ENVIRONMENTAL CHANGES INFERRED FROM POLLEN ANALYSIS AND ^{14}C AGES OF POND SEDIMENTS, GREEN MOUNTAINS, VERMONT

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ABSTRACT

Great environmental changes have taken place in Vermont and other part of New England since the Laurentide ice sheet started to retreat northward 18,000 years ago. Three sediment cores and nine ^{14}C analyses were used to estimate directly the timing of deglaciation and revegetation in the mountains of northeastern Vermont. Cores were collected from the deepest points of Sterling Pond (8.5 m deep and 917 m above sea level) and Ritterbush Pond (13.7 m deep and 317 m above sea level) in the Green Mountains of Vermont. Pollen grains were identified in samples recovered at 10 cm intervals from the cores. Similar pollen zones were observed in the percentage pollen diagrams of both pond cores.

The features on each zone and their climatic interpretations were: Zone A-1, spruce and fir (cool); Zone A-2,3, spruce and fir rare, oak abundant (warmer); Zone A-4, oak decline, birch increase, pine decrease, spruce and fir abundant, alder increase (cooler than the previous zone); Zone B, pine increase, alder decline, oak increase (warmer and drier); Zone C-1, hemlock increase, oak decline, boreal trees low (warm and moist); Zone C-2, hemlock decline, beech and birch high, pine slight resurgence (warmest and driest); Zone C-3, return of spruce, fir and pine, beech decline (cooler and moist). The early oak peak during Zone A-2-3, a later decline in Zone A-4 and the increase in Zone B suggests a cooling process. Similar features also have been observed in pollen diagrams from Connecticut and New Jersey which may be evidence of the Younger Dryas climatic oscillation.

Five samples of the Sterling Pond core and Ritterbush Pond cores were acid-and base-treated and dated by Accelerator Mass Spectrometery. Sterling Pond: 260 cm, 4,180+/-50 ^{14}C yr BP; 420 cm, 8,600+/-60 ^{14}C yr BP; 490 cm, 11,180+/-60 ^{14}C yr BP; 521-523 cm, 12,760+/-70 ^{14}C yr BP. Ritterbush Pond: 220 cm, 4,010 ^{14}C yr BP; 348.5 cm, 6,490 ^{14}C yr BP; 445 cm, 9,410 ^{14}C yr BP; 479 cm, 12,020 ^{14}C yr BP; 519 cm, 21,860 ^{14}C yr BP. A twig at 260 cm of the Sterling Pond core is 280 ^{14}C yr BP younger than adjacent gyttja. The basal dates of both cores are the oldest from this part of New England, indicating that ice likely left the mountains of northwestern Vermont before 13,000 ^{14}C years ago.

Pollen influx diagrams and Loss-on-Ignition data indicate that great environmental changes took place during the early deglaciation around 11,000 - 10,000 ^{14}C yr BP. Features on regional pollen diagrams are maintained in the Green Mountains sites although minor differences do exist. Pollen analysis results from the Sterling Pond core are more supportive of the Younger Dryas as promoted by Peteet (1993) than the data from the Ritterbush Pond core.

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TABLE OF CONTENTS

LIST OF TABLES

TABLE

LIST OF FIGURES

FIGURE

CHAPTER 1

INTRODUCTION

The latest geological period is the Quaternary during which the retreat of the last Wisconsinan ice sheet took place. If the Quaternary is the last volume in the geological journal, the Holocene epoch then can be treated as the last chapter in the issue. Great environmental changes have taken place in northern New England since the last glaciation. Much attention has been focused on the reconstruction of paleoclimate of the Quaternary. However, there are still many puzzles that remain unsolved.

1.1. Statement of Problem

This thesis uses pollen and sediment analysis to interpret the Quaternary paleovegetation and the paleoclimate of northern Vermont. Sediment cores from two ponds in the Green Mountains were studied. Chapter 1 is a brief introduction to the research and literature review; Chapter 2 describes the methodology applied in data collection and laboratory work; Chapter 3 presents the results and discussion; and Chapter 4 is a summary.

1.1.1. Review of Deglaciation History of Eastern North America

The most recent of the Pleistocene episodes of continental glaciation is called the Wisconsinan, at least for North America east of the Rocky Mountains (Wright, 1983).

After a long buildup during the early and middle Wisconsin, the Laurentide ice sheet reached its maximum southern extent on the eastern seaboard at Long Island about 18,000 ^{14}C years ago (Stone and Borns, 1986). The ice sheet retreated rapidly between 18,000 and 13,000 ^{14}C years B.P., mainly along the west and south margins (Dyke et al., 1987). The Laurentide ice front continued its full retreat along its southern perimeter soon after 14,000 ^{14}C years ago (Wright, 1983). By about 11,000 ^{14}C years B.P., the Gulf of St. Lawrence had opened, leaving a residual ice mass in northern New England, and the postglacial Great Lakes already had a complex history of different outlets and lake levels (Cronin, 1977). Retreat between 13,000 and 8,000 ^{14}C years was more rapid in the west than in the east (Dyke et al., 1987). By 10,000 ^{14}C years, the ice front had withdrawn north of the Great Lakes, and other glacial lakes had formed in Manitoba and northwestern Ontario, also with a complex history related to ice-margin fluctuations (Cronin, 1977). Great environmental changes have taken place in Vermont as well as New England since the ice front withdrew northward.

1.1.2. Review of Deglaciation History of New England

By about 13,500 ^{14}C years, the margin of the ice sheet that once covered all of New England and part of the continental shelf had retreated to roughly the position of the present Maine coast (Bonnichsen et al., 1985). From about 14,000 to 13,000 ^{14}C yr BP nearly all of Vermont, New Hampshire and Massachusetts became free from ice, and by 13,000 BP high mountain peaks in northern and western Maine had emerged as nunataks (Stone and Borns, 1986). By about 12,000 ^{14}C years BP a more or less continuous ice mass still remained over a portion of northern Maine and adjacent Quebec and New Brunswick. By about 11,000 years BP, ice remained on only a small portion of northern

Maine. What little ice remained was probably stagnant and separated by many bedrock features of relatively high relief (Stone and Borns, 1986).

1.1.3. Review of Deglaciation History of The Champlain Valley, Vermont

"In the Champlain Valley, the glacial margin retreated northward as water from the melting ice filled glacially dammed Lake Vermont. Leveling of the elevated shore line features on both sides of the Champlain valley clearly shows two stages of glacial Lake Vermont" (Chapman, 1937). "As soon as the ice passed north of Quebec City, marine water invaded landward through the St. Lawrence valley, which ended the long period of stability of Lake Vermont forming the Champlain Sea in the Champlain Valley and St. Lawrence Lowland" (Cronin, 1977). Cronin (1977) used Champlain Sea invertebrate fauna, particularly Ostracoda and Foraminifera, to determine paleoenvironments throughout the history of the Sea. Numerous radiocarbon ages indicate that the Champlain Sea occupied the Champlain valley from about 12,500 to 10,000 ^{14}C yr BP (Cronin, 1977). Figure 1.1 illustrates the maximum extent of the Champlain Sea, which covered more than 53,000 km^2 (Cronin, 1977). Following an initial maximum limit of inundation, isostatic crustal rebound caused the Sea's gradual regression, which is documented by "the parallel alignment of tilted shorelines at successively lower elevations along a north-south profile" (Cronin, 1977). When the invading marine water source was eventually cut off by continued tilting, the present-day Lake Champlain formed.

1.1.4. Problems Remaining to be Solved

The Wisconsin ice sheet eliminated the forest cover of Canada and the northern part of the United States. The retreat of the Laurentide ice sheet from the northern United States

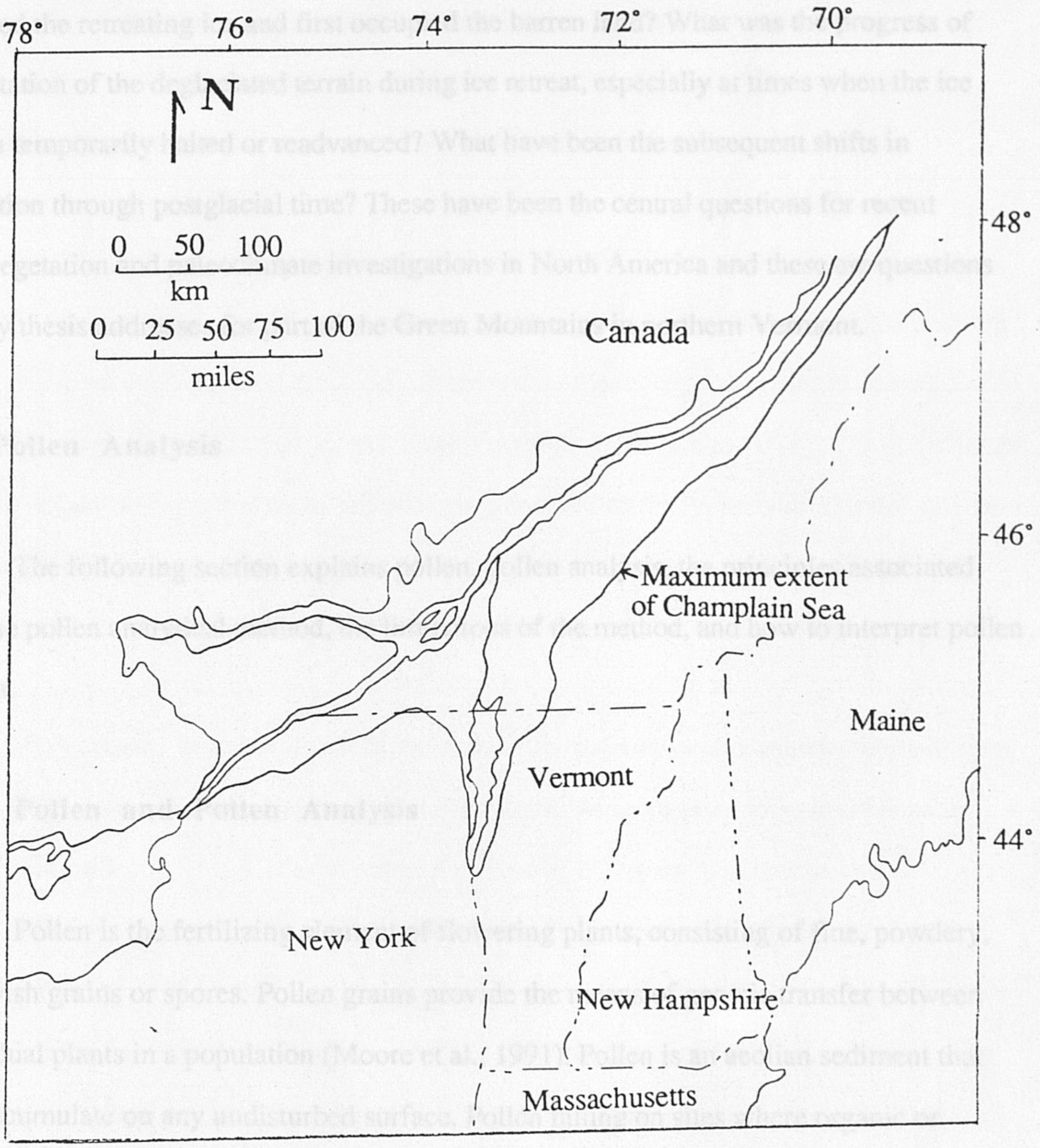


Figure 1.1. Map showing maximum extent of the Champlain Sea, which covered more than 53,000 km^2 (modified from Cronin, 1977).

left vast areas open for colonization by plants and animals (Wright, 1983). What vegetation followed the retreating ice and first occupied the barren land? What was the progress of revegetation of the deglaciated terrain during ice retreat, especially at times when the ice margin temporarily halted or readvanced? What have been the subsequent shifts in vegetation through postglacial time? These have been the central questions for recent paleovegetation and paleoclimate investigations in North America and these are questions that my thesis addresses for part of the Green Mountains in northern Vermont.

1.2. Pollen Analysis

The following section explains pollen, pollen analysis, the principles associated with the pollen analytical method, the limitations of the method, and how to interpret pollen spectra.

1.2.1. Pollen and Pollen Analysis

Pollen is the fertilizing element of flowering plants, consisting of fine, powdery, yellowish grains or spores. Pollen grains provide the means of genetic transfer between individual plants in a population (Moore et al., 1991). Pollen is an aeolian sediment that will accumulate on any undisturbed surface. Pollen falling on sites where organic or inorganic sediments are accumulating will be incorporated into the sediment and become part of the stratigraphic record (Moore et al., 1991).

Pollen analysis is the study of fossil assemblages of pollen grains and spores from sediment deposited in the recent past or as far back as the Paleozoic era (West, 1971). Pollen analysis is an effective way to interpret paleovegetation distribution and therefore infer changes in paleoclimate, especially with the modern Accelerator Mass Spectrometery (AMS) dating technique which makes the accurate dating of small samples possible.

The principles of pollen analysis are based on the following factors:

(1) The pollen grain wall, or exine, which is made of sporopollenin is resistant to all but the most extreme oxidizing or reducing agents. Due to its extremely resistant nature, pollen grains may have a long geologic life once they are incorporated into sediment. Some spores date back to the Silurian period, more than 400 millions ago (West, 1971). Different kinds of pollen resist oxidation to different degrees. In one study, by Miller and Thompson (1979), pine, oak, ash, and birch seem most resistant to *in situ* weathering, spruce less resistant, and fir seems mostly to be eliminated in same weathered sediments.

(2) Variation in exine structure and sculpture, together with variation in the number, shape, and symmetry of the apertures in pollen grain wall, provides the morphological diversity of pollen grains. The symmetry of apertures and scars is related to the arrangement of pollen grains and spores in the tetrad formed by meiosis from the mother cell (Moore et al., 1991). In the pollen grain, the apertures may be furrows, pores (which are believed to have evolved from furrows), or a combination of both (West, 1971). The unique morphological characteristics of pollen grains of each species make it possible to identify plant to species-level.

(3) Pollen of most plants are produced in large quantity and spread widely from their sources (Moore et al., 1991).

(4) The species distribution of vegetation producing the pollen determines the composition of pollen rain; therefore, the pollen rain is a function of the vegetation of the surrounding area. It is assumed that changes in frequencies of pollen type within the stratigraphic column reflect changes in the species composition of vegetation. Such changes are often interpreted as one of the major factors affecting species composition --- climate change.

(5) By retrieving sediment cores at the deepest part of lakes or ponds, one can retrieve a complete pollen archive through time.

1.2.2. Discussion of Pollen Analysis Method

Variation in pollen production and the dispersal rate of different species, lag time of vegetation to climate changes, sediment focusing, resuspension, and preferential deposition, and other non-climatic factors may complicate paleoenvironmental interpretation.

1.1.2.1. Pollen production and dispersal rate

It has long been recognized that the efficiency of pollen production and dispersal varies widely among species. The amount of pollen produced is inversely proportional to the probability of success in fertilization. For example, if the plant's dispersal agents are insects or animals, it produces less pollen than those pollinated by wind, while self-fertilizing plants produce only minute quantities of pollen (Moore et al., 1991). A reasonable interpretation of a pollen spectrum can be made only if the relative pollen dissemination efficiency of each species is known.

Attempts to estimate pollen production and dispersal distance have been made in Europe and Japan, but largely neglected in North America (Davis, 1960). Pollen dissemination characteristics of most forest trees of New England were poorly known before M.B. Davis and J.C. Goodlett (1960) compared the present vegetation of the Memphremagog quadrangle in northern Vermont with pollen spectra in samples collected from the bottom mud of Brownington Pond in that area. Their results, in regions of widely divergent vegetation, indicate that in forested regions, the majority of the pollen is contributed by trees within a few miles of the sampling site. Heide and Bradshow (1982) studied moss collected from forests. Their research indicated that birch is the most over-represented pollen type in the moss; pine, oak, and hemlock are equitably represented, whereas maple is under-represented.

Many researchers have attempted to analyze the relationship between pollen production and transport distance. Moore et al. (1991) suggested that vast majority of pollen grains dispersed by wind are carried no more than 0.5 km beyond their source. Dispersal by wind is a function of grain size, with the larger and heavier grains falling to the ground sooner than the smaller, lighter grains. Figure 1.2 shows the research results of West (1971) concerning the components of the atmospheric pollen rain and deposition. Janssen (1966) collected pollen samples along nine transacts across local vegetation belts bordering bogs or ponds in overall deciduous and coniferous-deciduous forest region. Three types of pollen rain were distinguished: local, extralocal, and regional. Local pollen is derived from plants that grow at or very close to the sample site, extralocal pollen is derived largely from trees that grow on the slopes and upland adjacent to the sample site, but not extensively over large areas, and regional pollen is derived from plants commonly far beyond the immediate basin slopes. When the extralocal and the local types are excluded

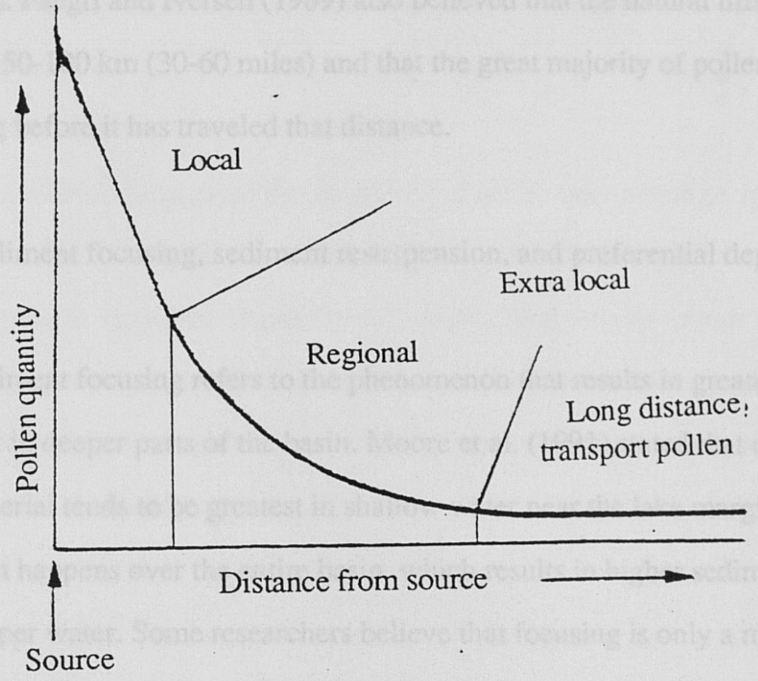


Figure 1.2. Components of atmospheric pollen rain. The curve shows quantities of pollen dispersed at increasing distance from pollen source. Pollen produced locally dominates the pollen influx (modified from West, 1971).

from the sum of upland pollen types, the regional pollen rain differs little from site to site (Janssen, 1986). Spear et al.'s (1994) work in the White Mountains, New Hampshire, focused on the vertical dispersal of pollen grains. They chose six study sites at different elevations in the White Mountains, and found no obvious differences in pollen components. Faegri and Iversen (1989) also believed that the natural limit of pollen transport is 50-100 km (30-60 miles) and that the great majority of pollen falls to the ground long before it has traveled that distance.

1.2.2.2. Sediment focusing, sediment resuspension, and preferential deposition

Sediment focusing refers to the phenomenon that results in greater net accumulation of sediment in deeper parts of the basin. Moore et al. (1991) stated that erosion of the surface material tends to be greatest in shallow water near the lake margin; however, redeposition happens over the entire basin, which results in higher sediment accumulation rates in deeper water. Some researchers believe that focusing is only a minor factor for macrofossils and that differential input can be avoided by coring near the center of the lake. Hilton (1985) provided a conceptual framework for predicting the occurrence of sediment focusing and sediment redistribution in small lakes. Davis and Ford (1982) studied sediment focusing in Mirror Lake in New Hampshire. Combined with radiocarbon ages, Davis et and Ford (1982) analyzed pollen, weight loss on ignition (LOI), sediment rate ($mm \cdot yr^{-1}$), and pollen accumulation rate ($mg \cdot cm^{-2} \cdot yr^{-1}$) in four cores from one lake. Results showed that sediment focusing played an important role in recording vegetational change. From 14,000 to 11,000 ^{14}C yr BP, inorganic gray silty sediment was deposited in the lake basin. This silt was deposited everywhere on the lake bottom without much later resuspension and movement due to its higher density compared with the organic material deposited later. Since 11,000 ^{14}C yr BP, the rate of organic sediment deposition increased gradually reaching its peak between 7,000 to 4,000 ^{14}C yr BP, whereas the inorganic sedimentation rate decreased sharply. The younger, organic-rich sediment was strongly focused into the deeper part of the basin. Davis et al. (1980) stressed that it would be misleading to infer a time of maximum organic input from any single core, because the rate of organic accumulation is influenced by sediment focusing with the accumulating rate changing over time.

Resuspension is caused by the inflow of water from rivers or springs into the lake, which may redistribute sediment within the lake basin and thus affect the final distribution of pollen grains in sediment. Davis (1980) stressed that the movement of sediments from shallow to deep water lowered the accumulation rates for all pollen types and for total sediment in shallow water, but increased pollen and sediment accumulation rates in deep water.

1.2.2.5 Non-climatic factors

The influence of non-climatic factors on pollen distribution, such as local soil type, fire and pathogens, is discussed by Spear et al. (1994). Several other authors (Wright et al., 1963; Davis, 1965, 1967, and Cushing, 1967) acknowledge that nonclimatic factors also influence past vegetation patterns. Swain (1973) noticed that fire has always been an important factor influencing the forest history of northeastern Minnesota. "Pollen analysis shows no change or only short-term changes in the percentages of major pollen types following charcoal peaks." (Swain, 1973). Davis (1980) explained the prehistoric decline of hemlock at about 4,800 ^{14}C yr BP by an outbreak of a pathogen. Allison et al. (1986) compared the rapidity of the hemlock pollen decline with the more recent decline of chestnut pollen recorded in the laminated sediments of Pout Pond in Belmont County, New

Hampshire. They also concluded that the hemlock decline was due to pathogen attack. Deevey (1939) suggested that the events of climatic significance were expected to occur over wider areas than those of local importance, such as soil.

Deevey (1939), who did the first pollen analytical work in southern New England, believed that in spite of all the factors that prevent complete reliance on pollen assemblage as a true reflector of the surrounding forest, the major postglacial changes in vegetation can be inferred if a reasonably large number of profiles is available for a region. Moore et al. (1991) also concluded that fossil pollen has great potential for the reconstruction of former vegetation cover and paleoclimatic conditions. In my study, paleoclimatic interpretations are based on the integrated results of radiocarbon dated pollen percentage and pollen influx diagrams along with LOI measurements and physical stratigraphy from two sites at different elevations in northern Vermont.

1.2.3. Quantitative Interpretation of Fossil Pollen Spectra

Differences in pollen production and dispersal rates can cause a significant problem for paleoclimatic reconstruction because there is no direct relationship between the abundance of pollen grains in a deposit and species abundance in an area. The analog and R-value methods may help solve this problem.

(1) Analog method

One way of quantitatively reconstructing the paleoclimate is to compare the contemporary distribution of pollen with modern vegetation using various mathematical methods. The identification of modern analogs is an established procedure that assists the reconstruction of past vegetation and climate from Late Quaternary pollen data (Davis and Jacobson, 1985). The basic assumption is that if the pollen assemblage in the modern pollen rain resembles the fossil pollen assemblage, the former vegetation is likely similar to that of today (Moore et al., 1991). However, two questions are frequently asked about this approach: (1) How does one sample the vast array of possible "natural vegetation" types?, and (2) Different species in a community migrate to a new site at various rates, therefore, the fossil pollen rain may reflect a vegetation community in transition, while the modern vegetation is closer to a climax state, if such exists.

Different workers using different mathematical methods have achieved different results. Lichti-Federovich and Ritchie (1968) analyzed the modern pollen rain from over 100 lake surface sediment samples along a transect crossing grassland and broad-leaved deciduous forests to conifer forest and tundra. They conclude that there is a direct correlation between the pollen spectra and broad biogeographical zones. Davis and Webb (1975) mapped and summarized 478 pollen counts from surface samples at 406 locations in eastern North America. Their research documents the relationship between the distribution of pollen and vegetation on a continental scale. Overpeck et al. (1985) used “dissimilarity coefficients” to compare the modern and fossil pollen samples. They found that modern samples are so similar to fossil samples that three late Quaternary pollen diagrams could be “reconstructed” by substituting modern samples for fossil samples. Webb's (1974) work can be treated as one of the most detailed and convincing demonstrations of correspondence between modern vegetation and modern pollen. He extracted pollen from the top 2 cm of short cores taken from 64 lakes in lower Michigan, and compared the pollen spectra to vegetation data from the forest inventory record. Using Principal Component Analysis, Webb (1974) showed that the pollen data reflected the patterns in the vegetation.

Another way to strengthen quantitatively pollen analysis is to replace percentage frequency calculations with counts of numbers of grains per cm^2 sediment surface per year of deposition (West, 1971). The idea behind this technique is that a known number of exotic marker pollen grains is added to a known volume of sample at the commencement of processing (Moore et al., 1991). Absolute pollen influx then can be inferred in relation to counts of the marker grains (Moore et al., 1991). In this project, *Eucalyptus* pollen was used as a marker to calculate the influx of fossil pollen.

(2) Adjustment method

A correction factor for variable pollen production rates among species would be helpful in interpreting pollen spectra. Davis (1963) first proposed such a correction factor, termed R value, which is the ratio of pollen in a surface assemblage to the abundance of that species in the surrounding vegetation:

$$R = \frac{\text{Pollen percentage of the species}}{\text{Vegetational percentage of the species}}$$

For over-represented species, $R > 1$; for under-represented species, $R < 1$. Davis (1963) suggested that if R values could be calculated from modern pollen rain in forest of known composition, they could then be used as adjustment factors in interpreting fossil pollen spectra. West (1971) stated that pollen diagrams can be corrected by multiplying pollen frequencies by the R-value.

Bradley, in his book Quaternary Paleoclimatology (1985), gives adjustment factors (R values) of pine, oak, birch, and alder as 1:4, which means their frequency suggested by pollen spectra is four times more frequent than the vegetation would indicate. Elm and spruce have R-values of 1:2, fir, 1:1, and maple 2:1. On the other hand, Bradley (1985) stated that R-value was so poorly understood that the uncertainty was probably greater than the total amount of postglacial change in the abundance of forest trees. It also appears that size of the catchment, vegetation structure, and local topography influence pollen release and transportation; therefore, R-values differ from site to site. The R-value method has proven to be quite successful in forest environments (Moore et al., 1991).

1.3. Review of Revegetation History

The most eventful portion of the Holocene was the very beginning when glacial conditions were rapidly changing to an interglacial climate. The Early Holocene is characterized by sharp environmental changes including a changing vegetation assemblage, flood plain aggradation, and the subsequent incision of rivers (Wright, 1983). The Middle Holocene was the warmest and driest period of postglacial time, based on the northward and upward advancement of deciduous trees, strong soil development, and flood plain stability (Wright, 1983). The Late Holocene was cooler and moister than the Middle Holocene and vegetation was most similar to today's vegetation (Davis and Jacobson, 1985).

1.3.1. Review of Revegetation History of North America

Colonization of plants on newly exposed land is controlled by several ecological factors, including the availability of suitable habitats and the dispersal mechanism of proagules from seed sources (Wright, 1983). Plant succession on deglaciated terrain has been studied in a few areas of modern glaciers. For example, in the St. Elias Mountains of southwestern Yukon Territory, the pollen stratigraphy implies a succession from herbs to shrubs to spruce forest, which matches the recent plant succession observed in a series of progressively older moraines.

1.3.1.1. Early Holocene

Early-Holocene vegetational history might be expected to reflect the northward movement of the major climatic zones as the climate warmed (Wright, 1983). The paucity of pollen sites near the Late Wisconsinan ice limits makes it difficult to compare the early postglacial vegetational history on newly deglaciated areas with that from outside the glacial boundary (Wright, 1983). In the western Plains, the fir forest shifted to prairie as early as 11,000 years ago (Wright, 1983). To the east, a brief interval of deciduous forest -- probably in a parkland structure -- intruded before prairie began its dominance about 9,500 years ago. Still farther east, the interval of deciduous forest was longer, extending to about 7,000 years ago (Wright, 1983).

1.3.1.2. Middle Holocene

Increasingly dry conditions are substantiated in the Midwest by the shift from spruce forest to deciduous forest to prairie, which culminated in the middle Holocene about 8,000 to 5,000 years ago (Wright, 1983), when the prairie / forest border was further east than its present position. This change indicated a decrease in the moisture available to plants rather than an increase in temperature and the more frequent occurrence of warm, dry, westerly air flow (Wright, 1983). Dry conditions peaked in the Midwest about 7000 years ago (Wright, 1983). The Eastern United States, except for parts of Florida, was forested throughout the Holocene. The general northward movement in the early Holocene of the southern limit of northern conifers such as spruce, fir, and northern pine species implies a trend toward warmer climate conditions. The long interval of higher temperature was further supported by the middle-Holocene upward expansion of white pine and hemlock in the White Mountain in New Hampshire to elevations above where they are presently found (Spear, 1989). The eastern states experienced a northward shift of coniferous forest and its elevation rose in New England in response to warmer conditions (Wright, 1983).

1.3.1.3. Late Holocene

The Late Holocene in the western mountains of North America is marked in many areas by regrowth of alpine glaciers. The prairie / forest border is progressively younger further west as the ecotone moved to the west (Wright, 1983). As an evidence of cooler conditions, the southward shift of the boreal forest occurred somewhat later (Wright, 1983). The gradual westward expansion of the big peatlands on the plain of Glacial Lake Agassiz in northern Minnesota is perhaps the best reflection of the trends of these climatic parameters (Wright, 1983).

1.3.1.4. Present

The modern vegetational zonation of eastern North America reflects the attitudinal and latitudinal climatic zonation (Wright, 1983). The latitudinal arrangement that prevails in northern and eastern North America -- tundra, boreal forest, mixed conifer/hardwood forest, temperate deciduous forest, and southern pine forest -- reflects the general southward increase in atmosphere temperature (Wright, 1983). At the same time, the westward change to grasslands and steppe is a response to decreasing moisture in that direction, reflecting greater distance from the Caribbean moisture source (Wright, 1983).

1.3.2. Review of Revegetation History of New England

Vegetational development happened rapidly as the new landscape was exposed from the changing patterns of ice and water throughout the late-glacial time (Davis and Jacobson, 1985). Plant colonization took place locally among dissipating ice masses (Moore et al., 1991). The landscape cover changed from tundra to woodland and to closed forest. Moore et al. (1991), suggested that the earliest spread of tree taxa in woodland and closed forest was along the lowlands of southern Vermont and New Hampshire, and along the coast of Maine. Spear (1989) also suggests that tundra appears to have remained for an extended period of time in areas of high elevation, even while closed forest was present in lower surrounding landscapes.

1.4. Literature Review of Pollen Research in Northern New England

The literature shows that less pollen research has been done in Vermont than in other states of northern New England.

1.4.1. Pollen Studies in Vermont

Figure 1.3 shows all sites discussed in this section as well as the two ponds in my project. Bugbee Bog (McDowell et al., 1971) is 72 km southwest of Columbia Bridge (Miller et al., 1979). Brownington Pond (Davis, 1960) is located 48 km to the northeast of Ritterbush Pond (Sperling et al., 1989), and Woodford Bog (Davis et al., 1995) is 210 km to the south of Ritterbush Pond in southern Vermont. Pownal Bog (Whitehead and Bentley, 1963) is 16 km to the southwest of Woodford Bog.

1.4.1.1. M.B. Davis and Goodlett (1960) Work at Brownington Pond, Vermont

In order to deduce accurately past vegetation, understanding the relations between present pollen rain and present vegetation is necessary. Little research has been done on pollen dissemination of New England forest trees. Davis and Goodlett (1960) compared pollen spectra in samples of bottom mud in Brownington Pond with present vegetation of Memphrenagog quadrangle in northern Vermont (Figure 1.3). The comparison reveals that slight differences in pollen content exists, as opposed to large local differences in the composition of the vegetation. This implies that the pollen composition of the sediment has little quantitative relation to the composition of the nearby vegetation, although all the species observed in the present vegetation are represented in the sediments. The authors assume that 80% of the tree pollen that originated within 50-100 km of Brownington Pond is from local trees. Davis and Goodlett (1960) classified vegetation surveyed into over-represented pollen types, such as oak, pine, birch and alder; proportionately represented pollen types, such as hemlock, beech, ash, elm, and spruce; underrepresented pollen types, such as maple, fir, poplar, larch and basswood. They also concluded that their results would not hold for other pollen spectra, even if other variables are the same, because pollen percentages are relative.

1.4.1.2. D.R. Whitehead and D.R. Bentley's (1963) Work at Pownal Bog, Vermont

Whitehead and Bentley's (1963) work at Pownal Bog contributes valuable data about postglacial vegetation and climate changes in western New England. The bog is located at the extreme southwest corner of Vermont between the Taconic and Green Mountain Ranges (Figure 1.3) at about 377 m in elevation. The stratigraphy of the core is various kinds of peat overlying gyttja and clay. Deevey's (1943) standard pollen zones for

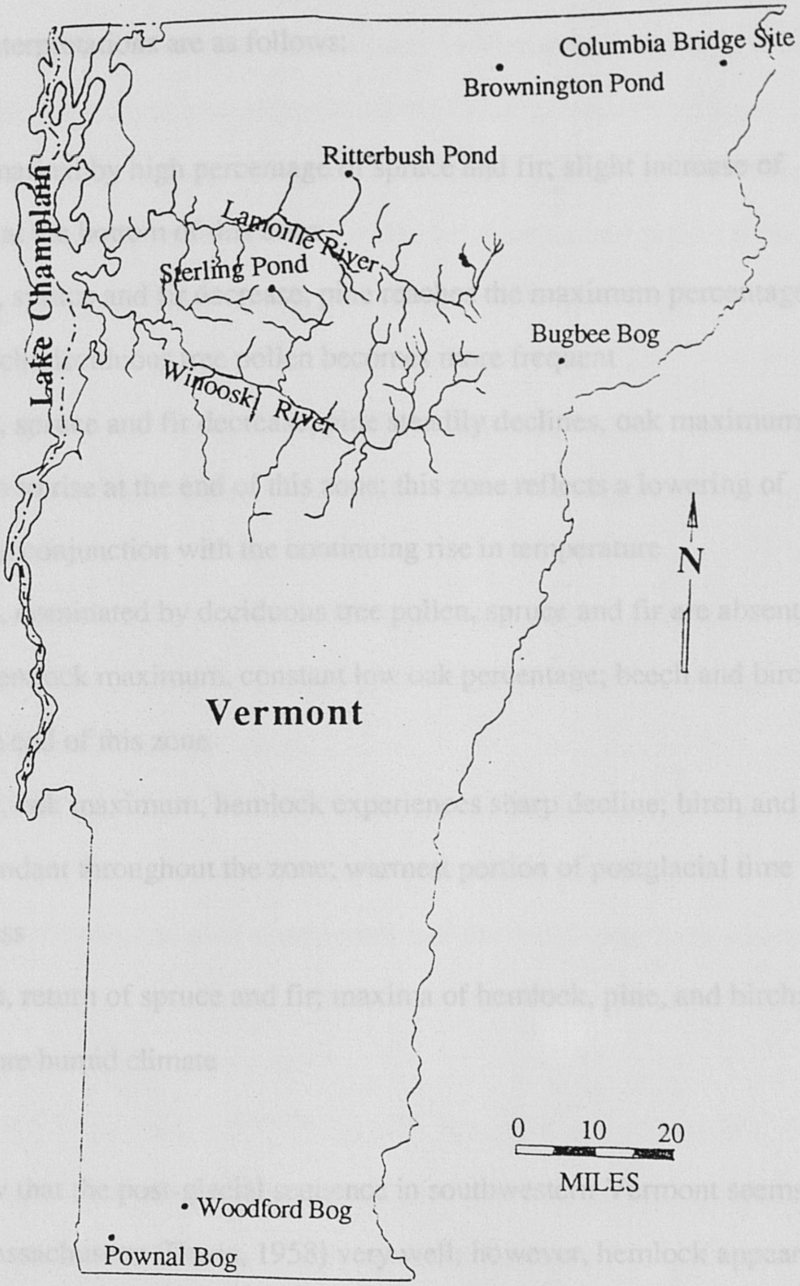


Figure 1.3. Pollen study sites in Vermont discussed in this paper, including Sterling Pond and Ritterbush Pond which are the focus of this thesis.

New England were used for comparison with other study sites. Since the sediments are not radiocarbon dated, pollen zones are marked by depth. Six pollen zones and their corresponding climate interpretations are as follows:

Zone A (7.00-6.53 m), marked by high percentage of spruce and fir; slight increase of birch and oak at the bottom of this zone

Zone B-1 (6.35-5.65 m), spruce and fir decrease, pine reaches the maximum percentage along with birch; deciduous tree pollen becomes more frequent

Zone B-2 (5.65-4.85 m), spruce and fir decrease, pine steadily declines, oak maximum, hemlock begin to rise at the end of this zone; this zone reflects a lowering of precipitation in conjunction with the continuing rise in temperature

Zone C-1 (4.85-4.05 m), dominated by deciduous tree pollen, spruce and fir are absent and pine is low, hemlock maximum, constant low oak percentage; beech and birch maxima at the end of this zone

Zone C-2 (4.05-1.35 m), oak maximum, hemlock experiences sharp decline; birch and beech are abundant throughout the zone; warmest portion of postglacial time with relative dryness

Zone C-3 (1.35-surface), return of spruce and fir; maxima of hemlock, pine, and birch; cooler and more humid climate

The results show that the post-glacial sequence in southwestern Vermont seems to match that in central Massachusetts (Davis, 1958) very well; however, hemlock appears to have been more important in the Pownal region.

1.4.1.3. L.L. McDowell et al.'s (1971) Work at Bugbee Bog, Vermont

McDowell et al.'s work at Bugbee Bog is one of the most widely-cited Vermont pollen studies. It is the first radiocarbon-dated pollen study in Vermont. The bog is situated on the northern boundary of Peacham township, Caledonia County, Vermont (Figure 1.3), 398 m in elevation. A 7.6-m-long sediment core was analyzed for pollen. The age of the sediment at 620-670 cm depth is 8,510+/- 180 ^{14}C yr BP. All the standard pollen zones of New England are represented in the percentage pollen diagram of Bugbee Bog.

Pollen zone A (10,500+/-200 to 9,300+/-200 ^{14}C yr BP), dominated by high a percentage of spruce and fir; the lack of deciduous tree pollen suggests a cooler climate

Pollen zone B (9,300+/-200 to 7,250+/-175 ^{14}C yr BP), post-glacial pine period with rapid decline of spruce and fir and the rapid increase in pine, indicating warmer and drier environment

Pollen zone C-1 (7,250+/-175 to 4,000+/-120 ^{14}C yr BP), increase pollen of hemlock, birch, oak, beech, a sharp decline of pine pollen, and the presence of maple, hickory and elm; the migration of the deciduous trees, which prefer a warmer and moister climate than zone B; the prevailing temperature higher than today

Pollen zone C-2 (4,000+/-120 to 1,600+/-100 ^{14}C yr BP), the minimum of hemlock and hickory, and corresponding maximum of pine and oak; interpreted as the warmest and driest period of post-glacial history

Pollen zone C-3 (1,600+/-100 to 0+/-80 ^{14}C yr BP), the return of spruce, fir, and pine; decrease in oak, beech, hemlock, representing a cooler and moister climate extending to the present

1.4.1.4. N.G. Miller and Thompson et al.'s (1979) Work at Columbia Bridge, Vermont

Macrofossil identification along with pollen analysis were used as means to interpret the distribution patterns of plants in the Holocene and late glacial environment in the upper Connecticut River valley south of the Columbia Bridge near Colebrook, New Hampshire (Figure 1.3). The plant fossils occur in sediments exposed on the west bank of the Connecticut River in Lemington Township, Essex County, Vermont. The site is at an elevation of 301 meters. Today, a hemlock-northern woodland is present on the slopes on the west and east sides of the Connecticut River valley near Columbia Bridge. A 1.76 m-long core into glacial lake sediments was recovered from the fossil site below river level. Radiocarbon analysis was conducted by the conventional method. Wood fragments picked from 1.52-1.58 m depth were radiocarbon dated at 11,540+/- 110 ^{14}C yr BP. Both the pollen percentage and the pollen influx diagrams suggest that the landscape was essentially treeless in the area of the site 11,500 radiocarbon years ago. In this paper, the pollen diagram is not zoned because the authors' primary interest is the interpretation of the Late-glacial environment. Also the pollen grains were severely deteriorated from these glacialacustrine sediments (Miller and Thompson, 1979).

1.4.1.5. J.A. Sperling et al.'s (1989) Work at Ritterbush Pond, Vermont

The mountain glaciation hypothesis that cirque and valley glaciers may have occupied northern Green Mountains during or immediately after Late Wisconsinan deglaciation (Wagner, 1970) was reexamined by Sperling et al. (1989). Two cirque-like basins, Lake Mansfield and Ritterbush Pond, were studied. Ritterbush Pond (Figure 1.3) is located in the Hyde Park Quadrangle in Lamoille County, Vermont. Its elevation is 317

m. The pond has a bedrock threshold at its outlet. A 9.1 m core was collected from the present-day delta at the west end of the pond. The basal radiocarbon age of the core is 10,079+/-230 ^{14}C year BP. The New England pollen zonation (Deevey, 1939) was used as the pattern for palynological interpretations. The pollen percentage diagram was divided into five zones and in general agreed with McDowell et al.'s (1971) study at Bugbee Bog and Davis (1960) results at Brownington Pond.

Although the Ritterbush core was truncated at the base (Sperling et al., 1989), the radiocarbon ages and pollen spectra support the idea that there was considerable vegetation at or near the site by 10,730+/-200 ^{14}C yr BP.

1.4.1.6. P.T. Davis et al.'s (1995) Work at Woodford Bog, Vermont

Woodford Bog (Figure 1.3) is located on the Woodford 7.5' quadrangle in southern Vermont. Its elevation is 703 m. The stratigraphy of the 7.7-m long core is 2.9 m of peat underlain by 3.6 m of gyttja underlain by 1.2 m of low organic lake mud, and sand at refusal. The authors accepted 12,420 +/- 420 ^{14}C yr BP as the basal age (6.72 - 6.82 m) for the core. Although a radiocarbon age of 20,575 +/- 1,250 ^{14}C yr BP was obtained from silt of very low organic content at the 7.54-7.75 m depth, this age was not used in the study because "too old" conventional radiocarbon ages of basal sediments in ponds and bogs are not uncommon in New England.

Tundra vegetation is indicated for the basal 0.3 m of the Woodford Bog core. Although grass, sedge, willow, sagebrush and saltbush reach their percentage maxima in this zone, spruce dominates. The appearance of arid species, such as sagebrush and saltbrush, could suggest drier conditions (personal communication, P.T. Davis). A spruce zone occurs between 7.3 m and 5.5 m, followed by an early birch zone at 5.3-4.7 m depth. A rise in fir and pine occur in the birch zone. Oak begins to increase at 4.7 m and hemlock begins to increase at 4.0 m. A later birch rise begins at 2.8 m, followed by a rise in beech at 2.4 m. The top 2.9 m of the core is also marked by peak values in pollen that are indicative of bog vegetation, with a rise in spruce between 0.4 and 0.1 m depth.

1.4.2. Some Pollen Studies from Other States in New England

1.4.2.1. M.B. Davis' (1958) Work in Central Massachusetts

Three sites from central Massachusetts were studied for pollen to outline the vegetational history (Figure 1.4). Results show that forests quickly colonized the narrow belt along the front of the receding ice. The mixed spruce and deciduous forests during Two Creeks time indicates a cool-temperate and maybe a dry climate. During the "Valders Stadial", climate became cooler and more moist, and change in the frequency of the forest species occurred. The pine zone is composed of two subzones. The second was probably warmer and drier than the first subzone. The deciduous forest zones observed in other parts of New England were also recognized in the three study sites. Oak and hemlock dominates the earliest deciduous zone; whereas oak, pine, and hickory are the main species in the second zone; and birch, oak, hemlock and chestnut maxima characterize the most recent zone.

1.4.2.2. M.B. Davis' (1968) Work at Rogers Lake, Connecticut

By using rates of deposition of pollen grains in the accumulating sediment rather than the traditional pollen percentage diagram, M.B. Davis (1968) cast new light on the

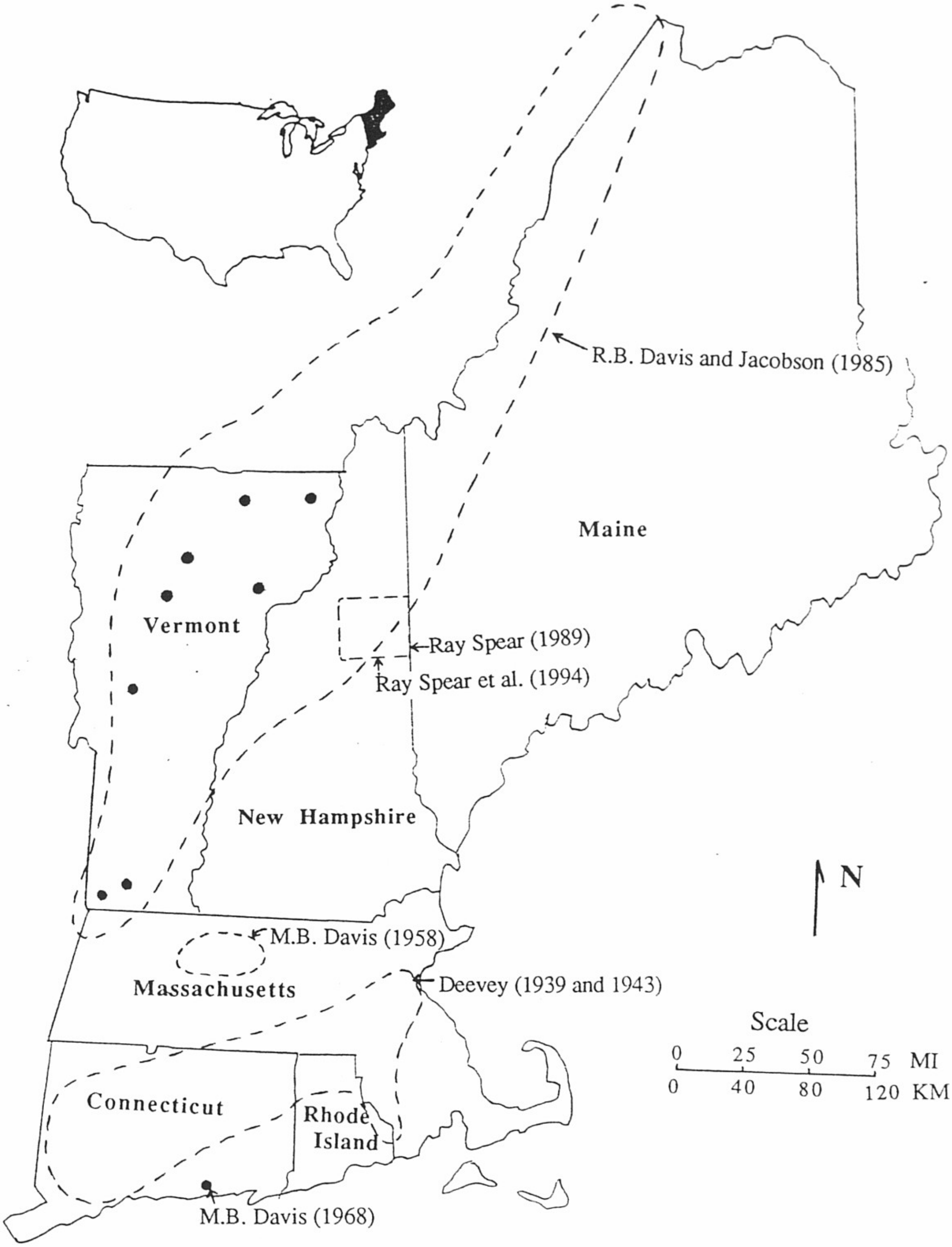


Figure 1.4. Outline map of New England showing the major pollen study sites mentioned in this paper. Dashed line indicates the relative research area of each study. See Figure 1.3. for names of the study sites in Vermont.

interpretation of climatic history of southern Connecticut. It was assumed that changes in pollen deposition rates reflect changes in species abundance since the yearly influx of each pollen type is independent of the influx of the other pollen types. Such conclusions can not be drawn based on pollen percentage diagrams. This work was the first absolute pollen influx study.

Rogers Lake (Figure 1.4) is 6 km east of the Connecticut River and 8 km north of Long Island Sound in southern Connecticut. The surrounding vegetation is deciduous forest, which is mostly second growth on abandoned farmland. Oak makes up almost half of the basal area followed in order by hickory, birch, and ash.

A 11.5-m core was taken in the south basin of the lake, whereas only a 4.6-m sediment core was recovered from the north basin. A known volume of suspension of pure *Eucalyptus* pollen was added to the sample before preparation so that the number of fossil pollen per ml could be calculated. Samples of at over 60 levels were radiocarbon dated, which allowed use of absolute age rather than depth as the ordinate in the diagrams. The standard pollen sequence in New England (Deevey, 1939 and 1943) is present in Rogers Lake. The zonation of pollen percentage and influx diagrams are as follows:

Herb pollen zone (14,300-12,150 ^{14}C yr BP ago), characterized by high percentages of pollen from herbaceous plants; but the deposition rate shows that all pollen types were in fact rare during this period compared with the sediment younger than 12,000 ^{14}C yr BP

Zone A-1, transition from herb to spruce zone (12,150-11,700 ^{14}C yr BP ago), a maximum of birch pollen, rising percentage of spruce pollen, maximum poplar percentage, but deposition rates show that the deposition rate of poplar pollen is very low

Zone A-2-3, spruce -oak zone (11,700-10,200 ^{14}C yr BP ago), characterized by high percentages of spruce, oak, and other temperate deciduous tree pollen; pine percentage rises to a maximum near the upper boundary of the zone

Zone A-4, spruce-fir zone (10,200-9,100 ^{14}C yr BP ago), is characterized by decreased oak pollen percentages and maximum spruce, fir, and larch frequencies; birch and alder pollen also increase along with maximum deposition of conifer pollen

Zone B, pine zone (8,100-7,900 ^{14}C yr BP ago), white pine dominates the assemblage with a high deposition rate; a rapid decrease in deposition rates, as well as percentages, for boreal genera such as spruce, fir, and larch; climate must have warmed considerably at this zone

Zone C-1, C-2, and C-3, oak zones (7,900 ^{14}C yr BP to present), the deposition rate for total pollen relatively stable during this period; trends in rates for individual types similar to the trends in percentages

Zone C-1, oak and hemlock with ragweed pollen occur at the lower portion of the zone (C-1a); beech pollen characterize the upper portion (C-1b)

Zone C-2, oak and hickory with beech percentage decline to a minimum

Zone C-3, oak and chestnut, percentage of ragweed pollen increases (C-3b)

It is worth mentioning that only during the last 2,000 years has the pollen assemblage in southern Connecticut been similar to modern assemblages, which suggests that the forest communities may be of very recent origin (Davis, 1968). By analyzing the changing abundance of tree pollen from 12,400-14,000 ^{14}C yr BP to 9,000 ^{14}C yr BP ago, the author concludes that a tundra vegetation was replaced by woodland and later replaced by forest.

1.4.2.3. M.B. Davis et al.'s (1980) Work in New England

Pollen and macrofossils from six sites at different elevation in the White Mountains of New Hampshire were used to interpret elevation distributions of four coniferous tree species during the Holocene and their climatic meaning, especially the correlation of the New England climatic sequence with changes in the Midwest. The species examined were white pine and hemlock (low-elevation species) and spruce and fir (high-elevation species).

The White Mountains were deglaciated between 14,000 and 13,000 ^{14}C yr BP. Spruce was the first tree to invade the New England tundra. Its pollen influx rate increases steeply about 12,000 ^{14}C yr BP. Fir was a later immigrant. The constant influx of fir pollen and the continuous occurrence of fir macrofossils through the Holocene at sites at 100 and 130 m indicates that fir become established about 10,000 ^{14}C yr BP and has remained dominant ever since. Spruce occurred at all elevations up to 1300 m until 10,000 ^{14}C yr BP, but it became infrequent at 9,000 ^{14}C yr BP and remains infrequent throughout the Holocene. A sudden resurgence in spruce macrofossils at 2,000 ^{14}C yr BP at sites between 650 and 1,000 m suggests an increase in its abundance of spruce in the modern forest at these elevations.

White pine appeared in Connecticut about 9,000 ^{14}C yr BP and grew 350 m above its present limit, which indicates that the climate was more favorable than today. Hemlock migrated into northern New Hampshire 7,000 ^{14}C yr BP and grew 300-400 m above its present limit soon after. Therefore, a change in the physical environment rather than lack of competition may be the explanation for the hemlock succession. Hemlock disappeared from the highest sites about 5,000 ^{14}C yr BP.

Davis et al. (1980) conclude that conditions of maximum warmth and dryness prevailed at lower elevations of eastern North America starting 9,000 ^{14}C yr BP and lasted at least until 5,000 ^{14}C yr BP, correlative with the Prairie Period in Minnesota. An estimate derived from modern lapse rates would suggest a 2°C increase in mean annual temperature. Davis et al. (1980) believe that pollen is widely dispersed from one elevation to another among the 33 lakes at different elevations in the White Mountains; however, pollen of spruce and fir, which are poorly distributed by air currents, are exceptions. Also, although the abundance of several tree species has changed as the result of human disturbance, the general pattern of vegetation zones along the elevation gradient has remained the same.

1.4.2.4. R.B. Davis and G.L. Jacobson's (1985) Work at Northern New England and Adjacent Areas of Canada

The landscape of northern New England and adjacent areas of Canada changed greatly between 14,000 and 9,000 ^{14}C yr BP; deglaciation occurred, relative sea level and shorelines shifted, and a vegetational transition from tundra to closed forest took place (Davis and Jacobson, 1985). "A continuum of tundra-woodland-forest passed northeastward and northward without major hesitation or reversal" (Davis and Jacobson, 1985).

Most New England pollen research has concluded that ice left Vermont about 14,000 ^{14}C yr BP, and that the landscape was characterized by the prevalence of tundra vegetation between 14,000 and 12,000 ^{14}C yr BP (Davis, 1968). Spruce pollen began to increase about 11,700 ^{14}C yr BP (Spear et al., 1994). An increased rate of progression of forest from 11,000 to 10,000 ^{14}C yr BP suggests a more rapid warming than in the prior 2000-3000 ^{14}C yr BP (Davis and Jacobson, 1985). M.B. Davis' (1968) work at Rogers Lake, Connecticut, shows that an increase in the rate of tree pollen deposition occurred at 12,000 ^{14}C yr BP, when boreal woodland became established. Davis (1968) also pointed out that pollen deposition rates continued to increase until a sudden sharp rise for white pine, hemlock, poplar, oak, and maple pollen occurred at 9,000 ^{14}C yr BP which marked the establishment modern forests.

1.4.2.5. Ray Spear's (1989) Work in the White Mountains, New Hampshire

A 13,000 ^{14}C yr paleoenvironment history was inferred from the pollen and plant macrofossil records from four small lakes in the subalpine and alpine zones of the White Mountains (Figure 1.4). The sites are located above 1,140 m within an area of 2,500 km^2. Three sites are in the subalpine fir forest and one site at 1,542 m is an alpine meadow. Rapid downwasting of the continental ice sheet caused the summits to project above the ice as nunataks with irregular tongues of ice persisting in the valleys.

The features of the pollen diagrams and their climatic interpretations are as follows:

13,000-11,750 ^{14}C yr BP: barren periglacial desert covered the highest altitudes in the White Mountains, while tundra vegetation occupied the lower slopes and valleys; temperature was 5-10 °C lower than today

11,750-10,300 ^{14}C yr BP: spruce tundra vegetation surrounding all four high-elevation sites which were subject to intensive periglacial activity; the temperature was 4-6 °C lower than today

10,300 ^{14}C yr BP: spruce arrived at high-elevation sites and shrubs invaded the tundra; spruce woodland dominated the lower slopes and valleys

9,750 ^{14}C yr BP: forest with poplar, spruce, and birch replaced the spruce woodland at lower elevations

From 10,300 to 5,000 ^{14}C yr BP, evidence from the alpine sites shows that fir trees were more abundant and treeline was higher than today. Thus, Spear (1989) concluded that treeline is a poor temperature indicator because wind and moisture are the major factors determining treeline position.

1.4.2.6. Ray Spear et al.'s (1994) Work in White Mountain, New Hampshire

The results of Ray Spear's research (Spear et al., 1994) reveal additional information in New Hampshire. At low elevations the sequence of vegetation change was:

13,700-11,500 ^{14}C yr BP, tundra characterized by a high percentage of nonarboreal pollen and silt, and a lack of macrofossils

11,500-9,000 ^{14}C yr BP, transitional mixed-conifer woodland of first spruce and then fir, larch, poplar, and paper birch

9,000-7,000 ^{14}C yr BP, forests dominated by pine and oak

7,000 ^{14}C yr BP, mixed hardwood forests

In Mirror Lake (Liken and Davis, 1975), spruce pollen begin to increase at 11,500 ^{14}C yr BP, peaked at 10,800 ^{14}C yr BP, dropped gradually by 10,000 ^{14}C yr BP, and later increased beginning at 2,000 ^{14}C yr BP. Fir pollen percentages at Mirror Lake peaked around 10,000 ^{14}C yr BP and dropped by 9,000 ^{14}C yr BP. The vertical expansion of both white pine and hemlock between the 6,000 to 4,000 ^{14}C yr BP suggests greater warmth. Also, during this period, most research sites in New England show that hemlock increased between 7,000 and 4,000 ^{14}C yr BP, reaching its peak around 4,850 ^{14}C yr BP, which is the minimum stage of pine. The pollen profile for beech shows the same trends as that for hemlock. The peak of birch came after the decline of hemlock. The reappearance of spruce occurred at 3,000 ^{14}C yr BP, following the increase of beech, and reached its peak between 1,500 and 1,250 ^{14}C yr BP. Fir pollen percentages reached a small peak at 3,000 ^{14}C yr BP. The pollen percentage changes of spruce, beech and fir represent a cooler and moister climate, which extended to the present (McDowell et al., 1971).

1.5. Hypotheses and Significance of My Research

There have been many questions about the timing and pattern of deglaciation in Vermont and the following plant secession. Pollen analysis is an effective tool for understanding paleoclimate. Two new pollen study sites with 10 AMS radiocarbon ages in the northern Green Mountains, Vermont, not only enrich the local and regional pollen data base for a more complete reconstruction of revegetation and paleoclimate in this region, but also help better interpret the deglaciation history of New England.

1.5.1. Hypotheses

I plan to test the following hypotheses:

(1) Did conifer species arrive at all elevations in the northern Green Mountains at about the same time following deglaciation, similar to the manner described by Spear (1989) in the White Mountains of New Hampshire?

(2) Is the Younger Dryas climatic oscillation recognized in pollen records from the northern Green Mountains to the same degree as described by Mott et al. (1986) in the mountains or by Peteet et al. (1993) in southern New England?

(3) Is a mid-Holocene dry period recognized in pollen records from the northern Green Mountains in similar fashion to that described by Davis (1968) in southern New England?

1.5.1.1. The Deglaciation Model and Quaternary Paleoenvironment of the northern Green Mountains

In this thesis, I present new data on the timing and pattern of deglaciation and revegetation, and hence interpret paleoclimate. It is known that vegetation quickly occupied the newly exposed land following the receding ice sheet (Wright, 1983). With AMS radiocarbon ages, the difference in the time of the initial arrival of individual vegetational species might indicate migration status of various forest assemblages. By assuming that (1) climate is the dominant factor influencing vegetation distribution, (2) pollen assemblages closely reflect the vegetational associations, and (3) the radiocarbon ages are accurate, the paleoclimate since the last deglaciation can be inferred.

1.5.1.2. Evidence for Younger Dryas

The Younger Dryas climate oscillation was the last glacial cold spell during deglaciation the onset of which has been numerically dated at 10,720 +/- 150 ^{14}C yr BP (Dansgarrd et al., 1989) and 10,740+/- 430 ^{14}C yr BP (Peteet et al., 1993). This climate oscillation is apparent in the isotope, snow accumulation, and dust shifts in polar ice cores, as well as in palynological data from Europe, which suggest that coniferous forests were replaced by tundra vegetation (Peteet et al., 1993). The duration of this event is about 800 ^{14}C years, roughly between 10,800 and 10,000 ^{14}C yr BP (Peteet et al., 1993). Little evidence has been found to support the existence of Younger Dryas in North America except for maritime provinces of eastern Canada (Mott et al., 1986). The mechanism that caused this climate oscillation might be the rapid retreat of sea-ice cover (Dansgarrd et al., 1989), the variations of earth's orbit (Ruddiman and McIntyre, 1981), or the combination of both. Peteet et al. (1990) suggested that such a climatic oscillation is possibly a worldwide event. A small oak decline and increase of boreal pollen, namely alder, in the A-4 pollen zone in the late glacial have been interpreted as evidence for the Younger Dryas in northeastern U.S.A. (Peteet et al., 1990, 1993). I have searched for evidence of the Younger Dryas suggested by Peteet et al. (1993) in the pollen percentage diagrams of my cores.

1.5.1.3. The Co-occurrence of the mid-Holocene Dry Period in the Northeast with the Prairie Period in the Midwest

Davis' (1968) study at Rogers Lake, Connecticut, indicates that ragweed pollen was deposited at relatively high rates 8,000 years ago, which she believe correlated with the prairie period in the Great Lakes region. My study will test the hypothesis of this co-existing of the dry period in the northern Green Mountains between 9,000 and 4,000 ^{14}C yr BP (Davis, 1968) with the prairie period in the Midwest.

1.5.2. Significance of My Research

My thesis will attempt to answer the following questions:

1. What was the timing of the first warming in the Green Mountains, north-central Vermont? When did continental ice leave the Green Mountains of Vermont?
2. What were the vegetation changes and what can be deduced about consequent climate change in the Green Mountains?
3. What is the tree migration model? Is there evidence for or against the existence of the Younger Dryas climate oscillation in northern Vermont.

Little pollen research has been done in Vermont in comparison to other states in New England. Even less pollen research has been done with systematic AMS radiocarbon dating, especially in northern Vermont. The pollen zonation used initially in Connecticut has been extended to other areas with few stratigraphic and numerical age measurements. Very few radiocarbon ages are available for correlation. Davis and Jacobson (1985) used 62 pollen sites in northern New England and the adjacent areas of Canada to reconstruct the late glacial and early Holocene landscape of these areas. Figure 1.5 shows the location of radiocarbon-dated pollen cores taken in northern Vermont and used by Davis and Jacobson (1985). There are four radiocarbon ages each from Bugbee Bog and South King Pond, and two from Columbia Bridge, Vermont.

In general, the chronology of climatic changes interpreted from pollen records in northern Vermont is based on correlation to pollen sites better dated elsewhere in New England. However, because of the large distance and elevation difference between sites, these time-stratigraphic sequences may not be the same. McDowell et al.'s (1971) work in Bugbee Bog is the only systematic attempt to combine pollen analysis of lake sediment

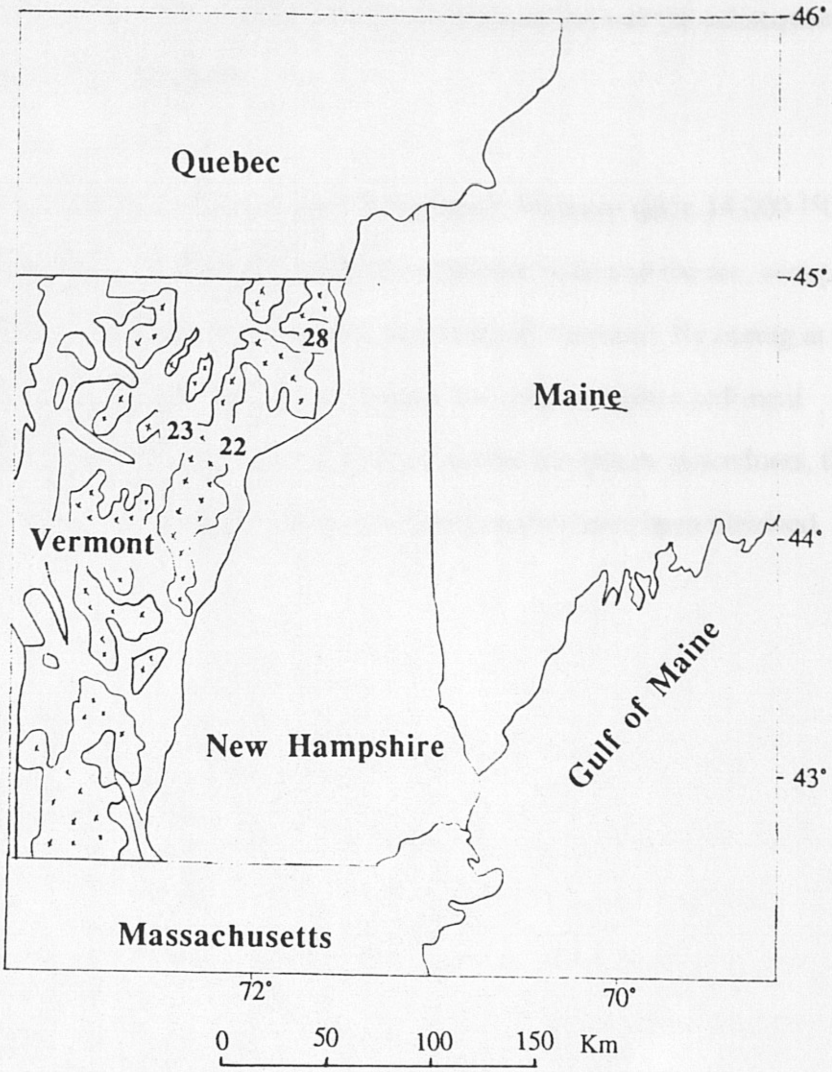


Figure 1.5. Location of three pollen study sites used in R.B. Davis et al.'s (1985) study of late glacial and early Holocene landscapes in New England and the adjacent area of Canada. Shaded areas are between 457 and 914 in elevation. Davis and Jacobson (1985) cited 62 pollen cores with radiocarbon ages, but only three are from Vermont.

with radiocarbon dating in Vermont. Their results are in general accord with other published findings for New England. My study provides ten new radiocarbon ages that will add to our understanding of the history of regional deglaciation and the subsequent revegetation in northern New England.

Dramatic environmental changes have taken place in Vermont since 14,000 ^{14}C yr BP. The continental glacier retreated northward and vegetation followed the ice, occupying the barren land. There are numerous glacial lakes and ponds in Vermont. By coring at the deepest part of ponds, I attempted to collect the longest and most complete sediment records possible. With radiocarbon dating control and careful laboratory procedures, the deposition rates of sediment and the arrival times of plant species have been obtained.

CHAPTER 2

METHODS

This project involved both field and laboratory work. In this chapter, the methodologies applied in the study are described and discussed.

2.1. Field Work

Field work involved two primary activities: 1) bathymetric surveys, and 2) sediment coring.

2.1.1. Site Selection

My goal was to choose two pollen sites from different elevations in the northern Green Mountains. Having examined many ponds in Vermont and considered other constraints, such as the availability of transportation for carrying the field equipment, Sterling and Ritterbush Ponds seemed to be the ideal sites for winter access. Sterling Pond is close to a ski resort with a chair lift and there is a public trail to Ritterbush Pond. The relative position of the two study sites is shown in Figure 2.1. Ritterbush Pond is 56 km north of Sterling Pond, whereas Sterling Pond is 600 m higher in elevation than Ritterbush Pond.

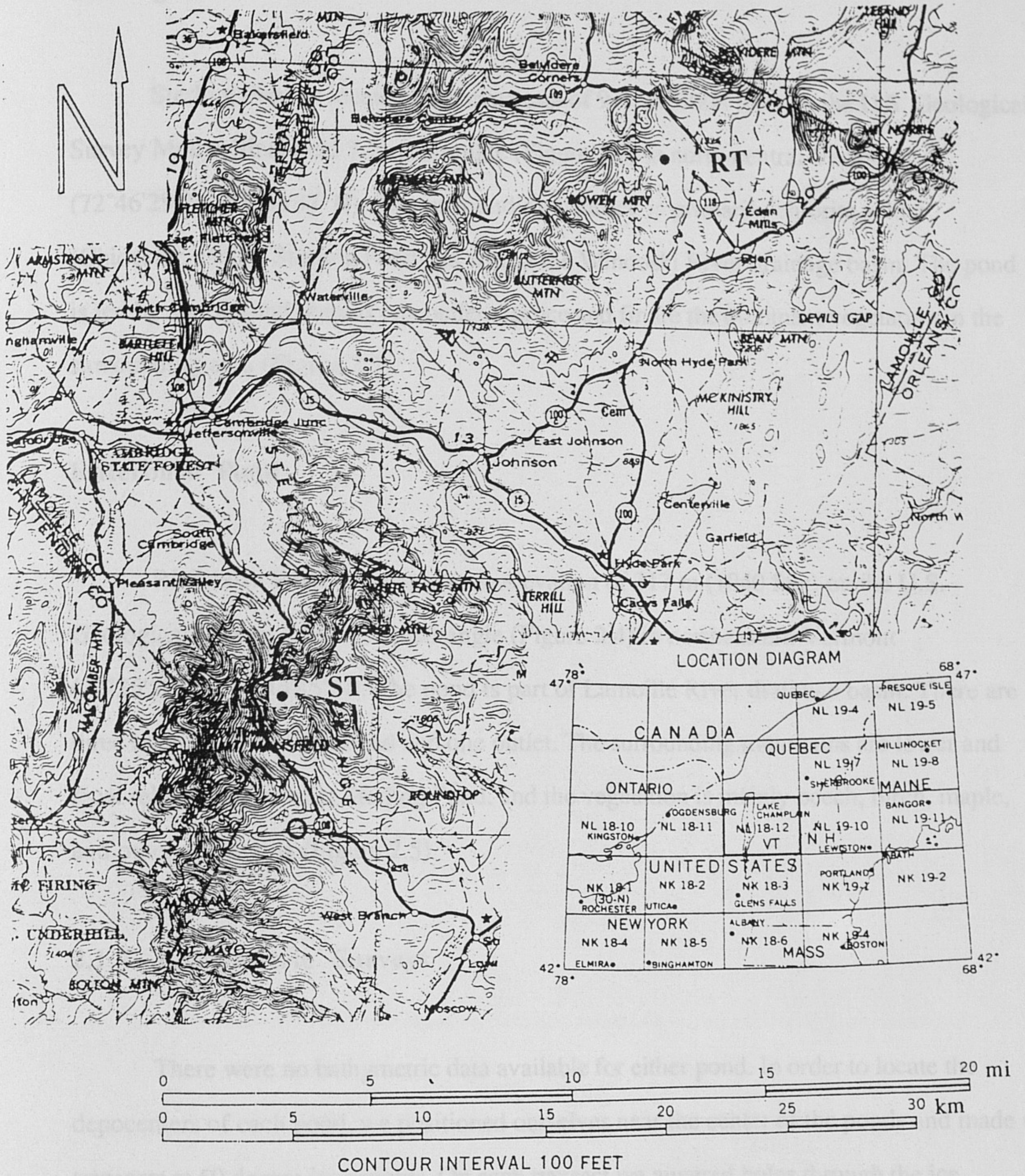


Figure 2.1. A section from U.S. Geological Survey 1:250,000 Lake Champlain Quadrangle, showing the relative position of Sterling Pond (ST) and Ritterbush Pond (RT). Sterling Pond is 600 m higher in elevation than Ritterbush Pond, whereas Ritterbush Pond is 56km northeast of Sterling Pond.

Sterling Pond

Sterling Pond is located at an elevation of 917 m (3008 feet) on the U.S. Geological Survey Mount Mansfield 7.5' quadrangle (Figure 2.2) in north-central Vermont (72°46'29"W, 44°33'37"N). The surrounding bedrock is primarily chlorite schist (Chidester, 1953). Sterling Pond lies within the Winooski River drainage basin. The pond is fed by springs and there is one outlet. Spruce and fir are the dominant vegetation in the surrounding area (Figure 2.3).

Ritterbush Pond

Ritterbush Pond is situated at an elevation of 317 m (1040 feet) on the U.S. Geological Survey Eden 7.5' quadrangle (Figure 2.4) in northeastern Vermont (72°35'59"W, 44°44'45"N). The pond is part of Lamoille River drainage basin. There are three inlets to Ritterbush Pond and one outlet. The surrounding mountains are lower and local relief is less than at Sterling Pond, and the vegetation is mainly beech, birch, maple, and other softwoods (Figure 2.5).

2.1.2. Bathymetric Surveys

There were no bathymetric data available for either pond. In order to locate the depocenters of each pond, we positioned ourselves near the center of the ponds and made 6 transects at 60 degree increments. On each transect we augered holes through the ice (Figure 2.6). Due to the irregular shape of Sterling Pond, three survey centers were used. The water depth was measured by lowering a tape with a weight at the end to the bottom.

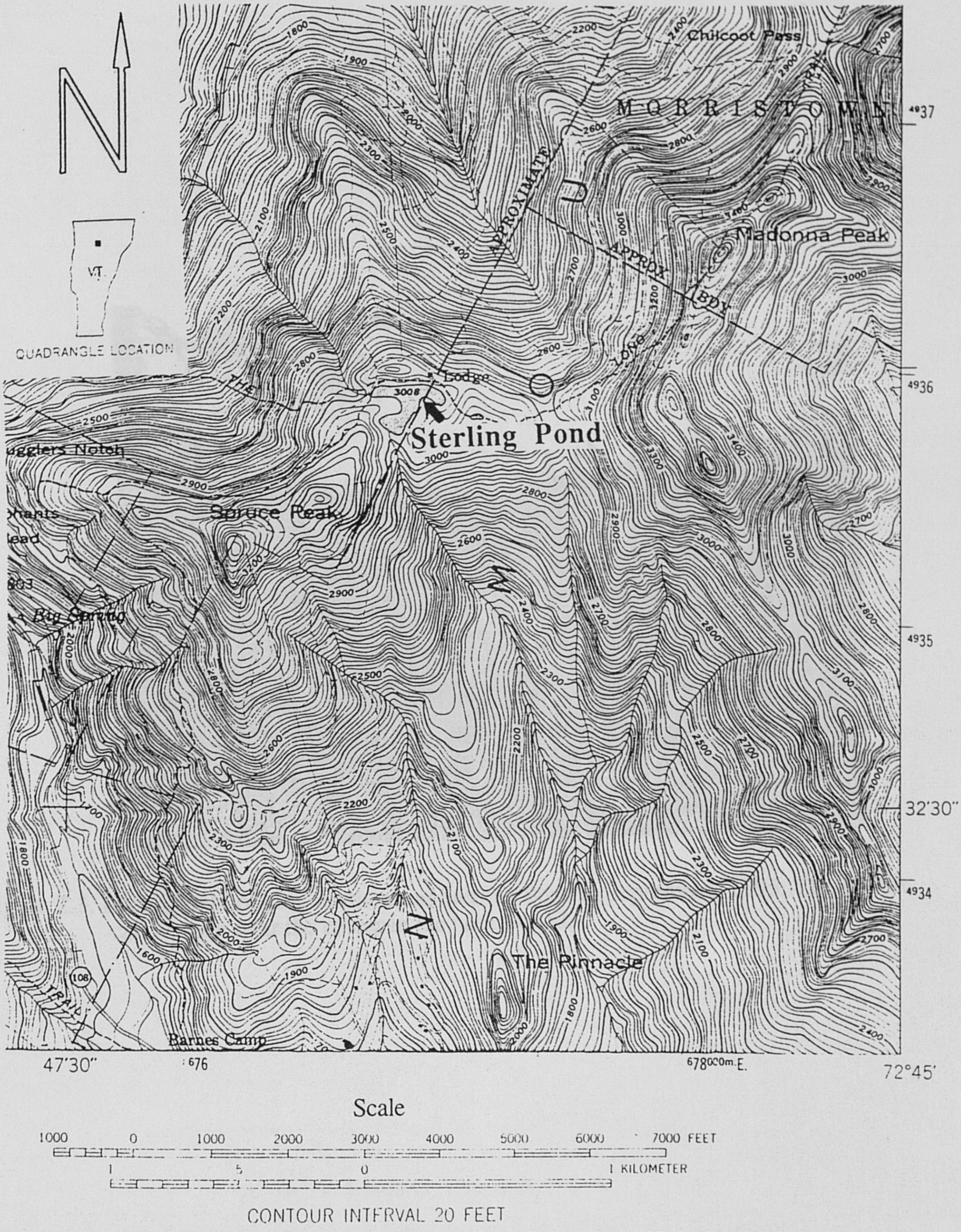
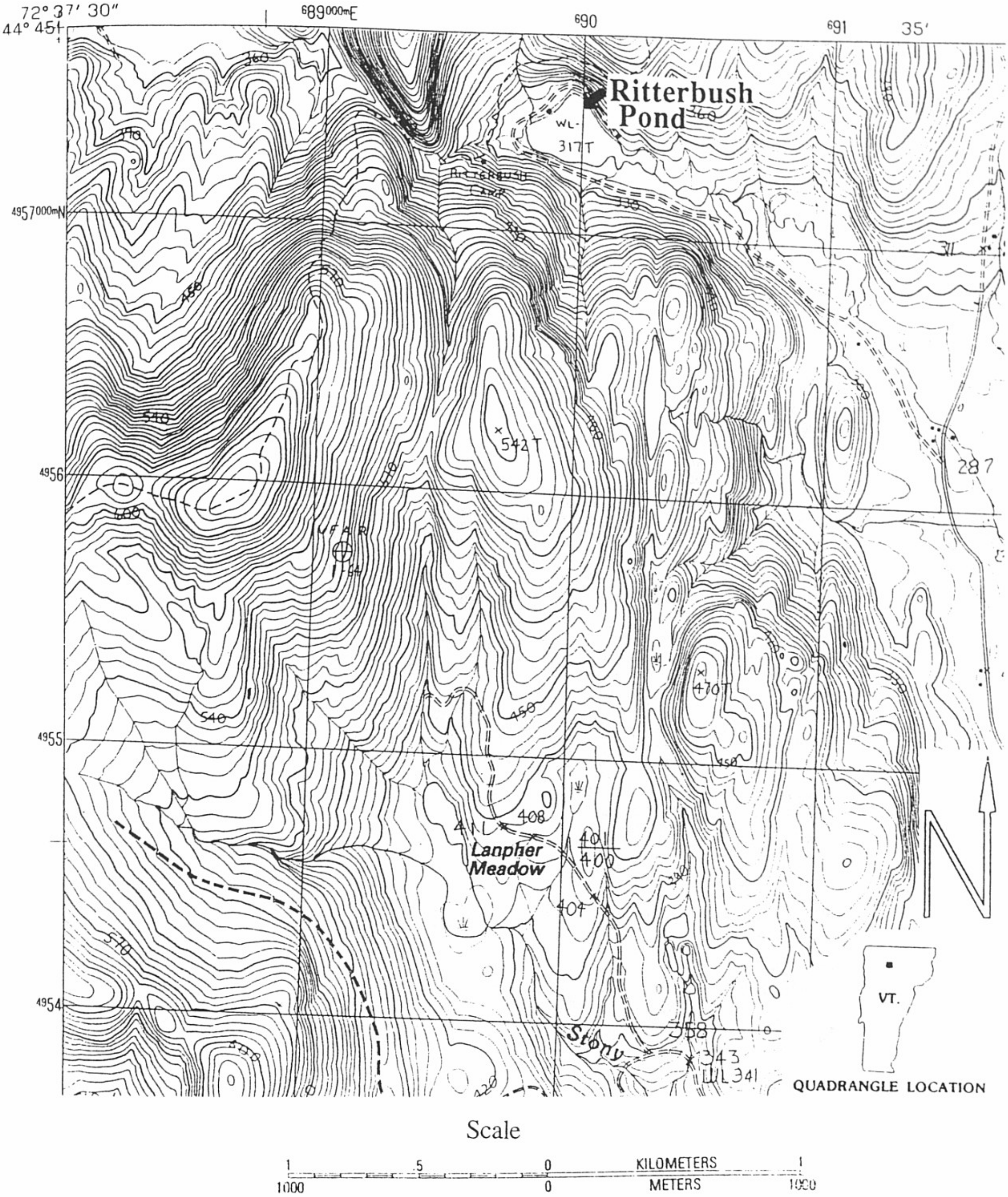


Figure 2.2. Drainage basin of Sterling Pond shown on a section of U.S. Geological Survey 1:24,000 Mount Mansfield, Vermont, Quadrangle. The elevation of the pond is 917 m (3008 feet).

Figure 2.3. Photograph looking northeast at Sterling Pond in September, 1995. The ski lift can be seen near the center in the background.



CONTOUR INTERVAL 6 METERS

Figure 2.4. Drainage basin of Ritterbush Pond shown on a section of U.S. Geological Survey 1:24,000 Eden, Vermont, Quadrangle. The elevation of the pond is 317 m (1040 feet).

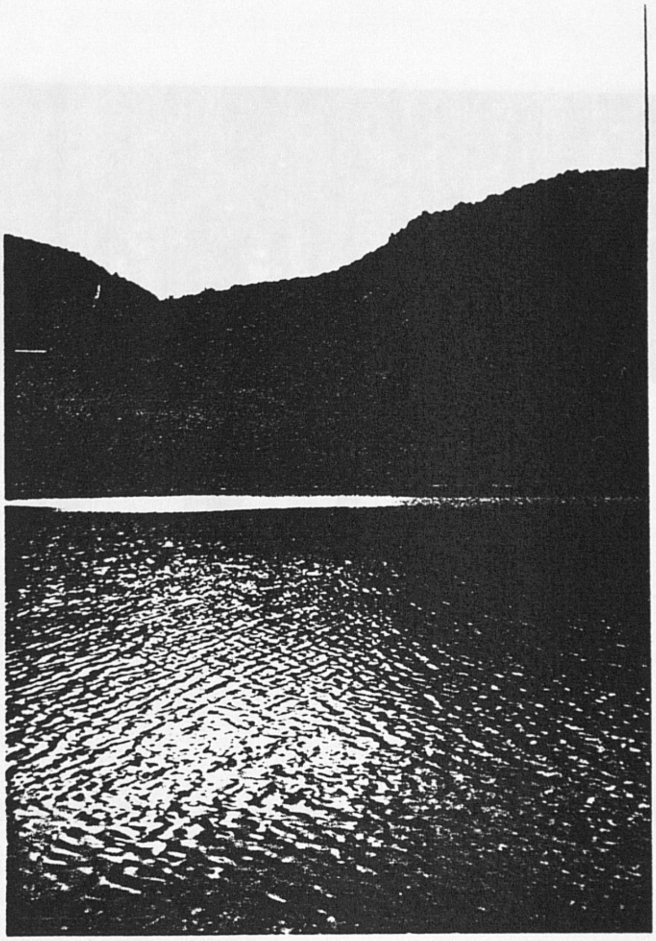


Figure 2.5. Summer view of Ritterbush Pond. The surrounding vegetation is mostly deciduous trees.

Figure 2.6. Photograph of bathymetric survey at Sterling Pond in winter 1995.

At places where transects met the shoreline, colored flagging was tied to a nearby tree so that we could orient ourselves on the next field trip.

Having augured nearly 300 holes through the ice of Sterling Pond and with the help of others, especially the Spring 1995 Geohydrology class for the survey of Ritterbush Pond, the bathymetric information was obtained. Sterling Pond has two deposition centers. The deepest part of the pond is 8.2 meters (28 feet), which is represented as ST-1 on Figure 2.7. This is where we collected the core. The second deepest point, ST-2, is 5.7m (18.6 feet), which is on the south side of the pond. The deepest portion of Ritterbush Pond is 13.7 m (45 feet), near the center of the pond (Figure 2.8).

2.1.3. Sediment Coring

A core sampling device commonly employed for lacustrine settings is the Livingston system (Livingston, 1955) and its modifications. The Livingston piston corer for lake deposits requires two or more people for transportation and operation and is restricted for use in water depths of less than approximately 30 m. The major advantage of coring in winter are: (1) accurate core locations are easy obtained, (2) a boat is not required for a coring platform or for transportation, and (3) the stable platform provided by the ice surface could be utilized for core penetration and removal.

Sediment cores were retrieved from both ice-covered ponds in winter using a modified Livingston piston corer (Wright, et al. 1984). The coring system (Figure 2.9) consists of five major components: 1) the core barrel, 2) the core head and the driver, 3) the drive rods, 4) the piston, and 5) the piston cable (Wright, 1980). Core barrels are 1.2 m lengths of thin-walled aluminum tubing. Inside the tube is a close-fitting piston to which a

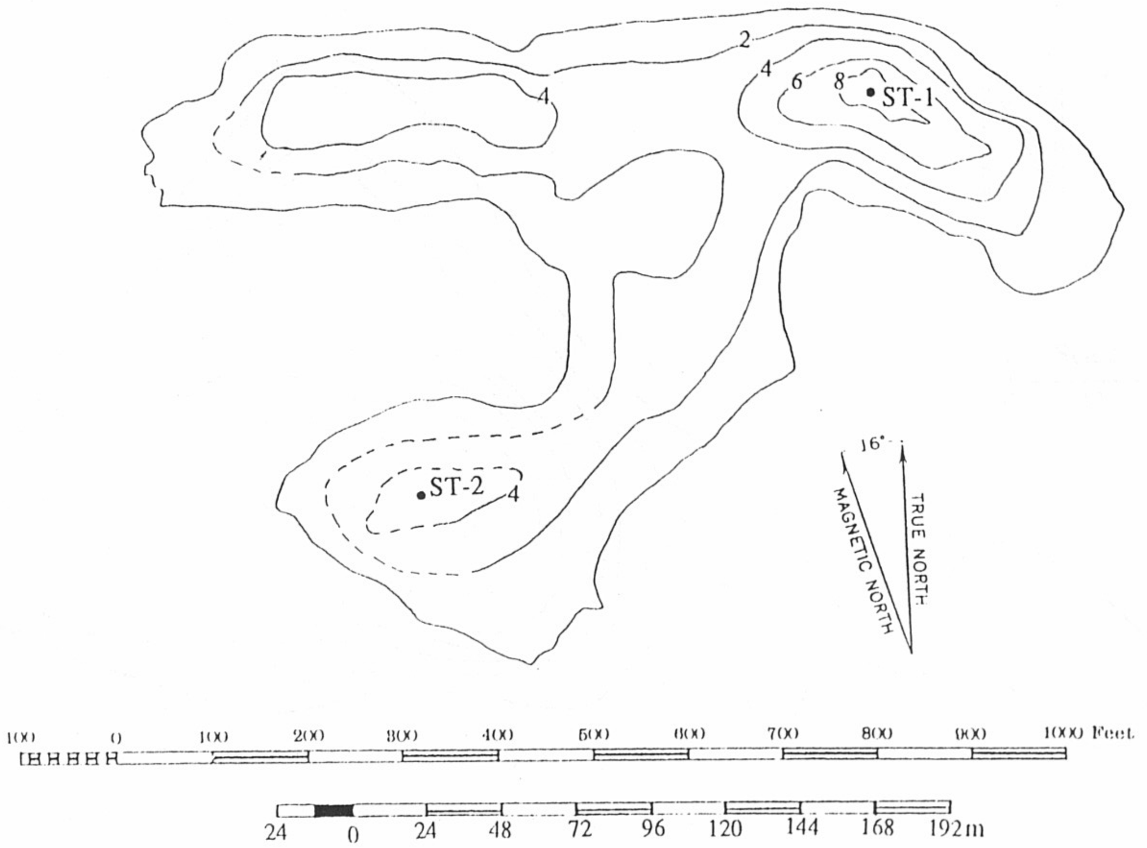


Figure 2.7. Bathymetric map of Sterling Pond, Vermont (contour interval = 2 meters). ST-1 and ST-2 mark the two coring sites. Samples from core ST-1 were analyzed for pollen.

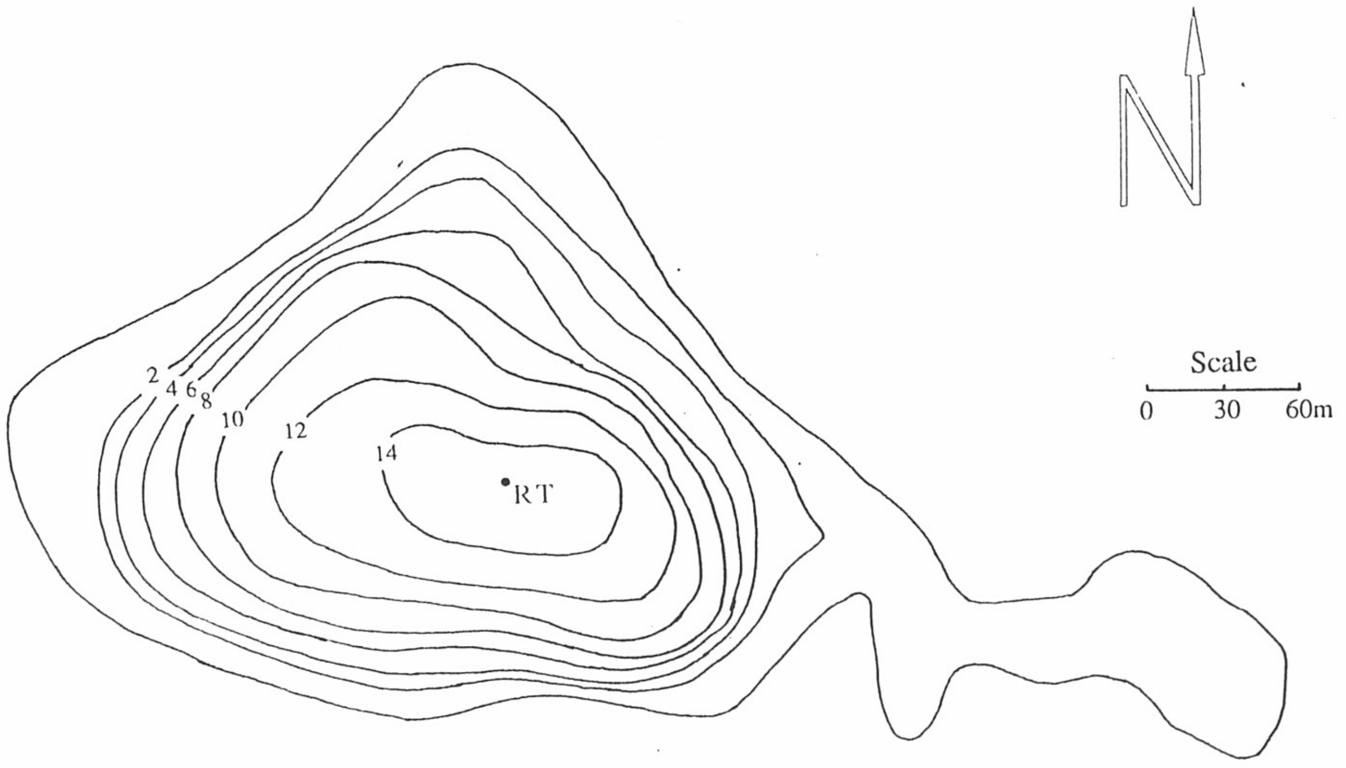


Figure 2.8. Bathymetric map of Ritterbush Pond, Vermont (contour interval = 2 meters). RT marks the coring site. Bathymetric data collected by Geohydrology Class at the University of Vermont, during Spring 1995. Map drafted by Lars Cherichetti.

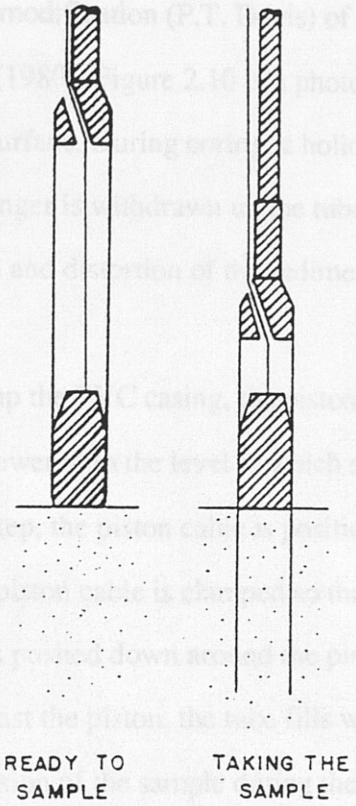


Figure 2.9. Schematic of modified Livingston coring device (from Wright, 1980).

steel cable is attached at the upper end. The head, which is attached to the sample tube by three screws, has two holes, one for the stem of 1/4 inch solid aluminum rods that move up and down inside the drive rods to hold the piston in place and one for the piston cable. The internal rod stem is a modification (P.T. Davis) of the square-rod Livingston coring system described by Wright (1980). Figure 2.10 is a photograph of the casing and the driving rod stem on the lake ice surface. During coring, a hollow tube is pushed vertically down into the sediment, as a plunger is withdrawn up the tube creating the negative pressure that prevents compression and distortion of the sediment column (Moore et al. 1991).

After setting up the PVC casing, the piston is fit to the lower end of the core tube. The sampler is then lowered to the level at which sampling is to start, in our case, the pond bottom. During this step, the piston cable is positioned freely; however, once the sampling depth is reached, the piston cable is clamped so that it can not move any farther down. Then, the core tube is pushed down around the piston by pushing on the driving rods. As the tube goes down past the piston, the tube fills with sediment. The function of the piston is to prevent compression of the sample during the drive and to prevent the sample from falling out while the filled core tube is being lifted up. A hammer was used to push the sampler down and to pull it back through the stiff, bottom-most sediments (Figure 2.11). A stopper was placed at the bottom open end of the tube immediately after it left the water, and then pushed along with the sediment column to the top of the core tube after the piston and the head were removed. The empty space at the bottom of the tube was then filled with plastic bags before a cap was secured over the stopper and another cap was attached at the top end. Tape was applied around both caps to make a water-tight seal for hanging in the water column to prevent freezing of the sediment. As the coring penetrates deeper and deeper into the sediment, the previous stop points were marked on the drive rods. The rods

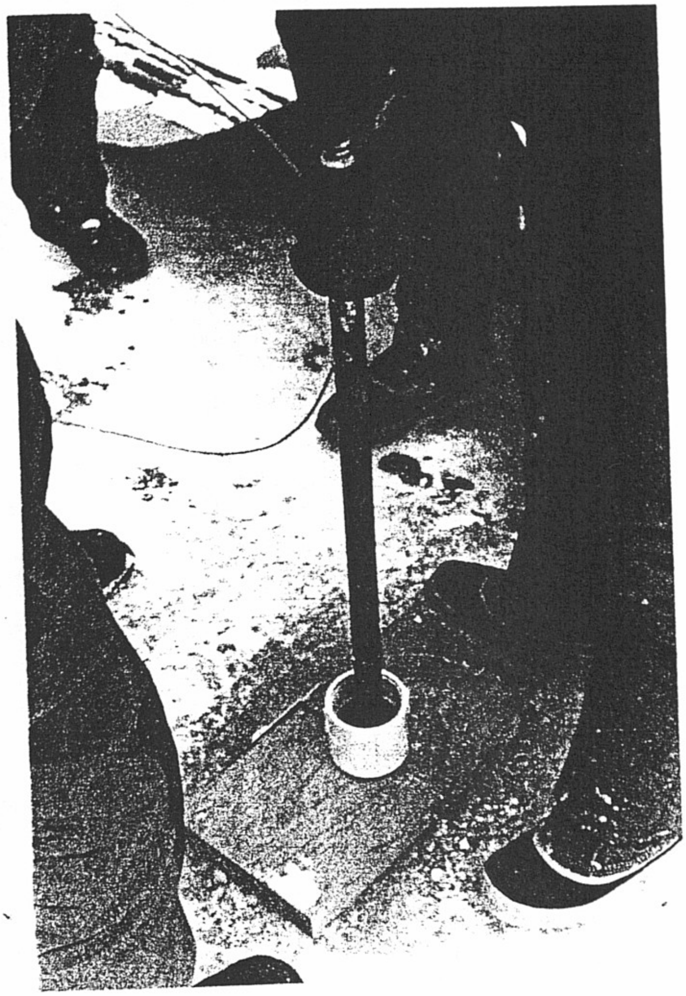


Figure2.10.Photograph of a coring site that exhibits casing system and driving rod, which is attached to the Livingston core below.

were kept in accurate order so that they could be connected in order for the next core. All the tubes with samples were clearly marked with top direction and sequence number.

2.2. Laboratory Work

The laboratory work was far more involved than the field work, and therefore is described in the following subsections.

2.2.1. Extruding the Samples from the Coring Tubes

Within a day after the field trips, sample cores were extruded and subsampled. A one-meter-long, half meter wide strip of aluminum foil was laid on a laboratory table, with a similar size strip of Saran wrap laid over the foil. After removing the tape, cap and stopper from the top end of the core tube, a thick wooden rod was used to push the stopper and the sediment core out of the core tube (Figure 2.12). Coordination among people pushing the rod and the people holding the tube is required. The speed of the extruding must be even, otherwise the sediment core might be disturbed.

After the sediment cores were extruded, they were measured for their "lab length." It turns out that our lab lengths averaged about 94% of the sample field thrust lengths, which means very little sample was lost between core sections (Wright, 1980). Table 2.1 records the lab lengths vs. thrust lengths of the Sterling Pond core, and Table 2.2 presents similar data for Ritterbush Pond.

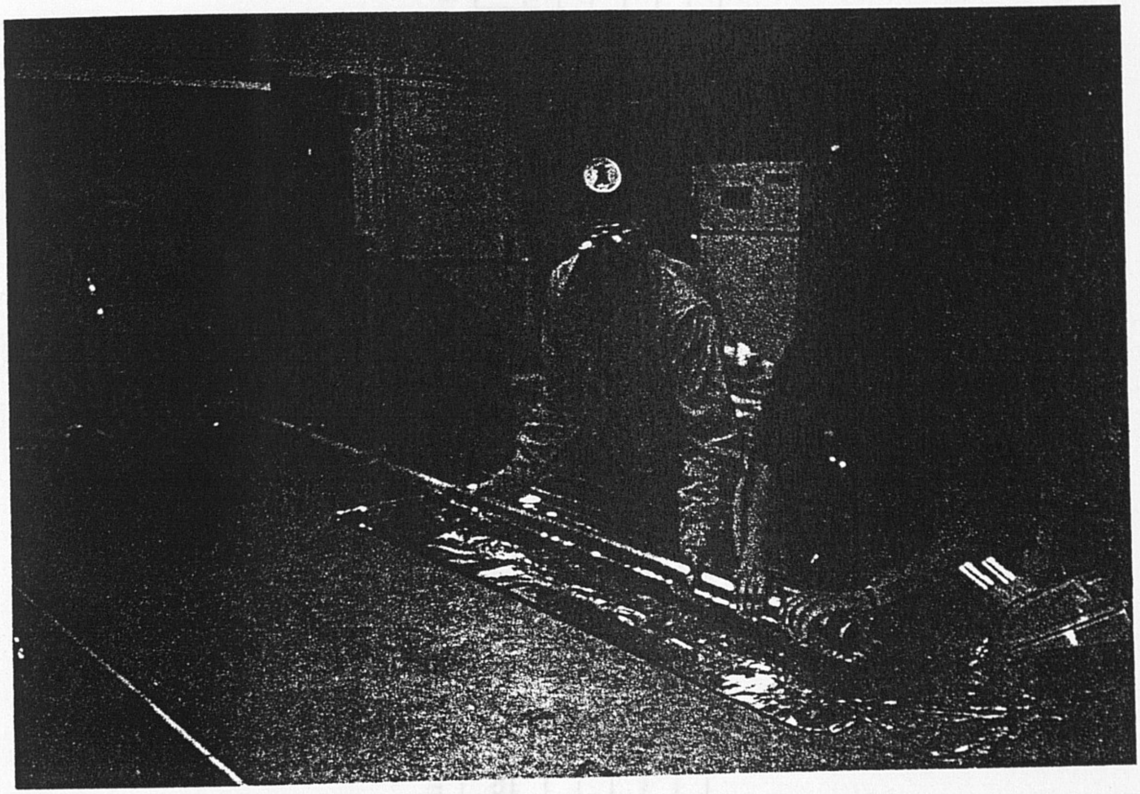


Figure 2.12. A wooden rod with an attached rubber stopper was used to extrude sediment cores from tubes.

Table 2.1. Lab length vs. thrust length of Sterling Pond core. The average recovery is 94.28%.

thrust #	surface-top of thrust (cm)	surface-bottom of trust (cm)	trust length (cm)	lab length (cm)	percentage recovery (%)
1	0	96.5	96.5	80	82.9
2	96.5	193	96.5	94	97.4
3	193	297	104	104	100
4	297	393	96.25	94	97.7
5	393	497	103.75	101	97.3
6	497	582	94	85	90.4

Table 2.2. Lab length vs. thrust length of Ritterbush Pond core. The average recovery is 93.55%.

thrust #	surface-top of trust (cm)	surface-bottom of trust (cm)	trust length (cm)	lab length (cm)	percentage recovery (%)
1	0	112	112	100	98
2	112	220	108	98	90.7
3	220	328	108	100	92.6
4	328	435	107	100	93.5
5	435	539	104	90	86.5
6	539	574	35	35	100

2.2.2. Subsampling

Several clean stainless steel spades and paper towels were used when splitting the samples to reveal more detailed stratigraphy. The spade was moved horizontally to prevent accidental contamination in a vertical plane. Since the exposure of fresh surface to oxygen causes rapid darkening, structure and color of the sediment were recorded as the cores were opened. Photographs of the split cores were taken as well. The top four meters of the Sterling Pond core is mainly dark homogeneous organic gyttja (Figure 2.13). There was more visible stratigraphy including graded bands and color bands in the Ritterbush Pond core (Figure 2.14) than in the Sterling Pond core.

Sediment for pollen analysis was subsampled every 10 centimeters according to total thrust depth for cores from both ponds (Figure 2.15). The samples were stored at 4°C in plastic vials. Visible macrofossils were also picked out and their depth recorded. For example, at 281 cm in the Sterling Pond core, a well-preserved birch leaf was found; at 298.5-299 cm a whole hemlock cone was recovered; at 311 cm a five-centimeter-long *Lycopodium* was pulled out; and a piece of pine cone broot was found at 443 cm. One half the core was subsampled, whereas the other half was stored for future use, such as detailed macrofossil analysis.

2.2.3. Preparation of Marker Pollen Slurry

As mentioned in Chapter 1, for absolute pollen influx calculations, a known quantity of exotic pollen or spores were added to the samples, in order to control for the loss of pollen during sample preparation (Davis, 1969). The number of these grains that occurred on the final slide preparation was counted along with the sample pollen. Since the

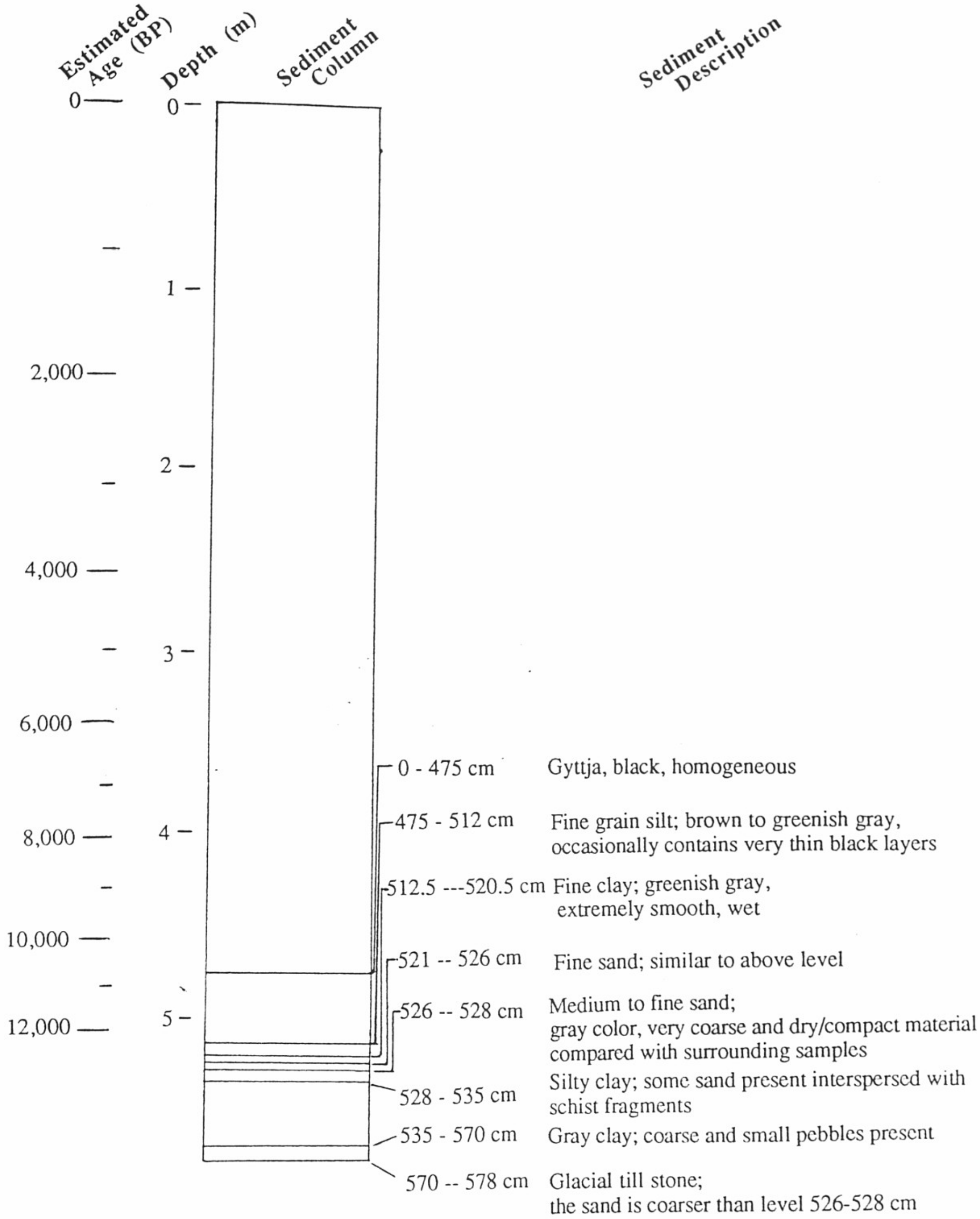


Figure 2.13. Sediment stratigraphy and description of the Sterling Pond core.

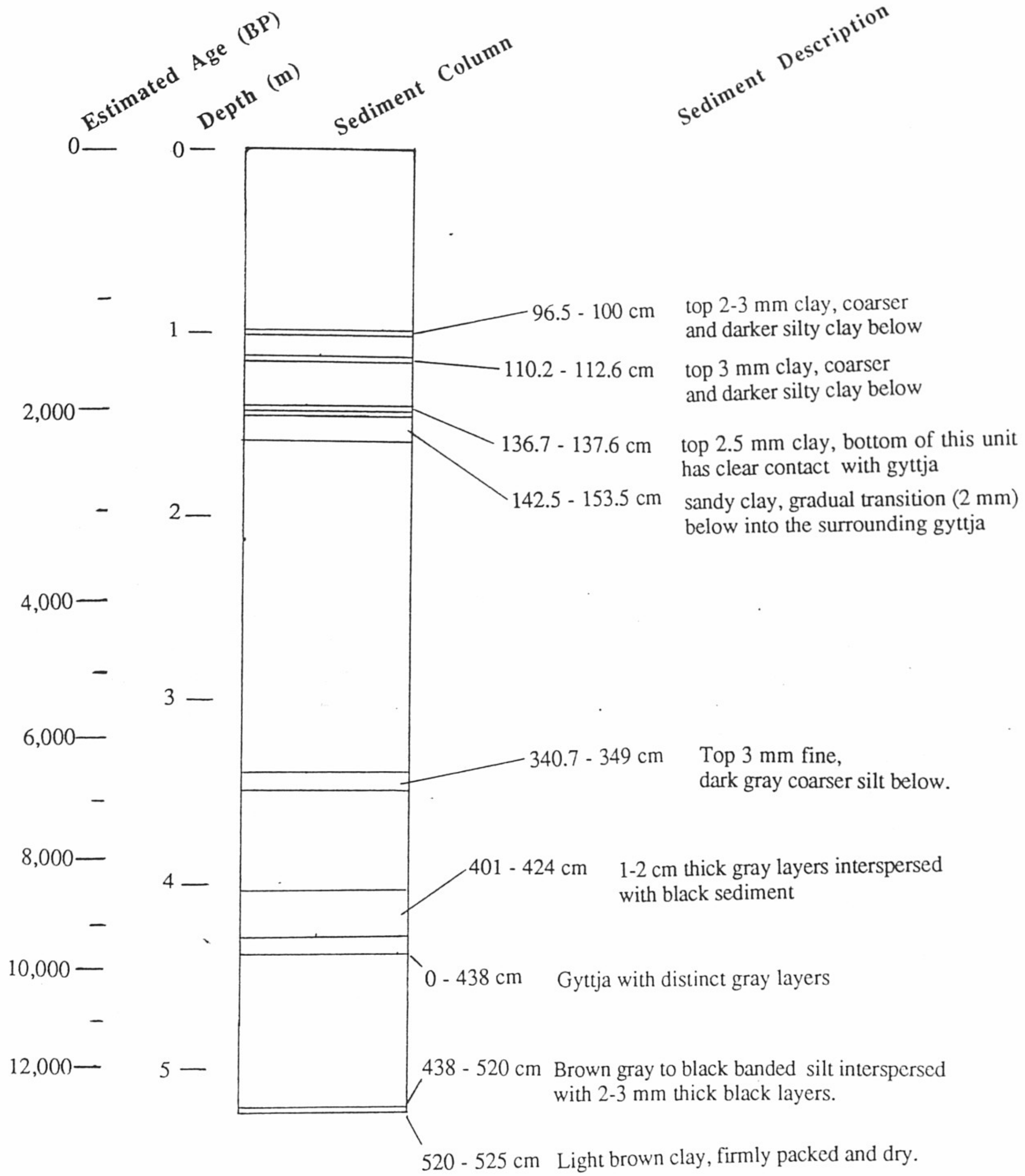


Figure 2.14. Sediment stratigraphy and description of the Ritterbush Pond core.

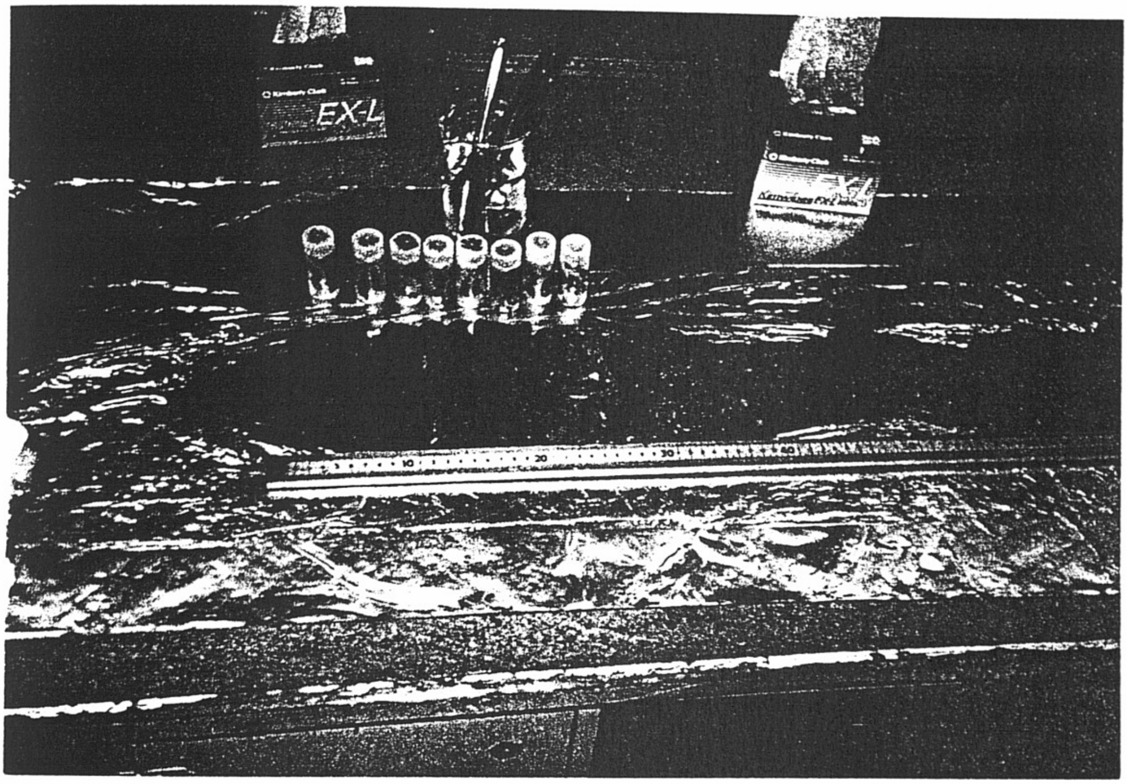


Figure 2.15 Photograph of subsampling procedure of a sediment core.

total number of marker pollen grains added to the slurry is known, the ratio of marker pollen counted to the number of marker pollen added originally can be used to calculate the total pollen density of the original sample. *Eucalyptus* pollen was chosen, because it is not a species grown in New England and it is also very distinguishable under the microscope. See Appendix C for the detailed labortary procedure for slurry preparation.

A red blood cell counting slide was used for counting the density of *Eucalyptus* pollen. Since there is a depression on the slide, a certain volume of slurry can be placed on the slides. There are grids marked on the bottom of the slide, which represents 0.1 mm^3 per grid. Therefore, a total of 0.9 mm^3 in volume of slurry was kept on the slide. By using the function (suggested by Dr. Ray Spear):

$$\overline{X}\left(\frac{1,000}{0.9}\right) \pm t\sqrt{\frac{\overline{X}}{n}}\left(\frac{1,000}{0.9}\right)$$

X represents the average of number of *Eucalyptus* pollen on 0.9 mm^3;

n represents the number of times counted;

t is a constant (Dr. Ray Spear suggested that I use 2);

the density (number of grains in one cubic centimeter) can thus be calculated. The density of *Eucalyptus* pollen is 59,800 grains·cm^{-3}. Therefore, the density of fossil pollen is the result of slurry density multiplied by sedimentation rate as discussed in Chapter 3.

$$\frac{\text{influx of fossil pollen grains}}{(\text{no. of grains}\cdot cm^{-2}\cdot yr^{-1})} = \frac{59{,}800 \textit{ Eucalyptus} \text{ pollen}}{\text{per } cm^{3}} \times \frac{\text{sediment accumulation rate}}{(cm\cdot yr^{-1})} \times \frac{\text{no. of fossil pollen}}{\text{grains counted}} \Big/ \text{no. of marker pollen counted}$$

2.2.4. Laboratory Treatment for Extracting Pollen

In order to isolate pollen grains from the matrix of organic or inorganic sediment, rigorous chemical treatment using hydrochloric, sulfuric, and hydrofluoric acid is generally required, as well as acetolysis by a mixture of acetic anhydride and sulfuric acid (Moore et al., 1991). The preparation processes are complicated and involve removal of lignin by oxidation, of cellulose by hydrolysis, and of mineral matter by hydrofluoric acid, following the technique of Faegri and Iversen (1950). The chemical treatment also removes a portion of the pollen grain, revealing structures that make identification possible (Moore et al., 1991). By removing the sediment matrix, the remaining pollen grains and spores can be seen clearly when mounted on slides for microscopic analysis (Figure 2.16). All the lab work was done at Dr. Ray Spear's lab at State University of New York, College of Geneseo, whereas the pollen counting was done at The University of Vermont.

The detailed labortary procedure for pollen preparation can be found in Appendix B. A measured volume of pure *Eucalyptus* pollen suspension was added to the sediment sample before preparation. Starting with a sediment sample of one cubic centimeter, the preparation sequence ends with the isolation of pollen at the bottom of a collection vial. Fifty-two samples from Ritterbush Pond at 10 centimeter intervals, and 70 samples from Sterling Pond at 10 centimeter intervals were treated during spring and summer, 1995. The deepest level sample for pollen in Ritterbush Pond is 515 cm, whereas in Sterling Pond, the deepest sample treated is 534.5 cm.

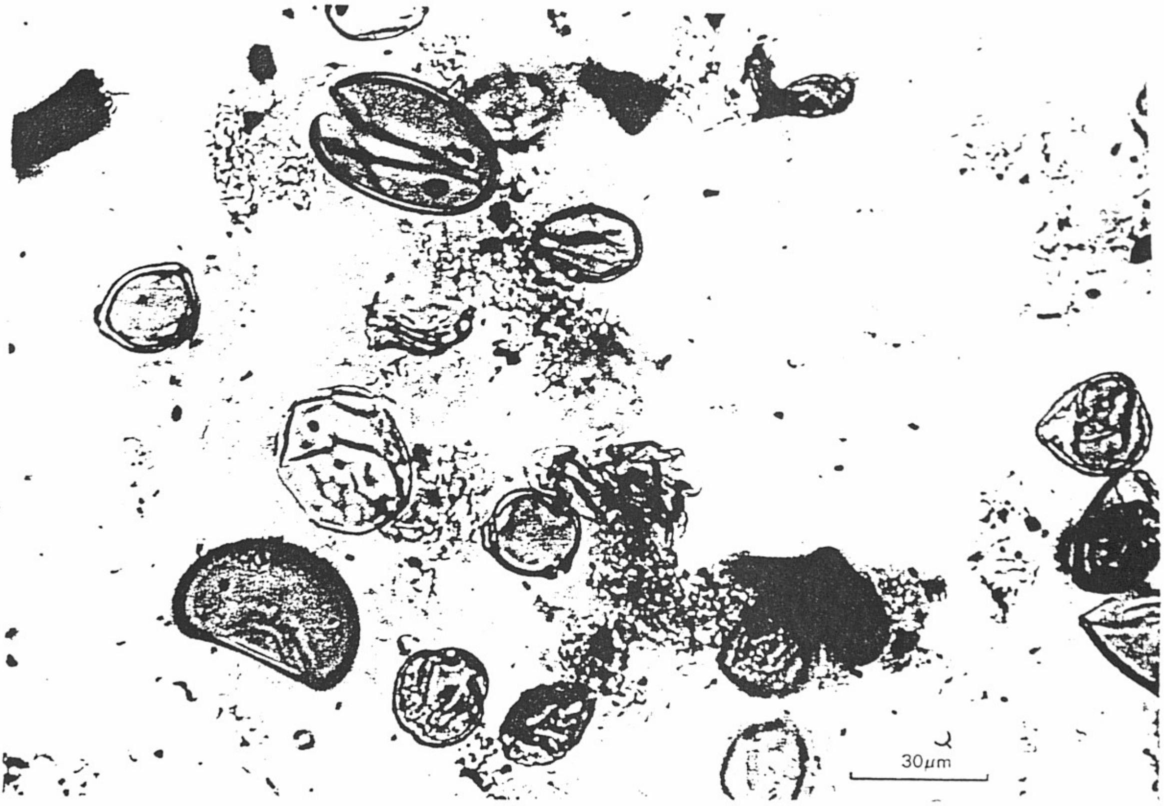


Figure 2.16 A clear field view of a typical pollen slide.

2.2.5. Lose-on-Ignition (LOI) Measurements

The organic content of the samples was estimated by making weight Loss-on-Ignition (LOI) measurements. In my study sites, the organic material is from lake primary productivity and hill slope detrital sediment supply. LOI measurements were made for every centimeter of the sediment cores from both ponds. A total of 523 samples from the Ritterbush Pond's site 2 core and a total of 578 samples of Sterling Pond's site 1 core were measured. See Appendix A for the LOI raw data sheet.

First, the dry crucible was weighed. Then the crucible with the wet sediment sample was put in the drying oven at 90 °C for 24 hours. After oven-drying, I randomly removed 10% of the crucibles and placed them in a desiccator. After the crucibles cooled, their weights were measured. Then I returned them to the drying oven and together with other samples dried them for one more hour. The same crucibles tested were taken out again, cooled and the weighed. When the last decimal place of the tested samples changed by only 1 or 2 units, the samples were considered totally dry. Then, all the samples were weighed, removed to a furnace and burned at 450 °C for 12 hours. Finally, a testing procedure was used for complete combustion as in the previous steps.

The raw data were recorded on a data sheet and typed into the computer spread sheet to calculate the percentage loss on ignition. The function for the LOI percentage as follows:

% LOI = (weight after burn-weight after dried)/(weight after dried - crucible weight)*100%

2.2.6. Radiocarbon Dating

Before radiocarbon dating was widely used, the chronologic sequences of sediment cores were obtained by either using pollen horizons as time indicators, which means comparing zones within pollen diagrams with and without radiocarbon ages. Also, prominent changes in pollen proportions may be correlated with particular events, such as the hemlock decline around 4,800 ^{14}C yr BP. However, because of the time-trangressive nature of vegetation transition, these approaches are not as reliable as direct radiocarbon dating of each pollen record.

Since the 1980's, extremely low concentrations of ^{14}C, such as samples that contain as little as 100 µg of carbon (Vogel et al., 1987), can be measured by mass spectrometry. Instead of measuring the quantity of ^{14}C in a sample indirectly by counting the emission of ß-particles, the concentration of individual ^{14}C ions are measured (Vogel et al., 1987). The size of the samples required for radiocarbon AMS dating are much smaller than in the traditional technique; for example, a small twig at 260 cm depth of the Sterling Pond core was dated. Five AMS radiocarbon ages were obtained on material from the Sterling Pond core, four from bulk sediment and one from a twig at the same level as a dated bulk sediment sample. Five AMS ^{14}C ages were obtained on bulk sediment samples from Ritterbush Pond core.

All of the radiocarbon samples were bulk gyttja, except for #17896, which was the small twig. All samples provided 1 mg or more of carbon, except for #17895, which was 0.33 mg, and #20197, which was only 0.19 mg of carbon. According to Dr. John Southon (pers. comm.), who works at Lawrence Livermore National Laboratory (LLNL) and prepared all my samples for radiocarbon dating, "all samples received a standard acid-base-acid treatment (1N HCl and NaOH, sonicated at 60 °C with repeated base treatments until the solutions remained clear). The samples were then combusted to CO_2 and measured as described by Nelson et al. (1986).

2.2.7. Pollen Slide Preparation and Counting

A binocular microscope with mechanical stage for recording the coordinates of any unknown pollen grains for later observation was used to identify and count pollen with 400X magnification. Some evidence suggests that the migration of pollen grains under the weight of the coverslip is inversely related to the size of the grain, therefore, it is necessary to avoid counting only in the center or only at the edge of the coverslip. The *Eucalyptus* maker pollen grains were counted along with the native pollen grains. The slides were counted by means of traverses passing from one edge to another to prevent overlap and insure randomness. The slides were always moved in one direction rather than reverse direction each time a new traverse was began. Standard counting sheets were used (see Appendix B).

Fifty-two samples from the Sterling Pond core and 51 samples from the Ritterbush Pond core were counted at 10-cm intervals. The total number of grains counted at each level varied, but usually at least 300 grains were counted, not including the *Eucalyptus* marker grains, for statistical reasons. Some levels from the basal parts of the sediment cores were so sparse in pollen that 300 counts were difficult to obtain.

CHAPTER 3

RESULTS AND DISCUSSION

My results are in general agreement with those of other studies in Vermont and elsewhere in New England. Sedimentation rate diagrams, loss-on-ignition (LOI), pollen percentage diagrams, and pollen influx diagrams are discussed and compared within the context of regional results. Tentative regional deglaciation models and reconstruction of postglacial paleoenvironments are also presented in this chapter.

3.1. Comparison of Results between Two Ponds

There are both similarities and differences between Sterling Pond and Ritterbush Pond in sediment accumulation rate, LOI, pollen percentage and the pollen influx.

3.1.1. Sediment Accumulation Rates

Five radiocarbon ages at selected depths were obtained for the sediment core from Sterling Pond. The depth vs. age graph and the function of the best fitting curve are shown in Figure 3.1. Four radiocarbon ages were obtained for the sediment core from Ritterbush Pond. Figure 3.2 is the depth vs. age graph and the function of the best fitting curve of Ritterbush Pond. Table 3.1 is the raw radiocarbon data measured by Dr. John Southon at Lawrence Livermore National Laboratory (LLNL).

Sedimentation accumulation rate is the net thickness of sediment accumulated per unit of time (Davis, 1968). The best fitting polynomial curve relates radiocarbon age and

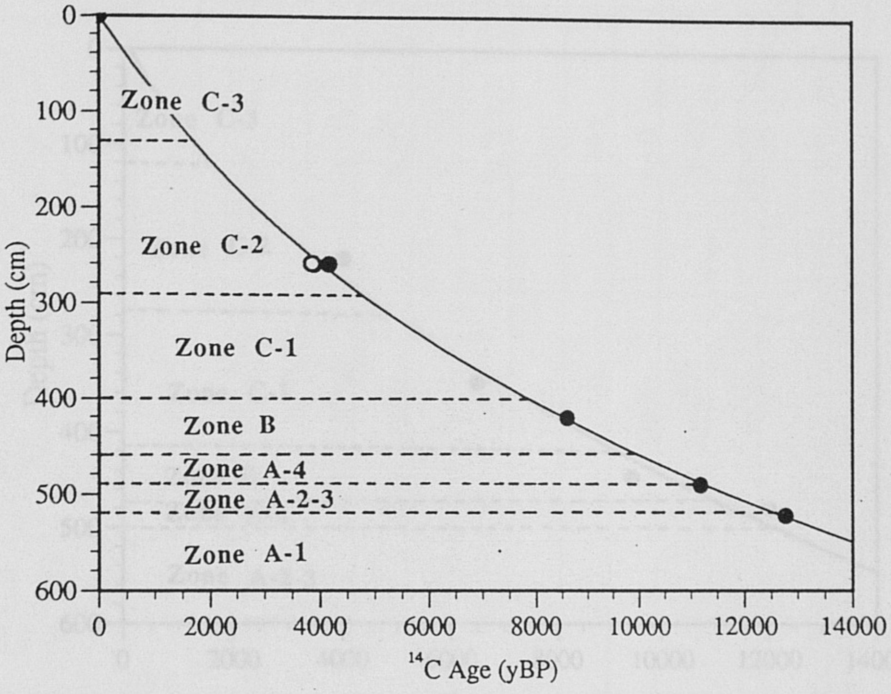


Figure 3.1. Depth vs. ^{14}C Age for Sterling Pond, Vermont. Solid circles represent the levels of dated gyttja, open circle represents the level of the dated twig.

$f(x) = 1.56 * 10^{-10} * x^3 - 5.28 * 10^{-6} * x^2 + 8.29 * 10^{-2} * x + 0.42$
(x represents the ^{14}C age, while f(x) represents the depth of the core.)

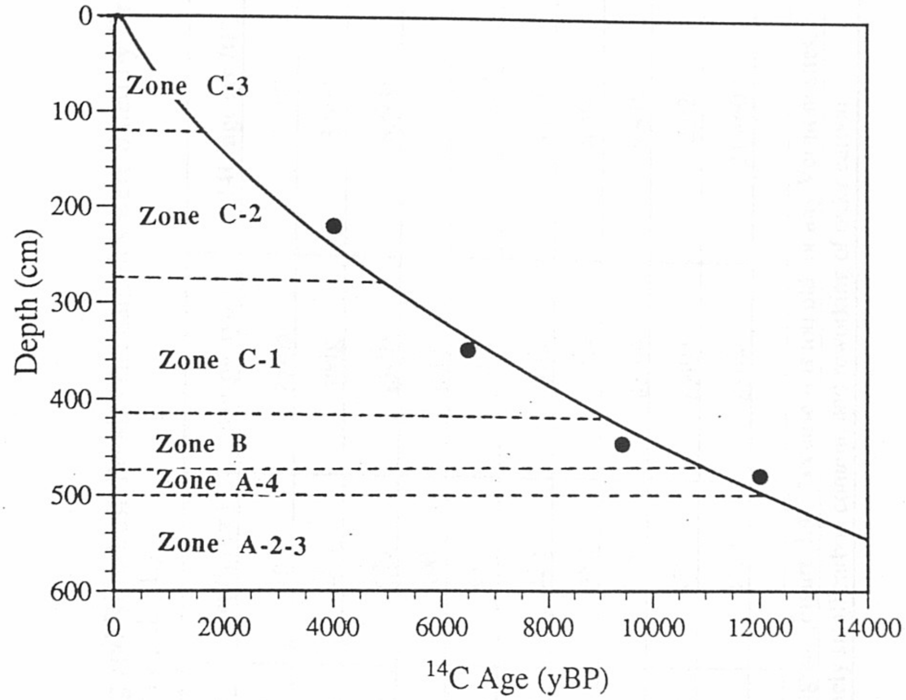


Figure 3.2. Depth vs. ^{14}C Age diagram for Ritterbush Pond, Vermont. Dots represent the levels of dated samples.

f(x) = $-1.90 * 10^{-6} * x^{2} + 6.55 * 10^{-2} * x - 2.88$
(x represnts the ^{14}C age, while f(x) represent the depth of the core.)

Table 3.1. Radiocarbon ages for Sterling and Ritterbush Ponds. The samples were dated by Dr. John Southon, at Lawrence Livermore National Laboratory (LLNL).

sample location	lab #	core	depth (cm)	sample type	14C age (yr BP)	uncertainty range (yr)
Sterling Pond	17893	ST-1	260	gyttja	4,180	50
Sterling Pond	17896	ST-1	260	twig	3,900	60
Sterling Pond	18923	ST-1	420	gyttja	8,600	60
Sterling Pond	17894	ST-1	490	gyttja	11,180	60
Sterling Pond	17895	ST-1	522	gyttja	12,760	70
Ritterbush Pond	22993	RT-2	220	gyttja	4,010	60
Ritterbush Pond	20195	RT-2	348.5	gyttja	6,490	70
Ritterbush Pond	20196	RT-2	445	gyttja	9,410	60
Ritterbush Pond	20902	RT-2	479	gyttja	12,020	90
Ritterbush Pond	20197	RT-2	519	gyttja	21,860 *	370

* This date is not used in the depth vs. age diagram (Figure 3.4.), because it is too old for any Vermont sites.

The old date can be explained by the extremely small carbon content, and reworking of older carbon.

sediment core depth. Using the function of the best fitting curve, the radiocarbon years for each centimeter of sample accumulation can be calculated, thus the sediment accumulation rate can be inferred from the slope of the best fitting curve. Figures 3.3 and 3.4 show the sediment accumulation rates for the Sterling and Ritterbush Pond sediment cores, respectively. Due to the overburden weight of deposited sediment and the increasing sediment influx over time, a greater number of years were required to deposit one centimeter of sediment toward the bottom of the cores, thus the sediment accumulation curve are concave rather than straight lines.

Ritterbush Pond exhibits a higher average sediment accumulation rate than does Sterling Pond. For example, at 3,000 ^{14}C yr BP, the sediment accumulation rate in Sterling Pond is 0.053 cm yr^{-1} vs. 0.065 cm yr^{-1} in Ritterbush Pond; at 7,000 ^{14}C yr BP, the sediment accumulation rate in Sterling Pond is 0.032 cm yr^{-1} vs. 0.050 cm yr^{-1} in Ritterbush Pond; and at 11,000 ^{14}C yr BP, the sediment accumulation rate in Sterling Pond is 0.023 cm yr^{-1} vs. 0.042 cm yr^{-1} in Ritterbush Pond.

3.1.2. Loss-on-Ignition (LOI) Results

Figure 3.5 shows the LOI results for Sterling Pond samples, and Figure 3.6 shows the LOI results of Ritterbush Pond provided by Chris Killian and Dr. P. Thompson (Bentley College, in Waltham, Massachusetts). Samples from both ponds were analyzed every centimeter. The solid lines on both graphs are the running averages seven data points, which smooth irregularities on the records.

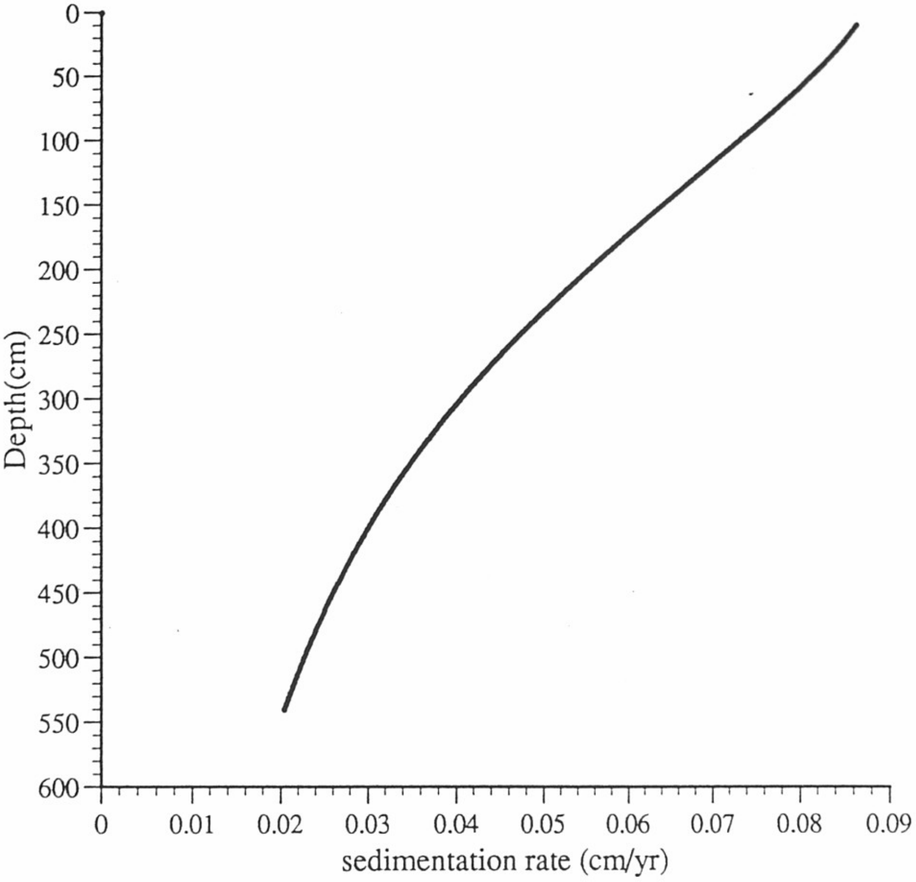


Figure 3.3.`Sediment accumulation curve for Sterling Pond, Vermont, based on five radiocarbon ages.

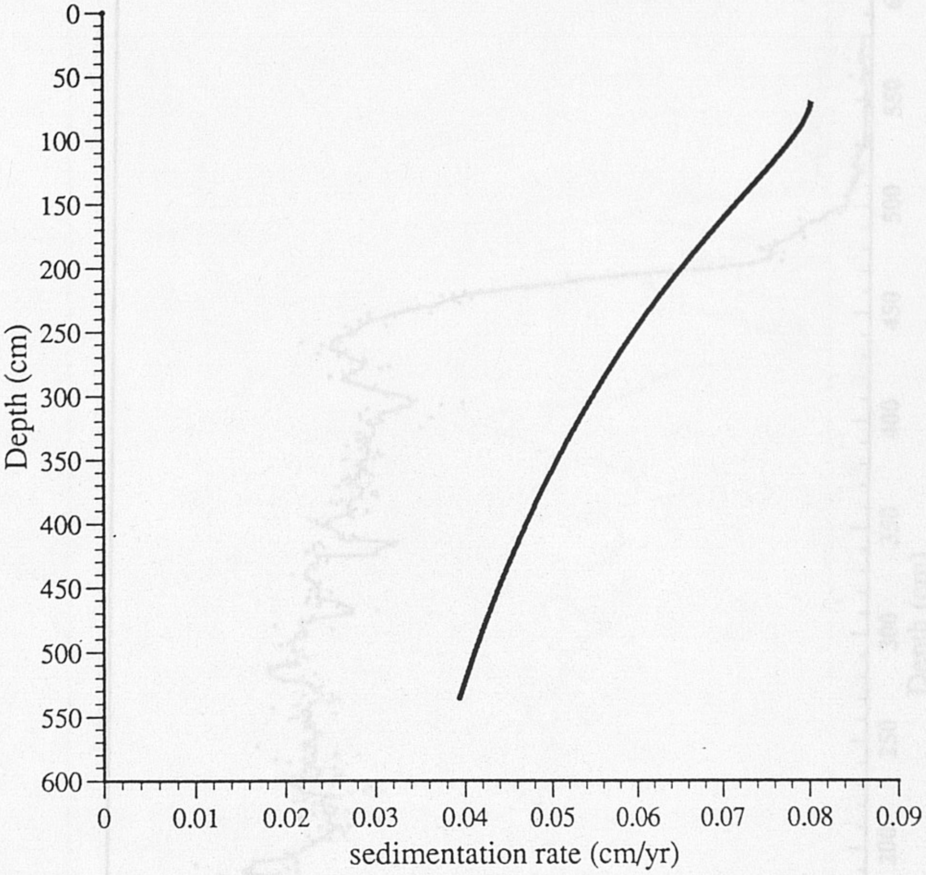


Figure 3.4. Sèdimentaccumulation curve for Ritterbush Pond, Vermont, based on four radiocarbon ages.

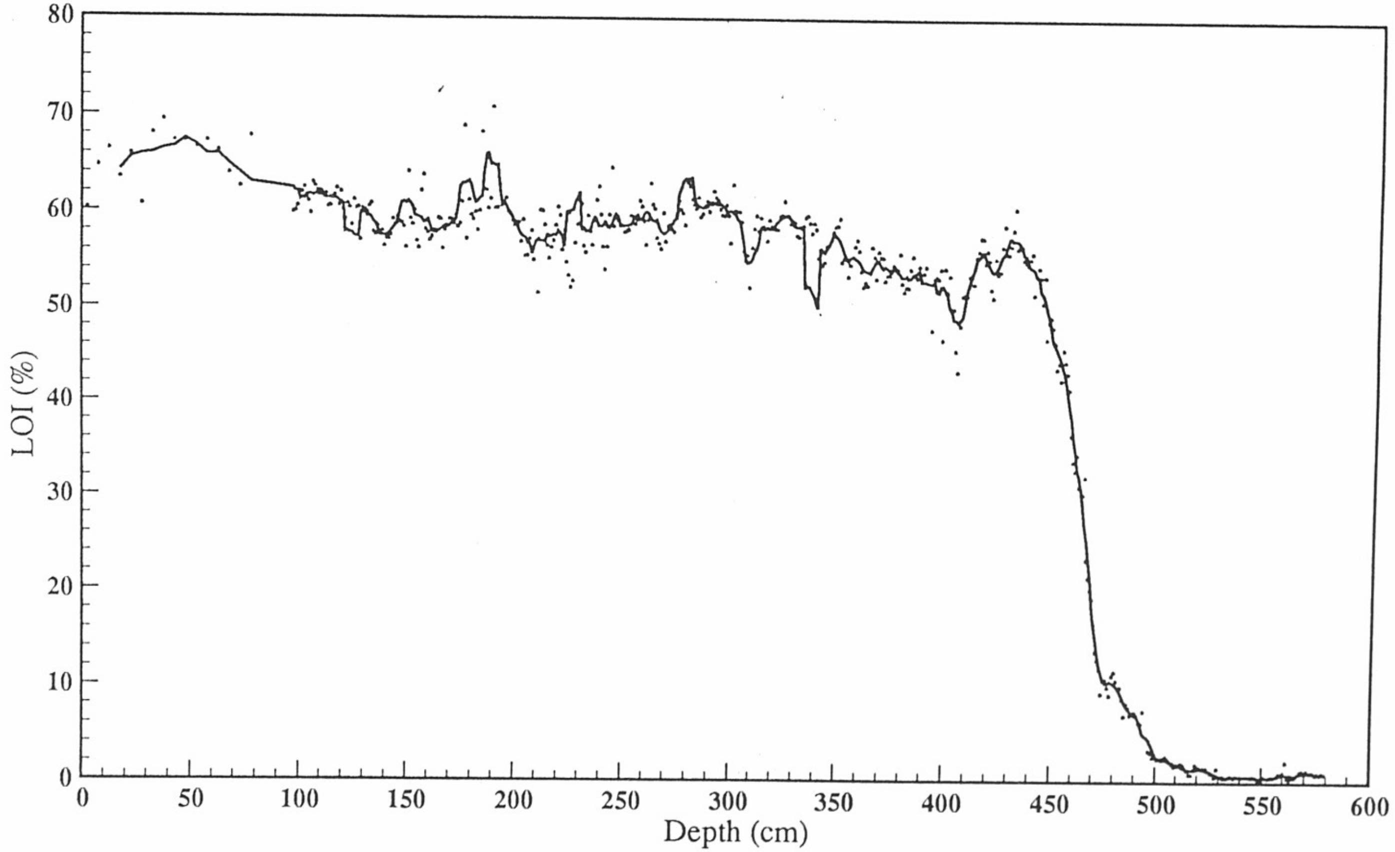


Figure 3.5. Loss-on-igition results from Sterling Pond core, Vermont. The dots represent the percentage lose-on-ignition. The solid line is a 7-point running average.

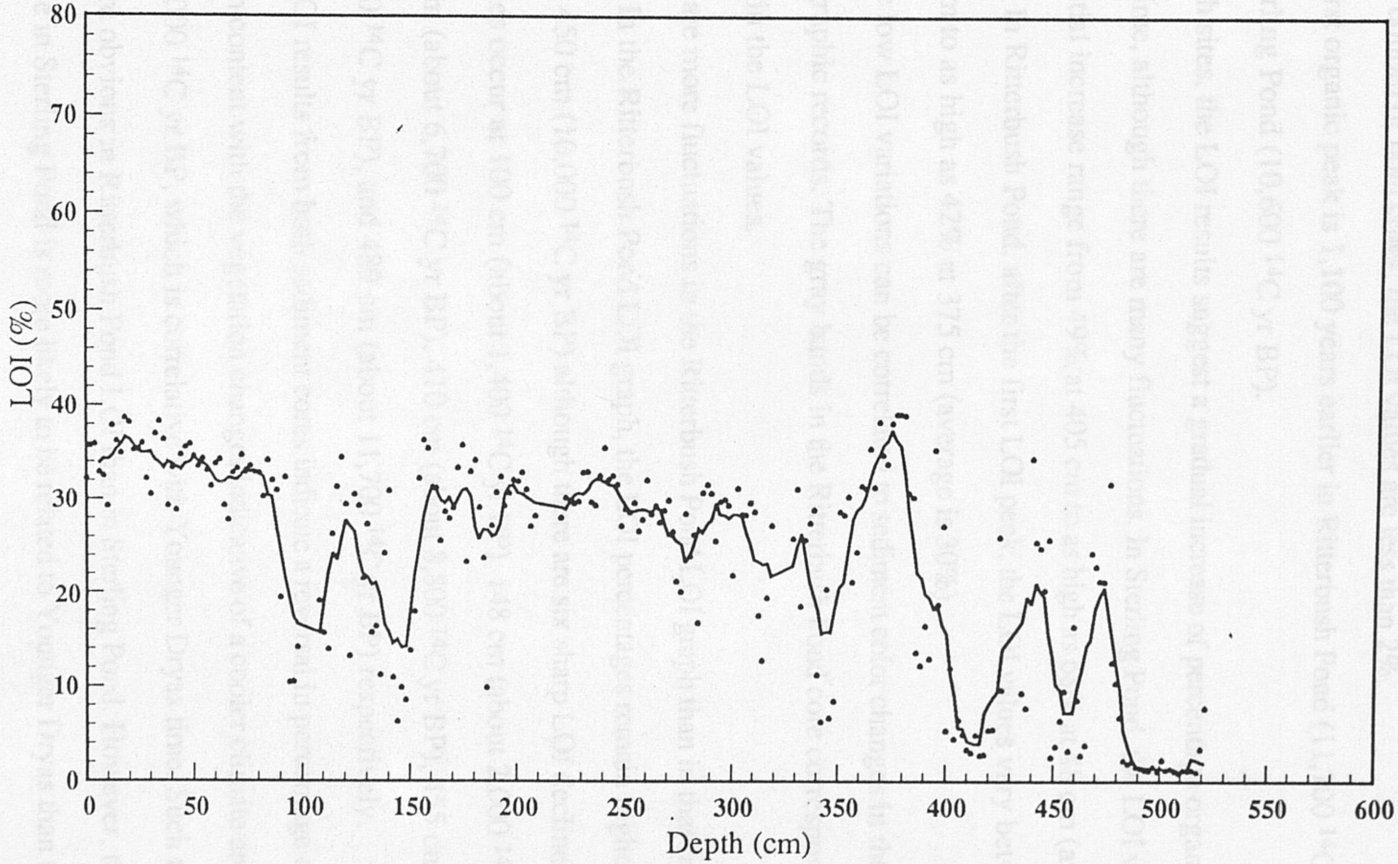


Figure 3.6. Loss-on-ignition results from Ritterbush Pond core, Vermont. The dots represent the percentage lose-on-ignition for each sample. The solid line is a 7-point running average.

There are some similarities and differences between the LOI results of the two ponds.

1. At the bottom of both cores, the LOI values are less than 2%.
2. The first organic peak is 1,100 years earlier in Ritterbush Pond (11,700 ^{14}C yr BP) than in Sterling Pond (10,600 ^{14}C yr BP).
3. At both sites, the LOI results suggest a gradual increase of percentage organic carbon over time, although there are many fluctuations. In Sterling Pond, the LOI values after the initial increase range from 49% at 405 cm to as high as 68% at 48 cm (average is 57%). In Ritterbush Pond, after the first LOI peak, the LOI values vary between 4% at 415 cm to as high as 42% at 375 cm (average is 30%).
4. All the low LOI variations can be correlated to sediment color changes in the stratigraphic records. The gray bands in the Ritterbush Pond core correspond with sharp drops in the LOI values.
5. There are more fluctuations in the Ritterbush Pond LOI graph than in that from Sterling Pond. In the Ritterbush Pond LOI graph, the LOI percentages remain higher than 45% above 450 cm (10,000 ^{14}C yr BP) although there are six sharp LOI declines. These declines occur at 100 cm (about 1,400 ^{14}C yr BP), 148 cm (about 2,000 ^{14}C yr BP), 342 cm (about 6,700 ^{14}C yr BP), 410 cm (about 8,800 ^{14}C yr BP), 455 cm (about 10,400 ^{14}C yr BP), and 489 cm (about 11,700 ^{14}C yr BP) respectively.
6. The LOI results from both sediment cores indicate a reversal in percentage organic carbon content with the vegetation changes indicative of a cooler climate around 11,000 to 10,000 ^{14}C yr BP, which is correlative with Younger Dryas time. Such a drop in LOI is more obvious in Ritterbush Pond LOI than in Sterling Pond. However, the LOI decline in Sterling Pond is more likely to be related to Younger Dryas than the LOI trend in Ritterbush Pond, because the LOI decline is Ritterbush Pond is too sharp and there

are five similar declines later in the core that may all be caused by sediment resuspension or flood events.

3.1.3. Pollen Data

Table 3.2 is the raw pollen counting data for the Sterling Pond sediment core. Table 3.3 is the raw pollen counting data for the Ritterbush Pond sediment core.

3.1.3.1. Percentage pollen diagrams

In this study, pollen percentage is defined as the percentage of any given pollen type among the total tree pollen counted in a sample, known as the pollen sum. Pollen percentages are plotted against depth in the percentage pollen diagrams. Figures 3.7 and 3.8 are percentage pollen diagrams for the Sterling and Ritterbush Pond sediment cores, respectively. The Y-axis scales represent depth below the sediment water interface, whereas the X-axis scales represent the percentage values for various pollen spectra, which include 15 tree species; tundra, herbaceous, and exotic pollen types are not included in the pollen sum. There is no enlargement to the X-axis for the rare pollen types, such as butternut, hickory, and walnut, as keeping all X axes in the same scale facilitates comparison among species. Unknown and unidentifiable pollen types were summarized in the unknown column of the percentage diagrams for one of the following reasons: 1) deterioration was so great the grains were recognized as spores or pollen grains only; 2) preservation was good, but the pollen grain was folded or obscured by debris; or 3) preservation was good, but the pollen type was unfamiliar.

Table 3.2. Raw pollen count data for Sterling Pond.

depth (cm)	fir	spruce	pine	birch	maple	oak	beech	alder	ash	hick.	hemlock	elm	walnut	butternut	willow	unk.	total	ragweed	grass	marker
0	30	25	49	198	29	17	15	7	15	1	10	9	2	1	0	5	413	43	8	153
12.5	42	65	62	123	6	7	25	3	16	1	10	8	0	1	0	7	376	14	8	216
22.5	22	57	75	125	9	20	22	3	8	1	36	4	1	0	0	4	387	0	1	132
32.5	12	33	28	84	4	17	19	2	7	0	17	1	1	0	0	2	227	2	3	39
42.5	16	51	40	185	11	20	46	9	15	0	23	7	0	0	1	5	429	0	2	65
52.5	30	28	29	159	9	8	41	1	10	0	29	7	0	0	0	3	354	1	4	51
62.5	13	77	48	191	12	38	70	3	21	2	55	14	0	1	0	4	549	0	2	78
72.5	18	12	41	160	14	13	45	2	11	1	32	4	0	0	0	2	355	0	1	57
100	20	32	38	184	25	24	35	5	17	3	35	10	0	0	0	7	435	0	0	174
110	12	19	26	150	14	10	36	3	8	0	45	4	0	0	0	2	329	0	3	119
120	13	13	38	174	14	20	54	2	17	3	30	8	0	1	1	15	403	1	4	120
130	13	3	19	78	7	11	45	9	8	0	35	10	0	0	0	5	243	0	1	60
140	44	8	34	182	18	23	52	4	13	0	41	12	2	1	0	6	440	1	0	81
150	15	2	39	114	9	12	40	4	7	0	24	2	0	0	0	6	274	0	3	35
160	10	3	39	220	21	27	52	7	9	6	37	4	1	0	1	8	445	1	2	63
170	21	5	29	111	14	7	29	5	6	0	35	6	0	0	0	10	278	0	0	69
180	19	6	26	167	19	24	72	6	21	0	23	9	0	0	0	4	396	0	6	78
190	17	3	27	95	10	11	38	1	11	1	20	4	0	0	2	3	243	0	13	56
200	19	3	44	185	25	15	66	5	11	1	14	12	3	0	1	3	407	1	9	83
210	13	1	37	110	14	17	29	3	5	1	17	2	0	0	0	1	250	0	4	66
220	24	28	51	157	16	23	40	3	15	3	9	3	1	1	0	3	377	1	13	68
230	10	3	57	104	15	14	39	6	13	2	17	6	0	0	0	6	292	0	4	30
240	15	16	56	158	22	25	57	8	20	3	7	14	5	0	1	6	413	0	34	80
250	8	2	47	124	15	16	38	3	6	1	9	4	0	0	0	4	277	0	17	67
260	15	18	35	175	25	21	59	4	12	2	4	6	1	1	1	10	389	0	10	49
270	15	2	49	116	26	15	25	3	23	0	3	8	0	2	0	11	298	0	15	58
280	6	3	10	221	25	24	54	3	10	0	5	6	3	1	0	3	374	1	17	55
290	10	0	42	118	7	8	37	6	22	1	47	9	0	1	0	12	320	3	24	47
300	0	14	28	116	18	11	33	4	14	4	40	12	3	2	1	5	305	2	12	36
310	10	1	33	130	10	11	34	1	7	1	26	9	0	0	0	5	278	1	13	29
320	5	5	32	147	29	15	51	4	7	1	66	12	0	0	0	3	377	1	25	110
330	11	3	43	140	12	12	24	0	12	1	49	10	0	0	0	7	324	2	15	54
340	7	18	48	188	12	29	38	14	1	2	50	8	2	1	0	5	423	2	49	52
350	10	2	66	139	17	21	11	4	13	0	35	6	0	0	0	5	329	0	53	45
360	1	4	55	138	10	28	10	2	4	2	28	1	0	0	0	4	287	2	282	62
370	12	1	54	120	4	26	7	5	8	0	27	5	1	0	0	7	277	0	125	26
380	8	18	90	113	23	47	16	5	14	2	22	7	1	2	0	2	370	1	134	60
388	8	2	18	88	5	41	0	2	10	1	12	2	0	0	0	7	196	0	73	40
400	19	24	112	96	29	46	8	6	1	1	14	4	3	0	0	2	365	0	163	39
420	10	33	92	117	23	42	16	9	3	0	2	6	0	0	0	10	363	0	176	44
430	28	0	108	112	5	14	0	5	9	0	1	4	0	0	0	0	286	1	98	35
440	18	13	106	185	8	19	8	20	16	1	1	7	1	0	0	2	405	0	213	54
450	36	2	92	110	1	28	0	18	6	0	4	6	0	0	0	2	305	0	75	36
460	37	14	26	124	0	5	1	123	3	0	2	1	1	1	0	4	342	1	131	50
470	21	34	68	47	2	11	0	72	3	0	0	1	0	0	0	3	262	1	39	88
480	6	133	82	80	17	4	5	24	0	0	0	2	0	1	0	7	361	3	139	341
490	22	220	103	26	15	5	4	5	0	0	0	5	1	0	3	8	417	2	58	248
502-503	15	25	99	12	19	15	0	3	5	0	0	0	0	1	0	2	196	10	3	483
510-511	0	17	27	5	4	2	0	0	0	0	0	0	1	0	0	2	58	1	0	167
523-524	7	55	85	2	8	0	1	3	2	1	1	1	0	0	0	7	173	3	3	630
534-535	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	3	4	0	0	425

Table 3.3. Raw pollen count data for Ritterbush Pond.

depth (cm)	fir	spruce	pine	birch	maple	oak	beech	alder	ash	hick.	hemlock	elm	walnut	butternut	willow	unk.	total	ragweed	grass	marker
5	5	25	57	231	13	29	51	5	12	0	51	9	1	1	0	6	496	1	100	109
15	11	16	42	175	12	9	33	4	13	61	6	61	0	0	0	9	452	0	95	88
25	2	10	30	191	22	18	41	5	10	0	77	3	0	1	0	5	415	1	13	106
35	3	5	25	161	29	13	52	5	8	1	47	9	0	0	0	6	364	0	29	144
45	5	4	20	177	14	7	47	1	11	0	71	6	0	0	0	2	365	0	3	149
55	4	7	37	173	13	12	57	1	2	3	42	7	1	0	0	8	367	1	31	161
65	3	1	24	169	8	13	49	6	15	0	52	7	0	0	0	3	350	0	10	97
75	1	1	30	143	28	11	79	11	10	2	52	5	0	0	0	6	379	1	38	131
85	0	1	30	142	15	21	59	10	4	5	63	11	0	0	1	4	366	1	25	297
95	1	1	7	102	5	4	17	4	7	0	17	3	0	1	0	1	170	0	23	225
114	0	2	28	170	18	30	47	6	15	4	36	11	0	0	0	0	367	0	42	143
124	0	2	23	161	13	8	50	0	9	1	59	3	0	0	0	1	330	0	27	75
134	1	4	22	166	15	18	43	7	10	1	51	5	0	0	0	2	345	1	66	125
144	0	2	31	181	18	5	52	5	9	3	57	7	0	0	0	10	380	0	82	234
154	0	1	16	109	3	8	30	2	10	5	29	6	0	0	0	7	226	2	20	469
164	1	8	18	231	12	18	53	1	12	1	37	14	0	0	0	5	411	0	35	77
174	0	3	15	207	26	22	67	2	11	0	30	14	1	0	0	3	401	2	16	109
184	2	0	26	151	29	14	47	6	11	0	32	8	0	0	0	9	335	1	66	113
194	0	3	35	165	20	22	56	8	1	2	30	9	0	0	0	3	354	0	20	85
204	2	3	38	216	21	7	35	3	11	1	11	3	1	1	0	5	358	1	25	151
214	0	3	33	161	23	13	60	4	14	4	25	8	0	0	0	9	357	0	41	140
225	1	0	30	201	19	21	59	6	9	4	12	1	0	0	0	6	369	0	90	117
235	0	2	38	165	20	8	49	5	15	4	6	5	0	0	0	9	326	0	50	103
245	0	1	19	240	23	9	60	3	9	3	2	6	0	0	1	6	382	0	43	78
255	5	0	33	190	9	8	66	3	11	1	7	8	0	0	0	5	346	0	36	135
265	0	0	15	231	11	14	40	3	5	0	11	16	0	0	1	3	350	0	43	129
275	0	0	25	169	15	14	38	6	8	0	69	10	0	0	0	7	361	2	23	111
285	1	0	12	177	10	10	39	8	10	0	101	7	0	0	1	3	379	1	69	94
295	0	0	20	118	12	8	47	1	4	1	116	7	0	0	0	7	341	0	58	98
305	0	3	36	261	13	12	43	10	7	2	64	8	0	1	0	3	463	0	69	97
315	0	2	19	163	8	22	26	1	10	0	113	6	0	0	0	4	374	0	75	88
320	0	2	24	128	11	9	20	1	8	1	105	5	0	0	0	6	320	0	101	62
330	0	8	30	189	12	8	20	2	8	0	55	12	0	0	0	4	348	0	89	80
335	0	2	35	245	12	14	27	3	13	3	47	10	1	0	0	5	417	0	176	131
345	0	0	12	48	0	1	1	0	3	0	40	5	1	0	0	1	112	0	23	178
355	1	3	32	193	7	12	14	3	15	1	100	8	2	0	0	2	393	1	156	57
365	0	2	46	199	13	17	4	1	9	0	64	5	0	0	0	3	363	0	190	47
375	0	0	39	244	8	41	1	4	10	0	56	14	0	0	2	2	421	1	193	55
395	7	0	135	53	16	67	0	2	27	0	25	13	0	0	0	0	345	0	547	71
405	3	4	172	28	9	57	0	1	4	2	14	11	0	0	0	1	306	0	1023	124
415	6	9	66	4	2	8	0	0	1	0	5	4	0	0	0	3	108	0	25	475
425	4	1	182	50	10	73	0	2	15	0	1	14	0	0	0	13	365	1	1245	87
440	7	5	59	16	5	9	0	1	0	0	0	0	0	0	0	1	103	0	41	141
445	10	6	128	125	10	38	0	1	14	0	2	13	0	0	0	6	353	0	1864	43
455	16	6	69	66	3	3	0	2	3	3	0	0	1	0	0	2	174	0	268	320
464	35	7	68	150	4	27	0	26	8	0	4	5	1	0	0	6	341	0	1531	95
475	39	6	25	47	2	10	0	62	5	5	0	4	0	0	0	2	207	0	2819	59
485	38	65	33	7	0	0	0	2	0	0	0	0	0	0	0	1	146	0	3012	118
495	1	5	24	0	0	0	0	0	2	0	0	0	0	0	0	10	42	1	344	403
505	1	13	6	0	0	1	0	0	0	0	0	0	0	0	0	5	26	2	194	212
515	2	10	19	2	1	7	0	0	2	0	0	0	0	0	0	7	50	1	260	634

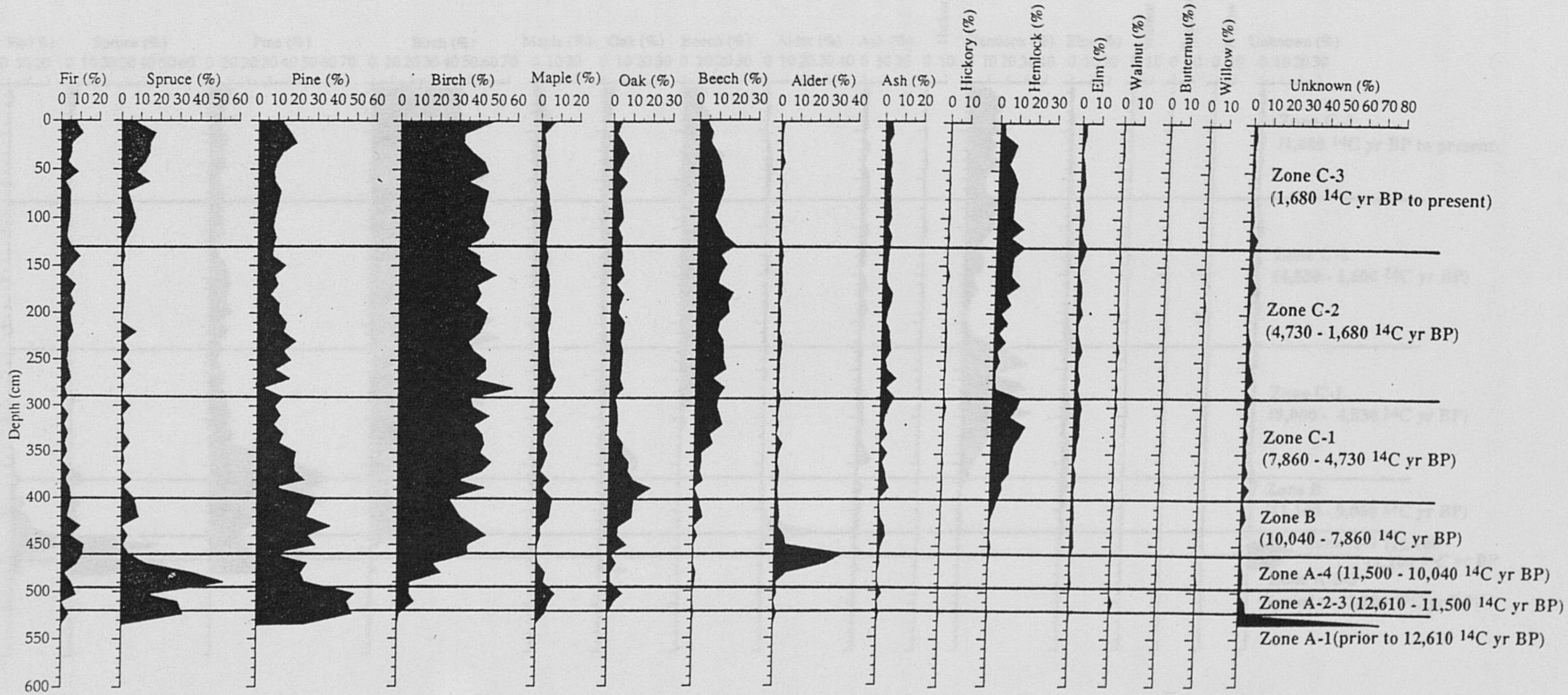


Figure 3.7. Pollen percentage diagram of Sterling Pond.

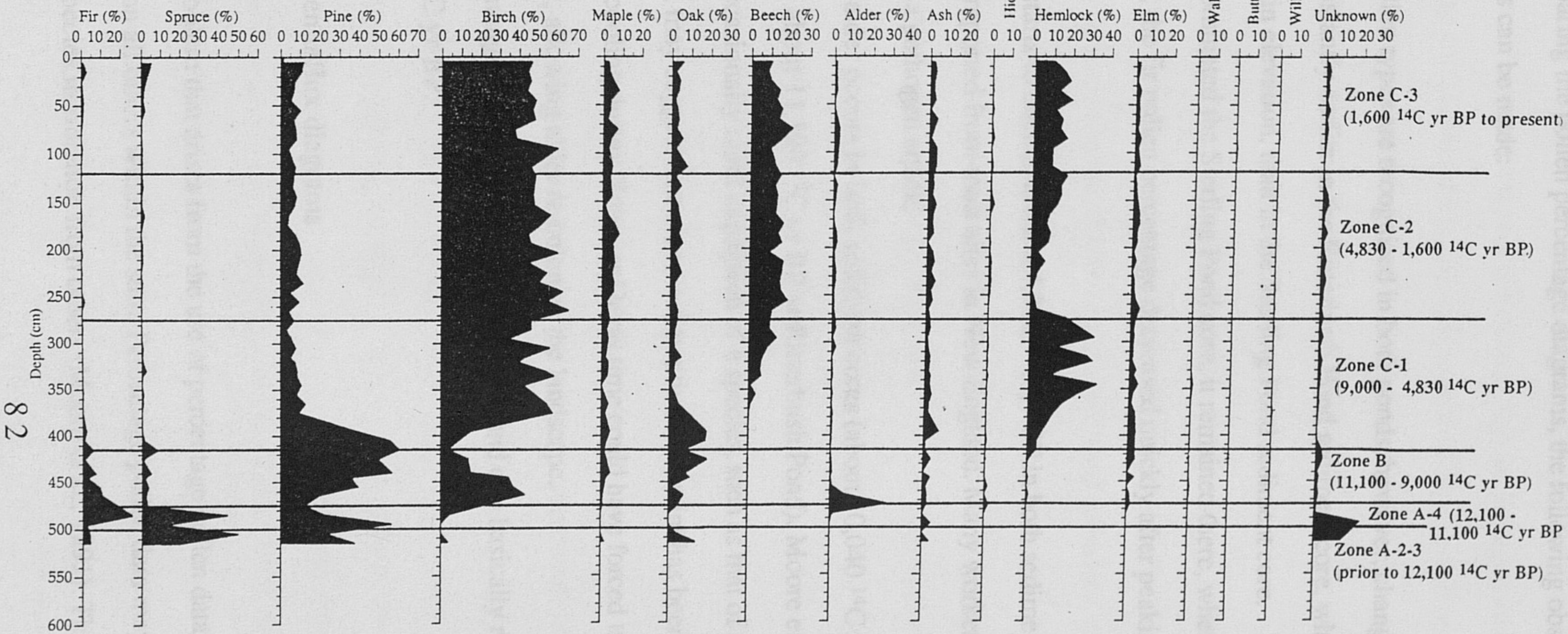


Figure 3.8. Pollen percentage diagram of Ritterbush Pond.

Comparing the pollen percentage diagrams, the following observations and interpretations can be made:

1. Similar pollen types are recognized in both ponds; however, changes in pollen types appear constantly earlier in the Ritterbush Pond sediment core, which is farther north and lower in elevation, than in the Sterling Pond sediment core.
2. Once fir dominated the Sterling Pond core, it remained there, whereas in Ritterbush Pond core, the fir pollen percentage decreased quickly after peaking around 11,500 ^{14}C yr BP.
3. Hemlock starts to decline around 4,800 ^{14}C yr BP in both sediment cores. The hemlock decline is reported from most sites in New England. Many workers believe that it was caused by a pathogen attack.
4. A peak of alder occurs in both sediment cores (about 10,040 ^{14}C yr BP at Sterling Pond, and about 11,190 ^{14}C yr BP at Ritterbush Pond). Moore et al. (1991) suggested that the occasionally rapid expansion of a species, such as that of alder in the early-Holocene, may suggest that some competitive constraint has been withdrawn. For example, cooling during Younger Dryas time could have forced tree species to lower elevations, allowing alder re-colonize the landscape.
5. The percentage values of maple, ash, hickory, and elm basically remain constant after 9,000 ^{14}C yr BP.

3.1.3.2. Pollen influx diagrams

A problem that arises from the use of percentage pollen data is the influence of each pollen type on all others within the sum. Percentage pollen data may obscure any study of individual species in isolation from others (Moore et al., 1991). Thus, it is not possible to assure that only one component of the pollen assemblage is varying. The problem becomes especially severe if certain local pollen taxa with high pollen input into the assemblage experience large fluctuations during the course of time represented by a pollen diagram. However, since most studies in New England have presented percentage pollen diagrams, comparison with other studies is usually made using the percentage pollen diagrams.

In this study, the pollen influx diagram is the number of pollen grains per square centimeter per year graphed against the depth of the sediment. Pollen influx diagrams provide a way of tracing species history individually and reveal the coincidence of one species' sharp decline with the invasion of another (Moore et al., 1991). The application of numerical techniques of pollen analysis has permitted paleoecologists to consider pollen spectra in terms of plant population dynamics rather than climate alone (follow Moore, et al. 1991). Figure 3.9 illustrates the changes in pollen influx for Sterling Pond, based on the sediment accumulation rate plotted in Figure 3.3 mentioned above. Figure 3.10 is the pollen influx diagram of Ritterbush Pond, based on the sediment accumulation rates plotted in Figure 3.4.

Pollen influx is far more valuable than pollen percentage as a record of changes from tundra to woodland or parkland (Davis, 1969). The sharp increase of tree pollen from the tundra stage to the woodland period around 10,000 ^{14}C yr BP is largely masked in the percentage diagram by the high frequency of tree pollen types in the pollen percentage diagram for Ritterbush Pond. Between 400 cm to 500 cm depth, there are some large fluctuations of pine and birch. When pine peaks at 425 cm, birch drops to less than 5%, whereas when birch peaks at 465 cm, pine drops to about 10%. Such apparent changes might not really reflect what happened to vegetation in the surrounding basin. Pollen influx in such cases better indicates the change in individual vegetation. For example, there are

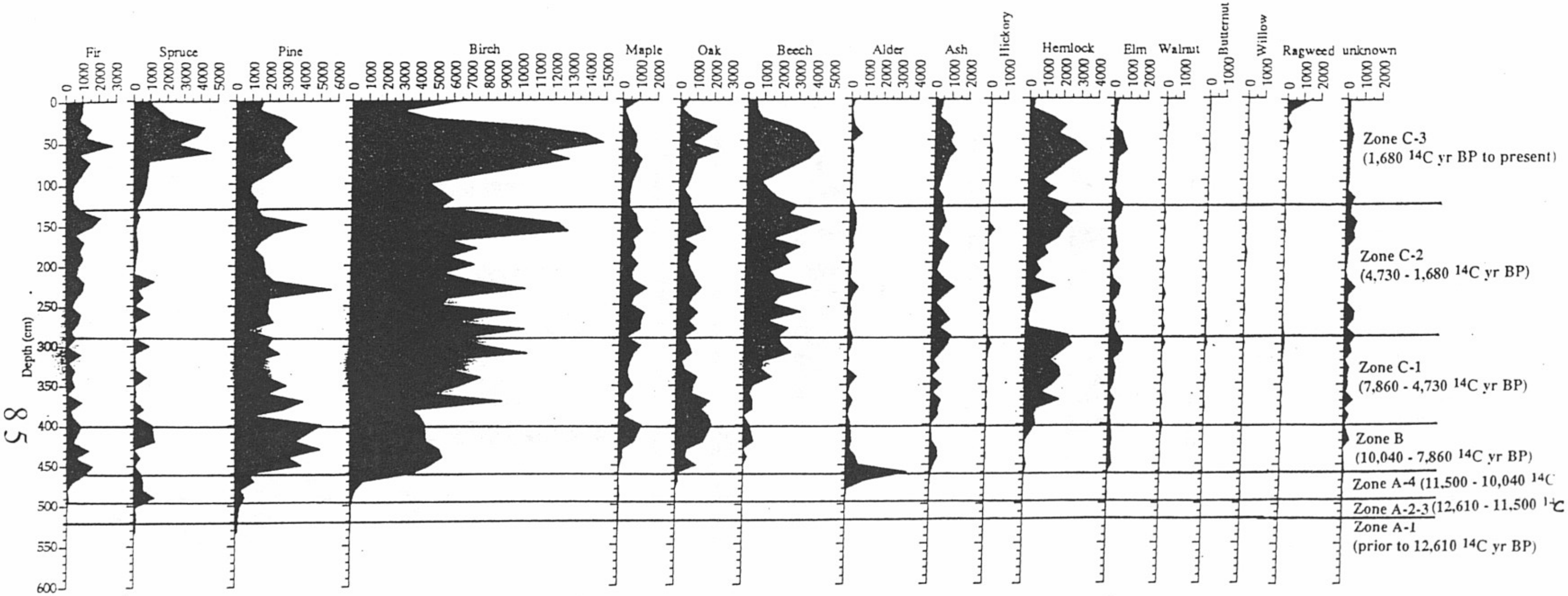


Figure 3.9. Pollen influx diagram of Sterling Pond.

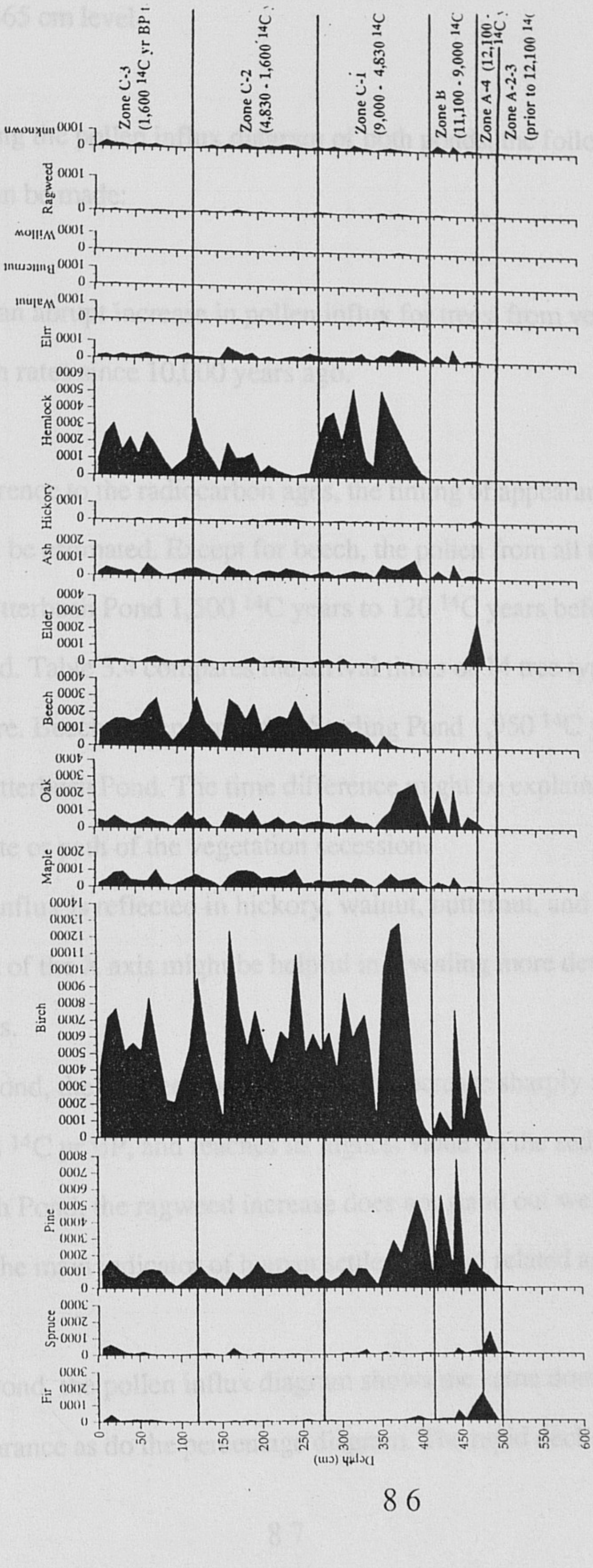


Figure 3.10 Pollen influx diagram of Ritterbush Pond.

relatively fewer birch pollen than pine pollen deposited at the 425 cm level, and more birch than pine at the 465 cm level.

Comparing the pollen influx diagram of both ponds, the following observations and interpretations can be made:

There is an abrupt increase in pollen influx for trees, from very low levels 12,000 years ago to high rates since 10,000 years ago.

1. With the reference to the radiocarbon ages, the timing of appearance of each species at each site can be estimated. Except for beech, the pollen from all the other tree species arrived at Ritterbush Pond 1,500 ^{14}C years to 120 ^{14}C years before they reached Sterling Pond. Table 3.4 compares the arrival times of 14 tree type identified in both sediment core. Beech pollen arrived at Sterling Pond 1,950 ^{14}C years earlier than it arrived at Ritterbush Pond. The time difference might be explained by variation in migration rate or path of the vegetation secession.
2. Low pollen influx is reflected in hickory, walnut, butternut, and willow. The enlargement of the X axis might be helpful in revealing more detail of migration of these species.
3. In Sterling Pond, the ragweed pollen begins to increase sharply at 23 cm depth, which is about 268 ^{14}C yr BP, and reaches its highest value on the sediment surface; whereas at Ritterbush Pond, the ragweed increase does not stand out well. In North America, ragweed is the main indicator of human settlement and related agriculture (Davis, 1968).
4. In Sterling Pond, the pollen influx diagram shows the same dominance of fir after its initial appearance as do the percentage diagram. The rapid decline of fir pollen influx in

Table 3.4. Comparison of the times of the first appearance of the most abundant genera between Ritterbush Pond and Sterling Pond.

Species	Arrival at Sterling Pond (14C yr BP)	Arrival at Ritterbush Pond (14C yr BP)	Time difference between the two ponds(yr)
fir	10,850	11,960	1,100
spruce	11,840	11,960	110
pine	10,040	10,800	800
birch	10,440	10,800	400
maple	9,650	10,440	800
oak	10,040	11,570	1,530
beech	9,650	7,700	1,950
alder	10,850	11,060	210
ash	10,040	11,370	1,350
hemlock	8,550	9,000	500
elm	10,040	11,570	1,530

the Ritterbush Pond core might be explained as an elevation factor with fir leaving lowland sites as the climate warmed.

5. The increase of spruce within the past 1,000 ^{14}C yr BP is 10% higher in Sterling Pond than in Ritterbush Pond on pollen percentage diagrams.
6. Although the initial influx of pine is higher at Ritterbush Pond than that at Sterling Pond, pine decreases rapidly at Ritterbush Pond, whereas influx of pine remains high at Sterling Pond throughout the core.
7. The influx of birch is about the same at both ponds, except at about 590 ^{14}C yr BP, there is a sharp increase in birch pollen influx in Sterling Pond, but a relatively small decrease in Ritterbush Pond.
8. The influx of maple is about the same at both sites, although Sterling Pond has a higher maple influx than that at Ritterbush Pond.
9. The "early oak peak" (Davis, 1968) is observed in Sterling Pond and Ritterbush Pond, but oak pollen remains relatively more abundant in Sterling Pond than in Ritterbush Pond sediments. In the upper part of the Sterling Pond core, there is an increase in oak pollen influx, whereas the oak pollen influx is constant in the Ritterbush Pond core.
10. There are more peaks in beech pollen influx in Sterling Pond than in Ritterbush Pond. At around 1,270 ^{14}C yr BP, a sharp decline in beech pollen influx is noted in both diagrams.
11. The alder peak is obvious in both percentage and influx diagrams. However, alder appears to arrive and leave earlier at Ritterbush Pond than at Sterling Pond, although the higher abundance occurred at Sterling Pond.
12. The average influx in ash pollen at Sterling Pond is higher than at Ritterbush Pond.
13. A few small peaks of hickory appear in the Sterling Pond pollen influx diagram, whereas there is almost no hickory pollen in the Ritterbush Pond core.

14. Hemlock appears earlier and is more abundant in Ritterbush Pond than in Sterling Pond. The regional hemlock decline occurs at about the same time in both cores, about 4,800 ^{14}C yr BP.
15. Elm, walnut, butternut, and willow all have low frequency influx values in sediment core from both ponds. However, pollen influx of these species is higher in Sterling Pond than in Ritterbush Pond.
16. The arrival sequence of the aboreal species is similar in the two ponds, although the timing of arrivals is different. At both sites, spruce and fir came first, followed by pine and birch, then oak and alder, followed by ash and hemlock.

3.1.4. Discussion of the Diagrams

3.1.4.1 Comparison of percentage pollen and pollen influx diagrams

As mentioned in the previous section, both the pollen percentage and pollen influx diagrams each have advantages and disadvantages in reflecting the vegetation in the surrounding study area. For example, at Sterling Pond, the initial pine increase at 460 cm depth in the pollen influx diagram was not shown in the percentage diagram; in contrast, there is a sharp decrease in pine at that level in the percentage diagram. At 500 cm depth in the Sterling Pond core, maple has a peak in the percentage diagram that does not exist in the influx diagram, and at 70 cm depth, the increase of hemlock is better shown by the influx diagram than by the percentage diagram.

Between 416 and 424 cm depth in Ritterbush Pond core, a "fining upward sequence" decreases the pollen abundance of pine and birch. The decline in pollen shows clearly in the influx diagram, whereas during the same period in the percentage diagram there are relative drops from a pine peak and birch remains abundant. At 515 cm depth, the oak has a peak in the percentage pollen diagram, but oak influx is extremely low. Due to the low total grains counted, some deciduous species, such as ash, show peaks of initial appearance early in percentage diagram. However, these species should be classified as long-distance transported regional pollen (Moore et al., 1991).

3.1.4.2. Percentage pollen diagrams vs. LOI diagrams

There are no obvious correlations between the pollen percentage diagrams and LOI diagrams. For example, in the Sterling Pond core, there is no equivalent increase in the percentage pollen diagram (Figure 3.7) from 445 cm (about 9,500 ^{14}C yr BP) to 475 cm (about 10,600 ^{14}C yr BP) where LOI peaks sharply (Figure 3.1). In the Ritterbush Pond core, the peaks and drops in the LOI diagram (Figure 3.2), which are closely related to the "fining upward sequences," do not have corresponding changes in the percentage pollen diagram (Figure 3.8).

3.1.4.3. Pollen influx diagrams vs. LOI diagrams

The sharp increase of LOI in Sterling Pond between 445 cm (about 9,460 ^{14}C yr BP) and 475 cm (about 10,640 ^{14}C yr BP), is well within the first influx increase of fir, pine, birch, oak; the first appearance of maple, beech, ash, hickory, hemlock, elm, and walnut; and the sudden decrease of tundra vegetation. None of the small variations in LOI above 445 cm depth correspond to changes in the pollen influx diagram.

At Ritterbush Pond, the drops in pollen influx of most species match well with the six "fining upward sequences" documented in the core stratigraphy (Figure 2.14). Such agreement is clearly reflected in the pollen influx of birch. Below 489 cm (about 11,700 ^{14}C yr BP) the sediment is mainly clayey silt, and the low pollen influx is reflected in all the deciduous trees. However, this low LOI value does not affect the influx of fir, spruce and pine, which experience their first peaks during that time.

The hemlock decline is observed in nearly all sites in New England (Davis, 1969). Many researchers suggest that such a decline was caused by an insect invasion that attacked only this species (Dr. Jeffrey Hughes, personal comm.). In the Ritterbush Pond pollen influx diagram, hemlock went through a sudden decline starting from 285 cm depth (about 5,100 ^{14}C yr BP) and reached its lowest influx at 245 cm depth (about 4,093 ^{14}C yr BP). During that period there is no "fining upward sequence" in the core stratigraphy (Figure 2.13). In Sterling Pond pollen influx diagram, hemlock experienced the decline from 290 cm (about 4,700 ^{14}C yr BP) to 270 cm (about 4,300 ^{14}C yr BP). Again, during that time, there is no evidence in the stratigraphy indicating a decrease in organic influx.

There are several possible interpretations for the correlation between pollen influx and LOI values, including storm events, changes in vegetation productivity, changes in long-term inorganic sediment influx, and/or the combination of some of the above. The hemlock decline with no evidence in low LOI at the same time suggests that when vegetation productivity declined the LOI did not necessarily decrease. A close match of pollen influx with LOI value might suggest changes in vegetation productivity and/or changes in long-term inorganic sediment flux rather than storm events for the variations. However, because it is also very common to observe inorganic sediment bands in glacial lake sediment, the sudden appearance of inorganic bands within gyttja were most likely caused by sedimentation events rather than vegetational change. The fining upwards character of the low LOI bands also argues for a catastrophic origin, such as that caused by storms. Davis (1969) observed similar inorganic layers in her study of Rogers Lake in Connecticut. She suggested a pattern of water circulation that decreases the rate of sediment accumulation which may also influence the pollen grains accumulated at the sampling site. Davis and Ford (1982) observed that there were parallel declines in accumulation rates of both pollen and inorganic sediments suggesting that the observed decline is due to the process of sediment focusing rather than to a change in decomposition rates or organic input. She reasoned that pollen grains themselves occupy too little volume to affect the sediment accumulation rate directly (Davis, 1969). In summary, the storm and sedimentation interpretation currently seems to make the most sense for the origin of inorganic layers in Ritterbush Pond sediment cores.

3.2. Pollen Zonation

The zonation for the pollen sequences in this study is based on that for Bugbee Bog (McDowell et al., 1971) and the standard pollen zonation for New England (Deevey, 1939, 1943). Such divisions as pollen zones are selected on the basis of pollen components. Each zone is an internally homogeneous "biostratigraphic unit". Therefore, pollen zone boundaries ideally should be placed at points where pollen abundances for many species change at the same time. Subzones are used to reflect the less definitive boundaries.

3.2.1. Standard Pollen Zones in New England by Deevey (1939, 1943)

Before pollen sequences could be dated, a threefold zonation of cores was noted from eastern North America: 1) a basal spruce-fir pollen zone, 2) an intermediate pine pollen zone, and 3) an upper oak pollen zone, which is subdivided into subzones based on the maxima of other taxa. Deevey (1939, 1943) found similar sequences in New England.

His work in southern New England first established the standard pollen zones for New England. These zones are so well-established that it seems certain that they are useful for all of New England, if not for all of eastern North America. Basically, Deevey (1939, 1943) designated "A" for the basal spruce-fir zone, "B" for the pine zone, and "C" for the oak pollen zone. The maxima of hemlock, hickory, and chestnut pollen were used for subdividing zone C. Many researchers who followed compared their results with those of Deevey's (1939, 1943). In addition to what Deevey (1939) found in Connecticut lakes, he produced 14 more pollen profiles from lakes and bogs in southern New England (Deevey, 1943) and proposed the following pollen zones and their climatic implications:

Zone A-1. A coniferous period, characterized by pine, spruce, and fir, with some deciduous species present; since pine pollen is over-represented, this zone may be designated as a spruce-fir period; sudden rises in birch are seen locally; climatic interpretation for this zone is cool.

Zone A-2. Fir, and particularly spruce, attain their maximum and decline; birch maxima are distinct in several profiles; zone named the secondary spruce maximum by Deevey (1943); the climatic interpretation is cooler compared with the zone below.

Zone B (renamed as Zone B-1 by Deevey, 1943). This is the pine period because pine reaches a more or less clearly defined maximum, locally as high as 95%; climatic interpretation is warmer and drier.

Zone C-1. Oak rises to a maximum, closely associated with and frequently preceded by a maximum in hemlock; climatic interpretation is warm and moist..

Zone C-2. Hemlock and oak decline, while hickory rises, usually reaching its maximum; climatic interpretation is warm and dry.

Zone C-3. Oak remains about constant, hickory declines, and chestnut and hemlock rise; an increase in spruce occurs; climatic interpretation is increased moisture and/or cooler; early C-3 and late C-3 subdivisions, which indicate warmer and cooler climate, respectively, proposed by Deevey (1943).

3.2.2. Pollen Zonation for Sterling and Ritterbush Pond Sediment Cores

This research compares favorably with many of the previous interpretations of pollen percentage diagrams from Vermont and other states in New England. The classical pollen stratigraphy, Zones A, B and C for southern New England, is utilized here because the pollen assemblage zones are similar to those first identified by Deevey (1939) and because it facilitates the comparison with pollen diagrams from other sites.

My work shows no evidence for a tundra herb zone, the "T" zone, which has high percentage of herb pollen, although some of the New England sites show such a basal zone. The absence of this zone in the Sterling and Ritterbush Pond sediment cores suggests that either: 1) we did not penetrate to this zone in the coring process 2) tundra vegetation did not occupy the sites long enough to produce pollen, or 3) tundra pollen grains were not recognized from the category "unknowns".

3.2.2.1. Sterling Pond pollen zones

The following are the main characteristics of the pollen zones for the sediment core from Sterling Pond (Figure 3.7). Seven pollen assemblage zones A-1, A-2-3, A-4, B, C-1, C-2, and C-3 can be distinguished from the percentage pollen diagram for Sterling Pond.

Zone A-1 follows what Deevey (1943) described, and zone A-2-3 follows Peteet et al. (1993).

Zone A-1(prior to 12,610 ^{14}C yr BP). This zone is characterized by high spruce percentages, with a maximum of over 30%. Although pine is high, its abundance might be due to over-representation (Davis, 1960; Whitehead and Bentley, 1963, and Moore, et al., 1991). The extremely low percentages of deciduous trees pollen are believed to be transported long distances. This zone probably represents a park-tundra landscape. This initial vegetation is a mixture of herbs, shrubs, and trees.

Zone A-2-3 (12,610-11,500 ^{14}C yr BP). Pollen in this zone indicates a mixture of fir and particularly spruce, which attains its maximum. Pine remains high, perhaps caused by over-representation. Oak and maple increase, almost reaching mid-Holocene and late-Holocene levels. Birch starts to increase along with the slight maxima of alder and elm. It is noted that high value of birch may indicate that the species is over-represented (Davis, 1960). The high spruce and birch values indicate a closed boreal forest succeeding the late-glacial tundra.

This zone represents a mixed of spruce and fir forest. Oak and maple were the dominant deciduous species although minor components of the forest. The climate is likely to be warmer and moister than that of A-2 due to the appearance of deciduous species, especially oak, on the pollen diagram. The oak-maximum suggests relatively drier conditions.

Zone A-4 (11,500-10,040 ^{14}C yr BP). The sharp rise of alder and dramatic increase of birch are the most significant features of this zone. Meanwhile, oak declines to a minimum and remains low for about 400 ^{14}C years. Maple also decreases. There is a clear drop of pine from 35% at the beginning to 7% at the end of the zone. Spruce experiences an obvious peak at the beginning of this zone, then quickly declines. The spruce peak appears to co-exist with the oak minimum. Fir reaches its highest level on the diagram and remains high thereafter. Changes occurring in this zone are also typical of many northeastern U.S. pollen diagrams (Peteet et al., 1993).

This rise in boreal tree species (spruce and fir) and the decline of thermophilous tress (oak and pine) suggest a climatic cooling, possibly as great as 3-4 °C (Peteet et al., 1993). The zone is correlative with the Younger Dryas event, which is a climate cooling well-observed in Europe between 10,800 and 10,000 ^{14}C yr BP. The large alder rise between 11,000 and 10,000 ^{14}C yr BP may indicate disturbance by severe winters (Peteet et al., 1993).

Zone B (10,040-7,860 ^{14}C yr BP). This is called the post-glacial pine period. Alder declines sharply from 35% to 7% at the end of the zone and remains low thereafter. Birch also declines, reaching its lowest level since its highest peak; however, the birch decline is not as clear as that of alder. Spruce and fir both decline while oak increases to maximum. Ash and elm for the first time appear in high percentages.

The steepness of the decline of boreal conifers and a rapid increase in pine pollen indicate a warmer and drier climate, which occurred between 10,000 ^{14}C yr BP and 7,500 ^{14}C yr BP (Loring, 1980). The maximum of pine precedes the establishment of deciduous forest, indicating a warmer and drier climate than the following zones. The gradual increase in oak indicates rise in temperature and a decrease in precipitation. Peteet et al. (1993) suggest that the warming after the Younger Dryas took place in as few as 50 to 100 years.

Zone C-1 (7,860-4,730 ^{14}C yr BP). Deciduous tree pollen begin to dominate the diagram. Pine declines and spruce and fir remain very low compared with previous abundances. After the oak peak (20%) early in this zone, hemlock rises to about 20% and beech continues to increase throughout the zone until peaking at the C-1/C-2 boundary. Alder, ash, and elm are present in small quantities. The percentage of maple is relatively constant and low.

Increasing percentages of hemlock along with high levels of birch and beech could suggest an increase in precipitation for this zone (Peteet et al., 1993). Oak is also a good moisture indicator. That hemlock increased after the decline of oak during this zone, also suggests an increase in moisture. The landscape was probably dominated by hemlock and the increasing mixture of beech, birch, and other deciduous trees.

Zone C-2 (4,730-1,680 ^{14}C yr BP). A pronounced hemlock decline appeared early in the zone. The extremely low abundance for hemlock lasted about 500 ^{14}C years. Birch and beech are abundant throughout the zone; oak and maple stay at moderate levels; alder, ash, and elm remain constant, reflecting a predominantly deciduous forest. Spruce and fir are at the same level as the in the C-1 zone. Pine experienced a slight resurgence.

This is the warmest period of post-glacial time. The minimum of hemlock, increase of pine, along with the oak and hickory maxima, suggests relative dryness (Whitehead and Bentley 1963). However, others believe that the sharp hemlock decline was caused by an insect attack. A hemlock cone was recovered from 290 cm (4,800 ^{14}C yr BP) of the Sterling Pond core, which is around the well-recognized time of this event.

Zone C-3 (1,680 ^{14}C yr BP to present). Spruce and pine increase while fir experiences a slight increase. Beech declines slowly and hemlock is abundant until the upper 20 cm of the core. Birch, maple, oak, alder, ash, and elm remain about the same as in C-2. This zone reflects a very recent cooling indicated by the rise of conifer trees and the decline of beech. This zone is cooler and more humid than zones C-1 and C-2.

3.2.2.2. Ritterbush Pond pollen zones

Five pollen zones A-2-3, B, C-1, C-2, and C-3 can be distinguished from the percentage pollen diagram of Ritterbush Pond (Figure 3.8). The A-1 zone as observed by Deevey (1939) is missing at the bottom of the Ritterbush Pond pollen diagram. The main characteristics of the pollen zones for the Ritterbush Pond sediment core are as follows:

Zone A-2-3 (prior to 12,020 ^{14}C yr BP). This zone is characterized by spruce reaching as high as 55%. Pine is also high but may be over-represented. There are very low abundances of birch, maple, and ash. At the base of the profile, there is a slight maximum of oak. The occurrence of spruce and fir pollen suggests a warming climate, but still cooler than in the mid- and late-Holocene.

Zone A-4 (12,100-11,100 ^{14}C yr BP). This zone is characterized by the sharp increase of alder, which rises as high as 30%. Oak declines to the minimum level and remains low for 380 ^{14}C years, whereas birch increases, although not as steeply as alder. Pine drops from 55% to 10% at the top of this zone. Spruce and fir are abundant. The increase in boreal conifers and a sharp increase in alder and birch indicates a climate cooling.

Zone B (11,100-9,000 ^{14}C yr BP). High pine percentages up to (60%) characterize this zone. Fir declines rapidly. Spruce keeps the same low level as seen at the top of zone A-4. Birch declines from the highest level (45%) at the beginning of the zone to the lowest level (5%) at the top of the zone. Alder also drops quickly and reaches the lowest point in the middle of the zone and remains low thereafter. Oak increases in frequency and reaches a peak. Maple, ash, and elm are at a relatively constant level. The oak maximum along with pine maximum later in this zone might suggest the existence of an oak-pitch pine forest (Whitehead and Bentley 1963). In general, hemlock begins to appear at an extremely low percentage. Deciduous tree pollen become more frequent. The upper boundary of the zone is marked by the pine peak, the birch maximum, and a major oak rise. The decline of alder and the increase of pine and oak suggest a warm and dry climate.

Zone C-1 (9,000-4,830 ^{14}C yr BP). In this zone, deciduous tree pollen begins to dominate the diagram. Spruce and fir are almost absent. Pine declines from a very high level (up to 60%) at the beginning of the zone to less than 5% at the top of the zone. Oak decreases from the maximum level at the beginning of the zone to the lowest level since deglaciation. Birch sharply increases and remains high throughout the zone. Beech first appears in the middle part of this zone. After its initial occurrence, beech increases steadily. The dominance of deciduous trees and the decline of pine and oak suggest a warmer and moister environment.

Zone C-2 (4,830-1,600 ^{14}C yr BP). This zone is characterized by the sharp decline in hemlock due to pathogen attack. The hemlock decline begins around 4,800 ^{14}C yr BP and hemlock pollen reaches the lowest level at about 4,100 ^{14}C yr BP, and gradually increases thereafter. Spruce and fir remain at low levels as they did in the later part of Zone C-2. There is a small increase of pine probably suggesting drier condition during time represented by Zone C-2. Birch and beech are abundant, and maple, oak, alder, ash, hickory, and elm remain stable throughout the zone.

Zone C-3 (1,600 ^{14}C yr BP to present). The increase of fir and spruce characterizes this zone. Beech was abundant at the beginning of this zone and somewhat declines toward the top on this zone. These changes indicate a cooler and more humid climate.

3.3. Vegetation and Climate Changes in the Green Mountains, Vermont since Deglaciation

3.3.1. Comparison of the Pollen Zones of two Ponds

The pollen zones for Sterling and Ritterbush Ponds are similar to those in southern New England (following Deevey 1943 in central Connecticut and Massachusetts). The Zone A-1 (spruce and fir period) is missing from Ritterbush Pond, which suggests that either we did not penetrate to this zone or that it was not present because the site might have been occupied by late-lying ice during this time. The main features observed in both diagrams are as follows:

Zone A-1: spruce fir period (Ritterbush Pond missing this zone.)
Zone A-2-3: spruce and fir high, pine maximum, initial occurrence of oak
Zone A-4: oak and pine minimum, alder and birch maximum
Zone B: the postglacial pine period, boreal trees decline along with alder, and oak increases
Zone C-1: deciduous trees and hemlock increase, oak declines, low spruce, fir and pine

Zone C-2: hemlock sharply declines, pine slightly increases, deciduous trees abundant

Zone C-3: return of spruce and fir, hemlock and beech decline

The same features are observed in pollen percentage diagrams for both sites, such as the alder peak, the hemlock decline, the early-Holocene oak peak, and the resurgence of spruce and fir in the late Holocene. The LOI diagrams and the total influx on the pollen influx diagrams for both ponds experience drops during the A-2-3 and A-4 zones, suggesting a low organic influx. These declines might be the evidence for Younger Dryas cooling, primarily in Zone A-4.

The duration and the timing of the A-4 and C-1 zones differ between the two sites. At Sterling Pond, the A-4 zone lasts for about 1,460 ^{14}C years, whereas Ritterbush Pond the zone is 920 ^{14}C years in duration. The C-1 zone is 3,070 ^{14}C years long at Sterling Pond but 4,170 ^{14}C years long at Ritterbush Pond. The B Zone (pine zone) occurred much earlier in Ritterbush Pond than in Sterling Pond, Woodford Bog in southern Vermont (Davis et al., 1995), or New Jersey and Connecticut (Peteet et al., 1993). Errors in the radiocarbon dating could explain such differences. The very basal sample from Ritterbush Pond is dated 21,860 ^{14}C yr BP at 518-520 cm with only 0.3% carbon content. This age is not used in this thesis because the limited organic matter from this bottom sediment is likely contaminated by older carbon, similar to the interpretation proposed for Woodford Bog in Southern Vermont (Davis et al., 1995). The basal age used for Ritterbush Pond, 12,020 ^{14}C yr BP at 479 cm, had 2.4% carbon content after pretreatment (J. Southon personal communication). The sediment between 479 and 525 cm is dark brown rather than black (Figure 2.14) suggesting that the 12,020 ^{14}C yr BP age maybe also be too old. I believe that the radiocarbon ages for Sterling Pond are more reliable because the sediment is more homogeneous and has higher carbon content that the basal sediments from Ritterbush Pond.

Assuming that the radiocarbon ages from the Ritterbush Pond sediment core are accurate, I conclude that vegetation arrived at Ritterbush Pond first, and then migrated upslope to Sterling Pond. The basal age of Sterling Pond suggests that higher elevations in the Green Mountains were deglaciated before the valleys by 12,700 ^{14}C yr BP. The revegetation model for the Green Mountains was that vegetation followed the retreating ice and occupied the valleys first and then climbed upwards along mountain slopes. This mode of vegetation migration is supported by Davis and Jacobson's (1985) work in northern New England and the adjacent area of Canada.

3.3.2. Comparison with Results from other Vermont Sites

There are seven sites in Vermont at which pollen diagrams have been produced. The radiocarbon ages for each site are listed in Table 3.5. There is no obvious correlation between the elevation and the basal sediment ages for the ponds. Thus, it appears that radiocarbon ages are insufficient for chronologic comparison between Vermont sites. Bugbee Bog (eastern Vermont), Pownal Bog (southwestern Vermont), and earlier work at Ritterbush Pond by Sperling et al. (1989) (north-central Vermont) are chosen to compare with Sterling Pond and my Ritterbush Pond results. The following is a comparison of vegetation change between these ponds and the regional deglaciation and vegetation migration model based on the comparison. There are some similarities and differences among these four sites.

Table 3.5. The status of the availability of radiocarbon ages from five Vermont pollen cores.

Site	Elevation (m)	Number of ^{14}C ages availabl	Basal age (^{14}C yr BP)	Comment
Woodford Bog	703	1	12,420+/-420	GSA Abstract, 1995
Bugbee Bog	398	4	11,290+/-200	
Pownal Bog	377	0	11,000	Basal age is a corelation.
Ritterbush Pond	317	4	10,090	
Columbia Bridge Site	301	1	11,540+/-110	The basal age is from a wood fragment.

Similarities:

1. The plant succession sequence is the same for all sites. The approximate order of arrival of species is spruce and fir, followed by pine, birch and alder, then oak, maple, ash, elm, and beech, and finally hemlock.
2. The hemlock decline is observed in all pollen diagrams at around 4,800 ^{14}C yr BP. This is also observed in many other New England pollen diagrams.
3. Beech starts to increase in the middle of Zone C-1 at all sites; however, the beginning of Zone C-1 varies in time among sites.

Differences:

1. A sharp peak in alder during late glacial time is only shown in the Sterling and Ritterbush Pond diagrams, although there are smaller alder peaks in Bugbee Bog and Pownal Bog cores.
2. Lack of basal age differences between other ponds in Vermont at different elevations supports Spear's (1989, 1994) results in the White Mountains that the mountain ranges were vegetated the same time as the valley.
3. Evidence consistent with the Younger Dryas climatic cooling event is only clearly seen in the Sterling Pond pollen diagram. At Ritterbush Pond, the alder peak is too old if the basal radiocarbon ages are correct. At the Columbia Bridge site (eastern Vermont), there is palynological evidence for the occurrence of alder. Alder, as a nitrogen-fixing plant, plays an important role in enriching nutrient poor glacial soils (Davis et al., 1980).
4. Fir persists today at high-elevation sites (Sterling Pond), whereas it disappeared in the mid-Holocene at lower elevation sites in eastern and southern Vermont.
5. Hickory, a species well-documented in central Massachusetts and Connecticut, is not abundant in the Sterling Pond and Bugbee Bog cores (1%), but it is more abundant in Ritterbush Pond (3-5%), and most frequent in Pownal Bog (>5%).

6. The oak peak in Zone A-2-3 in the early Holocene (Peteet et al., 1993) is reflected in only Sterling Pond, whereas Ritterbush Pond has only a high frequency of oak at the bottom of the core (Sperling et al., 1989). The pollen diagram from Pownal Bog is not detailed enough to reveal the characteristic of Zone A-4 as described by Peteet et al. (1993).
7. Birch is the most abundant species all sites since deglaciation, which is probably explained by over-representation of this pollen.
8. Ragweed pollen expansion since European settlement is observed in the Sterling Pond pollen influx diagram but not in the Bugbee Bog diagram. The top of Ritterbush Pond core could be missing because of the lack of ragweed pollen.

In summary, the Green Mountains of Vermont were deglaciated by 12,700 ^{14}C yr BP. Similar species succession and species abundance are observed in north-central Vermont, eastern Vermont, and southwest Vermont. Evidence for the Younger Dryas, Zone A-4 (Peteet et al., 1993), was only clearly observed at Sterling Pond; however, the lack for such evidence at other sites could be due to low resolution or missing sediment accumulated at the bottom of sediment cores. Based on the species composition of each zone, the climatic interpretation in Vermont is as follows:

Zone A-1: cool
Zone A-2-3: cool but warmer than A-1
Zone A-4: cooler and moister than A-2,3
Zone B: warmer and drier
Zone C-1: warm and moist
Zone C-2: warmest and driest
Zone C-3: cooler and more humid

3.3.3. Comparison with Results from Other Pollen Sites in New England

Extensive pollen analysis has been done in the White Mountains of New Hampshire (Spear, 1989, and Spear et al., 1994), central Connecticut (Deevey, 1943), central Massachusetts (Davis, 1958), and Maine (Davis and Jacobson 1985). Figure 1.4 shows the relative location of these study sites, along with those in Vermont. There are some similarities and differences among these regions:

Similarities:

1. Similar pollen zones are observed in Vermont as in the other New England states, although differences exist concerning the subzones of Zone A.
2. The correlation between ragweed expansion during the mid-Holocene (Davis, 1968) with the prairie period in the Midwest is suggested by the Sterling Pond pollen influx diagram and the Bugbee Bog percentage diagram, but not in other Vermont sites.
3. Zone B records the gradual warming of climate, and consequent replacement of spruce and fir by deciduous trees.
4. In Zone C-1, all the New England sites have the same character as described by Deevey (1939, p. 702), namely as "oak rises to a maximum, closely associated with and frequently preceded by a maximum of hemlock".
5. In Zone C-2, pine resurgence is observed in Vermont sites and in central Massachusetts. The oak decline happened in Vermont sites and central Connecticut.
6. In Zone C-3, the birch maximum took place in Vermont sites and central Massachusetts. The constant low frequency of oak is observed in Vermont sites and central Connecticut.

Differences:

1. Evidence for the Younger Dryas (Zone A-4) was observed only in Sterling Pond, Vermont, and Linsley Pond, Connecticut (Peteet et al., 1993).
2. In Zone C-2, hickory reaches its maximum in central Connecticut, but is not observed in Vermont, New Hampshire, and central Massachusetts. On the contrary, in Vermont a beech maximum is noted.
3. In Zone C-3, oak and hemlock maxima in central Massachusetts and Connecticut are not observed in Vermont. Also, sites in Vermont experienced a slight hemlock decline.
4. The ragweed increase in the past 200 years is not observed in all New England sites.

In summary, the vegetation pattern in the Green Mountains of Vermont since deglaciation is more similar to that of the White Mountains in New Hampshire than to southern New England (Connecticut and/or Massachusetts) sites. The main differences exist in the C zones. Oak and hickory are abundant in the C-2 zones in southern New England (Connecticut and Massachusetts), while northern New England (Vermont and New Hampshire) beech is frequent. The oak peaks and hickory recovery well-referenced in central Connecticut and Massachusetts (Deevey, 1939, 1943) are not seen in northern and eastern Vermont. However, in southwestern Vermont, Pownal Bog (Whitehead and Bentley, 1963) does have the high frequency of oak and hickory, which is similar to other southern New England sites. The climatic interpretation of Vermont sites is the same as that for New England, which include cooler, moister Zone A; a warmer, dryer Zone B; a warmer, moisture Zone C-1; a warmest, driest Zone C-2; and a cool, humid Zone C-3.

3.4. Tentative Reconstruction of Regional Paleoenvironment

Great environmental changes took place during and after retreat of Laurentide ice sheet in New England about 13,000 to 10,000 ^{14}C yr BP, as evidenced by percentage pollen and pollen influx diagrams of two ponds in the northern Green Mountains, Vermont. The rapid deglaciation and postglacial vegetational history of Vermont and other New England states, as evidenced by pollen sequences throughout the region, reveal a generally similar pattern of succession.

Using pollen analysis, a picture of the paleoenvironmental change since deglaciation can be reconstructed. In Vermont, a cold and moist climate prevailed during the existence of the Champlain Sea, as correlated with pollen Zone T and Zone A. The landscape was tundra-parkland, with a transition to woodland near the Zone A/B boundary. In the mid-Holocene (Zone B, Zone C-1 and Zone C-2), the mountains and their valleys were well-vegetated with densely closed forest, and the landscape was already like what we see today, except during the Zone C-2 time when the climate was warmer and drier than today. The late-Holocene (Zone C-3) records the most recent stage in the history of the landscape. The upper part of Zone C-3, with an increase of spruce and pine, may indicate a cooler and more humid climate.

Vegetation appears to have migrated to the sites of various elevation in the Green Mountains at various times, different from the pattern in the White Mountains (Spear et al., 1994). My data suggest that a plant succession and migration in northern Vermont showed spruce, replaced by pine, then by birch and oak, later by hemlock and beech, and finally spruce. This succession appears to occur earlier at Ritterbush Pond than at Sterling Pond, if the basal radiocarbon age is accurate for Ritterbush Pond. If the temperature lapse rate is the same during the Holocene as it is present, the 600-m elevation difference between the two ponds relates to between a 4 and 6 °C difference in temperature, if the lapse rate is assumed to be constant.

I found no persuasive evidence of the existence for the Younger Dryas (Peteet et al., 1993) in Vermont, except for the alder peak in Zone A-4 in Sterling Pond. However, Peteet et al. (1993) mentioned that most sites in the high mountains of Vermont were not deglaciated as early as the sites in New Jersey and southern New England where she found evidence for the Younger Dryas.

CHAPTER 4

CONCLUSIONS

I completed pollen analyses of postglacial sediments from two ponds in the Green Mountains, Vermont. Based on the data obtained from this project, a revegetation model for the Green Mountains is proposed.

1. Vegetation migrates upslope since deglaciation

The similar features on pollen diagrams are compared chronologically based on the radiocarbon ages for both ponds. Because changes appeared to occur at Ritterbush Pond before Sterling Pond, and due to the relative elevations and latitudes of the two ponds, it is reasoned that vegetation migrated to northern New England through lowland valleys and gradually migrated upslope. This conclusion supports the upslope vegetation migration model proposed by Davis (1960) and Davis and Jacobson (1985), but disputes the instantaneous vegetation model for the White Mountains (Davis et al., 1980; Spear, 1989; Spear et al., 1994).

2. The possibility of the existence of the Younger Dryas climate oscillation

There is much debate about whether the Younger Dryas affected North America. Some evidence in this study supports the existence of a Younger Dryas climate oscillation in northern Vermont. The alder peak, birch increase, pine increase, and boreal forest decline in the Zone A-4 suggest a somewhat cooler period compared with Zone A-2-3, which supported deciduous trees, such as oak. The tentative interpretation of the oak decline and the alder peak, which are the best evidence for Younger Dryas event in New England (Peteet et al., 1993), was clearly observed in Sterling Pond, Vermont, just as they are at Woodford Bog, southern Vermont (Davis et al., 1995), Linsley Pond, Connecticut (Peteet et al., 1993); and Rogers Lake, Connecticut (Davis, 1968).

M.B. Davis (1958) and R.B. Davis et al. (1985) do not believe that the Younger Dryas explains the features in Zone A-4 seen in the New England pollen diagrams. However, R.B. Davis et al. (1985, p. 366) stated " ...This does not rule out the possibility of climatic reversal or step changes too brief or mild to elicit a distinguishable vegetational response, as sensed by pollen diagrams."

3. Standard pollen sequence for southern New England (Deevey, 1939 and 1943) also found in northern Vermont

Three pollen zones, Zone A, Zone B, and Zone C, and their subzones proposed by Deevey (1939, 1943) in southern New England are maintained in the Green Mountains study sites, although the frequently observed Zone T is missing.

The similarity of Vermont pollen diagrams with those from southern New England indicates that the ice sheet retreated northward quickly, leaving vast areas of New England exposed for plant colonization.

3. Paleoclimate in the Green Mountains, Vermont

A tentative reconstruction of paleoclimate in the Green Mountains, Vermont, since deglaciation based on pollen data and radiocarbon dates would be:

1) before 12,610 ^{14}C yr BP, climate is cool

2) 12,610 - 11,500 ^{14}C yr BP, climate is cool but warmer compared with previous time

3) 11,500 - 10,040 ^{14}C yr BP, climate is cooler than the previous phase

4) 10,040 - 7,860 ^{14}C yr BP, climate is warmer and dry

5) 7,860 - 4,730 ^{14}C yr BP, climate is warmer and moist

6) 4,730 - 1,680 ^{14}C yr BP, climate is the warmest and driest

7) 1,680 ^{14}C yr BP until present, a return of cool and humid climate

However, the greatest environmental changes happened in the late Pleistocene, around 10,000 ^{14}C yr BP, suggesting a rapid warming.

4. The landscape went through a tundra--open woodland--closed forest stage in northern Vermont.

The landscape of the Green Mountains of Vermont went through a tundra (Zone A-1)--woodland (Zone A-2-3 and Zone A-4)--closed forest (Zone C-1, C-2 and C-3). The same sequence was observed by Davis and Jacobson (1985) in northern New England and the adjacent area of Canada.

5. Differences exist in Zone C in New England.

In Vermont and New Hampshire, beech is abundant in Zone C, whereas oak and hickory is common in southern New England (Massachusetts and Connecticut). There are several possible interpretations: 1) a vegetation migration lag, 2) geographic barrier, 3) dispersal speeds of the species, or 4) competition among species.

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Appendix A:
Loss-on-Ignition (LOI) Data Recording Sheet

Site		Date		Page #				
Trust		Lab length						
Depth (cm)	Crucible #	Crucible weight (g)	24 hr. drying (g)	1 more hour (g)	dry weight (g)	12 hr. burning (g)	1 more hour (g)	residue weight (g)

Appendix B:
Lab Procedure for Extracting Pollen and Making Pollen Slides

Step one: Quantitative subsample.

A quantitative subsampler of one cubic centimeter exact was designed and ordered. Fill but not pack the one-cubic centimeter-large container with sediment from certain depth. Push the 1 cm^3 sample into the centrifuge tube by a small rod.

Step two: Add exotic pollen.

The precise timing of marker grain addition varies with different workers. I added the marker pollen suspension before processing of the sediment sample, because any pollen lost during processing will be accompanied by an equivalent loss in exotic pollen, therefore the overall proportions of fossil taxa to marker pollen will remain unchanged. The quantity of marker pollen to be added is decided by the expected pollen density in the fossil sample (Moore, 1991). If too much is added, then lots of counting time may be used in recording marker grains. Theoretically, one should aim at a final ratio of exotic to fossil grains of between 1:5 and 2:5.

Add 1 ml of slurry (see Appendix 1 for procedure of making slurry) and distilled water to 10 ml, stir (all the sticks used for stirring up the solution in this lab are six-inch-long wood sticks) , centrifuge, decant the supernatant.

Step three: HCL treatment--To remove calcium carbonate.

(1). Add 10 ml 10% HCL to the pellet, stir, until bubbles cease to evoke, centrifuge, decant the supernatant.
(2). Add distilled water to the pellet to 10 ml, stir, centrifuge, decant.
(3). Repeat (2).

Step four: KOH treatment--To remove humic acid.

(1). Add 8 ml 10% KOH to the pellet, stir, put into water bath heating for 5 minutes. (stir while heating)
(2). Centrifuge, decant.
(3). Add 10 ml distilled water to the pellet, stir, centrifuge, decant.
(4). Repeat (3).

Step five: HF treatment (need to be finished in the hood)--To remove silica.

(1). Add 10 ml 49% HF to the pellet, stir, put into water bath for 15 minutes. Stir again after first 5 minutes in the water bath.
(2). Cool down a little while, Centrifuge, decant the supernatant to plastic bottle for waste HF.
(3). Add 10 ml distilled water to the pellet, stir, centrifuge, decant.

(4). (First glacial acetic acid wash.) Add 10 ml glacial acetic acid to the pellet, stir, centrifuge, decant.
(5). (Second glacial acetic wash.) Repeat (4).

Step six: Acetolysis treatment--To remove the organic material inside the pollen grains.

(1). The acetolysis solution consists of 9 parts (by volume) of acetic anhydride and one part (by volume) of concentrated sulfuric acid. Measure 54 ml of acetic anhydride and 6 ml of concentrated sulfuric acid. Mix them.
(2). Add 10 ml of acetolysis solution to the pellet. Stir as quickly as possible, put into water bath for no longer than 2 minutes.
(3). Centrifuge, decant the supernatant to bottle for waste acid.
(4). Add 5 ml of glacial acetic acid and then distilled water to 10 ml, stir, centrifuge, decant.
(5). Add 10 ml distilled water to the pellet, stir, centrifuge, decant.
(6). Repeat (5).

Step seven: Alcohol treatment.

(1). Add 10 ml 100% Ethanol alcohol to the pellet, stir, centrifuge, decant.
(2). Repeat (1).

Step eight: TBA (Tertiary Butyl Alcohol) treatment.

(1). Add 10 ml of TBA to the pellet, stir, centrifuge, decant.
(2). Add 1 ml of TBA to the pellet, stir and transfer to the vial. Add little more TBA to transfer pollen grains which stick to the side of the tube to the vial.
(3). Add few drops of silicone oil. Sit the vial in the hood for 12 hours.
(4). Centrifuge the vial, decant the supernatant which is mostly TBA.

Step nine: Making slides.

(1). Stir the pollen at the bottom of the vial as even as possible. Usually, clockwise 20 times and then counterclockwise 20 times.
(2). Put one drop of silicone oil on the slide, dip the stir in the recently well-mixed pollen in (1), smear the pollen stick on the wood stir as even as possible on the slide but within the range of the on-coming coverslip.
(3). Carefully apply the coverslip on the slide, try to avoid bubbles. Wait until the pollen-silicone mixture naturally extend to all the corners of the cover slip, put a little nail polish at the opposite corners of the coverslip to stabilized it.
(4). Label the slide with permanent marker about the sample site and depth.

Step ten: Making pollen slurry

(1). Put approximately 0.5 cubic centimeter eucalyptus pollen to a centrifuge tube, add a little distilled water to it.

(2). Repeat Step three.
(3). Repeat Step five.
(4). Add some glycerol to the pillet, stir. Meanwhile, put 300 ml glycerol into a beaker.
(5). Transfer the well stirred pellet to the beaker with 300 ml glycerol. Put a magnetic bar inside the beaker, and then turn on the magnetic stirrer. Stir the slurry for one hour before using it.

Appendix C:
Pollen Counting Sheet

Date		Sample Site				Page #
Depth (cm)					stop at	
maker pollen					subtotal	percentage
fir						
spruce						
pine						
birch						
maple						
oak						
beech						
elder						
ash						
hickory						
hemlock						
elm						
walnut						
butternut						
willow						
spore						
grass						
ragweed						
unidentified	scheme	position		number	total	

Appendix D:
Latin Name vs. Common Name of the Species Discussed in Thesis

Common name	**Latin name**
Fir	*Abies spp.*
Spruce	*Picea spp.*
Pine	*Pinus spp.*
Birch	*Betula spp.*
Maple	Acer spp.
Oak	*Quercus spp.*
Alder	*Alnus spp.*
Ash	*Fraxinus spp.*
Hickory	*Carya spp.*
Hemlock	*Tsuga spp.*
Elm	*Ulmus spp.*
Walnut	*Juglans nigra*
Beech	*Fagus grandifolia Ehrh.*
Butternut	*Juglans cinerea*
Willow	*Salix spp.*