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Holocene paleoclimatic reconstructions of the northern Rocky Mountains as determined from stable isotope analysis of carbonate minerals and organic matter in sediments from Morrison Lake, MT

By

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To the Graduate Faculty:

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Table of Contents

Holocene paleoclimatic reconstructions of the northern Rocky Mountains as determined from stable isotope analysis of carbonate minerals and organic matter in sediments from Morrison Lake, MT

Thesis Abstract – Idaho State University (2019)

Further understanding Holocene hydroclimatic dynamics in the northern Rocky Mountains is important for increasing the accuracy of future climate models. The southern Beaverhead mountain range of western Montana is characterized by an underrepresented, high-elevation and semi-arid climatic state in regional hydroclimatic reconstructions. Sediment deposited in Morrison Lake contains both carbonate minerals and organic material that can be utilized to interpret climatic variability through stable isotopic analysis. The $\delta^{18}O$ carbonate mineral record from Morrison Lake shows climatic state shifts throughout the late Pleistocene and Holocene. A majority of the early Holocene shows evidence of a dry climatic state (14,800-11,100 cal yrs. BP). Wet conditions existed during two periods of the late Pleistocene and early Holocene (15,600-14,800 and 11,100-10,000 cal yrs. BP). During the middle Holocene (10,000-6,000 cal yrs. BP), Morrison Lake experienced extremely dry conditions and a lack of carbonate preservation. At 6,000 cal yrs. BP, Morrison Lake shows a transition to a consistently wet climatic state. Spectral analysis indicates that the most recent $\delta^{18}O$ of carbonate sediments (2,300-(-68) cal yrs. BP) show periodicities of 25, 40, 52, 55 and 78-years.

Keywords: hydroclimate, stable isotope analysis, carbonate sediment

Thesis Introduction

Understanding future hydroclimate variability in the northern Rocky Mountains is vital for preparing for impacts on water resources and ecosystem services (Jewitt, 2002). Development of natural resource management strategies for water usage, fundamental for ecosystem service maintenance, requires detailed knowledge of long-term trends and previous climatic states (Grant et al., 2013). The northern Rocky Mountains have experienced variations in both the elevation of the rain/snow transition and decreased precipitation rates (Kitzberger et al., 2007; Goode et al., 2011). Shifts between precipitated rain vs snow can alter the timing and rate of spring runoff events and can increase the risk of droughts and wildfires, through reductions in mid to late summer stream flow (Mote et al., 2005). High alpine watersheds are extremely sensitive to temperature and hydrologic variability, yet few weather stations have been established long enough or at high enough elevations to develop long-term data sets, necessary for understanding centennial to millennial scale climatic trends (Hauer et al., 2007; McGuire et al., 2012). The goal of this research is to improve knowledge of past climatic and hydrologic change, to provide better context for understanding potential future shifts.

Water resource management strategies of the last few decades have been based on weather data collected and interpolated through the Parameter-elevation Regressions on Independent Slopes Model (PRISM) developed by the Spatial Climate Analysis Service of Oregon State University (Wang et al., 2005). PRISM data is limited to the period of 1895 until the present with an increasing number of weather stations added throughout this time. There are two significant issues that impact the utilization of this data set for water management programs. One is that this data set is limited temporally, lacking the ability to accurately predict centennial to millennial scale climatic variation (Grant et al., 2013). The second is that the accuracy of the interpolation method is limited spatially by station distribution and does not always match ground truthed data, especially in mountainous regions (Wang et al., 2005). The collection and analysis of paleoclimatic proxy data over the Holocene represents an opportunity to expand current water management models and to determine with greater certainty drought periodicity at multidecadal to centennial scales (Braconnot et al., 2012). Snow telemetry (SNOTEL) sites located throughout high elevation areas of the northern Rocky Mountains provide valuable data about temperature and hydroclimatic variability in areas where PRISM may be lacking ground truthed data. Temporal limitations of SNOTEL data sets are an issue with most sites having been installed between 1960 and 1980 (Serreze et al., 1999). Most SNOTEL sites only began to measure daily precipitation and temperature in the early 1980s, limiting the ability to infer multidecadal and longer trends (Serreze et al., 1999). Despite this, SNOTEL sites represent the most accurate spatially distributed long-term data from high-elevation areas and can be a valuable resource in connecting modern data trends to paleoclimatic proxies.

Current understanding of Holocene hydroclimate in the northern Rocky Mountains is too limited to predict future hydroclimatic variability (Meko et al., 2007; Anderson et al., 2016). Anthropogenically driven climate forcing cannot be directly compared to any previous climatic shifts in the Holocene. Despite this, increasing understanding of previous climate states will allow us to better predict the effects of different climatic regimes on various environments. Synthesizing existing paleoclimatic records to develop a general model of Holocene hydroclimate is challenging due to limitations of the sedimentary record, chronological uncertainty, proxy interpretation, small-scale variability of climate, local hydrologic control, geochemical evolution, and geographic scarcity of paleoclimatic proxies (Soon and Baliunas, 2003; Anderson et al., 2016). The development of additional paleohydrologic records over multidecadal to millennial scales is necessary to constrain future climatic models and to predict the timescales of hydroclimatic variability and periodicity (Gázquez et al., 2018; Kitzberger et al., 2007).

Existing isotope, diatom, and tree ring studies have hypothesized the occurrence of multidecadal megadrought events throughout the Holocene, with increased frequency in the mid-Holocene (Stone and Fritz, 2006; Meko et al., 2007; Shuman et al., 2010; Whitlock et al., 2012). Modern drought events appear to be of minor intensity when compared to the megadroughts of the Holocene (Woodhouse et al., 2010; Cook et al., 2014). Previous studies of paleoflows from the Colorado River indicate that during periods of intense drought, particularly from 1146 to 1155 BP, flow rates were reduced to 14.2 billion cubic meters (BCM/yr.) (Woodhouse et al., 2010). The lowest flow observed during recorded history is 18.3 BCM/yr., indicating that droughts in the late Holocene were at least 22% more intense than any observed in the instrumental record (Woodhouse et al., 2010). Lake level studies at the headwaters of the Snake-Columbia, Missouri-Mississippi, and Green-Colorado rivers indicate that arid conditions occurred at multidecadal to centennial scales throughout most of the Holocene (9,000 – 3,000 yrs. BP) (Shuman et al., 2010). This study seeks to build upon previous evaluations of drought duration and periodicity in the northern Rocky Mountains, particularly in the

Missouri-Mississippi watershed, and to address potential driving forces behind these events through time series analysis of sediment data.

The primary drivers of hydroclimatic variability over multidecadal to millennial time scales are poorly understood (Kitzberger et al., 2007; Anderson et al., 2016). Variations in insolation are hypothesized to affect the intensity of major climatic patterns on millennial timescales, such as the North American Monsoon (NAM), insolation additionally appears to affect the frequency and intensity of shorter-term events such as the El Nińo Southern Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and North American Monsoon (NAM) (Anderson, 2012). Variable rates of solar radiation alter the earth’s energy balance resulting in changes to ocean evaporation, storm cell size, the position of the rain/snow transition, and average precipitation (Anderson, 2012). Hydroclimate is also hypothesized to be driven by regional continental surface temperatures (Pederson et al., 2011). When multiple paleohydrologic proxies are compiled, it is possible to understand how major climatic patterns have varied over time.

Lake cores serve as valuable records of ecological, hydrological, and climatological variations at watershed and regional scales (Charles and Smol, 1994; Brock et al., 2006). Lacustrine sediments are composed of clastic material, authigenic minerals, diatoms, aquatic organic material, and terrestrial organic material (Meyers and Lallier-Vergès, 1999; Schnurrenberger et al., 2003). Isotopic variations of both the authigenic mineral and organic fractions of the lake sediment, when combined with sediment age determinations, can provide long-term and potentially high-resolution paleoclimatic data (Meyers and Lallier-Vergès, 1999; Leng and Marshall, 2004; Steinman et al., 2012; van Hardenbroek et al., 2018). Specifically, oxygen isotopes from authigenic carbonate ($\delta^{18}O_C$) provide information about lake water $\delta^{18}O$ values ($\delta^{18}O_L$) at the time of mineral precipitation (Leng and Marshall, 2004; Morrill et al., 2006). Fluctuation of $\delta^{18}O_C$ values over time records variations in the routing and volume of precipitation, as well as the amount of evaporative forcing and groundwater influence a given lake experiences (Gonfiantini, 1986; Gat, 1995; Shapley et al., 2008; Steinman et al. 2012; van Hardenbroek et al., 2018). Lake $\delta^{18}O_C$ records are unique to each lake and are based on hydrologic and geomorphic characteristics such as climate, elevation, and watershed size (Talbot, 1990). Although it is challenging to quantify variation in hydroclimate as captured by $\delta^{18}O_C$, relative shifts can provide valuable information about large scale climatic events and the scales over which climatic variability occurs.

$\delta^{18}O_L$ can be influenced by variations in precipitation amount, seasonality, and evaporation rates (Leng and Marshall, 2004, van Hardenbroek et al., 2018). Lakes in mid to upper latitudes are affected by larger annual ranges in $\delta^{18}O_L$ due to variable volumes of precipitation which can impact the expected $\delta^{18}O_L$ over longer time scales (Leng and Marshall, 2004). $\delta^{18}O$ values of precipitation are strongly correlated to mean annual temperature (Leng and Marshall, 2004). Holocene modeled mean annual temperature is useful for attempting to reconstruct the $\delta^{18}O$ of precipitation over multi centennial time scales. The relationship between the surface area of a given lake's catchment and its surface area can result in variations between evaporative flux relative to lake volume, impacting $\delta^{18}O_L$ values (Leng and Marshall, 2004). These two values, surface area and volume, can be used to estimate the residence time of water within a lake. $\delta^{18}O_L$ values are usually increased in topographically closed lakes located in arid or semiarid environments, relative to the $\delta^{18}O$ of precipitation (Leng and Marshall, 2004). Kinetic fractionation of the lighter isotope (^{16}O) relative to the heavier (^{18}O) occurs during evaporation (Leng and Marshall, 2004). Evaporation is a major source of water loss topographically closed lakes, resulting in seasonal variability in $\delta^{18}O_L$ (Leng and Marshall, 2004). Lakes with $\delta^{18}O_L$ and δ^2H that plot along the global meteoric water line (GWML) are considered to be open basins and record variations in the $\delta^{18}O$ of precipitation over time (Anderson et al., 2016). $\delta^{18}O_L$ and δ^2H that plot along a line with a reduced slope compared to the GMWL are considered to record variations in precipitation to evaporation (P-E) (Anderson et al., 2016). These lakes are valuable for paleoclimatic reconstructions because the $\delta^{18}O$ value of carbonate sediment records climatic variability rather than differences in the sources of precipitation.

Sediment description and classification can provide information about lake productivity, a function of climatic variability on centennial scales. Variations in water column temperatures and oxidation of lake water is controlled by the volume of surface water inflow and seasonal temperature variability (Platt and Wright, 1991). Topographically closed lakes in temperate climates stratify throughout the summer as epilimnion temperatures rise and hypolimnion temperatures remain low (Platt and Wright, 1991). Seasonal inputs of snowmelt can upset this stratification and cause the lake waters to mix due to decreasing the temperature gradient between the epilimnion and hypolimnion (Platt and Wright, 1991). Prolonged stratification of lake waters results in anoxic conditions in the hypolimnion as respiration of organic material consumes available oxygen, aiding in the preservation of organic-rich sediments (Platt and Wright, 1991). Additionally, the lack of significant organic material and the presence of high percentages of minerals can indicate periods when the lake was well-mixed and respiration rates were high relative to organic matter fluxes.

Carbonate mineral precipitation fundamentally depends on the availability of calcium ions entering the lake usually through the chemical weathering of bedrock, the pH of the lake water, concentration and speciation of dissolved inorganic carbon (DIC), and particles available for carbonate nucleation (Hammes and Verstraete, 2002). The primary mechanism of carbonate precipitation in perennial topographically closed lakes is photosynthetic activity (Platt and Wright, 1991; Zhu and Dittrich, 2016). Additional possible mechanism includes ureolysis, denitrification, ammonification, sulfate reduction, and methane oxidation (Platt and Wright, 1991; Zhu and Dittrich, 2016). Phytoplankton and algae in the photic zone of both the marginal and basinal regions of a lake mediate the production of carbonate minerals by providing an available nucleation site, reducing available CO_2 through photosynthetic activity, and increasing pH (Platt and Wright, 1991; Hammes and Verstraete, 2002). Because of this, most authigenic precipitation of carbonate takes place during the summer months as phytoplankton productivity increases (Leng and Marshall, 2004).

When CO_2 reacts with lake waters or precipitation, carbonic acid is formed.

$$H_2O + CO_2 \leftrightarrow H_2CO_3$$

In shallow water systems such as lakes, calcium carbonate precipitates and dissolves as described in the equilibrium reaction.

$$CaCO_3 + H_2CO_3 \leftrightarrow Ca^{+2} + 2(HCO_3^-)$$

Bio-mediated carbonate production primarily occurs in the microenvironment surrounding a photosynthetic organism (Zhu and Dittrich, 2016). A transfer of HCO_3^- into a cell in exchange for an OH^- ion raises the pH surrounding the cell, encouraging the precipitation of carbonate (Zhu and Dittrich, 2016). In groundwater-dominated, topographically closed systems with limestone bedrock, an abundance of H_2CO_3 and pCO_2 levels significantly higher than atmospheric are likely to occur regardless of climate condition. Increased chemical weathering of bedrock, groundwater inputs, or respiration of organic material will result in increased concentrations of H_2CO_3 in the water column. This increase will acidify the water and result in dissolution of carbonate (Brunskill, 1969). Biological productivity, reduction of physical weathering, CO_2 exchange with the atmosphere, or any action that reduces the amount of dissolved CO_2 in the water column will result in carbonate precipitation (Brunskill, 1969). Discharge of groundwater in particular can focus high levels of pCO_2 into localized areas, increasing rates of carbonate precipitation. Warmer waters can hold less CO_2 resulting in increased precipitation of carbonate (Brunskill, 1969). A stratified lake reduces the amount of CO_2 being released into the water column without a reduction in biological activity promoting carbonate production. A wet climate, increasing physical weathering of carbonate bedrock, as well as stratified lake waters could prevent preservation of carbonate in a system that would be expected to due to an increase in the concentration of carbonic acid and dissolution of carbonates.

Carbonate isotopic records can be confounded by detrital inputs which may add noise or completely disturb the primary paleoclimatic signals from a lake (Leng and Marshall, 2004). Detrital material is carbonate mineral sediment that did not precipitate in the lake, but instead was transported into the lake through fluid or eolian processes. The influence of detrital material on the isotopic values of lake sediments can be identified if of different minerology, $\delta^{18}O$, or $\delta^{13}C$ values of detrital material are significantly different (typically much higher) than those expected for authigenic minerals that form in equilibrium with lake water (Leng and Marshall, 2004). Despite interfering with a hydroclimatic isotopic signal in an individual lake sediment sample, the presence of detrital material contains a valuable climatic signal as well and can be an indicator of increased aridity or surface winds (depositing a larger eolian fraction of material into a lake) or more likely an indicator of increased erosion/physical weathering of bedrock (Leng and Marshall, 2004). Transportation of sediment during shifting climatic states may play a role in the presence of detrital material. A transition from a previously dry climatic state to one that is consistently wet may result in a flushing of weathered bedrock from the soil and act as a brief source of detrital material.

Carbon isotopes from carbonate sediment can provide useful information about hydrologic balance, lake productivity through carbon cycling, diagnostics of detrital material, and climatic variability (Li and Ku, 1997; van Hardenbroek et al., 2018). Covariance between $\delta^{18}O$ and $\delta^{13}C$ of authigenic carbonates is observed in topographically closed lakes over long periods of time (greater than 5,000 yrs.) (Li and Ku, 1997). Inputs of freshwater affect both $\delta^{18}O$ and $\delta^{13}C$ values of the bulk lake water and DIC in nearly equal ways. Increased precipitation or groundwater flow generally provides sources of both lighter oxygen and lighter carbon from surrounding environments (Li and Ku, 1997). In lake systems where volume and productivity can vary more dramatically over shorter time scales, this effect may not occur (Li and Ku, 1997). As discussed above, increased evaporation relative to precipitation will preferentially reduce the quantity of ^{16}O within a lake, driving the expected carbonate $\delta^{18}O$ values more positive. A similar effect will be seen in carbon isotope data from authigenic carbonates, where during periods of high evaporation and low lake levels $\delta^{13}C$ will become more positive (Li and Ku, 1997). Although the results seen in the data are similar, the causes of shifts in $\delta^{13}C$ can be based on several factors including CO_2 equilibrium variability during different climatic states and evaporation. Three effects can drive the carbonate $\delta^{13}C$ to higher values. Reduction of fresh water inputs and stable productivity will raise $\delta^{13}C$ values as fresh water is a source of lighter carbon, generally sourced from respired organic matter in the watershed of the lake (Li and Ku, 1997). Evaporation concentrates CO_2 within the water column, putting the lake out of equilibrium with the atmosphere (Li and Ku, 1997). This results in the lake becoming a source of CO_2 with preferential loss of lighter carbon (Li and Ku, 1997). Finally, lower lake water levels encourage vertical mixing of the water column, driving increased productivity which increases $\delta^{13}C$ values of dissolved inorganic carbon (Li and Ku, 1997). Lakes have also been recognized to have three different reactions to fluxes of dissolved inorganic carbon (DIC) and subsequent $\delta^{13}C$ values of DIC ($\delta^{13}C_{DIC}$): 1. Increases in DIC with decreases in $\delta^{13}C_{DIC}$, 2. Increases in DIC and increases in $\delta^{13}C_{DIC}$, 3. An inverse relationship between $\delta^{13}C_{DIC}$ and DIC until extremely high levels of DIC where a positive relationship occurs (Myrbo and Shapley, 2006). $\delta^{13}C_{DIC}$ dynamics within a given lake are extremely specific and are important to take into account prior to interpreting a $\delta^{13}C$ record from carbonate sediment (Myrbo and Shapley, 2006).

Isotopic analysis of organic matter from sediments can provide additional constraints on interpretations made from the authigenic fraction as well as provide data on variability of ecological processes and productivity. Organic matter found in sediment can come from a variety of sources including benthic organisms and plants, pelagic organisms and plants, and terrestrial material (Meyers and Ishiwatari, 1993; Thevenon et al., 2012). Plants in general, from both the lake itself and the surrounding watershed, are the dominant source of organic material (Meyers and Ishiwatari, 1993). Although plant material is subjected to chemical and biological breakdown, oxidation, consumption, and a range of other effects, the bulk $\delta^{13}C$ values show little to no deviation from primary values (Meyers and Ishiwatari, 1993). A diagnostic utilized from bulk organic $\delta^{13}C$ analysis of lake sediments is determination of relative composition of C3 and C4 plants in a lake or watershed. Expected mean $\delta^{13}C$ values for C3 plants are -28‰ and for C4 plants are -14‰ (Meyers and Ishiwatari, 1993). $\delta^{13}C$ values combined with carbon to nitrogen (C/N) mass ratios can provide valuable insight into the sourcing of organic matter within the sediment (Thevenon et al., 2012). Variation in $\delta^{13}C$ of bulk organic sediment has been used to interpret paleoclimate as well. Higher values of $\delta^{13}C$ in Lake Bosumtwi, Ghana are interpreted to represent the onset of a drier climate (Meyers and Ishiwatari, 1993). Lower values of $\delta^{13}C$ has been hypothesized to have been a result of a stagnant carbon pool or extremely high productivity (Meyers and Ishiwatari, 1993).

Significantly less is known about the more complicated nitrogen isotopic system in lakes and lake sediments than is known about carbon (Meyers and Ishiwatari, 1993). $\delta^{15}N$ values for bulk organic matter in sediment are hypothesized to primarily reflect nitrogen sourcing (Meyers and Ishiwatari, 1993; Thevenon et al., 2012). Terrestrial organic material tends to have lower values of $\delta^{15}N$ than sediment dominated by aquatic material (Meyers and Ishiwatari, 1993). Previous studies have shown that increases in $\delta^{15}N$ values have been associated with dry periods, a result of preferential loss of lighter nitrogen isotopes through mechanisms such as denitrification (Meyers and Ishiwatari, 1993).

Carbon and nitrogen mass ratios can provide information about the sourcing of bulk organic lake sediments (Meyers and Ishiwatari, 1993; Thevenon et al., 2012). C/N ratios span a wide range from planktonic values of 6-7 to white oak wood values of 276 (Meyers and Ishiwatari, 1993). Algae and plankton (10-14), aquatic plants (19-25), and surface soil (~17) all show unique ranges of C/N ratios which can be utilized to determine the relative contributions (Meyers and Ishiwatari, 1993; Thevenon et al., 2012). Nutrient limitation may affect the ability to identify principal biological components of sediments, as nitrogen limitation has been shown to increase the C/N ratio of primary producers (Dodds et al., 2004).

Time series analysis of paleoclimatic data can be a useful tool for quantifying trends in isotopic data. REDFIT software developed by Schulz and Mudelsee (2002), can be used on time series data that is unevenly spaced by testing to check if a signal peak at a specific frequency is the result of interpolated noise or not. Identification of a first-order autoregressive trend (AR1) can be used to extract any frequencies that are a result of interpolated noise (Schulz and Mudelsee, 2002). This noise, also referred to as “red” is a result of interpolation that enhances low frequencies and can inhibit the ability to identify high frequencies (Schulz and Mudelsee, 2002). REDFIT estimates AR1 and then compares it to the frequency of the time series to identify noise frequencies (Schulz and

Mudelsee, 2002). Estimations of both the frequencies of the unevenly spaced data and the AR1 are conducted through Fourier transformations (Ghil et al., 2001; Schulz and Mudelsee, 2002). A Fourier transformation is a method of calculating multiple frequencies from data that is represented by multiple sine or cosine waves, like paleoclimatic data (Ghil et al., 2008). Assumptions of this technique include that the noise can be estimated by the AR1, the data is stationary, and the distribution of data points are not extremely clustered (Schulz and Mudelsee, 2002). Additionally, the shortest frequency that can be identified based on the sampling method and sediment dating is the Nyquist frequency ($f_N = \frac{2}{\Delta t}$) (Ghil et al., 2001).

Goals of this study

The use of authigenic carbonate $\delta^{18}O$ as a paleoclimatic proxy is limited by the individuality, scarcity, and geographic distribution of lakes that precipitate carbonate minerals (Anderson et al., 2016). The most recent review paper of authigenic carbonate $\delta^{18}O$ records throughout the Rocky Mountains (Anderson et al., 2016) recognized the need for additional high-resolution data sets to further illuminate modes of climatic variability.

Morrison Lake is located at 2,490 m on the eastern side of the continental divide and is a headwater for the Missouri-Mississippi watershed. The lake has a high sedimentation rate with over 12 meters of sediment likely deposited since the Last Glacial Maximum. Surrounded by Paleozoic limestone bedrock and topographically closed at present lake stage with no apparent surface outflow, Morrison Lake also has significant depositions of authigenic carbonate, up to 80% of the total sediment in some portions of the lake core.

Morrison Lake provides ideal conditions for the development of a multidecadal to centennial resolution $\delta^{18}O_C$ record to enhance current regional understanding of Holocene hydroclimatic variations in the northern Rocky Mountains. Currently published records include a geographic gap in hydroclimate data in this region (Anderson et al., 2016). The nearest published isotopic paleoclimatic records are Foy, Jones, and Crevice lakes (Stevens et al., 2006; Stevens and Dean, 2008; Shapley et al., 2009; Anderson et al., 2016) which are over 200 km away. This research project seeks to expand on the existing $\delta^{18}O_C$ records across the northern Rocky Mountains to better constrain hydroclimatic variability over the Holocene with emphasis on mean drought duration and periodicity.

Research questions addressed in this study include:

- Does the isotopic composition of lake water in Morrison Lake record variations in the sourcing of precipitation or P-E?
- How has hydroclimate shifted in terms of frequency and severity over the length of time recorded in the sediment?
- Can sediment containing primarily detrital material be distinguished from sediment containing primarily authigenic carbonate?
- How did carbon cycling and lake productivity shift in response to climatic variability?

Stable isotope analysis of both the carbonate minerals and bulk organic material, as well as other proxies, in the sediment were conducted to answer these questions.

Radiocarbon analysis of identified terrestrial material was used to develop an age model to date the timing of isotopic shifts. Loss on ignition, magnetic susceptibility, and sediment description were utilized to provide additional data related to climatic variability. Data collected in this study was compared to historical weather station and SNOTEL data in an attempt to characterize modern sediments with the goal of interpreting climatic shifts where there is no historical data.

Chapter 1: 15,000 years of paleoclimatic variability inferred from stable isotope analysis of sediments from Morrison Lake, MT, northern Rocky Mountains, USA

1.1 Abstract

The northern Rocky Mountains act as vital stores of water that is even more critical during periods of low precipitation in the semiarid regions of the western United States. Hydrologically sensitive Morrison Lake is located in the southern Beaverhead Mountains, a location that lacks an isotope paleoclimatic proxy record that extends beyond the late Holocene. Stable isotope analysis of the carbonate, bulk organic fraction of the sediment, and other proxies show three distinct phases in the lake's evolution. The sediment record presented in this paper indicates that the late glacial melt waters likely flowed into the lake from ~15,500 to 14,800 cal yrs. BP. Following this period, climate warmed and precipitation was low until 11,000 cal yrs. BP. High amounts of residual material, primarily composed of quartz, silicate clays, and diatoms, and detrital carbonate indicate a reduction in carbon and calcium inputs into the lake, limiting authigenic precipitation. This is likely a result of decreased groundwater flow due to reductions in precipitation. Rapid onset of a wetter climate occurred at 11,000 cal yrs. BP and continued until 10,000 cal yrs. BP. Climate then began to dry again resulting in very little carbonate being preserved during the mid-Holocene (10,000-6,000 cal yrs. BP). Anoxia and reduced lake water pH appear to have occurred during this period, likely a result of extremely dry conditions and further reduced groundwater flows. At about 6,000 cal yrs. BP, the sediments shifted to a composition that has persisted under modern climate conditions, with significantly higher rates of authigenic carbonate production. Other regional lakes studied to date do not show such dramatic sedimentological changes at this

time. We explore factors that create threshold responses in this unique basin and how these thresholds may provide information about shifts in climatic state.

1.2 Introduction

Water conservation and hydroclimate variability in the western United States is a topic of significant interest as drought duration and severity have increased in the past several decades and the underlying connection between multidecadal drought events and long-term downstream water availability is poorly understood (Loon et al., 2016). In addition to generating economic value through recreation, snowpack in the northern Rocky Mountains store water critical to the economy of the central and western United States. Snowpack is vital for sustaining downstream ecosystems and contributing to streamflow during the dry season. Increases in the elevation of the rain/snow transition, decreases in the volume of annual precipitation, and increases in mean annual temperatures are expected to continue (Kitzberger et al., 2007; Goode et al., 2011; Tennant et al., 2015; Siler et al., 2019), which will all affect water supply and related processes. Despite these changes, snowpack in the western United States has not experienced a long-term trend over the past several decades (Siler et al., 2019). Sea surface temperatures and atmospheric circulation in the Pacific have been favorable for increased precipitation during this time period but this pattern is not expected in the longer term and snowpack loss is expected to accelerate in the upcoming decades, resulting in a loss of 60% of snowpack by 2050 (Siler et al., 2019). Increasing understanding of natural climatic variability, that may enhance or buffer modern warming, and understanding the effects that these climatic regimes have on sensitive high elevation regions is vital to address the future of climate change in the northern Rocky Mountains.

Understanding the nature of climatic variability and its drivers depends on a combination of ground-truthed metrological data and paleoclimatic proxies. Weather station data in the western United States has been collected for over 100 years at long-term weather stations, typically at lower elevations, and for the past several decades at snow telemetry (SNOTEL) sites, typically at higher elevations (Wang et al., 2005). This data is limited both spatially and temporally. Short-term weather monitoring (<100 yrs.) is not sufficient to characterize climatic variability that occurs on centennial to millennial scales (Serreze et al., 1999; Braconnot et al., 2012; Grant et al., 2013). Paleoclimatic proxies, such as tree ring and lacustrine sediment records, have been utilized to understand climate at these longer time scales (Meko et al., 2007).

Characterization of climatic behavior in the northern Rocky Mountains is currently too limited to project future changes in hydroclimates and its spatial variability (Meko et al., 2007; Anderson et al., 2016). Morrison Lake, Montana provides the opportunity to develop an additional paleoclimatic record at high elevation in the northern Rocky Mountains. The site is a topographically closed at present lake stage with high sedimentation rates, and the preservation of significant authigenic carbonates allows for the interpretation of multidecadal to centennial scale variability in precipitation to evaporation (P/E). This project aims to increase understanding of climatic variability and the timing of different climatic regimes at a high-elevation location in an understudied region.

1.2.1 Site description

Morrison Lake (44.601843 N, -113.036895 W) is a topographically closed lake (at present lake stage), located in the southern Beaverhead Mountains of southwestern Montana (Figure 1.1). Along the eastern side of the continental divide at 2,490 m, the lake is one of the most distal tributaries of the greater Missouri-Mississippi River watershed. Morrison Lake is characterized by two distinct sedimentary environments. The first is a shelf composed of calcium carbonate sediment, diatoms, shell fragments, shallow water emergent plants, and intricate mats of algae with an average depth of two meters. The shelf occurs along the southern, eastern, and northern margins of the lake. The second is a deeper basin occurring along the western edge with an average depth of eleven meters. Sediments found in the basinal area include a combination of organic material, diatoms, clastics, and carbonates. Steep slopes divide the two sedimentary environments. Vegetation along the eastern edge of the lake is sparse; minor tree cover (primarily lodgepole pines) exists along the northern, western, and southern edges, but a majority of the environment surrounding the lake is sagebrush steppe. Frequent strong winds promote shallow water mixing.

Morrison Lake has a surface area of 0.02 km^2, volume of approximately 120,000 m^3, and a watershed size of 2 km^2 (Bracht-Flyr, 2009). Primary surface inputs of snowmelt occur through two separate tributaries which are dry during the summer months and are both located on the western side of the lake. The first tributary is a small creek at the northwestern corner of the lake and the second flows through a boulder field along the western edge of the lake. Surface expression of groundwater occurs at a seep on the eastern side of the lake. The seep remains wet throughout the summer and fall as topographically higher ponds and marshes likely drain water into the lake. The residence time of water in Morrison Lake, based on the mean annual precipitation from Beagle Springs SNOTEL site (603 mm), is approximately 1-2 years.

Bedrock in the watershed is primarily composed of the Upper Mississippian Bluebird Mountain and Permian Snaky Canyon Formation with a minor outcropping of the Lower Permian Phosphoria Formation (Ruppel, 1998). The Bluebird Mountain and Snakey Canyon Formations are mapped as undivided sedimentary units and contain beds of limestone, sandstone, and sandy limestone (Ruppel, 1998). The surface sediments immediately around the lake are mapped as glacial deposits (Ruppel, 1998). Limestone outcropping along the eastern edge of the lake indicates that the lake is in a bedrock basin. Small ponds and marshes occur to the east and southeast of the lake and likely formed as kettles from dead ice moraines. Some ponds and marshes occur in topographically higher areas while others occur at slightly lower elevations than the lake and many of them dry up during periods of low precipitation and groundwater levels.

1.2.2 Climatic setting

The nearest full-time weather station that monitors both precipitation and temperature is the Beagle Springs SNOTEL site (44.4667 N, 112.9833 W). The site is located 15.25 km to the south of Morrison Lake, at a similar elevation (2,697 m) and aspect (NE), and has reported daily precipitation and temperature since 1979 with minor interruptions. Mean annual precipitation over the period of record is 603 mm. This contrasts with previous estimates of mean annual precipitation of 406 mm (Bracht-Flyr, 2009). The distribution of precipitation is seasonally variable, with mean annual precipitation dominated by spring (March, April, May) rain and snowfall (35.3%) (Figure 1.2).

Summer (June, July, August) and fall (September, October, November) provide nearly equal proportions of mean annual precipitation (25.4% and 22%). Winter (December, January, February) accounts for the smallest contribution to total annual precipitation (17.3%). Annual evaporation is estimated to be 1100 mm which is nearly double the mean annual precipitation (Bracht-Flyr, 2009).

The northern Rocky Mountains to the north and south of Morrison Lake including the Yellowstone region are classified according to the Köppen-Geiger climate classification as moist, mid-latitudinal climates (Figure 1.3) (Kottek et al., 2006; Rubel et al., 2017). Morrison Lake is in a narrow region classified as a dry semi-arid climate, even at high elevations (above 2,500 m) (Kottek et al., 2006; Rubel et al., 2017). The local region surrounding Morrison Lake is similar climatically to the lower elevation (1,500 m and below) Snake River Plain of southeastern Idaho (Kottek et al., 2006; Rubel et al., 2017). This climatic variation makes Morrison Lake an important place to reconstruct climate as it is located in an underrepresented climatic zone of the Rocky Mountains.

1.3 Methods

1.3.1 Field work

Initial sediment coring took place in the summer of 1996 with the collection of two cores from the deep basin. Multiple visits to Morrison Lake were made from fall 2017 to summer 2018 to collect samples to characterize watershed materials, including water, soil, vegetation, and bedrock. Primary field work and surface core collection was conducted during late July 2018. Bathymetric data was collected using the ArcGIS collector app on a GPS enabled Samsung tablet and a Hummingbird Fishin' Buddy Max attached to an inflatable kayak. Water depth data was utilized in the field to target the deepest section of the lake for collecting undisturbed sediment.

1.3.2 Core collection

Two overlapping sets of sediment cores were obtained during the 1996 field campaign. Cores were collected using a Livingston coring device, extruded in the field, wrapped in plastic wrap, and stored in split PVC tubing at the LacCore facility in Minneapolis MN. Permission to transport and study these cores at Idaho State University and loan of the working half of the cores was obtained in fall 2017. High-resolution digital linescans were provided by LacCore.

To capture the sediment-water interface and additional sediment to correlate into the existing core set, a core was collected from the basinal area (14 meters of water depth) of Morrison Lake (Figure 1.4) with a Bolivia coring device (Myrbo and Wright, 2008) in summer 2018. Two sequential 1.5-m drives were obtained, with the surface drive containing 30 cm of water over a well-preserved sediment water interface. Zorbitrol, a water absorbing gel, was used to prevent sediment disturbance during transit (Tomkins et al., 2008). An additional core was collected from the marginal bench in the northeastern portion of the lake in 2 meters of water depth.

1.3.3 Core description and sampling

Cores collected in 2018 were passed through a Bartington MS2 with a MS2C ring sensor to collect magnetic susceptibility data at 1 cm intervals. Sediment cores were then split, photographed, and described. The surface core was sampled at 0.5 cm intervals in the first meter of sediment from the surface. This sampling was conducted to capture a high-resolution multidecadal-scale record for the past ~2,000 yrs. Sediment below 1 meter of total depth was sampled at 1 cm intervals. Water content and wet and dry bulk-density was determined from volumetric samples from the 2018 cores, but was not conducted for the 1996 cores due to water loss that occurred during storage.

Loss-on-ignition (LOI) analysis was conducted on samples from both the 2018 and 1996 cores to assess percent carbon, carbonate mineral, and residual material. Samples were heated in cleaned crucibles at 100 °C for 12 hours to remove water. Dry samples were then reweighed and heated to 500 °C for 4 hours to combust the organic fraction. Samples were weighed again and heated to 1,000 °C for 2 hours to remove carbonate through decomposition. The mass of the remaining residual material represents silicate minerals and diatoms.

X-ray diffraction (XRD) was conducted on selected samples representing typical and extreme values of $\delta^{18}O$ from the fine-grained (<50μm) carbonate sediment to understand the types of carbonate minerals present. Analysis was conducted utilizing a Bruker D8 Advance. Parameters of XRD analysis included refraction angles from 0-60, 1 step per second, and 4,200 total steps. XRD analysis on a suite of common bedrock materials from the watershed and basin were used to characterize signatures of potential detrital material.

1.3.4 Stable isotope preparation

Carbonate mineral isolation was conducted by soaking sediment in 2.5% NaClO for 10-12 hours to oxidize organic material. Sediment was rinsed with 12.5 mL of high-purity (at least 18 MΩ) DI water and centrifuged at 2,500 rpm for 10 minutes five times to remove any remaining NaClO. A 50 µm nylon sieve was used to remove coarse-grained material. Samples were frozen and freeze dried for 36 hours to ensure complete removal of water. Analysis was conducted using a Finnigan GasBench II front end connected to a Delta V advantage mass spectrometer through the ConFlo IV system. Sample masses were adjusted based on percent carbonate mineral fraction. Carbonate isotopic values are reported relative to the international standard Vienna Pee Dee Belemnite (VPDB) with precision of ±0.2‰ for both $\delta^{18}O$ and $\delta^{13}C$.

Bedrock samples were collected from the area surrounding the lake. Samples represented each of the major contributing rock types from the bedrock in the watershed above the lake as well as the limestone that immediately surrounds the lake. Rocks were crushed and analyzed utilizing the same method as sediment carbonate samples.

Sediment (bulk organic fraction), soils, and plants were analyzed for carbon and nitrogen stable isotopes. 12.5 mL of 1 molar HCl was added to each of the subsamples to remove carbonate minerals. Vials were allowed to react for 30 minutes before being placed on a shaker tray for 6-8 hours. Samples were rinsed with 12.5 mL of high purity DI water and centrifuged at 2,500 rpm for 10 minutes five times to ensure removal of all remaining HCl. Samples were then frozen and freeze dried for 36 hours. Analysis was conducted utilizing a Costech ECS 4010 elemental analyzer connected to a Thermo Delta V Advantage continuous flow isotope ratio mass spectrometer (IRMS). Bulk organic sediment isotopic values are reported relative to VPDB with precision of ±0.2‰ for $\delta^{13}C$ and relative to atmospheric values (atm) for $\delta^{15}N$, and ±0.5% for %N and %C.

Stable isotopic data of lake water and shallow groundwater were analyzed for δD and $\delta^{18}O$ using a TC-EA coupled to the Thermo Delta V Advantage continuous flow isotope ratio mass spectrometer.

1.3.5 Chronology

Sediment ages were acquired through radiocarbon analysis of identified terrestrial organic material at Lawrence Livermore National Laboratory (Table 1). Sediment was prepared for radiocarbon analysis by first being wet screened with coupled 250 and 125 µm metal mesh. Terrestrial organic material was identified using a light microscope and placed into ashed vials. The Bacon software packages for R was used to conduct sedimentation rate calculations and age calibrations (Blaauw and Christén, 2013).

Two tephra deposits were observed in the sediment core and are interpreted to be the Mazama tephra (7597 ± 40 cal yrs. BP) and the Glacier Peak tephra (13,560 ± 150 cal yrs. BP) (Kuehn et al., 2009; Steinman et al., 2019) based on the stratigraphic distribution of radiocarbon dates.

1.3.6 Regional climate survey

A high-elevation regional average of mean annual precipitation and temperature was developed utilizing publicly available data sets from seven SNOTEL sites at similar elevations and aspects in the region surrounding Morrison Lake (Table 1.2, Figure 1.5). Values for daily precipitation (including both rain and snow) were totaled for each month over the period of record. Mean daily temperatures were averaged for each month. Monthly values for precipitation and temperature were then averaged between different years to identify seasonality and annual values were calculated to assess multiyear variability. Additionally, temperature and precipitation data from Beagle Springs SNOTEL was compared to the same data from the Lima long-term weather station (LAT/LONG: 44.63, -112.59; elevation: 1,913.8 m, reporting since 1898), which is 36 km to the northeast of Morrison Lake, to calculate correlation between a high-elevation location and the nearest lower elevation weather stations.

1.4 Results

1.4.1 Sediment description

Sediments show distinct variability throughout the entire core length from Morrison Lake (Figure 1.6). In the upper portion of the core, 0-1.76 m, sediments are laminated, carbonate and clay rich with minor amounts of sand, diatoms, and organic material. Individual layers (1-2 cm) of highly organic rich material occur.

From 1.76 to 2.78 m, sediment characteristics shift toward increasing amounts of clay, a significant reduction in carbonate, and generally massive in structure. During this period there is an increase in organic matter and minor amounts of sand and diatoms. Additionally, a 3 cm thick tephra deposit from the Mazama eruption occurs at 2.19 m. Minor features of Fe oxidation are observed in the lower portions of this unit.

From 2.78 to 4.5 m, the sediment is generally clay rich, thinly laminated, with common diatoms, and increased content of silts and sands. Throughout this unit there are a series of fining upward sequences that range in thickness from 0.5 to 3 cm. At 3.86 m the Glacier Peak tephra occurs with a thickness of 2.5 cm. Carbonate minerals compose a smaller fraction of the sediment and organic matter is variable but generally high.

Approximately 8 meters of sediment was recovered below 4.5 m. This sediment was not analyzed for the purposes of this project due to the presence of several sections of folded and possibly overturned layers. Sediments below 4.5 m are primarily composed of laminated, sand rich, layers. Depositional mechanisms, climatic state, and the origin of folded or overturned beds throughout the lower 8 meters is unclear.

1.4.2 Age model

The radiocarbon dates are in stratigraphic order, and were used to identify tephras, consistent with the regional tephra stratigraphy (Kuehn et al., 2009; Steinman et al., 2019). A calibrated age model developed through the use of Bacon software in R indicates that mean sedimentation resolution at Morrison Lake over the past ~15,000 yrs. BP has been 36 years per cm, or 0.03 cm/yr. (Figure 1.7; Figure 1.8). However, the age model indicates variability in the sedimentation rate throughout the core. The highest rates of deposition are seen in the most modern sediments (2000-(-68) cal yrs. BP). Extremely low rates of sedimentation are observed around 7,000 cal yrs. BP. The stratigraphically oldest age is the Glacier Peak tephra (13,560 cal yrs. BP). The sedimentation rate between the stratigraphically lowest radiocarbon date and the Glacier Peak tephra was used to extrapolate ages stratigraphically below Glacier Peak. These ages likely have large error values and are considered as provisional.

1.4.3 Water isotopes

Stable isotope analysis of lake water from across Idaho and including samples from Morrison Lake, collected over several months and years, shows that samples plot at a lower slope (4.4) than the global meteoric water line (GMWL, 8), indicating lake water across the Idaho to western Montana region is influenced by evaporation (Figure 1.9). Samples collected from Morrison Lake fit along the linear regression calculated for the regional averages. The intersection of the linear regression and the GMWL, which indicates the weighted isotopic values of the source water, is -18.7‰ (VSMOW; $\delta^{18}O$) and -139.5‰ (V-SMOW; $\delta^{2}H$). These values are similar to expected mean annual precipitation isotopic values at Morrison Lake (-16.9‰, VSMOW, $\delta^{18}O$; -127‰, V-SMOW, $\delta^{2}H$) (Bowen and Revenaugh, 2003). When expected monthly values for precipitation are calculated for Morrison Lake, the estimated lake source is most similar to precipitation occurring in April (-17.8‰, VSMOW, $\delta^{18}O$; -134‰, V-SMOW, $\delta^{2}H$), indicating that spring snowpack and melt strongly influence the isotopic composition of the lake water at Morrison Lake in western Montana other lakes across Idaho (Bowen and Revenaugh, 2003).

1.4.4 Stable isotope, LOI, and XRD

$\delta^{18}O$ of the fine-grained (<50µm) carbonate sediment ($\delta^{18}O_C$), stable isotopes from the bulk organic fraction, and sediment characteristics vary throughout three distinct intervals in the upper 4.5 m (Figure 1.5 and 1.11). The earlier sediment (15,600-10,000 cal yrs. BP) has an average $\delta^{18}O_C$ value of -8.85‰. The middle portion of the record (10,000-6,000 cal yrs. BP) contains very little to essentially no carbonate (6.3% on average, based on LOI). The most recent sediment unit (6,000 – (-68) cal yrs. BP) has an average $\delta^{18}O_C$ value of -12‰.

1.4.4.1 Unit 1: ~15,600-10,000 cal yrs. BP

Sediment in this interval is thinly laminated and clay-rich with organic material, sand, and minor amounts of carbonate minerals and silt. Multiple fining upward sequences are observed through this portion of the core, primarily composed of carbonate rich sediment with minor amounts of silt, sand, and clay. Multiple individual mm scale laminations are dominated by carbonate minerals.

Sediments deposited during this interval show a distinctly higher average $\delta^{18}O_C$ than the more modern sediments (Figure 1.12). Values vary dramatically in this portion of the core with fluctuations of up to 10‰. This unit is also characterized by high values of percent residual material (average value of 75%). Carbon to nitrogen mass ratios (C/N) are almost half of other units, with an average C/N value of 6.8. Weight percent carbon (organic fraction) in this unit average 4.4%, much lower than the younger two units.

While the average value for $\delta^{18}O_C$ throughout this period is -8.8‰, there are two major isotopic steps to lower values during unit 1. The earliest portion of the record (~15,600-14,800 yrs. BP) shows a high variability in $\delta^{18}O_C$ with values ranging from -7 to -15‰. An upward step of 7‰ occurs at 14,800 years. From 14,800 to 11,000 yrs. BP, there are consistently higher $\delta^{18}O_C$ values than any other portion of the record. A downward step of 9‰ occurs at 11,000 yrs. BP, followed by a brief period (11,100-10,000 yrs. BP) where the $\delta^{18}O_C$ values are consistently more negative than the preceding several thousand years, and the recent sediments, punctuated by several positive spikes in $\delta^{18}O_C$. Covariance of the entire unit of $\delta^{18}O_C$ and $\delta^{13}C$ from carbonate ($\delta^{13}C_C$) is -1.17 with an R^2 of 0.28, showing a weak inverse correlation. Much the carbonate in this unit 1 falls within values considered to be detrital from analysis of bedrock surrounding the lake, as discussed below (Figure 1.13). XRD analysis confirms that most samples analyzed contain nontrivial amounts of dolomite, found in the bedrock surrounding the lake. Total percent carbonate is relatively low with an average value of 15%.

1.4.4.2 Unit 2: 10,000-6,000 cal yrs. BP

Sediments deposited between 10,000-6,000 cal yrs. BP are characterized as massive organic and clay-rich material with minor amounts of sand and silt. Almost equal percent composition of organic matter and residual matter (average values: 44% and 50%) and extremely low concentrations of carbonate occur during this interval (average of 6.3% by LOI analysis). Sediment processed from this interval for carbonate isotopes produced essentially zero carbonate, indicating other components contributed to high-temperature weight loss. Nitrogen isotopic values for the bulk organic fraction of the sediment ($\delta^{15}N_O$) show dramatic variation from the other two periods of the record. Average $\delta^{15}N_O$ values drop to -0.6‰ contrasting with the much higher average values of the earlier and more recent time periods (2.6‰ and 4.1‰). Additionally, percent mass of nitrogen is higher during this time period with an average value of 2.1% compared to other time periods (1.13% and 1.64%). C/N ratios show an average value of 13. Carbon isotopic values of the bulk organic sediment ($\delta^{13}C_O$) average -27.5‰, and are intermediate relative to the other units.

1.4.4.3 Unit 3: 6,000 cal yrs. BP-present

Sediment characteristics shift during this portion of the core. Sediments gradually transition from clay-rich, thinly laminated material with minor amounts of carbonate, silt and sand, into thinly laminate carbonate and organic rich clay with minor amounts of silt and sand. $\delta^{18}O_C$ values are consistently more negative (average -12.8‰) than the earlier portion of the record (Figure 1.14). This unit is punctuated by several thin intervals with significant increases in $\delta^{18}O_C$, with some samples spiking up to -6‰. These thin intervals are observed to have fining upward sequences, capped by fine grained carbonate minerals. The average value for $\delta^{13}C_C$ is much lower during this time period than either of the previous units at -0.55‰. Covariance between $\delta^{18}O_C$ and $\delta^{13}C_C$ during this period is 0.13 with an R^2 of 0.0084 indicating a very weak positive correlation. Average values for $\delta^{15}N_O$ are higher during this period than either of the previous two (4.1‰). C/N mass values average at 12.54. Sediment composition is more evenly distributed than in other units, with nearly equal contributions of carbonate and residual material (39% and 36%, respectively). XRD analysis indicates samples contain a combination of calcite and aragonite with minor amounts of dolomite (likely detrital from the watershed). Calcite and aragonite XRD peaks are more numerous, wider, and have a higher count per second, than dolomite during this unit. This indicates that dolomite, while present in some samples, is not of significant quantity. Several samples that show high amplitude $\delta^{18}O_C$ indicate a higher amount of dolomite present.

1.4.5 Regional climate survey

Beagle Springs SNOTEL site shows similar mean annual temperatures compared to the regional average (Figure 1.15). Over the period of record (1981-2018), Beagle Springs show a mean annual temperature of 1.2 ℃ which is 0.3℃ higher than the regional average of 0.9 ℃. A strong correlation was found between the Beagle Springs SNOTEL site and the regional average of mean annual temperatures over the period of record (R^2=0.86).

The Morrison Lake region, as reflected by Beagle Springs SNOTEL site (2,697 m), receives on average 72% of the total mean annual precipitation as other high-elevation sites in the region (Figure 1.16), but can receive as little as 50% in a given year. Mean annual precipitation over the period of record (1982-2017) at Beagle Springs is 670 mm. Mean annual precipitation at other nearby high-elevation sites analyzed is this study, over the period of record, is 933 mm. There is a poor correlation between mean annual precipitation at Beagle Springs SNOTEL site and the lower elevation Lima long-term weather station (1,907 m) (R^2=0.28). This contrasts with a high correlation (R^2=0.64) when the Beagle Springs site is compared to a regional high-elevation average of mean annual precipitation.

Poor correlation was found in both mean annual temperature (R^2=0.18) and precipitation (R^2=0.13) between the regional survey of high elevation locations and the Lima low elevation long term weather station data. The Beagle Springs SNOTEL site showed a poor correlation between mean annual temperature (R^2=0.13) and precipitation (R^2=0.28) when compared to the Lima weather station. The Lima weather station shows a poor correlation (R^2=0.14) when compared to mean annual PDO intensity over the past 100 years. However, when the Lima weather station data is compared to PDO intensity averaged between spring and summer months (Mar-Aug), correlation is extremely high (R^2=0.94). Beagle Spring SNOTEL site shows extremely poor correlation between mean annual precipitation and mean annual PDO intensity (R^2=0.05) as well as spring and summer PDO intensity (R^2=0.06).

1.5 Discussion

1.5.1 Identifying sources of detrital carbonate material

Determining the influence of detrital carbonate material from the surrounding watershed is vital for the interpretation of the $\delta^{18}O_C$ record. Although samples were sieved and only the <50 µm fraction of the carbonate sediment was analyzed, there is evidence for detrital material in some samples. Analysis of bedrock samples shows that values of some of the $\delta^{18}O_C$ samples, especially in the earlier portion of the record (Unit 1), are similar to fine-grained detrital material (Figure 1.13). XRD analysis indicates that dolomite is likely a good tracer of detrital influence, as dolomite is common in the bedrock surrounding the lake but would be unlikely to precipitate within the lake itself. The geochemical environment of Morrison Lake naturally promotes carbonate formation and preservation. Despite this, it does not appear that authigenic carbonate was forming at high rates or for extended periods of time during most of Unit 1. Portions of Unit 1, particularly between 10,000-11,000 and 14,800-15,500 cal yrs. BP show increased occurrences of significantly lower $\delta^{18}O_C$ values than the rest of the unit and result from increased production of authigenic carbonate minerals, and a lower input of detrital materials.

The most recent sediment package (Unit 3), is dominated by authigenic carbonate, and an overall lack of dolomite. Several relatively brief periods of primarily detrital input occur. Ideal geochemical conditions for carbonate formation were met during this period due to increased rates of CO_2 input and higher Ca^+ and Mg^{2+} saturation. Increased pH, due to either reduction in respiration through lower fluxes of organic matter, increased productivity in the epilimnion, or seasonal turnover, would be necessary to buffer sediment pore water and preserve carbonate. Authigenic carbonate production is primarily driven by epilimnion carbon dynamics but would require hypolimnion buffering for preservation.

XRD analysis of sediment from all three sediment packages described shows an abundance of aragonite. Aragonite formation is primarily driven through concentration of solutes, usually through either high rates of solute flux or high rates of evaporation. A combination of both aragonite and calcite throughout the core indicates that Morrison Lake has been subjected to highly solute-rich (both Ca^{+} and Mg^{2+}) and likely evaporative conditions throughout the Holocene and into the late Pleistocene.

1.5.2 Preservation of carbonate minerals

A lack of fine-grained carbonate minerals during Unit 2 is likely a result of reduced mineral preservation and possibly production. A lake located in a limestone basin with sandy limestone bedrock in the watershed might be expected to receive detrital material in all climate conditions. The presence of both an apparent delta along the western side and a carbonate bench along the northern, eastern, and southern edges may act as controls on the flux of detrital material into the deeper basin. Wet climatic regimes would increase both chemical weathering and transport of sediment through runoff into the lake, while a dry climate would decrease vegetation therefore increasing sediment flux through increased erosion and eolian inputs. A pH decline in the hypolimnion is one potential cause of the lack of carbonate preservation during this period. Whether or not the lake was producing authigenic carbonate during this time is unclear. This pH shift in pore water, possibly from increases in organic matter flux into the deep basin relative to detrital inputs and carbonate formation in the epilimnion, likely resulted in increased rates of carbonate dissolution. Extended lake stratification may also be a mechanism for decreasing the pH of the hypolimnion without dramatically increasing the organic matter flux.

1.5.3 Unit 1: 15,600-10,000 cal yrs. BP – paleoenvironmental interpretation

A majority of the carbonate samples during this period have $\delta^{18}O_C$ and $\delta^{13}C_C$ values similar to bedrock. Samples also contain relatively higher amounts of dolomite, likely bedrock-derived. This indicates that Morrison was not consistently preserving authigenic carbonate minerals. It is possible that conditions were favorable for authigenic production during this time, but dissolution of authigenic minerals occurred allowing for preservation of more resistant detrital dolomite. Preservation of carbonate in the sediment indicates that the pH of the pore water was near neutral or high. It is unclear whether the pH of the epilimnion was high enough to produce carbonate, or if pH, carbon inputs, or calcium inputs were limited during this time. Overall percent organic matter in the sediment is very low with high concentrations of residual material. This indicates that the lake was likely unproductive, and sediment was primarily composed of weathered bedrock material. Low productivity and therefore low rates of organic matter burial and resultant respiration could have allowed for sediment pore waters to maintain a higher pH than under more productive conditions. C/N mass ratios indicate that algae were likely the primary organic component of the sediment with little to no input of terrestrial vascular plant material. Higher values of $\delta^{13}C_O$ throughout this period likely represent reduced dissolved inorganic carbon (DIC) inputs from surrounding bedrock, consistent with reduced groundwater input. Each of these proxies indicates that Morrison Lake experienced dry conditions throughout the late Pleistocene and into the early Holocene. There are noticeable deviations from this pattern. From 15,600 to 14,800 cal yrs. BP and from 11,100 to 10,000 cal yrs. BP, authigenic carbonate is produced by the lake and $\delta^{18}O_C$ values show abrupt declines with average values similar to the most modern sediments. These periods likely indicate higher rates of groundwater flow and/or precipitation increasing carbon and calcium fluxes into the lake. The earliest of these periods (15,600-14,800 cal yrs. BP) is possibly driven by glacier melt water, consistent with other regional dates on deglaciation (Krause et al., 2015). Receding glaciers in the higher elevation regions of the watershed to the west and north of Morrison Lake may have been providing a large source of seasonal runoff into the lake. Glacial melt water would be significantly more negative and in higher volumes than precipitation and could have resulted in the period of lower $\delta^{18}O_C$. The gradual transition of $\delta^{18}O_C$ from -14.5‰ to -8‰ indicates a shift into a drier climatic state and possible complete melting of glaciers.

The more recent period within this unit with lower $\delta^{18}O_C$ deviations (11,100 to 10,000 cal yrs. BP), indicates that Morrison Lake shifted, perhaps abruptly, away from the dry climatic state that had persisted from 14,800-11,100 cal yrs. BP and into some of the most negative $\delta^{18}O_C$ values throughout the entire record. Jones Lake in northern Montana also records a similar and rapid $\delta^{18}O$ excursion during this time, interpreted to represent a period of increased freshening (Shapley et al., 2009).

1.5.4 Unit 2: 10,000-6,000 cal yrs. BP – paleoenvironmental interpretation

From 10,000 to 6,000 yrs. BP, Morrison Lake preserved very little to no carbonate. This is an unexpected finding in a lake that is located within a limestone-rich watershed and is thus interpreted to reflect a shift in preservational state. This lack of preservation is likely a result of a reduction in the pH of the hypolimnion preventing preservation of carbonate minerals. The cause of this pH shift may be a result of increased lake stratification due to a warmer and drier climatic state or due to an increase in the organic matter flux into the deep basin. Reduced lake stage likely resulted in a reduced surface water area, reducing fetch and mixing. Even with a significant reduction in lake level (>50%), basin depths would be deep enough (~7 m) to allow for stratification to occur. $\delta^{15}N_O$ values are significantly lower during this period, dropping to atmospheric values. $\delta^{15}N_O$ provide information about nitrogen cycling, lake productivity, and hydroclimatic variability and likely indicate that productivity, relative to nitrogen availability, was higher during this time period. Under nitrogen limitation, increased nitrogen fixation results in, and lower $\delta^{15}N_O$. Extremely dry conditions result in reduced nitrogen delivery into the lake, which is primarily driven through groundwater flow. Additionally, anoxic bottom waters may also be a mechanism for a loss of nitrogen through denitrification which will result in increased concentrations of phosphorus relative to nitrogen, favoring nitrogen fixation. An extremely dry climate state during this time likely resulted in lower lake levels than modern levels. These lower lake levels would have a negative impact on groundwater outflow from the lake as both the hydraulic head and the permeability of the margins would shift. Weight percent carbon and nitrogen in the organic fraction of the sediment rise higher during this time period than earlier or later portions of the record. High rates of respiration, or poor mixing between the epilimnion and hypolimnion likely resulted in anoxic conditions that lowered the sediment pore water pH and prevented preservation of carbonates. Sediment in this portion of the record is thick, massive, and organic rich.

Our interpretation of a wet and highly productive period from 11,100 to 10,000 cal yrs. BP, preceding this period of significant reduction in precipitation (10,000-6,000 cal yrs. BP), would likely alter nutrient cycling. If lake level was lower during this time the carbonate bench that surrounds the northern, eastern, and southern edge of the lake would have begun to form. Sediments from the bench are primarily composed of photosynthetically mediated carbonate. This indicates that the bench likely formed and grew during periods of low lake level, where a majority of the basin was shallow enough to be within the photic zone, as access to light is necessary for growth of the bench. The bench is formed in areas where large portions of the watershed seasonally drain into the lake or where year-round groundwater flows occurs today. These areas are likely to be the most nutrient-, CO_2-, and calcium-rich environments encouraging rapid growth of carbonate producing algae and rapidly accumulating sediment. Notably, the frequent turbidite deposits observed in the earlier sediment dramatically reduce during this time. The formation of the bench likely stabilized large regions of the lake's edges preventing this depositional process.

1.5.5 Unit 3: 6,000 (cal yrs. BP)-present – paleoenvironmental interpretation

Around 6,000 cal yrs. BP Morrison Lake transitioned to a significantly and consistently wetter climate, as indicated by several sediment proxies. Although carbonate minerals begin to be preserved in the sediment again at 6,000 cal yrs. BP, this transition was likely gradual with the lake transitioning between low and high pore-water pH. Average $\delta^{18}O_C$ during this time period fall within the range of expected values for authigenic carbonate based on modern lake water isotopic values and known mean annual temperatures. This period was intermittently punctuated by $\delta^{18}O_C$ values that are considered to be dominated by detrital material. These periods are interpreted to represent high snow melt and runoff events that resulted in increased sediment transport from the watershed and gradual settling of fine-grained material. Sediment during these events is characterized by thin fining-upward sequences. This is supported by an increase in percent residual material during these isotopic excursions. The late Holocene in the southern Beaverheads was wetter than the early and mid-Holocene.

1.5.6 Geochemical thresholds and sediment trapping

The sedimentary record of Morrison Lake contains periods of significant geochemical change. Characteristics such as small basin size, arid climate, and topographic closure are likely factors promoting these rapid geochemical shifts. The boundary between Unit 3 and Unit 2 shows a dramatic shift in nitrogen isotopes where values drop to atmospheric level, indicating that nitrogen fixation became dominant, and carbonate preservation was halted. Productivity was high relative to nutrient fluxes, and preservation of organic matter in the deep basin increased. Anoxic bottom waters likely resulted which reduced the pH of sediment pore waters, eliminating carbonate preservation including those of an episodic nature. Perhaps formation of the carbonate bench greatly reduced detrital fluxes, including those of an episodic nature.

The previous climatic state of Unit 1, although dry, was likely wet enough for moderate nutrient availability and possibly authigenic carbonate mineral precipitation. Evidence of this is in higher values of $\delta^{15}N$ and the preservation of some carbonate mineral material. An even drier climatic state would result in further restriction of groundwater flow, solute flux, and nutrient availability. Productivity would therefore be restricted to regions of the lake where groundwater connections were still maintained, although significantly reduced. The bench would also act as a sediment trap, preventing detrital material from being washed into the deep basin. At this point the deep basin was cut off from high pCO_2 conditions and high solute concentrations required to precipitate carbonate minerals. Detrital inputs were also reduced with the deep basin primarily receiving organic matter from the margins of the lake as a dominant sedimentary component.

The transition between Unit 2 and Unit 1 show nitrogen isotopic values rising above atmospheric. A shift to a wetter climate state likely increased the amount of nitrogen being transported into the lake through groundwater flow. Increased available nitrogen in the lake shifted the nitrogen budget away from dependence on nitrogen fixation. Morrison Lake represents an extremely dynamic watershed and geochemical environment in which sediment compositon reacts strongly to climatic variability.

1.5.7 Climatic mechanisms and other records

1.5.7.1 Controls on regional climate variability

Hydroclimate at high elevations in the southern Beaverheads and northern Rocky Mountains can vary dramatically when compared to lower elevations. This is likely because high-elevation areas are subjected to different expressions of atmospheric forcing than lower elevation areas, including orographic effects.

The Morrison Lake area of the southern Beaverheads has similar mean annual temperatures as regions to the north and south but receives ~70% of the mean annual precipitation. This is likely due to the preferential routing of Pacific sourced precipitation to the north and south. Storm tracks originating from the Pacific funnel precipitation across the Snake River Plain and into the Yellowstone area, to the south. To the north, precipitation has a shorter path from the ocean and meets less orographic resistance. However, precipitation reaching Morrison Lake must first pass over the dense set of mountain ranges in central Idaho, relative to sites to the north, which likely results in significant rainout. Reduced precipitation results in stronger geochemical changes in response to different climate regimes, especially during dry periods. Commonly observed trends in hydroclimate and atmospheric circulation patterns in the modern system are thought to have been intensified in the mid to early Holocene in response to different insolation patterns (Huerta et al., 2009). This changed the mean strength and position of the Aleutian Low (AL) which drives directionality of precipitation as well as energy balance between the tropics and higher latitudes across the eastern Pacific (Overland et al., 1998). It is possible that shifts in precipitation at Morrison Lake are a result of a shifting AL, causing fewer storm tracks to reach the lake from 10,000 cal yrs. BP until 6,000 cal yrs. BP.

1.5.7.2 Comparison to other regional climatic records

Glacial advance studies from the Sawtooth Mountains of Idaho indicate that maximum glacial advance occurred at 16,900 cal yr. BP (Thackray et al., 2004). This is evident through basal dating of marsh sediments (Thackray et al., 2004). Lacustrine sediment basal dates showed a younger age of deglaciation (13,950 cal yrs. BP) (Thackray et al., 2004). Morrison Lake sediments show a transition from glacially influenced lake waters to a drier climate state at 14,800 cal yrs. BP, indicating an early glacial retreat in the southern Beaverheads relative to the Sawtooths.

Paleoclimatic proxies that record glacial advance and retreat into the late Pleistocene in the northern Rocky Mountains are rare, but a sedimentary record from Glacier National Park, MT region provides some insight into how other regions responded to the Younger Dryas and other post glacial climatic shifts (Schachtman et al., 2015). Swiftcurrent Lake records gradual warming from ~17 to 12.75 ka, a brief cooling period during the Younger Dryas (12.75 to 11.6 ka), followed by continued and gradual warming from 11.5 to 11.2 ka (Schachtman et al., 2015). Morrison Lake sediments do not show significant variability during the Younger Dryas, but instead show variability that extended from 14,800 to 11,000 cal yrs. BP. It is possible that the Younger Dryas only had a minor effect on the Morrison Lake region. As discussed above, the $\delta^{18}O_C$ excursion indicating rapid onset of increased hydroclimate intensity occurs after the Younger Dryas, between 10,000 and 11,100 cal yrs. BP consistent with the $\delta^{18}O$ record of Jones Lake to the north (Shapley et al., 2009).

The Yellowstone National Park region is the closest area to Morrison Lake with extensive paleoclimatic records. Three primary climatic regimes from the late Pleistocene to Holocene have been identified; summer-wet, transitional, and summer-dry (Huerta et al., 2009). Pollen and charcoal records from the northern region of Yellowstone National Park (summer-wet to transitional) indicate that the climate of the northern Rocky Mountains was dramatically colder and drier before 12,000 cal yrs. BP (Huerta et al., 2008). Between 12,000 – 7,600 cal yrs. BP, winter precipitation was high, but summers were drier than present (Huerta et al., 2008). Moisture continued to decrease from 7,600 cal yrs. BP into the modern with increased rates of wildfire frequency and reduced effective moisture (Huerta et al., 2008). The southern/central region of Yellowstone (summer-dry) most closely matches the record at Morrison Lake. Storm track directionality favors the northern Yellowstone because of a funneling effect of the Snake River Plain. Before 11,000 yrs. BP the area was cooler and drier than the present (Huerta et al., 2009). Between ~11,000 and ~5,000 yrs. BP the climate shifted to its warmest and driest of the Holocene and late Pleistocene (Huerta et al., 2009). Then from ~5,000 yrs. BP to the modern, the region developed wetter winters and cooler summers than expressed in earlier portions of the record (Huerta et al., 2009). This climatic interpretation is generally consistent with the interpretation made of Morrison Lake's late Pleistocene and Holocene climatic states, indicating some regional consistency in hydroclimate.

Holocene lake level reconstructions across the northern Rocky Mountains indicate significant variability over time (Shuman et al., 2009). At Foy Lake, north of Morrison, a 13,000-year record of diatom reconstruction and authigenic carbonate shows low lake level at 12,000 yrs. BP and 6,000 to 3,000 yrs. BP (Shuman et al., 2009). From 12,000 to 6,000 yrs BP, Foy lake levels gradually increase with the highest lake levels of the record starting at 3,000 yrs. BP to modern (Shuman et al., 2009). Morrison Lake does not seem to record these variations based on our interpretation that Morrison was significantly drier between 10,000 and 6,000 cal yrs. BP.

Pollen and wildfire reconstructions from Crevice Lake and Blacktail Pond in the northern Yellowstone area indicate drier conditions developed between 6,000 and 4,000 yrs. BP, a result of warmer winter conditions and drier summer conditions (Whitlock et al., 2012). This contrasts with our interpretation of a wetter climate during this time period at Morrison Lake.

1.6 Conclusion

Morrison Lake provides a complex record of lake response to Late glacial and Holocene environmental variability. Stable isotopic analysis of lake sediments indicates three distinct sediment regimes resulting primarily from changes in effective precipitation, and associated feedbacks with sediment delivery and lake stratification. The late deglacial and early Holocene was likely drier compared to the modern. Preservation of primarily detrital carbonate and lack of authigenic carbonate indicates a reduction in inputs of carbon and calcium. The mid-Holocene at Morrison was likely extremely dry. Lack of preservation of carbonate minerals is likely a result of a reduction in the pH of the lake water. Nitrogen limitation and the preservation of significant organic matter indicates stratified and anoxic bottom waters. Late Holocene sediments indicate a significant increase in annual precipitation. The climate surrounding Morrison Lake, an arid region at high elevation, allows it to act as a unique climatic proxy for reconstructions of climate in the northern Rocky Mountains throughout the Holocene.

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1.8 Tables and Figures

1.8.1 Tables

Sample ID	Depth (cm)	Age (yrs. BP)	Error (yrs.)	Calibrated Age (yrs. BP)	2σ age range (yrs.)	Sample Composition
ISU_14C 2019 Morrison1	34	740	110	679	517-879	leaf material and charcoal
ISU_14C 2019 Morrison4	66	1385	30	1309	1213-1400	charcoal
ISU_14C 2018 Morrison1	99.5	2270	70	2258	2048-2482	pine needle
ISU_14C 2018 Morrison6	121	2750	30	2840	2722-2980	charcoal
ISU_14C 2019 Morrison5	181	5000	60	5720	5461-5927	leaf material and charcoal
ISU_14C 2019 Morrison6	216	6410	70	7320	7053-7553	charcoal
Mazama tephra	219	7585	40	7512	7393-7630	3 cm thick
ISU_14C 2019 Morrison8	310	10130	30	11710	11337-12026	woody material and charcoal
Glacier Peak tephra	386	13560	150	13847	13408-14502	2.5 cm thick

Table 1.1 Radiocarbon and tephra chronology data (Kuehn et al., 2009; Steinman et al., 2019). Dates calibrated utilizing Bacon v2.3.5 (Blaauw and Christen, 2013).

SNOTEL site	Latitude	Longitude	Elevation (m)	Years of Operation
Beagle Springs	44.4667	112.9833	2697.5	1979-2018
Clover Meadow	45.0167	111.8500	2621.3	1979-2017
Darkhorse Lake	45.1667	113.5833	2726.4	1981-2018
Evening Star	44.6500	109.7833	2804.2	1981-2018
Lakeview Ridge	44.5833	111.8167	2255.5	1979-2018
Meadow Lake	44.4333	113.3167	2788.9	1982-2018
Saddle Mountain	45.7000	113.9667	2420.1	1979-2018

Table 1.2. Data table containing information about SNOTEL sites utilized in regional temperature and precipitation reconstruction of the Morrison Lake area.

1.8.2 Figures

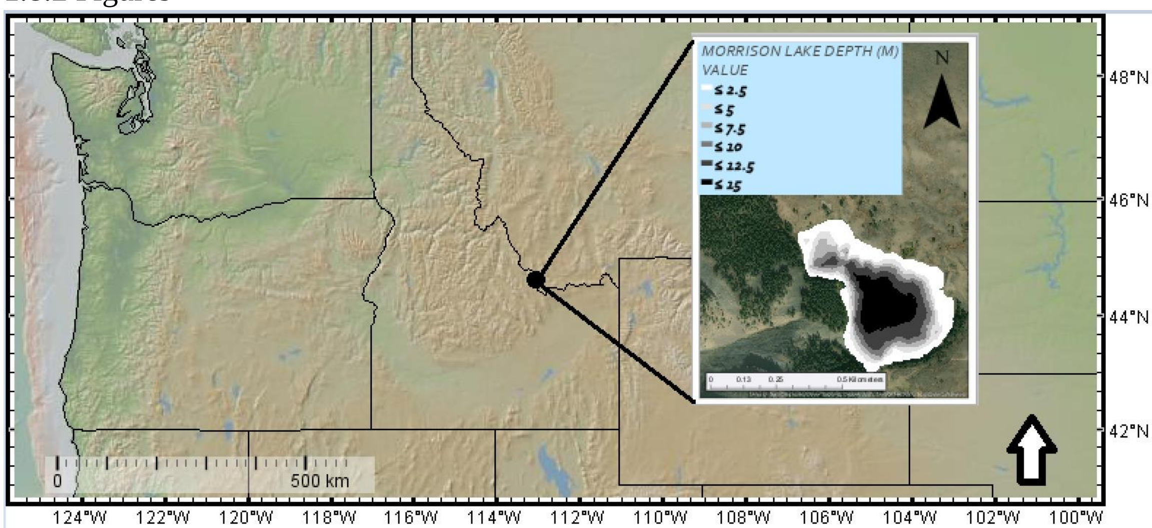

Figure 1.1. Location map of Morrison Lake, Montana.

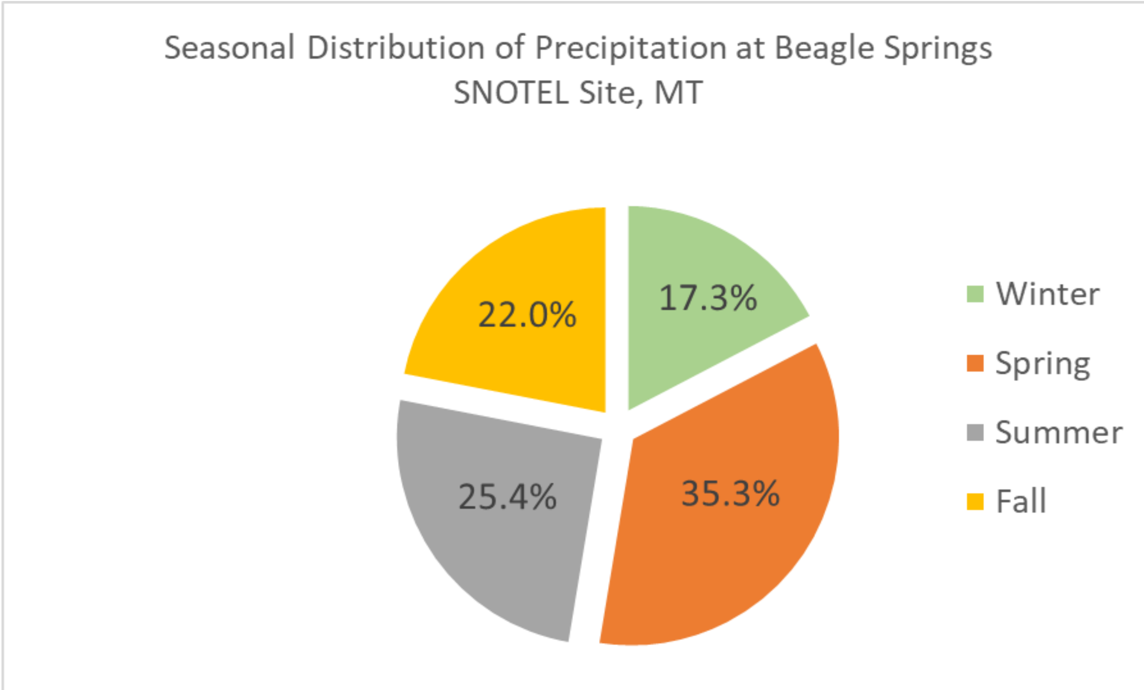

Figure 1.2. Mean seasonal distribution of precipitation at Beagle Springs SNOTEL site Montana during winter (Dec, Jan, Feb), spring (Mar, Apr, May), summer (Jun, Jul, Aug), and fall (Sept, Oct, Nov) from 1979 to 2018.

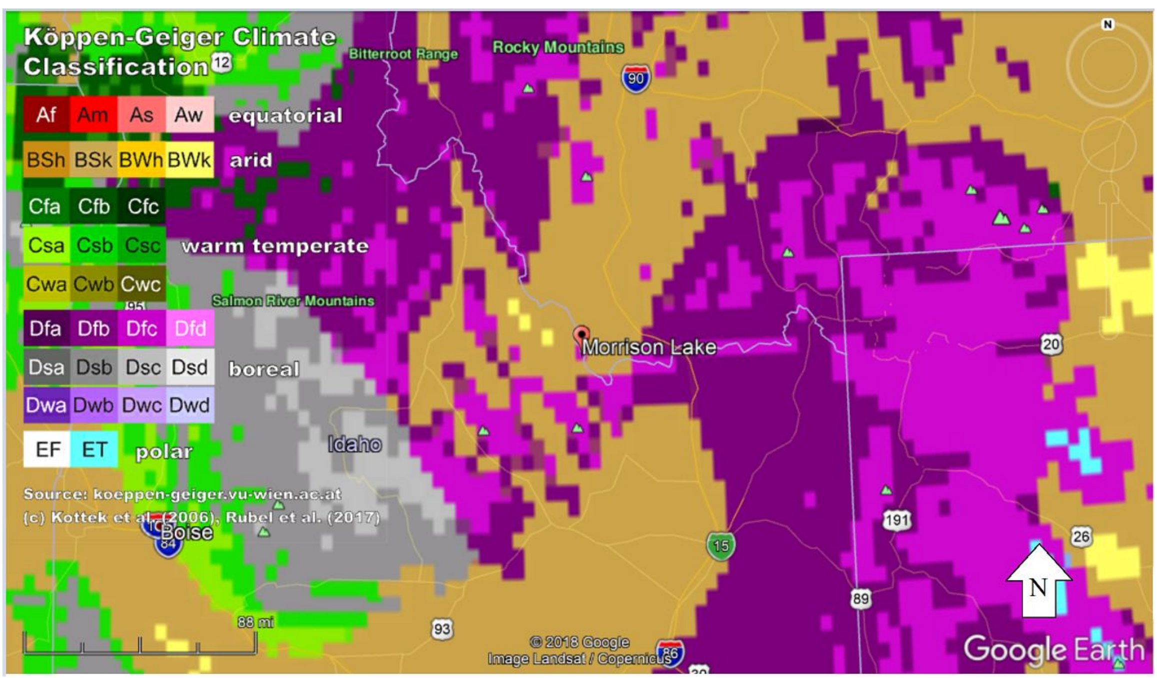

Figure 1.3. Köppen-Geiger climate classification of the Morrison Lake area after (Kottek et al., 2006; Rubel et al., 2017).

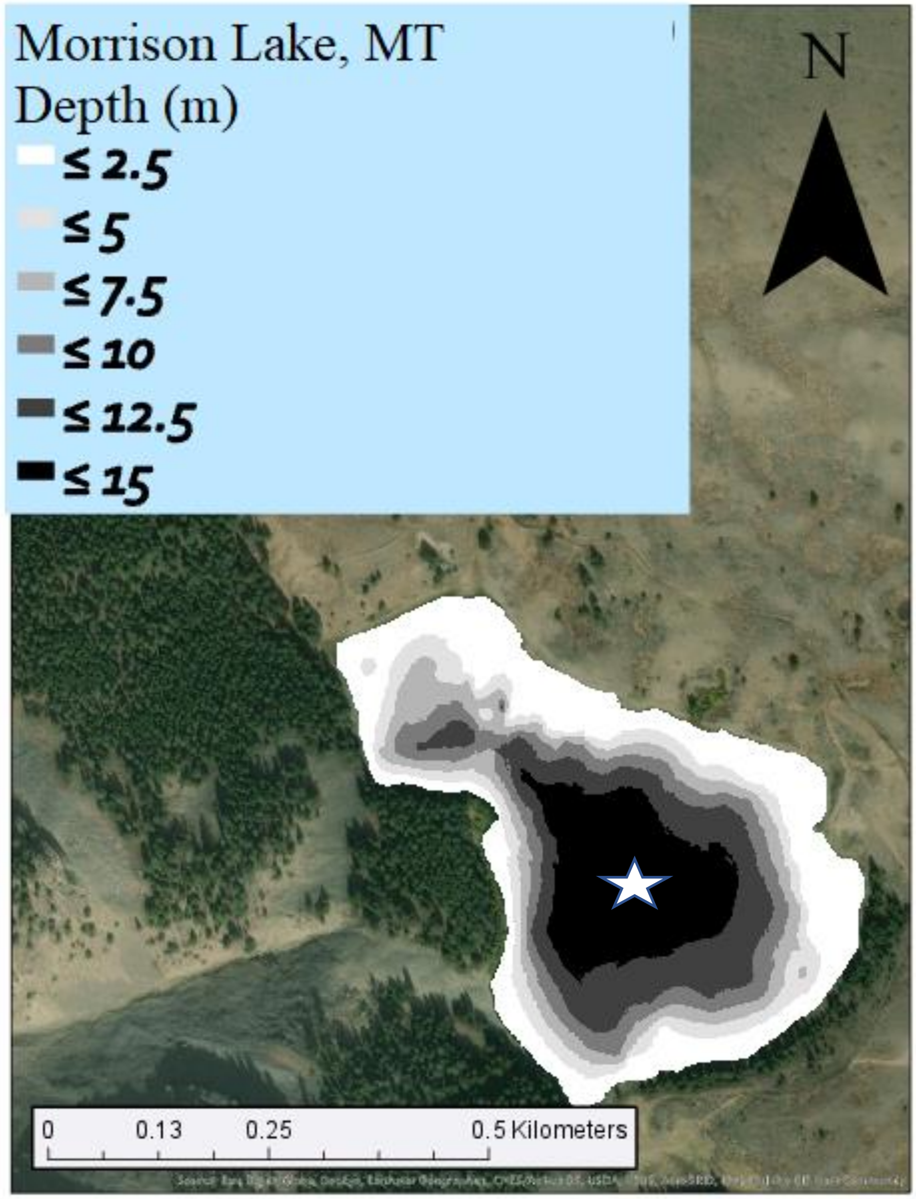

Figure 1.4. Bathymetric map of Morrison Lake, MT. Star indicates location of 2018 coring (nearly identical location of 1996 coring). Interpolation of collected depth data points conducted with the kriging function of ArcGIS Pro software.

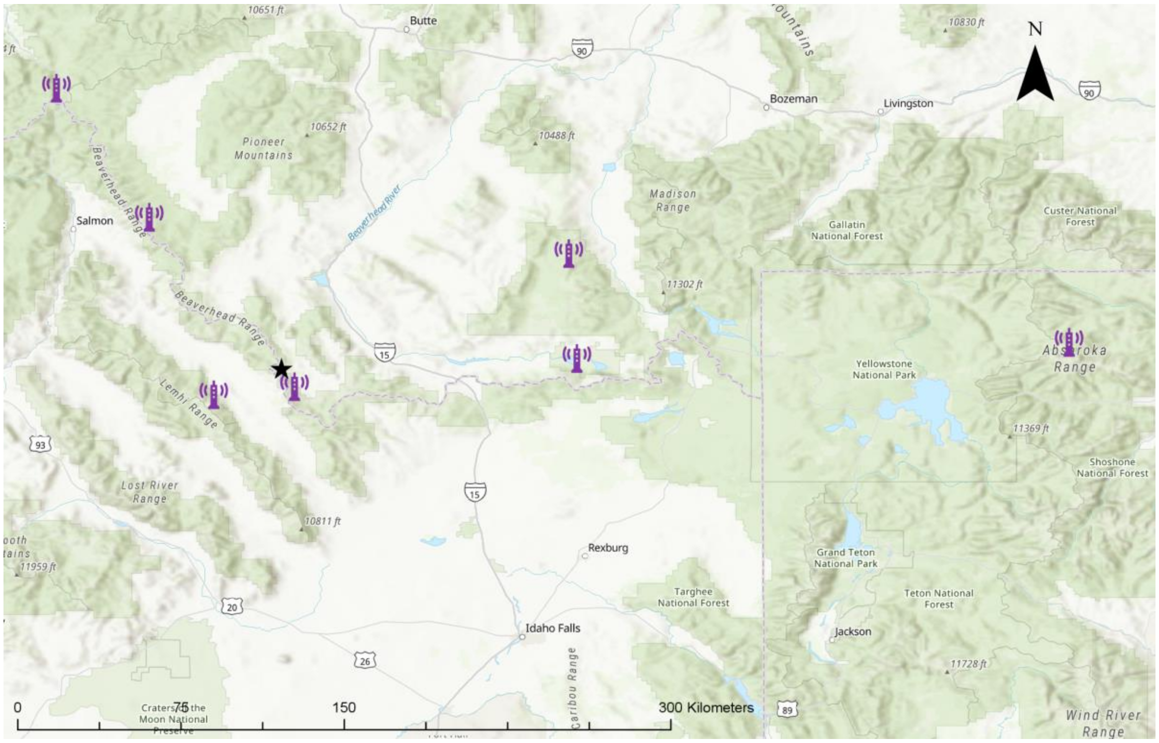

Figure 1.5. Map of SNOTEL sites utilized in regional reconstruction of precipitation and temperature at elevations between 2255-2804 m. Antenna symbols represent SNOTEL site locations and the black star represents Morrison Lake.

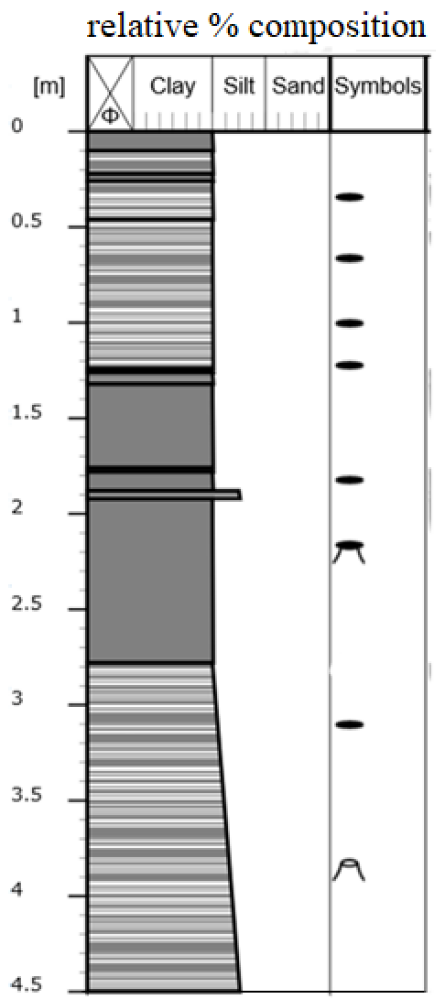

Figure 1.6. Sediment characteristics and locations of radiocarbon dates (black circles) and tephra deposits (volcano symbol). Thinly laminated carbonate and clay-rich sediments with organic-matter and minor silt and sand are represented by the thin lines. Massive clay and organic-rich sediment with minor carbonate, silt and sand are represented by the grayed-out areas. The width of the stratigraphic column represents the relative composition of the sediment with increasing amounts of silt and sand occurring in the lowermost portion of the core and primarily clay occurring in the uppermost position.

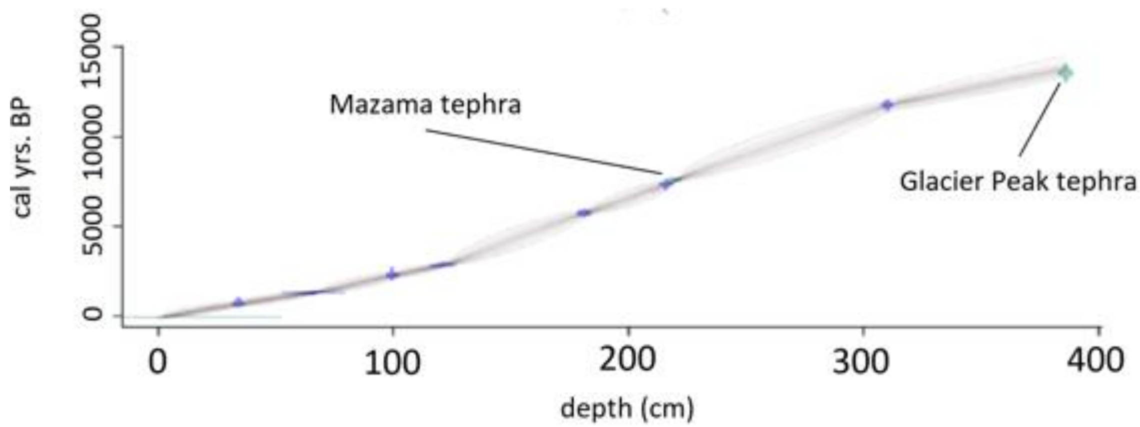

Figure 1.7. Calibrated depth-age relationship for Morrison Lake, MT. Dark blue symbols indicates radiocarbon samples and light blue symbols is the location of tephras used in the age model.

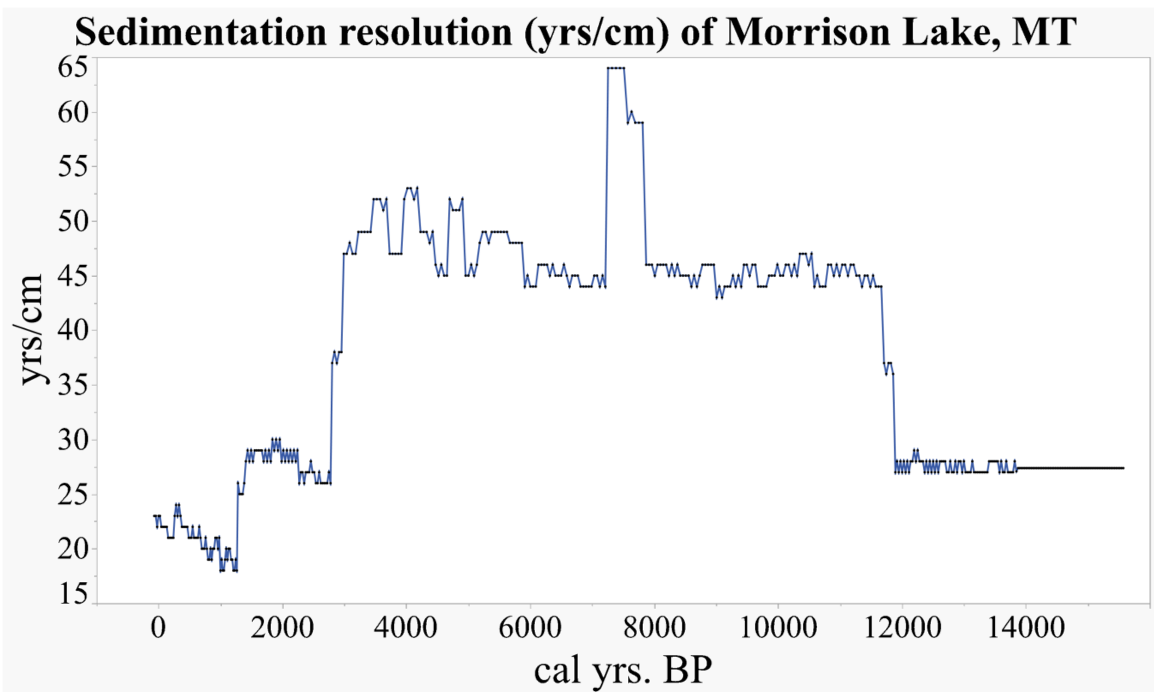

Figure 1.8. Temporal resolution of 1 cm sediment samples from Morrison Lake, MT. Results indicate that sedimentation rates increased in both the earlier and most recent portion of the core. The lowest sedimentation rates occurred during the middle Holocene, when the sediment was primarily composed of organic-matter.

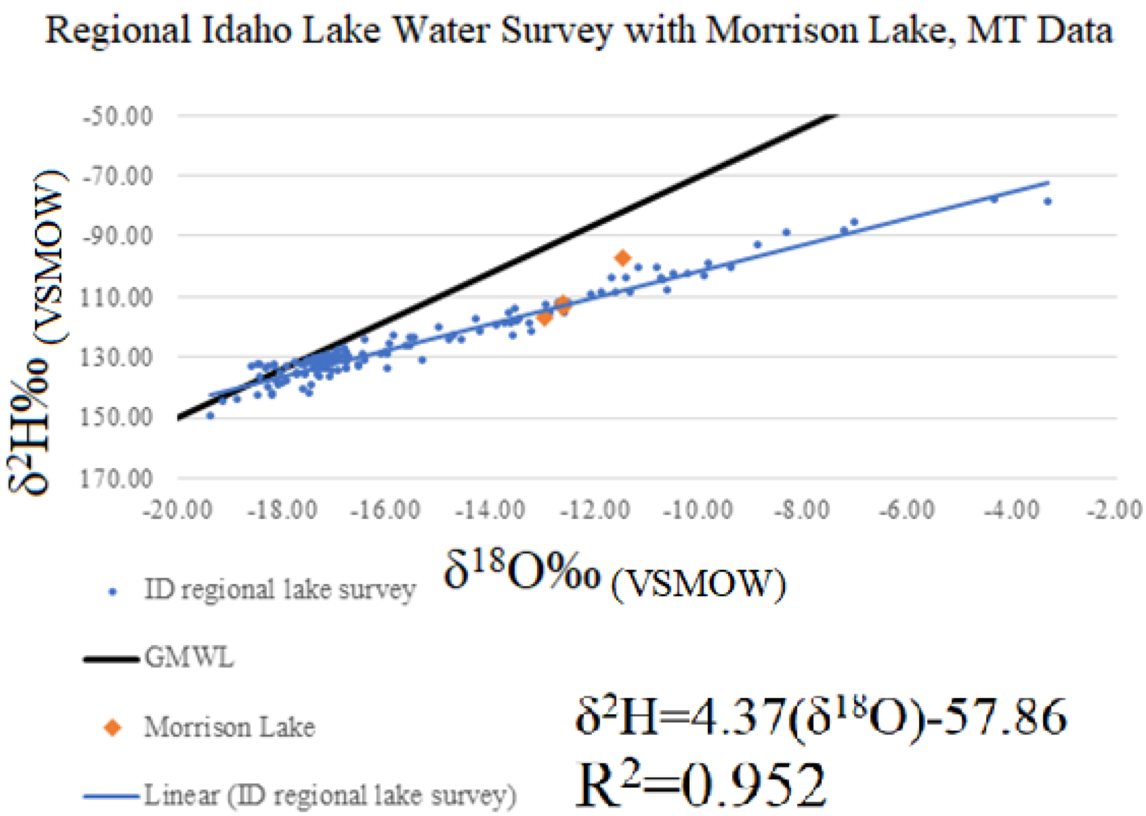

Figure 1.9. Regional lake water isotopic values from Idaho with lake water data from Morrison Lake, MT, compared to the global meteoric water line (GMWL). The blue line is the regional evaporation line for surface water across Idaho and western Montana. The orange diamonds are surface water samples from Morrison Lake and indicate that the lake is subjected to similar evaporative effects as other regional lakes.

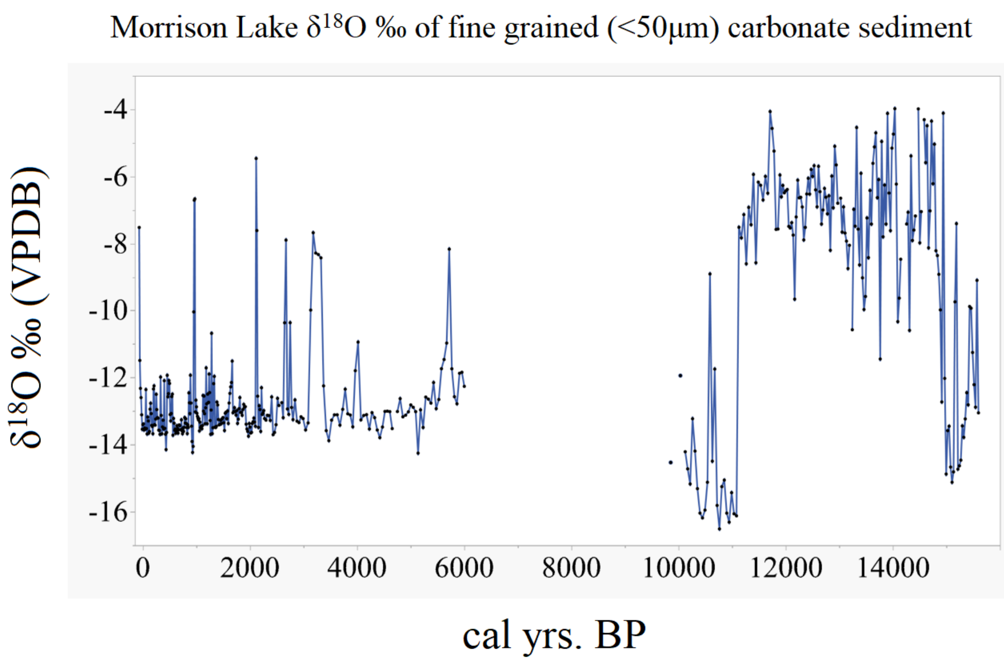

Figure 1.10. $\delta^{18}O$ of fine grain (<50 μm) carbonate sediment from 15,600 to (-68) cal yrs. BP at Morrison Lake, MT. Gaps indicate zones that do not contain carbonate.

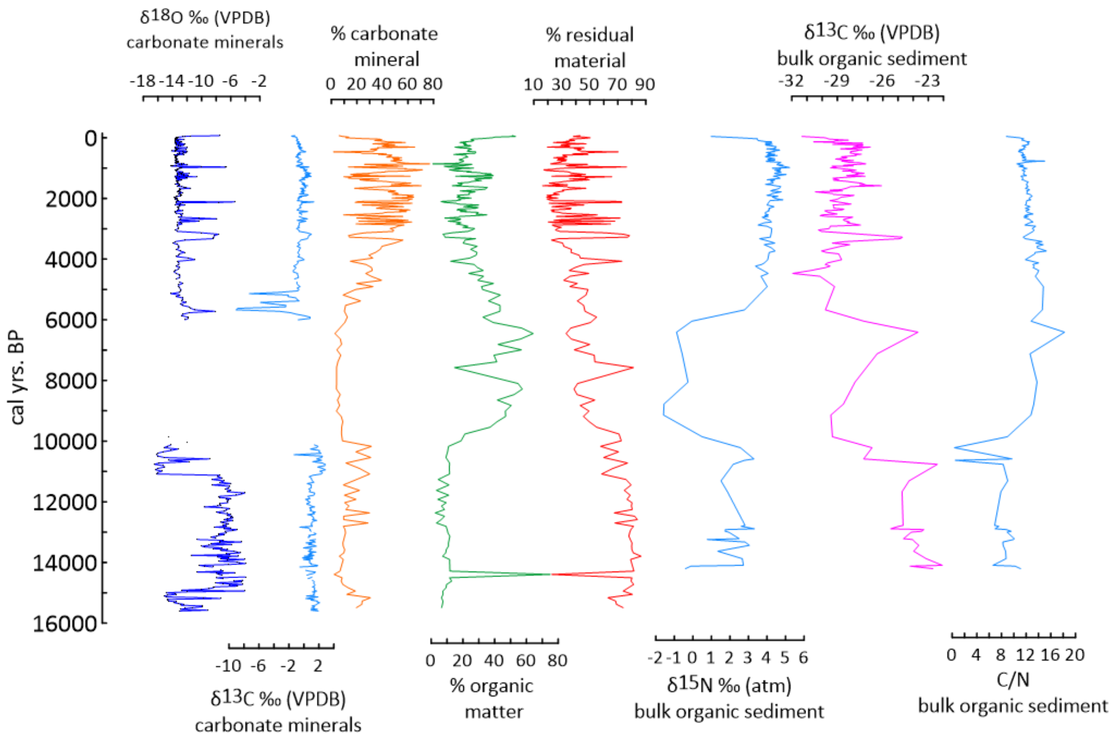

Figure 1.11. Multiproxy results from Morrison Lake, MT. Data suggests that Morrison Lake transitions from primarily high $\delta^{18}O$ in the late Pleistocene to early Holocene (15,800-10,000 cal yrs. BP), to a lack of carbonate preservation in the middle Holocene (10,000-6,000 cal yrs. BP), and then finally to consistently lower $\delta^{18}O$ in the late Holocene (6,000 cal yrs. BP to present). $\delta^{15}N$ value show significant change during the middle Holocene where values drop to near atmospheric, indicating nitrogen fixation occurred within the lake as the dominate nitrogen source.

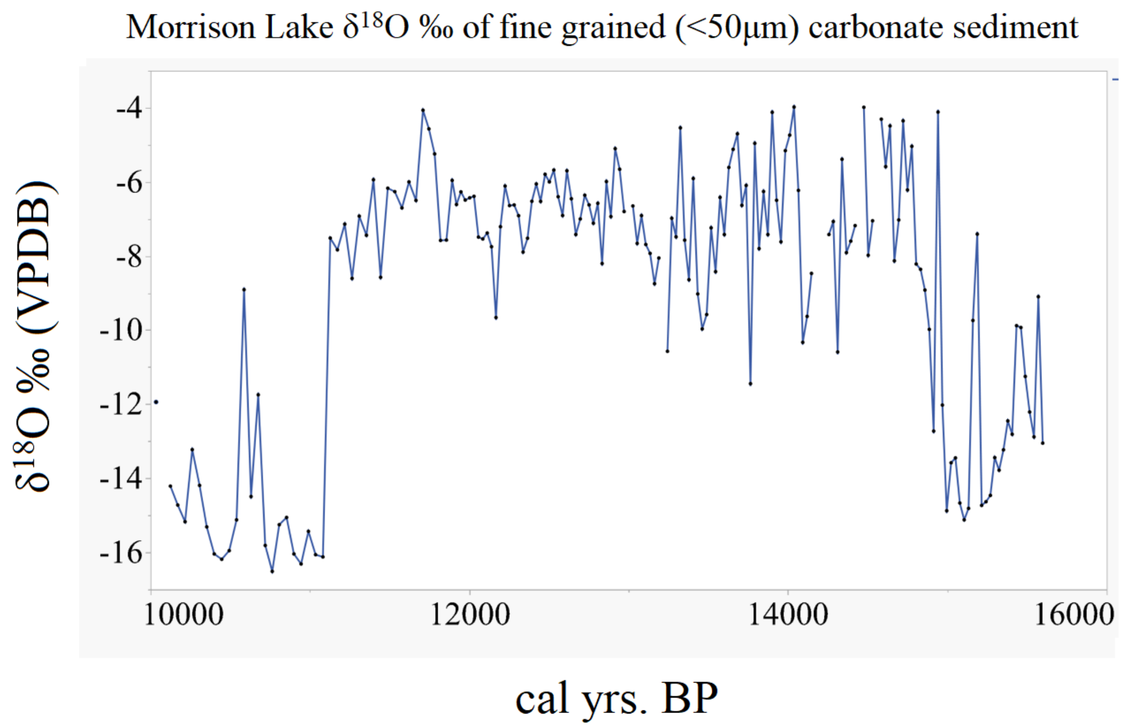

Figure 1.12. $\delta^{18}O$ of fine grain (<50 µm) carbonate sediment for the period from 15,600 to 10,000 cal yrs. BP at Morrison Lake, MT. Gaps indicate samples that contained no carbonate.

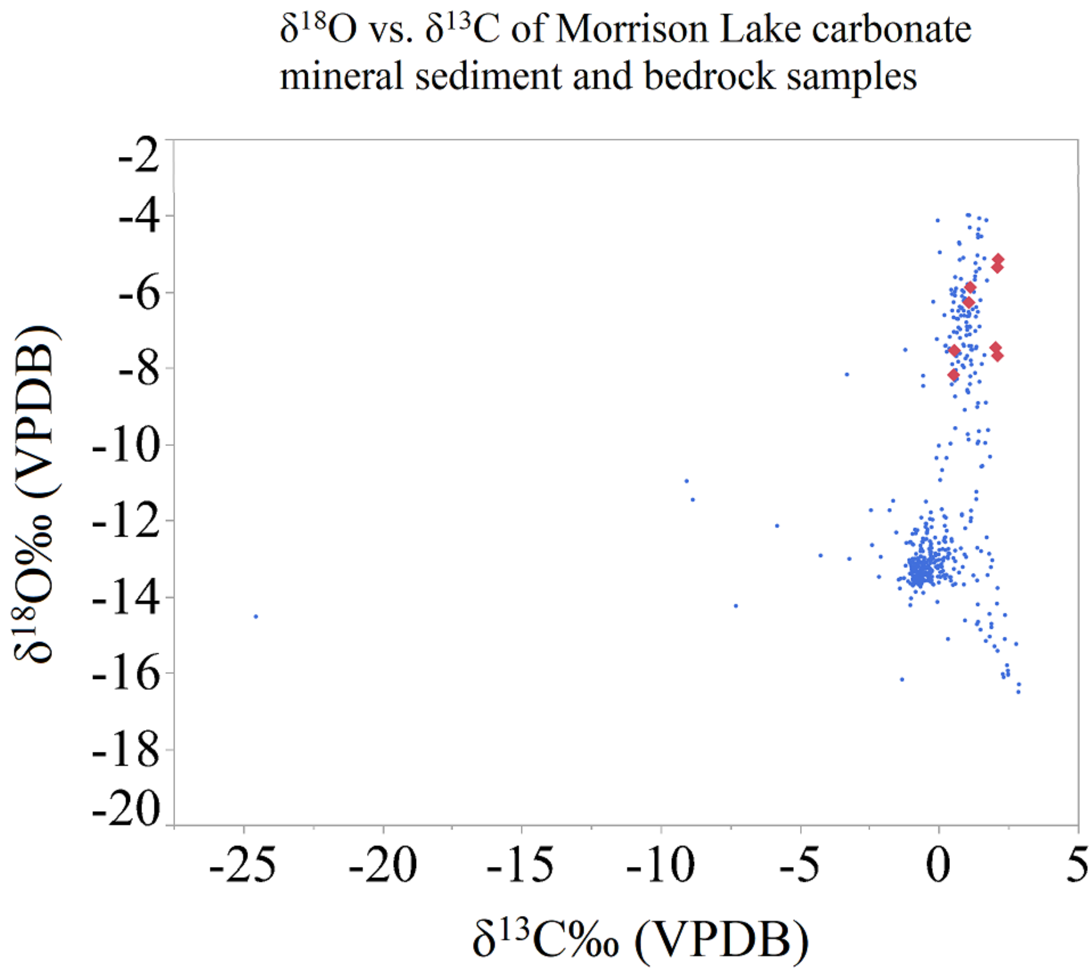

Figure 1.13. $\delta^{18}O$ vs $\delta^{13}C$ of fine grain (<50 μm) carbonate mineral fraction (blue dots) compared to watershed bedrock samples (red diamonds) at Morrison Lake, MT from 15,600-10,000 cal yrs. BP.

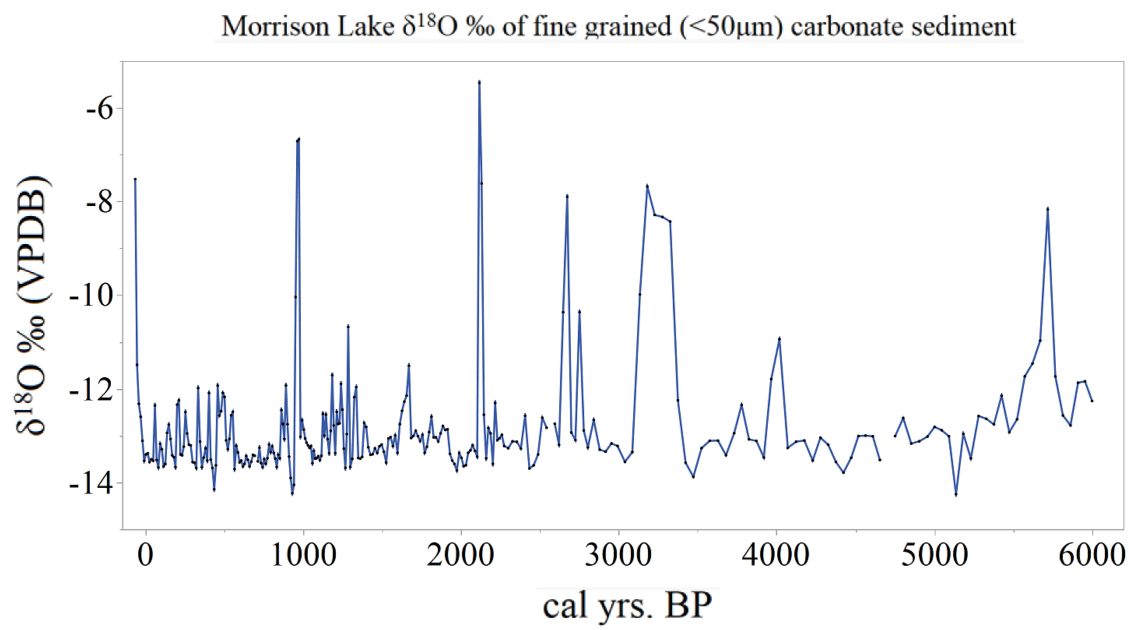

Figure 1.14. $\delta^{18}O$ of fine grain (<50 µm) carbonate sediment from 6,000 to (-68) cal yrs. BP at Morrison Lake, MT. Gaps indicate samples that contained no carbonate. Consistently negative $\delta^{18}O$ indicate that precipitation rates were higher relative to evaporation during this period. The record is punctuated by several event deposits that are fining-upward sequences of primarily detrital material.

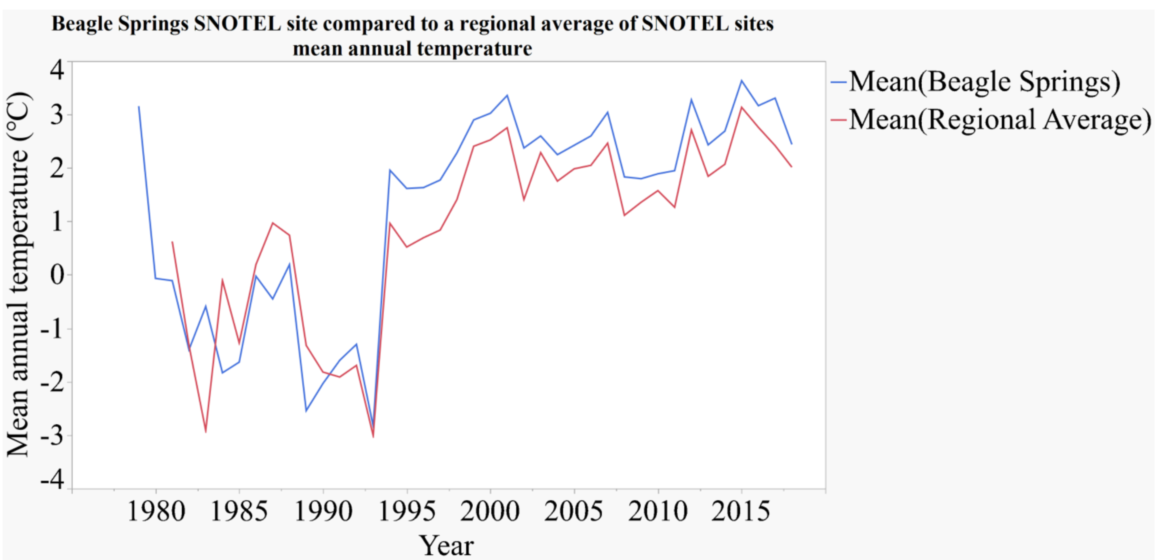

Figure 1.15. Mean annual temperatures of Beagle Springs SNOTEL site and regional average for other high elevation SNOTEL sites.

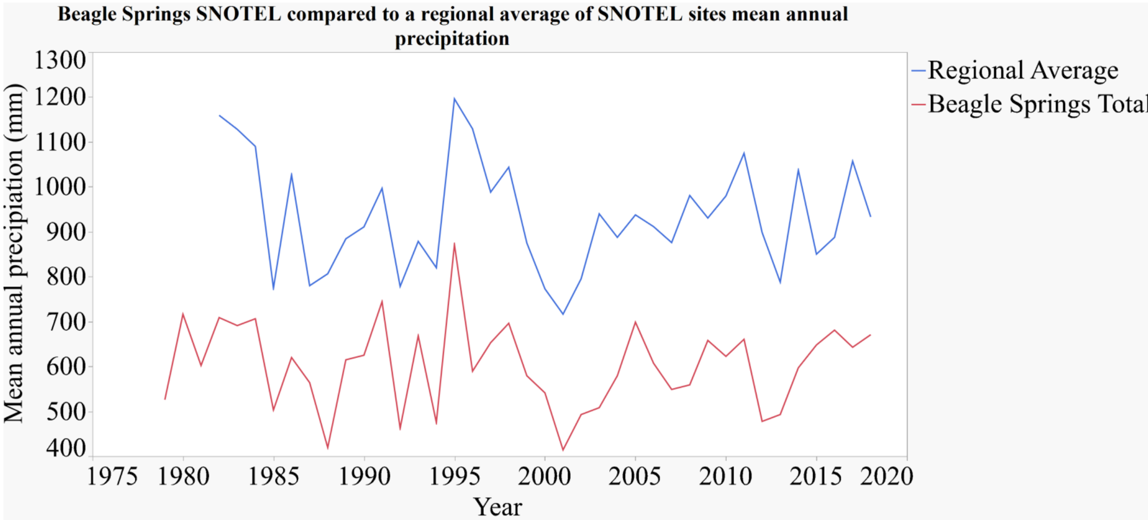

Figure 1.16. Mean annual precipitation of Beagle Springs SNOTEL site and regional average for other high elevation SNOTEL sites.

Chapter 2: A 2,300-year record hydroclimate frequency from Morrison Lake, MT, northern Rocky Mountains, USA

2.1 Abstract

The past 2,000 cal yrs. BP are a time when modern atmospheric circulation and hydroclimatic dynamics appear to have been largely in place, therefore analysis of climatically sensitive proxies during this period allows for better understanding of modern climatic trends. The southern Beaverhead Mountains of western Montana, a range of the northern Rocky Mountains, are more arid than ranges to the north and south, and therefore sensitive to past changes in the balance between precipitation and evaporation. Morrison Lake, presently a topographically closed lake, is characterized by high rates of carbonate mineral sedimentation. Variations in the $\delta^{18}O$ of the fine grained (<50µm) carbonate mineral fraction show variability in precipitation to evaporation ratio (P/E). High-resolution sampling (0.5 cm; ~12-year/sample) was conducted on the upper meter of sediment to characterize multidecadal variability in hydroclimate in the northern Rocky Mountains. $\delta^{18}O$ values are consistent through this period (average of 12.9‰) but show multicentennial variability through global climatic events such as the Little Ice Age and Medieval Climate Anomaly. Spectral analysis of $\delta^{18}O$ values indicate significant hydroclimate periodicities of 25, 40, 52, 55, and 78 years. These intervals are likely attributed to changes in atmospheric circulation patterns, such as the Pacific Decadal Oscillation (PDO) (25 years) and the Atlantic Multidecadal Oscillation (AMO) (50-80 years).

2.2 Introduction

The modern climatic state in the northern Rocky Mountains is thought to have initiated by 4,000 yrs. BP and contains periodic shifts and multicentennial periods such as the Medieval Warming Period (MWP; 1000-650 yrs. BP) and Little Ice Age (LIA; 700-100 yrs. BP) (Hadley 1995; Barron and Anderson, 2010). Drivers of previous climate states are poorly understood and were likely very different than modern systems (Anderson, 2012). Characterization of the mechanisms behind modern climatic variability is important for understanding the pre-anthropogenic climate drivers and necessary to assess modern and future climatic states. Expression of ENSO (El Niño Southern Oscillation; 2-5-year periodicity) and the PDO (Pacific Decadal Oscillation; 20-30-year periodicity) became enhanced from 4,000 yrs. BP to the modern, having strong effects on hydroclimate dynamics in the western US (Barron and Anderson, 2010). Insolation shifts occur across this time frame as well, with mean summer insolation decreasing to the lowest level in the Holocene and mean winter insolation increasing to its highest level (Barron and Anderson, 2010). Paleoclimatic proxies from across the northern Rockies show increased hydrologic balance, punctuated by prominent multidecadal drought events, relative to the drier middle and early Holocene (Shapley et al., 2009; Shuman et al., 2009).

Research suggests that the intensity and expression of the Aleutian Low (AL), which historically is well-explained by the Pacific Decadal Oscillation (PDO) (an alternating pattern of states of sea surface temperature in the northern Pacific) influences the directionality of storm tracks along western North America (Yu and Zwiers, 2007). This plays a major role in the mitigation or amplification of anthropogenic warming

(Siler et al., 2018). Natural shifts in these systems, particularly the PDO, combined with anthropogenic warming are expected to impact the northern Rocky Mountains by reducing total snowpack by up to 60% by 2050 (Siler et al., 2018). By examining hydroclimate records spanning from southern Alaska to southern Colorado, Anderson et al (2016), recognized the need for additional high-resolution records to better explain hydroclimate patterns. Understanding variability in hydroclimatic change is vital in determining the possible mechanisms that drive modern snowpack variability critical to the ecology and economy of the western United States.

Carbonate-producing lakes can provide a valuable source of information about hydroclimate dynamics over long periods of time (McKenzie and Hollander, 1993; Anderson et al., 2016). Morrison Lake, MT preserves a sediment record that extends to at least 15,600 yrs. BP. This paper focuses on the past ~2,300 years, where authigenic carbonates are a primary component of the sediment and deposited at a rapid rate, resulting in a high-resolution record.

Stable isotope analysis of authigenic carbonate sediments in a hydrologically sensitive lake such as Morrison can provide information about precipitation to evaporation ratios (P/E) (Talbot, 1990; McKenzie and Hollander, 1993; Anderson et al., 2016). Authigenic carbonate minerals that form in isotopic equilibrium with the lake water record how the stable oxygen isotopic composition ($\delta^{18}O$) of the lake water shifted over time (Talbot, 1990; McKenzie and Hollander, 1993). Because evaporation results in a loss of the lighter isotope (^{16}O) relative to the heavier isotope (^{18}O), higher values for $\delta^{18}O$ of carbonates ($\delta^{18}O_C$) are interpreted to represent periods of lower P/E ratios (Anderson et al., 2016).

Additional paleoclimatic and paleoecological proxies, such as the carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) stable isotope composition of organic matter, and organic matter and carbonate mineral content, provide a source of complimentary evidence about nutrient and sediment dynamics that are impacted by shifts in climate state. Previous research conducted on Morrison Lake is limited to a single study (Bracht-Flyr and Fritz, 2012) that focused on diatom assemblage variation over the past ~2,300 years. The study presented here has the goal of expanding on previous interpretations to further understand mechanisms that influence hydroclimate variability in the northern Rocky Mountains and how arid high elevation regions respond to global climatic events.

2.3 Study site and regional setting

Morrison Lake (44.601843 N, -113.036895 W) is located in the southern Beaverhead Mountains of southwestern Montana, a chain of the northern Rocky Mountains of the United States (Figure 2.1). The lake is located in a high elevation (2,490 m) and topographically closed basin (at present lake stage) of Paleozoic limestone. Production of carbonate sediment is extremely high, evident in both sediment analysis of cores from the deep basin (~14 m) and cores from the shallow (2-4-meter-deep) sedimentary bench along the northern, eastern, and southern margins of the lake.

The Morrison Lake area of the southern Beaverheads receives a majority of its mean annual precipitation during Spring (March, April, May) as both rain and snowfall (35.3%). The northern Rocky Mountains to the north and south of Morrison Lake and the Yellowstone Area are classified according to the Köppen-Geiger climate classification as moist mid latitudinal climates (Figure 2.2) (Kottek et al., 2006; Rubel et al., 2017). Morrison Lake is in a narrow region classified as a dry semi-arid climate, even at high elevations (above 2,500 m) (Kottek et al., 2006; Rubel et al., 2017). The local region, although due to different mechanisms, is similar climatically to the lower elevation (1,500 m and below) Snake River Plain of southeastern Idaho (Kottek et al., 2006; Rubel et al., 2017). This climatic variation makes Morrison Lake an important place to reconstruct past climate as it is located in an underrepresented climatic regime of the Rocky Mountains. Hydroclimatic mechanisms that result in reduced snowpack in the southern Beaverheads, relative to areas to the north and south, are unclear. It is likely that orographic effects play a major role. The presence of a series of northwest-trending mountain ranges across central Idaho likely affect the volume of precipitation reaching the Morrison Lake area. This may be caused by both diversion of storm tracks to the north or south, or orographic effects resulting in local rain shadows.

2.4 Methods

2.4.1 Field work

Multiple visits to Morrison Lake were made from fall 2017 to summer 2018 to collect basin characterizing samples including water, soil, vegetation, and bedrock. Primary field work and surface core collection was conducted during late July 2018. Bathometric data was collected using the ArcGIS collector app on a GPS enabled Samsung tablet and a Hummingbird Fishin' Buddy Max attached to an inflatable kayak. Water depth data was utilized in the field to target the deepest section of the lake for collecting undisturbed sediment.

2.4.2 Core collection

A 1.5-meter surface sediment core was collected from the basinal area (14 meters of water depth) of Morrison Lake in summer 2018 (Figure 2.3) utilizing a Bolivia coring device (Myrbo and Wright, 2008). The core included 30 cm of water over a well-preserved sediment water interface. Zorbitrol was used to prevent sediment disturbance during transit (Tomkins et al., 2008).

2.4.3 Core description / sampling

The core was passed through a Bartington MS2 with a MS2C ring sensor to collect magnetic susceptibility data at 1 cm intervals. The sediment core was then split, photographed, and described (Figure 2.4). Sediment was sampled at an interval of 0.5 cm over the upper meter. This sampling was conducted to capture a high-resolution (multidecadal scale) record for the past 2,000 yrs., as estimated from previous dating of material from nearby cores (Bracht-Flyr and Fritz, 2012). Water content and wet and dry bulk-density was determined from continuous volumetric samples every 1 cm over the upper 1.3 meters, that were freeze dried to remove water.

Loss on ignition (LOI) analysis was conducted at 2 cm intervals on the 0.5 cm samples. Values for percent organic matter and carbonate mineral content were calculated based on mass loss between heating at 100 °C, 500 °C and 1,000 °C using standard methods (Dean, 1974). The mass of the remaining residual material represents remaining material, which is dominated by silicate minerals and diatoms.

X-ray diffraction (XRD) analysis was conducted on selected samples with different $\delta^{18}O_C$ values to understand the mineralogy of the sediments and assess the extent that variations in the $\delta^{18}O_C$ values may be attributed to detrital materials. XRD was conducted utilizing a Bruker Discovery D8 with scans ranging from 0-60 degrees, 4200 steps, and 1 step per second.

2.4.4 Isotopic analysis methods

Carbonate mineral isolation was conducted by soaking sediment in 2.5% NaClO for 10-12 hours to oxidize organic material. Sediment was rinsed with 12.5 mL of high-purity DI water and centrifuged at 2,500 rpm for 10 minutes five times to remove any remaining NaClO. A 50 µm nylon sieve was used to remove coarse grained material. Samples were frozen and freeze dried for 36 hours to ensure complete removal of water. Analysis was conducted using a Finnigan GasBench II front end connected to a Delta V advantage mass spectrometer through the ConFlo IV system. Sample masses were adjusted based on percent carbonate mineral fraction. Carbonate isotopic values are reported relative to VPDB with precision of ±0.2‰ for both $\delta^{18}O$ and $\delta^{13}C$.

Bedrock samples were collected from the area surrounding the lake. Samples represented each of the major contributing bedrock types in the watershed above the lake as well as the limestone that immediately surrounds the lake. Rocks were crushed and analyzed utilizing the same method as sediment carbonate samples.

Sediment (bulk organic fraction), soils, and plants were analyzed for carbon and nitrogen stable isotopes. 12.5 mL of 1 molar HCl was added to each of the subsamples to remove carbonate minerals. Vials were allowed to react for 30 minutes before being placed on a shaker tray for 6-8 hours. Samples were rinsed with 12.5 mL of high purity DI water and centrifuged at 2,500 rpm for 10 minutes five times to ensure removal of all remaining HCl. Samples were then frozen and freeze dried for 36 hours. Analysis was conducted utilizing a Costech ECS 4010 elemental analyzer connected to a Thermo Delta V Advantage continuous flow isotope ratio mass spectrometer (IRMS). Bulk organic sediment isotopic values are reported relative to VPDB with precision of ±0.2‰ for $\delta^{13}C$, relative to atmosphere for $\delta^{15}N$, and ±0.5% for %N and %C.

Stable isotopic data of lake water and shallow ground water was collected from previous exploratory research. These were run for δD and $\delta^{18}O$ using a TC-EA coupled to the Thermo Delta V Advantage continuous flow isotope ratio mass spectrometer and are reported relative to VSMOW with precision of ±0.2‰.

2.4.5 Chronology

Sediment ages were acquired through radiocarbon analysis of visually identified terrestrial organic material at Lawrence Livermore National Laboratory (Table 1). Sediment was prepared for radiocarbon analysis by wet sieving with coupled 250 and 125 μm metal sieves. Terrestrial organic material was identified using a light microscope and placed into ashed vials with 3 drops of a 1% HCl solution. Calibration of radiocarbon dates and a sediment age model were calculated with Bacon software in R (Figure 2.5) (Blaauw and Christén, 2013).

2.4.6 Spectral Analysis

REDFIT software was utilized to understand statistically significant periodicity in the isotopic data (Schulz and Mudelsee, 2002). REDFIT software was chosen for this analysis because of its ability to calculate how different time scales contribute to the variance in time series data, even when those samples are unevenly spaced (Schulz and Mudelsee, 2002). Some methods of spectral analysis rely on either evenly spaced data sets or interpolation of data between unevenly spaced points (Schulz and Mudelsee, 2002). Interpolation in particular can interfere with analysis of underlying frequencies in the data as it adds false data points and noise frequencies (Schulz and Mudelsee, 2002). Output values utilized to plot the spectral data include frequencies, G_{xx}_corr (the power or amplitude of different frequencies in the data set corrected for uneven time series), Gred_th (background signal of the data), and the 95% and 99% chi^2 confidence intervals (Tiwari et al., 2006). Based on the mean time interval represented by each sample (12 yrs.), the Nyquist frequency ($f_N = \frac{2}{\Delta t}$) is calculated to be 0.17 or 5.9 years (Ghil, et al., 2001). Assumptions of the REDFIT software include stationarity in the data, that the first-order autoregressive function (AR1) utilized to identify the noise or "redness" of the data can properly identify this noise, and that there is not significant data clustering (Schulz and Mudelsee, 2002).

2.5 Results

Sediments deposited at Morrison Lake over the past 2,300 cal yrs. BP are generally thinly laminated (sub cm to mm) carbonate minerals with organic material, clays and minor amount of silt and sand. Periodic massive (0.5-2 cm) organic-rich layers occur. Carbonate minerals compose a large portion of the sediment during this time period (mean=41%) with a nearly equal portion of residual material (mean=35%) and smaller average contribution from organic material (mean=23%) (Figure 2.6). Residual material is composed of a combination of both silicate minerals, clays, and diatoms. Sedimentation rate was calculated to average 0.44 mm/year, which equated to an average sample resolution of 12 years per 0.5 cm sampling interval.

Isotopic analysis of the carbonate mineral fraction of the sediment shows a mean value of -12.9‰ for $\delta^{18}O_C$ and -0.3‰ for $\delta^{13}C$ of carbonate sediment ($\delta^{13}C_C$). Variability in $\delta^{18}O_C$ values during this period show varying amplitudes. Sections where amplitude between individual samples is at least 0.5‰ occurs between 2,300-2,150, 1,416-1,070, 922-834, and 553-9 cal yrs. BP. Sections where there is very little amplitude and no large shifts over 0.5‰ occur between 2,086-1,944, 1,599-1,430, 1,071-986, and 834-574 cal yrs. BP.

XRD, magnetic susceptibility, dry bulk density, and LOI results indicate that the large shifts toward higher values (>4‰) in $\delta^{18}O$ of carbonate sediment ($\delta^{18}O_C$) during the past 2,300 cal yrs. BP represent increases in the amount of detrital material in the sediments (Figure 2.7). XRD results from samples that contained a high $\delta^{18}O_C$ value showed a peak characteristic of dolomite which used as an indicator for the presence of detrital material, due to the unlikelihood that dolomite was precipitating within the lake and the presence of dolomite in each of the bedrock samples. Magnetic susceptibility results indicate that high amplitude peaks in susceptibility occur during high amplitude peaks in $\delta^{18}O_C$, providing further evidence that these intervals are composed of high amounts of bedrock material. Dry bulk-density and composition of residual material increase during the period of abundant detrital material consistent with increased inputs of bedrock material. Observation of sediment structure during the high amplitude $\delta^{18}O_C$ excursions show thin (sub cm) fining upward sequences capped by fine-grained carbonate-rich material. An exception to this is the most modern sediment, where high amplitude $\delta^{18}O_C$ values correspond with a decrease in magnetic susceptibility instead of an increase. This sample shows an XRD peak characteristic of dolomite indicating a detrital composition. Increases in magnetic susceptibility and dry bulk density values do not track the high $\delta^{18}O_C$ values and are likely masked by high water content of the surface sediments. The upper most sediments do not show a fining upward sequence as other $\delta^{18}O_C$ excursions.

Spectral analysis of $\delta^{18}O_C$ at Morrison Lake yielded a variety of statistically significant frequencies (Figure 2.8). 25, 40, 52, 55- and 78-year periodicities were calculated to occur with a confidence interval of 95%.

The mean value for the bulk organic fraction of sediment $\delta^{13}C$ is -28.4‰, $\delta^{15}N$ is 4.3‰, and C/N ratio of the sediment is 11.8 (Figure 2.9). Terrestrial plants collected from the immediate area around the lake were found to have average $\delta^{13}C$ value of -27‰, $\delta^{15}N$ of 2.3‰, and C/N of 24. Aquatic plants collected from the shallow, carbonate sediment-rich margin of the lake have an average $\delta^{13}C$ value of -24‰, $\delta^{15}N$ of 3.9‰, and a C/N of 21. Soil samples collected from the immediate area around the lake have an average $\delta^{13}C$ value of -26‰, $\delta^{15}N$ of 3.7, and C/N of 9.8.

2.6 Discussion

2.6.1 Detrital influence

Identification of potential detrital influence on the composition of carbonate sediment is necessary in systems where such material is possible, for effective interpretation of $\delta^{18}O_C$ data. Morrison Lake is located in a watershed of limestone-rich bedrock and may receive detrital material during climatic states that increase sediment transport. Despite screening samples to analyze only the fine-grained carbonate sediments (<50μm), it appears that there is significant detrital material in several of the samples (Figure 2.10). These samples are those that are identified above as having $\delta^{18}O_C$

values that have high amplitudes (>4‰) above the previous sample. Additionally, XRD analysis of both bedrock and these detrital samples indicates that they contain dolomite. These detrital rich samples represent minor (sub cm) event deposits, as evident through the presence of a fining upward sequence (Figure 2.11). The origin of these event deposits is unclear, as they could be either turbidites or high runoff events. Periods of extremely high snowpack and runoff could result in large increases in sediment transport from the watershed, with grain size and density proportionate settling.

2.6.2 Authigenic $\delta^{18}O$ trends and spectral analysis

Authigenic $\delta^{18}O_C$ values indicate that hydroclimatic state has shifted throughout this record. Periods of high variability between data points (>0.5‰) and periods of low variability (<0.5‰) occur on multicentennial scales. Low variability is observed between 2,300-1,300 and 1,000-600 cal yrs. BP. Higher variability, occurring over multidecadal scales occurs throughout the remaining portion of the record.

Results from spectral analysis of the $\delta^{18}O_C$ data indicates that hydroclimatic regimes in the Morrison Lake region fluctuate on 25, 40, 52, 55 and 78-year time periods. Commonly attributed drivers of hydroclimate in the northern Rocky Mountains include the PDO and the El Nińo Southern Oscillation (ENSO) (Stevens et al., 2006). These patterns can reinforce each other when both are expressed in ways that promote or reduce intensity of storm tracks. The PDO is considered by some to have a periodicity of 20-30 years, though the instrumental record is too short to determine if the longer periods inferred from this are robust, and ENSO has a periodicity of 2-7 years (Kuss and Gurdak, 2014). Combined, they are hypothesized by some to fluctuate on scales of 5 and 15 years (Caňón et al., 2007). It is important to note that many reconstructions of the PDO do not agree and therefore there are multiple interpretations on the periodicity of the PDO during pre-instrumental times. Morrison Lake is shown to record a frequency that fits with hypothesized variability in the PDO (25 year) (Kuss and Gurdak, 2014). A 50-80 year periodicity, known as the Atlantic Multidecadal Oscillation (AMO), is recognized in many paleoclimatic records, but its cause is unclear (Mazzarella, 2012; Scafetta, 2012; Kuss and Gurdak, 2014). It is hypothesized that gravitational forcing on the sun's magnetic field by the orbits of Jupiter and Saturn cause shifts in solar energy on ~60-year time scales (Mazzarella, 2012; Scafetta, 2012). These shifts in solar energy may result in differences in ocean-atmosphere energy balance and cause variability in hydroclimate (Mazzarella, 2012; Scafetta, 2012). The frequency of combined PDO and ENSO cycles (5-15 years), and ENSO cycles (2-7 years) are too high to be effectively detected by the sample resolution of this analysis (~12 years).

Previous research on diatom assemblages in Morrison Lake by Bracht-Flyr and Fritz (2012), which are interpreted to represent hydroclimatic variability, identified statistically significant periodicities (>99%) of 54-58 and 74-78 years. Both of these frequencies are observed in the $\delta^{18}O_C$ record of Morrison Lake, consistent with a common hydroclimatic driver. The 54-58-year frequency was attributed to shifts in the PDO (Bracht-Flyr and Fritz, 2012). Though sampling frequencies of this study and the diatom assemblage study (Bracht-Flyr and Fritz, 2012) are the same (0.5 cm), the 25- and 40-year frequencies observed in the Morrison Lake $\delta^{18}O_C$ record are not recorded in the diatom abundance record. This may indicate that the carbonate mineral fraction likely responds to shorter-term variability in hydroclimate (Figure 2.12) (Bracht-Flyr and Fritz, 2012).

Spectral analysis conducted on $\delta^{18}O$ values from the fine-grained carbonate mineral fraction (<63 µm) of the sediment from Foy Lake to the north (385 km) of Morrison (Stevens et al., 2006) showed statistically significant (>99%) frequencies of 53.2, 30.8, 21.5, 19.5, and 14.3 years. The 21.5 and the 53.2-year cycles, which are similar to the 25, 52, and 55-year cycles observed at Morrison Lake, were hypothesized to be a result of variations in the Aleutian Low and 'pentadecadal' variations in sea surface temperatures (55-75-year periodicity) respectively (Stevens et al., 2006). These observed frequencies among two northern Rocky Mountain lake $\delta^{18}O$ system indicates that observed atmospheric trends such as the PDO and Aleutian Low, during the instrumental period, as well as longer-term (semicentennial) periodicity in sea surface temperatures have been a strong control on hydroclimatic dynamics of the past 2,000 cal yrs. BP. Additionally, a study of diatom assemblages in Foy Lake, showed statistically significant periodicities of 58-62, 43, and 32-36 (Bracht-Flyr and Fritz, 2012). The 58-62-year frequency was attributed to the PDO and the 32-36-year frequency was attributed to the AMO (Bracht-Flyr and Fritz, 2012).

2.6.3 Bulk Organic Isotopes

Stable isotopic analysis, $\delta^{13}C$, of the bulk organic fraction of the sediment, averages -28.4‰, indicating that C3 plants are the dominant component of the sediment, with little to no influence of C4 plants. Due to a lack of aquatic algae sampling and analysis, this study is unable to quantify the influence of algae, terrestrial material, and other aquatic plants in the bulk organic fraction of the sediment. However, a very negative $\delta^{13}C$ (between -25 and -30‰) and a low C/N ratio (between 3-10) is characteristic of an algal-dominated system (Meyers and Lallier-Vergés, 1999), which indicate that the bulk organic fraction of the sediment at Morrison Lake is primarily composed of algae (Figure 2.13). Samples of plants and soil from around Morrison Lake show that soil and emergent aquatic plants show similar values of $\delta^{13}C$ and C/N as much of the sediment. This shows that end member compositions are not unique from each other.

Notable reductions in $\delta^{13}C$, $\delta^{15}N$, and C/N occur in the most modern sediments (134-(-68) cal yrs. BP; 1816-2018 AD). These excursions are likely attributed to human impacts on global carbon and nitrogen cycles (Gruber et al., 1999; Wolfe et al., 2001). A moderate relationship was recognized between the percent organic fraction of the sediment and the $\delta^{15}N$ of the bulk organic fraction (R^2=0.21). This indicates that the availability of nitrogen in the lake is a control on organic productivity. A poor correlation was found between $\delta^{15}N$ of the bulk organic fraction and $\delta^{18}O_C$ (R^2=0.001), indicating that $\delta^{18}O_C$ is a poor predictor of nitrogen availability. This poor correlation may be a result of variations in the utilization of nitrogen within the lake and possible shifts in $\delta^{15}N$ baselines in groundwater based on shifts in climatic state.

2.6.4 Relationship to regional and global climatic events

Variation between portions of the record, other than the extremely high amplitude peaks (>4‰), with increased amplitude in $\delta^{18}O_C$ (>0.5‰) and portions with lower amplitudes (<0.5‰) indicate periodic shifts in the mean hydroclimate state over centennial scales. For example, during the Little Ice Age (~600-150 yrs. BP) higher amplitudes indicate more intense interdecadal variability with periods of high snowpack and cool summers, and periods of low snowpack and warm summers. (Figure 2.12) (Dahl-Jenson et al., 1998; Mann, 2002).

The Morrison Lake record agrees with other regional paleoclimatic reconstructions of the late Holocene. Steinman et al. (2012) showed that in the Pacific Northwest during the MCA winters were consistently wetter, whereas during the LIA drier conditions were more common. The similarity between the Morrison Lake $\delta^{18}O_C$ record and the Castor Lake record from Steinman et al. (2012), indicates that Morrison Lake's $\delta^{18}O_C$ values track winter precipitation volume at least over the past 1,500 cal yrs. BP. ENSO and PDO were found to play a major role in winter precipitation variability during the LIA and until the modern (Steinman et al., 2012). A diatom assemblage study conducted by Bracht-Flyr and Fritz (2012), showed that between 2,300 to 1,200 cal yrs. BP, Morrison Lake experienced seasonal oscillations in precipitation. During the MCA diatom abundances indicates a shift toward consistently wetter winters, followed by a return to seasonal oscillation during the LIA (Bracht-Flyr and Fritz, 2012).

During the Medieval Warm Period, the Morrison Lake region experienced consistently wetter winters. This was likely driven by consistent generation of strong winter storm tracks. During the Little Ice Age, Morrison experience increased variability in hydroclimate. These multidecadal shifts in hydroclimate are likely a result of increased fluctuations of the Aleutian Low driven by cooler ocean temperatures and more variable energy transport from the equator to higher latitudes.

2.7 Conclusion

Morrison Lake is located in an arid high-elevation region of the northern Rocky Mountains, where it receives ~75% of the mean annual precipitation compared to areas to the north and south (Glacier and Yellowstone regions respectively). This increases the sensitivity of the lake to recording periods of climatic fluctuation. A high sedimentation rate allows for high resolution analysis (~11 years/sample).

Hydroclimate has fluctuated periodically at Morrison Lake over at least the past 2,000 cal yrs. BP. This periodicity is punctuated by multicentennial periods of alternating hydroclimate state. During the period of the Little Ice Age, Morrison experienced increased variability in $\delta^{18}O_C$ indicating that hydroclimate shifted between states of high snowpack and low snowpack/greater evaporation. The Medieval Warm Period is expressed in the Morrison Lake record as a period of consistently low $\delta^{18}O_C$ with low amplitude of variation between individual samples, indicating that snowpack was consistently high during this time, and summers were either cooler or wetter.

Spectral analysis suggests that Morrison Lake's hydroclimate record is dominated by multidecadal variability, that has been previously described as forcing from patterns such as the PDO and AMO. Periodicity in the $\delta^{18}O_C$ shows frequencies of 25, 40, 52, 55 and 78-years. The 25-year periodicity is commonly attributed to the PDO and the 52-80-year periodicities are attributed to fluctuations in the AMO (Kuss and Gurdak, 2014). The source of the observed 40-year frequency is unclear.

Morrison Lake has a paleoclimatic proxy record that is in a unique arid climatic region of the northern Rocky Mountains even at high elevation. This aridity is evident in both modern measurements of hydroclimate from SNOTEL sites and in the strong variability in the $\delta^{18}O_C$ record during the past 2,300 cal yrs. BP. This record shows variability of hydroclimate driven primarily by fluctuations in winter-spring storm tracks from the Pacific that change over multidecadal periods in response to changes in ocean-atmospheric circulation. Regional and global similarities in timing and frequency may indicate reorganization of such circulation teleconnections.

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2.9 Figures and Tables

2.9.1 Tables

Sample ID	Depth (cm)	Age (yrs. BP)	Error (yrs. BP)	Calibrated Age (yrs. BP)	2σ Range (cal yrs. BP)	Sample Composition
ISU_14C 2019 Morrison1	34	740	110	679	517-879	leaf material and charcoal
ISU_14C 2019 Morrison4	66	1385	30	1309	1213-1400	charcoal
ISU_14C 2018 Morrison1	99.5	2270	70	2258	2048-2483	pine needle

Table 2.1. Radiocarbon data table. Dates are calibrated with Bacon software for R (Blaauw and Christen, 2013).

2.9.2 Figures

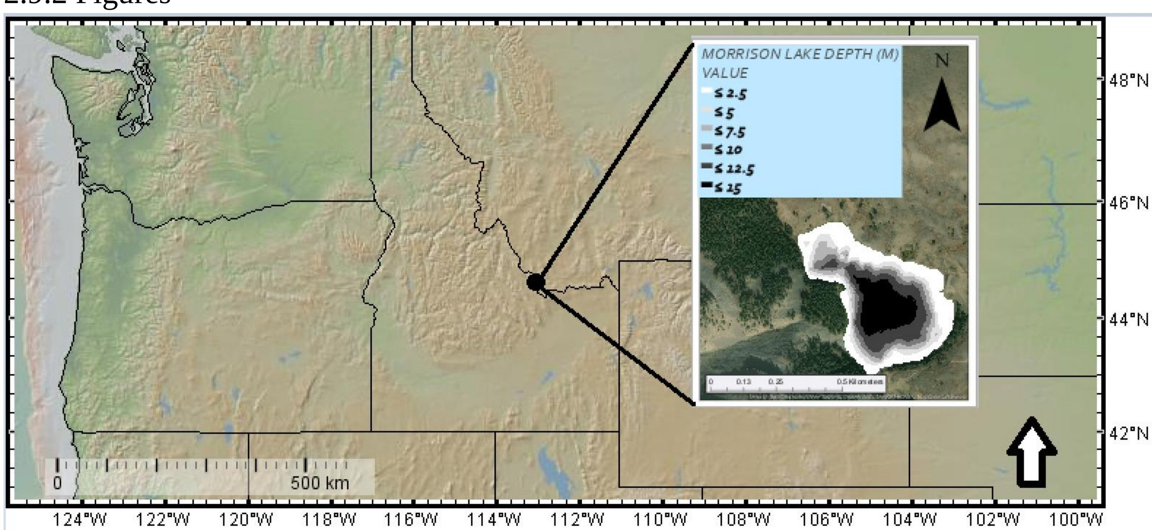

Figure 2.1. Location map of Morrison Lake, MT. Inset shows a bathymetric profile of Morrison Lake.

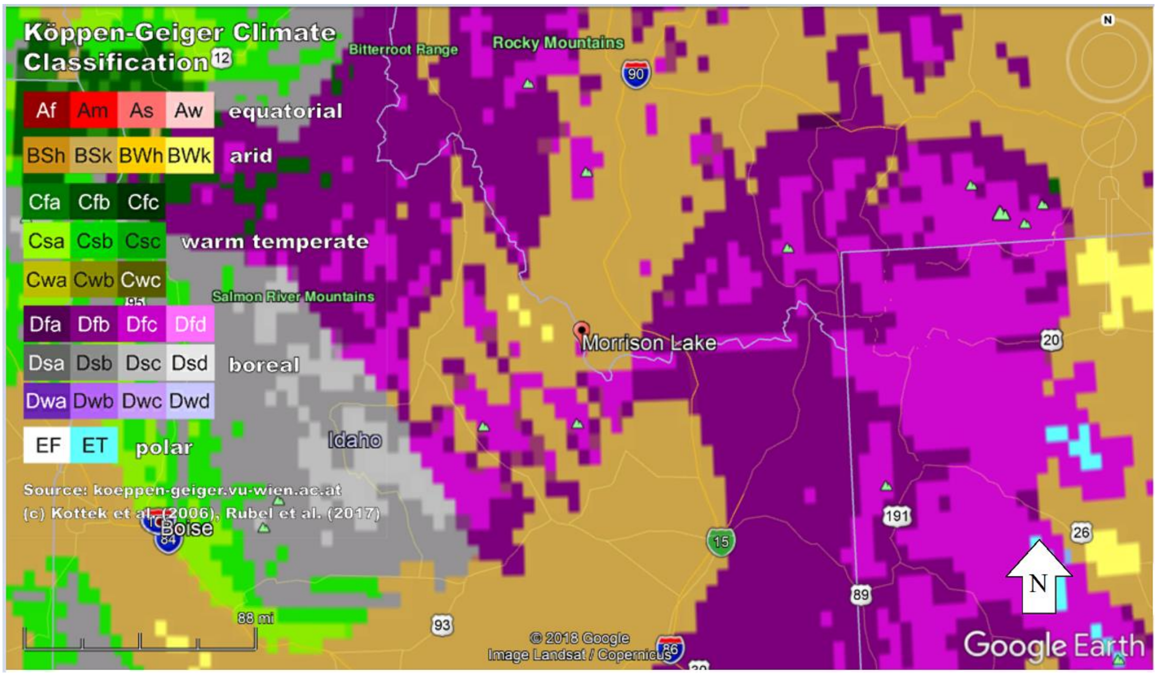

Figure 2.2. Köppen-Geiger climate classification of the Morrison Lake area after (Kottek et al., 2006; Rubel et al., 2017).

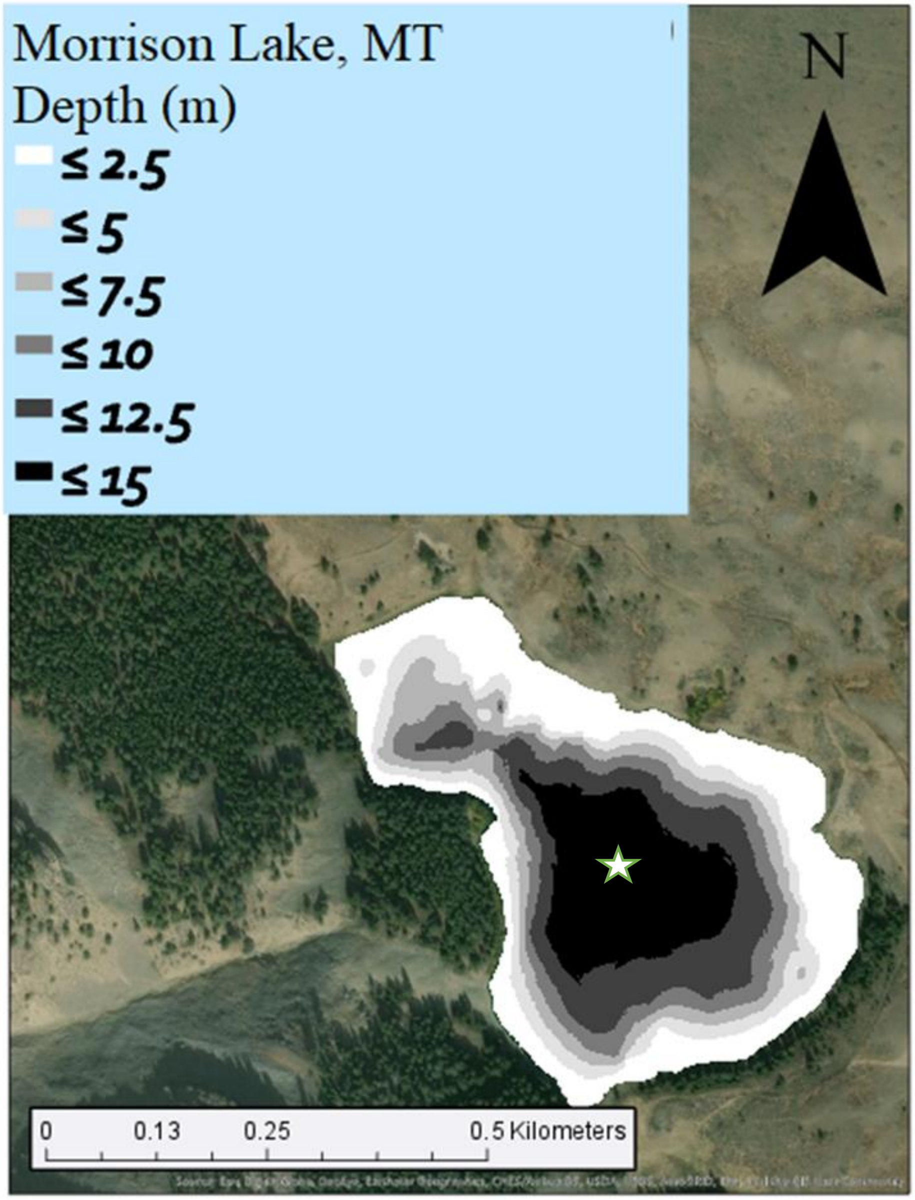

Figure 2.3. Bathymetric map of Morrison Lake, MT. Star indicates location of 2018 coring.

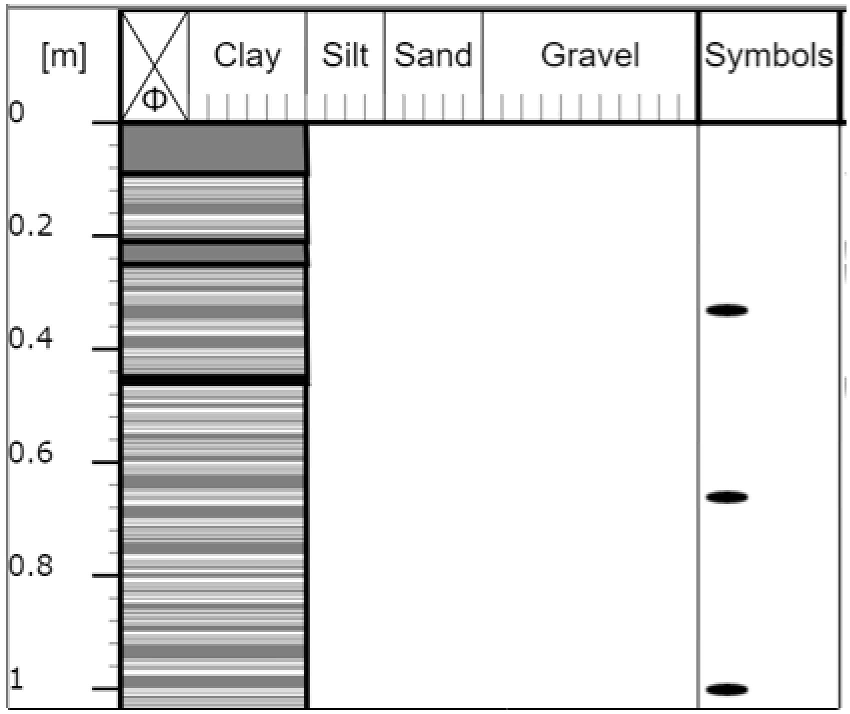

Figure 2.4. Sediment characteristics and locations of radiocarbon dates (black circles). Thinly laminated carbonate and clay-rich sediments with organic matter and minor silt and sand are represented by the thin lines. Massive clay- and organic-rich sediment with minor carbonate, silt and sand are represented by the grayed-out areas.

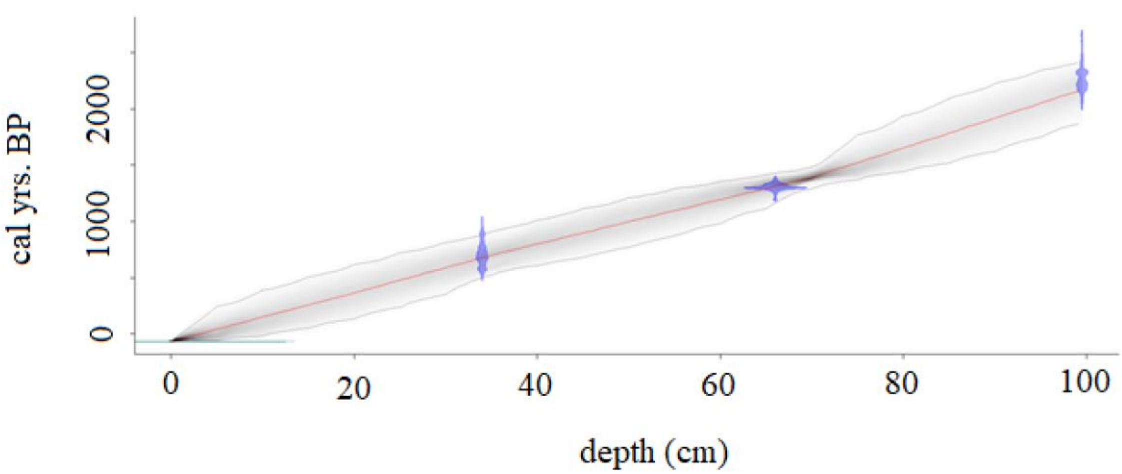

Figure 2.5. Calibrated radiocarbon dates and sedimentation rates.

Physical properties and δ¹⁸O of Morrison Lake, MT

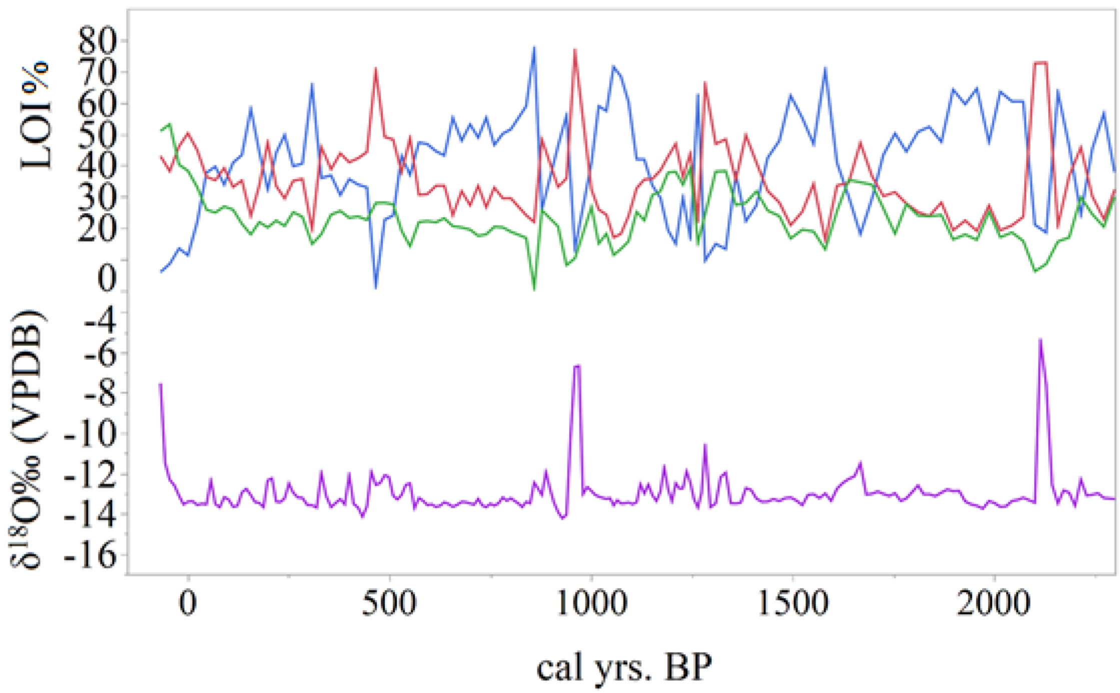

Figure 2.6. LOI (blue line, % carbonate; red line, % residual material; green line, % organic matter) and $\delta^{18}O_C$ results from Morrison Lake, MT.

Physical properties and δ¹⁸O of Morrison Lake, MT

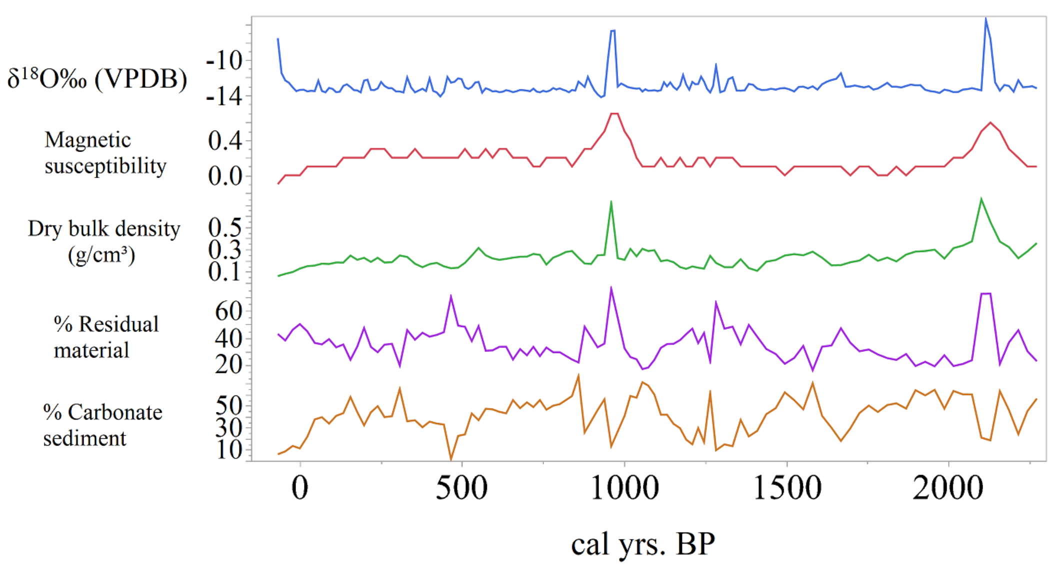

Figure 2.7. $\delta^{18}O$ of fine grain (<50 µm) carbonate sediment from 2,270 to (-68) cal yrs. BP compared to magnetic susceptibility, dry bulk density, and LOI data from Morrison Lake, MT.

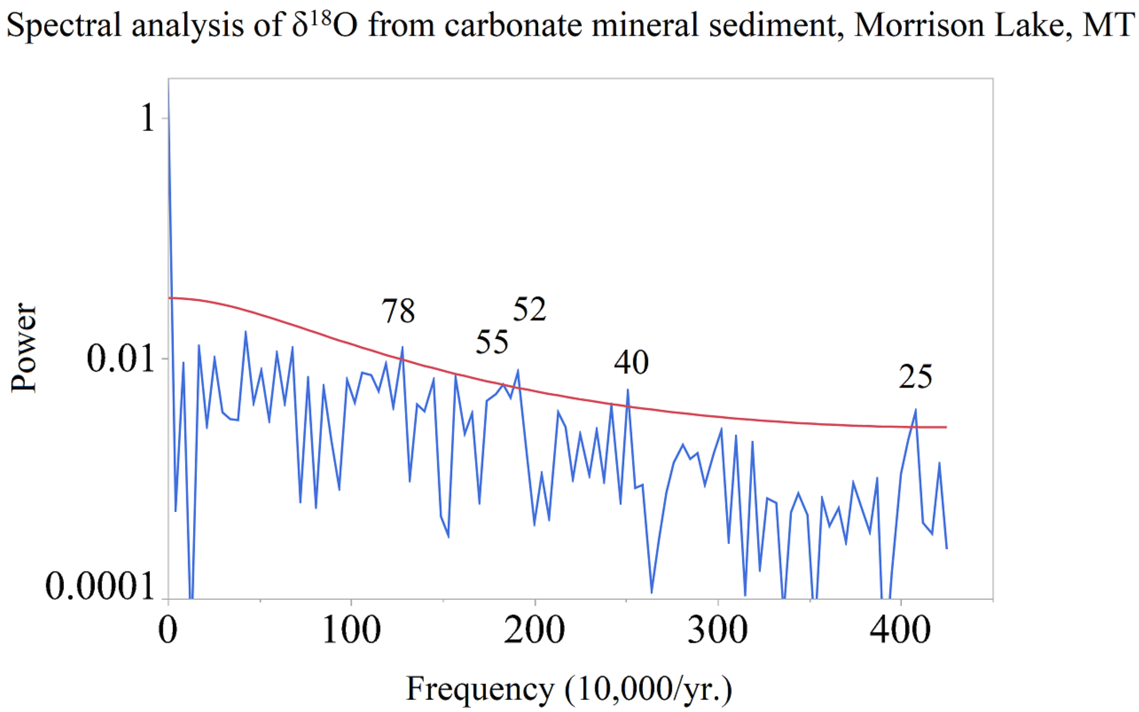

Figure 2.8. Spectral analysis of $\delta^{18}O$ from carbonate sediments at Morrison Lake, MT. The output variable Gxx_corr is plotted as the blue line (spectral power of individual frequencies that is corrected for non-constant samples). The red line indicates a chi test result of above 95%.

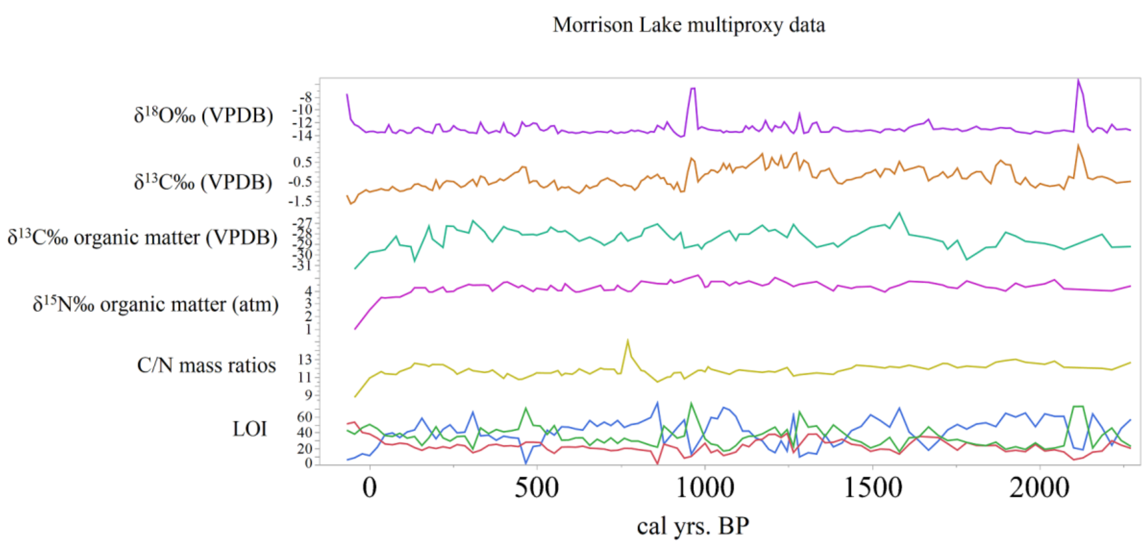

Figure 2.9. Morrison Lake multiproxy record including $\delta^{18}O$ of fine grained carbonate fraction (dark purple), $\delta^{13}C$ of fine grained carbonate fraction (orange), $\delta^{13}C$ of bulk organic fraction (teal), $\delta^{15}N$ of bulk organic fraction (light purple), C/N mass ratios (yellow), and LOI data (% carbonate=blue; % organic matter=red; % residual material=green).

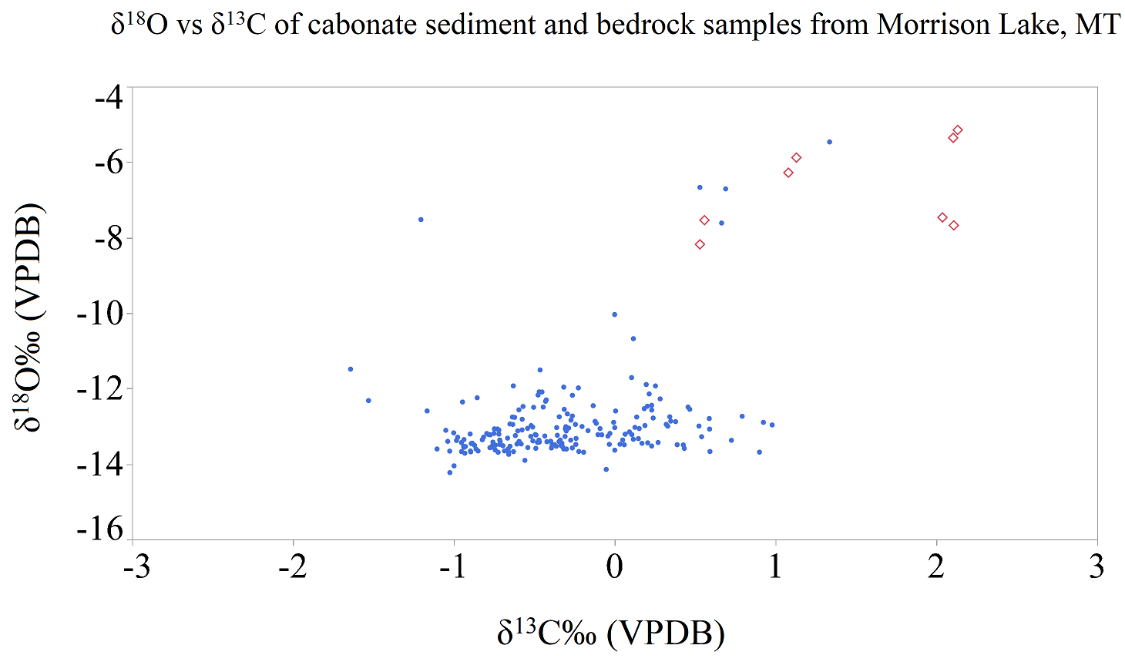

Figure 2.10. $\delta^{18}O$ vs $\delta^{13}C$ of both the fine grained (<50µm) carbonate mineral fraction of Morrison Lake sediment (blue dots), and bedrock samples (red diamonds).

Figure 2.11. Images of turbidite deposits that represent high amplitude $\delta^{18}O$ peaks.

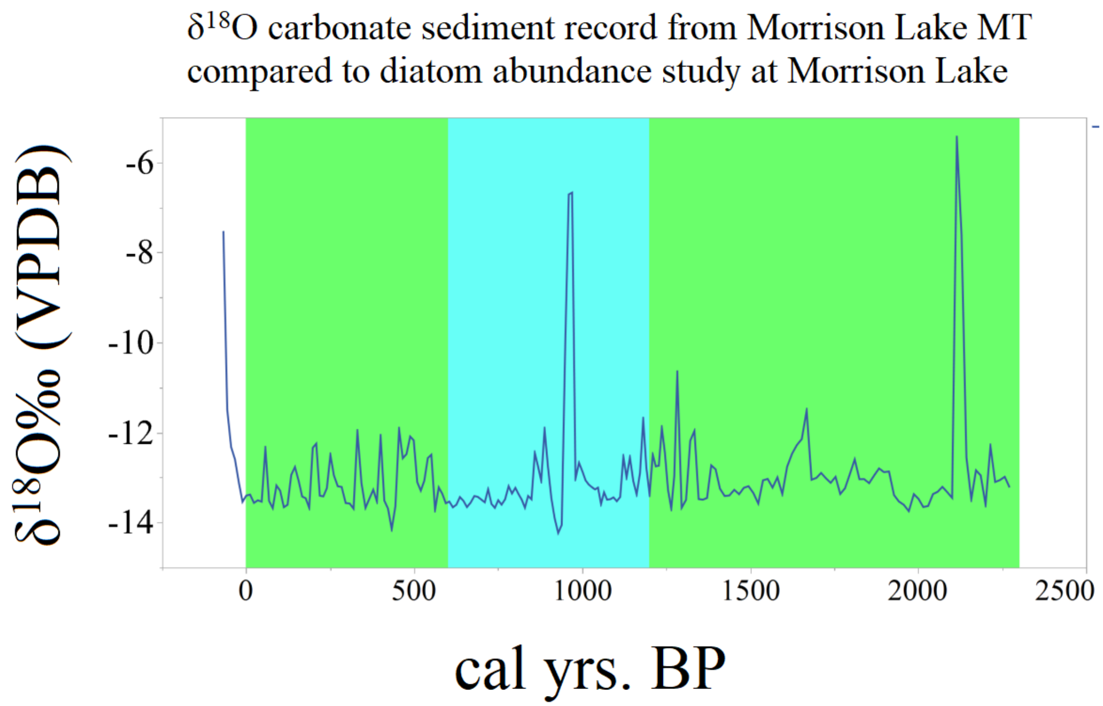

Figure 2.12. Morrison $\delta^{18}O$ data compared to hydroclimate interpretations from previous diatom study (After Bracht-Flyr and Fritz, 2012). Green highlighted portions of the record show time periods interpreted by Bracht-Flyr and Fritz (2012) to be times when Morrison Lake experienced oscillating seasonality of precipitation. Blue highlighted portion of the record show a time period where Bracht-Flyr and Fritz (2012) interpreted the climate to have consistently increased winter precipitation.

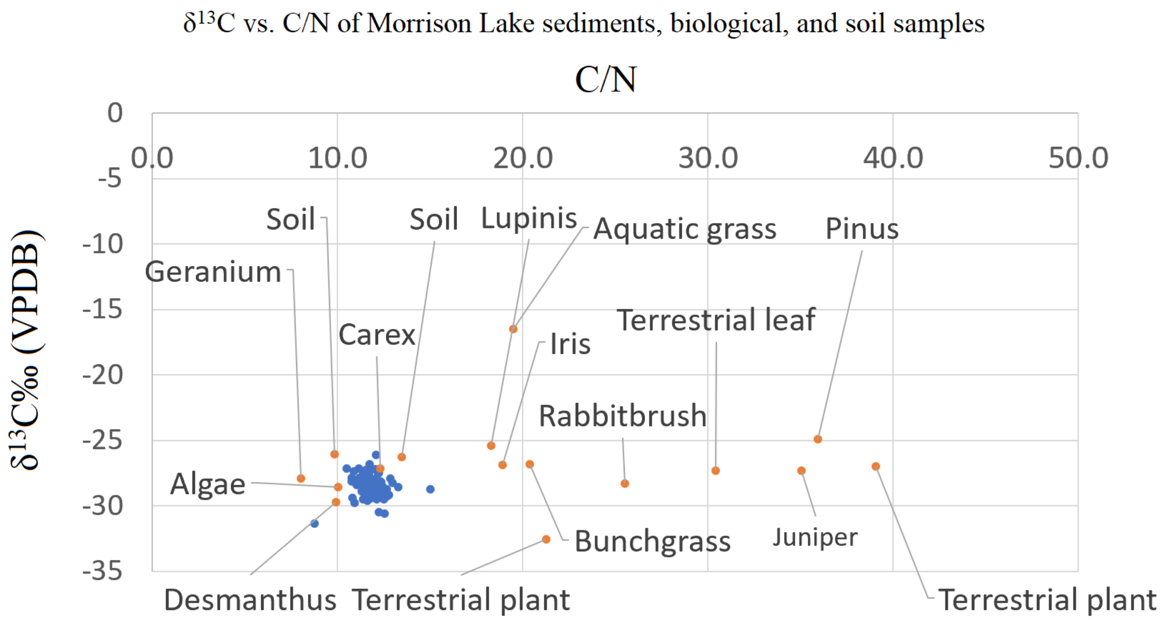

Figure 2.13. $\delta^{13}C$ vs C/N of the organic matter from Morrison Lake sediments, watershed plants, and soil samples.

Thesis Conclusion

Morrison Lake records climatic and hydroclimatic variability in the northern Rocky Mountains in an area that is more arid, even at high elevations, than regions to the north and south. Climatic and environmental signals are recorded in both the composition of the bulk organic fraction and the fine-grained (<50 µm) carbonate mineral fraction of the lake sediments.

Stable isotope data from the organic fraction of the sediment ($\delta^{15}N$ and $\delta^{13}C$) indicate that productivity and nutrient cycling in the lake varied through three distinct stages. In the earlier portion of the record (15,600 to 10,000 cal yrs. BP), C/N mass ratios are low (~6.8) and $\delta^{15}N$ values are high, indicating productivity dominated by algal activity with nitrogen from watershed cycling. During the middle unit of the sediment record (10,000-6,000 cal yrs. BP), $\delta^{15}N$ values drop to near atmospheric values with C/N mass ratios rising. Both of these values indicate that the lake experienced a significant reduction the amount of nitrogen available, resulting in nitrogen limitation. The most modern portion of the record (6,000 cal yrs. BP-present) has organic isotopic values similar to the oldest portion of the record, indicating that nitrogen availability increased during this time relative to the middle portion of the record, likely due to increased precipitation.

These three stages in the organic isotopic values are tracked by three distinct shifts in the isotopic values of the carbonate mineral fraction of the sediment. Carbonate minerals compose only a small percentage of the total sediment during the earliest portion of the record (15,600-10,000 cal yrs. BP), with most of the samples being primarily composed of detrital material. Evidence for this is in LOI and XRD data, which show that higher concentrations of dolomite (found in the bedrock surrounding the lake) and quartz sand are also found in the sediments during this time. During the middle of the sediment record (10,000-6,000 cal yrs. BP), there is no carbonate mineral preservation. This indicates that the pH of the pore water and potentially the whole lake shifted toward carbonate dissolution. Carbonate was preserved again during the most recent portion of the record (6,000-(-68) cal yrs. BP), dominated by authigenic mineral precipitation. Despite a few periods of significant detrital material, a vast majority of the carbonate mineral sediment is authigenically precipitated calcite and aragonite. This portion of the record contains a valuable high-resolution hydroclimatic proxy record as the authigenically produced carbonate record variations in the P/E ratios of the lake water.

The three distinct periods of the stable isotopic sedimentary record at Morrison Lake are recognized in both the bulk organic and fine-grained carbonate mineral fraction, indicating that the Morrison Lake region underwent significant climate shifts over the past 15,600 cal yrs. BP.

The oldest portion of the record (15,600-14,800 cal yrs. BP) shows negative $\delta^{18}O_C$, similar in value to the most modern sediments. This indicates either a wet climate state or the presence of glacial discharge affecting the $\delta^{18}O_L$. From 14,800-11,100, the $\delta^{18}O_C$ data shows a dry climate state with reduced calcium and carbon inputs into the lake, and an increase in the amount of detrital material. This is likely driven by increased overland flow and sediment transport during rewetting events and increased eolian inputs. Between 11,100-10,000 cal yrs. BP Morrison Lake shows evidence of a rapid shift into a wetter climatic state. Some of the most negative $\delta^{18}O_C$ values occur during this time period. The mechanism responsible for this rapid shift is unclear, but there is evidence in

Jones Lake in northern Montana for similar timing of a rapid shift into a wetter climate state (Shapley et al., 2009).

The middle portion of the record (10,000-6,000 cal yrs. BP) shows a time where the climate was extremely dry, with significant reduction of nutrient flux to the lake, and a drop in the pH of the lake water. Low lake levels likely occurred during this time. Organic preservation was likely enhanced by stratified bottom waters due to shifting groundwater discharge at lower lake stage.

The most recent portion of the record (6,000-(-68) cal yrs. BP) shows a climate state more similar to the modern. Morrison Lake shows evidence of hydroclimate forcing similar to global climatic events during this period. Increased amplitude $\delta^{18}O_C$ values during the Little Ice Age, indicating multidecadal shifts in climatic state between wet and dry, and reduced amplitudes during the Medieval Warm Period, indicating consistently higher rates of precipitation. Reorganization of atmospheric circulation with broad teleconnections may play a role in this pattern.

Spectral analysis of the most recent 2,300 yrs. indicates that periodicity in the climatic state over this timeframe is likely driven by the intensity of the Pacific Decadal Oscillation (PDO) and Atlantic Mean Oscillation (AMO). Statistically significant (>95%) frequencies of $\delta^{18}O_C$ variations include 25, 40, 52, 55 and 78-years.

Further studies are necessary to understand where the boundaries of the high elevation arid climate region in the northern Rocky Mountains and located and what drives precipitation to be lower and temperatures to be higher there than in other regions to the north and south. This region, shown through other paleoclimatic proxies may provide clues toward how modern climatic warming will affect snowpack in regions that are already sensitive to aridity and becoming more arid. Morrison Lake contains an extremely valuable paleoclimatic record as it provides evidence for the hypothesis above. A wealth of additional paleoclimatic information may be obtained through future analysis of Morrison Lake sediments, including possibly identifying periods of glacial advance and retreat during the Last Glacial Maximum, developing a highly resolved late Pleistocene paleoclimatic record, and furthering understanding of how small basin highly evaporated lakes shifts in geochemical state in response to climatic forcing.

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