Cosmogenic $^3$He Exposure age dating of glacial and landslide deposits on Boulder Mountain, Utah

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Senior Integrative Exercise
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Abstract
The Quaternary features on the northwest slope of Boulder Mountain in south-central Utah have never been assigned absolute dates. This study determines the absolute ages of Miller Creek Blob glacial feature and two landslide deposits using cosmogenic $^3$He exposure age dating. Samples on lateral moraines have been exposed for 20,378 +/- 506 years and 19,767 ± 424 years. Exposure for drift samples range from 49,438 +/- 1,123 years to 27,842 ± 689 years. Both landslides showed a high degree of variation in exposure ages (up to 200 kyr of variation) and must be re-dated. The largest relative error for any single sample exposure age was 2.7%. Accurate dates of Quaternary deposits are vital to understanding climatic history and its affects on the landscape. Absolute ages measured in this study make it necessary to change previous maps of Boulder Mountain Quaternary deposits.

Keywords: He-3, exposure age, geochronology, Utah, Bull Lake Glaciation, Pinedale Glaciation
Introduction

The field of geomorphology suffers from a paucity of broadly applicable absolute dating techniques. Popular methods for dating landforms such as $^{14}$C dating, thermochronology, and optically stimulated luminescence are limited by the constraints of effective timescales and dateable material (Cockburn and Summerfield, 2004). However, cosmogenic nuclide exposure dating has proven useful for dating landforms on an age scale ranging from thousands to millions of years for a wide range of geologic materials. These qualities have shown cosmogenic nuclide exposure dating to be a versatile solution to the geomorphologic dating problem (Cockburn and Summerfield, 2004).

Using the cosmogenic nuclide $^3$He, absolute rather than relative dates have been assigned to debris flows (Cerling et al., 1999) and glacial moraines (Licciardi et al., 2001). Dave Marchetti of the University of Utah at Salt Lake City is currently collecting samples on Boulder Mountain in southern Utah in order to assign absolute dates to the landforms in the area (Fig. 1). The sequence of absolute dates discovered from glacial and mass wasting events in the region will culminate in a detailed understanding of the effect that Pleistocene climate had on the landscape. The current study was conducted along with Dave Marchetti in August, 2004 in an area where landforms have not previously been dated.

We test the relative ages assigned by previous work to three geomorphic features on the flanks of Boulder Mountain’s northwest corner (Fig. 2). Over the course of this work the cosmogenic dates disagree with the relative dates. This work contributes to the revision of the chronology of Quaternary landscape change on Boulder Mountain.
Fig. 1. a) Map of Colorado Plateau with location of Boulder Mountain (revised from Fillmore (2000)). b) Boulder Mountaintop with Quaternary features numbered (revised from Flint and Denny (1958) and Williams and Hackman (1971)):
1. Miller Creek Drift Lobe (MCB, MCR)
2. Aquarius Ranger Station Slide (PCS)
3. Trailer Park Slide
4. Bulberry Creek Fan
5. Colman Slide
6. Donkey Creek Drift Lobe
7. Fish Creek - Grover Drift Lobe
8. Singletree Slide
9. Pleasant Creek Drift Lobe
10. Boulder Creek Drift Lobe
Figure 2. a) Boulder Mountaintop with location of field site. b) Field site: Government Point DEM image with sampling locations numbered:

1. Trailer Park Slide
2. Aquarius Ranger Station Slide (Pine Creek Slide)
3. Miller Creek Drift Lobe: (Miller Creek Blob and Miller Creek Ridges)
Fillmore (2000) writes that the glacial drift on Boulder Mountain has not been directly dated with ages ranging from 70 ka to 12 ka. In the seminal work on Boulder Mountain’s quaternary history, Flint and Denny (1958) mark glacial drift lobes and landslides with various ages, but these ages are determined according to subjective means. Flint and Denny (1958) assign glacial landforms to Bull Lake Stage and Pinedale Stage. Neither of these stages are given numerical ages. Instead, their relative ages are determined by relative amounts of CaCO$_3$ or caliche observed in soils as well as relative weathering usually discerned on each glacial feature. Flint and Denny (1958) admit the difficulty of dating mass wasting features and assign dates tentatively. Williams and Hackman (1971) map Boulder Mountain with slightly more precision. A large, heavily weathered landslide off the northwest edge of the mountain is acknowledged for the first time, and a tongue of glacial drift that Flint and Denny (1958) give one uniform age is reassigned to two glacial stages.

Using cosmogenic nuclides, Repka et al. (1997) dated outwash on river terraces north of Boulder Mountain. Their work suggests that the climate on the western edge of the Colorado Plateau during the Pleistocene was more complex than previously thought (Fillmore, 2000). The current project dates the glacial drift and moraines themselves rather than inferring glacial history from outwash terraces downstream. The simple theory of two glacial stages in the region (Flint and Denny, 1958) is no longer tenable, and the maps produced under this outdated theory must be corrected.
**Geologic Setting**

The Aquarius Plateau stands on the eastern margin of the southern half of the High Plateaus region. The High Plateaus form the eastern front of the Colorado Plateau in Utah. This region is broken by a series of normal faults that strike generally north-south and transition into the extensional Basin and Range Province (Maldonado et al., 1997). The Paunsaugunt normal fault is the first of these faults on the western edge of the Aquarius Plateau. The Thousand Lake fault zone cuts a path through the Aquarius Plateau forming the steep western face of Boulder Mountain and Thousand Lake Mountain (Fig. 3). On its eastern edge, the Aquarius Plateau is bounded by the crustal shortening structures of the Waterpocket Fold as well as the Circle Cliffs and Miners Mountain uplifts. These features express blind thrust and reverse faulting (Davis, 1999).

Structural shortening features east of the Aquarius Plateau formed ~70 Ma during the Laramide Orogeny (Davis, 1999). The Aquarius Plateau is composed of a sequence of Permian through Tertiary marine and lake sediments uplifted and protected from weathering by an igneous cap (Flint and Denny, 1958). These volcanics erupted ~23 Ma (Rowley et al., 1998), and were followed by normal faulting west of the Aquarius Plateau as early as ~20 Ma (Maldonado et al., 1997). To the west, extensional block faulting commenced in the Basin and Range province by 17 Ma (Best and Hamblin, 1978). To the east, slow uplift of the Colorado Plateau occurred at 20 – 5 Ma, and fast uplift has been taking place from 5 Ma – present (Sahagian et al., 2002). Among the High Plateaus, Aquarius Plateau stands out as the sole location exhibiting effects of glaciation (Fillmore, 2000). Moraines and drift from more than one glacial maximum can be found on Boulder
Figure 3. Map of the Colorado Plateau in southern Utah with structural features and inset locator map.
Mountain, the highest elevation on the Aquarius Plateau (Flint and Denny, 1958; Richmond, 1965).

The Pleistocene climate of the region is not well understood. For example, it is interesting to note that the Henry Mountains show no evidence of glacial activity despite the fact that they lie within 30 miles east of Boulder Mountain and rise to an equal elevation of ~11,000 feet. Fillmore (2000) suggests that this could have been caused by a “rain shadow effect” in which clouds from the west dropped heavy precipitation over the high plateaus, leaving little moisture in their wake to the east. However, this does not explain why the La Sal Mountains even farther to the east show evidence of glaciation.

In any case, Boulder Mountain’s broad area at high elevation provided excellent conditions for the formation of an ice cap (Gould, 1939). As the ice cap gained mass it spread out over the surface of Boulder Mountaintop until it drained over the edge of the plateau or thinned to stagnation. Drift lobes extend outward from Boulder Mountain between plateau promontories (Fig 1). Several prominent slope failures include broad, mantling debris flows, narrow landslides, and slump blocks (Flint and Denny, 1958). These lie along the periphery of Boulder Mountain, an area currently considered high risk for landsliding (Williams, 1972).

Cosmogenic $^3$He Exposure Dating

Cosmogenic nuclide dating was first employed for in-situ terrestrial (as opposed to atmospheric or meteoric) dating in 1955. However, the technique has been developed for the most part over the past 30 years with the last five years seeing a vigorous bloom in the number of papers applying cosmogenic dating to geomorphological applications
The attractiveness of cosmogenic dating lies in the widespread presence of cosmogenic target elements in ordinary minerals and the fact that cosmogenic nuclides can remain trapped in those minerals for millions of years (Cockburn and Summerfield, 2004; Schafer et al., 1999).

As ordinary terrestrial atoms are bombarded by cosmic rays they change into new isotopes called cosmogenic nuclides. Accumulations of cosmogenic nuclides indicate exposed surfaces because the effect of cosmic rays weakens greatly below a few centimeters from the rock surface (Cerling and Craig, 1994b). The dating technique is based on the premise that larger accumulations of cosmogenic nuclides mean greater exposure time. Cosmogenic nuclides are produced at specific rates. The calibration of production rates allows geomorphologists to determine exact exposure ages (Kurz, 1986; Nishiizumi et al., 1986).

Yet, it is first necessary to understand the process of cosmogenic nuclide production. Cosmic rays are generated in active cosmic bodies such as supernovae as well as the interiors of ordinary stars (Schlickeiser, 2002; Sokolsky, 1989). However, the generation process and the acceleration mechanism for cosmic rays are still not well understood (Schlickeiser, 2002).

Sunspot cycles and variations in solar activity affect the cosmic ray flux to the earth (Neidermann, 2002). Also, a fraction of cosmogenic rays are solar in origin, but these are three orders of magnitude less energetic than galactic cosmogenic rays and therefore do not play as significant a role in the cosmic ray flux (Cerling and Craig, 1994b). It is the geomagnetic field that poses the greatest obstacle to the cosmic ray flux.
Due to the shape of the geomagnetic field there is a greater cosmic ray flux at higher latitudes (Cerling and Craig, 1994b). Gosse and Phillips (2001) explain the corrections that should be made for latitude as well as the corrections for variations in the geomagnetic field, solar activity and sunspot cycles over time. Calibrating production rates for altitude is also important since cosmic ray flux to the earth’s surface decreases with prolonged travel through the atmosphere (Lal, 1991).

The particle composition of cosmic rays at atmospheric entry is ~87% protons and ~12% particles (Neidermann, 2002). An particle consists of a helium nucleus which is simply two protons and two neutrons. As these particles collide with atmospheric elements spallation reactions take place causing a secondary shower of particles (Neidermann, 2002). Spallation reactions occur when high speed particles collide with nuclei, breaking off protons and neutrons. An example of a widely recognized spallation reaction is the formation reaction of $^{14}$C. Neutrons are usually more likely to break off a nucleus than protons during spallation reactions (Neidermann, 2002). Also, neutrons can travel greater distances than protons unaffected by other charged particles. Thus, the secondary shower of particles consists mostly of neutrons (Neidermann, 2002).

Most terrestrial cosmogenic nuclides are formed by further spallation reactions as the secondary shower of neutrons bombard the Earth’s surface (Neidermann, 2002). The cosmogenic nuclide of helium, $^3$He, is found in relative abundance because $^3$He and $^3$H (which eventually becomes $^3$He through $^3$H - decay) can be spalled off of the nuclei of all elements except for hydrogen (Neidermann, 2002). Smaller amounts of cosmogenic $^3$He are produced through a process called negative muon capture (Neidermann, 2002).
However, non-cosmogenic $^3\text{He}$ can also be created by thermal neutron capture. Unlike spallation reactions which are endothermic (Lal, 1987), thermal neutron capture is an exothermic reaction. Thermal neutrons are produced by the decay of uranium and thorium. When lithium is present, $^3\text{He}$ can be formed through the thermal neutron reaction:

$$^6\text{Li} (n, \beta) ^3\text{H} (\gamma) ^3\text{He}$$

where $n$ is the projectile, $\beta$ is a by-product, and $^3\text{H}$ undergoes $\gamma$ decay to form $^3\text{He}$ (Dickin, 1995). Uranium-thorium decay also produces particles independent of lithium presence. Terrestrial particles immediately acquire electrons to become $^4\text{He}$. It is therefore possible to distinguish the amount of cosmogenic $^3\text{He}$ from amount of thermal $^3\text{He}$ if the amount of radiogenic $^4\text{He}$ is found (Licciardi et al., 1999a). Since it is possible to produce cosmogenic $^4\text{He}$ in small amounts, it is necessary to measure radiogenic $^4\text{He}$ from unexposed rock.

The rate at which $^3\text{He}$ accumulates in rock is determined by counting nuclides found in previously dated landforms such as lava flows that are exposed to cosmic rays as they form (Cerling and Craig, 1994a). $^3\text{He}$ production rate is determined to be $\sim 116$ atoms/g/year at sea level between the latitudes $39^\circ$ N and $46^\circ$ N. (Cerling and Craig, 1994a; Cerling and Craig, 1994b; Licciardi et al., 1999b).

With the discovery of production rates it is possible to use cosmogenic nuclides to determine the exposure ages of an extremely wide variety of landforms ranging from cinder cones to meteorite impacts to river terraces to the nose of the sphinx at Giza (Cerling and Craig, 1994b; Cockburn and Summerfield, 2004). A tight crystalline structure is required to ensure that cosmogenic helium is not lost through diffusion over
time since its formation. Among the most common cosmogenic nuclides, helium is the only nuclide that cannot be used to date quartz due to problems of diffusion. Still, the high production rate of helium is particularly useful for dating olivine, pyroxene, hornblende, and garnet target minerals (Cockburn and Summerfield, 2004).

Cosmogenic $^3$He Dating of Mass Movements and Glacial Phenomena

Cerling et al. (Cerling et al., 1999) used $^3$He from olivine phenocrysts in basalt to date a series of debris fans draining into the Colorado River. Since cosmogenic $^3$He is only produced in significant amounts near the surface of exposed rock (Kurz, 1986), it is possible to date debris flows by collecting samples off the surfaces of exposed boulders that have not been reburied since the exposure event. $^3$He ages were confirmed with $^{14}$C dates to assign absolute ages to the separate debris flows (Cerling et al., 1999).

Licciardi et al. (2001) combined $^3$He and $^{10}$Be dating to constrain the age of the late Pinedale glacial maximum. Boulders were sampled from moraines. This technique assumes no pre-exposure for samples. Ice either scraped away pre-exposed surfaces or exhumed buried rock, and exposure commenced with ablation. Sample suitability was determined by a number of criteria. Sample boulders were either glacially striated or showed surfaces that lacked pitting or spalling to ensure that negligible material had been lost since glacial cover due to weathering including the effects of fire. Corrections for shielding from cosmogenic rays due to sample thickness or surrounding terrain were also taken into account. The effect of snow cover on exposure age was also treated and a correction figure given (Licciardi et al., 2001).
Licciardi et al. (2001) also used olivine phenocrysts as the source for $^3$He. However, cosmogenic $^3$He exposure dating has also been conducted from pyroxene phenocrysts (Cockburn and Summerfield, 2004). Schafer et al. (1999) showed that pyroxene retains cosmogenic He nuclides for at least 10 Ma.

Field Site

The field site is within the Government Point quadrangle on the northwest corner of Boulder Mountain (Fig 2). While there is a good mix of both mass movement and glacial features on all sides of Boulder Mountain, the field site was chosen due to the peculiarity of its primary glacial feature and the proximity of slope failures that could be dated with limited time in the field.

The glacial feature consists of the Miller Creek Drift Lobe which drops out of the steep terrain of Miller Creek Cove to form the kidney-shaped feature on the floor of Dark Valley called The Potholes. We refer to this feature as the Miller Creek Blob (MCB) (Fig. 4). The MCB feature formed a unique drift lobe of the kind that have been observed dropping from great heights and stagnating abruptly due to a lack of sufficient ice mass at the base of the slope (Fig. 5) (Sharp, 1988). It is possible to mistake MCB for a landslide deposit, but the glacial origin of MCB is substantiated by the fact that ridges cordoning MCB at the mouth of Miller Creek Cove are much too high to be levees from a mass movement. We name these ridges Miller Creek Ridges (MCR).

Despite its relatively small size among the Boulder Mountain landslides, the Aquarius Ranger Station Slide cuts a prominent figure in aerial and topographic images with its sharply defined slump scarp and bulging toe (Fig 2). The Aquarius Ranger
Figure 4. Sampling sites (see figure 2b for location):

a) Aquarius Ranger Station Slide - Pine Creek Slide.
b) Miller Creek Drift Lobe: Miller Creek Blob and Miller Creek Ridges.
c) Trailer Park Slide.
(See table 3 for sample coordinates)
Figure 5. a. Aerial photograph of Miller Creek Drift Lobe showing the confusing array of discontinuous terminal moraines (TM) and well-defined young lateral moraines (LM). Striation marks observed on Boulder Mountaintop suggest that ice descended from the Boulder Mountain ice cap rather than from the apparent cirque to form Miller Creek Blob.

Figure 5. b. What did Miller Creek Blob look like during MIS-2? This Austin Post oblique aerial photograph of an Ellsmere Island piedmont bulb shows similar characteristics to MCB. Note the outer moraines, marked M, that show familiar discontinuity (Sharp, 1988).
Station Slide is referred to here as Pine Creek Slide (PCS). Nearby, we sampled and named an undulating, boulder-strewn deposit Trailer Park Slide (TPS).

**Methods**

*Field Methods*

Seventeen boulders were sampled within the field site. In order to collect cosmogenic material from boulders that had not been buried or moved subsequent to their original exposure, all boulders sampled were larger than 1m in diameter and height and preferably perched on ridge crests. Boulders showing large amounts of pitting or spalling were also avoided since these boulders would have lost their original exposure surfaces (Fig. 6).

Sample material was removed with hammers, chisels, and a portable airless jackhammer. Samples were stripped from boulders to a maximum depth of 4 cm below the rock surface. The latitude, longitude, and elevation of boulders were recorded with a handheld GPS receiver and topographic maps (Appendix Table 3). A clinometer was used to measure the shielding angles of surrounding topography. Several samples of shielded boulder were collected by Dave Marchetti for the purpose of distinguishing amounts of cosmogenic $^3$He from amounts of thermal $^3$He. Two samples failed to provide mineral separates in lab.

*Laboratory Methods*

Helium is found as an excess rare gas in the spodumene component of pyroxene ($\text{LiAlSi}_2\text{O}_6$) (Mamyrin and Tolstikhin, 1984). In order to separate the pyroxene, samples were pulverized in a rock crusher and then sieved to collect 400 mL of grains from the
Figure 6. Sampling locations:

a. Old debris, old till, or bedrock? The sampling site of MCB - 05 looking due east into Miller Creek Cove

b. Typical sample MCB - 01 on a ridge of Miller Creek Blob. The boulder is 2.5 meters across.

c. In search of man-sized rocks: despite the old age of the deposit, the boulders on Trailer Park Slide show tenacious resistance to weathering.
0.5 – 2 mm size fraction. The basalt on Boulder Mountain is highly magnetic. Magnetite was removed by thoroughly running samples over with a hand magnet. The remainder of the sample was immersed in Lithium meta-Tungstate heavy liquid ($\rho = 3.0$). Minerals that sank through the heavy liquid were frozen with liquid nitrogen so that buoyant minerals adhering to the surface could be poured off (spodumene density = 3.2). The remainder was rinsed with HCl 10% to remove residual carbonate. Finally, the surviving mineral grains were treated in HF 10% in a sonicator for four hours to etch their surfaces and dissolve tenacious matrix coating the grains. It is necessary to collect between 200-500 mg of spodumene in order to obtain a representative atomic count. $^3$He and $^4$He concentrations were measured at the University of Utah Noble Gas Laboratory on a MAP-251 noble gas mass spectrometer.

**Results**

Table 1 gives calculated exposure ages. The $^3$He/$^4$He value from shielded samples was averaged at 2.1* $10^7$. Amounts of measured $^3$He and $^4$He with uncertainties, discussion of the corrections used to determine exposure ages, and propagation errors for determining uncertainties are provided in the appendix.

**Discussion**

*Marine Isotope Stage (MIS) Correlation of Exposure Ages*

In order to determine the meaning of exposure ages, it is useful to locate these exposure ages in the climate record. Marine isotope stages (MIS) determined by Shackleton and Opdyke (1973) through the correlation of paleomagnetic data with
Table 1. Exposure ages of Boulder Mountain samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Exposure Age (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCS-test</td>
<td>60,103 ± 1,621</td>
</tr>
<tr>
<td>PCS-01 rr cr</td>
<td>130,248 ± 3,281</td>
</tr>
<tr>
<td>PCS-02</td>
<td>54,702 ± 1,447</td>
</tr>
<tr>
<td>TPS-01</td>
<td>525,054 ± 11,071</td>
</tr>
<tr>
<td>TPS-02</td>
<td>534,410 ± 10,884</td>
</tr>
<tr>
<td>TPS-03</td>
<td>347,755 ± 7,574</td>
</tr>
<tr>
<td>MCR-02 rr</td>
<td>20,378 ± 506</td>
</tr>
<tr>
<td>MCR-03 rr</td>
<td>19,767 ± 424</td>
</tr>
<tr>
<td>MCB-01</td>
<td>49,438 ± 1,123</td>
</tr>
<tr>
<td>MCB-02</td>
<td>27,842 ± 689</td>
</tr>
<tr>
<td>MCB-03</td>
<td>NO MINERAL SEPARATE</td>
</tr>
<tr>
<td>MCB-04</td>
<td>NO MINERAL SEPARATE</td>
</tr>
<tr>
<td>MCB-05</td>
<td>410,170 ± 8,789</td>
</tr>
<tr>
<td>MCB-06</td>
<td>28,527 ± 667</td>
</tr>
<tr>
<td>MCB-07</td>
<td>32,440 ± 809</td>
</tr>
<tr>
<td>MCB-08</td>
<td>31,430 ± 732</td>
</tr>
<tr>
<td>MCB-09</td>
<td>42,457 ± 940</td>
</tr>
</tbody>
</table>
oxygen isotope analysis from foraminifera were used to correlate cosmogenic ages with climatic stages. The Bull Lake glaciation is the alpine glaciation correlated with the Illinoisan ice sheet advance which is associated with MIS – 6 (~195 – 128 ka) (Phillips et al., 1997). The Pinedale glaciation is the alpine glaciation correlated with the Wisconsinan ice sheet advance and the late glacial maximum (LGM) which are associated with MIS – 2 (~32 – 13 ka) (Colman and Pierce, 1992).

Of the Miller Creek glacial features, no dates fell within the age range of the Bull Lake stage. Four of seven MCB dates fall within MIS – 2. Anderson et al. (2000) date the last full glaciation on the Colorado Plateau to ~27.5 – 17 ka, and Phillips et al. (1997) date the original Pinedale terminal moraines at Wind River, Wyoming from ~23 – 14 ka. The two MCR dates fall comfortably within this range. Two MCB samples and two PCS samples lie in interglacial MIS – 3. Sample PCS – 01 dates to MIS – 6, and all remaining samples are older than Bull Lake age.

**Miller Creek Samples (MCB and MCR)**

Flint and Denny (1958) map the Miller Creek Drift Lobe as Bull Lake in age. From observations on the ground we found that the southern and western outer rim of MCB shows increased prevalence of carbonate rinds precipitated on boulders and in the soil as well as a rounded and gently sloping topography that contrasts with the inner soil and topography of the feature. Williams and Hackman (1971) agree with this pattern, mapping the outer edge of the MCB as Bull Lake and the inner component of the drift lobe as early Pinedale in age (Fig 3). Nevertheless, cosmogenic dates do not show Bull Lake ages.
While the oldest MCB exposure age, MCB – 05, is in fact much older than Bull Lake, it was unclear whether this sample was located on the drift lobe or collected from bedrock derived boulders beyond the lobe (Fig 5). Williams and Hackman (1971) map this area as the margin between bedrock tertiary lava flows, pre-Bull Lake landslide deposits, and Bull Lake glacial drift. It is possible that the boulder field from which MCB – 05 was sampled is bedrock that was incised by the Dark Valley Draw ~410 ka. Nevertheless, the boulder field morphology more closely resembles landslide debris than stream-incised bedrock (Fig. 6a). If drift of a similar old age were found elsewhere around Boulder Mountain, MCB – 05 could represent the tip of very old overrun till. Yet, without this evidence, we conclude that MCB – 05 represents very old landslide debris. This may suggest that Miller Creek Cove was scoured out by landslides before it ever hosted glacial ice.

On the apparently older outer rim of MCB, sample MCB – 01 is dated much older than Pinedale but much younger than Bull Lake. Samples MCB – 03 and MCB – 04 were collected nearby, but no dateable mineral separates were obtained and no ages were discovered. Sample MCB – 09, the sample with the closest age to MCB – 01 is found close to the mouth of Miller Creek Cove and therefore provides no evidence for a concentric rim of an older outer moraine. All other MCB samples are closely aged and fit nicely in MIS – 02 if not the early Pinedale (Anderson et al., 2000; Shackleton and Opdyke, 1973).

The lack of soil carbonate along with the steep slopes and sharp crests of the Miller Creek Ridges hints toward a young age. MCR sample exposure ages fit in the Pinedale even more appropriately than MCB ages (Phillips et al., 1997). In addition to their
morphology and age, the ridges consist of unconsolidated material with no sign of bedrock outcroppings. Evidence conclusively indicates that MCR samples are LGM lateral moraines.

Flint and Denny (1958) recognize that the portion of Miller Creek Drift Lobe lying in Miller Creek Cove has been removed to a large extent by landsliding. It is possible that landsliding could have taken place before and after Bull Lake glaciation especially with the relatively wet and warm interstadials occurring during MIS – 3 (Voelker, 2002). These samples might have been exposed during MIS – 3 landsliding and then buried and re-exhumed by Pinedale ice. There are not yet enough dates from other Boulder Mountain drift lobes to suggest that these older ages represent the inception of Pinedale glaciation during the latter part of MIS – 3.

Evidence points to a much younger age for the Miller Creek Drift than previously thought. Cosmogenic nuclide ages show that MCB was younger than assumed by Flint and Denny (1958). Without data from outer rim samples MCB – 03 and MCB – 04, it is not exactly clear how the outer rim of MCB should be dated. However, part of the drift is conclusively LGM in age due to the young ages of the MCR lateral moraines.

**Pine Creek Slide**

Flint and Denny (1958) do not assign a specific age to Pine Creek Slide. Williams and Hackman (1971) map the slide as Pinedale in age. None of the three PCS exposure ages match the Pinedale. The sharply cut slump scarp seems to indicate a young age for the slump event. It is possible that slope failures subsequent to the original slope failure keep
the scarp face fresh, yet no evidence of continued retreat of the scarp face is found in the
field.

Given the thin crust of rock affected by cosmic rays, it seems highly unlikely that all
three samples saw exposure previous to the slumping event. Even if this were true, it
would still be difficult to determine the date considering the conflict between the younger
PCS ages and the older PCS age. Did the slump occur \(\sim 60\) ka and one sample was pre-
exposed? Or did the slump occur \(\sim 130\) ka and the two other samples have seen an
unusual degree of weathering? Could it be that the slump is \(\sim 130\) ka and that the two
other boulders have been moved or buried and re-exhumed?

Field observations show that PCS – test was threatened by the fact that its flat top
surface could have spent time under soil cover. Neither PCS – test nor PCS – 02 showed
signs of unusual amounts of weathering. Employing the methodology of Flint and Denny
(1958), we observed that carbonate was absent from the soils on Pine Creek Slide. These
observations seem to indicate a young age for the slump. While the dates disagree with
the Pinedale age of Williams and Hackman (1971), they also disagree with each other.
The cosmogenic dating of this feature is therefore inconclusive. If a greater number of
samples were collected from a broader area on PCS a definitive age might be found.

*Trailer Park Slide*

It is interesting that in their extensive survey, Flint and Denny (1958) pay no attention
to the immense deposit we call Trailer Park Slide. They map the massive wasting feature
as bedrock. On the ground it is clear that the area does not consist of bedrock: large
boulders are curiously stranded on the slopes of erratically spaced, well-rounded knolls (Fig. 6c).

Williams and Hackman (1971) map the area correctly as landslide debris. They assign three relative ages to the features in the vicinity: pre-Bull Lake age, Bull Lake age, and Pinedale age. The cosmogenic exposure ages are more than two and three times that age. The variation in age between the ~500 ka samples and the ~300 ka sample probably indicates that there is more than one debris flow blanketing this area. The younger boulder, TPS – 03 was part of a younger mass movement that did not extend as far as the older debris flow that carried TPS – 01 and TPS – 02. More sampling in this area might conclusively constrict the ages of these different slope failures.

Conclusion

In the most detailed survey of the quaternary features on Boulder Mountain, Flint and Denny (1958) employ conjectural, relative ages for glacial features and slope failures. In their compilation map of the Salina Quadrangle, Williams and Hackman (1971) include a more precise picture of the material and variety of ages for features lying off the northwest corner of Boulder Mountain. Still, both surveys are unable to provide absolute dates.

Cosmogenic $^3$He dating was used to date three geomorphic features on Boulder Mountain. Our dates suggest that the relative ages assigned by Flint and Denny (1958) and Williams and Hackman (1971) should be reconsidered. The Miller Creek Drift Lobe exhibits exposure ages markedly younger than previously thought. No Bull Lake ages were found on this feature and lateral moraines of ~20 – 19 ka were identified. Pine
Creek Slide gave exposure ages far older than its mapped Pinedale age. However, the dates discovered at Pine Creek Slide, ~55 ka, ~60 ka, and ~130 ka do provide a decisive new age for the slump event. Finally, Trailer Park Slide was found to be far older than it had previously been mapped, giving ages of ~530 ka and ~350 ka rather than Bull Lake age (~189 – 132 ka) (Phillips et al., 1997).

With future extensive cosmogenic $^3$He dating, the simplistic notion of two stages of Pleistocene glaciation on the Colorado Plateau might possibly be undermined. If they are carefully sampled, the larger landslides and more extensive glacial deposits on the north, south, and east sides of Boulder Mountain together will provide complex absolute chronologies of landslide sequences and glacial maxima. The general consistency of ages found across MCB show the feasibility of employing cosmogenic $^3$He exposure dating for dating the rest of Boulder Mountain’s quaternary features. Once a sufficient dataset is compiled, the dates measured from glacial and landslide features on Boulder Mountain will provide interesting insight into the relationship of climate change to landscape alteration. The re-writing of Boulder Mountain’s past will be illuminating for our understanding of the quaternary history of the Colorado Plateau.
Acknowledgements

This project was made possible by Carleton College’s Bernstein Endowment. With gratitude, I acknowledge my advisor Bereket Haileab for assistance in arranging my field and lab positions in Utah. His eagerness to provide for my future will be recalled with copious appreciation through whatever discipline I pursue. This project would not have been possible without Dave Marchetti of the University of Utah at Salt Lake City who organized this project and provided me with excellent lessons in quality musical tastes, washboard SUV driving, politics, and of course, geomorphology. Special thanks for the hospitality, mentoring, and company of John Dohrenwend and Paisley as well as Scott Hynek, Ben Passey, Matt Newguy, and a gracious circle of associated Utahans.
References


Fillmore, R., 2000, The geology of the parks, monuments, and wildlands, of southern Utah: Salt Lake City, University of Utah Press, 268 p.


Lal, D., 1987, Production of \(^3\)He interrestrial rocks: Chemical Geology, v. 66, p. 89-98.


Williams, P. L., 1972, Map showing landslides and areas of potential landsliding in the Salina Quadrangle, Utah: U. S. Geological Survey.

## Appendix

Table 2 provides the following data:

A) Sample designation (‘rr’ indicates that the sample has been rerun after an unsuccessful trial)

B) Number of $^3$He atoms / gram

C) Mass spectrometer uncertainty for $^3$He atomic count

D) Number of $^4$He atoms / gram

E) Mass spectrometer uncertainty for $^4$He atomic count

F) $^3$He/$^4$He value for shielded sample

G) Amount of cosmogenic $^3$He: determined by equation given in corrections section of appendix

H) Production rate of cosmogenic $^3$He with altitude, latitude, and shielding taken into account.

I) Exposure age

J) Relative age error determined by the equation given in error section of appendix

K) Absolute age error determined by (Column I)*(Column J)
### Table 2. Data from which exposure age was discovered with error and correction figures (see appendix for explanation)

<table>
<thead>
<tr>
<th>Sample</th>
<th>3He atoms / g ±</th>
<th>4He atoms / g ±</th>
<th>Correction 3/4</th>
<th>cosmogenic 3He P. rate atoms/g/yr</th>
<th>exposure age ± relative</th>
<th>± absolute</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCS-test</td>
<td>5.59E+07 ± 1.5E+06</td>
<td>2.73E+13 ± 2.7E+11</td>
<td>2.1E-07</td>
<td>5.03E+07</td>
<td>836</td>
<td>60,103</td>
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<tr>
<td>PCS-01 rr cr</td>
<td>1.16E+08 ± 2.9E+06</td>
<td>2.93E+13 ± 2.9E+11</td>
<td>2.1E-07</td>
<td>1.10E+08</td>
<td>845</td>
<td>130,248</td>
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<td>PCS-02</td>
<td>5.22E+07 ± 1.4E+06</td>
<td>2.48E+13 ± 2.5E+11</td>
<td>2.1E-07</td>
<td>4.70E+07</td>
<td>859</td>
<td>54,702</td>
</tr>
<tr>
<td>TPS-01</td>
<td>3.56E+08 ± 7.5E+06</td>
<td>1.55E+13 ± 1.7E+11</td>
<td>2.1E-07</td>
<td>3.53E+08</td>
<td>672</td>
<td>525,054</td>
</tr>
<tr>
<td>TPS-02</td>
<td>3.62E+08 ± 7.3E+06</td>
<td>1.49E+13 ± 1.6E+11</td>
<td>2.1E-07</td>
<td>3.59E+08</td>
<td>672</td>
<td>534,410</td>
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<tr>
<td>TPS-03</td>
<td>2.38E+08 ± 5.2E+06</td>
<td>1.69E+13 ± 1.8E+11</td>
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<td>2.35E+08</td>
<td>674</td>
<td>347,755</td>
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<tr>
<td>MCR-02 rr</td>
<td>2.18E+07 ± 5.2E+05</td>
<td>1.84E+13 ± 2.8E+11</td>
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<td>1.79E+07</td>
<td>881</td>
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<tr>
<td>MCR-03 rr</td>
<td>2.17E+07 ± 4.4E+05</td>
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<td>1.76E+07</td>
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<td>19,767</td>
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<td>MCB-01</td>
<td>4.70E+07 ± 1.0E+06</td>
<td>2.65E+13 ± 2.6E+11</td>
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<td>4.15E+07</td>
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<td>49,438</td>
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<tr>
<td>MCB-02</td>
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<td>2.33E+07</td>
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<td>MCB-05</td>
<td>3.40E+08 ± 7.3E+06</td>
<td>2.80E+13 ± 2.8E+11</td>
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<td>3.35E+08</td>
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<tr>
<td>MCB-06</td>
<td>2.89E+07 ± 6.5E+05</td>
<td>2.24E+13 ± 2.2E+11</td>
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<td>2.43E+07</td>
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<td>MCB-07</td>
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<td>2.46E+13 ± 2.5E+11</td>
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<td>2.81E+07</td>
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<td>MCB-08</td>
<td>3.20E+07 ± 7.2E+05</td>
<td>2.29E+13 ± 2.3E+11</td>
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<td>2.73E+07</td>
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<td>MCB-09</td>
<td>3.90E+07 ± 8.6E+05</td>
<td>1.05E+13 ± 1.0E+11</td>
<td>2.1E-07</td>
<td>3.68E+07</td>
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<td>42,457</td>
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### Table 3. Sample locations, NAD27 Datum

<table>
<thead>
<tr>
<th>Sample</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Elevation (m)</th>
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<td>PCS-test</td>
<td>38.19685</td>
<td>111.55876</td>
<td>2780</td>
</tr>
<tr>
<td>PCS-01 rr cr</td>
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<td>111.55916</td>
<td>2784</td>
</tr>
<tr>
<td>PCS-02</td>
<td>38.20133</td>
<td>111.56368</td>
<td>2826</td>
</tr>
<tr>
<td>TPS-01</td>
<td>38.23956</td>
<td>111.59767</td>
<td>2433</td>
</tr>
<tr>
<td>TPS-02</td>
<td>38.24303</td>
<td>111.58971</td>
<td>2433</td>
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<tr>
<td>TPS-03</td>
<td>38.24022</td>
<td>111.58954</td>
<td>2439</td>
</tr>
<tr>
<td>MCR-02 rr</td>
<td>38.14844</td>
<td>111.57561</td>
<td>2904</td>
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<tr>
<td>MCR-03 rr</td>
<td>38.148</td>
<td>111.57892</td>
<td>2855</td>
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<tr>
<td>MCB-01</td>
<td>38.42</td>
<td>111.59306</td>
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<td>MCB-02</td>
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<td>2786</td>
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<td>MCB-05</td>
<td>38.15253</td>
<td>111.5974</td>
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<td>MCB-08</td>
<td>38.15724</td>
<td>111.58359</td>
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<tr>
<td>MCB-09</td>
<td>38.15668</td>
<td>111.58279</td>
<td>2828</td>
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</tbody>
</table>
Corrections

Since samples may host both cosmogenic and thermal $^3$He, it is necessary to correct $^3$He counts in order to determine the amount of cosmogenic nuclide produced. For these corrections shielded samples were used for the equation:

$$^3\text{He}_\text{cosmo.} = ^3\text{He}_\text{total} - ^3\text{He}_\text{thermal}$$

where thermal $^3$He is determined by the equation:

$$^3\text{He}_\text{thermal} = ^4\text{He}_\text{total} \times (^3\text{He}/^4\text{He})_{\text{shielded}}$$

Rather than simply subtracting the shielded $^3$He from the total $^3$He, this equation takes into account the fact that due to radioactive decay, older samples will have larger amounts of thermal $^3$He despite the fact that the shielded ratio has remained the same (Kurz, 1986). The shielded $^3\text{He}/^4\text{He}$ was found to be 2.08E -7.

Error

The relative uncertainty is the percentage error derived from the square root of the sum of the squares for variables used to propagate the age:

$$\left(\frac{\text{relative uncertainty for } ^3\text{He}^2}{^3\text{He}} + \frac{\text{relative uncertainty for } ^4\text{He}^2}{^4\text{He}} + \frac{\text{relative uncertainty for correction}^2}{\text{correction}}\right)^{1/2}$$