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A Lateglacial Paleofire Record for East-Central Michigan

A Thesis submitted to the

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In partial fulfillment of the requirements for the degree of

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by

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Slack Lake, Michigan, February 2008.
Justin Stroup, Tom Lowell, Mike Oestreich, Joanne Ballard with
the Livingstone coring rig.

Abstract

This study provides a lateglacial paleofire record for Michigan which will help to reconstruct the larger geographic pattern of fire during lateglacial time, as very few charcoal studies have been carried out for the Midwest. This work is anticipated to be integrated into the Global Charcoal Database at the World Data Center for Paleoclimatology for future studies relating to fire patterns and regions, and vegetation and climate change.

This study was initially designed to test the biomass burning aspect at 12,900 BP of the Firestone *et al.* (2007) extraterrestrial impact hypothesis. Four lakes near Flint Michigan were sampled because of their proximity to the Gainey Paleoindian site featured in the Firestone *et al.* (2007) paper. Charcoal was quantified in these four lakes to develop a multi-site lateglacial fire record for the Midwest. The results show contemporaneous fire not only at 12,900 BP but multiple times between 14,500 and 12,900 BP. This synchronicity of the fires between 14,500 and 12,900 BP suggests some as-yet-indeterminate large-scale natural cause, or causes. From 12,900 BP on into the Holocene, the pattern changes. Fires are continuous with high charcoal peaks at Swift Lake, continuous at Slack Lake but with slightly lower charcoal peaks compared to Swift, and having much lower peaks at Lake Sixteen and Big Fish Lake (charcoal is present but at very low levels). This pattern is interpreted to be a result of the distance from the Paleoindian site. Swift and Slack Lakes are each less than one km from the Gainey site, while the other two lakes are 30 km and 16 km away from it. The bimodality of the amplitude of the signals in the fire patterns between the two pair of lakes from 12,900 BP forward in time suggests Paleoindian origin for fire.

Additional radiocarbon dates are needed to refine the chronology of the timeline and gain a better understanding of the sedimentation rate. More charcoal research should be conducted on lakes across a larger region, for the interval from the Last Glacial Maximum into the Holocene.

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1. Introduction

1.1 The Problem

Why is it important to study paleofire? Bowman *et al.* (2009) state it succinctly: *"Fire is a worldwide phenomenon that appears in the geological record soon after the appearance of terrestrial plants. Fire influences global ecosystem patterns and processes, including vegetation distribution and structure, the carbon cycle, and climate."* An example of such change is fire as the agent for the expansion of C4 grasslands in the Miocene (Keeley & Rundel, 2005).

From the Last Glacial Maximum (LGM) approximately 20,000 years ago until the Pleistocene/Holocene boundary ~11,600 years ago in the Midwest was a time of large-scale landscape upheaval as a continental glacier receded from what is now a temperate region. Major climatic changes were taking place, and noted in the 18 oxygen isotopes, proxies for temperature and moisture, in the Greenland ice cores. Postglacially this was apparently tundra, followed by spruce-dominated parkland, then rather abruptly by pine-dominated forests by the end of the Younger Dryas (YD) (Hupy & Yansa 2009). The pine phase finally progressed to predominantly deciduous species which had been present in earlier phases as shown by low pollen counts. The YD is defined to be approximately 12,900 to ~11,600 years Cal BP (Fig. 1.8) (Alley *et al,* 1993). The transition from glacial to interglacial conditions is a unique situation in recent geological history that is still not well understood. Michigan is an ideal location to investigate fire's role in lateglacial vegetation dynamics, given its proximity to the ice sheet margin. Fig. 1.1 shows the position of the Laurentide Ice Sheet (LIS) around 13,000 years ago, with the LIS margin in the Upper Peninsula of Michigan.

The analysis of charcoal from lake and peat sediments is suitable for fire reconstruction due to the stratigraphic nature of these archives. Small deep lakes are considered the best sites for Quaternary fire studies, providing precise spatial reconstructions (Carcaillet 2007). Yet such paleofire studies are

lacking in the Midwest. In Marlon *et al.* (2009), that deficit is graphically apparent in the map of North America (Fig 1.1). This study provides a network of four new high-resolution paleofire records from Michigan lakes that track the regional pattern, giving a broader understanding of paleoenvironmental changes across the north central Midwest.

In addition to building a paleofire record for Michigan, this study also aims to address the validity of the biomass burning aspect of the Firestone *et al.* (2007) extraterrestrial impact hypothesis at 12,900 years BP. Firestone *et al.* (2007) state that at 12,900 BP an extraterrestrial body impacted North America, causing the extinction of the mammoths and the end of the Clovis culture, triggering the Younger Dryas cooling period, and setting off widespread biomass burning. This hypothesis features a black mat layer as evidence (Firestone *et al.* 2007, Haynes 2008) which contains some or all of the following markers: carbon microspherules containing nanodiamonds, charcoal, magnetic microspherules, magnetite grains, fullerenes with extraterrestrial helium, soot, and remnants of an algal mat. All of their study sites are archaeological. The Gainey archaeological site near Flint, Michigan was targeted for this study as it is a key locality in the Firestone *et al.* (2007) paper. Lakes were chosen for charcoal analysis as these repositories are a geological archive which provides a continuous record over time.

1.2 Background

Although many *Holocene* charcoal studies have been done in the North American West (e.g. Marlon *et al.* 2006, Whitlock *et al.* 2004, Whitlock *et al.* 2003, Brunelle & Whitlock 2003) and some for the Midwest (e.g. Lynch *et al.* 2006, NW Wisconsin; Umbanhowar 2004, MN) there are few *lateglacial* charcoal studies for the Midwest.

1.3 Setting

All of the lakes that were sampled in this study are situated south-southeast of Flint, Michigan (Fig 1.2). Lake Sixteen and Big Fish Lake are southeast of the Saginaw Lobe moraine. The Saginaw Lobe retreated to the northwest (Fig. 1.2). This region features ice-contact topography such as

kettle lakes and ponds, and extensive wetlands surround many of the lakes where ice blocks once stood. Marl and peat deposits have been extensively mined here in the past. The glacial drift that forms the moraines is largely derived from the local limestone bedrock (Albert, 2004). As the lobe continued to retreat, Slack and Swift lakes began their existence. Lake Sixteen and Big Fish Lake are therefore older than Slack and Swift lakes, which are located less than 2 km apart in Genesee county, just inside the Saginaw lobe moraine. The Gainey archaeological site (Don Simons, pers. comm.) is approximately equidistant from Swift and Slack Lakes, .94 km and .73 km, respectively, on a cultivated field.

1.4 The nature of fire and the study of charcoal

Fire (combustion)
Physical and chemical process, the "reverse of Photosynthesis"

$$\text{Organic matter } (C_6H_{10}O_5)n + O_2 \longrightarrow \text{Charcoal (C)} + CO_2 + CO + CH_4 + H_2 + H_2O + \text{Ash + Aerosols + Heat + Light}$$

The chemical formula for fire (after Finkelstein 2004).

Wildfires can be of three basic types: ground fires (e.g. in peatlands), surface fires, or crown fires. Fires of high intensity will produce larger-sized charcoal particles than low intensity, smouldering fires. In addition, the composition of the charcoal changes with the temperature of the fire. Studies of modern charcoal accumulation in lakes indicate that charcoal deposition can take place immediately after fire, primary charcoal, or several years after the actual fire, secondary charcoal (Fig. 2. 3, Whitlock and Larsen 2002, p. 77). For the purposes of Younger Dryas-age studies, the several years redeposition time of secondary charcoal is negligible, as the calibration of radiocarbon dates during this time gives large error bars due to the plateau in radiocarbon dating (Guilderson *et al.* 2005).

Anthracology is the study of wood charcoal. Charcoal, a form of carbon, is the focus of this study and is used as evidence of past biomass burning. Charcoal can be tracked in the geological record, and this study looks at lakes as the repository of the charcoal evidence. Fossil charcoal in lakes appears to be stable over time (C. Whitlock, pers. comm.). Charcoal is formed by the combustion of

organic material in the presence of oxygen, with a source of ignition. Burning can be considered as the reverse of photosynthesis (Finkelstein 2004). Charcoal is produced at temperatures between 280 and 500°C. Temperatures of 350°C appear to provide the greatest amount of charcoal in laboratory experiments. Ash is a byproduct of fire at higher temperatures (Neary *et al.* 2005, Whitlock & Larsen, 2001). In addition to charcoal, burning vegetation produces large amounts of particulates and gases (NASA 2001).

For an overview of fire, see Pyne (2001) and Cottrell (2004). For an overview of charcoal particle analysis, see Carcaillet (2007) and Smol *et al.* (2004) including Whitlock and Larsen's charcoal methodology. Charcoal analysis protocol from Jacquelyn Gill (2008) at the University of Wisconsin was used, with some modification for the so-called coarse methodology. An additional protocol from the Montana State University Paleoecology Lab was also used for the fine methodology.

1.5 Lateglacial paleoenvironmental studies

Since specific pollen and vegetational analysis for these lakes was beyond the scope of a Master's thesis, this information has been collected from the literature in the form of palynological studies, mastodon dig studies, and a peatlands study. The reason for looking at the vegetation is because it is closely linked to the fire regime. Coniferous forests are more combustible, for instance, than deciduous trees. Some species are fire-dependent, such as jack pine, which requires the heat of fire to open its resinous cones and to clear the forest floor of litter so that the seeds may germinate and grow.

Following ice sheet retreat around 20,000 years BP, tundra-type plant species colonized, and were succeeded by a spruce-sedge dominated parkland until around the end of the Younger Dryas, and was then succeeded by pine domination for approximately 1,000 years. Deciduous species then became the predominant species until modern times. A summary of the characteristics of some of the main species will be given, particularly in their relation to moisture and fire in order to understand the ecology of the lateglacial fire landscape, and then the literature will be reviewed.

Today there are oak-hickory forests with hardwood swamps, prairie fens, and bogs in the Big Fish and Lake Sixteen region. The Swift and Slack Lakes region has beech-maple forest and hardwood swamps (Albert, 2004). Postglacially, much of Michigan was barren sand and gravel with shallow ponds, deep lakes and rivers (MDNR, 2003). The succession of vegetation is approximately as follows (Fig. 4.2 sidebar): 17,000 to 14,000 Calendar years BP, tundra; 14,000- 11,500 Cal. years BP, spruce-sedge parkland; 11,500- 10,300 Cal. years BP, pine-dominated forests (with some birch, ironwood and elm); 10,300 – 9,500 Cal. years BP, increasing oak and maple; 9,500 Cal. years BP, oak-dominated forests (with elm, maple, ironwood and birch) (Hupy & Yansa 2009).

There are no known lateglacial limnological charcoal studies in Michigan, although the presence of charcoal is described and dated in the Shelton mastodon study (Shoshani *et al*., 1989), which is approximately 8 km northwest of Lake Sixteen. Charcoal and pollen across the Younger Dryas are the foci of the Appleman Lake study (Lininger 2008, Gill 2008) at the northern Indiana border with Michigan. These dated pollen and charcoal studies help link the vegetation to fire incidence.

A caveat in regards to pollen analysis may be worth noting. Williams *et al.* (2009) report that correlating modern pollen studies to remote sensing of vegetation and then applying that relationship to paleopollen studies indicates that vegetation is typically overrepresented in paleoenvironmental reconstructions due to prolific pollen producers such as *Picea* (spruce) and *Pinus* (pine).

Additional vegetation information can be gleaned from mastodon digs, which report macrofossils (see *e.g.,* Shoshani *et al*. 1989, McAndrews & Jackson 1988), and a peatlands study (Halsey & Vitt, 2000). Some macrofossils have been identified in the lakes in this study (C. Yansa, E. Grimm, B.L.Brett, B. Curry, G.v. Reenen, pers. comm.). A table of common and scientific names for species occurring in the literature for this region and time interval can be found in Table 1.1.

1.5a. Charcoal

At Appleman Lake (Lininger 2008) the charcoal data (Fig. 1.4) show that there is fire evidence prior to the Younger Dryas (YD) to a maximum age of ~14,000 and throughout the YD. However, the most significant fires are in the Holocene.

The Shelton Mastodon site (Shoshani *et al.* 1989) is an important lateglacial study for its proximity to the study location. *In situ* spruce tree stumps that grew on a glacial clay lakebed were uncovered. The Shelton mastodon dated to around 12,800 Cal BP years, and charcoal stringers at this site dated to 14,400 Cal BP years. Macrofossil cones at this site were predominantly (93%) spruce (black and white), with tamarack (4%), balsam fir(1.5%), and jack, red, and white pines (<1%). Palynology studies on seven soil samples showed predominantly spruce (20-95%), ~0-40% pine, and 10% or less of oak, birch, sedge, grass, larch and cattail (Shoshani *et al*. 1989).

On a broader geographic scale, Marlon *et al.* (2009) present a synopsis of 30 existing charcoal studies from the Global Charcoal Database that span the Younger Dryas plus 5 new YD fire records for North America addressing the Firestone *et al.* (2007) study. The only sites in the Midwest are Sharkey Lake, Minnesota, and Moon Lake, North Dakota. Marlon *et al* (2009) show elevated charcoal at the beginning of the YD, as well as mid-YD and end-YD with fires increasing in magnitude in the Holocene (Fig. 1.5). However, they state "No continent-wide fire response is observed at the beginning of the Younger Dryas chronozone, the time of the hypothesized comet impact. The results provide no evidence of synchronous continent-wide biomass burning at any time during the LGIT [Last Glacial-Interglacial Transition, 15-10 ka]."

1.5b. Pollen

Pollen studies for the Michigan region include Andersen (1954), Hupy & Yansa (2009), Yu (2000, 2003) and across east-central North America, Shuman *et al.* (2002), and Shane & Anderson (1993).

Andersen (1954) took cores from George Reserve Lake in Livingstone County, which is south of Swift and Slack Lakes. His pollen cores are not dated but do show the typical spruce and sedge

domination that is dramatically replaced by pine, with background species including ash and oak throughout. Sediment is reported as clay during the spruce –dominated interval, and became clay gyttja across the transition interval from spruce to pine. Hupy & Yansa (2009) discuss the last 17,000 years of Michigan's vegetative history. Pollen from Wintergreen Lake shows spruce dropping dramatically at 11,000 Cal years BP, pine-dominating for the next 1,000 years, and then oak becoming the dominant species for the rest of the Holocene.

Yu (2000, 2003) has researched ecosystem response to lateglacial and early Holocene climate oscillations in the Great Lakes region of North America east of the study area. Summary pollen percentages at Crawford Lake (Yu 2003) show a reduction in spruce at the end of the YD with attendant increase in pine, although spruce then increased with a drop in pine until 10,984 Cal BP years, when pine again dominated and spruce dropped to near 0%. Twiss Marl Pond (Yu, 2000) shows decline in spruce and increase in pine percentage around 11,690 Cal years BP.

Szeicz & MacDonald (1991) did a pollen study on Decoy Lake, Ontario showing spruce domination until 11,800 Cal BP, when it diminished very abruptly to almost 0% spruce pollen and was displaced by pine, which jumps from almost 0% to 80%. Around 7254 Cal BP pine diminished from 80% to about 20% when oak pollen increased to about 35%.

Shuman *et al.* (2002) studied lakes in a transect across eastern North America and also discussed the shift in vegetation type linked to lake levels. Lake level drop seems to be linked to spruce decline and pine proliferation. In areas where the lake levels remained high until the end of the YD in MN and the Northeast, there was a persistence or resurgence in spruce at 7 of 9 sites studied, in a transect across eastern North America until the end of the YD, after which pine invaded.

Gonzalez & Grimm (2009) reconstructed lateglacial to early Holocene vegetation and climate conditions at Crystal Lake, McHenry Co., Illinois with a high resolution pollen record and 36 radiocarbon dates. They report four phases of vegetational change since the LGM. Phase I following LGM, the typical rise of spruce (*Picea*)dominance (with low percentages of *Larix* (tamarack) and *Abies* (fir),

Fraxinus nigra (ash), *Quercus* (oak) and *Ostrya/Carpinus* (ironwood/hornbeam) and lesser amounts of upland herbaceous taxa such as *Artemisia, Ambrosia* (ragweed) and Poaceae (grass), and sedges (Cyperaceae). Phase II is typified by a decrease in *Picea* and expansion of deciduous taxa, particularly *Fraxinus nigra*-type, but also *Ostrya/Carpinus* and *Quercus*. In other locations in the Midwest, the authors note that other deciduous taxa appear, such as *Carya* (hickory), *Ulmus* (elm) *Salix* (willow), *Fagus* (beech), *Juglans* (walnut) and *Populus* (poplar or aspen). Phase III exhibits an increase in *Picea* with a concurrent decline in deciduous taxa. *Larix* and *Abies* also expand, and the end of this phase is marked by sharp peaks in *Alnus* (alder), *Betula* (birch) and sometimes *Pinus* (pine). The final phase, at the onset to the Holocene, sees *Picea* decline dramatically. In northern Minnesota and Wisconsin, *Pinus* increases, and in the southern Midwest, deciduous tax increase, particularly *Ulmus* and *Quercus*.

Shane and Anderson (1993) did a multi-lake pollen study across Illinois, Indiana, Ohio, Michigan, Wisconsin, Kentucky and Ontario (Fig. 1.3). For an overview, from the time of sediment accumulation during ice retreat phase, Picea (spruce) pollen reaches 70-80% but drops to <50% by 15,600 -14,800 Cal BP years. During this time there are also low frequencies of *Larix* (tamarack), *Abies* (fir) and *Pinus* (pine). During the next phase, 15,600-14,800 to 12,900 Cal years, pine pollen frequencies increase, although remain low, along with *Larix* pollen. Spruce pollen frequencies decline abruptly on the Till Plains to below 10%. The deciduous tree pollen assemblages increase to over 60% with oak, hornbeam/hophornbeam and ash. Other deciduous species that also begin to exceed 1% include hickory, elm, willow, beech, walnut and poplar.

The end of this phase is abrupt and marks the beginning of the Younger Dryas. The Younger Dryas phase, 12,900 to 11,510-10,490 Cal. years, "is marked by rapid overlapping pollen shifts, and has strikingly different forms on the Allegheny Plateau and the Till Plains" according to Shane & Anderson (1993).

Shane & Anderson (1993) break the region into Allegheny Plateau and Till Plains because of these differences in pollen behavior. On the Allegheny Plateau during the Younger Dryas, there was

rapid expansion of *Pinus* pollen from less than 10% to 50-75% and included two species, jack pine and red pine. Spruce pollen frequencies declined to 0% by the end of the YD. Fire reached a peak and then declined. Deciduous taxa also declined in pollen frequency. At the end of this phase there was a shift to oak-dominated pollen assemblages (>40%). On the Till Plains during the Younger Dryas there was an increase or recurrence of spruce pollen frequencies from 5-10% to highs of ~12-30%, and overlapping, increase in *Pinus* as seen on the Plateau, from <10% to 20-50%. The spruce recurrence increased from south to north, and was an abrupt shift. There was a slight increase concurrent with the spruce increase, of hemlock, fir, and tamarack (from ~1% to <2-4%. Deciduous pollen declined. At the end of this phase, spruce declined to 0% and pine rapidly declined to 2-10% while all deciduous taxa began to increase. *Quercus* (oak) pollen exceeded 40%. The main difference between the Allegheny Plateau (>300 m) and the Till Plains (300 m or less) is elevation. The vegetation history of this region shows east to west gradients during lateglacial times. The pollen for the western part of this region seems to indicate a climatic reversal parallel to the European Allerod/Younger Dryas warm to cold sequence, according to Shane (1987, 1989).

1.5c Other mastodon sites' pollen & vegetation.

Joyce (2006) gives dates of 15,742 ±405 to 13,954 ± 211 Cal years on wood, almost certainly spruce wood, associated with the Schaefer mastodon site in the southeastern corner of Wisconsin. Joyce (2006) also reports the palynology of the area, with spruce at 63%, *Artemisia* 9%, oak 7%, sedge 7%, pine .5% for the Schaefer mammoth site and spruce at 82%, *Artemisia* 4%, oak 1%, sedge 6%, and pine 6% for the Hebior mastodon site a few miles away. These 2 fossil sites are also associated with Paleoindians, and Goebel (2009) concludes from these sites that they were here 14,600 Cal BP years. Dreimanis (1968) reported that 600 late Wisconsin mastodons have been found in eastern North America, and that these mastodons were associated with open spruce woodlands or spruce forests. 80% of them fall within the time frame of 14,000-10,100 years BP (Calibrated). Dreimanis (1968) attributes

mastodon extinction to climate rapidly shifting to arid 12900 to 11500 years BP (Calibrated) causing the spruce food source to diminish.

The Eldridge Mastodon (Kapp *et al.* 1990) is considered a butchered mastodon site near Crystal Lake, Montcalm county, in west-central Michigan around 12,900 Cal BP years in a spruce-dominated and mixed hardwood forest.

Jackson *et al.* (1986) report vegetation associated with the Kolarik mastodon in northwestern Indiana which dates 13,000 to 12,000 Cal year BP to be open, spruce-dominated forest or woodland, with ash and herbs. The presence of crowberry (*Empetrum*) and dwarf birch (*Betula glandulosa*), both arctic-alpine species, suggests open vegetation transitional between tundra and closed boreal forest.

McAndrews & Jackson (1986) concluded in their study of 61 mastodont and 27 mammoth sites in southwestern to southcentral Ontario that the time span of these animals is 14,0151–11,588 Cal years BP, a time of spruce-dominated tundra woodland and forest. They also conclude that extinction coincided with climatically-induced succession to jack pine and hardwood forest and shrinkage of wetlands.

Summarizing, mastodons went extinct around the time of the end of the Younger Dryas, and fossils are typically found in marl or muck. These studies have been used for insight into lateglacial vegetation, which shows mastodons in association with a spruce-sedge parkland habitat.

1.5d Peatlands

A lateglacial peatlands study for North America was conducted by Halsey and Vitt (2000) with time-slice distribution maps (Fig. 1.6). During postglacial time, 18,000-16,000 years BP there were very little peatlands in Michigan. From 14,000 to 12,000 years, Michigan was covered in peatlands, and from 10,000 to 8,000 years, peatlands had declined significantly in the Midwest and were practically non-existent in Michigan. Today, peatlands cover most of Michigan. The changes in peatland distribution over time is interpreted as changes in moisture levels.

1.5e Pollen & vegetation summary

In summary, from the time of ice retreat around 20,000 years BP, first sedimentation occurred, followed by tundra species, and until 15-16,000 Cal years, spruce (*Picea*) predominated although fluctuated in its pollen intensity in some places, and it was accompanied by low counts of other coniferous species (fir, tamarack, pine) and deciduous species, as well as sedge, *Ambrosia* (ragweed, a disturbance indicator), grass, and *Artemisia,* according to Shane & Anderson (1993) , Gonzalez & Grimm (2009), and Hupy & Yansa (2009). Although Shane & Anderson report 30% spruce by the beginning of the Younger Dryas, other sources indicate spruce predominance lasting to the end of the Younger Dryas, at which time a dramatic change occurred, with spruce being replaced by pine dominance for about 1,000 years. Pine was then displaced by deciduous species (Hupy & Yansa 2009, Anderson 1954, Szeicz & MacDonald 1991, Yu, 2003, Yu 2000). According to Lininger (2008), in northern Indiana spruce ended around 12,000 Cal years BP, and pine began to escalate around 13,000 Cal years BP, declining to near 0% around 11,000 Cal years BP. In some locations, spruce returned briefly after the end of the YD (Shane & Anderson 1993, Jackson *et al*. 1986, Yu 2003, Gonzalez & Grimm, 2009). Spruce and sedge prefer wet, cool conditions in general, and pine thrives in drier, warmer environments. In fact, black spruce (*Picea mariana*) is also known as bog spruce or swamp spruce. Black spruce is often a postfire pioneer species. White spruce on the other hand, has a high susceptibility to fire, and is easily destroyed by it.(USDA NRCA Plants database 2009). The source for white spruce seed can be eliminated with fire intervals of more than once in ten years (Olson & Weyrick 1987). Fires stimulate spring growth of sedge, which prefers saturated conditions. Established sedge will make it difficult for other species to move in. However, if the water table lowers, shrubs and trees may be able to invade (USDA NRCS Plants database 2009). Red pine, like jack pine, needs fire for regeneration, as fire clears the forest floor litter and competition, and reduces the number of cone-destroying insects, and thins the overstory (Farrar 1995) Pine will not thrive in the understory (USDA NRCS Plants database 2009), and therefore spruce must

have been decimated by some agent at work during the Younger Dryas that allowed pine to predominate in the ecosystem.

1.6 Historical fires in Michigan

For analog purposes, historical fires in Michigan are mentioned here for background. Near Mack Lake in the northern Lower Peninsula a prescribed jack pine fire was set on May 5, 1980 that got out of control. It was a fast-moving crown fire with an average speed 2 mi/hr and max speed of 6 to 8 mi/hr. Although this fire is the largest fire recorded for the Huron National Forest since record-keeping started in 1911, it does not compare to the historically "Great" fires in the Lake States. Between 1871 and 1918 fires in Michigan, Wisconsin and Minnesota burned 1 million or more acres in each of six different years and resulted in 2,500 deaths (Plummer 1912, Guthrie 1936). Dickmann & Cleland (2002) mention the fuel-creating circumstances for fire, such as insect infestations, e.g. spruce budworm and jack pine budworm causing mortality. Severe downburst-producing storms, though not common, have caused massive windthrows of trees(Palik & Robl 1999, Dickmann & Cleland 2002.)

1.7 Climate and fire

The most severe fire weather in the Great Lakes region occurs when there are high pressure cells moving into the region from Hudson Bay, Northwest Canada, or the Pacific. The Pacific High causes more high fire danger than any other type. "Lightning fires are common on both sides of the St. Lawrence and in the northern Great Lakes area. Strong winds are common with intense storms in fall, winter, and spring, and with squall lines and strong cold fronts in the summer." (Schroeder & Buck 1970, Ch. 12, p.215). The fire season typically lasts from April through October with peaks in the spring and fall (Schroeder & Buck 1970, Ch. 12, p.216). Generally air masses and associated frontal systems move through the region in a southeasterly direction every 3 to 5 days. When a high pressure system persists longer than normal, however, fuels have more time to dry out. The approach of a cold front aggravates the situation by increasing the flow of warm, dry air from the southwest. Consequently peak fire danger is expected when the Lake States have been under extended high pressure influence just before the

passage of a cold front as happened, for example, prior to the Peshtigo and Great Chicago Fires of 1871 (Haynes & Kuehnast 1970). Precipitation associated with frontal passages normally ends the period of high fire danger. The fast spread rate at the Mack Lake Fire resulted from 3 factors: relative humidity averaging 23%, windspeed averaging 15 mi/hr and gusting to 30 mi/hr and dense pole-sized jack pine. The average interval between major jack pine crown fires is 28 years (Simard *et al*., 1983).

Fire is perceived as a necessary and vital part of an ecosystem. "In the Great Lakes region, a large area of virgin forest exists in the [Boundary Waters Canoe Area] of northeastern Minnesota. Here short- and long-term studies show that for at least 9000 years the principal stabilizing factor has been the frequent occurrence of fire."… "Nevertheless, despite the fire regime, the resulting long-term equilibrium of the forest mosaic, characterized by severe and irregular fluctuations of individual elements, reflects regional climate." (Wright 1974).

1.8 Predictions for this study

Four hypotheses were generated to provide a framework within which to examine the results derived from this study (Fig. 1.7). What charcoal signals might one expect for lateglacial fire? Postglacially, after the ice retreated and the landscape was wet with glacial meltwater, remnant ice blocks were forming kettle lakes, and the vegetation was changing from colonization vegetation to a spruce-sedge parkland. Under these conditions, we might not expect many fires. Once the spruce-sedge parkland was established, fires would most likely have been linked to warming, drought, insect blight, storms and/or windiness. Indications of this in lake sediments could be wind-blown loess, and shallowing indications. A further study, though, would be necessary to address a lake shallowing analysis, one where cores would be taken in a transect from the shoreline.

Hypothesis 1 considers a possible charcoal signal for an arid YD. Initially vegetation flourishes during a wet Bolling Allerod if GISP2 increased oxygen isotopes represent more moisture, and spruce-sedge predominant at this time is also moist. Then if drought sets in during the YD represented by a drop in ^{18}O isotopes in the GISP2 ice core, and an abrupt transition in vegetation from moisture-loving

spruce and sedge to drier-tolerating pine species by the end of the YD, fires occur and the vegetation is reduced.

Hypothesis 2 considers the possibility of few fires postglacially up to the YD due initially to a wetter environment as the ice sheet melted, exposing barren ground which would have been colonized by herbs and shrubs, and then it would have gradually progressed to a predominantly spruce-sedge parkland, which was still wet. During the Allerod, increased ^{18}O isotopes in the GISP2 ice core may reinforce the view of a wet environment, but this interpretation may be subject to regional variation in climate.

In **Hypothesis 3**, anthropogenic fires are contemplated. Fires may increase when *Homo sapiens* appears on the landscape. The Schaefer ?mammoth (the author questions that it is a mammoth as the habitat points to a mastodon) and Hebior mastodon both in extreme southeastern Wisconsin have associations with humans, cut marks on the bones and stone tools, and date to 14,600-14,400 Cal BP years ago (Joyce 2006, Overstreet & Kolb, 2003, Goebel, 2009). Paleoindians may have set fires to clear the brush from the landscape in order to create edge areas for game (Williams 2000) and to allow for easier travel. Two of the lakes in this study, Swift and Slack, are less than 1 km from an investigated Paleoindian site, the Gainey archaeological site (Don Simons, pers. comm.). Big Fish Lake and Sixteen are 16 and 30 km from this site, respectively.

Hypothesis 4 considers the Firestone *et al.* (2007) extraterrestrial impact hypothesis. For a global or at least continental-scale catastrophe, a large spike might be predicted at 12,900 years BP that stands out from all other fires.

2. Methodology

2a. Site Selection

The ideal lake for charcoal study would have relatively steep sides to the lake basin, but in the lake itself, sides that are not too steep or there will be too much redeposition and slumping. In Lower Michigan, the topographic relief is not particularly pronounced, so because lateglacial deep varved lakes are relatively uncommon, several relatively shallow lakes were chosen, at depths between 5 -10 m. This allowed for more data collection and increased the likelihood of success in finding lakes with Younger Dryas-age sediment.

The Flint Michigan area was selected for its proximity to the Gainey archaeological site, and for being an area where there was a dearth of limnological charcoal studies. Lake selection was facilitated by using the Michigan Department of Natural Resources Inland Lake database for information and bathymetric maps (MDNR 2008). In addition, permission was obtained by Gainey site investigator Don Simons to access two private lakes, Slack and Swift Lakes, that are located within a km of the Gainey site in Genesee County. Another consideration for lake selection was easy access to the lake. Big Fish Lake in Lapeer County, in the Ortonville State Recreation Area, and Lake Sixteen, in Orion Oaks County Park in Oakland County met these criteria. All four lakes have never been sampled before. Table 2.1 contains a synopsis of the field information about these lakes, and Fig. 2.1 has Google Earth images of the lakes.

Lake name	**Slack**	**Swift**	**Sixteen**	**Big Fish**
State	Michigan	Michigan	Michigan	Michigan
Latitude	42.87167	42.88523	42.75542	42.88396
Longitude	83.61042	83.62281	83.28473	83.39243
Water Depth	31’ or 9.45 m	32’ or 9.75 m	17’ or 5.18 m	31’ or 9.45 m
Elevation	282 m	286 m	302 m	320 m
Area	~18.5 ha	~1.6 ha	36.8 ha	42.5 ha
LRC Name style	GNY-SLK08-1A-1A-1	GNY-SFT08-1A-1L-1	GNY-SXT08-1A-1L-1	GNY-BFH08-1A-1L-1
UC Core Lab No.	0812	0813	0814	0815
Total meters of Core collected	8	8	3	9

Table 2.1 Summary of field data for the lakes in this study.

2b. Field Methods

The lake sediment cores for this study were collected in 2 days in February 2008. Bathymetric maps were acquired for Big Fish and Lake Sixteen, but these were not available for Slack and Swift lakes. A transect was made across each of these lakes using an ice auger and portable depth sounder to get depths of the lake bottom, and the deepest location was selected. GPS coordinates were taken at each borehole.

Two inch diameter cores, in one meter sections, were taken with a Livingstone piston corer. Since this study has a Younger Dryas temporal focus, target sediments were glacial contact stratigraphy, gravel or sand in the deepest sediments into the Holocene, often dark organic sapropel. Typically in lake coring, a second borehole is made in the vicinity of the first borehole, and offset by half a meter depth to overlap the break in cores of the first borehole. This enables construction of a composite stratigraphic section of lake sedimentation.

All cores were extruded, wrapped in plastic wrap, and placed in split polyvinylchloride (PVC) one-meter-length tubes. Both halves were marked as to lake name, thrust, sediment depth, and which direction is up. PVC halves were secured with plastic cable ties and placed in a large insulated box for transportation. Cores were stored under refrigeration until ready to be processed.

2c. Lab Methodology

2c.1. Limnological Research Center

The lake cores were analyzed in June 2008 at the Limnological Research Center (LRC) at the University of Minnesota in Minneapolis. All cores were assigned LRC nomenclature. Multiple analyses were performed, including gamma logging/magnetic susceptibility, splitting the cores, high resolution digital photography of the freshly split cores, initial core description, high resolution magnetic susceptibility (a second analysis), and core correlation by observation of the cores and by using Corelyzer software of the core images. In addition some seeds were identified using the LRC reference

library and seed reference set. Raw data can be found in Appendix 1. Images appear with the graphed data for each lake in the Results chapter.

Magnetic susceptibility and gamma logging were systematically performed on a Geotek multi-sensor core logger (MSCL) and later on a more precise Split-Core Logger (Geotek XYZ MSCL). High resolution images were captured with a Geotek Corescan-V digital linescan camera with a resolution of 10 pixels/mm. Orthogonal polarizing filters were used over the light source and lens. For detailed descriptions of the processes and equipment, see http://lrc.geo.umn.edu/corefac-icd.htm and for Initial Core Description, see http://lrc.geo.umn.edu/icd.pdf

Gamma logging is a measure of density, and **magnetic susceptibility** reveals the presence of magnetic particles in the sediment. For magnetic susceptibility, "the type, concentration and grain size of magnetic minerals found in lake sediments vary according to a variety of processes operating in response to changes in climate, human activity and limnology. Examination of ancient sediments enables inferences to be made about past environments." (Sandgren & Snowball 2001).

2c.2. Core Lab – University of Cincinnati

2c.2a.Loss on Ignition (LOI) (Myrbo 2005, Dean 1974). was performed according to standard procedure at 2 cm intervals. Samples are put in weighed and numbered crucibles and placed in an oven at 100 °C overnight to dry them out. Sample & crucible are then weighed and returned to the oven to be heated at 550°C for an hour. Samples are cooled and weighed in the crucibles. This process is repeated one more time at 1000°C. Using the differences in sample weights, the mass lost during the 550°C treatment is organic mass, and the mass lost during the 1000°C heating is carbonate mass. The mass that is not burned off is clay, silica or other non-organic, non-carbonate minerals.

2c.2b. Powder X-ray diffraction was performed in the UC Geology Department with a Siemens X-ray Diffractometer on samples from Slack Lake 1500-1600 cm, to determine the mineral composition of the laminations.

2c.2c. Additional photography of Big Fish cores was done with a Nikon digital camera at the UC Core Lab because some images of the B core were lost during processing at LRC. Microphotography was performed on samples of interest during fine methodology counting, using the Leica top-lighted EC3 microscope and camera, and Firecam Software Version 3.2.

2c.2d. Two radiocarbon dates were obtained for each lake. The first round of sampling targeted the oldest dates possible above the glacial contact to get a baseline date. The second set targeted post-Younger Dryas time to constrain the area of interest. Table 3.1 contains radiocarbon data. Photographs were taken of all macrofossil samples before shipment. All samples were processed at the National Oceanographic Science Accelerator Mass Spectrometry (NOSAMS) Facility at Woods Hole, Massachusetts. CalPal (University of Cologne Radiocarbon Calibration, quickcal2007 ver.1.5, 2005) was used to calibrate radiocarbon dates to 68% range Cal BP using the calibration curve CalPal2007_HULU. The calibration algorithm calculates the same results as CalPal-Beyond the Ghost. HULU refers to Hulu Cave, near Nanjing, China, where 5 stalagmites were dated with Thorium-230 from 70,000 years ago through the Holocene. The oxygen isotopes from the stalagmites were correlated with GISP2's ice core oxygen isotopes (Wang et al., 2001). An age-depth model was graphed for each lake (Appendix A, Fig.8), and a fire timeline constructed (Fig. 4.1).

2c.2e. The constructed fire timeline. A fire timeline was constructed in Adobe Illustrator using the charcoal data graphs (Fig. 4.1). The top date was pinned to a time scale and the bottom date stretched to the correct date on the scale. This was repeated for all 4 lakes. Caveats for this timeline are 1. There are error bars on the radiocarbon dates (25 to 110 radiocarbon years). 2. There may be issues with hard lakes and aquatic samples for some of the dates. 3. The sedimentation rate is assumed to be uniform, but it is not likely it was deposited at a steady rate, and 4. There are issues with calibrating dates across the Younger Dryas (Muscheler *et al.* 2008, Reimer & Hughen 2008, Hughen *et al.* 2006). The age-depth model would be improved by the acquisition of more radiocarbon dates.

2c3. Charcoal analysis

2c3a. Introduction

Charcoal macroscopic analysis methodology is discussed in *e.g*. Whitlock & Larsen (2002) and Schlachter & Horn (2009). Whitlock & Larsen (2002) and Gill (2008) were followed in this study with some modifications. Charcoal particles greater than 125 µm in diameter have been analyzed in this study. Standard macroscopic charcoal analysis refers to particles larger than 100 µm. This is because charcoal particles less than 100 µm, microscopic particles, travel well beyond 100 meters. Particles smaller than 200 µm should be deposited within 6 km of a fire's convecting column and therefore represent local fires. (Whitlock & Larsen 2002).

Charcoal is quantified in this study by counts of the number of particles in a given sample, in all cases a sample volume of 2cc. The volume of charcoal might be considered a better way to quantify charcoal using software and a viewscreen, but fine visual details do not show up on the viewscreen compare to viewing through binocular lenses on the microscope. Therefore, particle counting is the better method, and care must be taken in charcoal sample processing not to break up the charcoal in the sample. In other words, sieve gently.

The morphology of charcoal types has been reported in the literature (Jensen *et al.* 2007; Orvis *et al*. 2005, Lininger 2009) and can be used to identify burned macrofossils when possible. Collecting or generating charcoal for study and breakage under the microscope is essential for proper charcoal identification. Examples of charcoal types from the lakes in this study can be seen in Figs. 2.5, 2.6 and 2.7. Almost all microphotographs were taken at 80X, so these are small particles, indicating local fires. Charcoal morphotypes that can be identified are wood such as wood particles, twigs, leaf veins, and leaf fragments, galls, grass, occasional insects, and aquatic vegetation.

2c.3b. Chronology issues and CharAnalysis.

CharAnalysis is a free software program for analyzing sediment-charcoal records with the goal of peak-detection to reconstruct "local" fire history, developed by Higuera (2008). In non-varved lakes, the

variability of sedimentation rate affects the calculations of charcoal accumulation rates and fire frequency. Due to this contingency, charcoal records need to be converted to intervals that are regularly spaced when there are sufficient dates. Because direct interpolation of charcoal data to a constant time interval may not conserve the quantity of charcoal within the intervals, concentration values and deposition times should be interpolated to pseudo-annual intervals. (Whitlock & Larsen 2002). For two dates per lake in nonvarved lakes, CharAnalysis, can be applied only in a limited way. CharAnalysis is in units of number of particles per square cm per year. CharAnalysis divides the charcoal into two components, a background component (low frequency, slow variation) and peaks component (rapid variations). A rough estimate of above background charcoal is 50 particles per 1 cc of sample or 100 for the 2 cc volume samples in this study (C. Whitlock, personal comm.) Background values may be affected by changes in fuel accumulation and its influence on charcoal production, secondary charcoal--wetter climates may amplify this factor, and extralocal or regional fires. (Whitlock & Larsen 2002). Since this study deals with macroscopic charcoal, the latter is not a major factor. The following site has the software for this analysis. http://www.montana.edu/phiguera/software/software.html

2c.3c. Charcoal Coarse Methodology, Fine Methodology

In this study, two methodologies were implemented, a "coarse" and a "fine" methodology (Fig. 2.4). Initially, 4 cm depth samples were taken (2cc volume) continuously to get a coarse scale overview of the charcoal content of the core, the so-called "coarse methodology." This amounts to not more than 25 samples per meter of core. Then the fine resolution sampling methodology utilized by the Paleoecology Lab at Montana State University, was implemented, 1 cm depths, also 2 cc volume, to get more detailed information. This generates up to 100 samples per meter of core and yields more precise charcoal data for shorter temporal duration. This is the so-called "fine methodology".

Coarse methodology samples were treated with 6% hydrogen peroxide, placed in a 50° C oven for at least 24 hours, sieved with a 125 µ sieve using distilled water from a squeeze bottle, transferred to square Petri dishes, and dried in a 50° C oven. Then the charcoal in each sample was counted on a

gridded jig at ~23X with a Leica binocular top lighted microscope. Sampling (2cc volume) was done by cutting 1 cm x 4 cm "V" channels continuously down the length of the core (Fig. 2. 4). This methodology has an averaging effect because the sampling is over a broader depth/time interval. Samples are stored after counting.

The fine methodology samples were treated with 50 ml bleach and 50 ml 5% sodium hexametaphosphate for 24 hours, sieved, transferred to a Petri dish, counted wet, and flushed. During fine resolution counting, photographs were taken of charcoal samples and macrofossils using the Leica EC3 camera and Firecam software Version 3.2. (Figs. 2.5- 2.7. A hand-held tally counter was used to record charcoal counts during fine resolution counting and grid sheets were used during coarse methodology counting.

Cores from the overlapping boreholes were sampled, one with coarse, and the other with fine methodology sampling technique. This serves as a reproducibility check and has been done in Lake Sixteen, 850-1050 cm, fine methodology, and Big Fish, 900-1200 cm depth, fine methodology, across the temporal zone of interest, pre-YD through YD to early Holocene and partially analyzed in Swift, 1400 – 1800 cm depth, fine methodology. Lake Sixteen and Big Fish Lake show good correlation of charcoal peaks between coarse and fine methodology (Figs. 3.7 and 3.9). In Swift Lake (Fig 3.4), coarse and fine methodologies were compared in cores A6 and A4, both at a depth of 1700-1800 cm. Core A4 is problematic because there is some deformation of stratigraphy. LOI analysis confirmed a lack of correlation, and ultimately core A6 is used for the charcoal timeline. Only coarse sampling was performed on Slack Lake through depths of 1500-1800 cm due to time constraints.

2c.3d. Note on black particle differentiation for charcoal

Differentiating the black particles under the microscope requires practice. Charcoal sometimes appears black, shiny, and iridescent due to intense fires, sometimes matte black, and sometimes partially charred. As a check on the questionable black particles, pressure from a dissecting probe can determine if it is charcoal. If it does not crush under pressure, it is most likely a mineral or rock

fragment. If it breaks only with high pressure and is glassy looking, it is probably vitrinite or coal. If it is soft it is likely organic. Organic particles can be blackened or dark brown, despite bleaching agents. If a black particle is brittle and crushes easily it is almost certainly charcoal. An exception to this guideline is greigite, a magnetic form of pyrite, which forms biogenically as tiny round grains that clump together often in framboids. These will crush under pressure, but when these tiny spherical grains are seen, charcoal can be ruled out. The morphology of charcoal may be either grass, twigs, leaf particles, various plant remains, insect parts, spherical (plant galls perhaps), or look like "expanded sheet metal," or it may appear spongy or lacy or as a "bubble" on a stem (Figs. 2.5, 2.6 and 2.7, this study, Lininger 2008, Jensen et al., 2007, Orvis et al. 2005, Umbanhowar & McGrath 1998). Biotite/mica can sometimes mimic charcoal with its iridescence and darkness. When probing this mineral, the sheets of the "book" will slide. Counting samples in water (fine methodology) has the added benefit of slight flotation of charcoal vs. non-flotation of mineral grains.

2c.4. Reproducibility & testing

2c.4a. Charcoal control samples.

Samples of wood charcoal from a camp fire on an Ohio River beach were collected for control samples and reference purposes to aid in identifying charcoal. The large pieces were crushed with a glass stirring rod, and examined under the microscope. Some lake mud was seeded with different sizes of (sieved and sorted) charcoal, and dried in the oven to see if charcoal could be discerned in the mud. Charcoal particles were highly reflective and wood grain structures were visible. To the naked eye, the 125µ sieved size of charcoal in the mud makes it look peppered. After mixing the reference charcoal into sediment and water, and observing under the microscope, many of the charcoal particles were observed floating. Some did not, however. The floating charcoal is highly reflective and the submerged particles are dark and opaque. Most particles appeared elongate and sometimes as slivers.

2c.4b. Consistent results in coarse methodology charcoal counting.

To test how reliable the author's consistency is in counting charcoal, oven-dried coarse methodology samples for one core (21 samples) were recounted by the author. Stored samples from Lake Sixteen, 850-950 cm depth, which had been counted first on June 22nd, 2008 were recounted on January 11th 2009. The results show the same pattern. Overall, the consistency in results obtained from duplicate counting of dried samples by this researcher is considered reasonable. The percentage of error ranges from 2 to 113%. In the high percentage errors, the actual count variability is low, with a maximum difference of 38 particles difference across the whole analysis. The 113% differenced amounts to 34 particles difference, and was on a sample with a low original count. Graphed data is shown in Fig. 2.8, and raw data on the counts are shown in Appendix A.

2c.4c. Homogeneity of charcoal in lake sediments: multiple sampling at the same level

An extrapolation test was performed at selected stratigraphic depths to see how uniform the charcoal distribution in the lake sediments might be. Multiple coarse methodology samples were taken to test two depths in Swift Lake, 1712-1716 cm and 1776-1780 cm. Five samples were taken from a previously sampled level to check the uniformity of charcoal distribution in lake sediment. To insure maximum contrast, samples were chosen from a sample depth with a high count (1713-1717 cm) and a low count (1777-1781 cm). Figure 2.11 shows a diagram of the method, and Figure 2.10 shows the graphed results. There is some variability in the counts. This is likely due to non-uniform dispersal of charcoal in lake sediments when taking a small cross-section sample. A larger cross-section sample might give more consistent results. Further testing needs to be done to assess how charcoal is distributed in lakes. Whitlock & Anderson (2002) report that "the amount of charcoal in the upper sediments of the deep water cores was highly variable" referring to a study in Duck Lake of the post-1988 fire in Yellowstone National Park. They consider two possibilities for this variability. One is that the charcoal may not be evenly distributed across the lake bottom and postfire focusing of the charcoal may

have intensified core-to-core variability. The second possibility is variability in sedimentation rate and bioturbation since 1988.

2c.4d. Resampling Lake Sixteen 850-935 cm a third time

Lake Sixteen 850-935 cm had some variability between the coarse methodology results and the fine methodology results. This was the first core to undergo the fine methodology process. Lake Sixteen 950-1050 cm, the second core to be processed with the fine methodology, had good agreement with the coarse methodology results. Therefore, Lake Sixteen 850-935 cm underwent a 3rd analysis, with results which fell between the first two but agreed better with the 1st coarse methodology results than the initial fine methodology results (Fig. 2.9). The most likely explanation for the discrepancy of the first fine methodology results for this core is the fact that it was the first core run on the new methodology. Perhaps initial inexperience in processing is a factor. The MSU Paleoecology Lab has distilled tap water at the faucet rather than squeeze bottles used at UC Core Lab, so water flow control with that technique may have been a factor with the initial core processed.

2c.4e. Reproducibility on overlapping cores, for LOI and MS

Loss on ignition performed on overlapping cores shows excellent reproducibility in Lake Sixteen 1014-1100 cm and 950-1050 cm cores, Big Fish 1035-1125 cm and 1055–1120 cm core depths, Figs. 3.7 and 3.9. Magnetic susceptibility and gamma log data show good reproducibility on overlap cores, with the exception of MS in some parts of Big Fish (Fig 3.9).

3. Results

3.1 Introduction

In this section, the results will be discussed by lake, except for charcoal data and radiocarbon dates, which will be discussed across the 4 lakes as a group. First the stratigraphy will be presented, followed by magnetic susceptibility, gamma logging, loss on ignition, and where applicable, X-ray diffraction. Magnetic susceptibility reveals the presence of magnetic particles in the sediment. Gamma logging is a measure of bulk density. Loss on ignition (LOI) provides organic and carbonate weight percentages in the sediment. Powder X-ray diffraction results will be presented for Slack Lake, where some laminations were analyzed.

3.2 The two younger lakes, Slack and Swift

3.2a Slack Lake

All data for Slack Lake are shown in Fig 3.1. Refer to this figure throughout this section. The general stratigraphy in Slack Lake starts at the base of the core with the glacial contact, silty clay, sand and gravel through what appears to be an erosional sand bed at ~1762-1767 cm depth because both upper and lower contacts are not horizontal and there appears to be an uneven clayey edge in the sand bed. Fig. 3.3 shows detailed images. There is a sharp contact at ~1762 cm where the erosional contact meets a 4 cm thick bed with some silty laminations upsection. At 1759.5 cm there is a distinct 2 mm light-colored clay lamination that is iron-rich chlorite based on X-ray diffraction analysis (Fig. 3.2). Above this there are many fine sub-mm microlaminae. From 1721-1758 cm there is bioturbation of alternating dark and light beds. The dark beds coincide with increased organics and charcoal peaks. Continuing upsection, in the 1711-1721 cm interval there is massive light-colored bedding with bioturbation. At 1705-1711 cm there is massive dark sediment that coincides with the largest charcoal peak in Slack Lake. The estimated start of the YD occurs at approximately 1712 cm, based on calculating a constant

sedimentation rate between the two radiocarbon dates and then calculating the depth for 12,900 years BP.

There is a 25 cm light-colored bed at 1670 – 1695 cm that includes charcoal peaks and a slight elevation in carbonate and a drop in organics, seen in the LOI graph (Fig. 3.1).

From 1670 cm upcore to the top (1400 cm) there is organic-rich massive sapropel punctuated by 2 episodes of carbonate peaks at ~1630 cm and ~1535 cm fine laminations that are clearly visible in the stratigraphy. Fires continue (charcoal graph) during this sapropel unit but do not reach the counts seen in the 14,000 Cal BP to 11,000 Cal BP dated interval. Bioturbation is present except for the 1535 cm laminated interval.

Magnetic susceptibility (MS) in Slack Lake shows high levels near the glacial contact at the base where SI units are 300, the highest in all four lakes. Moving upcore, there is a slight elevation seen around 1675 cm, coincidental with the thick light-colored bed. From 1675 on upcore, SI units are very low. Overall the SI units are 40 above the glacial contact and very gradually decrease to 25 at the top of the core. SI units are dimensionless units of magnetic susceptibility (Goldfarb & Fickett, 1985).

Gamma log data demonstrate the same trend as the MS with slight exaggeration of the graph line compared to MS between 1650 and 1750 cm (Fig. 3.1).

Loss on Ignition (LOI) was performed on samples from 1400 to 1800 cm, at 2 cm intervals. From the base of the core at 1800 cm, organics (green line) are zero at the glacial contact while carbonate (gold line) has some peaks to ~20%. Organics begin to rise at ~1755 cm, and shortly thereafter the large charcoal peak is seen at the level of a radiocarbon date, 14,073 Cal BP date. Organics drop at ~1690 cm and charcoal peaks persist during this interval 1660-1690 cm. At 1660 cm, organics begin to rise and continue rising upcore in a sawtooth pattern punctuated by the 2 small peaks in carbonate. The carbonate is low overall, only up to ~20% for low peaks seen at depths of 1535 cm, 1632 cm, 1660-1690 cm, 1710-1716 cm, 1731 cm, 1760-1771 cm, 1779 cm and 1783 cm, and visible as lighter bands in the core sediment images. When carbonate increases, organics decrease, as a dilution effect.

In this lake, some samples were prepared for powder X-ray diffraction analysis by collecting the clay sample from the core and smearing thinly on a glass slide with some distilled water. There is a light-colored lamination at 1759.5 cm that stands out in the sedimentation (Fig 3.3), and this horizon and other depths were analyzed, including 1721, 1725.5, 1730, 1732.5, 1767, 1738, 1756.4, and 1758.4 cm. The results can be seen in Fig 3.2. These samples are all predominantly iron-rich chlorite, illite, quartz and dolomite. These clay laminations may represent deep water, non-bioturbated sediment. This happens in a meromictic lake where the water column does not completely mix. Normally temperate zone lakes mix completely from top to bottom when water temperatures are the same throughout. Meromictic lakes, though, do not have a spring or fall overturn of the lake water and are not completely mixed. This typically occurs in very deep lakes or lakes that have a chemical gradient. The surface of the lake is mixed by the wind and this stratum is called the mixolimnion. The stratum at the bottom of the lake is denser, does not mix with the water above and is called the monimolimnion. In between these two strata is the chemocline. (McGraw-Hill, 2005)

Slack Lake also contains an *in situ* fish skeleton at 1540 cm depth with perhaps 100 associated unidentified bead-like structures (Appendix B, Fig.2). These are not testate amoebae (Bob Booth, pers. communication). The beadlike structures are hard, dark amber-colored, and about 1 mm or less in diameter. They appear to be some sort of tiny mummified fruits or berries, perhaps eaten by the fish before it died. Perhaps acids in the fish's stomach affected preservation of these structures. The fish horizon is younger than the area of interest, but nevertheless a curious unresolved feature of this lake.

3.2b. Swift Lake

Refer to Figure 3.4 throughout this section for all graphs for Swift Lake. Sedimentation in Swift shows a very high level of fine laminations, over 3 meters of mm-thickness laminae. Starting at the base of the core, 1900-1970 cm is massive sand and gravel, the glacial contact. There is a significant charcoal-rich dark bed above the glacial contact at ~1880 cm. This appears to be a 5 cm thick erosional bed with

moss, twigs, and debris as well as abundant charcoal. 1800-1900 cm has fewer laminations, and appears bioturbated, particularly below 1844 cm. Bioturbation indicates oxygenation to the sediment-water interface, and may indicate shallower conditions. 1600-1800 cm is finely laminated throughout with possible bioturbation at 1695-1800 cm. Laminations occur when the sediment is undisturbed by organisms, a condition that can occur when bottom water is anoxic and unsuitable for those sediment churning creatures. Hypolimnetic anoxia is typical in eutrophic lakes with high nitrogen, as bacterial decomposition of organic matter consumes more oxygen near the the sediment-water interface, and *Daphnia*, present in abundance in this lake are particularly sensitive to the change in oxic states (Antoniades 2007). The core section 1500-1600 cm contains fine laminations from 1510-1600 cm while 1500-1510 cm contains vivianite-rich massive sapropel. Although the sediment appears black and organic, fine laminations are masked, and by using Adobe Photoshop's equalizer tool, these structures become evident.

The core section 1400-1500 cm alternates between vivianite-rich massive sapropel (1400-1420 cm and 1467-1500 cm) and finely laminated units (1420-1467 cm). Vivianite appears as random specks of bright blue in the high resolution images, and the light-colored laminations do not appear blue, hence are not vivianite. There were many blue-green particles, massive and acicular, observed in the water during counting of the sieved charcoal samples. These particles are probably vivianite. Swift is a diatom-rich lake, and also iron-rich. If laminations indicate anoxic bottom waters, then the diatoms are most likely planktonic species.

The magnetic susceptibility (MS) in Swift is at its maximum of 100 SI at the glacial contact 1920-1980 cm. At 1850 cm, MS drops close to zero, in a very low zigzag pattern due to alternations and stays there going upcore to 1400 cm. The gamma log follows the same general pattern as the MS, with a slight peak at 1440 cm and 1460 cm where light bedding can be seen in the image. This is non-carbonate (no increase in the LOI gold line for carbonates, Fig. 3.4), and dilutes the organics.

The loss on ignition (LOI) for Swift Lake shows that organics are, as expected, 0% at the glacial contact at the base of this core at 1900 cm. At 1865 cm, organics begin to rise and continue rising to the top of the core at 1400 cm in a marked sawtooth pattern. A major drop in organics occurs at 1440 and 1460 cm, apparently due to dilution by a non-carbonate source. The other sawtooths in organics may be linked to lamination influx. Other than the elevated carbonate (<20%) at the base, and the low peaks in carbonate at 1640 cm, 1460 and 1440 cm, there is very little carbonate in this lake. Two thrusts were taken at the 1700-1800 cm depth. One has lenses and disturbed laminations, and the other has normal laminations. A lack of correlation in LOI between these two parallel cores is attributed to disturbance in one of the cores, which is not used in the final fire timeline.

This lake is typified by the highest number of fine laminations (over 4 meters), mm to sub-mm in scale, of any of the lakes. There are also lots of diatoms, algal mats through time, ostracodes, some charophytes, and an abundance of iron and vivianite. During the image acquisition at LRC, the white vivianite specks were visibly oxidizing to a brilliant blue.

There are topographic maps of Swift and Slack Lakes in Appendix C, Fig. 4.

3.3. The two older lakes

3.3a. Lake Sixteen

Refer to Fig 3.7 for all graphed data in this section. Where Lake Sixteen is situated, Quaternary sediments are end moraines of medium-textured till, glacial outwash sand and gravel and postglacial alluvium (Albert 1994). At the base (1097 cm) of the sequence in Lake Sixteen is the glacial contact, and 1052-1097 cm is sand. 1040-1052 cm is a transitional bed from sand to slightly silty clay. Depth 1020-1040 cm contains 2 light-colored beds which correspond to a carbonate influx (up to ~25%, see LOI graph Fig. 3.7) and 2 dark beds which correspond to increases in organics (dark green line). This section contains the 16,287 Cal BP date and the earliest fires are coincident with the increase in organics at this time. The interval 924-1020 cm appears dark, organic, and is bioturbated throughout.

Depths 892-905 cm and 912-918cm consist of sapropel with bioturbated laminations, which are evident throughout these sections. At 911 cm and 920 cm there are 2 light-colored beds that correspond to an increase in carbonate. The light-colored bed at 850 – 892 cm also corresponds to an increase in carbonate and is shell-rich.

The sand unit at the glacial contact, 1052-1097 cm, has the highest magnetic susceptibility in the core, at 35 SI units (Fig. 3.7). The depth from 1013 to ~1052 cm, has a couple of intervals where the MS increase to ~25 SI. Moving upsection from 1013 cm depth, MS is zero or close to it until the light-colored bed begins around 890 cm. The MS rises to ~25 SI units at the top, at a depth of 850 cm.

The gamma log has elevated levels at the base of the core and then drops at ~1045 cm and remains low with very minor changes that relate to the carbonate influx at 850-925 cm depth.

The loss on ignition (LOI) in Lake Sixteen is distinctive, in that organic and carbonate have an inverse relationship with one another. As one goes up, the other goes down. The carbonate influx is the highest of all four lakes in this section with a maximum of 25%. The sand unit at the base of the core contains low levels of carbonate. At 1040 cm, organics displace carbonate, but at 1035 cm that switches. At 1020-1030 cm there is a peak in carbonate, to ~25 %. At 1020 cm, carbonate drops close to zero, organics rise to over 50%, until there are carbonate peak intervals at 910 cm and 920 cm, where organics drop. From 850-890 cm, carbonate rises and stays high with a low sawtooth pattern (Fig 3.7).

Lake Sixteen is typified by the occurrence of gastropods, ostracodes, bivalves, some charophytes, limonite, occasional vivianite occurrence, and occasional cattail seeds. Appendix D, Fig. 5 shows topographic and bathymetric maps of Lake Sixteen.

3.3b. Big Fish

Refer to Fig. 3.9 for all graphed data discussed in this section. Big Fish is situated on in the Marshall Formation, Late Mississippian gray pink or red sandstone and siltstone, and end moraines of medium-textured till (Albert 1994). Big Fish lake sediments are gray clay with many fine black laminations that disappear upon exposure to air. At the base of the core, 1250-1290 cm, there is coarse sand and gravel

at the glacial contact (Fig 3.9). From 1250 cm upcore to a silt lamination at 1065 cm, the sediment is predominantly gray clay, with fine dark laminations that disappear upon exposure to the air. There are *Cytherissa lacustris* ostracodes in this unit. From 1065 to 1190 cm the sediment is iron-rich. In processing sediment for charcoal, the water in some Petri dishes turned orange from the oxidizing iron in the sample. Irregular orange shapes of limonite were also observed. From 1110 cm upcore to 1020 cm there are abundant *Najas* seeds visible as black specks in the gray sediment. The common name is water nymph, and it is a common completely submersed annual plant (USDA 2009, Washington State Dept. of Ecology 2009) and therefore not suitable for radiocarbon dating (possible hardwater effect due to obtaining its carbon from the water rather than the atmosphere). These seeds are typically tan but will turn black in anoxic sediments (E. Grimm, pers. comm.) At 1065 cm there is a thin silt lamination, above which the sediment becomes slightly more organic. At ~1020 cm there is a 5 cm thick bed of sand. From 1020 cm upcore to 900 cm, the sediment is organic but adjusting the photos in Photoshop by equalizing brings out alternating bands of light and dark bedding. These can be seen in the LOI pattern as rounded sawtooths (Fig. 3.9). This is not related to carbonate, which remains close to zero.

Regarding magnetic susceptibility, the base of the core is over 50 SI units but elevations in MS are typical in the coarse glacial sediments (T. Lowell, pers. comm.). There is a small spike at 1058 cm that corresponds to the silt lamination. The rest of the MS results above the glacial contact are not close to zero as is the case in the other 3 lakes, but ranges up to 25 SI units. There is a distinct spike at ~1020 cm that corresponds to the 5 cm thick sand bed.

Gamma logging shows there are spikes at the base of the core corresponding to the coarse sand/gravel sediments. Overall there is a small but steady decrease from the base of the core up. There is also a large peak at a depth of 1015 cm at the sand bed strata (Fig 3.9). There is a smaller spike at 1058 cm corresponding to the silt lamination.

Loss on ignition (LOI) has been measured from 934 cm to 1120 cm. From 1120 cm to 1060 cm, carbonate is at its highest, not above 20%, and organics are close to zero. At 1060 cm, organics begin to

rise, but slowly up to 1040 cm where they continue to rise, then get interrupted upsection by the sand bed at ~1020 cm. Above the sand bed, organics rise rapidly but in a rounded sawtooth pattern, which can be seen in the lighter laminations hidden in the organic sediment. The larger percentage of non-organic, non-carbonate is likely clay, based on the clay texture of the sediment.

Big Fish Lake is an oligotrophic or low productivity lake characterized by being iron-rich and having a lot of "greasy" gray clay sediments with dark laminations that disappear upon exposure to air. There is a distinct interval of *Najas* seeds, a common aquatic plant. There are also alternating ostracode (*Cytherissa lacustris*) and charophyte horizons (Fig. 3.8) which may be a function of solubility of the tests, ostracodes being aragonite, and charophytes utilizing carbonate. This has been a deep lake (benthic ostracodes) with very fresh water (indicated by *Cytherissa lacustris* ostracodes, B.B. Curry, pers. comm.) See Appendix D, Fig. 6 for topographic and bathymetric maps of Big Fish Lake. It is 21.3 m (70 ft.) deep today and cores were taken at 9.45 m (31 ft.) depth.

3.4 Radiocarbon Dates

Radiocarbon dates for all four lakes are summarized in Table 3.1. There are a total of eight radiocarbon dates obtained for this study, two for each lake. The goal for obtaining the first sample in each lake was to get an organic sample as low as possible in the core to get a baseline date. The goal for the second sample was to get a date above the Younger Dryas in order to bracket the time interval in question.

Three of the dates were obtained on bulk sediment, lower Lake Sixteen, upper Lake Sixteen, and upper Big Fish, as no identifiable macrofossils were found at the desired stratigraphic levels. The lower Big Fish date is on *Najas* seeds, abundant in sections of Big Fish. The upper Swift lake date was taken on a sample containing egg cases of the Cladoceran *Daphnia,* or water flea, which is an aquatic species. Terrestrial plants and animals use carbon from CO_2 from the atmosphere; aquatic species get their carbon from dissolved carbon in the water. The bulk samples, *Najas* seeds and *Daphnia*, are considered

to be subject to the possibility of contamination with carbonate (old carbon) if it is a hard water lake (Moore 1998, Reimer 2007). If this is the case, the dates may be skewed older by perhaps 250 years. In a study in the Michigan area Moore *et al.* (1998) assessed the hard water effects (HWE) in Lakes Michigan and Huron and reported that 237 years of correction were needed for Lake Michigan and 500 years for Lake Huron, based on mollusk samples from pre-atomic bomb time. Appendix C, Figure 2 shows Moore *et al's* (1986) Michigan carbonate map with the current study area marked with a red dot. It falls within a shale region (not carbonate) in the Lake Erie basin. Although the Moore (1986) study is close in location to the study site, Great Lakes have a different geochemistry than the small inland lakes (T. Lowell, pers. comm.); therefore, the HWE error, if present, is likely to be closer to or less than the lower figure of 237 years.

Coal contamination could give a date of 45,000 radiocarbon years which could be due to either fungi or bacterial activity, or a radioactive component of the coal (Lowe, 1989). Appendix D, Figure 3 shows the coal distribution of the region. During analysis for charcoal in these lake sediments, all black particles at ~23X magnification under the microscope have been scrutinized and coal or vitrinite is not a common occurrence.

The glacial morphology of the region supports the integrity of the dates obtained on aquatic species and bulk sediment. Slack and Swift Lakes are less than 2 km apart just inside the Saginaw lobe moraine, and can be grouped spatially and temporally. The two oldest dates for these lakes group them together, and puts their origin close to 14,000 -14,250 Cal BP. Lake Sixteen and Big Fish, on the other hand, are situated outside the Saginaw Lobe moraine and are therefore geomorphologically older than Swift and Slack Lakes. The radiocarbon dates for these older lakes agrees with this interpretation, with these two lakes having the dates near their inception as correspondingly older, 16,287 ±418 and 15,407 ±255 Cal BP, respectively compared to Swift and Slack. Provisionally these dates are reasonable, in view of the glacial geomorphological information. The broad patterns show consistency. The radiocarbon results and the charcoal data from these four lakes have been used to generate a fire timeline (Fig. 4.1).

3.5 Charcoal data for all four lakes

The charcoal results can be seen in Figures. 3.1 for Slack Lake, 3.4 for Swift Lake, 3.7 for Lake Sixteen and 3.9 for Big Fish Lake. Starting with the older pair of lakes, Lake Sixteen (Fig. 3.7) has 2 peaks at 16,287 ±418 Cal years BP and some fire evidence predating this time. Big Fish (Fig 3.9) has very low levels of charcoal during postglacial time. Fires were occurring then, in the two older lakes before 15,000 Cal years BP. Between roughly 15,000 and 12,000 Cal years BP Lake Sixteen and Big Fish show prominent peaks, on the order of 100-200 particles per sample. Charcoal counts drop dramatically post-12,900 Cal years BP in both lakes going up-core, to 34 in Big Fish, and 54 in Sixteen. So, during pre-Younger Dryas and YD fires were occurring. During post-YD fire occurrence diminished considerably. Vegetation during the Younger Dryas is considered to be a spruce-sedge parkland (e.g. Hupy & Yansa 2009, Shoshani *et al*. 1989, McAndrews & Jackson 1988, Shane & Anderson 1993). Swift Lake has counts of up to 400 charcoal particles postglacially through YD, and up to 1000 in the Holocene, while the other three lakes have counts of a little over 200 at most at any time. In Slack and Swift, the two younger lakes, apart from a significant charcoal peak at ~14,000 Cal years BP, there are high charcoal counts at the beginning of the Younger Dryas (12,900 to 11,600 years) and during it--200-400 particles per sample. Since the counts have been performed on macroscopic charcoal, that is, greater than 125 µ in size, this indicates a fire in the lake basin.

A photograph of the base meter of extruded sediment from Lake Sixteen during field collection shows the sandy glacial contact and several dark bands (Fig 3.8). The double dark band in Lake Sixteen at 16,287 ±418 Cal BP (Fig. 3.7) likely represents two fire events. One is in the dark sediment, and one is in the light sediment above it. The second dark band is overlain by an even thicker bed of light-colored sediment, 25% carbonate, probably an influx of sediment from the basin. This pattern is less clear in the later group of charcoal spikes preceding the beginning of the YD at ~1000 cm depth. There are low charcoal peaks at 930 cm, 917 cm, and 904 cm. At the top of the core, there is a 40 cm thick bed of light-colored shell-rich sediment, 35-50% carbonate, with charcoal peaks (Fig. 3.7).

In Big Fish Lake, there were background fires before 15,407 ±255 Cal years BP and fires increase in number and intensity after this date (Fig. 3.9). Moving upcore, there are multiple charcoal spikes from 15,407 ±255 Cal years BP followed by an erosional influx of sand around ~1018 cm depth. Fires continue after the sand influx, and dark bedding can be seen alternating with the light-colored sediment, which is not carbonate (LOI graph, Fig 3.9). The darkening of the sediments appears to correlate to charcoal peaks, and can be seen across the 970-1070 cm depth, by equalizing the photos in Adobe Photoshop (Fig. 3.9).

Regarding the younger pair of lakes, beginning with Swift Lake (Fig. 3.4) and moving upward from the glacial contact, from 1850-1900 cm there is light-colored clayey silt sediment, less than 15% carbonate though, with a distinct dark band coinciding with the high charcoal spike at ~14,245 ±241 Cal years BP. This is a 6 cm thick bed, an event horizon extremely rich in charcoal, twigs, debris, and moss, likely *Drepanocladus* or sickle moss (Johnson *et al.* 1995, van Reenen, pers. comm., Fig 3.6). This charcoal spike is very high, despite organics in the lake being less than 25%. This probably represents vegetation from around Swift Lake washing into the lake. From 1800-1850 cm there are 3 or 4 significant peaks. Upcore from the start of the YD, around 1800 cm, fires continue with intensively laminated sediment and intense fire activity through the YD and into the Holocene. During post-8924 ±87 Cal years BP (Fig 3.9) there is a lull in fires throughout 1550-1650 cm, still occurring but lesser intensity, and then they increase in intensity to the highest levels in this lake and any of the 4 lakes. The sudden decreases in charcoal particle counts seen at 1430 and 1460 cm coincide with light-colored, noncarbonate sediment influx (Fig. 3.4). This lake also has high levels of vivianite, a phosphate, as evidenced by bright blue specks on freshly split core surfaces, and abundant soft blue-green particles in the sieved samples, and seeing the abundant bright blue specks on the freshly split core surfaces during initial processing at LRC. The other three lakes in this study did not have the levels of vivianite that Swift has. The formation of siderite, vivianite and magnetite are generally attributed to the activity of metal reducing bacteria (Lemos *et al.* 2007). Vivianite typically occurs in anoxic low-sulfide sediments (Berner 1981) and in

sediments that underlie eutrophic lakes (Cornwell 1987, Manning *et al.* 1991). Perhaps the vivianite is linked to ash production at this site, but this is beyond the scope of this study. Swift has double the charcoal counts of any of the other 3 lakes, and records intensive fire activity in the Holocene.

The Slack Lake core (Fig. 3.1) has alternating beds of light and dark sediment with bioturbation across the 1600-1800 cm interval. The dark bands (Fig. 3.3) correlate to charcoal peaks. Above a sand bed at 1760 cm with two irregular contacts that have some clay in that contact, there is a charcoal spike at 14073 ±263 Cal years BP. This is close to the first spike in Swift Lake and thus, they could be the same fire, particularly since the lakes are less than 2 km apart. At 1720 cm there appears to be an influx of light-colored sediment, a drop in organics, a drop in charcoal and a slight increase in carbonate (Fig 3.1). At 1670-1700 cm there is a light-colored clayey bed with little silt, containing several charcoal spikes. This seems atypical of the charcoal-darkening-the-sediments trend, but may represent an influx of sediment containing charcoal, from the basin, or it could be secondary or redeposited charcoal (Fig. 2.3).

Comparing all four lakes in the timeline (Fig 4.1), there appears to be (a) contemporaneous fire(s) around 14,000 years BP. Broadly speaking there seems to be a suite of charcoal peaks from 14,000 to 13,000 years BP, during the tundra phase (Hupy & Yansa 2008). The sedimentation in these 4 lakes reflects an increase in organics (LOI) followed by an increase in fire. Organic-rich sediment, darker in color, often contains charcoal. This may be due to an increase in terrestrial vegetation, providing fuel for fire. When organics are low (LOI), there may not be much terrestrial fuel available to burn. When organics are high (LOI) but charcoal is low, as in intervals in Lake Sixteen and Big Fish Lake, the organics may be due to algae production in the lake.

4. Discussion

4.1 Introduction

The pattern of fire in Michigan during lateglacial time, that has emerged from the charcoal analysis and construction of the fire timeline will be discussed in context of the radiocarbon dates. Caveats for the radiocarbon dates will be addressed. The hypotheses generated in the Introduction will be evaluated in view of the data, including the Firestone *et al.* (2007) hypothesis.

4.2 The fire timeline and how robust it is

In general, bulk dates and aquatic samples are suspected of being modified by the hard-water effect (HWE), which could make dates seem older than they are. To cover all possible uncertainties regarding dating, coal is considered, as there is coal in Michigan (see Appendix D, Fig. 3). Coal is of Carboniferous age, so any ^{14}C would be long gone, unless more recent fungi or bacteria grew in the substrate, or there were radioactive contamination (Lowe, 1989, Gabbard, 2008). Lowe reports that in testing coal specimens for ^{14}C content, resulting ages were 25 – 40 kyr at one lab, and 30-40 kyr at another. Therefore it is unlikely that coal affected any of the dates in this study. In this study there are five dates that are bulk sediment or aquatic samples (see Table 3.1). The upper Swift date is on organic material that included *Daphnia* egg cases, which was just about the only organic material present at that level. Lake Sixteen has 2 bulk dates while Big Fish has one bulk date and one date on *Najas* seeds.

Having noted the coal and HWE caveats, there is actually good support for the validity of the dates for this study. The fact that Lake Sixteen and Big Fish are in situated in older terrain outside the Saginaw Lobe moraine, and also have dates, 16,287 and 15,407 Cal BP years, collectively older than the oldest dates for the younger pair of lakes, Swift and Slack, 14,245 and 14,073 Cal BP years, lends support to the validity of these bulk and aquatic dates. Additional macrofossils have been collected during subsequent analyses, and these are tabulated in Appendix A, Figure 9 and could be utilized to obtain additional radiocarbon dates in the future.

Variability in the rate of sedimentation was a concern in the construction of the timeline. Big Fish, Slack and Swift lake cores average around .3 mm/year or 30 cm/1000 years between each pair of Calibrated dates. But in the Lake Sixteen cores, sedimentation is only .09 mm/year or 9 cm/1000 years. When projected, this puts the upper part of the core into the future. Scouring or slumping of bottom sediments is not a likely reason, as this lake is in fairly flat terrain with no major inlets or outlets but just connections to some adjacent ponds.

In Big Fish Lake there is a ~10 cm thick sand bed, which may be a short term, high sedimentation event. This would affect the time estimated between the charcoal spikes above and below it in the graph on the timeline. Additional dating will probably show that the spikes from 12,000 to 13,500 Cal yrs BP on the timeline are actually closer in time, but separated by high sedimentation rate.

The final caveat for the fire timeline regards the ± error bars for calibrated dates which range from 87 years in one of the Swift Lake dates to a high of 418 years in Lake Sixteen. This is typical for dates across the Younger Dryas, due to a plateau in 14C for that time interval. (Hughen *et al.* 2006, Beck *et al.* 2001, Goslar *et al.* 1999)

In summary, each pair of dates in each lake is in stratigraphic order, and even with the maximum error bars the dates provide useful dated information on lateglacial fire activity. In addition, the glacial geomorphology of the region supports the pattern of dates obtained from these lakes.

4.3. Comparing the lakes

Why would Swift Lake have such markedly different paleofire results such as 4X higher charcoal counts and much more intensive burning, particularly in the Holocene? Swift and Slack Lakes are younger than Lake Sixteen and Big Fish Lake, as documented by the radiocarbon dates and the glacial geomorphology. Swift and Slack are ales than 2 km apart. Swift is the smallest of the four lakes and has the most laminations, the most vivianite, and is a highly productive lake. The Gainey archaeological site is approximately equidistant from Slack and Swift Lakes. Big Fish Lake and Lake Sixteen (Fig. 1.2) are 16 and 30 km, respectively, from the Gainey site, and they are larger lakes. The Lake Sixteen coring site

was the shallowest, and the other three were all close to the same depth (Table 2.1).The fact that the two lakes with the higher fire activity are closest to a known Paleoindian site may be a factor. The fact that Swift is the smallest of the four lakes may be another factor. It has several meters of finely laminated sediment, indicating a meromictic lake, probably due to its small size. Dickmann & Cleland (2002) discuss pre-European large scale blow-down of trees and insect infestations, e.g. spruce budworm, causing tree mortality which in turn provides fuel for fires in the boreal forest regime. Drought could be another killer of forests. If any or all of these factors were operating in lateglacial time, it seems that all four lakes would be affected in the same way by these factors. Therefore, a large scale regional cause can probably be ruled out for the time interval from 12,900 Cal years into the Holocene.

4.4 Results in context of regional fires

There are not many lateglacial charcoal studies for the Midwest. The charcoal results for Appleman Lake (Lininger 2008), near the Indiana border with Michigan are graphed for comparison (Fig. 4.2). There are fires between 14,000 and 13,000 Cal years BP, and 13,000 and 12,000 Cal years BP, but the fires are less intense and fewer in number until about 11,500 Cal years BP, the end of the Younger Dryas, and then fires become more frequent and charcoal counts increase. In this Michigan study, charcoal counts at Swift Lake are eight times higher than Appleman Lake's (Lininger 2008) pre-Holocene counts.

The Shelton Mastodon study (Shoshani *et al.* 1989), a dig site 8 km northwest of Lake Sixteen in Oakland County, reports many charcoaled fragments (Appendix C, Fig. 2). Charcoal from this dig dated to 14,492 ±376 Cal years BP. Mastodon bones dated at 12,994 ±279 Cal years BP. Shoshani *et al*. (1989) state, "Localized charcoaled wood in this zone [on the spruce forest floor that developed on a lake bed] attests to forest fire(s) in the surrounding area." They also report that numerous logs and wood fragments littered a large portion of the excavation area, with logs varying in size from 8.4 m long and 25.9 cm in diameter with roots still attached, not in growth positions. Uprooted trees may indicate

windthrow, supporting the Dickmann & Cleland (2002) statements for fuel loading due to storms. Shoshani *et al.* (1989) conclude, "Forest fires followed by episodic sedimentation events buried some elements of the vertebrate fauna along with numerous logs and charcoaled wood fragments."

4.5. Results in the context of historical fire analogs

There were historical fires that swept the Michigan, Illinois and Wisconsin regions in 1871 (Sodders 1997,MDNR 2007, Haines & Kuehnast 1970). The conditions surrounding these regional fires can possibly give insights into large scale fires that happened in lateglacial time. Although vegetation would have been different, coniferous domination then vs. hardwood predominance now, there could be common factors in fire weather (Schroeder & Buck 1970). The catastrophic and widespread historical fires of 1871 in Michigan, Illinois and Wisconsin were preceded by some unusual conditions, including the extended stay of a high pressure cell, above normal temperatures for the 10 days preceding the fires, and tornado-like winds (Sodders 1997). The summer was one of the driest on record. Fires started in August and continued in following months. On October 8th, 1871, the town of Peshtigo, Wisconsin was totally destroyed and the city of Chicago burned (Sodders 1997). Fires swept across the Saginaw Valley and raged through Genesee county and the Thumb region of Michigan. The smoke prevented traffic on the Great Lakes due to lack of visibility. Ten years later, 1881, the Thumb Fire was far more intense. These fires also came at the end of a severe drought and were fueled by a lot of logging debris and hundreds of land-clearing fires whipped up by hurricane-force winds. The fires began in early September and once again the Saginaw Valley and Thumb region was burned. (Sodders 1997).

If similar fires occurred during lateglacial time, we should expect to see contemporaneous spikes in all four lakes. This does occur between 14,500 Cal BP years to approximately the beginning of the Younger Dryas, so it is possible that drought occurred during this time. Analyzing historical lake sediments to quantify the charcoal evidence would enable a comparison of the intensities of the historical to the paleofires and strengthen the interpretation. Other conditions besides drought, during lateglacial time, that might have contributed to major contemporaneous fires are insect infestation,

and/or windthrow that killed trees and set the stage for large fires (Dickmann & Cleland, 2002). Tree disease might possibly have been a factor, considering Dutch elm disease (Haugen 2009) of historical times and e.g. chestnut blight (US Forest Service 2009) of modern times.

On the other hand, if fires were a regular revitalizing factor on a shorter fire return interval, the effects would be less devastating than in wouthe case where a buildup of fuel load occurs over a much longer interval, followed by drought, windthrow and/or insect devastation that would set the stage for a destructive fire. An example of an ecosystem in equilibrium with fire is the 9,000 years of stabilization through the frequent occurrence of fire in the Boundary Waters Canoe Area of northeastern Minnesota (Wright 1974), which Wright considers to reflect regional climate.

4.6 Results in context of fires across North America

This study, when placed in context of the Marlon *et al.* (2009) synthesis of 30 existing lateglacial charcoal studies and five new YD fire records for North America, provides a dataset for a spatial gap in the Midwest. Compared to Marlon's (2009) results (Fig. 1.5), this study's lakes had fire evidence of equal or higher intensity before the Younger Dryas, in contrast to Marlon *et al.'s* (2009) results (Fig. 4.1). In two of this study's lakes, Sixteen and Big Fish, fires diminished markedly after 12,900 Cal years BP, in contrast to Marlon *et al.'s* results. One lake, Swift, increased in intensity and frequency and one, Slack, continued to have fires but of a lesser intensity than lateglacially. So for this study, there are contemporaneous fires 14,500 Cal BP years up to the YD and possibly across part of it, but there is variability among the four lakes going into the Holocene.

Marlon *et al.* (2009) show elevated charcoal at the beginning of the YD (Fig 1.5) as well as mid-YD and end-YD with fires increasing in magnitude in the Holocene (their Fig. 1c) although they state "No continent-wide fire response is observed at the beginning of the Younger Dryas chronozone, the time of the hypothesized comet impact. The results provide no evidence of synchronous continent-wide biomass burning at any time during the LGIT."

4.7 The Hypotheses evaluated.

Introduction

In this section the predicted hypotheses of charcoal count results made at the beginning of this study (Fig 1.7) will be revisited and examined, in view of the charcoal data.

Hypothesis 1: Younger Dryas is arid. Peatlands (Fig. 1.6) were extensive during the 14-12 ka time slice covering the beginning of the YD but much reduced by 10 ka (Halsey *et al*. 2000). The authors state that peatlands co-occur with boreal forests and infer peat association by spruce occurrence. By lateglacial time, a spruce-sedge parkland had developed in Michigan (e.g. Shane & Anderson 1993, Andersen 1954, Shoshani *et al.* 1989, Hupy & Yansa 2009). A spruce-sedge parkland indicates moist and probably cool conditions, and at the end of the Younger Dryas, the pollen data show that spruce was rather dramatically replaced by pine. Pine flourishes in more arid climates, so the Younger Dryas aridity hypothesis seems supported by the vegetation record.

Regarding the fire occurrences reconstructed from the charcoal counts in this study and how they relate to aridity, the aridity of a region should affect the entire area, and therefore should be seen in all four lakes. In two of the four lakes, Swift and Slack, there are above-background fires across the Younger Dryas. In Big Fish, one or two occurrences are above background, and in lake Sixteen charcoal counts are low (Fig. 4.1). If fires are an indication of aridity, then it was arid at 14,250-14,000 Cal years BP, predating the YD by at least 1100 years. So this study seems to support aridity from 14,500 to the beginning of the Younger Dryas, and possibly continuing through it. For this to be true, Lake Sixteen and to a lesser extent, Big Fish, would have to be in an area with less to burn. Fires occurred across the Bolling as well as the Younger Dryas, indicating that conditions were suitable for fire during different oxygen isotope stages. In other words, there may have been variations during these climate intervals that would support paleofire. To investigate this hypothesis further, lateglacial lake levels should be the focus of an investigation, by coring lakes in a transect from littoral to deep water. Coring and dating bogs in the area would provide additional insight into water table levels as well as vegetation.

Hypothesis 2: Few fires prior to the Younger Dryas. Postglacially we might not expect very many fires as the ice sheet retreated. The landscape would have been soggy initially, as ice blocks melted into kettle lakes. But, clearly there were small fires early on (Fig 4.1) even at 17,500 Cal BP according to the record in Big Fish Lake. There is evidence of a larger fire in the Lake Sixteen record at 16,387 Cal BP. Around 14,000 Cal BP there are major charcoal spikes in all four lakes, although Big Fish is a little later. Improving the age-depth model would refine the accuracy of the contemporaneity of these spikes. There are additional fires in all four lakes records prior to the Younger Dryas. A sand influx interrupts the charcoal spikes in Big Fish around 13,500 Cal yrs BP. So there are fires from postglacial to lateglacial time. Therefore, this hypothesis can be excluded.

Hypothesis 3. Humans set fires. Paleoindians may have set fires to clear brush and create edge areas for deer, to heat-modify stone tools (Kooyman 2001, Pavlish & Sheppard 1983), or remove points from hafts for reworking. Spruce gum was used as a waterproofing agent and heat removes the gum (Don Simons, pers. comm.) Williams, G.W. (2000, 2003) reports extensively on the use of fire by native Americans, and remarks that evidence for the purposeful use of fire by American Indians is difficult to document but he suggests they did it to increase ecosystem diversity, increase edge areas for game, and many other reasons (Williams 2000). Stephen Pyne discusses the extensive use of fire by American Indians, stating that "people transformed ignition from chance into choice, from something that was sparked through lightning's lottery into something as chronic as sunshine." (Pyne 2000). Remus questions how common that fire usage was.

"Even though fires started by Native Americans apparently were more common and had more influence on the land than lightning, this question remains an interesting one. Many Native American land fire managers have postulated that the number of historic ignitions—or possible fire starts—were similar to today. In other words, *historically, fires started by Native Americans occurred across the landscape, but generally were more frequent around areas of settlement and habitation.* Additionally, just like today, these fires' intensity, severity, and ability to increase in size and area would be contingent on the site's dryness. Thus, Cleland's point holds true—then and now. The historical fire return interval would therefore be shortened even more."

--Tom Remus, regional Fire Management Officer, Bureau of Indian Affairs' Midwest Region. Italics added by J. Ballard.

The Gainey Paleoindian site lies less than 1 km from both Swift and Slack Lakes, equidistantly (Fig. 1.2). Anderson (1990) estimates that earliest Gainey phase occupation in the Eastern Great Lakes region occurred around 11,500 to 11,000 Cal years BP. Two thermoluminescence (TL) dates were obtained by Donald B.Simons on Upper Mercer chert artefacts from pit features, 12,360±1240 B.P. and 11,420 ±400 B.P. TL dating was performed by Dr. Ralph Rowlett, University of Missouri. (Simons 1997). Shoshani *et al.* (1989) estimate Paleoindians in the area 10,000 ybp (11,500 Cal BP years) according to the Kessell and LeCroy projectiles in the bog deposits above the bone-bearing layer at the Shelton mastodon site (Shoshani *et al*. 1989). The Schaefer mammoth? and Hebior mastodon sites, both in extreme southeastern Wisconsin, have associations with humans as evidenced by cut marks and stone tools, and date to 14,900 ±289 -14,400±320 years ago (Goebel *et al.,* 2008, Overstreet 2003, Joyce 2006). Thus, it is plausible that Paleoindians could have been southeast of this site earlier than 12,000 years ago. The fact that Swift and Slack Lakes, close to the Gainey Paleoindian site, have charcoal records that show continuous fires from their inception through the Holocene, while Big Fish and Sixteen have low incidence of fires after 12,000 and 12,900 Cal years BP respectively, tends to support the Paleoindian-proximity hypothesis, particularly after 12,900 Cal years BP. The fact that the two lakes that are the farthest from the Gainey site seem to have contemporaneous charcoal spikes with Swift and Slack ranging from 14,000 to 12,900 Cal years BP points to larger scale (regional), non-Indian fires.

This hypothesis then, is viable but tentative. Further investigations would be to obtain better chronology on the Gainey site, if possible. If 12,000 years ago is an accurate time of habitation for Paleoindians in the east-central Michigan area, then this hypothesis is strengthened and the non-anthropogenic cause for the pre-12,000 year fires needs to be investigated further.

Hypothesis 4: The Firestone *et al.* (2007) hypothesis. A bolide strikes North America, and triggers biomass burning. One of the goals of this study was to look for contemporaneous fire at 12,900 years ago to see if there was any substantiation in the paleofire record. If contemporaneous biomass burning did not occur at this time, the case against the Firestone *et al.* (2007) hypothesis would be

strengthened. Finding contemporaneous fire at this time does not necessarily support the Firestone *et al*. (2007) hypothesis, but if this study were put in context of charcoal studies of a larger geographic region, as Marlon *et al.* (2009) have done, a larger-scale picture of paleofire is constructed. The larger scale the fire is at this time, the more support there is for an event of some sort.

If there were a large-scale extraterrestrial event, widespread fires would be expected. Given the caveats in the fire timeline, there are very likely contemporaneous fires at 12,900 Cal years BP. There is a strong signal for contemporaneous fires is about 1,100 years earlier. Swift Lake has an impressive charcoal bed that looks like an event horizon, which dates to 14,245 ±241 Cal BP years. If the charcoal peaks around 12,900 years ago represent a bolide strike, then it might be argued that there were several bolide strikes during lateglacial time. Basically, from this dataset, there is contemporaneous fire at the beginning of the Younger Dryas, but also earlier. The charcoal peaks in all four lakes in the interval from 14,500 to 12,900 Cal BP years suggests contemporaneous fires in the Flint Michigan region.

5. Summary & Conclusions

Analytical results of charcoal in lake sediments have led towards the following conclusions. All dates discussed are calibrated years.

- The fire timeline is relatively robust despite hard water effect concerns and sedimentation variability. Lake Sixteen and perhaps Big Fish may be 250 to 500 years too old at the most. The dates are in stratigraphic order and supported by the glacial geomorphology. Sedimentary rates may account for some displacement of peaks in the timeline; more radiocarbon dates would resolve this uncertainty.
- There were actually more fires than predicted by one of the initial study hypotheses, between postglacial time and the beginning of the Younger Dryas. Fires occur across the Bolling-Allerod as well as the Younger Dryas discontinuously implying nonuniformity of conditions favorable for fire across these interstadials and stadial. The fact that there are a cluster of fires in *all four lakes* between ~14,500 and ~12,900 Cal years BP, indicates widespread contemporaneous fires on multiple occasions and suggests that these fires are not anthropogenic in origin. One possible cause for these early synchronous fires may be storm-induced lightning.
- The evidence for fire in all four lakes at 12,900 BP does not manifest as having larger charcoal peaks than fires evident at other times in the interval since LGM to early Holocene, except in the case of Slack Lake. While it can be argued that synchronous fire is evident around 12,900 BP in east-central Michigan, there is insufficient evidence from synchronicity alone to demonstrate an extraterrestrial source of ignition.
- The pattern of fires from 12,900 BP into the Holocene point to Paleoindians as the originators of the fire. This is supported by the fact that the pair of lakes with high fire activity during this interval, Slack and Swift, are within one km of the Gainey site. The pair of lakes with markedly diminished fire activity post-12,900 BP, Big Fish and Lake Sixteen, are farther from this site, 16 and 30 km respectively.

Future work

- Refine the chronology by obtaining more radiocarbon dates. Some macrofossils have already been prepared (Appendix A, Fig.9).
- Collect historical lake sediments in Michigan to allow comparison of the charcoal data collected in this study to the known historical fires of 1871 and 1881.
- Expand this study to a larger geographic region to determine the extent of lateglacial synchronous fires across the Midwest.
- Launch a study to assess lateglacial aridity by

    --analyzing lake level variations by coring transects from littoral to deep water, and

    --coring bogs for analysis of bog inception and chronology.

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Figures

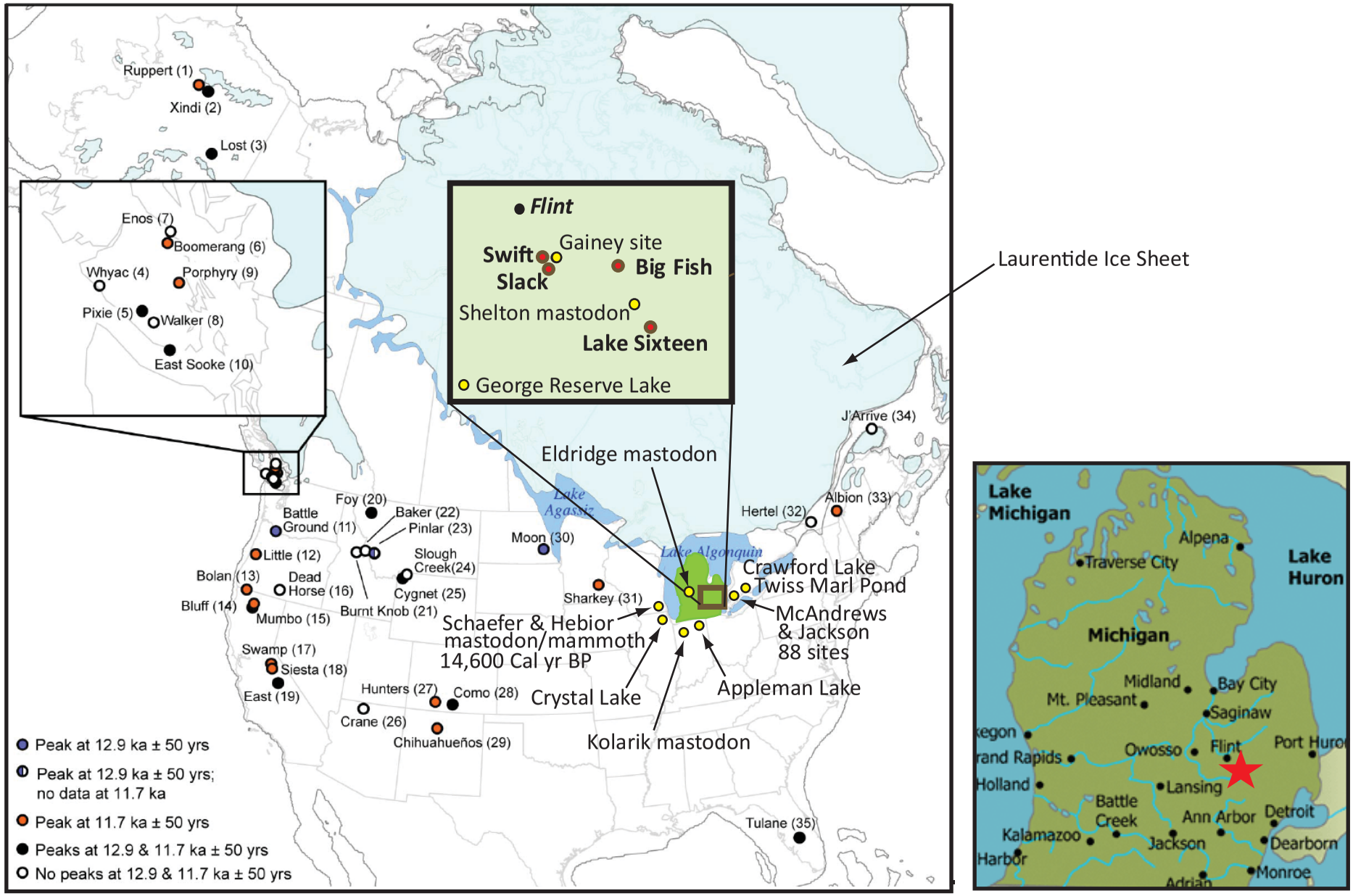
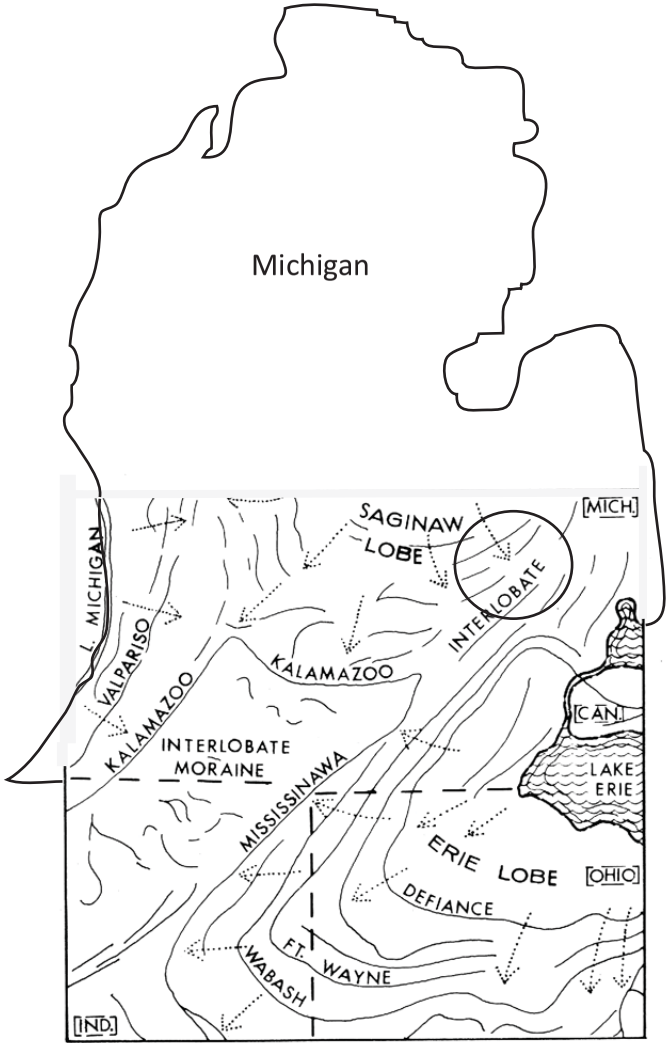


Figure 1.1. Location in North America of the four Michigan lakes in this study (red dots in green blowout box), the Gainey archaeological site, and other regional sites used to reconstruct vegetation and Paleoindian presence (yellow dots), and in a few cases, fire reconstruction (Shelton mastodon and Appleman Lake). After Marlon et al. (2009).

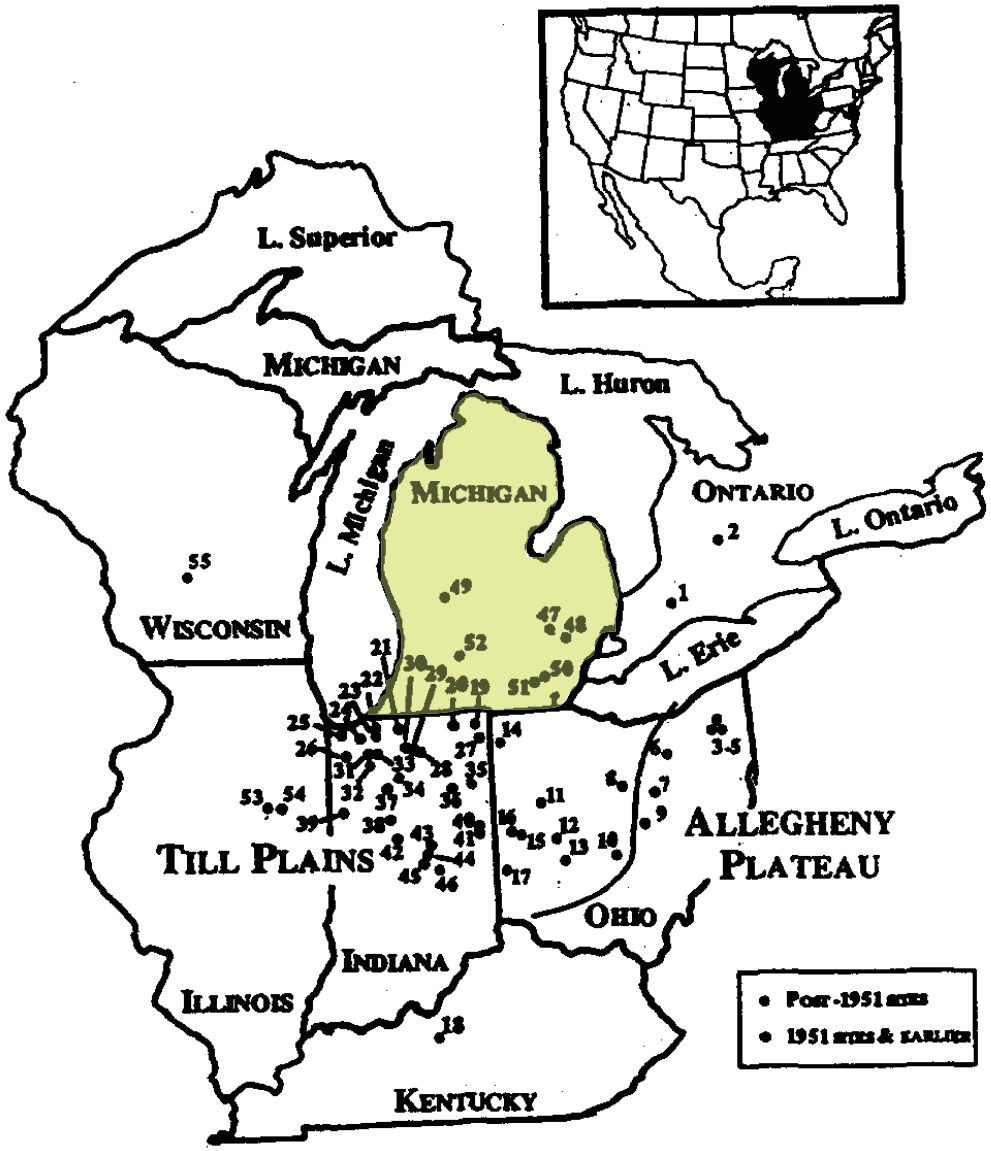


a.



b.

Fig. 1.2. a. Detail map of study site locations south of Flint, Michigan. Swift and Slack Lakes are less than 2 km apart, and the Gainey archaeological site is within that circle. Big Fish Lake is in Ortonville State Recreation Area, and Lake Sixteen can be found in Orion Oaks County Park. Rough distances are shown in km.
b. Detail of the Saginaw Lobe, with study site within the circle. As the Saginaw Lobe retreated, Lake Sixteen and Big Fish formed first, and Slack and Swift developed later. After Schaetzl (2002).



Sites closest to Flint study site

Michigan sites
47. George Reserve Lake, Livingstone Co., Andersen, 1954
48. Shelton Mastodon, Oakland Co., Shoshani *et al.* 1989
49. Crystal Lake [Eldridge mastodon], Montcalm Co., Kapp *et al.* 1990
50. Frains Lake, Washtenaw Co., Kerfoot, 1974
51. Third Sister Lake, Washtenaw Co., Potzger, 1946
52. Wintergreen Lake, Kalamazoo Co., Manny *et al.*, 1978

W. Ontario
1. Pond Mills Pond, McAndrews, 1981

Indiana
19. Pretty Lake, LaGrange Co., Williams, 1974
20. Shipshewana Lake, LaGrange Co., Keller, 1943; Potzger, 1946
21. Lakeville Bog,St. Joseph Co., Hamp, 1940
27. Altona Bog, Dekalb Co., Moss, 1940
28. Tippecanoe Bog, Kosciusko Co., Potzger, 1946
29. Shoe Lake, Kosciusko Co., Oliver 1951
30. Loon Lake Bog, Kosciusko Co., Moss 1940
33. Kolarik mastodon, Starke Co., Jackson *et al.*, 1986
34. Wells mastodon, Fulton Co., Gooding and Ogden, 1965
35. Pyle Site, Adams Co., Shane, 1987, 1993.

Ohio
14. Ladd Lake, Defiance Co., Shane 1991, 1993

Fig. 1.3. Shane & Anderson's (1993) lateglacial pollen synthesis study region, with list of sites closest to the Flint study site..

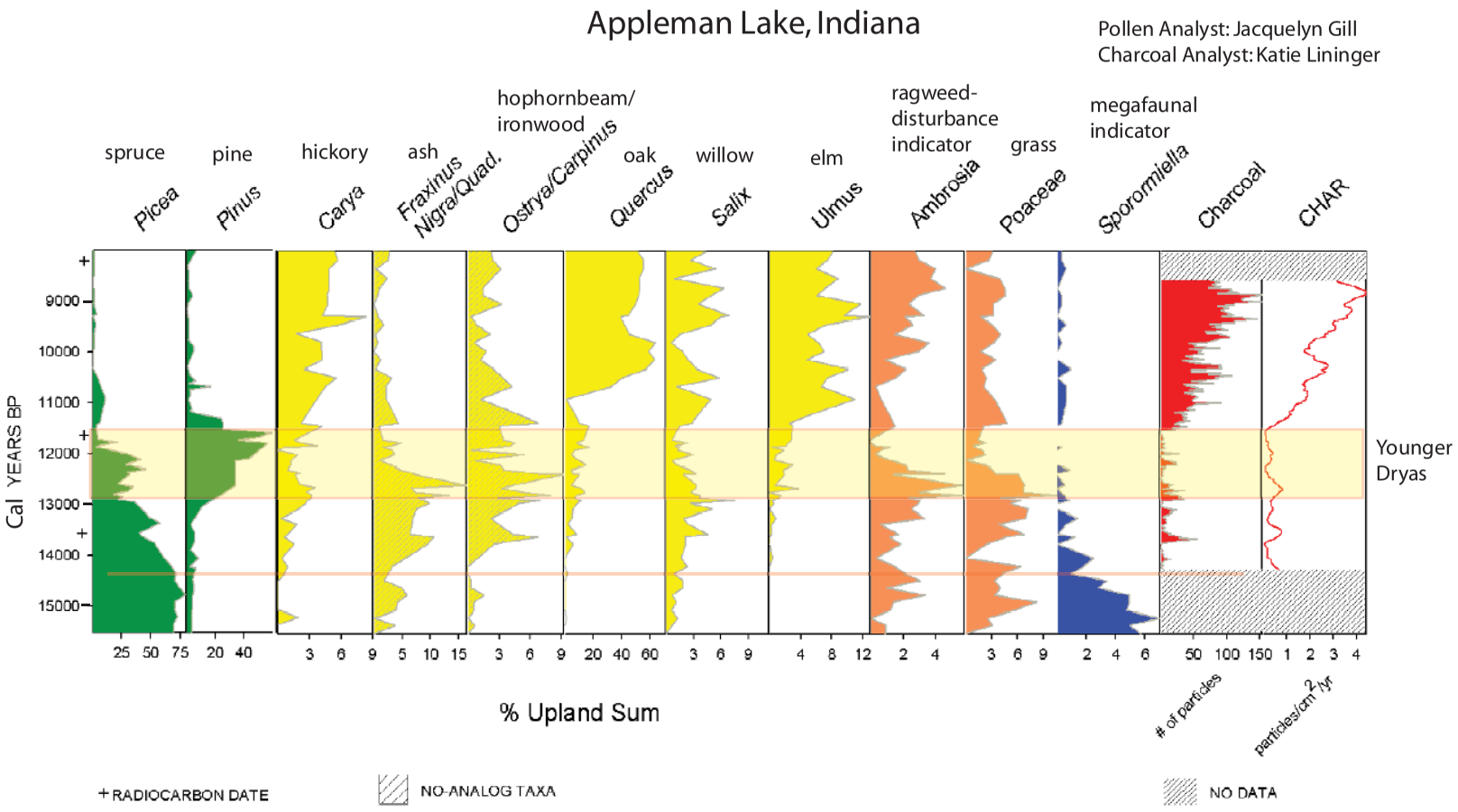


Fig. 1.4. Charcoal and pollen data from Appleman Lake. After Lininger (2008).

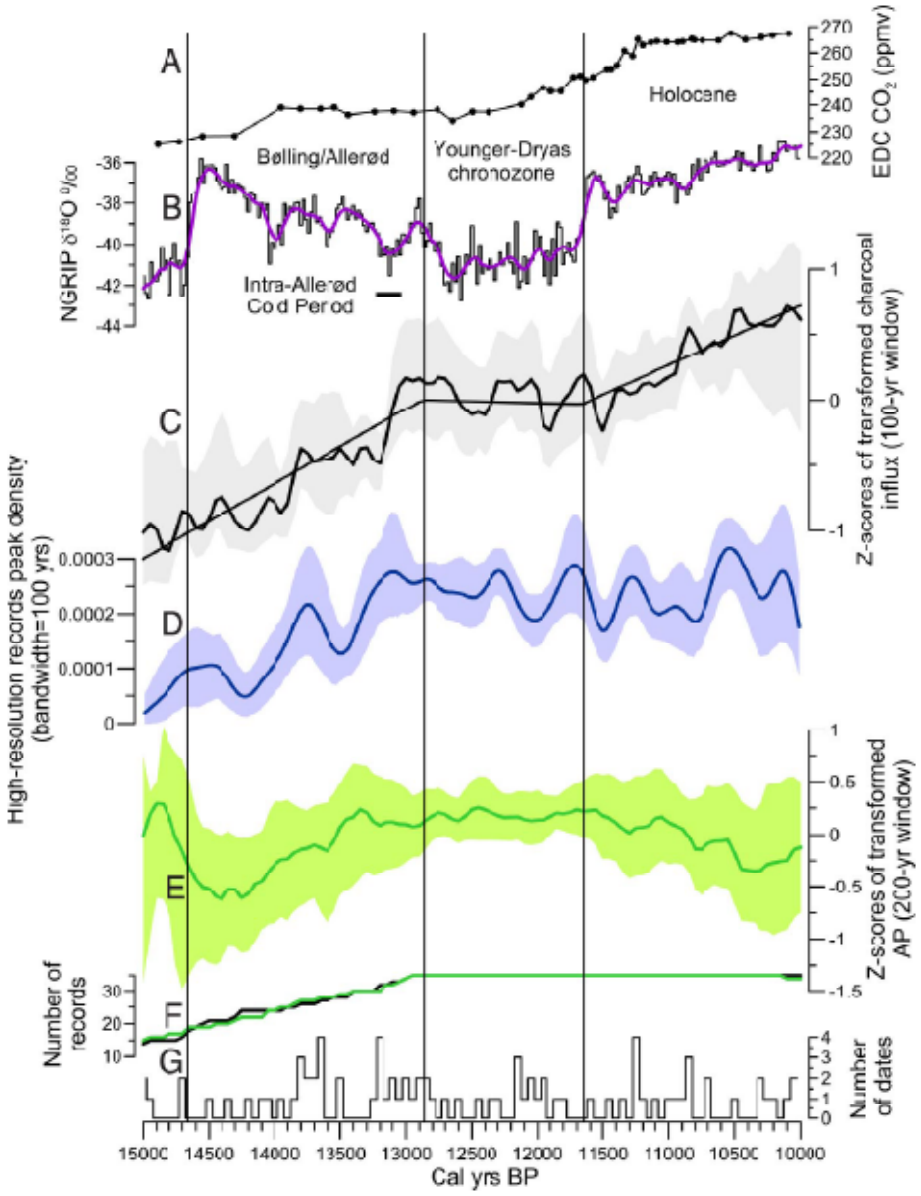
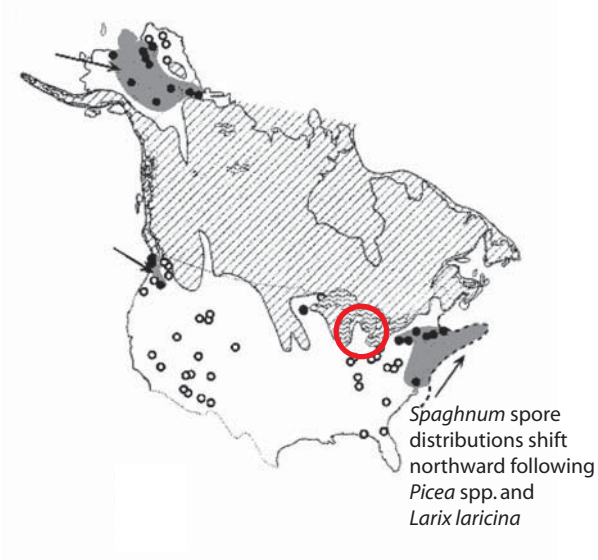
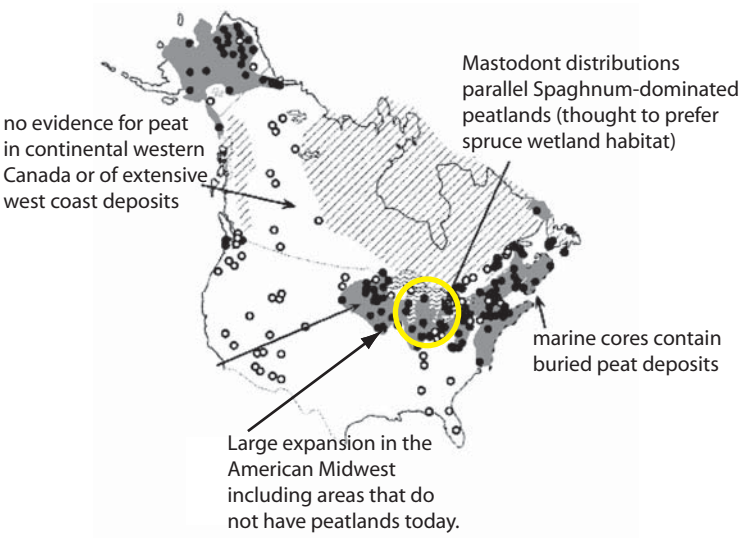


Fig. 1.5. From Marlon *et al.* 2009. Their Fig. 1. Reconstructions of biomass burned, fire frequency, and woody biomass levels in North America. (A) The CO_2 ice–core record from Antarctica (41). (B) the NGRIP $d^{18}O_{ice}$ record, a proxy for North Atlantic temperatures (21). (C)Reconstruction of biomass burned based on 35 records; the straight lines are segmented regression curves, and the smooth curves are local-regression fitted values (D) Reconstruction of fire frequency based on 15 high-resolution records, expressed as the density of peaks per site-year (E) Trends in woody biomass based on 35 records (F) Number of records contributing to the biomass burning (black) and woody biomass (green) trends (G) Number of dates per 50 year interval in the 35 paleo records. Confidence intervals (95%) are based on bootstrap resampling of sites. Vertical lines mark the beginning (~12.9 ka) and ending (~11.7 ka) of the YDC [Younger Dryas Chronozone].



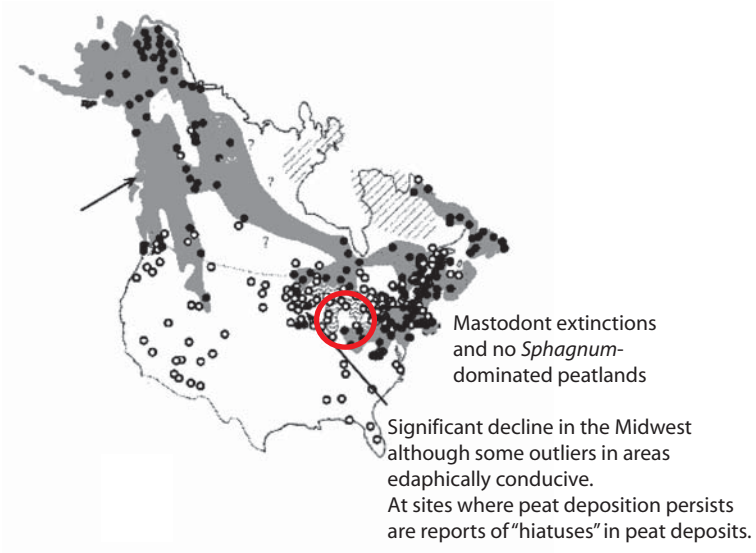
18-16 ka

no peatlands in Michigan



14-12 ka

Michigan is covered in peatlands in the Bolling Allerod



10-8 ka

decline in Michigan peatlands at end of YD



Modern - peatlands return to Michigan

Spagnum-dominated peatlands

ice sheet

approximate limit of coastline

Closed circles represent sites whose *Sphagnum* spore records suggest the presence of *Sphagnum*-dominated peatlands, while open circles represent sites whose spore records suggest that *Sphagnum*-dominated peatlands were absent.

Fig. 1.6 Peatland expansion in Michigan during the first part of the Younger Dryas. After Halsey & Vitt.2000.

Predicted patterns of charcoal counts based on multiple working hypotheses

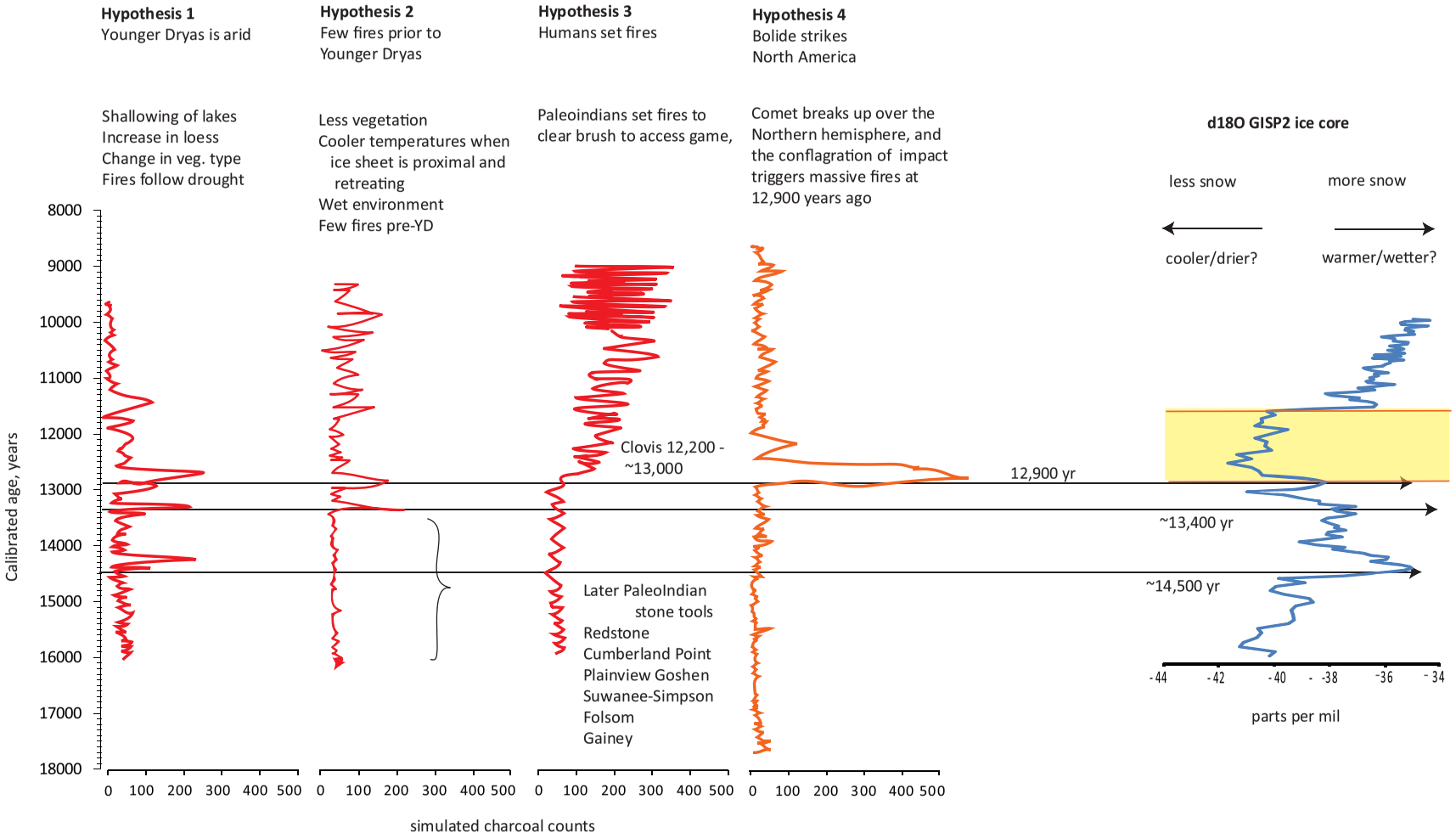
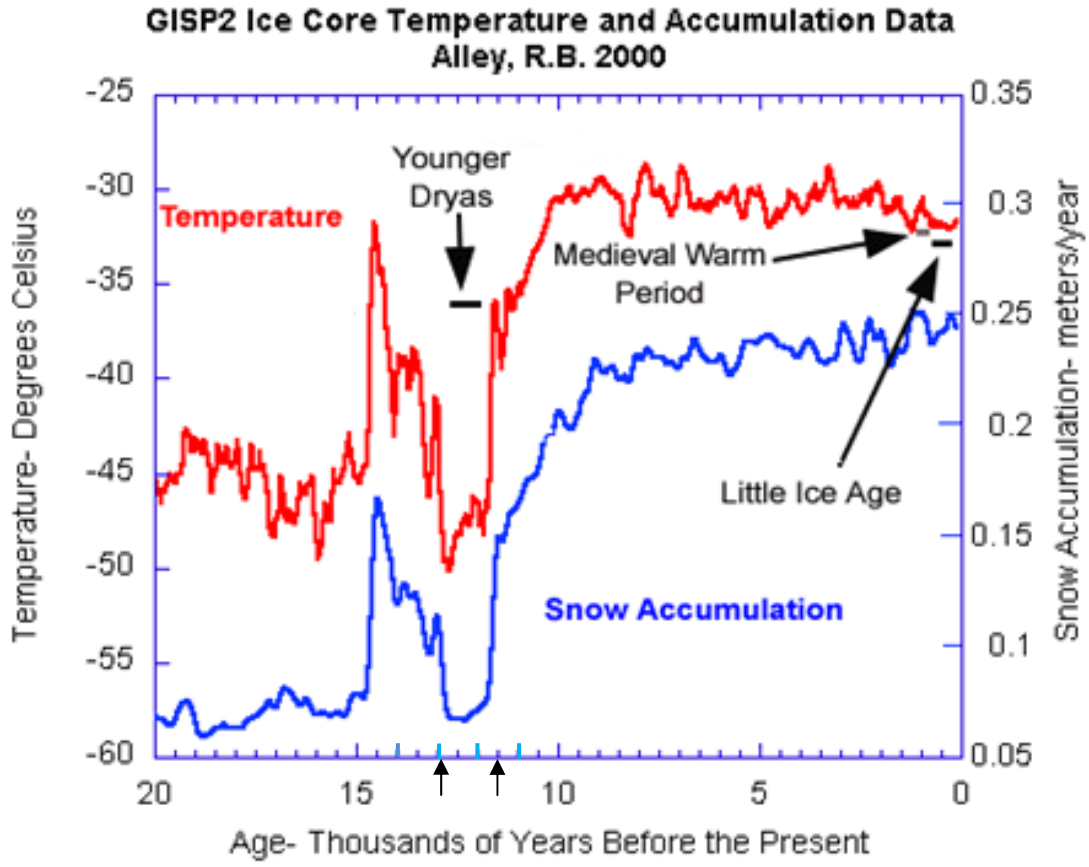


Fig. 1.7 Timeline with multiple working hypotheses modeled for lateglacial wildfire patterns compared with the GISP2 ice core d18O.

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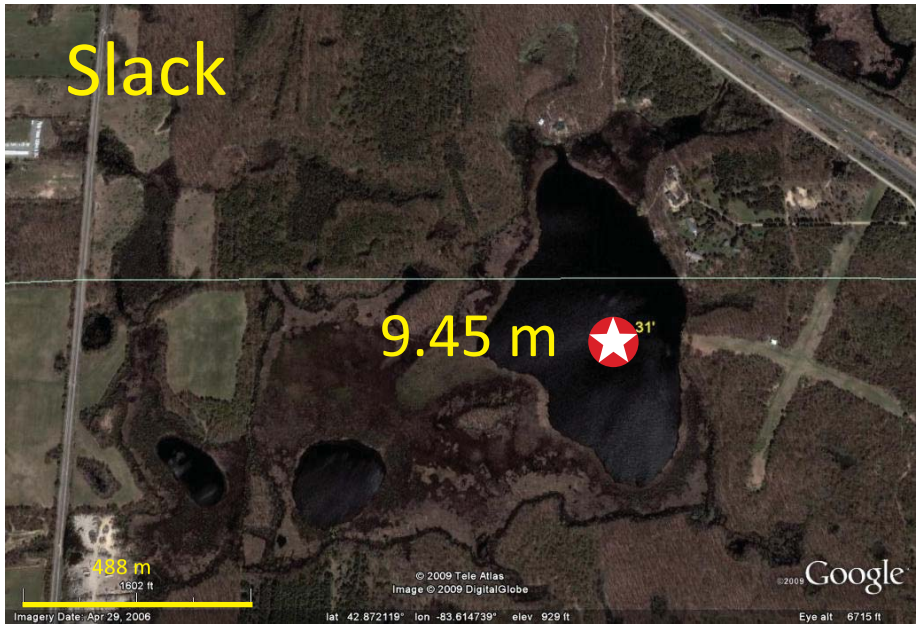


Flower phase, and seed phase of Dryas octopetala in Iceland 2008.

Figure 1.8. Graph of d18O data from the Greenland ice cores (GISP2). After Alley (2000). The Younger Dryas is characterized by a sudden drop in the heavy oxygen isotopes at 12,900 years BP which continues for 1300 years. The rise at 11,600 years BP of the d18O marks the end of the Pleistocene and the beginning of the Holocene, which is an interglacial period. The Younger Dryas is named for the Arctic-alpine perennial flower, *Dryas octopetala*, because its pollen has been found in high abundance in cores from this interval.

Picea glauca	white spruce
Picea mariana	black spruce
Abies	fir
Pinus banksiana	jack pine
Pinus resinosa	red pine
Pinus strobus	Eastern white pine
Tsuga canadensis	Eastern hemlock
Larix laricina	tamarack
Betula	birch
Ostrya/Carpinus (in Betulaceae family)	hophornbeam or ironwood/hornbeam
Populus (in Salicaceae)	poplar, aspen or cottonwood
Juglans	walnut
Corylus	hazel
Ulmus	elm
Fraxinus	ash
Quercus	oak
Fagus	beech
Tilia	basswood, linden
Carya	hickory
Salix	willow
Alnus	alder
Gramineae	grass family
Poaceae	grass family
Ambrosia	ragweed, disturbance indicator
Cyperaceae	sedge family
Carex	sedge
Chenopodium	herb, goosefoot or lambsquarter
Artemesia	herb, wormwood, mugwort, sagebrush
Asteraceae	daisy, aster, sunflower family
Typha	cattail
Potamogeton	type of pondweed

Table 1.1. Common names for lateglacial plant occurrences of the Midwest using species from Shane & Anderson 1993.







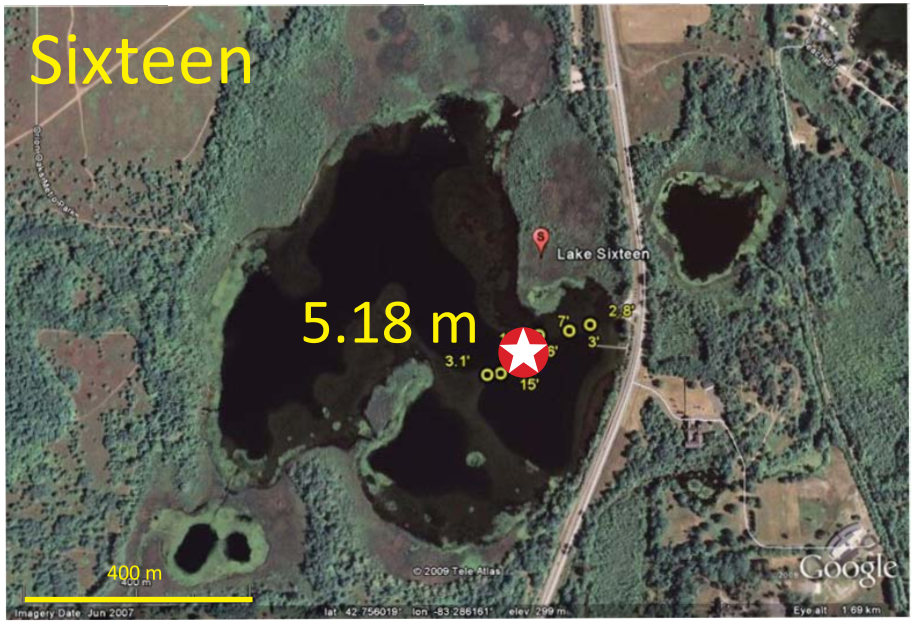


Fig. 2.1 Google Earth images of the four lakes in this study, with drill site locations marked with stars. Depths are for the sediment-water interface. See scale for each lake.72



a.



b.



c.

Fig. 2. 2. a. Lake Sixteen 1014-1114 cm core on site. The deepest part of the core is facing the reader. The bottom portion was discarded. The Livingstone corer is set up behind, bolted to the ice.
b. Rods being added to the Livingstone corer at Lake Sixteen. Rods must be dipped in antifreeze when they are removed from the lake to prevent icing of the threads. c. Extruding lake sediment at Slack Lake.

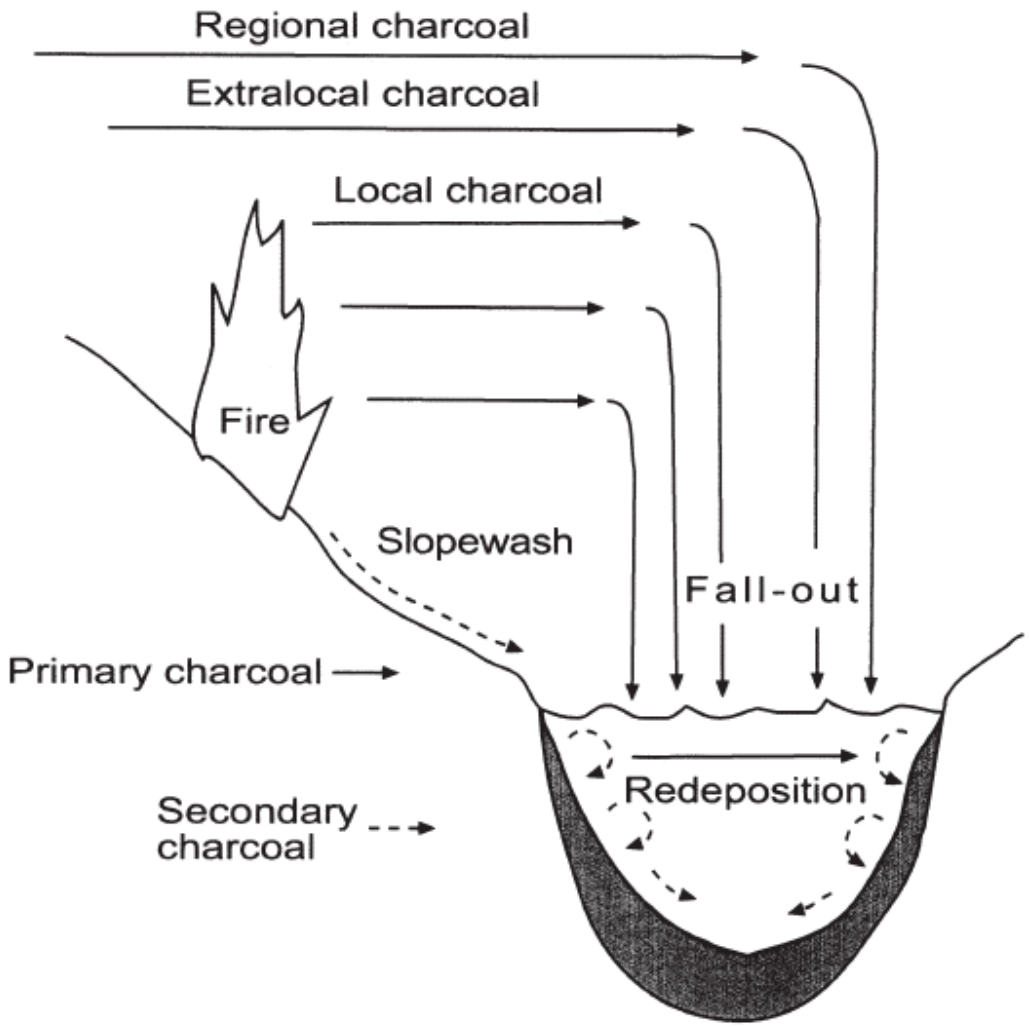


Fig. 2.3 **Primary** (introduced during or shortly after a fire) and **secondary** (introduced in non-fire years from surface runoff and lake sediment mixing) **charcoal activity in a watershed**. After Whitlock & Larsen (2002).

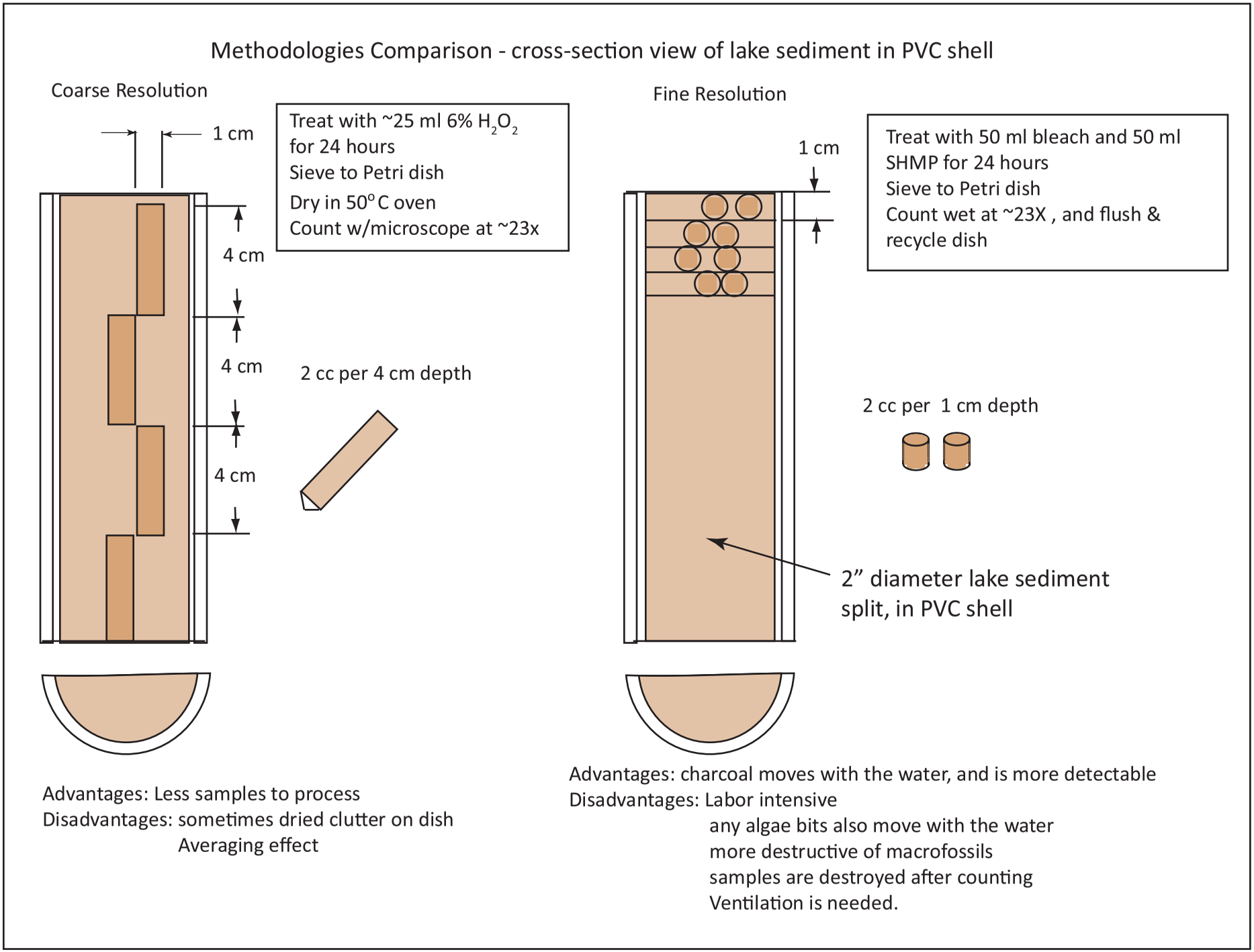


Fig. 2.4 Comparison of coarse sampling and fine resolution sampling methods.

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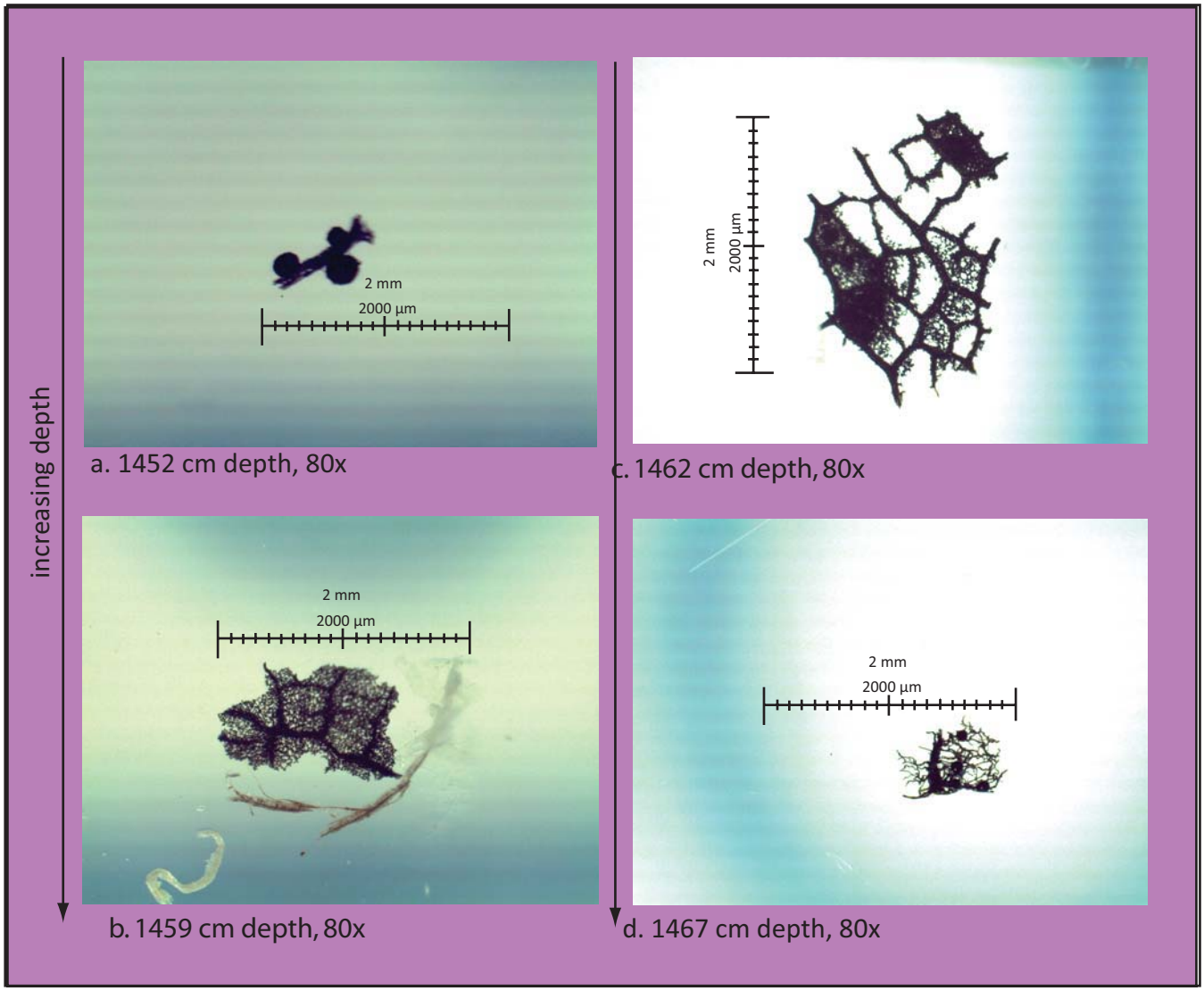


Fig. 2.5. Examples of charcoal from Slack Lake, 80x magnification.

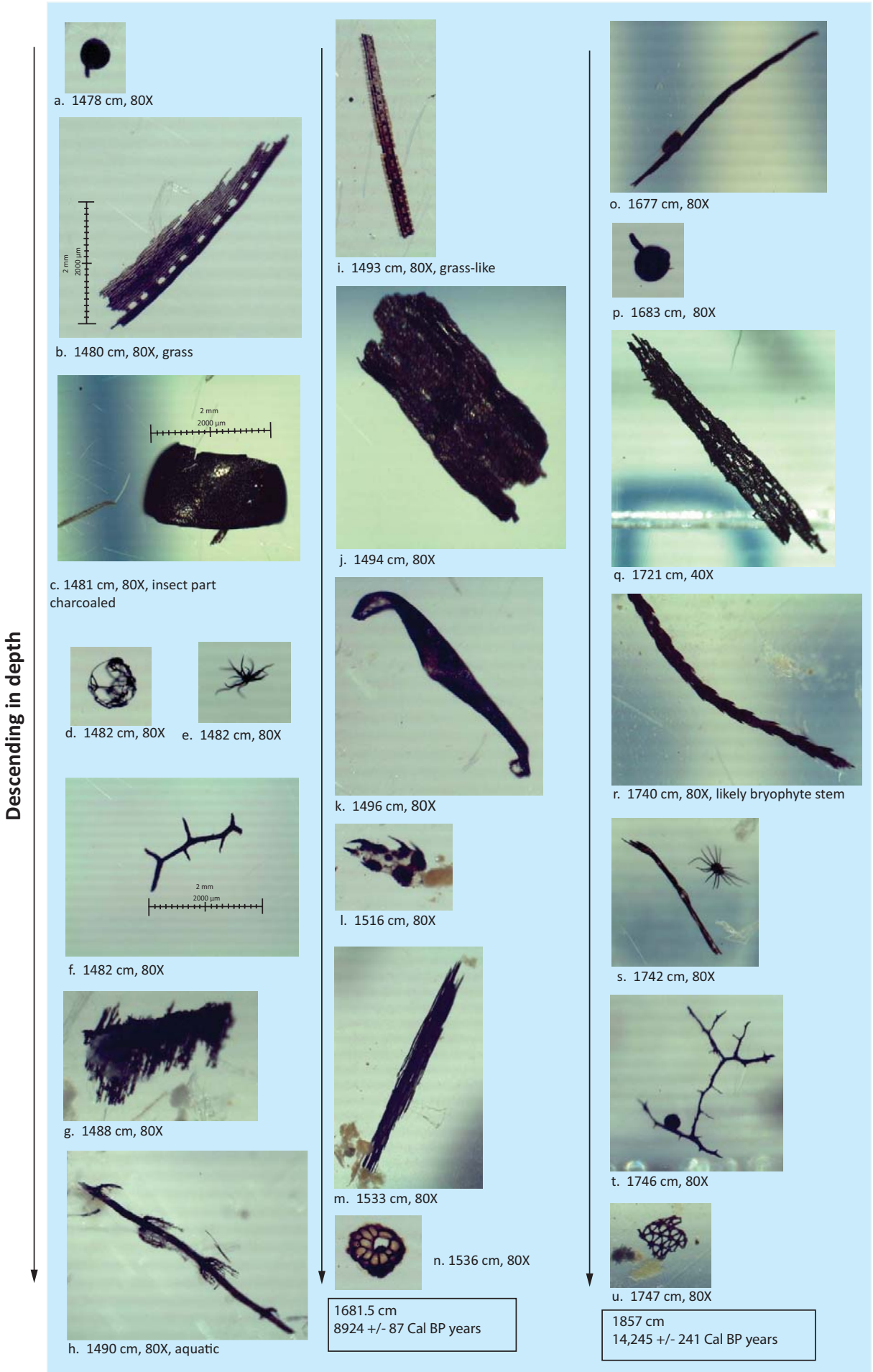


Fig. 2.6. What's burning? Examples of charcoal from Swift Lake, arranged in order of increasing depth.
Wood or twig, f,g,j,m,o,q,s,t; **Gall**: a, p, t; **Grass**: b,i; **Moss**: r; **Aquatic**: h, l; **Insect**: c; **Unknown**: d,e,k,n, s, u.

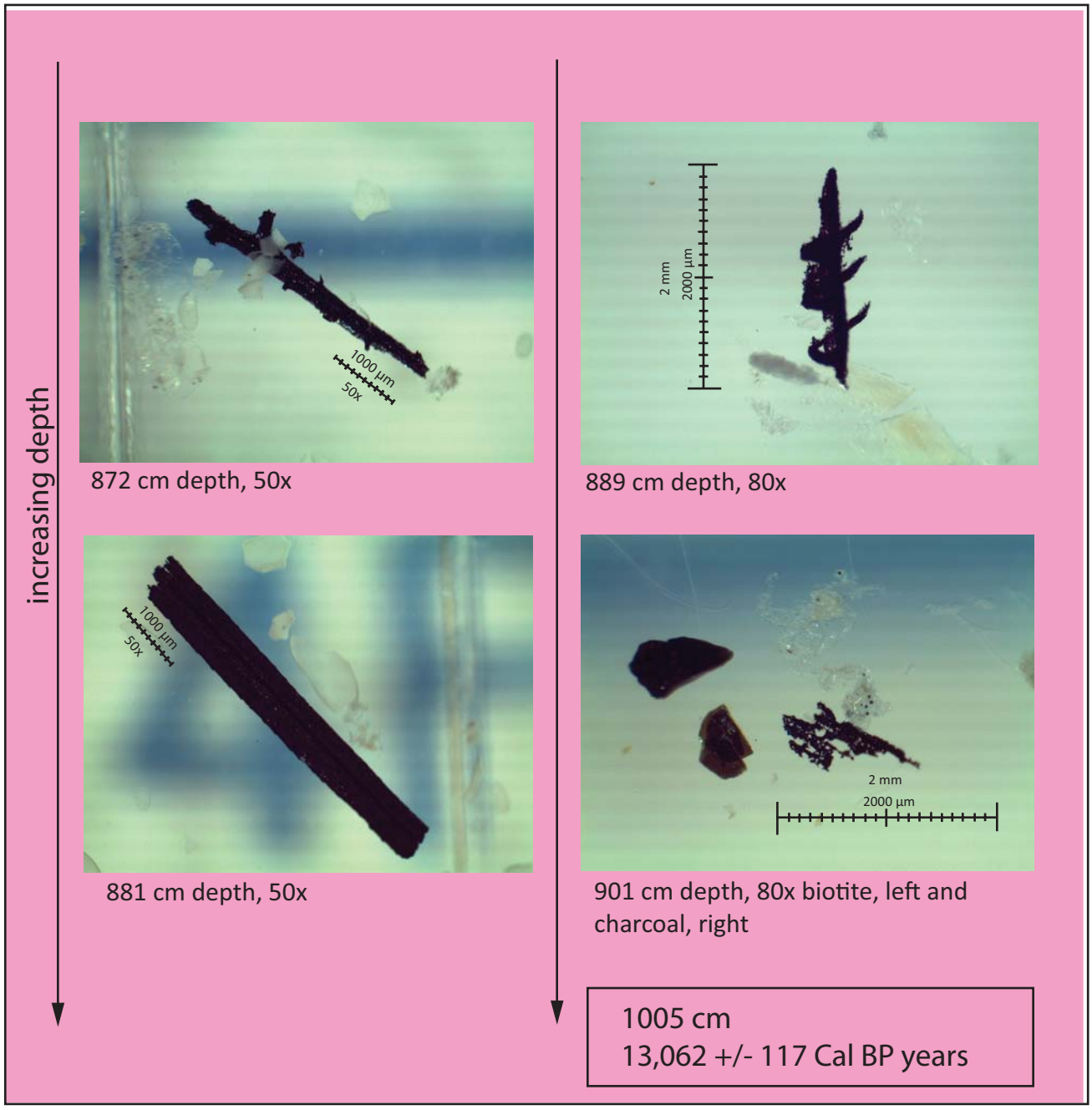


Fig. 2.7 Charcoal specimens from Lake Sixteen arranged by depth.

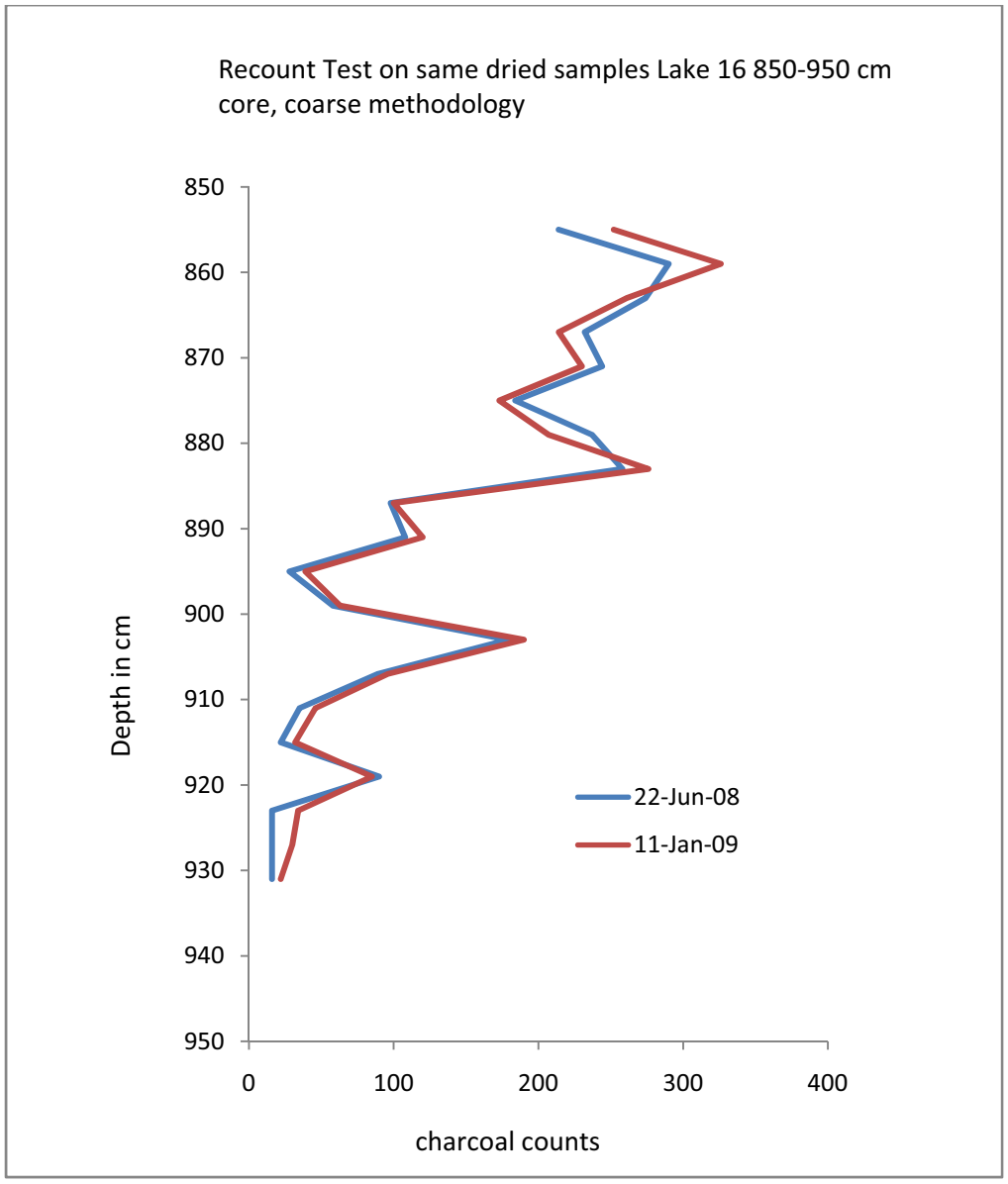


Fig. 2.8 Recount of stored dried samples to check consistency in counting.

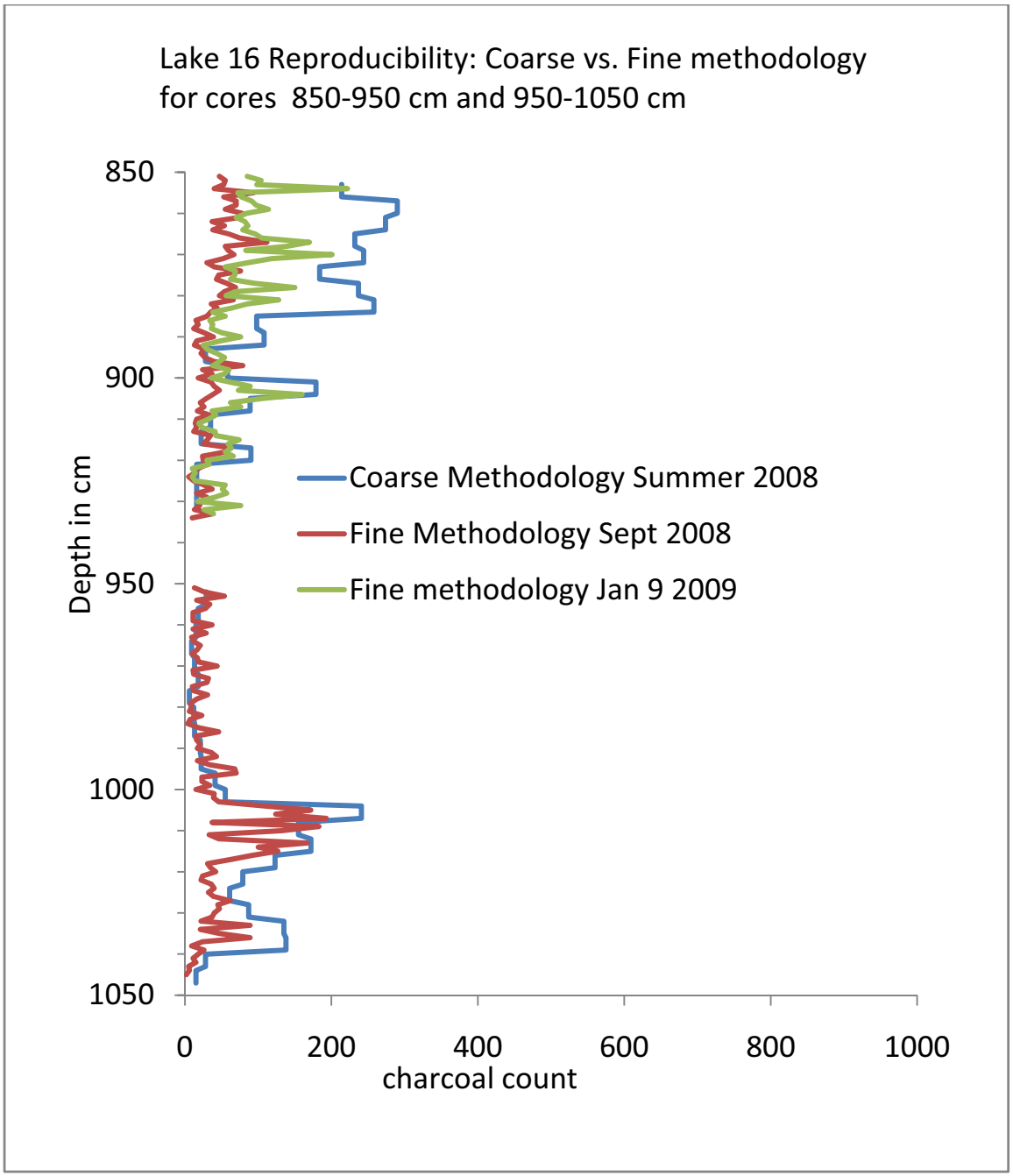


Fig. 2.9 Lake Sixteen 850-950 cm depth was sampled 3 times, 950-1050 cm depth was sampled 2 times. The shallower core exhibits some variability in results.

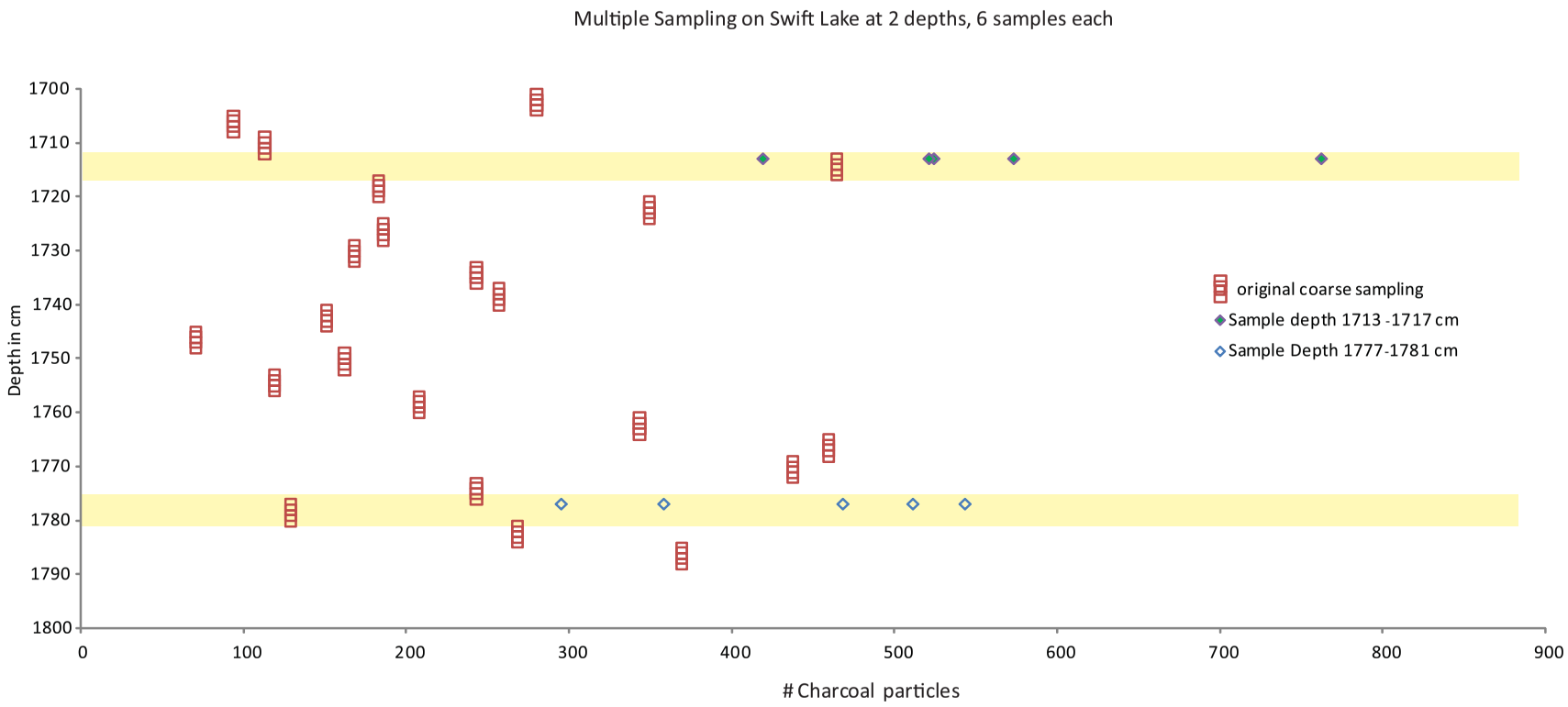


Fig. 2.10 Multiple sampling experiment on Swift Lake to test homogeneity of charcoal distribution in lake cores. One high count sample and one low count sample were selected from the original set of charcoal samples, to test replicability. Original 4 cm depth coarse sampling is shown with red rectangles. Original high count sample at 1713-1717 cm has reproduced well for 4 of 5 samples. The original low count at 1778-1781 cm depth shows all five samples as being considerably higher in count. This may be due to non-uniform dispersal of charcoal in lakes when taking a small cross-section sample. A larger cross-section may produce better correlation. Further testing needs to be done to assess the distribution of charcoal in lakes.81

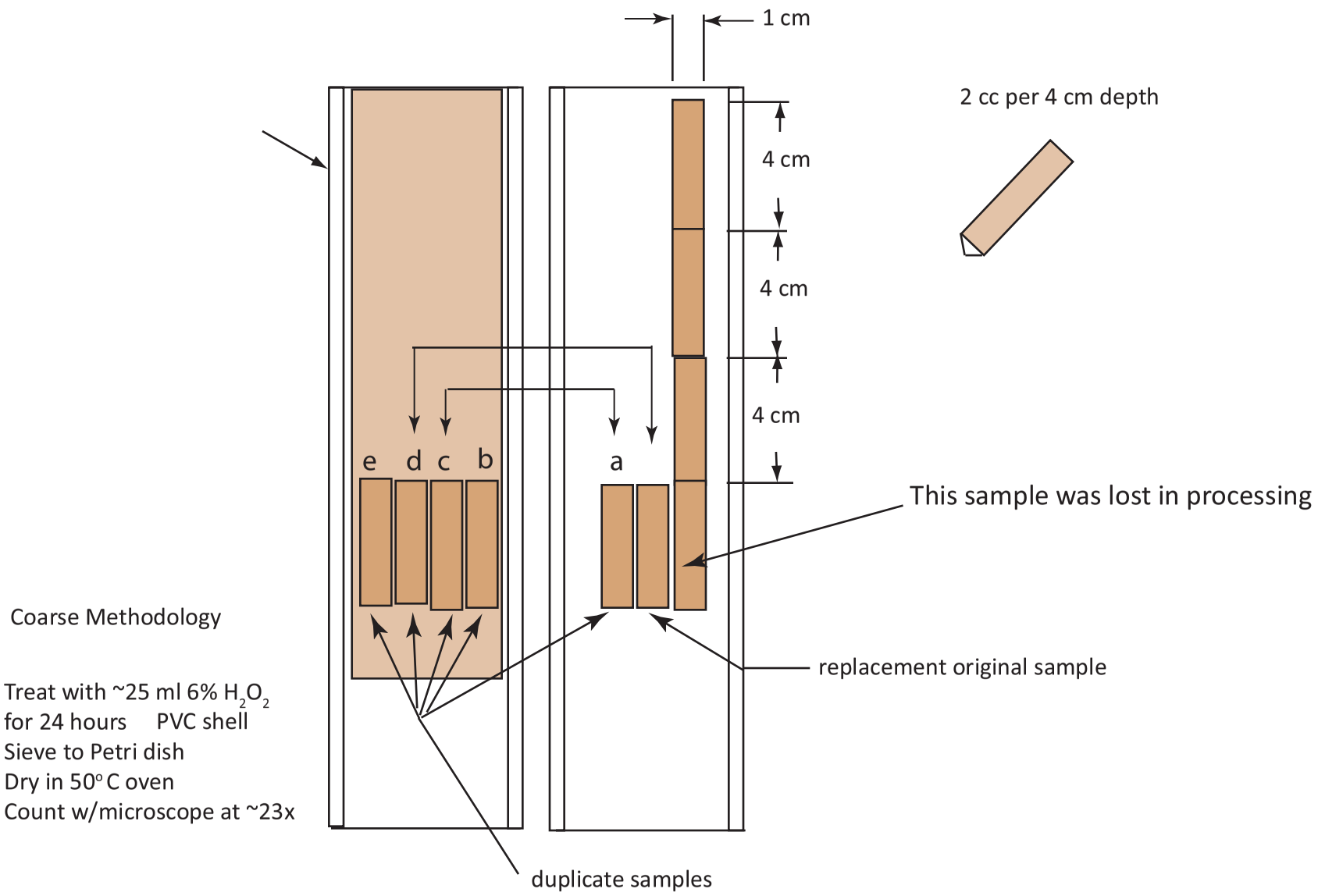


Fig. 2.11 Multiple sampling methodology diagram. Cross-section of lake sediment in PVC shell. Test was performed to check uniformity of charcoal distribution in lake sediments - Swift Lake A6, sample 3, 1776-1780 cm

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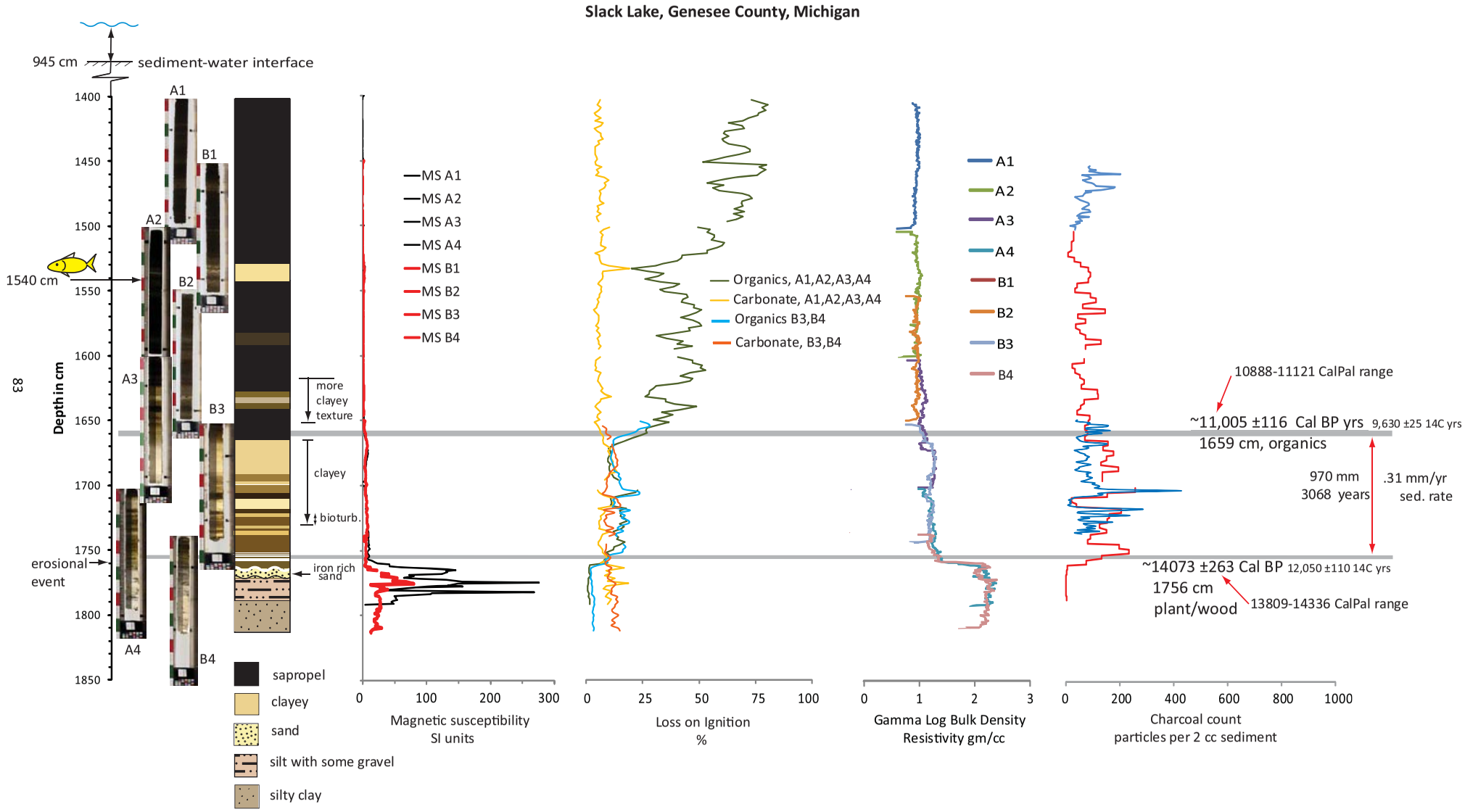


Fig. 3.1. Slack Lake data. Magnetic susceptibility, Loss on ignition, gamma log, charcoal counts (coarse methodology in red, fine in blue), and radiocarbon dates.

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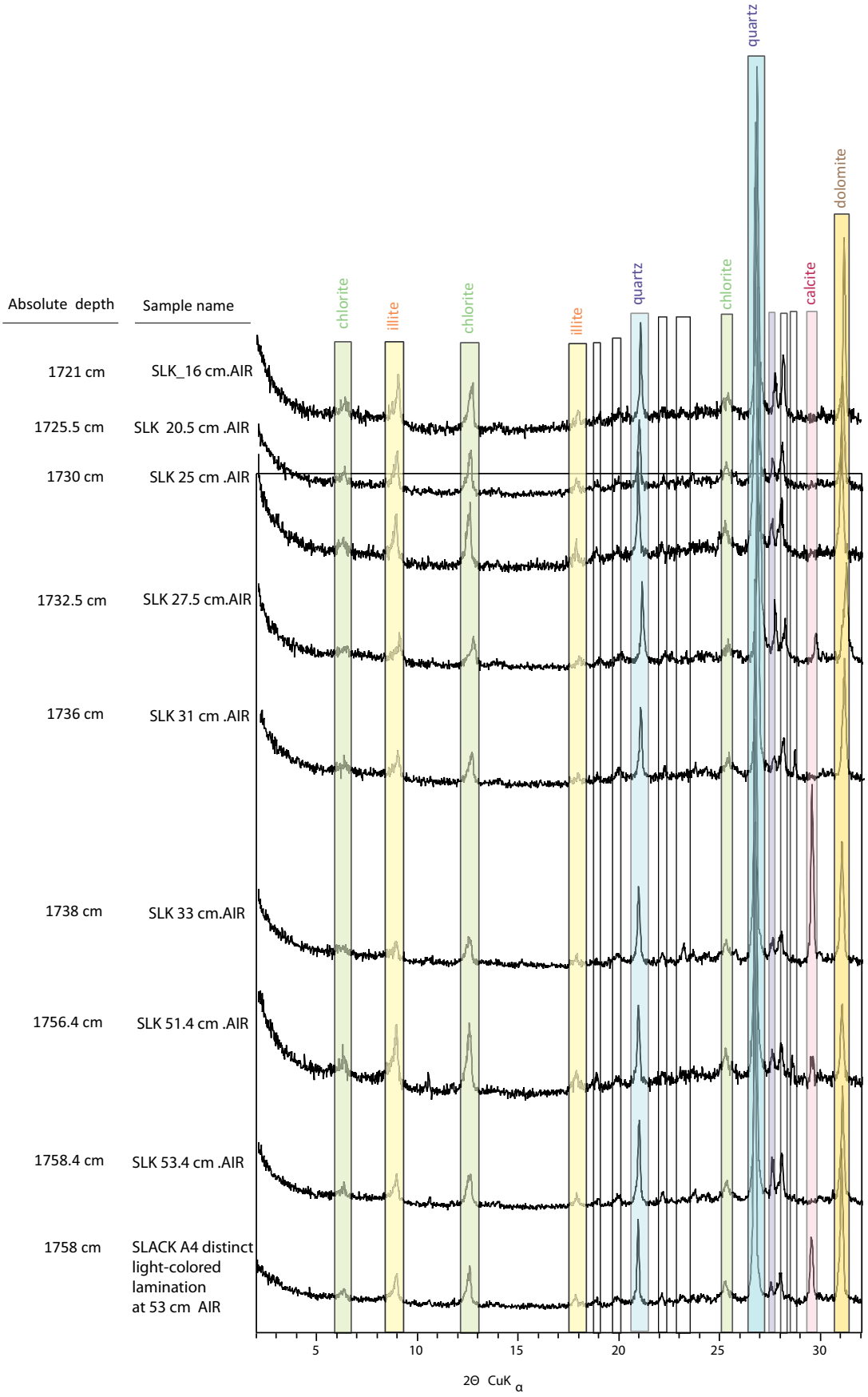


Fig. 3.2 Powder X-ray Diffraction, Slack 1705-1805 cm depth,

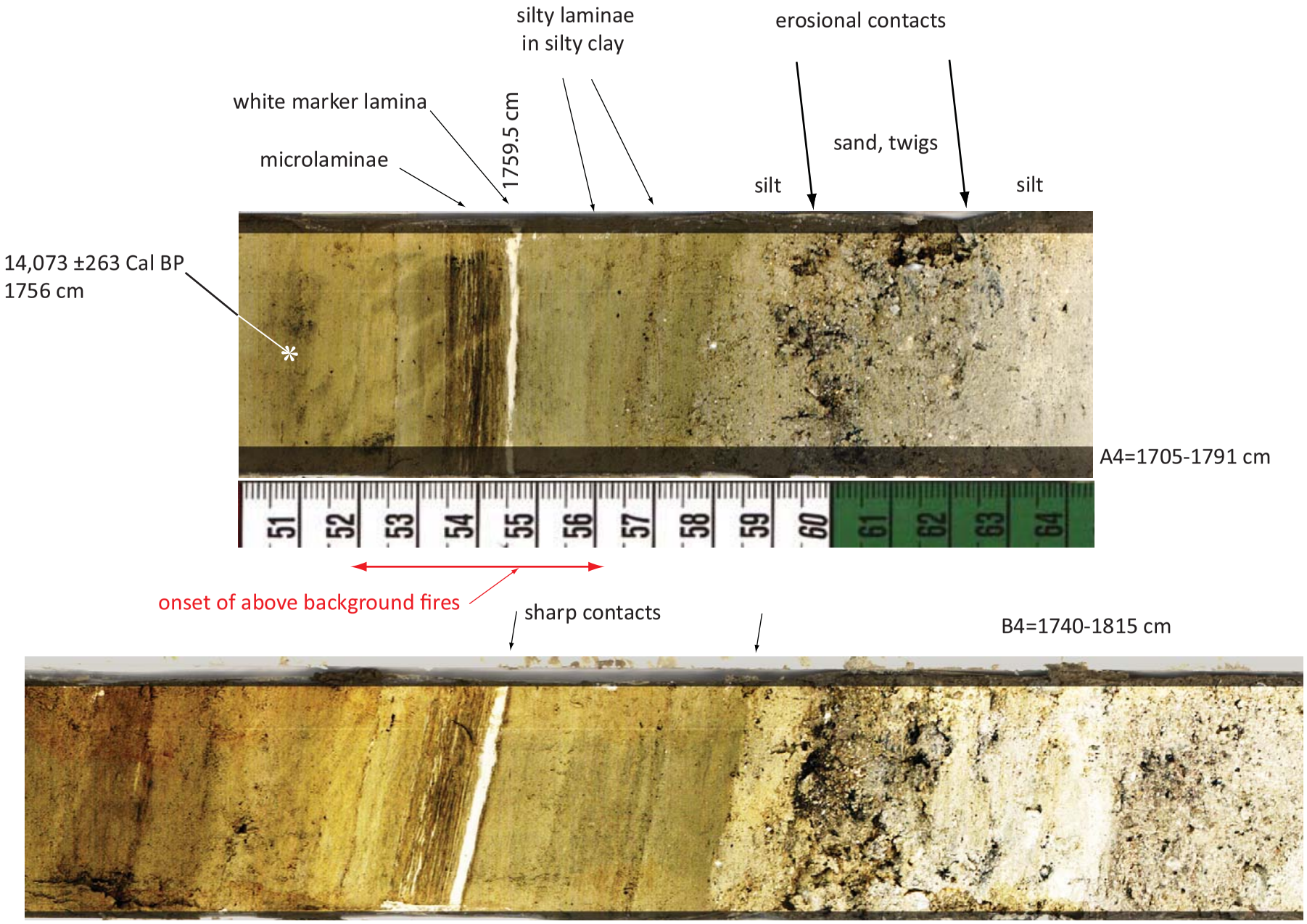


Fig. 3.3 Detail of Slack cores 1705-1791 cm and 1740-1815 cm showing sand bed and marker lamina overlain by microlaminae. Onset of significant fires occurs across the white lamina indicated by the arrows (coarse methodology).

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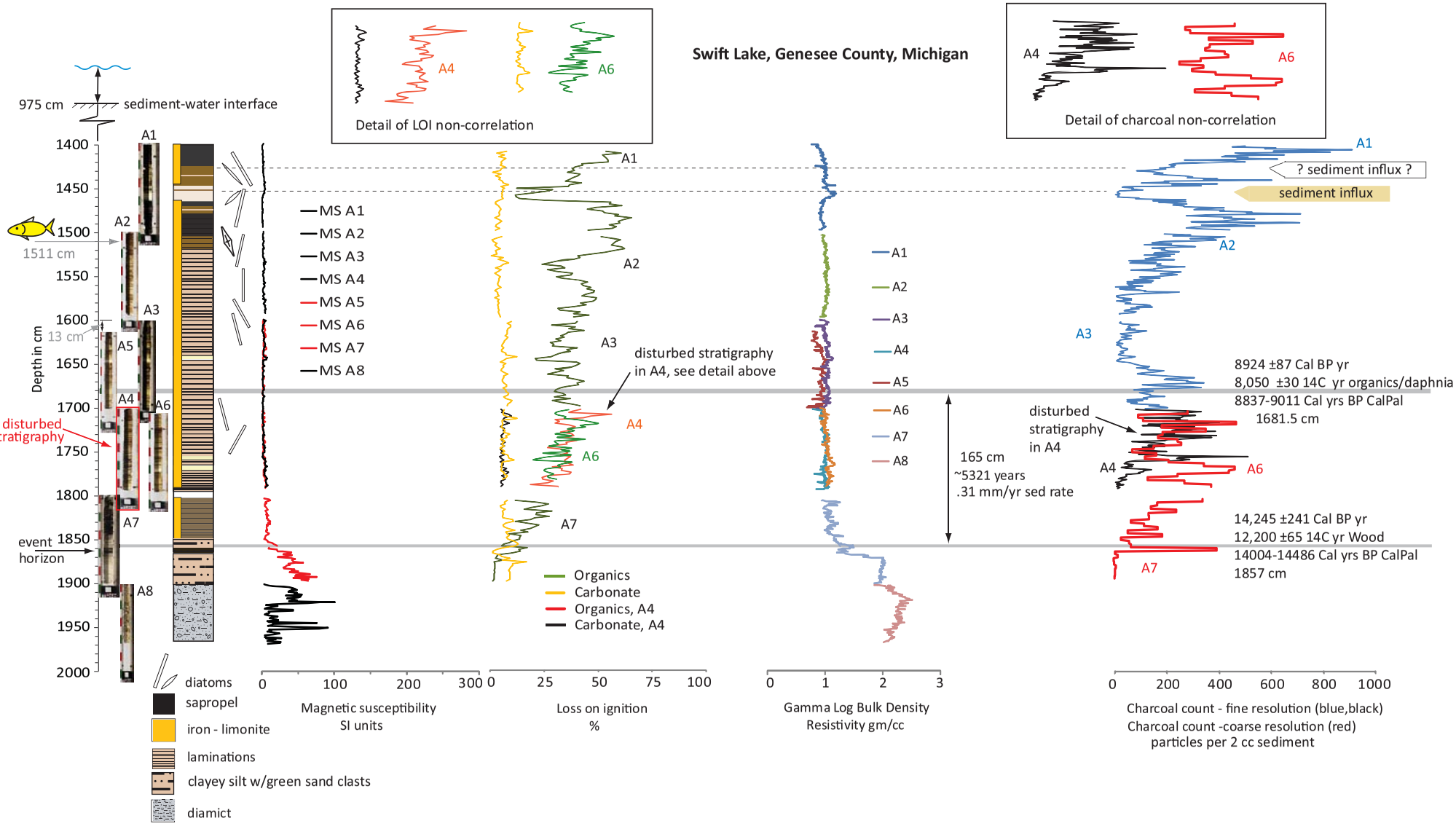


Fig. 3.4 Swift Lake Data. Magnetic susceptibility, Loss on Ignition, Gamma Log, Charcoal counts, and radiocarbon dates. Disturbed stratigraphy in thrust A4 is responsible for the lack of agreement with thrust A6 at the same depth. Thrust A6 is robust with undisturbed stratigraphy.

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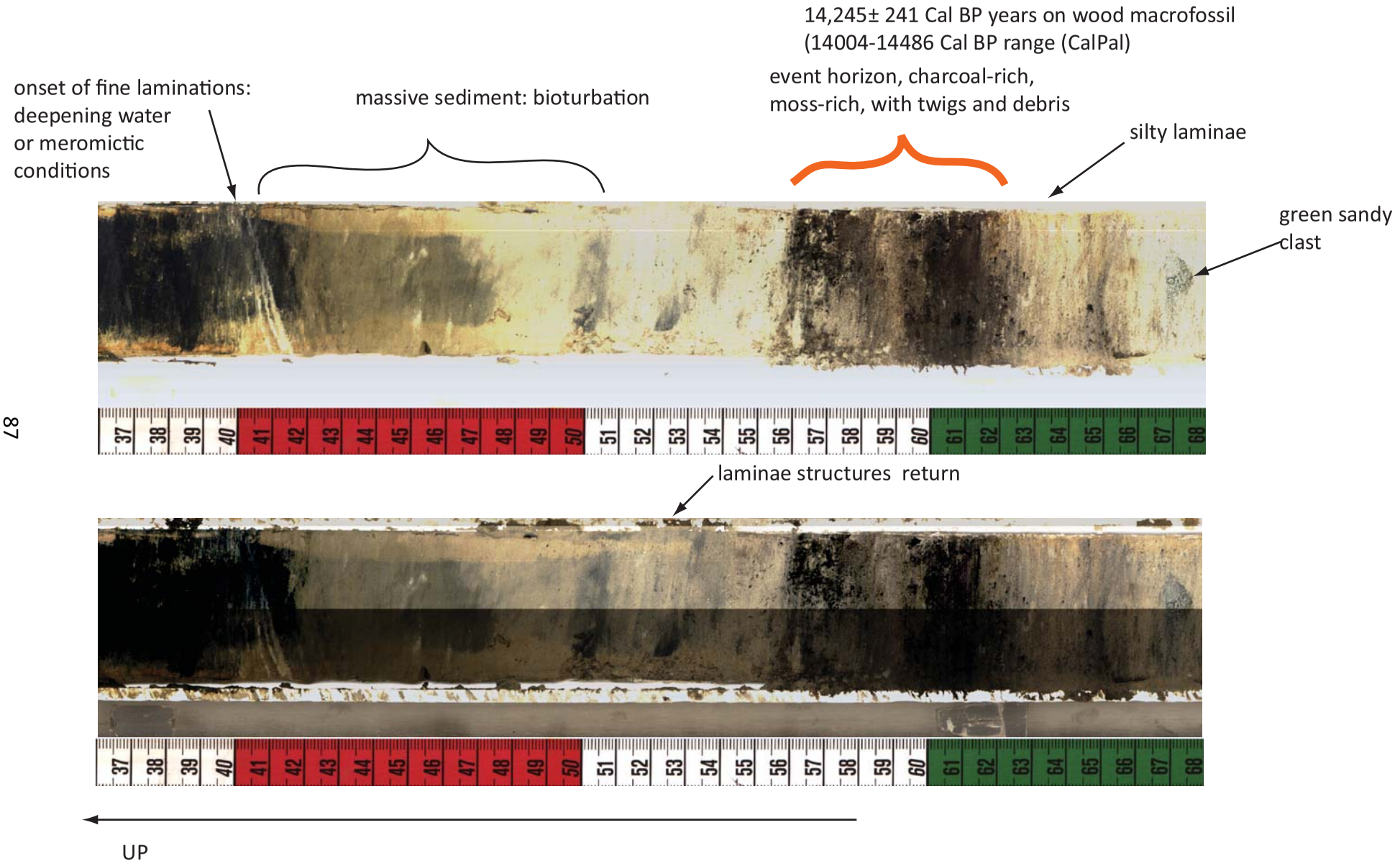
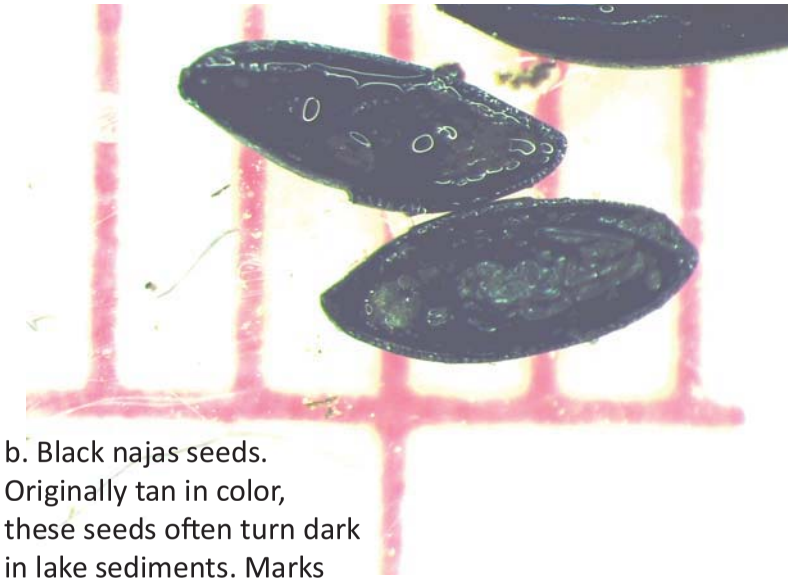


Fig. 3.5. Detail of Swift Lake core 1800-1900 cm. The top photo is taken at a different exposure that shows the structure below the event horizon to better advantage, and the light laminations above the massive bed. Notice the oxidation occurring on the surface of the core. This is an iron-rich lake, with much limonite also visible under the microscope during charcoal counting.



a. Various charcoal and seeds found in the erosional bed.



b. Black najas seeds. Originally tan in color, these seeds often turn dark in lake sediments. Marks are 1 mm increments.



c. Large (5-10 mm) charcoal pieces were found in the erosion bed. 1 mm increments.



d. Big Fish 1058 cm, probable sickle moss and spruce needle from the silt lamination which is 10 cm above the 15,407 ±255 Cal BP date . The same type of moss was found in the charcoal event horizon of Swift Lake. 1 mm increments.

Fig. 3.3 Images of the charcoal "event" in Swift 1855-1861 cm depth. This was evidently a large and intense fire, with spruce needles burning at ~14,245 Cal years BP. Seeds of the aquatic Najas flexilis are also present, with abundant moss and various other seeds, twigs anddebris. Scale is in mm.

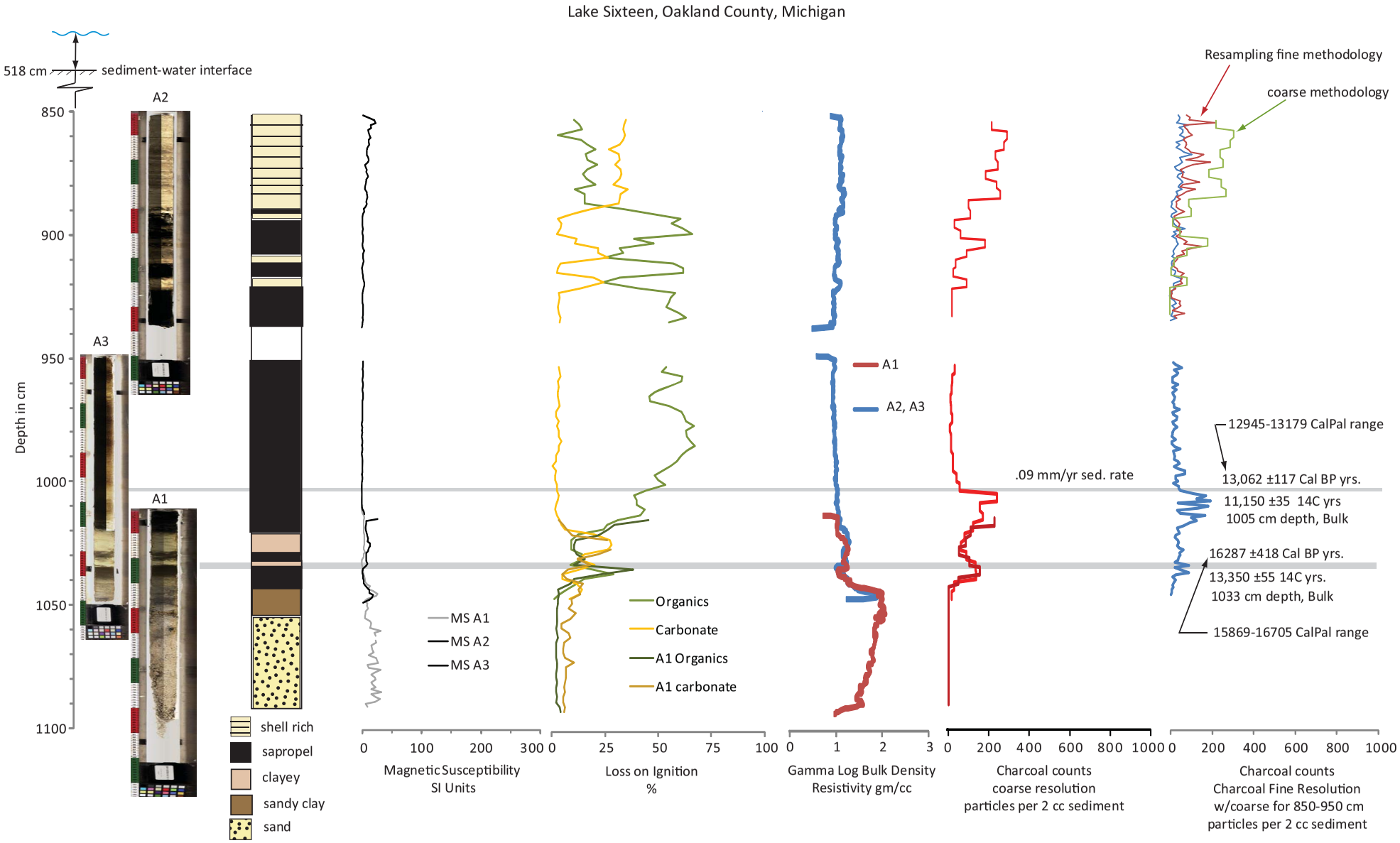


Fig. 3.7. Lake Sixteen Data. Magnetic susceptibility, Loss on Ignition, Gamma Log, Charcoal counts, and radiocarbon dates. 850-950 cm depth sampled 3 times to check reproducibility.

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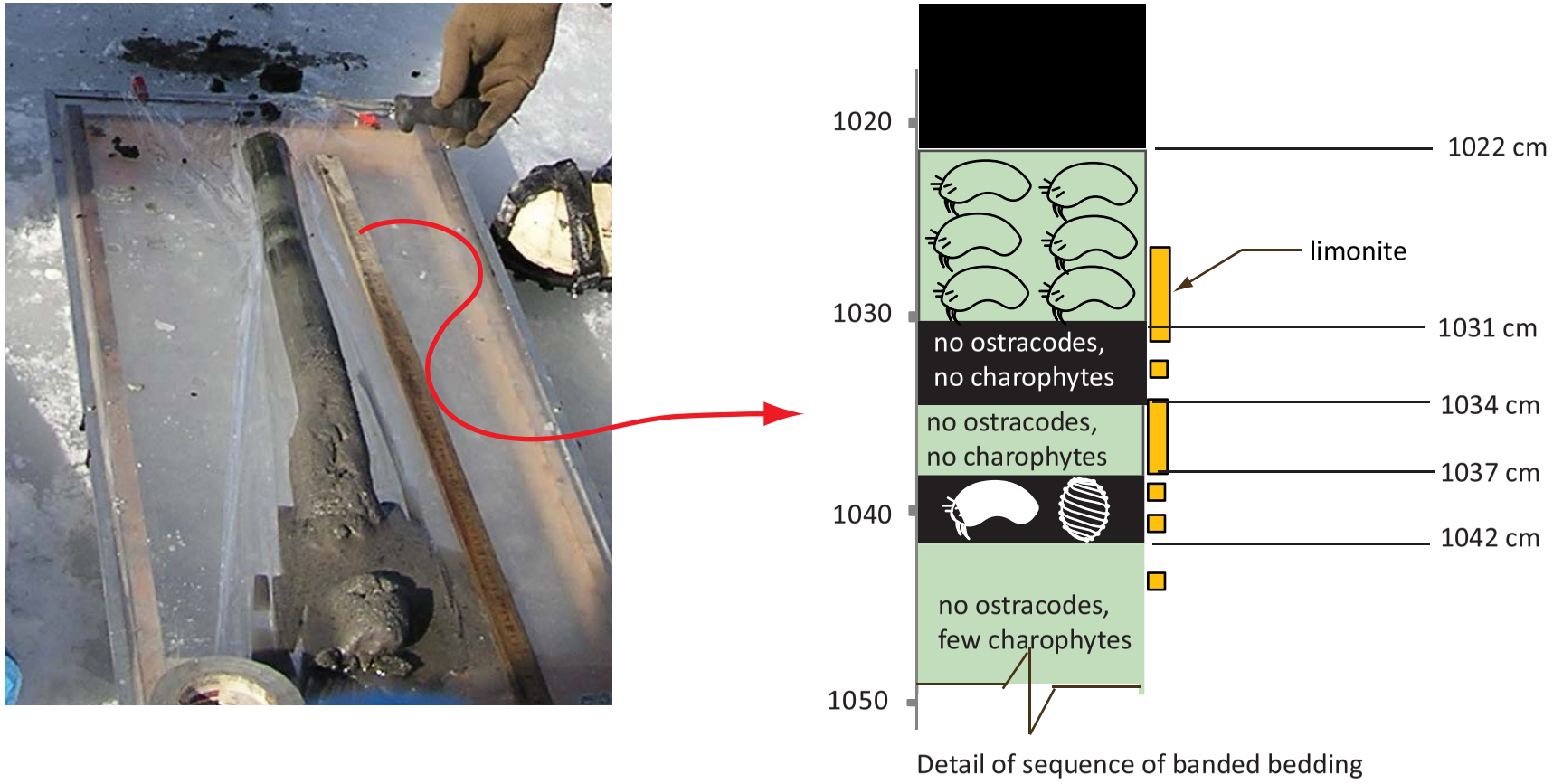


Fig. 3.8. On site, Lake Sixteen, Feb. 2008, extruded 2" ϕ lake sediment core from 1012-1112 cm depth. The the sandy glacial contact is closest to the reader. Notice the 3 dark bands in the upper part of the core. These correspond to LOI organic peaks, and the lowermost and uppermost dark bands contain charcoal peaks. There were charophytes (type of algae) and ostracodes in the lake at this time (see detail). The 2 intermediate lighter bands contain low peaks in carbonate (~25%) and high clay content.

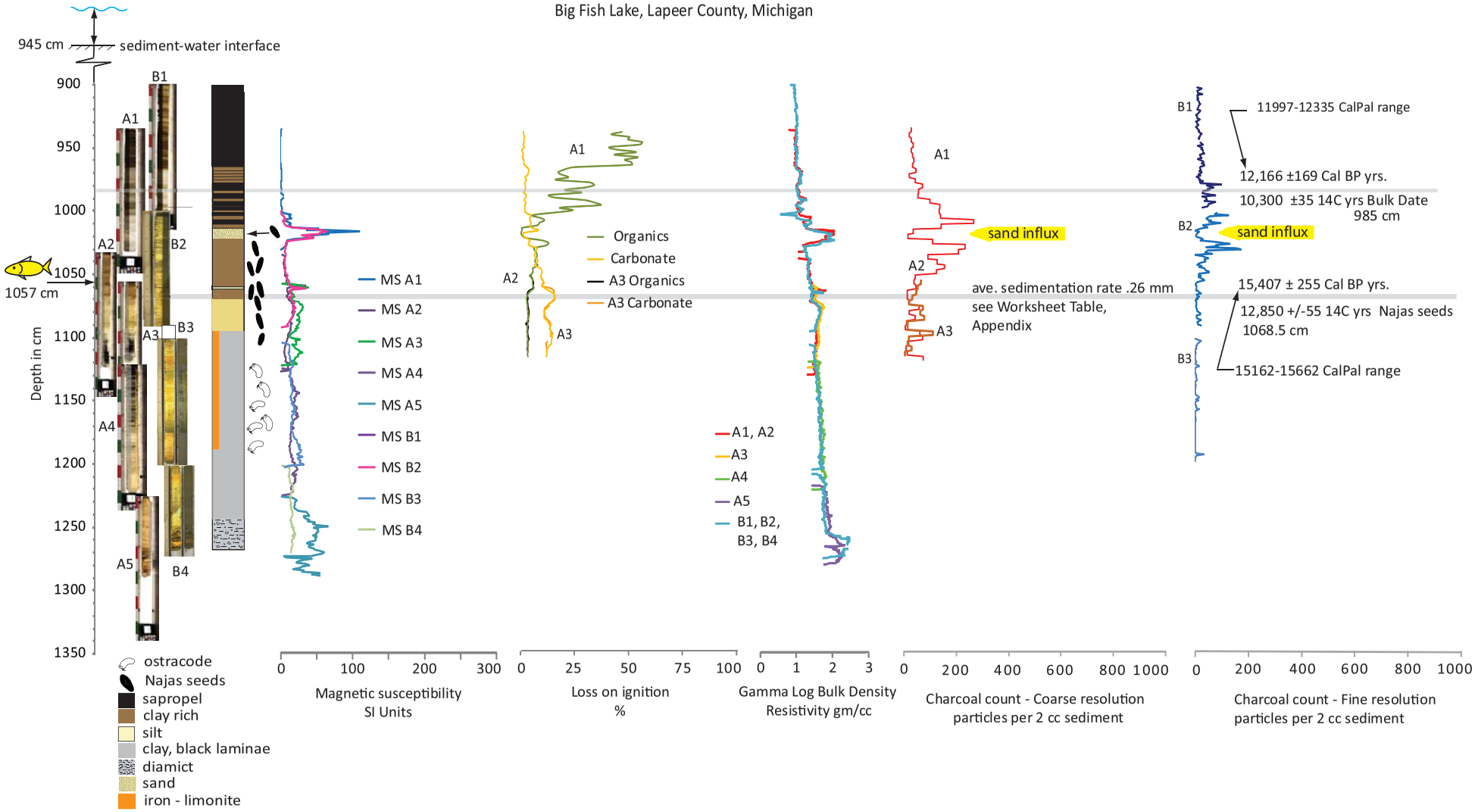


Fig. 3.9 Big Fish Data. Magnetic susceptibility, Loss on ignition, gamma log, charcoal counts (red/coarse, blue/fine methodology) and radiocarbon dates.

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Radiocarbon results - Michigan samples processed by Woods Hole Oceanographic Institute Laboratory

Lake	Sample ID	Type of sample	Abs. Depth	d13C	Fm Error	14C Age	Age Error	CalPal±	CalPal 68%	NOSAMS
Slack	GNY-SLK A4 51	Lacustrine, Plant/wood	1756	-24.25	0.003	12050	110	14073±263	13809-14336	OS-70592
Slack	GNY-SLK-A3- 58-60 cm	Lacustrine, organics	1659	-24.95	0.001	9630	25	11005±116	10888-11121	OS-71334
Swift	GNY-SFT-A7-57	Lacustrine, Wood	1857	-24.41	0.0017	12200	65	14245±241	14004-14486	OS-70562
Swift	GNY-SFT-A5-67-71 cm	Lacustrine, organics, *Daphnia*	1680	-27.26	0.0013	8050	30	8924±87	8837-9011	OS-71335
Sixteen	GNY-lake-16 A1 21.5 cm	Lacustrine, Bulk	1033	-30.83	0.0013	13350	55	16287±418	15869-16705	OS-70884
Sixteen	GNY-SXT-A3-55 cm	Lacustrine Bulk	1005	-32.87	0.001	11150	35	13062±117	12945-13179	OS-71333
Big Fish	GNY-BF A2 34-37	Lacustrine, *Najas* seeds	1067.5	-12.39	0.0015	12850	55	15407±255	15152-15662	OS-70532
Big Fish	GNY-BF-B1-85 cm	Lacustrine Bulk	985	-25.25	0.0012	10300	35	12166±169	11997-12335	OS-71332

Table 3.1 Radiocarbon results for Slack, Swift, Sixteen and Big Fish Lakes. Radiocarbon results have been converted to Calibrated dates using CalPal, with ± error shown.

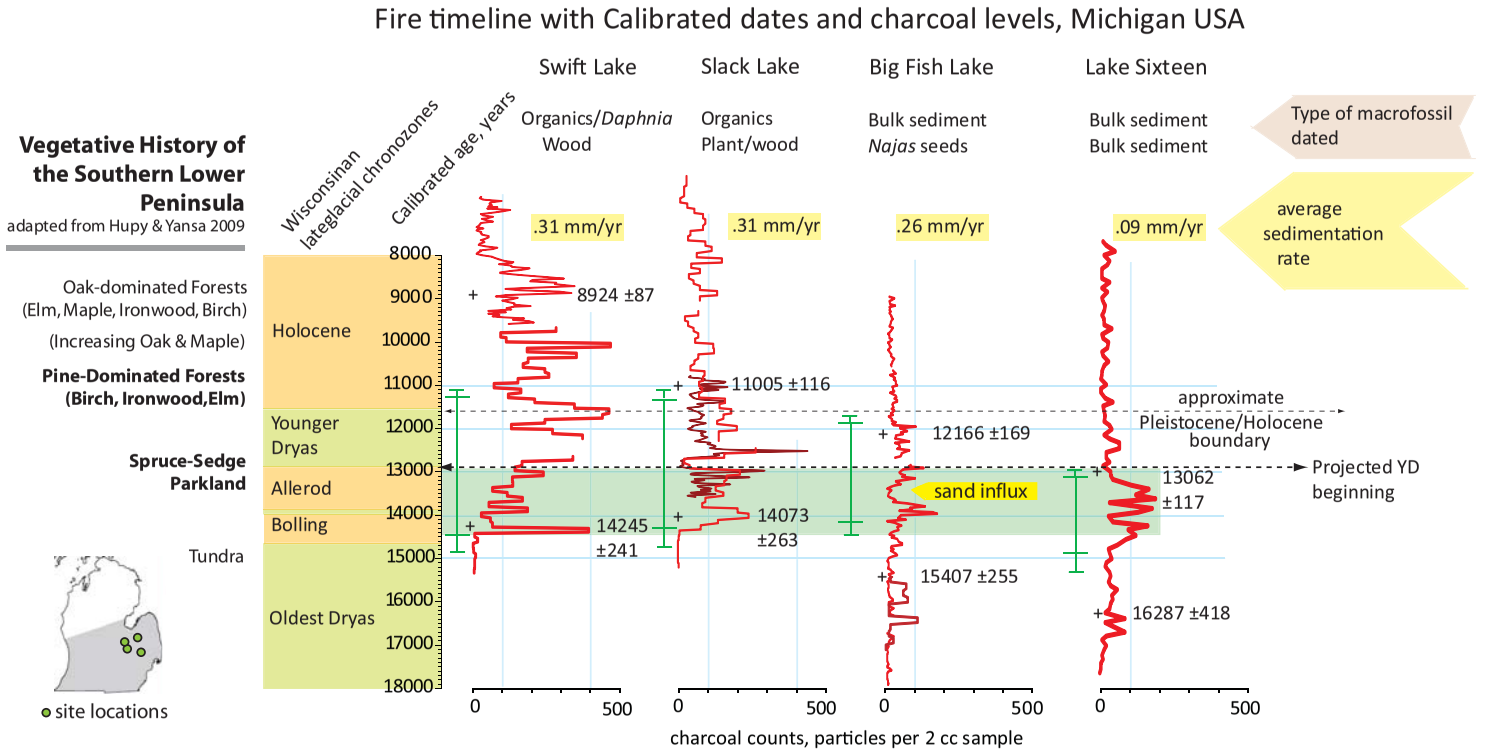


Fig. 4.1 Timeline with charcoal counts from Swift, Slack, Big Fish and Lake Sixteen with representative vegetation, adapted from Hupy & Yansa, 2009. Calibrated radiocarbon dates (Cal BP years) for each lake are marked with +'s, type of macrofossil dated is shown, and average sedimentation rates noted. YD is estimated by calculations of sedimentation rate using the pair of radiocarbon dates (Appendix A, Fig. 7 shows the calculations). Fire clusters are indicated by green bars with error bars. Green band shows contemporaneous fire interval. Typical chronozones are shown, but there may be some variation regionally.

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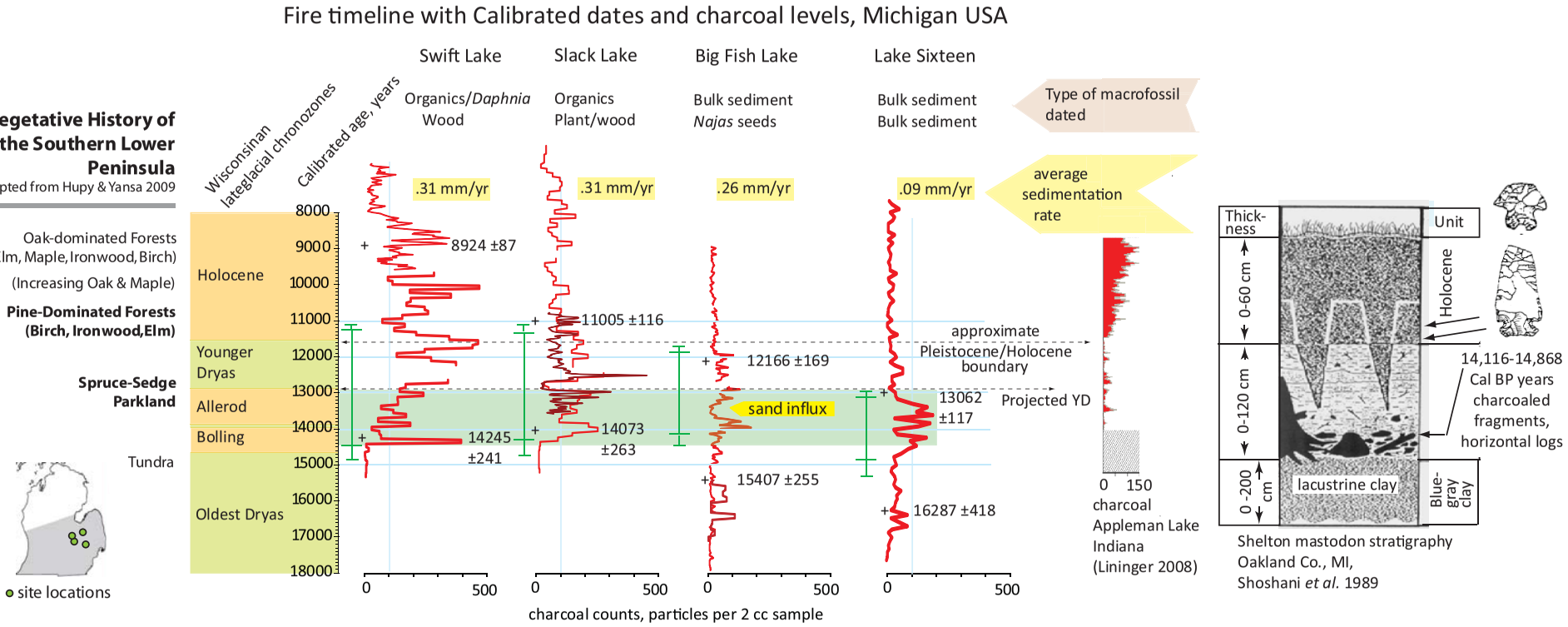


Fig. 4.2 Timeline with charcoal counts from Swift, Slack, Big Fish and Lake Sixteen with representative vegetation, adapted from Hupy & Yansa, 2009. Calibrated radiocarbon dates (Cal BP years) for each lake are marked with +'s, type of macrofossil dated is shown, and average sedimentation rates noted. Fire clusters are indicated by green bars with error bars. Green band shows contemporaneous fire interval. See Table 3 in Appendix 2 for sedimentation calculations. Typical chronozones are shown, but there may be some variation regionally. Appleman Lake charcoal (Lininger 2008) and Shelton mastodon charcoal (Shoshani *et al.*, 1989) are shown for paleofire and Paleoindian comparison.

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Appendix A

Charcoal Data & Miscellaneous Tables

Raw charcoal data, Slack Lake, 1451 -1787 cm, coarse methodology, fine methodology

Slack B1	Fine
Depth cm	charcoal ct
1451	92
1452	85
1453	90
1454	114
1455	89
1456	131
1457	205
1458	62
1459	84
1460	97
1461	86
1462	65
1463	81
1464	98
1465	107
1466	115
1467	185
1468	179
1469	132
1470	74
1471	96
1472	73
1473	67
1474	66
1475	37
1476	50
1477	54
1478	64
1479	85
1480	87
1481	88
1482	81
1483	68
1484	62
1485	89
1486	94
1487	63
1488	55
1489	44
1490	88
1491	50
1492	58
1493	62
1494	40
1495	55
1496	37
1497	18
1498	38
1499	37
1500	36

Slack A2	coarse		
Depth cm	Charcoal ct	Depth cm	charcoal ct
1501		1548	36
1502	30	1549	36
1503	30	1550	93
1504	30	1551	93
1505	30	1552	93
1506	31	1553	93
1507	31	1554	113
1508	31	1555	113
1509	31	1556	113
1510	23	1557	113
1511	23	1558	64
1512	23	1559	64
1513	23	1560	64
1514	23	1561	64
1515	23	1562	146
1516	23	1563	146
1517	23	1564	146
1518	10	1565	146
1519	10	1566	46
1520	10	1567	46
1521	10	1568	46
1522	32	1569	46
1523	32	1570	73
1524	32	1571	73
1525	32	1572	73
1526	55	1573	73
1527	55	1574	39
1528	55	1575	39
1529	55	1576	39
1530	85	1577	39
1531	85	1578	53
1532	85	1579	53
1533	85	1580	53
1534	92	1581	53
1535	92	1582	74
1536	92	1583	74
1537	92	1584	74
1538	85	1585	74
1539	85	1586	131
1540	85	1587	131
1541	85	1588	131
1542	43	1589	131
1543	43	1590	73
1544	43	1591	73
1545	43	1592	73
1546	36	1593	73
1547	36		

Slack A3	coarse		
Depth cm	charcoal ct	Depth cm	charcoal ct
1600	69	1648	84
1601	69	1649	84
1602	69	1650	84
1603	69	1651	84
1604	25	1652	71
1605	25	1653	71
1606	25	1654	71
1607	25	1655	71
1608	35	1656	83
1609	35	1657	83
1610	35	1658	83
1611	35	1659	83
1612	54	1660	72
1613	54	1661	72
1614	54	1662	72
1615	54	1663	72
1616	69	1664	159
1617	69	1665	159
1618	69	1666	159
1619	69	1667	159
1620	59	1668	140
1621	59	1669	140
1622	59	1670	140
1623	59	1671	140
1624	120	1672	180
1625	120	1673	180
1626	120	1674	180
1627	120	1675	180
1628	121	1676	153
1629	121	1677	153
1630	121	1678	153
1631	121	1679	153
1632	68	1680	131
1633	68	1681	131
1634	68	1682	131
1635	68	1683	131
1636	57	1684	197
1637	57	1685	197
1638	57	1686	197
1639	57	1687	197
1640	42	1688	138
1641	42	1689	138
1642	42	1690	138
1643	42	1691	138
1644	89	1692	137
1645	89	1693	137
1646	89	1694	137
1647	89	1695	137

Slack A4	Coarse		
Depth cm	charcoal ct	Depth cm	charcoal ct
1700	258	1748	235
1701	258	1749	235
1702	258	1750	235
1703	258	1751	235
1704	153	1752	132
1705	153	1753	132
1706	153	1754	132
1707	153	1755	132
1708	22	1756	75
1709	22	1757	75
1710	22	1758	75
1711	22	1759	75
1712	38	1760	4
1713	38	1761	4
1714	38	1762	4
1715	38	1763	4
1716	205	1764	3
1717	205	1765	3
1718	205	1766	3
1719	205	1767	3
1720	162	1768	1
1721	162	1769	1
1722	162	1770	1
1723	162	1771	1
1724	154	1772	0
1725	154	1773	0
1726	154	1774	0
1727	154	1775	0
1728	125	1776	0
1729	125	1777	0
1730	125	1778	0
1731	125	1779	0
1732	151	1780	0
1733	151	1781	0
1734	151	1782	0
1735	151	1783	0
1736	92	1784	2
1737	92	1785	2
1738	92	1786	2
1739	92	1787	2
1740	81		
1741	81		
1742	81		
1743	81		
1744	199		
1745	199		
1746	199		
1747	199		

Appendix A. Raw Data of charcoal counts for Slack Lake. Coarse methodology at continuous 4 cm depth samples, 2 cc sample volume. Sampling is done from bottom to top.

Swift A6-coarse	1700 - 1800 cm				
Sample No.	Depth cm	charcoal count	Sample No.	Depth cm	charcoal count
22	1700	280	11	1744	71
22	1701	280	11	1745	71
22	1702	280	11	1746	71
22	1703	280	11	1747	71
21	1704	94	10	1748	162
21	1705	94	10	1749	162
21	1706	94	10	1750	162
21	1707	94	10	1751	162
20	1708	113	9	1752	119
20	1709	113	9	1753	119
20	1710	113	9	1754	119
20	1711	113	9	1755	119
19	1712	464	8	1756	208
19	1713	464	8	1757	208
19	1714	464	8	1758	208
19	1715	464	8	1759	208
18	1716	183	7	1760	343
18	1717	183	7	1761	343
18	1718	183	7	1762	343
18	1719	183	7	1763	343
17	1720	349	6	1764	459
17	1721	349	6	1765	459
17	1722	349	6	1766	459
17	1723	349	6	1767	459
16	1724	186	5	1768	437
16	1725	186	5	1769	437
16	1726	186	5	1770	437
16	1727	186	5	1771	437
15	1728	168	4	1772	243
15	1729	168	4	1773	243
15	1730	168	4	1774	243
15	1731	168	4	1775	243
14	1732	243	3	1776	129
14	1733	243	3	1777	129
14	1734	243	3	1778	129
14	1735	243	3	1779	129
13	1736	257	2	1780	268
13	1737	257	2	1781	268
13	1738	257	2	1782	268
13	1739	257	2	1783	268
12	1740	151	1	1784	369
12	1741	151	1	1785	369
12	1742	151	1	1786	369
12	1743	151	1	1787	369

Swift A7-coarse	1800 - 1900 cm				
Sample No.	Depth cm	Charcoal ct.	Sample No.	Depth cm	Charcoal ct.
23	1802	337	12	1846	27
23	1803	337	12	1847	27
23	1804	337	12	1848	27
23	1805	337	12	1849	27
22	1806	165	11	1850	58
22	1807	165	11	1851	58
22	1808	165	11	1852	58
22	1809	165	11	1853	58
21	1810	142	10	1854	65
21	1811	142	10	1855	65
21	1812	142	10	1856	65
21	1813	142	10	1857	65
20	1814	238	9	1858	391
20	1815	238	9	1859	391
20	1816	238	9	1860	391
20	1817	238	9	1861	391
19	1818	133	8	1862	6
19	1819	133	8	1863	6
19	1820	133	8	1864	6
19	1821	133	8	1865	6
18	1822	135	7	1866	15
18	1823	135	7	1867	15
18	1824	135	7	1868	15
18	1825	135	7	1869	15
17	1826	65	6	1870	0
17	1827	65	6	1871	0
17	1828	65	6	1872	0
17	1829	65	6	1873	0
16	1830	115	5	1874	1
16	1831	115	5	1875	1
16	1832	115	5	1876	1
16	1833	115	5	1877	1
15	1834	167	4	1878	9
15	1835	167	4	1879	9
15	1836	167	4	1880	9
15	1837	167	4	1881	9
14	1838	54	3	1882	5
14	1839	54	3	1883	5
14	1840	54	3	1884	5
14	1841	54	3	1885	5
13	1842	184	2	1886	6
13	1843	184	2	1887	6
13	1844	184	2	1888	6
13	1845	184	2	1889	6
			1	1890	3
			1	1891	3
			1	1892	3
			1	1893	3

Appendix A. Raw Data for Swift Lake. Coarse methodology data. Since the sample is taken across a 4 cm depth, the same data is entered for all 4 cm, for the purpose of graphing.

Swift A1 - fine	1400-1500 cm		
Depth cm	Charcoal ct	Depth cm	Charcoal ct
1400		1447	41
1401	506	1448	31
1402	458	1449	73
1403	622	1450	70
1404	584	1451	111
1405	919	1452	23
1406	827	1453	15
1407	617	1454	16
1408	835	1455	20
1409	467	1456	8
1410	486	1457	18
1411	658	1458	17
1412	430	1459	16
1413	418	1460	96
1414	515	1461	83
1415	476	1462	275
1416	631	1463	150
1417	273	1464	275
1418	458	1465	174
1419	505	1466	233
1420	342	1467	282
1421	232	1468	228
1422	213	1469	268
1423	235	1470	274
1424	220	1471	424
1425	233	1472	324
1426	178	1473	311
1427	200	1474	426
1428	154	1475	409
1429	90	1476	532
1430	151	1477	512
1431	159	1478	721
1432	189	1479	370
1433	154	1480	279
1434	208	1481	390
1435	277	1482	453
1436	304	1483	426
1437	284	1484	544
1438	399	1485	460
1439	346	1486	427
1440	609	1487	300
1441	196	1488	715
1442	211	1489	512
1443	105	1490	430
1444	399	1491	338
1445	226	1492	542
1446	334	1493	308
		1494	280
		1495	335
		1496	446

Swift A2 - fine	1500-1600 cm		
Depth cm	Charcoal ct	Depth cm	Charcoal ct
1500		1548	202
1501	196	1549	155
1502	296	1550	101
1503	229	1551	177
1504	429	1552	119
1505	394	1553	76
1506	295	1554	150
1507	385	1555	53
1508	395	1556	142
1509	307	1557	50
1510	175	1558	70
1511	146	1559	57
1512	221	1560	109
1513	119	1561	8
1514	264	1562	80
1515	312	1563	21
1516	246	1564	45
1517	149	1565	123
1518	197	1566	119
1519	184	1567	250
1520	211	1568	179
1521	250	1569	86
1522	157	1570	41
1523	156	1571	11
1524	231	1572	11
1525	119	1573	21
1526	217	1574	67
1527	180	1575	37
1528	142	1576	67
1529	121	1577	10
1530	232	1578	42
1531	57	1579	62
1532	73	1580	43
1533	161	1581	124
1534	61	1582	139
1535	179	1583	87
1536	169	1584	148
1537	167	1585	65
1538	272	1586	94
1539	193	1587	48
1540	156	1588	40
1541	157	1589	85
1542	67	1590	77
1543	175	1591	21
1544	258	1592	23
1545	231		
1546	181		
1547	243		

Swift A3 fine	1600-1700 cm		
Depth cm	Charcoal ct	Depth cm	Charcoal ct
1600		1650	104
1601	24	1651	136
1602	23	1652	132
1603	32	1653	87
1604	97	1654	129
1605	59	1655	134
1606	54	1656	191
1607	62	1657	170
1608	52	1658	127
1609	80	1659	91
1610	47	1660	92
1611	126	1661	139
1612	99	1662	195
1613	66	1663	258
1614	25	1664	310
1615	32	1665	201
1616	65	1666	197
1617	46	1667	285
1618	28	1668	282
1619	44	1669	304
1620	67	1670	348
1621	24	1671	224
1622	22	1672	110
1623	19	1673	157
1624	10	1674	296
1625	31	1675	335
1626	16	1676	183
1627	12	1677	112
1628	27	1678	78
1629	25	1679	151
1630	28	1680	133
1631	51	1681	100
1632	50	1682	116
1633	40	1683	140
1634	24	1684	141
1635	34	1685	194
1636	36	1686	137
1637	22	1687	113
1638	19	1688	129
1639	41	1689	50
1640	80	1690	110
1641	65	1691	51
1642	21	1692	89
1643	26	1693	66
1644	14	1694	90
1645	9	1695	172
1646	28	1696	138
1647	63	1697	190
1648	75	1698	208
1649	88	1699	122

Swift A4 fine	1700-1800 cm		
Depth cm	Charcoal ct	Depth cm	Charcoal ct
1700		1749	202
1701	85	1750	57
1702	105	1751	147
1703	257	1752	97
1704	335	1753	171
1705	273	1754	207
1706	225	1755	516
1707	166	1756	251
1708	314	1757	243
1709	267	1758	292
1710	262	1759	263
1711	112	1760	67
1712	253	1761	46
1713	240	1762	46
1714	284	1763	41
1715	189	1764	73
1716	406	1765	55
1717	342	1766	69
1718	134	1767	28
1719	191	1768	49
1720	110	1769	123
1721	308	1770	143
1722	182	1771	114
1723	328	1772	115
1724	246	1773	95
1725	225	1774	98
1726	391	1775	46
1727	245	1776	48
1728	201	1777	46
1729	231	1778	40
1730	105	1779	28
1731	394	1780	19
1732	173	1781	46
1733	378	1782	28
1734	309	1783	25
1735	243	1784	7
1736	203	1785	20
1737	196	1786	9
1738	71	1787	36
1739	131	1788	15
1740	188	1789	10
1741	196	1790	23
1742	131	1791	16
1743	197		
1744	111		
1745	154		
1746	130		
1747	82		
1748	119		

Appendix A. Raw data of charcoal for Swift Lake, A1, A2, A3, and A4. Fine resolution at 1 cm increments.

Sixteen A1 Coarse

Depth cm	Charcoal Count	Depth cm	Charcoal Count
1002	229	1051	0
1003	229	1052	0
1004	229	1053	0
1005	229	1054	0
1006	110	1055	0
1007	110	1056	0
1008	110	1057	0
1009	110	1058	0
1010	86	1059	0
1011	86	1060	0
1012	86	1061	0
1013	86	1062	0
1014	52	1063	0
1015	52	1064	0
1016	52	1065	0
1017	52	1066	0
1018	105	1067	0
1019	105	1068	0
1020	105	1069	0
1021	105	1070	0
1022	157	1071	0
1023	157	1072	0
1024	157	1073	0
1025	157	1074	0
1026	49	1075	0
1027	49	1076	0
1028	49	1077	0
1029	49	1078	0
1030	1		
1031	1		
1032	1		
1033	1		
1034	1		
1035	1		
1036	1		
1037	1		
1038	1		
1039	1		
1040	1		
1041	1		
1042	0		
1043	0		
1044	0		
1045	0		
1046	0		
1047	0		
1048	0		
1049	0		
1050	0		

Sixteen A2 Coarse

Core Depth	Charcoal Count	Core Depth	Charcoal Count
853	214	901	179
854	214	902	179
855	214	903	179
856	214	904	179
857	290	905	89
858	290	906	89
859	290	907	89
860	290	908	89
861	274	909	35
862	274	910	35
863	274	911	35
864	274	912	35
865	232	913	22
866	232	914	22
867	232	915	22
868	232	916	22
869	244	917	90
870	244	918	90
871	244	919	90
872	244	920	90
873	184	921	16
874	184	922	16
875	184	923	16
876	184	924	16
877	237	925	16
878	237	926	16
879	237	927	16
880	237	928	16
881	258	929	16
882	258	930	16
883	258	931	16
884	258	932	16
885	98		
886	98		
887	98		
888	98		
889	108		
890	108		
891	108		
892	108		
893	28		
894	28		
895	28		
896	28		
897	58		
898	58		
899	58		
900	58		

Sixteen A3 Coarse

Core Depth	Charcoal Count	Core Depth	Charcoal Count
952	29	1000	55
953	29	1001	55
954	29	1002	55
955	29	1003	55
956	18	1004	241
957	18	1005	241
958	18	1006	241
959	18	1007	241
960	15	1008	155
961	15	1009	155
962	15	1010	155
963	15	1011	155
964	9	1012	172
965	9	1013	172
966	9	1014	172
967	9	1015	172
968	13	1016	123
969	13	1017	123
970	13	1018	123
971	13	1019	123
972	18	1020	79
973	18	1021	79
974	18	1022	79
975	18	1023	79
976	6	1024	61
977	6	1025	61
978	6	1026	61
979	6	1027	61
980	12	1028	87
981	12	1029	87
982	12	1030	87
983	12	1031	87
984	13	1032	135
985	13	1033	135
986	13	1034	135
987	13	1035	135
988	21	1036	138
989	21	1037	138
990	21	1038	138
991	21	1039	138
992	22	1040	28
993	22	1041	28
994	22	1042	28
995	22	1043	28
996	41	1044	15
997	41	1045	15
998	41	1046	15
999	41	1047	15

Appendix A. Raw data of charcoal counts for Lake Sixteen. Coarse methodology. Sampling is done from bottom to top.

Sixteen A2	Fine - CW Lab		
Core Depth	Charcoal count	Core depth	charcoal count
851	47	902	40
852	55	903	47
853	53	904	38
854	40	905	29
855	94	906	21
856	53	907	26
857	70	908	17
858	70	909	33
859	55	910	16
860	78	911	14
861	73	912	16
862	37	913	12
863	54	914	35
864	38	915	31
865	60	916	25
866	75	917	63
867	112	918	55
868	55	919	24
869	59	920	25
870	67	921	30
871	52	922	18
872	30	923	14
873	40	924	5
874	76	925	12
875	46	926	26
876	43	927	37
877	57	928	16
878	69	929	30
879	54	930	22
880	47	931	20
881	66	932	13
882	36	933	37
883	44	934	10
884	35		
885	30		
886	15		
887	18		
888	12		
889	26		
890	39		
891	16		
892	13		
893	27		
894	22		
895	27		
896	40		
897	79		
898	24		
899	37		
900	18		
901	36		

Sixteen A3	Fine CW lab		
Depth cm	Charcoal ct.	Depth cm	Charcoal ct.
951	13	1003	46
952	26	1004	109
953	54	1005	172
954	16	1006	124
955	34	1007	193
956	28	1008	37
957	11	1009	183
958	11	1010	132
959	11	1011	33
960	37	1012	46
961	11	1013	167
962	29	1014	100
963	9	1015	127
964	12	1016	92
965	21	1017	63
966	17	1018	31
967	10	1019	35
968	17	1020	42
969	18	1021	24
970	44	1022	22
971	11	1023	36
972	12	1024	40
973	32	1025	32
974	30	1026	39
975	10	1027	62
976	12	1028	45
977	31	1029	47
978	16	1030	40
979	8	1031	37
980	9	1032	22
981	6	1033	89
982	23	1034	21
983	7	1035	47
984	4	1036	89
985	19	1037	24
986	46	1038	9
987	15	1039	26
988	16	1040	18
989	21	1041	11
990	17	1042	15
991	36	1043	5
992	43	1044	6
993	17	1045	2
994	34		
995	68		
996	70		
997	23		
998	23		
999	34		
1000	15		
1001	40		
1002	39		

Sixteen A2	Fine Repeat UC		
Depth cm	Charcoal ct	Depth cm	Charcoal ct
851	85	904	160
852	104	905	105
853	98	906	62
854	222	907	76
855	72	908	37
856	77	909	42
857	91	910	32
858	97	911	19
859	114	912	23
860	84	913	41
861	70	914	42
862	82	915	74
863	86	916	59
864	79	917	63
865	96	918	55
866	105	919	66
867	170	920	30
868	139	921	33
869	83	922	10
870	201	923	14
871	118	924	10
872	86	925	14
873	55	926	55
874	69	927	51
875	68	928	57
876	62	929	40
877	95	930	17
878	150	931	76
879	69	932	26
880	56	933	39
881	128		
882	85		
883	64		
884	38		
885	55		
886	34		
887	38		
888	36		
889	50		
890	76		
891	48		
892	25		
893	30		
894	43		
895	54		
896	47		
897	38		
898	60		
899	54		
900	36		
901	62		
902	89		
903	73		

Appendix A. Raw data of charcoal counts for Lake Sixteen. Fine methodology. Sampling is done from top to bottom.

Big Fish Lake	A1				
Sample No.	Depth in cm	Charcoal count	Sample No.	Depth in cm	Charcoal count
24	935	26	11	987	51
24	936	26	11	988	51
24	937	26	11	989	51
24	938	26	11	990	51
23	939	18	10	991	98
23	940	18	10	992	98
23	941	18	10	993	98
23	942	18	10	994	98
22	943	27	9	995	134
22	944	27	9	996	134
22	945	27	9	997	134
22	946	27	9	998	134
21	947	33	8	999	132
21	948	33	8	1000	132
21	949	33	8	1001	132
21	950	33	8	1002	132
20	951	26	7	1003	137
20	952	26	7	1004	137
20	953	26	7	1005	137
20	954	26	7	1006	137
19	955	30	6	1007	264
19	956	30	6	1008	264
19	957	30	6	1009	264
19	958	30	6	1010	264
18	959	35	5	1011	141
18	960	35	5	1012	141
18	961	35	5	1013	141
18	962	35	5	1014	141
17	963	31	4	1015	33
17	964	31	4	1016	33
17	965	31	4	1017	33
17	966	31	4	1018	33
16	967	44	3	1019	14
16	968	44	3	1020	14
16	969	44	3	1021	14
16	970	44	3	1022	14
15	971	17	2	1023	106
15	972	17	2	1024	106
15	973	17	2	1025	106
15	974	17	2	1026	106
14	975	40	1	1027	230
14	976	40	1	1028	230
14	977	40	1	1029	230
14	978	40	1	1030	230
13	979	68			
13	980	68			
13	981	68			
13	982	68			
12	983	54			
12	984	54			
12	985	54			
12	986	54			

Big Fish	A2				
Sample No.	Depth in cm	Charcoal count	Sample No.	Depth in cm	Charcoal count
22	1031	205	9	1083	42
22	1032	205	9	1084	42
22	1033	205	9	1085	42
22	1034	205	9	1086	42
21	1035	89	8	1087	9
21	1036	89	8	1088	9
21	1037	89	8	1089	9
21	1038	89	8	1090	9
20	1039	125	7	1091	3
20	1040	125	7	1092	3
20	1041	125	7	1093	3
20	1042	125	7	1094	3
19	1043	153	6	1095	60
19	1044	153	6	1096	60
19	1045	153	6	1097	60
19	1046	153	6	1098	60
18	1047	122	5	1099	70
18	1048	122	5	1100	70
18	1049	122	5	1101	70
18	1050	122	5	1102	70
17	1051	41	4	1103	16
17	1052	41	4	1104	16
17	1053	41	4	1105	16
17	1054	41	4	1106	16
16	1055	35	3	1107	5
16	1056	35	3	1108	5
16	1057	35	3	1109	5
16	1058	35	3	1110	5
15	1059	43	2	1111	11
15	1060	43	2	1112	11
15	1061	43	2	1113	11
15	1062	43	2	1114	11
14	1063	11	1	1115	72
14	1064	11	1	1116	72
14	1065	11	1	1117	72
14	1066	11	1	1118	72
13	1067	10			
13	1068	10			
13	1069	10			
13	1070	10			
12	1071	18			
12	1072	18			
12	1073	18			
12	1074	18			
11	1075	55			
11	1076	55			
11	1077	55			
11	1078	55			
10	1079	19			
10	1080	19			
10	1081	19			
10	1082	19			

Big Fish	A3				
Sample No.	Depth in cm	Charcoal count	Sample No.	Depth in cm	Charcoal count
15	1055	62	2	1107	28
15	1056	62	2	1108	28
15	1057	62	2	1109	28
15	1058	62	2	1110	28
14	1059	51	1	1111	2
14	1060	51	1	1112	2
14	1061	51	1	1113	2
14	1062	51	1	1114	2
13	1063	45			
13	1064	45			
13	1065	45			
13	1066	45			
12	1067	29			
12	1068	29			
12	1069	29			
12	1070	29			
11	1071	18			
11	1072	18			
11	1073	18			
11	1074	18			
10	1075	70			
10	1076	70			
10	1077	70			
10	1078	70			
9	1079	60			
9	1080	60			
9	1081	60			
9	1082	60			
8	1083	74			
8	1084	74			
8	1085	74			
8	1086	74			
7	1087	13			
7	1088	13			
7	1089	13			
7	1090	13			
6	1091	11			
6	1092	11			
6	1093	11			
6	1094	11			
5	1095	108			
5	1096	108			
5	1097	108			
5	1098	108			
4	1099	16			
4	1100	16			
4	1101	16			
4	1102	16			
3	1103	11			
3	1104	11			
3	1105	11			
3	1106	11			

Appendix A. Raw data for charcoal for Big Fish using coarse methodology. Sampling is from the bottom up. Value for each sample has been entered four times for the purposes of graphing.

Big Fish	B1	Big Fish	B1
Depth-cm	Charcoal count	Depth-cm	Charcoal count
900		950	23
901	8	951	30
902	24	952	31
903	17	953	34
904	9	954	17
905	11	955	21
906	28	956	20
907	8	957	25
908	10	958	10
909	8	959	31
910	14	960	32
911	8	961	26
912	15	962	34
913	15	963	34
914	19	964	21
915	16	965	18
916	14	966	23
917	14	967	15
918	9	968	24
919	19	969	20
920	17	970	13
921	13	971	20
922	10	972	5
923	3	973	18
924	8	974	16
925	8	975	29
926	18	976	18
927	12	977	23
928	3	978	99
929	8	979	46
930	8	980	70
931	13	981	47
932	4	982	55
933	7	983	30
934	10	984	29
935	15	985	27
936	12	986	76
937	18	987	27
938	25	988	42
939	17	989	43
940	18	990	44
941	12	991	35
942	16	992	76
943		993	49
944		994	51
945	20	995	47
946	30	996	28
947	10	997	
948	20	998	
949	28	999	

Big Fish	B2		
Depth cm	charcoal count	Depth cm	charcoal count
1000		1050	14
1001	81	1051	23
1002	73	1052	12
1003	124	1053	31
1004	55	1054	36
1005	43	1055	19
1006	46	1056	5
1007	62	1057	3
1008	53	1058	2
1009	95	1059	6
1010	64	1060	7
1011	30	1061	7
1012	47	1062	3
1013	23	1063	14
1014	11	1064	15
1015	1	1065	23
1016	16	1066	7
1017	10	1067	16
1018	7	1068	5
1019	3	1069	11
1020	10	1070	2
1021	26	1071	4
1022	31	1072	6
1023	20	1073	6
1024	70	1074	3
1025	129	1075	4
1026	79	1076	6
1027	85	1077	5
1028	43	1078	8
1029	157	1079	9
1030	171	1080	21
1031	46	1081	20
1032	38	1082	6
1033	63	1083	6
1034	1	1084	6
1035	25	1085	10
1036	37	1086	23
1037	49	1087	9
1038	35	1088	11
1039	39	1089	11
1040	23	1090	24
1041	12	1091	
1042	8	1092	
1043	25	1093	
1044	15	1094	
1045	34	1095	
1046	40	1096	
1047	53	1097	
1048	53	1098	
1049	16	1099	

Big Fish	B3		
Depth cm	charcoal count	Depth cm	charcoal count
1100	0	1151	0
1101	9	1152	0
1102	22	1153	4
1103	17	1154	2
1104	7	1155	5
1105	5	1156	14
1106	4	1157	6
1107	2	1158	0
1108	5	1159	1
1109	0	1160	1
1110	0	1161	1
1111	2	1162	1
1112	0	1163	2
1113	0	1164	1
1114	0	1165	2
1115	1	1166	1
1116	1	1167	1
1117	0	1168	1
1118	4	1169	0
1119	1	1170	0
1120	1	1171	0
1121	11	1172	1
1122	16	1173	0
1123	3	1174	0
1124	0	1175	0
1125	0	1176	0
1126	1	1177	1
1127	0	1178	0
1128	2	1179	0
1129	3	1180	0
1130	5	1181	0
1131	3	1182	0
1132	8	1183	1
1133	5	1184	0
1134	0	1185	1
1135	0	1186	0
1136	0	1187	0
1137	2	1188	1
1138	2	1189	1
1139	1	1190	0
1140	0	1191	6
1141	0	1192	33
1142	0	1193	4
1143	0	1194	0
1144	0	1195	0
1145	2	1196	0
1146	15	1197	1
1147	12	1198	
1148	3	1199	
1149	12		
1150	2		

Appendix A. Big Fish Raw Data of charcoal counts. Fine resolution at 1 cm increments of B1, B2, B3.

Recount on Original Methodology lake 16 A2, Jun 22, 2008 and Jan 11, 2009							
850- 950 cm	sampling was started at the bottom of the core.						
		sample	22-Jun-08	11-Jan-09			
	sample number	midpoint	count 1	Count 2	difference		%
853-857 cm	20	855	214	252	38	0.18	18
857-861 cm	19	859	290	326	36	0.12	12
861-865 cm	18	863	274	261	-13	-0.05	-5
865-869 cm	17	867	232	214	-18	-0.08	-8
869-873 cm	16	871	244	230	-14	-0.06	-6
873-877 cm	15	875	184	173	-11	-0.06	-6
877-881 cm	14	879	237	207	-30	-0.13	-13
881-885 cm	13	883	258	276	18	0.07	7
885-889 cm	12	887	98	100	2	0.02	2
889-893 cm	11	891	108	120	12	0.11	11
893-897 cm	10	895	28	39	11	0.39	39
897-901 cm	9	899	58	63	5	0.09	9
901-905 cm	8	903	179	190	11	0.06	6
905-909 cm	7	907	89	96	7	0.08	8
909-913 cm	6	911	35	46	11	0.31	31
913-917 cm	5	915	22	32	10	0.45	45
917-921 cm	4	919	90	85	-5	-0.06	-6
921-925 cm	3	923	16	34	18	1.13	113
925-929 cm	2	927	16	30	14	0.88	88
929-933 cm	1	931	16	22	6	0.38	38

Appendix A, Data for the recount check of lake 16, A2, 850-950 cm depth dried samples.

Charcoal Multiple Sampling at 2 depths, Test for homogeneity of charcoal distribution in lake sediments

Swift Lake, Samples 3 (1713-1717 cm depth) and 19 (1777-1781 cm depth) resampled and counted

Coarse methodology | Swift Lake 1700-1800 cm depth

Sample No.	Depth, cm	Abs.depth	Original Sample Count	Sample a	Sample b	Sample c	Sample d	Sample e	Range	Average	Max Deviation from ave.
22	0-4	1701	280								
		1702	280								
		1703	280								
		1704	280								
21	4 - 8	1705	94								
		1706	94								
		1707	94								
		1708	94								
20	8-12	1709	113								
		1710	113								
		1711	113								
		1712	113								
19	12-16	1713	464	573	419	524	762	521	343	544	218
		1714	464								
		1715	464								
		1716	464								
18	16-20	1717	183								
		1718	183								
		1719	183								
		1720	183								
17	20-24	1721	349								
		1722	349								
		1723	349								
		1724	349								
16	24-28	1725	186								
		1726	186								
		1727	186								
		1728	186								
15	28-32	1729	168								
		1730	168								
		1731	168								
		1732	168								
14	32-36	1733	243								
		1734	243								
		1735	243								
		1736	243								
13	36-40	1737	257								
		1738	257								
		1739	257								
		1740	257								
12	40-44	1741	151								
		1742	151								
		1743	151								
		1744	151								
11	44-48	1745	71								
		1746	71								
		1747	71								
		1748	71								
10	48-52	1749	162								
		1750	162								
		1751	162								
		1752	162								
9	52-56	1753	119								
		1754	119								
		1755	119								
		1756	119								
8	56-60	1757	208								
		1758	208								
		1759	208								
		1760	208								
7	60-64	1761	343								
		1762	343								
		1763	343								
		1764	343								
6	64-68	1765	459								
		1766	459								
		1767	459								
		1768	459								
5	68-72	1769	437								
		1770	437								
		1771	437								
		1772	437								
4	72-76	1773	243								
		1774	243								
		1775	243								
		1776	243								
3	76-80	1777	129	543	295	468	511	358	414	384	255
		1778	129								
		1779	129								
		1780	129								
2	80-84	1781	268								
		1782	268								
		1783	268								
		1784	268								
1	84-88	1785	369								
		1786	369								
		1787	369								
		1788	369								

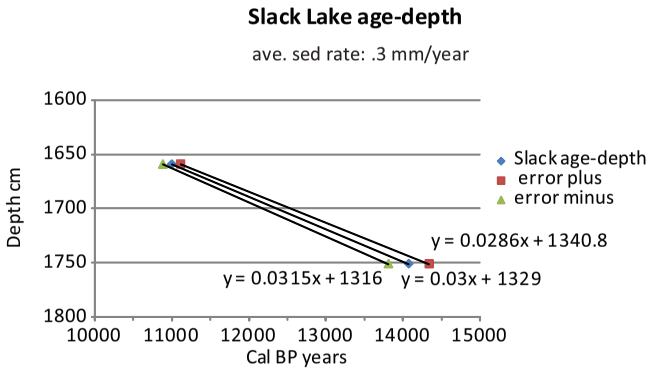
Appendix A. Results of multiple sampling at two depths in Swift Lake to test for homogeneity of charcoal distribution in lake sediments.

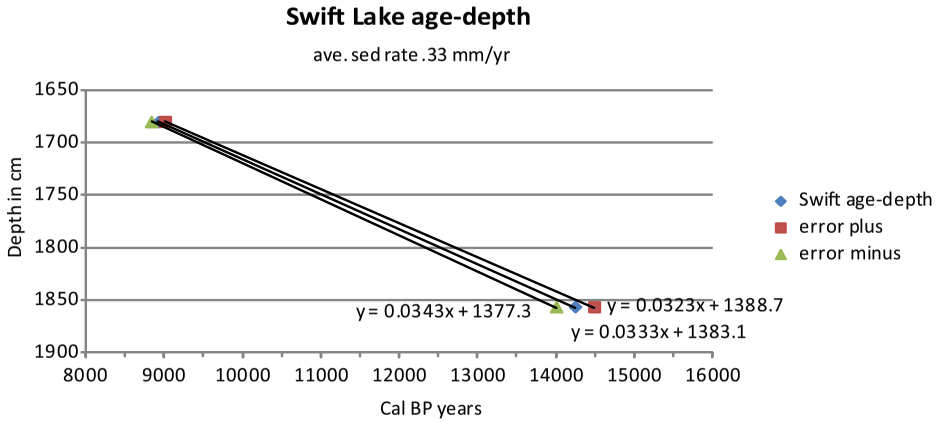
	Older date data				Younger date data			
	14C older date	Ave older date Cal	Min Older Cal	Max Older Cal	14C younger date	Ave younger date Cal	Min younger Cal	Max younger Cal
Big Fish	12850±55	15407	15152	15662	10300±35	12166	11997	12335
Sixteen	13350±55	16287	15869	16705	11150±35	13062	12945	13179
Swift	12200±65	14245	14004	14486	8050±30	8924	8837	9011
Slack	12050±110	14073	13809	14336	9630±25	11005	10888	11121

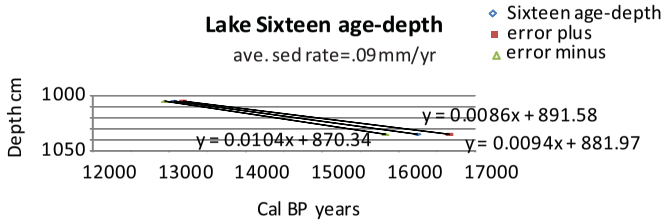
	Calculations dates			Depth data		
	Ave Cal. older minus ave. younger	Max Cal. older minus min. younger	Min. Cal older minus max Cal older	Ave depth mm	mm Depth min	mm Depth max
Big Fish	3241	3665	2817	835 BF 1067-1070 cm, 985 cm	820	850
Sixteen	3225	3760	2690	280 Sixteen, fixed depth range	280	280
Swift	5321	5649	4993	1650 Swift 1857 cm, 1692-1695 cm	1620	1650
Slack	3068	3448	2688	970 Slack, 1756 cm,1658-1660 cm	960	980

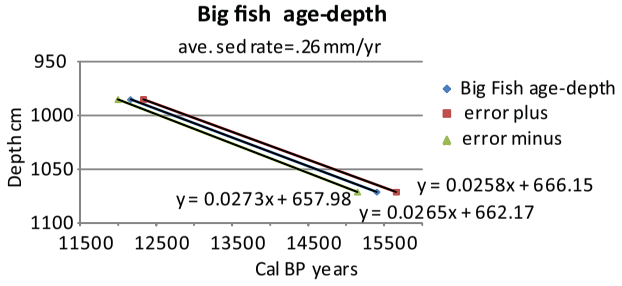
	Sedimentation Calculations with Cal BP years error ranges and depth ranges				
	mm/yr ave depth/ ave time	mm/yr min depth/ max years	mm/yr min depth/ min years	mm/yr max depth/ max years	mm/yr max depth/ min years
Bg Fish	**0.26**	0.22	0.29	0.23	0.30
Sixteen	**0.09**	0.07	0.10	n/a	n/a
Swift	**0.31**	0.29	0.32	0.29	0.33
Slack	**0.32**	0.28	0.36	0.28	0.36
	Results	**Range of variation**			

Appendix A. Calculations for sedimentation rates for the four lakes, using Calibrated radiocarbon dates with error values, and also calculated for maximum, average, and minimm depths if macrofossil samples were taken from a 3 cm interval (sometimes macrofossils were scarce).









Appendix A. Age-depth graphs for Slack, Swift, Sixteen and Big Fish Lakes, using 2 calibrated radiocarbon dates per lake. Errof bars for calibrated dates are also shown. Lake Sixteen appears to have a much lower sedimentation rate than the other three lakes.

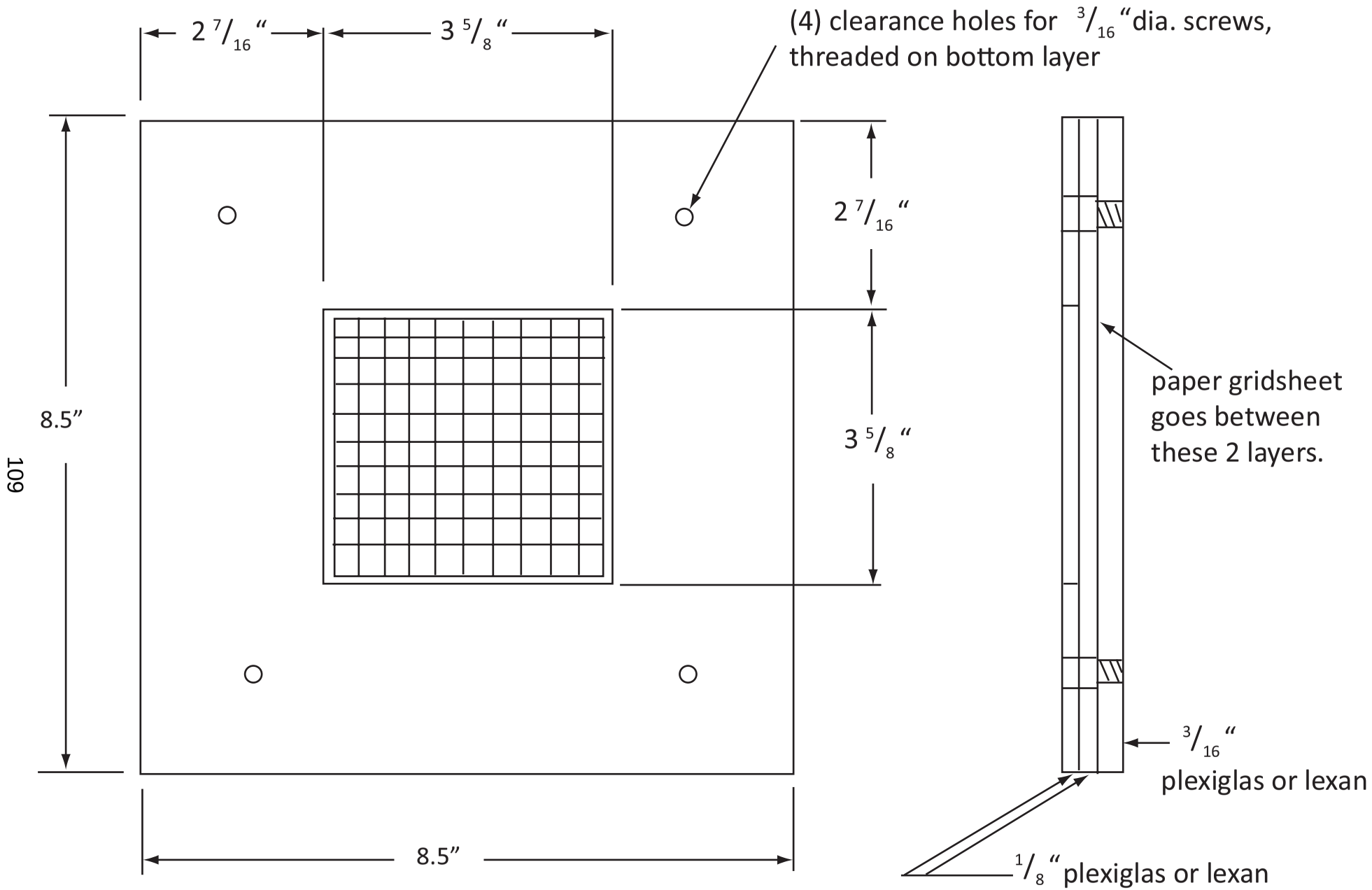
Macrofossils ready to send, Michigan lakes: Slack, Swift, Sixteen, Big Fish

Lake	Thrust	Depth	Abs. depth	Type of sample	Weight	Notes
Sixteen	A3	50-51 cm	1000.5	charcoal		
Sixteen	A3	52-53 cm	1002.5	charcoal, burned spruce needle		
Sixteen	A3	53-54 cm	1003.5	charcoal, glassy		
Sixteen	A3	54-55 cm	1004.5	charcoal		
Sixteen	A3	55-56 cm	1005.5	charcoal		
Sixteen	A3	56-57 cm	1006.5	charcoal		
Sixteen	A3	58-59 cm	1008.5	charcoal		
Sixteen	A1	0-4 cm	1012-1016	charcoal of woody type		
Sixteen	A1	4-8 cm	1016-1020	charcoal, orange splinters		
Sixteen	A1	12-16 cm		charcoal, piece of coal?, brown fishbone		
Sixteen	A1	16-20 cm		charcoal, shell bits		
Sixteen	A1	24-28 cm		charcoal +		
Sixteen	A1	36-40 cm	1050	charcoal & woody mat	.006g	
Sixteen	A1	42 cm	1054	large root/twig from basal sand. May be too much older than dep.	0.008g	
Big Fish	B2	58 cm	1058	wood etc. from silt	.0012g	
Big Fish	B1	61 cm	961	large organic flake	.016g	
Slack	B1	74-75 cm	1524.5	large black seed	.006g	Holocene
Slack	A4	1-5 cm		blackened spruce needles, fish		
Slack	A4	25-30 cm		maybe charcoal?		
Slack	A4	30-35 cm		bugs, (beetle), charcoal, wood		
Slack	A3	54-55 cm		(color black) spruce needle, charcoal		
Slack	A3	55-56 cm		bug burned, & spruce		
Slack	A3	56-57 cm		bug husk, charcoal, spruce wing		
Swift	A6	33 cm	1733	flakes	.013g	
Swift	A6	58.5 cm	1758.5	deciduous skeletonized leaf	.011g	
Swift	A7	29 cm	1828	charcoal spruce needle	0g	
Swift	A7	57 cm	1857	woody bits, spruce needles	.027g	

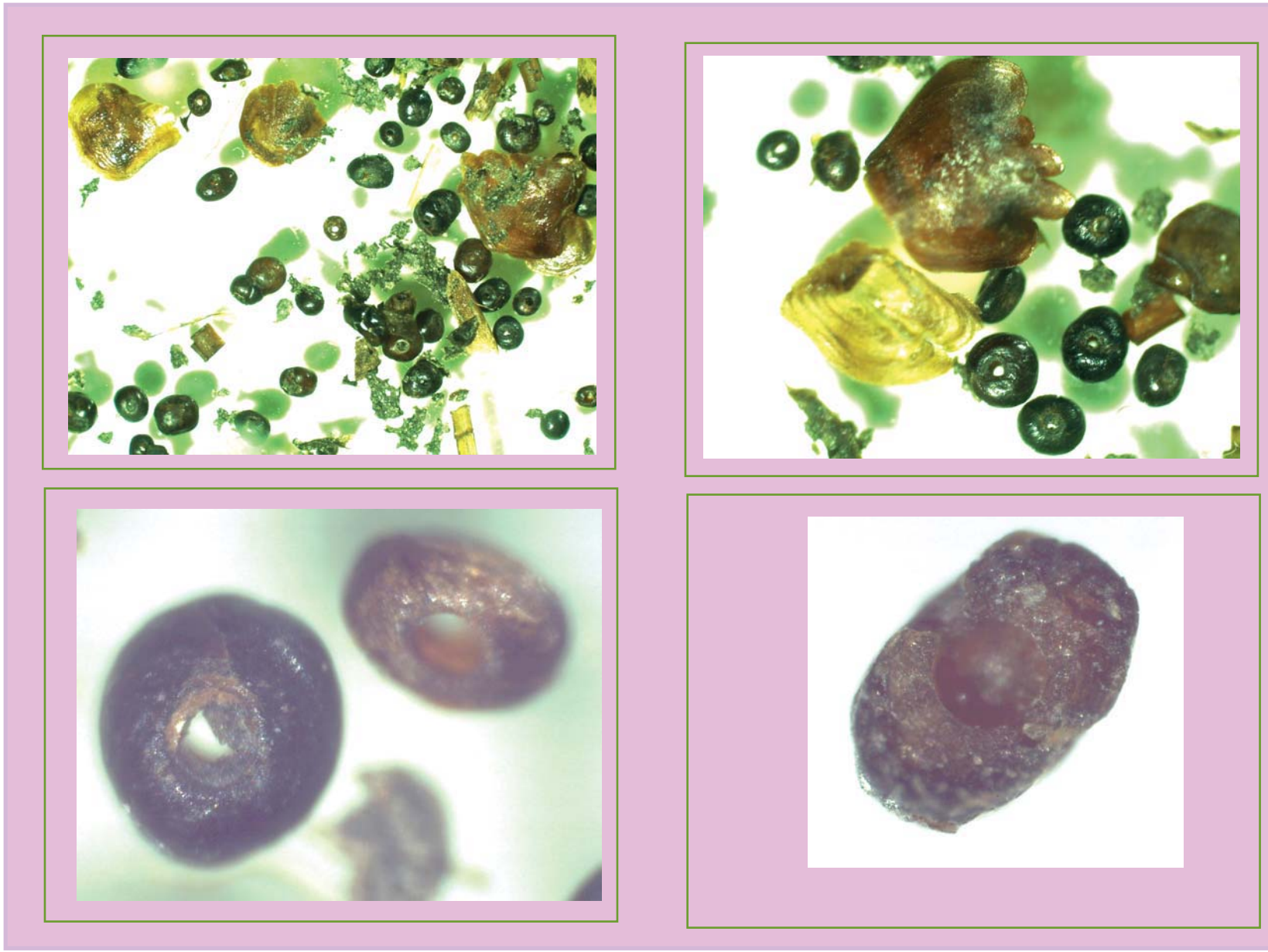
Appendix A, Macrofossils secured for future radiocarbon dating.

Appendix B

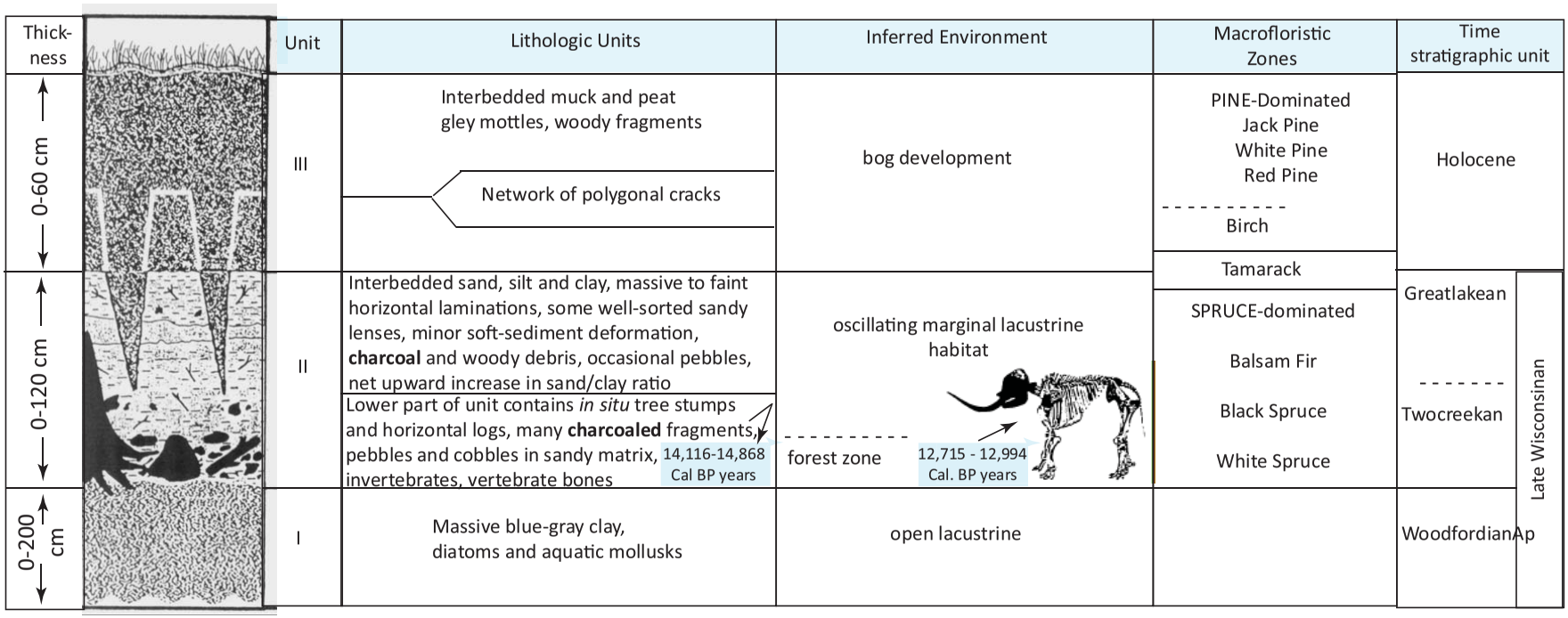
Miscellaneous Images & Methodology diagrams



Appendix B, Fig 1. Plans for a charcoal counting jig to accommodate 100 x 100 mm square lidded plastic Petri dish boxes. Design by Mike Oestreich.



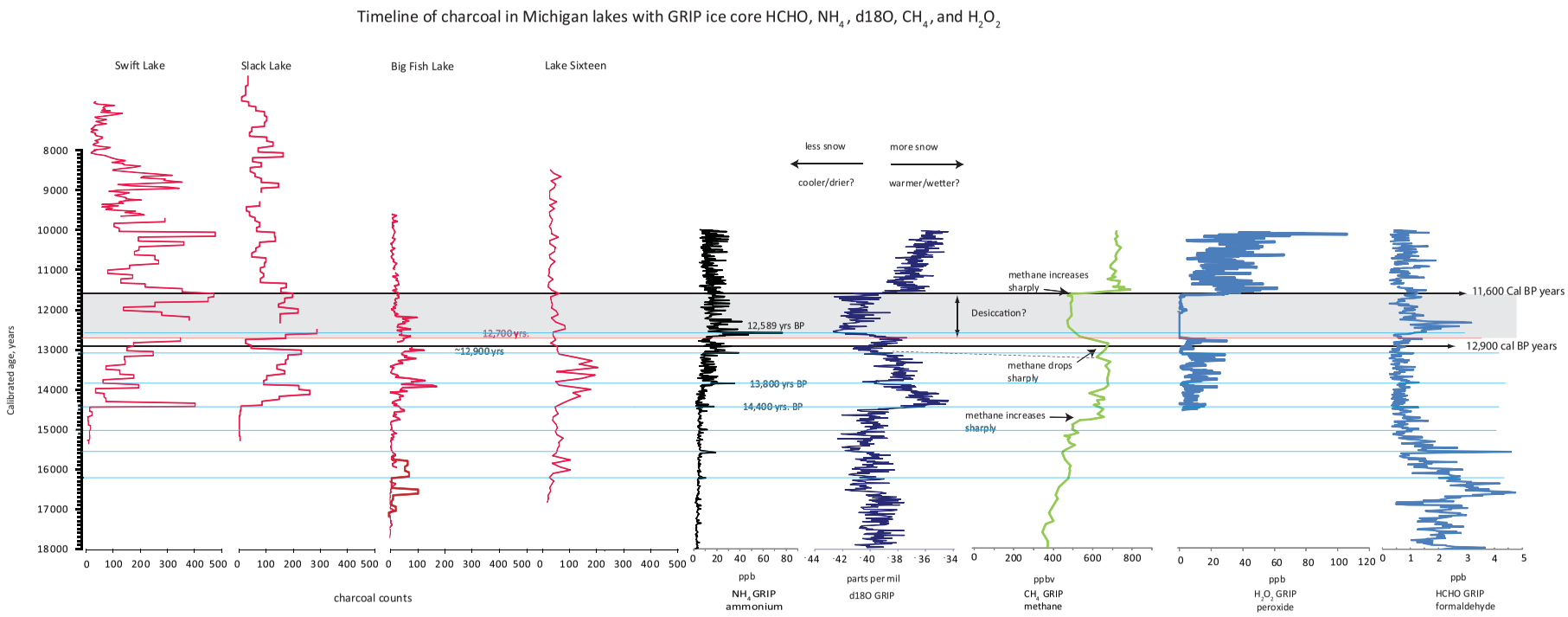
Appendix B, Fig. 2. The unidentified bead-like oblate spheres. There are over 100 associated with the fish remains in Slack A2, 40 cm. These structures are 1 mm or less in diameter and have a hole all the way through, with a larger chamber in the center. (see cross-section image, lower right). These are not testate amoebae (Bob Booth, personal comm.).



Appendix B, Fig 3. Shelton Mastodon stratigraphy, near Lake Sixteen. Charcoal dates to 12,320±110 radiocarbon years or 14,116-14,868 Cal BP years. Date on Mammut bone is 10,875±155 radiocarbon years or 12,715 - 12,994 Cal. BP years. After Shoshani *et al.* (1989).



Appendix B, Fig. 4. Gainey phase artefacts from the Butler site (< 1 km from the Gainey site) in Genesee county, Michigan. Courtesy Donald B. Simons.

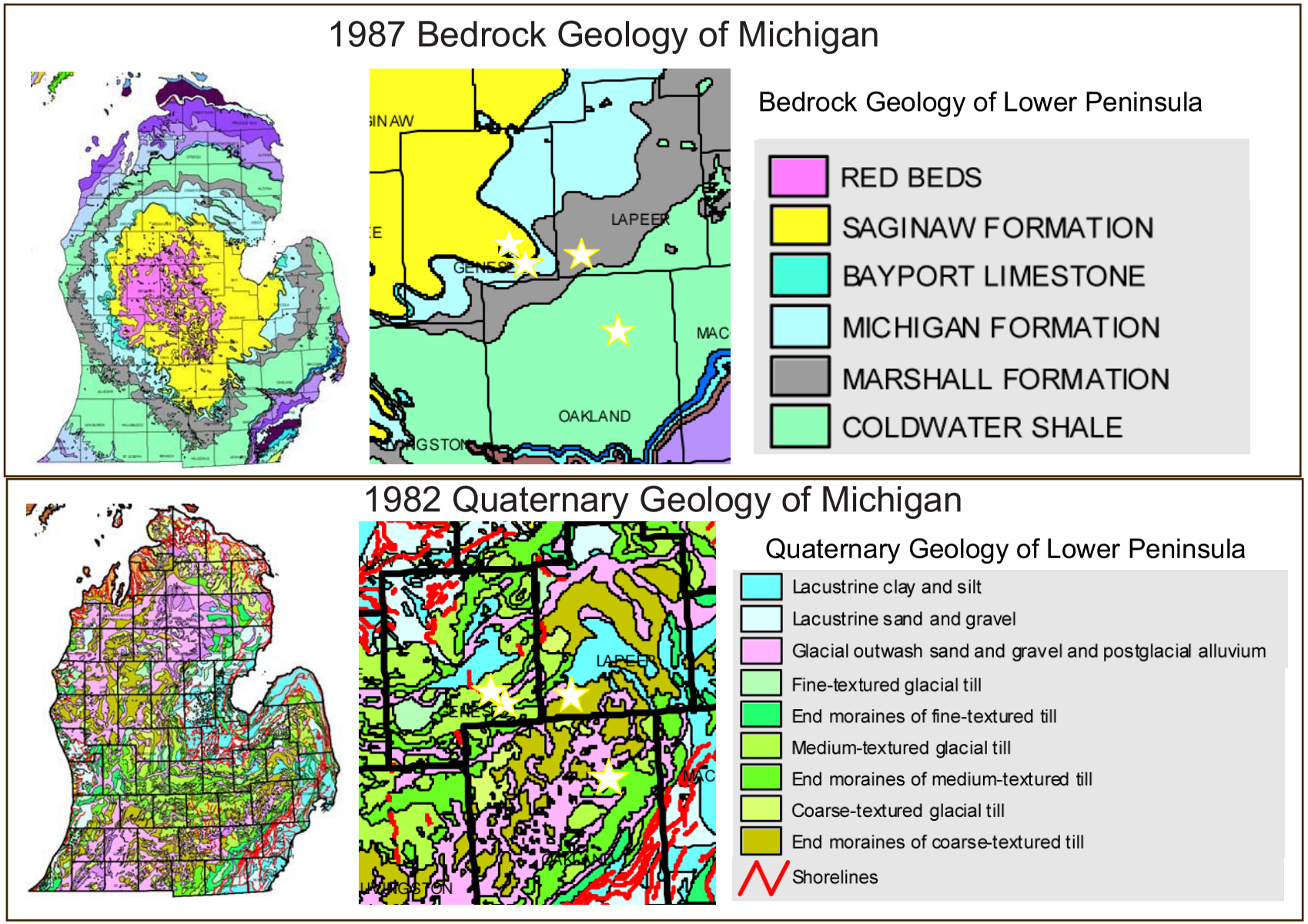


Appendix B,Fig. 5. Timeline of charcoal data from Slack, Swift, Sixteen and Big Fish lakes in Michigan, compared to GRIP ice core d18O and possible combustion markers - trace compounds ammonium, formaldehyde, methane and hydrogen peroxide. The GRIP ice core differs from the GISP2 ice core by 200 years. Light blue lines are on ammonium peaks. Aerosol data is from the GRIP core.

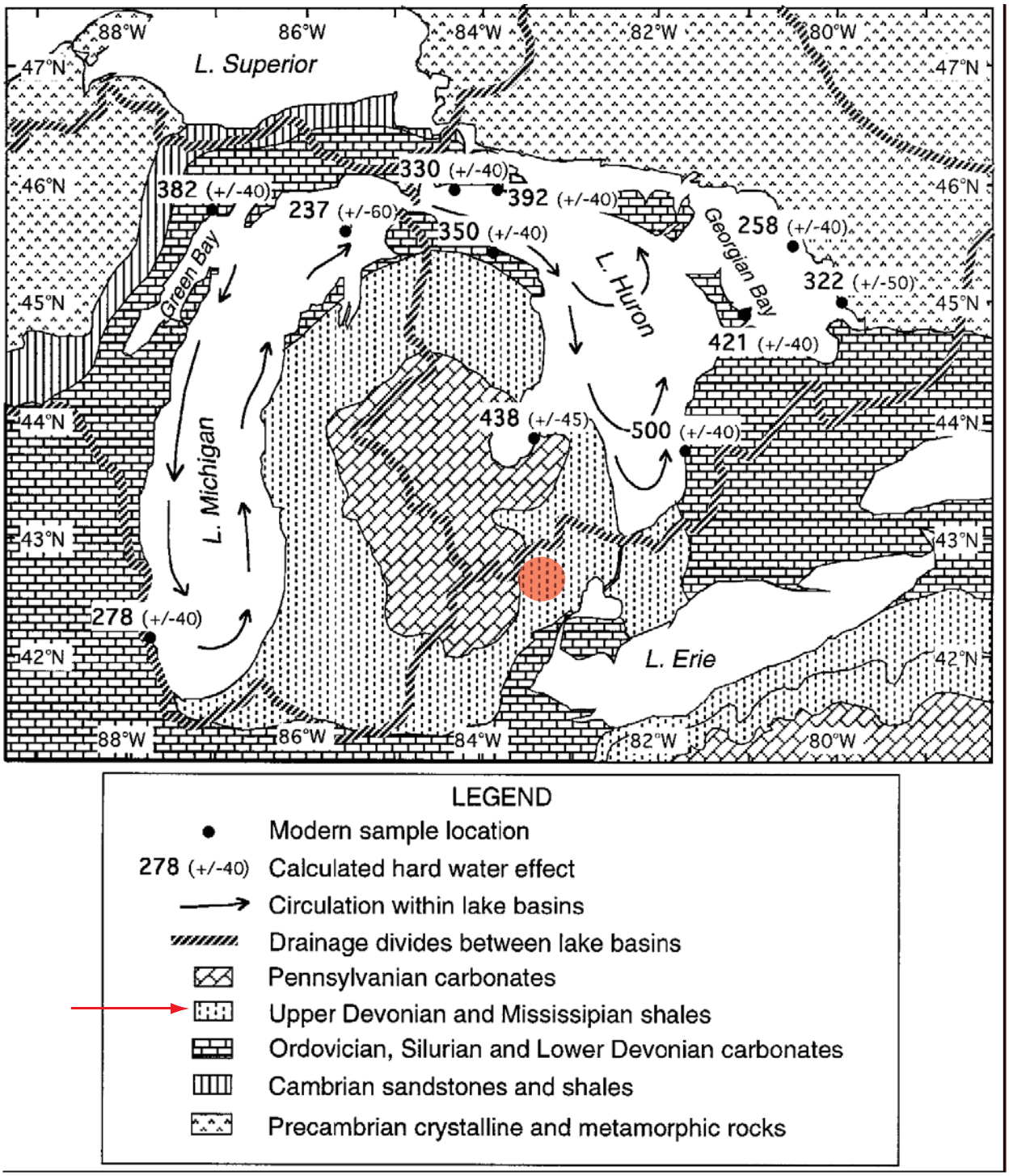
Joanne P Ballard 7-26-2009

Appendix C

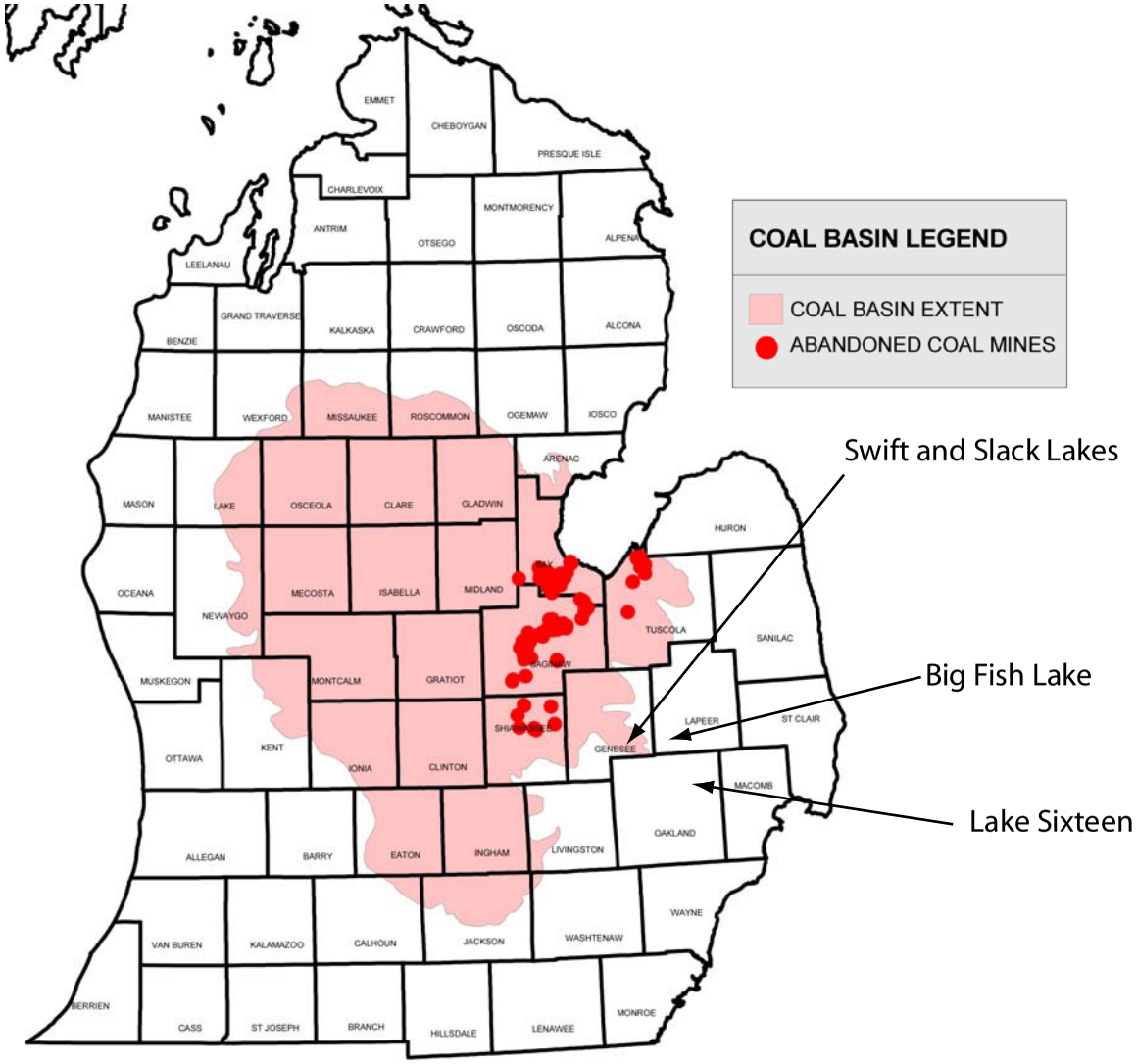
Maps



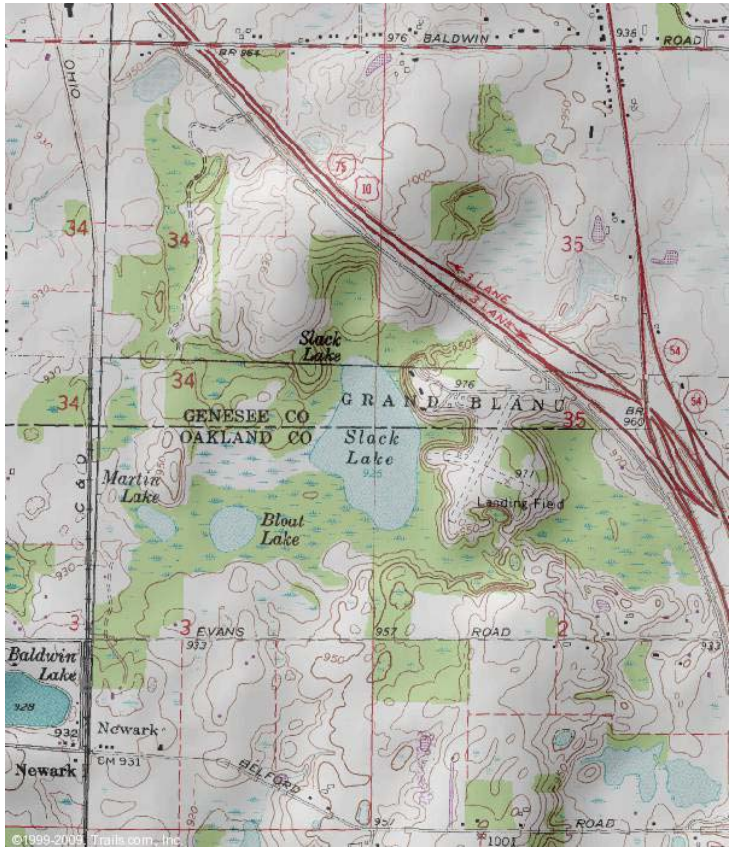
Appencix C,Fig. 1. Bedrock and Quaternary Geology maps of Michigan, with lake locations starred. Clockwise from upper left: Swift, Slack, Big Fish, Sixteen. After Milstein 1987, W.R. Farrand, 1982 and the Michigan Department of Natural Resources.



Appendix C, Fig 2. Geology for the Michigan area, showing carbonates, with study area shown with a red dot. The study area is underlain by shales. After Moore et al. (1998).

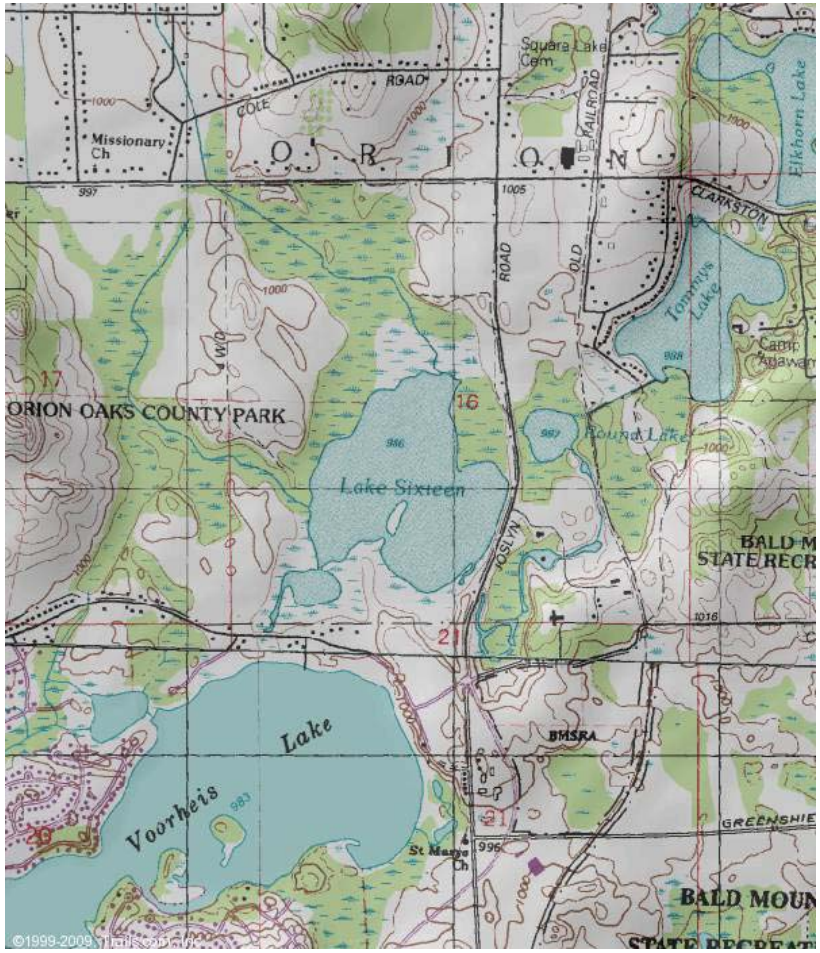


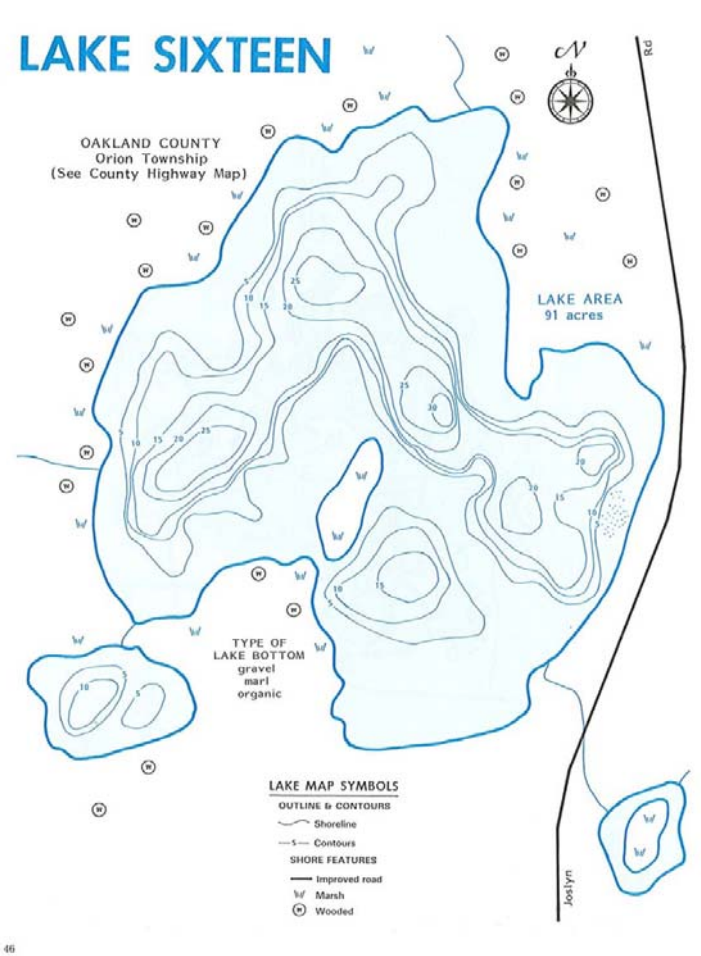
Appendix C, Fig.3 Coal extent in Lower Peninsula of Michigan. The lower southeast corner of Genesee county, where Swift and Slack Lakes are located could be affected by coal. Big Fish and Sixteen, in Lapeer, and Oakland, respectively, are outside of the coal basin extent. After Michigan Department of Natural Resources.



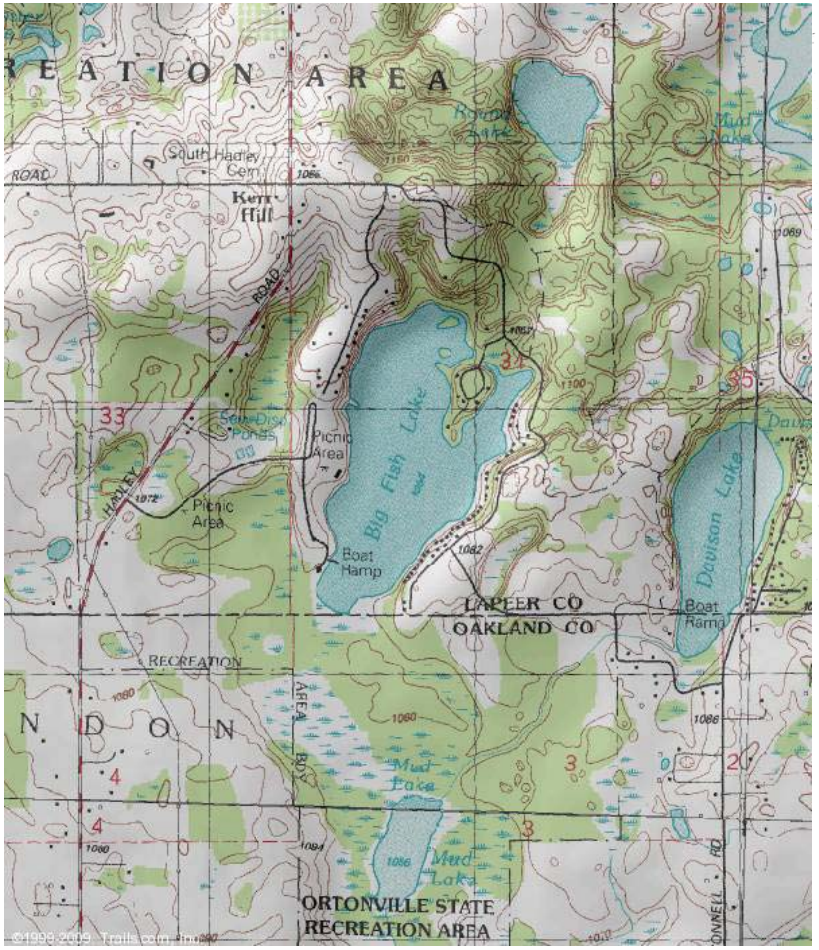


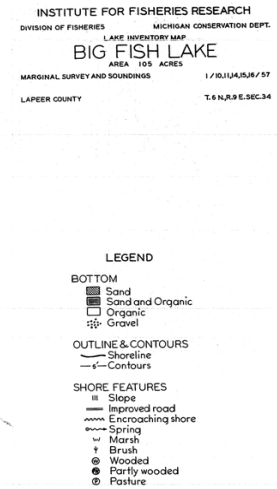
Appendix C, Fig.4. Topographic maps of Slack Lake, left image, and Swift Lake, right image, both in Genesee county, MI. Not to scale.

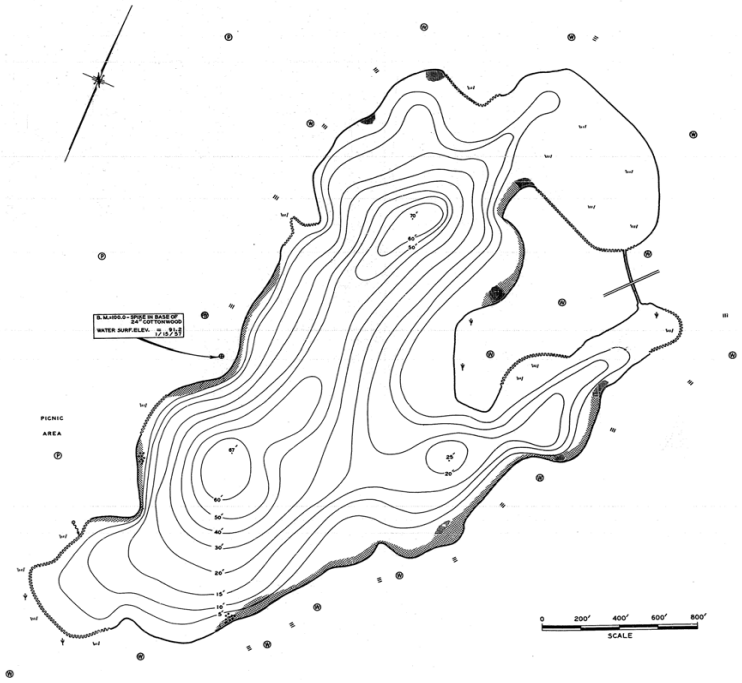




Appendix C, Fig 5. Topographic map and bathymetric map of Lake Sixteen, Oakland county.







Appendix C, Fig 6. Topographic and bathymetric maps of Big Fish Lake, Lapeer county, T. 6N, R. 9E, Sec. 34.

Appendix D

Protocols, forms, counting jig underlay sheet, jack pine reference

1A	2A	3A	4A	5A	6A	7A	8A	9A	10A
1B	2B	3B	4B	5B	6B	7B	8B	9B	10B
1C	2C	3C	4C	5C	6C	7C	8C	9C	10C
1D	2D	3D	4D	5D	6D	7D	8D	9D	10D
1E	2E	3E	4E	5E	6E	7E	8E	9E	10E
1F	2F	3F	4F	5F	6F	7F	8F	9F	10F
1G	2G	3G	4G	5G	6G	7G	8G	9G	10G
1H	2H	3H	4H	5H	6H	7H	8H	9H	10H
1I	2I	3I	4I	5I	6I	7I	8I	9I	10I
1J	2J	3J	4J	5J	6J	7J	8J	9J	10J

Charcoal counting grid for the counting jig,
to be printed in a non-black color

Charcoal count sheet

University of Cincinnati Geology Department, T.V. Lowell Core Laboratory

Sample#_____ Lake_____Core section_____

Date_____Start time_____End time_____Analyst_____

Depth in thrust, cm_____ Absolute depth, cm_____

1	2	3	4	5	6	7	8	9	10
1A	2A	3A	4A	5A	6A	7A	8A	9A	10A
1B	2B	3B	4B	5B	6B	7B	8B	9B	10B
1C	2C	3C	4C	5C	6C	7C	8C	9C	10C
1D	2D	3D	4D	5D	6D	7D	8D	9D	10D
1E	2E	3E	4E	5E	6E	7E	8E	9E	10E
1F	2F	3F	4F	5F	6F	7F	8F	9F	10F
1G	2G	3G	4G	5G	6G	7G	8G	9G	10G
1H	2H	3H	4H	5H	6H	7H	8H	9H	10H
1I	2I	3I	4I	5I	6I	7I	8I	9I	10I
1J	2J	3J	4J	5J	6J	7J	8J	9J	10J

Total of all rows_____Total charcoal particles

Charcoal Form

Site_____ Volume_____

Core_____

cup #	Depth	total volume	sample volume	grass	>250 microns	>125 microns	notes
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
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37							
38							
39							
40							
41							
42							
43							

Charcoal Form

Site_____ Volume_____

Core_____

cup #	Depth	total volume	sample volume	grass	>250 microns	>125 microns	notes
44							
45							
46							
47							
48							
49							
50							
51							
52							
53							
54							
55							
56							
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81							
82							
83							
84							
85							
86							

Charcoal Form

Site_____ Volume_____

Core_____

cup #	Depth	total volume	sample volume	grass	>250 microns	>125 microns	notes
87							
88							
89							
90							
91							
92							
93							
94							
95							
96							
97							
98							
99							
100							

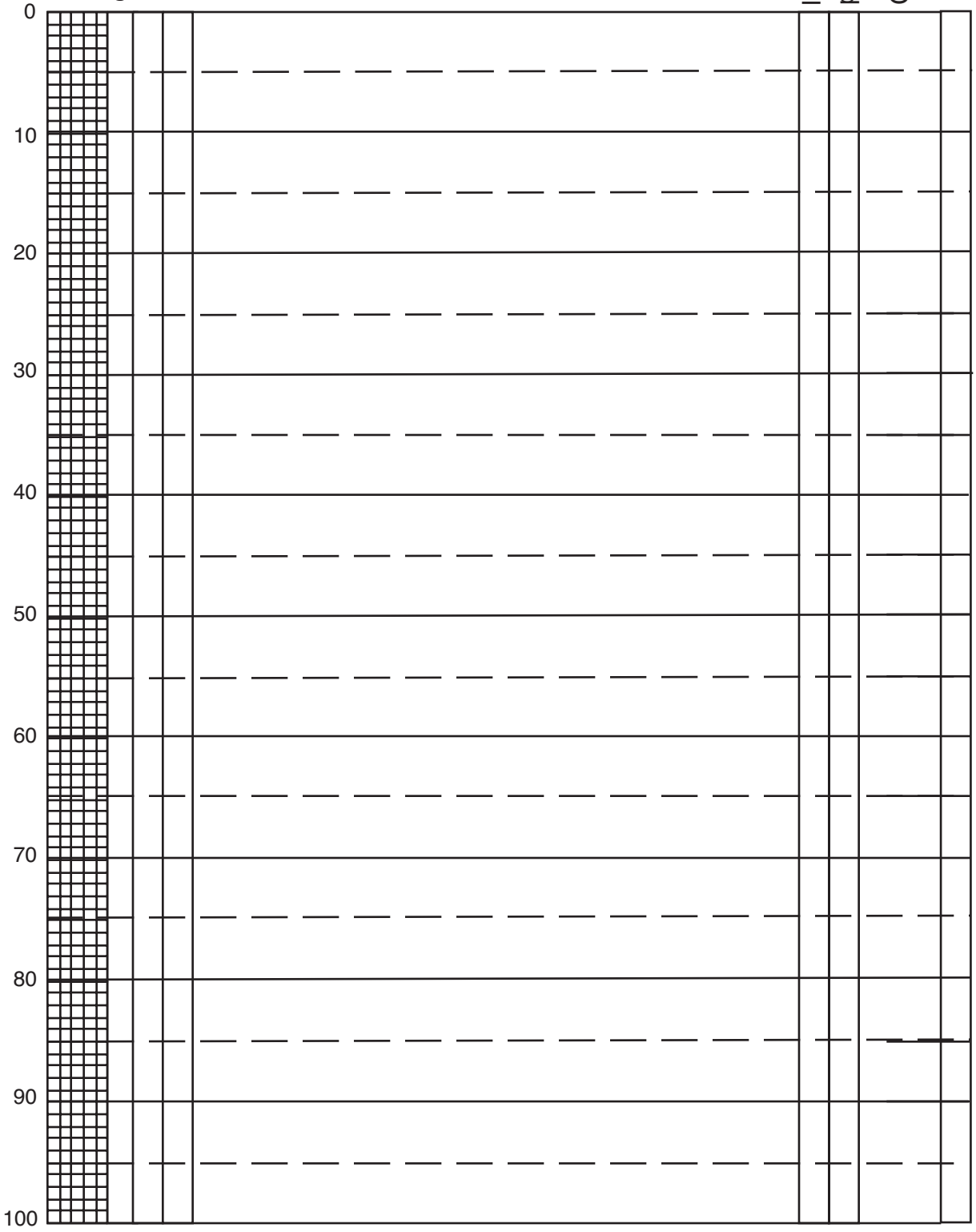
SITE: _____ Page ___ of ___

casing _____

CORE: _____ DEPTH _____to_____cm Date _____

THRUST: _____ Recovery length _____

water depth _____



Comments:

Coring Site Information

Site Name_____ Date_____

Location:
Quadrangle_____ Lat_____ Long_____
County_____ State_____

Location Description:

Contact Information:
Owners Name_____
Mailing Address _____
Town_____ State_____ Zip_____
Comments:

Access Directions

General Geologic Setting

Regional associated landforms:

Estimated glacial retreat age_____

Site Geologic Setting
Basin Description

Size_____ Surrounding Slopes_____ Hydrology_____
Present use_____

Comments:

Jack pine background and comments relevant to this study.

Jack pine, *Pinus banksiana*, is called a "fire species" because it is fire-dependent, thrives on sandy outwash wastelands in warm, dry conditions (MDNR, 2003; Rouse, 1986). This species, along with red pine and white pine, according to the pollen records, became dominant as conditions became unfavorable for spruce, around 11,500 Cal years BP. The presence of jack pine may cause fire to proliferate. Jack pine ecology is such that it needs fire to melt the resin in its serotinous cones at 49 to 60°C (120 - 140°F) to liberate the seeds. These temperatures can usually only be reached by adding heat to existing air, except on sandy soil (jack pine is typically found on sandy soils) where temperature can reach 77° C (170°F) at the surface, hot enough to open the cones. Therefore, serotinous cones are an adaptation to fire. If the cones themselves are burned, however, the seeds will be destroyed. Seeds will not germinate unless there is less than 0.2 inch of organic matter (reduced by fire). Sedges can rapidly occupy a site to the exclusion of almost all other vegetation, including jack pine, without the intervention of fire (Rouse, 1992). Boreal spruce-fir, wet grasslands, conifer bogs, and tundra, and prairie are among vegetation types that are associated with stand replacement fires, meaning the stand is destroyed. In contrast, eastern white pine, red pine, jack pine, northern hardwoods, and mixed mesophytic hardwoods are vegetation types that are associated with mixed severity fire regimes in the United States and Canada (Neary et al. 2005) Deciduous stands burn at the lowest rates, and black spruce at the highest rates in a boreal mixed-wood forest study (including jack pine, white spruce, balsam fir, tamarack) ,(Cumming, 2001).

Regarding Rouse's (1993) statement that sedges can rapidly occupy a site to the exclusion of almost all other vegetation, including jack pine, without the intervention of fire-- fires were clearly occurring in this study postglacially and during lateglacial time, and the pollen and mastodon investigations indicate a spruce-sedge parkland environment lateglacially. If fires were keeping the sedge in check, jack pine should have been able to take hold on the sandy outwash areas, if climatic

conditions were favorable for it. Pine is present during the spruce dominated period, but in low numbers. It is being kept in check during lateglacial time, perhaps by the abundance of wet conditions that spruce thrive in, or the lack of exposed ground for germination to occur.

Loss-on-Ignition

Purpose
Water content, organic matter and carbonate content are estimated by seqentially measuring weight loss in sediment core subsamples after burning at selected temperatures.

A compositional profile can be generated rapidly and for very low cost. This is sufficient to develop a general sense of core stratigraphy and often is sufficient for correlation between cores.

The results are accurate to 1-2% for organic matter and carbonate in sediment with over 10% organic matter. In high clay sediment, water of hydration is lost during the carbonate burn resulting in errors of up to 5% for carbonate analyses. If high precision (0.1%) is needed, or if sediment is in short supply, coulometric analysis is recommended.

The muffle furnace is the Lindberg Hevi-Duty Type B Controller. This is a 2 mode instrument capable of controlling temperatures to better than ± 10º C. The automatic reset circuit will provide the necessary corrections to maintain temperatures at established set point.

Procedure Summary
Subsamples are placed in weighed crucibles and weighed. Weight loss is measured after heating at 100º C overnight to remove water, at 550º C for four hours to remove organic matter, and at 1000º C for two hours to remove carbonates. After each heating step, the firebrick holding crucibles is placed in a desiccator to cool completely before weighing so that the samples do not absorb atmospheric water and so that convection currents do not affect the balance.

Ash left at the end of the procedure can be saved for analysis of remaining elements as oxides.

About 100 samples can be processed in 2 days of concentrated work.

Equipment
Ceramic crucibles
Firebricks drilled to accept crucibles
Sampling device (spatula, syringe)
Desiccator(s)
Drying oven
Muffle furnace capable of reaching 1000°C
Balance weighing in grams to 4 decimal places

Safety

The most obvious hazard in LOI is being burned by hot samples fresh out of the furnace. Be patient and let them cool down as much as possible before handling. The high-temp gloves and mitts are only good to about 350° C and can be awkward to use.

The muffle furnace has a thermocouple (looks like a white stick with metal protruding from the end) which sticks in through the back of the chamber. It is easily damaged, so be careful when adding or removing samples not to bump it.

Procedure Detail

1. Select and weigh 25 crucibles per fire brick tray. You can prepare up to 50 samples (two trays) for analysis at a time.
    a. Never touch crucibles with your hands. Skin oils will add weight and introduce error to your results. Always use a pair of tweezers when handling crucibles.
    b. Make sure you record some notes that help you identify which sample is which in your fire brick. Most bricks have had a corner knocked off or have had an "X" or some such mark carved in a side. Put a marked crucible in a corner or with reference to the X and use that as a reference point. Keep good notes! As soon as you've mixed things up the data are useless.
    c. From now on, when not burning or being weighed, the crucibles and the samples they contain should be stored in a dessicator. Make sure there is enough dessicator space for the number of samples you hope to analyze. Wait until the samples are cool (<50° C) before putting them in the desiccator: the decrease in pressure upon cooling of the air in the desiccator will vacuum-seal the desiccator shut and it'll be very difficult to open.
2. Record your crucible weights in the LOI template spreadsheet.
3. Place some sample (~1-5 cc) in each crucible and weigh. This is your *wet weight*. Record in LOI spreadsheet. *Note:* if you use the **LOI macro** (more about which later), the samples do not have to be volumetric.
4. Heat these samples at **100-105° C overnight** in either the muffle furnace or the drying oven. This will evaporate water and the resulting weight will be your *dry weight*. Let samples cool in a dessicator for at least half an hour before weighing. Warm samples will yield inconsistent weights due to the heat-generated convection currents in the balance, so be patient.
5. After weighing and recording your dry weight, return the samples to the furnace for a **4-hour burn at 550° C**. This will burn off organics and will likely stink pretty badly for the first hour or so. Remember that the oven will have to ramp up and down from the burning temp of 550°. This adds time, so budget accordingly. When the oven has cooled down to around 50° C you can remove the samples and place them in a dessicator to cool further. Use the mitts and gloves that are stored in the drawers below the oven Do not let the samples cool outside of the oven or a desiccator: this will allow samples to take in air moisture and throw off your weights.
6. Record your post-550 burn weights in the spreadsheet and return the samples to the oven for a **2-hour 1000 °C** burn. This will burn off a combination of carbonate material and some of the water stored in the lattice of clay minerals and diatom silica.

7. After cooling, record this weight as your final measurement! You may throw out the sample remaining in the crucible, or save it for another analysis. Crucibles should be washed using tap water and Liquinox, and rinsed with deionized water. Let fully air dry overnight in tray and then return to storage dessicator.
8. Use the LOI macro (created and graciously provided by D.R. Engstrom) to calculate your percent component fractions, wet and dry bulk density, etc. To use the macro [*saved on the desktop as* **LOI.2.xls**], the spreadsheet that contains your LOI data must be in the following format (column titles):

Depth, Wt. Crucible, Wt. Wet, Wt. 100, Wt. 500, Wt.1000.
Or
Top depth, Bottom depth, Wt. Crucible, Wt. Wet, Wt. 100, Wt. 500, Wt.1000.

These columns and the data within them are the ONLY cells that may be filled in on the page, or the macro will malfunction. If you have supplementary data such as core names, notes to self, etc., cut them from this spreadsheet and put them in another sheet in the same workbook.

Save the data spreadsheet and close it. Open up the LOI.2 file. (Click “enable macros” in the warning window that pops up.) Go to Tools--> Macro--> Macros. The "macro name" line should read "A1" and be highlighted. The the first line of the section below A1 should read "LOI." Click "Run."

The next box that pops up asks for the file name (as saved on the spreadsheet), some info about the coring site (nonessential), whether your depth intervals are single or you've used two columns for top and base depths (determined by which format for column titles you used above), and whether you did a $CaCO_3$ (1000° C) burn. Once you've filled in and selected the appropriate options, click "OK" and the macro will perform its magic. It will probably not find your file at first, but you have the option of browsing for it.

The resulting data will be placed in a bunch of columns to the right of your original data.

For a comprehensive review of best practices and comparative LOI methods, please see Heiri et al, Journal of Paleolimnology 25, p. 101-110.

Image Acquisition

The LRC Core Facility has two systems for imaging cores:

Geotek Geoscan-V
DMT CoreScan Colour

Both systems employ line-scan CCD cameras with fluorescent lights fixed in position relative to the cameras. In each system, polarizing filters cover both the light source and the camera lens, and are oriented perpendicular to each other (such that the direction of polarization is 90 degrees relative to the other filter). In this manner, glare reflected from the surface of wet or moist cores is completely eliminated, and core stratigraphy is revealed perfectly. For example, both of the following images are from the same section of core, and show the results of imaging with (bottom) and without (top) polarizing filters.





Cores are typically scanned at 10 pixels/mm (~300dpi), although higher resolutions are possible. The digital files produced are uncompressed Windows Bitmap (.bmp) format, and are approximately 30MB per meter of core.

CoreScan operation instructions
Image Analysis

Image Analysis

See also Image Acquisition

Calibration

Accurate color rendition is achieved through calibrating to known standards. Images produced by both LRC cameras (DMT CoreScan Colour and Geotek Geoscan-III) are calibrated to known standards during acquisition. In this way, the colors in images closely approximate reality. Cores are imaged together with a Gretag-Macbeth Minichecker color card that contains 18 calibrated color patches and 6 calibrated grayscale patches. Images may be later adjusted to the known color values of the patches; thus perfect color rendition may be obtained.

Color profiles

High-resolution color time series may be extracted from core images for revealing color-specific changes in core stratigraphy and for comparison with other core datasets. Matlab, or Photoshop and NIH Image/ImageJ (a freeware Java version of NIH Image, available for both Mac and PC) may be used to generate color profiles directly from the core images.

It is usually best to convert RGB values into the CIE (Commission Internationale de l'Éclairage) L*a*b* color system, because it was designed to match human color vision, and because it separates lightness from color information. For these reasons, L*a*b* color profiles are significantly easier to interpret and more reliably reveal changes in sediment character than profiles in RGB or other color systems. The L* variable represents lightness, and varies between 0 (black) and 100 (white); a* and b* vary between -128 and +128 and represent the color, with a* describing green (negative values) or red (positive values) and b* describing blue (negative) or yellow (positive). Conversion is performed via the equations in the publications shown below.

The following publications provide greater detail regarding these and other image analysis procedures:

Pierre Francus, Ed., 2004
IMAGE ANALYSIS, SEDIMENTS AND PALEOENVIRONMENTS
Book series: Developments in Paleoenvironmental Research: Volume 7
ISBN 1-4020-2061-9, 338 pp.

Naderbragt et al., 2000
COLOR RECORDS FROM THE CALIFORNIA MARGIN: PROXY INDICATORS FOR SEDIMENT COMPOSITION AND CLIMATIC CHANGE
Proc. ODP, Scientific Results, v. 167.
http://www-odp.tamu.edu/publications/167_SR/VOLUME/CHAPTERS/SR167_29.PDF