciations. Therefore, glaciated mountain ranges in Alaska provide an opportunity to use moraine sequences to reconstruct late Quaternary climatic variations at high northern latitudes. Mountain glaciers that originated in the Alaska Range advanced unhindered to the north during glacial periods and deposited a complex sequence of moraines that constitute dominant landforms in the foothills of the northern Alaska Range (Wahrhaftig, 1958; Péwé, 1975; Ten Brink and Waythomas, 1985; Thorson, 1986). The ages of late Pleistocene moraines in and around the Alaska Range are primarily based on tephrostratigraphy, radiocarbon dating, and ^{10}Be cosmogenic exposure dating (Porter et al., 1983; Hamilton, 1994; Kaufman and Manley, 2004; Kaufman et al., 2004; Briner and Kaufman, 2008; Young et al., 2009). Although these ages indicate that glaciers advanced during global periods of maximum ice volume (>140 ka, 55–60 ka and 11–21 ka), detailed chronologies exist from only a few valleys (Briner and Kaufman, 2008).

Our study area is the Delta River Valley (Fig. 1), a reference locality for glaciation in the northern Alaska Range (Péwé, 1975). We sampled boulders, single large clasts, and gravel from moraine surfaces to elucidate pre- and post-depositional processes that affect moraine exposure age distribution. These processes include on one hand long pre-depositional exposure that results in the overestimation of the moraine age, and on the other hand post-depositional boulder weathering and erosion and moraine exhumation, which result in the underestimation of the moraine age. Cosmogenic ^{10}Be exposure ages (hereafter referred to as ^{10}Be ages) of the moraine sequences deposited during the Delta and Donnelly glaciations, indicate that at least part of the Delta moraine stabilized during MIS 4/3, and that the Donnelly moraine stabilized ~17 ka. Our results confirm correlation of the Donnelly glaciation with marine oxygen isotope stage 2 (MIS 2; Martinson et al., 1987), but contrast with the previous correlation of the Delta moraine to MIS 6 (Péwé, 1975; Hamilton, 1994; Begét and Keskinen, 2003). The results suggest that the bulk of moraine weathering and erosion likely occurs, within the limits of ^{10}Be exposure age dating resolution, during and immediately after glacial periods that occurred subsequent to moraine deposition. These erosional periods reset the cosmogenic exposure clock over parts of the moraine and result in multiple exposure ages that diminish the chronological significance of the moraine.

Methods

We collected 28 samples from the Donnelly Dome area (Table 1, Fig. 1) on two different occasions (August, 2004; June, 2005). Samples included chips from the top surface of boulders located on moraine crests ($n=9$), single large clasts ($n=5$), and gravel samples adjacent to boulders ($n=6$) and not adjacent to boulders ($n=10$). Gravel samples included tens to hundreds of angular clasts, 1–2 cm in diameter, collected from the moraine surface at crests of hummocks and ridges (Fig. 2). Two gravel samples (DDDL-4G and DDDL-4Q) were collected from locally derived colluvium that accumulated on a bedrock bench on the eastern slope of Donnelly Dome; the elevation of the bench corresponds with the top of the nearby Delta moraine and may have been carved during the Delta glaciation. Hence, the colluvium is younger than the Delta moraine and accumulated during later glaciations. By comparing ^{10}Be concentrations in boulders and other sediment types at the same location, we aim to elucidate the geomorphic processes operating on these surfaces and evaluate their effects on ^{10}Be accumulation.

Our sampling strategy was dictated by previous mapping of Quaternary glacial features in the Donnelly Dome area (Péwé and Holmes, 1964). Thus, we *a priori* associated each sample with either the Donnelly or Delta glaciation. Fifteen samples are from the Delta moraine (6 boulders, 2 single large clasts, and 7 gravel samples). Eleven samples are from the Donnelly moraine (3 boulders and 8 gravel samples). Two samples, one a well-rounded single large quartzite cobble and the other an amalgamation of tens of small rounded pebbles, were collected from the top of the alluvial sequence that fills the Ober Creek valley. This alluvial sequence is not directly related to either the Delta or Donnelly moraines; however, it may result from the deposition of recycled moraine material. Thus, the ages of these two samples are expected to correlate with an interglacial period.

Post-depositional processes acting on geomorphic surfaces affect the accumulation of ^{10}Be in surface samples and result in underestimated exposure ages. Periglacial processes mix dosed surface and less-dosed subsurface material (cryoturbation) and erosion of moraine crests removes well-dosed material from moraine surfaces. Boulder erosion removes the most heavily dosed outer surface of the boulder. These processes ultimately result in the exposure of material that has not been continuously exposed over the entire life of the moraine. In an attempt to avoid such "young" samples, we did not sample boulders that showed obvious indications of recent rotation and spalling; rather, we sampled boulders with smooth, presumably glacially molded, surfaces.

Shielding of exposed rock and soil surfaces by dust, snow, or topographic obstacles reduces the production rate of cosmogenic isotopes and will result in an underestimated exposure age. Interior Alaska is dry and the amount and water equivalent of snowfall is small. To evaluate the contemporary effect of snow cover, we obtained measurements (http://www.ncdc.noaa.gov/oa/climate/stationlocator.html) from stations located near the study area. All stations indicate a maximum annual snow cover of 33 cm in the study region. This snow thickness (at a density of 0.2 g cm^{-3}) is equivalent to a thickness of 1–2 cm of rock, and the effect of such shielding (which occurs only 6–8 months a year) on the exposure ages is <2%. Thus, in our age calculations we make no adjustments for snow shielding. The boulders we sampled did not show signs of weathering, thus reducing the possibility of recent mass loss from the boulder faces. Nevertheless, we are aware that weathering and erosion could have occurred. Boulder

https://doi.org/10.1016/j.yqres.2010.04.007 Published online by Cambridge University Press

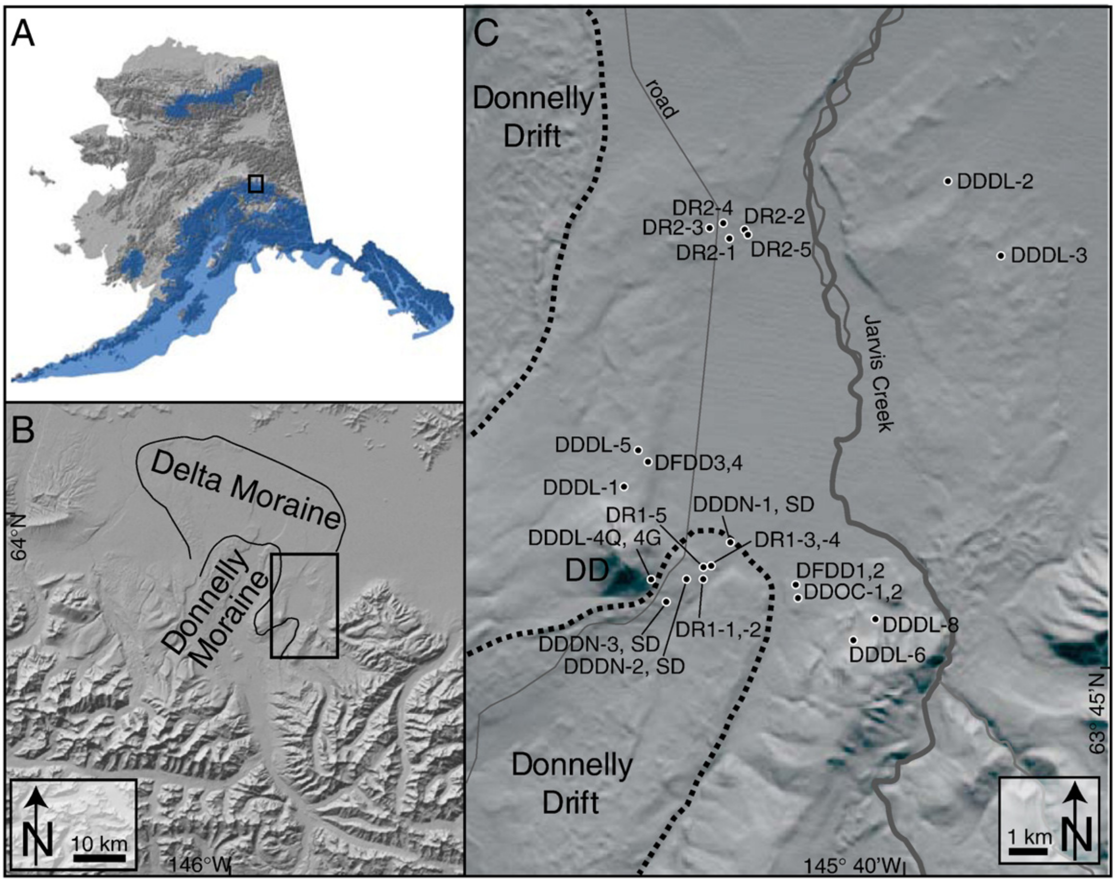

Figure 1. Digital elevation model of study area showing significant landforms. A. DEM of Alaska showing the location of the Delta River outlet (open black box) in the Alaska Range. B. A close-up DEM image of the Delta River outlet from the Alaska Range showing location of Delta and Donnelly moraines. C. Close up of specific study area. Sample locations marked with black and white dots and names of samples.

erosion rates have been estimated by previous studies in the Arctic (1 to 3 mm per thousand years; e.g. Briner et al., 2005). Our calculations show that the impact of such rates of boulder erosion on age calculations of Holocene and late Pleistocene samples is 1–8% (Table 2). Due to the limited influence of boulder erosion on the exposure ages, in the following discussion we consider boulder, cobble, and clast ages calculated with no erosion correction (Table 2).

Samples for ^{10}Be dating were processed at the University of Vermont and at the State University of New York at Buffalo following the method modified from Bierman and Caffee (2001). ^{10}Be was measured at the Center for Accelerator Mass Spectrometry (AMS) at Lawrence Livermore National Laboratory (LLNL). ^{10}Be/^{9}Be ratios were normalized to the LLNL KNSTD3110 standard with a value of 2.85×10^{-12}. ^{10}Be ages were calculated considering a sea-level, high-latitude production rate of 4.68 ^{10}Be atoms g^{-1} yr^{1} (Nishiizumi et al., 2007). Latitude/altitude scaling of the nucleonic production rate was done using Stone (2000). We use Eq. (1) to calculate simple, model exposure ages (Lal, 1988):

$$N_{(t)} = \left(\frac{P}{\lambda}\right) * (1 - e^{-\lambda t}) \quad (1)$$

where $N_{(t)}$ = measured concentration (atoms g^{-1} quartz), P = production rate (atoms g^{-1} quartz yr^{-1}), $\lambda = {}^{10}$Be decay constant ($5.1 * 10^{-7}$ yr^{-1}), which is calculated from the presently-accepted ^{10}Be half life of 1.36 ± 0.07 Ma (Nishiizumi et al., 2007).

Results and interpretation

^{10}Be concentrations in all samples collected from the Donnelly Dome area range between 1.03 and 5.73×10^{5} atoms g^{-1} quartz (Table 2). Analysis of the age distribution of the entire data set exhibits a composite peak at 12–17 ka, a minor peak around 25–30 ka, and a broader mode of ages at 40–70 ka (Figs. 3 and 4). The period represented by the entire data set (between 12 and 70 ka) includes two major glaciations at MIS 4 and MIS 2.

Considering the data from the Delta and Donnelly moraines separately, the results suggest several major episodes of sediment deposition and/or exposure. Samples associated with the Delta glaciation ($n = 15$) yield ^{10}Be concentrations between $1.10 \pm 0.04 \times 10^{5}$ and $5.32 \pm 0.44 \times 10^{5}$ atoms g^{-1} quartz (Table 2), corresponding to ages between 12.4 ± 1.4 ka and 70.8 ± 7.8 ka (Table 2, Figs. 3 and 4). Eight of the samples yielded ages that range between ~40 ka and ~70 ka. The large spread in ages is difficult to interpret and is likely due to post-depositional processes. In part, the wide range of ages may be explained by the variety of sample types (boulders, moraine surface gravel) and locations (e.g. moraine hummock crests and bedrock bench on slope of Donnelly Dome). Generally, we identify an early episode associated with the MIS 4 glaciation, about 40–70 ka, an intermediate episode around 25–30 ka, and a latest Pleistocene episode around 12–17 ka. A single sample (DDDL-5) corresponds with the Pleistocene–Holocene boundary. Regardless of the wide range of ages, we note that in the Delta moraines investigated in this study, there are no ages older than MIS 4 nor are there ages younger than 12 ka.

The two samples that were collected from the top of the Ober Creek alluvial sequence yielded cosmogenic ^{10}Be concentrations of $2.86 \pm 0.1 \times 10^{5}$ and $2.92 \pm 0.08 \times 10^{5}$ atoms g^{-1} quartz, which correspond to exposure ages of 32.5 ± 3.6 ka and 34.1 ± 3.8 ka (Fig. 3). These ages are between the MIS 4 and MIS 2 glaciations and may represent reworking of glacial material during an interglacial period;

https://doi.org/10.1016/j.yqres.2010.04.007 Published online by Cambridge University Press

Table 1
Locations and details of cosmogenic samples from the Donnelly Dome area.

Name	Location	Lat	Long	GPS elev (masl)	Type	Lithology
Donnelly moraine						
DDDN-1	Donnelly terminal moraine	63°47.057′	145°44.540′	649 ± 10	Boulder	Quartz diorite
DDDN-1-SD	Donnelly terminal moraine	63°47.057′	145°44.540′	649 ± 10	Gravel	Quartz
DDDN-2	Donnelly lateral moraine	63°46.659′	145°45.800′	716 ± 7	Boulder	Granite
DDDN-2-SD	Donnelly lateral moraine	63°46.659′	145°45.800′	716 ± 7	Gravel	Quartz
DDDN-3	Donnelly lateral moraine	63°46.418′	145°46.441′	736 ± 9	Boulder	Quartz diorite
DDDN-3-SD	Donnelly lateral moraine	63°46.418′	145°46.441′	736 ± 9	Gravel	Quartz
DR1-1	Donnelly terminal moraine	63°46.631′	145°45.359′	683 ± 10	Gravel	Quartz
DR1-2	Donnelly terminal moraine	63°46.633′	145°45.401′	681 ± 10	Gravel	Quartz
DR1-3	Donnelly terminal moraine	63°46.760′	145°45.161′	687 ± 10	Gravel	Quartz
DR1-4	Donnelly terminal moraine	63°46.784′	145°45.157′	669 ± 10	Gravel	Quartz
DR1-5	Donnelly terminal moraine	63°46.752′	145°45.342′	679 ± 10	Gravel	Quartz
Ober Creek alluvial sequence						
DDOC-1	Ober Creek	63°46.298′	145°42.894′	671 ± 7	Gravel	Quartz
DDOC-2	Ober Creek	63°46.298′	145°42.894′	671 ± 7	Clast	Quartzite
Delta moraine						
DFDD3	Delta medial moraine	63°48.099′	145°46.624′	734 ± 5	Boulder	Granite
DFDD4	Delta medial moraine	63°48.099′	145°46.624′	734 ± 5	Clast	Quartz cobble
DDDL-1	Delta medial moraine	63°47.809′	145°47.298′	764 ± 6	Boulder	Granite
DDDL-2	Delta eastern lateral moraine	63°51.707′	145°37.592′	536 ± 7	Boulder	Quartz diorite
DDDL-3	Delta eastern lateral moraine	63°50.665′	145°36.277′	566 ± 5	Boulder	Granite
DDDL-4Q	Donnelly Dome eastern slope (High Delta bench)	63°46.626′	145°46.685′	882 ± 10	Gravel	Quartz
DDDL-4G	Donnelly Dome eastern slope (High Delta bench)	63°46.626′	145°46.685′	882 ± 10	Gravel	Granite and diorite
DDDL-5	Delta medial moraine	63°48.229′	145°46.850′	728 ± 11	Boulder	Granite
DDDL-6	High Delta bench-east of hwy	63°45.756′	145°41.498′	795 ± 10	Cobble	Granite
DDDL-8	High Delta bench-east of hwy	63°45.988′	145°40.865′	748 ± 10	Boulder	Granite
DR2-1	Delta intermediate ground moraine	63°51.228′	145°43.961′	552 ± 10	Gravel	Quartz
DR2-2	Delta intermediate ground moraine	63°51.255′	45°43.531′	552 ± 10	Gravel	Quartz
DR2-3	Delta intermediate ground moraine	63°51.352′	145°44.489′	560 ± 10	Gravel	Quartz
DR2-4	Delta intermediate ground moraine	63°51.411′	145°44.065′	559 ± 10	Gravel	Quartz
DR2-5	Delta intermediate ground moraine	63°51.238′	145°43.437′	555 ± 10	Gravel	Quartz

All locations were taken using NAD 27 Alaska.
Elevation and uncertainty given in meters and measured using a hand-held Garmin 76S GPS.
Thickness of all boulder samples ranges between 3 and 5 cm.
Topographic shielding is insignificant for all samples.

such material could contain a significant inherited component of ^{10}Be. However, the similarity in age between the randomly picked single cobble sample and the amalgamated gravel sample suggests a relatively simple exposure history and that the calculated exposure ages actually do represent the age of sediment deposition.

Samples associated with the Donnelly glaciation ($n = 11$) yielded cosmogenic ^{10}Be concentrations between $1.03 \pm 0.08 \times 10^5$ and $5.73 \pm 0.50 \times 10^5$ atoms g^{-1} quartz (Table 2). These concentrations correspond to ages between 11.9 ± 1.3 ka and 67.6 ± 7.4 ka (Table 2, Figs. 3 and 4). Excluding the oldest sample (DR-5; 67.6 ± 7.4 ka), which is an outlier likely influenced by prior exposure, all other samples ($n = 10$) yielded ages between 11.9 ± 1.3 ka and 23.6 ± 2.6 ka. Gravel samples that were collected around boulders yield consistent ages of ~17 ka. The source of this gravel is unknown. However, at least in two cases (DDDN-1 and DDDN-1SD; DDDN-3 and DDDN-3SD) the similarity in isotopic concentration in the gravel and the nearby boulder suggests a genetic relation: small pieces of vein quartz were detached from the boulder a short time after moraine deposition and have been sitting at the surface since. Generally, samples associated with the Donnelly moraine yielded concentrations that correspond to the culmination of MIS 2 glaciation with some ages at the Pleistocene–Holocene boundary.

Discussion

Considering previous mapping and understanding of the glacial history of the Donnelly Dome area (Péwé, 1975; Hamilton, 1994; Begét and Keskinen, 2003), we expected two sets of ages: those that correspond to the culmination of the Delta glaciation (MIS 6, ~135 ka) and those that correspond to the culmination of the Donnelly glaciation (MIS 2, ~20–15 ka). However, exposure ages yielded a more complex pattern.

^{10}Be ages of samples from the Donnelly age moraines

Calculated exposure ages of the eleven samples from the Donnelly moraine imply that post- and pre-depositional processes influence ^{10}Be ages. Nine exposure ages cluster between 11.9 ± 1.3 ka and 18.1 ± 2.0 ka and correlate with MIS 2 (Fig. 4). Two samples, one boulder and one gravel sample, yielded older ages of 24 ka and 68 ka, respectively. The older one implies the influence of inheritance on the exposure ages. The younger one may also be influenced by inheritance. However, its age corresponds to earlier stages of the last glacial maximum (LGM) and may actually represent a real exposure age. Excluding these two samples, the age distribution in samples from the Donnelly age moraine implies a stabilization processes that may have lasted several thousand years; most of the moraine material was deposited at the culmination of MIS 2 glaciation (~17 ka), but the conditions along the northern slope of the Alaska Range did not allow stabilization until the end of the Pleistocene. A similar pattern is found on the southern slope of the Alaska Range (Fig. 4; Matmon et al., 2006). There, in all the moraines that were dated to LGM by exposure ages of boulders, gravel samples yielded exposure ages of 11–13 ka, suggesting a similar stabilization period to that of the Donnelly moraine. In contrast, in all moraines dated to the Pleistocene–Holocene boundary (11–13 ka), boulders yielded exposure ages similar to those of gravel samples, implying the rapid stabilization of the moraine. Similar to the northern slope, Holocene exposure ages were not found along the southern slope.

https://doi.org/10.1016/j.yqres.2010.04.007 Published online by Cambridge University Press

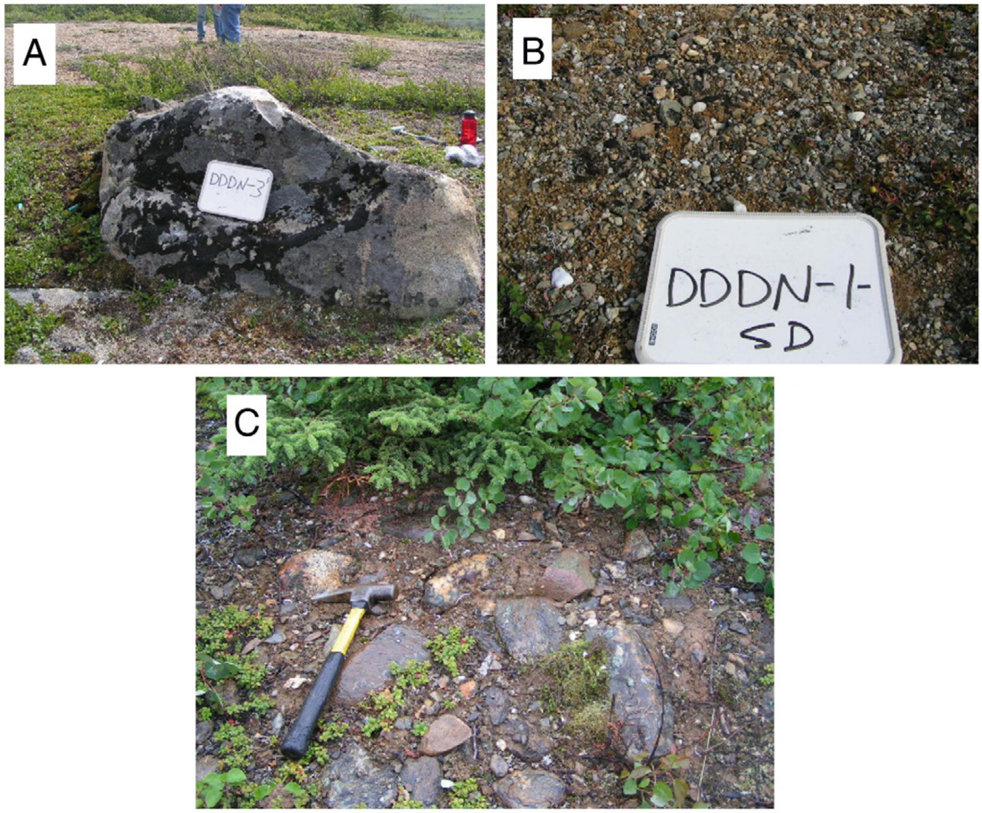

Figure 2. Examples of sampled features. A. Erratic boulder (>1 m *c*-axis) on flat crest of early Wisconsin Delta moraine. B. Clasts coating the surface around boulders on top of late Wisconsin Donnelly moraine. C. Well rounded cobbles from alluvial sequence exposed along the bank of Ober Creek (samples DDOC1 and DDOC2).

The absence of ages younger than 12 ka may be interpreted in two ways. On one hand, this absence may suggest that conditions during the Holocene were not severe enough to catalyze significant erosion and thus the exhumation of the moraine and its boulders. Alternatively, assuming steady state and constant erosion, cosmogenic isotope concentrations may be interpreted as a Holocene-averaged maximum moraine exhumation rate of 56 ± 6 mm per thousand years. Although the truth most likely lies somewhere in between these end member scenarios, the cluster ($n = 6$) of ages around 17 ka, which is the expected age of the Donnelly moraine, suggests that the actual Holocene exhumation rate is much slower than the above calculated maximum rate.

^{10}Be ages in samples from the Delta age moraine

The relative consistency in ages of the Donnelly moraine samples contrasts with the wide spread in ages of samples from the Delta moraine. However, the spread in ages of the Delta moraine samples appears not to be random. We interpret the largest mode (40–70 ka) as the time of moraine deposition. The other age groups (25–30 ka and 12–17 ka) are the result of post-depositional processes that affected the exposure ages of sediment on the moraine. It is interesting that the middle age group correlates with the exposure ages of the Ober Creek alluvium samples and the younger age group correlates with the ages from the Donnelly age moraine. It is possible that during the interstadial period (MIS 3), moraine sediment was re-transported by alluvial processes that also deposited material in the Ober Creek sequence. These processes resulted in exhumation of the moraine and the exposure of new material. Although the older Delta moraine was not over-ridden by ice during the MIS 2 glaciation, it may have been affected by the climatic conditions at the waning stages of the glacial period. These climatic conditions may have resulted in significant boulder erosion and the exhumation of gravel at the moraine surface during that time. The four youngest samples (12.4 ± 1.4 ka to 18.4 ± 2.0 ka) from the Delta moraine correlate with MIS 2 and may be the result of rapid weathering, exhumation, and exposure of boulders and clasts.

The four anomalously young ages are derived from either boulder samples situated close to the perimeter of the Delta moraine (DDDL-1 and DDDL-5) or from gravel samples collected from locations that may have been situated slightly above the ice limit on Donnelly Dome. Specifically, the ages of samples DDDL-4Q and DDDL-4G can be explained by rapid freeze–thaw weathering of exposed bedrock perched above the ice and the consequential exposure of previously shielded rock fragments at the final stages of MIS 2. After the MIS 2 glacier retreat, these fragments were not washed off the slopes of Donnelly Dome and were continuously exposed, providing MIS 2 ages.

The ages of the other eleven samples from Delta age deposits can be divided into two groups: 1) those that overlap MIS 4 (between 41.5 ± 4.5 ka and 70.8 ± 7.8 ka; $n = 8$) and 2) those that correlate with MIS 3 (between 25.7 ± 2.8 ka and 28.9 ± 3.28 ka; $n = 3$). This large range of exposure ages may be the result of moraine crest degradation, random exposure of buried boulders, and inherited cosmogenic nuclides. Taken together, the ages from the Delta moraine samples indicate that initial exposure could have occurred as early as 70 ka. However, instability of the moraine caused the exposure of buried boulders, a process that most likely was intensified during MIS 2.

The absence of ages older than 70 ka in the study area is consistent with a glaciation that postdates MIS 6, as demonstrated elsewhere in Alaska (Briner and Kaufman, 2008). Alternatively, the measured ^{10}Be concentrations may be the result of intensive erosion that modified the boulders, and thus the cosmogenic record, such that older glaciations are undetectable; in that case, cosmogenic isotope concentrations in samples collected from Delta moraines have little chronological significance. Similar to the Donnelly moraine, the

https://doi.org/10.1016/j.yqres.2010.04.007 Published online by Cambridge University Press

Table 2
^{10}Be concentrations and exposure ages of Donnelly Dome samples.

Name	^{10}Be (10^5 atoms g^{-1} quartz)	Normalized ^{10}Be (10^5 atoms g^{-1} quartz)	Age ($\varepsilon = 0$) (ka)	Age ($\varepsilon = 1$ mm ky^{-1}) (ka)	Age ($\varepsilon = 3$ mm ky^{-1}) (ka)
Donnelly moraine					
DDDN-1	1.55 ± 0.05	0.81 ± 0.03	17.4 ± 1.9	17.6 ± 1.9	18.2 ± 2.0
DDDN-1-SD	1.50 ± 0.05	0.80 ± 0.03	17.2 ± 1.9	17.5 ± 1.9	18.0 ± 2.0
DDDN-2	2.17 ± 0.07	1.10 ± 0.03	23.6 ± 2.6	24.1 ± 2.7	25.1 ± 2.8
DDDN-2-SD	1.56 ± 0.05	0.78 ± 0.03	16.8 ± 1.9	17.1 ± 1.9	17.5 ± 1.9
DDDN-3	1.67 ± 0.06	0.84 ± 0.03	18.1 ± 2.0	18.4 ± 2.0	18.9 ± 2.1
DDDN-3-SD	1.60 ± 0.05	0.79 ± 0.03	17.0 ± 1.9	17.2 ± 1.9	17.7 ± 2.0
DR1-1	1.13 ± 0.10	0.62 ± 0.06	13.2 ± 1.5	13.4 ± 1.5	13.7 ± 1.5
DR1-2	1.44 ± 0.12	0.78 ± 0.07	16.8 ± 1.9	17.0 ± 1.9	17.5 ± 1.9
DR1-3	1.03 ± 0.08	0.56 ± 0.05	11.9 ± 1.3	12.0 ± 1.3	12.2 ± 1.4
DR1-4	1.11 ± 0.10	0.61 ± 0.06	13.1 ± 1.5	13.3 ± 1.5	13.6 ± 1.5
DR1-5	5.73 ± 0.50	3.11 ± 0.30	67.6 ± 7.4	71.6 ± 7.9	82.0 ± 9.0
Ober Creek alluvial sequence					
DDOC-1	2.86 ± 0.10	1.51 ± 0.05	32.5 ± 3.6	33.5 ± 3.7	35.4 ± 3.9
DDOC-2	2.92 ± 0.08	1.58 ± 0.04	34.1 ± 3.8	35.0 ± 3.9	37.2 ± 4.1
Delta moraine					
DFDD3	3.63 ± 0.17	1.84 ± 0.09	39.7 ± 4.4	41.1 ± 4.5	44.1 ± 4.9
DFDD4	2.63 ± 0.12	1.33 ± 0.06	28.6 ± 3.2	29.3 ± 3.2	30.8 ± 3.4
DDDL-1	1.74 ± 0.07	0.85 ± 0.03	18.2 ± 2.0	18.4 ± 2.0	19.0 ± 2.1
DDDL-2	4.43 ± 0.14	2.64 ± 0.08	57.2 ± 6.3	60.1 ± 6.6	67.1 ± 7.4
DDDL-3	4.42 ± 0.14	2.56 ± 0.08	55.5 ± 6.1	58.1 ± 6.4	64.7 ± 7.1
DDDL-4Q	1.71 ± 0.05	0.75 ± 0.02	16.0 ± 1.8	16.2 ± 1.8	16.7 ± 1.8
DDDL-4G	1.71 ± 0.06	0.75 ± 0.02	16.0 ± 1.8	16.2 ± 1.8	16.7 ± 1.8
DDDL-5	1.10 ± 0.04	0.58 ± 0.02	12.4 ± 1.4	12.5 ± 1.4	12.8 ± 1.4
DDDL-6	4.41 ± 0.12	2.14 ± 0.06	46.3 ± 5.1	48.1 ± 5.3	52.4 ± 5.8
DDDL-8	2.60 ± 0.09	1.31 ± 0.04	28.2 ± 3.1	28.9 ± 3.2	30.3 ± 3.3
DR2-1	3.86 ± 0.33	2.36 ± 0.22	51.2 ± 5.6	53.4 ± 5.9	58.8 ± 6.5
DR2-2	5.32 ± 0.44	3.26 ± 0.30	70.8 ± 7.8	75.3 ± 8.3	86.9 ± 9.6
DR2-3	3.33 ± 0.29	2.03 ± 0.19	43.8 ± 4.8	45.4 ± 5.0	49.2 ± 5.4
DR2-4	4.32 ± 0.37	2.63 ± 0.25	57.0 ± 6.3	59.8 ± 6.6	66.8 ± 7.4
DR2-5	1.95 ± 0.17	1.19 ± 0.11	25.7 ± 2.8	26.2 ± 2.9	27.4 ± 3.0

Ages used in discussion are simple ages without considering erosion ($\varepsilon = 0$). Ages calculated with erosion consider ρ (density of sampled material) = 2.65 g cm^{-3}, ε erosion rate in cm yr^{-1}, and Λ (attenuation depth) = 165 g cm^{-2}. The analytic precision of the samples (considering AMS) is 3–5% (1σ).

absence of any samples with exposure ages younger than ~12 ka suggests conditions during the Holocene that did not cause significant moraine exhumation.

The effect of glaciations on the exposure age of morainal sediments

Generally, an age agreement between a boulder sample and its associated surrounding gravel sample indicates rapid moraine stabilization soon after boulder deposition (Matmon et al., 2006; Briner, 2009). A disagreement between these ages implies that surface disturbance continued long after boulders were deposited. Comparison of ages derived from boulders with those derived from nearby gravel suggests the effects of post-depositional processes such as moraine degradation and boulder erosion on exposure ages. On the Donnelly age moraine, boulders ($n = 4$) yielded a relatively clustered MIS 2 ages that range between 17.6 ± 1.9 ka and 24.1 ± 2.7 ka. Gravel samples that were collected immediately around boulders yielded consistent ages of ~17 ka ($n = 3$), similar to the boulders (Fig. 4, Table 2). Only gravel samples that were not associated with boulders yielded younger ages that correspond with the Pleistocene–Holocene boundary ($n = 3$). These ages may be the result of weathering of the MIS 2 moraine during the Younger Dryas. Thus, boulders suggest an MIS 2 age whereas gravel samples indicate the process of boulder weathering and erosion, overall exhumation of the moraine crest, and the accumulation of rock fragments of different ages at the surface. The exposure age of one gravel sample (DR1-5; 67.6 ± 7.4 ka) clearly points at the influence of inheritance on exposure ages. There is no unique explanation for the high concentration of ^{10}Be measured in this sample but the similarity in age to samples collected from the nearby Delta age moraine suggests that the material collected in samples DR1-5 may have been reworked from the Delta moraine.

A similar pattern, indicating the long-term influence of moraine degradation and the continuous exposure of boulders on ^{10}Be ages, can be seen from the age distribution of boulder samples collected from the Delta moraine (Fig. 4B, Table 2). In these samples, boulders range between 60.1 ± 6.6 ka and 12.5 ± 1.4 ka. Sediment samples (cobbles and clasts) are also widely distributed in age (70.8 ± 7.8 ka and 16.0 ± 1.8 ka). Whereas the oldest ages of 40–70 ka ($n = 8$) may represent the age of the moraine, other ages correspond to the MIS 3 interstadial period ($n = 3$) and the final stages of the MIS 2 glaciation (12–18 ka ($n = 4$)).

In spite of the similarity in the general patterns of age distribution mentioned above, it is worth noting one important difference. In the Donnelly age samples, boulders yielded a relatively restricted MIS 2 age (three ages ~17 ka and one age at ~24 ka). Gravel samples that were collected immediately around boulders yielded consistent ages of ~17 ka, similar to their associated boulders, while gravel samples that were not associated with boulders yielded ages that correspond with the Pleistocene–Holocene boundary. On the other hand, both boulder and gravel samples from the Delta age moraine present a large range of ages (Fig. 3). We explain this difference as a result of the total age of the moraine. While enough time has passed to allow exhumation of buried boulders and sufficient boulder erosion on the Delta moraine, resulting in a large age range of both boulders and gravel, the Donnelly moraine is younger, and buried boulders have not yet been exposed. The Delta and Donnelly moraines may exhibit two discrete temporal stages of moraine evolution. The Donnelly moraine exhibits an initial stage of moraine erosion whereas the Delta moraine is at a more mature and advanced erosional stage.

The influence of subsequent glacial periods on the erosion of moraines can be shown by examining other locations dated with cosmogenic isotopes. One end member example, which includes late glacial and LGM moraines, is in the southern slope of the

https://doi.org/10.1016/j.yqres.2010.04.007 Published online by Cambridge University Press

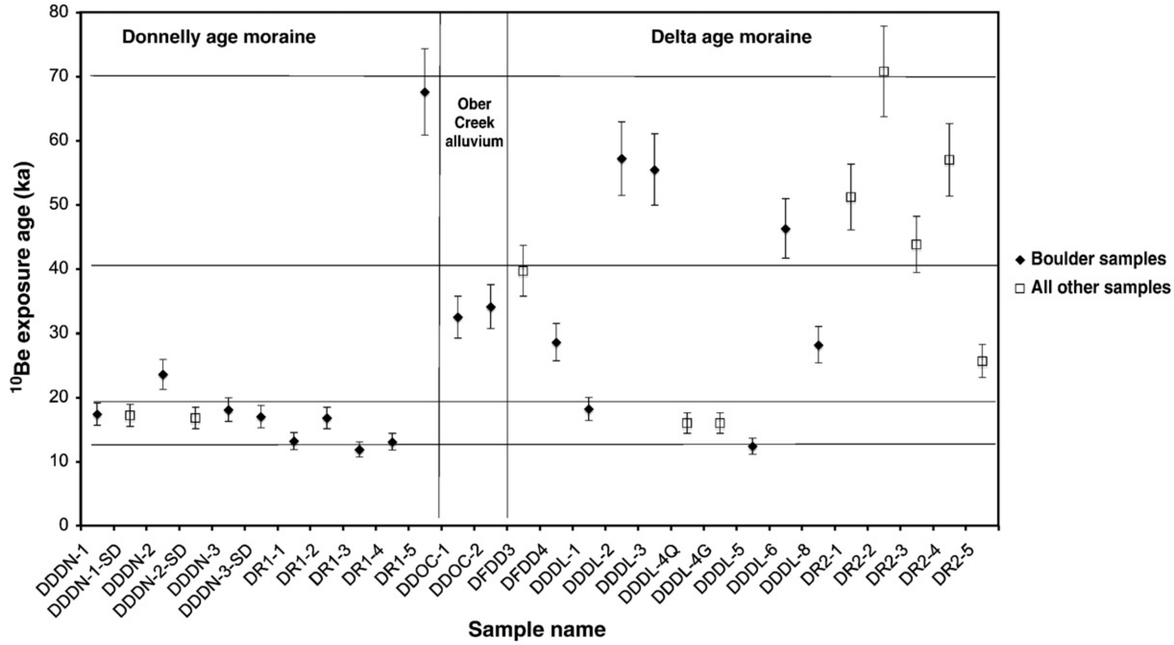

Figure 3. Exposure ages of all samples collected in the Donnelly Dome area. Other samples — large single clasts and gravel samples. Middle vertical section in graph includes samples DDOC-1 and DDOC-2, which were collected from the Ober Creek alluvial section. The 12–18 ka period is marked between the two lower horizontal lines. The 40–70 ka period is marked between the two upper horizontal lines.

Alaska Range (Fig. 4D). In this location, several moraines, all deposited during MIS 2 were dated using cosmogenic isotopes (Matmon et al., 2006). As most of the moraines in this location were deposited ~12 ka, exposure ages calculated from boulder and gravel samples cluster at ~12 ka, indicating insignificant post-depositional effects. As there were no major glaciations after 12 ka, this observation is understandable: there were no subsequent glacial cycles that could enhance the weathering and erosion of the late glacial moraines.

The other end member is illustrated using two examples. In the Himalaya Mountains, five sets of moraines, ranging in age between >430 ka and ~8 ka were dated by Owen et al. (2006) using cosmogenic exposure ages of exposed boulders. Several important observations are apparent in this study: 1) the range of exposure

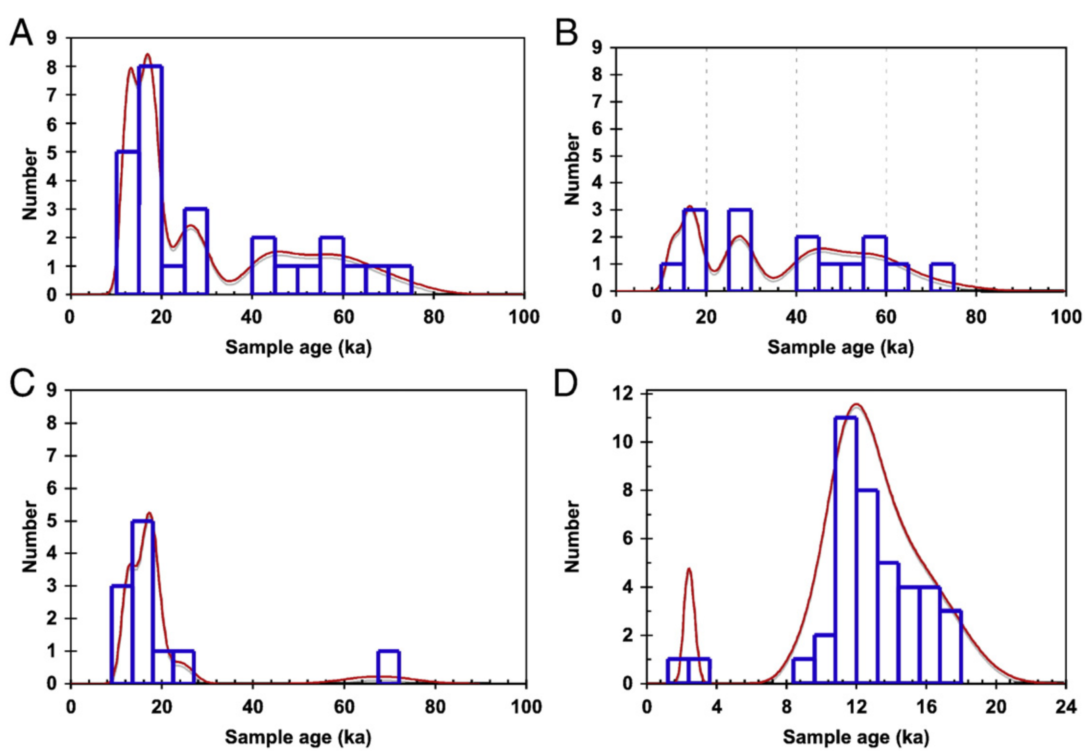

Figure 4. Age probability distribution plots using Isoplot (www.bgc.org/isoplot_etc/IsoplotEx3ReadMe.pdf). A. All samples from Donnelly Dome area (excluding the 2 Ober Creek samples). B. Samples from early Wisconsin Delta age moraine. C. Samples from late Wisconsin Donnelly age moraine. D. Samples from dated moraines on the southern side of the Alaska Range (Matmon et al., 2006). Notice the different scales of plot D.

https://doi.org/10.1016/j.yqres.2010.04.007 Published online by Cambridge University Press

ages increases with the age of the moraine, 2) in each moraine sequence, exposure ages can be correlated to subsequent glaciations (although this correlation is coarse due to low age resolution), and 3) inheritance in the sampled boulders is insignificant, a phenomena mainly expressed in the younger moraines. Owen et al. (2006) call on post-depositional boulder erosion and moraine exhumation to explain their broad age distribution. To this explanation, we add the argument, which is supported by the data presented in the present study, that most of erosion and exhumation occur during, or immediately after, glaciations that follow moraine deposition.

The second example is from the northern Cascade Mountains. Porter and Swanson (2008) present >70 cosmogenic ^{36}Cl exposure ages of boulders that were collected from seven moraines. Four moraines yielded clustered ages that correspond with MIS 2. One moraine, assigned an age of ~70 ka, yielded a wide age range that also included ages that correspond to MIS 2. Although in a very different climatic setting, the cosmogenic exposure age distribution of samples collected from MIS 2 and MIS 4 moraines in the Cascade Mountains is similar to that found in the Delta area. Two much older moraines (>100 ka) yielded clustered age ranges. It is possible that in the climatic conditions of the Cascade Mountains, most boulders on the oldest moraines have been completely weathered over the 10^5 yr time scale and only boulders composed of the very resistant lithologies are present, thus presenting a restricted and old age range.

Glacial history of the Alaska Range and elsewhere in Alaska

Despite a widely scattered set of ages, we are still able to draw broad conclusions regarding glacial chronology in the Donnelly Dome area: (1) at least some part of Delta moraine complex stabilized near MIS 4/3 boundary, and (2) Donnelly moraine stabilized several thousand years following peak MIS 2 glaciation. These new ^{10}Be ages from the north-central Alaska Range, which yield the first direct moraine chronology from the reference locality of the Donnelly and Delta glaciations, are comparable to other glacial chronologies in the Delta River valley and elsewhere in Alaska. The MIS 4 age assignment of Delta drift might indicate that the Delta glaciation occurred during MIS 4, which is in conflict with the finding of Old Crow Tephra (~140 ± 10 ka) overlying Delta age outwash, and Sheep Creek tephra reworked into alluvium thought to be associated with the Delta moraine (Begét and Keskinen, 2003). However, new work has shown that the Sheep Creek tephra is actually multiple tephras and at some locations may be as young as 80 ka (Westgate et al., 2008).

Our ^{10}Be ages may be reconciled with the tephra-based age assignments of Delta age deposits in several ways. We recognize three possibilities: 1) the drift associated with the Delta glaciation comprises drift of different ages; the drift just down-valley of the Donnelly terminal moraine was deposited during MIS 4, whereas the extensive terminal moraine near Delta Junction may have been deposited during MIS 6; 2) all Delta drift was deposited during MIS 4, and the correlation between the alluvium beneath the Old Crow Tephra and the Delta moraine is incorrect; or 3) all Delta drift was deposited during MIS 6 and our ^{10}Be ages are influenced by post-depositional exhumation. Because of the close correspondence in age between our ^{10}Be ages and those from pre-MIS 2 moraines elsewhere in the region (see below), we favor scenarios 1 or 2.

In the Nenana River valley, ~140 km west of the Delta River Valley, Dortch (2006) obtained ^{10}Be ages from landforms created during the Healy glaciation indicating that it culminated 54.6 ± 3.5 ka (all studies referred to in this discussion used the same ^{10}Be production rate, AMS standards, and ^{10}Be half life). This age assignment is similar to our seven oldest ^{10}Be ages from the Delta deposits, which average 55.6 ± 8.9 ka. These 50–60 ka ages are also similar to other locations where pre-MIS 2 drift has been dated: 53–58 ka in the western Alaska Range (Briner et al., 2005), 54–56 ka in the Ahklun Mountains, southwestern Alaska (Briner et al., 2001), and 52–55 ka in the Yukon Territory (Ward et al., 2007). Collectively, there is strong evidence that the penultimate glaciation in the Delta River valley and throughout Beringia culminated near the onset of MIS 3.

The age assignment of the Donnelly moraine at 17.3 ± 0.6 ka, which marks the culmination of MIS 2 glaciation in the Delta River Valley, postdates the global peak in MIS 2 ice volume by ~5000 years. However, the finding that alpine glaciers remained near their MIS 2 maximum positions until ~17 ka is not rare. Rather, MIS 2 terminal moraine ages of ~17–19 ka are widespread globally (Schäfer et al., 2006) as well as in Alaska (Briner and Kaufman, 2008). In the Fish Lake valley, a north-flowing drainage in the northern Alaska Range ~70 km east of the Delta River valley, Young et al. (2009) used ^{10}Be dating of moraine boulders to assign an age of ~17 ka to the terminal MIS 2 moraine. Because exposure dating of moraines constrains the timing of moraine stabilization, it is difficult to know whether these ages indicate that the maximum glacier extent was achieved just prior to ~17 ka in the northern Alaska Range, or rather that peak glaciation was reached during the global ice volume maximum 20–22 ka, but that glaciers remained near their termini for several thousand years before retreating. In any case, this first direct age control in the type locality for the Donnelly and Delta glaciations reveals synchronicity across Beringia during pulses of late Pleistocene glaciation.

Our new moraine chronosequence, combined with emerging late Pleistocene glacial chronologies from across Beringia, point to a coherent pattern of maximum late Pleistocene glaciation occurring during MIS 4/3, followed by less extensive glaciation during the latest Pleistocene (Briner and Kaufman, 2008). This pattern reveals that climate conditions in Beringia were less favorable for glacier growth during the global LGM than during earlier stadials within the late Pleistocene, similar to other arctic regions (e.g., Svendson et al., 2004). In Beringia, limited glacier expansion during the LGM has been attributed to increased aridity due to an expanded continental shelf as eustatic sea level lowered, which is compatible with relatively modest lowering of equilibrium line altitudes (e.g., Balascio et al., 2005). In addition, recent modeling results depict relatively mild temperatures in Alaska during the LGM (Otto-Bliesner et al., 2006). On the other hand, slightly higher eustatic sea level during MIS 4/3 may have led to less arid conditions across Beringia more favorable for glacier growth. In any case, despite a poor understanding of the climate conditions in Beringia during the late Pleistocene, glacial chronologies are generally coherent in depicting more extensive glaciation during MIS 4/3 than during MIS 2.

Conclusions

The influence of pre- and post-depositional processes is revealed by comparing exposure ages of several sample types: boulders, single large clasts, and gravel samples. The results produce evidence that moraine exhumation, boulder exposure, and boulder erosion occur because of intensified weathering and erosion during glacial episodes, mostly during MIS 2 and the Younger Dryas. These major phases of erosion can be explained by rapid freeze–thaw weathering of exposed bedrock and sediment from previous glaciations, perched above the ice and the consequential exposure of shielded rock fragments. The absence of ages younger than 12 ka suggests that exhumation and weathering of moraines and boulders was insignificant during the Holocene in the study area.

Cosmogenic ^{10}Be exposure ages of boulders and clasts from moraines in the Delta River valley provide the first direct age control in the reference locality for late Quaternary glaciation in the northern Alaska Range. The results indicate that at least part of the Delta moraine stabilized during MIS 4/3. This age assignment agrees with several other recently published ages for the penultimate glaciation across Beringia, but contradicts the accepted correlation of the Delta

https://doi.org/10.1016/j.yqres.2010.04.007 Published online by Cambridge University Press

glaciation with MIS 6 (Péwé, 1975). Our ^{10}Be chronology also indicates that the Donnelly moraine stabilized ~17 ka, similar to the stabilization age of other moraines in the Alaska Range.

Acknowledgments

We thank J. Larsen, L. Håkansson, and N. Young for assistance in sample preparation. Y. Axford assisted JPB with sample collection. We appreciate the thoughtful review of an early draft by R. Reger as well as constructive reviews by L. Owen, D. Froese, and D. Dethier. This study was funded by Alyaska, PG&E, and Hebrew University of Jerusalem internal fund 034-7982.

References

Balascio, N.L., Kaufman, D.S., Manley, W.F., 2005. Equilibrium-line altitudes during the Last Glacial Maximum across the Brooks Range, Alaska. Journal of Quaternary Science 20, 821–838.
Balco, G., Stone, O.H., 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 21, 2127–2135.
Begét, J.E., Keskinen, M.J., 2003. Trace-element geochemistry of individual glass shards of the Old Crow tephra and the age of the Delta glaciation, central Alaska. Quaternary Research 60, 63–69.
Benn, D.I., Evans, D.J.A. (Eds.), 1997. Glaciers and Glaciation. A Hodder Arnold Publication, London. 760 pp.
Benson, L., Madole, R., Phillips, W., Landis, G., Thomas, T., Kubik, P., 2004. The probable importance of snow and sediment shielding on cosmogenic ages of north-central Colorado Pinedale and pre-Pinedale moraines. Quaternary Science Reviews 23 (1–2), 193–206.
Bierman, P.R., 2007. Cosmogenic glacial dating, 20 years and counting. Geology 35, 479–480.
Bierman, P.R., Caffee, M.W., 2001. Slow rates of rock surface erosion and sediment production across the Namib Desert and escarpment, southern Africa. American Journal of Science 301, 326–358.
Briner, J.P., 2009. Moraine pebbles and boulders yield indistinguishable ^{10}Be ages: a case study from Colorado, USA. Quaternary Geochronology 4, 299–308.
Briner, J.P., Kaufman, D.S., 2008. Late Pleistocene mountain glaciation in Alaska: key chronologies. Journal of Quaternary Science 23, 659–670.
Briner, J.P., Swanson, T.W., Caffee, M., 2001. Late Pleistocene cosmogenic Cl–36 glacial chronology of the southwestern Ahklun Mountains, Alaska. Quaternary Research 56, 148–154.
Briner, J.P., Kaufman, D.S., Werner, A., Caffee, M., Levy, L., Manley, W.F., Kaplan, M.R., Finkel, R.C., 2002. Glacier readvance during the late glacial (Younger Dryas?) in the Ahklun Mountains, southwestern Alaska. Geology 30, 679–682.
Briner, J.P., Kaufman, D.S., Manley, W.F., Finkel, R.C., Caffee, M.W., 2005. Cosmogenic exposure dating of late Pleistocene moraine stabilization in Alaska. Geological Society of America Bulletin 117, 1108–1120.
Davis, P.T., Menounos, B., Osborn, G., 2009. Holocene and latest Pleistocene alpine glacier fluctuations: a global perspective. Quaternary Science Reviews 28, 2021–2033.
Dortch, J., 2006. Defining the timing of glaciation in the central Alaska Range using terrestrial cosmogenic nuclide and optically stimulated luminescence dating of moraines and terraces. Master's thesis, University of Cincinnati.
Dortch, J.M., Owen, L.A., Caffee, M.W., Brease, P., 2010. Late Quaternary glaciation and equilibrium line altitude variations of the McKinley River region, central Alaska Range. Boreas 39, 233–246.
Fabel, D., Fink, D., Fredin, O., Harbor, J., Land, M., Stroeven, A.P., 2006. Exposure ages from relict lateral moraines overridden by the Fennoscandian ice sheet. Quaternary Research 65 (1), 136–146.
Gillespie, A.R., Burke, R.M., Komatsu, G., Bayasgalan, A., 2008. Late Pleistocene glaciers in Darhad Basin, northern Mongolia. Quaternary Research 69 (2), 169–187.
Gosse, J.C., Phillips, F.M., 2001. Terrestrial in situ cosmogenic nuclides: theory and application. Quaternary Science Reviews 20, 1475–1560.
Gosse, J.C., Evenson, E.B., Klein, J., Lawn, B., Middleton, R., 1995. Precise cosmogenic ^{10}Be measurements in western North America; support for a global Younger Dryas cooling event. Geology 23 (10), 877–880.
Hallet, B., Putkonen, J., 1994. Surface dating of dynamic landforms — young boulders on aging moraines. Science 265, 937–940.
Hamilton, T.D., 1994. Late Cenozoic glaciation of Alaska, the geology of Alaska. In: Plafker, G., Berg, H.C. (Eds.), The Geology of North America: Boulder, Geological Society of America, vol. G-1. Geological Society of America, Boulder, Colorado, pp. 813–844.
Kaufman, D.S., Manley, W.F., 2004. Pleistocene Maximum and Late Wisconsin glacier extents across Alaska, USA. In: Ehlers, J., Gibbard, P.L. (Eds.), Quaternary Glaciations — Extent and Chronology, Part II: North America. : Developments in Quaternary Science, vol. 2B. Elsevier, Amsterdam, pp. 9–27.
Kaufman, D.S., Porter, S.C., Gillespie, A.R., 2004. Quaternary alpine glaciation in Alaska, the Pacific Northwest, Sierra Nevada, and Hawaii. In: Gillespie, A.R., Porter, S.C., Atwater, B.F. (Eds.), The Quaternary Period in the United States. : Developments in Quaternary Science, vol. 1. Elsevier Press, pp. 77–103.
Lakeman, R.T., Clague, J.J., Menounos, B., 2008. Advance of alpine glaciers during final retreat of the Cordilleran ice sheet in the Finlay River area, northern British Columbia, Canada. Quaternary Research 69, 188–200.
Lal, D., 1988. In-situ-produced cosmogenic isotopes in terrestrial rocks. Annual Reviews of Earth and Planetary Science 16, 355–388.
Marsella, K.A., Bierman, P.R., Davis, P.T., Caffee, M.W., 2000. Cosmogenic ^{10}Be- and ^{26}Al ages for the Last Glacial Maximum, eastern Baffin Island, Arctic Canada. Geological Society of America Bulletin 112, 1296–1312.
Martinson, D.G., Pisias, N.G., Hays, J.D., Imbrie, J., Moore Jr., T.C., Shackleton, N.J., 1987. Age dating and orbital theory of the ice ages: development of a high-resolution 0 to 300,000-year chronostratigraphy. Quaternary Research 27, 1–29.
Matmon, A., Schwartz, D.P., Haeussler, P.J., Finkel, R., Lienkaemper, J.J., Stenner, H.D., Dawson, T.E., 2006. Denali fault slip rates and Holocene–late Pleistocene kinematics of central Alaska. Geology 34, 645–648.
Meriaux, A.S., Sieh, K., Finkel, R.C., Rubin, C.M., Taylor, M.H., Meltzner, A.J., Ryerson, F.J., 2009. Kinematic behavior of southern Alaska constrained by westward decreasing postglacial slip rates on the Denali Fault, Alaska. Journal of Geophysical Research – Part B – Solid Earth 114, B03404 19 pp.
Narama, C., Kondo, R., Tsukamoto, S., Kajiura, T., Ormukov, C., Abdrakhmatov, K., 2007. OSL dating of glacial deposits during the Last Glacial in the Terskey-Alatoo Range, Kyrgyz Republic. Quaternary Geochronology 2 (1–4), 249–254.
Nishiizumi, K., Imamura, M., Caffee, M.W., Southon, J.R., Finkel, R.C., McAninch, J., 2007. Absolute calibration of ^{10}Be AMS standards. Nuclear Instruments and Methods in Physical Research Section B 258–403.
Otto-Bliesner, B.L., Brandy, E.C., Clauzet, G., Tomas, R., Levis, S., Kothavala, Z., 2006. Last glacial maximum and Holocene climate in CCSM3. Journal of Climate 19, 2526–2544.
Owen, L.A., Finkel, R.C., Caffee, M.W., Gualtieri, L., 2002. Timing of multiple late Quaternary glaciations in the Hunza Valley, Karakoram Mountains, northern Pakistan: defined by cosmogenic radionuclide dating of moraines. Geological Society of America Bulletin 114 (5), 593–604.
Owen, L.A., Caffee, M.W., Bovard, K.R., Finkel, R.C., Sharma, M.C., 2006. Terrestrial cosmogenic nuclide surface exposure dating of the oldest glacial successions in the Himalayan orogen: Ladakh Range, northern India. Geological Society of America Bulletin 118 (3–4), 383–392.
Owen, L.A., Robinson, R., Benn, D.I., Finkel, R.C., Davis, N.K., Yi, C., Putkonen, J., Li, D., Murray, A.S., 2009a. Quaternary glaciation of Mount Everest. Quaternary Science Reviews 28 (15–16), 1412–1433.
Owen, L.A., Thackray, G., Anderson, R.S., Briner, J.P., Kaufman, D.S., Roe, G., Pfeffer, W., Yi, C., 2009b. Integrated mountain glacier research: current status, priorities and future prospects. Geomorphology 103, 158–171.
Péwé, T.L., 1975. The Quaternary Geology of Alaska: U.S. Geological Survey Professional Paper 385. 145 pp.
Péwé, T.L., Holmes, G.W., 1964. Geology of the Mt. Hayes (D-4) quadrangle, Alaska. U.S. Geological Survey Misc. Investigations Map I-394, scale 1:63, 360.
Phillips, F.M., Zreda, M.G., Smith, S.S., Elmore, D., Kubik, P.W., Sharma, P., 1990. Cosmogenic chlorine-36 chronology for glacial deposits at Bloody Canyon, eastern Sierra Nevada. Science 248 (4962), 1529.
Porter, S.C., Swanson, T.W., 2008. ^{36}Cl dating of the classic Pleistocene glacial record in the northeastern Cascade Range, Washington. American Journal of Science 308 (2), 130–166.
Porter, S.C., Pierce, K.L., Hamilton, T.D., 1983. Late Wisconsin mountain glaciation in the western United States. In: Porter, S.C. (Ed.), Late Quaternary Environments of the United States. The Late Pleistocene, vol. 1. University of Minnesota Press, Minneapolis, pp. 71–111.
Putkonen, J., Swanson, T., 2003. Accuracy of cosmogenic ages for moraines. Quaternary Research 59 (2), 255–261.
Putkonen, J., Connolly, J., Orloff, T., 2008. Landscape evolution degrades the geologic signature of past glaciations. Geomorphology 97, 208–217.
Schäfer, J.M., Denton, G.H., Barrell, D.J.A., Ivy-Ochs, S., Kubik, P.W., Andersen, B.G., Phillips, F.M., Lowell, T.V., Schlüchter, C., 2006. Near-synchronous interhemispheric termination of the last glacial maximum in mid-latitudes. Science 312, 1510–1513.
Sharp, R.P., 1969. Semiquantitative differentiation of glacial moraines near Convict Lake, Sierra Nevada, California. Journal of Geology 77, 68–91.
Sharp, R.P., 1972. Pleistocene glaciation, Bridgeport Basin, California. Geological Society of America Bulletin 83, 2233–2260.
Sharp, R.P., Birman, J.H., 1963. Additions to the classical sequence of Pleistocene glaciations, Sierra Nevada, California. Geological Society of America Bulletin 74, 1079–1086.
Smith, J.A., Seltzer, G.O., Rodbell, D.T., Klein, A.G., 2005. Regional synthesis of last glacial maximum snowlines in the tropical Andes, South America. Quaternary International 138–139, 145–167.
Smith, J.A., Mark, B.G., Rodbell, D.T., 2008. The timing and magnitude of mountain glaciation in the tropical Andes. Journal of Quaternary Science 23 (6–7), 609–634.
Stone, J.O., 2000. Air pressure and cosmogenic isotope production. Journal of Geophysical Research 105, 23753–23759.
Svendson, J.I., et al., 2004. Late Quaternary ice sheet history of northern Eurasia. Quaternary Science Reviews 23, 1229–1271.
Ten Brink, N.W., Waythomas, C.F., 1985. Late Wisconsin glacial chronology of the north-central Alaska Range: a regional synthesis and its implications for early human settlements. In: Powers, W.R., et al. (Ed.), North Alaska Range Early Man Project: National Geographic Society Research Reports, National Geographic Society, pp. 15–32.
Thackray, G.D., Owen, L.A., Yi, C., 2008. Timing and nature of late Quaternary mountain glaciation. Journal of Quaternary Science 23, 503–508.

https://doi.org/10.1016/j.yqres.2010.04.007 Published online by Cambridge University Press

Thorson, R.M., 1986. Late Cenozoic glaciation of the northern Nenana River valley. In: Hamilton, T.D., Reed, K.M., Thorson, R.M. (Eds.), Glaciation in Alaska — the Geologic Record: Anchorage, Alaska Geological Society, pp. 171–192.
Wahrhaftig, C., 1958. Quaternary geology of the Nenana River valley and adjacent parts of the Alaska Range: U.S. Geological Survey Professional Paper, 293A. 118 pp.
Ward, B.C., Bond, J.D., Gosse, J.C., 2007. Evidence for a 55- to 50-ka (early Wisconsin) glaciation of the Cordilleran ice sheet, Yukon Territory, Canada. Quaternary Research 68, 141–150.
Westgate, J.A., Preece, S.J., Froese, D.G., Pearce, N.J.G., Roberts, R.G., Demuro, M., Hart, W.K., Perkins, W., 2008. Changing ideas on the identity and stratigraphic significance of the Sheep Creek tephra beds in Alaska and the Yukon Territory, northwestern North America. Quaternary International 178, 183–209.
Young, N.E., Briner, J.P., Kaufman, D.S., 2009. Late Pleistocene and Holocene glaciation of the Fish Lake valley, northeastern Alaska Range, Alaska. Journal of Quaternary Science 24 (7), 677–689.
Zazula, G.D., Froese, D.G., Elias, S.A., Kuzmina, S., Mathewes, R.W., 2007. Arctic ground squirrels of the mammoth-steppe: paleoecology of Late Pleistocene middens (24000–29450 14C yr BP), Yukon Territory, Canada. Quaternary Science Reviews 26, 979–1003.
Zreda, M.G., Phillips, F.M., Elmore, D., 1994. Cosmogenic ^{36}Cl accumulation in unstable landforms, 2. Simulations and measurements on eroding moraines. Water Resources Research 30, 3127–3136.