PALEOECOLOGICAL RECONSTRUCTION OF THE HOLOCENE FIRE REGIME AT MUD LAKE, EASTERN ONTARIO, NEAR ST. LAWRENCE ISLANDS NATIONAL PARK

by

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Abstract

Wildfire is an ecological disturbance that plays an important role in ecosystem function and interacts with climate and vegetation, relationships that may be altered by ongoing climate change. Insights from paleoecology can provide context for environmental change, including the natural range of variability. Here, the Holocene fire history of a small watershed in eastern Ontario, Canada is reconstructed. A high-resolution macroscopic charcoal series was derived from the lacustrine sediment of Mud Lake, north of Gananoque, Ontario and within the Frontenac Arch. Analysis of the charcoal record estimates a mean fire-return-interval (FRI) of 175 yr/fire around Mud Lake during the Holocene, and similar mean FRIs during different time periods indicates that it has been a largely stationary fire regime. The analysis suggests that fire activity may have recently increased, but a lack of documentary fire records for the area leaves this uncertain. There is no indication that humans have significantly impacted the fire regime, though anthropogenic ignition could have played a role in the area's recent fires. The fire regime around Mud Lake does not appear to have shifted in association with major changes in regional vegetation. Fire activity does correlate with some paleoclimate trends. The estimated fire frequency decreased around 7500 yr BP, when wetter summers became more common in eastern Canada, and a recent increase in fire frequency would parallel with more frequent incursions of dry and cool air masses into the region. During other parts of the record, however, the fire activity does not appear to reflect the major climate impacts. The fire history of Mud Lake is relevant to the ecological management of eastern Ontario's St. Lawrence Islands National Park and its restoration of a rare, fire-dependent tree species, the pitch pine. Though predictions vary, this area's climate may become more favorable to fire through an increase in temperature and a decrease in summer precipitation. By providing information about the natural variability of fire activity in eastern Ontario, this research can be applied towards setting appropriate management goals during future environmental change.

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Table of Contents

List of Figures

List of Tables

List of Abbreviations and Acronyms

ºC	degrees Celsius
^{214}Bi	radioisotope of bismuth (Bi)
^{14}C	radioisotope of carbon (C)
^{137}Cs	radioisotope of caesium (Cs)
^{210}Pb	radioisotope of lead (Pb)
AD	*Anno Domini*
AMS	accelerator mass spectrometry
AO	Arctic Oscillation
CHAR	charcoal accumulation rate
CI	confidence interval
CLPP	Charleston Lake Provincial Park
CO_2	carbon dioxide
CRS	constant rate of supply model (^{210}Pb sediment dating)
ENSO	El Niño/Southern Oscillation
FRI	fire return interval
GOF	goodness-of-fit
LIA	Little Ice Age
mFRI	mean fire return interval
MWP	Medieval Warm Period
NaClO	sodium hypochlorite

N_{FRI}	number of fire return intervals
OFR	Outside of the Fire Region
OMNR	Ontario Ministry of Natural Resources
PDO	Pacific Decadal Oscillation
PEARL	Paleoecological Environmental Assessment and Research Laboratory
SD	standard deviation
SLINP	St. Lawrence Islands National Park
SNI	signal-to-noise index
SOI	Southern Oscillation Index
Wbl *b*	Weibull model b-parameter (scale)
Wbl *c*	Weibull model c-parameter (shape)
yr BP	calendar years before present (present at 1950 AD)

Chapter 1

Introduction

1.1 Overview

This project is investigating the history of wildfire in eastern Ontario during the Holocene. The key goal is the fire-history reconstruction of a small watershed in this region over approximately the past 12000 years using sediment-charcoal techniques. Few studies of paleofire exist in eastern Ontario, although fire is an ecological process important in its forest habitats (Van Sleeuwan 2006).

As fire is often perceived as a destructive force to human settlement, it is not necessarily viewed in a positive light. Fire can be used as an agricultural tool for land clearing, but humans more frequently affect fire activity by suppressing them, limiting fire size, or through unintentional ignitions (Johnson 1992). Fire suppression became a common environmental management tool over the last century to prevent damage to property, natural resources, and undeveloped areas. It has become less frequent, though, as the exclusion of fire led to uncontrollable burns and negative impacts on forest health (Stephens and Ruth 2005). Moreover, anthropogenic climate change will increasingly impact fire regimes in the future (Flannigan et al. 2005). For instance, a 3 x CO_2 global climate model (GCM) predicts a 50% to 100% increase in area burned by fire in eastern Ontario by 2100 (Flannigan et al. 2005). As a result of these influences, fire regimes considered ‘natural’ are rare.

Interest in long-term fire activity has grown through an increased emphasis placed on fire management in natural areas. This new approach seeks to restore natural fire regimes (Flannigan et al. 2008), and prescribed fire has been increasingly adopted in ecosystem management (Fernandes and Botelho 2003). Information about long-term fire frequency is an asset, particularly when it provides details on pre-settlement fire regimes (Hallett and Walker 2000). A federally administered protected area in eastern Ontario, St. Lawrence Islands National Park, is seeking additional knowledge on past fire activity in this region. The application of paleofire research will assist in the implementation of a fire management and enhance the ecological integrity of its forest ecosystems.

1.2 Fire Ecology and History

Study on the patterns and impacts of landscape fire provides information on the ecological processes acting on vegetation communities. Fire varies by many characteristics such as size, type, intensity, and severity, and fire regimes can be described by frequencies, cycles, and return intervals (Agee 1993). There are numerous associations between wildfire, vegetation, and climate (Johnson 1992; Fig 1.1). Fire results in plant mortality, requiring biomass for fuel, but it can act to renew fire-adapted species and alter landscape structure. Lightning is the only natural source of ignition for fire. From 1990-2001, it caused ~11% of the fires in eastern Ontario, with human ignitions such as brush burn, matches, and campfires accounting for the remaining ~89% (Roswell 2005). Other climatic factors, including temperature, precipitation, wind, and humidity, can influence fire activity (Johnson 1992). These relationships are changing as a result of anthropogenic impacts such as fire exclusion, human-caused ignitions, habitat fragmentation, human-mediated invasive species, forestry techniques, and climate change (Pyne and Goldammer 1997; Fig. 1.1).

The role of fire in a landscape can change over time, and this may be in association with changes in climate and vegetation. Techniques used in studying fire history have traditionally involved the physical evidence of past fire, such as fire scars and stand ages, as well as human records of fire events (Agee 1993). Except in rare cases, these techniques can only reconstruct fire-history of the past several hundred years. The analysis of sediment-charcoal overcomes this limitation as its records can extend back thousands to tens of thousands of years (Clark et al. 1996; Long et al. 1998; Higuera et al. 2007).

1.3 Paleoecology and Sediment-Charcoal

The most reliable records of charcoal accumulation over long periods of time are derived from lake sediments (Power et al. 2008). Charcoal can be used as a proxy of paleofires as it is produced by fires and deposited into adjacent bodies of water (Clark 1988a). The charcoal content of sediment cores is generally analyzed contiguously to provide a continuous record. An associated core chronology provides information on sedimentation rates and enables the estimation of the fire event dates, fire-return-intervals, and fire frequencies (Long et al. 1998). As larger charcoal particles travel shorter distances from source fires than smaller charcoal particles, their study is considered to provide a local fire signal within a radius of ~1-10 km (Whitlock and Millspaugh 1996). Variations in the shapes of charcoal particles, or morphotypes, may provide supplemental information about an area's fire history (Enache and Cumming 2006; Enache and Cumming 2007).

1.4 Rationale

The data collected and analyzed will be provided to St. Lawrence Islands National Park to assist its staff in managing the protected area's fire activity and enhancing the park's ecological integrity. The history of fire in this area is of particular interest as a rare coniferous tree species, *Pinus rigida* (pitch pine), has several populations within the park boundaries and has been present in this region for several thousand years (Francis and Leggo 2004). The population of pitch pine in Ontario population has, however, been declining for at least several decades (Mosseler et al. 2004). The park has a mandate to protect the species as a nationally significant example of natural heritage (Ellsworth et al. 2009). Pitch pine has several adaptations that allow it to regenerate or become established at a burned site. Its thick bark protects it, it is able to sprout post-disturbance, and it produces both serotinous and non-serotinous cones (Meilleur et al. 1997). Serotiny refers to the release of seeds in response to an environmental trigger, and it is commonly fire (Johnson 1992). Periodic fires also enhance seed-bed suitability by exposing mineral soil, reducing competition from other tree seedlings, and increasing light availability

(Greenwood et al. 2002). Knowledge of the fire activity that has existed in its range will assist in managing its restoration (Francis and Leggo 2004; Rogeau 2007). Long-term fire history provides a range of natural variability that can be used in developing appropriate management goals. The concept of natural variability refers to the temporal and spatial variability of an area's ecological conditions when it has not been affected by people (Landres et al. 1999).

Furthermore, the information collected will contribute to the knowledge of paleoenvironments in eastern Ontario through the Holocene. The variability of paleofire supplies context for shifts in ecological and climate conditions. The fire history results will be compared to regional Holocene vegetation and climate trends. This research will also contribute to a growing network of reconstructed fire regimes from sites in eastern North America, which provides insight into regional activity (Clark et al. 1996; Carcaillet et al. 2001a; Ali et al. 2009b). Additionally, the project will be contributing to an international research project aggregating charcoal records for comparison with global circulation climate models (Power et al. 2008).

1.5 Research Objectives

There are several research objectives around which this thesis is structured.

a) What type of fire regime has been present in a small watershed in eastern Ontario during the Holocene?

b) What is the charcoal morphotype composition of the sampled sediment?

c) Did the impacts of humans in the area affect the fire regime? Is there any evidence of fire regime transitions during the first appearance of humans into the region, the later colonization by European settlers, or the modern industrial age?

d) What is the relationship between the reconstructed fire regime and long-term regional vegetation and climate trends?

e) What is the relationship between the reconstructed fire regime and regional biomass burning trends?

f) How can this information be applied to fire management and ecological restoration?

1.6 Thesis Structure

The thesis begins with an introduction, followed by a literature review. Research methodology is then overviewed. The next section contains the results of the analysis of Mud Lake's charcoal record. This is followed by a discussion of the implications of the findings, including the fire regime trends, a comparison with regional fire activity, assessment of the possible impact of humans and the composition of charcoal morphotypes, comparison of the fire history with long-term regional vegetation, climate, and biomass-burning trends, and applications of the results to protected areas management. The conclusion revisits the research objectives and considers future research opportunities.

Chapter 1 Figure Caption

Figure 1.1 Conceptual model of the relationship between fire, climate, and vegetation, with the addition of human influence on all three factors and the resulting increase in complexity. Climate is generally dominant in its relationships with fire and vegetation. Moisture and temperature are major determinants in vegetation growth and biomass-burning, while wind and lightning events also impact fire. The particulate and CO_2 emissions from fire have an impact on climate, and vegetation growth intakes CO_2 and also affects landscape albedo. People impact these relationships through changes in fire regimes, changes in vegetation and landscape characteristics, and direct emissions into the atmosphere.

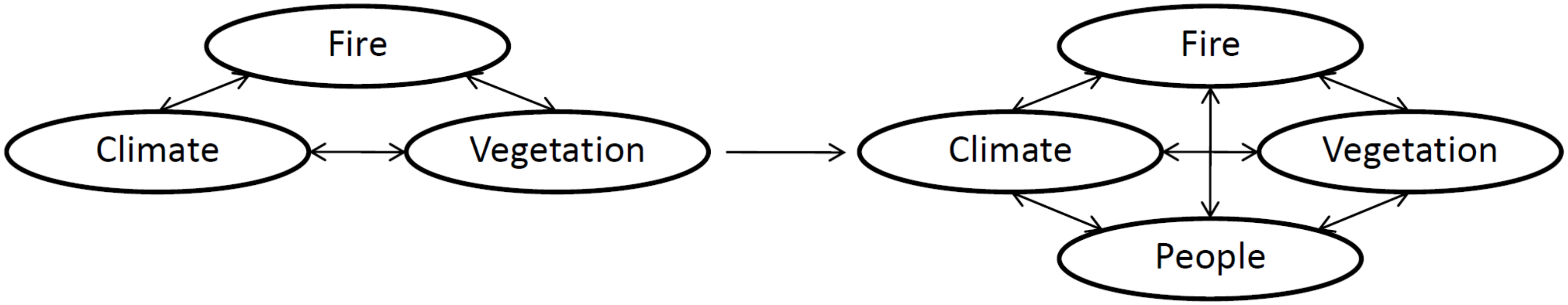


Figure 1.1

Chapter 2

Literature Review

2.1 Introduction

Long-term fire history studies benefit from an interdisciplinary approach that uses multiple avenues of research. Knowledge of the dynamics of individual fires and its impacts on species and landscapes assists with understanding fire regimes. Monitoring modern fires is an important component of this, and there are also many methods of studying past burns, such as documentary sources, dendrochronology, soil charcoal, and sediment-charcoal. Fire is a component of paleoenvironments, and its patterns interact with shifts in vegetation assemblages and climate. While fire is actively excluded from developed areas, it may be introduced into environments where we seek to maintain natural processes and landscapes, such as protected areas. Additional information about the spatial and temporal aspects of wildfire, particularly in a local context, assists with fire management.

2.2 Fire Ecology

Fire is an ecological disturbance that plays a role in ecosystem structure and function, landscape processes, and the life cycles of many organisms. In its natural cycles, it acts as an agent of change for forests (Agee 1993; Pyne and Goldammer 1997). Abiotic factors influencing fire include climate, local weather, frequency and seasonality of ignition sources, physical fire breaks, landscape connectivity, topography, moisture, and soil texture (Johnson 1992). Biotic factors, the impact of vegetation on fire, include the physical and chemical characteristics of biomass fuel, fuel load, and rate of fuel accumulation (Johnson 1992). The quantity and quality of these factors results in substantial variability in fire regimes, both within and between areas.

As a physical, terrestrial disturbance, forest fires are a perturbation on many ecological systems, but most species are adapted to periodic fires and many benefit from wildfire (Paine et al. 1998). Fire causes damage to individual plants and mortality to some taxa, while it also provides open space for species to inhabit, leading to succession, and enables others to propagate (Johnson 1992). Fires can trigger seed release and vegetation reproduction, create seedbeds, release nutrients, and decrease competition (Johnson 1992; Agee 1993). On a landscape scale, fires act to decrease the age of forest stands, decreasing their vulnerability to insects, disease, and blowdown (Johnson 1992; Agee 1993). The elapsed time since last fire relates to many forest attributes, including species composition, structure, quantity of organic matter, and abundance of woody debris (Johnson 1992). In some habitats, fire may recur frequently enough to have major implications on the long-term status of the community, while in others fire is comparably infrequent and only occasionally has a direct impact on ecological function (Agee 1993). Fire affects the landscape through production and deposition of charcoal, which impacts terrestrial carbon storage (Ohlson and Tryterud 2000). Fire regimes can also affect the vegetation, hydrological, and geomorphological processes that impact the stability of a landscape (Pierce et al. 2004).

Fire and its patterns can be described with numerous characteristics: frequency, return interval, cycle, magnitude, type, spatial extent, and seasonality. Fire frequency describes the average number of fires within a given length of time, while a mean fire-return-interval (mFRI) is the average number of years between two successive fire events over a set period of time (Johnson and Van Wagner 1985; Johnson and Gutsell 1994). The fire cycle, or rotation, is the length of time necessary to burn an area equal to the area or landscape of interest (Johnson 1992). A fire's magnitude can be described in terms of its intensity, the rate of heat energy production from a fire per unit time, and severity, the effects of fire on a site (Van Sleewen 2006). There are several types of fire, defined by location in the habitat, including ground, surface, and crown. Ground fires take place in the forest's litter layer and may only smolder, surface fires take place in the surface fuel area, and crown fires extend into the forest crown layer (Van Sleewen 2006). Spatial extent is the area covered by a fire and the patterns created, while fire seasonality is the period of the year during which fires are likely to start and spread (Van Sleeuwen 2006).

2.3 Reconstructing Fire-History

There are several techniques that can be used to study past fires. They differ in temporal and spatial scope, and they are often used in combination.

2.3.1 Documentary Sources

Documentary sources such as historical land surveys and early descriptions by travelers, naturalists, and foresters may provide information about forest and fire history in North America since European settlement (Pyne 2007). More recent fires have been recorded by government agencies, which also monitor modern events (Van Sleeuwen 2006). Technology is also being used to monitor global fires with contemporary satellite data (Flannigan et al. 2009).

2.3.2 Dendrochronology Research

Dendrochronology is a science based on analysis of tree-rings that can yield information about past fires. Techniques include forest-age structure and fire-scar analysis (Agee 1993). Stand-age analysis provides information about the length of time since the last fire as well as fire size in habitats where there are distinct age cohorts in homogeneous stands. The use of stand age in fire history studies can be inaccurate as there are many sources of tree mortality such as insect outbreak, disease, and resource extraction (Johnson 1992; Agee 1993). Fire-scar analysis can identify the year that a tree was damaged, but not destroyed, by a fire (Agee 1993). This technique can provide excellent temporal and spatial resolution of past burns, but it also has limitations. Consecutive annual burns may not produce distinctive fire scars, more recent fires may obscure older records, and wounds originating from non-fire sources can be difficult to distinguish from fire scars (Johnson 1992; Agee 1993; McEwan et al. 2007). Both methods rely on existing trees to provide information, so they can only reveal fire history from the past few hundred years.

2.3.3 Soil Charcoal Research

Charcoal is produced by a fire's incomplete combustion of organic matter, and it is deposited in soils following fires (Ohlson and Tryterud 2000). Soil cores may be undisturbed to the extent that a temporal profile of charcoal deposition can be constructed. Alternatively, charcoal samples may be individually dated to identify past fires (Lertzman et al. 2002; Hallett et al. 2003). Soil charcoal is relatively easy to sample, in comparison with tree rings and lake sediment, and can provide independent verification for fire history established by other means (Gavin et al. 2003). Site characteristics may limit the available soil charcoal to that deposited in the last several hundred years. Additionally, wood charcoal has an in-built age exceeding the time since fire as it may have lived several decades to centuries before burning, and that must be accounted for (Gavin 2001).

2.3.4 Sediment-Charcoal Research

Long-term fire history can also be reconstructed through the analysis of particulate charcoal in dated lake-sediment cores. Sediment-charcoal is used as a proxy for past vegetation burning as it is aerially deposited into aquatic environments following its production by fire (Clark 1988a). In contrast to other fire history methods, the analysis of sediment-charcoal extends the period of fire history that can be studied from hundreds to thousands of years (Clark et al. 1996; Whitlock and Bartlein 2004). This technique focuses on the history of large, stand-replacing fires as these burns are most clearly indentified in charcoal records (Whitlock and Larsen 2001). Interpreting fire history from the charcoal record requires an understanding of its taphonomic processes, which includes transportation, deposition, and burial (Gavin et al. 2007; Higuera et al. 2007).

2.3.4.1 Sediment-Charcoal as a Fire Proxy

The use of charcoal as a proxy of past fires is possible if the sequence of charcoal deposition is well preserved in lake sediments. Lake-sediment cores are frequently used in paleolimnology to study shifts of indicators such as diatoms, chironomids, and pollen, providing insights into past environmental conditions (Smol 1992). As with pollen, charcoal is created outside of lake systems, and both production and taphonomic processes impact its eventual deposition. The quantity of charcoal produced varies by the characteristics of the fire and the type of vegetation burned, and the amount deposited is affected by the location of the fire relative to the depositional basin (Clark 1988b). The charcoal record is composed of primary and secondary components. Primary charcoal is aerially deposited into a lake during and immediately following a fire, and it enables charcoal to be used as a proxy for fire episodes. Its deposition is impacted by the weather conditions at the time of the fire, such as wind and precipitation (Whitlock and Millspaugh 1996). Secondary charcoal is deposited into lakes during non-fire years through erosion, from charcoal that remains in the terrestrial environment, and through within-lake mixing and re-deposition. Its presence results in a background level of activity in the charcoal record (Whitlock and Millspaugh 1996). Sediment mixing also impacts the charcoal record, with forces such as bioturbation causing deposited lake sediments to mix horizontally and vertically (Higuera et al. 2007). The noise is limited, though, by the physical properties of charcoal particles, which restrict the extent of its redistribution (Clark 1988b). Empirical studies have also found that erosion and within-lake redistribution are generally not significant enough processes to obscure the primary charcoal signal, though it must be accounted for in the analytical methods applied (Whitlock and Millspaugh 1996; Carcaillet et al. 2006).

Sediment cores are usually sampled contiguously to allow for the analysis of a chronological sequence of charcoal deposition. While other paleoenvironmental indicators may be subsampled centimeters apart, it is preferable to subsample each core interval for charcoal analysis (Clark 1988b). Lake cores can be sampled contiguously by slicing its varves, visual sediment layers that represent annual periods and are similar to tree rings (Clark 1990). When lakes cores are not varved, changes in sedimentation rate make it difficult, if not impossible, to sample a core at equally spaced time intervals. As a result, the cores are divided into intervals of equal length, commonly between 0.25 and 1 cm (Whitlock and Larsen 2001). Each layer’s subsample is processed and the amount of charcoal tabulated. The two main methods of quantification are charcoal particle count and total charcoal surface area in a known volume, with charcoal particles individually counted and measured under a microscope (Whitlock and Larsen 2001). A comparison of particle count, surface area, and volume methods for larger, macroscopic charcoal found that they produce equivalent local fire history results (Ali et al. 2009a).

Constructing a satisfactory core chronology is essential to processing a charcoal record as it enables the dating of past fire events and the comparison of the results with other paleoenvironmental data (Long et al. 1998). As annually-laminated sediments are rare, lake-core chronologies are commonly developed through ^{210}Pb and ^{14}C dating of sediment and organic material (Whitlock and Larsen 2001). Unique layers in cores, such as tephras from identifiable volcanic events, can also be used in development of a chronology (Gavin et al. 2007).

2.3.4.2 Development of Methodology

The use of sediment-charcoal in the study of fire history began during the 1960s as a sub-field within palynology, with charcoal particles tallied as part of standard pollen analysis. While this method provided a degree of information about past fires, particularly as it reflected on changes in vegetation, it was limited. Palynology preparation methods resulted in charcoal breakage, leading to an artificial amount of smaller pieces, and pollen samples are commonly taken in non-contiguous intervals, leaving gaps in the fire record and preventing the determination of fire frequencies (Clark 1984). Charcoal analysis gained status as a separate technique in the late 1980s. Initial work stemming from palynology focused on microscopic charcoal, particles <100 µm in size. They can travel distances from tens to hundreds of kms, and their study results in the reconstruction of regional fire history (Carcaillet et al. 2001b). More recent methodologies have been developed using macroscopic charcoal size classes >100 µm. Whitlock and Millspaugh (1996) was the first major work to analyze the assumptions of charcoal analysis, using Yellowstone National Park’s extensive 1988 fires as the experimental site. They found that significant quantities of charcoal were introduced into lakes after the fire event, over several years and through several centimeters of sediment. The amount varied by the proximity of the lake to the burned area, with more distant lakes showing smaller quantities of charcoal. They also found that lakes generally down-wind of the burned area received more charcoal than lakes generally up-wind (Whitlock and Millspaugh). This finding shows the limited resolution of fire dates possible as well as the presence of secondary charcoal. This study also concluded that the preferable location to collect cores is the deepest part of deep lakes where the sediments are less impacted by within-lake re-deposition and where charcoal accumulation tends to be most consistent. Through the comparison of charcoal abundances in burned and unburned sites within the park, this work also concluded that larger charcoal particles better reflect geographically local fires (Whitlock and Millspaugh 1996). Macroscopic charcoal has been shown to reflect local fire history in other research, though the distance it has been found to travel varies. Experimental studies have found that macroscopic charcoal travels a maximum of tens to hundreds of metres from its source (Clark et al. 1998; Lynch et al. 2004), while other researchers has observed macroscopic particles travelling between 1 km to 20 km from the source fire (Whitlock and Millspaugh 1996; Gardner and Whitlock 2001; Pisaric 2002; Tinner et al. 2006). Weather conditions, such as precipitation and wind speed and direction, also impact particle deposition (Higuera et al. 2007).

Macroscopic charcoal samples are commonly processed through thin section and wet-sieve techniques. Thin sectioning is possible with varved sediments. It provides annual temporal resolution, and the number and area of particles in each subsample slide are tabulated using a grid (Clark et al. 1996). Wet sieving is generally used with non-varved sediments and requires deflocculation and careful separation of the sediment matrix (Millspaugh and Whitlock 1996).

2.3.4.3 Charcoal Record Analysis

Analysis of charcoal accumulation data is crucial to interpreting fire history. Because the charcoal record is composed of primary and secondary components, the fire signal derived from primary charcoal must be separated from the noise produced by secondary charcoal. This is done through a decomposition approach, separating charcoal data into a low-frequency component, representing the background charcoal level, and a high-frequency component, which contains charcoal peaks (Long et al. 1998; Higuera et al. 2007). The identification of charcoal peaks above a certain threshold as 'fire events or episodes' is the goal of the analysis and serves as a basis of fire history interpretation (Whitlock and Larsen 2001).

2.3.4.4 Morphological Features

In addition to accumulation, charcoal particles may be analyzed by their morphological features. This type of research originated with Enache and Cumming (2006) on sediments from Prosser Lake, British Colombia. This analysis is believed to provide additional information on the source of the charcoal. Seven morphotypes were identified, categorized by shape, ratio of major-minor axis length, and the presence or absence of porosity (Enache and Cumming 2006; Enache and Cumming 2007). Charcoal's morphological traits can vary depending on the vegetation source as well as the characteristics of the fire that produced it. Charcoal particles can also be further altered through transportation and burial. An additional study in Wisconsin (Jensen et al. 2007) identified a set of charcoal morphotypes based on pre-burn fuel type and generated a modern reference collection. Different charcoal morphotypes were produced in this study than were seen by Enache and Cumming (2006), and this indicates that charcoal shapes vary as a result of landscape, vegetation, or fire characteristics. Jensen et al. (2007) observed changes in the frequency of charcoal morphotypes that coordinated with the area's vegetation changes, suggesting that morphotypes can provide additional information about past vegetation and fire regimes. Use of this technique may be confounded by the possible obscuring of a particle's morphological traits between its production and sampling.

2.3.4.5 Application with Other Techniques

Sediment-charcoal research may be used in association with other fire history techniques. Other methods with greater resolution for recent fires, such as documentary evidence and fire-scar analysis, are particularly helpful as they can calibrate and confirm the results of charcoal data. This involves comparing the overlap between sets to identify corresponding fire event dates (Whitlock and Bartlein 2004). Soil charcoal evidence may also be applied alongside sediment-charcoal fire history records (Gavin et al. 2003; Hallett et al. 2003). These other techniques are more spatially explicit than charcoal analysis, while sediment-charcoal research has a significant temporal advantage.

Sediment cores analyzed for charcoal content may be assessed for magnetic susceptibility, a measure of the degree to which a substance may be magnetized. Fire can increase this characteristic in some soils, and it may act as an erosion proxy in lake sediments and can be correlated with past fires (Long et al. 1998; Carcaillet et al. 2006). Fossil pollen in sediment cores, as a proxy for past vegetation assemblages, can be compared with the core's charcoal accumulation levels. Additional information on paleofires can be inferred when fire events correspond with shifts in key pollen taxa or groups of pollen taxa that indicate the occurrence of forest succession (Clark 1990; Clark et al. 1996; Long et al. 1998). Such comparisons may also indicate the response of vegetation to historic fires. Long-term changes in fire frequency can also be compared with variation in the amount of fire-adapted and fire-sensitive species in the pollen record (Long et al. 1998).

2.3.4.6 Limitations

There are several limitations to sediment-charcoal research. The fire history derived tends to reflect the catchment area as opposed to the stand scale, while the later would be more ecological meaningful (Whitlock and Larsen 2001). It can be difficult to distinguish individual fires if they are temporally close (Clark 1988a). This method generally provides minimal information about fire characteristics such as size, intensity, severity, and type (Whitlock and Millspaugh 1996). This is partly due to the non-stationarity of charcoal records, which may be a result of changes in the fire regime such that the level of charcoal production varies as well as changes in the nature of charcoal transport and deposition into the lake (Higuera et al. 2007; Enache and Cumming 2009). This technique captures large fires, particularly of high-severity, and it is generally not possible to isolate small, surface fires in a charcoal record (Whitlock and Larsen 2001). Small burns do not produce a great deal of charcoal, and most particles do not become airborne (Whitlock and Larsen 2001). The fire history derived, including the fire-return-interval (FRI), applies to the area's stand-replacing fires, and other sources of information, such as documentary or fire-scar research, is required for information on surface burns. The technique may also not successfully capture all applicable fires, so this technique can underestimate the FRI, the amount of time between large fires (Whitlock and Larsen 2001). The charcoal record is also impacted by the factors that impact the quantity of charcoal deposited into a lake following a fire, including the amount and pattern of subsequent precipitation, variation in wind velocity and direction, and rate of soil stabilization by vegetation recovery (Figueiral and Mosbrugger 2000; Higuera et al. 2007). Additionally, differences in methodologies, particularly the choice of size classes and analytical techniques, have made comparing and synthesizing sediment-charcoal studies more difficult (Whitlock and Bartlein 2004).

2.4 Regional Environmental Research

2.4.1 Fire in Ontario

Ontario's fire activity is characterized by much variability throughout its landscapes. The range of ecological regions, climate conditions, fire-weather frequency, and population densities of fire-prone vegetation all play a role. Fire is a major natural disturbance in the environments of northern Ontario, particularly in the boreal forests. Smaller events (<100 ha) are the most frequent type in both the warmer, drier west and the cooler, more humid east, while a greater number of large fires occur in the east than the west due to greater fuel build-up (Van Sleeuwen 2006). The region's fire activity results in forest mosaics of pure or mixed, even-aged stands at many stages of post-fire recovery, with mFRIs in the coniferous forests ranging from 12 to 300 years (Van Sleeuwan 2006). In contrast, much of southern Ontario contains habitats that are naturally less prone to fire. Though less frequent, fire also has an important role in this area, with low-intensity surface fires taking place at fairly short intervals and stand-replacing fires occurring at much longer intervals (Van Sleeuwan 2006). Some boreal environments in the region experience FRIs as short as those in northern Ontario, but the greater dominance of deciduous forests with FRIs ranging from 150-1200 years leads to, overall, fewer fires and greater landscape heterogeneity (Van Sleeuwen 2006). Eastern Ontario contains a boreal-hardwood transition, so its forest fire activity may differ from regions in Ontario with more homogenous vegetation (Uhlig et al. 2001).

The province's landscapes, particularly those in its southern part, have also been subject to considerable anthropogenic impacts. The first presence of humans in southern Ontario dates to approximately 8000 years ago, when the land was used seasonally for hunting, fishing, and some agriculture (Francis and Leggo 2004). Aboriginal influences on the landscape increased for several thousand years, with more permanent settlements existing between approximately 1200 to 300 yr BP (calendar years before present, present at 1950 AD) (Francis and Leggo 2004). Anthropogenic impacts on fire regimes in Ontario began with aboriginal burning, occurring for several centuries until the 1700s. It is known that First Nations populations in this region, such as the Iroquois, manipulated ecosystems through fire (Clark and Royall 1995; Dey and Guyette 2000). The fires tended to be of low- to moderate-intensity, and they were started to clear land for hunting, settlement, or agriculture. Many details of this fire use, such as frequency and extent, are poorly known as there has been limited research (Van Sleeuwen 2006). In charcoal-based fire records, they are indistinguishable from fires caused by lightning ignitions, but aboriginal burning may have increased fire activity in some parts of Ontario (Clark and Royall 1995).

The arrival and impact of European settlers further affected fire regimes, altering forests to a much greater degree than aboriginal activities. Areas were logged and cleared for agriculture, transportation, and human settlements. Fires were used to facilitate these activities, and unintentional anthropogenic ignitions also occurred (Dey and Guyette 2000). Fire exclusion policies began to be implemented in Ontario in 1917, partially in response to a large fire that devastated part of north-central Ontario (Van Sleeuwen 2006). Fire suppression was common across North America most of the 20th century (Stephens and Ruth 2005). Less was known at the time regarding the beneficial role of fire as an ecological disturbance. Fire-return intervals increased, the quantity of low-intensity fires decreased, while the amount of flammable biomass increased. Where land was not cleared, older forests and fire-sensitive, shade-tolerant species dominated, while populations of fire-tolerant, shade-intolerant species decreased (Uhlig et al. 2001). Beginning in the 1960s and culminating in the 1980s, the effects of long-term fire suppression were increasingly recognized, the most obvious impacts being extensive and uncontrollable wildfires such as Yellowstone’s 1988 event. It is no longer a dominant policy, and the ecological role of fire has become better incorporated into management practices in Canada (Stephens and Ruth 2005).

2.4.2 Regional Fire History

Eastern Ontario contains deciduous forests, mixed forests, and coniferous forests as it is a transition area between the Canadian Shield and the Adirondacks (Francis and Leggo 2004; Van Sleeuwan 2006). The human history of burning, resource extraction, agriculture, and urban development have impacted the landscape, obscuring physical evidence of wildfire and fragmenting modern forests (Van Sleeuwan 2006). There is a deficit of information about the historical role of fire in this region, though fire is believed to be less common than in the ecoregion that dominates to the north, the Great Lakes-St. Lawrence forest (Uhlig et al. 2001). Studies using dendrochronological and sedimentary charcoal research to reconstruct fire history have taken place within central and southwestern Ontario, Quebec, and northeastern U.S. states. While they are geographically closest to the study region and warrant consideration, the variations in vegetation, landscape, and climate may limit their applicability.

Amongst the earliest cited sediment-charcoal studies, Cwynar (1978) examined a varved lake sediment core from Greenleaf Lake, Algonquin Park, Ontario. It covered the period of 770 to 1270 AD, and charcoal, pollen, aluminum, and vanadium content was analyzed. Looking for peaks in influxes of charcoal and the minerals, it was estimated that six fires had taken place during the five-hundred year period, a frequency of one fire every 80 years. Cwynar (1977) used historical documents and dendrochronological evidence to determine a major fire mean return interval of 45 years in the same region between 1696 and 1920 AD. This period differed from the earlier one as it was largely before 20th century fire suppression, but after European colonization; both humans and lightning may have been acting as sources of fire ignition. Cwynar (1977) also proposed a relationship between large fires and drought years, using Ontario precipitation data to link fire activity in this area to weather. He noted that Algonquin fires in 1875 and 1864 coincided with burns during the same years in Minnesota and suggested that subcontinental droughts correspond with these and, potentially, additional fire events.

Another example of early research in the field of charcoal analysis, Clark (1988a) and Clark (1990) analyzed lake sediments in Minnesota. These papers considered fire regimes from a climate change perspective and argued that climate had impacted the fire cycle in the region, with return intervals ranging from 11-95 yr/fire over the past 750 years. Clark et al. (1996) sampled an annually-laminated core from Devil’s Bathtub in western New York State, analyzing and comparing the sediment-charcoal and fossil pollen deposited over approximately the last 10400 years. This was the first such analysis covering the length of the Holocene. Results indicated that changes in fire regime occurred alongside the major vegetation and climate changes over the period. The study found that FRIs in the region ranged from 50-200 yr/fire during the early Holocene. The researchers were not able to isolate fire episodes in the mid- and late-Holocene, but that may have been a result of the less sophisticated methods applied (Clark et al. 1996).

Several lakes in Quebec's eastern North American boreal forest region have been sampled for sediment-charcoal records (Carcaillet and Richard 2000; Carcaillet et al. 2001a). FRIs for the lakes in this region through the Holocene were estimated from around 100-1000 yr/fire, with most ranging from 100-300 yr/fire (Carcaillet et al. 2001a). A notable influence of climate on the fire regime was identified, but vegetation assemblage was not determined to have impacted the fire frequency at these sites. For the boreal regions studied, future warming is deemed likely to reduce fire frequency as in this region it will be accompanied by wetter summer weather, and dry-cool conditions have historically accompanied this area's increased fire activity (Carcaillet et al. 2001a). The fire history records from the three lakes in Carcaillet et al. (2001a) were later analyzed to compare the forest structure imposed by current forest management with historic variability (Cyr et al. 2009). With the mFRI ranges calculated using Weibull distributions, Cyr et al. (2009) assessed that the logging practices in the region are not replicating natural disturbance regimes. Instead, they are pushing the forest structures out of the range of natural variability with an overabundance of regenerating and young stands (Cyr et al. 2009). Separate sites in western Quebec's boreal forests were used in an analysis of Holocene fire and climate conditions that found mixed support for links between fire and climate (Ali et al. 2009b). The results indicated that between 8000 yr BP and 4000 yr BP, fire frequency was controlled by climate as established by the region's fire synchrony and comparable fire-free intervals. In contrast, the fire activity after 4000 yr BP appears to be more influenced by a combination of climate and local-scale controls such as fuel, local-weather, fire ignitions, and landscape features (Ali et al. 2009b). The mFRIs of the four lakes sampled range from 90-230 yr/fire. Periods of higher fire activity include 5800 to 2400 yr BP and 1400 to 600 yr BP while periods of lower fire activity include 8000 to 5800 yr BP and 750 yr BP to present (Ali et al. 2009b).

Additional charcoal research has investigated the potential impact of aboriginal fire on forests in Ontario. At Crawford Lake, southwestern Ontario, Clark and Royall (1995) used charcoal and pollen to link the transition from northern hardwoods to white pine/oak forests to an increase in charcoal accumulation in lake sediments. They proposed that aboriginal burning in this area changed the forest composition. The importance of cultural fire use has been debated, with some results showing that notable changes in the forest composition resulted (Clark and Royall 1995; Clark and Royall 1996) while others (Campbell and McAndrews 1995) have contested this conclusion, proposing that climate is the overriding influence on forest composition and fire activity.

These studies have helped to create a network of fire history records in eastern North America. In the subcontinental region, overall burning levels were greatest before

7500 yr BP, low from 7500 to 3000 yr BP, and increased from 3000 yr BP to present (Carcaillet and Richard 2000; Carcaillet et al. 2002; Power et al. 2008). The variation of vegetation, climate conditions, and landscapes within eastern North America emphasizes the value of further local-fire research.

2.4.3 Regional Vegetation History

Deglaciation in eastern Ontario occurred between approximately 12700-11700 yr BP with the retreat of the Laurentide ice sheet (Anderson and Lewis 1985). Pollen deposited since that period has been studied in several lakes close to the study site and represent regional trends. Lambs Pond, Ontario (N 44º39', W 75º48'), northwest of Brockville, is located ~25 km from the study region (Fig. 2.1). The inferred end of glacio-lacustrine deposition in this basin is estimated as 11700 yr B.P. (Anderson 1987). Seven zones, 1-5, 7, and 9, were identified in the diagram; there are no zones 6 and 8 as the zones were regionally assigned and Lambs Pond does not have them (Anderson 1987). The earliest pollen assemblage (Zone 9) is characterized by a shrub-herb community. Zone 7 shows a *Picea-Populus* mix, which is succeeded by a *Pinus* dominated assemblage (5). *Tsuga* peaks in Zone 4, and *Betula-Pinus-Qurcus-Fagus* dominated next (3). Zone 2 contains a *Tsuga*-mixed hardwoods assemblage. The top Zone (1) is represented by increases in herb pollen, including *Ambrosia*, *Graminaeae*, and *Rumex*, and decreases in tree pollen, such as *Tsuga*, *Fagus*, and *Pinus* (Anderson 1987). The pollen from Atkins Lake, Ontario (N44º45' W75º51'), also NW of Brockville and ~35 km from the study region, contains six assemblages (Appendix A,

Fig. A.1). Zone 6 features herb pollen, as with Lambs Pond, and the dominant arboreal patterns are generally similar. Differences in Atkins Lake include less variation in *Tsuga* pollen levels, larger proportions of *Pinus* pollen, and larger modern levels in *Picea* (Terasmae 1980). The resolution and chronology of the two cores is fairly limited as subsamples for pollen counts were taken approximately every 15 cm and only sediment near the bottom of the core was dated. Studying pollen records from lakes in the region does provide an opportunity for initial comparisons of charcoal and inferred vegetation zones.

2.4.4 Regional Paleoclimates

General climate shifts in eastern North America can provide context for other historical environmental changes. The retreat of the Laurentide ice sheet in this region coincided with the last major period of the Pleistocene, the Younger Dryas, from approximately 12900 to 11500 yr BP (McFadden et al. 2004). The early Holocene, post-Younger Dryas period between 11500 and 9400 yr BP was also a cold period, believed to be a result of the discharge of large volumes of melt-water from the receding ice sheet. The Holocene Hypsithermal from 9400 to 5300 yr BP had warmer summers than present (by ~2-4 ºC) in the northern hemisphere, a result of increased summer insolation (Flannigan et al. 2001; McFadden et al. 2004). In eastern North America, climate variation includes a cold, dry interlude from 8400 to 8000 yr BP, and regional cooling around eastern Ontario also took place between 6300 to 5300 yr BP as a result of the Nipissing flood (Anderson and Lewis 1985). From 5300 to 100 yr BP, the Holocene

Neoglacial experienced a drop in average temperatures (by ~1-2 ºC) as summer insolation in this region decreased (McFadden et al. 2004). Recent variation during this period in eastern North America includes the Medieval Warm Period (MWP), from 1150 to 650 yr BP, and the subsequent Little Ice Age (LIA), from 650 to 100 yr BP (McFadden et al. 2004). From 100 yr BP, or 1850 AD, to the present, anthropogenic climate impacts have become significant.

2.5 Fire and Climate

The processes of fire and climate are interrelated. Large-scale climate and small-scale weather impact the occurrence and frequency of wildfires. Fire-weather varies hourly and daily, and it includes meteorological conditions that control the ignition, spread, and suppression of fires (Pyne et al. 1996). The possibility of fire depends on past and present weather and its impact on fuel moisture, precipitation, relative humidity, lightning, air temperature, and wind (Bergeron and Flannigan 1995). Fire-climate operates over weeks, seasons, and years, and it consists of atmospheric circulation configurations and surface-temperature anomalies (Flannigan et al. 2005). On these longer time scales, variations in atmospheric composition, atmosphere-ocean interactions, and insolation cycles can also influence fire regimes (Bergeron and Flannigan 1995; Flannigan et al. 2005). While general conclusions can be made about climate periods, the effects of large-scale climate controls are mediated by the influence of smaller, regional controls, resulting in a heterogeneous mosaic of climate conditions (Flannigan et al.

2001).

Fire, in turn, contributes to the global carbon cycle. Forests are carbon sinks and burning them releases greenhouse gases, aerosols, and particulates into the atmosphere (Carcaillet et al. 2002). At the same time, fire also sequesters carbon as charcoal, ash, and other charred material, which remain in the terrestrial environment post-burn (Forbes et al. 2006).

2.5.1 Fire and Past Climate Change

Modern studies analyze the fire-climate relationship on short time-scales. The study of past environments is required to understand their relationship on longer time spans of hundreds to thousands of years. Several studies have used sediment charcoal to reconstruct fire activity, including frequency and area burned, in the context of past climate change.

Much research has focused on this relationship within one or more regional sites. A comparison of recent climate change and fire in Minnesota concluded that fire was more common during warm and dry periods, including the MWP, and there was a drop in fire frequency during the LIA (Clark 1988a; Clark 1990). In the eastern Canadian boreal-tundra region of northern Quebec, a similar relationship between these two climate periods and forest burning has been observed (Payette et al. 2008). Over the last 2000 years, drier and warmer conditions more conducive to fire gave way to wetter and colder conditions, decreasing fire frequency and the perceived health of the forest habitat (Payette et al. 2008). Holocene-scale research in western Quebec found that more frequent fires occurred in the early Holocene, concurrent with increased summer insolation and drier ground conditions. Fire frequency decreased after 8000 yr BP, at the same time as an increase in humid Atlantic air masses, while the presence of dry Pacific air and cool Arctic air led to more fire activity after 3000 yr BP, in contrast to the boreal region north of it (Carcaillet and Richard 2000). There was also a lack of synchrony between shifts in fire frequency and vegetation assemblages at these sites, indicating that climate impacted fire and vegetation differently (Carcaillet et al. 2001a). An analysis of the fire history derived from four western Quebec lakes observed that the interactions between the atmosphere and anomalies in sea-surface temperatures or sea level pressures correlate with the region's fire frequency variations (Ali et al. 2009b). Dynamics of the Atlantic, Arctic, and Pacific oceans lead to air mass circulations and moisture/drought balances that influence fire regimes in eastern North America (Skinner et al. 1999). It is believed that the periods in this region with higher fire activity featured ocean-atmosphere interactions favourable to fire ignition (Ali et al. 2009b).

While fire and climate interactions at one or a small number of sites may provide a nuanced interpretation of the relationship, synthesizing networks of fire-climate histories within broader temporal and spatial zones reveals large-scale patterns. In Australia during the Holocene, fire frequencies often increased during periods of climate change and environmental flux. For this region, this appears to reinforce the relationship between fire and the El Nino-Southern Oscillation (ENSO) activity (Lynch et al. 2007). This link between global climate factors and wildfire has been observed elsewhere.

Studies of large-scale fire-climate dynamics in North America have found that the area burned in much of its landscapes is controlled by changes in ocean-atmospheric patterns such as ENSO, the Pacific Decadal Oscillation (PDO), and Arctic Oscillation (AO) that control the frequency of mid-tropospheric blocking highs over North America (Skinner et al. 1999; Macias Fauria and Johnson 2008). These circulation anomalies can cause rapid fuel drying, increasing the likelihood and extent of fire (Macias Fauria and Johnson 2008). This observation has the most relevance to large fires, which in Canada make up 5% of total events but account for at least 85% of the area burned (Stocks et al. 2002). Studies of paleofire and climate change in western North American boreal forests have found that climate factors had a clear impact on fire frequency (Gavin et al. 2007). Climate was determined to have its largest impact when it has high variability. A lack of synchrony between adjacent regions indicates, though, that local dynamics frequently outweigh regional climate (Gavin et al. 2006; Gavin et al. 2007). This variation, even between neighbouring forest habitats, demonstrates the complexity of fire behaviour, and many studies have observed that multiple regional records are required to draw conclusions about an area's fire-climate relationship (Whitlock and Bartlein 2004; Gavin et al. 2006; Hotchkiss et al. 2007). Even with that information, the considerable range in the relationship over time and space makes reconstruction and assessment challenging. However, understanding the relationship between fire and climate, as well as their links with vegetation, greatly assist in forecasting the role of fire in the context of anthropogenic climate change.

2.5.2 Fire and Future Climate Change

Modern climate change is considered a substantial threat to the integrity of ecosystems worldwide, and it is an area of intense research interest. Paleoenvironments can provide context that can assist in addressing shifts in climate and other environmental dynamics. Fire regimes are one environmental characteristic that may shift as a result of climate change, with resulting impacts on forests and ecosystems in general (Ryan 1991; Colombo et al. 1998). Climate change will directly alter fire weather. Increases in temperature, a primary impact, will lengthen the fire season and cause an increase in the drying capacity of the air (Flannigan et al. 2005). Changes in summer precipitation and lightning events will also affect fire activity (Flannigan et al. 2005). As fires result in the release of atmospheric carbon from forest sinks, increased fires may contribute to warming conditions that become more conducive to burning, playing a part in a positive feedback loop.

Predictions are being made regarding how fire activity may shift in the face of modern climate change, including the possibility of increased fire frequency (Flannigan et al. 2005). In Canada, it has been predicted that many regions will experience more frequent fires, with the average increase in area burned by the end of this century ranging from 74-118% per ecoregion in a 3 x CO_2 global climate model projection (Flannigan et al. 2005). Eastern Ontario has been predicted to experience an increase of 50-100% in area burned under those circumstances (Flannigan et al. 2005). Increased knowledge of a region’s paleoenvironments and the range of conditions that have existed, including fire regimes, can assist in modeling and managing projected future changes (Bartlein et al. 1998). It has been suggested, for example, that future climate in eastern Ontario may resemble conditions during the Holocene Hypsithermal, when temperatures averaged 2-4 ºC above current conditions (McFadden et al. 2004). Fire management policy must also be modified in response to these changes (Stephens and Ruth 2005).

2.6 Fire Management

Fire is purposefully excluded in many regions due to human development, while in other areas it is managed. Successful wildfire management over requires prediction, detection, and control (Flannigan et al. 2008). As fire is a vital component of many terrestrial landscapes, where landscapes are ecologically managed fire must be included. Since fire is a complex process, its management must be as well. In Canada, there are numerous pressures that impact fire management including climate change, declining forest health, competition for forested regions, wildland-urban interface, and declining fire-management resources (Flannigan et al. 2008).

Fire suppression is a necessary technique that is applied to prevent loss and damage. Techniques include rapid containment of ignited fires, targeted burning, forest thinning to decrease fuel load, and replanting to create open conditions (Whitlock 2004). In North America, fire suppression became widespread in the 19th and 20th centuries in protected areas and forestry regions (Stephens and Ruth 2005). As lumber is a commodity, fires are undesirable in forested regions earmarked for extraction.

Additionally, while parks are valued for their ecological features, fire alters this value, at least for a time, and may endanger the park's users. After this relatively short time of environmental application, however, it became clear that there were drawbacks to this technique (Stephens and Ruth 2005). Lack of fire can decrease the health of a forest habitat, and it can also lead to massive fires as a result of a fuel accumulation (Dellasala et al. 2004). While this was known and prescribed fires were used to mitigate these issues, efforts were not sufficient in at least some areas. The negative impacts of fire suppression are strongly associated with the Yellowstone National Park fires of 1988, which burned 40% of the park (Millspaugh and Whitlock 1995), though that fire event coordinated with the region's estimated mFRI of around 300 to 500 yr/fire over the past 2000 yr (Millspaugh et al. 2000). Though the application of fire suppression has improved over time, it has not developed to simulate natural patterns and is generally associated with human control over the environment.

Alternatively, fire management may be used to help restore an environment. In parks in North America, protection and conservation have become more prominent in the past few decades, rivaling recreation as the primary objective. The fields of park and ecosystem management have seen an increasing amount of study and application in recent years (Grumbine 1994). Emphasis has been on the sustainability of parks and reserves as well as the need to understand the processes and natural conditions of the environments (Nelson et al. 2000; Zorn et al. 2001). Reconstructing and restoring the 'natural' state of an ecological system can be difficult as humans have been artificially affecting them for centuries. It is here that knowledge of paleoenvironments can be useful as it provides information on the range of past fire frequencies that can inform management actions and goals (Cyr et al. 2009). Fire management with an aim of ecological restoration may also apply prescribed burns and fuel manipulation, though with an aim of replicating processes and achieving management goals. Prescribed fire is the application of fire to forest biomass under specific conditions (Fernandes and Botelho 2003), while forest fuel manipulation may involve a removal of surface fuels, decreasing crown density, and the maintenance of large, fire-resistant trees (Agee and Skinner 2005). Management goals include the triggering of community succession, the restoration of soil beds, range management, the control of weeds, insects, and diseases, and the reproduction of one or more species (Pyne et al. 1996).

2.6.1 Paleoecology and Management

Paleoecological research provides knowledge on a region's historical environments. It supplies perspective on the range of conditions that have been present at a given location and increases understanding of the dynamic nature of landscapes (Swetnam et al. 1999). It also establishes a frame of reference and provides context on how the current and future patterns and processes coordinate with an environment's natural variability (Millar et al. 2007). Additionally, historical ecology can overcome the loss of information caused by the obscuring of recent environmental history caused by human impacts (Swetnam et al. 1999).

Paleoecology can inform land management in several ways. It can be used to help make and justify decisions towards management and restoration programs designed to emulate natural processes, circumventing or undoing human impacts (Millar and Brubaker 2006). It can also assist in setting appropriate goals in these plans (Millar and Brubaker 2006). Paleofire data may, for example, supply the range of FRIs that have been present in an environment over time, including extremes and an overall mean (Hannah et al. 2002). Historical environmental conditions can also be used as a basis for ecological modeling (Suffling and Scott 2002). For instance, it can contribute to identifying relevant climate-fire linkages for use in fire hazard forecasting. In addition, paleoclimate data can provide perspective on how a changing climate may impact a fire regime, including alterations in precipitation, temperature, lightning events, and fuel availability (Spittlehouse and Stewart 2003).

It is beneficial to apply local studies when linking theory and practice. Extrapolating from the past environments of other regions adds further uncertainty and difficulties (Millar and Brubaker 2006). Historical conditions cannot, however, be used as an exact template for future ecological processes (Swetnam et al. 1999). It is erroneous to assume that changes in environmental aspects will take place in-sync with or in patterns equivalent to as those that occurred in the past, even at the same geographic location. The transitions between states may be different, influencing the resultant conditions (Millar and Brubaker 2006). Human impacts over the last two centuries in North America have also altered communities and ecological processes, including physical states as well as levels of integrity and resilience (Swetnam et al. 1999). These variations may result in species assemblages and conditions, including fire frequency and local fire controls, dissimilar to what would be expected from historical trends (Millar and Brubaker 2006). There are additional limitations in the application of paleoecology into ecological management and restoration. Historical data often has gaps or a region's profile may not be complete (Swetnam et al. 1999). Nonetheless, the detection and explanation of past trends and variability are important to informed management decisions, particularly in light of the many modern environmental stressors.

2.7 St. Lawrence Islands National Park

St. Lawrence Islands National Park (SLINP) is a small, federally administered protected area in eastern Ontario. The park is ~20 km^2 in area and consists of all or part of 24 islands in the St. Lawrence River, most of which are only accessible by boat, and some on-shore territory. It is a protected area in the Thousand Islands-Frontenac Arch Biosphere Reserve, and the region's climate is moderated by the Great Lakes and the St. Lawrence seaway (Francis and Leggo 2004). The Frontenac Arch and the St. Lawrence River act as ecological corridors for wildlife dispersal (Francis and Leggo 2004). It is also in a transitional zone between the Canadian Shield and the Adirondacks and has high natural biodiversity, among the highest of all Canadian National Parks (Rivard et al. 2000).

SLINP incorporates park management concepts into its State of the Park Report, which provides an overview of the ecological context of the park, the park's objectives and plans, and the ecological integrity goals within the park (Francis and Leggo 2004). Additionally, with these issues in mind and in the context of fire management, a preliminary fire regime study was undertaken by SLINP in 2006 (Rogeau 2007). The park commissioned this study in order to provide more information to their fire management staff and to assist in the development of their fire management policy. This report used the methodologies of aerial photography assessment, fire-scar observations, tree-age analysis, and a literature review to gather information on the area's paleofire (Rogeau 2007). Due to the methods and the land-use impacts in the study site, the field work by the consultant was only able to provide information on fires that occurred in the 1900s and was unable to determine any details about the pre-settlement fire regime in the region. The study suggested that the area's fire regime is dominated by small, low-intensity fires, enabled by a lack of available fuel, rocky outcrops, and minimal fire-weather conditions (Rogeau 2007). Coniferous-dominated sites experienced fires of light to moderate intensity at intervals of 8 to 35 yr. It also speculated on the connection between regional First Nations communities, burning, and vegetation changes, but these links remain unconfirmed (Rogeau 2007).

As with all national parks, SLINP will be increasingly impacted by anthropogenic climate change in the next several decades. Visits to the national parks system are projected to increase as a result of a longer warm-weather tourism season, from ~9-25% by 2050 to ~10-40% by 2080 (Jones and Scott 2006). This will provide economic benefits while increasing human-related ecological pressures (Jones and Scott 2006).

The climate in SLINP is expected to become warmer, with GCM-based research predicting a temperature increase of ~2-5 ºC over the next century (Suffling and Scott 2002; Flannigan et al. 2005). Furthermore, winter precipitation over that period may rise between 5–10%, while summer precipitation is predicted to fall by ~7% (Suffling and Scott 2002). The change in summer conditions may be a result of increased incursion of dry air masses over the region from the Pacific or Arctic oceans, caused by changes in atmospheric anomalies and sea-surface temperatures and pressure (Carcaillet and Richard 2000; Ali et al. 2009b). These shifts in climate conditions will also result in environmental changes (Jones and Scott 2006). In SLINP, the alterations in temperature and precipitation will likely lead to warmer, drier weather during the summer as well as longer fire seasons, with a possible increase in both fire events and intensity (Suffling and Scott 2002). More early successional communities would result. Additional climate change impacts of parks in the Great-Lakes-St Lawrence Basin could include increased levels of disease and insect outbreaks, altered breeding and migration patterns, acid rain stress, and expansion of southern exotic species (Suffling and Scott 2002). Conservation strategies in the context of changing climate are needed for protected areas, such as SLINP. This may be achieved through management techniques, such as species translocation and invasive species suppression, that aim to help species and habitats adapt to altered conditions, maintaining ecological integrity (Suffling and Scott 2002).

2.7.1 Pitch Pine Management

Pitch pine (*Pinus rigida*) grows in variable mixtures in communities, typically with an open canopy, and it frequently co-exists with white oak and red oak. It is a shade intolerant, early successional species that requires an open canopy (Mosseler et al. 2004). Pitch pine has a wide range of site tolerance and can establish in very dry to poorly drained habitats including dry-to moderately-fresh soils, shallow sands, and coarse loams over bedrock (Parshall et al. 2003). In Ontario, where it is at the northwestern edge of its range, it is restricted to shallow substrates and bare-rock surfaces (Mosseler et al. 2004). While there is little information on fire frequency in Ontario rock barrens, the soil and moisture conditions provide a fire-prone environment (Van Sleeuwan 2006). Pitch pine's main characteristics are thick bark, extensive root systems, early seed production, the ability to re-sprout from basal or epicormal buds, and variable levels of serotiny (Van Sleeuwen 2006). It is one of Canada's rarest trees, so SLINP has a mandate to restore the populations in its territory (Mosseler et al. 2004). Palynological research from Hill Island, the site of the main pitch pine population in the park, indicates that pitch pine and the associated pine-oak-juniper communities have been present for around 7000 yr (Warner and Masters 1993). The populations in this area are believed to have unique traits for the species, such as cold-hardiness and the ability to grow on dry rock sites; these characteristics should be protected for the future gene pool (Mosseler et al. 2004). It has also been suggested that the pitch pine population in Canada was much larger during past periods of warmer climate (Mosseler et al. 2004). The current populations are considered over-mature, and a lack of reproduction has been observed (Ellsworth et al. 2009). Maintaining pitch pine populations in Ontario requires frequent disturbance to maintain open-canopy conditions, expose mineral soil, and limit encroachment by oaks and succession to hardwood forest (Van Sleeuwen 2006). There is limited information on the natural fire regime of the pitch pine-oak communities in Ontario. Populations in the northeastern United States have been studied, with fire return intervals in some habitats ranging from 20 to 40 years (Parshall et al. 2003). Overall, though, the associated fire regime is not sufficiently understood.

SLINP has a pitch pine management framework in place, initially spanning 2009-2012, with a focus on the main Hill Island population (Ellsworth et al. 2009). The overall objective is to ensure the maintenance of a regional meta-population of pitch pine over the next 15 years, applying stewardship and experimental principles. Before any direct intervention in pitch pine growth can take place, the deer population on Hill Island must be reduced as past restoration efforts have been limited by the deer's consumption of any new pitch pine sprouts. Upon completing that step, both restoration of the current stands and the establishment of new stands is planned. Long-term monitoring and ongoing ecological management will follow (Ellsworth et al. 2009). This plan could be complicated by environmental alterations induced by climate change in the next several decades. On the other hand, the projected temperature increase in SLINP would create conditions closer to those in the United States where pitch pine is a common tree species, while increased fire frequency may also benefit the species. It has been speculated that climate warming may enable pitch pine to expand northward, becoming ecologically important in new habitats (Mosseler et al. 2004). On the other hand, rapid climate change is a major stressor, and it can be very difficult to predict the response of individual species (Millar and Brubaker 2006).

Chapter 2 Figure Caption

Figure 2.1 Pollen diagram for Lambs Pond, Ontario (N 44º39’, W 75º48’). Lambs Pond is near Brockville, Ontario, and ~25 km northeast of the study site. It is the geographically closest published Holocene-length lake-based pollen study to Mud Lake. Pollen was studied in the mid-1980s, and only samples from the deepest sediment were radiocarbon dated. Most of the core is gytta, fine organic sediment, and the core ends with glacially deposited clay. The oldest date, 12300 yr BP, was considered by the researchers to be too old when compared to other lake studies in the region, and it was likely contaminated by deeper sediments. The basal date was assumed to be ~11700 yr BP (Anderson 1987).

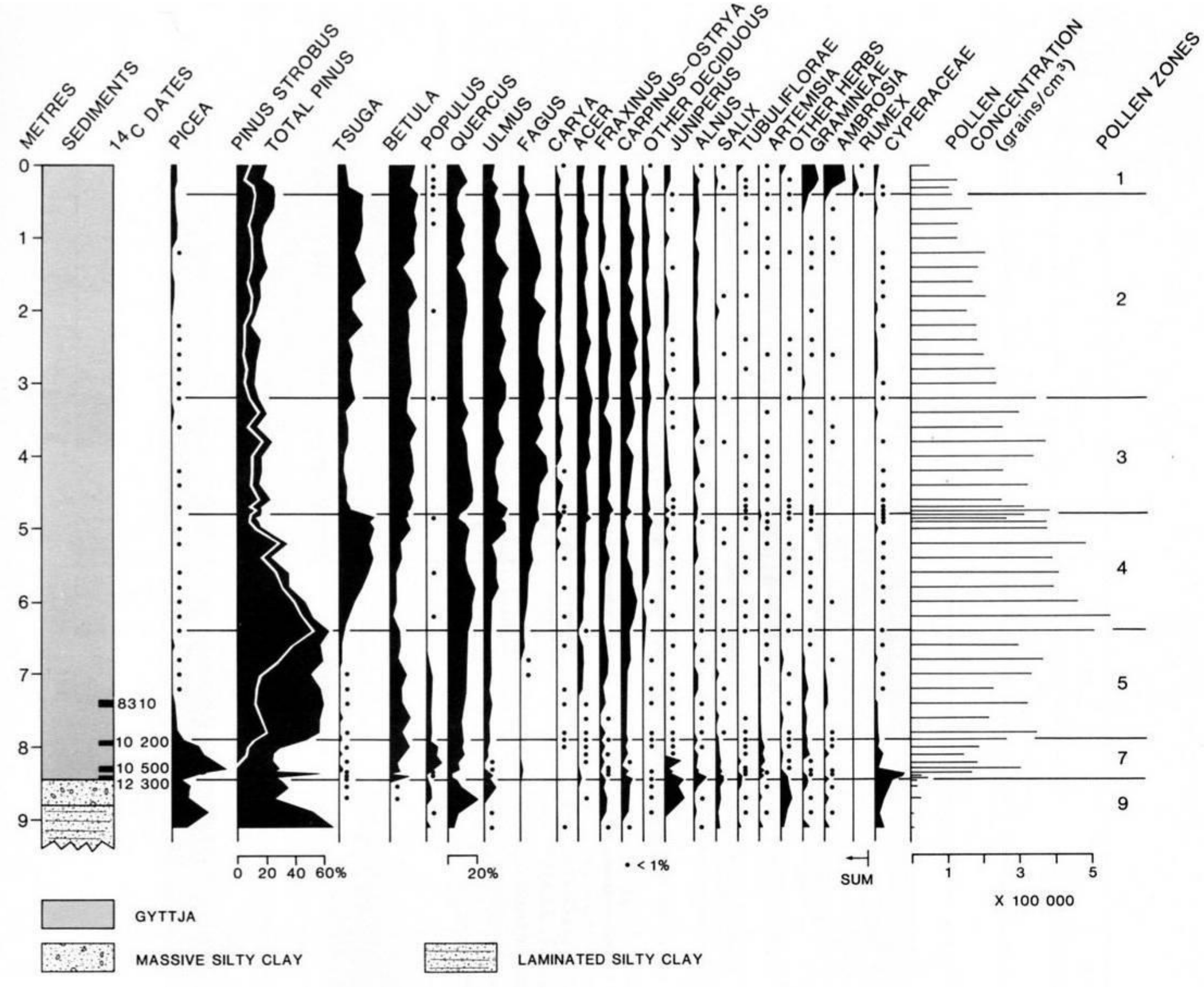

METRES
SEDIMENTS
^{14}C DATES
PICEA
PINUS STROBUS
TOTAL PINUS
TSUGA
BETULA
POPULUS
QUERCUS
ULMUS
FAGUS
CARYA
ACER
FRAXINUS
CARPINUS-OSTRYA
OTHER DECIDUOUS
JUNIPERUS
ALNUS
SALIX
TUBULIFLORAE
ARTEMISIA
OTHER HERBS
GRAMINEAE
AMBROSIA
RUMEX
CYPERACEAE
POLLEN CONCENTRATION (grains/cm^3)
POLLEN ZONES
0
1
2
3
4
5
6
7
8
9
8310
10 200
10 500
12 300
0 20 40 60%
20%
• < 1%
SUM
1
3
5
X 100 000
1
2
3
4
5
7
9
GYTTJA
MASSIVE SILTY CLAY
LAMINATED SILTY CLAY

Figure 2.1

Chapter 3

Research Methodology

3.1 Study Site Description

A suitable lake site was located within Charleston Lake Provincial Park (CLPP) approximately 25 km northwest of SLINP. Both parks are within the Frontenac Arch, or Frontenac Axis, a narrow extension of the Canadian Shield that intersects the St. Lawrence Seaway east of Kingston and connects with the Adirondack region (Francis and Leggo 2004). The Frontenac Arch contains different forest cover and physical features that distinguish it from areas to its west and east. It has uneven terrain and acidic, shallow soils that are characteristic of the Canadian Shield, and the landscape and vegetation is generally quite heterogeneous (Gilbert 1994). Fire is more frequent in the boreal landscapes of the Canadian Shield than in southern Ontario habitats, so this region of eastern Ontario may experience different fire regimes than adjacent areas. Charleston Lake is also the northern edge of SLINP's greater park ecosystem (Ellsworth et al. 2009; Fig. 3.1). The two main pitch pine populations in Ontario are the Charleston Lake population and the St. Lawrence population.

The study site, Mud Lake, is located approximately 700 m southeast of Charleston Lake (Fig. 3.2). Mud Lake was selected because it has a small surface area (~2-3 ha) and is relatively deep (~14 m), preferable characteristics for lakes used in charcoal studies

(Whitlock and Millspaugh 1996). Small and deep lakes are more likely to give a precise signal of local fire as the accumulation of macroscopic charcoal is more consistent, compared to larger or shallower lakes (Whitlock and Millspaugh 1996). It was also advantageous to sample a lake within a protected area and adjacent to a pitch pine population. Mud Lake has one inlet, and its one outlet is connected to seasonal beaver habitats. The landscape surrounding Mud Lake features mesic to dry-mesic mixed forest, with poor, sandy soil and some rock barrens (Fig. 3.3). Major tree species include white pine (*Pinus strobus*), red oak (*Quercus rubra*), white oak (*Quercus alba*), eastern red cedar (*Juniperus virginiana*), balsam fir (*Abies balsamea*), and white birch (*Betula populifolia*). A pitch pine population is centred around a rocky cliff on the southeast side of the lake. CLPP and SLINP are the two core protected areas within this region, the Thousand Islands-Frontenac Arch Biosphere Reserve (Francis and Leggo 2004).

There are no cottages or permanent campsites near the lake. It was used as a fishing spot while it was crown land, before the creation of CLPP in 1972, and continued to be used as such afterwards (Chant 1975). The region was logged prior to the 20th century, but the details of logging around Mud Lake are not known (Chant 1975). The park's climate is generally typical for eastern Ontario, with elevation, vegetation, proximity to small water bodies, and the St. Lawrence River impacting local weather conditions. The Lyndhurst station within the park collected weather data from 1976-1993 AD. The mean annual temperature for that period was 6.8 ºC, ranging from a mean of -9.0 ºC in January to a mean of 21.0 ºC in July. Mean annual rainfall from 1976-1993

AD was 800 mm, with mean annual snowfall (November to April) at 178 cm (Ontario Parks 2002).

3.2 Core Retrievals

3.2.1 Surface Core Retrieval

Two surface cores were extracted from Mud Lake from a frozen surface on March 28th, 2008 using a Glew gravity corer equipped with a 7.6 cm diameter core tube. The surface core, Mud Short 1 (44º30.793’N 75º58.919’W) is 58.5 cm in length, and Mud Short 2 (44º30.787’N 75º58.921’W) is 64.5 cm in length. The cores are dark brown, organic sediment, and a sulphur smell was noted upon retrieval. Both surface cores were extruded at the lake site into 0.5 cm intervals using a close-interval sectioning device (Glew 1988). Each sample yielded approximately 20 cm^3 of sediment. Mud Short 2 was selected for analysis as the water-sediment interface was judged as superior to Mud Short 1.

3.2.2 Piston Core Retrieval

Piston cores were extracted from Mud Lake on May 24th, 2008 using a 5-cm-diameter modified Livingstone piston corer (Wright et al. 1983). Two overlapping cores were collected and contain sediment that has accumulated for the length of the Holocene (Whitlock and Larsen 2001). The piston core, Mud Long 1 (44º30.785’N, 75º58.929’W) is 6-m long, composed of six 1-m drives. Mud Long 2 (44º40.781’N 75º58.926’W) is 5-m long, composed of five 1-m drives. Mud Long 2 was selected for analysis as it contained a superior record of the uppermost lake sediment, though the nature of piston coring results in some loss of the youngest sediment. The bases of both cores feature a section of clay, which indicates glacial deposit and, at the transition from clay to sediment, the beginning of the Holocene period (Anderson 1987). Mud Long 1 has approximately 1.5m of clay at its base while Mud Long 2 has approximately 0.35m of clay at its base. The remainder of the piston cores is composed of gytta, dark brown organic sediment. Following retrieval, each drive was wrapped in a layer of plastic wrap and a layer of aluminum foil, labeled, and encased in two halves of plastic tubing for transport and storage. The drives were brought back to the lab and stored in a cold room at approximately 4 ºC.

3.3 Piston Core Preparation

3.3.1 Core Description

Mud Long 2 contains two lithologic units, separated by a gradual transition. The bottom section of drive 5, from 4.53 m to 4.88 m, is composed of gray clay. From 4.39 to 4.53 m is a gray-brown sediment transition between the adjacent sections. The top section, 0.0 to 4.39 m, is dark brown, organic gytta, with no significant visual layers through its length. Mud Short 2 is composed of the same gytta sediment as Mud Long 2's top section.

Though Mud Long 2 was cored over 5 m, the drives extracted are shorter than the 1-m drive length. The extracted lengths, from 1, top-most, to 5, bottom-most, are 80 cm, 85 cm, 77 cm, 85 cm, and 88 cm. As two overlapping cores were taken, filling in these gaps from Mud Long 1 sediment was investigated. The six drive lengths of Mud Long 1, from 1 to 6, are 77 cm, 82 cm, 84 cm, 77 cm, 100 cm, and 102 cm; drive 5 contains 12cm of gytta and 88cm of clay, while drive 6 is entirely clay. Coring depth information was insufficient to determine how the two cores coordinate. Visual cues were sought in Mud Long 2 drives to enable core matching. There was helpful visual information in drive 5 due to the transition from clay to gytta, but the remainder of the drives lacked any change in sediment colour. While the bases could be matched, the nature of sedimentation within a lake varies to such a degree that more coordinating information is required. The magnetic susceptibility of Mud Long 2 was also measured, and a clear record of values could have enabled core matching. However, there was little magnetic susceptibility measurements in any sediment later than the clay-gytta transition. As a result, the sediment record, Mud Long 2, was prepared and analyzed as a contiguous sediment core.

3.3.2 Sectioning

Drives of Mud Long 2 were subsampled at 0.5-cm intervals and placed in 7-cm^3 or 5-cm^3 plastic, snap-cap labeled vials. Each subsample yielded approximately 2-4 cm^3 of sediment; this varied by the amount of exterior mud removed from the core and by the subsampling consistency, given the nature of the sediment. The vials were then placed in a cold room at approximately 4 ºC for storage until analysis. During core sectioning, macrofossils were removed from each drive and stored individually in sterile glass vials. The vials were stored in a freezer until removed in order to prepare for AMS dating.

3.4 Magnetic Susceptibility

Magnetic susceptibility is the degree of magnetization of a material once a magnetic field is applied to it. Fires may heat soils, leading to the formation of paramagnetic minerals, and it often removes the top layer of soils, destabilizing slopes (Thompson and Oldfield 1986). Both traits allow it to be used as an erosion proxy, as a greater amount of soil erosion into a lake may result in a higher level of magnetic susceptibility, and it has been previously used in sediment-charcoal studies (Long et al. 1998; Carcaillet et al. 2001a). Following sectioning, the sediment samples of Mud Long 2 were analyzed for magnetic susceptibility.

The volume of each piston core subsample was measured by flattening the sediment and measuring its height in the vial, then calculating the volume based on the measurements of the vial. This volume is needed to calibrate the magnetic susceptibility reading, as all samples differed from the idealized sample volume of 10 cm^3 of the equipment used. Each vial was run through the Bartington MS2B cup meter (Bartington Instruments, Witney, United Kingston), and three measurements in dimensionless cgs units (x 10^{-6}) at 0.1 range were taken of each sample. The sensor was zeroed following each sample; this prevents drift in the measurements and minimizes any background noise that could alter the measurements. The magnetic susceptibility readings for each sample were averaged and calibrated using the volume measurement: calibratedvalue = originalvalue x (10/volume). The results were graphed and assessed visually for peaks in activity.

3.5 Sample Preparation and Enumeration

3.5.1 Sample Preparation

Two cm^3 of sediment was removed from each 0.5-cm interval of the Mud Short 2. The entire volume of each 0.5-cm interval of Mud Long 2 was processed, with volumes ranging between 1.5 cm^3 and 5 cm^3. Each sample was digested in 5% lab grade sodium hypochlorite (NaClO) (Fisher Scientific, Ottawa, Ontario) for a minimum of two days. This deflocculated the sediment and digested much of the organic matter, enabling easier counting. The sediment was gently wet-sieved through a 125 µm sieve with deionized water and back-washed into a petri dish. It remained hydrated with deionized water for visual counting. While charcoal greater than 50 µm may represent the local fire signal (Clark 1988b), it is more practical to count the charcoal that is >125 µm and comparisons have shown that it produces equivalent results (Whitlock and Millspaugh 1996).

3.5.2 Counting Procedure

Each petri dish was analyzed using a Leica® MZ12.5 dissecting microscope (Leica Microsystems, Richmond Hill, Ontario) at 25X magnification. A grid was placed under the petri dish and each square was assessed individually and sequentially, to ensure that all dish area was covered. Charcoal is visually identifiable by its black colour, reflective surface, and angular structure. All charcoal particles in each subsample were tallied, and photos were taken of each particle of surface core samples.

3.6 Charcoal Morphotypes

The morphological traits of the charcoal within the surface and the piston cores were assessed. The hierarchy of morphotypes developed by Enache and Cumming (2006) was applied (Fig. 3.4). While there can be regional variations, the framework was appropriate for the charcoal structures seen in the surface and piston cores.

The charcoal morphotype counts were analyzed to determine how the proportions change through the charcoal record. The total charcoal accumulation rate (CHAR) and the CHAR for each morphotype was graphed using Origin 8.1 (OriginLab, Northampton, Massachusetts). The graphs were then visually inspected for relevant trends.

3.7 Core Chronology

3.7.1 ^{210}Pb Dating

The top 20- cm of the surface core was analyzed for ^{210}Pb, ^{137}Cs and ^{214}Bi content using a gamma counter following the methods outlined in Schelske et al. (1994). The results are in Table 3.1. This procedure works well for dating sediments accumulated in the last 200 years. Every other 0.5-cm section starting from 0.0-cm was subsampled, for 20 samples. The sediment was freeze dried, compacted, placed into plastic vials, and given an airtight seal with 2 Ton® Epoxy (Devcon, Danvers, Massachusetts). Each vial contained approximately 0.5 g of dried sediment. After resting for a minimum of two weeks to ensure equilibrium between ^{226}Ra and ^{214}Bi, the samples were dated using the in-house gamma counters in the Paleoecological Environmental Assessment and

Research Lab (PEARL) facilities at Queen's University.

3.7.2 ^{14}C Dating

The bottom section of the surface core and the entirety of the piston core were dated using ^{14}C accelerator mass spectrometry (AMS) radiocarbon methods (Table 3.2). This analysis was performed at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratories in Livermore, California. Macrofossils were extracted from sediment samples of the bottom 20 cm of the surface core and from all drives of the piston core. Coniferous needles were the most common organic material sent for dating; a seed pod and a large piece of charcoal were also sent for dating. Macrofossils were strategically chosen, given the available samples, to provide a continuous chronology throughout the core. After removal from the core, the specimens were stored in a freezer until needed. Once removed, the samples were cleaned with double deionized water and dried in individual, sterile containers in an oven at 100 ºC. The dating samples were then sent to the lab, where they underwent an acid-base-acid (ABA) pre-treatment and were measured for 4/7 cycles at 25 Kcts/cycle. Thirteen samples were sent for ^{14}C dating. Two sample dates seemed inverted or out of sequence so they were rejected. This may be due to the movement of the material during coring such that the specimen did not represent the deposition date of the location in which it was found. The topmost ^{14}C from the piston core was also excluded as it had a large amount of error and as the top section of the core was well-dated by material from the surface core. The ^{14}C dates were calibrated using Calib 5.0 (Stuiver and Reimer 1993; Reimer et al. 2004; Stuiver et al.

2005; intcal.qub.ac.uk/calib/).

3.7.3 Age-Depth Model

The ^{14}C dates were used to determine the overlap between the surface and piston cores, creating one continuous record between them. This was relatively straightforward as the oldest ^{14}C calibrated date in the surface core, MS63.0-63.5 at 1114 yr BP, is 10 years younger than the second date from the piston core, ML51.5-52.0 at 1124 yr BP. As these dates are so similar as to be considered equivalent, the piston core date was adjusted to a depth 11.5 cm deeper than the surface core date, from 51.5-52.0 cm to 63.0-63.5 cm, to match the depths of the two ^{14}C dates. For the age-depth model and the charcoal record analysis, all piston core depths were adjusted by adding 11.5 cm, coordinating them with the surface core.

Age-depth models use radiometric dates at discrete intervals in a sediment core to predict the dates of the remainder of the core levels. MCAgeDepth is software that combines ^{210}Pb and ^{14}C dates from continuous sediment cores to produce age-depth models (Higuera 2008; webpages.uidaho.edu/phiguera/software/software.html). The program uses a Monte Carlo approach to generate confidence intervals that incorporate the probabilistic nature of the calibrated dates (Higuera 2008). It runs a chosen number of simulations, each of which develop a chronology based on ages randomly selected from the probability distribution of each calibrated date. In the outputted data, the ^{210}Pb and ^{14}C dates are weighted by their standard deviation such that ages with greater error have less impact on the model (Higuera 2008).

3.8 Documentary Research

Documents describing the areas around CLPP and SLINP were consulted for information on human land-use records and information on fire events over the past two centuries. Relevant information was found in a written history of Charleston Lake (Chant 1975), a written history of Lanark County (Currie 2009), and in Ontario Forest Fire History: An Interactive Digital Atlas (Ontario Forest Research Institute 1998).

3.9 Charcoal Record Analysis

3.9.1 Charcoal Accumulation Rate

The macroscopic charcoal concentration (pieces/cm^3) is divided by sample deposition time (yr/cm) to calculate CHAR (pieces$\bullet$cm^{-2}$\bullet$yr^{-1}). These quantities are plotted against the core depth to provide the CHAR profile for the lake. The goal of analysis is the isolation of primary charcoal peaks that are taken to represent historic fire episodes. Secondary charcoal is the average accumulation in sediments over extended intervals (Long et al. 1998). The threshold level of secondary charcoal is determined through modeling, with peaks above this level, representing primary charcoal, assessed as fire events (Higuera et al. 2007). In practice, this is a multi-step process.

3.9.2 CharAnalysis

CharAnalysis is a set of diagnostic and analytical tools for processing sedimentary charcoal data, developed by Philip Higuera of Montana State University and University of Idaho (Higuera 2009; sites.google.com/site/charanalysis). Its focus is fire history reconstruction through the detection of charcoal peaks, using the decomposition approach previously developed by Clark and Royall (1996), Long et al. (1998), and Carcaillet et al. (2001a), among others. CharAnalysis models the components of the charcoal record, separating them to allow for the identification of charcoal peaks, and estimating the occurrence of fire episodes, FRIs, and fire frequencies (Higuera et al. 2008). Peak detection takes into account the processes of charcoal production, dispersal, deposition, and mixing, as well as sediment sampling (Higuera et al. 2007). CharAnalysis targets peaks that represent fires within 500 m - 1 km of the study lake, equivalent to an area of 100-300 ha or 1-3 km^2 (Higuera et al. 2009). The high- and low-frequency elements of the charcoal record are separated, distinguishing the fire signal from the noise (Higuera et al. 2007). Building on past analytical procedures, this program also provides the option of a locally-defined threshold. This allows for a more sensitive analysis as it incorporates changes in the level of low-frequency charcoal over time (Higuera 2009). An overview of the analytical steps and the parameter choices is given below, and additional details are available in Appendix C.

The first analysis step re-samples the data based on the sampling interval selected, re-calculating each interval's CHAR value. This new series is referred to as C_{int}. This step changes the type of sampling interval from core length (i.e. 0.5-cm) to a period of time (i.e. 5 yr) (Higuera 2009). The second step models the background charcoal, $C_{back,}$ using a globally- or locally-defined threshold and smoothes it with a regression using a defined, moving time-window. C_{back} is the low-frequency variation, reflects long-term variation in charcoal production, secondary charcoal accumulation, and sediment mixing (Higuera et al. 2007). The third step removes C_{back} from C_{int} to define the CHAR peak series, C_{peak}. C_{peak} represents the high-frequency component of the charcoal record (Higuera 2009). The fourth step separates C_{peak} into two further components: C_{noise}, a normally-distributed population around C_{back} that reflects natural and analytical effects, and C_{fire}, which are high CHAR values that exceed variability in the C_{noise} distribution and are assumed to represent local fires (Higuera et al. 2008). C_{noise} is modeled by the software and a chosen percentile (i.e. 95th) of its distribution is taken as the threshold value separating C_{fire} and C_{noise} (Higuera et al. 2008). The fifth and final step screens for insignificant peaks through a minimum count requirement. A peak is removed if its maximum charcoal count has a >5% chance of coming from the same Poisson-distributed population as the minimum charcoal count within the proceeding 75 years. The non-parametric Kolmogorov-Smirnov goodness-of-fit test is used to determine if the samples come from the same probability distribution (Higuera 2009).

The Holocene charcoal record is a composite of the surface and piston cores, created by adding together the counts and volumes of the overlap between the surface and piston cores. The top 11.5 cm are surface core values, 11.5-64.5 cm are surface and piston core values, and 64.5-392.5 cm are piston core values. The record was analyzed with CharAnalysis using a selected set of parameters that define each analysis step. The parameters were chosen in order to achieve a robust local-fire record. The interpolated charcoal record, C_{int}, was defined using the median sampling interval, 16 yr, in the raw record (Step 1). C_{back} was estimated using a Lowess smoother robust to outliers, and it was smoothed with a local, 500-yr moving window (Step 2). A sensitivity analysis was run within CharAnalysis to determine the most appropriate smoothing window, looking at the noise distribution goodness-of-fit (GOF) and signal-to-noise index (SNI) for a range of time lengths. There was little difference in the combined totals for range of windows lengths, so a 500-yr moving-window was selected for all sections as it enhances the local nature of the analysis. As the length of the smoothing window should include a minimum of 30 samples, a 500-yr window is also the smallest possible for the median sampling resolution. C_{peak} was defined using residuals, assuming that the charcoal that represents peaks is additive to background charcoal (Step 3). In Step 4, the detection of charcoal peaks was defined locally with a threshold value at the 95th percentile separating C_{noise} and C_{fire}. The p-value cut off for insignificant peaks is 0.05 (Step 5). Finally, the fire frequency (fires per 1000 yr) and FRIs were smoothed within a 1000-yr moving-window to summarize long-term trends.

CharAnalysis also outputs a Weibull model to characterize the record's FRI distribution (Higuera 2009). The proportion of FRIs is displayed in a histogram with 20-yr bins (Higuera et al. 2008). It provides an mFRI estimate as well as Maximum Likelihood estimates of the Weibull parameters b, the scale parameter, and c, the shape parameter (Johnson and Gutsell 1994). The b-parameter represents the 63.2 percentile of the FRI probability distribution, and the c-parameter is estimated from the shape of the histogram (Johnson and Gutsell 1994). The model is only produced if it passes a one-sample Kolmogorov-Smirnov goodness-of-fit test for the b parameter with a p-value >0.10 (if nFRI <30) or >0.05 (if nFRI >30) (Higuera 2009). The fit of the maximum likelihood estimate of the b parameter for the distribution of FRIs within the zone is tested. Zones within the record can be selected to compare the mFRIs of different periods of time (Higuera 2009).

The surface-core charcoal record was analyzed separately to provide additional information about Mud Lake’s recent fire history. The same age-depth model and the same parameters as the Holocene charcoal record were used, with three exceptions. The median sampling resolution for the 64.5-cm long, 1050 yr record was 10 yr. Additionally, a 300-yr moving-window was used to model and smooth C_{back}, as the sensitivity analysis established that it has the best combination of noise-distribution goodness-of-fit and SNI. Finally, a 500-yr moving-window was used to smooth the fire frequency and FRI to better reflect the length and resolution of the record.

Table 3.1 Mud Lake, Ontario surface core ^{210}Pb dates. The dating was performed at the Queen's Paleoecological Environmental Assessment and Research Laboratory (PEARL) following the methods outlined in Schelske et al. (1994). A constant rate of supply (CRS) model (Binford 1990) was used to process the ^{210}Pb, ^{137}Cs, and ^{214}Bi activity and produce the ages. Raw activities are in Appendix B3. Depth is distance below sediment-water interface. Cal yr BP refers to 1950 AD. SD refers to standard deviation.

Interval Depth (cm)	Age of Interval Top (cal yr BP)	Error (± 1 SD)	Year (AD)
0.0-0.5	-58	0.19	2008
1.0-1.5	-52	0.21	2002
2.0-2.5	-46	0.24	1996
3.0-3.5	-40	0.27	1990
4.0-4.5	-33	0.32	1983
5.0-5.5	-26	0.38	1976
6.0-6.5	-19	0.47	1969
7.0-7.5	-7	0.64	1957
8.0-8.5	6	0.95	1944
9.0-9.5	19	1.39	1931
10.0-10.5	29	1.82	1921
11.0-11.5	41	2.64	1909
12.0-12.5	51	3.58	1899
13.0-13.5	64	5.31	1886
14.0-14.5	81	8.89	1869
15.0-15.5	94	13.24	1856

Table 3.2 Mud Lake, Ontario surface and piston core accelerator mass spectrometry (AMS) ^{14}C radiocarbon dates. All AMS dates were produced by the Lawrence Livermore National Laboratory, Center for Accelerator Mass Spectrometry on terrestrial macrofossils or charcoal fragments. All terrestrial macrofossils appeared to be coniferous needle fragments or grass fragments. The raw data are in Appendix B4. Uncalibrated ^{14}C dates were calibrated using Calib 5.0 (Stuiver et al. 2005) based on the calibration data of Reimer et al. (2004). Depth refers to distance below mud surface. Note that recovery of the top of the piston core was not complete as the top 11.5 cm was missing (see text for details). Cal yr BP refers to 1950 AD.

Core Section	**Depth (cm)**	**CAMS laboratory No.**	**Uncalibrated ^{14}C age (^{14}C yr BP) and error**		**Calibrated age with 2-sigma age range (cal yr BP)**		**Material dated**
Surface Core	47.0-47.5	142833	790	± 35	710	(670-766)	terrestrial macrofossil
Surface Core	63.0-63.5	142834	1190	± 30	1116	(1006-1230)	terrestrial macrofossil
Piston Drive 1	17.5-18.5	142835	180[a]	± 40	176	(-3-301)	terrestrial macrofossil
Piston Drive 1	51.5-52.0	142836	1200	± 35	1126	(1009-1257)	terrestrial macrofossil
Piston Drive 1	71.5-72.0	142837	1435	± 40	1334	(1290-1394)	charcoal fragment
Piston Drive 2	92.5-93.5	142838	2120	± 45	2098	(1953-2305)	terrestrial macrofossil
Piston Drive 2	155.5-156.0	142839	3690	± 40	4031	(3908-4147)	terrestrial macrofossil
Piston Drive 3	173.5-174.0	142840	3245[b]	± 35	3463	(3391-3558)	terrestrial macrofossil
Piston Drive 3	196.5-197.0	142841	4505	± 40	5163	(4994-5308)	terrestrial macrofossil
Piston Drive 3	226.5-227.0	142842	5555	± 45	6350	(6283-6435)	terrestrial macrofossil
Piston Drive 4	282.0-282.5	142843	7675	± 50	8469	(8387-8575)	terrestrial macrofossil
Piston Drive 4	302.0-302.5	142844	8285	± 45	9294	(9132-9427)	terrestrial macrofossil
Piston Drive 5	330.5-331.5	142845	7480[c]	± 60	8296	(8183-8390)	terrestrial macrofossil

[a] Date not used in the age-model as it was considered too young for its position

[b] Rejected date due to inversion when compared to the age and position of the date at depth 155.5-156.0 cm

[c] Rejected date due to inversion when compared to the age and position of the dates at depths 282.0-282.5 cm and 302.0-302.5 cm

Chapter 3 Figure Captions

Figure 3.1 Map of the main properties of St. Lawrence Islands National Park (SLINP) and the surrounding area (map centre N44º25’44.3”, W76º05’46.5”). The largest SLINP properties are highlighted. The map’s location within the Province of Ontario is shown. The location of Charleston Lake, Charleston Lake Provincial Park, Mud Lake, the St. Lawrence River, main highways, and nearby cities is also shown. This map was created from the Ontario Ministry of Natural Resources: Land Information Ontario Make-a-Map service (OMNR 2009; www.mnr.gov.on.ca/en/Business/LIO/index.html).

Figure 3.2 Map of Charleston Lake, Charleston Lake Provincial Park, and Mud Lake (map centre N44º31’47.4”, W76º00’31.5”). The black internal border is the territory of Charleston Lake Provincial Park. This map was created from the Ontario Ministry of Natural Resources: Land Information Ontario Make-a-Map service (OMNR 2009; www.mnr.gov.on.ca/en/Business/LIO/index.html).

Figure 3.3 Satellite image of Mud Lake, Ontario. It is a close-up on Mud Lake and highlights the outlet and surrounding terrain. (Google Earth 2009; Google, Mountain View, California).

Figure 3.4 Diagram showing a simplified scheme for identification of charcoal morphotypes. There are seven types and each have been assigned a letter. Charcoal pieces are first partitioned by their shape: they may be irregular with uneven edges, or geometric with relatively straight sides. Irregular pieces are divided into those with structure, or pores (M), and those without (P). Compact geometric pieces are equivalently divided: they may have no internal structure (C) and those with structure may be black (S) or partially black (B), the latter type only partially burnt. Finally, elongated geometric pieces may have ramifications (D) or not (F) (from Enache and Cumming 2006).

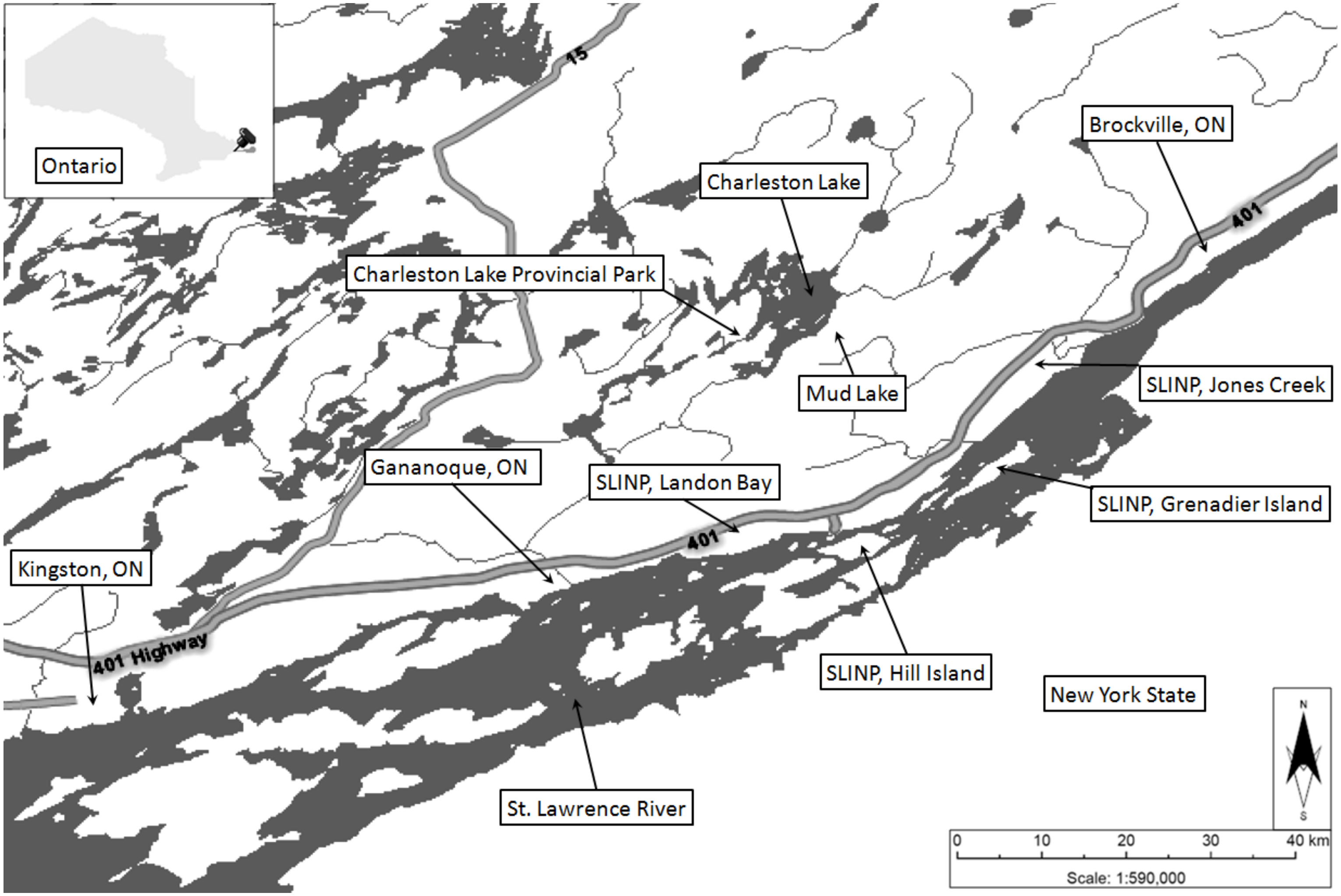

Ontario
15
Brockville, ON
Charleston Lake
401
Charleston Lake Provincial Park
Mud Lake
SLINP, Jones Creek
Gananoque, ON
SLINP, Landon Bay
SLINP, Grenadier Island
401
Kingston, ON
401 Highway
SLINP, Hill Island
New York State
N
S
St. Lawrence River
0
10
20
30
40 km
Scale: 1:590,000

Figure 3.1

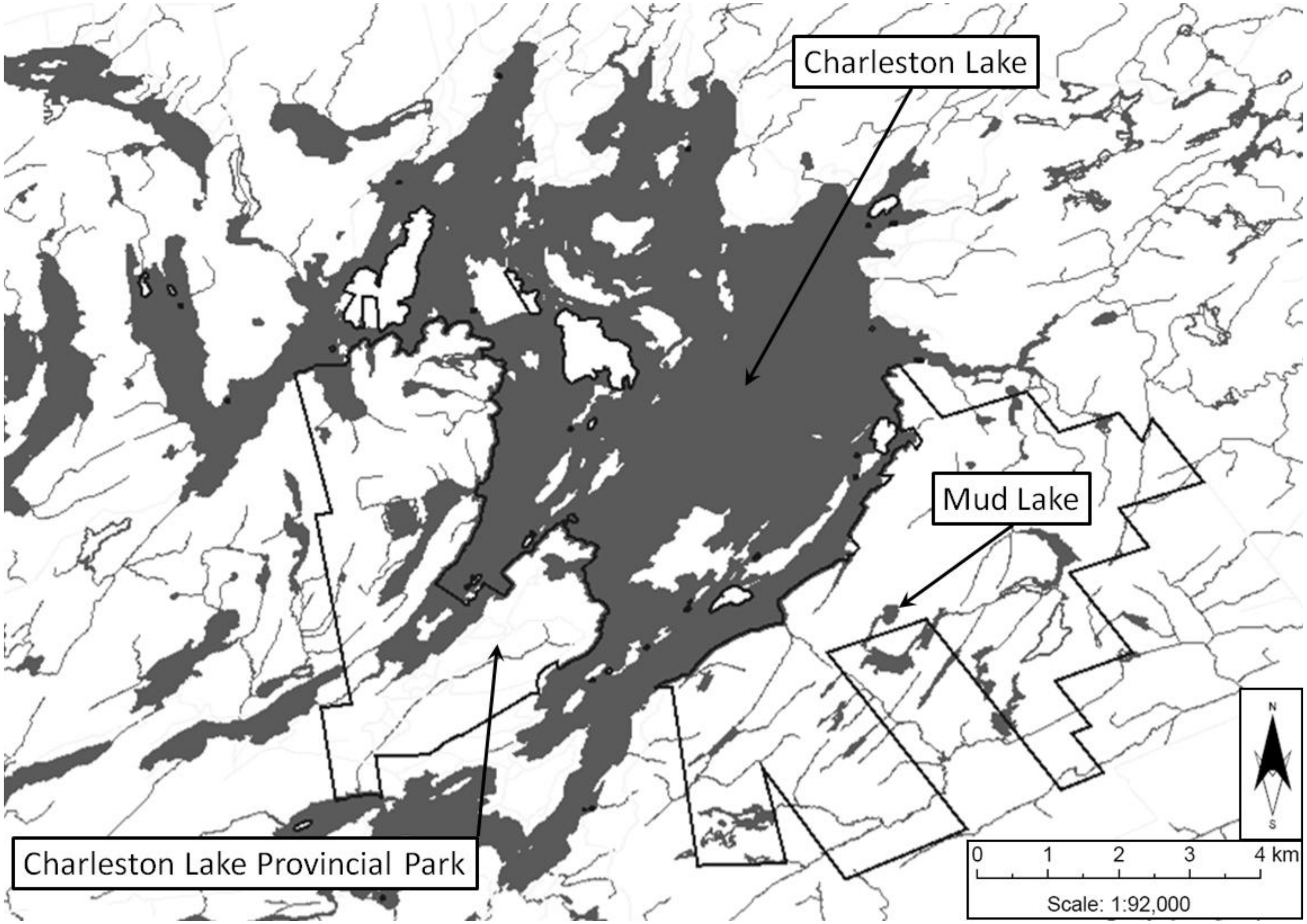
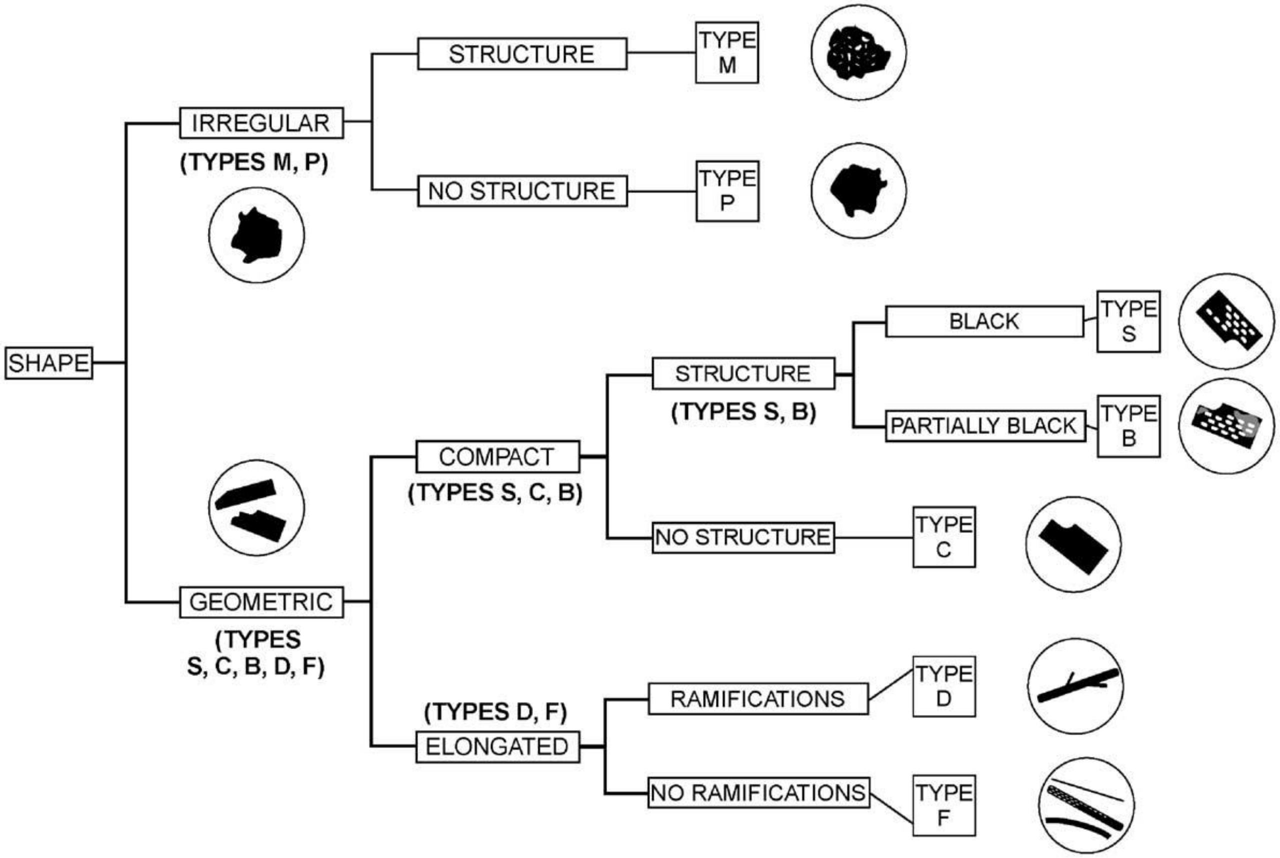

Charleston Lake
Mud Lake
Charleston Lake Provincial Park
N
S
0 1 2 3 4 km
Scale: 1:92,000

Figure 3.2

Figure 3.3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IRREGULAR
(TYPES M, P)
STRUCTURE
TYPE M
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TYPE P
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(TYPES S, C, B, D, F)
COMPACT
(TYPES S, C, B)
STRUCTURE
(TYPES S, B)
BLACK
TYPE S
PARTIALLY BLACK
TYPE B
NO STRUCTURE
TYPE C
(TYPES D, F)
ELONGATED
RAMIFICATIONS
TYPE D
NO RAMIFICATIONS
TYPE F

Figure 3.4

Chapter 4

Results

4.1 Documentary Fire History

Documentary records of fire in the study area were sought from several sources. There was a fire ~50 km southwest of the study lake in 1954, with a size of ~312 ha (Ontario Forest Research Institute 1998). While this is a large burn, it is outside the broad 20-km local fire range that macroscopic charcoal analysis provides and far outside of the 1 km range that CharAnalysis targets; it may have been identified in a regional fire history. This fire is one of only two recorded for eastern Ontario during that time period. The other occurred in 1963 ~150-km northeast of the study site. While substantial (~1483 ha), it is not local, and the distance is even large enough to question its presence in the regional, microscopic charcoal fire record of Mud Lake (Ontario Forest Research Institute 1998). Unfortunately, this part of eastern Ontario is designated by the Ontario Ministry of Natural Resources (OMNR) as Outside of the Fire Region (OFR), so its fire activity is not actively included in their records (OMNR 2004). It is likely that these fires were recorded due to their size, so information about smaller fires that occurred in eastern Ontario between 1920 and 1981 AD is not available from OMNR. Since that period, there was a ~20 ha fire around CLPP’s Blue Mountain region in 1988 (Ellsworth et al. 2009). This area is ~3 km from the study site, and, while that is the closest recorded fire, it is outside of the local-fire range of the macroscopic-charcoal research used here.

A human history of the Charleston Lake region details fires in the area from 1903 to 1969. Most recorded fires are those of individual homes and cottages, with the majority caused by people and subdued before they spread into vegetated regions. An exception to this, Hogsback Island, ~4 km from the study site and burned in 1956. The island is ~6 ha in size, so an incomplete burn of the island would likely not have been sufficient to leave a stratigraphic record of macroscopic charcoal in lake sediment, and documentary records do not provide any additional details. 4 km is also not considered a local fire within the context of this research. Aside from this event, no other fire is described as significant enough in scale or identifiable as local to Mud Lake to potentially appear in the charcoal record (Chant 1975). An additional fire took place in 1870 AD in what is currently Lanark County, between Ottawa and Smith’s Falls. Over several weeks in the summer, it was estimated to have burned around 100000 ha of developed and natural areas (Currie 2009). This is outside of Mud Lake’s local fire area, but it is possible there were regional factors, such as drought, that were affecting eastern Ontario at that time.

4.2 Magnetic Susceptibility

There is magnetic susceptibility activity in the clay section of the piston core, including a notable peak around interval 383-384 cm (Fig. 4.1). The activity decreases through the clay-gytta transition in Drive 5, and it ends at 342 cm. No pattern or trend was detected in the subsequent changes in magnetic susceptibility in the remainder of

Mud Long 2 (Fig. 4.1). As the most discernible magnetic susceptibility peaks are wholly associated with the core's clay content, the activity does not stem from fire-related soil magnetization.

While in some studies comparison with magnetic susceptibility has proved useful (Millspaugh and Whitlock 1995), others have found no correlation with fire activity (Long et al. 1998). Steep-sided watersheds show greater magnetism than low-gradient watersheds, so Mud Lake may have no signal as a result of its low-elevation topography (Whitlock and Larsen 2001). In addition, the landscape around the lake is includes rocky areas, which would limit soil erosion. The sediment-core gytta is also mainly organic, and little silt or sand was observed in it. It may be that there were no significant amounts of erosion into Mud Lake, which would also indicate limits on the input of secondary charcoal in the record. It is also possible that the lack of activity in the gytta suggests that the soil minerals in the Mud Lake area are not affected by fire. In this case, these results do not rule out erosion events into Mud Lake during the Holocene. As it is, there are no fluctuations in magnetic susceptibility that can be correlated with fire events.

4.3 Age-Depth Model

Using the calibrated ^{210}Pb and ^{14}C dates collected from the surface and piston cores, a composite age-depth model was created with the software MCAgeDepth (Higuera 2008; Fig. 4.2). 100 simulations were run by the program. The ^{210}Pb dates were fitted with a spline stiffness of 0.20, and the ^{14}C dates were fitted with a spline stiffness of 0.001. The process of choosing spline stiffness parameters began with estimating values based on the number of samples in the ^{210}Pb and ^{14}C chronology. The estimate for the ^{210}Pb chronology, spline = $1/(1+h^3/60)$, where h is the average distance (cm) between ^{210}Pb dates, has a value of ~0.90 (Higuera 2008). The estimate for the ^{14}C chronology, spline = $1/(1+h^3/12)$, where h is the average distance (cm) between ^{14}C dates, has a value of ~0.0005 (Higuera 2008). The spline stiffness chosen for the ^{14}C chronology was larger than the estimate to enable greater flexibility in the interpolation of ages between ^{14}C dates. While the ^{210}Pb dates have such high density in the top 15 cm of the core chronology that a spline stiffness approaching 1.0 is possible, it was preferable to have a value closer to the spline stiffness of the ^{14}C dates as it enables a superior transition between the two dating periods. The alpha level of confidence intervals around calibrated dates and the chronology is 0.05.

The sedimentation rate (cm-deposited/yr) at the top of the combined core varies over the most recent 20 cm, reaching its highest values. Its subsequent variation through most of the core is smaller in magnitude. The sedimentation rate (cm/year) has a mean of 0.076 cm/year, with a maximum of 0.34 cm/year in the top interval and a minimum of 0.050 cm/year over the last 20 cm of the age-depth model. The sample resolution, the inverse of sedimentation rate, has a mean of 30 yr/cm, with a high of 40 yr/cm at the oldest part of the record and a low of 6 yr/cm at the youngest part of the record. The confidence intervals estimated by MCAgeDepth increase from ±0.34 yr for the youngest interval to ±130 yr at the end of the interpolated age-depth model (9500 yr BP).

The sediment intervals' dates between the ^{14}C and ^{210}Pb dated samples were interpolated by the software. The age-depth model ends after the last ^{14}C date as the extrapolation is difficult with uncertain errors. The remainder of the sediment core was manually given an interval of 20 yr per 0.5 cm interval, or 40 yr/cm, the rate for the section of core before the last ^{14}C date. The extrapolated date of the transition between the core's gytta and glacial clay is 12420 yr BP. This date is likely too old, compared to the basal dates of other cores in the region which place the start of gytta sediment deposition at ~11700 yr BP (Terasmae 1980; Anderson 1987). The possible explanations for this include a decrease in sedimentation rate for the section of core for which dates have been extrapolated. Additionally, there is visual evidence from Mud Long 2 that the last 14 cm of sediment containing charcoal pieces is a mixture of clay and gytta, given its grey-brown colour and silt content. This would elongate the end of the core, obscuring the accurate dates. It is also possible that the oldest ^{14}C date is too old for its core position. There are a lack of dates from the end section of the core; an additional AMS ^{14}C date is being processed, and the extrapolated interval rate remains in the interim.

4.4 Holocene Sediment-Charcoal Record

4.4.1 Interpolated Data

The Holocene-length record is a composite of the surface core and the piston core charcoal counts such that all counts were used. The raw charcoal data for the surface and the piston cores are available in Appendix B. The counts and volumes were added together for the overlap of the piston and surface cores. The charcoal data were resampled to a constant 16-yr interval period with 780 interpolated samples. They range in length from 2.6 cm at the top of the core to 0.40 cm at the bottom of the core. The resampled counts have a mean of 27 charcoal pieces and a range of 0 to 1355 charcoal pieces. The record has a global SNI of 0.73 (Appendix A, Fig. A.3).

4.4.2 Charcoal Accumulation Rate

The CHAR for the record's interpolated intervals (C_{int}) has a mean of 0.24 pieces•cm^{-2}•yr^{-1} and a range of 0.00 pieces•cm^{-2}•yr^{-1} to 21.74 pieces•cm^{-2}•yr^{-1} at 1430 yr BP (Fig. 4.3a). The maximum CHAR level is part of a multi-sample charcoal peak identified as a fire event at 1480 yr BP; the peak's largest value is an order of magnitude larger than the maximum value of the next largest CHAR peak, 1.04 pieces•cm^{-2}•yr^{-1} at 2580 yr BP. The background CHAR level (C_{back}) has a mean of 0.16 pieces•cm^{-2}•yr^{-1} and a range of 0.010 pieces•cm^{-2}•yr^{-1} to 0.50 pieces•cm^{-2}•yr^{-1} (Fig. 4.3a).

4.4.3 Fire Events

The analysis identified 71 charcoal peaks representing fire episodes in the Mud Lake record (Fig. 4.3b). An additional 10 peaks were determined to be statistically insignificant based on the minimum count test and removed from the record. The most recent fire in this charcoal record is estimated as 250 yr BP. It is likely, however, that there has been a more recent fire than the results from the full, Holocene-length core indicate. The top 11.5cm of the combined core, representing the most recent 110 yrs, is sediment from only the surface core, which has a smaller sample volume (2 cm^3) and smaller counts, related to its high sedimentation rate. While alternative parameters, such as $\log_{10}$ transformation and a less stringent confidence level for the minimum-count test, were investigated to overcome this problem, no additional charcoal peaks entered the record. Because of this uncertainty, the surface core charcoal record has been analyzed separately, to provide additional insight into recent fire activity.

4.4.4 Fire-Return-Intervals

With 71 fire events, there are 70 intervals between episodes. The largest length of time between two peaks is ~490 yr, between fire events at 6770 yr BP and 6280 yr BP, and the shortest length of time between two peaks is ~30 yr, occurring between episodes at 4070 yr BP and 4100 yr BP and episodes at 9930 yr BP and 9960 yr BP. From the Weibull model, the global mFRI (95% CI) is 175 (146-204) yr (Fig. 4.4). Within the smoothed, interpolated FRIs, the mean FRI is 204 yr/fire with a range of 115 to 483 yr/fire (Fig. 4.3c; Appendix A, Fig. A.2).

4.4.5 Fire Frequency

The mean of the smoothed, interpolated fire frequency series is 5.7 fires/1000 yr. It has a range of 1.8 fires/1000 yr to 7.8 fires/1000 yr (Fig. 4.3d). The fire frequency is fairly consistent prior to 10000 yr BP, ranging from 4.6 to 5.6 fires/1000 yr. It rises from 10000 yr BP (5.6 fires/1000 yr) to 7500 yr BP (7.5 fires/1000 yr), and then decreases to 6200 yr BP (3.4 fires/1000 yr). From 6100 to 4000 yr BP, the fire frequency increases back up to 7.8 fires/1000 yr. It decreases from 4000 to 3200 yr BP (5.1 fires/1000 yr), rises to 2500 yr BP (7.4 fires/1000 yr), and then decreases until modern times (1.8

fires/1000 yr) (Fig. 4.3d; Appendix A, Fig. A.2).

4.4.6 Alternative Parameter Options

As different parameter choices result in changes to the fire record, it's worthwhile to consider alternate parameters and the extent to which the results vary.

No transformation was performed in the main analysis. The data were separately run with a $\log_{10}$ transformation of the CHAR values. Incorporating this transformation into the analysis should be considered if the data is heteroscedastic, or changes in variability. The results are similar between the transformed and the untransformed data sets. When log-transformed, there are 74 peaks identified in the record, 3 more than in the main analysis (Appendix A, Fig. A.4). As there is minimal differences between the analyses, this indicates that the large charcoal peaks do not limit the likelihood that nearby peaks will be found to be significant. This demonstrates that a locally defined background and threshold is beneficial as it reflects changes in background charcoal.

The data set was also run with a less stringent minimum-count confidence level; 0.90 instead of 0.95. This was done as there were concerns that the low counts in the surface core made it more likely that peaks in that section of the record would be rejected, leading to false negatives. Two peaks that were previously rejected were included in this alternate parameter CharAnalysis run, at 5130 yr BP and 10440 yr BP. These dates were not in the section of the record that included charcoal counts from surface core samples. Thus, this alternate parameter was not used as it did not contribute to clarification of the top section of the record. Instead, the surface core was also analyzed separately to better understand recent fire activity in the Mud Lake area.

4.4.7 Charcoal Record and Pollen-Paleoclimate Zones

The zone divisions parameter in CharAnalysis was used to analyze the mFRIs for periods corresponding to the main pollen trends in eastern Ontario (Fig. 4.5). This may provide information on the relationship between fire and vegetation in this region. While pollen records for this region had up to six zones, the lack of radiometric dating for most of the cores and the limited resolution with which pollen was studied led to a lack of confidence in their specifics. Additionally, as the study site is within the heterogeneous Frontenac Arch region, its historic vegetation trends may have varied from those of the greater region. The pollen trends were amalgamated into three zones that represent major vegetation shifts described earlier in the text (Anderson 1987). The zones selected also coordinate with broad, millennial-scale climate trends in eastern North America.

The oldest pollen zone (3) covers the period of 12420 to 9800 yr BP, which includes the initial vegetation of the study site as well as the first arboreal community. A generally wet climate that saw increasing temperature through the period mediated this assemblage (Anderson 1987; McFadden et al. 2004). The mFRI (95% CI) for this period is 185 (129-247) yr/fire and there were 14 fire events (Fig. 4.5). The fire frequency for this period ranges from 4.6 to 5.9 fires/1000 yr.

The second pollen zone (2) covers the period 9800 to 5300 yr BP. *Pinus* dominates during much of this time period. *Tsuga* also peaks in this zone (Anderson 1987). The end of the period coincides with the *Tsuga* decline, a continent-wide event attributed to the spread of a forest pathogen (Fuller 1998). This period experienced a generally warmer climate (McFadden et al. 2004). The mFRI (95% CI) for this period is 172 (128-222) yr/fire and there were 25 fire events (Fig. 4.5). The fire frequency for this period ranges from 3.4 to 7.5 fires/1000 yr.

The most recent zone (1) spans from 5300 yr BP to present day. The vegetation during most of this period is a mixed-hardwood forest, with less dominance by coniferous species (Anderson 1987). This period had a generally colder climate than the subsequent zone (McFadden et al. 2004). The mFRI (95% CI) for this period is 162 (126-203) yr/fire and there were 32 fire events (Fig. 4.5). The fire frequency for this period ranges from 1.8 to 7.8 fire/1000 yr.

While the mFRIs increase in size as the zones get older, the confidence intervals overlap a great deal. This indicates that there is little difference between the mFRI of each time period. The smoothed fire frequencies in the two most recent zones have around the same range, while the oldest zone has less variability.

4.4.8 Charcoal Record and Biomass Burning Trends

The charcoal record was also run with zones representing the three periods of varying biomass burning in eastern North America, as estimated by Carcaillet et al.(2002) and Power et al (2008) (Fig. 4.6). These periods were developed by aggregating all available sediment-charcoal records from the region, standardizing them, and analyzing them to determine overall trends (Carcaillet et al. 2002; Power et al. 2008) The period of 12420 to 7500 yr BP has an mFRI (95% CI) of 170 (132-211) yr/fire and 29 fire events.

Overall subcontinental biomass burning was high during this time (Carcaillet et al. 2002; Power et al. 2008). The period of 7500 to 3000 yr BP has an mFRI (95% CI) of 163 (114-211) yr/fire and 25 fire events. Overall subcontinental biomass burning was low during this time, dropping from past levels (Carcaillet et al. 2002; Power et al. 2008). The period of 3000 yr BP to present has an mFRI (95% CI) of 165 (121-220) yr/fire and 17 fire events. Overall subcontinental biomass burning was again high during this time, increasing from past levels, though it had increased hetereogeneity within the subcontinent (Carcaillet et al. 2002; Power et al. 2008). The zone mFRIs are very similar and the confidence intervals overlap.

4.5 Surface Core Sediment-Charcoal Record

4.5.1 Interpolated Data

The surface core charcoal data were resampled to a constant 10-yr interval with 112 interpolated samples. The raw charcoal data for the surface coresare available in Appendix B. The core starts at -58 yr BP and ends at 1050 yr BP. The samples range in length from 1.64 cm, at the top, to 0.49 cm at the bottom. The resampled counts have a mean of 6 pieces, with a range of 0 to 16 pieces. Though the resolution of the record is high, the raw counts are low for interpretation. Additionally, the record has a global SNI of 0.43, which is somewhat low (Appendix A, Fig. A.6).

4.5.2 Charcoal Accumulation Rate

The CHAR for the interpolated intervals has a mean of 0.17 pieces•cm^{-2}•yr^{-1} with a range of 0.00 to 0.56 pieces•cm^{-2}•yr^{-1} (Fig. 4.7a). The background CHAR values have a mean of 0.17 pieces•cm^{-2}•yr^{-1} and range from 0.078 to 0.28 pieces•cm^{-2}•yr^{-1} (Fig. 4.7a). The difference between the means for total CHAR and background CHAR, which are, with an additional digit, 0.172 pieces•cm^{-2}•yr^{-1} and 0.166 pieces•cm^{-2}•yr^{-1}, respectively, is small, but peaks are derived as the relative values for each vary throughout the core (Fig. 4.7b).

4.5.3 Fire Events

Within the surface core, 7 charcoal peaks were identified as fire episodes in recent Mud Lake fire history, ranging from 10 to 790 yr BP (Fig. 4.7b). There are 4 peaks during this time period in the Holocene-length record (Fig. 4.3b). In the surface core record, the minimum-count test determined 4 additional peaks to be statistically insignificant, and they were removed from the record.

4.5.4 Fire-Return-Intervals

With 7 fire events, there are 6 time intervals between episodes. The largest length is 250 yr, between the fire events at 90 yr BP and 340 yr BP, and the shortest is 30 yr, between the fires at 600 yr BP and 630 yr BP. From the Weibull model, the mFRI (95% CI) is 130 (80-188) yr/fire (Fig. 4.8). Within the smoothed, interpolated FRIs, the mean value is 145 yr/fire, and the range is 66 to 186 yr/fire (Fig. 4.7c; Appendix A, Fig. A.5). Because of the short length of time covered by the surface core analysis, the smoothed FRI series does not provide much information about the period's fire activity.

4.5.5 Fire Frequency

The mean of the smoothed, interpolated fire frequency series for the surface core record is 6.3 fires/1000yr. It ranges from 1.9 to 8.2 fires/1000 yr (Fig. 4.7d; Appendix A, Fig. A.5). The minimum fire frequency is at the oldest part of the core, and increases to its peak at 500 yr BP. It then decreases to 6.5 fires/1000 yr by 200 yr BP and remains at that level until present (Fig. 4.7d)

4.6 Charcoal Morphotypes

The CHAR levels of charcoal morphotypes (Fig. 3.4) were graphed (Fig. 4.9) to enable their visual analysis. Total CHAR has few discernible patterns. The most prominent is the period of 2000 yr BP to present, which has higher CHAR levels than the earlier record. The period of 4000 to 2000 yr BP, except for one large peak, has lower CHAR levels than surrounding time periods. The morphotypes in order of overall CHAR abundance are C, P, M, F, S, D, and B. C-type and P-type, the most robust charcoal shapes, are the two most abundant morphotypes (Fig. 4.9). C-type levels have no notable patterns, while P-type generally has greater abundance from 12000 to 7500 yr BP. M-type, the third most abundant, has irregular pores and is the most fragile charcoal shape (Fig. 4.9). M-type has its highest CHAR levels from 2000 yr BP to present. F-type, long and thin charcoal pieces, is the fourth most abundant (Fig. 4.9). Though F-type has an overall greater presence in the record than P-type and M-type, P-type and M-type have higher peaks around 1480 yr BP resulting in greater overall CHAR totals. S-type, D-type and B-type are the least abundant morphotypes and, like total CHAR and M-type, have higher CHAR levels since 2000 yr BP (Fig. 4.9). Though it has the lowest overall abundance, B-type, which are partially burned pieces, has a higher CHAR level at the 1480 yr BP peak than S-type and D-type.

Chapter 4 Figure Captions

Figure 4.1 Magnetic susceptibility data collected from Mud Lake piston core (Mud Long 2). Figure can be read from left to right, with the left being the bottom of the core and the right the top of the core. The clay portion of the core, from 381 to 415 cm, is not datable and was likely deposited in a relatively short period of time, so the magnetic susceptibility values are graphed by depth. As there is a large range of magnetic susceptibility values, there is a break between 150 cgs and 900 cgs to enhance the series' smaller values.

Figure 4.2 Age-depth model for Mud Lake, combining calibrated ^{210}Pb dates and calibrated ^{14}C dates from the surface-core and the piston-core. Cal yr BP refers to calendar years before present (present at 1950 AD). Sed. rate refers to sedimentation rate (cm/yr), and resolution refers to sample resolution (yr/cm). The inset ^{210}Pb dates graph has the same units as the larger graph. The grey squares represent excluded dates. All ^{210}Pb dates were taken from freeze-dried sediment samples. All ^{14}C dates were taken from terrestrial macrofossils except for the date at 1334 yr BP, which was taken from a piece of charcoal.

Figure 4.3 a-d Mud Lake Holocene-length composite-core charcoal record analysis and fire-history characteristics. Cal yr BP refers to calendar years before present (present at 1950 AD). a) The interpolated charcoal accumulation rate, CHAR (pieces$\bullet$cm$^{-2}\bullet$yr^{-1}), C_{int} (black line), and the smoothed CHAR background levels, C_{back} (red line). b) The CHAR peak levels, C_{peak} (black line) and the 0.95-peak threshold level, C_{noise} (red line). The areas of the CHAR peak series above the threshold series, C_{fire}, that have been deemed fire events are represented by + symbols. c) The smoothed fire-return-intervals (FRIs) of yr per fire. The dashed line is the mean FRI. d) The smoothed fire frequencies of fires per 1000 yr. The dashed line is the mean fire frequency.

Figure 4.4 Mud Lake composite-core charcoal-record Weibull probability-distribution, with the global-mean fire-return-interval (mFRI). Each fire-return-interval (FRI) is placed in a 20-year bin to develop the histogram, and the number of FRIs (N_{FRI}) is shown. The line represents the Weibull c-parameter, and its value is in figure. The Weibull b-parameter is the 63.2 percentile of the FRI probability distribution, and its value is in the figure. The 95% confidence intervals for the mFRI, the c-parameter, and the b-parameter are also shown in brackets.

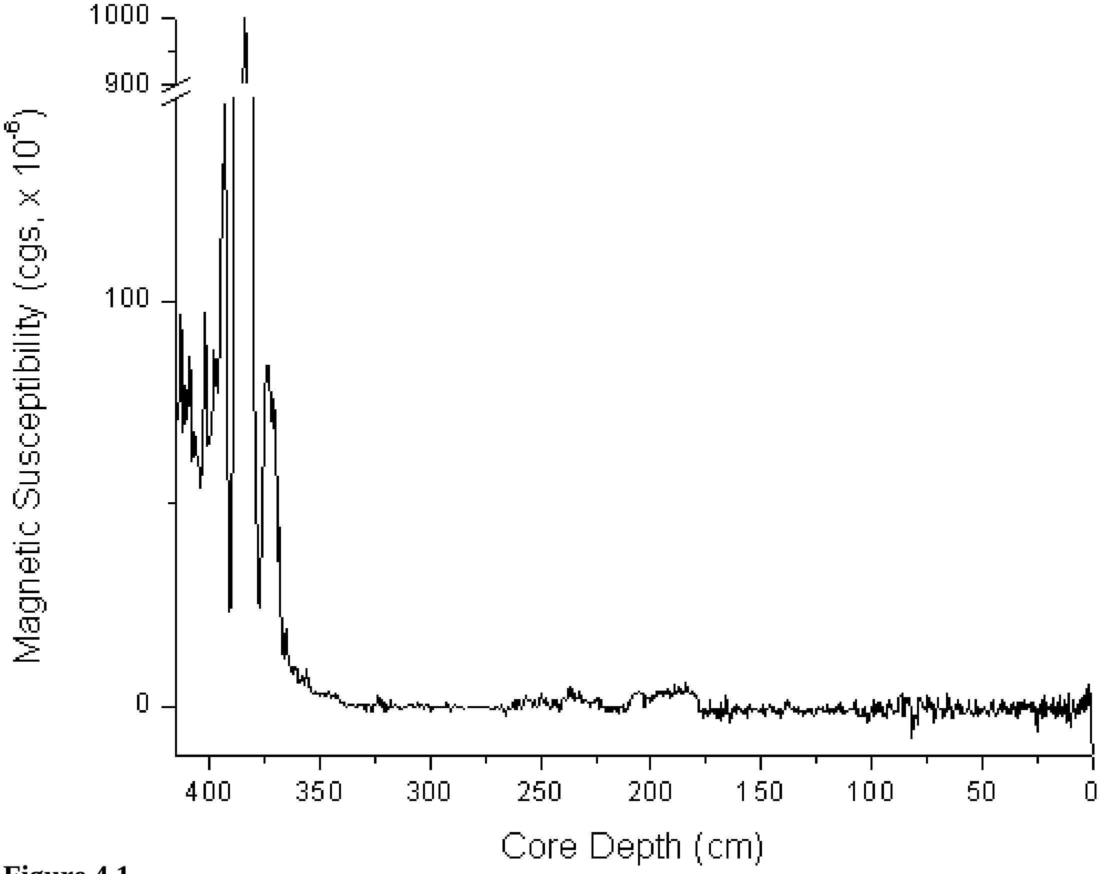
Figure 4.5 Mud Lake composite-core charcoal-record Weibull probability-distributions and mean fire-return-intervals (mFRI) for eastern Ontario Holocene pollen/paleoclimate zones. Each fire-return-interval (FRI) is placed in a 20-year bin to develop the histogram, and the number of FRIs (N_{FRI}) is shown. The line represents the Weibull c-parameter, and its value is in figure. The Weibull b-parameter is the 63.2 percentile of the FRI probability distribution, and its value is in the figure. The 95% confidence intervals for the mFRI, the c-parameter, and the b-parameter are also shown in brackets. Zone 3 includes 12420-9800 yr BP, Zone 2 includes 9800-5300 yr BP, and Zone 1 includes 5300 yr BP to modern times.

Figure 4.6 Mud Lake composite-core charcoal-record Weibull probability-distributions and mean fire-return-intervals (mFRI) for eastern North American Holocene biomass-burning trends. Each fire-return-interval (FRI) is placed in a 20-year bin to develop the histogram, and the number of FRIs (N_{FRI}) is shown. The line represents the Weibull c-parameter, and its value is in figure. The Weibull b-parameter is the 63.2 percentile of the FRI probability distribution, and its value is in the figure. The 95% confidence intervals for the mFRI, the c-parameter, and the b-parameter are also shown in brackets. Zone 3 includes 12420-7500 yr BP, Zone 2 includes 7500-3000 yr BP, and Zone 1 includes 3000 yr BP to modern times.

Figure 4.7 a-d Mud Lake surface-core charcoal-record analysis and fire-history characteristics. Cal yr BP refers to calendar years before present (present at 1950 AD). a) The interpolated charcoal accumulation rate, CHAR (pieces$\bullet$cm$^{-2}\bullet$yr^{-1}), C_{int} (black line), and the smoothed CHAR background levels, C_{back} (red line). b) The CHAR peak levels C_{peak} (black line) and the 0.95-peak threshold level, C_{noise} (red line). The areas of the CHAR peak series above the threshold series C_{fire}, that have been deemed fire events are represented by + symbols. c) The smoothed fire-return-intervals (FRI) of yr per fire. The dashed line is the mean FRI. d) The smoothed fire frequencies of fires per 1000 yr. The dashed line is the mean fire frequency.

Figure 4.8 Mud Lake surface-core charcoal record Weibull probability-distribution, with the global-mean fire-return-interval (mFRI). Each fire-return-interval (FRI) is placed in a 20-year bin to develop the histogram, and the number of FRIs (N_{FRI}) is shown. The line represents the Weibull c-parameter, and its value is in figure. The Weibull b-parameter is the 63.2 percentile of the FRI probability distribution, and its value is in the figure. The 95% confidence intervals for the mFRI, the c-parameter, and the b-parameter are also shown in brackets.

Figure 4.9 Charcoal accumulation rate, CHAR (pieces$\bullet$cm$^{-2}\bullet$yr^{-1}), levels for total charcoal and charcoal morphotypes of the Holocene-length composite-core. Cal yr BP refers to calendar years before present (present at 1950 AD). Due to a large peak, several figures have breaks in the CHAR y-axis. The red lines mark the pollen/paleoclimate zones for eastern Ontario: 12420-9800 yr BP, 9800-5300 yr BP, and 5300 yr BP to modern times. The charcoal morphotypes are presented in descending order for overall CHAR abundance, from left to right.


1000
900
100
0
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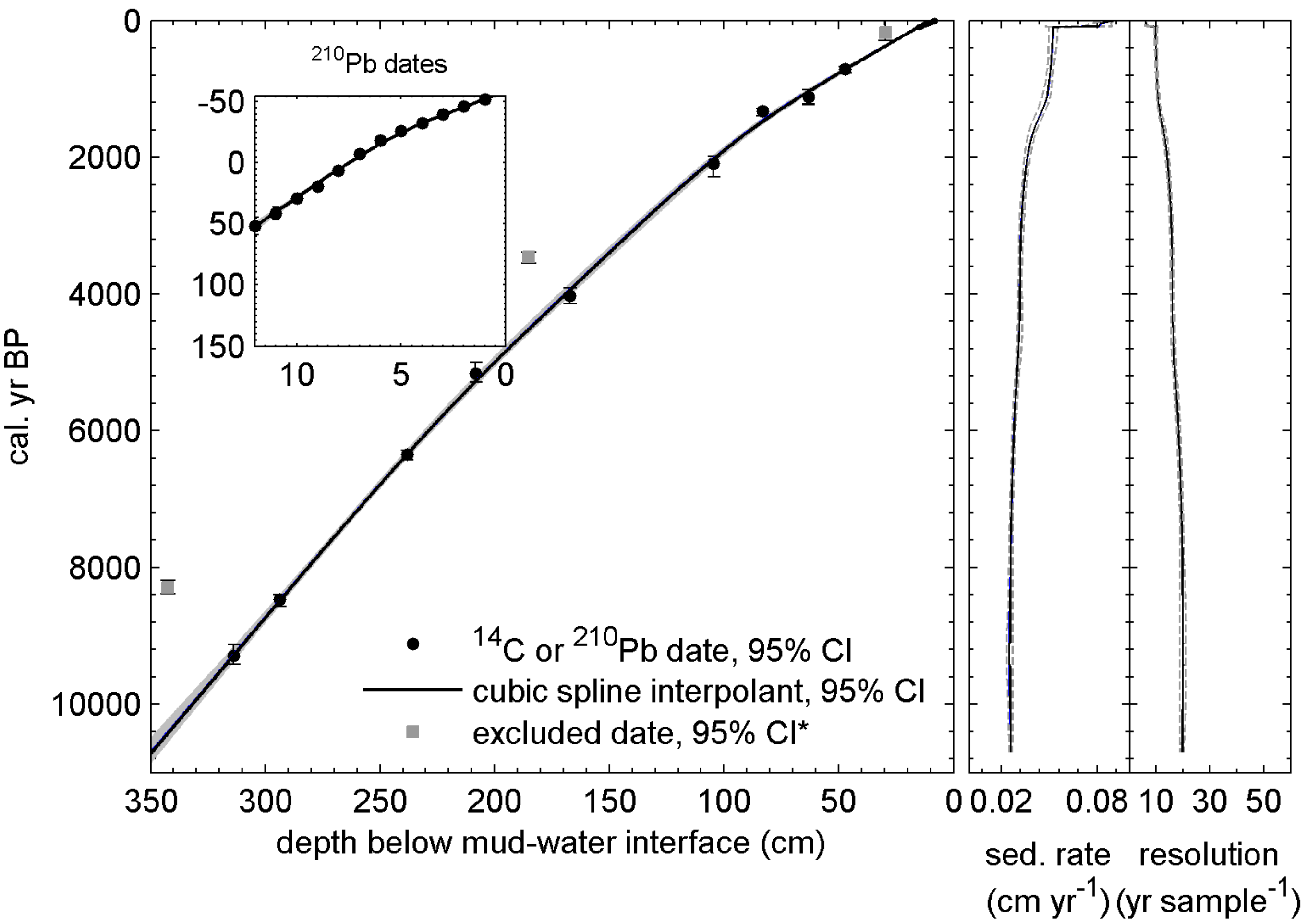
350
300
250
200
150
100
50
0
Core Depth (cm)

Figure 4.1



^{210}Pb dates
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0
50
100
150
10
5
0
0
2000
4000
6000
8000
10000
cal. yr BP
● ^{14}C or ^{210}Pb date, 95% CI
cubic spline interpolant, 95% CI
■ excluded date, 95% CI*
350
300
250
200
150
100
50
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resolution (yr sample^{-1})

Figure 4.2

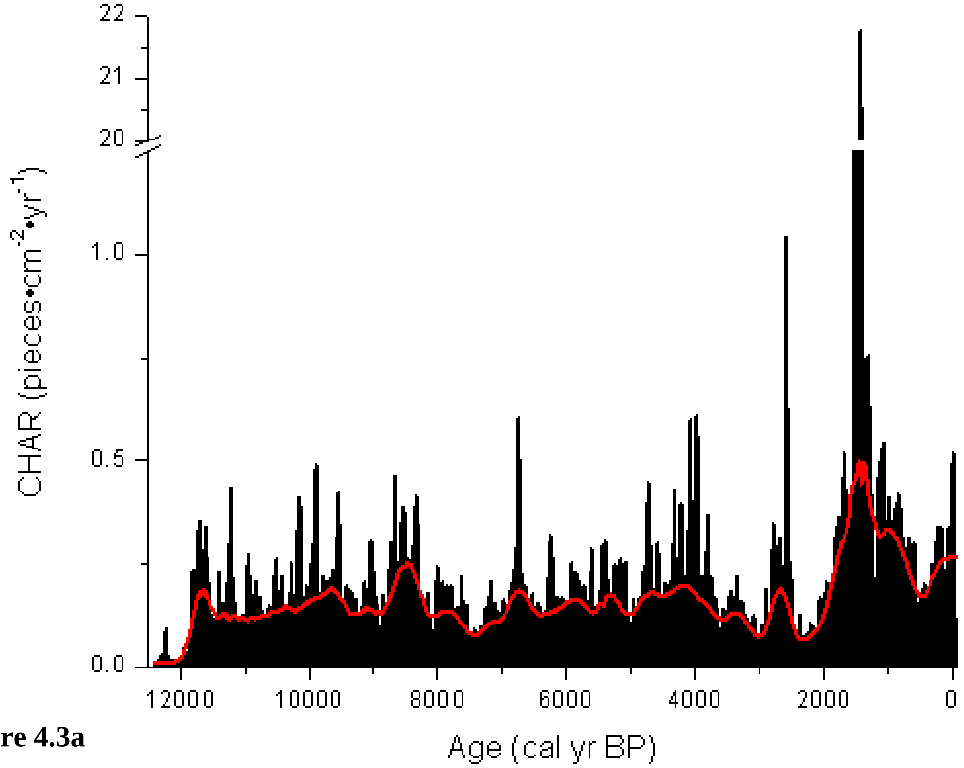

Figure 4.3a

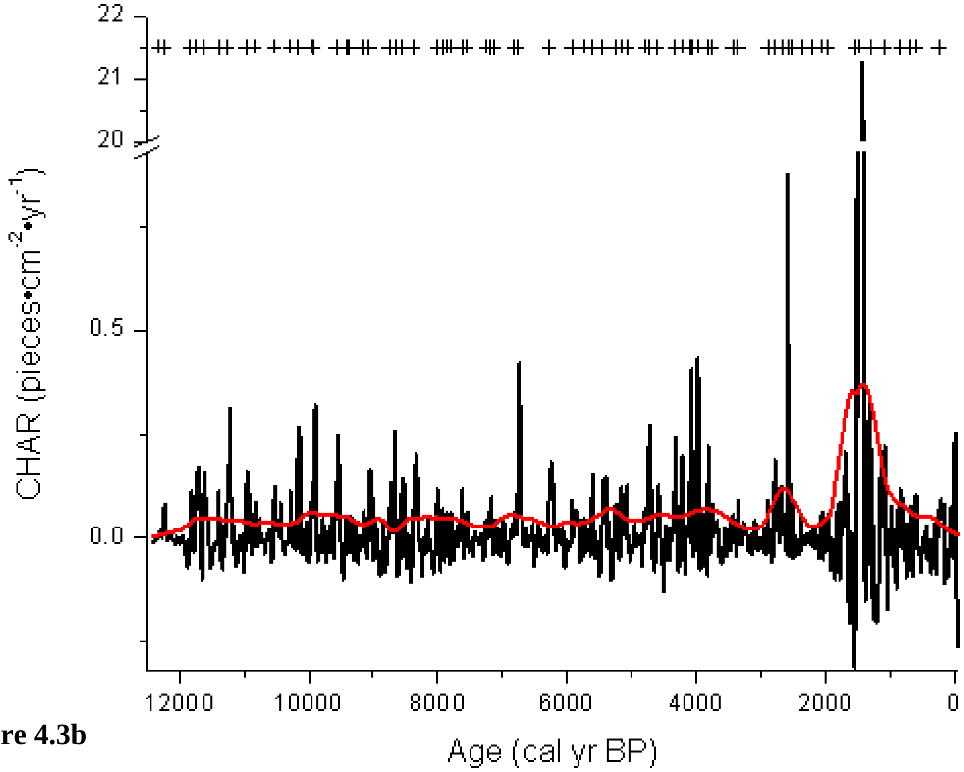

Figure 4.3b

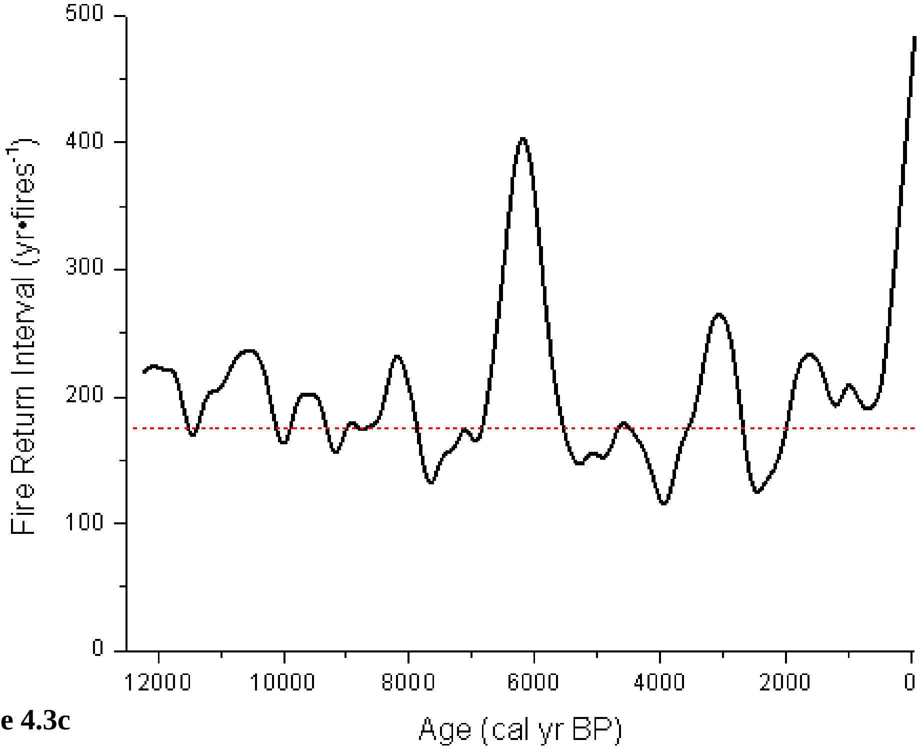

Figure 4.3c

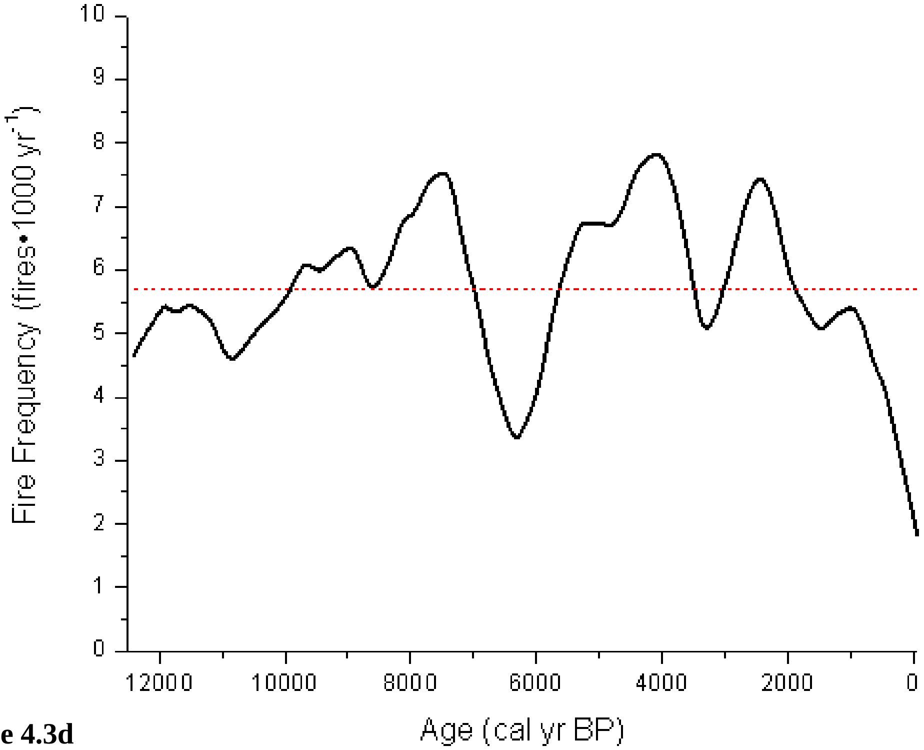

Figure 4.3d

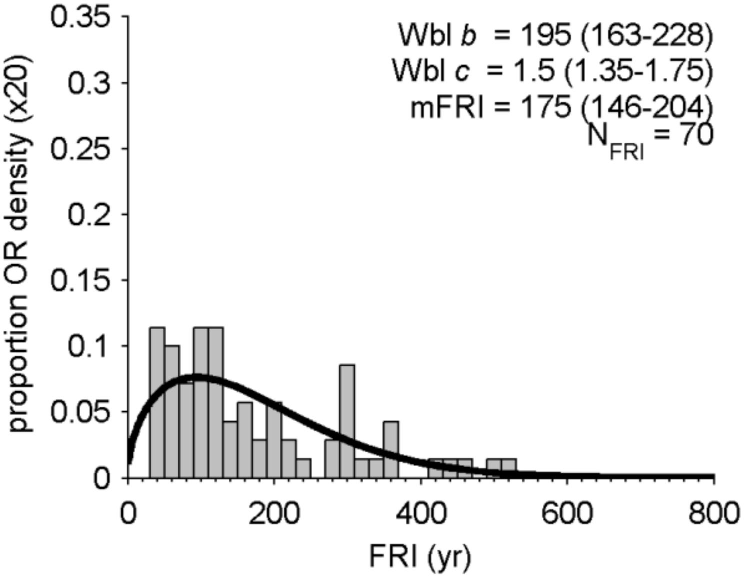
Wbl *b* = 195 (163-228)
Wbl *c* = 1.5 (1.35-1.75)
mFRI = 175 (146-204)
N_{FRI} = 70
proportion OR density (x20)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
200
400
600
800
FRI (yr)

Figure 4.4

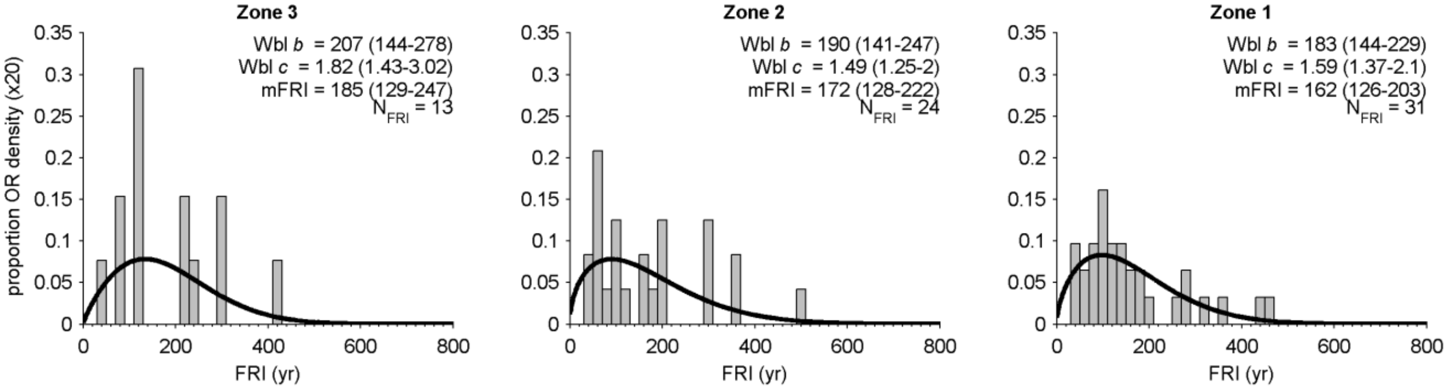

Figure 4.5

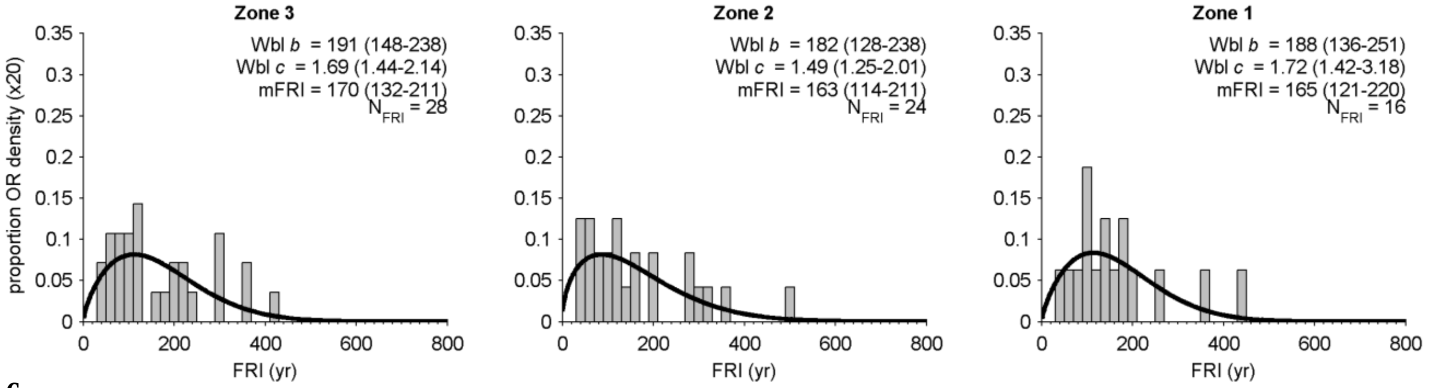

Figure 4.6

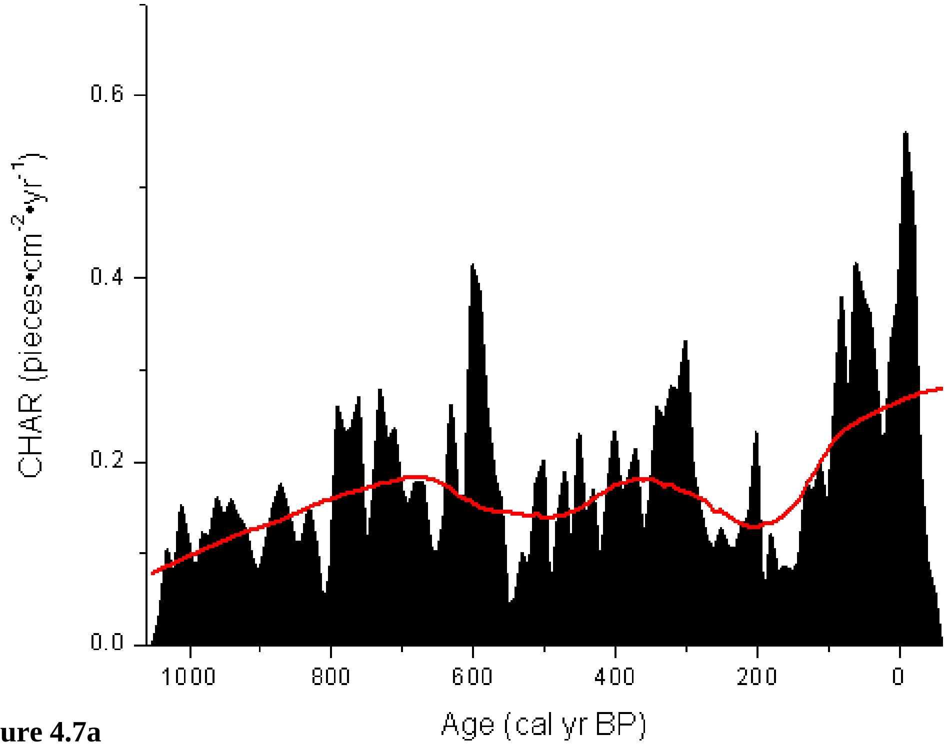

Figure 4.7a

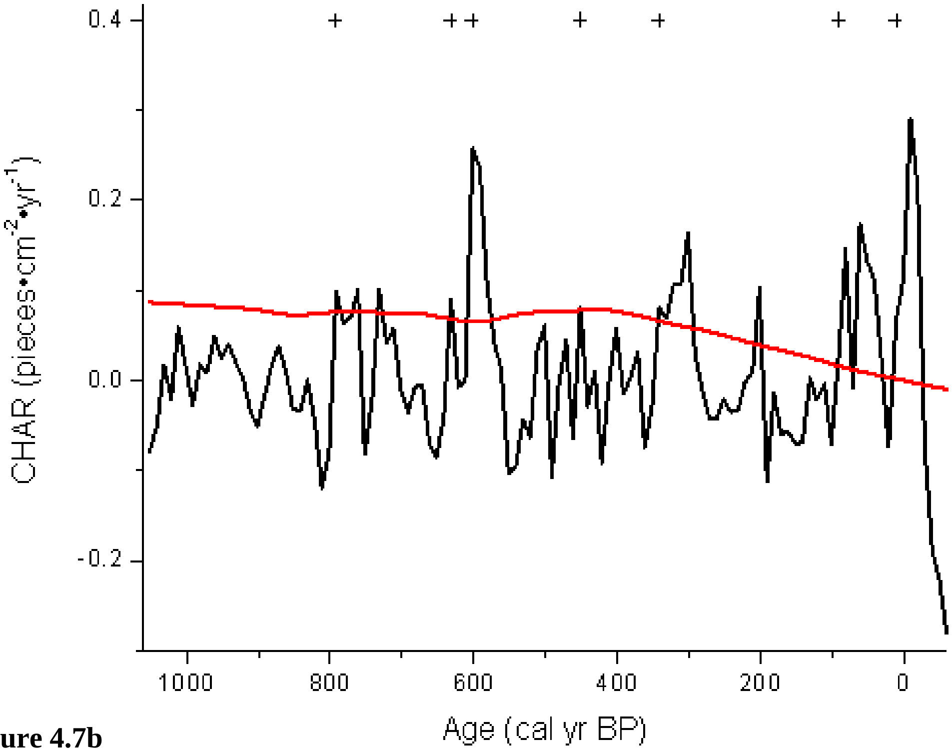

Figure 4.7b

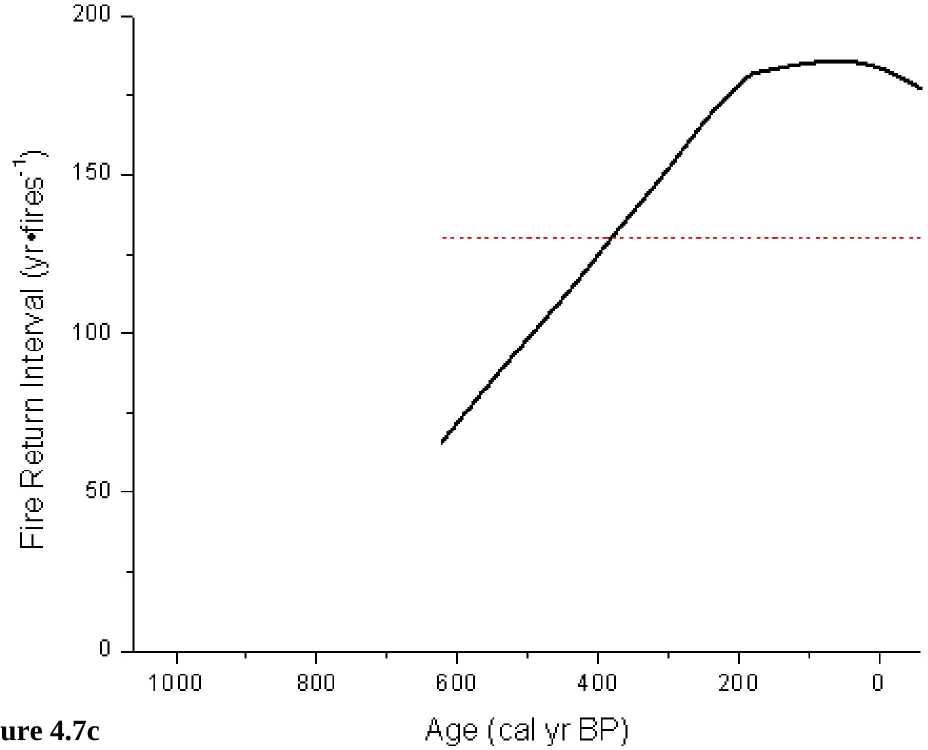

Figure 4.7c

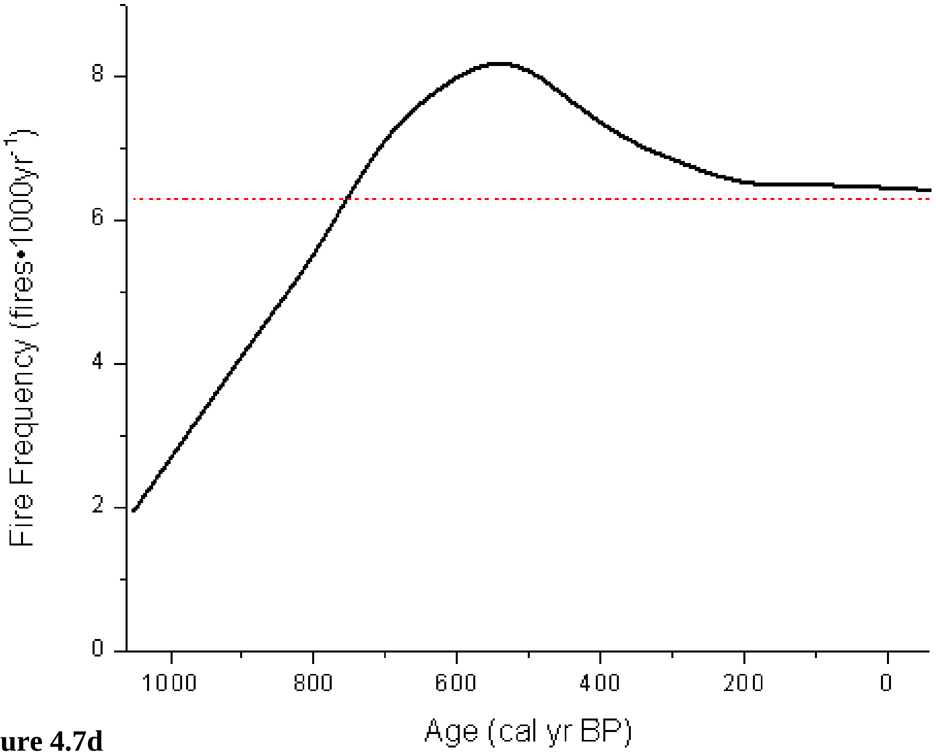

Figure 4.7d

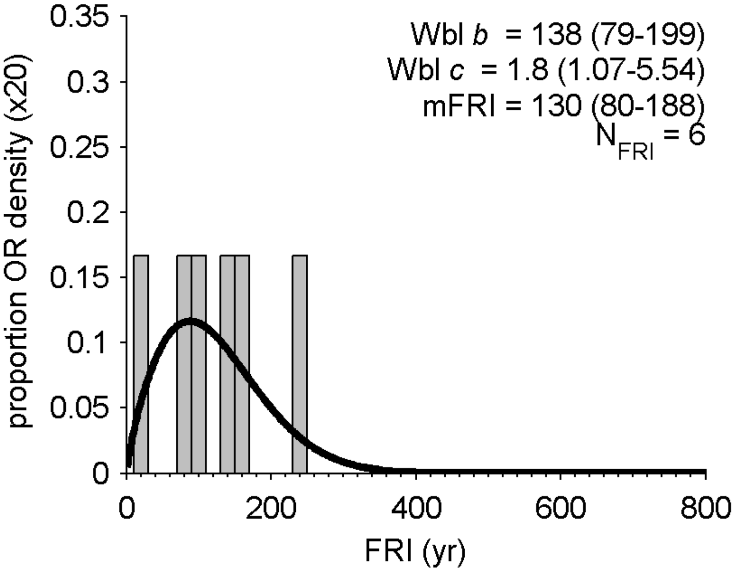
Wbl *b* = 138 (79-199)
Wbl *c* = 1.8 (1.07-5.54)
mFRI = 130 (80-188)
N_{FRI} = 6
proportion OR density (x20)
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
0
200
400
600
800
FRI (yr)

Figure 4.8

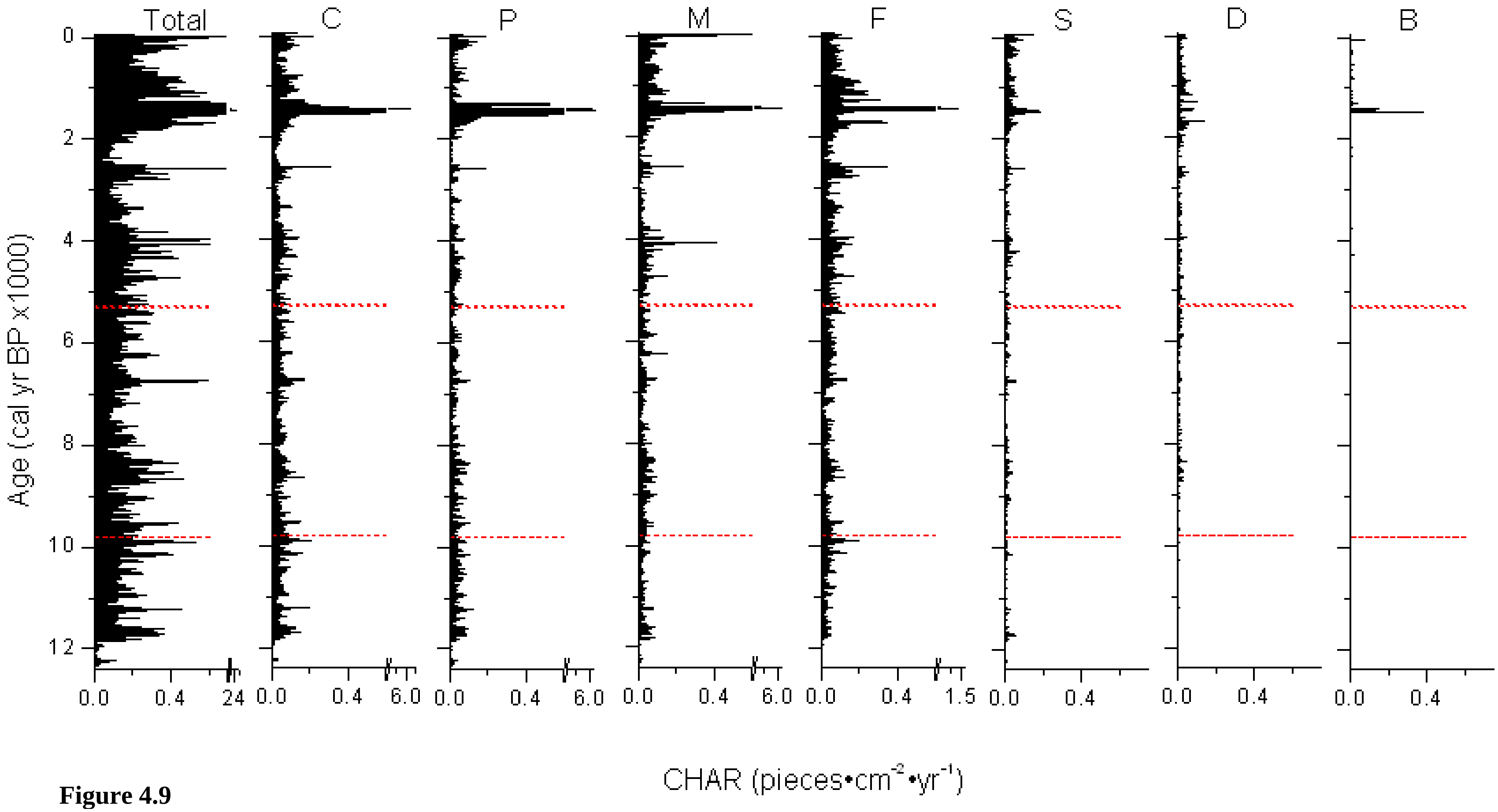
Total
C
P
M
F
S
D
B
Age (cal yr BP x1000)
0
2
4
6
8
10
12
0.0
0.4
24
6.0
1.5
CHAR (pieces•cm⁻²•yr⁻¹)

Figure 4.9

Chapter 5

Discussion

5.1 Introduction

The sediment-charcoal record analysis for the Mud Lake area provides insight into the Holocene fire history in this part of eastern Ontario. The FRI and fire frequency values estimate long-term trends in the site's biomass-burning. To investigate links between Mud Lake's historic fire regime and other environmental dynamics, the fire record is compared to regional information on paleoclimates and past vegetation communities (Anderson 1987; Carcaillet and Richard 2000; McFadden et al. 2004). It is also considered in the context of subcontinental biomass-burning trends (Carcaillet et al. 2002; Marlon et al. 2008; Power et al. 2008). The area's paleofire record is relevant to the fire management practices of the region as it provides an estimate of natural variability that can be used for setting appropriate goals (Cyr et al. 2009). CLPP and SLINP are two prominent parks in the Frontenac Arch, and paleoenvironmental data can be applied to their park management (Francis and Leggo 2004). The maintenance of populations of fire-dependent pitch pine in both protected areas may also be improved upon. Additionally, future environmental impacts, including climate change, will impact the parks' landscapes and ecological integrity, warranting the application of this knowledge towards adapting to these potential shifts.

5.2 Sediment-Charcoal Fire-History Record

The number and distribution of fire episodes as well as the FRI and fire frequency series provide insight into Mud Lake's long-term fire history.

Results of this study indicate that, during the early to middle Holocene (~12000 to 5000 yr BP), fire activity around Mud Lake initially increased. Between de-glaciation and ~7500 yr BP, the FRI and fire frequency trends reflect an increasing number of fire episodes (Fig. 4.3c, 4.3d). During the middle Holocene, however, fire activity dropped between ~7500 and ~6100 yr BP to the lowest level (excluding the modern portion of the Holocene record, which is superimposed by the surface-core record). The activity rose again to levels equivalent to ~7500 yr BP by ~5000 yr BP, the end of the period.

The late Holocene (~5000 to 1000 yr BP) began following a rapid change in fire activity. Though there is variability in the FRIs and fire frequencies during this period, there is no clear trend. There was a second dip in activity, larger in magnitude than any prior to ~7500 yr BP, centred around 3000 yr BP. The period ended with an increase to ~2000 yr BP and a decrease towards ~1000 yr BP. Though fire activity decreased during that time, the charcoal peak around the fire episode around 1480 yr BP is notable for its size. The raw count and the interpolated CHAR values are an order of magnitude above the values for any other peak in the record. Though fire characteristics such as extent and severity are not generally determinable from charcoal records, the level of this peak is so large that it indicates that a huge amount of biomass burning occurred around this time. The fire activity measures treat this fire as equivalent to all others, so the overall fire activity measures do not reflect its size. Considering the indications that there was a great deal of burning around 1480 yr BP, it suggests that there may have been considerable build-up of fuels up to that point, with fewer or smaller fires in the period preceding it. There is a fire episode estimated at 1530 yr BP, and the previous event is estimated at 1960 yr BP. A fire episode at that time may also have been impacted by favourable climate conditions. There is evidence that a natural catastrophe brought on climate destabilization around 1415-1414 yr BP, 535-536 AD (Stothers 1999). A volcanic eruption has been suggested as a likely cause. There was diminished sunlight, persistent cold, and mass droughts around the world, and there has been further speculation about large wildfires at numerous global locations (Stothers 1999). Mud Lake's largest charcoal peak covers 3 cm of sediment, dated 1483 to 1413 yr BP. Though it appears to begin earlier, the confident intervals for the dates are ±50 yr, and sediment mixing could have also been an impact. The overlap indicates that this fire episode may have coincided with the worldwide event.

Regarding the most recent ~1000 yr BP, the Holocene record is weak in estimating recent fire history as the counts from the top of the core are lower and less robust statistically. It is possible that there has been a more recent fire than the Holocene-length results estimate. If that is the case, the alternate FRIs for the intervals since 250 yr BP would be lower, and the fire frequency would be higher, to reflect greater fire activity. The surface core analysis does estimate two fire events more recent than 250yr BP as fire episodes at 10 yr BP (1940 AD) and 90 yr BP (1860 AD) are part of the surface core's charcoal peak series. While the counts from this part of the core are low, these events were not eliminated by the minimum-count test. Unfortunately, it is not possible to match these episodes with documentary fire history as there is no record of local fires (<1 km) around Mud Lake; there are only regional fires to consider. The earliest peak is somewhat close in age to both a large, regional fire in 1954 AD which took place ~50km from the study lake, as well as a small fire in 1956 AD on Hogsback Island ~4km from the study site (Chant 1975; Ontario Forest Research Institute 1998). The similarity in timing of the two fires recorded in the documentary record indicates that there may have been a degree of regional synchrony of fires at that time, perhaps as a result of regional-scale climate impacts. The fires from the documentary record are 14 yr and 16 yr more recent than the charcoal peak. The surface core's 10-yr resolution and sediment mixing limit exact dating, so it's possible that the Mud Lake episode may have occurred later. The age resolution at this part of the core is very good (±1 yr), though, so the association with documentary records is weak. Nonetheless, a fire around 1940 AD may have occurred near Mud Lake and failed to have been recorded. The area is outside of OMNR's fire region, crown land surrounded the lake at the time, and it is not adjacent to any settlements, so there may not have been notice of a fire there at the time (Chant 1975; OMNR 2004). In particular, the rocky cliff on the east side of Mud Lake, where the pitch pine population exists, could burn locally if ignited. The Mud Lake fire episode estimated at 90 yr BP, 1860 AD, occurred temporally close to a large eastern Ontario fire north of the study side, between Smith's Falls and Ottawa, that took place in 1870 AD.

The age error at this date is ±7 yr and, given sediment-mixing and the median resolution of 10 yr, the potential age range indicates that the Mud Lake fire could have occurred at the same time. It has been speculated that drought greatly exacerbated the extent and severity of the 1870 AD fire, so regional climate trends, such as cool, dry air masses that increase the flammability of fuel, may have also led to the Mud Lake fire (Currie 2009).

It is worth considering how the composite core and the surface core compare the overlap between so to better assess the strength of the recent fire estimates. The two core records are not independent as the composite, Holocene-length record was created using both the surface-core and piston-core data sets. The surface-core record did contribute proportionately less to the composite record than the piston-core record. The two most recent fires in the surface core record have some correspondence with two rejected peaks in the Holocene record, at 5 yr BP, 1945 AD and at 50 yr BP, 1900 AD. Following the two additional modern fires, the Holocene record fire at 250 yr BP is only similar to the surface core fire at 340 yr BP. The 90 yr gap is beyond the 95% CI of the age model, which ranges around ±20 yr at these dates, though other sources of error may contribute to the temporal gap between the two episodes. The surface-core fire at 450 yr BP has no analogous event in the Holocene fire series. The Holocene-record fires at 600 yr BP and 680 yr BP are statistically similar to the fire episodes in the surface core record at 600 yr BP and 630 yr BP. The 600 yr BP fires are directly equivalent, while the age model 95% CI of the earlier fires overlap (661 to 608 yr BP and 712 to 656 yr BP). Finally, the oldest fire in the surface core record, at 790 yr BP, also has an analogous event in the

Holocene record, at 840 yr BP, as their age model 95% CIs overlap. Overall, the two records generally compare favourably, with the surface record adding three fire events to the Mud Lake history within the last 500 years.

Looking at the average activity within each record, the mFRI for the surface-core record is 130 yr/fire, and the mFRI for the same period in the Holocene-record is 197 yr/fire. While 95% CIs are not available for the Holocene-record mFRI, the 95% CI for the surface core mFRI is 80-189 yr/fire. This suggests that the two mFRI values are not statistically separate, though the surface-core record mFRI is smaller. The surface- core record mFRI range does clearly overlap with the range of the overall Holocene-record mFRI , 175 yr/fire, so it is notably lower but not beyond the range of variability. The time since the last fire to present day is also much smaller in the surface record than in the Holocene record, at 70 yr compared to 310 yr. In sum, these values estimate that during the past ~1000 year, the most recent part of the Holocene, Mud Lake has experienced above-average fire activity. The surface-core record's fire frequency rises from ~1000 to 600 yr BP, then decreases slightly and levels off until present (Fig. 4.7d). As a result of greater fire activity, the vegetation around the lake may contain more early- to mid-successional species than during earlier periods of the Holocene. The above-average activity also may have favoured species that can survive fires of low- to moderate-severity or those that have serotinous cones, such as some coniferous tree species (Johnson 1992). The forest around Mud Lake may also have been disturbed by logging in the 1800s, which makes assessing impacts on the area's vegetation composition more difficult (Chant 1975).

The estimated increase in fire activity is, however, based on the addition of three fires to surface-record record, compared to the Holocene-length record, with the recent record containing seven fires in total. The charcoal counts for the surface-core are small (<20 pieces per interval) as is the SNI (0.43), and this diminishes confidence in the results. There are indications that surface-core record replicates the Holocene-length record and supplements it with additional peaks as a result of increased temporal resolution. If one or more of the three additional peaks are false positives, though, then the estimated fire activity for the past ~1000 yr is lower, approaching average or below average activity within the Holocene. While the presence of other recent fires in eastern Ontario indicate that conditions, such as precipitation and ignitions, led to burning that may have also occurred around Mud Lake, there is no way to be certain of the accuracy of the estimated fires in Mud Lake's recent history.

5.2.1 Comparison to Regional Records

The Mud Lake fire history adds to a regional network of charcoal-based paleofire reconstructions within eastern North America. At what may be the most similar site in terms of vegetation, the fire history of Devil's Bathtub in upper New York State was investigated using sediment-charcoal, with an attempt to isolate local events (Clark et al. 1996). In *Picea* and *Pinus* dominated landscapes during the early Holocene, from 10400 to 9200 yr BP, the mFRI was ~90 yr/fire, indicating more frequent fires than Mud Lake, where the mFRI for its early period is 185 (129-247) yr/fire. Devil's Bathtub's range of individual FRIs has a similar lower limit, 50 yr/fire, but a smaller upper level, 200 yr/fire, than Mud Lake, suggesting that the latter site had greater variability in its FRIs during that period. Eastern Ontario was also contained *Picea* and *Pinus* dominated forests during the early Holocene, but the composition of vegetation around Mud Lake is not known. The area around Devil's Bathtub transitioned to deciduous-dominated forests several thousand years earlier than forests in eastern Ontario. Clark et al. (1996) was unable to identify fire events during the remainder of the core when the area contained a mixed hardwood habitat, though, so no comparison during that period is possible. Earlier work by Clark in northwestern Minnesota (1988a, 1990) over the most recent 750 yr estimated that fire return times ranged from 11 to 95 yr/fire, while at Mud Lake they ranged from 30 to 160 yr/fire. The Minnesota studies took place in a prairie-forest transition where fire may frequently disturb the prairie landscape, maintaining its community structure, (Clark 1990). Fire does not appear to be as dominant of a disturbance in the Mud Lake area.

The fire history of Greenleaf Lake in Algonquin Park, central Ontario from around 1180 to 680 yr B.P. was studied with a varved core. Its dating was considered accurate to within 100 yr, less than modern standards, and charcoal peaks were identified by large amounts of charcoal and influx minerals, a far less sophisticated method than currently used. The 500-yr period was estimated to consist of 6 fire episodes, with an average FRI of 80 yr/fire (Cwynar 1978). This compares to 3 fire events in the Mud Lake fire history during that time period, and an mFRI of approximately 200 yr/fire from the Holocene-length results as it includes this entire period. As the Cwynar (1978) study looked at microscopic charcoal its results reflect regional fires, so it can be expected that more episodes will be part of the record. Compared to the pollen studies near Mud Lake, the Greenleaf Lake landscape also had a higher proportion of coniferous taxa such as *Pinus* and *Cupressineae* in that period, indicating greater resemblance to boreal forest regions which experience more frequent fire disturbance (Cwynar 1978). Algonquin Park is in central Ontario and so may be more impacted by dry, cold Arctic air masses, resulting in drier summers and more opportunities for successful fire ignitions (Van Sleeuwan 2006).

The past 8000 years of fire history around several lakes in Quebec also contributes to the regional network of fire history studies. Three sites within boreal landscapes in western Quebec were found to have FRIs ranging from 49 to 502 yr/fire and global mFRIs of 130 yr/fire, 149 yr/fire, and 241 yr/fire (Carcaillet et al. 2001a). Mud Lake’s mFRI (95% CI) of 175 (146-204) yr/fire is intermediate to the mFRI of the lakes in Quebec (Fig. 4.4). In a later analysis of the lakes, the natural variability of the region’s mFRIs was studied (Cyr et al. 2009). It was conservatively estimated as 111 to 267 yr/fire, with an extended range of 82 yr/fire to 419 yr/fire based on 95% CIs (Cyr et al. 2009). The 95% CI for Mud Lake’s zone mFRIs, based on vegetation and climate trends, provide a range from 126-247 yr/fire (Fig. 4.5). In contrast to the Mud Lake analysis, the Quebec lakes’ fire history had more variability within millennial time-scales, with a major shift in mFRI ~3000 yr BP. Accordingly, the 95% CIs of Cyr et al.

(2009) have a much larger range than Mud Lake's. This indicates that lakes studied in Cyr et al. (2009) activity had greater variability than Mud Lake, including a more extreme minimum and maximum. The fire activity around one lake is likely to have less range than the activity around several regional lakes, though, and if a group of regional lakes near and including Mud Lake was analyzed analogously, it is possible that greater variability in fire activity would be seen within the region. Ali et al. (2009b) also studied charcoal records from a network of lakes in western Quebec. The regional mFRI trends indicated periods of higher fire activity include 5800 to 2400 yr BP and 1400 to 600 yr BP while periods of lower fire activity included 8000 to 5800 yr BP and 750 yr BP to present (Ali et al. 2009b). Mud Lake fire activity overlapped with this region between ~5800 yr BP and ~2400 yr BP when its activity was generally high. It was dissimilar between 8000 and 7000 yr BP and possibly since 500 yr BP, when Mud Lake experienced high fire activity, and between 1400 and 600 yr BP, when Mud Lake's fire activity was low. These Quebec lakes are in a boreal region, while the Mud Lake area contains mixed forest. They are also subject to different climatic conditions. Eastern Ontario is more influenced by southern moist air masses during the summer, leading to a wetter fire season and decreased fire frequency (McFadden et al. 2004). Variations in fuel type, climate, and local-scale factors such as weather all play a role in the differences in fire regimes between eastern Ontario's Mud Lake and others in eastern North America.

5.2.2 Issues and Uncertainties

The charcoal record is not contiguous due to the gaps between drives, so it does not contain all of the study site's fire history details. As it contains a large majority of the sediment record, it is representative of the local-fire regime. This method is not used to pinpoint fire episode dates beyond the past ~200 yr but to provide an overview of long-term history, so the results are not greatly impacted by the loss of sediment.

Additionally, the section of the core with extrapolated dates (>9500 yr BP) presents problems. As discussed, it does not reflect the core's true sedimentation rate, and the end of the core is likely dated older than it is. This may elongate the fire history from this section of the core, causing the fire regime to seem less active as it took place over a longer period of time. The problem may be rectified in the future through additional AMS ^{14}C dates and an updated age-depth model.

The parameter choices have an impact on the fire results. The tendency is for there to be fewer fires in the record as the interpolated sampling resolution increases (Carcaillet et al. 2001a). The use of the median sampling resolution is the best option for studying the entire sampled core, but it does result in a loss of resolution in the top section of the core (i.e. where resolution was <16 yr per interval). While this was rectified for the surface core record through its separate analysis, the resolution was still decreased for sediment after this period as the time intervals for the raw data first become 16 yr per interval at ~3000 yr BP.

While the resolution for the surface core record was increased, the counts and the SNI for that section were low. Interpretations can still be made, but, as discussed, these issues decrease the quality of its results and introduces uncertainty into its application.

5.3 Charcoal Morphotypes

The total CHAR levels and morphotype-specific (Fig. 3.4) CHAR levels were graphed to visualize patterns that may correspond to long-term vegetation trends (Fig. 4.9). Overall, no clear patterns emerged. The CHAR levels for total CHAR, M-type, and F-type were the highest in the period 2000 yr BP to present. For M-type, greater abundance in more recent sediments may indicate greater primary transport of charcoal and more accurate fire predictions. M-type may also be more prominent in the recent record as they may not be as well preserved in older sediments due to fracturing and size reduction, failing to remain within the macroscopic size-class. C-type and P-type were the most frequent morphotypes, which reflects their robust shape. These types may originate from wood and bark, and their abundance suggests that this type of biomass may be best preserved in the Mud Lake charcoal-record (Enache and Cumming 2006). All types have the largest peak around the fire event at 1480 yr BP. B-type, though least frequent overall, has a higher CHAR level at that date than S-type and D-type. Given the contribution of partially burnt particles as well as the large size (>1 cm) of some charcoal pieces deposited around that peak, this further indicates that the fire activity around that date was severe. S-type, angular pieces with pore structure, has been one of the most dominant types found in other charcoal morphotype analyses (Enache and Cumming 2006). It was not abundant in the Mud Lake record, which could indicate that, as a more fragile type, it was not well preserved in this system. The S-type charcoal observed in the Mud Lake core is most similar to the morphotype identified by Jensen et al. (2007) as grass, or other monocot, charcoal, so its low levels may also suggest that grass-type biomass did not substantially contribute to the fires around Mud Lake. Alternatively, the indications that there are high proportions of wood charcoal and low proportion of grass charcoal could suggest that the fires recorded in the Mud Lake charcoal record tended to be high-intensity and convection-driven as experiments have shown that larger, wood charcoal particles are the most commonly produced by such fires (Whitlock and Larsen 2001).

5.4 Long-term Fire History and Anthropogenic Impacts

It is during the top, late-Holocene section of the core that human settlements were first built in eastern Ontario and any pre- or post-European impact on the fire regime, if present, may be seen. There does not appear to be any perceivable anthropogenic impact on the fire regime. The surface-core record contains two fire events within recent history, at 10 yr BP and 90 yr BP (Fig. 4.7b). As these are within both the composite core mFRI of 175 yr/fire and the surface core mFRI of 130 yr/fire, they do not indicate that modern fire suppression had an impact on the local fire history of the study site. If both of these fire are false positives, the most recent fire predicted by the Holocene-length record was 250 yr BP, or 310 years ago. If that’s the case, it indicates that fire suppression could have been a factor since European settlement and that the time since fire has disturbed the Mud Lake area may be outside of its natural variability. There is an increase in charcoal influx during the most recent 300-yr period. which could partly reflect increased land-use in the Mud Lake area, including logging and recreational use, but there is no way to separate the contribution of human impacts from other factors affecting fire activity and charcoal deposition. It is possible that the two most recent fires identified by the surface core record, if accurately predicted, could have been affected by humans through accidental ignition.

It is unknown if aboriginal burning took place in the region and impacted the fire regime. To attempt to assess this, the CHAR levels during 600 to 300 yr BP were considered. This is a period during which there were aboriginal settlements in southern Ontario, and Clark and Royall (1995) concluded that higher charcoal levels during that time suggested the presence of aboriginal burning. The average CHAR values between 600 and 300 yr BP for the Mud Lake Holocene-length composite core are lower than in adjacent, 300-yr periods (Fig. 4.3a). The values for 600 to 300 yr BP are also below the average values for the full core. As the level of CHAR do not appear elevated, they do not follow the same trend as Crawford Lake in southwestern Ontario. There are several lines of evidence that strongly indicate there was a large Iroquois settlement near Crawford Lake that employed agriculture (Clark and Royall 1995), while anecdotal information about aboriginal populations around Charleston Lake suggest that they lived in the area seasonally for hunting and fishing (Chant 1975). In the latter scenario, much less anthropogenic fire would be expected. Though this assessment does not eliminate the possibility that there was such activity in eastern Ontario, it does not indicate the presence of analogous aboriginal burning.

5.5 Long-term Fire History, Vegetation Trends, and Paleoclimate

As there was no study-site specific research into vegetation and climate history, their comparison with Mud Lake's fire history relies upon regional trends. As a result, it is appropriate to use broad, millennial-scale vegetation and climate patterns. While substantiating links between fire and climate in a region requires multiple records, comparing one site with significant regional climate trends may reveal some level of correlation. Based on the available research, there are three time periods that encapsulate both vegetation and climate shifts: de-glaciation to 9800 yr BP (early vegetation and *Picea*- and *Populus* dominated community), 9800 to 5300 yr BP (*Pinus*- and *Tsuga*-dominated community), and 5300 yr BP to present (mixed-hardwood community). As these changes in vegetation and climate occur at about the same time, it indicates that climate played a role in the vegetation shifts. The mFRIs (95% CI) for the three zones are 185 (129-247) yr/fire, 172 (128-222) yr/fire, and 162 (126-203) yr/fire, from early to late Holocene. While the means decreased, they did not statistically vary as their confidence intervals are largely equivalent. At the millennial-scale, the Mud Lake fire regime was stationary through the Holocene. There is, however, variation within zones, as seen in the smoothed FRI and fire frequency values, that warrants consideration (Fig. 4.3c, 4.3d).

The early Holocene period (~12400 to 9800 yr BP), following the Younger Dryas, includes the region's initial, post-glaciation vegetation, likely an herb-shrub assemblage and a subsequent *Picea*- and *Populus*-dominated arboreal community

(Anderson 1987; McFadden et al. 2004). Solar radiation was high throughout the period (Carcaillet and Richard 2000). Climatically, the first part of this period in eastern Canada may have been cool and dry as a result of the strong adiabatic winds from the retreating Laurentide ice sheet (Carcaillet and Richard 2000). The pollen composition, as well as general climate trends, indicates that the latter part of this period may have become warmer and wetter (Anderson 1987; McFadden et al. 2004). In addition, *Picea* is fire-sensitive, so is less likely to be present during periods with a high frequency of fire disturbance (Whitlock and Bartlein 2004), and *Populus* has low flammability as its a broad-leaved deciduous species (Carcaillet et al. 2001a). The fire frequency and FRI during this period do indicate below-average fire activity, with less variability than the rest of the record (Fig. 4.3c, 4.3d). Dry conditions at the beginning of the Holocene would support greater fire frequency, but that's not seen. Wet conditions and vegetation characteristics in the latter part of this period correspond with less fire. The fire activity during this period may be impacted by the dating issues of the early Holocene sediment, which could be decreasing the apparent fire frequency.

There was a shift in the vegetation assemblage of the next zone (9800 to 5300 yr BP) towards increased coniferous species, particularly *Pinus* and *Tsuga*. This period encompasses most of the Holocene Hypsithermal, during which there were generally warmer summers (~2-4ºC) than present as a result of greater summer insolation (McFadden et al. 2004). The level of fire activity as estimated by FRI and fire frequency is largely above-average from ~9800 to ~7000 yr BP, peaking around ~7500 yr BP. The record suggests that the area's fire activity is below-average from ~7000 to ~5300 yr BP, hitting a low at ~6100 yr BP. There was a cooling period in the early part of this period, around 8000 yr BP, possibly as a result of the break-up of the Laurentide ice sheet in the north (Carcaillet and Richard 2000; McFadden et al. 2004). While in some regional sites this coincided with a drop in fire activity (Clark et al. 1996; Ali et al. 2009b), Mud Lake experienced a period of higher fire activity. There are indications that eastern Ontario experienced dry conditions around that time, however, which coordinates with higher fire frequency (McFadden et al. 2004). Following this, eastern Canada in the middle Holocene may have been dominated by wet summers due to the consistent presence of the humid Atlantic Maritime Tropical air mass (Carcaillet and Richard 2000). The onset of these conditions coincided with the drop in Mud Lake fire activity beginning ~7500 yr BP. Eastern Ontario experienced an anomalous climate period from around 6300 to 5300 yr BP as a result of the Nipissing flood, which led to regional cooling (McFadden et al. 2004). The wetter summers and general cooling may have happened impacted the area at the same time. These are climate conditions that would result in decreased fire activity, which is what is predicted for Mud Lake.

The most recent period (5300 yr BP to present) begins with vegetation change, including a significant drop in *Tsuga* abundance and increased hardwood presence, along with generally colder conditions (Fuller 1998; McFadden et al. 2004). The FRI and fire frequency indicate that fire activity was above-average from ~5300 to ~3500 yr BP, and then vacillated between below-average and above-average levels twice, with the surface-core analysis predicting that the period ended with above-average activity (Fig. 4.3c, 4.3d, 4.7c, 4.7d). There was perhaps the most variability in fire activity levels during this period. From ~5300 to ~4000 yr BP in eastern Canada the humid Atlantic Maritime Tropical air mass still tended to dominate, leading to wet summers. The air mass patterns also appear to have been stable during this period, which would tend not to support increased lightning occurrence (Carcaillet and Richard 2000). However, fire activity around Mud Lake was generally high during this time. Since ~3000 yr BP eastern Canada has been influenced by Arctic dry or modified Cool Pacific dry air masses during the late-spring or summer; both of these climate dynamics are conducive to fire weather, (Carcaillet and Richard 2000). The humid Atlantic Maritime Tropical air masses, which dominated during the middle Holocene, were blocked by those from the Arctic and Pacific (Carcaillet and Richard 2000). During this period, an anomalously large fire around ~1480 yr BP took place. Given its size, it’s likely that climate conditions very favourable to fire dominated at that time, such as dry air masses originated from the Arctic or Pacific, and fuel availability likely also played a role.

Overall, the major regional vegetation trends do not appear to mediate shifts in Mud Lake’s fire regime. The comparison is made difficult, though, by the limited, broad patterns available. Regional climate trends coincide with some, but not all, of Mud Lake’s fire activity. The climate change from the cold, early Holocene to the warmer Holocene Hypsithermal generally accompanies an increase in fire activity. There is a drop in fire activity during the climate shift in eastern Ontario around 7500 yr BP, though the activity subsequently rebounded to a high level. Since then, the fire regime has been variable but generally above-average, including the present, coinciding with favourable air mass trends. As the zone mFRIs, fire frequencies, and FRIs indicate, Mud Lake's fire activity is stationary at broad, millennial temporal scales, with greater variability at decadal- to centennial- scales, which may be reflecting changes in climate conditions and the characteristics of local fire controls such as weather, fire ignitions, topography, watershed size, landscape connectivity, and fuel availability.

5.6 Long-term Fire History and Regional Biomass Burning Trends

Carcaillet et al. (2002) set out broad biomass burning trends for eastern North America. The mFRIs for the three zones were similar (170 yr/fire vs. 163 yr/fire vs. 165 yr/fire) and their confidence intervals overlap a great deal, indicating that there was little difference between each zone's overall fire activity. There is some correspondence between Mud Lake's activity and the regional burning trends before and after ~7500 yr BP. The higher level of fire frequency between ~10000 to 7500 yr BP corresponds with high sub-continental burning levels before 7500 yr BP (Carcaillet et al. 2002). The decrease in fire activity around Mud Lake from ~7500 to 6100 yr BP (Fig. 4.3c, 4.3d) corresponds with the sub-continental levels from 7500 yr BP to 3000 yr BP, during which there were lower levels of sub-continental biomass burning in eastern North America. Near Mud Lake, however, the fire activity appears to have rebounded early, increasing by 5000 yr BP.   While there is some correlation between Mud Lake and the greater region, the lack of correlation is not surprising as both climate and local-scale factors vary within eastern North America. The considerable similarity of the Mud Lake mFRIs during time periods further emphasizes that this is a stationary fire regime in the long-term.

A more recent global analysis of charcoal records found greater-than-present levels of fire activity throughout eastern North America from 12000 to 9000 yr BP (Power et al. 2008). The estimated fire frequency around Mud Lake shows an increase through this period, though the FRI shows a less distinct trend (Fig. 4.3c, 4.3d). The overall fire activity shifts towards less fire by 8000 yr BP, and by 6000 yr BP the fire activity in eastern North America dropped to less-than-present levels (Power et al. 2008). As with the trends in Carcaillet et al. (2002), the Mud Lake record mirrors this with a large drop in fire activity (Fig. 4.3c, 4.3d) from ~7500 yr BP to a low level at ~6100 yr BP. The subcontinent was experiencing hetereogeneous fire regimes from ~3000 yr BP to the present, with variable climate conditions (i.e. decreased insolation, decreased summer precipitation) impacting parts of eastern North America to different degrees (Power et al. 2008). That may have been the case for the area around Mud Lake as the fire activity has risen and fallen twice over that period (Fig. 4.3d, 4.7d).

An analysis of the last 2000 yr of global biomass burning provides additional details on recent fire history (Marlon et al. 2008). Overall biomass burning dropped between ~1950 and 200 yr BP (alongside global cooling), rose between 200 yr BP and 80 yr BP (as human influences increased), then dropped sharply (as forest cover decreased and fire management increased) (Marlon et al. 2008). The Mud Lake fire regime has been fairly active during this period. Despite decreasing solar insolation, climate conditions appear to have been more conducive to fire in eastern North America, in contrast to other parts of the world. The Mud Lake record does not have enough fire episodes since 200 yr BP to fully compare with the global record. There does not appear to have been a recent decrease in fire activity, however. Though it is in an region where fire is managed, the Mud Lake area remains forested, and there is no clear indication that humans have caused the fire activity to deviate from the natural range of fire-return-intervals.

5.7 Applying Fire-History to Eastern Ontario Forests

As discussed, long-term fire history can contribute to ecological management. Fire regimes in eastern Ontario are composed of frequent ground fires (on the order of decades) and less frequent stand-replacing crown fires (on the order of centuries) (Johnson 1992). Sediment-charcoal research estimates the return interval of stand-replacing burns. This provides an range of how often large patches of forest should be substantially impacted by fire to allow for regenerating stands of new growth. Ground fires are also important as they clear litter, expose seed beds, and produce nutrients, assisting fire-adapted tree species in their growth (Johnson 1992). Charcoal accumulation does not capture small, ground fires, so alternate sources of fire-history information must be sought to fill this gap. Accordingly, fire management must consider the application of both types of fires. Much more time will be applied to prescribed, ground fires as they are more frequent, and they are also much easier to carry out. While large fires occur much less frequently, they are necessary as, on top of exposing seed beds and cycling nutrients, they also increase landscape diversity, open canopies, and allow shade-intolerant and disturbance-adapted species to establish. The natural variability of Mud Lake's fire activity can be estimated from the 95% CI for mFRIs during different Holocene periods (Cyr et al. 2009). From the periods coinciding with climate and vegetation shifts, the total range is 126 to 247 yr/fire. If the surface core mFRI is included, the range becomes 80 to 247 yr/fire. The fire regime has been fairly constant through time, so the lack of extreme values is consistent. These values are a guide for management goals within similar eastern Ontario habitats for the application of large prescribed fires.

Fire suppression was not identified in recent Mud Lake fire history as fire activity appears to be above-average. This observation relies upon the surface-core record, which had lower counts than the overall Holocene record. Recent climate trends in eastern North America may have supported higher fire activity (Carcaillet and Richard 2000). Additionally, there have been several recent fires in eastern Ontario, some in more densely populated areas than Mud Lake. It is likely that the surface-core record accurately predicted the presence of one or two fires since 90 yr BP and is the better estimate of recent fire activity than the Holocene core. The surface-core results indicate that recent fire activity around Mud Lake is above-average within Holocene activity and within the higher level of its variability. It is possible that an increase in the area's fire activity would move its mFRI beyond the range of variability seen in the Mud Lake record. This would lead to younger vegetation and change the composition of the area's plant species (Cyr et al. 2009). The fire history could also be applied to similar habitats in eastern Ontario, such as those within SLINP, where fire suppression may have occurred. Information on an area's most recent large fire would indicate whether the habitat is currently within the natural variability suggested by the Mud Lake record. If it has been over ~250 yr since a recorded fire or significant disturbance, the introduction of fire may be warranted to re-establish the disturbance regime.

Modern climate change in eastern Ontario may lead to increased temperature, higher winter precipitation, and lower summer precipitation (Suffling and Scott 2002). This will lengthen the fire season and provide generally warmer and drier conditions, conducive to burning (Suffling and Scott 2002). As it was ~2-4 ºC warmer than present, the Holocene Hypsithermal (9400 to 5300 yr BP) provides a climate analogue to what future conditions may resemble (McFadden et al. 2004). The Mud Lake fire activity was above-average for the earlier part of the period, 9400 to 7000 yr BP and was below-average during the later part of this period, 7000 to 5300 yr BP. Paleoclimate trends indicate that the dominating air mass changed ~7500 yr BP, from dry, cool Pacific or Arctic air masses to the moist, Atlantic Tropical Maritime air mass. Though the temperature was high throughout the period, it appears that the moisture regime influenced the area's fire to a greater degree. The activity of large-scale ocean-atmosphere connections that impact summer precipitation may be the better predictor for future fire frequency. Climate modeling may be the best source for information on future precipitation conditions as paleoenvironments cannot be used as templates (Flannigan et al. 2001). Models, however, have a hard time predicting precipitation trends, and there is often a great deal of variation between the results of different models (Whitlock and Bartlein 2004). Nonetheless, enhancing this tool will enable superior fire-weather predictions and fire management.

There are several techniques available for managing fire regimes. Prescribed fires can be used to decrease fuel loads while providing habitats with the benefits of biomass burnings (Agee and Skinner 2005). Should fire regimes in eastern Ontario become more active, prescribed fires may be used to target species that rely on fire for persistence while fires in other areas are prevented or quickly ended.   It may become less acceptable to use prescribed burning, though, as it could be perceived as reducing carbon sinks, contributing to anthropogenic carbon emissions, and exacerbating climate change. While targeted fire suppression can be a useful tool, the suppression of fire in or near populated areas in North America has led to widespread increases in available forest fuels. The levels may be up to three times as under a more active fire regime (Clark 1990). This does not appear to have been a problem around Mud Lake, but it could be a concern in other parts of eastern Ontario that have lacked recent fires. This scenario leads to additional concerns regarding the occurrence and intensity of fires under new and more burn-friendly climate conditions. An additional technique, manual fuel reduction, could be used to moderate an increase in fire frequency.

5.7.1 Pitch Pine Management

Individual species may also benefit from paleofire insights. Pitch pine management requires that people actively interact with vegetation, fire, and climate factors to achieve a conservation goal. Pitch pine is a fire-adapted species that relies on fire disturbances for favourable environmental conditions (Parshall et al. 2003). It is estimated that pitch pine has been in eastern Ontario for ~7000 yr (Warner and Marsters 1993). It may have established during the Holocene Hypsithermal and taken advantage of that period's higher temperatures, and it has persisted through different climate conditions since then (McFadden et al. 2004). It has been speculated that pitch pine may have had a larger range earlier in the Holocene (Mosseler et al. 2004)

As with other species, climate change could be both a threat and an opportunity for this type of tree. As the pitch pine populations in eastern Ontario are at its northernmost limits, increased temperatures may make the study region more appropriate for the species (Mosseler et al. 2004). This scenario also opens up the possibility for the additional establishment of populations north of the current ones. Tree species migration is slow compared to that of animals and many other plants. Additionally, Ontario's pitch pine sites are small and many are in areas of higher elevation, which could inhibit its migration (Ellsworth et al. 2009). Additional establishment may need to be human-mediated. It is worthwhile considering the establishment of additional populations of pitch pine at appropriate sites within the Frontenac Arch, including SLINP and CLPP. This would provide an added buffer against its regional extirpation, increasing the species' resilience against future stresses. It may also enable the species to take advantage of future climate conditions.

The pitch pine populations in eastern Ontario have genetic traits that distinguish them from southern populations and believed to provide increased cold hardiness (Mosseler et al. 2004). These traits may become less beneficial for current populations. Pitch pine populations from the U.S. may be more suited to the new conditions in eastern Ontario, while the current Ontario populations may be more suited to regions north of their current locations. If migration is assisted through management, decisions will need to be made on how the species' genetic diversity is handled.

The FRIs of moderate to large fires for some pitch pine habitats in the U.S. have been estimated as 20 to 40 yr/fire (Parshall et al. 2003). There are indications that this fire frequency is anomalous, though, and unique to certain habitats (Ellsworth et al. 2009). Mud Lake's extended FRI range of 80 to 247 yr/fire does not overlap with the short range suggested. As there is a pitch pine population beside Mud Lake, it can be assumed that the fire activity in the area has supported its persistence. It benefits from both more-frequent small fires as well as less-frequent large fires, and the sediment-charcoal based analysis discussed here can provide guidance on the application of large fires. As fire provides pitch pine with a competitive advantage, an FRI for large fires in the more active part of the range may be appropriate for areas targeted towards pitch pine restoration. Larger fires are necessary for opening canopies, which benefits the shade-intolerant tree and would allow for habitat expansion. This should be done in association with more frequent application of small prescribed burns. Establishing pitch pine in new habitats would also require the application of fire disturbance to enable its growth.

Chapter 6

Conclusions

6.1 Summary of Research Objectives

Several research objectives, outlined in the introduction, structured this thesis. Primarily, the research set out to investigate the fire regime around Mud Lake during the Holocene. The mFRI for the Holocene-length record is 175 yr/fire, with a 95% CI range of 146-204 yr/fire (Fig. 4.4). The lack of variability in the mFRIs estimated for different time periods (Fig. 4.5, 4.6) suggests that Mud Lake has a relatively stationary fire regime. The fire activity does, however, vary within these broad time periods. The range of mFRI 95% CIs for the vegetation and climate zones is 126 to 247 yr/fire (Fig. 4.5). With the surface core mFRI included, the range is 80 to 247 yr/fire (Fig. 4.8). These 95% CI extremes provide a rough estimate for the extended natural variability of Mud Lake's fire regime (Cyr et al. 2009). In particular, the surface core record analysis indicates that the fire activity of the last ~1000 yr may have been above-average for the Holocene, with an mFRI of 130 yr/fire, but a lack of documentary evidence leaves this unclear (Fig. 4.8).

The composition of the charcoal morphotypes of the Mud Lake sediment did not show any trends that corresponded to shifts in vegetation. The most frequent types are the more robust charcoal shapes, while fragile morphotypes tended to be more common in recent history. As such, it may be that burned wood and bark contributed the most to the charcoal record, while grass charcoal contributed little.

The impact of humans on the fire regime was also investigated. Given the resolution and level of fire activity, it was not possible to delineate any clear anthropogenic effects on the fire activity within the last 1000 yr. The surface core mFRI was higher than the mFRI of periods earlier in the Holocene, and it is possible that humans impacted that by caused the ignitions of the most recent fires.

The relationship between the reconstructed fire regime and long-term regional vegetation and climate trends was considered. As the Mud Lake fire regime is stationary, it did not vary between millennial-scale periods with different vegetation and climate conditions. There did not appear to be any point where changes in fire and vegetation happened around the same time, though the broad vegetation trends available meant this was a limited comparison. The fire activity did vary at smaller temporal-scales. Some of the variation appears to correlate with climate trends, while other variation is not explained by regional paleoclimate. While paleoclimate would predict higher fire activity during the early Holocene (Carcaillet and Richard 2000), that was not the case at Mud Lake. A subsequent drop in Mud Lake's fire activity ~7000 yr BP does coincide with regional climate trends, including the onset of wetter summers caused by the moist Atlantic Maritime Tropical air mass (Carcaillet and Richard 2000; McFadden et al. 2004). Mud Lake's subsequently high level of activity, however, contrasts with the continued influence of the moist Atlantic air masses until ~4000 yr BP. Since ~3000 yr BP, dry Arctic and Pacific air masses have dominated eastern Canada, and this is reflected in generally high fire activity around Mud Lake (Carcaillet and Richard 2000).

The last ~1000 yr, in particular, may have been an increase in fire frequency that corresponds to these air mass influences. Overall, the Mud Lake fire regime has partial correlation with the regional paleoclimate. The variation may be partially a result of local-scale characteristics such as weather, topography, landscape connectivity, and fuel availability. Additionally, it is difficult to find correlation between one site and broad climate trends as a local fire-history has low sample size and spatial extent. Comparing a regional network of sites in eastern Ontario with climate trends may offer more insights into the area's fire-climate relationship.

Additionally, the reconstructed fire regime is discussed in the context of regional biomass burning trends. Biomass burning in eastern North America had three main periods of activity during the Holocene, >7500 yr BP, 7500 yr BP to 3000 yr BP, and 3000 yr BP to present (Carcaillet et al. 2002). While the Mud Lake's zone mFRIs do not vary, there was variation in its fire activity starting ~7500 yr BP, suggesting that the impacts that caused a regional decrease also influenced Mud Lake's fire frequency. There is also some correlation between Mud Lake's recent above-average activity and eastern North America's higher levels of burning, which, as discussed, may have been climate-mediated. A separate analysis of eastern North America's charcoal trends also reflects a drop in activity ~7500 yr BP, so the incursion of moist air masses, which decrease the likelihood of fire, may have been widespread (Power et al. 2008). A global analysis of the last 2000 yr BP of fire history found that after a trend of decreased activity, humans first increased then decreased the levels of biomass burning (Marlon et al. 2008). In contrast, though, Mud Lake fire activity appears to have been generally high during this period, perhaps as a result of fire-conducive climate. As well, humans do not appear to have impacted the fire regime in the area as drastically as in other parts of the world, and the Mud Lake fire regime does not appear to have been altered beyond its range of natural variability.

Finally, the last objective addressed the application of the Mud Lake fire history to ecological management. Past conditions indicate that precipitation is more of a determining factor than temperature in fire activity around Mud Lake, so modeling for summer precipitation levels would be the most useful in predicting future fire frequency in this area. Mud Lake's recent activity appears to be within the long-term range of fire activity, but should a similar habitat in eastern Ontario not have experienced a large fire or major disturbance within ~250 yr, it may warrant prescribed fire. Given the range of FRIs in this part of eastern Ontario, pitch pine would likely benefit from large fire intervals towards the more active end of the spectrum alongside more frequent applications of ground fire. It may also be beneficial to establish additional pitch pine populations within the Frontenac Arch, including SLINP and CLPP.

6.2 Opportunities for Further Research

A high-resolution reconstruction of a local fire regime is one aspect of an area's paleoecology. While it provides detailed information about past activity, it is of additional value when it can be compared to other long-term environmental trends and considered within a regional network of sites. Initial comparisons were made between the fire history of Mud Lake and regional vegetation climate trends, providing some insight into potential linkages. Further paleoecological research in eastern Ontario and the broader region would provide more details about the area's long-term ecological history. This knowledge will be useful in the future during what may be rapid environmental change as information on a habitat's range of natural variability will help predict and compensate for these conditions.

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Appendix A - Supplementary Figures

Appendix A Figure Captions

Figure A.1 Pollen diagram for Atkins Lake, Ontario (N44º45’ W75º51’). Atkins Lake is northwest of Brockville, Ontario and approximately 35 km from Mud Lake, Ontario (Terasmae 1980).

Figure A.2 Alternative representation of fire episode distribution, fire return intervals (FRI), and fire frequency series from the Holocene-length composite-core record. The plus symbols represent fire episodes. The FRIs are in units of yr/fire, and the actual FRI values as well as the smoothed FRI series are shown. The fire frequency series is in units of fires/1000 yr. Cal yr BP refers to calendar years before present, present at 1950 AD.

Figure A.3 Analysis of the sensitivity and quality of the Holocene-length composite-core charcoal-record. Cal yr BP refers to calendar years before present, present at 1950 AD. a) Sensitivity of the record to alternative peak threshold (95%, 99%, 99.9%, bottom to top). This graph shows the peak distributions when different peak threshold percentiles are used. b) Mean fire-return-interval (FRI) and 95% confidence intervals (CI) for each peak threshold, 95%, 99%, 99.9%, left to right. c) The local signal-to-noise index (SNI). d) The global SNI.

Figure A.4 a-b Log-transformed Mud Lake composite-core charcoal-record analysis. Cal yr BP refers to calendar years before present, present at 1950 AD. (a) The interpolated charcoal accumulation rate (CHAR: pieces•cm^{-2}•yr^{-1}) levels (black line) and the smoothed CHAR background levels (red line). b) The CHAR peak levels (black line) and the 0.95-peak threshold level (red line). The points of the CHAR peak series above the threshold series that have been deemed fire events are represented by + symbols.

Figure A.5 Alternative representation of fire episode distribution, fire return interval (FRI), and fire frequency series from the surface-core record. The plus symbols represent fire episodes. The FRIs are in units of yr/fire, and the actual FRI values as well as the smoothed FRI series are shown. The fire frequency series is in units of fires/500 yr. Cal yr BP refers to calendar years before present, present at 1950 AD.

Figure A.6 Analysis of the sensitivity and quality of the surface-core charcoal-record. Cal yr BP refers to calendar years before present, present at 1950 AD. a) Sensitivity of the record to alternative peak threshold (95%, 99%, 99.9%, bottom to top). This graph shows the peak distributions when different peak threshold percentiles are used. b) Mean fire-return-interval (FRI), and 95% confidence intervals (CI) for each peak threshold, 95%, 99%, 99.9%, left to right. c) The local signal-to-noise index (SNI). d) The global SNI.

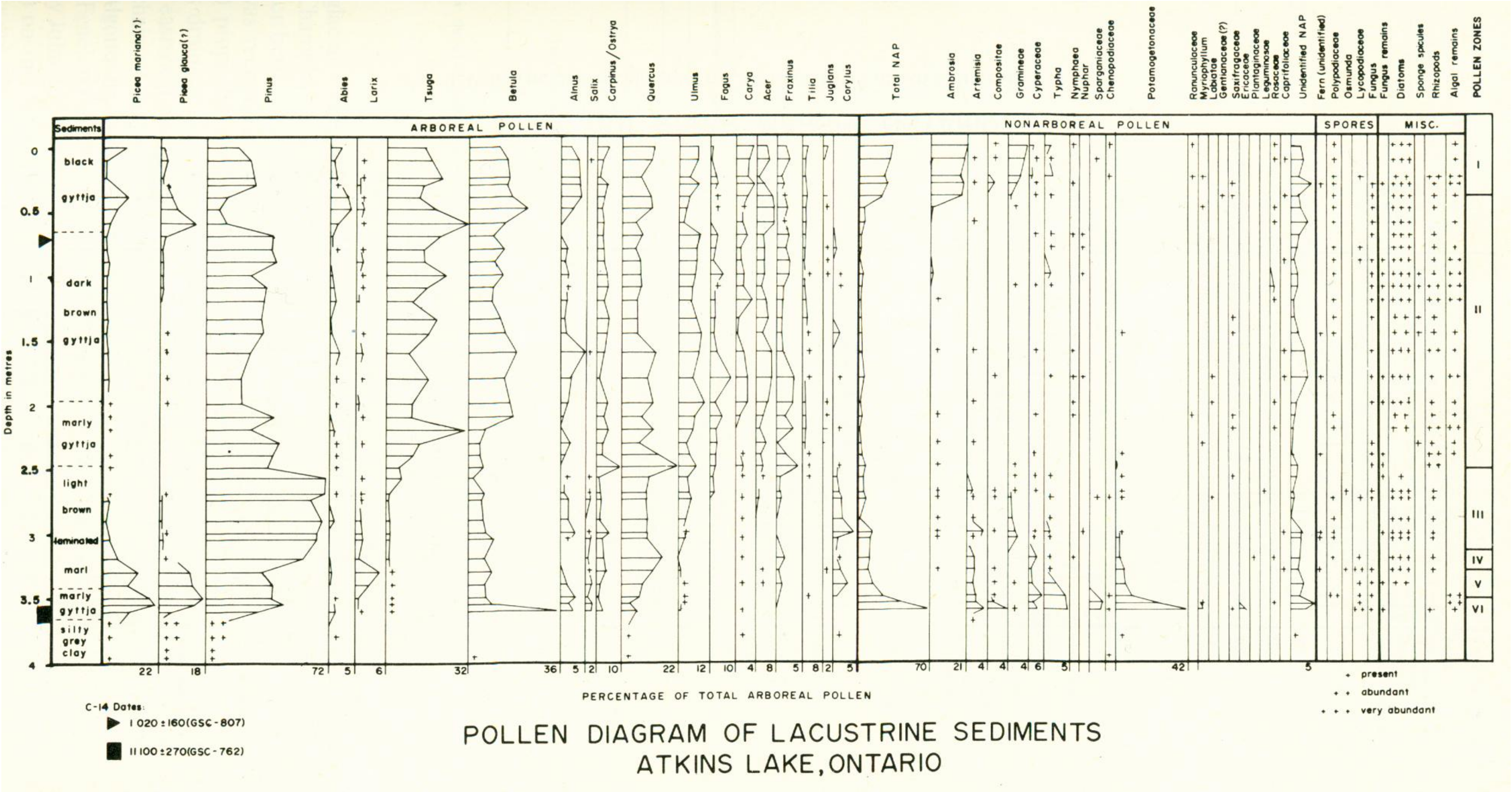

Picea mariana(?)
Picea glauca(?)
Pinus
Abies
Larix
Tsuga
Betula
Alnus
Salix
Carpinus/Ostrya
Quercus
Ulmus
Fagus
Carya
Acer
Fraxinus
Tilia
Juglans
Corylus
Total NAP
Ambrosia
Artemisia
Compositae
Gramineae
Cyperaceae
Typha
Nymphaea
Nuphar
Sparganiaceae
Chenopodiaceae
Potamogetonaceae
Ranunculaceae
Myriophyllum
Labiatae
Gentianaceae(?)
Saxifragaceae
Ericaceae
Plantaginaceae
Leguminosae
Rosaceae
Caprifoliaceae
Unidentified NAP
Fern (unidentified)
Polypodiaceae
Osmunda
Lycopodiaceae
Fungus
Fungus remains
Diatoms
Sponge spicules
Rhizopods
Algal remains
POLLEN ZONES
Sediments
ARBOREAL POLLEN
NONARBOREAL POLLEN
SPORES
MISC.
Depth in metres
0
0.5
1
1.5
2
2.5
3
3.5
4
black
gyttja
dark
brown
gyttja
marly
gyttja
light
brown
laminated
marl
marly
gyttja
silty
grey
clay
I
II
III
IV
V
VI
22
18
72
5
6
32
36
5
2
10
22
12
10
4
8
5
8
2
5
70
21
4
4
4
6
5
42
5
PERCENTAGE OF TOTAL ARBOREAL POLLEN
+ present
+ + abundant
+ + + very abundant
C-14 Dates:
▶ 1 020 ±160(GSC-807)
■ 11 100 ±270(GSC-762)
POLLEN DIAGRAM OF LACUSTRINE SEDIMENTS
ATKINS LAKE, ONTARIO

Figure A.1

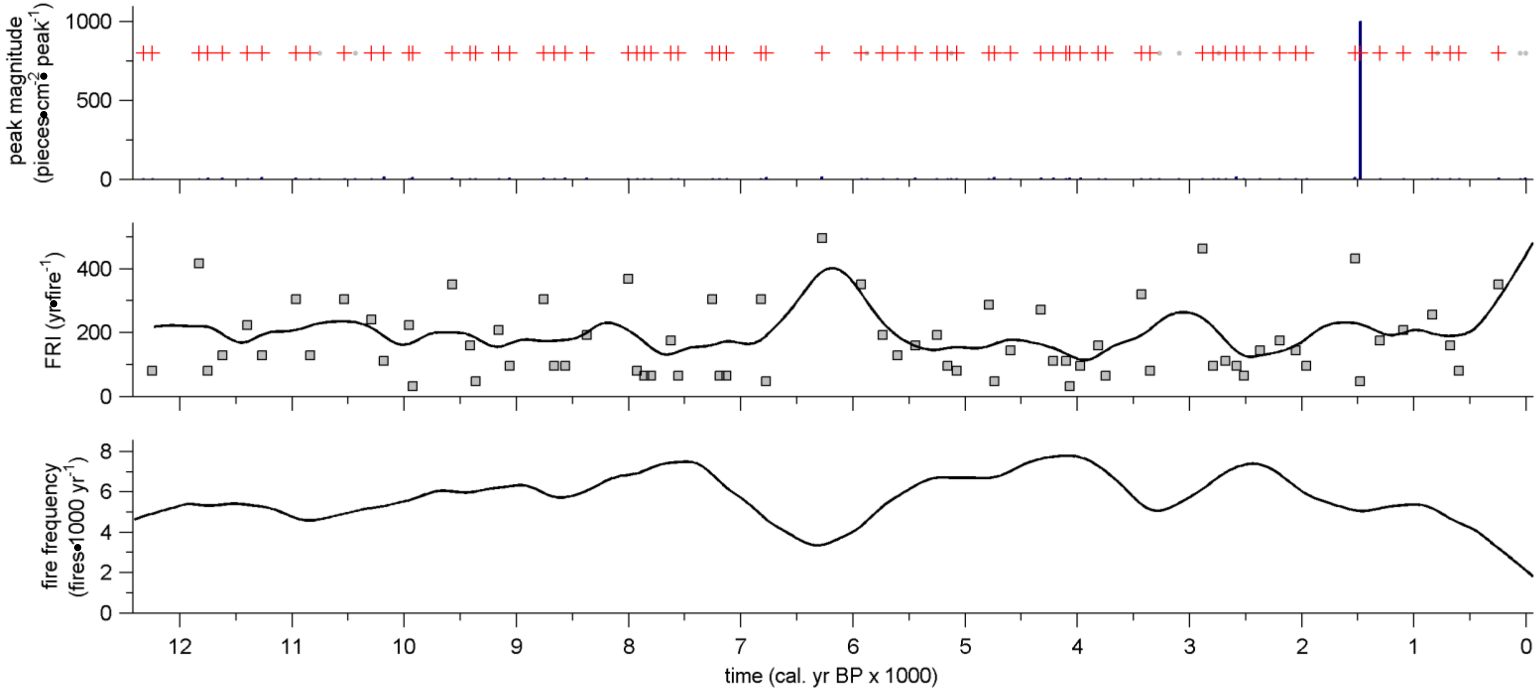

peak magnitude
(pieces•cm^{-2}• peak^{-1})
1000
500
0
FRI (yr•fire^{-1})
400
200
0
fire frequency
(fires•1000 yr^{-1})
8
6
4
2
0
12
11
10
9
8
7
6
5
4
3
2
1
0
time (cal. yr BP x 1000)

Figure A.2

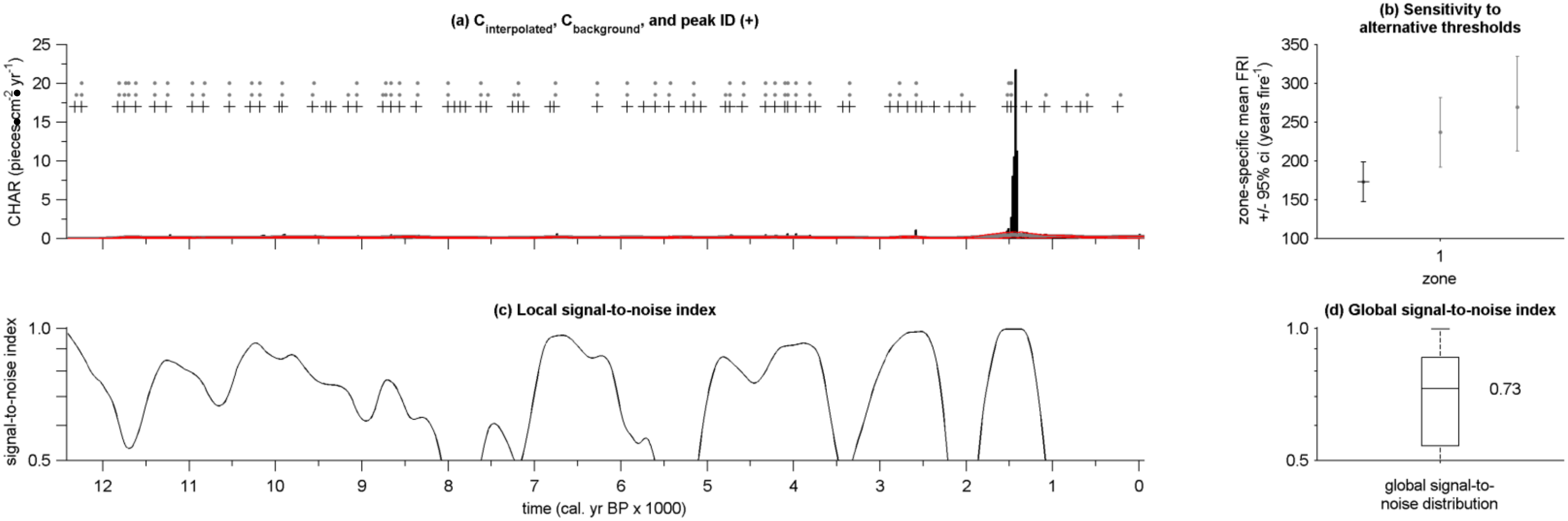

(a) $C_{interpolated}$, $C_{background}$, and peak ID (+)
CHAR (pieces cm^{-2} yr^{-1})
25
20
15
10
5
0
(b) Sensitivity to alternative thresholds
zone-specific mean FRI +/- 95% ci (years fire^{-1})
350
300
250
200
150
100
1
zone
(c) Local signal-to-noise index
signal-to-noise index
1.0
0.5
12
11
10
9
8
7
6
5
4
3
2
1
0
time (cal. yr BP x 1000)
(d) Global signal-to-noise index
1.0
0.5
0.73
global signal-to-noise distribution

Figure A.3

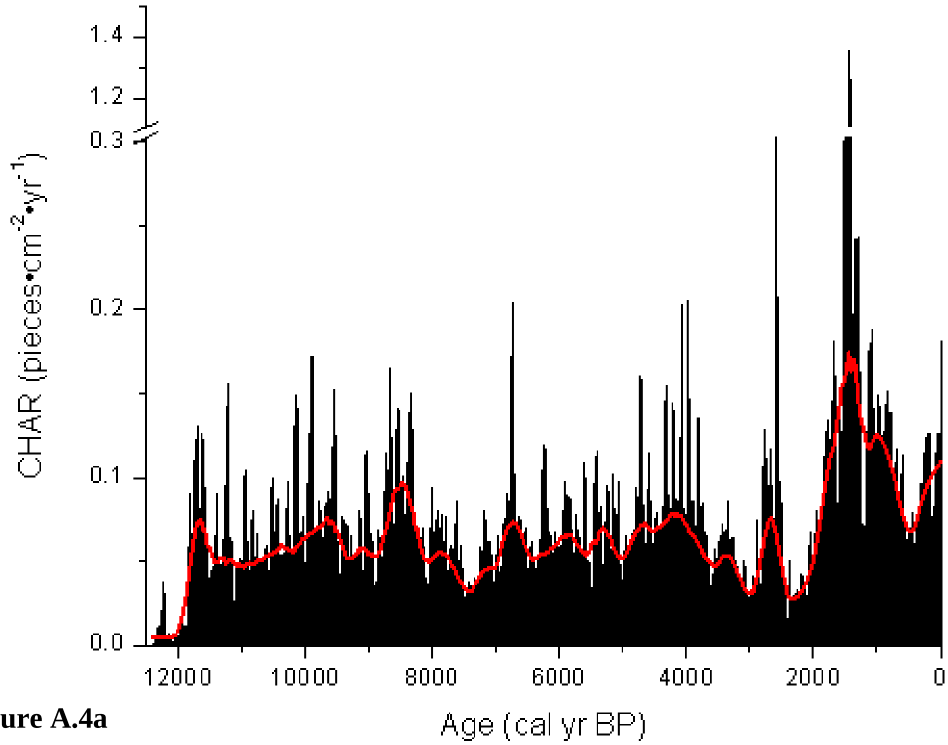


Figure A.4a

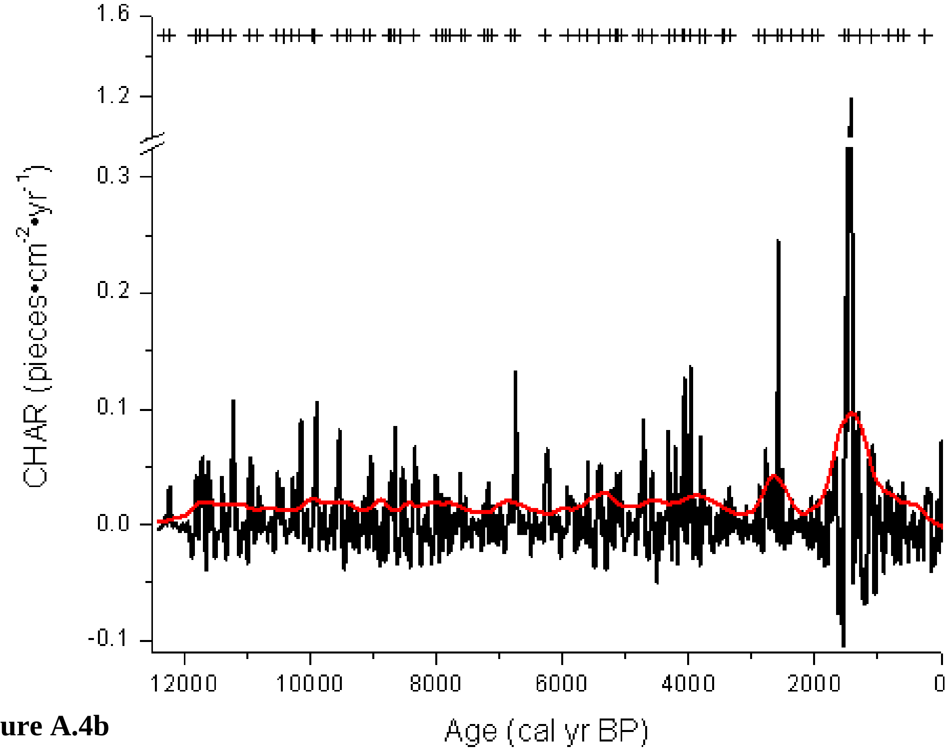


Figure A.4b

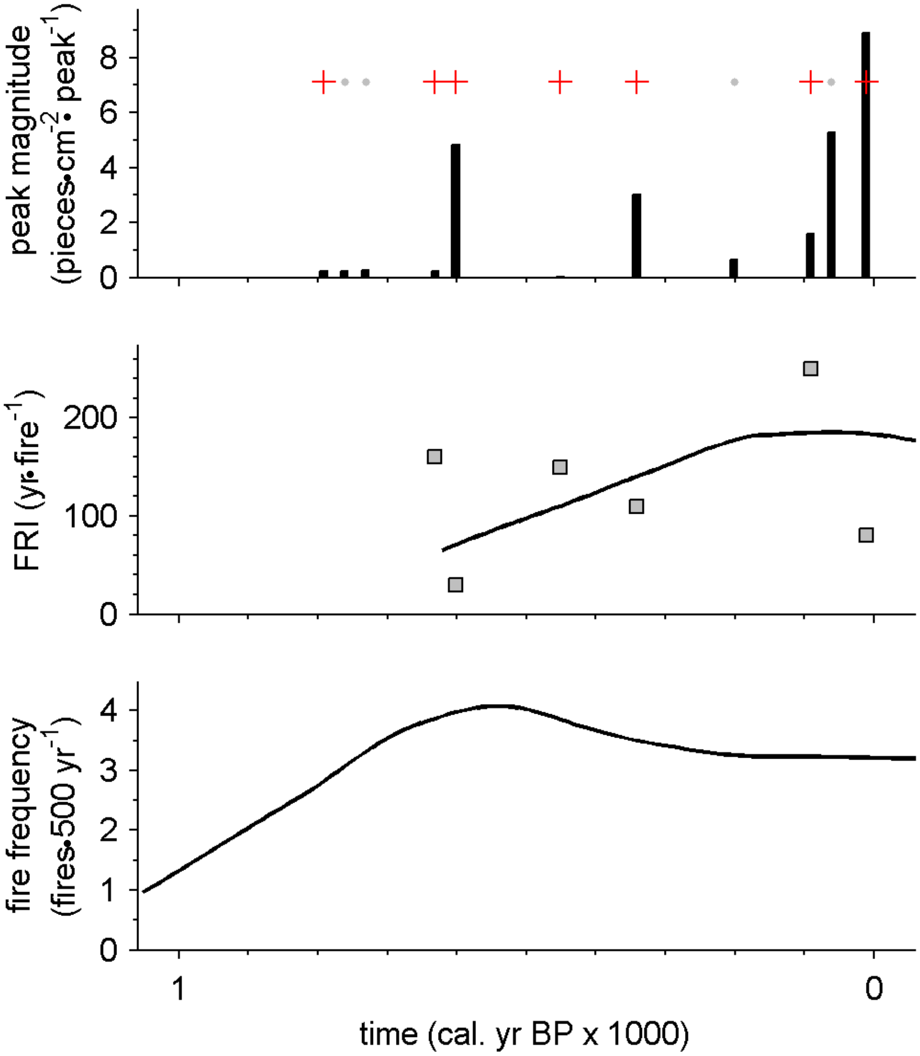
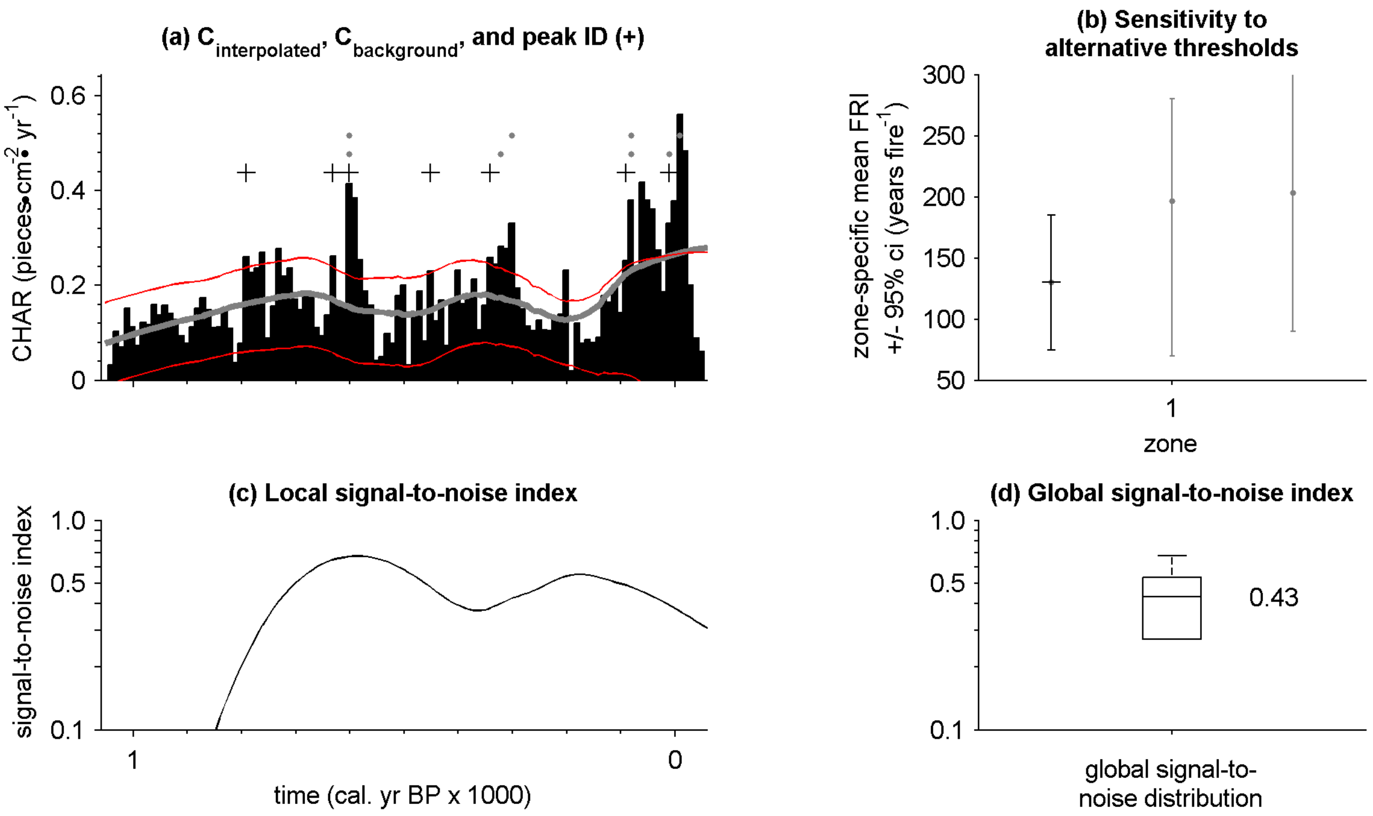

peak magnitude
(pieces•cm^{-2}• peak^{-1})
0
2
4
6
8
FRI (yr• fire^{-1})
0
100
200
fire frequency
(fires•500 yr^{-1})
0
1
2
3
4
1
0
time (cal. yr BP x 1000)

Figure A.5



(a) $C_{interpolated}$, $C_{background}$, and peak ID (+)
CHAR (pieces•cm^{-2}• yr^{-1})
0.6
0.4
0.2
0
(b) Sensitivity to alternative thresholds
zone-specific mean FRI +/- 95% ci (years fire^{-1})
300
250
200
150
100
50
1
zone
(c) Local signal-to-noise index
signal-to-noise index
1.0
0.5
0.1
1
0
time (cal. yr BP x 1000)
(d) Global signal-to-noise index
1.0
0.5
0.1
0.43
global signal-to-noise distribution

Figure A.6

Appendix B - Data Tables

Appendix B1 - Mud Lake Piston-Core Charcoal Data

Charcoal counts for total charcoal and charcoal morphotypes at each sediment interval of the Mud Lake piston-core (Mud Long 2). The drive section, interval depth, calendar yr before present, volume, and magnetic susceptibility reading are listed for each sediment interval along with the charcoal piece counts. Cal yr BP refers to calendar years before present, present at 1950 AD. See Figure 3.4 for a description of the charcoal morphotypes.

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)	Magnetic Susceptib-ility (cgs $x10^{-6}$)
1	0.0	0.5	46	52	1	1	0	0	1	0	0	3	0.51	-11.7
1	0.5	1.0	52	58	0	3	0	0	1	0	0	4	1.61	-2.5
1	1.0	1.5	58	64	1	2	0	0	0	0	1	4	1.39	3.6
1	1.5	2.0	64	70	2	1	0	0	0	0	0	3	1.45	0.2
1	2.0	2.5	70	76	3	1	0	0	0	0	0	4	1.34	5.7
1	2.5	3.0	76	82	2	6	0	0	2	0	0	10	2.05	-1.0
1	3.0	3.5	82	89	2	2	0	0	2	0	3	9	2.44	0.3
1	3.5	4.0	89	97	0	3	0	0	1	0	0	4	2.16	-1.1
1	4.0	4.5	97	107	2	1	1	0	0	0	0	4	1.72	2.9
1	4.5	5.0	107	116	1	5	0	0	2	0	2	10	2.60	-0.6
1	5.0	5.5	116	126	3	6	0	0	5	0	1	15	2.71	0.9
1	5.5	6.0	126	135	3	5	0	0	1	0	0	9	2.55	-1.7
1	6.0	6.5	135	145	2	1	2	0	4	0	1	10	1.94	1.7
1	6.5	7.0	145	155	0	1	0	0	1	0	0	2	2.27	-1.8
1	7.0	7.5	155	164	1	4	0	0	2	0	1	8	1.83	0.5
1	7.5	8.0	164	174	12	10	3	0	10	1	2	38	2.38	-2.0
1	8.0	8.5	174	183	4	4	1	0	1	0	0	10	1.83	-2.9

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)	Magnetic Susceptib-ility (cgs x10^{-6})
1	8.5	9.0	183	193	4	7	3	0	12	0	4	30	2.33	1.9
1	9.0	9.5	193	203	5	6	1	0	5	0	1	18	2.66	-0.8
1	9.5	10.0	203	212	8	7	2	0	1	0	0	18	1.89	-3.4
1	10.0	10.5	212	222	3	2	2	0	1	1	2	11	1.34	-5.5
1	10.5	11.0	222	231	11	2	4	0	6	2	3	28	1.94	0.9
1	11.0	11.5	231	241	5	2	3	0	3	1	0	14	1.39	3.6
1	11.5	12.0	241	251	1	3	1	0	3	2	4	14	2.00	-3.8
1	12.0	12.5	251	260	4	2	4	0	6	1	4	21	1.94	-3.3
1	12.5	13.0	260	270	2	3	2	0	5	1	5	18	2.16	1.5
1	13.0	13.5	270	280	3	2	1	0	1	0	4	11	1.78	1.7
1	13.5	14.0	280	289	2	2	0	0	2	0	0	6	2.27	-2.3
1	14.0	14.5	289	299	1	0	0	0	1	0	2	4	2.44	-1.5
1	14.5	15.0	299	308	3	0	0	0	2	0	3	8	1.50	-1.8
1	15.0	15.5	308	318	5	0	0	0	2	0	4	11	2.00	3.0
1	15.5	16.0	318	328	3	2	0	0	3	0	1	9	2.99	-2.3
1	16.0	16.5	328	337	0	1	2	0	0	0	0	3	1.17	-2.6
1	16.5	17.0	337	347	2	1	1	0	2	0	0	6	1.67	-3.2
1	17.0	17.5	347	357	2	0	0	0	0	0	1	3	1.78	0.0
1	17.5	18.0	357	366	1	0	0	0	2	0	1	4	1.56	-1.9
1	18.0	18.5	366	376	1	0	1	0	1	0	1	4	1.67	2.4
1	18.5	19.0	376	386	0	0	1	0	1	0	2	4	1.56	-1.5
1	19.0	19.5	386	395	2	0	1	0	1	1	2	7	1.94	-0.7
1	19.5	20.0	395	405	0	0	0	0	1	0	1	2	1.61	-1.0
1	20.0	20.5	405	415	2	0	0	0	1	1	2	6	2.22	-0.2
1	20.5	21.0	415	424	0	0	0	0	0	1	0	1	1.50	-2.7
1	21.0	21.5	424	434	0	0	0	0	1	0	5	6	1.94	1.2
1	21.5	22.0	434	444	3	0	0	0	4	0	0	7	2.00	-2.3
1	22.0	22.5	444	453	4	2	1	0	4	0	0	11	1.83	2.5
1	22.5	23.0	453	463	3	0	0	0	4	0	3	10	2.00	0.3
1	23.0	23.5	463	473	1	0	0	0	0	1	2	4	2.27	-3.2
1	23.5	24.0	473	482	0	1	0	0	1	2	2	6	2.44	0.5
1	24.0	24.5	482	492	1	0	0	0	4	1	0	6	2.60	-2.0
1	24.5	25.0	492	502	3	0	2	0	5	1	6	17	2.49	-0.7
1	25.0	25.5	502	512	0	1	0	0	2	0	0	3	0.79	-6.4
1	25.5	26.0	512	521	0	0	0	0	0	0	2	2	2.22	-1.8

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)	Magnetic Susceptib -ility (cgs x10^{-6})
1	26.0	26.5	521	531	1	0	0	0	1	0	0	2	2.16	-1.1
1	26.5	27.0	531	541	1	0	2	0	2	1	6	12	2.55	1.0
1	27.0	27.5	541	551	3	0	0	0	0	2	5	10	2.60	-1.5
1	27.5	28.0	551	560	1	2	1	0	0	2	3	9	3.00	0.9
1	28.0	28.5	560	570	3	3	0	0	2	0	6	14	2.77	-1.6
1	28.5	29.0	570	580	0	0	0	0	0	1	4	5	2.55	0.4
1	29.0	29.5	580	590	0	0	0	0	2	1	0	3	2.82	-0.4
1	29.5	30.0	590	599	2	0	1	0	2	1	4	10	2.16	-0.6
1	30.0	30.5	599	609	1	1	1	0	5	1	5	14	2.93	-0.7
1	30.5	31.0	609	619	2	2	0	0	5	0	2	11	2.44	1.6
1	31.0	31.5	619	629	4	3	0	0	5	2	8	22	3.10	-1.1
1	31.5	32.0	629	639	5	1	0	0	2	0	1	9	2.77	1.1
1	32.0	32.5	639	648	2	1	2	0	3	1	8	17	2.99	-0.9
1	32.5	33.0	648	658	0	1	0	0	2	0	2	5	2.16	1.1
1	33.0	33.5	658	668	0	2	0	0	1	0	0	3	2.22	-1.8
1	33.5	34.0	668	678	3	1	2	0	4	1	1	12	2.77	1.3
1	34.0	34.5	678	688	3	1	0	0	6	0	10	20	2.49	-2.9
1	34.5	35.0	688	698	9	5	1	0	4	1	3	22	2.49	0.0
1	35.0	35.5	698	708	7	4	2	0	2	0	2	17	2.44	-2.2
1	35.5	36.0	708	717	1	4	0	0	5	0	2	12	2.38	1.1
1	36.0	36.5	717	727	2	4	1	0	1	0	2	10	2.27	-1.0
1	36.5	37.0	727	737	7	5	2	0	3	1	1	19	2.55	0.8
1	37.0	37.5	737	747	2	0	0	0	5	0	3	10	2.88	-2.0
1	37.5	38.0	747	757	4	2	2	0	4	0	1	13	2.66	-1.6
1	38.0	38.5	757	767	3	3	2	0	3	0	1	12	2.49	-0.8
1	38.5	39.0	767	777	1	1	2	0	5	1	6	16	3.04	-0.3
1	39.0	39.5	777	787	4	4	1	0	2	0	4	15	2.49	-1.9
1	39.5	40.0	787	797	4	2	2	0	9	1	7	25	2.49	1.3
1	40.0	40.5	797	807	8	2	2	2	4	3	7	28	3.15	-0.6
1	40.5	41.0	807	817	3	4	2	0	5	2	11	27	2.82	-1.2
1	41.0	41.5	817	827	4	3	1	0	4	2	6	20	3.48	1.5
1	41.5	42.0	827	837	9	7	6	0	11	1	8	42	3.59	-1.0
1	42.0	42.5	837	847	9	4	3	0	9	2	8	35	3.10	0.8
1	42.5	43.0	847	857	7	9	4	0	12	2	7	41	2.93	-1.0
1	43.0	43.5	857	867	2	1	2	0	3	1	4	13	2.93	-0.7

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)	Magnetic Susceptib-ility (cgs x10^{-6})
1	43.5	44.0	867	877	6	2	3	0	8	8	20	47	3.59	-2.6
1	44.0	44.5	877	887	6	5	1	0	5	1	10	28	3.48	-1.4
1	44.5	45.0	887	897	4	0	1	0	7	3	15	30	3.37	-1.6
1	45.0	45.5	897	907	5	0	2	0	6	3	9	25	3.21	1.7
1	45.5	46.0	907	917	3	1	0	0	4	2	5	15	3.54	-0.4
1	46.0	46.5	917	927	2	0	2	0	8	0	12	24	3.37	1.0
1	46.5	47.0	927	937	4	0	0	0	7	5	20	36	3.15	-2.4
1	47.0	47.5	937	947	5	0	5	0	6	2	10	28	3.26	-2.4
1	47.5	48.0	947	958	4	1	2	0	8	1	4	20	3.70	-0.9
1	48.0	48.5	958	968	8	1	1	0	3	4	11	28	3.59	-1.9
1	48.5	49.0	968	978	12	2	4	0	12	3	15	48	4.47	-0.7
1	49.0	49.5	978	988	7	1	2	0	11	2	13	36	3.37	-0.1
1	49.5	50.0	988	998	12	0	3	0	10	3	21	49	4.03	-1.5
1	50.0	50.5	998	1008	6	0	2	0	9	5	12	34	3.81	-0.5
1	50.5	51.0	1008	1018	7	2	4	0	7	2	13	35	3.98	-0.8
1	51.0	51.5	1018	1029	10	1	5	0	10	2	12	40	4.09	-1.6
1	51.5	52.0	1029	1039	2	1	4	0	6	1	9	23	3.54	-1.4
1	52.0	52.5	1039	1049	9	1	3	0	10	0	7	30	3.43	-2.6
1	52.5	53.0	1049	1059	2	0	1	0	4	1	1	9	3.54	1.6
1	53.0	53.5	1059	1070	2	1	1	1	10	1	5	21	3.92	-1.1
1	53.5	54.0	1070	1080	8	1	3	1	11	3	12	39	3.70	-2.3
1	54.0	54.5	1080	1090	12	2	3	0	7	2	17	43	3.54	-2.0
1	54.5	55.0	1090	1100	5	1	3	0	5	0	15	29	3.37	-0.9
1	55.0	55.5	1100	1111	9	0	4	0	8	3	18	42	3.48	-2.0
1	55.5	56.0	1111	1121	4	2	2	0	6	1	8	23	3.48	-0.5
1	56.0	56.5	1121	1131	8	1	1	0	0	1	12	23	3.43	1.6
1	56.5	57.0	1131	1142	4	1	2	1	1	1	15	25	3.21	-1.5
1	57.0	57.5	1142	1152	9	4	4	0	5	5	3	30	3.04	-0.3
1	57.5	58.0	1152	1163	10	4	5	0	4	1	19	43	3.76	-1.9
1	58.0	58.5	1163	1173	3	1	0	0	0	0	5	9	3.26	-1.9
1	58.5	59.0	1173	1184	3	1	2	0	7	1	8	22	3.92	-2.0
1	59.0	59.5	1184	1194	3	0	0	1	4	1	2	11	3.04	-0.4
1	59.5	60.0	1194	1205	0	0	1	0	1	1	6	9	3.43	0.3
1	60.0	60.5	1205	1215	3	0	1	0	1	0	6	11	3.15	-2.0
1	60.5	61.0	1215	1226	1	0	3	0	0	0	4	8	3.26	1.5

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)	Magnetic Susceptibility (cgs x10^{-6})
1	61.0	61.5	1226	1237	3	1	0	0	2	0	6	12	2.93	-1.0
1	61.5	62.0	1237	1247	3	1	0	0	2	0	6	12	2.44	0.5
1	62.0	62.5	1247	1258	1	0	0	0	2	1	3	7	2.99	-0.4
1	62.5	63.0	1258	1269	3	0	2	0	1	1	5	12	3.04	-0.8
1	63.0	63.5	1269	1280	3	2	2	0	12	2	22	43	3.26	-2.8
1	63.5	64.0	1280	1291	1	0	1	1	5	0	3	11	2.60	-3.2
1	64.0	64.5	1291	1301	2	4	0	0	3	1	4	14	2.27	0.1
1	64.5	65.0	1301	1312	2	2	2	2	8	5	9	30	2.11	-0.2
1	65.0	65.5	1312	1323	7	30	2	1	10	1	5	56	2.60	-0.9
1	65.5	66.0	1323	1334	2	2	2	0	4	0	5	15	2.11	3.5
1	66.0	66.5	1334	1346	16	14	1	0	9	0	3	43	2.11	-1.3
1	66.5	67.0	1346	1357	7	6	1	0	5	0	1	20	2.38	-1.4
1	67.0	67.5	1357	1368	2	15	1	0	9	0	4	31	3.04	-0.9
1	67.5	68.0	1368	1379	3	9	3	0	13	1	6	35	2.27	-3.2
1	68.0	68.5	1379	1390	1	2	0	0	3	1	2	9	2.16	-1.9
1	68.5	69.0	1390	1402	4	7	6	0	6	0	1	24	2.27	-0.4
1	69.0	69.5	1402	1413	4	4	1	0	4	0	2	15	2.22	-0.9
1	69.5	70.0	1413	1425	99	89	4	7	15	0	38	252	1.94	-0.2
1	70.0	70.5	1425	1436	367	621	9	0	372	2	85	1456	2.55	2.4
1	70.5	71.0	1436	1448	304	602	5	0	340	1	27	1279	2.82	-0.9
1	71.0	71.5	1448	1460	105	158	10	4	164	5	27	473	2.38	-1.0
1	71.5	72.0	1460	1471	118	235	3	21	188	1	57	623	2.33	-3.4
1	72.0	72.5	1471	1483	25	55	11	0	48	1	4	144	2.44	-4.1
1	72.5	73.0	1483	1495	28	39	4	0	39	1	10	121	1.78	1.1
1	73.0	73.5	1495	1507	7	8	1	0	8	0	2	26	2.22	-0.9
1	73.5	74.0	1507	1519	5	9	5	0	8	1	4	32	2.05	-0.5
1	74.0	74.5	1519	1531	14	55	3	0	30	0	6	108	2.05	-0.2
1	74.5	75.0	1531	1543	5	2	0	0	4	1	7	19	2.44	2.7
1	75.0	75.5	1543	1555	1	2	0	0	1	0	1	5	2.11	-1.1
1	75.5	76.0	1555	1568	0	1	1	0	0	0	4	6	1.94	-0.9
1	76.0	76.5	1568	1580	1	3	0	0	2	0	2	8	2.66	-0.3
1	76.5	77.0	1580	1592	7	8	1	0	7	0	1	24	2.00	-0.2
1	77.0	77.5	1592	1605	1	8	0	0	7	1	4	21	2.33	-0.3
1	77.5	78.0	1605	1617	3	1	2	0	0	2	4	12	1.94	1.5
1	78.0	78.5	1617	1630	2	1	0	0	3	0	1	7	2.11	1.9

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)	Magnetic Susceptib-ility (cgs x10^{-6})
1	78.5	79.0	1630	1642	3	0	1	0	0	0	1	5	1.34	2.5
1	79.0	79.5	1642	1655	4	1	0	0	0	0	3	8	1.34	-4.5
1	79.5	80.0	1655	1668	3	4	1	0	3	0	2	13	1.23	-1.9
2	80.0	80.5	1668	1681	1	0	1	0	1	2	2	7	0.57	-2.9
2	80.5	81.0	1681	1693	2	2	0	0	1	0	4	9	0.90	-2.2
2	81.0	81.5	1693	1706	1	2	2	0	3	2	12	22	1.34	-5.7
2	81.5	82.0	1706	1719	1	1	0	0	0	0	5	7	1.23	-5.2
2	82.0	82.5	1719	1732	1	2	1	0	2	0	2	8	0.90	-7.8
2	82.5	83.0	1732	1745	4	3	2	0	8	0	14	31	3.43	0.0
2	83.0	83.5	1745	1758	0	1	2	0	5	2	4	14	2.60	2.0
2	83.5	84.0	1758	1771	3	2	3	0	7	4	10	29	2.71	2.0
2	84.0	84.5	1771	1784	3	2	2	0	9	1	10	27	3.04	0.9
2	84.5	85.0	1784	1798	1	0	1	0	2	1	4	9	2.55	2.2
2	85.0	85.5	1798	1811	6	0	2	0	6	2	9	25	2.77	-1.6
2	85.5	86.0	1811	1824	3	2	2	0	5	4	11	27	2.88	-2.7
2	86.0	86.5	1824	1838	3	5	0	0	3	2	7	20	2.77	2.9
2	86.5	87.0	1838	1851	4	1	0	0	1	0	5	11	2.66	2.9
2	87.0	87.5	1851	1864	0	0	1	0	2	2	3	8	2.66	2.5
2	87.5	88.0	1864	1878	2	1	2	0	5	0	7	17	2.93	2.3
2	88.0	88.5	1878	1891	5	2	1	0	0	0	7	15	2.99	-1.0
2	88.5	89.0	1891	1905	4	3	0	0	6	0	6	19	3.15	-0.7
2	89.0	89.5	1905	1919	1	0	0	0	1	1	5	8	2.82	-1.2
2	89.5	90.0	1919	1932	3	2	1	0	3	0	1	10	3.04	-1.8
2	90.0	90.5	1932	1946	2	1	0	0	0	0	2	5	2.55	-1.3
2	90.5	91.0	1946	1960	4	5	0	0	4	1	4	18	3.10	-0.6
2	91.0	91.5	1960	1973	5	3	0	0	3	4	5	20	3.59	0.4
2	91.5	92.0	1973	1987	0	1	1	0	3	1	6	12	2.71	-0.1
2	92.0	92.5	1987	2001	2	3	2	0	1	0	2	10	3.04	1.4
2	92.5	93.0	2001	2015	0	0	0	0	1	1	1	3	2.93	0.7
2	93.0	93.5	2015	2029	2	0	2	0	4	2	5	15	3.04	-2.8
2	93.5	94.0	2029	2043	1	0	0	0	1	1	4	7	2.93	-2.5
2	94.0	94.5	2043	2057	1	1	1	0	1	0	1	5	3.59	-1.7
2	94.5	95.0	2057	2071	3	0	2	0	4	2	5	16	2.88	-1.9
2	95.0	95.5	2071	2085	2	1	1	0	1	1	1	7	2.16	-2.2
2	95.5	96.0	2085	2099	2	1	0	0	3	3	1	10	3.87	0.1

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)	Magnetic Susceptib -ility (cgs x10^{-6})
2	96.0	96.5	2099	2113	1	0	0	0	0	0	2	3	2.60	-1.4
2	96.5	97.0	2113	2127	1	0	0	0	1	0	2	4	2.93	1.1
2	97.0	97.5	2127	2141	2	1	0	0	1	1	2	7	3.26	0.3
2	97.5	98.0	2141	2155	0	0	1	0	4	0	3	8	3.21	-1.5
2	98.0	98.5	2155	2170	0	0	0	1	1	1	6	9	3.37	0.2
2	98.5	99.0	2170	2184	0	0	0	0	2	2	3	7	2.44	-2.3
2	99.0	99.5	2184	2198	1	1	0	0	0	0	2	4	3.10	1.3
2	99.5	100.0	2198	2213	2	0	0	0	2	1	5	10	3.21	0.6
2	100.0	100.5	2213	2227	3	1	1	0	0	0	1	6	3.26	-1.4
2	100.5	101.0	2227	2241	0	1	0	0	2	0	1	4	3.04	-1.5
2	101.0	101.5	2241	2256	2	1	1	0	1	0	3	8	3.26	-3.2
2	101.5	102.0	2256	2270	1	0	0	0	1	0	4	6	2.82	-2.5
2	102.0	102.5	2270	2285	1	0	0	0	0	1	4	6	2.66	-3.8
2	102.5	103.0	2285	2299	0	0	0	0	0	0	5	5	2.49	-1.2
2	103.0	103.5	2299	2314	0	1	1	0	1	0	1	4	3.04	-2.3
2	103.5	104.0	2314	2328	1	0	0	0	1	1	5	8	3.37	-0.1
2	104.0	104.5	2328	2343	0	0	1	0	2	0	3	6	3.87	-0.8
2	104.5	105.0	2343	2357	1	0	0	1	1	0	4	7	3.54	-2.4
2	105.0	105.5	2357	2372	0	0	2	0	0	0	2	4	3.48	-2.6
2	105.5	106.0	2372	2387	7	1	0	0	2	2	3	15	3.59	-2.3
2	106.0	106.5	2387	2401	0	0	0	0	2	0	1	3	3.26	-2.4
2	106.5	107.0	2401	2416	0	1	0	0	1	0	1	3	2.66	-0.1
2	107.0	107.5	2416	2431	0	0	0	0	1	0	1	2	2.93	-2.0
2	107.5	108.0	2431	2446	1	1	1	0	0	0	2	5	2.93	1.6
2	108.0	108.5	2446	2460	0	0	0	0	3	0	4	7	2.88	-0.6
2	108.5	109.0	2460	2475	0	1	2	0	3	1	4	11	3.54	-0.8
2	109.0	109.5	2475	2490	0	0	1	0	1	0	1	3	3.26	-0.6
2	109.5	110.0	2490	2505	3	0	0	0	4	0	1	8	4.14	-1.1
2	110.0	110.5	2505	2520	2	0	1	0	3	0	6	12	3.04	-0.8
2	110.5	111.0	2520	2535	5	4	1	0	3	0	8	21	2.55	-0.7
2	111.0	111.5	2535	2550	2	2	3	0	4	0	9	20	3.21	-1.0
2	111.5	112.0	2550	2565	1	2	1	0	3	0	2	9	3.04	-1.2
2	112.0	112.5	2565	2580	1	2	2	0	3	0	2	10	3.37	-1.8
2	112.5	113.0	2580	2595	23	19	10	0	31	4	35	122	3.32	-0.8
2	113.0	113.5	2595	2610	2	1	0	0	4	2	3	12	3.26	-0.1

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)	Magnetic Susceptib-ility (cgs x10^{-6})
2	113.5	114.0	2610	2625	1	1	0	0	3	0	12	17	3.32	-2.0
2	114.0	114.5	2625	2640	3	2	0	0	1	0	6	12	3.54	1.0
2	114.5	115.0	2640	2655	2	3	2	0	9	1	20	37	4.20	1.3
2	115.0	115.5	2655	2670	0	0	1	0	4	2	7	14	2.66	-0.6
2	115.5	116.0	2670	2685	1	2	5	0	4	3	13	28	3.98	-0.8
2	116.0	116.5	2685	2701	6	0	3	0	8	6	16	39	3.32	-0.1
2	116.5	117.0	2701	2716	1	0	0	0	3	0	10	14	2.99	-1.2
2	117.0	117.5	2716	2731	6	1	1	0	0	0	7	15	2.66	-0.8
2	117.5	118.0	2731	2746	2	2	0	0	6	5	9	24	3.98	-1.9
2	118.0	118.5	2746	2762	2	5	0	0	8	1	23	39	3.87	-0.5
2	118.5	119.0	2762	2777	2	0	2	0	5	2	8	19	3.87	-0.4
2	119.0	119.5	2777	2792	7	5	2	0	12	3	21	50	4.14	-0.9
2	119.5	120.0	2792	2807	2	4	3	0	11	2	8	30	3.98	-1.9
2	120.0	120.5	2807	2823	2	1	0	0	4	0	4	11	3.87	0.7
2	120.5	121.0	2823	2838	0	5	0	0	1	0	2	8	3.76	-1.1
2	121.0	121.5	2838	2854	1	2	0	0	1	0	3	7	3.65	-1.0
2	121.5	122.0	2854	2869	2	0	0	0	4	2	4	12	4.20	-0.9
2	122.0	122.5	2869	2884	1	0	0	0	3	1	3	8	3.65	-0.2
2	122.5	123.0	2884	2900	2	0	3	0	5	1	11	22	3.59	-1.2
2	123.0	123.5	2900	2915	1	0	0	0	2	1	8	12	3.92	-0.7
2	123.5	124.0	2915	2931	1	1	0	0	2	0	1	5	4.03	-0.9
2	124.0	124.5	2931	2946	0	0	2	0	0	0	4	6	2.88	-0.2
2	124.5	125.0	2946	2962	1	0	2	0	5	2	7	17	4.47	0.1
2	125.0	125.5	2962	2977	0	0	0	0	1	0	3	4	4.36	-2.0
2	125.5	126.0	2977	2993	1	0	0	0	1	2	6	10	4.09	-1.8
2	126.0	126.5	2993	3008	1	1	0	0	3	0	3	8	3.87	-2.1
2	126.5	127.0	3008	3024	2	0	0	0	1	0	1	4	3.32	-2.4
2	127.0	127.5	3024	3039	3	0	1	0	3	0	3	10	3.59	-0.7
2	127.5	128.0	3039	3055	0	0	1	0	3	0	1	5	3.54	-1.2
2	128.0	128.5	3055	3071	0	2	1	0	1	1	2	7	4.47	-0.7
2	128.5	129.0	3071	3086	0	1	1	0	2	0	2	6	4.25	-1.2
2	129.0	129.5	3086	3102	4	0	0	0	0	1	10	15	3.26	-1.1
2	129.5	130.0	3102	3117	4	0	0	0	1	2	3	10	3.21	-0.4
2	130.0	130.5	3117	3133	1	0	1	0	4	1	5	12	3.98	-1.8
2	130.5	131.0	3133	3149	0	2	0	0	0	0	3	5	3.21	-1.0

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)	Magnetic Susceptib -ility (cgs $x10^{-6}$)
2	131.0	131.5	3149	3164	1	1	0	0	3	0	2	7	3.92	-2.3
2	131.5	132.0	3164	3180	2	5	0	0	5	2	3	17	3.87	-0.9
2	132.0	132.5	3180	3196	2	0	0	1	1	1	2	7	3.70	-1.2
2	132.5	133.0	3196	3212	1	1	0	0	4	0	4	10	4.03	-1.6
2	133.0	133.5	3212	3227	2	6	0	0	4	0	1	13	3.04	0.1
2	133.5	134.0	3227	3243	1	1	2	0	3	0	6	13	3.54	-2.1
2	134.0	134.5	3243	3259	4	1	0	0	3	0	7	15	3.70	-0.5
2	134.5	135.0	3259	3274	2	1	0	0	5	1	8	17	4.03	-0.7
2	135.0	135.5	3274	3290	2	1	2	1	3	2	8	19	3.54	0.2
2	135.5	136.0	3290	3306	2	1	2	0	2	0	2	9	3.32	-1.1
2	136.0	136.5	3306	3322	1	0	1	0	5	3	5	15	3.65	-0.9
2	136.5	137.0	3322	3338	1	1	2	0	3	2	10	19	3.65	-0.2
2	137.0	137.5	3338	3353	1	1	0	0	1	0	7	10	3.26	-0.5
2	137.5	138.0	3353	3369	1	1	1	0	12	1	13	29	3.54	1.1
2	138.0	138.5	3369	3385	3	2	0	0	2	2	4	13	3.32	1.5
2	138.5	139.0	3385	3401	1	1	0	0	3	0	3	8	3.32	0.0
2	139.0	139.5	3401	3417	0	0	2	0	2	1	7	12	2.66	1.0
2	139.5	140.0	3417	3433	3	1	1	0	4	1	5	15	2.93	-0.9
2	140.0	140.5	3433	3448	1	2	2	0	4	3	9	21	3.54	-1.4
2	140.5	141.0	3448	3464	2	1	0	0	4	1	5	13	3.37	-1.9
2	141.0	141.5	3464	3480	1	0	0	0	2	2	3	8	2.82	-0.7
2	141.5	142.0	3480	3496	0	2	3	0	2	1	10	18	3.15	-2.9
2	142.0	142.5	3496	3512	0	0	1	0	2	1	4	8	3.21	-0.7
2	142.5	143.0	3512	3528	2	1	0	0	5	3	8	19	4.09	-1.8
2	143.0	143.5	3528	3544	0	0	0	0	3	0	4	7	3.65	-1.8
2	143.5	144.0	3544	3560	1	0	1	0	6	1	8	17	4.25	-2.0
2	144.0	144.5	3560	3575	2	2	0	0	5	1	10	20	4.42	0.2
2	144.5	145.0	3575	3591	2	2	0	0	4	0	3	11	3.65	-1.6
2	145.0	145.5	3591	3607	0	1	2	0	1	1	5	10	3.98	-0.5
2	145.5	146.0	3607	3623	1	0	0	0	2	0	4	7	4.03	-1.0
2	146.0	146.5	3623	3639	1	1	1	0	2	0	3	8	3.98	0.8
2	146.5	147.0	3639	3655	1	1	0	0	1	1	7	11	3.54	-0.3
2	147.0	147.5	3655	3671	1	0	0	0	2	1	4	8	3.21	-0.4
2	147.5	148.0	3671	3687	4	2	0	0	6	0	8	20	3.65	-0.9
2	148.0	148.5	3687	3703	0	3	2	0	4	1	8	18	3.92	-0.5

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)	Magnetic Susceptib-ility (cgs x10^{-6})
2	148.5	149.0	3703	3719	3	6	1	0	2	0	5	17	3.76	-2.7
2	149.0	149.5	3719	3735	2	3	0	0	7	2	6	20	3.65	-0.6
2	149.5	150.0	3735	3751	2	0	1	0	3	1	7	14	3.32	0.3
2	150.0	150.5	3751	3767	7	4	3	1	8	1	8	32	4.47	-0.9
2	150.5	151.0	3767	3782	8	6	0	0	7	0	3	24	4.42	-1.6
2	151.0	151.5	3782	3798	4	0	0	0	2	1	4	11	3.43	-1.0
2	151.5	152.0	3798	3814	5	1	0	0	4	1	5	16	3.65	-1.0
2	152.0	152.5	3814	3830	13	4	3	0	12	1	10	43	3.54	-0.8
2	152.5	153.0	3830	3846	1	1	0	0	1	0	1	4	2.71	-0.6
2	153.0	153.5	3846	3862	2	5	0	0	7	0	9	23	3.92	-0.3
2	153.5	154.0	3862	3878	0	0	1	0	3	1	4	9	3.32	-1.0
2	154.0	154.5	3878	3894	3	2	0	0	4	2	4	15	2.99	-1.2
2	154.5	155.0	3894	3910	6	3	2	0	10	1	6	28	3.98	-1.5
2	155.0	155.5	3910	3926	4	4	4	0	9	2	6	29	4.14	0.4
2	155.5	156.0	3926	3942	4	1	0	0	5	0	2	12	3.59	-0.8
2	156.0	156.5	3942	3958	4	2	0	0	3	0	1	10	3.54	0.0
2	156.5	157.0	3958	3974	5	3	0	0	5	4	7	24	2.88	-2.8
2	157.0	157.5	3974	3990	16	9	5	1	17	4	20	72	3.70	-1.5
2	157.5	158.0	3990	4006	5	1	3	0	5	1	1	16	2.82	-0.7
2	158.0	158.5	4006	4021	2	2	3	0	8	0	10	25	3.98	-1.8
2	158.5	159.0	4021	4037	2	0	1	0	6	1	8	18	3.59	-0.8
2	159.0	159.5	4037	4053	2	0	3	0	5	1	5	16	3.54	-0.7
2	159.5	160.0	4053	4069	4	1	3	0	6	0	2	16	3.26	-1.1
2	160.0	160.5	4069	4085	44	2	3	0	3	0	13	65	3.37	-0.7
2	160.5	161.0	4085	4101	7	0	2	0	3	0	9	21	3.70	-0.9
2	161.0	161.5	4101	4117	6	0	1	0	6	1	13	27	2.55	0.8
2	161.5	162.0	4117	4133	4	3	0	0	6	1	9	23	3.26	-1.7
2	162.0	162.5	4133	4149	8	1	2	0	3	1	6	21	3.32	-1.1
2	162.5	163.0	4149	4165	2	0	1	0	4	0	9	16	2.60	0.0
2	163.0	163.5	4165	4181	2	1	2	0	9	0	10	24	3.32	-0.5
2	163.5	164.0	4181	4197	2	3	2	0	1	0	2	10	3.37	-2.7
2	164.0	164.5	4197	4213	7	1	1	0	6	1	4	20	1.72	-3.9
2	164.5	165.0	4213	4229	5	2	4	0	5	0	5	21	1.61	-1.7
3	165.0	165.5	4229	4245	2	1	0	0	2	0	3	8	1.56	-1.7
3	165.5	166.0	4245	4261	2	2	1	0	3	1	2	11	1.67	0.8

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)	Magnetic Susceptib-ility (cgs x10^{-6})
3	166.0	166.5	4261	4277	2	1	0	1	2	0	2	8	1.45	2.8
3	166.5	167.0	4277	4293	1	0	0	1	5	0	1	8	2.38	-1.7
3	167.0	167.5	4293	4309	1	1	0	0	5	1	6	14	2.22	-0.3
3	167.5	168.0	4309	4324	1	3	3	0	8	0	7	22	2.49	-0.8
3	168.0	168.5	4324	4340	5	5	2	0	9	0	8	29	2.05	-3.6
3	168.5	169.0	4340	4357	6	3	1	0	4	1	6	21	2.93	1.1
3	169.0	169.5	4357	4373	3	4	2	0	2	1	4	16	2.60	-2.8
3	169.5	170.0	4373	4389	4	4	1	0	4	0	6	19	2.82	-0.9
3	170.0	170.5	4389	4405	3	4	0	0	1	2	3	13	2.27	-0.3
3	170.5	171.0	4405	4421	1	1	3	0	4	2	6	17	3.43	-2.9
3	171.0	171.5	4421	4437	4	2	0	0	2	1	3	12	3.04	-1.0
3	171.5	172.0	4437	4453	0	4	1	0	1	0	4	10	2.60	-0.4
3	172.0	172.5	4453	4469	5	5	0	0	5	1	6	22	3.43	-0.5
3	172.5	173.0	4469	4485	3	1	5	0	5	2	8	24	3.70	-0.7
3	173.0	173.5	4485	4501	5	1	1	0	6	2	4	19	3.10	-1.7
3	173.5	174.0	4501	4517	1	1	0	0	2	0	0	4	2.99	1.8
3	174.0	174.5	4517	4533	8	2	1	0	2	0	3	16	3.32	-2.6
3	174.5	175.0	4533	4549	2	5	0	0	0	0	5	12	3.54	-0.9
3	175.0	175.5	4549	4566	6	7	0	0	5	2	5	25	4.36	-1.8
3	175.5	176.0	4566	4582	4	3	0	0	5	0	9	21	3.54	-0.8
3	176.0	176.5	4582	4598	9	8	2	0	12	1	8	40	4.09	-0.6
3	176.5	177.0	4598	4614	7	6	1	0	5	1	6	26	3.21	-2.7
3	177.0	177.5	4614	4630	3	4	2	0	8	2	6	25	4.80	-1.2
3	177.5	178.0	4630	4646	3	4	0	0	2	1	8	18	3.87	-0.9
3	178.0	178.5	4646	4663	2	3	1	0	2	0	6	14	4.42	-1.4
3	178.5	179.0	4663	4679	2	7	1	0	0	0	8	18	3.59	0.5
3	179.0	179.5	4679	4695	2	5	1	0	3	0	7	18	4.31	2.5
3	179.5	180.0	4695	4711	4	6	1	0	10	1	11	33	4.25	2.4
3	180.0	180.5	4711	4728	8	6	4	1	15	5	25	64	4.47	2.5
3	180.5	181.0	4728	4744	16	6	2	0	9	2	12	47	3.21	2.7
3	181.0	181.5	4744	4760	4	5	3	0	9	4	7	32	3.98	3.7
3	181.5	182.0	4760	4777	9	3	0	0	6	1	8	27	4.20	3.0
3	182.0	182.5	4777	4793	5	7	1	0	9	1	4	27	4.25	3.6
3	182.5	183.0	4793	4809	7	7	0	0	12	1	8	35	4.20	3.1
3	183.0	183.5	4809	4826	6	3	0	0	5	2	5	21	3.70	3.4

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)	Magnetic Susceptib-ility (cgs x10^{-6})
3	183.5	184.0	4826	4842	7	2	2	0	4	0	4	19	4.20	3.7
3	184.0	184.5	4842	4859	2	0	0	0	2	0	4	8	3.32	5.8
3	184.5	185.0	4859	4875	2	4	0	0	6	1	12	25	3.59	4.3
3	185.0	185.5	4875	4892	5	4	0	0	5	1	5	20	4.69	3.1
3	185.5	186.0	4892	4908	4	1	1	0	6	2	8	22	4.86	3.2
3	186.0	186.5	4908	4925	6	0	1	0	5	2	5	19	3.81	4.4
3	186.5	187.0	4925	4941	1	1	1	0	4	0	4	11	3.59	3.0
3	187.0	187.5	4941	4958	3	3	0	0	6	3	5	20	3.81	3.6
3	187.5	188.0	4958	4974	5	2	0	0	3	3	9	22	3.92	4.8
3	188.0	188.5	4974	4991	2	0	0	0	3	0	8	13	4.03	3.6
3	188.5	189.0	4991	5008	2	2	0	0	3	1	3	11	3.76	3.0
3	189.0	189.5	5008	5024	3	0	1	0	1	1	5	11	3.04	3.1
3	189.5	190.0	5024	5041	1	0	0	0	0	0	4	5	3.04	5.4
3	190.0	190.5	5041	5058	1	3	3	0	3	2	5	17	3.92	2.8
3	190.5	191.0	5058	5075	1	2	2	0	3	1	3	12	4.47	3.3
3	191.0	191.5	5075	5091	8	3	3	0	9	2	10	35	3.81	1.9
3	191.5	192.0	5091	5108	5	4	1	0	1	1	3	15	3.48	2.4
3	192.0	192.5	5108	5125	6	4	1	0	3	3	5	22	4.42	4.2
3	192.5	193.0	5125	5142	1	5	1	0	5	2	12	26	3.76	3.7
3	193.0	193.5	5142	5159	1	2	0	0	3	0	9	15	3.04	2.6
3	193.5	194.0	5159	5175	0	3	2	0	11	5	9	30	3.26	3.5
3	194.0	194.5	5175	5192	1	0	1	0	4	1	10	17	4.53	3.8
3	194.5	195.0	5192	5209	2	2	0	0	5	1	5	15	4.25	2.5
3	195.0	195.5	5209	5226	1	4	3	0	2	2	8	20	3.81	2.8
3	195.5	196.0	5226	5243	4	2	2	0	7	0	5	20	3.26	3.5
3	196.0	196.5	5243	5260	5	9	4	0	7	1	14	40	4.14	4.1
3	196.5	197.0	5260	5277	1	4	2	0	13	2	9	31	4.20	3.2
3	197.0	197.5	5277	5295	2	6	2	0	6	0	4	20	4.42	4.0
3	197.5	198.0	5295	5312	3	2	0	0	5	0	3	13	4.09	2.6
3	198.0	198.5	5312	5329	2	0	2	0	0	0	2	6	3.48	3.0
3	198.5	199.0	5329	5346	2	4	3	0	3	1	5	18	3.87	1.9
3	199.0	199.5	5346	5363	4	6	2	0	7	0	13	32	4.36	3.1
3	199.5	200.0	5363	5380	4	3	1	0	7	3	12	30	4.47	1.6
3	200.0	200.5	5380	5398	3	2	1	0	12	1	8	27	5.41	1.4
3	200.5	201.0	5398	5415	8	2	0	0	11	3	13	37	3.48	1.1

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)	Magnetic Susceptibility (cgs x10^{-6})
3	201.0	201.5	5415	5432	6	1	1	0	14	2	13	37	4.36	2.4
3	201.5	202.0	5432	5450	6	7	3	0	18	2	24	60	5.68	2.1
3	202.0	202.5	5450	5467	2	3	2	0	12	3	13	35	4.14	2.5
3	202.5	203.0	5467	5484	3	2	0	0	5	1	5	16	3.32	2.6
3	203.0	203.5	5484	5502	0	0	0	0	4	0	0	4	2.99	-0.2
3	203.5	204.0	5502	5519	1	1	3	0	3	1	3	12	4.42	2.9
3	204.0	204.5	5519	5537	3	1	2	0	4	2	2	14	4.25	3.3
3	204.5	205.0	5537	5554	3	0	2	0	4	3	6	18	4.09	3.4
3	205.0	205.5	5554	5572	6	1	0	0	4	5	5	21	4.91	3.6
3	205.5	206.0	5572	5589	4	1	0	0	2	1	3	11	3.81	3.7
3	206.0	206.5	5589	5607	10	3	4	0	10	0	12	39	5.08	3.4
3	206.5	207.0	5607	5625	8	3	5	0	18	4	8	46	4.47	3.3
3	207.0	207.5	5625	5642	1	0	1	0	6	1	7	16	3.98	3.6
3	207.5	208.0	5642	5660	5	0	1	0	5	0	1	12	3.81	3.0
3	208.0	208.5	5660	5678	2	0	2	0	6	1	6	17	3.21	2.8
3	208.5	209.0	5678	5695	2	5	1	0	8	1	10	27	4.58	2.3
3	209.0	209.5	5695	5713	4	3	0	0	1	3	4	15	4.47	1.8
3	209.5	210.0	5713	5731	5	0	1	0	7	3	7	23	3.98	0.3
3	210.0	210.5	5731	5749	5	2	1	0	11	1	10	30	4.20	0.5
3	210.5	211.0	5749	5767	2	6	1	1	6	0	2	18	4.64	0.9
3	211.0	211.5	5767	5784	3	6	0	0	6	2	3	20	4.09	-0.7
3	211.5	212.0	5784	5802	2	2	0	0	7	1	5	17	4.58	-0.6
3	212.0	212.5	5802	5820	5	1	2	0	6	1	1	16	4.47	-1.5
3	212.5	213.0	5820	5838	9	4	3	0	12	0	10	38	4.36	0.2
3	213.0	213.5	5838	5856	6	9	3	0	2	1	8	29	4.03	0.5
3	213.5	214.0	5856	5874	12	2	3	0	10	3	8	38	4.91	-0.4
3	214.0	214.5	5874	5892	15	5	4	0	3	5	5	37	4.36	0.2
3	214.5	215.0	5892	5910	4	9	1	0	7	2	3	26	4.42	-0.5
3	215.0	215.5	5910	5928	7	4	1	0	9	1	7	29	3.65	-1.8
3	215.5	216.0	5928	5946	4	4	3	0	17	3	13	44	4.75	-0.1
3	216.0	216.5	5946	5964	0	3	1	0	9	1	3	17	4.64	0.0
3	216.5	217.0	5964	5982	1	10	0	0	9	1	8	29	4.86	-0.5
3	217.0	217.5	5982	6000	0	1	1	0	7	2	9	20	4.36	-0.5
3	217.5	218.0	6000	6018	4	3	0	0	2	2	7	18	3.81	-0.2
3	218.0	218.5	6018	6036	1	1	1	0	6	2	12	23	4.25	-1.5

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)	Magnetic Susceptib -ility (cgs x10^{-6})
3	218.5	219.0	6036	6055	3	1	2	0	3	0	2	11	3.92	-0.3
3	219.0	219.5	6055	6073	3	2	1	0	6	1	12	25	4.47	-1.3
3	219.5	220.0	6073	6091	7	3	2	0	8	2	12	34	5.46	-0.4
3	220.0	220.5	6091	6109	3	3	0	0	3	3	3	15	3.65	0.0
3	220.5	221.0	6109	6128	3	4	0	0	6	2	8	23	4.53	-1.0
3	221.0	221.5	6128	6146	2	7	0	0	8	1	5	23	4.36	-0.6
3	221.5	222.0	6146	6164	4	4	1	0	8	2	13	32	5.02	0.1
3	222.0	222.5	6164	6182	3	0	1	0	6	1	9	20	4.97	-0.1
3	222.5	223.0	6182	6201	4	5	1	0	0	0	3	13	3.48	1.3
3	223.0	223.5	6201	6219	2	5	2	0	3	1	9	22	3.04	-0.7
3	223.5	224.0	6219	6237	5	7	3	0	20	1	14	50	4.97	1.2
3	224.0	224.5	6237	6256	24	4	5	0	12	0	8	53	4.31	2.6
3	224.5	225.0	6256	6274	8	9	4	0	12	3	14	50	4.75	1.5
3	225.0	225.5	6274	6293	8	3	1	0	9	2	10	33	3.70	1.5
3	225.5	226.0	6293	6311	1	8	2	0	7	2	12	32	5.57	1.3
3	226.0	226.5	6311	6330	0	0	0	0	8	0	5	13	4.14	0.6
3	226.5	227.0	6330	6348	1	4	0	0	7	0	7	19	3.59	0.9
3	227.0	227.5	6348	6367	1	3	2	0	9	1	6	22	4.80	1.2
3	227.5	228.0	6367	6385	2	2	1	0	3	1	5	14	4.14	-0.2
3	228.0	228.5	6385	6404	0	2	1	0	3	2	5	13	3.54	1.0
3	228.5	229.0	6404	6422	2	1	0	0	11	0	5	19	5.08	0.9
3	229.0	229.5	6422	6441	3	1	0	0	8	2	6	20	3.92	1.4
3	229.5	230.0	6441	6459	4	5	2	0	4	1	14	30	5.08	1.4
3	230.0	230.5	6459	6478	1	1	2	0	7	0	6	17	4.03	1.4
3	230.5	231.0	6478	6496	2	4	0	0	4	1	8	19	4.03	1.8
3	231.0	231.5	6496	6515	0	2	0	0	4	0	3	9	4.20	0.6
3	231.5	232.0	6515	6534	5	3	1	0	4	1	7	21	4.20	2.7
3	232.0	232.5	6534	6552	6	5	0	0	10	1	5	27	4.14	1.3
3	232.5	233.0	6552	6571	2	9	0	0	8	1	4	24	4.36	3.7
3	233.0	233.5	6571	6590	5	5	0	0	7	1	6	24	3.98	2.4
3	233.5	234.0	6590	6608	6	6	0	0	5	0	6	23	4.53	2.4
3	234.0	234.5	6608	6627	2	6	1	0	9	3	6	27	4.58	2.0
3	234.5	235.0	6627	6646	5	4	0	0	6	0	11	26	3.59	3.2
3	235.0	235.5	6646	6665	6	1	3	0	11	2	7	30	4.14	1.5
3	235.5	236.0	6665	6683	2	1	2	0	7	2	4	18	3.21	4.5

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)	Magnetic Susceptibility (cgs x10^{-6})
3	236.0	236.5	6683	6702	5	3	0	0	11	2	5	26	4.20	3.6
3	236.5	237.0	6702	6721	6	7	1	0	14	2	7	37	4.47	2.4
3	237.0	237.5	6721	6740	8	10	3	0	10	0	5	36	3.54	4.8
3	237.5	238.0	6740	6759	14	15	9	0	24	3	19	84	3.70	4.5
3	238.0	238.5	6759	6777	6	4	4	0	22	1	14	51	4.03	2.1
3	238.5	239.0	6777	6796	6	6	0	0	8	2	5	27	3.43	1.8
3	239.0	239.5	6796	6815	0	4	1	0	10	0	6	21	3.37	1.5
3	239.5	240.0	6815	6834	5	2	1	0	15	0	8	31	3.32	2.3
3	240.0	240.5	6834	6853	3	1	1	0	8	0	10	23	3.48	2.5
3	240.5	241.0	6853	6872	3	3	0	0	11	0	5	22	3.04	-0.8
3	241.0	241.5	6872	6891	7	0	1	0	6	0	7	21	3.10	0.9
3	241.5	242.0	6891	6910	2	4	0	0	4	1	2	13	2.49	0.3
4	242.0	242.5	6910	6929	1	0	1	0	3	0	1	6	1.90	-1.4
4	242.5	243.0	6929	6948	3	0	0	0	0	1	2	6	2.22	1.8
4	243.0	243.5	6948	6967	4	0	1	0	5	2	3	15	3.79	0.0
4	243.5	244.0	6967	6986	3	0	0	0	7	0	2	12	2.93	1.4
4	244.0	244.5	6986	7005	6	5	3	0	7	1	3	25	3.63	0.6
4	244.5	245.0	7005	7024	0	1	0	0	5	1	3	10	4.10	1.7
4	245.0	245.5	7024	7043	2	2	0	0	3	0	3	10	3.32	0.0
4	245.5	246.0	7043	7062	0	2	1	0	5	0	3	11	4.03	-0.7
4	246.0	246.5	7062	7081	3	6	0	0	9	1	2	21	4.10	0.3
4	246.5	247.0	7081	7100	1	3	0	0	4	1	1	10	4.42	0.2
4	247.0	247.5	7100	7119	3	1	1	0	13	2	3	23	4.10	1.1
4	247.5	248.0	7119	7138	2	6	1	0	2	1	9	21	3.32	2.1
4	248.0	248.5	7138	7157	4	2	0	0	4	1	1	12	3.71	0.4
4	248.5	249.0	7157	7176	1	0	0	0	4	0	5	10	3.87	1.2
4	249.0	249.5	7176	7195	6	5	1	0	11	1	10	34	3.79	1.3
4	249.5	250.0	7195	7215	2	5	0	0	9	0	6	22	3.79	2.8
4	250.0	250.5	7215	7234	3	3	0	0	5	2	3	16	4.58	3.1
4	250.5	251.0	7234	7253	4	5	0	0	10	2	6	27	4.89	1.0
4	251.0	251.5	7253	7272	6	5	1	0	9	0	4	25	4.58	0.1
4	251.5	252.0	7272	7291	3	0	0	0	3	0	1	7	3.55	-0.4
4	252.0	252.5	7291	7311	0	2	1	0	2	0	0	5	4.03	0.2
4	252.5	253.0	7311	7330	3	4	0	0	5	0	0	12	3.87	0.3
4	253.0	253.5	7330	7349	4	2	1	0	8	0	1	16	4.34	1.6

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)	Magnetic Susceptibility (cgs x10^{-6})
4	253.5	254.0	7349	7368	2	2	0	0	4	0	3	11	3.40	-0.5
4	254.0	254.5	7368	7388	3	1	0	0	5	0	2	11	4.81	1.0
4	254.5	255.0	7388	7407	2	1	0	0	4	1	4	12	3.95	1.5
4	255.0	255.5	7407	7426	3	4	0	0	6	0	2	15	4.58	1.2
4	255.5	256.0	7426	7445	3	6	0	0	4	3	2	18	5.13	1.4
4	256.0	256.5	7445	7465	1	1	0	0	1	0	3	6	4.65	1.1
4	256.5	257.0	7465	7484	3	4	0	0	4	1	3	15	4.34	2.9
4	257.0	257.5	7484	7503	1	0	0	0	3	0	3	7	3.63	2.1
4	257.5	258.0	7503	7523	2	2	0	0	3	2	1	10	4.34	0.3
4	258.0	258.5	7523	7542	1	0	0	0	7	0	1	9	4.58	0.4
4	258.5	259.0	7542	7561	2	1	0	0	10	2	14	29	4.89	-0.6
4	259.0	259.5	7561	7581	2	2	1	0	9	1	7	22	4.58	-0.5
4	259.5	260.0	7581	7600	0	2	2	0	6	2	4	16	3.79	1.2
4	260.0	260.5	7600	7620	2	1	0	0	1	0	0	4	3.87	1.5
4	260.5	261.0	7620	7639	9	9	3	0	9	0	12	42	4.89	1.5
4	261.0	261.5	7639	7658	4	1	0	0	5	0	4	14	3.95	-0.8
4	261.5	262.0	7658	7678	4	4	2	0	10	2	5	27	4.03	-0.8
4	262.0	262.5	7678	7697	1	1	0	0	9	0	2	13	4.18	1.5
4	262.5	263.0	7697	7717	4	4	0	0	7	0	7	22	3.87	1.1
4	263.0	263.5	7717	7736	9	3	0	0	5	0	3	20	3.87	0.2
4	263.5	264.0	7736	7756	4	2	0	0	6	3	8	23	4.18	-0.6
4	264.0	264.5	7756	7775	4	1	0	0	4	0	3	12	3.79	-1.0
4	264.5	265.0	7775	7795	2	0	0	0	5	1	1	9	3.55	-0.8
4	265.0	265.5	7795	7814	2	7	1	0	13	3	7	33	4.34	0.0
4	265.5	266.0	7814	7834	0	1	0	0	6	0	1	8	3.16	-1.9
4	266.0	266.5	7834	7853	5	1	2	0	10	2	8	28	4.81	-2.4
4	266.5	267.0	7853	7873	4	8	3	0	13	1	9	38	4.42	-0.8
4	267.0	267.5	7873	7892	5	2	1	0	7	0	5	20	3.63	-0.5
4	267.5	268.0	7892	7912	2	1	0	0	4	0	6	13	4.26	0.2
4	268.0	268.5	7912	7931	2	4	3	0	11	1	6	27	3.79	0.3
4	268.5	269.0	7931	7951	7	1	2	0	10	3	11	34	4.03	-0.7
4	269.0	269.5	7951	7970	0	0	0	0	3	0	1	4	3.24	-0.8
4	269.5	270.0	7970	7990	2	7	2	0	11	0	4	26	4.97	-0.4
4	270.0	270.5	7990	8010	4	7	2	0	5	1	5	24	3.48	-0.4
4	270.5	271.0	8010	8029	12	13	2	0	10	3	6	46	4.42	0.0

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)	Magnetic Susceptibility (cgs $x10^{-6}$)
4	271.0	271.5	8029	8049	3	4	0	0	3	0	3	13	4.34	-0.5
4	271.5	272.0	8049	8068	3	2	4	0	3	1	4	17	4.65	-1.0
4	272.0	272.5	8068	8088	2	1	0	0	0	3	1	7	4.65	-0.4
4	272.5	273.0	8088	8108	1	1	2	0	1	2	2	9	3.40	-0.5
4	273.0	273.5	8108	8127	4	5	0	0	3	0	7	19	4.81	-0.3
4	273.5	274.0	8127	8147	7	4	1	0	7	0	0	19	4.10	-0.2
4	274.0	274.5	8147	8167	4	9	3	0	7	2	5	30	4.34	-0.4
4	274.5	275.0	8167	8186	7	2	0	0	3	1	2	15	4.10	-0.2
4	275.0	275.5	8186	8206	9	10	1	0	8	1	9	38	5.13	-0.2
4	275.5	276.0	8206	8226	8	1	0	0	8	0	2	19	4.50	-0.3
4	276.0	276.5	8226	8245	5	5	0	0	10	1	8	29	4.73	-0.3
4	276.5	277.0	8245	8265	4	2	0	1	5	0	2	14	4.18	-0.1
4	277.0	277.5	8265	8285	8	3	0	0	14	3	4	32	4.34	-0.2
4	277.5	278.0	8285	8304	5	6	0	0	7	1	3	22	4.42	-0.5
4	278.0	278.5	8304	8324	14	10	6	1	12	2	9	54	3.87	0.0
4	278.5	279.0	8324	8344	9	10	3	0	13	3	14	52	5.20	-0.3
4	279.0	279.5	8344	8363	18	23	4	0	21	10	18	94	5.44	-0.3
4	279.5	280.0	8363	8383	9	15	2	0	10	3	5	44	3.63	-0.3
4	280.0	280.5	8383	8403	15	17	1	0	14	2	10	59	5.05	-0.2
4	280.5	281.0	8403	8423	9	6	0	0	8	1	6	30	4.42	-0.3
4	281.0	281.5	8423	8442	7	0	3	0	6	0	9	25	4.50	-0.4
4	281.5	282.0	8442	8462	11	6	5	0	12	1	6	41	5.28	-0.2
4	282.0	282.5	8462	8482	5	15	0	0	14	3	20	57	5.05	-0.4
4	282.5	283.0	8482	8502	11	9	3	0	10	2	8	43	6.07	-0.2
4	283.0	283.5	8502	8521	6	8	2	0	13	5	3	37	4.58	-0.2
4	283.5	284.0	8521	8541	12	15	6	0	16	5	22	76	4.73	-0.6
4	284.0	284.5	8541	8561	8	16	7	0	16	5	11	63	4.34	-0.3
4	284.5	285.0	8561	8581	15	13	6	0	25	1	9	69	4.97	-0.6
4	285.0	285.5	8581	8601	6	8	4	0	19	0	8	45	5.99	-0.3
4	285.5	286.0	8601	8620	4	4	1	0	10	2	9	30	4.26	-0.5
4	286.0	286.5	8620	8640	6	5	0	0	11	0	2	24	4.97	-0.2
4	286.5	287.0	8640	8660	3	1	2	0	9	0	9	24	4.26	-0.2
4	287.0	287.5	8660	8680	19	10	0	0	34	6	25	94	5.13	0.0
4	287.5	288.0	8680	8700	9	5	1	0	8	1	9	33	4.81	0.1
4	288.0	288.5	8700	8719	11	8	1	0	9	1	7	37	4.26	-0.1

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)	Magnetic Susceptib-ility (cgs x10^{-6})
4	288.5	289.0	8719	8739	11	9	3	0	13	6	12	54	4.26	0.3
4	289.0	289.5	8739	8759	6	10	3	0	7	2	8	36	4.65	0.1
4	289.5	290.0	8759	8779	19	16	2	0	11	0	6	54	5.68	-0.1
4	290.0	290.5	8779	8799	4	5	3	0	4	0	3	19	5.28	-0.2
4	290.5	291.0	8799	8819	3	2	2	0	4	1	3	15	4.50	-0.2
4	291.0	291.5	8819	8838	4	2	2	0	0	0	3	11	4.81	-1.3
4	291.5	292.0	8838	8858	10	8	2	0	16	3	10	49	6.85	-0.1
4	292.0	292.5	8858	8878	8	4	1	0	6	1	3	23	4.97	-0.1
4	292.5	293.0	8878	8898	0	0	0	0	4	1	3	8	5.20	0.9
4	293.0	293.5	8898	8918	4	1	0	0	1	0	1	7	3.87	-0.5
4	293.5	294.0	8918	8938	2	3	0	0	2	1	0	8	3.55	-0.1
4	294.0	294.5	8938	8958	5	7	1	0	6	1	5	25	4.97	0.1
4	294.5	295.0	8958	8977	11	3	2	0	10	0	2	28	4.18	-0.4
4	295.0	295.5	8977	8997	8	10	4	0	6	2	6	36	5.75	-0.1
4	295.5	296.0	8997	9017	3	4	0	0	4	0	4	15	4.73	-0.1
4	296.0	296.5	9017	9037	18	12	5	0	4	1	6	46	4.50	-0.1
4	296.5	297.0	9037	9057	14	22	4	0	24	0	16	80	6.46	0.0
4	297.0	297.5	9057	9077	13	9	7	0	17	3	11	60	5.20	0.2
4	297.5	298.0	9077	9097	4	5	0	0	9	0	1	19	4.42	-0.5
4	298.0	298.5	9097	9116	5	2	0	0	5	2	4	18	5.28	0.1
4	298.5	299.0	9116	9136	6	7	2	0	4	0	7	26	5.44	0.1
4	299.0	299.5	9136	9156	11	6	4	0	10	1	8	40	4.89	-0.3
4	299.5	300.0	9156	9176	2	15	1	0	8	2	11	39	5.20	-1.4
4	300.0	300.5	9176	9196	5	4	1	0	9	0	5	24	5.91	-0.2
4	300.5	301.0	9196	9216	7	5	3	0	5	1	2	23	4.50	0.2
4	301.0	301.5	9216	9236	6	3	0	0	8	0	5	22	4.42	-0.1
4	301.5	302.0	9236	9256	1	4	0	0	5	0	2	12	4.50	0.8
4	302.0	302.5	9256	9276	3	12	0	0	11	0	3	29	5.75	0.3
4	302.5	303.0	9276	9296	9	13	2	0	13	0	9	46	6.15	0.0
4	303.0	303.5	9296	9316	1	3	0	0	5	1	3	13	4.50	-0.6
4	303.5	304.0	9316	9336	3	0	0	0	7	2	5	17	4.73	0.1
4	304.0	304.5	9336	9356	2	1	2	0	6	0	6	17	4.34	0.4
4	304.5	305.0	9356	9376	7	5	3	0	18	0	10	43	4.65	0.1
4	305.0	305.5	9376	9396	4	4	1	0	7	0	1	17	4.73	0.1
4	305.5	306.0	9396	9416	6	7	3	0	13	0	4	33	4.97	0.9

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)	Magnetic Susceptib-ility (cgs x10^{-6})
4	306.0	306.5	9416	9436	5	14	1	0	12	0	4	36	4.50	0.5
4	306.5	307.0	9436	9456	4	1	1	0	6	0	8	20	4.65	0.1
4	307.0	307.5	9456	9476	4	1	0	0	2	0	2	9	4.03	-0.2
4	307.5	308.0	9476	9496	1	3	0	0	10	0	3	17	4.81	-0.2
4	308.0	308.5	9496	9516	3	7	2	0	10	0	7	29	5.28	0.3
4	308.5	309.0	9516	9536	10	8	1	0	11	0	10	40	4.81	0.2
4	309.0	309.5	9536	9556	8	24	4	0	35	0	25	96	5.52	0.7
4	309.5	310.0	9556	9576	15	10	2	0	16	0	20	63	4.81	0.4
4	310.0	310.5	9576	9596	8	11	2	0	15	0	13	49	4.50	0.4
4	310.5	311.0	9596	9616	6	9	1	0	11	1	10	38	4.42	-0.2
4	311.0	311.5	9616	9636	4	5	1	0	4	0	5	19	4.10	0.0
4	311.5	312.0	9636	9656	10	7	0	0	8	1	6	32	3.40	-0.4
4	312.0	312.5	9656	9676	3	5	1	0	15	1	12	37	5.44	0.1
4	312.5	313.0	9676	9696	6	5	3	0	11	2	10	37	3.79	-0.4
4	313.0	313.5	9696	9716	2	6	2	0	10	0	4	24	4.10	-0.6
4	313.5	314.0	9716	9736	7	5	2	0	8	0	4	26	4.03	-0.1
4	314.0	314.5	9736	9756	1	1	2	0	6	0	8	18	3.95	-0.7
4	314.5	315.0	9756	9776	6	4	0	0	12	0	4	26	3.87	-0.6
4	315.0	315.5	9776	9796	4	6	0	0	13	1	13	37	4.10	-0.2
4	315.5	316.0	9796	9816	9	3	0	0	18	0	2	32	4.34	0.5
4	316.0	316.5	9816	9836	4	5	0	0	5	0	10	24	4.50	0.6
4	316.5	317.0	9836	9856	6	9	0	0	15	0	7	37	4.58	0.2
4	317.0	317.5	9856	9876	6	1	0	0	3	1	6	17	4.10	-0.2
4	317.5	318.0	9876	9896	1	9	2	0	11	0	5	28	3.87	-0.2
4	318.0	318.5	9896	9916	3	15	2	0	33	1	32	86	4.03	1.3
4	318.5	319.0	9916	9936	4	6	2	0	16	0	19	47	3.00	-0.8
4	319.0	319.5	9936	9956	10	6	1	0	9	2	9	37	4.42	-0.3
4	319.5	320.0	9956	9976	5	8	1	0	16	1	14	45	4.50	0.4
4	320.0	320.5	9976	9996	1	3	0	0	10	0	4	18	3.55	0.1
4	320.5	321.0	9996	10016	2	3	2	0	4	0	4	15	3.55	-1.3
4	321.0	321.5	10016	10036	4	2	0	0	5	0	4	15	4.34	-0.1
4	321.5	322.0	10036	10056	2	10	0	0	11	0	10	33	4.26	1.6
4	322.0	322.5	10056	10076	1	3	0	0	7	0	6	17	3.40	-0.3
4	322.5	323.0	10076	10096	5	10	0	0	9	0	6	30	3.87	0.2
4	323.0	323.5	10096	10116	2	1	3	0	8	0	3	17	4.03	2.2

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)	Magnetic Susceptibility (cgs x10^{-6})
4	323.5	324.0	10116	10136	9	3	1	0	2	0	2	17	3.71	2.6
4	324.0	324.5	10136	10156	7	9	7	0	25	0	24	72	4.34	1.4
4	324.5	325.0	10156	10176	12	22	5	0	33	0	13	85	5.20	0.7
4	325.0	325.5	10176	10196	6	10	2	0	16	0	10	44	3.87	0.2
4	325.5	326.0	10196	10216	6	2	0	0	5	0	3	16	3.63	0.6
4	326.0	326.5	10216	10236	5	6	1	0	8	0	5	25	4.58	0.6
4	326.5	327.0	10236	10256	2	2	2	0	6	0	3	15	3.71	-1.3
5	327.0	327.5	10256	10276	3	6	1	0	7	0	4	21	3.16	-0.3
5	327.5	328.0	10276	10296	4	9	1	0	15	2	11	42	4.18	0.2
5	328.0	328.5	10296	10316	3	7	0	0	9	0	11	30	4.42	0.5
5	328.5	329.0	10316	10336	4	5	0	0	5	0	5	19	3.87	0.0
5	329.0	329.5	10336	10356	2	7	0	0	3	0	4	16	2.93	-1.1
5	329.5	330.0	10356	10376	3	11	1	0	9	1	3	28	5.44	0.5
5	330.0	330.5	10376	10396	1	2	0	0	4	0	8	15	3.63	-0.8
5	330.5	331.0	10396	10416	4	9	0	0	9	2	7	31	6.15	0.5
5	331.0	331.5	10416	10436	3	4	3	0	7	0	7	24	4.50	0.3
5	331.5	332.0	10436	10456	1	12	0	0	15	0	7	35	3.95	0.3
5	332.0	332.5	10456	10476	4	3	1	0	7	0	7	22	4.34	0.5
5	332.5	333.0	10476	10496	3	6	2	0	16	1	8	36	4.81	0.1
5	333.0	333.5	10496	10516	4	11	1	0	3	1	7	27	4.89	0.6
5	333.5	334.0	10516	10536	2	12	2	0	11	1	13	41	3.95	-0.3
5	334.0	334.5	10536	10556	5	14	1	0	10	0	7	37	3.95	-0.3
5	334.5	335.0	10556	10576	4	4	0	0	6	0	3	17	5.05	0.1
5	335.0	335.5	10576	10596	2	5	1	0	5	0	0	13	5.05	0.3
5	335.5	336.0	10596	10616	3	10	0	0	10	1	6	30	5.44	0.2
5	336.0	336.5	10616	10636	4	17	2	0	9	0	4	36	6.07	0.4
5	336.5	337.0	10636	10656	3	11	2	0	7	0	3	26	4.81	0.5
5	337.0	337.5	10656	10676	1	13	0	0	5	0	4	23	5.05	0.3
5	337.5	338.0	10676	10696	0	5	0	0	7	0	7	19	5.52	0.1
5	338.0	338.5	10696	10716	7	5	0	0	11	0	2	25	5.05	0.1
5	338.5	339.0	10716	10736	10	3	0	0	4	0	6	23	5.05	0.3
5	339.0	339.5	10736	10756	2	10	1	0	7	0	6	26	5.68	1.1
5	339.5	340.0	10756	10776	5	8	1	0	8	1	9	32	4.81	1.0
5	340.0	340.5	10776	10796	2	4	0	0	12	0	2	20	5.05	1.2
5	340.5	341.0	10796	10816	4	1	2	0	10	1	2	20	4.97	0.9

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)	Magnetic Susceptib-ility (cgs x10^{-6})
5	341.0	341.5	10816	10836	5	8	2	0	15	1	18	49	5.91	1.5
5	341.5	342.0	10836	10856	6	7	0	0	14	0	14	41	5.75	1.5
5	342.0	342.5	10856	10876	8	8	0	0	6	1	3	26	4.81	2.5
5	342.5	343.0	10876	10896	1	1	0	0	8	0	3	13	5.44	1.8
5	343.0	343.5	10896	10916	2	3	0	0	13	0	3	21	4.81	3.0
5	343.5	344.0	10916	10936	2	4	0	0	10	1	3	20	4.65	2.7
5	344.0	344.5	10936	10956	8	20	1	0	20	0	13	62	5.60	2.7
5	344.5	345.0	10956	10976	7	18	1	0	19	0	13	58	5.36	2.2
5	345.0	345.5	10976	10996	3	8	0	0	13	0	6	30	4.50	2.1
5	345.5	346.0	10996	11016	0	2	1	0	3	0	0	6	4.65	2.8
5	346.0	346.5	11016	11036	3	8	3	0	6	0	5	25	5.05	3.8
5	346.5	347.0	11036	11056	8	8	0	0	7	1	3	27	5.36	3.7
5	347.0	347.5	11056	11076	5	4	1	0	5	0	2	17	5.13	2.4
5	347.5	348.0	11076	11096	7	10	1	0	4	0	2	24	5.05	3.2
5	348.0	348.5	11096	11116	2	5	0	0	1	0	8	16	5.60	2.7
5	348.5	349.0	11116	11136	0	4	0	0	4	0	1	9	4.50	3.3
5	349.0	349.5	11136	11156	2	1	0	0	5	0	3	11	4.73	3.1
5	349.5	350.0	11156	11176	7	6	1	0	12	0	8	34	5.68	3.3
5	350.0	350.5	11176	11196	5	10	2	0	7	0	7	31	4.81	3.1
5	350.5	351.0	11196	11216	3	5	0	0	5	0	3	16	4.81	2.6
5	351.0	351.5	11216	11236	7	26	7	0	40	2	12	94	5.13	3.2
5	351.5	352.0	11236	11256	15	7	0	0	14	1	7	44	4.58	2.8
5	352.0	352.5	11256	11276	13	16	0	0	18	1	5	53	4.81	3.5
5	352.5	353.0	11276	11296	2	8	1	0	6	0	4	21	4.97	3.2
5	353.0	353.5	11296	11316	3	10	5	0	10	0	6	34	5.28	3.3
5	353.5	354.0	11316	11336	4	5	2	0	6	1	3	21	4.65	3.2
5	354.0	354.5	11336	11356	1	4	1	0	1	0	1	8	4.81	4.8
5	354.5	355.0	11356	11376	2	6	0	0	4	0	2	14	4.81	4.3
5	355.0	355.5	11376	11396	4	5	1	0	11	0	3	24	4.89	6.9
5	355.5	356.0	11396	11416	8	14	0	0	15	0	6	43	4.65	6.4
5	356.0	356.5	11416	11436	7	10	1	0	3	0	1	22	5.60	8.9
5	356.5	357.0	11436	11456	4	2	3	0	10	0	6	25	5.75	7.8
5	357.0	357.5	11456	11476	7	6	0	0	6	0	4	23	4.97	5.2
5	357.5	358.0	11476	11496	4	2	1	0	7	0	6	20	4.97	6.0
5	358.0	358.5	11496	11516	1	3	0	0	7	0	9	20	4.65	7.5

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)	Magnetic Susceptibility (cgs x10^{-6})
5	358.5	359.0	11516	11536	0	1	0	0	2	0	8	11	5.68	6.6
5	359.0	359.5	11536	11556	8	4	1	0	7	1	5	26	4.50	6.6
5	359.5	360.0	11556	11576	5	8	2	0	9	0	4	28	4.81	5.6
5	360.0	360.5	11576	11596	13	18	6	0	16	0	5	58	5.91	7.4
5	360.5	361.0	11596	11616	7	17	0	0	23	0	6	53	5.44	9.4
5	361.0	361.5	11616	11636	16	18	0	0	24	0	10	68	4.65	9.1
5	361.5	362.0	11636	11656	3	8	1	0	8	0	6	26	4.58	10.0
5	362.0	362.5	11656	11676	1	6	0	0	7	0	3	17	5.44	8.4
5	362.5	363.0	11676	11696	5	11	1	0	14	1	6	38	5.28	8.1
5	363.0	363.5	11696	11716	10	16	8	0	26	0	5	65	4.42	9.7
5	363.5	364.0	11716	11736	7	17	3	0	22	0	7	56	5.68	10.0
5	364.0	364.5	11736	11756	14	18	12	0	20	1	7	72	5.28	11.1
5	364.5	365.0	11756	11776	3	8	2	0	11	0	10	34	4.81	12.7
5	365.0	365.5	11776	11796	2	2	3	0	4	1	6	18	4.58	12.7
5	365.5	366.0	11796	11816	3	6	4	0	13	0	3	29	4.89	19.3
5	366.0	366.5	11816	11836	13	8	1	0	9	1	5	37	3.79	15.8
5	366.5	367.0	11836	11856	8	4	2	0	5	0	1	20	5.05	11.6
5	367.0	367.5	11856	11876	0	1	0	0	2	0	1	4	3.79	15.8
5	367.5	368.0	11876	11896	0	0	0	0	0	0	0	0	4.18	19.3
5	368.0	368.5	11896	11916	1	0	0	0	1	0	0	2	4.50	29.7
5	368.5	369.0	11916	11936	0	1	0	0	2	0	1	4	4.73	44.4
5	369.0	369.5	11936	11956	2	2	0	0	3	0	2	9	4.65	36.1
5	369.5	370.0	11956	11976	1	3	1	0	1	0	0	6	5.20	54.1
5	370.0	370.5	11976	11996	1	1	0	0	0	1	0	3	4.50	63.0
5	370.5	371.0	11996	12016	0	1	0	0	0	0	0	1	4.58	73.1
5	371.0	371.5	12016	12036	0	1	0	0	1	0	1	3	4.18	68.8
5	371.5	372.0	12036	12056	1	2	0	0	0	0	0	3	4.42	76.2
5	372.0	372.5	12056	12076	0	0	0	0	0	0	0	0	3.63	70.0
5	372.5	373.0	12076	12096	0	0	0	0	0	0	0	0	3.87	74.2
5	373.0	373.5	12096	12116	0	0	0	0	1	0	0	1	4.97	83.9
5	373.5	374.0	12116	12136	1	0	1	0	0	0	0	2	4.58	83.3
5	374.0	374.5	12136	12156	0	1	1	0	1	0	0	3	4.73	80.4
5	374.5	375.0	12156	12176	3	0	0	0	0	0	0	3	5.91	83.9
5	375.0	375.5	12176	12196	0	1	0	0	0	0	0	1	4.97	71.0
5	375.5	376.0	12196	12216	0	1	1	0	0	0	0	2	3.95	61.4

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)	Magnetic Susceptib-ility (cgs $x10^{-6}$)
5	376.0	376.5	12216	12236	2	5	0	0	2	0	0	9	4.65	55.4
5	376.5	377.0	12236	12256	5	8	3	0	8	0	1	25	5.28	43.2
5	377.0	377.5	12256	12276	1	1	0	0	1	0	0	3	4.03	26.8
5	377.5	378.0	12276	12296	2	0	0	0	0	0	0	2	4.26	24.3
5	378.0	378.5	12296	12316	1	4	0	0	0	0	0	5	4.50	26.8
5	378.5	379.0	12316	12336	0	3	1	0	1	0	0	5	4.50	39.8
5	379.0	379.5	12336	12356	0	0	1	0	0	0	1	2	4.03	56.8
5	379.5	380.0	12356	12376	0	1	0	0	0	0	0	1	3.87	70.1
5	380.0	380.5	12376	12396	0	0	0	0	1	0	0	1	5.44	77.9
5	380.5	381.0	12396	12416	0	0	0	0	0	0	0	0	4.50	165.1
5	381.0	382.0			0	0	0	0	0	0	0	0	8.11	196.8
5	382.0	383.0			0	0	0	0	0	0	0	0	8.90	153.6
5	383.0	384.0			0	0	0	0	0	0	0	0	9.84	820.8
5	384.0	385.0			0	0	0	0	0	0	0	0	10.15	1007.8
5	385.0	386.0			0	0	0	0	0	0	0	0	8.82	710.6
5	386.0	387.0			0	0	0	0	0	0	0	0	9.21	221.0
5	387.0	388.0			0	0	0	0	0	0	0	0	9.13	220.8
5	388.0	389.0			0	0	0	0	0	0	0	0	9.53	270.3
5	389.0	390.0			0	0	0	0	0	0	0	0	7.72	196.3
5	390.0	391.0			0	0	0	0	0	0	0	0	6.30	26.2
5	391.0	392.0			0	0	0	0	0	0	0	0	8.74	23.1
5	392.0	393.0			0	0	0	0	0	0	0	0	8.58	69.1
5	393.0	394.0			0	0	0	0	0	0	0	0	7.64	148.4
5	394.0	395.0			0	0	0	0	0	0	0	0	7.72	127.6
5	395.0	396.0			0	0	0	0	0	0	0	0	7.48	110.5
5	396.0	397.0			0	0	0	0	0	0	0	0	7.48	77.4
5	397.0	398.0			0	0	0	0	0	0	0	0	6.30	79.0
5	398.0	399.0			0	0	0	0	0	0	0	0	8.98	88.0
5	399.0	400.0			0	0	0	0	0	0	0	0	4.97	68.7
5	400.0	401.0			0	0	0	0	0	0	0	0	6.62	66.3
5	401.0	402.0			0	0	0	0	0	0	0	0	6.38	64.1
5	402.0	403.0			0	0	0	0	0	0	0	0	5.52	97.0
5	403.0	404.0			0	0	0	0	0	0	0	0	6.38	67.4
5	404.0	405.0			0	0	0	0	0	0	0	0	6.38	53.6
5	405.0	406.0			0	0	0	0	0	0	0	0	5.91	60.3

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)	Magnetic Susceptib -ility (cgs x10^{-6})
5	406.0	407.0			0	0	0	0	0	0	0	0	7.17	62.0
5	407.0	408.0			0	0	0	0	0	0	0	0	6.23	67.8
5	408.0	409.0			0	0	0	0	0	0	0	0	6.85	60.1
5	409.0	410.0			0	0	0	0	0	0	0	0	7.09	86.5
5	410.0	411.0			0	0	0	0	0	0	0	0	6.62	70.9
5	411.0	412.0			0	0	0	0	0	0	0	0	6.15	79.3
5	412.0	413.0			0	0	0	0	0	0	0	0	6.46	67.3
5	413.0	414.0			0	0	0	0	0	0	0	0	7.80	96.6
5	414.0	415.0			0	0	0	0	0	0	0	0	5.91	70.5

Appendix B2 - Mud Lake Surface-Core Charcoal Data

Charcoal counts for total charcoal and charcoal morphotypes at each sediment interval of the Mud Lake surface-core (Mud Short 2).

The interval depth, calendar yr before present, and volume are listed for each sediment interval along with the charcoal piece counts.

Cal yr BP refers to calendar years before present, present at 1950 AD. See Figure 3.4 for a description of the charcoal morphotypes.

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)
Surface	0.0	0.5	-58	-55	0	0	0	0	0	0	0	0	2.00
Surface	0.5	1.0	-55	-52	0	0	0	0	0	0	0	0	2.00
Surface	1.0	1.5	-52	-49	0	0	0	0	0	0	0	0	2.00
Surface	1.5	2.0	-49	-46	0	0	0	0	0	0	0	0	2.00
Surface	2.0	2.5	-46	-43	0	0	0	0	0	0	0	0	2.00
Surface	2.5	3.0	-43	-40	0	0	2	0	0	0	0	2	2.00
Surface	3.0	3.5	-40	-36	0	0	0	0	0	0	1	1	2.00
Surface	3.5	4.0	-36	-33	0	1	0	0	2	0	0	3	2.00
Surface	4.0	4.5	-33	-29	0	0	0	0	0	0	0	0	2.00
Surface	4.5	5.0	-29	-25	0	0	0	0	0	0	0	0	2.00
Surface	5.0	5.5	-25	-20	1	0	0	0	0	0	0	1	2.00
Surface	5.5	6.0	-20	-16	11	1	0	0	1	0	2	15	2.00
Surface	6.0	6.5	-16	-11	5	1	1	0	1	0	0	8	2.00
Surface	6.5	7.0	-11	-6	4	1	0	0	0	0	1	6	2.00
Surface	7.0	7.5	-6	-1	7	4	0	0	1	1	1	14	2.00
Surface	7.5	8.0	-1	5	9	1	0	0	1	0	2	13	2.00
Surface	8.0	8.5	5	10	2	0	1	0	2	0	0	5	2.00
Surface	8.5	9.0	10	16	4	1	0	0	5	0	2	12	2.00
Surface	9.0	9.5	16	22	0	0	0	0	2	1	1	4	2.00
Surface	9.5	10.0	22	28	3	0	0	0	1	0	0	4	2.00
Surface	10.0	10.5	28	34	2	1	1	0	1	0	0	5	2.00
Surface	10.5	11.0	34	40	3	1	2	0	0	0	1	7	2.00
Surface	11.0	11.5	40	46	0	0	0	2	1	0	4	7	2.00
Surface	11.5	12.0	46	52	1	2	3	0	2	0	2	10	2.00

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)
Surface	12.0	12.5	52	58	3	1	2	0	1	0	0	7	2.00
Surface	12.5	13.0	58	64	3	2	0	0	3	2	3	13	2.00
Surface	13.0	13.5	64	70	2	0	3	1	1	1	3	11	2.00
Surface	13.5	14.0	70	76	0	0	0	0	1	1	0	2	2.00
Surface	14.0	14.5	76	82	0	1	3	0	3	0	1	9	2.00
Surface	14.5	15.0	82	89	1	1	3	0	4	0	0	9	2.00
Surface	15.0	15.5	89	97	7	3	1	0	2	0	0	13	2.00
Surface	15.5	16.0	97	107	3	0	1	0	0	0	0	4	2.00
Surface	16.0	16.5	107	116	1	2	1	0	2	0	1	7	2.00
Surface	16.5	17.0	116	126	2	3	0	0	2	1	0	8	2.00
Surface	17.0	17.5	126	135	1	2	0	0	2	0	0	5	2.00
Surface	17.5	18.0	135	145	2	2	0	0	2	0	2	8	2.00
Surface	18.0	18.5	145	155	0	0	0	0	0	0	1	1	2.00
Surface	18.5	19.0	155	164	0	0	0	0	1	0	3	4	2.00
Surface	19.0	19.5	164	174	1	0	0	0	0	1	1	3	2.00
Surface	19.5	20.0	174	183	0	1	0	0	1	0	1	3	2.00
Surface	20.0	20.5	183	193	0	0	1	0	0	0	4	5	2.00
Surface	20.5	21.0	193	203	0	0	0	0	0	0	0	0	2.00
Surface	21.0	21.5	203	212	3	0	1	0	1	1	4	10	2.00
Surface	21.5	22.0	212	222	1	0	2	0	1	0	1	5	2.00
Surface	22.0	22.5	222	231	0	1	0	0	2	0	2	5	2.00
Surface	22.5	23.0	231	241	1	0	0	0	0	0	3	4	2.00
Surface	23.0	23.5	241	251	0	0	2	0	0	0	2	4	2.00
Surface	23.5	24.0	251	260	0	1	2	0	1	0	1	5	2.00
Surface	24.0	24.5	260	270	0	0	1	0	1	0	2	4	2.00
Surface	24.5	25.0	270	280	1	0	0	1	1	0	1	4	2.00
Surface	25.0	25.5	280	289	3	0	0	0	1	0	2	6	2.00
Surface	25.5	26.0	289	299	1	0	2	0	0	1	1	5	2.00
Surface	26.0	26.5	299	308	3	0	2	0	3	1	5	14	2.00
Surface	26.5	27.0	308	318	2	0	3	1	0	0	4	10	2.00
Surface	27.0	27.5	318	328	4	2	0	0	1	1	4	12	2.00
Surface	27.5	28.0	328	337	1	0	2	0	2	0	4	9	2.00
Surface	28.0	28.5	337	347	4	0	4	0	1	0	1	10	2.00
Surface	28.5	29.0	347	357	5	2	1	0	1	0	1	10	2.00
Surface	29.0	29.5	357	366	1	0	0	0	0	1	0	2	2.00
Surface	29.5	30.0	366	376	2	0	2	0	0	0	2	6	2.00

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)
Surface	30.0	30.5	376	386	4	0	3	0	0	0	3	10	2.00
Surface	30.5	31.0	386	395	1	0	1	0	0	0	3	5	2.00
Surface	31.0	31.5	395	405	1	0	0	0	1	1	4	7	2.00
Surface	31.5	32.0	405	415	4	0	0	0	1	0	5	10	2.00
Surface	32.0	32.5	415	424	1	1	0	0	0	1	2	5	2.00
Surface	32.5	33.0	424	434	1	0	0	0	0	0	1	2	2.00
Surface	33.0	33.5	434	444	2	3	1	0	0	0	2	8	2.00
Surface	33.5	34.0	444	453	1	0	0	0	1	0	2	4	2.00
Surface	34.0	34.5	453	463	2	0	0	0	2	1	5	10	2.00
Surface	34.5	35.0	463	473	1	0	0	0	1	0	0	2	2.00
Surface	35.0	35.5	473	482	2	0	1	0	0	0	5	8	2.00
Surface	35.5	36.0	482	492	2	0	0	0	0	0	3	5	2.00
Surface	36.0	36.5	492	502	0	0	0	0	0	0	1	1	2.00
Surface	36.5	37.0	502	512	3	1	0	0	2	0	2	8	2.00
Surface	37.0	37.5	512	521	0	1	1	0	2	0	3	7	2.00
Surface	37.5	38.0	521	531	0	0	1	1	0	0	1	3	2.00
Surface	38.0	38.5	531	541	0	0	1	0	0	0	3	4	2.00
Surface	38.5	39.0	541	551	0	0	0	2	0	0	0	2	2.00
Surface	39.0	39.5	551	560	0	0	0	0	0	0	1	1	2.00
Surface	39.5	40.0	560	570	0	0	2	0	0	0	4	6	2.00
Surface	40.0	40.5	570	580	1	2	1	0	0	1	2	7	2.00
Surface	40.5	41.0	580	590	2	1	1	0	0	1	4	9	2.00
Surface	41.0	41.5	590	599	7	2	0	0	2	1	2	14	2.00
Surface	41.5	42.0	599	609	2	7	2	0	2	2	4	19	2.00
Surface	42.0	42.5	609	619	1	1	0	0	0	1	4	7	2.00
Surface	42.5	43.0	619	629	1	0	0	0	1	2	0	4	2.00
Surface	43.0	43.5	629	639	5	1	1	0	2	1	2	12	2.00
Surface	43.5	44.0	639	648	2	1	1	0	2	0	0	6	2.00
Surface	44.0	44.5	648	658	1	0	0	1	1	0	1	4	2.00
Surface	44.5	45.0	658	668	1	0	0	0	1	0	1	3	2.00
Surface	45.0	45.5	668	678	4	0	1	0	0	1	1	7	2.00
Surface	45.5	46.0	678	688	3	0	1	0	1	1	1	7	2.00
Surface	46.0	46.5	688	698	2	0	2	0	1	0	2	7	2.00
Surface	46.5	47.0	698	708	1	0	0	0	1	0	2	4	2.00
Surface	47.0	47.5	708	717	3	3	1	0	1	0	3	11	2.00
Surface	47.5	48.0	717	727	4	0	0	0	1	0	2	7	2.00

Drive	Interval Top (cm)	Interval Bottom (cm)	Age Top (cal yr BP)	Age Bottom (cal yr BP)	M Pieces (#)	P Pieces (#)	S Pieces (#)	B Pieces (#)	C Pieces (#)	D Pieces (#)	F Pieces (#)	Total Charcoal Pieces (#)	Volume (ml)
Surface	48.0	48.5	727	737	3	0	0	0	2	2	4	11	2.00
Surface	48.5	49.0	737	747	5	0	0	0	0	4	2	11	2.00
Surface	49.0	49.5	747	757	0	0	0	0	0	0	0	0	2.00
Surface	49.5	50.0	757	767	3	1	1	0	1	0	2	8	2.00
Surface	50.0	50.5	767	777	2	2	4	0	5	0	1	14	2.00
Surface	50.5	51.0	777	787	0	0	1	0	2	0	1	4	2.00
Surface	51.0	51.5	787	797	3	2	2	0	6	1	1	15	2.00
Surface	51.5	52.0	797	807	0	1	0	0	3	0	1	5	2.00
Surface	52.0	52.5	807	817	0	0	0	0	1	0	0	1	2.00
Surface	52.5	53.0	817	827	0	0	0	0	0	0	2	2	2.00
Surface	53.0	53.5	827	837	0	1	0	0	4	0	2	7	2.00
Surface	53.5	54.0	837	847	0	0	1	0	1	0	3	5	2.00
Surface	54.0	54.5	847	857	0	0	1	0	1	0	2	4	2.00
Surface	54.5	55.0	857	867	0	0	0	0	2	0	3	5	2.00
Surface	55.0	55.5	867	877	2	0	0	0	2	0	3	7	2.00
Surface	55.5	56.0	877	887	1	1	1	0	3	0	1	7	2.00
Surface	56.0	56.5	887	897	1	0	0	0	0	0	4	5	2.00
Surface	56.5	57.0	897	907	0	1	0	0	0	1	2	4	2.00
Surface	57.0	57.5	907	917	0	1	0	0	1	0	0	2	2.00
Surface	57.5	58.0	917	927	0	1	0	0	3	0	2	6	2.00
Surface	58.0	58.5	927	937	1	1	0	0	0	0	2	4	2.00
Surface	58.5	59.0	937	947	1	1	0	0	2	1	3	8	2.00
Surface	59.0	59.5	947	958	0	0	0	0	2	0	2	4	2.00
Surface	59.5	60.0	958	968	1	0	0	0	3	0	4	8	2.00
Surface	60.0	60.5	968	978	0	1	0	0	0	0	3	4	2.00
Surface	60.5	61.0	978	988	1	2	0	0	2	0	1	6	2.00
Surface	61.0	61.5	988	998	0	2	0	0	1	0	0	3	2.00
Surface	61.5	62.0	998	1008	0	1	0	0	0	0	2	3	2.00
Surface	62.0	62.5	1008	1018	0	3	0	0	3	0	2	8	2.00
Surface	62.5	63.0	1018	1029	1	0	0	0	1	0	0	2	2.00
Surface	63.0	63.5	1029	1039	1	1	0	0	0	1	2	5	2.00
Surface	63.5	64.0	1039	1049	0	0	0	0	1	0	1	2	2.00
Surface	64.0	64.5	1049	1059	0	0	0	0	1	0	0	1	2.00

Appendix B3 - Gamma Counter Data for Mud Lake Surface-Core Sediment

Raw data for dried sediment from the Mud Lake surface-core that was analyzed for ^{210}Pb, ^{137}Cs, and ^{214}Bi content. The coring date was March 28, 08. A constant rate of supply (CRS) model was used to process the ^{210}Pb, ^{137}Cs, and ^{214}Bi activity and produce the ages. This took place at the Paleoecological Environmental Research and Assessment Laboratory (PEARL), Queen's University.

Interval Depth (cm)	**Date Counted**	**Counting Time (s)**	**Mass g/dry wt.**	**Height in tube (mm)**	**Bkgr ROI1**	**^{210}Pb ROI2**	**Bkgr. ROI3**	**Bkgr. ROI4**	**^{214}Bi ROI11**	**Bkgr ROI12**	**Bkgr. ROI13**	**^{137}Cs ROI14**	**Bkgr ROI15**
0.0-0.5	22-Apr-09	80000	0.4101	16.92	563	4443	376	125	254	95	73	324	71
1.0-1.5	23-Apr-09	80000	0.4990	21.14	509	4056	349	99	237	91	78	374	68
2.0-2.5	24-Apr-09	80000	0.4150	20.62	448	3025	372	111	234	88	65	375	91
3.0-3.5	25-Apr-09	80000	0.4781	21.32	466	3006	396	104	262	107	89	473	67
4.0-4.5	26-Apr-09	80000	0.5500	21.98	447	2375	379	114	239	95	96	698	72
5.0-5.5	15-May-09	80000	0.6025	22.34	460	2193	395	118	237	85	93	1100	81
6.0-6.5	28-Apr-09	80000	0.5969	21.48	479	2345	407	103	256	105	106	2347	72
7.0-7.5	16-May-09	80000	0.6168	21.56	464	1829	385	88	267	103	80	663	81
8.0-8.5	1-May-09	80000	0.5869	22.46	419	1502	395	115	257	101	87	285	80
9.0-9.5	2-May-09	80000	0.5437	22.72	425	1088	356	110	254	93	81	256	72
10.0-10.5	3-May-09	80000	0.6262	21.30	392	1193	397	82	255	80	86	257	91
11.0-11.5	4-May-09	80000	0.5684	20.77	426	1023	368	115	262	101	79	233	78
12.0-12.5	5-May-09	80000	0.5599	22.11	411	949	342	92	247	78	84	261	71
13.0-13.5	6-May-09	80000	0.4970	20.54	397	947	350	100	248	86	84	214	87
14.0-14.5	7-May-09	80000	0.5120	21.81	395	817	329	116	245	87	79	221	74
15.0-15.5	8-May-09	80000	0.5317	19.88	369	899	367	95	289	81	79	207	77
16.0-16.5	9-May-09	80000	0.5802	19.42	386	875	370	112	288	91	74	206	80
17.0-17.5	10-May-09	80000	0.4910	18.39	396	812	329	111	255	109	85	213	70
18.0-18.5	11-May-09	80000	0.5505	20.88	415	765	355	111	232	103	75	225	86
19.0-19.5	12-May-09	80000	0.5647	20.75	402	772	350	105	266	88	86	218	75

	corrected for efficiency & density		corrected for sampling date	cumulative error x correction factors		
Interval Depth (cm)	^{210}Pb (dpm/g)	^{214}Bi (dpm/g)	^{137}Cs (dpm/g)	^{210}Pb error 1 standard deviation (dpm/g)	^{214}Bi error 1 standard deviation (dpm/g)	^{137}Cs error 1 standard deviation (dpm/g)
0.0-0.5	175.17	0.27	3.10	2.96	0.05	0.23
1.0-1.5	139.79	0.65	3.38	2.47	0.10	0.22
2.0-2.5	114.53	0.31	3.88	2.44	0.05	0.26
3.0-3.5	97.94	0.82	4.92	2.12	0.11	0.28
4.0-4.5	62.30	0.09	7.21	1.58	0.02	0.31
5.0-5.5	49.50	0.19	11.57	1.35	0.03	0.38
6.0-6.5	53.79	0.57	27.08	1.41	0.08	0.58
7.0-7.5	35.02	1.30	6.07	1.12	0.15	0.27
8.0-8.5	26.13	0.39	1.50	1.00	0.06	0.14
9.0-9.5	12.58	0.73	1.42	0.72	0.10	0.14
10.0-10.5	14.15	1.72	0.94	0.70	0.18	0.10
11.0-11.5	8.72	0.54	0.98	0.58	0.08	0.11
12.0-12.5	7.71	1.47	1.41	0.55	0.17	0.14
13.0-13.5	8.65	1.14	0.62	0.61	0.14	0.10
14.0-14.5	3.95	0.48	0.98	0.41	0.07	0.12
15.0-15.5	6.53	2.60	0.69	0.51	0.24	0.10
16.0-16.5	4.34	1.60	0.64	0.40	0.17	0.10
17.0-17.5	3.66	0.26	0.84	0.39	0.04	0.11
18.0-18.5	-0.25	-0.26	0.85	0.11	0.06	0.11
19.0-19.5	0.72	1.32	0.73	0.16	0.15	0.10

Interval Top (cm)	Interval Bottom (cm)	Interval MidPoint (cm)	Age Top (yr before coring)	Age Top Standard Deviation	Age Bottom (yr before coring)	Age Bottom Standard Deviation	Sedimentation Rate (cm/yr)	Sedimentation Rate Standard Deviation	Sum Top
0	0.5	0.25	0	0.19	2.96	0.20	0.0058	0.0010	15.39
1	1.5	1.25	5.88	0.21	8.75	0.22	0.0061	0.0012	12.81
2	2.5	2.25	11.77	0.24	14.97	0.25	0.0062	0.0013	10.66
3	3.5	3.25	18.39	0.27	22.08	0.30	0.0058	0.0014	8.68
4	4.5	4.25	25.43	0.32	28.4	0.35	0.0075	0.0019	6.97
5	5.5	5.25	31.62	0.38	35.16	0.41	0.0077	0.0021	5.75
6	6.5	6.25	39.47	0.47	44.87	0.54	0.0054	0.0019	4.50
7	7.5	7.25	50.81	0.64	57.46	0.77	0.0058	0.0024	3.16
8	8.5	8.25	64.37	0.95	71.54	1.16	0.0051	0.0027	2.07
9	9.5	9.25	77.34	1.39	81.54	1.56	0.0076	0.0043	1.38
10	10.5	10.25	86.70	1.82	93.25	2.20	0.0049	0.0036	1.03
11	11.5	11.25	99.12	2.64	104.08	3.04	0.0057	0.0048	0.70
12	12.5	12.25	109.43	3.58	115.24	4.25	0.0047	0.0049	0.51
13	13.5	13.25	122.47	5.31	131.96	7.07	0.0026	0.0042	0.34
14	14.5	14.25	139.33	8.89	144.10	10.25	0.0041	0.0070	0.20
15	15.5	15.25	152.35	13.24	168.72	21.88	0.0013	0.0047	0.13

Appendix B4 - Accelerator Mass Spectrometry (AMS) ^{14}C Dating Results for Samples in Mud Lake Cores

Raw data for the organic matter from the Mud Lake surface and piston cores that were dated using AMS ^{14}C methods. They were processed by the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory, and the data were received May 20, 2009.

Sample Name	**CAMS #**	**Other ID**	**d^{13}C**	**Fraction Modern**	**± error**	**D^{14}C**	**± error**	**^{14}C age**	**± error**
MS 47.0-47.5	142833	N87826	-25	0.9062	0.0036	-93.8	3.6	790	35
MS 63.0-63.5	142834	N87827	-25	0.8625	0.0030	-137.5	3.0	1190	30
ML-1 17.5-18.5	142835	N87828	-25	0.9777	0.0046	-22.3	4.6	180	40
ML-1 51.5-52.0	142836	N87829	-25	0.8611	0.0036	-138.9	3.6	1200	35
ML-1 71.5-72.0	142837	N87830	-25	0.8366	0.0037	-163.4	3.7	1435	40
ML-2 92.5-93.5	142838	N87831	-25	0.7683	0.0040	-231.7	4.0	2120	45
ML-2 155.5-156.0	142839	N87832	-25	0.6315	0.0031	-368.5	3.1	3690	40
ML-3 173.5-174.0	142840	N87833	-25	0.6676	0.0027	-332.4	2.7	3245	35
ML-3 196.5-197.0	142841	N87834	-25	0.5708	0.0025	-429.2	2.5	4505	40
ML-3 226.5-227.0	142842	N87835	-25	0.5008	0.0027	-499.2	2.7	5555	45
ML-4 282.0-282.5	142843	N87836	-25	0.3847	0.0024	-615.3	2.4	7675	50
ML-4 302.0-302.5	142844	N87837	-25	0.3566	0.0018	-643.4	1.8	8285	45
ML-5 330.5-331.5	142845	N87838	-25	0.3942	0.0028	-605.8	2.8	7480	60

Appendix C - Supplementary Methods for Mud Lake Charcoal-Record Analysis using CharAnalysis

CharAnalysis applies a decomposition-approach to modeling charcoal records. At each step in the analysis, the user makes one or more parameter decisions. CharAnalysis can be run within MATLAB, and it can also run outside of MATLAB in association with MATLAB Component Runtime. The latter option was used here, and data was inputted and outputted through excel spreadsheets. In both cases, the modeling steps in CharAnalysis use MATLAB functions that can be performed by MATLAB separately. The details of the parameter choices applied in to the Holocene-length composite-core charcoal analysis and the surface-core charcoal record analysis are explained below. The information was taken from the following sources, and additional details about CharAnalysis are available from them.

Higuera, P. E., L. B. Brubaker, P. M. Anderson, T. A. Brown, A.T . Kennedy, and F. S. Hu. 2008. Frequent fires in ancient shrub tundra: implications of paleorecords for Arctic environmental change. PLoS ONE. **3**:1-7.

Higuera, P. E. 2009. CharAnalysis. University of Idaho, Moscow, Idaho. [software and manual] Accessed on May 5, 2009 at URL: http://sites.google.com/site/charanalysis

Higuera, P. E., L. B. Brubaker, P.M . Anderson, F. S. Hu, and T. A. Brown. 2009. Vegetation mediated the impacts of postglacial climate change on fire regimes in the south-central Brooks Range, Alaska. Ecological Monographs **79**:201-219.

Step 1

The raw charcoal record is interpolated to equal intervals to define C_{int}. The charcoal concentration (pieces•cm^{-3}) and the sedimentation accumulation rate (cm/yr) were re-sampled into 16-yr intervals for the Holocene-length record and 10-yr intervals for the surface-core record. These values were automatically chosen by CharAnalysis as they are the median sampling resolution for each record. The interpolated charcoal concentration and sedimentation accumulation rates are multiplied for each interval to define the interpolated charcoal accumulation rate (pieces•cm^{-2}•yr^{-1}). There is an option of log-transformation at this step of the analysis. No transformation was done on the composite-core record or the surface-core record. Log-transformation reduces the non-stationarity, or change in variance, of a data series. Non-stationarity arises when there are variations in the overall input of charcoal into a system. This may be a result of changes in fire regime, including the type of vegetation burned and the intensity of fires. It may also be a result of changes in the processes that deposit secondary charcoal into the system. Non-stationarity must be addressed to ensure that charcoal peaks in all parts of the record have an equivalent chance of being isolated in the analysis. There are methods that use locally-weighted modeling, described later, that lack the disadvantages of transformation. Log transformation may reduce or amplify peaks in a data set. As peak detection is the goal, this is a drawback. Log transformation also makes separating the noise-attributable variation from the high-frequency charcoal peaks signal more difficult.

Step 2

C_{int} is smoothed to model the slowly-varying mean within its values, which represents the low-frequency charcoal series. This defines the background charcoal level, C_{back}. For the composite-core and surface-core record, this was done with a Lowess smoother, robust to outliers. A Lowess smoother performs locally-weighted scatterplot smoothing on the interpolated charcoal series. It uses linear least-squares polynomial regression within localized subsets of the data. The Lowess option that is robust to outliers was chosen as it weights extreme values to a lesser degree. As peak detection is the goal, this is an advantage.

The Lowess smoother also addresses non-stationarity within a record as it assigns a value to each interval by analyzing a specified time-period (here, a constant number of samples) surrounding the value being estimated. This technique deals with change in variance by using a local-window when estimating values, assuming that the type of fire regime and the processes that deposit charcoal into a lake are consistent over that time period. For the composite-core record, a 500-yr time window was used, and a 300-yr time window was used for the surface-core record. The values closer to the point being estimated are weighted more than those at the edges of the time-window chosen. These time windows were chosen through the sensitivity analysis option within CharAnalysis. The threshold value goodness-of-fit (GOF) for the threshold cut-off for charcoal peaks and the signal-to-noise index (SNI) of the high-frequency charcoal component for different time-windows are assessed, and the time-windows chosen have the highest combined value for each record. The threshold GOF is a measure of how well the noise component of high-frequency charcoal series coordinate with the fitted noise distribution.

The SNI is a measure of how clearly the noise-attributable variability and the charcoal peak signal within the high-frequency charcoal series are separated. The GOF and SNI values are both estimates of how well the high-frequency charcoal series is modeled.

Step 3

C_{back} is removed from C_{int} to define a series which contains the high-frequency variations, C_{peak}. For both records, the residual method was used to remove C_{back} from C_{int} ($C_{peak} = C_{int} - C_{back}$) This method assumes that there is an additive relationship between high-frequency, primary charcoal and low-frequency, secondary charcoal. The alternative option, the ratio method, assumes a multiplicative relationship between primary and secondary charcoal ($C_{peak} = C_{int}/C_{back}$). The ratio method is a transformation option for the data, and it may amplify smaller peaks. It minimizes the changes in variance within the record, but, like log-transformation, it also makes the noise-attributable component of the high-frequency charcoal series more difficult to separate from the fire-attributable component of the high-frequency charcoal series.

Step 4

A threshold value is defined and applied to the C_{peak} to separate the fire-related samples from the non-fire related samples. The fire-related samples define C_{fire}, which is the population of large CHAR levels that signify past fire episodes. The non-fire related samples define $C_{noise,}$ which is the normally-distributed variability around C_{back} caused by sediment-mixing, changes in the amount of long-distance charcoal deposition, and sampling and analytical effects. For both charcoal records, $C_{noise,}$ was estimated with a Gaussian mixture model. The Gaussian mixture model estimates the mean and the variance for the two components of C_{peak}, C_{noise} and C_{fire}. Only the mean and variance for C_{noise} are applied to the charcoal-record modeling. Using this method assumes that C_{noise}, the noise-attributable variability in C_{peak}, is normally-distributed, and theoretical and empirical research have shown that this is a valid assumption. Similar to the Lowess smoother, using a local-window with the Gaussian mixture model accounts for any changes in variance within C_{peak} as it selects a threshold for each interval based on the noise-variance in the defined subset of the record. The same window was used for smoothing C_{back} in the composite-core and surface-core records was used for modeling C_{noise}. For the composite-core and surface core analyses, the threshold for C_{fire} was defined as the 95 percentile of the modeled C_{noise} distribution. Charcoal peaks, C_{fire}, were those values in C_{peak} that exceeded the 95% percentile of the C_{noise} distribution, which was estimated for each interval.

Step 5

The charcoal peaks, C_{fire}, identified in Step 4 as intervals above of the defined threshold are screened by the Minimum Count Test. This test removes any peak that fails to pass a minimum-count criterion by examining the possibility that the differences in counts between two samples may result from sampling effects. This step is applied to eliminate false positives. The charcoal counts for the intervals of C_{fire} are assessed and if any has a greater than 5% change of coming from the same Poisson probability distribution as the minimum charcoal count within the previous 75-yr, then it is rejected. The Kolmogorov-Smirnov non-parametric goodness-of-fit test is used to assess whether the samples come from the same distribution. The standard confidence level of 0.05 was chosen for this step.