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FORMATION OF BASEMENT-INVOLVED FORELAND ARCHES: INTEGRATED STRUCTURAL AND SEISMOLOGICAL RESEARCH IN THE BIGHORN MOUNTAINS, WYOMING
Faculty: CHRISTINE SIDDOWAY, MEGAN ANDERSON, Colorado College, ERIC ERSLEV, University of Wyoming
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EXPLORING THE PROTEROZOIC BIG SKY OROGENY IN SOUTHWEST MONTANA
Faculty: TEKLA A. HARMS, JOHN T. CHENEY, Amherst College, JOHN BRADY, Smith College
Students: JESSE DAVENPORT, College of Wooster, KRISTINA DOYLE, Amherst College, B. PARKER HAYNES, University of North Carolina - Chapel Hill, DANIELLE LERNER, Mount Holyoke College, CALEB O. LUCY, Williams College, ALIANORA WALKER, Smith College.

INTERDISCIPLINARY STUDIES IN THE CRITICAL ZONE, BOULDER CREEK CATCHMENT, FRONT RANGE, COLORADO
Faculty: DAVID P. DETHIER, Williams College, WILL OUMIT, University of Connecticut
Students: ERIN CAMP, Amherst College, EVAN N. DETHIER, Williams College, HAYLEY CORSON-RIKERT, Wesleyan University, KEITH M. KANTACK, Williams College, ELLEN M. MALEY, Smith College, JAMES A. MCCARTHY, Williams College, COREY SHIRCLIFF, Beloit College, KATHLEEN WARRELL, Georgia Tech University, CIANNA E. WYSHNYSZYK, Amherst College.

SEDIMENT DYNAMICS & ENVIRONMENTS IN THE LOWER CONNECTICUT RIVER
Faculty: SUZANNE O’CONNELL, Wesleyan University
Students: LYNN M. GEIGER, Wellesley College, KARA JACOBAZZI, University of Massachusetts (Amherst), GABRIEL ROMERO, Pomona College.

GEOMORPHIC AND PALEOENVIRONMENTAL CHANGE IN GLACIER NATIONAL PARK, MONTANA, U.S.A.
Faculty: KELLY MACGREGOR, Macalester College, CATHERINE RIIHIMAKI, Drew University, AMY MYRBO, LacCore Lab, University of Minnesota, KRISTINA BRADY, LacCore Lab, University of Minnesota
GEOLOGIC, GEOMORPHIC, AND ENVIRONMENTAL CHANGE AT THE NORTHERN TERMINATION OF THE LAKE HÖVSGÖL RIFT, MONGOLIA
Faculty: KARL W. WEGMANN, North Carolina State University, TSALMAN AMGAA, Mongolian University of Science and Technology, KURT L. FRANKEL, Georgia Institute of Technology, ANDREW P. deWET, Franklin & Marshall College, AMGALAN BAYASAGALN, Mongolian University of Science and Technology.
Students: BRIANA BERKOWITZ, Beloit College, DAENA CHARLES, Union College, MELLISSA CROSS, Colgate University, JOHN MICHAELS, North Carolina State University, ERDENEBAYAR TSAGAANNARAN, Mongolian University of Science and Technology, BATTOGTOH DAMDNSUREN, Mongolian University of Science and Technology, DANIEL ROTHBERG, Colorado College, ESUGEI TRANBOLD, ARANZAL ERDENE, Mongolian University of Science and Technology, AFSHAN SHAIKH, Georgia Institute of Technology, KRISTIN H. TADDEI, Franklin and Marshall College, GABRIELLE VANCE, Whitman College, ANDREW ZUZA, Cornell University.

LATE PLEISTOCENE EDIFICE FAILURE AND SECTOR COLLAPSE OF VOLCÁN BARÚ, PANAMA
Faculty: THOMAS GARDNER, Trinity University, KRISTIN MORELL, Penn State University
Students: SHANNON BRADY, Union College. LOGAN SCHUMACHER, Pomona College, HANNAH ZELLNER, Trinity University.

KECK SIERRA: MAGMA-WALLROCK INTERACTIONS IN THE SEQUOIA REGION
Faculty: JADE STAR LACKEY, Pomona College, STACI L. LOEWY, California State University-Bakersfield
Students: MARY BADAME, Oberlin College, MEGAN D’ERRICO, Trinity University, STANLEY HENSLEY, California State University, Bakersfield, JULIA HOLLAND, Trinity University, JESSLYN STARNES, Denison University, JULIANNE M. WALLAN, Colgate University.

EOCENE TECTONIC EVOLUTION OF THE TETONS-ABSOROKA RANGES, WYOMING
Faculty: JOHN CRADDOCK, Macalester College, DAVE MALONE, Illinois State University
Students: JESSE GEARY, Macalester College, KATHERINE KRAVITZ, Smith College, RAY MCGAUGHEY, Carleton College.

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INTERDISCIPLINARY STUDIES IN THE CRITICAL ZONE, BOULDER CREEK CATCHMENT, FRONT RANGE, COLORADO
Project Faculty: DAVID P. DETHIER: Williams College, WILL OUIMET: University of Connecticut

CORING A 12KYR SPHAGNUM PEAT BOG: A SEARCH FOR MERCURY AND ITS IMPLICATIONS
ERIN CAMP, Amherst College
Research Advisor: Anna Martini

EXAMINING KNICKPOINTS IN THE BOULDER CREEK CATCHMENT, COLORADO
EVAN N. DETHIER, Williams College
Research Advisor: David P. Dethier

THE DISTRIBUTION OF PHOSPHORUS IN ALPINE AND UPLAND SOILS OF THE BOULDER CREEK, COLORADO CATCHMENT
HAYLEY CORSON-RIKERT, Wesleyan University
Research Advisor: Timothy Ku

RECONSTRUCTING THE PINEDALE GLACIATION, GREEN LAKES VALLEY, COLORADO
KEITH M. KANTACK, Williams College
Research Advisor: David P. Dethier

CHARACTERIZATION OF TRACE METAL CONCENTRATIONS AND MINING LEGACY IN SOILS, BOULDER COUNTY, COLORADO
ELLEN M. MALEY, Smith College
Research Advisor: Amy L. Rhodes

ASSESSING EOLIAN CONTRIBUTIONS TO SOILS IN THE BOULDER CREEK CATCHMENT, COLORADO
JAMES A. MCCARTHY, Williams College
Research Advisor: David P. Dethier

USING POLLEN TO UNDERSTAND QUATERNARY PALEOENVIRONMENTS IN BETASSO GULCH, COLORADO
COREY SHIRCLIFF, Beloit College
Research Advisor: Carl Mendelson

STREAM TERRACES IN THE CRITICAL ZONE – LOWER GORDON GULCH, COLORADO
KATHLEEN WARRELL, Georgia Tech
Research Advisor: Kurt Frankel

METEORIC 10Be IN GORDON GULCH SOILS: IMPLICATIONS FOR HILLSLOPE PROCESSES AND DEVELOPMENT
CIANNA E. WYSNYSZKY, Amherst College
Research Advisor: Will Ouimet and Peter Crowley

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INTRODUCTION

Is some agent of tectonism necessary to explain the dramatic relief of the Front Range or are isostatic responses to erosion induced by climate change sufficient? Could a post-Eocene change in climate and integration of channel systems alone allow for increased incision to dominate this landscape and create the high relief of deeply incised canyons and large stream valleys, or is some tectonism necessary to account for the observed amount of warping, tilting, and erosion? Understanding the evolution of Front Range hillslopes in relation to late Cenozoic climatic and tectonic evolution, hillslope processes, and fundamental critical zone principles could provide a more thorough understanding of the modern geomorphology of the region.

This research used the accumulation of meteoric $^{10}$Be to determine the age of soils on hillslopes in Gordon Gulch and helps constrain interpretations of regolith transport, extending current information about the recent evolution of Colorado’s Front Range. This research contributes to research done by the Boulder Creek Critical Zone Observatory (BC-CZO) within the extents of their focus area in the Front Range and complements ongoing research in Gordon Gulch. This is the first project in the region using LiDAR analysis and meteoric $^{10}$Be as a tracer of modern hillslope evolution.

Due to its adherence to sediment within soils and its constant rate of production in the atmosphere, soil age can be constrained by using the inventory of total meteoric $^{10}$Be of a soil profile. Erosion rates and estimated soil transport rates can then be quantified (Jungers et al., 2009; Graly et al., 2010; Willenbring and von Blackenburg, 2010). Studies in North Carolina (Jungers, et al., 2009) and Australia (Fifield, et al., 2010) have traced hillslope sediment production and transport using meteoric $^{10}$Be, after which the theoretical framework of this research has been modeled. Graly et al. (2010) have shown that the concentration of meteoric $^{10}$Be in soil profiles typically conforms to one of three general profile shapes: exponentially declining, bulge, and bulge/declining (small bulge towards the top of the profile). As a soil profile evolves, so does its meteoric $^{10}$Be inventory due to soil formation and mixing processes. Given a steady state hillslope, the peak concentration of meteoric $^{10}$Be is expected in one horizon (Jungers et al., 2009). Concentration then decreases with depth, and the inventory is expected to increase downslope, creating a bulge profile. Given a young and eroding hillslope profile, the highest concentration of meteoric $^{10}$Be will still be in a single layer, but erosion prevents this concentration from moving to depths beyond near-surface (Graly et al., 2010).

GEOGRAPHIC AND GEOLOGIC SETTING

Gordon Gulch is a focus area of the BC-CZO located below and east of the modern alpine environment and late Pleistocene glacial limit and generally above and west of the deeply incised landscape that characterizes the lower portion of Front Range rivers. The degree to which the drainage basin may be affected by upstream-migrating rejuvenation from the lower portion of the range and/or alpine environmental processes (i.e. periglacial activity) is debated (Anderson et al., 2006). Gordon Gulch is a 2.75 km$^2$ catchment with exposed bedrock in various places. It can be subdivided into two primary floral and spatial environments: the north- and south-facing hillslopes (Fig. 1).

METHODS

Sample Collection and Transect Selection

Hillslope transects were chosen using a combination
cm intervals from 1-2 cm thick slots, beginning below the O-horizon (Fig. 1). Each soil profile was photographed and individual horizons were described in detail.

**Meteoric \(^{10}\text{Be}\)**

Samples were dried to remove excess moisture and hand sieved through a wire-mesh 2 mm sieve to remove coarse particles, since meteoric \(^{10}\text{Be}\) binds to particles with high surface area (Fifield, 2010). Sieved samples were ground into fine powders using a tungsten carbide shatterbox triplet.

Beryllium was extracted from samples at the Cosmogenic Nuclide Laboratory at the University of Vermont from ~0.5 g aliquots by ion exchange acid elutions in a method adapted from the flux fusion methods originally presented by Stone (1998). Atoms of \(^{10}\text{Be}\) were counted using an accelerator mass spectrometer (AMS) by the GeoCAMS group at the Center for Accelerator Mass Spectrometry (CAMS) at the Livermore National Laboratory in California.

In addition to the analysis of \(^{10}\text{Be}\) on hillslopes of unknown age, \(^{10}\text{Be}\) analysis of samples from stable reference sites (with known ages) were run to quantify how much \(^{10}\text{Be}\) has been delivered to the region by precipitation and dustfall during the past ~15,000 to 25,000 years. The analysis of meteoric \(^{10}\text{Be}\) in these stable reference sites also improves the understanding of correlations between other methods of dating, such as optically stimulated luminescence (OSL), \(^{14}\text{C}\) of charcoal layers, and in situ \(^{10}\text{Be}\), something which could expand this method of dating throughout the geologic research community. The reference sites are a known Pinedale moraine (~15 ka) at Silver Lake and a soil pit in Upper Gordon Gulch recently dated using OSL (~26 ka) (Völkel et al., 2010).

**Digital Elevation Map (DEM) Analysis**

Snow-off Light Detection and Ranging (LIDAR) data (National Center for Airborne Laser Mapping, August 2010) were used to produce digital elevation maps (DEM) for use in ArcMap. Profiles of the north- and south-facing hillslopes of Gordon Gulch were made in ArcMap using Spatial Analyst to create profiles of topographic profile and field observations of the character of hillslopes at proposed soil pit locations. Areas containing evidence of recent fire were avoided to not incorporate fire as an agent of erosion, and gullies, bedrock outcrops, trails/roads, and miners’ pits were avoided to obtain the most representative and continuous downslope path from ridge to stream. These criteria affected transect selection so that the smoothest profile on each hillslope was found to act as a proxy for overall hillslopes of the area. Samples from 9 hillslope pits (5 on the north-facing hillslope, 4 on the south-facing hillslope) were collected in 10

Figure 1. Gordon Gulch. a) air photo (1m B&W DOQ, 1999), b) shaded relief map, c) slope map. (b and c derived from ~1m resolution LiDAR data). Blue dots indicates sample pit locations.
RESULTS

Map Analysis

The air photo clearly depicts differences in present vegetation on the north- and south-facing hillslopes of lower Gordon Gulch. Vegetation is less dense on the south-facing hillslope, whereas little except vegetation is visible on the north-facing hillslope.

With the addition of a hillshade layer, the DEM depicts both elevation and topographic features. Bedrock outcrops are seen extruding 1-10 m above the dominant soil mantled hillslopes. These bedrock outcrops are characterized by shallow slope upslope and close to vertical slope on the downslope sides. The density of bedrock outcrops between the north- and south-facing hillslopes appears similar in upper Gordon Gulch. However, there is a disparity of bedrock outcrop density between the north- and south-facing hillslopes of lower Gordon Gulch (Trotta, 2010). More bedrock outcrops are present on the south-facing hillslope, and these are larger than those on the north-facing hillslope. The north-facing hillslope is dissected by numerous gullies, whereas few gullies are visible on the south-facing hillslope.

The slope map shows that many of the north-facing hillslopes have a parabolic shape in which the highest slopes are in the middle-range of the transect and the lowest slopes at the bottom of the gulch and the drainage divide. In contrast, the slope is fairly constant on the south-facing hillslope of lower Gordon Gulch, except where the slope increases in the downslope direction of bedrock outcrops and as the slope shallows near the ridge of the drainage basin.

Hillslope Profiles

The north-facing hillslope of Gordon Gulch is shorter and shallower (Fig. 2a) than the south-facing hillslope, which is longer and steeper overall (Fig. 2b). Using data drawn from ArcMap hillslope profiles (Fig. 2) beginning at the first stream encountered and ending at the drainage divide, the average slope of all north-facing hillslopes is 9.6° and of all south-facing hillslopes is 12.2°. Taking the average from the sampled pit transect and the two transects parallel on each side yields slopes of 15.0° on the north-facing hillslope and 19.6° on the south-facing hillslope. The steepest local (and non-bedrock outcrop) slopes are found in the lower half of the north-facing hillslope, as seen in the slope map, but not reflected in profile
data due to profile length averages. In lower Gordon Gulch, the north-facing hillslope profiles are characterized by a ridge creating a break in slope followed by a second slope ending at the drainage basin boundary. The first slope (before the ridge break) is parabolic in nature. Bedrock outcrops are found almost solely at the top of the profile, but above the break in slope. In contrast, the south-facing hillslope profiles are more linear than parabolic and have a more consistent slope from ridge to stream, except where broken by bedrock outcrops. Bedrock outcrops are more abundant on this slope than the north-facing hillslope, and are seen as the many small spikes on the profiles.

Meteoric $^{10}$Be

**Lower Gordon Gulch**

North-facing hillslope soils have $^{10}$Be concentrations of $5.8 \times 10^8$ atoms/g in the uppermost samples and decline to $<2 \times 10^8$ atoms/g at depths $>60$ cm (Table 1). Pits NGG-01 and NGG-05 show exponentially declining profiles with some variability and small bulges, corresponding to the highest concentration of $^{10}$Be in the B-horizon and the Cox-horizon respectively. Pits NGG-02, NGG-03, and NGG-04 show exponentially declining profiles (with some variability) with peak meteoric $^{10}$Be concentrations towards the top of the profiles. The lowest concentration for each pit is at depth, except for NGG-01 in which the lowest concentration is in the Cox2-horizon (Fig. 3a). Pits NGG-01 and NGG-02 decline to a steady concentration at depth, whereas the other three pits on this hillslope show no clear indication of approaching a steady concentration.

South-facing hillslope soils have $^{10}$Be concentrations of $2.5-5 \times 10^8$ atoms/g near the surface and decline to $<2.7 \times 10^7$ atoms/g at depths $>32$ cm (Table 1). Pits SGG-00 and SGG-02 show approximately linear declining profiles. Pit SGG-02 also shows a bulge, corresponding to the highest concentration of $^{10}$Be in the SGG-02 A/Cox1-horizon border. Pit SGG-03 shows an exponentially declining profile with a small bulge, corresponding to the highest concentration of $^{10}$Be in the Cox1-horizon. Pit SGG-01 shows no clear declining trend with a bulge corresponding to the highest concentrations of $^{10}$Be in the SGG-01A-horizon. The lowest concentration for each pit is at depth (Fig. 3b).

<table>
<thead>
<tr>
<th>Sample</th>
<th>$^{10}$Be</th>
<th>Bulk Density</th>
<th>Thickness</th>
<th>$^{10}$Be inventory</th>
<th>Total Pit Inventory</th>
<th>Soil Age</th>
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<tbody>
<tr>
<td>NGG-01-0</td>
<td>2.02E+08</td>
<td>1.4</td>
<td>10</td>
<td>1.06E+10</td>
<td>3.36E+10</td>
<td>18,300</td>
</tr>
<tr>
<td>NGG-01-8</td>
<td>8.06E+08</td>
<td>1.4</td>
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<td>1.97E+10</td>
<td>5.94E+10</td>
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<tr>
<td>NGG-01-18</td>
<td>3.85E+08</td>
<td>1.6</td>
<td>10</td>
<td>9.42E+09</td>
<td>2.82E+10</td>
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<tr>
<td>NGG-01-28</td>
<td>2.09E+08</td>
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<td>10</td>
<td>6.22E+09</td>
<td>1.87E+10</td>
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<tr>
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<td>1.20E+08</td>
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<td>NGG-01-98</td>
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<td>10</td>
<td>4.38E+09</td>
<td>1.31E+10</td>
<td>4,380</td>
</tr>
</tbody>
</table>

The Silver Lake moraine section shows a bulge profile with the highest concentration in the Bw-horizon (Fig. 4a). In the Bw-horizon at 25 cm and 35 cm deep, $^{10}$Be concentrations (1.00 x 109 and 9.34 x 108 atoms/g) are greater than twice the next highest concentration (4.35 x 108 atoms/g) in the Ej-horizon at 15 cm deep (Tab. 1). Concentrations decrease to as low as 2.28 x 107 atoms/g in the Cu-horizon and appear to be approaching a steady concentration.
The soil originally sampled for OSL dating by Jörg Völkel (2010) has a maximum $^{10}$Be concentration of $1.66 \times 10^{10}$ atoms/g near the surface. The concentration decreases to $3.13 \times 10^9$ atoms/g at depth (Tab. 1) and creates an exponentially declining profile (Fig. 4b).

Inventory and Soil Age Calculations

Meteoric $^{10}$Be inventories $I_{Be}$ (atoms/cm2) were calculated using an equation taken from Jungers et al. (2009):

$$I_{Be} = \sum(C_{Be} - C_{inh}) \rho_s h$$

where $C_{Be}$ is depth-integrated $^{10}$Be concentration, $C_{inh}$ is the inherited component of meteoric $^{10}$Be, $\rho_s$ is depth-integrated soil bulk density, and $h$ is soil thickness for each depth subsample.

Inheritance for NGG-01 was assumed as the average concentration of the three deepest samples ($1.85 \times 10^8$ atoms/g) and for NGG-02 as the average of the two deepest samples ($7.87 \times 10^7$ atoms/g). The average of the NGG-01 and NGG-02 inheritance values ($1.32 \times 10^8$ atoms/g) was used as the value for the remaining NGG pits and the SGG pits. The deepest concentration ($9.21 \times 10^7$ atoms/g) was used for the OSL-dated pit. Inheritance has not yet been taken into account for the Silver Lake moraine, because it is assumed to be minimal. Bulk soil density was measured in the field for several sample locations and other bulk density values were assumed as standard values for soil and till density. The soil thickness for each depth subsample was calculated by establishing a mid-point between sample locations. The midpoint value was added to bottom samples to account for un-collected soil.

Figure 3. Meteoric $^{10}$Be from soils on the north (a.) and south (b.) facing hillslopes of lower Gordon Gulch.

Figure 4. Meteoric $^{10}$Be concentration plots for the Silver Lake moraine (a.) and upper Gordon Gulch pit dated with OSL (b.).
Soil ages (t, in years) were calculated for each pit using an equation adapted from Graly et al. (2010):

\[ t = (-1/\lambda) \ln(1-\lambda I_{Be}/q) \]

where \( \lambda \) is the \(^{10}\text{Be} \) disintegration constant (5.1 x 10\(^{-7} \)), \( I_{Be} \) is the total inventory of \(^{10}\text{Be} \) (atoms/cm\(^2 \)), and \( q \) is the local annual meteoric \(^{10}\text{Be} \) flux (atoms/cm\(^2 \)). The value of \( q \) was estimated from Figure 4 of Graly et al. and according to an annual precipitation rate of ~45 cm in Gordon Gulch (1.1 x 10\(^6 \) atoms/cm\(^2 \)) and ~90 cm at Silver Lake (1.8 x 10\(^6 \) atoms/cm\(^2 \)), both at ~40º latitude, (Graly et al., 2010).

DISCUSSION

Meteoric \(^{10}\text{Be} \)

**Lower Gordon Gulch**

Meteoric \(^{10}\text{Be} \) data suggest that the two opposite facing hillslopes of lower Gordon Gulch are evolving differently (Fig. 3). The three soil pits in the middle of the transect on the north-facing hillslope all show declining profiles of meteoric \(^{10}\text{Be} \) concentration, suggesting an eroding slope because upper soil has been stripped from the column and \(^{10}\text{Be} \) has not had the time to concentrate in a certain layer. Potential explanations for small bulges in the lowest (NGG-01) and highest (NGG-05) profiles include their locations and horizon profiles. Pit NGG-05 is located above the major break in slope on the hillslope, and therefore represents a different environment than the four lower pits. The highest concentrations of meteoric \(^{10}\text{Be} \) in pits NGG-01 and NGG-03 are in the B-horizons.

Meteoric \(^{10}\text{Be} \) concentration data obtained from the south-facing slope differs from the concentrations from the north-facing slope. The only declining profile of the four sampled pits is the lowest (SGG-00), whereas the other profiles all contain a small bulge. Preliminary analysis suggests that perhaps the upper portion of the soil column on the south-facing hillslope has been stripped and evacuated. Had this not occurred, the profile shape on the south-facing hillslope may have resembled those on the north-facing hillslope with small bulges but overall decline profiles and greater inventories. Therefore consistent meteoric \(^{10}\text{Be} \) concentration profile shapes across the two opposite facing hillslopes of Gordon Gulch would have been seen.

Preliminary \(^{10}\text{Be} \) inventory calculations show differences between the two hillslopes (Table 1). The north-facing hillslope has a greater inventory than the south-facing hillside, particularly in the upper ~30 cm of the profiles. Preliminary soil age calculations (Table 1) correlate to inventory differences and suggest that the south-facing hillslope of lower Gordon Gulch is eroding faster than the north-facing hillslope.

**Upper Gordon Gulch**

The \(^{10}\text{Be} \) profile shows a declining profile (Fig. 4b), suggesting a young, eroding landscape. The preliminary soil age calculation drawn from an inventory of 2.43 x 10\(^10 \) atoms/cm\(^2 \) suggests an age of ~22,200 years (Table 1), matching the age obtained from OSL dating of the same soil profile (~26,500 years) (Völkel et al., 2010).

**Silver Lake**

The \(^{10}\text{Be} \) profile shows a bulge profile (Fig. 4a) with the highest \(^{10}\text{Be} \) concentration in the Bw-horizon, further emphasizing a correlation between \(^{10}\text{Be} \) and Fe-rich B-horizons from previous studies. Preliminary soil age calculations suggest an age of ~54 ka (Table 1), older than the known age of this moraine at ~15ka.

**Sources of Error**

Potential sources of error in all inventory and soil age calculations include lack of soil bulk density measurements, estimated annual \(^{10}\text{Be} \) flux rates, and estimated \(^{10}\text{Be} \) inheritance. Inheritance also comes into question when contemplating what this may mean for hillslope evolution. Additionally, some pits may not have been dug deep enough to sample the entire meteoric \(^{10}\text{Be} \) inventory, due to regolith and potential bedrock composition.
CONCLUSION

More detailed analysis of processes, soil ages, meteoric $^{10}$Be flux, and $^{10}$Be inventories will lead to further analysis and discussion of the differences between the north-and south-facing hillslopes of Gordon Gulch and more precise dating of Gordon Gulch hillslopes and the Silver Lake moraine. Preliminary age calculations show that Gordon Gulch regolith is latest Pleistocene or Holocene in age or younger, not evolving throughout the Cenozoic, and that the soil flux here is rapid.

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REFERENCES


