Research Proposal

Using in situ ^{26}Al and ^{10}Be to Reveal the Erosivity and Behavior of the Quebec-Labrador Ice Dome of the Laurentide Ice Sheet

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Abstract

We have minimal knowledge about the Laurentide Ice Sheet's (LIS) behavior prior to the Last Glacial Maximum (LGM) because as the ice sheet advanced to its greatest extent, it erased most evidence of previous margins. A recent study based on cosmogenic nuclides in the marine sediment record proposed that the LIS did not fully melt during most interglacials of the past million years (LeBlanc et al., 2023). Seeking terrestrial evidence to test this hypothesis, we employ a dual isotope approach (^{10}Be and ^{26}Al) and analyze ratios between cosmogenic nuclides ^{10}Be and ^{26}Al. We also seek to understand how erosive this portion of the LIS was—which will be reflected in the concentration of nuclides in deglacial sediment. We sampled deglacial and modern river sediments across eastern Canada—a landscape overrun by the LIS during the LGM. In the lab, I reduced these samples to pure quartz and extracted aluminum and beryllium. These cosmogenic nuclides will help us construct a more complete story of LIS's erosivity and climate sensitivity throughout the Pleistocene. This knowledge will allow for better modeling of current ice sheet and glacial melt in response to anthropogenic climate change.

Introduction

During the Last Glacial Maximum (LGM) about 20-25,000 years ago, more than half of the continental Northern Hemisphere was covered by ice (Ullman, 2023). The Laurentide Ice Sheet (LIS) was the most expansive body of ice during the LGM. At its peak, the LIS covered most of Canada and advanced southward enough to cover parts of Illinois and Indiana (Ullman, 2023). The power of such a vast body of ice was felt on a global scale. LIS influenced global climate, atmospheric circulation, ocean currents, and sea level. Its disappearance during the Holocene (characterized by collapse of northern Canadian ice domes) revealed a complicated paraglacial landscape: one in which cycles of advance and retreat leave behind deglacial landforms while destroying ones created by previous interglacials (Occhietti et al., 2011). Because of this, it is difficult to ascertain anything about LIS behavior prior to the LGM from the record on land.

My research seeks to provide new knowledge of LIS's erosivity throughout the Pleistocene. Because ice coring and marine sediment records cannot provide this depth of information, we will use cosmogenic nuclides to extract the stories hidden in the LIS paraglacial landscape.

Using cosmogenic nuclides to date and understand paleo landscape change is a relatively recent technique, with the first studies taking place in the 1980's (Blanckenburg & Willenbring, 2014). These nuclides are rare isotopes created when cosmic radiation from the galaxy bombards Earth's atmosphere (Gosse & Phillips, 2001). The high energy rays collide with atoms in the atmosphere, creating secondary rays via spallation. The particles formed from spallation that reach the Earth's surface (and a few meters below it) create *in situ* (in the position of collision) cosmogenic nuclides such as ^{26}Al and ^{10}Be in minerals like quartz (Schaefer et al., 2022).

Rates and dates of landscape change can be measured using only one cosmogenic nuclide. However, a dual isotope approach allows for a detailed understanding of glacial behavior because of the different decay rates of ^{10}Be (half life ~1.36 My) and ^{26}Al (half life ~730,000 years). When exposed to cosmic radiation, *in situ* ratios of ^{26}Al/^{10}Be are around 7.5 (Corbett et al., 2017). When a landform is covered by a thick layer of ice such as the LIS, it is shielded from cosmic radiation. This inhibits the creation of *in situ* ^{26}Al and ^{10}Be. As these isotopes decay, the ratio falls (Bierman et al., 2016). For example, it would take ~1.4 My for a ratio to fall from 7 to 3.5. This is because one ^{10}Be half life and two ^{26}Al half lives would pass in that time. Despite Holocene exposure to cosmic rays following LIS retreat, ratios depressed by the LIS for geologically significant time periods can be preserved. This would require a scenario of high concentrations of nuclides under a portion of the ice sheet, coupled with a brief exposure time during an interglacial. However, if a low concentration of nuclides being preserved under the ice is then exposed for a significant amount of time, ratios will rise and erase the previous cosmogenic nuclide signal. Because of this, we will analyze ratios from quartz isolated from deglacial and modern river sediments to infer paleo ice sheet coverage, LIS's erosion efficiency, and concentrations of ^{10}Be left behind after permanent LIS retreat.

Objectives

Below are the major questions guiding our analysis of cosmogenic nuclides in eastern Canadian deglacial and modern river sediments.

1) Is there evidence for deep erosion by the LIS during the LGM (near-zero nuclide concentrations)?
    a) What can this tell us about LIS basal thermal conditions?
2) Do different sources of sediment have different cosmogenic nuclide concentrations and ^{26}Al/^{10}Be ratios?
3) Do depressed ^{26}Al/^{10}Be ratios in terrestrial sediments support LeBlanc et al.'s (2023) inference from marine sediments that the LIS rarely deglaciated during the last million years?

Background

As the LIS grew to its greatest extent during the LGM, it erased most moraines, eskers, and other deglacial landforms created during smaller LIS extents. Because of this, few geologic records remain of LIS pre-LGM behavior. This severely limits our knowledge about how erosive or extensive the LIS was prior to the LGM (Batchelor et al., 2019). However, because cosmogenic isotopes can retain a memory of past landscapes if erosion is not efficient or deep, they allow researchers to circumvent the limitations of traditional terrestrial records (Bierman et al., 2016).

Cosmogenic isotopes have been used in recent studies to identify sediment sources for both modern and paleo ice sheets. Nelson et al. (2014) used ^{10}Be to understand when and how quickly the paraglacial portion of Southern and Western Greenland became deglaciated. ^{10}Be samples were taken from boulders and bedrock as fixed locations of exposure. To find the source of sediment leaving Greenland, sediment samples from streams and moraines were taken along the Greenland Ice Sheet's (GrIS) margin and compared to samples from glacierized, non-glacierized, and mixed terrain (Nelson et al., 2014). ^{10}Be concentrations indicated that the moraine and river sediments originated from under the GrIS (Nelson et al., 2014). The results of this study revealed that the majority of sediment on glacial and paraglacial landscapes in Greenland comes from the glacier opposed to the adjacent deglaciated areas (Nelson et al., 2014). Applied to paleoclimate, this means that most of the sediment being carried to the ocean would be glacial, even while ice sheets are retreating (Nelson et al., 2014, p. 1096).

This finding is integral to LeBlanc et al.'s (2023) investigation into LIS persistence during Pleistocene interglacials. This study employed cosmogenic nuclides (^{26}Al and ^{10}Be) in ice-rafted debris (IRD) from LIS discharge to infer the burial and exposure history of glacial sediment prior to its transport to the ocean (LeBlanc et al., 2023). Because the sediment in the IRD was likely originally LIS iceberg till, sample ^{26}Al/^{10}Be ratios reflect the extent of ice cover prior to the LGM (LeBlanc et al., 2023). All IRD samples had a low (~4) ratio. This corresponds with long LIS burial periods throughout the Pleistocene, as interglacials with little to no ice would have yielded IRD with higher ratios (LeBlanc et al., 2023 ; Berger et al., 2016). This challenges the assumption that all Pleistocene interglacials are virtually ice free intervals of 10,000-15,000 years (D. LeBlanc, personal communication, April 19, 2023).

Further studies have investigated LIS sensitivity to climate shifts leading to the collapse of the Quebec-Labrador Ice Dome. Coutte et al.'s study found close ties between regional deglaciation and climate fluctuations by collecting and dating 37 bedrock samples throughout Quebec and Labrador (Couette et al, 2023). The mean ^{10}Be concentration among these bedrock samples was 67394 atoms/gram (see Table 1). This data revealed 5 stagnations or re-advances of the LIS margin (~12.9 ka, ~11.5 ka, ~10.4 ka, ~9.3 ka, and ~8.4-8.2 ka) (Couette et al, 2023). Because these events temporally correspond to shifts in climate, they suggest that the LIS was very sensitive to climate fluctuations in the Northern Hemisphere—having a short response time to changes before once again reaching an equilibrium state. Couette also proposes that LIS glacial dynamics were synchronous along entire margins and theorizes that the

Quebec-Labrador Ice Dome was “artificially sustained” during the early Holocene because of localized cooling from meltwater discharge (Couette et al, 2023, p. 1057).

A similar study, Ullman et al. (2016), also sought to understand climate shifts and ice dynamics leading to the collapse of the Quebec-Labrador Ice Dome. This study also sampled glacial erratic boulders and dated exposure using ^{10}Be (Ullman et al., 2016). However, during analysis, samples were sorted into three theorized “transects” of the ice dome’s historical margin (Ullman et al., 2016). ^{10}Be ages from the southern transect suggested average rates of retreat between 70-1000 m/a (Ullman et al., 2016). The eastern transect estimated that the rate of retreat was between 40-310 m/a, while the western transect was estimated at ~860 m/a (Ullman et al., 2016). This goes against Couette et al. 's evidence of a more uniform dynamic across the margin of the ice dome, as each transect behaves differently. Furthermore, factoring in the retreat rates of all three transects, the study concluded an overall deglaciation lag of ~4 ka by comparing the ^{10}Be data to preexisting ^{14}C dating from the same geographic area (Ullman et al., 2016). This lag time corresponds with a less responsive (and therefore less climate sensitive) LIS, opposing Couette et al.’s evidence. These two studies illustrate how much is still unknown about LIS behavior. Table 1 compares the ^{10}Be concentrations from each study. I removed outliers when calculating sample number, maximum, minimum, IQR, and mean.

Table 1. ^{10}Be Concentration Comparison for Ullman et al. and Couette et al.

	Ullman et al.	Couette et al.
Mean ^{10}Be (atoms/gram)	48462	67394
Interquartile Range (atoms/gram)	6068	15183
Minimum (atoms/gram)	38879	35473
Maximum (atoms/gram)	59598	199659
N (sample number)	50	37

Methods

Sample Collection

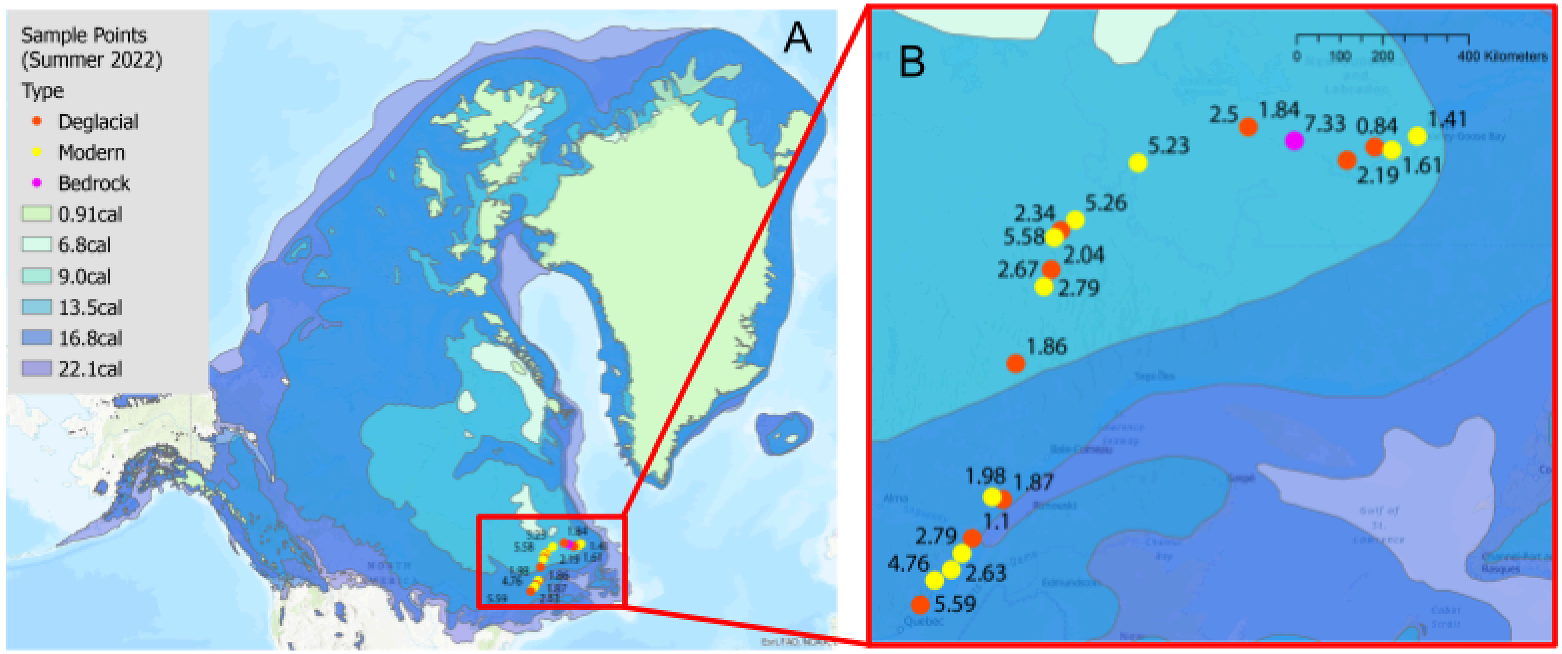
We chose sample sites based on proximity to the Trans-Labrador Highway and Route 389 in the Quebec-Labrador Ice Dome area following suggestions from Dr. Pierre-Olivier Couette. Starting in Goose Bay, we sampled northeast to southwest across the former area of the ice dome. We sampled glacial landforms (n=11) such as deglacial deltas, eskers, and bedrock to constrain nuclide concentrations in materials directly affected by the ice sheet. We took sediment from deltas and eskers on clean faces in gravel pits at least several meters below the surface to ensure negligible nuclide production following deglaciation. We sought out bedrock samples for their potential to provide insight into fixed locations of ice exposure. Modern river sediment (n=10) was also collected to compare its ^{10}Be concentration to the deglacial samples.

Figure 1. Field Sample Collection

In this photo I am collecting modern river sediment from a tributary to the Churchill River (sample ID:GB-04).

To sample deglacial deltas, modern river sediment, and eskers, we used shovels to dig ~0.3 meters into the landform before collecting about 500 grams of sand. When taking from sandbars with a substantial amount of pebbles and cobbles, we wet sieved samples between 250-850 micrometers before collection. We chiseled off 2-3 handfuls of bedrock to use as sample material.

Figure 2. 2022 Sample Locations



A. Location of sample sites in geographical span of historic LIS extent. Layers of LIS extent provided from findings in Dalton et al,. 2020. Each LIS extent layer corresponds to a different calibrated age in ka (see legend).

B. A closer view of sample sites and their overlaid historical LIS extent layers. Samples are color coded by type for both figures. Labels on each sample site show concentration of ^{10}Be (*10^{4}) in atoms/gram of quartz.

Sample Processing

To isolate pure quartz for cosmogenic nuclide analysis, I “cleaned” my samples with a series of physical and chemical processes.

I dried all sediment samples in the oven before mechanically sieving them for 3-5 minutes. After sieving, I had sample material less than 250 micrometers, between 250 and 850 micrometers, and greater than 850 micrometers. I only saved the sediment between 250 and 850 um for further processing. I then used magnetic separation to isolate the non-magnetic sediment (quartz in non-magnetic) from all samples. Bedrock samples were crushed and ground into sediment before I both sieved and magnetically separated them.

Next, I rinsed each sample to remove mica and other less dense minerals leftover from magnetic separation. I used a series of short and long acid etches to purify the quartz. I performed two series of Hydrochloric Acid etches to remove grain coatings from my quartz samples. Next, I used diluted (1%) Hydrofluoric acid and Nitric acid for three 24 hour etches. After each etch, old acid was poured off and replaced with fresh acid. Long term (minimum of a week) acid etches were done using dilute Hydrofluoric Acid to dissolve feldspar in the samples. These procedures are based on Kohl and Nishiizumi’s 1992 paper on the chemical isolation of quartz (Kohl & Nishiizumi, 1992).

I then tested the purity of my quartz samples using inductively coupled plasma spectrometry. The samples that were sufficiently pure moved forward to clean lab extraction while samples that were not pure were subject to 2-3 more weeks of acid etching. In the cosmogenic extraction lab, I followed the procedures developed at the

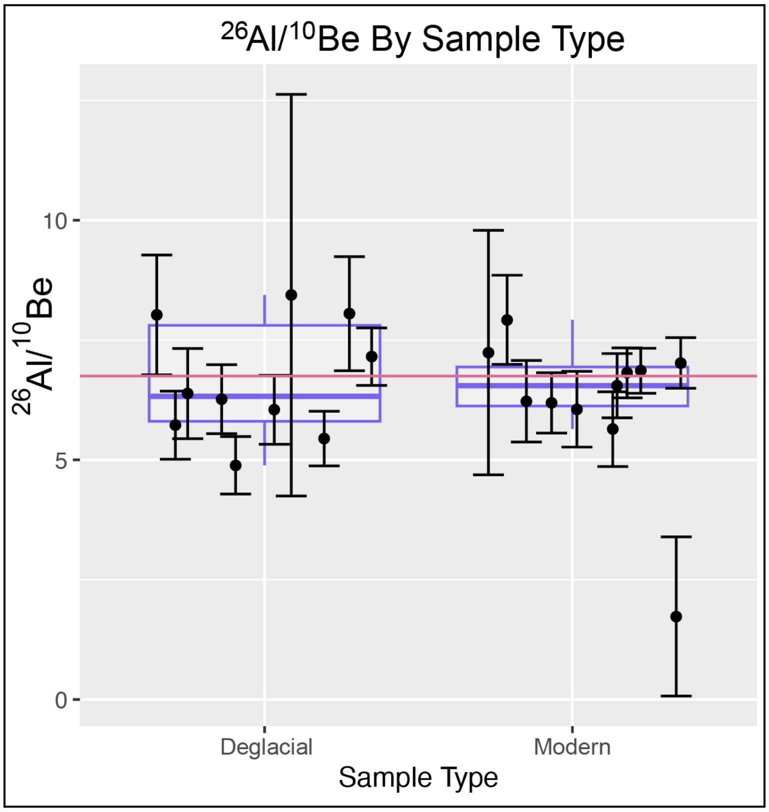
UVM/NSF Community Cosmogenic Laboratory (Corbett, 2018). Extraction procedures included dissolving my samples into solution with HF, taking sample aliquots, treating my samples with Perchloric acid, and using column chemistry (anion and cation) to remove elements such as aluminum, titanium, and magnesium from my samples. Detailed descriptions of procedures are included in the UVM community cosmogenic laboratory methods (Corbett, 2018).

After extraction, we sent ^{10}Be and ^{26}Al cathodes to PRIME Laboratory for analysis. ^{10}Be/^{9}Be ratios were measured at PRIME using mass spectrometry. I used the known concentration of 9Be added as carrier to calculate how many atoms of ^{10}Be were in each sample. My extraction blanks were used to correct for lab contamination. The same procedure was used to calculate how many atoms of ^{26}Al were in each sample from the PRIME ^{26}Al/^{27}Al ratios. For each sample, the concentrations of ^{10}Be (atoms/gram) and ^{26}Al (atoms/gram) were used to calculate the ratio between the two.

Initial Results and Implications

The average ^{10}Be concentration for my deglacial samples ($2.2 \pm 1.3 * 10^4$ atoms/g) is less than the average concentration for modern samples ($3.3 \pm 1.6 * 10^4$ atoms/g). However, I performed a Welch two sample t-test that yielded a p-value of 0.14, reporting 95% confidence that the difference between the two means is not statistically significant. The modern samples have more concentration variability, with an interquartile range (IQR) of $3.3 * 10^4$ atoms/g compared to the IQR of $0.5 * 10^4$ atoms/g for deglacial samples. The bedrock sample had a concentration of $7.3 * 10^4$ atoms/g, the greatest of all samples (See Figure 3).

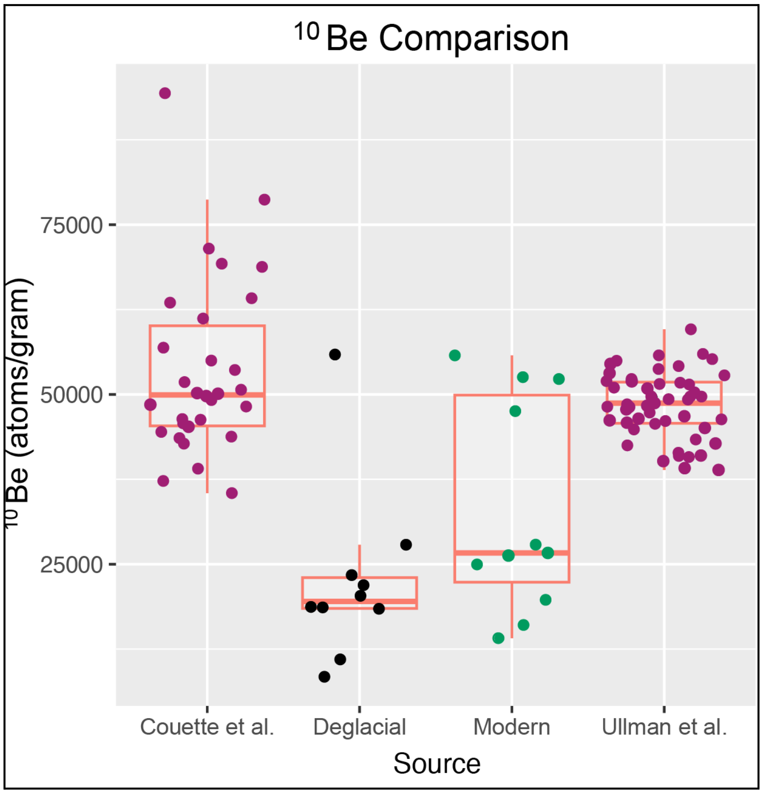
Figure 3. Box and Whisker Plot of Nuclide Ratios



Prior work suggests deglaciation of the region between 10 and 8 ka (LeBlanc et al., 2023; Ullman et al., 2016; Couette et al., 2023). The relatively high concentrations of ^{10}Be (compared to the statistically equal modern river sediment samples) in both the deglacial and bedrock sample suggest that the LIS did not deeply erode sediment and bedrock exposed to cosmic radiation during prior interglacials. Based on the average concentration of ^{10}Be in my samples (mean of $3.01*10^4$) and the production rate of ~4 atoms/(g*yr), this would suggest an average of 5500 years of exposure needed to create this amount of ^{10}Be. Concentrations of ^{10}Be are too high to have been created during this past interglacial exposure alone. We know this interglacial exposure did not affect my deglacial samples because this sediment was buried several meters below the surface at that time. Thus, concentrations from deglacial samples measure what was in those sediments when the LIS deposited them. Conversely, the bedrock sample was exposed during the Holocene. This helps explain its high concentration of ^{10}Be.

Alternating periods of the ice being cold-based (low erosivity) or warm-based (high erosivity) likely explain this inheritance of ^{10}Be from a previous interglacial. A warm-based portion of the ice sheet will be more erosive because it can move across the landscape opposed to being frozen to it (cold-based). Thus, this evidence suggests that our sampled portion of the Quebec-Labrador Ice Dome was likely cold-based. However, the fact that this bedrock outcrop was rounded requires a more complex explanation. The rounded shape suggests erosion by ice. A LIS that was cold based for much of the LGM, before transitioning to a warm base towards the end of the glacial, would explain both the rounded outcrop and the inheritance of ^{10}Be. The low IQR of deglacial sediment indicates relatively homogeneous concentrations of inherited ^{10}Be at the base of the LIS. The high IQR of modern fluvial samples suggests rivers carry different mixtures of sediment sourced from deglacial deposits such as deltas and sediment derived from landscapes exposed during the Holocene.

Figure 4. Comparison of My Data with Previous Publications



Comparing my data to both Ullman et al.'s (2016) and Couette et al.'s (2023), I found that despite my significantly smaller sample size (n=22 and see Table 1), my ^{10}Be concentrations have the largest IQR of all three sample groups (see Figure 4). My data mean is lower than both Ullman et al. 's and Couette et al.'s data—with most of my ^{10}Be concentrations being well below the IQRs of either other dataset. My maximum concentration (GB-06 with 73,309 atoms/gram), when situated in the range of the other two datasets, appears less like an outlier (see Figure 4). This is especially true because all of Couette et al.'s (2023) data are bedrock samples. We expected Couette et al.'s data to have many times more ^{10}Be than my deglacial or modern samples. Couette's 37 bedrock outcrops have been exposed to ~8000 years of cosmic rays. This should result in much higher concentrations of cosmogenic nuclides than what we see in Figure 4.

Timeline

Semester	**Tasks**	**Complete?**
Summer 2022	- Collect field samples - Clean and start sample prep.	Yes
Fall 2022	- Complete sample cleaning and preparation	Yes
Spring 2023	- Sample extraction - Data analysis	Yes
Summer 2023	- Collect second round of samples - Continue data analysis	- Delayed field work due to wildfires - Partially
Fall 2023	- Complete analysis - Begin writing - Present Progress Report	Partially Yes
Spring 2024	- Continued data analysis (for new samples) - Complete writing	No
Summer 2024	- Finish and defend in summer	No

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