Fire Frequency During the Last Millennium in the Grinnell Glacier and Swiftcurrent Valley Drainage Basins, Glacier National Park, Montana

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Abstract

Fire is a natural process, influenced by climate and vegetation (fuel source). The relationships between fire, climate and vegetation under changing climatic conditions are important to understand. Fire frequency in the western United States has significantly increased in the past three decades. This study examined the top two meters of a sediment core taken from the northern sub-basin of Swiftcurrent Lake, Glacier National Park, Montana, with the goal of using variability in charcoal flux into the lake as a proxy for fire history in the Grinnell Glacier and Swiftcurrent Valley drainage basins. Previous work suggests that an increase in fire-frequency occurred in the western United States over the more recent record, and because this core site has a higher sedimentation rate, the fire record will be more finely resolved in time. A preliminary model suggests that the core represents the last ~1700 years of sedimentation, at an average sedimentation rate of 1.2 mm/yr. Based on the sedimentation rates and the charcoal concentrations, charcoal accumulation rates (CHAR) range from 0 to 72 grains cm^{-2} yr^{-1}. The 1700-year fire record shows a higher amount of fire events than previously found in a nearby, upvalley core. The fire return interval of the northern Swiftcurrent sub-basin is roughly 46 years between fires, whereas the southern sub-basin had an average return interval of 363 years between fires. The lower accumulation rates in the southern sub-basin could be due to the two large lakes (Lake Josephine and Lower Grinnell Lake) that serve as sediment sinks in the watershed, or it could be the result of the smaller drainage area. This shorter, more detailed record provides a new evaluation of the fire record of the Swiftcurrent Lake drainage basin.

Chapter 1 - Introduction

Fire is widely accepted among researchers as a driver of ecological change(Whitlock et al., 2003; Daniau et al., 2012). Fire is an integral process involving vegetation and climate that has significant effects on atmospheric chemistry, global carbon cycle, terrestrial ecosystems and biodiversity (Gill, Burrows and Bradstock, 1995). For this reason, the relationships between fire, climate and vegetation are important to understand under changing climatic conditions. Long-term fluctuations of climate (on millennial time scales) have been used to explain shifts in global fire history (Daniau et al., 2012; Whitlock et al., 2003). Thus, fire regimes are tied to global temperature changes, where increased temperatures lead to increased fire frequency. In the western United States, fire has played an important role historically in the maintenance of forest vegetation through the disturbance regime, evident in the paleoecological record (Whitlock et al., 2003). Lake sediment cores provide an accurate view into climate history and provide insight into the relationship between fire, climate and vegetation (Brunelle and Whitlock, 2003; MacGregor et al., 2011). This study aims to reconstruct fire history in the Grinnell Glacier and Swiftcurrent Valley drainage basins, located in Glacier National Park, Montana with the aim of better understanding the regional history and evaluate shifts that have occurred in recent history (Fig. 1).

Fire frequency in the western United States has significantly increased in the past three decades (Westerling et al., 2006; Whitlock et al., 2003). The magnitudes of these fires are also increasing; since 1980, an average of 22,000 km^2/yr has been burned in U.S. wildfires, compared to the average of 13,000 km^2/yr from the years 1920-1980 (Schoennagel et al., 2004). This environmental issue has greatly impacted the nation, and annual costs for fire suppression now exceed 1.7 billion dollars (National Interagency Fire Center, 2013). Wildfires are an issue of national concern. Fire researchers and fire managers are seeking an explanation to the recent increase in fire frequency, examining climate change and shifts in historical land-use as likely causes (Westerling et al., 2006). The greatest increase in fire frequency in the western United States (including Alaska) has occurred in the middle-to-high elevation (1680 m +) northern Rocky Mountain region forests (Westerling et al., 2006). Westerling's analysis suggest that this increase has been associated with earlier snowmelt dates in the region (Westerling et al., 2006).

Climate history in the northern Rocky Mountain region is largely known from lake sediment cores (Brunelle and Whitlock, 2003; MacGregor et al., 2011). Lake sediment cores allow for a perspective into the past regarding the fire history and climatic shifts. This study examines the top two meters of a core taken from Swiftcurrent Lake during summer 2014 with the goal of using variability in charcoal flux into the lake as well as the character of the charcoal to reconstruct a fire history for the drainage (Whitlock and Larson, 2001). The drainage tributary to the core site include the Grinnell Glacier, Upper and Lower Grinnell Lakes, Lake Josephine, Swiftcurrent Glacier, Windmaker, Bullhead, Redrock and Fishercap Lakes, as well as most of the developed area of the park, including Park Service facilities and campgrounds, hotels and septic systems. Core chronology, which is critical to development of a fire history, is established using an age model based on stratigraphic correlation to a well-dated core taken from the northern sub-basin of the lake in an earlier study (Oddo, 2011). The earlier study also examined charcoal influx, and one of the goals of the current study is to compare the fire history records from the two sub-basins.

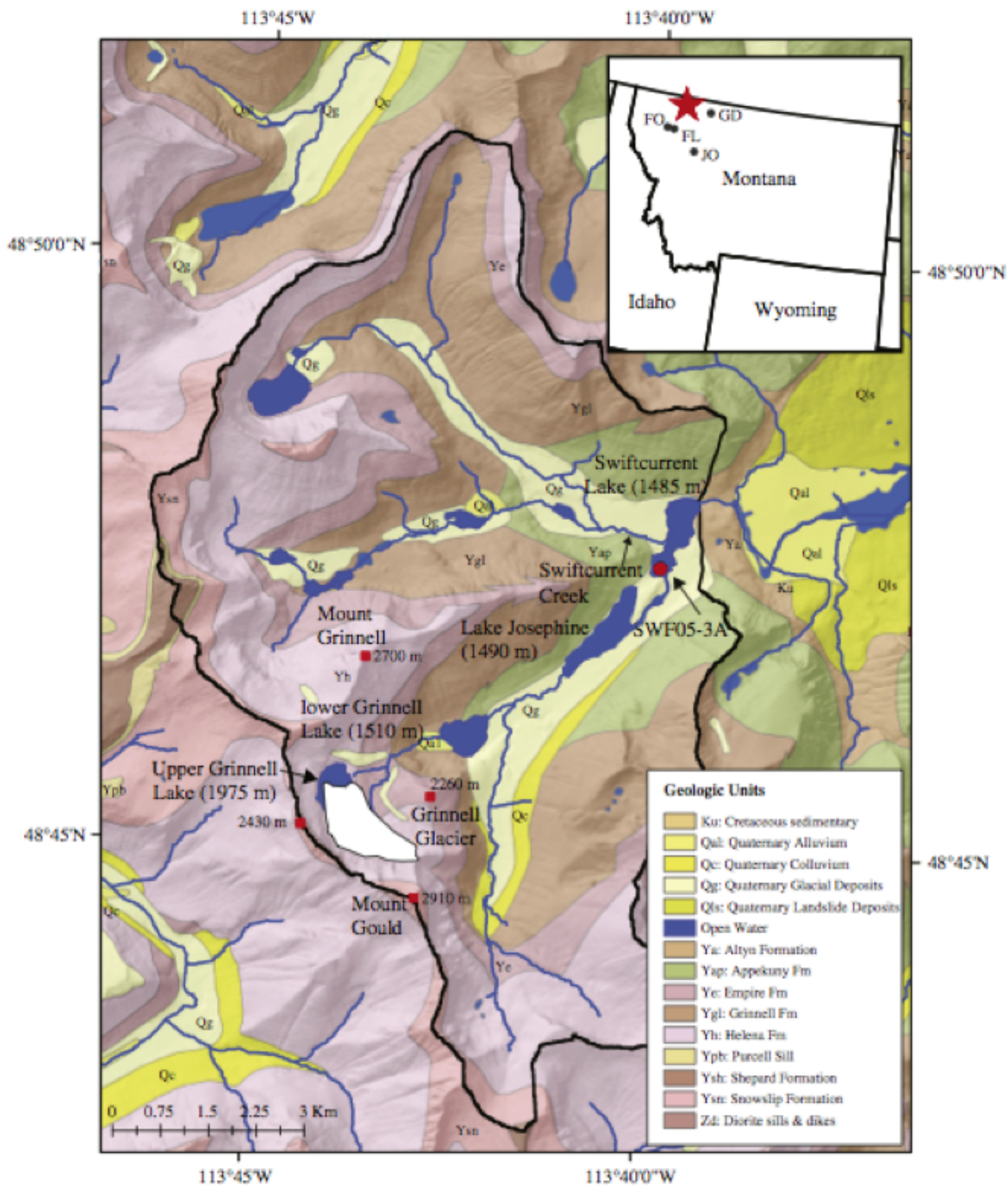


Figure 1. Geologic Map of the Many Glacier region of Glacier National Park. Swiftcurrent Lake catchment basin outlined in black (MacGregor et al., 2011). Coring site SWF05 3A is labeled.

Swiftcurrent Lake contains two sub-basins, separated by a discontinuous ridge (3-4 m water depth) (MacGregor et al., 2011). The northern sub-basin, from which a new core was retrieved in 2014 has a larger tributary area and, appears to have a higher sedimentation rate, than the southern sub-basin. The higher sedimentation rate should allow the establishment of a higher-resolution fire record than was available from the earlier study. In addition, the new core from the northern sub-basin should contain a record of fire associated with park development, a record which would be much less clearly reflected in the southern sub-basin, which does not receive sediment directly from the main developed areas of the park.

Chapter 2-Previous Work

<u>Fire as an Earth System Process</u>

Fire is an inevitable process on the earth's surface due to the widespread cover of carbon-rich plants, seasonally dry climates, widespread lightning, and the presence of free oxygen in the atmosphere (Bowman et al., 2009). Depending on the region of the world, there will be a different fire regime, which leads to a variety of ecological effects. Ecologists define fire regimes to include fuel type (ground, surface, and crown), temporal nature (rate of spread, seasonality, and frequency), spatial pattern (size and patchiness), and consequences (impacts on vegetation and soils) in order to define and create boundaries between regions (Bond and Keeley, 2005). Fire regimes are closely tied to vegetation structure in an environment, and when these regimes change over time, due to fire protection, grazing, or invasive species, vegetation structure is known to shift (Bowman et al. 2009). In the western United States, fire management is often cited as a cause for shifts in vegetation structure via understory thinning and prescribed burns, although underlying climate patterns also play an important role (Whitlock, 2004; Bowman et al., 2009; Westerling et al., 2006).

Current fire management practices in the western United States are heavily debated (Bowman et al., 2013; Whitlock 2004). Management methods including prescribed burning and understory thinning have proven to reduce larger crown fires in the area, but these processes have also been criticized for reducing the role of fires as an ecosystem process (Whitlock, 2004; Bowman et al., 2009). Fires accelerate the natural cycle of primary production and respiration in forests (Bowman et al., 2009). Current management practices reducing crown fires in conjunction with warming mean annual temperature trends in the western United States have led to the hypothesized existence of a "fire deficit," with low levels of biomass burning in the past century compared to what might be expected to occur naturally under a similar climate (Marlon et al., 2012). Despite increased temperatures and drier climates in the western United States management practices continue excluding and suppressing fire, which calls into question the sustainability of fire suppression. These conclusions make the study of fire in the west an important topic for further investigation.

Fire Records

Fire-history studies are typically conducted using a combination of charcoal counts (burn evidence), sedimentation (evidence for watershed adjustments), and pollen (evidence for vegetation) (Whitlock and Larson, 2001). Charcoal records are direct evidence for a fire, whereas the pollen record shows evidence for vegetation shifts (Whitlock and Larson, 2001). Though dendrochronology is an extremely accurate way to date fire events and evaluate severity, the method is limited temporally. Charcoal records taken from sediment cores are able to date back much further in time than tree rings, but are reduced in accuracy unless an adequate chronology is created (Whitlock, 2004; Whitlock and Larson, 2001). Use of historical and dendrochronological records to aid core chronology is important to analysis (Whitlock and Larson, 2001).

Although charcoal is produced only during a fire, it may be deposited at the lake core site at the time of the fire (primary charcoal) or it may be deposited sometime later as terrestrial charcoal deposits are eroded and the charcoal is transported into the lake (secondary charcoal) (Whitlock and Larson, 2001). Either process may result in a statistically significant peak in charcoal analysis, and the presence of secondary charcoal can make it more difficult to establish the timing of the actual fire event from the core record (Fig. 2). For this reason, it is important to distinguish between background charcoal, which may be introduced via secondary processes, and primary charcoal peaks that represent fire events (Whitlock and Larson, 2001).

One way to constrain the number of statistically significant peaks in a record is to limit the size of charcoal counted in the analysis process. Studies have also shown that charcoal size is an important factor to constraining the location of the fire (Whitlock and Larson, 2001). Previous studies have indicated that macroscopic charcoal particles (>125 μm in diameter) are not transported more than 7 km from the burned source area (Gardner and Whitlock, 2001; Whitlock and Larson, 2001).

Fire in the northern Rocky Mountains

The increased risk of wildfires in the northern Rocky Mountains, and the western United States, has made charcoal analysis in sediment cores increasingly popular (Gardner and Whitlock, 2001; Westerling et al., 2006; Whitlock and Larson, 2001). Given the high altitude environment of the northern Rocky Mountains, the states of Montana, Idaho, Wyoming and Colorado account for 25.1% of the total acres burned in United States fires during 2013 (National Interagency Fire Center, 2013). Fires characterize this regions ecology, which makes it a fascinating location to study. The region is greatly impacted by management (Bowman et al., 2013), increased temperatures (Westerling et al., 2006), and shifts in climate through precipitation patterns (Brunelle et al., 2005).

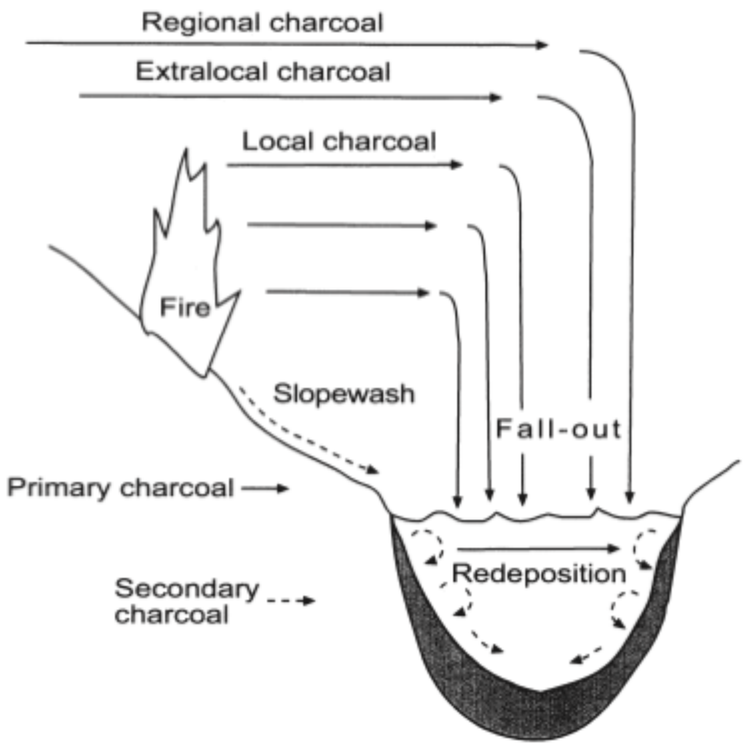


Figure 2. Schematic diagram of illustrating the sources of primary and secondary charcoal in a watershed (Whitlock and Larson, 2001).

Fire in Glacier National Park

Since Glacier National Park's development in the late 1800's, there has been one documented fire event in the Many Glacier area: the Heavens Peak Fire. This fire occurred in the summer of 1936, caused by a lightning strike in the middle of August (Larson, 2012). The event sparked two weeks of fire-fighting activity in the Many Glacier region in order to keep inhabitants and the hotel safe. This event is likely recorded in the core given the proximity of this large fire to Swiftcurrent Lake. Although the Heavens Peak Fire is the only documented fire, there are likely many more that will be present in the fire record.

In the summer of 2010, a Keck Project went to GNP and took sediment cores in Swiftcurrent Lake, Lake Josephine and Lower Grinnell Lake (Fig. 1). In that project one student studied the Holocene fire history for the park (Kutvirt, 2011). That work focused on a core from the southern sub-basin of Swiftcurrent Lake. A study performed in 2010 also analyzed charcoal accumulation in the southern sub-basin of Swiftcurrent Lake (Fig. 3). This record evaluated fire frequency for a longer, 7630 year record and showed low levels of fire activity from 7630 - ~3600 Cal yr BP, when fire frequency and intensity increased until ~2100 Cal yr BP. Fire frequency decreased between 2100 Cal yr BP and the present, with a slight increase in BCHAR levels in the most recent 150 years. (Kutvirt, 2011). Kutvirt also reported on pollen analysis work to supplement her charcoal analysis and was able further analyze high and low fire activity with respect to vegetation.

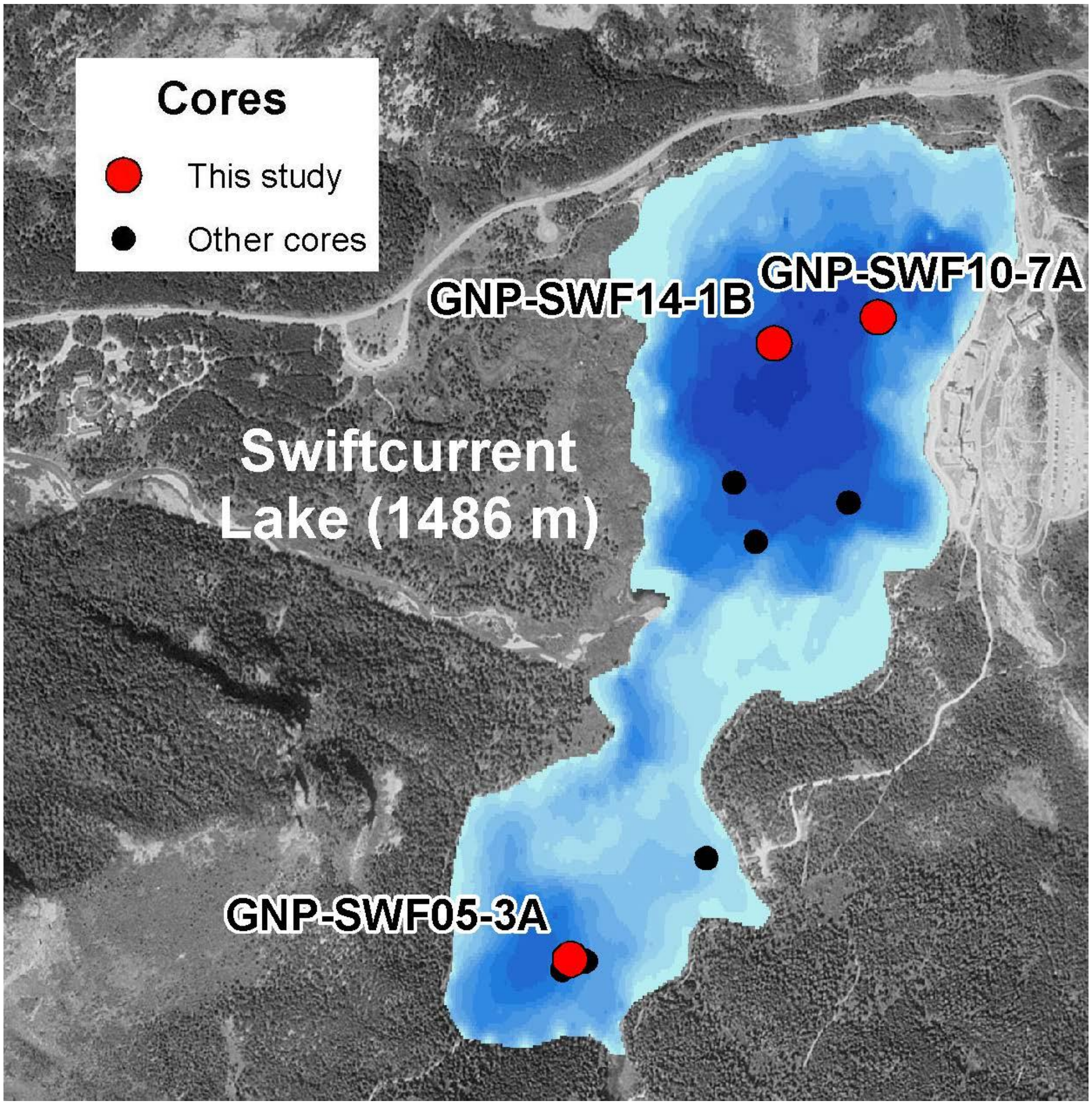


Figure 3. Bathymetric Data for Swiftcurrent Lake. Samples for this project were taken from the GNP-SWF14-1B site. GNP-SWF10-7A represents where the correlated ^{210}Pb core was taken in 2010. GNP-SWF05-3A represents the site where Kutvirt (2011) reconstructed fire history. Black dots indicate locations where the Keck 2010 project worked (created by Catherine A. Riihimaki).

Chapter 3 - Study Area

Swiftcurrent Lake is located east of the Continental Divide in Glacier National Park (GNP), Montana (Fig. 1). The park includes a large, mountainous region (4,080 km^2) of northwestern Montana that borders southern Alberta and British Columbia, Canada (Key et al., 2002). Due to the orographic effects of high topography in the center of the park, climate differs greatly east and west of the Continental Divide. East of the Continental Divide, the climate is generally drier than west and is characterized by long, harsh winters and short, mild summers (Geddes et al., 2005). Severity in these winter temperature changes is illustrated by the former world record temperature drop of 56°C in 24 hours in Browning, MT, a town nearby the eastern slopes of the park (Arno, 1976). Total annual rainfall in east Glacier is 66 cm, 9.3 cm lower than West Glacier (Table 1) (Western Regional Climate Center, 2014). Throughout the park, peak annual rainfall occurs in June (9.1 cm in St. Mary's) and peak temperatures occur in August (average temperature in St. Mary's 17.7 °C) (Western Regional Climate Center, 2014). Snowfall is another important source of water for St. Mary's, which receives 3.05 meters of snow a year (Western Regional Climate Center, 2014). The impact of snow in this sub-alpine environment is primarily felt through snowmelt. In the past 25 years earlier snowmelt has caused a longer dry season, creating increased fire intensity in the western U.S. (Westerling et al., 2006).

Swiftcurrent Lake is located at an elevation of 1490 m, which is a lower altitude than most sub-alpine forests in east Glacier. Despite this, vegetation surrounding Swiftcurrent Lake is in a sub-alpine forest due to it's northern latitude and proximity to the Continental Divide. Primary arboreal species in the forest surrounding Swiftcurrent Lake are the Lodgepole Pine (*Pinus contorta*), Subalpine Fir (*Abies lasiocarpa*), Engelmann spruce (*Picea engelmannii*) and Mountain Alder (*Alnus viriduis*) (Johnson, 2001). Sub-alpine forests in the Northern Rocky Mountains are characterized by stand-replacing fires (fires with variable fire return intervals and high intensity) (Barrett et al., 1991; Brown et al., 2000). The regional fire return interval for Northwest Montana is a severe, crown-burning fire once every 200-300 years (Brown et al., 2000). The arboreal species in east Glacier are susceptible to fires because of their thin bark, but have adapted to live in cool, moist environments where fire is less frequent (National Park Service).

The high-elevation Rocky Mountains, which run through the entirety of Glacier National Park, run roughly from north to south. Elevations through this spine of peaks range from 950 m to 3190 m. Topography near Swiftcurrent Lake is steep, with local relief approaching 1500m. Peaks that lie west of the lake are all roughly 2500 m, the highest being Mount Gould which reaches 2910 m. Topography steeply drops down moving east and plateaus at 1500 m, roughly the same elevation as Swiftcurrent Lake. The area is characterized by rugged peaks and dissected valleys as the evidence for glaciation as a geomorphic process, a feature that occurs across the northern Rocky Mountain region (Brunelle, 2005). Swiftcurrent Lake is located in the Many Glacier region of GNP and is about 1.6 km long and about .5 km wide, roughly 400 m^2 of the park. Figure 1 shows the Many Glacier area, with Swiftcurrent Lake to the east. As previously mentioned, the lake contains two sub-basins of similar depth (12 m), separated by a discontinuous ridge (3-4 m water depth) (MacGregor et al., 2011). The Swiftcurrent Valley drainage basin has a catchment area of 44 km^2 and the Grinnell Glacier drainage basin has a catchment area of 36 km^2 (MacGregor et al., 2011).

Table 1. Monthly climate summary for St. Mary, MT located just south of the Many

Glacier area. Data was collected and averaged from 1981-2014 (Western Regional Climate Center, 2014)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Average Max. Temp. (C)	.167	2.55	5.67	10.9	15.9	20.4	25.6	25.9	19.7	12.1	3.83	-.278	11.9
Average Min. Temp. (C)	-10.1	-8.6	-5.6	-2.17	2	5.67	8.28	7.44	3.77	.05	-4.55	-9.5	-1.06
Average Total Precip. (in.)	2.00	1.70	1.79	1.93	2.95	3.58	1.82	1.65	2.00	2.17	2.44	2.07	26.11
Average Total SnowFall (in.)	19.9	18.3	17.9	13.4	4.7	0.9	0.0	0.4	1.5	7.5	16.8	18.9	120.3

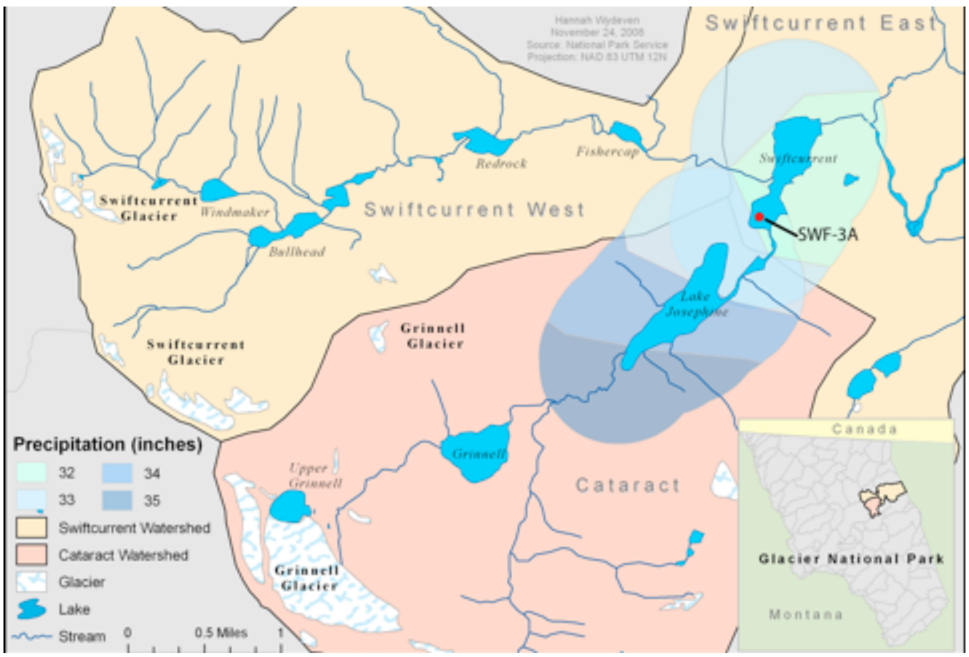


Figure 4. Image of the 3 drainage basins that feed into Swiftcurrent Lake (Kutvirt, 2011)

Table 2. Average annual visitation rate to Glacier National Park (National Parks Service, 2012)

Years	Average Annual Visitation Rate (persons)
2011-2012	2,007,800
2001-2010	1,929,653
1991-2000	1,910,485
1981-1990	1,807,208

An important distinction between these two sub-basins that the northern sub-basin is largely fed by Swiftcurrent Creek, which is not glacier fed and contains few sediment sinks above the lake, whereas the southern sub-basin is fed by Grinnell Glacier, through Upper Grinnell Lake, Lower Grinnell Lake, and Lake Josephine. These lakes create sediment sinks in transport and given the lack of these sinks in the northern sub-basin, different sedimentation rates in the two sub-basins are expected (Arp et al., 2006; MacGregor et al., 2011).

The northern sub-basin is fed by three different watersheds: the Cataract, Swiftcurrent West and Swiftcurrent East (Fig. 4). The Cataract basin includes the Grinnell Glacier, Upper and Lower Grinnell Lakes and Lake Josephine. Swiftcurrent West includes Swiftcurrent Glacier, Windmaker, Bullhead, Redrock and Fishercap Lakes.

The northern sub-basin of the lake is partially surrounded by paved roads around the lake and abuts the historic Many Glacier Hotel, founded in 1914. Human impact in the park has increased greatly over the years, largely due to the increase in visitors to the park (Table 2). In 2013, there were over 2.1 million visitors to Glacier National Park (National Parks Service, 2013).

The Swiftcurrent Lake drainage basin lies on top of the Middle Proterozoic Belt Supergroup, which comprises primarily of siltstones, shales, and sandstones (Fig. 1) (MacGregor et al., 2011). Grinnell Glacier sits upon exposures of the Helena Formation, which is the only source of dolomite in the drainage basin (Fig. 1).

Chapter 4 - Methods

Field Methods

In the summer of 2014, lake sediment cores were taken from the bottom of the northern sub-basin of Swiftcurrent Lake (Fig. 3). Before coring, a site was selected using bathymetry data collected from a kayak and a Garmin GPSMAP 541S to determine the point of greatest depth near the center of the lake. The coring site (GNP-SWF14-1A/1B) is at the deepest point in the northern sub-basin at a water depth of 12m. Coring methods varied by the section of core that was taken; MUCK (Multi-Use Coring Kit) piston coring was used to obtain the sediment-water interface and the Bolivia piston corer was used for long cores at greater depth (Nesje, 1992). For this study, samples were taken from one MUCK piston core and two Bolivia piston cores, each roughly 1.5 m long: GNP-SWF14-1B-1P (length used: 1.2m), GNP-SWF-1A-2B (length used: .68m), and GNP-SWF14-1B-2B (length used: .2m). Sites 1A and 1B were collected within 2 meters of each other in order to obtain alternating cores for the long-core site. After collection, the cores were capped and taped in order to prepare cores for transport.

All cores were transported and stored at the Limnological Research Center (LacCore Lab) at the University of Minnesota. Initial core descriptions and core samples were also performed as described in following sections.

Laboratory Methods

Initial Core Descriptions

All cores were initially described following LacCore Lab's protocol for initial core description (ICD). First, the core was run through the Geotek Multisensor Core Logger (MSCL) to obtain measurements of sediment density and magnetic susceptibility at 1-cm-scale resolution. After these tests, the piston and Bolivia cores were cut in half using a cast saw, then split longitudinally using fishing line and guillotines into two equal sections. One half of the core was wrapped and stored as an archive core, and the other, working half was photographed using a high-resolution digital line scanner (10 pixels per millimeter). Then, cores were scanned using the Geotek XYZ for high-resolution (0.5 cm) point-sensor magnetic susceptibility. Cores composition and grain size were described on the macroscopic and microscopic scales (using smear slides) in order to better compare cores and finalize the ICD sheets. Sections of the core were then selected for sampling (adapted from Kutvirt, 2011).

Charcoal Methods

Methods for charcoal sampling were based on Whitlock and Larson (2001) and on the LacCore Lab's protocol for charcoal analysis. Each of the 3 cores was sampled continuously at 1-cm intervals in order to obtain a high-resolution charcoal record. These high-resolution, continuous samples are necessary to avoid missing peaks in the charcoal record, which can lead to false interpretation of background trends as peaks (Whitlock and Larson, 2001).

Samples for charcoal analysis were taken from the core and measured in a 1-cm^3 cut-tip syringe. These measured samples were placed in Erlenmeyer flasks and treated with 6% H_2O_2 (50°C for 24 hours) in order to remove organic matter in the sample. Then samples were sieved through a 125 μm sieve and dried in plastic petri dishes (50°C for 24 hours). This sieve size was consistent with theoretical and empirical charcoal studies that charcoal particle size is correlated to the proximity to the source (approximately 7 km) (Whitlock and Larson, 2001).

After drying in the petri dish, samples were examined using a laboratory microscope, and charcoal was counted for each petri dish. Each dish was placed upon a 1.125cm × 1.125 cm grid in order to increase accuracy of each count. Charcoal type was classified as either grass- or miscellaneous-type, which largely tend to be wood charcoal (Whitlock and Larson, 2001). In experiments that run at higher temperatures (>500°C), leaves and grass material combust first leaving a high proportion of wood charcoal in the sample (Whitlock and Larson, 2001). Thus, classifying charcoal can help to determine fire severity in an area.

Charcoal counts were then entered into the computer program CharAnalysis, which used the raw charcoal count data as well as a parameter file (Table 3) in order to reconstruct fire frequency and visually represent the data. CharAnalysis produces results that separate the background levels of charcoal from events that rise above that level in order to recreate a local fire history for the area. Background levels are created using a combination of a moving average of the charcoal data as well as a standard score (or z-score) between peak and noise values (Kelly et al., 2011). CharAnalysis smoothed both charcoal count data as well as background levels over a 100-year interval.

Dating Techniques

In order to create an age-to-depth model, loss on ignition were performed throughout the sampled core. Loss on ignition methods were based on the LacCore Lab's protocol. Loss on ignition (LOI) was performed at the LacCore lab in order to correlate the GNP-SWF14 core to the GNP-SWF10 core where ^{210}Pb dates have already been obtained. The top 30 cm of the core were sampled individually at .5 cm intervals, and then baked at 100°C in order to remove water, 500°C to remove organic matter, and finally 1000°C to remove carbonates. Organic carbon profiles proved to produce similar records, and were correlated to date the top 17.5 cm of the core. The resulting age-depth model is largely interpolated to create a sedimentation rate for deposits at the bottom of Swiftcurrent Lake. Once this rate is determined, it will help to create the charcoal accumulation rate for the area.

Table 3. Parameter file input for CharAnalysis, used to create the CHAR and BCHAR rates, and fire-frequency figures.

Stage	Variable	Parameter	Units	Description
Pretreatment	zoneDiv	-64.4	Cal yr BP	Years representing zone divisions
		650		
		1703		
	yrInterpolate	8	yr	Years to interpolate record to.
	transform	1	Index	1=base-10 log transform
Smoothing	method	4	Index	4=moving median
	yr	100	yr	Years to smooth record over for estimating BCHAR
PeakAnalysis	cPeak	1	Index	1=residuals ($C_{peak}=C_{interpolated} - C_{background}$)
	threshType	2	Index	2=locally defined
	threshMethod	3	Index	3=base threshold values on a percentile cut-off of a noise distribution, determined by a Gaussian mixture model
	threshValues	0.95	Variable	What threshold values do you want to evaluate
		0.95		
	minCountP	0.05	Probability	Cut-off probability for minimum count analysis.
Peak Analysis Results	peakFrequ	200	Yr	Years to smooth fire frequency and fire return intervals over
	$C_{background}$ sensitivity	1	Index	1=evaluate the sensitivity of your results to varying smoothing windows
	saveFigures	1	Index	1=save figures as .tiff and .pdf files
	saveData	1	Index	1=save data by appending it to this file
	allFigures	1	Index	1=display all diagnostic figures

Chapter 5 - Results

Lithology

The GNP-SWF-1A/1B cores are largely characterized by brown clayey silt, with interspersed pink clay layers and a few macro-scale organic layers. Laminations in the cores were visible, but appeared not to be varves. Under detailed smear-slide analysis, the brown background is composed of primarily siliciclastics (~80%) and smaller amounts of algal amorphous organic matter and diatoms. Pink clay layers also were composed primarily of siliciclastics (~40%), but also included carbonates, glass, diatoms, and algal amorphous organic matter. Major minerals found throughout the cores are quartz, clay and dolomite. Sediment density values range from ~1.0-1.6 g/cm^3 and magnetic susceptibility varies from 3-32 x 10^{-6} SI (Fig. 5).

Chronology

Core chronology was established by correlating the low-temperature (500°C) loss on ignition (LOI) profile from the upper part of core GNP-SWF14-1A/1B and compared to the % Total Organic Carbon (% TOC) from the ^{210}Pb-dated core of Oddo (2011) (Fig. 6). Correlation of the high-temperature (1000°C) LOI profile from the upper part of core GNP-SWF14-1A/1B and with the % TOC profile from the the ^{210}Pb-dated core of Oddo (2011) produced similar results, but 1000°C LOI correlation was not as clear. Field notes on coring depths, along with color matching of laminations were also used to correlate the two cores into a continuous depth series. Radiocarbon charcoal samples were taken at the bottom of the core (194 cm core depth) and mid-core, at a peak in the charcoal counts (74 cm core depth). These ages are not yet available. They will be used in the future to create a more accurate age-depth model.

An age-depth model was created using the %TOC/ 500°C LOI correlations in order to establish a mean sedimentation rate that could be extrapolated to the lower sections of the core correlation, made on the basis of organic matter profiles (Fig. 6), extends only for the uppermost 17.5 cm of the core (or approximately 150 years) of the new core. Sedimentation rate between the tie-points at 11 cm and 17.5 cm in the bottom of the correlated section was then extrapolated to the base of the core (Fig. 7). This extrapolation leads to significant uncertainty in the age-depth model. Adjusting the sedimentation rate slightly (1.2 mm/yr, used at present, to 1.76 mm/yr, the mean sedimentation rate between each tie-point) creates a 30% difference in the total age for the record, which highlights the importance of the pending radiocarbon ages lower in core GNP-SWF14-1A/1B. The preliminary model suggests that the core represents the last ~1700 years of sedimentation, at an average sedimentation rate of 1.2 mm/yr. The following discussion of fire history, below, is based on this preliminary age-depth model. Once radiocarbon ages for the lower core sections become available, both the age-depth model and the inferred fire history discussed below will be revised, if corrections need to be modified.

Charcoal Results

Figure 8 shows interpolated charcoal accumulation rates from raw charcoal counts over the past 1700 years in Swiftcurrent Lake. Overall interpolated charcoal accumulation rates (CHAR) range from 0 to 72 grains cm^{-2} yr^{-1} with a mean of 1.9 grains cm^{-2} yr^{-1}. Background charcoal levels (BCHAR) range from 0.1 to 6.8 grains cm^{-2} yr^{-1}. Charcoal GNP-SWF14-1A/1B, as well as to date specific events in the core record (Fig. 7). The

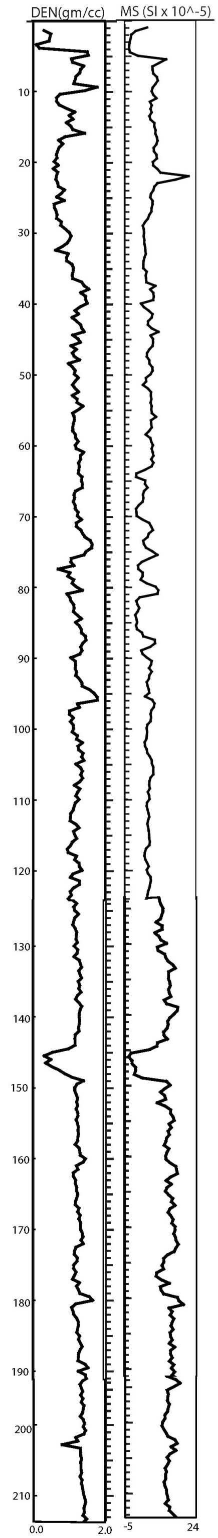


Figure 5. Swiftcurrent lithologic results. Plot of density (g/cm^3) and magnetic susceptibility (SI units) over the 1700 year record, acquired using the GeoTek Multisensor Core Logger.

Peaks (CHAR - BCHAR) ranges from 1.1 to 4.0 grains cm^{-2} yr^{-1} with an average threshold value for fire events being 1.4 grains cm^{-2} yr^{-1}. 37 statistically significant peaks occur in the 1700-year Swiftcurrent Lake record, each of which are considered to be a fire event in the record (Fig. 8).

Low levels of both CHAR and BCHAR were present from 1700-700 yr BP, with the exception of a large peak that occurred around 1290 yr BP. CHAR levels peak at 590 years BP when accumulation rates reach 72 grains cm^{-2} yr^{-1}. BCHAR levels peak at the same location within the core at 590 years BP, when rates exceed 6.3 grains cm^{-2} yr^{-1}. Peak charcoal accumulation rates indicate high fire activity during the most recent 700 years. BCHAR rises from a level of 1.4 to 1.8 grains cm^{-2} yr^{-1} and significant peaks in the CHAR record increase in frequency over the past 650 year record. Fire return intervals from 1700-700 yr BP are roughly around 52 years between events, and in the more recent 650 years there are roughly 41 years between events.

Figure 9 shows fire frequency for the core, smoothed over 200 years. There is a steady increase in fire frequency from 1700 yr BP to the peak in fire frequency that occurs at roughly 1150 yr BP. This peak is followed by a decline in fire frequency until 900 yr BP, when fire frequency once again begins to increase to a second peak at 600 yr BP. This peak in fire frequency is the largest, surpassing 6 fire events per 200 years, and corresponds to high CHAR rates and BCHAR levels (Fig. 8). This peak is followed by another fall and rise in the record, with a third peak in the record occurring at 225 yr BP. This peak is followed by a steady decline to present day.

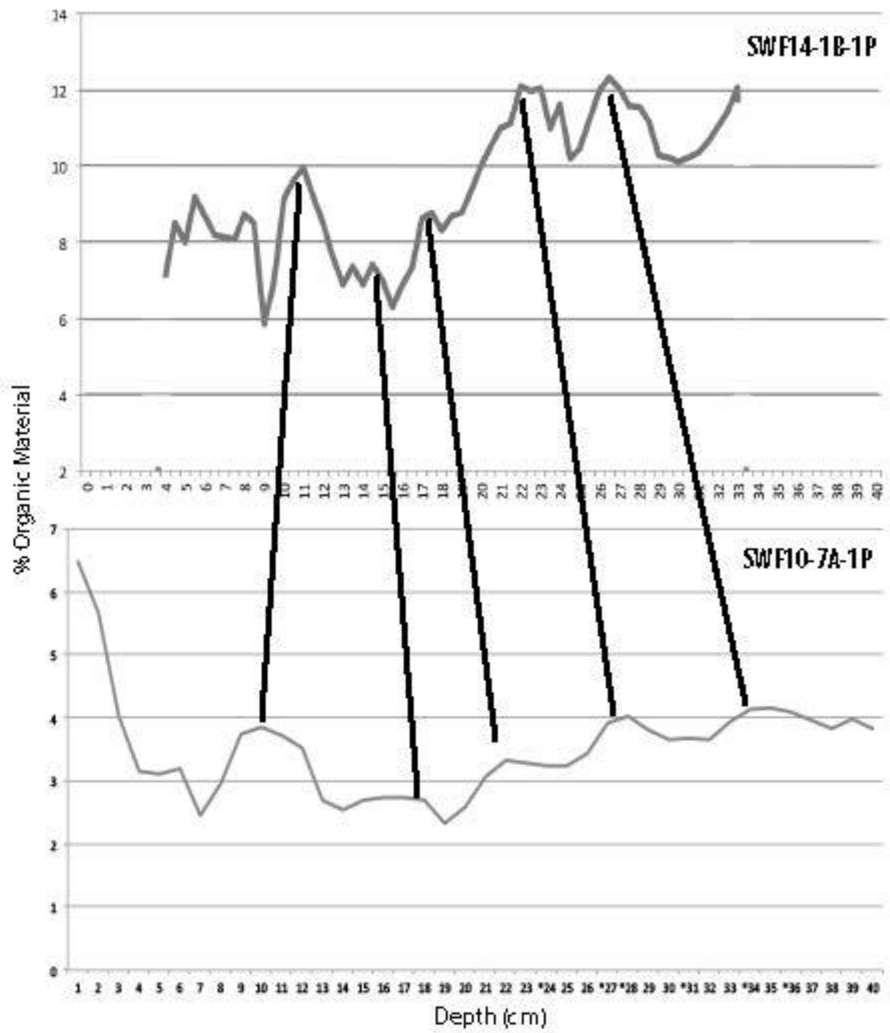


Figure 6. Comparison of the loss-on-ignition data for organic carbon versus the % total organic carbon in Oddo (2011)'s core. Lines across graphs represent correlations of peaks identified in the cores.

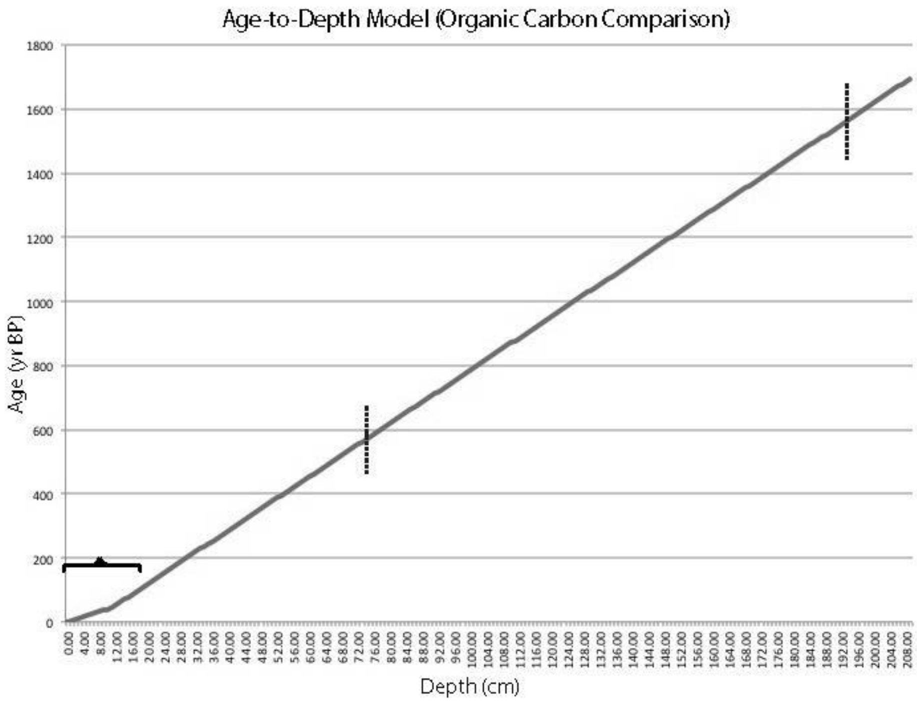


Figure 7. Age-to-Depth Model based on organic carbon correlation. Bracket represents depths that are controlled by the correlation and dashed lines represent locations of pending radiocarbon dates.

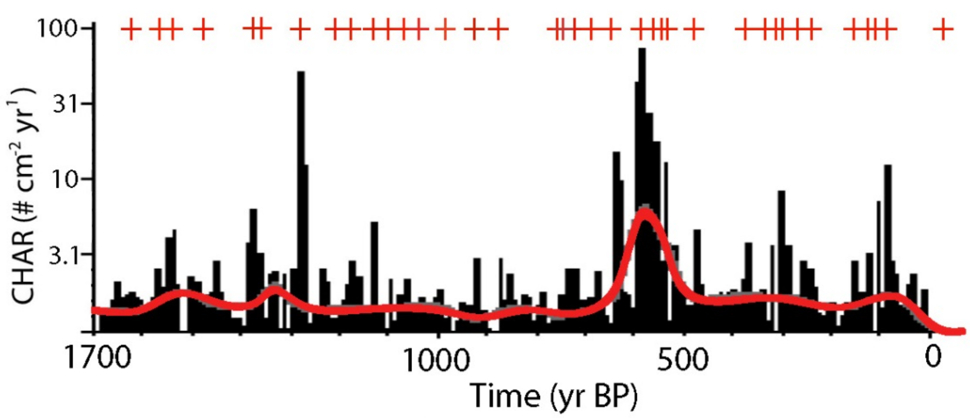


Figure 8. CharAnalysis graph showing the charcoal accumulation rate over the 1703-year record. Black line shows charcoal abundance (grains/cm^3/year) and the red line shows background charcoal levels (BCHAR). Red plus signs indicate significant fire events.

A large CHAR peak that rises above the BCHAR level falls within a well-constrained ^{210}Pb age control, with an age of 1924 AD±3.5 years based on the age/depth model, likely corresponding to the Heavens Peak Fire in 1936 AD. This historical fire completely burned the northeast Grinnell Glacier Valley, then blew over the Continental Divide into West Glacier (Larson, 2012). Presence of the Heavens Peak Fire in the record places confidence in CHAR peaks linking to local fire activity.

Chapter 6 - Discussion and Conclusions

The Swiftcurrent Lake sediment core collected in 2014 allows for further examination of the relationships between fire, environmental shifts, and climate for the past 1700 years in GNP. This record also is compared to previous records of fire history, both throughout GNP and in the northern Rocky Mountain region. This discussion assumes that the charcoal measurements taken by this study (CHAR, BCHAR, fire frequency) together constitute evidence of local fire activity for the Swiftcurrent Valley and Grinnell Glacier drainage basins. These measurements are sensitive to seasonal character as well as long-term shifts in climate, which makes interpretations challenging. For example, annual precipitation may remain constant in the drainage basins, but increased summer storminess may cause an increase in hillslope erosion or change in in glacier size. An increase in hillslope erosion could, alternatively, be the result of cooler temperatures, with less vegetation to hold sediment down, or of increased annual precipitation. Increases in fire frequency could be the result of increased aridity in the climate or a shift in snowmelt dates for the region. Interpretations for this study should be considered preliminary, especially because sampling resolution does not allow for seasonality to be constrained.

The ~1700 year record taken from the northern sub-basin in Swiftcurrent Lake contains a short record of the late-Holocene fire history in the Many Glacier area. A promising correlation in the record is evidence of the Heaven's Peak fire in 1936 (peak at ~1924±3.5 AD) (Larson, 2012). Although the age of the peak determined by our age-depth model does not match exactly the historically documented age of the fire, it is close in age and it seems reasonable that it is likely the result of the 1936 crown fire.

There are two distinct zones in the fire frequency record: one from 1700-650 yr BP and one from 650 yr BP-present (Fig. 9). The most recent zone is characterized by higher CHAR and BCHAR rates as well as a higher frequency of peaks within the fire-frequency record. Although 650 yr BP is characterized by high fire activity, the most recent 100 years show a steady decline in BCHAR rates and fire frequency. Previous work completed on other sediment cores suggests the opposite result as fire frequency in the western United States has been shown to increase over the past century (Westerling et al., 2006; Kutvirt, 2011; Whitlock et al., 2003). A possible explanation for this result is increased hydrologic energy in the northern Swiftcurrent Lake drainage basin. This would lead to lighter charcoal, otherwise retained in the Grinnell Valley sub-basin, being swept through the system leaving a less statistically significant amount of charcoal.

The record collected in 2014 contains a mean CHAR rate (0.3272 grains cm^{-2} yr^{-1}) that is lower than CHAR rates in lakes from similar settings (Table 4) (Marlon et al., 2006; Kutvirt 2011). CHAR accumulation rates reflect a variety of factors, some indicative of climate and others specific to physical site characteristics (Marlon et al., 2006). Studies have shown that CHAR rates can be extremely variable between different sites, depending on lake size, watershed area, elevation, precipitation regimes and vegetative cover. Marlon et al. (2006) found that lake area, watershed area, elevation and arboreal pollen percentages (%AP) explain much of the variation between charcoal accumulation rates. Lake size is positively correlated with mean charcoal accumulation (larger lakes generally have higher accumulation rates), whereas elevation is negatively correlated (higher elevations have lower accumulation rates). Forest cover (%AP) is positively correlated with CHAR rates. Table 4 compares this Swiftcurrent site to previous studies with respect to elevation, lake surface area, annual precipitation, and winter and summer mean temperatures for 6 other northern Rocky Mountain region sites.

Comparison of raw charcoal counts between the northern and southern sub-basin also produces interesting results. The record from the southern sub-basin was collected from a site with a much lower sedimentation rate, and the northern sub-basin record fits within the lower fire frequency period from 2100 Cal yr BP to the present. CHAR accumulation rates differ greatly between these two sites. This 2010 record reached charcoal accumulation rates of 0.36 grains cm^{-2} yr^{-1} for the most recent 2100 yr BP. Charcoal accumulation in the 2014 record reached 1.8 grains cm-2 yr-1. This difference is likely due to the geomorphic differences between the two drainage basins; two deep lakes occur within the watershed in the Grinnell Glacier drainage basin and serve as sediment sinks during transport. The differences in charcoal accumulation between these two sub-basins could be a result of differing watershed attributes for the respective locations.

Raw charcoal concentrations per cm^3 did not exceed 88 grains in Kutvirt's (2011) core from the southern sub-basin, whereas peaks in this core reached 914 grains per cm^3 in the northern sub-basin. This is likely the result of the larger drainage area in the northern sub-basin that increases the area eroded within the watershed. The Swiftcurrent core collected in 2014 correlates to sections of Kutvirt's (2011) core that were determined to be periods of cooling and lower fire frequency than the rest of the 7630 year record. This result was supported by a lower fire frequency and lower severity in the last 2100 yr BP (Kutvirt, 2011). The large increase in charcoal abundance on my core over the most recent 700 yr BP may also be a result of the larger drainage size for the northern sub-basin, and still represents this lower charcoal accumulation rate, but it could be a result of a different fire record from the northern sub-basin.

The lower CHAR rate for Swiftcurrent Lake compared to the results of Brunelle et al. (2006) is unexpected, given its relatively lower elevation and larger lake area. This record has other anomalous characteristics (decreasing fire frequency to present), which could indicate an abnormal record at this location. A potential explanation for these anomalous characteristics is Swiftcurrent being surrounded by a subalpine environment where glaciers play a key geomorphic role in the environment. This would lead to more water associated with the environment compared to other locations, which would increase hydrologic energy in the watershed. Forest cover was not evaluated for Swiftcurrent Lake in this study, but previous work has assessed the glacial valley as an area of low vegetative cover (Kutvirt, 2011). Reduced forest cover compared to other locations in this area could also be one of the factors contributing to this lower CHAR rate in Swiftcurrent Lake.

Peaks in the fire frequency record (1150 yr BP, 600 yr BP, and 225 yr BP) appear not to be consistent with what might be expected from regional climate history. The Little Ice Age, which occurred from roughly 1500-1850 AD, was a time of cooler temperatures in the northern hemisphere (Mann et al., 2009). The peak in fire frequency during this time could be the result of the ecosystem's recovery and development towards becoming a stand forest, which results in lower fire frequency, from the Little Ice Age to present. Grassland environments in north-central Montana are characterized by higher fire frequency than the later-successional hardwood tree forests, and occur earlier in ecological succession of the northern Rocky Mountain region (Brown et al., 2000).

Another unexpected result in fire frequency is that the global Medieval Climate Anomaly (roughly 950-1250 AD), which is represented by warmer, drier climate in the western United States (Mann et al., 2009), is represented in the new Swiftcurrent Lake record by a trough in the fire frequency. Given the history of the region, where increases in temperature correlate to increases in fire frequency (Westerling et. al, 2006), the decrease in fire frequency is unanticipated. A possible explanation for this trough in the record is that the sub-alpine environments may not be as affected due to the lower amount of vegetation compared to lower elevation regions, which would reduce the number of plants available for fuel. Another explanation could be that a warmer, more arid environment leads in increase ice and snowpack melt in these sub-alpine environments. This melt would increase water in the system, which may lead to a decrease in large fires.

Currently, due to the degree of interpolation in the age-depth model (Figure 5), confidence is limited in the dating of these specific intervals of high and low fire frequency. The most recent 150 years of the core's record are well correlated to the ^{210}Pb-core, so the decrease in charcoal influx over the last 150 years, following a peak not much earlier (and likely during the Little Ice Age) seems robust. However, given the difficultly of estimating sedimentation rates for the segment of the core more than about 150 years old makes assignment of ages for earlier shifts in charcoal influx very uncertain. If a revised age-depth model were to reduce the total age of the record by 200 years these fire-frequency peaks over the last millennium would be more consistent with the expected regional climate history.

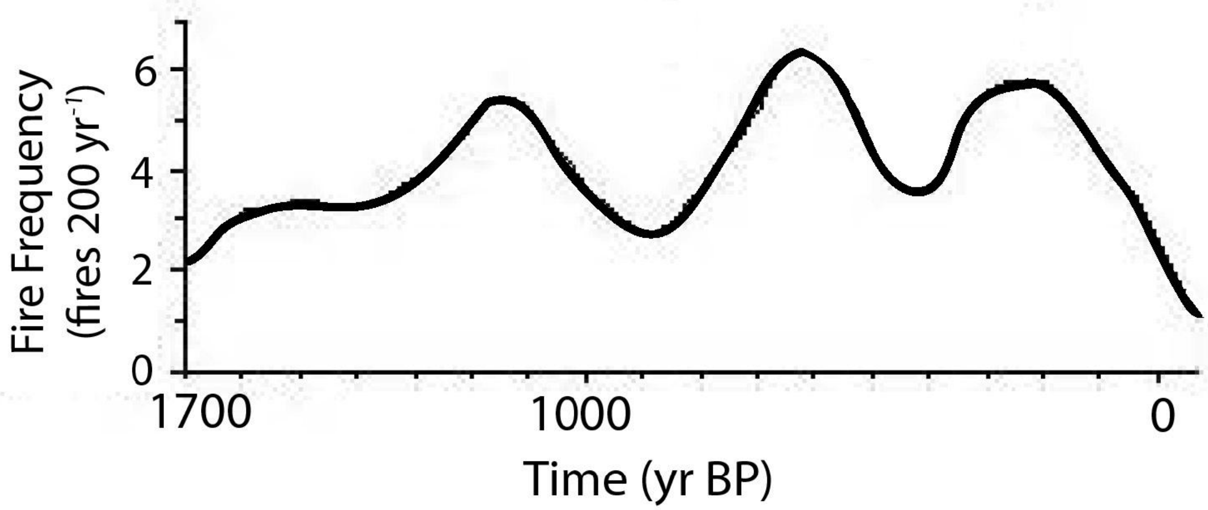


Figure 9. CharAnalysis graph of fire frequency (fires/200 years) over the 1703 year record.

Table 4. Comparison of factors contributing to CHAR rates for 6 lakes in the northern Rocky Mountain region (Marlon et al., 2009).

Lake	Elevation (m)	Lake Area (ha)	Annual Precip. (cm)	Avg. Jan. Temp. (deg C)	Avg. Jul. Temp. (deg C)	CHAR ($p/cm^{-2}yr^{-1}$)
Swiftcurrent, MT	1486	42	66.31	-5	16.9	.3272
Burt Knob, ID	2250	1.1	46	-7.1	16.4	.11
Foy Lake, MT	1006	85	40	-6.3	17.3	14.88
Pintlar, MT	1921	4.3	31	-6	17.4	3.05
Baker, MT	2300	2.2	34	-7.7	16.2	.3
Hoodoo, ID	1770	2.5	41	-5.7	17.3	.68

The 1700-year fire record shows a higher number of fire events than previously found in the core evaluated in 2011. The fire return interval of the northern Swiftcurrent sub-basin is roughly 46 years between fires, whereas the southern sub-basin had an average return interval of 363 years between fires. Although uncertainty in the preliminary age-depth model limits confidence in the dating of specific intervals of high and low fire frequency, comparison of this record and the Kutvirt (2011) record provides interesting insight into how charcoal is transported through the system. The lower raw charcoal counts in the southern sub-basin could be due to the two large lakes (Lake Josephine and Lower Grinnell Lake) that serve as sediment sinks in the watershed, or it could be the result of the smaller drainage area. Despite these difficulties in interpreting the record from the new core, comparison to a third core within either sub-basin would help to resolve the discrepancies between the 2011 and 2014 charcoal records.

References

Arp, C. D., Schmidt, J. C., Baker, M. A. and Myers, A. K., 2007. Stream geomorphology in a mountain lake district: hydraulic geometry, sediment sources and sinks, and downstream lake effects. *Earth Surf. Process. Landforms*, v. 32, pp. 525–543.

Barrett, S.W., S.F. Arno, and S.H. Key, 1991. Fire regimes of western larch - lodgepole pine forests in Glacier National Park. *Canadian Journal of Forest Research*, v. 21, pp. 1711-1720.

Bond, W. J., and J. E. Keeley, 2005. Fire as a global 'herbivore': the ecology and evolution of flammable ecosystems. *Trends in Ecology and Evolution*, v. 20, n. 7.

Bowman, D. M. J. S., J. K. Balch, P. Artaxo, W. J. Bond, J. M. Carlson, M. A. Cochrane, C. M. D'Antonio, R. S. DeFries, J. C. Doyle, S. P. Harrison, F. H. Johnston, J. E. Keeley, M. A. Krawchuk, C. A. Kull, J. B. Marston, M. A. Moritz, I. C. Prentice, C. I. Roos, A. C. Scott, T. W. Swetnam, G. R. van def Werf, S. J. Pyne, 2009. Fire in the Earth System. *Science*, v. 324 pp. 481-484.

Bowman, D. M. J. S., B. P. Murphy, M. M. Boer, R. A. Bradstock, G. J. Cary, 2013. Forest fire management, climate change, and the risk of catastrophic carbon losses. *Frontiers in Ecology and the Environment*, v. 11, pp. 66-68.

Brown, J., K. Smith, J. Kapler, 2000. Wildland fire in ecosystems: effects of fire on flora. Gen. Tech. Rep. RMRS-GTR-42-vol. 2. Ogden, UT: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 257 p.

Brunelle A. and C. Whitlock, 2003. Postglacial fire, vegetation, and climate history in the Clearwater Range, Northern Idaho, USA. *Quaternary Research*, v. 60, no.3, pp. 307-318.

Brunelle, A., C., Whitlock, P. Bartlein, K. Kipfmueller, 2005. Holocene fire and vegetation along environmental gradients in the northern rocky mountains. *Quaternary Science Reviews* 24 (20-21) (11): 2281-300.

Daniau et al, P. J. B., S. P. Harrison, I. C. Prentice, S. Brewer, P. Friedlingstein, T. I. Harrison-Prentice, J. Inoue, K. Izumi, J. R. Marlon, S. Mooney, M. J. Power, J. Stevenson, W. Tinner, M. Andric, J. Atanassova, H. Behling, M. Black, O. Blarquez, K. J. Brown, C. Carcaillet, E. A. Colhoun, D. Colombaroli, B. A. S. Davis, D. D'Costa, J. Dodson, L. Dupont, Z. Eshetu, D. G. Gavin, A. Genries, S. Haberle, D. J. Hallett, G. Hope, S. P. Horn, T. G. Kassa, F. Katamura, L. M. Kennedy, P. Kershaw, S. Krivonogov, C. Long, D. Magri, E. Marinova, G. M. McKenzie, P. I. Moreno, P. Moss, F. H. Neumann, E. Norstrom, C. Paitre, D. Rius, N. Roberts, G. S. Robinson, N. Sasaki, L. Scott, H. Takahara, V. Terwilliger, F. Thevenon, R. Turner, V. G. Valsecchi, B. Vannière, M. Walsh, N. Williams, Y. Zhang (2012) Predictability of biomass burning in response to climate changes. *Global Biogeochemical Cycles,* 26, 12.

Gardner, J. J. & C. Whitlock, 2001. Charcoal accumulation following a recent fire in the Cascade Range, northwestern USA, and its relevance for fire-history studies. The Holocene. 11: 541–549.

Geddes, Christine A., Daniel G. Brown, and Daniel B. Fagre, 2005. Topography and Vegetation as Predictors of Snow Water Equivalent across the Alpine Treeline Ecotone at Lee Ridge, Glacier National Park, Montana, U.S.A. *Arctic, Antarctic, and Alpine Research*: May 2005, Vol. 37, No. 2, pp. 197-205.

Gill, A. M., N. D. Burrows and R. A. Bradstock, 1995. Fire modelling and fire weather in an Australian desert. *Landscape Fires '93: Proceedings of an Australian Bushfire Conference, Perth, Western Australia, 27-29 September 1993.*, 29-34.

Kelly, R. F., P. E. Higuera, C. M. Barrett, and F. S. Hu, 2011. A signal-to-noise index to quantify the potential for peak detection insediment–charcoal records. *Quaternary Research*, v. 75, pp. 11-17.

Key, Carl H., D.B. Fagre, and R.K. Menicke, 2002. United States Geological Survey Professional Paper: Washington, D.C., U.S. Goevernment Printing Office p.1365.

Kutvirt, Jacqueline C., 2011. Holocene Fire History of the Southern Swiftcurrent Basin: a Paleoenvironmental Study of Glacier National Park. Keck Symposium Volume 24.

Larson, Rolf, 2012. Firestorm!:The Story of the Heaven's Peak Fire of 1936. Web. Accessed Jan 2015. <http://www.glacierparkfoundation.org/History/firestorm.html>.

MacGregor, K.R., C.A. Riihimaki, A.Myrbo, M.D. Shapley, K. Jankowski, 2011. Geomorphic and climatic change over the past 12,900 yr at Swiftcurrent Lake, Glacier National Park, Montana, USA. *Quaternary Research*, v. 75.

Mann, M.E., Z. Zhang, S. Rutherford, R.S. Bradley, M.K. Hughes, D. Shindell, C. Ammann, G. Faluvegi, F. Ni, 2009. Global signitures and Dynamical Origins of the Little Ice Age and Medieval Climate Anomaly. Science, 326 (5957): 1256-1260.

Marlon, J. R., P. J. Bartlein, D. G. Gavin, C. J. Long, R. S. Anderson, C. E. Briles, K. J. Brown, D. Colombaroli, D. J. Hallett, M. J. Power, E. A. Scharf, and M. K. Walsh, 2012. Long-term perspective on wildfires in the western USA. *Proceedings of the National Academy of Sciences*, v. 109, pp. E535-E543.

Marlon, J. R., P. J. Bartlein and C. Whitlock, 2006. Fire-fuel-climate linkages in the northwestern USA during the Holocene. *The Holocene* v. 16, no. 8, pp. 1059-1071.

National Interagency Fire Center, 2013. Web. Accessed Jan 2015. National fire statistics <http://www.nifc.gov/fireInfo/fireInfo_statistics.html>.

National Parks Service, 2013. Web. Accessed Jan 2015. Visitor statistics <https://irma.nps.gov/Stats/>.

National Park Service. Accessed Feb 2015. Fire Ecology of Yellowstone National Park <http://www.nps.gov/yell/learn/management/fireecology.htm>

Nesje, Atle. A Piston Corer for Lacustrine and Marine Sediments. *Arctic and Alpine Research*, v. 24, pp. 257-259.

Oddo, P., 2011. Geochemical Evidence of Anthropogenic Impacts on Swiftcurrent Lake, Glacier National Park, MT. Keck Symposium Volume 24.

Schoennagel, T., T.T. Veblen, and W.H. Romme, 2004. The interaction of fire, fuels, and climate across Rocky Mountain forests. *BioScience* v. 54, no. 7, pp. 661-676.

Westerling, A., H. Hidalgo, D. Cayan, T. Swetnam, 2006. Warming and Earlier Spring Increases Western U.S. Forest Wildfire Activity. *Science*, v. 313, pp. 940-943.

Whitlock, C., 2004. Land management: Forests, fires and climate. *Nature* 432 (7013): 28.

Whitlock, C. and C. Larson, 2001. Charcoal as a fire proxy, J.P. Smol, H.J.B. Birks, W.M. Last (Eds.), Tracking Environmental Changes Using Lake sediments. Volume 3: Terrestrial, Algal, and Siliceous Indicators, Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 75–96.

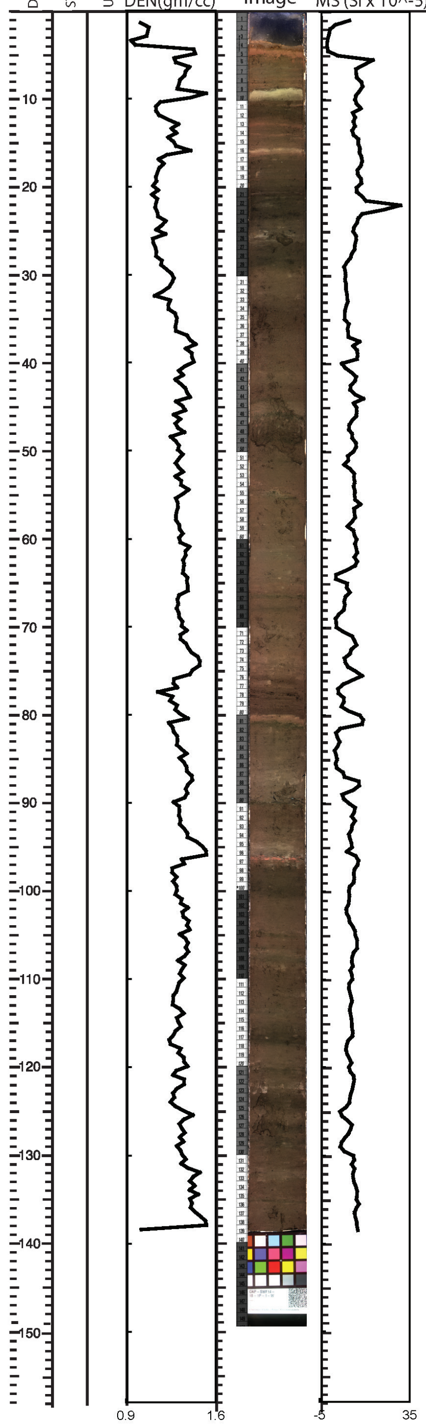
Whitlock, C., S. Shafer, J. Marlon, 2003. The role of climate and vegetation change in shaping past and future fire regimes in the northwestern US and the implications for ecosystem management. *Forest Ecology and Management*, v. 178, pp. 5-21.

Appendix I: Initial Core Description Sheets

INITIAL CORE DESCRIPTION

LAKE SWIFTCURRENT
CORE ID GNP-SWF14-1B-1P-1-W
SECTION LENGTH (cm) 138.4 mblf top
SED. LENGTH (cm) 135.0 mblf bot
Describer Ashleigh Covarrubias
Date 08/07/2014

Depth (cm) | STRUC. | UNIT | DEN(gm/cc) | Image | MS (SI x 10^-5) | LITHOLOGIC DESCRIPTION



0-3.4 cm: sediment-water interface
(SS 3.3 cm: sediment-water interface)

3.4-138.4 cm: massive brown-gray silt, diffuse grayish-pink clay layering

4.3-5.0 cm: reddish-pink clay layer

9.0-10.2 cm: distinct light gray to dark gray clay layer

96.0-96.4 cm: semi-distinct pinkish layer

INITIAL CORE DESCRIPTION

LRC

LAKE SWIFTCURRENT

CORE ID GNP-SWF14-1A-2B-1-W

SECTION LENGTH (cm) 150.5

SED. LENGTH (cm) 150.4

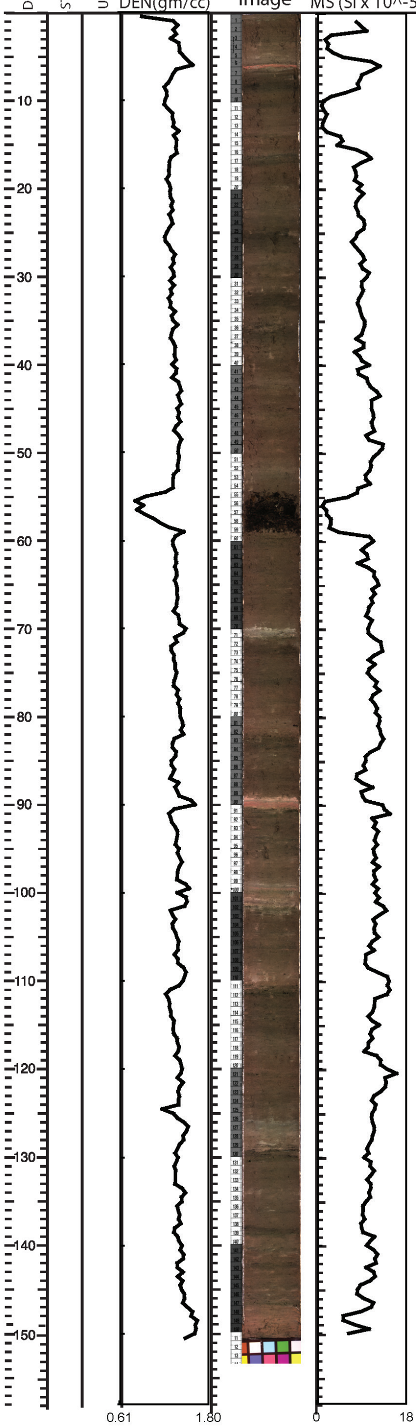
mblf top

mblf bot

Describer Ashleigh Covarrubias

Date 08/07/2014

Depth (cm) | STRUC. | UNIT | DEN(gm/cc) | Image | MS (SI x 10^-5) | LITHOLOGIC DESCRIPTION



0-150.4 cm: massive brown-gray silt, diffuse layering

5.9-6.1 cm: red to pink clay layer

(SS 6.1cm: reddish clay layer)

54.3-58.7 cm: macro scale black organic layer

69.7-70.6 cm: dark gray clay layer

(SS 89.6cm: pink-gray clay layer)

89.0-90.1 cm: three well defined layers of clay, light pink gray to gray green and bottom layer is reddish pink

INITIAL CORE DESCRIPTION

LAKE SWIFTCURRENT

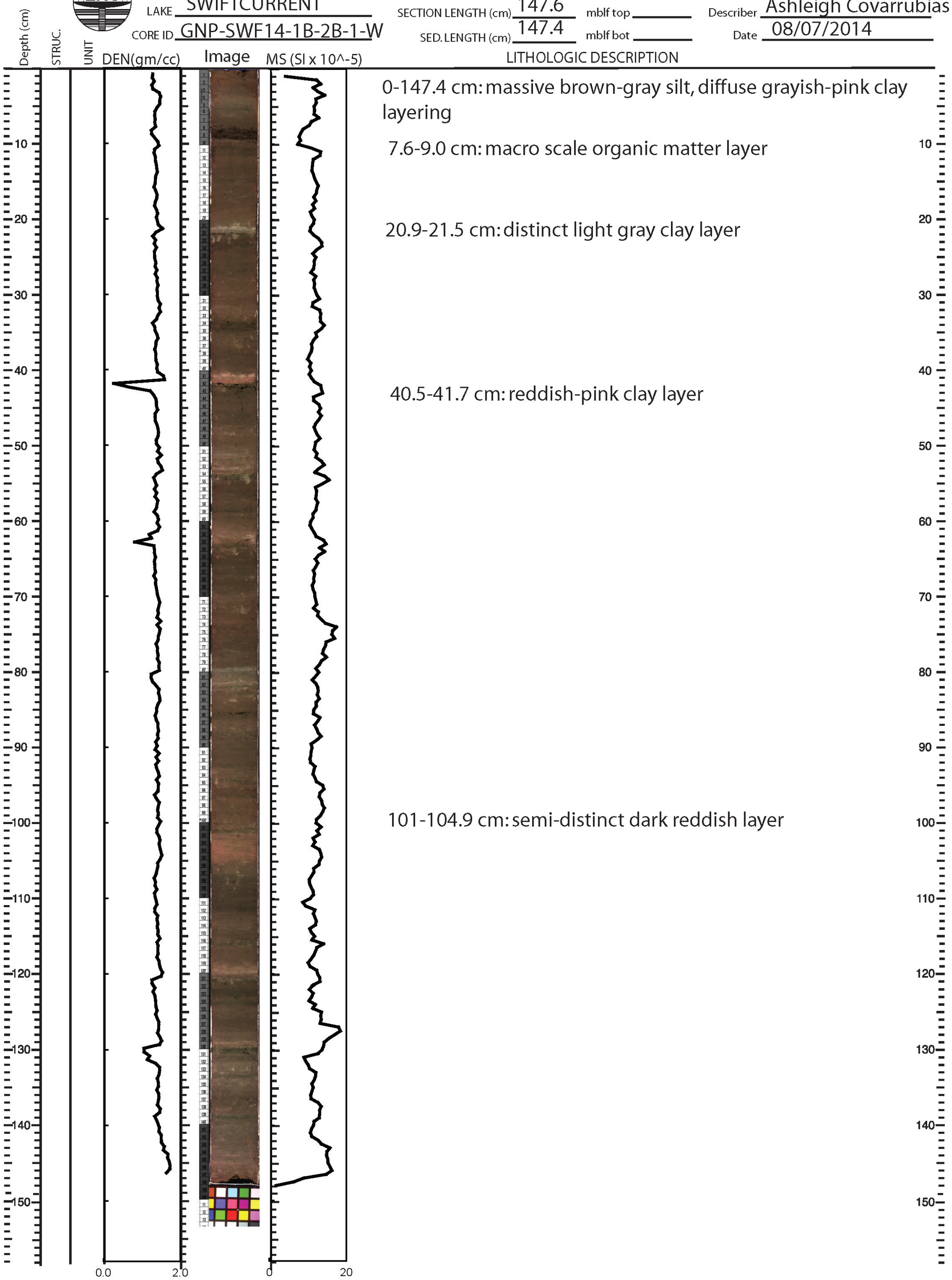
CORE ID GNP-SWF14-1B-2B-1-W

SECTION LENGTH (cm) 147.6 mblf top

SED. LENGTH (cm) 147.4 mblf bot

Describer Ashleigh Covarrubias

Date 08/07/2014



LITHOLOGIC DESCRIPTION

0-147.4 cm: massive brown-gray silt, diffuse grayish-pink clay layering

7.6-9.0 cm: macro scale organic matter layer

20.9-21.5 cm: distinct light gray clay layer

40.5-41.7 cm: reddish-pink clay layer

101-104.9 cm: semi-distinct dark reddish layer

Appendix II: Charcoal Count Sheets

cmTop (cm)	cmBot (cm)	ageTop (yr BP)	ageBot (yr BP)	charVol (cm^3)	charCount (#)
2.00	3.00	8	12	1	7
4.00	5.00	16	20	1	0
6.00	7.00	24	28	1	3
8.00	9.00	32	36	1	6
10.00	11.00	38	45	1	11
12.00	13.00	53	61	1	5
14.00	15.00	70	78	1	14
16.00	17.00	86	95	1	106
18.00	19.00	103	111	1	53
20.00	21.00	120	128	1	19
22.00	23.00	136	145	1	7
24.00	25.00	153	161	1	19
26.00	27.00	170	178	1	6
28.00	29.00	186	195	1	1
30.00	31.00	203	211	1	8
32.00	33.00	220	228	1	4
34.00	35.00	236	245	1	20
36.00	37.00	253	261	1	21
38.00	39.00	270	278	1	6
40.00	41.00	286	295	1	25
42.00	43.00	303	311	1	62
44.00	45.00	320	328	0.5	11
46.00	47.00	336	345	1	8
48.00	49.00	353	361	1	8
50.00	51.00	370	378	1	31
52.00	53.00	386	395	1	8
54.00	55.00	403	411	1	13
56.00	57.00	420	428	1	12
58.00	59.00	436	445	1	9
60.00	61.00	453	461	1	7
62.00	63.00	470	478	1	37
64.00	65.00	486	495	1	4
66.00	67.00	503	511	1	7
68.00	69.00	520	528	1	22
70.00	71.00	536	545	1	110
72.00	73.00	553	561	1	172
74.00	75.00	570	578	1	303
76.00	77.00	586	595	1	914

78.00	79.00	603	611	1	6
80.00	81.00	620	628	1	12
82.00	83.00	636	645	1	180
84.00	85.00	653	661	1	3
86.00	87.00	670	678	1	15
88.00	89.00	686	695	1	6
90.00	91.00	703	711	1	5
92.00	93.00	720	728	1	13
94.00	95.00	736	745	1	14
96.00	97.00	753	761	1	7
98.00	99.00	770	778	1	3
100.00	101.00	786	795	1	10
102.00	103.00	803	811	1	2
104.00	105.00	820	828	1	11
106.00	107.00	836	845	1	5
108.00	109.00	853	861	1	15
110.00	111.00	870	878	1	20
114.00	115.00	903	911	1	3
116.00	117.00	920	928	1	17
118.00	119.00	936	945	1	4
120.00	121.00	953	961	1	5
123.00	124.00	978	986	1	5
125.00	126.00	995	1003	1	12
127.00	128.00	1011	1020	1	8
129.00	130.00	1028	1036	1	9
131.00	132.00	1045	1053	1	4
133.00	134.00	1061	1070	1	13

135.00	136.00	1078	1086	1	7
137.00	138.00	1095	1103	1	10
139.00	140.00	1111	1120	1	4
141.00	142.00	1128	1136	1	36
143.00	144.00	1145	1153	1	3
145.00	146.00	1161	1170	1	13
147.00	148.00	1178	1186	1	23
149.00	150.00	1195	1203	1	8
151.00	152.00	1211	1220	1	3
153.00	154.00	1228	1236	1	21
155.00	156.00	1245	1253	1	5
157.00	158.00	1261	1270	1	1
159.00	160.00	1278	1286	1	495
161.00	162.00	1295	1303	1	14
163.00	164.00	1311	1320	1	11
165.00	166.00	1328	1336	1	13
166.00	167.00	1336	1345	1	11
169.00	170.00	1361	1370	1	24
171.00	172.00	1378	1386	1	65
173.00	174.00	1395	1403	1	1
175.00	176.00	1411	1420	1	3
177.0	178.0	1428	1436	1	7

0	0				
179.00	180.00	1445	1453	1	18
180.00	181.00	1453	1461	1	9
182.00	183.00	1470	1478	1	7
184.00	185.00	1486	1495	1	10
186.00	187.00	1503	1511	1	11
189.00	190.00	1528	1536	1	9
190.00	191.00	1536	1545	1	32
191.00	192.00	1545	1553	1	25
192.00	193.00	1553	1561	1	4
193.00	194.00	1561	1570	1	6
194.00	195.00	1570	1578	1	15
195.00	196.00	1578	1586	1	1
196.00	197.00	1586	1595	1	4
197.00	198.00	1595	1603	1	2
198.00	199.00	1603	1611	1	3
199.00	200.00	1611	1620	1	6
200.00	201.00	1620	1628	1	5
201.00	202.00	1628	1636	1	8
202.00	203.00	1636	1645	1	3
203.00	204.00	1645	1653	1	10
204.00	205.00	1653	1661	1	6

205.00	206.00	1661	1670	1	2
206.00	207.00	1670	1678	1	3
207.00	208.00	1678	1686	1	3
208.00	209.00	1686	1695	1	4
209.00	210.00	1695	1703	1	3