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History of formation, limnologic change, and salmon abundance at Situk and Mountain Lakes, Yakutat, Alaska

by

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To the Graduate Faculty:

The members of the committee appointed to examine the thesis of Carl Vincent Jurkowski find it satisfactory and recommend that it be accepted.

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History of formation, limnologic change, and salmon abundance at Situk and Mountain Lakes, Yakutat, Alaska

Thesis Abstract-Idaho State University (2018)

Situk and Mountain lakes, Yakutat, Alaska are active salmon spawning lakes that economically support the city of Yakutat. Little is known about the formation of the two lakes and the history of subsequent fluctuations of salmon abundance in this glacially dynamic region. ^{210}Pb and ^{14}C dates obtained from sediment cores, and basal ^{14}C dates on two muskegs located between the two Holocene terminal moraines suggest a retreat of Hubbard Glacier from the outer moraine and formation of the lakes ~1400 cal AD during an early phase of the Little Ice Age (LIA). Physical properties and stable isotopes indicate a period of high suspended sediment load, inferred to result from glacial runoff from Russell Fiord into Situk and Mountain lakes from Hubbard Glacier, erosion of periglacial sediment deposited during the advances and retreats of Hubbard Glacier, and/or from local glaciers within the Mountain Lake watershed. Regardless of source, such influence only recently subsided, at the end of the Little Ice Age. Since ~1750 AD, the lakes turned into clear-water systems that ultimately supported higher abundances of sockeye salmon. Sedimentary $\delta^{15}N$ remained at a base level state until measurable enrichment beginning ~1750 AD and increased, peaking in the late 1800's AD (sedimentary $\delta^{15}N$ of 7‰). Following this peak, sedimentary $\delta^{15}N$ declined to its current level of 3.2‰. These data show that under natural conditions, salmon abundances increased until the development of a salmon cannery in 1903 AD, when salmon abundance subsequently decreased.

Keywords: *Oncorhynchus nerka*, Sockeye salmon, Stable isotope analysis, Pacific decadal oscillation, Little Ice Age

Thesis Introduction

Salmon play an important role in the economic, ecological, and cultural well-being of Alaskans (Finney et al., 2000; Holtham et al., 2004). Understanding trends in salmon productivity in relation to geologic, climatic and anthropogenic influences is necessary to implement more effective management practices (Holtham et al., 2004). This study focuses on two lakes, Situk and Mountain lakes, near Yakutat, Alaska. As the salmon runs associated with these lakes are highly important to the region's economy and ecosystem services, impacts of glacial advances and climactic change on salmon productivity are of great concern.

The purpose of this study is to use stable isotope data from lake sediment cores collected from Situk and Mountain lakes to reconstruct salmon abundance. Past changes in abundance are then related to geologic, climatic, and anthropogenic influences. I also determine the timing of the origin of the lakes, and their subsequent environmental history using lake sediment records and radiocarbon samples from two muskeg pits hand dug between two Holocene terminal moraines that enclose the lakes.

Situk Lake is located ~20 km northeast of Yakutat, Alaska. It is situated between two terminal moraines that were created by advances of nearby Hubbard Glacier through Russell Fiord (Figure 1). Barclay et al. (2001), hypothesized that the outermost terminal moraine, which borders the western side of Situk Lake and continues to the eastern wall of Russell Fiord, was formed by the advance of Hubbard Glacier through Russell Fiord and deposited 10-15 kya during a late Wisconsin glacial episode (Figure 1). The inner moraine was dated by Barclay et al. (2001), using submerged trees, and the dates intercept the calibration curve at 1525, 1558, and 1631 cal AD, constraining the age to a latter phase of the Little Ice Age (LIA). More recently however, several researchers studying the LIA in southern Alaska (Wiles and Calkin, 1994;

Barclay et al., 2001; Calkin et al., 2001a), concluded that the onset of LIA glaciation began 1180-1320 A.D and culminated in two major advance phases in the 1540's-1710's AD and in the 1810's-1880's AD. I hypothesize that a glacial advance during the early phase LIA may be responsible for the deposition of the outer moraine in the study area, based on a number of characteristics that suggest it is of more recent origin.

Hubbard Glacier, the largest surging tidewater calving glacier in North America, is capable of damming Disenchantment Bay, transforming Russell Fiord into a lake (Russell Lake) (Barclay et al., 2001; Gubernick and Paustian, 2007). Russell Fiord has experienced moraine damming from advances of Hubbard Glacier in 1986 and 2002. If the dam created by the advance of Hubbard Glacier is sustained in this high precipitation region (842 cm annually (Barclay et al., 2001), Russell Lake will then overflow the terminal moraine drainage divide (41 m elevation) in the southern region of Russell Fiord into Situk River, vastly altering its geomorphic and ecological character. Overflow would cause the drainage area for Situk River to increase from 215 km^2 to over 2,072 km^2 (Gubernick and Paustian, 2007), potentially affecting the local economy of Yakutat by altering the ecology of Situk River, currently a clear water stream supporting multiple species of resident and anadromous salmonids (Gubernick and Paustian, 2007). Impacts from increased drainage and resultant high, turbid discharge could degrade spawning and rearing habitat within Situk River, potentially reducing numbers of spawning salmon (Thedinga et al., 1994) and future salmon derived nutrient (SDN) inputs into the Situk Lake system from salmon carcasses.

Hubbard Glacier is currently in the beginning stages of tidewater calving glacier advance with an accumulation area ratio (AAR) of 0.96. It is predicted that most tidewater calving glaciers will advance until an AAR of ~0.7 is reached. Because Hubbard glacier is in the beginning stages of advance, it is predicted to continue its advance into Yakutat Bay and Russell Fiord (Trabant et al., 1991, 2003; Barclay et al., 2001). Given the high probability of future damming, understanding the effects of Hubbard Glacier advances into Russell Fiord on future salmon runs is important.

The $\delta^{15}N$ signals in lake sediments have been shown to be a reliable proxy for past changes in salmon abundance in some systems (Finney et al., 2002; Barto, 2004; Holtham et al., 2004; Rogers et al., 2013; Loso et al., 2017). One goal of this research is to use stable isotope analysis of lake sediment cores from Situk and Mountain lakes to infer historical changes in salmon production. I assessed the fidelity of the method through analysis of other core proxy data, lake and watershed characteristics, and historical salmon data. In addition, I used the multi-proxy core data to reconstruct past salmon abundance and lake ecosystem response to climatic and anthropogenic influences (Finney et al., 2000; Holtham et al., 2004; Rogers et al., 2013).

Recent records of $\delta^{15}N$, beginning around 1900, can be influenced by anthropogenic causes, such as commercial and recreational salmon harvesting (Rogers et al., 2013). Such influences can affect interpretations of isotopic signals in terms of environmental factors, if they are not understood and accounted for. Fishing, both commercial and recreational, can reduce year-to-year escapement (number of salmon not captured by fishing). It has been shown in some systems that reduced salmon escapement can alter the amount of SDN being delivered back into the system. Therefore, populations of lower trophic level organisms that rely on SDN will decline, leading to a lack of food for juvenile salmon. Salmon production will diminish with a decrease in food sources, ultimately depleting the $\delta^{15}N$ signal (Cederholm et al., 1999; Gende et al., 2002). The lake-nutrient feedback cycle and $\delta^{15}N$ are tightly linked in some sockeye nursery lakes (Finney et al., 2000). However, other studies (Hobbs and Wolfe, 2007) have shown that

SDN delivery into lakes, in which salmon minimally contribute to the systems nutrient budget, are not strongly influenced by SDN delivery, and do not show a similar feedback cycle. A goal of this paper is to determine the importance of SDN in the Situk River system.

Although there are anthropogenic influences on salmon production, lakes throughout the region experience varying changes in productivity independent of human factors, such as climatic change (Rogers et al., 2013). Regional ocean-atmosphere climate variability can alter salmon production during the ocean phase of their life history (Beamish and Bouillon, 1993; Mantua et al., 1997). For example, changes in the Aleutian Low and the Pacific decadal oscillation (PDO) affect ocean circulation and sea surface temperatures, which then alters the productivity of marine systems (Mantua et al., 1997; Finney et al., 2002; Anderson et al., 2005), and ultimately the survival rates of Alaskan salmon. Understanding the relationships between such past climate variability and the history of salmon production in these Yakutat lakes will be beneficial in understanding the response of their salmon in this region to past climatic change.

This study is motivated by several research questions:

- When was the outer moraine near Situk Lake constructed and how does that alter the recorded chronology of Hubbard Glacier?
- When did Situk and Mountain lakes become ice free?
- Is salmon density large enough to leave a $\delta^{15}N$ stable isotope signal in Situk and Mountain lakes?
- How do $\delta^{15}N$ stable isotope signals from Situk Lake compare to Mountain Lake?
- How has the advance of Hubbard Glacier affected the populations of salmon in Situk Lake and Mountain Lake?

- How does climate change and anthropogenic influences, such as commercial and recreational salmon harvesting, affect $\delta^{15}N$ signatures?

To answer these questions, chronologic methods including ^{210}Pb and ^{14}C were used to determine the timing of the retreat of Hubbard Glacier from the outer moraine. $\delta^{15}N$ stable isotope ratios have been derived from sediment cores from each lake. These data are then compared to historical escapement to determine a probable correlation between $\delta^{15}N$ stable isotope ratios and escapement size. Historical salmon productivity is compared to known glacial advances of Hubbard Glacier and damming events of Russell Fiord to understand their effects on salmon abundance.

Chapter I. Historic Salmon Abundance in Situk Lake, Alaska Inferred from Lake Sediment δ15N Stable Isotopes

Abstract

Situk Lake, Yakutat, Alaska is an active salmon spawning lake that has economically supported the city of Yakutat since the introduction of a salmon cannery in 1903. Little is known about the historic abundance of salmon in Situk Lake. Using $\delta^{15}N$ stable isotopes and other proxies from lake sediment cores, I have determined trends in historic abundances of sockeye salmon (*Oncorhynchus nerka*), fluctuations in primary productivity, and other environmental factors spanning the last 500 years. Isotope data suggests that Situk Lake sockeye salmon abundance increased in the early ~1750's, following glacial retreat from the system and subsequent lake turbidity reduction, and peaked in salmon abundance in the late 1800's (sedimentary $\delta^{15}N$ of 7‰). Since then, isotope values steadily decreased until present levels were reached (sedimentary $\delta^{15}N$ of 2.7‰). Therefore, these data suggest that under natural circumstances salmon abundance increased during the transition from glacial to non-glacial conditions until the development of a cannery in 1903. After cannery establishment, salmon abundance decreased to present day levels. Factors leading to this decline likely include both fish management practices and climatic and environmental changes.

1. Introduction

Salmon play an important role in the economic and cultural well-being of Alaskans and as an important source of nutrients for freshwater watersheds (Finney et al., 2000; Holtham et al., 2004). Anadromous sockeye salmon (*Oncorhynchus nerka*) spend the later part of their developmental stages in marine environments where they obtain ~95% of their biomass (Schindler et al., 2005). Sockeye salmon therefore acquire stable isotope signatures indicative of marine sources, as seen in the $\delta^{15}N$ of spawning salmon (~12‰) (Finney et al., 2000) due to trophic enrichment in the marine system. Availability of this enriched salmon $\delta^{15}N$ relative to terrestrial $\delta^{15}N$ (0‰) allows for distinguishing the presence of salmon-derived N in freshwater watersheds. It has been shown in previous studies that the $\delta^{15}N$ signals in lake sediments can be a reliable proxy for past changes in salmon abundance in some lake systems (Finney et al., 2002; Barto, 2004; Holtham et al., 2004; Rogers et al., 2013; Loso et al., 2017). Spawning sockeye salmon have the potential to transport large quantities of nutrients into freshwater systems, and are responsible, in some cases, for the contributions of >50% N delivery into the system (Karluk Lake, (Finney et al., 2000). An increased nutrient delivery into freshwater systems has the potential to create a positive feedback cycle of productivity. In such a case nutrient abundance has the potential to increase primary productivity which would be beneficial to sockeye fry and smolt by increasing carrying capacity and survivability (Burgner, 1991; Cederholm et al., 1999). A higher survival rate for salmon has potential to increase subsequent returns to the spawning lake, and further nutrient delivery. However, other studies (Hobbs and Wolfe, 2007) have shown that SDN delivery into lakes, in which salmon minimally contribute to the systems nutrient budget systems, are not strongly influenced by SDN delivery, and do not show a similar feedback cycle. One goal of this study was to determine the importance of SDN on Situk Lake primary productivity and its importance in subsequent salmon runs using proxy data from sediment cores.

Recent changes in salmon escapement, and hence $\delta^{15}N$, can be influenced by anthropogenic causes, such as commercial and recreational salmon harvesting (Rogers et al., 2013). Anthropogenic influences not completely understood or accounted for in a lake system might be interpreted as a local environment or climate forcing. Our data encompasses a history of pre- and post-settlement influences on the salmon runs in the Situk Lake system. Therefore, I expect to observe evidence for impacts of both natural and anthropogenic processes on salmon abundance due to factors such as climate change and the onset of salmon harvesting in Situk Lake's stable isotope record.

Climactic change in the North Pacific region over the period of the instrumental record on multi-decadal timescales is well described by the Pacific Decadal Oscillation (PDO). The PDO is defined by sea surface temperatures (SST) anomalies that shift on multidecadal timescales between warm (ca. 1925-1946 and 1997-1998) and cold (ca. 1890-1924 and 1947-1976) SST regimes. These shifts are thought to have an effect on ocean primary productivity and subsequent salmon abundance (Beamish and Bouillon, 1993; Mantua et al., 1997; Mantua and Hare, 2002). Our sediment record analyzed in this study dates back to ~1500 yr AD and therefore should capture many shifts in climate, including PDO.

Hubbard Glacier, located approximately 50 km north northeast of Yakutat, is the largest surging tidewater calving glacier in North America (Trabant et al., 1991). Hubbard glacier has advanced twice in recorded history (1986 and 2002) to an extent to dam Russell Fiord turning it into a lake, Russell Lake. If the dam is sustained long enough, there is a potential for the lake to overflow a terminal moraine located at the southern end of Russell Fiord, altering the morphologic and ecologic character of the Situk River form increased turbid discharge. Oral history of the Tlingit indigenous peoples and dendrochronology data suggest Russell Lake last overflowed the terminal moraine during the early to late 1800's AD (Gubernick and Paustain, 2007). If this were to occur, it could impact up to ~70% of juvenile rearing salmon in Situk River. Cores collected from Situk Lake in the summer of 2014 have been analyzed to determine historical salmon abundance and how climate, glacial influences, environmental change, and anthropogenic impacts affect salmon abundance.

2. Study Site, Materials, and Methods

2.1 Site location and limnology

This study focused on Situk Lake (59.6425°N 139.4003°W), with an elevation of 42 m masl, and located ~20 km northeast of Yakutat, Alaska (Figure 1). The lake is situated between two terminal moraines that were formed during advance and retreat of nearby Hubbard Glacier through Russell Fiord (Barclay et al., 2001). Situk Lake is bounded by flat lying muskegs and forest. The lake has an area of 4,092 km^2 and a water residence time of 0.74 years (Barto, 2004). Annual precipitation at Yakutat is 3550 mm and the mean temperature is -3.1 °C in January and 11.9 °C in July classifying Yakutat as maritime (Barclay et al., 2001). Climate variability on decadal timescales in this region are strongly related to the Pacific Decadal Oscillation (PDO) (Mantua and Hare, 2002).

Previous limnologic data has been collected and reported by Schmidt (1981) and Barto (2004). Situk Lake is dimictic, with mixing in the spring and the fall, and surface summer water temperatures of 14.5 degrees Celsius. It has a mean spring total phosphorous of 3.1 ug/l, a pH of 7.3, and a secchi disk visibility of 6 m. These data classify Situk Lake as oligotrophic.

2.2 Total run size and escapement

Historically, Situk Lake has provided spawning habitat for sockeye salmon. Annual escapement data has been collected since 1938 AD (Clark et al., 1995, 2002, and from the Alaska Department of Fish and Game online database). Prior to this time, run sizes have been estimated from cannery data beginning from its origin in 1903. Hindcasts of salmon runs (catch + escapement) were determined from the cannery data (Shaul, 2017, pers. comm.), and a range of fishing exploitation rates (47% and 70%) (Figure 2).

2.3 Coring and physical properties

Situk Lake has a relatively simple bathymetry, with a large flat basin at a water depth of ~25 m. Sediment cores were collected in this basin through gravity and hammer coring in the summer of 2014. A gravity core (SIT14 G5) was taken to preserve the sediment water interface and was completely extruded at 0.5 cm intervals in the field. A second core was collected using a hammer corer (SIT14 H1). A total of 120 cm of sediment was recovered but only the top 64 cm of sediment was analyzed from core SIT14 H1 for this study. Further analysis of the deeper sediment is described in Chapter 2 of this thesis. The top of the H1 core was stabilized for transportation using Zorbitrol. Following collection, cores and extruded samples were sent to Idaho State University (ISU) where they were opened and processed in the summer of 2016. Extruded samples were kept frozen in 532 ml polyethylene bags until processing. Samples for physical properties, geochemistry, and stable isotopes were taken using extruded samples (SIT14 G5), or continuous 1 cm downcore samples using a 2 cc volumetric sampler to a depth of 64 cm. Samples were weighed to calculate wet bulk density and then freeze-dried in a Labconco FreeZone plus 6 liter console freeze dry system. Dried samples were reweighed to determine dry bulk density and water content then run on a Barington MS2 magnetic susceptibility system to determine SI and SI normalized to dry sediment weight (Dry SI) for each sample.

2.4 Biogenic silica

Biogenic silica measurements were made following the modified procedure of Mortlock and Froehlich (1989). 52 samples from SIT14 HI were treated with 1N HCl overnight to remove carbonates and rinsed with distilled Nanopure water three times. Sediments were then freeze-dried, and ~45 mg was placed in a 0.1 M Na_2CO_3 solution at 85°C for four hours. Samples then cooled to room temperature overnight, and 100 microliters were reacted with a molybdate blue complex. Sample absorbances were measured at 812 nm wavelength using a Thermo Scientific GeneSys 10S spectrophotometer with sipper cell module. Biogenic silica measurements were converted to opal concentrations using a 2.4 multiplication factor assuming 10% hydration (SiO_2 • 0.4 H_2O).

2.5 Stable isotopes

Dried sediment was homogenized and packed into tin capsules for isotope analysis. Isotope analysis was done at the Idaho State University Interdisciplinary Laboratory for Elemental and Isotopic Analysis (ILEIA) using a Costech ECS 4010 elemental analyzer interfaced to a Thermo Delta V Advantage continuous flow isotope ratio mass spectrometer. All stable isotopic data are reported in standard delta notation ($\delta^{13}C$, $\delta^{15}N$) relative to the Vienna PeeDee Belemnite (VPDB) and atmospheric N_2 (air), reference standards. Analytical precision, calculated from analysis of standards distributed throughout each run, deviated less than ± 0.2‰ for both carbon and nitrogen stable isotopes, and less than ± 0.5% of the sample value for %N and %C. Bulk samples were analyzed, as the research question are primarily focused on N, and carbonate was not detected in samples based on smear slide analysis and HCl testing, except for one isolated interval (6 cm depth in SIT14 G5).

2.6 Chronology

A chronology was determined for recent sediments using ^{210}Pb measurements over the top 24 cm of the SIT14 H1 core and the top 12 cm of the SIT14 G5 core (Figure 3). Analysis was completed at the St. Croix Watershed Research station using standard techniques. A constant rate of supply (CRS) model was used to estimate ages from the ^{210}Pb activity. A radiocarbon date obtained from organic material with structure indicative of a terrestrial origin collected at 107 cm depth from SIT14 H1 core was used to construct a sediment age model for the core. This age model assumes a constant sedimentation rate between the uppermost interval, where unsupported ^{210}Pb reached equilibrium with supported ^{210}Pb, and the calibrated radiocarbon date.

3. Results

3.1 Stratigraphy and chronology

The upper sediment in SIT14 H1 is laminated, relatively organic and diatom rich, followed by a prominent gradational stratigraphic change to grey, organic-poor glaciolacustrine centered at ~22 cm depth (Figure 4). This lithostratigraphic change can be seen in the physical properties data as well as in the elemental and isotope data. Dry SI and water content show increasing values, and bulk density shows decreasing values upward across the lithological change (Figure 6). Below this transition, the sediment is homogeneous, fine grained glaciolacustrine material.

Both cores were dated using the ^{210}Pb constant rate of supply model. Figure 3 indicates that ^{210}Pb reached supported levels below 9 cm in the SIT14 H1 core, but that the SIT14 G5 core, which ended at 12 cm, did not penetrate to the level of supported ^{210}Pb. The activity of supported ^{210}Pb in SIT14 H1 was used to develop a provisional age model for the SIT14 G5 core. This may introduce error in correlating these cores, but the use of other data (physical properties and isotopes) allows for additional means to compare the two cores.

Dates to the 64 cm interval of the SIT14 H1 core were interpolated from the calibrated ^{14}C date obtained at 107 cm, and the lowermost date from the CRS model. The radiocarbon age of the 107 cm sample, 1050 ± 40, calibrates to 988 AD (2-sigma, 892-1035 AD). Error associated with ^{210}Pb dates increase from a minimum of ± 1 yr in the core top sediment to a maximum of ± 24 yrs at the bottom most sediment above supported levels. Error propagation likely would increase at the older end of the ^{210}Pb data, especially considering the transition into a different sediment lithology centered at the ~22 cm sediment depth interval (discussed below). Larger errors would be associated with older intervals, assuming an increase in sedimentation rate during the time of greater glacial-lacustrine deposition found in the lower lithologic unit. This trend is displayed by the steeper slope of the line connecting the oldest ^{210}Pb date to the radiocarbon sample, vs. that defined by the ^{210}Pb data, in the age model (figure 5). Regardless, the upper, more recent intervals of the core are confidently constrained by ^{210}Pb and extended caution was taken when interpreting the age model for the older dates.

3.2 Elemental, stable isotope, and biogenic silica analysis

Average %C/%N ratios (C/N) in SIT14 G5 core is 8.2 and the average C/N in SIT14 H1 is 9.3. Cores SIT14 G5 and SIT14 H1 cores show a general trend towards an increasing C/N ratio up core (Figure 6). A large spike in C/N at the 6 cm interval in the SIT14 G5 core corresponds to an isolated occurrence of calcium carbonate within the sediment. The two cores were taken at different locations in the deep basin of the lake, and a similar spike is not observed in the SIT14 H1 core.

$\delta^{15}N$ values in core SIT14 G5 are relatively enriched at the bottom of the core with a value of 5.2‰ and decrease to a present-day value of 2.6‰. $\delta^{13}C$ also generally upward from the bottom of the core. The bottom of the core has a value of -30.3‰ and the surface has a value of -32.8‰. The large increase in $\delta^{13}C$ at the 6 cm interval is due to the isolated occurrence of calcium carbonate.

$\delta^{15}N$ in core SIT14 H1 varies around 2‰ for a majority of the lower section of the core up to the 24 cm interval above which $\delta^{15}N$ increases until it reaches its maximum value of 7‰ at the 10 cm interval. From this interval, a steady decline in ^{15}N to 3.3‰ is observed at the 1 cm interval. $\delta^{13}C$ values at 64 cm of the SIT14 H1 core are relatively enriched at -20‰ and decrease to the 1 cm interval to a value of -31‰. SIT14 G5 displays similar trends in $\delta^{15}N$ and $\delta^{13}C$ in recent sediments.

Biogenic silica is relatively low and stable between the 60 and 30 cm interval in SIT14 H1 (Figure 7). It then increases subtly starting at the ~30 cm interval and then rapidly increases from the 15 cm interval to the core top. %C has a similar trend, whereas it subtly increases beginning at ~30 cm and rapidly increases at the 15 cm interval to the core top (Figure 6). The subtle and rapid changes correlate with the sedimentary lithologic change. There is a prominent decrease in biogenic silica and %C, along with other geochemical and physical properties at the 9 cm interval in SIT14 H1 core (Figure 6).

4. Discussion

4.1 Anadromous sockeye relative abundance inferred from sediment $\delta^{15}N$ stable isotopes

Situk Lake sediments have an average C/N of 8.9 which is indicative of an aquatic source (Meyers and Ishiwatari, 1993; Barto, 2004). Therefore, interpretation of salmon derived nutrients (SDN) over time are largely uncomplicated by changes in source or dilution from terrestrial organic matter, which have complicated isotope interpretations in some southeast Alaskan lakes (Selbie et al., 2009). Higher C/N recorded in recent sediments in the higher-resolution SIT14 G5 core tops may indicate mixed signals of both aquatic and terrestrial sources. Reasons for this minor intra-site difference in C/N trends is unclear but may be due to different locations in the lake.

Situk Lake sedimentary $\delta^{15}N$ values beginning ~1750 AD are higher in comparison to the average sedimentary $\delta^{15}N$ from 33 Alaska lakes without salmon (1.5 ± 0.9‰) (Finney et al., 2000). The relationship between average sedimentary $\delta^{15}N$ and salmon density (escapement/lake area) over the historical period indicate that Situk Lake sediment isotope values are generally consistent with expectations based on nursery lakes from Kodiak Island and Bristol Bay, Alaska (Finney et al., 2000) (Figure 8). This suggests that the elevated $\delta^{15}N$ found over the past 150 years in Situk Lake is likely due to salmon contributions.

Other factors that can influence $\delta^{15}N$ signals have been discussed in previous papers by Finney et al. (2000), Brock et al. (2006), Hobbs and Wolfe (2007), Selbie et al. (2009), Child and Moore (2017), and Loso et al. (2017) and include artificial fertilizers, sequestration of atmospheric nitrogen, increased nitrogen delivery from alders, and watershed properties promoting terrestrial erosion and mass wasting. None of these factors appear to present any significant influence on the Situk Lake system. Situk Lake is located on the border of Russell

Fiord Wilderness and has seen no artificial fertilization. Atmospheric deposition in this region is considered minimal and would have very low, if any, effect on sedimentary ^{15}N. Lastly, alders, though part of the vegetation succession of the Yakutat region, occur in relatively low abundance in the modern-day forest surrounding Situk Lake. If alders did influence the ^{15}N, their effects would have been seen early in the history of the lake.

Selbie et al. (2009), describe watershed properties that can influence ^{15}N preservation and fluctuations of C/N ratios such as topography, organic coverage and litter, glacial coverage and influence, and soil production. Topographically, Situk Lake is bounded by flat lying muskegs and forests. Though these reservoirs do contain large amounts of terrestrial and soil organic matter, the flat lying topography of the region likely prevents large quantities of terrestrial organic matter from being transported to Situk Lake.

4.2 Fluctuations in trends of salmon abundance

Sedimentary $\delta^{15}N$ show an increasing trend beginning around ~1750 AD and culminating at ~1870 AD with a sedimentary $\delta^{15}N$ maximum of 7‰. A steady decrease in sedimentary $\delta^{15}N$ has been occurring since ~1870 AD until present. Situk Lake is a relatively young, presently clearwater lake, no longer receiving sediment-rich, glacially-derived meltwater. The transition from a glacial dominated system to a clearwater system is recorded by the change in sediment characteristics between 27 and 18 cm in core SIT14 H1. This interval coincides with an increase in sedimentary ^{15}N, indicating a shift in salmon abundance during the transition into a clear water system. While salmon can find suitable spawning habitats in silt-rich glacially dominated systems (Burgner, 1991), the change in environment was likely to enhance both spawning and rearing conditions. The lack of an enriched $\delta^{15}N$ signal prior to this time does not imply that salmon were not spawning in the system but could have been present in lower abundance. Loso et al. (2017), show that up to 20,000 salmon can be present in the Eklutna Lake system without leaving a sedimentary $\delta^{15}N$ signature. Therefore, while the exact timing of when salmon started to spawn in the lake in unresolved, the time when the density of salmon spawning in Situk Lake was large enough to leave an isotopic signature in the lake sediment is clear.

Lake productivity has the potential to be influenced by factors such as water clarity and nutrient supply, including the addition of SDN. The transition from glacio-lacustrine to clearwater conditions would have increased euphotic volume. Changes in salmon escapement can alter the amount of SDN being delivered back into the lake system, and if these nutrients are important to primary produces, would affect primary production, and ultimately carrying capacity for juvenile salmon. (Cederholm et al., 1999; Finney et al., 2000; Gende et al., 2002). Overall salmon production would increase, further enriching $\delta^{15}N$ signals. Similarly, a decrease in escapement would have the opposite effects on the lake system.

The increase in sedimentary $\delta^{15}N$ starting ~1750 AD was likely the beginning of a positive feedback cycle between lake productivity and salmon. Improved spawning habitats following the transition into a clearwater system, may have also been important. Sedimentary $\delta^{15}N$ constantly increased by an average of 0.04‰ per year to a maximum sedimentary $\delta^{15}N$ signal of 7‰ approximately ~1870 AD. This transition is accompanied by increases in lake primary productivity indicators such as biogenic silica and %C. SDN may have contributed to this change, but the extent of this contribution is unknown. From ~1870 AD until present time there has been a decrease of sedimentary $\delta^{15}N$ (~0.04‰ per year). However, lake productivity indicators do not show a parallel decline during this period, suggesting that reduction in SDN was not important, or that diagenetic processes, or change in organic matter source near the core top complicate this comparison.

The data suggest that the decline in $\delta^{15}N$ began prior to the onset of commercial fishing (before 1903 in Figure 9). This may be due to a magnitude 8 earthquake that occurred near Yakutat in 1899. Earthquakes of this size have the potential to alter spawning habitats or dilute sediment $\delta^{15}N$ with input via gravity-related depositional process of material with lower $\delta^{15}N$. Rapid changes in geochemical and physical properties at the 9 cm intervals in the SIT14 H1 also coincide with the timing of the 1899 earthquake (within ^{210}Pb error). Changes in sediment physical properties, such as %$H_2 0$, bulk density, and SI, suggest that there was a sedimentation event, separate from shifts in salmon abundance, that altered its character. Alternatively, a switch to a negative PDO pre-1900 AD (MacDonald and Case, 2005) could decrease salmon abundance through a decrease in oceanic salmon survival rates. The continued $\delta^{15}N$ depletion to present day tracks estimated and measured escapement and may be due to the construction of a salmon cannery in Yakutat and high initial exploitation, followed by management practices favoring a low/constant escapement. The cannery began harvesting salmon at a time when many Alaskan salmon fisheries were experiencing high salmon runs (Rogers et al., 2013). Overharvesting of the sockeye would reduce the amount of $\delta^{15}N$ being delivered into the Situk Lake system by reducing escapement.

Increasing lake productivity during the transition from a glacial to non-glacial system is marked by increasing %C (Figure 6) and biogenic silica (Figure 7). As Situk Lake transitioned into a clear water system, light was likely able to penetrate deeper into the water column and fuel greater primary production increasing the abundance of siliceous algae present in the lake, which would subsequently lead to an increase in food sources for salmon. Continued increase in %C in the top of the sediment core does not follow the same pattern of $\delta^{15}N$. %C does, however, correlate with an increase in biogenic silica and C/N, suggesting that an increase in %C may be due to an increase in abundance of siliceous algae (Conley, 1988), and/or deposition and utilization of vascular terrestrial material (Meyers and Ishiwatari, 1993).

Shifts in climate, such as the PDO, have had measured effects on salmon and fish productivity over the recorded history in Alaska (Beamish and Bouillon, 1993; Mantua et al., 1997; Hare et al., 1999). A shift to the negative phase of the PDO in 1947 saw a widespread decrease in salmon abundance while a positive shift in the PDO in 1977 saw an increase in salmon abundance in Alaska. Changes in salmon abundance relative to shifts in the PDO has been documented in a number of publications (Mantua et al., 1997; Mantua and Hare, 2002; Hare et al., 1999; Finney et al., 2000, 2002; Rogers et al., 2013). Available data suggests that salmon run sizes in Situk River decreased in 1947, similar to other Alaskan fisheries, that has been ascribed in part to the shift to the negative PDO regime. However, the Situk system does not show a rebound in run size following the 1977 shift, recorded by many Alaskan stocks. A lack of positive response to a more favorable PDO might be due to several factors. There is the possibility that Situk River/Lake sockeye system respond differently than many Alaskan salmon stocks to shifting ocean conditions in their migration patterns or feeding behavior. Situk sockeye are unique genetically and are most similar to a few distinct stocks found in recently deglaciated regions (Gavin, 2018, personal communication; Shaul, 2018, personal communication). Shifts in sockeye run size may also be due to the maturing habitat and food webs of the Situk River. Sockeye could have been the pioneering species of salmon in the Situk River. Other salmon species such as coho, and consumers of sockeye fry that have increased in the Situk River and feed on sockeye fry which would diminish run sizes (Neal, 2018, personal communication).

In summary, isotope data recovered from the sediment core support the measured and hindcast salmon run and escapement data. Our data also suggest that salmon runs started increasing since ~1750 AD as the local influence of glacial activity on the lake decreased and reached a peak at ~1870 AD Since then, run sizes have diminished and showed little response to positive shifts in the PDO.

5. Conclusion

We assessed sedimentary composition, %C, %N, $\delta^{13}C$, $\delta^{15}N$, and biogenic silica, to reconstruct salmon abundance and environmental conditions in Situk Lake, Alaska over the past 500 years. As local effects of Little Ice Age glaciation waned beginning ~1750 AD glacial sediment influx to the lake decreased, eventually leading to a clear water system with increasing primary productivity and a subsequent increasing abundance of anadromous sockeye salmon. During this time, it is likely that spawning habitat improved, and lake carrying capacity increased, possibly abetted by an increased amount of SDN entering the Situk Lake system. Collectively, this suggests lake conditions changed, allowing for a positive feedback cycle to salmon productivity. Sedimentary ^{15}N continued to increase until ~1870 AD to a maximum $\delta^{15}N$ of 7‰. After ~1870 AD, sedimentary ^{15}N steadily decreased to present $\delta^{15}N$ levels of 2.7‰. Some of the decrease in sedimentary ^{15}N corresponds with the introduction of a salmon cannery in Yakutat and an increase in commercial and recreational fishing in the region. The initial decrease in sedimentary ^{15}N may not reflect a decrease in salmon abundance, but rather dilution from reworking of older sediment due a large magnitude 8 earthquake that occurred in the Yakutat region in 1899 (Figure 9). Changes in geochemical and physical properties of the sediment correlating with the 1899 earthquake suggest that tectonic processes should be considered in interpreting sediment core of primary productivity and salmon abundance.

Relationships between salmon abundance in Situk Lake and shifts in the Pacific Decadal Oscillation are complicated by changing environmental conditions and salmon harvesting. Following the time (1903), the salmon cannery opened, total run size decreased, which may have been subsequently abetted by a negative shift in PDO state in 1947. However, the most recent shift in the PDO (1977) which has been shown to correlate with an increase in salmon runs across multiple systems in Alaska (Finney et al., 2000, 2012; Rogers et al., 2013) did not occur in the Situk Lake system.

This study illuminates the fact that large numbers of sockeye salmon are a relatively new phenomenon to this area. River and lake systems in glacially active regions, such as Glacier Bay, that have only been recently deglaciated are rapidly colonized, and can quickly develop substantial salmon runs. For example, Milner et al. (2000), observed juvenile coho salmon in streams as young as 43 years old, suggesting that salmon colonize river and lake systems quickly after they become available. It is important to realize that salmon have quickly adapted to the system and continue to do so in the Yakutat salmon system. Understanding the consequences of regional glaciation, tectonics, and subsequent habitat alteration in the region is important when managing for future salmon runs.

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References

Anderson, L., Abbott, M.B., Finney, B.P., and Burns, S.J., 2005, Regional atmospheric circulation change in the North Pacific during the Holocene inferred from lacustrine carbonate oxygen isotopes, Yukon Territory, Canada: Quaternary Research, v. 64, p. 21–35, doi: 10.1016/j.yqres.2005.03.005.

Barclay, D.J., Calkin, P.E., and Wiles, G.C., 2001, Holocene history of Hubbard Glacier in Yakutat Bay and Russell Fiord, Southern Alaska: Bulletin of the Geological Society of America, v. 113, p. 388–402, doi: 10.1130/0016-7606(2001)113<0388:HHOHGI>2.0.CO;2.

Barto, D., 2004, Assessing the production of sockeye salmon (onocorhynchus nerka) at Chilkat Lake, southeast Alaska, using current trophic conditions and the paleoclimnologic sediment record: University of Alaska Fairbanks, 111 p.

Beamish, R.I., and Bouillon, D.R., 1993, Pacific salmon production trends in relation to climate: Canadian Journal of Fisheries and Aquatic Sciences, v. 50, p. 1002–1016.

Brock, C.S., Leavitt, P.R., Schindler, D.E., Johnson, S.P., and Moore, J.W., 2006, Spatial variability of stable isotopes and fossil pigments in surface sediments of Alaskan coastal lakes : Constraints on quantitative estimates of past salmon abundance: American Society of Limnology and Oceanography, v. 51, p. 1637–1647.

Burgner, R.L., in Pacific Salmon Life Histories, 1991, Groot, C., Margolis, L., Life History of Sockeye Salmon: Vancouver, British Columbia, University of British Columbia Press, 564 p

Calkin, P.E., Wiles, G.C., and Barclay, D.J., 2001, Holocene coastal glaciation of Alaska.pdf: Quaternary Science Reviews, v. 20, p. 449–461.

Cederholm, C.J., Kunze, M.D., Murota, T., and Sibatani, A., 1999, Pacific salmon carcasses: essential contributions of nutrients and energy for aquatic and terrestrial ecosystems: Fisheries, v. 24, p. 6–15, doi: 10.1577/1548-8446(1999)024<0006:PSC>2.0.CO;2.

Child, A.W., and Moore, B.C., 2017, Stable isotope (δ13C, δ15N, δ34S) analysis of sediment cores suggests sockeye salmon (Oncorhynchus nerka) did not historically spawn in Lake Roberta, Washington (USA): Journal of Paleolimnology, v. 57, p. 67–79, doi: 10.1007/s10933-016-9928-9.

Clark, J.H., S.A. McPherson, and G.F. Woods 2002. Biological escapement goal for sockeye salmon in the Situk River, Yakutat, Alaska. Alaska Department of Fish and Game, Special Publication No. 02-03, Anchorage.

Clark, John H., McPherson, Scott, A., Burkholder, Alan 1995. Biological escapement goal for Situk River sockeye salmon. Alaska Department of Fish and Game, Douglas.

Conley, D.J., 1988, Biogenic silica as an estimate of siliceous microfossil abundance in Great Lakes sediments: Biogeochemistry, v. 6, p. 161–179.

Finney, B.P., Alheit, J., Emeis, K.C., Field, D.B., Gutiérrez, D., and Struck, U., 2010, Paleoecological studies on variability in marine fish populations: A long-term perspective on the impacts of climatic change on marine ecosystems: Journal of Marine Systems, v. 79, p. 316–326, doi: 10.1016/j.jmarsys.2008.12.010.

Finney, B.P., Bigelow, N.H., Barber, V.A., and Edwards, M.E., 2012, Holocene climate change and carbon cycling in a groundwater-fed, boreal forest lake: Dune Lake, Alaska: Journal of Paleolimnology, v. 48, p. 43–54, doi: 10.1007/s10933-012-9617-2.

Finney, B.P., Gregory-Eaves, I., Douglas, M.S., and Smol, J.P., 2002, Fisheries productivity in the northeastern Pacific Ocean over the past 2,200 years: Nature, v. 416, p. 729–733, doi:

10.1038/416729a.

Finney, B.P., Gregory-Eaves, I., Sweetman, J., Douglas, M.S. V., and Smol, J.P., 2000, Impacts of climatic change and fishing on Pacific salmon abundance over the past 300 years: Science, v. 290, p. 795–799, doi: 10.1126/science.290.5492.795.

Gende, S.M., Edwards, R.T., Willson, M.F., and Wipfli, M.S., 2002, Pacific salmon in aquatic and terrestrial ecosystems: BioSci., v. 52, p. 917–928, doi: 10.1641/0006-3568(2002)052[0917:PSIAAT]2.0.CO;2.

Gubernick, R., and Paustian, S., 2007, Hubbard Glacier, Russell Fiord and Situk River – A Landscape in Motion: , p. 18–22.

Hare, R.S., Mantua, J.N., and Francis, C.R., 1999, Inverse production regimes: Alaska and west coast Pacific salmon: Fisheries, v. 24, p. 6–14, doi: 10.1577/1548-8446(1999)024<0006.

Hobbs, W.O., and Wolfe, A.P., 2007, Caveats on the use of paleolimnology to infer Pacific salmon returns: Limnology and Oceanography, v. 52, p. 2053–2061, doi: 10.4319/lo.2007.52.5.2053.

Holtham, A.J., Gregory-Eaves, I., Pellatt, M.G., Selbie, D.T., Stewart, L., Finney, B.P., and Smol, J.P., 2004, The influence of flushing rates, terrestrial input and low salmon escapement densities on paleolimnological reconstructions of sockeye salmon (Oncorhynchus nerka) nutrient dynamics in Alaska and British Columbia: Journal of Paleolimnology, v. 32, p. 255–271, doi: 10.1023/B:JOPL.0000042998.22164.ca.

Hu, F.S., Finney, B.P., and Brubaker, L.B., 2001, Effects of holocene Alnus expansion on aquatic productivity, nigrogen cycling, and soil development in southwestern Alaska: Ecosystems, v. 4, p. 358–368, doi: 10.1007/s10021.

Loso, M., Finney, B., Johnson, R., and Sinnott, R., 2017, Evaluating evidence for historical anadromous Salmon runs in Eklutna Lake, Alaska: Arctic, v. 70, p. 259–272, doi: 10.14430/arctic4665.

MacDonald, G.M., and Case, R.A., 2005, Variations in the Pacific Decadal Oscillation over the past millennium: Geophysical Research Letters, v. 32, p. 1–4, doi: 10.1029/2005GL022478.

Mantua, J.N., and Hare, R.S., 2002, The pacific decadal oscillation: Journal of Oceanography, v. 58, p. 35–44.

Mantua, J.N., Hare, R.S., Zhang, Y., Wallace, M.J., and Francis, C.R., 1997, A Pacific interdecadal climate oscillation with impacts on salmon production: Bulletin of the American Meteorological Society, v. 78, p. 1069–1079, doi: 10.1175/1520-0477(1997)078<1069:apicow>2.0.co;2.

Meyers, P.A., and Ishiwatari, R., 1993, Lacustrine organic geochemistry - an overview of indicators of organic-matter sources and diagenesis in lake-sediments: Organic Geochemistry, v. 20, p. 867–900, doi: 10.1016/0146-6380(93)90100-p.

Mortlock, Richard A., and Froelich, Philip N., 1989, A simple method for the rapid determination of biogenic opal in pelagic marine sediments: Deep Sea Research Part A, Oceanographic Research Papers, v. 36, p. 1415-1426, doi: 10.1016/0198-0149(89)90092-7.

Rogers, L.A., Schindler, D.E., Lisi, P.J., Holtgrieve, G.W., Leavitt, P.R., Bunting, L., Finney, B.P., Selbie, D.T., Chen, G., Gregory-Eaves, I., Lisac, M.J., and Walsh, P.B., 2013, Centennial-scale fluctuations and regional complexity characterize Pacific salmon population dynamics over the past five centuries: Proceedings of the National Academy of Sciences, v. 110, p. 1750–5, doi: 10.1073/pnas.1212858110.

Schindler, D.E., Leavitt, P.R., Brock, C.S., Johnson, S.P., and Quay, P.D., 2005, Marine-derived nutrients, commercial fisheries, and production of salmon and lake algae in Alaska:

Ecology, v. 86, p. 3225–3231.

Selbie, D.T., Finney, B.P., Barto, D., Bunting, L., Chen, G., Leavitt, P.R., Macisaac, E.A., Schindler, D.E., and Shapley, M.D., 2009, Ecological, landscape, and climatic regulation of sediment geochemistry in North American sockeye salmon nursery lakes: Insights for paleoecological salmon investigations: American Society of Limnology and Oceanography, v. 54, p. 1733–1745.

Stuiver, M., Reimer, P.J., and Reimer, R.W., 2018, CALIB 701 [WWW program] at http;//calib.org, accessed 2018-3-19

Thedinga, J.F., Murphy, M.L., Johnson, S.W., Lorenz, J.M., and Koski, K. V., 1994, Determination of salmonid smolt yield with rotary-screw traps in the Situk River, Alaska, to predict effects of glacial flooding: North American Journal of Fisheries Management, v. 14, p. 837–851, doi: 10.1577/1548-8675(1994)014<0837:DOSSYW>2.3.CO;2.

Trabant, D.C., Krimmel, R.M., Echelmeyer, K.A., Zirnheld, S.L., and Elsberg, D.H., 2003, The slow advance of a calving glacier: Hubbard Glacier, Alaska, U.S.A: Annals of Glaciology, v. 36, p. 45–50, doi: 10.3189/172756403781816400.

Trabant, D.C., Krimmel, R.M., and Post, a. S., 1991, A preliminary forecast of the advance of Hubbard Glacier and its influence on Russell Fiord, Alaska: USGS Water-Res. Invest. Rep., v. 90–4172, http://agris.fao.org/agris-search/search/display.do?f=1992/US/US92097.xml;US9147262.

Wiles, G.C., and Calkin, P.E., 1994, Late Holocene , high-resolution glacial chronologies and climate , Kenai Mountains , Alaska: , p. 281–303.

Figures

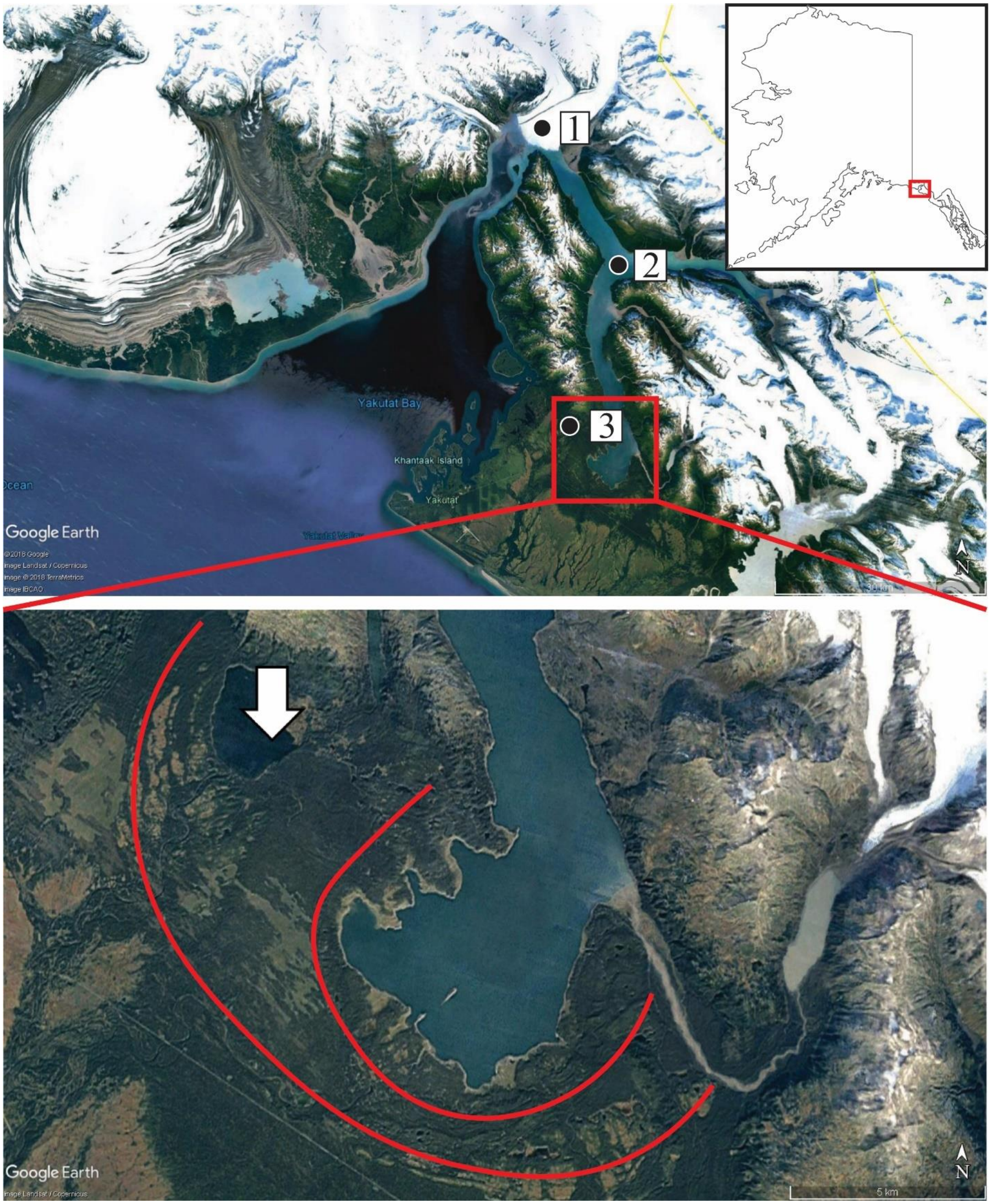

Figure 1. Location map of the study area. 1-Hubbard Glacier; 2-Russell Fiord; 3-Situk Lake; Red lines on the second image denote the location of two terminal moraines. White arrow indicates sample location.

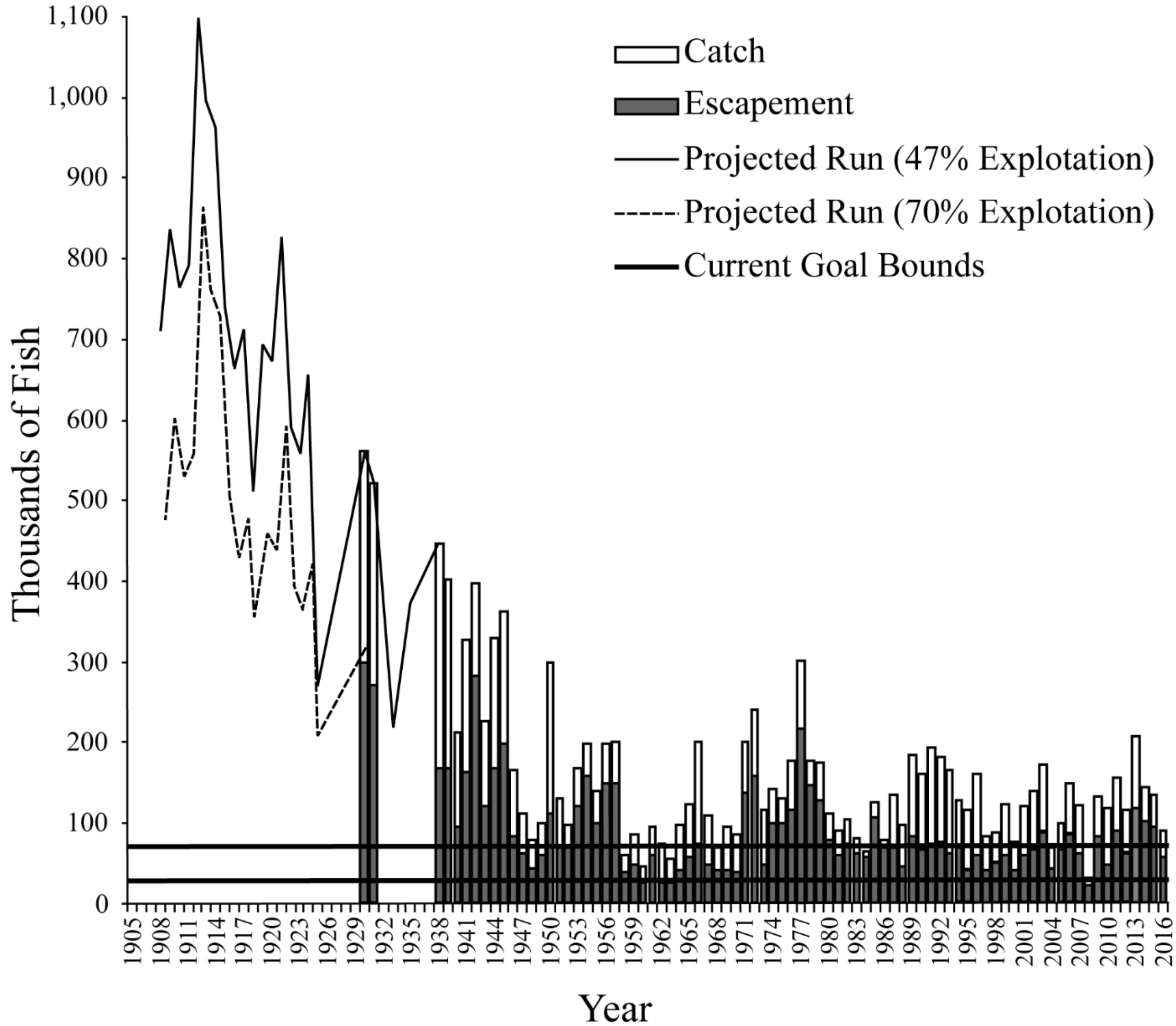

Figure 2. Sockeye salmon run totals for Situk River. Shaded sections of the bar graph represent escapement and the clear sections represent catch, together they represent total run. The two horizontal lines denote the upper and lower limits of escapement goals. Solid and dashed lines prior to 1938 represent hindcast runs with 47% and 70% exploitation respectively. hindcast runs were estimated using salmon cannery data.

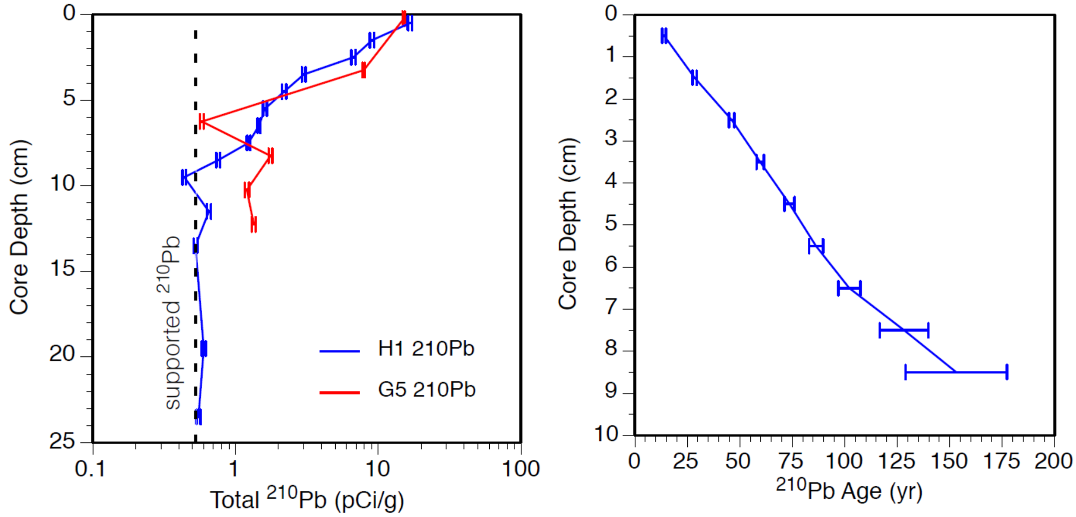

Figure 3. (left panel) Results from ^{210}Pb analysis. ^{210}Pb reached support levels at 9 cm sediment depth in the SIT14 H1 core (blue). ^{210}Pb levels did not reach supported levels in the SIT14 G5 core (red). (right panel) CRS modeled age with depth for SIT14 H1.

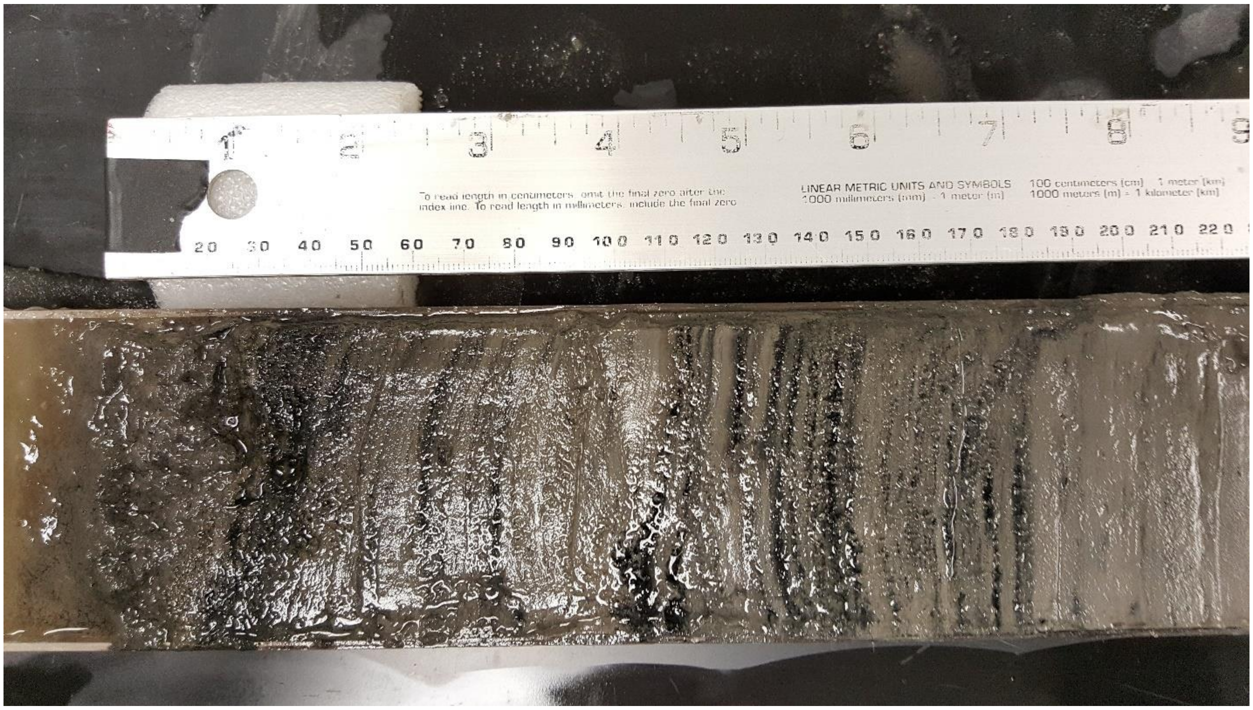

Figure 4. Picture show the lithologic transition centered at the ~22 cm sediment depth in sediment core SIT14 H1. This transition denotes the time at which the lake ceased to be fed with fine glacial sediment and transitioned into a clearwater lake.

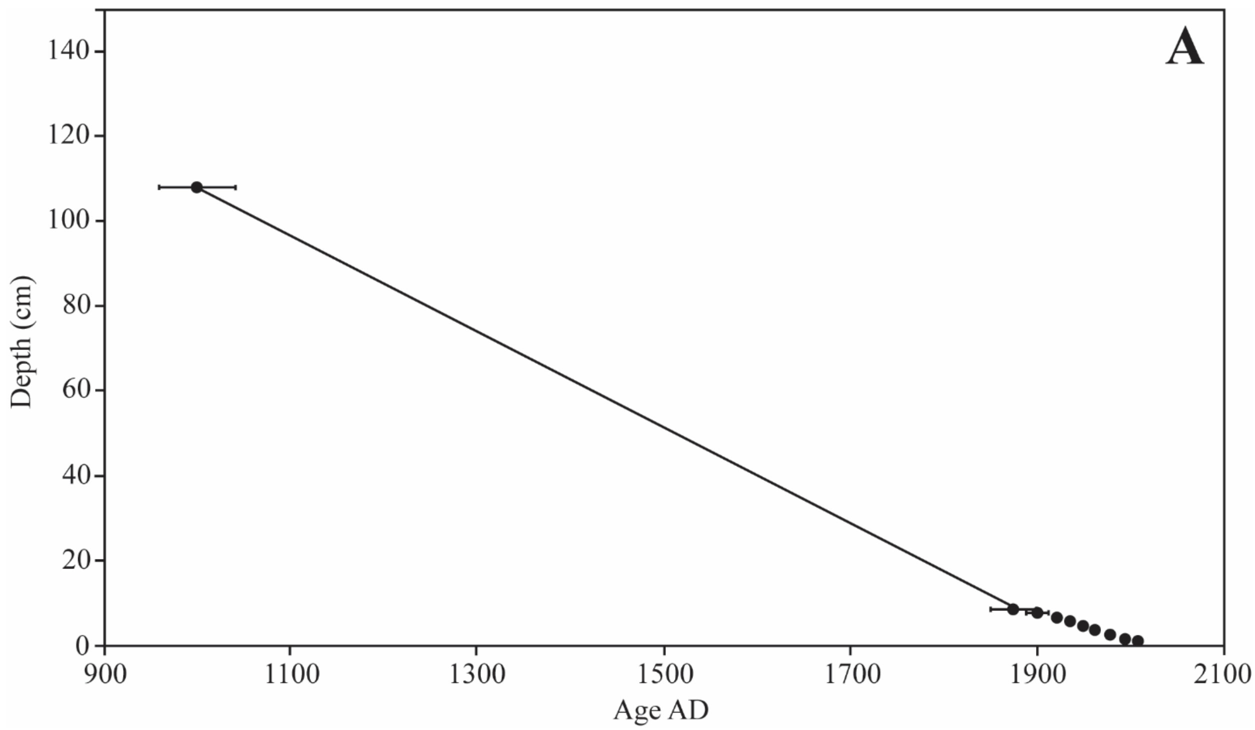

Figure 5. Age-depth relationships of Situk Lake core SIT 14 H1 using ^{210}Pb and a ^{14}C basal anchor.

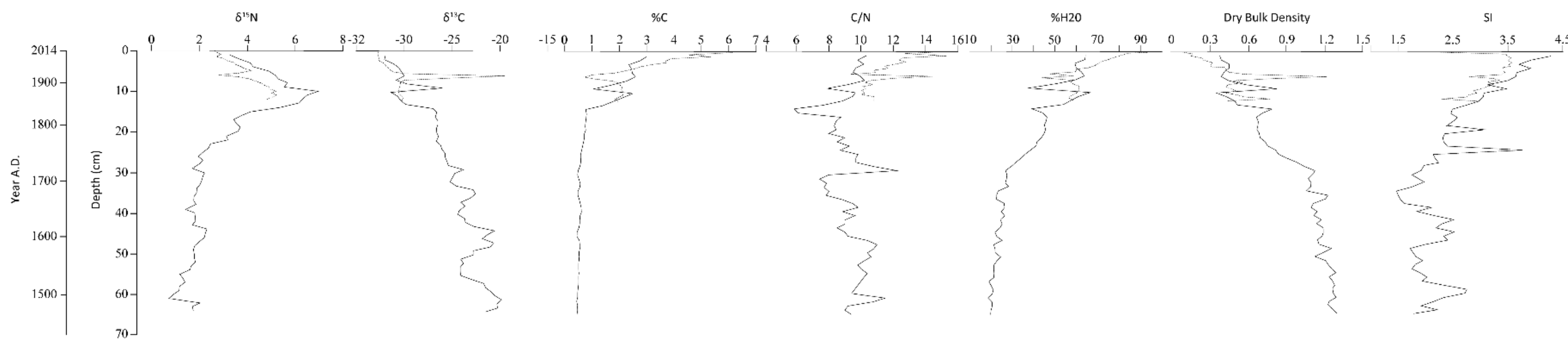

Figure 6. Geochemical results and physical properties from SIT14 H1 (solid line) and SIT G5 (dashed line).

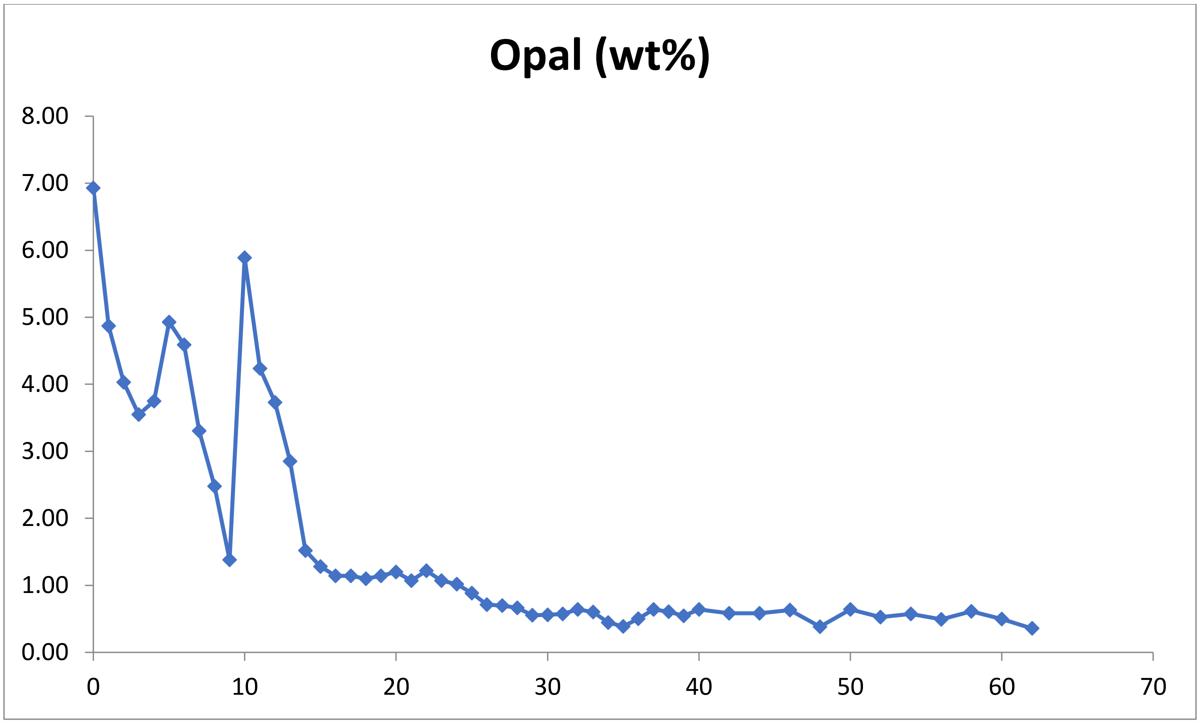

Figure 7. Results from weight percent biogenic silica analysis.

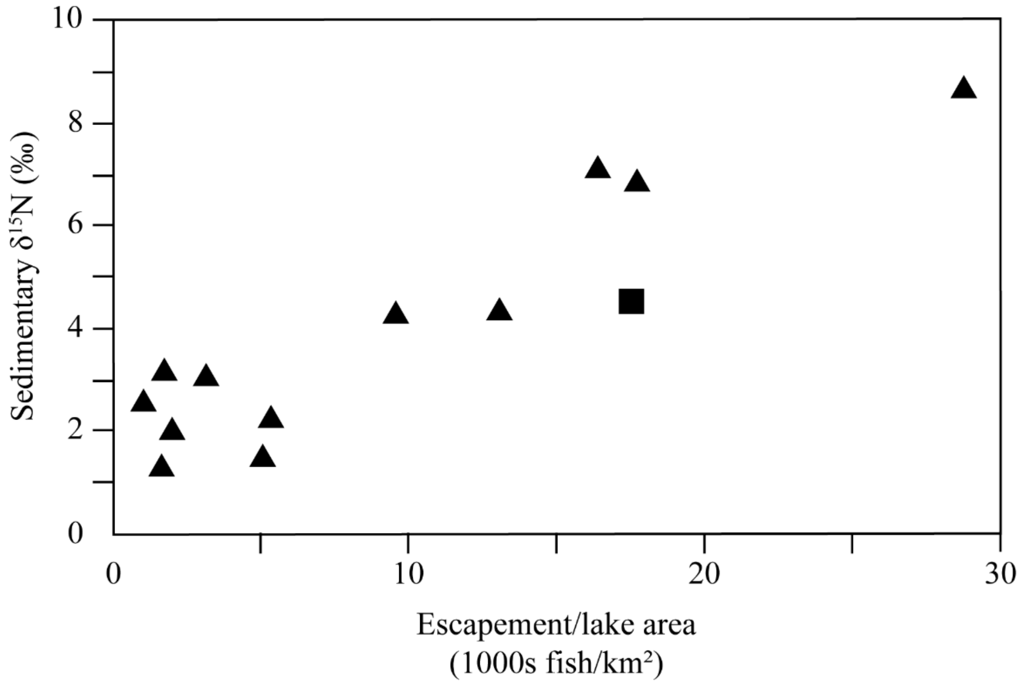

Figure 8. Plot modified from Finney et al. (2000) with Situk Lake position (square) in relation to other salmon spawning lakes in Alaska (triangles). Escapement includes Situk Lake and a smaller lake upstream (Mountain Lake, described in more detail in chapter 2 of this thesis).

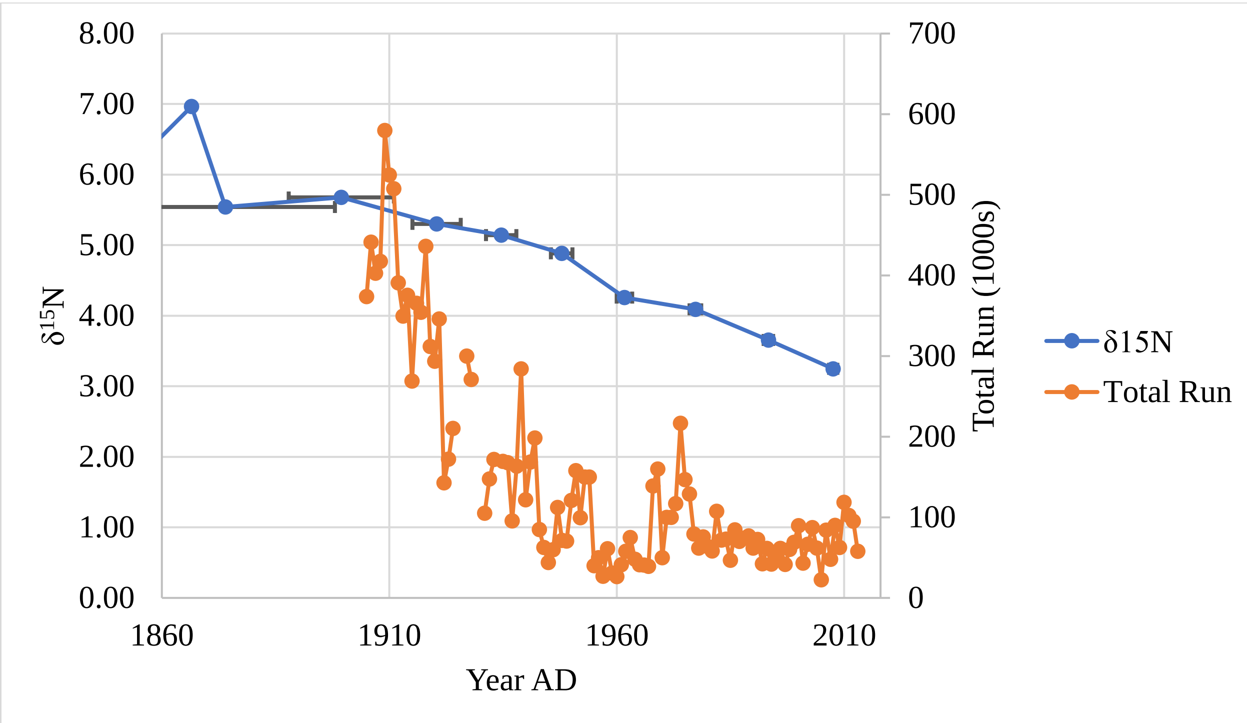

Figure 9. Graph displaying $\delta^{15}N$ of Situk lake (orange) and total sockeye run size (blue) since the initial decline in $\delta^{15}N$ beginning ~1870 AD. Errors on $\delta^{15}N$ points are the dating errors associated with ^{210}Pb.

Chapter II. Glacial and salmon history of Situk and Mountain lakes, Yakutat, Alaska

Abstract

Situk and Mountain lakes near Yakutat, Alaska, are active salmon spawning lakes that are economically vital to the city of Yakutat. Little is known about the formation of the two lakes and the history of subsequent fluctuations of salmon abundance in this glacially dynamic region. Using a multiproxy analysis from sediment cores, and chronologic data from the lakes and associated moraines, I have determined the timing of formation and final deglaciation of Situk and Mountain lakes, and how that timing relates to fluctuations in primary productivity and salmon abundances over the last millennia. Dates collected from sediment cores and a muskeg located between the two Holocene terminal moraines suggest a retreat of Hubbard Glacier from the outer moraine and formation of the lakes ca ~1400 AD during an early phase of the Little Ice Age (LIA). Sediment characteristics and physical properties indicates the lakes were strongly impacted by glacially-derived, suspended sediment loads following formation. Possible sources of this sediment include, glacial runoff from Russell Fiord into Situk and Mountain lakes, erosion and transport of periglacial sediment deposited during the advances and retreats of Hubbard Glacier in the lakes watershed, or from LIA glaciers on mountains within Mountain Lake watershed. Only recently, since ~1750 AD, has the Situk Lake system turned into a clear water system. Sedimentary $\delta^{15}N$, a proxy for sockeye salmon (*Oncorhynchus nerka*), remained at low levels from the base of the cores until ~1850 AD where it increased and peaked in the early 1900's AD (sedimentary $\delta^{15}N$ of 7‰). Following this peak, sedimentary $\delta^{15}N$ declined to its current level of 3.2‰. Mountain Lake showed more variability in sedimentary $\delta^{15}N$ since the retreat of glaciers, suggesting that salmon utilization of the lakes differ following glacial retreat. Data from Situk Lake, likely the more important rearing lake, show that under natural conditions,

salmon abundances increased from deglaciation until the development of a salmon cannery in 1903 AD.

1. Introduction

Yakutat is a coastal town in southeast Alaska located at the foot of the St. Elias Mountains, built on glacial moraines and glacial outwash sediments from the Little Ice Age (LIA) expansion of Hubbard and Malaspina Glaciers (Barclay et al., 2001; Zurbuchen et al., 2015). Nearby Hubbard Glacier (Figure 1), is the largest surging tidewater glacier in North America. Currently, Hubbard Glacier is about 120 km long, with a calving face width of 11.4 km and, seasonally, a calving face height of 100 m (Barclay et al., 2001; Trabant et al., 2003). This glacier has had two recent advances, in 1986 and 2002, that dammed Russell Fiord and turned it into a lake, Russell Lake. Hubbard glacier is currently inferred to be poised to advance, based on its accumulation area ratio (AAR) of 0.96 (Trabant et al., 1991). It is predicted that most tidewater calving glaciers will advance until an AAR of ~0.7 is reached. Because Hubbard glacier is in the beginning stages of observed advance, it is predicted to continue its advance into Yakutat Bay and Russell Fiord (Trabant et al., 2003). An advance into Russell Fiord, past Gilbert Point (location 3 in Figure 1) has the potential to turn Russell Fiord into a lake again, similar to the advances of 1986 and 2002. If Russell Lake is sustained long enough it will overflow a 41 m masl terminal moraine spillway located on the southern end of the fiord (Figure 2). Such an overflow would flood Situk River, an economically important salmon spawning river, and inundate Yakutat’s airport (Gubernick and Paustian, 2007).

Past studies completed by Barclay et al. (2001); Trabant et al. (2003); Gubernick and Paustain (2007); suggest multiple Holocene advances of Hubbard Glacier into Russell Fiord. These advances also had the potential for water stored in Russell Lake to overflow over the terminal moraine spillway located on the southern end of the fiord, which could result in changes in morphological and ecological characteristics of Situk River. I hypothesize that Situk

(59.6425°N, 139.4003°W) and Mountain (59.6617°N, 139.3456°W) lakes (Figure 1), the primary spawning lakes of sockeye salmon (*Oncorhynchus nerka*), and the primary focus of our study, are relatively new lakes formed during the late Holocene Neoglacial period, a time when other glaciers throughout Alaska were advancing (Wiles et al., 1999). If these lakes are relatively young, the occurrence of sockeye salmon may be a rather recent phenomenon of the Situk River system. Situk and Mountain lakes are a linked system via Situk River, where Mountain Lake is upstream of Situk Lake. Both lakes are thought to have been continuously connected throughout their history (Schmidt, 1981).

It has been shown in previous studies that the $\delta^{15}N$ signals in lake sediments can be a reliable proxy for past changes in salmon abundance in some lake systems (Finney et al., 2002; Barto, 2004; Holtham et al., 2004; Rogers et al., 2013; Loso et al., 2017). Anadromous sockeye salmon acquire ~95% of their biomass while in the ocean (Schindler et al., 2005). As adult salmon have high $\delta^{15}N$ (~12‰) relative to a depleted terrestrial source (~0‰) (Finney et al., 2000), changes in input of salmon-derived nutrients (SDN) over time, and hence salmon abundance, can be seen inferred from lake sediment $\delta^{15}N$. Recent changes in $\delta^{15}N$ can be influence by anthropogenic causes, such as commercial and recreational salmon harvesting (Rogers et al., 2013). Such influences need to be accounted for, in interpreting sediment records. Our data include a history of pre-anthropogenic and post settlement influences on the salmon runs in the Situk River system.

Regional climate variability, such as the Pacific Decadal Oscillation (PDO), has been shown to influence salmon abundance, precipitation patterns, and glacial activity. The PDO explains multidecadal shifts in warm (ca. 1925-1946 and 1997-1998) and cold (ca. 1890-1924 and 1947-1976) sea surface temperature regimes which are thought to have an effect on ocean primary productivity and subsequent salmon abundance (Beamish and Bouillon, 1993; Mantua et al., 1997; Mantua and Hare, 2002). A sustained negative phase in the PDO when coupled with a solar minimum has been shown to influence regional glacier dynamics (Wiles et al., 2004).

The purpose of this study is to use lake sediment cores collected from Situk and Mountain lakes, and basal dates on muskeg pits between glacial moraines, to determine the origin of the lakes, their subsequent environmental history, and other information on regional glaciation. I will also use stable isotope and elemental data to reconstruct salmon productivity and lake environments subsequent to their formation.

2. Materials and Methods

2.1 Sample location and limnology

Situk and Mountain lakes are located ~20 km northeast of Yakutat, Alaska. Situk Lake lies between two terminal moraines that were created during the advance of nearby Hubbard Glacier through Russell Fiord (Barclay et al., 2001) and Mountain Lake is bounded by a steep valley that was likely formed by advances of Hubbard Glacier down Russell Fiord (Figure 1). Annual precipitation at Yakutat is 3550 mm and the mean temperature is -3.1 °C in January and 11.9 °C in July classifying Yakutat as maritime (Barclay et al., 2001). The glacial outwash fan that covers most of the region surrounding the lakes consists of temperate forests and muskegs.

Situk Lake has simple basin like bathymetry with a maximum depth of 25 m in the central basin of the lake. It has area of 4.092 km^2 with a water residence time of 0.74 years. Mountain Lake is elongate with two basins, the larger located in the northern end of the lake with a maximum depth of 46 m. Mountain Lake has an area of 0.829 km^2, and a water residence time of 0.48 years (Barto, 2004). Additional limnologic data reported by Schmidt (1981) and Barto (2004) can be seen in Table 2.

2.2 Sediment coring, sampling, and analytical framework

Situk and Mountain lakes were sampled in the summer of 2014. Cores were collected through gravity, hammer, and piston coring techniques. Coring was conducted in multiple sites on each lake (Figure 1). Collected cores were sent to Idaho State University, where they were opened in the summer of 2016. Correlation of cores within and between sites on the lakes was completed using ^{210}Pb, physical properties (bulk density, magnetic susceptibility, and smear slide analysis), and stable isotope data. Correlation was completed to obtain the most complete stratigraphic records of both Situk and Mountain lakes. Situk Lake reached refusal (unable to further penetrate the glacio-lacustrine sediment) in fine glacial outwash deposits and Mountain Lake reached refusal in coarse glacial sand and gravel till.

Select gravity cores, collected to preserve the sediment water interface, were extruded in 0.5 cm – 1 cm intervals in the field. Extruded samples were collected in 523 ml polyethylene bags and were kept frozen at ISU until processing.

Laboratory sampling entailed taking 2 cm^3 samples continuously every 1 cm downcore. Samples were weighed before and after freeze-drying to determine water content and wet and dry bulk density. Dried samples were measured for magnetic susceptibility (SI) on a Barington MS2 magnetic susceptibility system, which was normalized to dry weight (Dry SI).

2.3 Elemental and stable isotopes

Isotopic and elemental analysis was done at the Idaho State University Interdisciplinary Laboratory for Elemental and Isotopic Analysis (ILEIA) using a Costech ECS 4010 elemental analyzer interfaced to a Thermo Delta V Advantage continuous flow isotope ratio mass spectrometer. Dried sediment was homogenized and packed into tin capsules, bulk samples were analyzed, as carbonates are absent, and due to the focus of nitrogen for this project. All stable isotopic data are reported in standard delta notation ($\delta^{13}C$, $\delta^{15}N$) relative to the Vienna PeeDee Belemnite (VPDB) and atmospheric N_2 (air), reference standards. Analytical precision, calculated from analysis of standards distributed throughout each run, deviated less than ± 0.2‰ for both carbon and nitrogen stable isotopes, and less than ± 0.5% of the sample value for %N and %C.

2.4 Chronology

Ages of Situk and Mountain lakes sediment core samples were determined from ^{210}Pb and AMS ^{14}C-dating. ^{210}Pb from Situk and Mountain lakes were measured from the top 24 cm of the SIT14 H1 core and MOUNT14 G5 core respectively. A constant rate of supply (CRS) model was used to determine the ^{210}Pb-based dates (Figure 4 and 5). Radiocarbon samples were collected from the basal most intervals of the SIT14 P2 sec 2 core and MOUNT14 P6 sec 3 cores, where organic materials could be located. To obtain material to date, samples were sieved through 125 and 250 um sieves, picked for organic material (Table 1) and were sent for analysis at Lawrence Livermore National Laboratory Center for Accelerator Mass Spectrometry. Radiocarbon samples were calibrated using Calib 7.1 (Stuiver et al., 2018). Two soil pits were hand dug during the summer of 2017 in a muskeg ice-proximal to the outermost moraine that bounds the south and west sections of Situk Lake (Figure 1). A soil pit description was taken along with samples at distinct horizons. Samples were collected in polyethylene bags and shipped to ISU. Muskeg samples were frozen until processing. Samples from the bottom most interval above the inferred glacial-non-glacial sediment contact (a transition between pebble size glacial outwash and the accumulation of peat) of two muskeg pits were sieved, processed, and dated as described above. Radiocarbon ages are reported in Table 1.

3. Results

3.1 Sediment core characteristics and chronology

The general stratigraphy of sediments from both lakes share similar trends, characterized by two distinct lithostratigraphic units. The top 22 cm in Situk Lake and the top 15 cm in Mountain Lake, display fine grained, thinly laminated, organic-rich sediment. Below a gradational contact is a lithostratigraphic unit spanning much of the remainder of the cores, that displays thickly laminated to massive bedding (3-15 cm) grey fine-grained, organic-poor glacio-lacustrine sediment (Figure 6). Grain size is very fine silt to clay, and the sediment has a greasy texture. The age of the gradational contact was determined using results from ^{210}Pb analysis. Core retrieval for both Situk and Mountain lake cores ended with refusal, however, the lithologic unit in which refusal was reached differed between the two lakes. Refusal in Situk Lake was reached in the lower lithostratigraphic unit of dense glaciolacustrine material. Refusal in Mountain Lake occurred in a coarse sand diamicton unit that contained small to large cobble beginning at 326 sediment depth.

Figure 4 and 5 show the results from ^{210}Pb analysis of Situk and Mountain lakes, respectively, and the ^{14}C dates are reported in Table 1. Calibrated ^{14}C dates from Situk Lake resulted in ages of 988 cal AD, 6542 cal BP, and 8301 cal BP. Dates from Mountain Lake resulted in an age of 1285 cal AD (Table 1). An age-depth model was created using a line fit from the lowest interval dated using ^{210}Pb-dating and a basal ^{14}C date (Figure 7). Error associated with ^{210}Pb dates from Situk Lake increase from a minimum of ± 1 years in the core top sediment to a maximum of ± 24 years at the bottom most sediment with excess ^{210}Pb. Error propagation likely increases at the older end of the ^{210}Pb data, given the transition into a different sediment regime centered at the ~22 cm depth and the long intervening interval to the radiocarbon date.

^{210}Pb errors for Mountain Lake increase from a minimum of ± 3 years in the core top sediment to ± 84 years at the bottom most sediment with excess ^{210}Pb. Error propagation in Mountain Lake is thought to be similar to Situk Lake. Transitions into the period of high sedimentation rate in both lakes can be seen by an increasing slope in the age models (Figure 7).

A date derived from a basal soil sample collected from MUSK17 Soil 3 resulted in an age of 1429 cal AD and MUSK17 Soil 2 resulted in an age of 1540 cal AD. Radiocarbon samples from the muskeg soil pits were taken at the transition from pebbles into peat, inferred to be when Hubbard Glacier retreated from the region, glacial outwash decreased, and initiation of peat formation.

3.2 Stable isotopes, C, N and C/N ratios

The organic content of the upper unit is relatively high in both lakes ~3% and 2%, respectively in Situk and Mountain lakes. Carbon content in the glacio-lacustrine unit in both lakes is much lower, averaging ~0.6%. The average C/N ratio throughout the Situk Lake core(s) is 11.7 and 9 in the Mountain Lake core without significant variation. Figures 9 and 10 show relationships between ^{13}C and C/N for Situk and Mountain lakes, including samples of particulate organic matter (POM) and soil, representing aquatic and terrestrial sources, respectively. Situk and Mountain lake C/N are indicative of an aquatic source (<15) (Meyers and Ishiwatari, 1993) and isotopes from both lakes group around POM (the aquatic source end member) in the mixing model.

Situk Lake $\delta^{15}N$ consistently averaged around 2‰ for a majority of the core, prior to the last ~200 years (Figure 8). Nitrogen increases from this baseline above 24 cm depth to a maximum of 7‰ at the 10 cm interval. $\delta^{15}N$ decreases following the peak to core top values of

3.3‰. $\delta^{13}C$ is relatively enriched at the bottom of the core (-13.6‰) without the presence of carbonates, and shows gradual depletion to present day levels of -32

Mountain Lake $\delta^{15}N$ averages 1.5‰ for most of the core. It begins to increase upward above the 175 cm depth where it stabilizes at ~2‰ until the 100 cm interval. The uppermost 100 cm shows relatively higher values, and higher variability (4.5‰ and 1.3‰, maximum and minimum respectively). $\delta^{13}C$ of Mountain Lake is -25‰ below 175 cm, from which it declines upward to the 28 cm interval. Most recent $\delta^{13}C$ is variable and ranges from its most enriched value of -22‰ to its most depleted value of -27‰.

Isotopic values of Situk and Mountain lakes generally show a response to the reduction of glacial influence, as indicated by changes in lithology as registered in C%. The lithologic change in Situk Lake corresponds to the enrichment of $\delta^{15}N$ and the depletion of $\delta^{13}C$. Though less obvious, Mountain Lake $\delta^{15}N$ also see a gradual increase following the reduction in glacial sediment and more variable $\delta^{15}N$ following the lithologic change at the 27-18 cm interval (centered at ~22 cm).

4. Discussion

4.1 Lake formation and glacial chronology

The outer moraine that constrains the western side of Situk Lake is prominent near the lake but is difficult to trace in areas eastward south of Russell Fiord based on available topography and imagery. The outer moraine has less distinct topographic expression compared to the inner moraine constraining Russel Fiord (Figure 1) suggesting to Barclay et al. (2001), that the outer moraine is most likely late Wisconsinan in age. Where prominent, however, soil development on the outer moraine is minor, consistent with a Neoglacial origin (Mann, written communication). The inner moraine has a more defined structure and has been dated using radiocarbon from submerged tree stumps, which crossed the calibration curve at 1525, 1558, and 1631 cal AD. Tilted and arched trunks on the oldest trees located on the inner moraine suggest movement of the moraine due to melting of dead ice suggesting that ice began to retreat from the southern end of Russell Fiord during the late eighteenth century (Barclay et al., 2001).

Basal dates from both muskeg soil pits (MUSK SOIL 2 & 3), which are located between the two terminal moraines result in ages of 1540 and 1429 cal AD (Table 1), consistent with a retreat of Hubbard Glacier from its terminal position during the early phases of the LIA, and stratigraphically consistent with late LIA ages on the inner moraine. The basal core date obtained from Mountain Lake resulted in an age of 1285 cal AD (Table 1), suggests retreat of Hubbard Glacier out of the Mountain Lake valley, during the early phases of the LIA. Both the muskeg and Mountain Lake dates are similar within dating error and confirm glacial retreat and subsequent deposition of organic matter during the early phases of the LIA. Figure 11 displays a sketch map of the recent glacial activity of Hubbard Glacier showing the advances and retreats of Hubbard Glacier during the LIA. Dates from Situk lake (Table 1) are older than this hypothesized chronology. Material suitable for radiocarbon dating was difficult to obtain due to the lack of organics in the glacial sediment, and the fine material that was obtained was difficult to identify. Material that was sampled may have been sourced from elsewhere in the watershed that had soil and/or plant development substantially before the LIA. Subsequent glacial activity and outwash during the LIA could have eroded and transported this older organic material to Situk Lake, resulting in old, non-contemporaneous, out of sequence dates.

The presence of clay rich, glacially-derived sediment that composed a majority of the Situk and Mountain lake sediment cores suggest that Hubbard glacier may not have completely retreated out of Russell Fiord following lake formation. Rather, Hubbard Glacier may have stayed within the Fiord at an elevation high enough to supply sediment via the pass north of Mountain Lake (Figure 11 b). Alternatively, glacial outwash sediments were also potentially delivered into Mountain Lake during this time via transport of paraglacial sediment, or from glaciers that were possibly present on the higher elevation ridge within its watershed, north and west of the lake. In the first two scenarios, Mountain Lake might have acted as a retention basin, eventually delivering sediment-laden water downstream through Situk River to Situk Lake. As the inner moraine had not yet been deposited (prior to a late LIA advance and moraine deposition), Situk Lake could have received glacial outwash from smaller tributaries emanating from the front of Hubbard Glacier into Russell Fiord. Hubbard Glacier then saw another advance during the later phases of the LIA (late 1700s) (Barclay et al., 2001; Calkin et al., 2001b) to a position denoted by the inner moraine which currently confines Russell Fiord (Figure 11 c.).

Three distinguishable glacial advances during the LIA have been documented across southern Alaska (Wiles et al., 1999) which supports the idea that Hubbard Glacier could have seen multiple advances during this time. It has been suggested by Wiles et al. (2008), that advances of land terminating glaciers in southern Alaska are influenced by climate, but Hubbard glacier is a surging tidewater calving glacier. Surging glaciers can advance rapidly regardless of climate forcing. Therefore, LIA advances of Hubbard glacier may be a combination of climate forcing and surging events allowing for multiple LIA advances, and our chronology is unable to precisely correlate these advances into the regional record.

4.2 Fluctuations of salmon abundance

Sedimentary $\delta^{15}N$ show an increasing trend beginning ~1750 AD and culminating ~1870 AD with a sedimentary $\delta^{15}N$ maximum of 7‰ in Situk Lake. A steady decrease in sedimentary $\delta^{15}N$ has been occurring since ~1870 AD. Situk Lake is a relatively young, clear lake with the system no longer glacially fed. It appears that the switch from a glacial dominated system to a clear system led to a large increase in salmon abundance in the lake. This increase was likely fueled by increased primary productivity, and improved spawning habitat that followed glacial retreat. The LIA advances following formation would likely not have prevented salmon from migrating into the lakes, and salmon are often able to find suitable spawning habitats in silt-rich, glacially dominated systems (Burgner, 1991). Salmon may have been present in the Situk River system prior to the observed increase in $\delta^{15}N$. For example, Loso et al. (2017), show that up to 20,000 salmon could have been present in the Eklutna Lake system without leaving a sedimentary $\delta^{15}N$ signature. Therefore, while the exact timing when salmon started to spawn in the lake is unknown, it is clear when there were sufficient salmon to influence the nutrient balance of the lake systems.

The increased sedimentary $\delta^{15}N$ signal starting at ~1750 AD coincides with the beginning of increased primary productivity as described by increasing %C and biogenic silica content.

Sedimentary $\delta^{15}N$ constantly increased by an average of 0.04‰ per year to a maximum sedimentary $\delta^{15}N$ signal of 7‰ approximately at ~1870 AD. From ~1870 AD until present, there has been a steady decline of sedimentary $\delta^{15}N$ (~0.04‰ per year). Part of the decrease tracks the history of salmon catch following the construction of a salmon cannery in Yakutat and subsequent reductions in escapement. However, our dating suggests the decline started prior to the cannery, and possible explanations are discussed in chapter 1 of this thesis. Briefly, one is that climate/ocean changes during this time, such as the PDO state, could have adversely effected Situk sockeye salmon. Alternately, the decrease in $\delta^{15}N$ may reflect impact influenced by a large, magnitude 8 earthquake that occurred in the Yakutat region in 1899.

Higher sedimentary $\delta^{15}N$ in Situk Lake compared to Mountain Lake, which displays comparatively lower and varying sedimentary $\delta^{15}N$ begin ~ 1800 AD, may be due its higher salmon density, being the primary spawning lake in the system, in addition to its downstream position allowing delivery of any nutrients from Mountain Lake and the stretch of Situk River between Mountain and Situk lakes. Fluctuations in Mountain Lake sedimentary $\delta^{15}N$ may be due to the combination of fluctuations in salmon abundance, episodic events of sediment delivery, as well as watershed characteristics that lead complicated relationships between salmon and sedimentary $\delta^{15}N$ (Selbie et al., 2009). Mountain Lake is surrounded by steep topography which has the potential to deposit substantial autochthonous sediment into the lake system low in $\delta^{15}N$, thus diluting the salmon signatures and producing some of the noise seen in the data. The 0.48 year water residence time of Mountain Lake is also relatively short (Barto, 2004). A short water residence time has to potential to flush out nutrients rather than incorporate them into the lake food webs and sediments. In addition, the utilization of Mountain Lake by salmon may vary depending on overall salmon returns. For example, years of high runs to the Situk River system when spawning habitats in Situk Lake are more fully utilized may be ones where escapement to Mountain Lake is relatively high. Connectivity between the lakes has likely not changed, and therefore should have little influence on the sediment records of salmon (Schmidt, 1981).

5. Conclusion

This chapter redefines the late Holocene glacial chronology of Hubbard Glacier, and the timing of lake origin. Our dating suggests that Situk and Mountain lakes are relatively young and related to glacial retreat during the early phase of the LIA. From the time of their formation to approximately ~1750 AD, both lakes experienced relatively large inputs of glacio-lacustrine sediments influenced from paraglacial reworking of glacial sediment, glaciers located on the peaks of western Russell Fjord, and/or from runoff of Hubbard Glacier. After ~1750 AD both Mountain and Situk lakes became clear water lakes that increased in primary productivity and began supporting anadromous sockeye runs large enough to leave an isotopic signal in the lake sediment. Sedimentary ^{15}N continued to increase until about 1870, and then steadily decreased until present day. This period of decreasing ^{15}N initially corresponded, within error, with a large magnitude 8 earthquake occurring in 1899, followed by the introduction of a salmon cannery in Yakutat in 1903. Since then, decreased escapement into the systems is well documented by the sedimentary $\delta^{15}N$ record in the lakes. In such a dynamic system, the major changes in lake condition due to glaciation, earthquake activity, and harvest level are dominant controls on salmon abundance, relative to the role of climatic change during the ocean phase of salmon.

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References

Anderson, L., Abbott, M.B., Finney, B.P., and Burns, S.J., 2005, Regional atmospheric circulation change in the North Pacific during the Holocene inferred from lacustrine carbonate oxygen isotopes, Yukon Territory, Canada: Quaternary Research, v. 64, p. 21–35, doi: 10.1016/j.yqres.2005.03.005.

Barclay, D.J., Calkin, P.E., and Wiles, G.C., 2001, Holocene history of Hubbard Glacier in Yakutat Bay and Russell Fiord, Southern Alaska: Bulletin of the Geological Society of America, v. 113, p. 388–402, doi: 10.1130/0016-7606(2001)113<0388:HHOHGI>2.0.CO;2.

Barto, D., 2004, Assessing the production of sockeye salmon (onocorhynchus nerka) at Chilkat Lake, southeast Alaska, using current trophic conditions and the paleoclimnologic sediment record: University of Alaska Fairbanks, 111 p.

Beamish, R.I., and Bouillon, D.R., 1993, Pacific salmon production trends in relation to climate: Canadian Journal of Fisheries and Aquatic Sciences, v. 50, p. 1002–1016.

Burgner, R.L., in Pacific Salmon Life Histories, 1991, Groot, C., Margolis, L., Life History of Sockeye Salmon: Vancouver, British Columbia, University of British Columbia Press, 564 p

Calkin, P.E., Wiles, G.C., and Barclay, D.J., 2001a, Holocene coastal glaciation of Alaska.pdf: Quaternary Science Reviews, v. 20, p. 449–461.

Calkin, P.E., Wiles, G.C., and Barclay, D.J., 2001b, Holocene coastal glaciation of Alaska.pdf: Quaternary Science Reviews, v. 20, p. 449–461.

Cederholm, C.J., Kunze, M.D., Murota, T., and Sibatani, A., 1999, Pacific salmon carcasses: essential contributions of nutrients and energy for aquatic and terrestrial ecosystems:

Fisheries, v. 24, p. 6–15, doi: 10.1577/1548-8446(1999)024<0006:PSC>2.0.CO;2.

Finney, B.P., Bigelow, N.H., Barber, V.A., and Edwards, M.E., 2012, Holocene climate change and carbon cycling in a groundwater-fed, boreal forest lake: Dune Lake, Alaska: Journal of Paleolimnology, v. 48, p. 43–54, doi: 10.1007/s10933-012-9617-2.

Finney, B.P., Gregory-Eaves, I., Douglas, M.S., and Smol, J.P., 2002, Fisheries productivity in the northeastern Pacific Ocean over the past 2,200 years: Nature, v. 416, p. 729–733, doi: 10.1038/416729a.

Finney, B.P., Gregory-Eaves, I., Sweetman, J., Douglas, M.S. V., and Smol, J.P., 2000, Impacts of climatic change and fishing on Pacific salmon abundance over the past 300 years: Science, v. 290, p. 795–799, doi: 10.1126/science.290.5492.795.

Gende, S.M., Edwards, R.T., Willson, M.F., and Wipfli, M.S., 2002, Pacific salmon in aquatic and terrestrial ecosystems: BioSci., v. 52, p. 917–928, doi: 10.1641/0006-3568(2002)052[0917:PSIAAT]2.0.CO;2.

Gubernick, R., and Paustian, S., 2007, Hubbard Glacier, Russell Fiord and Situk River – A Landscape in Motion: , p. 18–22.

Hare, R.S., Mantua, J.N., and Francis, C.R., 1999, Inverse production regimes: Alaska and west coast Pacific salmon: Fisheries, v. 24, p. 6–14, doi: 10.1577/1548-8446(1999)024<0006.

Hobbs, W.O., and Wolfe, A.P., 2007, Caveats on the use of paleolimnology to infer Pacific salmon returns: Limnology and Oceanography, v. 52, p. 2053–2061, doi: 10.4319/lo.2007.52.5.2053.

Holtham, A.J., Gregory-Eaves, I., Pellatt, M.G., Selbie, D.T., Stewart, L., Finney, B.P., and Smol, J.P., 2004, The influence of flushing rates, terrestrial input and low salmon escapement densities on paleolimnological reconstructions of sockeye salmon

(Oncorhynchus nerka) nutrient dynamics in Alaska and British Columbia: Journal of Paleolimnology, v. 32, p. 255–271, doi: 10.1023/B:JOPL.0000042998.22164.ca.

Hu, F.S., Finney, B.P., and Brubaker, L.B., 2001, Effects of holocene Alnus expansion on aquatic productivity, nigrogen cycling, and soil development in southwestern Alaska: Ecosystems, v. 4, p. 358–368, doi: 10.1007/s10021.

Loso, M., Finney, B., Johnson, R., and Sinnott, R., 2017, Evaluating evidence for historical anadromous Salmon runs in Eklutna Lake, Alaska: Arctic, v. 70, p. 259–272, doi: 10.14430/arctic4665.

Mantua, J.N., and Hare, R.S., 2002, The pacific decadal oscillation: Journal of Oceanography, v. 58, p. 35–44.

Mantua, J.N., Hare, R.S., Zhang, Y., Wallace, M.J., and Francis, C.R., 1997, A Pacific interdecadal climate oscillation with impacts on salmon production: Bulletin of the American Meteorological Society, v. 78, p. 1069–1079, doi: 10.1175/1520-0477(1997)078<1069:apicow>2.0.co;2.

Meyers, P.A., and Ishiwatari, R., 1993, Lacustrine organic geochemistry - an overview of indicators of organic-matter sources and diagenesis in lake-sediments: Organic Geochemistry, v. 20, p. 867–900, doi: 10.1016/0146-6380(93)90100-p.

Rogers, L.A., Schindler, D.E., Lisi, P.J., Holtgrieve, G.W., Leavitt, P.R., Bunting, L., Finney, B.P., Selbie, D.T., Chen, G., Gregory-Eaves, I., Lisac, M.J., and Walsh, P.B., 2013, Centennial-scale fluctuations and regional complexity characterize Pacific salmon population dynamics over the past five centuries: Proceedings of the National Academy of Sciences, v. 110, p. 1750–5, doi: 10.1073/pnas.1212858110.

Schindler, D.E., Leavitt, P.R., Brock, C.S., Johnson, S.P., and Quay, P.D., 2005, Marine-derived nutrients, commercial fisheries, and production of salmon and lake algae in Alaska: Ecology, v. 86, p. 3225–3231.

Schindler, D.E., Leavitt, P.R., Brock, C.S., Johnson, S.P., and Quay, P.D., 2005, Marine-derived nutrients, commercial fisheries, and production of salmon and lake algae in Alaska: Ecology, v. 86, p. 3225–3231.

Schmidt, Artwin E., 1981, Inventory of high quality recreational fishing waters in southeast Alaska, Alaska Department of Fish and Game, Sport Fish Division. Federal Aid in Fish Restoration, Annual Preformance Report, 1980-1981, Project F-9-13(22)G-I-R, Juneau.

Selbie, D.T., Finney, B.P., Barto, D., Bunting, L., Chen, G., Leavitt, P.R., Macisaac, E.A., Schindler, D.E., and Shapley, M.D., 2009, Ecological, landscape, and climatic regulation of sediment geochemistry in North American sockeye salmon nursery lakes: Insights for paleoecological salmon investigations: American Society of Limnology and Oceanography, v. 54, p. 1733–1745.

Stuiver, M., Reimer, P.J., and Reimer, R.W., 2018, CALIB 701 [WWW program] at http;//calib.org, accessed 2018-3-19

Thedinga, J.F., Murphy, M.L., Johnson, S.W., Lorenz, J.M., and Koski, K. V., 1994, Determination of salmonid smolt yield with rotary-screw traps in the Situk River, Alaska, to predict effects of glacial flooding: North American Journal of Fisheries Management, v. 14, p. 837–851, doi: 10.1577/1548-8675(1994)014<0837:DOSSYW>2.3.CO;2.

Trabant, D.C., Krimmel, R.M., Echelmeyer, K.A., Zirnheld, S.L., and Elsberg, D.H., 2003, The slow advance of a calving glacier: Hubbard Glacier, Alaska, U.S.A: Annals of Glaciology, v. 36, p. 45–50, doi: 10.3189/172756403781816400.

Trabant, D.C., Krimmel, R.M., and Post, a. S., 1991, A preliminary forecast of the advance of

Hubbard Glacier and its influence on Russell Fiord, Alaska: USGS Water-Res. Invest. Rep., v. 90–4172, http://agris.fao.org/agris-search/search/display.do?f=1992/US/US92097.xml;US9147262.

Wiles, G.C., Barclay, D.J., and Calkin, P.E., 1999, Tree-ring-dated "Little Ice Age" histories of maritime glaciers from western Prince William Sound, Alaska: The Holocene, v. 9, p. 163–173, doi: 10.1191/095968399671927145.

Wiles, G.C., and Calkin, P.E., 1994, Late Holocene , high-resolution glacial chronologies and climate , Kenai Mountains , Alaska: , p. 281–303.

Wiles, G.C., D'Arrigo, R.D., Villalba, R., Calkin, P.E., and Barclay, D.J., 2004, Century-scale solar variability and Alaskan temperature change over the past millennium: Geophysical Research Letters, v. 31, p. 2–5, doi: 10.1029/2004GL020050.

Zurbuchen, J.M., Gulick, S.P.S., Walton, M.A.L., and Goff, J.A., 2015, Imaging evidence for Hubbard Glacier advances and retreats since the last glacial maximum in Yakutat and Disenchantment Bays, Alaska: Geochemistry, Geophysics, Geosystems, v. 16, p. 1962–1974, doi: 10.1002/2015GC005815.

Figures and Table

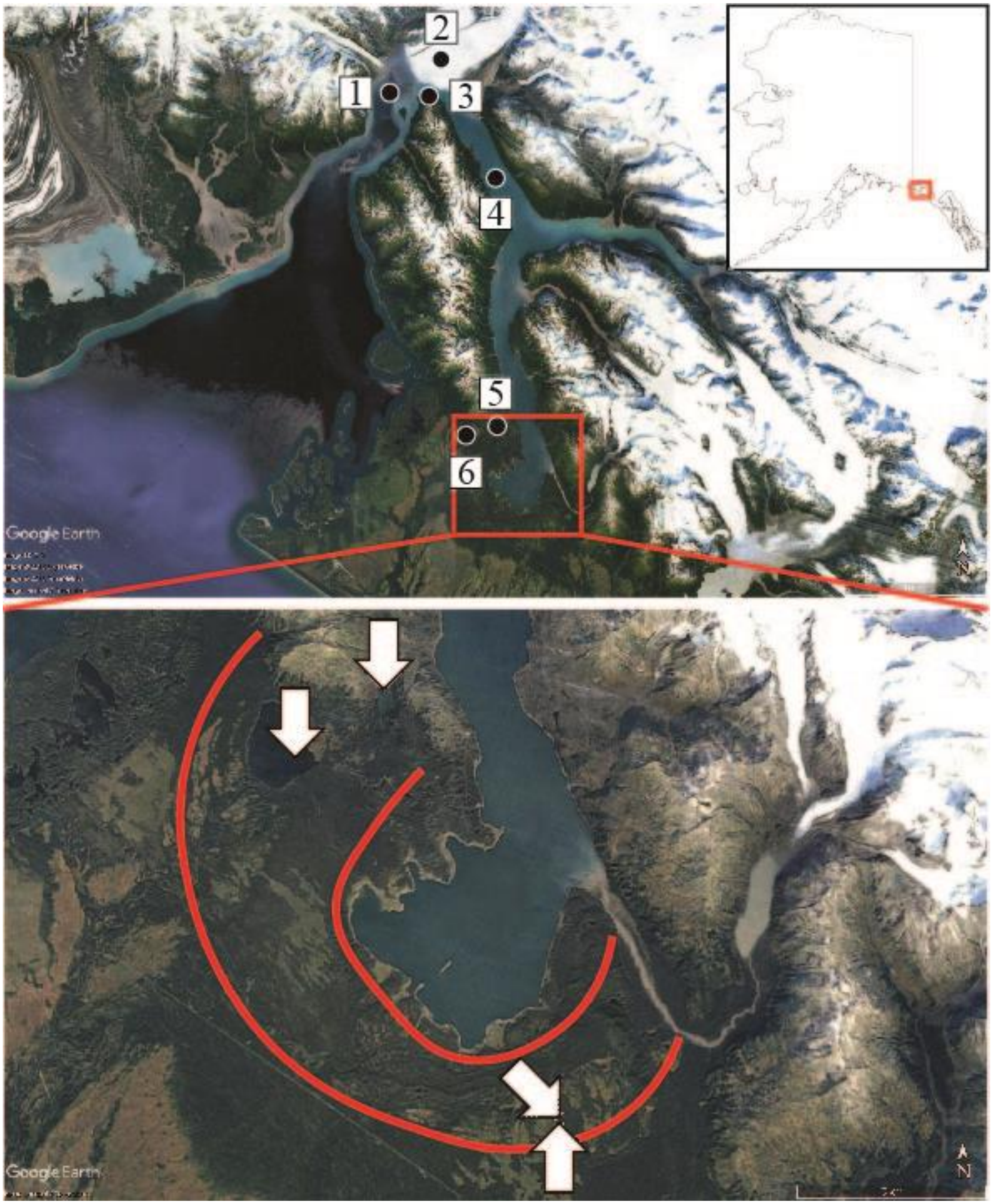

Figure 1. Location map of the study area. 1-Disenchantment Bay; 2-Hubbard Glacier; 3-Gilbert Point; 4-Russell Fiord; 5-Mountain Lake; 6-Situk Lake. Red lines on the second image denote the location of two terminal moraines. White arrows indicate sample locations.

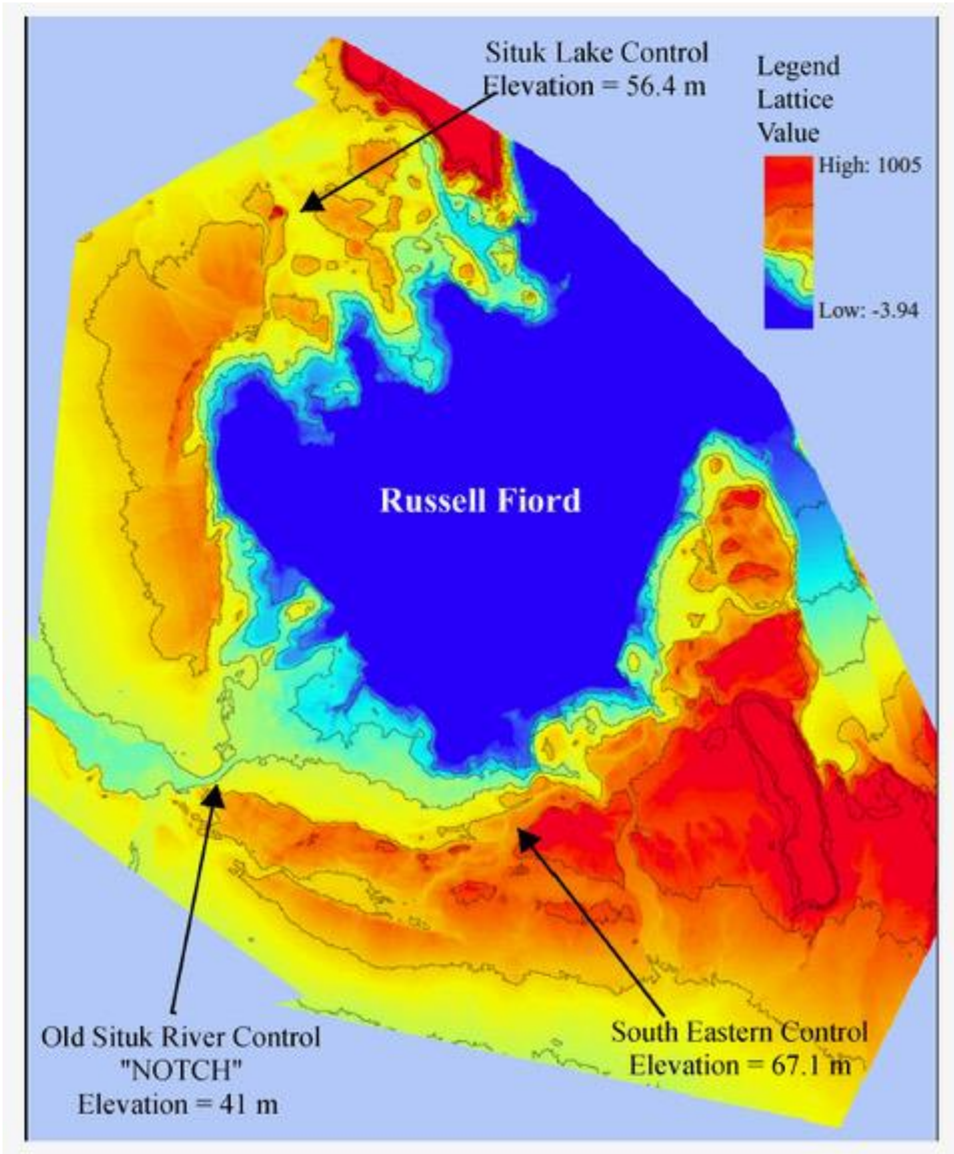

Figure 2. LIDAR derived DEM showing elevations of outflow points on the inner moraine constraining Russell Fiord. Figure modified from Gubernick and Paustain (2007).

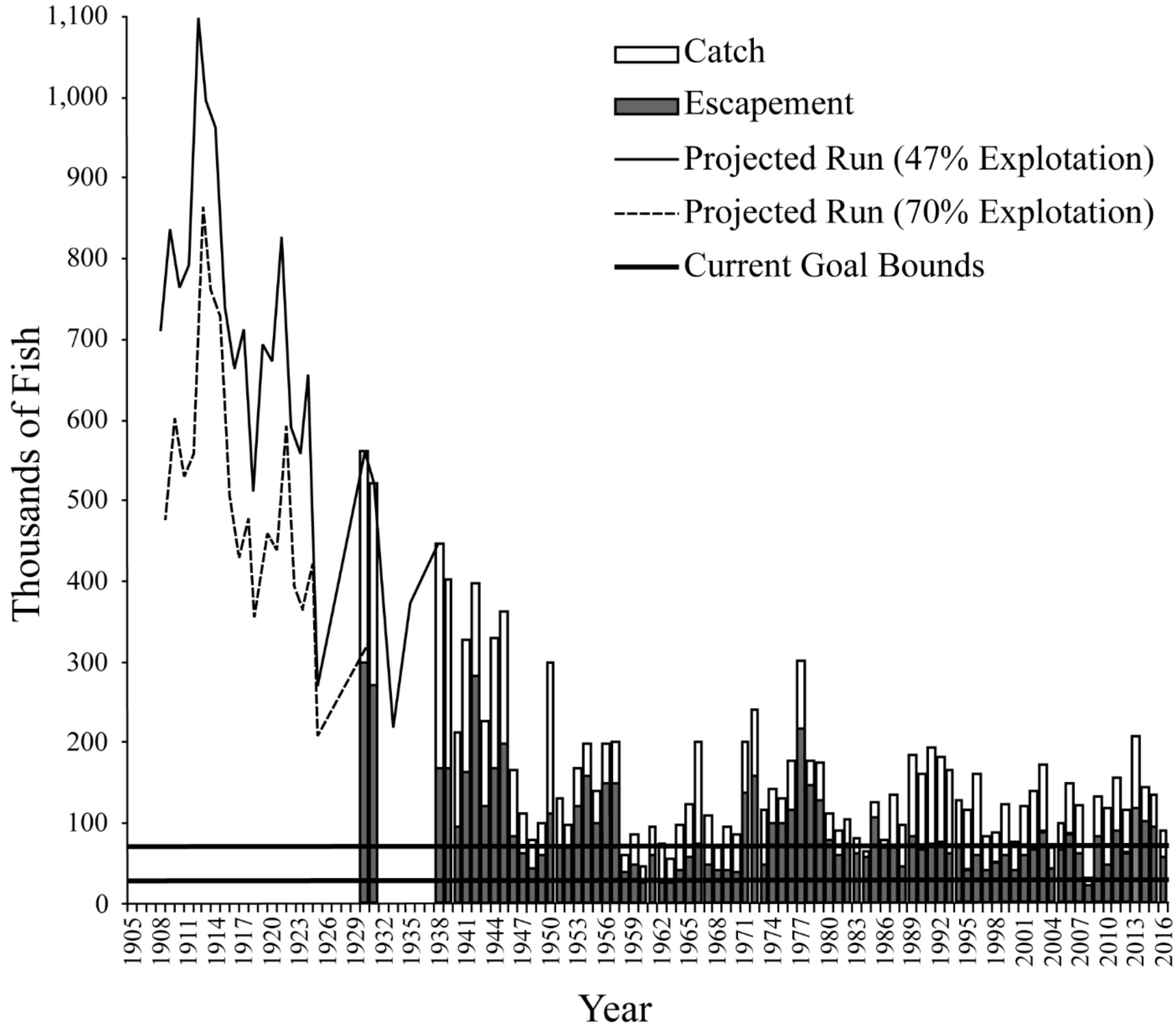

Figure 3. Sockeye salmon run totals for Situk Lake. Shaded sections of the bar graph represent escapement and the clear sections represent catch, together they represent total run. The two horizontal lines denote the upper and lower limits of escapement goals. Solid and dashed lines prior to 1938 represent hindcast runs with 47% and 70% exploitation respectively. hindcast runs were estimated using salmon cannery data.

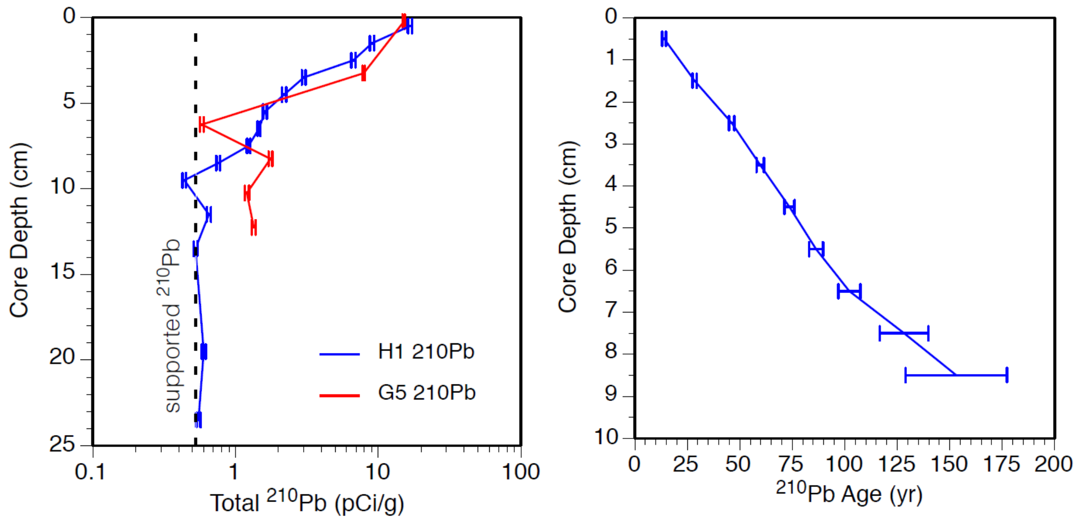

Figure 4. (left panel) Results from ^{210}Pb analysis. ^{210}Pb reached support levels at 9 cm sediment depth in the SIT14 H1 core (blue). ^{210}Pb levels did not reach supported levels in the SIT14 G5 core (red). (right panel) CRS modeled age with depth for SIT14 H1.

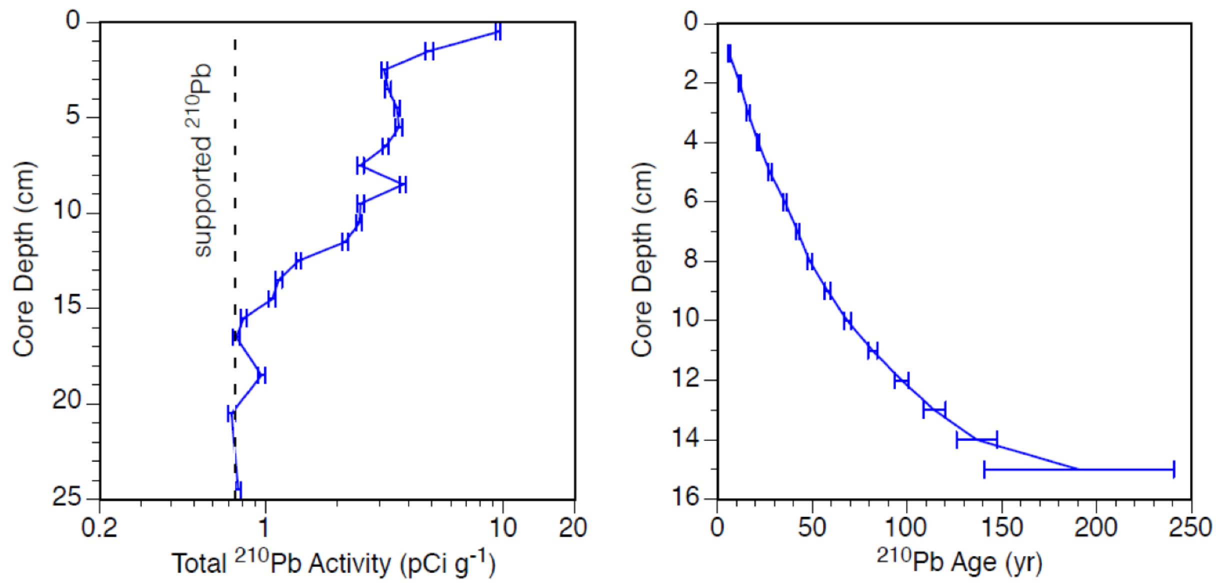

Figure 5. (left panel) Results from Mountain Lake ^{210}Pb analysis. ^{210}Pb reached support levels at 16 cm sediment depth. (right panel) CRS modeled age with depth.

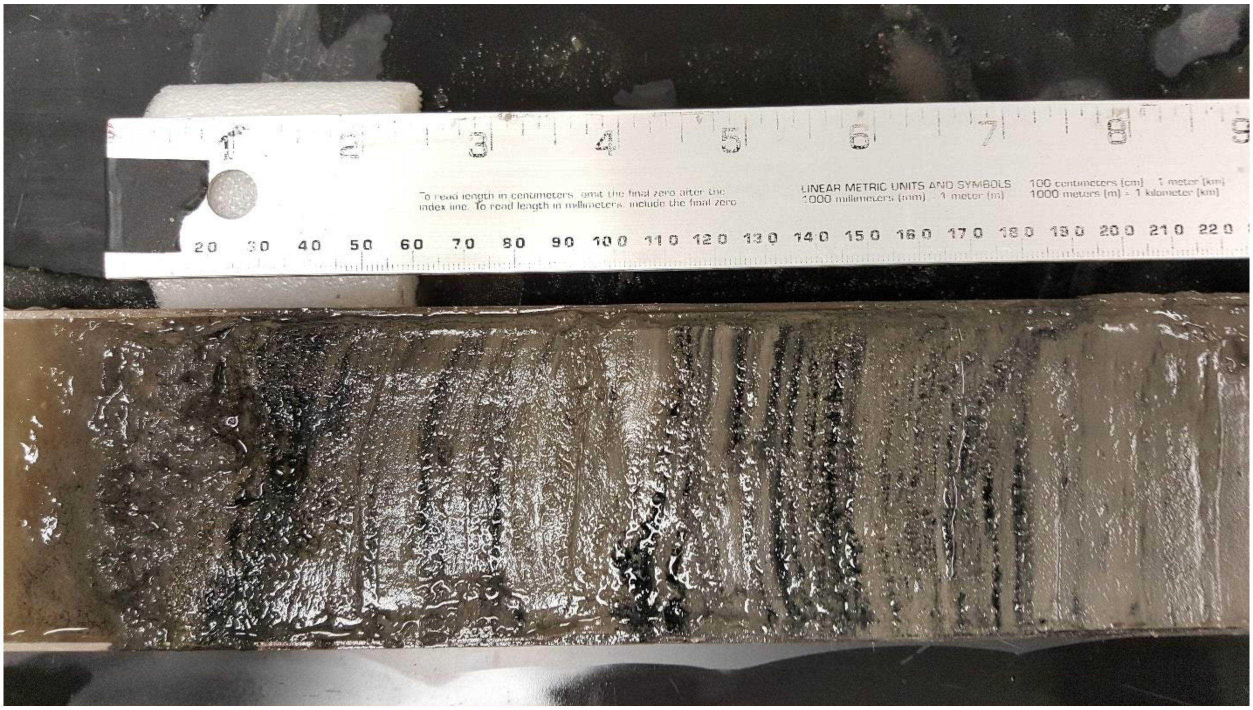

Figure 6. Picture show the lithologic transition centered at the ~22 cm sediment depth in sediment core SIT14 H1. This transition denotes the time at which the lake ceased to be fed with fine glacial sediment and transitioned into a clearwater lake.

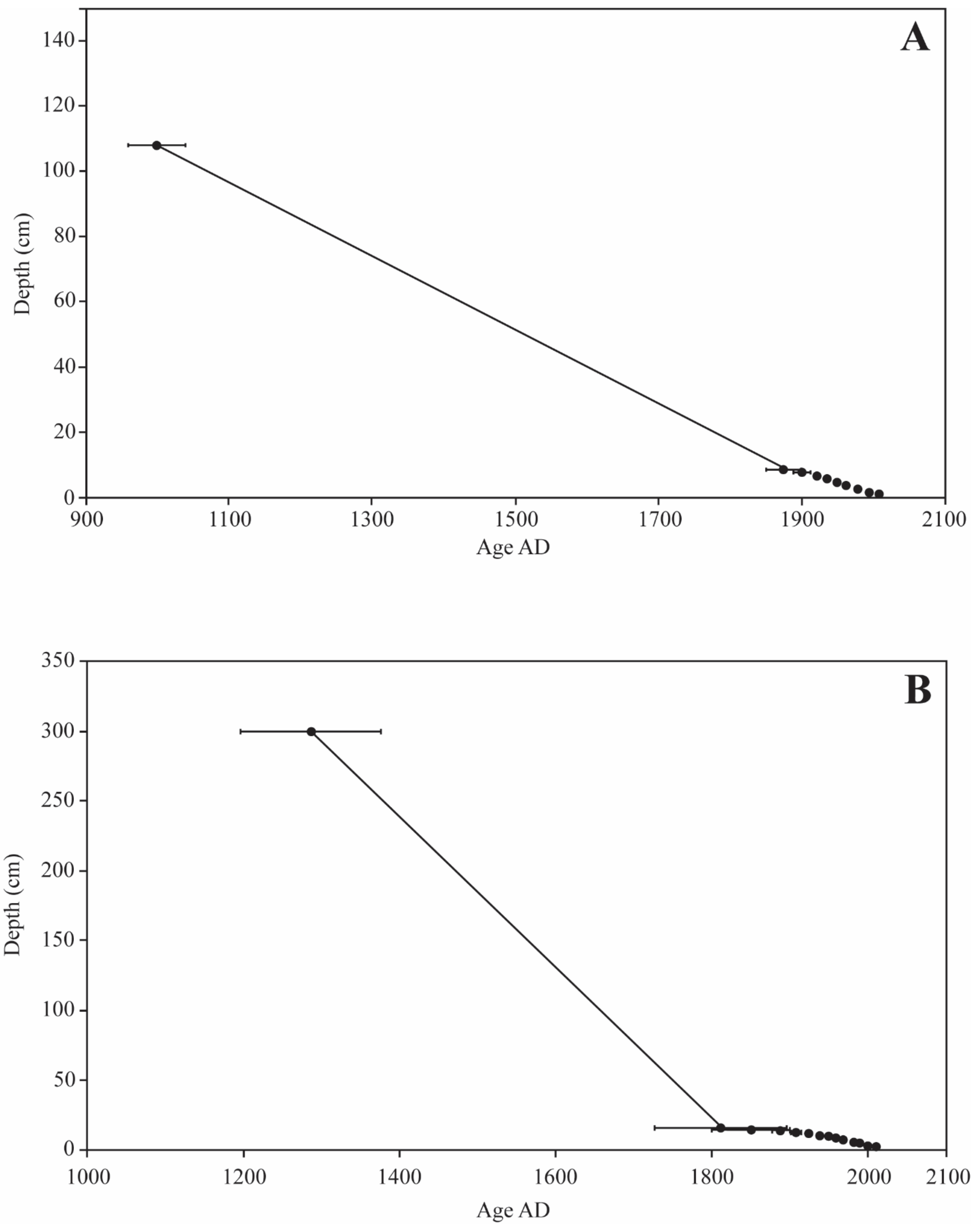

Figure 7. Age depth (A) Situk lake, (B) Mountain Lake, relationships using ^{210}Pb and a ^{14}C basal anchor.

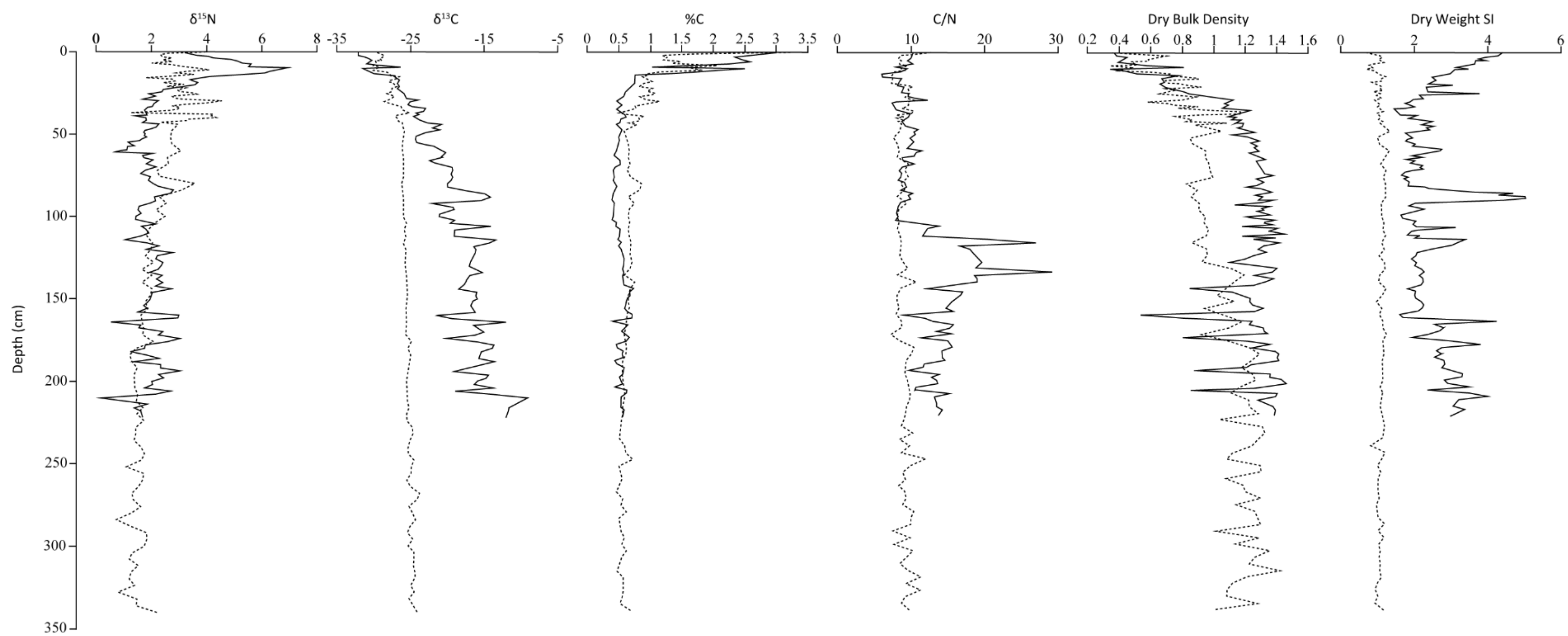

Figure 8. Geochemical results and physical properties from Situk Lake (solid line) and Mountain Lake (dashed line).

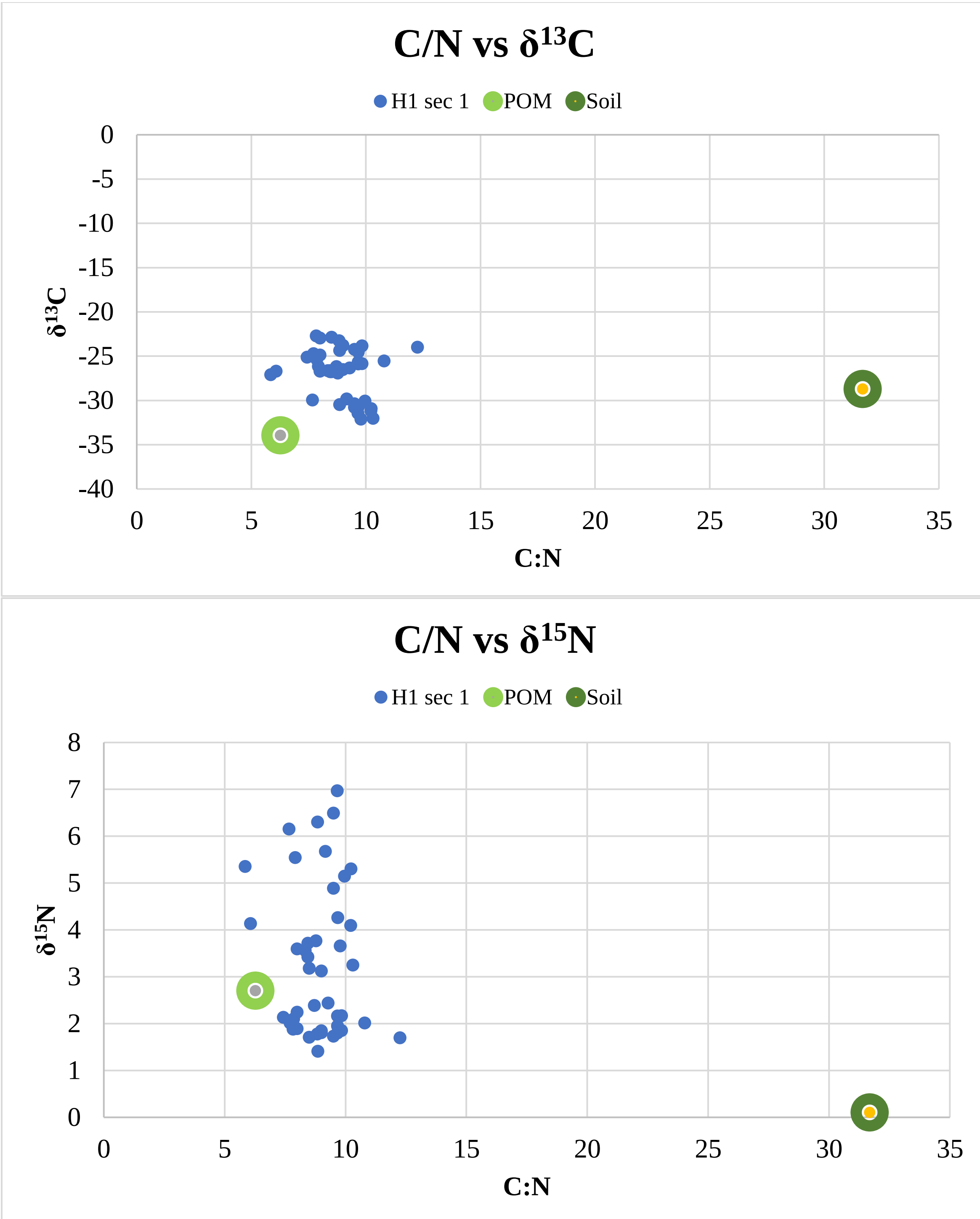

Figure 9. 2 Scatter plots of $\delta^{13}C$ (upper) and $\delta^{15}N$ (lower) vs. C/N (weight ratio) for Situk lake sediments and potential sediment sources. The data suggests that sediment composition can be explained by an end member mixing model. End members are POM and soil representing an aquatic source and terrestrial source respectively, and in the case of $\delta^{15}N$, changes in the strength of salmon-derived nitrogen to aquatic sources.

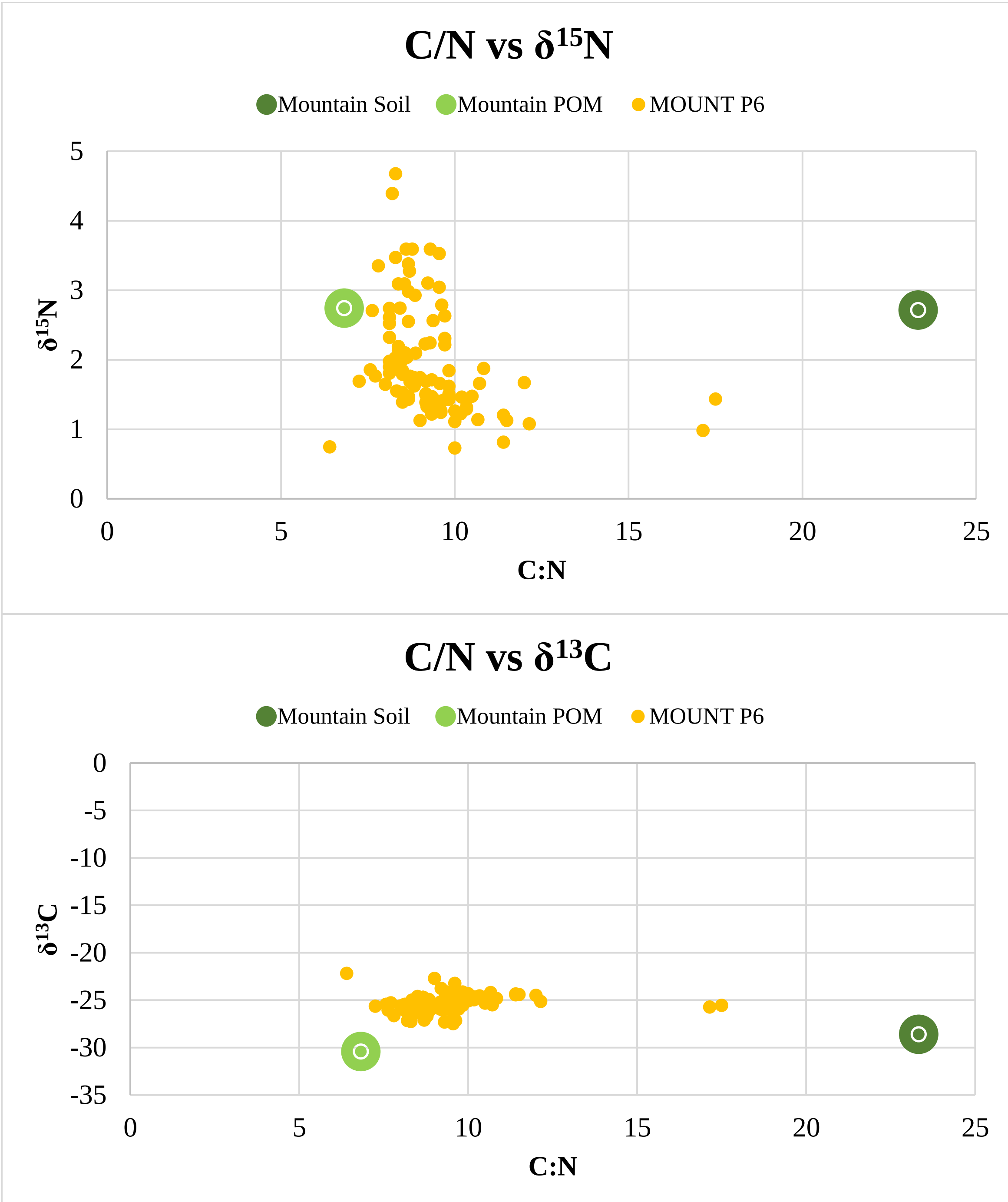

Figure 10. 2 Scatter plots of $\delta^{13}C$ (upper) and $\delta^{15}N$ (lower) vs. C/N (weight ratio) for Mountain Lake sediments and potential sediment sources. The data suggests that sediment composition can be explained by an end member mixing model. End members are POM and soil representing an aquatic source and terrestrial source respectively, and in the case of $\delta^{15}N$, changes in the strength of salmon-derived nitrogen to aquatic sources.

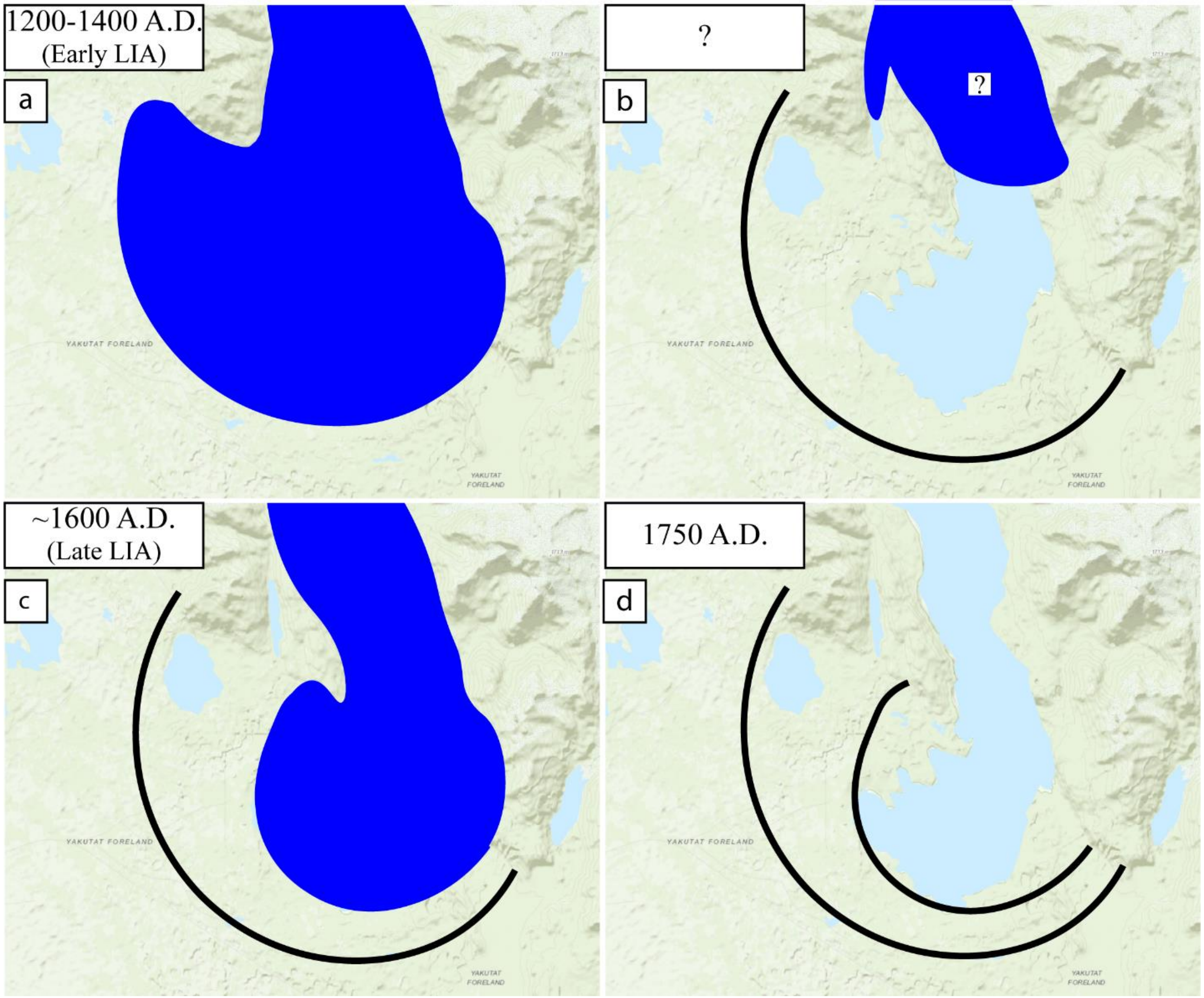

Figure 11. Sketch map of glacial activity in Russell Fiord. a-terminal location of Hubbard Glacier during the early phases of the LIA; this advance is responsible of the deposition of the outer moraine, constrained by dates obtained by radiocarbon ages from Mountain lake and muskeg soil pits. b-retreat of Hubbard Glacier into Russell Fiord to a position consistent with ice thickness that allowed glaciolacustrine sediment transport to Mountain lake; c-terminal location of an advance of Hubbard Glacier during the late phase of the LIA; d-complete retreat of Hubbard glacier from Russell Fiord allowing for Russell Lake to drain into Disenchantment Bay and cease delivery of glaciolacustrine sediment to Mountain and Situk Lakes.

Depth (cm)	Material Dated	Lab Code	Radiocarbon age (± 1-sigma)	Calibrated age -2-sigma (median) +2-sigma
Situk Lake				
107-110	Homogenous mixture of structured organics	CAMS-176293 ISU_14C 2016 SIT14	1050 ± 40	892 (988) 1035
282	Heterogeneous mixture of organics	CAMAS-178258 ISU_14C 2017 SIT01	5730 ± 160	6264 (6542) 6930
276	Woody debris, material with visible structure	CAMAS-178925 ISU_14C 2018 SIT01	7500 ± 150	8012 (8301) 8584
Mountain Lake				
265-270	Homogeneous mixture of structured organics	CAMS-176993 ISU_14C 2016 SIT 16+16B	700 ± 130	1039 (1285) 1442
Muskeg				
107-110	Wood	CAMAS-178261 ISU_14C 2017 MUSK01	485 ± 30	1407 (1429) 1450
60-65	Wood	CAMAS-178877 ISU_14C 2018 MUSK01	360 ± 35	1450 (1540) 1635

Table 1. Accelerator Mass Spectrometry (AMS) radiocarbon dates and calibrated ages (Stuiver et al., 2018).

Lake	Mean Spring Total Phosphorous (μg/l)	Mean Spring Total Nitrogen (μg/l)	pH	Secchi Disk Depth (m)
Situk	3.1	65.3	7.3	6.0
Mountain	4.2	173.0	7.3	6.0

Table 2. Limnologic data for Situk and Mountain lakes.

Thesis Conclusion

Situk and Mountain lakes are relatively young lakes that formed during glacial retreat of during the early phase of the LIA. Following formation of the lakes until approximately 1750 AD, they were strongly influenced from silt-laden glacial meltwater, suggesting glacial ice of significant magnitude in southern Russell Fiord that its meltwater could enter the system via a pass north of Mountain Lake. Silt-laden glacial meltwater may also be result of transport of periglacial material following the retreat of regional glaciers, runoff and transport of sediment from glaciers located on the peaks of western Russell Fjord, and from runoff of Hubbard Glacier After ~1750 A.D the lakes became clear-water and began supporting higher abundance of anadromous sockeye salmon. The change in lake conditions lead to higher primary productivity, and the reduction in silt input lead to better spawning habitat, both of which likely increased salmon carry capacity. During this time increasing sockeye abundance increased the amount of SDN entering the Situk Lake system. A steady increase of SDN was recorded in the lake sediment shown by an increase in ^{15}N. Sedimentary ^{15}N which peaked in about 1870 AD, reached a maximum $\delta^{15}N$ of 7‰. Afterwards sedimentary ^{15}N steadily decreased until present day level of 2.6‰. Some of the decrease in sedimentary ^{15}N corresponds with the introduction of a salmon cannery in Yakutat, and the subsequent decline is consistent with records of salmon abundance and escapement.

Mountain Lake sees an increase in sedimentary ^{15}N around the same time as Situk Lake (1750 AD). However, it has much more variability compared to Situk Lake (chapter 2 figure 8). Greater variability in Mountain Lake may be due to watershed characteristics such as a short water residence time and steep surrounding topography which has the potential to deliver large quantities of sediment that, in turn, alter sediment composition.

Under natural environmental condition the abundance of sockeye increased in the years following the retreat of Hubbard glacier. A decline in salmon abundance prior to the introduction of the salmon cannery may have been influenced by a large magnitude 8 earthquake occurring in Yakutat in 1899. Large regional earthquakes have the potential to impact spawning habitats of salmon, by altering and/or destroying them. Additionally, large seismic even can also increase the flux of sediment entering the lake systems which may dilute the salmon-isotope signal retained in the lake sediment. Destruction of habitats in Situk and Mountain lakes can diminish subsequent salmon runs in the lake systems. Following the initial decline in salmon abundance, a salmon cannery was built in Yakutat which began harvesting large quantities of salmon from the Situk River system. Harvesting lead to a continued decline in salmon abundance to relatively consistent levels seen in recent years.

Prior to commercial fishing, changes in lake conditions related to glacial sediment input were large, and override direct climatic influence, such as changes in the PDO. Since the time of onset of commercial fishing and construction of the cannery, anthropogenic factors confound detecting influences related to the PDO. A 1997 shift to a positive phase of the PDO has been shown to generally increase salmon abundance throughout Alaska (Rogers et al., 2013; Finney et al., 2002, 2000; Mantua et al., 1997). However, the same response of salmon abundance is not observed in Situk or Mountain lakes. Possible reasons include mechanisms acting in ocean and freshwater environments. We encourage future studies to determine the cause or causes of the phenomenon.

References

Anderson, L., Abbott, M.B., Finney, B.P., and Burns, S.J., 2005, Regional atmospheric circulation change in the North Pacific during the Holocene inferred from lacustrine carbonate oxygen isotopes, Yukon Territory, Canada: Quaternary Research, v. 64, p. 21–35, doi: 10.1016/j.yqres.2005.03.005.

Barclay, D.J., Calkin, P.E., and Wiles, G.C., 2001, Holocene history of Hubbard Glacier in Yakutat Bay and Russell Fiord, Southern Alaska: Bulletin of the Geological Society of America, v. 113, p. 388–402, doi: 10.1130/0016-7606(2001)113<0388:HHOHGI>2.0.CO;2.

Barto, D., 2004, Assessing the production of sockeye salmon (onocorhynchus nerka) at Chilkat Lake, southeast Alaska, using current trophic conditions and the paleoclimnologic sediment record: University of Alaska Fairbanks, 111 p.

Beamish, R.I., and Bouillon, D.R., 1993, Pacific salmon production trends in relation to climate: Canadian Journal of Fisheries and Aquatic Sciences, v. 50, p. 1002–1016.

Brock, C.S., Leavitt, P.R., Schindler, D.E., Johnson, S.P., and Moore, J.W., 2006, Spatial variability of stable isotopes and fossil pigments in surface sediments of Alaskan coastal lakes : Constraints on quantitative estimates of past salmon abundance: American Society of Limnology and Oceanography, v. 51, p. 1637–1647.

Burgner, R.L., in Pacific Salmon Life Histories, 1991, Groot, C., Margolis, L., Life History of Sockeye Salmon: Vancouver, British Columbia, University of British Columbia Press, 564 p

Calkin, P.E., Wiles, G.C., and Barclay, D.J., 2001a, Holocene coastal glaciation of Alaska.pdf: Quaternary Science Reviews, v. 20, p. 449–461.

Calkin, P.E., Wiles, G.C., and Barclay, D.J., 2001b, Holocene coastal glaciation of Alaska.pdf: Quaternary Science Reviews, v. 20, p. 449–461.

Cederholm, C.J., Kunze, M.D., Murota, T., and Sibatani, A., 1999, Pacific salmon carcasses: essential contributions of nutrients and energy for aquatic and terrestrial ecosystems: Fisheries, v. 24, p. 6–15, doi: 10.1577/1548-8446(1999)024<0006:PSC>2.0.CO;2.

Child, A.W., and Moore, B.C., 2017, Stable isotope (δ13C, δ15N, δ34S) analysis of sediment cores suggests sockeye salmon (Oncorhynchus nerka) did not historically spawn in Lake Roberta, Washington (USA): Journal of Paleolimnology, v. 57, p. 67–79, doi: 10.1007/s10933-016-9928-9.

Clark, J.H., S.A. McPherson, and G.F. Woods 2002. Biological escapement goal for sockeye salmon in the Situk River, Yakutat, Alaska. Alaska Department of Fish and Game, Special Publication No. 02-03, Anchorage.

Clark, John H., McPherson, Scott, A., Burkholder, Alan 1995. Biological escapement goal for Situk River sockeye salmon. Alaska Department of Fish and Game, Douglas.

Conley, D.J., 1988, Biogenic silica as an estimate of siliceous microfossil abundance in Great Lakes sediments: Biogeochemistry, v. 6, p. 161–179.

Finney, B.P., Alheit, J., Emeis, K.C., Field, D.B., Gutiérrez, D., and Struck, U., 2010, Paleoecological studies on variability in marine fish populations: A long-term perspective on the impacts of climatic change on marine ecosystems: Journal of Marine Systems, v. 79, p. 316–326, doi: 10.1016/j.jmarsys.2008.12.010.

Finney, B.P., Bigelow, N.H., Barber, V.A., and Edwards, M.E., 2012, Holocene climate change and carbon cycling in a groundwater-fed, boreal forest lake: Dune Lake, Alaska: Journal of Paleolimnology, v. 48, p. 43–54, doi: 10.1007/s10933-012-9617-2.

Finney, B.P., Gregory-Eaves, I., Douglas, M.S., and Smol, J.P., 2002, Fisheries productivity in the northeastern Pacific Ocean over the past 2,200 years: Nature, v. 416, p. 729–733, doi: 10.1038/416729a.

Finney, B.P., Gregory-Eaves, I., Sweetman, J., Douglas, M.S. V., and Smol, J.P., 2000, Impacts of climatic change and fishing on Pacific salmon abundance over the past 300 years: Science, v. 290, p. 795–799, doi: 10.1126/science.290.5492.795.

Gende, S.M., Edwards, R.T., Willson, M.F., and Wipfli, M.S., 2002, Pacific salmon in aquatic and terrestrial ecosystems: BioSci., v. 52, p. 917–928, doi: 10.1641/0006-3568(2002)052[0917:PSIAAT]2.0.CO;2.

Gubernick, R., and Paustian, S., 2007, Hubbard Glacier, Russell Fiord and Situk River – A Landscape in Motion: , p. 18–22.

Hare, R.S., Mantua, J.N., and Francis, C.R., 1999, Inverse production regimes: Alaska and west coast Pacific salmon: Fisheries, v. 24, p. 6–14, doi: 10.1577/1548-8446(1999)024<0006.

Hobbs, W.O., and Wolfe, A.P., 2007, Caveats on the use of paleolimnology to infer Pacific salmon returns: Limnology and Oceanography, v. 52, p. 2053–2061, doi: 10.4319/lo.2007.52.5.2053.

Holtham, A.J., Gregory-Eaves, I., Pellatt, M.G., Selbie, D.T., Stewart, L., Finney, B.P., and Smol, J.P., 2004, The influence of flushing rates, terrestrial input and low salmon escapement densities on paleolimnological reconstructions of sockeye salmon (Oncorhynchus nerka) nutrient dynamics in Alaska and British Columbia: Journal of Paleolimnology, v. 32, p. 255–271, doi: 10.1023/B:JOPL.0000042998.22164.ca.

Hu, F.S., Finney, B.P., and Brubaker, L.B., 2001, Effects of holocene Alnus expansion on aquatic productivity, nigrogen cycling, and soil development in southwestern Alaska:

Ecosystems, v. 4, p. 358–368, doi: 10.1007/s10021.

Loso, M., Finney, B., Johnson, R., and Sinnott, R., 2017, Evaluating evidence for historical anadromous Salmon runs in Eklutna Lake, Alaska: Arctic, v. 70, p. 259–272, doi: 10.14430/arctic4665.

MacDonald, G.M., and Case, R.A., 2005, Variations in the Pacific Decadal Oscillation over the past millennium: Geophysical Research Letters, v. 32, p. 1–4, doi: 10.1029/2005GL022478.

Mantua, J.N., and Hare, R.S., 2002, The pacific decadal oscillation: Journal of Oceanography, v. 58, p. 35–44.

Mantua, J.N., Hare, R.S., Zhang, Y., Wallace, M.J., and Francis, C.R., 1997, A Pacific interdecadal climate oscillation with impacts on salmon production: Bulletin of the American Meteorological Society, v. 78, p. 1069–1079, doi: 10.1175/1520-0477(1997)078<1069:apicow>2.0.co;2.

Meyers, P.A., and Ishiwatari, R., 1993, Lacustrine organic geochemistry - an overview of indicators of organic-matter sources and diagenesis in lake-sediments: Organic Geochemistry, v. 20, p. 867–900, doi: 10.1016/0146-6380(93)90100-p.

Mortlock, Richard A., and Froelich, Philip N., 1989, A simple method for the rapid determination of biogenic opal in pelagic marine sediments: Deep Sea Research Part A, Oceanographic Research Papers, v. 36, p. 1415-1426, doi: 10.1016/0198-0149(89)90092-7.

Rogers, L.A., Schindler, D.E., Lisi, P.J., Holtgrieve, G.W., Leavitt, P.R., Bunting, L., Finney, B.P., Selbie, D.T., Chen, G., Gregory-Eaves, I., Lisac, M.J., and Walsh, P.B., 2013, Centennial-scale fluctuations and regional complexity characterize Pacific salmon population dynamics over the past five centuries: Proceedings of the National Academy of Sciences, v. 110, p. 1750–5, doi: 10.1073/pnas.1212858110.

Schindler, D.E., Leavitt, P.R., Brock, C.S., Johnson, S.P., and Quay, P.D., 2005, Marine-derived nutrients, commercial fisheries, and production of salmon and lake algae in Alaska: Ecology, v. 86, p. 3225–3231.

Schindler, D.E., Leavitt, P.R., Brock, C.S., Johnson, S.P., and Quay, P.D., 2005, Marine-derived nutrients, commercial fisheries, and production of salmon and lake algae in Alaska: Ecology, v. 86, p. 3225–3231.

Schmidt, Artwin E., 1981, Inventory of high quality recreational fishing waters in southeast Alaska, Alaska Department of Fish and Game, Sport Fish Division. Federal Aid in Fish Restoration, Annual Preformance Report, 1980-1981, Project F-9-13(22)G-I-R, Juneau.

Selbie, D.T., Finney, B.P., Barto, D., Bunting, L., Chen, G., Leavitt, P.R., Macisaac, E.A., Schindler, D.E., and Shapley, M.D., 2009, Ecological, landscape, and climatic regulation of sediment geochemistry in North American sockeye salmon nursery lakes: Insights for paleoecological salmon investigations: American Society of Limnology and Oceanography, v. 54, p. 1733–1745.

Stuiver, M., Reimer, P.J., and Reimer, R.W., 2018, CALIB 701 [WWW program] at http;//calib.org, accessed 2018-3-19

Thedinga, J.F., Murphy, M.L., Johnson, S.W., Lorenz, J.M., and Koski, K. V., 1994, Determination of salmonid smolt yield with rotary-screw traps in the Situk River, Alaska, to predict effects of glacial flooding: North American Journal of Fisheries Management, v. 14, p. 837–851, doi: 10.1577/1548-8675(1994)014<0837:DOSSYW>2.3.CO;2.

Trabant, D.C., Krimmel, R.M., Echelmeyer, K.A., Zirnheld, S.L., and Elsberg, D.H., 2003, The slow advance of a calving glacier: Hubbard Glacier, Alaska, U.S.A: Annals of Glaciology, v. 36, p. 45–50, doi: 10.3189/172756403781816400.

Trabant, D.C., Krimmel, R.M., and Post, a. S., 1991, A preliminary forecast of the advance of Hubbard Glacier and its influence on Russell Fiord, Alaska: USGS Water-Res. Invest. Rep., v. 90–4172, http://agris.fao.org/agris-search/search/display.do?f=1992/US/US92097.xml;US9147262.

Wiles, G.C., Barclay, D.J., and Calkin, P.E., 1999, Tree-ring-dated “Little Ice Age” histories of maritime glaciers from western Prince William Sound, Alaska: The Holocene, v. 9, p. 163–173, doi: 10.1191/095968399671927145.

Wiles, G.C., and Calkin, P.E., 1994, Late Holocene , high-resolution glacial chronologies and climate , Kenai Mountains , Alaska: , p. 281–303.

Wiles, G.C., D’Arrigo, R.D., Villalba, R., Calkin, P.E., and Barclay, D.J., 2004, Century-scale solar variability and Alaskan temperature change over the past millennium: Geophysical Research Letters, v. 31, p. 2–5, doi: 10.1029/2004GL020050.

Zurbuchen, J.M., Gulick, S.P.S., Walton, M.A.L., and Goff, J.A., 2015, Imaging evidence for Hubbard Glacier advances and retreats since the last glacial maximum in Yakutat and Disenchantment Bays, Alaska: Geochemistry, Geophysics, Geosystems, v. 16, p. 1962–1974, doi: 10.1002/2015GC005815.