Testing $^{10}$Be Exposure Dating of Holocene Cirque Moraines using Glaciolacustrine Sediments in the Sierra Nevada, California

Thesis Proposal for the Master of Science Degree
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1.0 Introduction

Alpine glaciers are sensitive indicators of climate and associated climate changes (Meier, 1962); glaciers advance or retreat in response to changes in winter precipitation and summer ablation (Leonard, 1989). These glacial fluctuations effect local ecosystems, geology, and people. Temperate glaciers, like those in the Western Cordillera of the contiguous U.S., are often a dominant source of late-season cold water for local drainages (Fountain and Tangborn, 1985). Rapidly retreating glaciers can also produce geomorphic hazards including debris flows, mass failures of over-steepened valley walls, outburst floods from proglacial moraine lakes (Moore et al., 2009), and may even contribute to sea level rise (Meier et al., 2007). As such, it is crucial to understand how glaciers have fluctuated in the past in order to understand how they might respond in the future; patterns of glacier extents during warmer and drier climates in the mid-Holocene may provide a closer analogy to future climate conditions than records related to the more recent Little Ice Age (LIA, ~1,000-100 yr B.P.) (Menounos et al., 2009) and historical observations. Few studies, however, provide records of glacier changes over the entire Holocene and, consequently, little is known of potential spatial and temporal variability in glacial fluctuations with respect to regional climate change within a given range in the contiguous United States. Proxy records provide a longer, more complete records of glacial advance and retreat.

Two primary means of constraining glacial climate records are direct dating of moraines and indirect dating of glaciolacustrine sediment records down-valley of glacial deposits; each method has benefits and limitations. Moraines directly record periods of maximum advance and, therefore, cooling and/or increased winter precipitation. With the advent of cosmogenic radionuclide (CRN) exposure dating, moraines within the contiguous Unites States, which did not advance into forests and cannot be dated by radiocarbon isotopes (e.g., Mood and Smith, 2015; Wiles et al., 2011) can be directly dated. This method offers a means of constraining patterns of such climate intervals across broad regions. Conversely, glaciolacustrine deposits provide detailed, continuous records of glacier activity in individual valleys, from growth to maxima and then retreat. However, glacial lake sediment cores are difficult to collect and are typically restricted to only a few locations, hindering testing of regional patterns of glacier activity.

$^{10}$Be CRN analysis of boulders is now a well-established method for dating Pleistocene moraines (Doughty et al., 2015; Schaefer et al., 2015; Putnam et al., 2013; Schaefer et al., 2009; Licciardi et al., 2004; Brugger, 2007). Earth is constantly being bombarded by cosmic radiation, some of which reaches the Earth’s surface where it is progressively absorbed within the upper few meters and interacts with specific elements in rocks to produce several rare isotopes, or CRNs (Cockburn and Summerfield, 2004). By analyzing the concentrations of CRNs in rocks, and the rates at which they are produced, timing and rates of various geomorphic processes or events can be quantified. In terms of dating, CRN
concentrations are used to estimate the time elapsed since a rock was exposed at the surface. Until recently, however, the analytical uncertainties were too large to reliably date boulder emplacement in Holocene deposits. Recent advances in analytic methods at a few labs have enabled precise $^{10}$Be exposure dating of boulders as young as late LIA (Zimmerman, 2014). Early results from an ongoing study testing the viability of this new ability on outermost Holocene moraine boulders in the Sierra Nevada in CA has yielded some unexpected findings; whereas some moraines have boulder ages that are all consistent with late LIA formation (150-300 yr B.P.), other moraines have groupings of ages that are all thousands of years older (Figures 1-5) (Clark et al., 2015).

This wide spread of moraine exposure ages conflicts with previous studies of Holocene glaciation in the range based on geomorphic mapping and lake sediment coring, which indicate that maximum Holocene glacial extents occurred during the late LIA (Konrad and Clark, 1998; Bowerman and Clark, 2011). Although inheritance (prior exposure of rocks in the cirque headwalls) may account for some of the pre-LIA boulder ages, this explanation is inconsistent with both the groupings of older ages, and with the absence of any LIA ages in several of these deposits. Alternative explanations are that the ages are accurate and Holocene glaciation in the Sierra Nevada was far more complex than previously thought, or that other processes affect moraine formation on these cirque glaciers (e.g., periglacial activity and/or rockfall events).

My research objective is to analyze lake sediments below pertinent Holocene cirque glaciers in the Sierra Nevada of California to test these disparate hypotheses. As glaciers grow the glacial abrasion of bedrock increases due to larger affected surface area and higher flow rates. This abrasion increases the flux of glacial rock flour (fine-grained suspended rock powder that is produced by basal abrasion) into downstream proglacial lakes where it gradually settles onto the lake bottom (Dahl et al., 2003; Karlén, 1981). Conversely, as glaciers shrink, rock flour production and deposition will decrease. These changes in rock flour production are recorded in pro-glacial lake sediment stratigraphy (Leonard, 1985; Karlén, 1981). Such sediment records can thus yield continuous records of glaciation in a basin. Rock flour sedimentation rates may remain relatively high with respect to ice extent for up to the first century after ice decline due to unstable glaciogenic deposits being exposed to fluvial processes during ice recession; this process may create a lag of peak rock flour deposition in the glaciolacustrine record with respect to the glacier mass-balance (Leonard, 1986). In the Sierra Nevada, however, Bowerman and Clark (2011) argue that the small, boulder-dominated moraines typical of Holocene deposits in the range do not exhibit the same lag effect.

By developing high-resolution continuous lake core records below three of the dated moraine sequences, my study will help test whether the wide spread of $^{10}$Be CRN ages in the Sierra Nevada accurately records Holocene glacial events or, alternatively, may reflect other largely unrecognized
geomorphic processes. Either result will have substantial implications for the study of Holocene moraine deposits and glacial records both in the Sierra Nevada and elsewhere. If CRN ages are accurate as depicted in the glaciolacustrine record, then CRN dating will be an important tool in future study of Holocene glacial fluctuations worldwide and would indicate a much more spatially and temporally complex climate in the Sierra Nevada than the current literature suggests. If the CRN ages are not validated, it would imply other non-glacial processes are affecting these exposure ages and further work needs to be completed for CRN dating to be a viable option for reliably dating small Holocene cirque moraines.

2.0 Background

2.1 Geologic Setting

This study will focus on Holocene cirque glaciers in the Sierra Nevada of California, part of the Western North American Cordillera (Figure 6). Specific field locations include the moraines and lakes below the Lyell and Maclure Glaciers in Yosemite National Park and near Lake Tahoe in the Desolation Wilderness. At each site, the cirques have steep north to northeast-facing headwalls that act as wind-traps for snow in the winter and provide sun shielding during the summer, minimizing ice ablation. The Lyell Glacier has recently stagnated, however, and is no longer considered a glacier by definition (Stock and Anderson, 2012). Conversely, as of 2007, the Maclure Glacier is still flowing at the same rate (2.6 cm per day) that John Muir first measured in 1872 despite losing over half its total surface area. Stock and Anderson (2012) suggested that this consistent flow rate may reflect a shift from internal deformation to basal sliding as the main mode of flow. All of the Desolation glaciers, near Mt. Price, are extinct with no permanent snow/ice features in the associated cirques.

Bedrock of the Maclure and Lyell field sites consists of granodiorite, metavolcanic rock, diorite, and gabbro (Huber et al., 2003). Bedrock of the Desolation field site comprises granodiorite, diorite, gabbro, and granite (Saucedo et al., 2005). These high-alpine regions in the Sierra Nevada have been scoured by multiple generations of glaciation throughout the Pleistocene (e.g., Tahoe, Tenaya, Tioga, Recess Peak, Matthes) (Rood et al., 2011; Phillips et al., 2009; Sharp and Birman, 1963; Clark and Gillespie, 1997), such that the field sites near the Holocene moraines are predominantly stripped, relatively fresh, and often polished bedrock. The Holocene moraines at each field site are characterized by steep, unstable slopes, a lack of vegetation (even lichen in many cases), and sharp, well-defined contacts with surrounding bedrock; these features indicate a very young age of deposition (Figure 7).
The target lakes associated with these glaciers are well suited for lake sediment core analysis because they are all bedrock dammed, directly fed by glacier outwash from the cirques, and are immediately down-slope of the mapped Neoglacial maxima at each site (Figures 8 & 9) (Clark and Gillespie, 1997). Consequently, these lakes should have captured continuous sedimentation (glacial rock flour) from glacial advances and retreats throughout the entire Holocene (e.g., Bowerman and Clark, 2011). There are also historical accounts and photographic evidence of the last glacial advance at each site during the late LIA. Lake sediment cores can be correlated with these known historical advance to calibrate and validate core analysis.

2.2 Post-LGM Climate and Glacial fluctuations of the western North American Cordilleran

Mountain glaciers throughout most of the American Cordillera reached their late-Pleistocene maxima during Oxygen Isotope Stage 2 (~25-18 ka), after which most experienced rapid retreat and largely disappeared in most regions by ~15-16 ka (e.g., Margold et al., 2014; Riedel et al., 2010; Brugger, 2007; Guido et al., 2007; Licciardi et al., 2004; Briner et al., 2005). Following a short interval of warmer and drier conditions, portions of the highest mountains experienced a brief period of glacier advance during or immediately before the European Younger Dryas period (e.g., Clark and Gillespie, 1997; Davis et al., 2009; Menounos et al., 2009; Osborn et al., 2012). In the Sierra Nevada, this event is termed the Recess Peak advance and ended before ~13,100±85 cal. years BP (Clark and Gillespie, 1997), shortly before the beginning of the Holocene at 11.7 ka. In most regions, including the Sierra Nevada, these latest Pleistocene advances extended beyond any subsequent Holocene advances (Davis et al., 2009; Clark and Gillespie, 1997), and, thus, provide a distinct limit on extent of any Neoglacial activity.

Globally, the early Holocene, ~11.0-5.0 ka, was characterized by relatively warm conditions, known as the Altithermal. Following the Altithermal, overall cooling of ~0.7°C through the middle to late Holocene culminated in the Little Ice Age of the last Millennium (Marcott et al., 2013). Glaciers in the North American Cordillera appear to have responded to these shifts in temperatures through a series of advances and retreats. Alaskan glaciers advanced at about 4.5-4.0, 3.3-2.9, 2.2-2.0, 1.4-1.2 ka and then with progressively larger advances during the last millennium at 1180-1320, 1540-1710 and 1810-1880 CE (broadly encompassing the extent of the LIA) (Solomina et al., 2015; Wiles et al., 2011). Glaciers in western Canada were the least extensive in the early Holocene from ~11-7 ka. However, several minor advances occurred in this period at ~8.6-8.2, ~7.4-6.5, ~4.4-4.0, ~3.5-2.8, ~1.7-1.3 ka and the past millennium (LIA) (Menounos et al., 2009). Mood and Smith (2015) documented similar timings of glacial fluctuations in the British Columbia Coast Mountains with the addition of one advance from 5.4-5.3 ka. Neoglacial advances on Mt Baker in the North Cascades occurred at ~6.0 ka, ~2.2 ka, ~1.6 ka,
~0.9 ka, ~0.4 ka, and peaked with the maximum LIA extents in the mid-1800s (Osborn et al., 2012). In all accounts these glacier advances are characterized by successively larger glacial extents through the Holocene, peaking during the height of the LIA (~18th & 19th centuries). Since the end of the LIA (~200 yrs BP), global temperatures have increased and are now warmer than during ~75% of the Holocene (Marcott et al., 2013).

Most moraine evidence of early Neoglacial activity in the U.S. Cordillera prior to the latest LIA push has been over-ridden and obliterated, obscuring the terrestrial Neoglacial record in many ranges. Additionally, because these glaciers predominantly terminate above the treeline (in contrast to those in Alaska, Canada, and the larger Cascade volcanoes), these deposits contain little or no datable organic material associated with the timing of formation. Accordingly, alternative methods must be employed to date moraines and discern longer-term histories (pre-LIA maximum), primarily CRN dating and glaciolacustrine proxy records.

2.2.1 Sierra Nevada Glacial Record

Early studies documented the activity and extent of glaciers in the Sierra Nevada. John Muir (1875) first documented “living glaciers” in the range in 1871 by recording flow rates on the Maclure Glacier in 1872. The first glacier map in the Sierra Nevada, of the Lyell and Maclure glaciers (Figure 10), indicates that both glaciers were at or near their Holocene maximum positions in 1885 (Russell, 1889). More recent studies by Basagic and Fountain (2011) and Basagic (2008) compare these early studies with subsequent historical observations to document a consistent overall decrease in glacial extent from the first observations to the present.

Stock et al. (2013) recently measured flow rates over four years (2009-2012) of both the Lyell and Maclure glaciers in Yosemite National Park. Their measurements showed no detectable movement at the Lyell Glacier, indicating that the glacier had stagnated by 2012. Despite a significant decrease in size, the Maclure Glacier is still flowing at about 7.2 meters per year, the same rate John Muir measured in 1872. The dominant mode of movement for the Maclure Glacier may have shifted from dominantly internal deformation to basal sliding because the glacier is melting more rapidly and has less volume and, thus, less mass to cause deformation (Stock and Anderson, 2012).

Glacial fluctuations during the Holocene in the Sierra Nevada appear to follow a similar, though abbreviated, overall pattern to glaciers in the mountain ranges farther north. Following the retreat of the late-glacial Recess Peak glaciers (~12,000 cal yr BP), the Sierra Nevada appears to have remained essentially unglaciated until the late Holocene (Clark and Gillespie, 1997; Phillips et al., 2009). Based on the rock flour record below the Palisade Glacier (Bowerman and Clark, 2011) and the Conness Glacier
(Konrad and Clark, 1998), glacial maxima of progressively larger extent were interpreted at ~3200, ~2200, ~1600, ~700, and ~250-170 cal yr BP. The most recent advance (Matthes in the Sierra Nevada, traditionally regarded as LIA) was considered the most extensive Neoglacial advance and apparently obliterated geomorphic evidence of previous Neoglacial advances. This interpretation, however, is based on local records of a few glaciers and the correlation of mapped moraine extents. Inferring regional significance and glacial fluctuations for the entire Sierra Nevada from two sites may be problematic.

3.0 Methods

3.1 Site Selection

Three glacial systems were selected in two field areas located in the Sierra Nevada (Figure 6) to test Holocene glacial-age disparities for numerous reasons. The associated moraine sequences have preliminary CRN dates, which show dramatic differences in exposure ages between various moraines. Moraines are distinct and geomorphically well defined. There are no existing glaciolacustrine records at the sites and the proglacial lakes are well-situated down-valley of the maximum Neoglacial extent as to record a complete sediment record. The granitic basins have been stripped by prior glacier advances, which should result in a clean rock flour record. The Yosemite field sites (Lyell and Maclure) exhibit two distinct moraine records according to preliminary 10Be ages despite close proximity (directly adjacent glaciers), so the potential local variability of glacier activity can be directly tested. Additionally, the Desolation field site is the northernmost location of mapped Neoglacial moraines in the Sierra Nevada, so I can test the regional variability of glacier responses. All sites are accessible by trail and pack mules are available in Yosemite to aid with equipment transport.

3.2 Remote and Field Mapping

I have completed preliminary mapping of both the modern glacier extents and the maximum potential Neoglacial extents at each target sites using lidar imagery (2007-Yosemite NP) and georeferenced Google Earth imagery (2013-Yosemite NP, 2012-Desolation) in ArcGIS 10.3.1. For this study, I consider “modern” to be 2013 in Yosemite and 2012 in the Desolation Wilderness because these are the dates of the most recent low-snow imagery available. This ensures that the imagery depicts actual glacial extents versus residual winter snow. Surface areas of the glaciers were calculated for each extent of each respective glacier using ArcGIS.
During this summer (2016), I will conduct additional field mapping of specific moraines that were poorly resolved in remote mapping. I will record moraine positions on aerial imagery as well as with either a Trimble GeoXH 6000 GPS unit or a Garmin 64 S GPS unit. I will also attempt to map the current ice limits of the Maclure and Lyell glaciers. This mapping will only be feasible if weather and snow conditions permit.

3.3 Lake Sediment Coring

Proglacial lakes in the Sierra Nevada provide excellent sites for recording changes in glacial rock flour production. The glacially stripped granitic cirque basins typical of the range have only a few primary sources of clastic sediment: rock flour (if a glacier is present), slope-wash, stream bedload, and aeolian dust. In contrast to the fine silt size of rock flour, slope wash and bedload in Sierra Nevada basins are generally dominated by sand-sized gruss and larger sediments (Bowerman and Clark, 2011). Additionally, aeolian dust, although similar in size to rock flour, is generally more weathered, less magnetic, and so has a weaker magnetic susceptibility (MS) signal (Rosenbaum et al., 2012; Matthews et al., 2000; Snowball, 1993). Rock flour is typically blue-grey in color, which is reflected in the visual stratigraphy of glaciolacustrine sediments (Dahl et al., 2003) and during times of increased glacial activity, the rock flour signal inundates the organic signal, which is reflected by a coincident decrease in Loss on Ignition (LOI) (Bakke et al., 2005; Dahl et al., 2003; Matthews et al., 2000; Karlén, 1981). Terrestrial macrofossils are usually present, having been deposited and incorporated into the lake sediments, providing a means to date interpreted glacial maxima using radiocarbon dating (e.g., Bowerman and Clark, 2011; Konrad and Clark, 1998; Clark and Gillespie, 1997). These ages of glacial maxima, interpreted and dated from the glaciolacustrine record, can then be directly compared to the preliminary CRN ages.

3.3.1 Bathymetry

The deepest portions of lake basins usually provide the highest resolution and most complete sediment records (Larsen et al., 1998). For this reason, mapping the bathymetry of each targeted lake basin is crucial to retrieving a sediment core record that captures the longest duration of sedimentation. The depth of the lake is also crucial to establish which and how much coring equipment will be needed for successful core recovery. I will primarily use the Livingston piston corer, which can be used in lake depths of up to ~20 meters from a raft. During the summer of 2015, I collected detailed bathymetric data of all potential lake core sites below the Price cirques, and the Lyell and Maclure glaciers. For each lake, I
recorded depth data along a systematic grid in a 2-man inflatable raft, taking GPS points every ~5-15 meters, using the Trimble GeoXH 6000, and recording the water depth using a handheld bathymetry meter. In the lab, the GPS data were differentially corrected (most uncertainties were < 1m). In Surfer 8, the GPS data were compiled and used to create detailed bathymetry maps from which specific coring targets were identified.

3.3.2 Coring and Coring Equipment Protocol

I will core at least one lake below each glacier using two lake coring systems, operated from a backpackable floating raft. For deeper sediments, I will use a 2-in (50.8 mm) diameter modified Livingston piston corer (Wright Jr., 1967). This system uses a series of solid extension rods to reach from the lake surface to the sediment-water interface, coring in one-meter pushes. At each lake, I will collect two adjacent, but vertically offset, Livingston cores. This will ensure a complete stratigraphic record without any gaps between pushes. The cores will then be extruded into split PVC pipes with foam filling any void space and duct taped together for safe transport out of the field area and to the lab. The foam will help preserve core stratigraphy until it can be stored and analyzed.

To recover high-resolution samples of the poorly consolidated uppermost sediments, I will use a Glew corer (Glew, 1991). This system is a single-push percussion system and so does not require casing. The core barrel and the core head (with attached weight) are lowered on a rope line to within a meter of the sediment-water interface. From this position, the system is dropped to the bottom for the initial drive into the sediment; after which, a secondary weight, centered on the main line, is lowered from the surface using a secondary line. Upon reaching the core head, the weight is raised and lowered repeatedly to pound the core barrel to its final depth. Because the uppermost sediments recovered by the Glew corers are so poorly consolidated, transporting them out of the field is not feasible. Instead, I will sample them in the field; prior to sampling though, I will record magnetic susceptibility using a battery-operated Bartington MS2-C meter, recording every cm. I will collect bulk samples at 1-cm intervals through the cores and preserve them in plastic sample bags for transport back to the lab.
3.4 Lab Work

3.4.1 LacCore Analyses

Detailed and high-resolution analysis of core stratigraphy is critical in order to establish the timing and magnitude of the glacial rock flour signal and to differentiate it from other non-glacial components such as organic matter and slope-wash. I have received a 2016 LacCore Visiting Graduate Student Travel Grant which will supply me with $1,000 to cover the cost of shipping cores to the LacCore facility at the University of Minnesota, airfare, housing, and any incidental lab fees/equipment costs while I complete the Initial Core Description (ICD) process under direct supervision. I plan to focus data collection within the ICD on whole and split cores using the MSCL (targeting magnetic susceptibility), core splitting and surface preparation, visual stratigraphy / macroscopic sediment description, and capturing high resolution imagery. Additional analyses, including electrical resistivity, gamma density, color spectrophotometry and laser size analysis are also available at the lab and may be beneficial, but access to these tests will depend on availability of funding not directly covered by the grant. All the analyses above would yield critical information about glacial and non-glacial sediment production in the basin.

3.4.2 WWU Sediment Coring Lab Analyses

Further core analyses will be conducted in the Sediment Coring Lab at WWU, including loss-on-ignition (LOI), laser particle size analysis, $^{210}$Pb dating, and tephra analysis on our SEM microprobe. LOI provides a measure of the proportion of organic matter vs. minerogenic sediment in a sample and is often used in glacial studies as an inverse indicator for inorganic deposition (Bakke et al., 2005; Dahl et al., 2003; Matthews et al., 2000; Karlén, 1981). Laser particle size analysis will likely be conducted using the WWU Department Malvern Mastersizer 2000. This analysis can be critical to distinguish glaciogenic clastic sediments (i.e. rock flour that is typically fine-silt sized) from non-glaciogenic clastic sediments (typically coarser, deposited by inlet creeks and slope-wash into the target basins) (Dahl et al., 2003). Based on other cores collected in the region (Clark and Gillespie, 1997; Konrad and Clark, 1998), I anticipate encountering at least one late-Holocene Mono Craters tephra (~650 cal yr B.P.) in the Yosemite lakes and early Holocene Mazama ash (7600 cal yr B.P.) or Tsoyowata ash (Mazama precursor) in all lakes. $^{210}$Pb dating, to be conducted in the Wetlands Ecology Lab using a Canberra GL 282R Ge gamma spectrometer, will yield age constraints on the uppermost, young core stratigraphy and tephra analysis will provide additional reference points for age control.
3.4.3 LLNL Radiocarbon Dating

I will sample the cores for macrofossils to radiocarbon date via accelerator mass spectrometry (AMS). For each lake, I plan to constrain the stratigraphy with at least 3-5 radiocarbon dates. I will process and analyze the samples at the Center for Accelerator Mass Spectrometry at LLNL. WWU’s Geology Department has a collaborative agreement with LLNL, which will allow me to process my samples at their lab facility and, in return, receive a reduced rate of $250 per sample. For each lake, I will establish a composite master stratigraphy, and by incorporating age constraints from the AMS radiocarbon analyses, the tephrachronology, and the $^{210}$Pb into a Bacon age-depth model (Blaauw and Christen, 2011), I will develop continuous high-resolution age models for each lake. These age constraints will allow me to determine the timing of glacial fluctuations including advances, retreats, nonglacial periods, and any other event recorded in the lake sediments. Upon the completion of my core analysis, I will be able to directly compare $^{10}$Be CRN ages to periods of glacial activity as reflected by the rock flour signal in the cores.

4.0 Preliminary Results

4.1 Mapping of Maximum Neoglacial Extent

Maximum Neoglacial glacier extents in Yosemite are 0.329 km$^2$ (Maclure Glacier), 0.456 km$^2$ (West Lyell lobe), and 0.653 km$^2$ (East Lyell lobe). Modern (2013) glacier extents are 0.140 km$^2$ (Maclure Glacier), 0.244 km$^2$ (West Lyell lobe), and 0.0481 km$^2$ (East Lyell lobe), marking a substantial decrease in size of these glaciers (Figure 11). The smallest decrease in size was about 47% on the West Lyell Glacier from Neoglacial to modern. The East Lyell Glacier lobe exhibits the largest decrease from Neoglacial to modern in Yosemite losing ~93% of its surface area. Desolation Wilderness maximum Neoglacial extents are 0.023 km$^2$, 0.0241 km$^2$ and 0.037 km$^2$ and 0.117 km$^2$ (both occurring in the same cirque reflecting different neoglacial events). All of these glaciers have since disappeared entirely.

4.2 Bathymetry

The results from preliminary fieldwork during the summer of 2015 show all lakes can be cored from an anchored raft during summer conditions. Five out of the six target lakes beneath the Lyell and Maclure glaciers are less than eleven meters deep (Figures 12-16). The lowermost lake below the Maclure Glacier (Maclure Lake) is approximately seventeen meters deep, which is still feasible to core from a raft (Figure 17). The uppermost basin of Lake Aloha, beneath the Price cirque moraines, is 12 meters at its
deepest point (Figure 18). All of these target lakes fall within the water depth limit of ~20 meters for the Livingston coring system from a floating raft.

5.0 Anticipated Results

There are two end-member possibilities of anticipated results:

1) Periods of glacial activity, particularly peaks in glaciation as recorded in the glaciolacustrine records, are largely consistent with the $^{10}$Be moraine exposure ages determined by LLNL. This consistency between proxy records would support the viability and accuracy of applying high precision CRN dating to young Holocene cirque glacier deposits. Exposure dating is a much more convenient and less labor-intensive method of dating glacial deposits across a broad region than is lake coring. As such, proving the effectiveness for CRN dating would have a significant influence on future studies of Holocene glaciation. This result would also have profound implications for Holocene glaciation in the Sierra Nevada and elsewhere in the western Cordillera, indicating it is much more spatially and temporally complex than previously thought.

2) Alternatively, my lake sediment cores may indicate little or no glacial activity during the time intervals indicated by the early and mid-Holocene CRN ages (pre-4000 yr ago), as indicated by previous studies in the region (Bowerman and Clark, 2011; Konrad and Clark, 1998). This result would indicate that other non-glacial, geomorphic processes complicate the moraine CRN ages including possible slope processes (e.g., rockfall events), unusual periglacial processes (e.g., enhanced freeze-thaw activity, protalus rampart formation, slow-flow phenomena), or some unrecognized processes related to inheritance in the cirque headwalls and/or reworking past moraine deposits (e.g., Li et al., 2016). It is possible that some of these processes may be reflected in the lake core records (e.g., enhanced gruss related to rockfall/earthquake events), which may allow me to further constrain these options.

My results could also indicate explanations that lie somewhere between these two end-member anticipated results. The CRN ages could be corroborated by lake core analysis during a certain time period, but not for others. Regardless, my study will yield relevant and robust results regarding Holocene glaciation in the Sierra Nevada as well as provide some potentially significant new constraints to this new capability of CRN dating.
Table 1: Detailed schedule of tasks and the predicted time frame respectively.

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<th>Task</th>
<th>2016</th>
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7.0 References


Margold, M., Stroeven, A.P., Clague, J.J., and Heyman, J., 2014, Timing of terminal Pleistocene deglaciation at high elevations in southern and central British Columbia constrained by 10Be


8.0 Tables

Table 2. Maximum Neoglacial and modern glacier surface area extent as well as the respective decrease in extent from Neoglacial to Modern.

<table>
<thead>
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<th>Glacier</th>
<th>Area of glacial extent (km²)</th>
<th>Decrease in glacial extent (%)</th>
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<tr>
<td>Maclure (Neoglacial)</td>
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9.0 Figures

Figure 1. Preliminary CRN ages displayed for the associated boulders along each moraine sequence of the Lyell Glacier and Maclure Glacier in Yosemite National Park. Moraine crests are shown by yellow lines and sampled boulder locations are shown by red dots. Figure from Clark (2015).
Figure 2. Preliminary CRN ages are displayed along each moraine sequence of the Price glaciers in the Desolation Wilderness. Moraine crests are shown by yellow lines and sampled boulder locations are shown by red dots. Figure from Clark (2015).
Figure 3. Camel diagram of preliminary $^{10}$Be ages from the Lyell A lobe of the Lyell Glacier in Yosemite National Park.
Figure 4. Camel diagram of preliminary $^{10}$Be ages from the Maclure Glacier in Yosemite National Park.
Figure 5. Camel diagram of preliminary $^{10}$Be ages from the extinct glaciers beneath Mt Price in the Desolation Wilderness.
Figure 6. Location map of Sierra Nevada field sites. Lake coring sites for this study are indicated by yellow stars. Red stars indicate the remaining $^{10}$Be CRN study sites. From north to south: Price glaciers, Conness Glacier, Lyell and Maclure glaciers, and the Palisade Glacier and Agassiz rock glacier. (Base map from http://www.mapproxy.com/California-elevation-Map).
Figure 7. Photographs of the (a) Lyell terminal Neoglacial moraine and upper lake, (b) Desolation terminal Neoglacial moraine, and (c) Maclure terminal Neoglacial moraine. All are fresh, sharp crested with steep sides, boulder covered, and lacking vegetation.
Figure 8. Aerial imagery of the Yosemite field sites indicating primary targets for lake coring (all in glacial melt-water streams). Red lines indicate the maximum Neoglacial extents and yellow dots indicate $^{10}$Be CRN sample sites on terminal moraines of Maclure Glacier and both lobes of the Lyell Glacier. Imagery taken from 9/14/2013 (Google Earth).
Figure 9. Aerial imagery of the Desolation field site indicating primary targets for lake coring (all in glacial melt-water streams). Red lines indicate the maximum Neoglacial extents. Imagery taken from 8/28/2012 (Google Earth).
Figure 10. Map of the Lyell and Maclure glaciers in Yosemite National Park as they appeared in 1885. This map was created by W.D. Johnson and published in (Russell, 1889).
Figure 11. Neoglacial extent (light blue) and modern extent (dark blue) of the Lyell Glacier and Maclure Glacier. Five of the six target lakes are outlined in green (lower Lyell lake is farther north). Hillshade created from a 2007 LIDAR survey of Yosemite National Park.
Figure 12. Bathymetry map of the upper Lyell lake based off measured water depths (blue triangles). Contours are in meters. The star indicates the target coring location for this lake.
Figure 13. Bathymetry map of the middle Lyell lake based off measured water depths (blue triangles). Contours are in meters. The star indicates the target coring location for this lake.
Figure 14. Bathymetry map of the lower Lyell lake based off measured water depths (blue triangles). Contours are in meters. The star indicates the target coring location for this lake.
Figure 15. Bathymetry map of the upper Maclure lake based off measured water depths (blue triangles). Contours are in meters. The star indicates the target coring location for this lake.
Figure 16. Bathymetry map of the middle Maclure lake based off measured water depths (blue triangles). Contours are in meters. The star indicates the target coring location for this lake.
Figure 17. Bathymetry map of the lower Maclure lake based off measured water depths (blue triangles). Contours are in meters. The star indicates the target coring location for this lake.
Figure 18. Bathymetry map of the two uppermost basins of Lake Aloha based off measured water depths (blue triangles). Contours are in meters. The stars indicate target coring locations for these basins.