2003

12,000-Year Record of Lake-Level and Vegetative Change at Mathews Pond, Piscataquis County, Maine, USA

Andrea Masterman Nurse

12,000-YEAR RECORD OF LAKE-LEVEL AND VEGETATIVE CHANGE AT MATHEWS POND, PISCATAQUIS COUNTY, MAINE, USA

By

Andrea Masterman Nurse

B.S. Springfield College, 1971

M.B.A. Thomas College, 1991

A THESIS

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

(in Quaternary Studies)

The Graduate School

The University of Maine

August, 2003

Advisory Committee:

George L. Jacobson Jr., Professor of Biological Sciences and Quaternary Studies, Advisor

Daniel F. Belknap, Professor of Geological Sciences and Quaternary Studies

Ann C. Dieffenbacher-Krall, Associate Research Scientist, Quaternary Studies

David Sanger, Professor of Anthropology and Quaternary Studies

12,000-YEAR RECORD OF LAKE-LEVEL AND VEGETATIVE CHANGE AT MATHEWS POND, PISCATAQUIS COUNTY, MAINE, USA

By Andrea Masterman Nurse

Thesis Advisor: Dr. George L. Jacobson, Jr.

An Abstract of the Thesis Presented
in Partial Fulfillment of the Requirements of the
Degree of Master of Science
(in Quaternary Studies)
August, 2003

This study of late-glacial and Holocene changes in lake-level and vegetation at Mathews Pond contributes new information about Holocene environments in northeastern North America. The research establishes a 12,000-year record of paleohydrology for the watershed adjacent to Big Reed Forest Reserve, the largest stand of old-growth forest in the northeastern United States. Mathews Pond is a 7.4 ha, closed-basin, groundwater-seepage lake located in an upland, forested region of the Aroostook River drainage system. Glacial meltwater briefly filled the basin ~ 13.0 ka (1 ka = 1000 ^{14}C yr BP)). The lake existed as a shallow pool in the deep area of the basin between 11.0 and 9.4 ka. Water levels rose to near-modern levels by 8.4 ka, and, except for a slight decline around 7.5 ka (8200 cal yr BP), remained high until 4.8 ka, when a distinct low-stand lasted until 3.0 ka. After 3.0 ka the lake level rose to the modern level with intermittent low and high fluctuations of 200-500 year duration. Synchrony of lake-level changes between Mathews Pond and Whited Lake, a groundwater seepage lake in an adjacent watershed,

and from additional sites across northeastern North America provides strong evidence that Holocene climate varied with 1500-2000 year periodicity and with sufficient intensity to alter regional moisture balance. Synchrony of groundwater response between watersheds and across broad geographic regions suggests that changes in moisture balance are driven by external influences such as solar insolation or shifts in atmospheric circulation. Integration of lake-level, charcoal, and pollen data at centennial-scale temporal resolution identified subtle increases in groundwater recharge in response to decreased forest transpiration following local forest fires.

ACKNOWLEDGMENTS

I thank the members of my advisory committee - George L. Jacobson Jr., Ann Dieffenbacher-Krall, Daniel Belknap, and David Sanger - for their guidance, technical support, patience, and perseverance over the years that I took to complete this project.

I am grateful to Bill Nurse, Christopher Dorion, Ann Dieffenbacher-Krall, Daniel Belknap, Rick Dyer, and Matts Lindbladh for their assistance in the field. Caitlin Jamison, Kristy Palmer, Steve Barteaux, and Elizabeth Braman supplied many hours of laboratory assistance. Ann Dieffenbacher-Krall, Molly Schauffler, Matts Lindbladh, Kirk Maasch, Alan White, and Alan Gontz guided me through learning the technical skills essential to completion of this project.

I am especially grateful to Hal Borns, whose support gained my admission to the Institution for Quaternary and Climate Studies, and to Geneva Chase, my fellow student in Quaternaryl Science. There is no way to adequately express my gratitude to my husband, Bill Nurse, for his patience and his unfailing confidence in my abilities.

This study was a collaborative research project between University of Maine Department of Forest Ecosystem Science and Institute for Quaternary and Climate Studies to investigate the effects of natural disturbance in Big Reed Forest Reserve, an old-growth forest stand. The project was funded by The Nature Conservancy with field support from University of Maine Association of Graduate Students.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

INTRODUCTION

Holocene climate fluctuations led to changes in vegetation and hydrology in the Acadia region (Maine, southeastern Quebec, and Maritime Canada). Three major air masses converge on Acadia (Figure 1): cold, dry Arctic air from the northwest; mild, dry Pacific air from the west; warm, wet Maritime tropical air from the south. Relative changes in the strength of these air masses influence changes in the temperature and moisture regimes of the region (Bryson 1966).

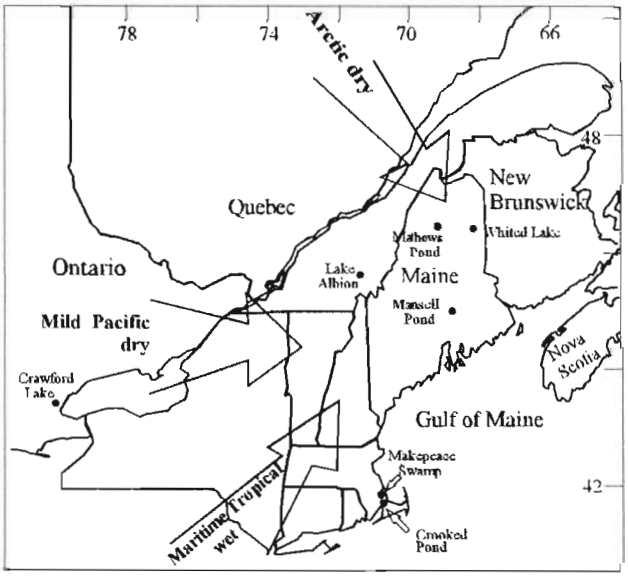


Figure 1 Location of paleohydrology investigation sites reviewed in this study. Air-mass positions from Bryson (1966) and Bryson and Hare (1974).

While fossil pollen, oxygen isotope, and insect assemblage studies are often used to reconstruct past shifts in temperature, these parameters generally do not reveal changes in paleohydrology. Changes in lake level, indicated by changes in sediment morphology

and aquatic macrofossil assemblages, are used to reveal changes in regional moisture balance (Precipitation - Evapotranspiration) and in ground water levels within a watershed (Digerfeldt 1986; Dearing 1997).

To construct a 12,000-year record of paleohydrology for eastern North America, Harrison (1989) reviewed various sedimentary data from 26 sites ranging eastward from South Dakota and south into Alabama and Florida. While studies at many of the sites reviewed did not employ multi-proxy techniques to evaluate lake-level change, 22 of the sites analyzed sediment lithology plus at least one additional, independent indicator of paleohydrologic change. At 1000-year resolution, these lake-level reconstructions indicated that conditions were wetter than today between 12,000 and 10,000 cal yrs BP. Lake levels were lower by 9000 cal yrs BP, with maximum aridity occurring around 6000 cal yrs BP. Lake levels rose to modern levels by 2000 cal yrs BP. Spatially and temporally coherent patterns of lake-level change across eastern North America implied climatic control. Community Climate Model simulations generated by the National Center for Atmospheric Research showed major shifts in atmospheric circulation patterns coinciding with fluctuations in paleohydrology (Kutzbach 1987, Harrison 1989).

Objectives

The multi-proxy lake-level study at Mathews Pond, T8 R10 WELS, Piscataquis County, Maine had three objectives:

Objective 1: Establish a 10,000-year paleohydrology record for the watershed surrounding Big Reed Forest Reserve (BRFR), Piscataquis County, Maine.

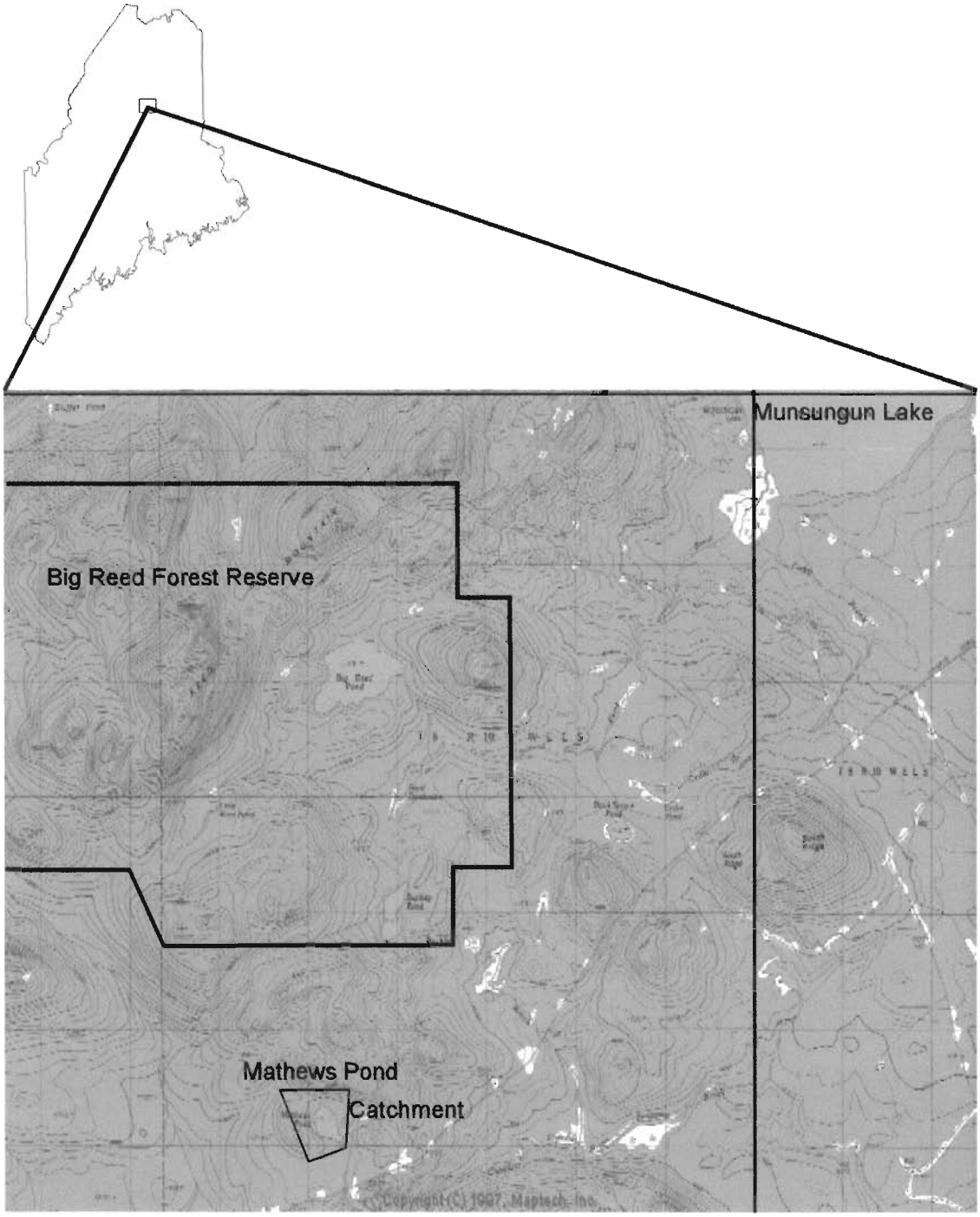


Figure 2 Big Reed Forest Reserve and Mathews Pond, 46^0 19' N, 69^0 3.7' W. Beetle Mountain, Maine, quadrant 46069-C1-TF-024, U.S. Geological Survey, 1989 edition . Image from MapTech Terrain Navigator (www.maptech.com).

Mathews Pond is located 1.5 km south of BRFR, at 1954 ha the largest stand of old-growth forest in New England, 7.5 km southwest of Munsungun Lake, the site of paleamerican chert quarries, and within the same Aroostook River watershed (Figure 2). BRFR is owned and managed by The Nature Conservancy (TNC), and is surrounded by large tracts of privately owned and actively harvested timberland. TNC commissioned University of Maine Department of Forest Ecosystem Science and Institute for Quaternary and Climate Studies to examine recent and natural disturbance regimes that shaped prehistoric forests in northern Maine. TNC will use this information to determine an appropriate spatial scale for northern Appalachian forest reserves and to establish management program that will best conserve the boreal forest ecosystem. TNC hypothesized that "an area large enough to capture, absorb, and reflect the scale of natural disturbances, historic and expected" is a key factor in site viability (Vickery 1999).

Adequate definition of disturbance regimes requires integration of multiple research methods (Foster *et al.* 1996). Begun in 1999, this study will integrate data from dendrochronology, palynology, paleohydrology, spatial analysis, GIS modeling, and historical techniques to examine effects of recurring fire, wind, drought, and disease on the structure of small forest stands (<50 ha), landscapes (*e.g.* 2000 ha), and regions *(e.g.* 3 million ha). Because the hardwood, conifer, and mixed forests of Piscataquis County are part of a similar forest landscape stretching from northern New York through Maine and into the Canadian Maritimes, results of this study may apply to a broad ecoregion. This study provides paleoecologic and paleoclimatic perspectives on the effects of natural disturbance on forest biodiversity.

Objective 2: Construct well-dated, stratigraphic pollen and charcoal records to examine the link between regional hydrologic changes and changes in composition and disturbance regimes of forests in BRFR.

Integration of lake-level data with analyses of fossil pollen and large, air-borne charcoal particles from lake sediments reveals changes in regional vegetation patterns, periods of regional wildfire activity, and the associated effects on groundwater recharge. The 12,000-year regional record from Mathews Pond will be integrated with stand-level data obtained during studies of vegetation history and natural disturbance in BRFR (*e.g.*, Schauffler and Jacobson 2002).

Objective 3: Determine the degree of synchrony of lake-level change for northeastern United States, southeastern Quebec, and Maritime Canada.

When Harrison published her 1989 study, lake-level data was not available from Acadia. Since 1997, data from five sites across Acadia (Table 3: Yu *et al.* 1997, Shuman *et al.* 2001, Newby *et al.* 2000, Almquist *et al.* 2001, Lavoie and Richard 2000) suggested that the time transgressive, mid-Holocene warm, dry period observed in mid-western North America (Wright 1992, Yu *et al.* 1997) extended across northeastern North America. Additional paleohydrology studies from Acadia, at centennial-level resolution and over extended time periods, will identify fine-scale, cyclical shifts in moisture balance and past drought cycles. Comparative data from these studies aid in determining causal factors for changes in regional moisture balance and identify variations between coastal and continental moisture balance.

Water-balance classification

Sensitivity of a lake to climate change depends on several factors: presence or absence of an outlet; water-balance regime of the lake; basin and catchment geomorphology; sediment type; degree of human intervention. Mean annual water balance of a lake is represented by the equation:

$V = A_L(P_L - E_L) + (R - D) + (G_{In} - G_{0ut})$ (Street-Perrott and Harrison, 1985).

V = net change in the volume of lake water. A_L = area of the lake (changes in lake depth are directly related to changes in lake area). P_L and E_L = precipitation onto and evaporation from the lake expressed as depth of the water. R = runoff from the catchment. D = surface discharge through the lake outlet (D = zero for a closed lake. Surface discharge depends on the height of the lake surface over the floor of the spillway. G_{In} and G_{0ut} = groundwater flows into and out of the lake.

The high concentration of lakes around 45^0 N is the result of glacial scouring by northern ice sheets (Street-Perrott and Roberts 1983). Retreat of the Laurentide ice mass left numerous small, closed kettle ponds and ice-scoured basins across northeastern North America. Hydrologic factors relevant to water balance in glacial-terrain lakes include: 1) regime dominance - the relative amount of groundwater in the water budget of the lake; 2) system efficiency - the rate of surface and groundwater movement through a lake system; and 3) lake position within the groundwater flow system (Born *et al.* 1979). Born *et al.* (1979) classified lakes according to regime dominance: groundwater-dominated lakes (seepage lakes); surface water-dominated lakes (flow-dominated lakes); and

atmosphere-controlled lakes (perched lakes). Most lakes fall along a graded continuum, with degree of groundwater inflow and outflow difficult to assess.

Extreme flow-dominated lakes are essentially "wide places in a river" with precipitation and surface runoff flushed out through outlet discharge in <1 to 10 years (Street-Perrott and Harrison 1985). Sediment cores from these lakes are not suitable for paleoclimate studies.

Atmosphere-controlled lakes are closed systems perched on impermeable substrates such as glaciolacustrine or glaciomarine clays. Mansell Pond in Penobscot County, Maine, sits atop thick deposits of Presumpscot Formation clay (Almquist-Jacobson and Sanger 1995, Almquist *et al.* 2001) laid down during a late-Pleistocene marine incursion. The clays provide sufficient seal to separate the lake basin from groundwater influences.

Water level at Mathews Pond, a small, closed-basin, groundwater seepage lake, fluctuates with changes in precipitation, evapotranspiration across the groundwater aquifer, and intermittent, non-channelized surface runoff. System efficiency in basins of this type depends on the groundwater hydraulogic pressure gradient and the permeability characteristics of soils surrounding the lake (Born *et al.* 1979). Groundwater feed into such lakes often occurs along the littoral zone through springs or by diffuse seepage from rising water tables, while groundwater outflow occurs though deep-basin fracture zones (McBride and Pfannkuch 1975).

Depending on topographic lake position within the aquifer drainage system and the height of the groundwater pressure mound, dominant water movement in the lake may be

discharge, recharge, or flow-through. A comparative lake-level study of three lakes located on Parkers Prairie sandplain in west-central Minnesota showed that, while the level of all three lakes lowered between 7.2 ka and 6.7 ka (1 ka = 1000 ^{14}C yr BP), the magnitude of decline (from 2.8 meters to 6.2 meters) was directly proportional to the distance away from the river that drained the sandplain (Digerfeldt *et al.* 1992). That study and related modeling (Almendinger 1990) demonstrated that change in surface hydrology in groundwater-dominated lakes is influenced by external factors beyond P - E ratios.

The internal structure of stratified lake sediments is determined by the dominant sediment distribution mechanism at time of deposition (Dearing 1997). Mechanisms that influence lake sedimentation include: 1) sliding, slumping, and turbidity currents on underwater slopes with inclines as low as 4^0; 2) wave action along shore lines; 3) random sediment redistribution from wave action on the lake bed where sediment accumulation is independent of water depth; and 4) intermittent mixing following temperature stratification overturn, where sediment accumulation rate is proportional to water depth (Dearing 1997, Nichols 1999, Håkanson and Jansson 2002). Rich vegetative growth in littoral zones may reduce resuspension and thereby increase loading of organic sediment. Organic loading and vegetative encroachment ultimately result in natural lake in-filling. Lakes best suited for lake-level studies are those in which temperature stratification is the dominant sediment distribution mechanism (Dearing 1997).

Site selection

Appropriate site selection is the critical first step in unraveling these intertwined, sedimentary processes. Small, closed-basin ponds with no inlet, no outlet, and relatively small catchment areas reveal past changes in regional water balance better than large water bodies with extensive catchment regions and complex, external influences on sediment deposition. When the catchment region is relatively small, less exogenous sand and gravel, pollen, and organic debris enter the lake in surface runoff. Minimization of surface runoff more closely links changes in sediment deposition to changes in catchment area hydrology (precipitation and evapotranspiration effects on local ground water levels) (Dearing 1997). Lakes of areal distribution <50 ha, depths of <10 m, catchment/lake area ratios less than 5:1, and with littoral vegetation growing along sheltered, gently sloping shores best exhibit distinct, stratified, sediment units (Digerfeldt 1986; Dearing 1997).

Digerfeldt (1986) pioneered analytic techniques to reconstruct past lake fluctuations according to changes in distribution of littoral vegetation, sediment composition, and level of deep-water sediment deposition. Digerfeldt's multi-proxy, multi-core methodology has been expanded to accommodate the diversity of trophic states, temperature stratification, and geophysical composition found in small, temperate-region lakes (Dearing 1997, Almquist *et al.* 2001, Dieffenbacher-Krall and Halteman 2000, Håkanson and Jansson 2002, Dieffenbacher-Krall 2003).

Sedimentary evidence of lake-level change varies with changes in lake geochemistry and topography. Multiple sediment cores, taken in a transect from the deepest point to the near-shore zone, are examined, often at centimeter-scale, for evidence

of lake-level change. Analytical methods are designed to identify the following independent lines of sediment evidence: 1) progradation and aggradation of littoral vegetation relative to the lake center, deduced from the presence of coarse organic matter (Digerfeldt 1986) or from aquatic macrofossil assemblages (Hannon and Gaillard 1997, Dieffenbacher-Krall and Halteman 2000); 2) distinct transitions between sediment types that are linked to specific hydrological conditions, *i.e.*, peat overlain by gyttja; 3) coarse, minerogenic layers identified by visual description or by clastic grain-size analysis; 4) loss-on-ignition (LOI) analysis to identify changes in bulk density, organic content, and carbonate content. While vegetation response time of <200 years has been documented for climatic temperature shifts, only a few studies (*e.g.*, Williams *et al.* 2002, Almquist and Sanger 2000, Almquist *et al.* 2001) relate changes in regional vegetation to changes in regional water balance.

Site-to-site comparisons

Climate-driven changes in lake levels are inferred by correlating data from independent lake-level studies across a region. Catchment-driven changes in lake levels are identified by correlating changes in lake level with landscape changes surrounding the watershed.

Differences in timing of reconstructed paleohydrologic events at sites across a broad geographic region may result from the time-transgressive nature of the causal event, or from different methodologies, lake-basin morphologies, or discrepancies in age/depth correlations. Time transgressive changes in water balance across northeastern North

America, *e.g.*, the warm, dry mid-western prairie period (Baker *et al.* 1992, Wright 1992) and its extension eastward into southern Ontario (Yu *et al.* 1997) and into Maine (Dieffenbacher-Krall 2003, this study), are identified by comparison of lake-level studies across a continental transect.

Short-term or localized changes in groundwater levels, not apparent across a geographic region, may result from changes in local landscape, *e.g.*, forebulge migration during isostasy, vegetation change, forest fire, and altered land-use. High-resolution charcoal and pollen analysis, along with a thorough history of local land-use, augment centennial-scale lake-level resolution.

Most difficulties in correlating lake-to-lake, or even core-to-core data, result from inadequate chronologies. Radiocarbon dates with one standard deviation >100 ^{14}C years carry a potential uncertainly of >200 years. Bulk sediment dates from zones with low sedimentation rates may span hundreds of years. Water-residence time in closed lake basins may exceed fifty years (Street-Perrott and Harrison, 1985). Aquatic plants may take up old carbon from aquatic carbon reservoirs during photosynthesis. The large number of dates required to compile an accurate and precise age-depth curve for each core sometimes exceeds the available budget. Dating precision is further compromised when radiometric dates are converted to calendar years. Unless otherwise specified, all dates in this study are reported as radiocarbon years before present.

Chapter 2

METHODS

Mathews Pond (Figure 3) is a 7.4 ha pond with no inlet and a high-water, seepage outlet of 0.3 meters over an ice-deposited, boulder sill. Maximum depth of the pond is 5.5 meters. The glacially-scoured basin sits in Devonian-age, volcanic tuff bedrock (Hall 1970) overlain by an unconsolidated, glacial till layer of gravel and boulders. Mathews Pond formed as glacial meltwater filled the basin. The low topographic relief surrounding the pond and a catchment/lake area ratio of ~3:1 buffer surface runoff into the pond from storms and melting snow pack.

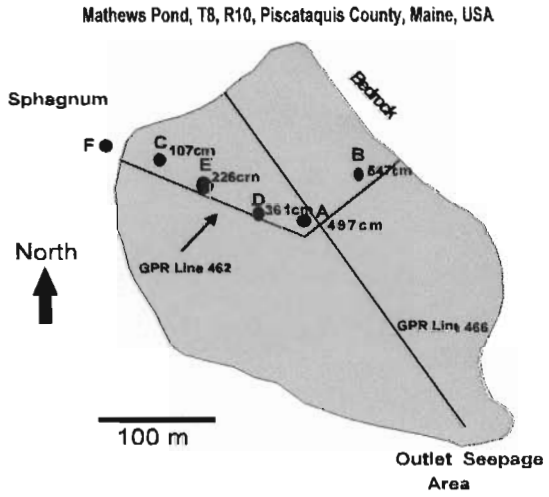


Figure 3 Mathews Pond with core sites and Ground Penetrating Radar (GPR) pathways.

Ground Penetrating Radar

PulseEKK0 100 Ground Penetrating Radar (GPR) manufactured by Sensors and Software was used to chart the bathymetry of the basin and the depth, distribution, and stratigraphy of lacustrine sediments at Mathews Pond. The unit was compact and portable

enough that three people transported the equipment over 0.5 km of rough terrain. GPR is operational through ice or through the flat bottom of a non-metallic boat or raft (Belknap, personal communication). Because motorized vehicles create electromagnetic (EM) noise, we conducted the survey at Mathews Pond from a paddle-propelled, ABS plastic canoe. Transmitter and receiver antennae were placed one meter apart on either side of the center of the canoe. As the canoe traveled along north-south and east-west transects, the transmitter antennae emitted 100 Mhz EM pulses at regular time intervals. Each pulse was differentially reflected back to the receiving antennae by interface surfaces of stratified lake sediments. The receiver amplified and digitalized reflected pulses, and then passed the information to the control unit. Digital pulses were converted to "time versus energy" data points known individually as trace points. When trace points were plotted side-by-side along the transect profile, they combined to create a digital image of the reflective surfaces. GPR mapping depends on the physical and EM (*i.e.*, electrical conductivity, dielectric constant, velocity of EM pulse, attenuation of EM energy, and reflective coefficient) contrasts between water and lacustrine sediments (Moorman 2001).

Sediment collection

Five lake-sediment cores were collected across a water-depth gradient in June of 1999 using a Wright, 7.5-cm diameter, square-rod, piston corer (Wright 1967) for all but the loose, surface gyttja. As each meter-long section of core was extruded from the core barrel, the section was measured, and the visible stratigraphy was recorded. Cores were

wrapped in plastic, transported to the laboratory within 48 hours, and stored at 5^0 C until analyzed.

Surface-sediment cores were obtained with an 8-cm diameter transparent pipe. The pipe was attached to metal rods and gravity-fed into the surface sediments. An internal piston held surface sediments in the pipe; the bottom of the pipe was capped with a gasketed stopper before the pipe and core broke the water surface. Surface cores were transported to the shore in an upright position, and the sediment was extruded in five-cm sections starting at the sediment/water interface. Whirlbags containing the samples were transported to the laboratory within 48 hours, and stored at 5^0 C until analyzed.

A pond-side peat core (MPF) was obtained with a 10-cm Russian corer in October 1998. The 73-cm core was wrapped in plastic, transported to the laboratory within 24 hours, and stored at 5^0 C until analyzed. Water seepage into the core hole showed the surface of the core to be six centimeters above current lake surface.

Sediment analysis

All cores were visually examined in the field immediately after extrusion. Core photographs obtained in the laboratory failed to achieve the resolution necessary to show sediment changes in the dark gyttja. Analysis of X-ray images revealed subtle changes in sediment density not visible by eye. Each meter-long core section was divided lengthwise into 1/3 by 2/3 sections. The larger portion was retained for analytical sampling; the smaller section was wrapped in plastic and archived at 5^0 C.

Analyses for bulk density, total inorganic content (loss-on-ignition), and carbonate

content followed Bengtsson and Enell (1986) and were simultaneously performed on core MPA. For physical analyses, sediment samples of 2-cm^3 were taken at 0.5-cm to 1-cm intervals from all cores. Because bulk density showed minimal variation and carbonate content was less than 4% of sediment by weight in MPA, these parameters were not assessed in the remaining cores. Total inorganic content was measured at 0.5-cm to 1-cm intervals in all cores.

All cores were simultaneously examined at 2-cm to 5-cm intervals for change in inorganic particle (clast) size, charcoal content, and plant macrofossil content. Sediment samples ranging from 20 cm^3 to 100 cm^3 were measured by liquid displacement in a 5% solution of potassium hydroxide. Samples incubated in 5% KOH for one hour at 50^0C (or overnight at room temperature) to break up the soil matrix and dissolve humic acids. Each sample was then gently washed through 500 μm, 250 μm, and 63 μm wire sieves. After examining the 500 μm and 250 μm sieved portions for charcoal and plant macrofossils, all size fractions were heated in a muffle furnace for two hours at 550^0 C. Combined weights of the ash residue at each sample interval were calibrated to 100 cm^3, and the percent of clastic particles larger than silt and clay (>63 μm) calculated.

Charcoal particles

Contiguous, 2-cm to 5-cm bulk-sediment slices of 20 cm^3 to 100 cm^3 were taken along the core. This sampling regime identified periods of forest fire activity rather than individual fire events. Bulk samples were gently washed through 500 μm and 250 μm wire sieves. The entire sieved sample was placed in a channeled tray or gridded petri dish,

covered by water, and scanned under a Nikon SMZ-U dissecting microscope. Charcoal particles were identified and counted simultaneously with plant macrofossils. Charcoal identification counted only fragments that were black, completely opaque, angular, and highly reflective. Recorded number of charcoal particles in each sample level were standardized to 100 cm^3 of sediment and plotted using Tilia and TiliaGraph programs (Grimm 1994).

Plant macrofossil analysis

Macroscopic plant remains were identified to the lowest possible taxonomic level with reference to Martin and Barkley (1961), Montgomery (1977), Lévesque *et al.* (1988), and Holmgren (1998). All identifications were verified by comparison with the extensive reference collection of seeds, fruit, and preserved plant parts at the Laboratory of Quaternary Paleoecology and Paleohydrology, University of Maine. Ann Dieffenbacher-Krall (Climate Change Institute, University of Maine) provided assistance with some identification. Nomenclature follows Gleason and Cronquist (1991). Recorded numbers of individual plant macrofossils in each sample level were standardized to 100 cm^3 of sediment, grouped by hydrologic preference, and plotted in Tilia and TiliaGraph programs (Grimm 1987).

Submergent macrofossil assemblages included aquatic plants with either submerged leaves (*i.e., Chara* spp., *Nitella* spp., and *Najas* spp.) or floating-leaved aquatics generally found in deeper water regions (*i.e.*, *Potamogeton* spp., *Nuphar*, and *Brasenia*). Macrofossils classified as emergent species were those plants commonly found

in shallow waters less than 0.5 m or along muddy shores. Facultative hydrophytes were defined as species occurring in wet soils, but also tolerant of terrestrial conditions (Dieffenbacher-Krall and Halteman 2000). Terrestrial macrofossils signified the presence of upland species.

Pollen analysis

Pollen analysis was done on core MPB, the longest and only continuous core. In an effort to achieve 100 to 200-year resolution during post-glacial and early-Holocene transitions, 1-cm^3 samples were counted at 0.5 to 2-cm intervals along core section 915-cm to 800-cm. The remainder of the core (800-cm to 550-cm surface sample) was examined at five-cm intervals to identify broad trends in vegetative change. Pollen analyses were conducted at the Laboratory of Quaternary Paleoecology and Paleohydrology, University of Maine. Pollen concentration techniques were developed from chemical and physical methods presented by Faegri *et al.* (1989). After deflocculation of the original 1-cm^3 sample, extraneous matter (calcium carbonate, humic acids, coarse particles, and siliceous matter) was either sieved or dissolved out of the sample. The remaining sediment was suspended in silicon oil, and permanently mounted on a glass slide under a 24x24 mm coverslip. Working on a Nikon Phase microscope at 40X, a minimum of 300 arboreal and herbaceous pollen cells were counted and identified. Pollen identification guides included the extensive pollen reference collection at the Laboratory of Quaternary Paleoecology and Paleohydrology, University of Maine, and identification keys in Faegri *et al.* (1989), Moore *et al.* (1991), and McAndrews *et al.*

(1973). *Picea* pollen was identified to species using binary regression classification techniques developed by Lindbladh *et al.* (2002). Pollen data were plotted in percentage diagrams using Tilia and TiliaGraph programs (Grimm 1994), and local pollen assemblage zones were based on stratigraphically constrained cluster analysis (CONISS) (Grimm 1987).

Radiocarbon dating

I obtained twenty-eight radiocarbon dates from the six cores on samples of bulk sediment and terrestrial macrofossils. Dated material taken from the base of sediment transitions represented the minimum age of initiation of the overlying unit. Where macrofossil-poor sections precluded AMS dating, low carbonate content in the lake sediment allowed use of bulk gyttja samples. All samples were dried, weighed, and submitted to Beta Analytic Incorporated for standard radiocarbon dating. Beta Analytic pre-treated bulk gyttja samples with an acid wash. Age determinations on bulk samples included both soluble and insoluble fractions. The radiocarbon time scale is used throughout this report to minimize calibration error and to facilitate systematic regional correlation of lake-level change data.

Chapter 3

RESULTS

Ground penetrating radar

A north-to-south GPR transect (Figures 3 and 4) showed a gently sloping littoral zone along the north shore, abrupt deepening at the center of the pond, and sediment accretion into the basin at the seepage outlet. The east-to-west transect (Figures 3 and 5) identified the deepest point of the basin as off the rock outcrop along the eastern shoreline. The deep basin extended to the middle of the pond to a low hummock 20 meters west of the outcrop. From the hummock, the sediment interface rose westward in a gradually sloping littoral zone. Figures 5 and 6 show approximate locations of five lake-sediment cores along the east-to-west transect. Core MPF was taken from the shoreline heath zone.

Lacustrine Material	Velocity m/ns
Fresh water	0.033
Loose, surface gyttja	0.035
Coarse organics	0.037 - 0.038
Deep water gyttja	0.034 - 0.037
Silt and clay	0.035 - 0.038

Table 1 Effective EM pulse velocity of lacustrine sediments at Mathews Pond, T8 R10 WELS, Maine, USA. Velocity values in meters/nanosecond are based on reflectors in the cores and on velocity values listed in Pulse EKKO 100 Run User's Guide (1996).

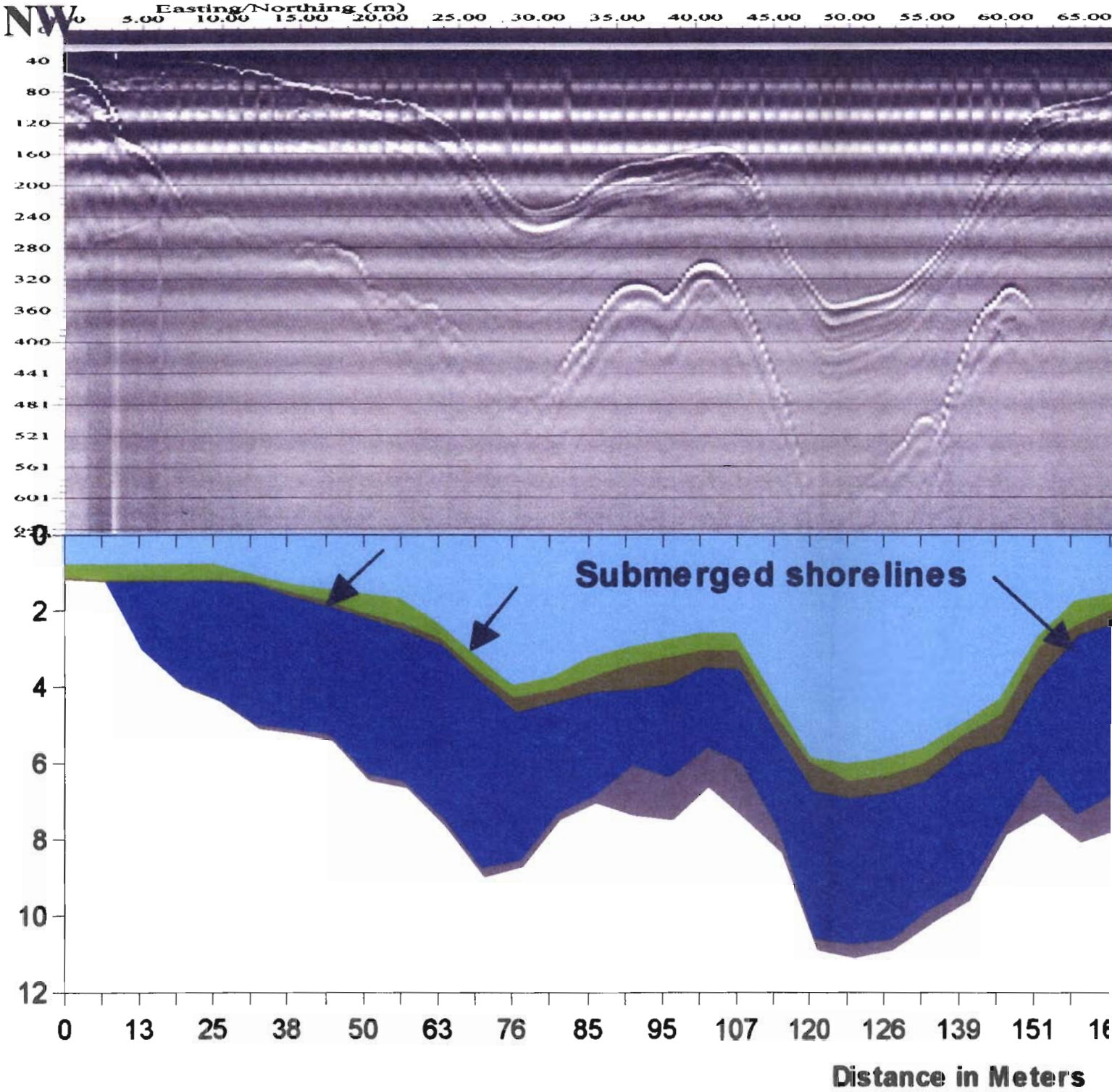
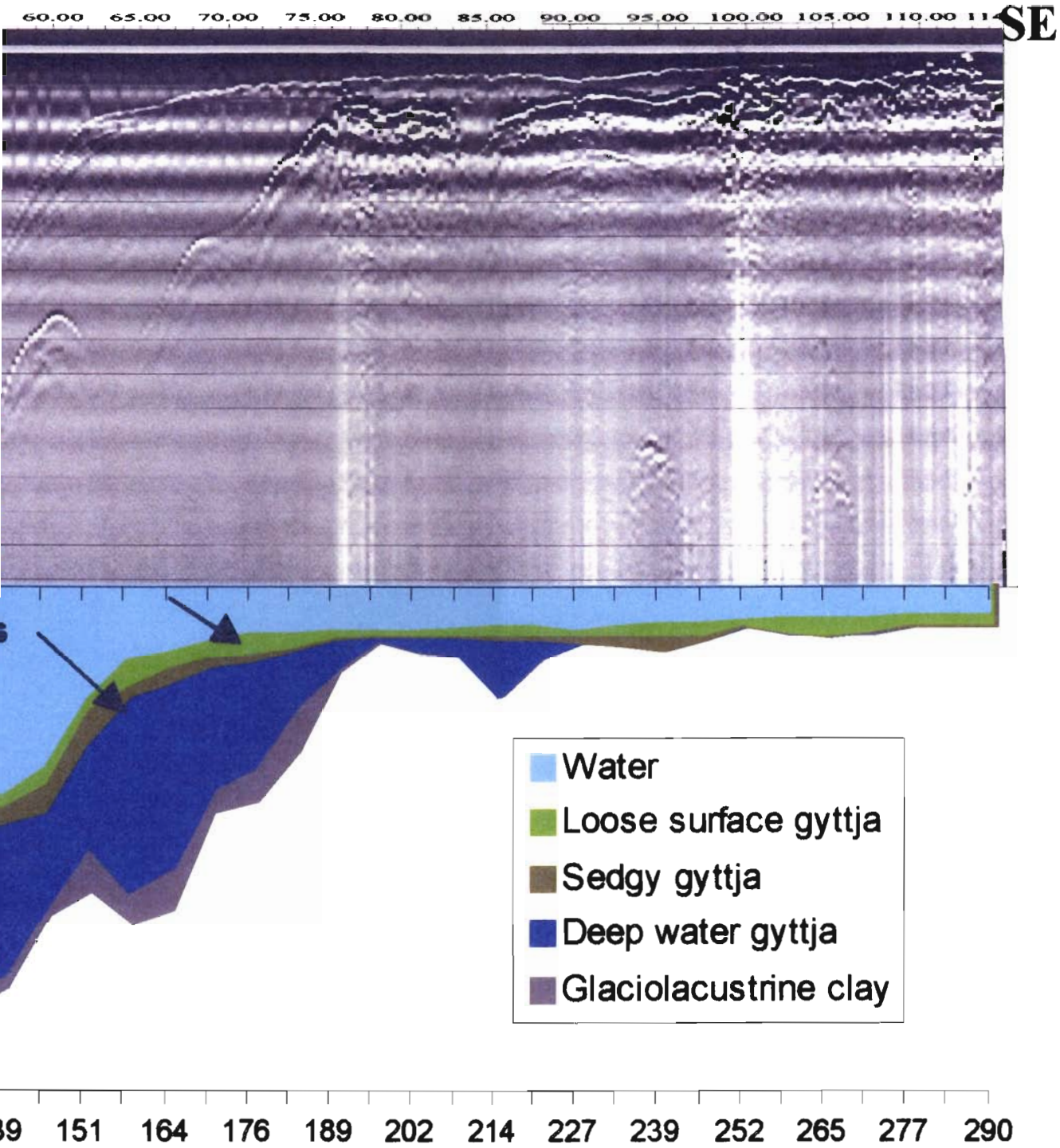


Figure 4 Top: GPR image along northwest to southeast transect. Y-axis represents two-way pulse travel time in meters/nan
Bottom: Graphic sediment interpretation of GPR image. Arrows indicate possible submerged shorelines. Mathews Pond lake-l



39 151 164 176 189 202 214 227 239 252 265 277 290

in Meters

me in meters/nanosecond. Effective sediment velocities are listed in Table 1.
thews Pond lake-level curve (Figure 18) suggests that water did not spill over the sill until ~ 1.5 ka.

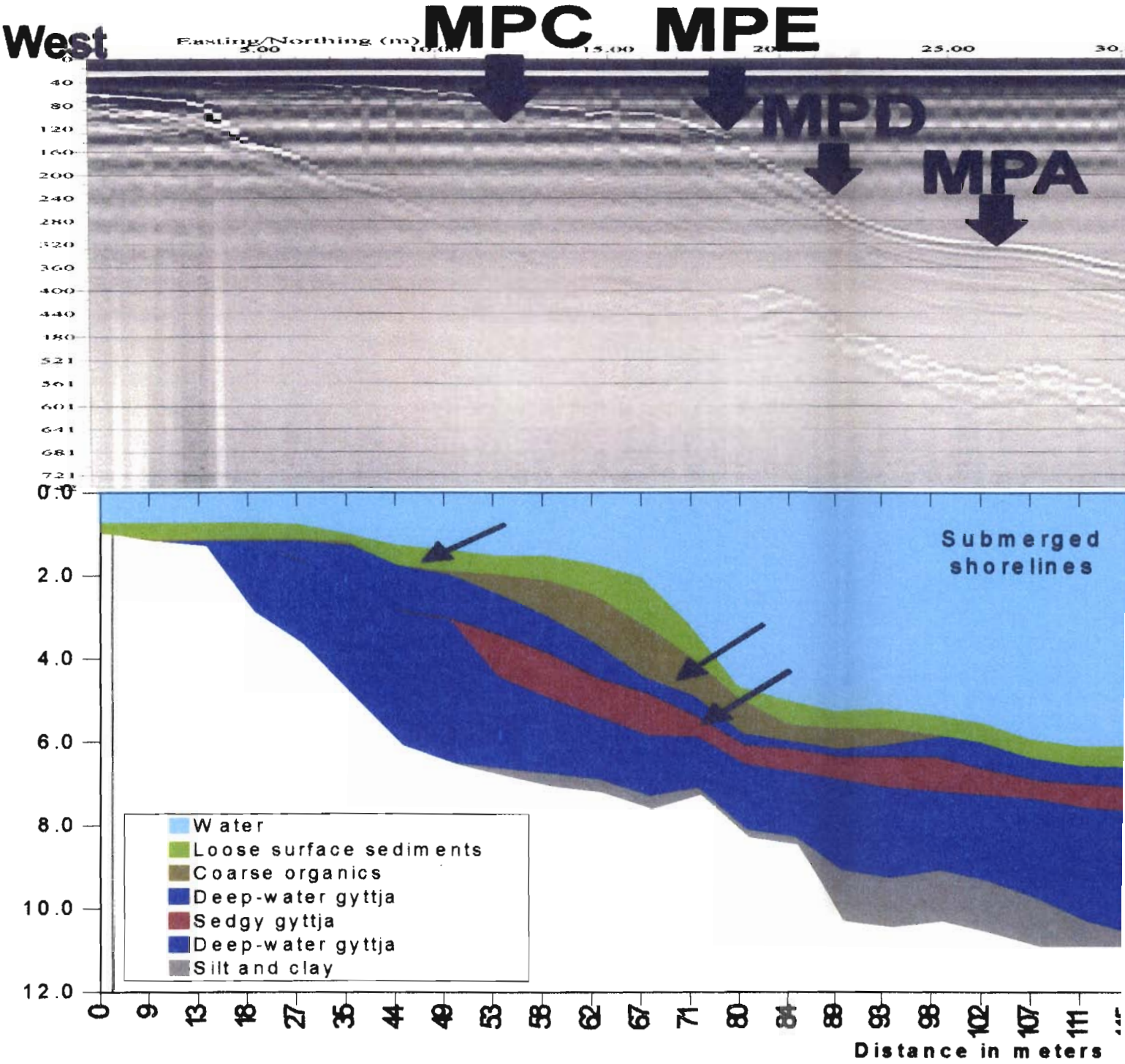
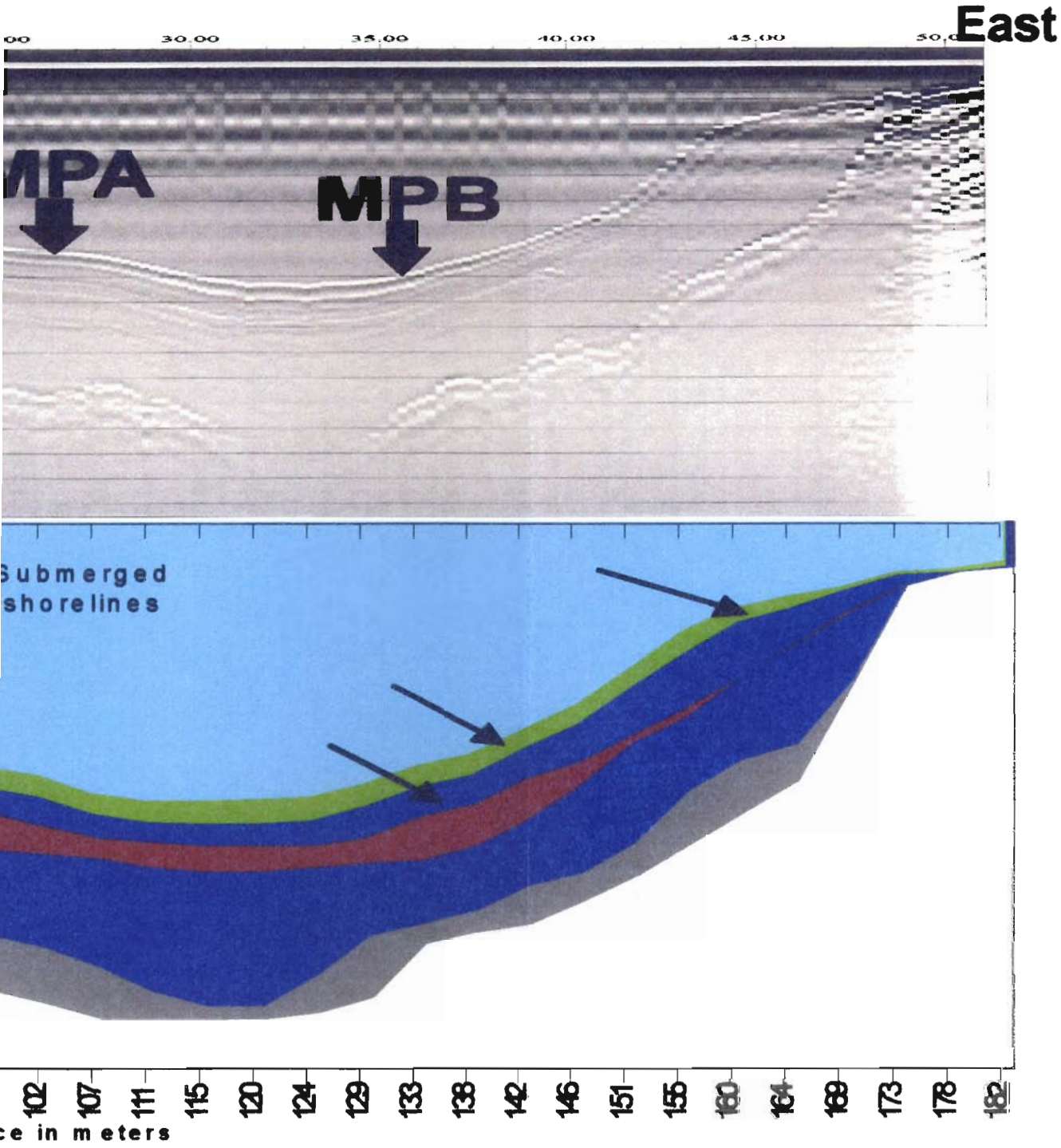


Figure 5 Top: GPR image of Mathews Pond core transect with inferred core sites. Y-axis represents two-way pulse trav
Cliniform strata at the Core MPE site suggest prograding sedimentation associated with natural lake in-filling..
Bottom: Graphic sediment interpretation of GPR image. Arrows indicate possible submerged shorelines.



s two-way pulse travel time in meters/nanoseconds. Effective sediment velocities listed in Table 1.
in-filling..
nes.

Chronology

Age models were developed by linear interpolation between radiocarbon dates (Table 2, Figure 18). Because sediment accumulation rates vary among sediment types, dates bracketed changes in sediment type whenever possible. Except for MPB and MPF, all cores contained disconformities. These abrupt sediment transitions occurred between glaciolacustrine deposits and overlying gyttja in MPA, MPD, and MPE. Although no sediment transition was visually or geochemically obvious in the upper portion of MPC, a date of 5.14 ka just 60 cm below the sediment/water interface strongly suggested a disconformity.

Sediment units

Sediment cores included six types of sediment: 1) deep-water gyttja - olive green gyttja composed of >45% fine-grained, organic materials; 2) sedgy gyttja containing either visible sedge-like plant material or abundant aquatic and emergent macrofossils; 3) rhythmic banding - alternating light and dark bands; 4) light gray gyttja - clear to gradual transitional zones between deep-water gyttja and glaciolacustrine clay containing 45% - 20% fine-grained, organic materials; 5) glaciolacustrine clay - blue gray, fine-grained sediment containing <20% organic materials; 6) angular sand and gravel - medium to coarse-grained sand and small, glacially-striated pebbles. Figure 6 diagrams individual core stratigraphy, and profiles sediment units across the basin.

Beta Analytic Lab number	Core	Depth (cm) below modern water surface	Material	$^{13}C/^{12}C$ Ratio	^{14}C yr (years BP)	Calibrated calendar years BP
171686	MPA	640-645	gyttja	-25.0 o/oo*	4380+/-120	4915
171687	MPA	750-755	gyttja	-25.0 o/oo*	8160+/-170	9082
171688	MPA	795-800	gyttja	-25.0 o/oo*	9250+/-110	10451
165209	MPB	655-660	gyttja	-30.8 o/oo	3380+/-70	3634
165210	MPB	722	seeds, leaves	-25.5 o/oo	4020+/-40	4477
165211	MPB	745	wood	-24.0 o/oo	5020+/-40	5742
165212	MPB	799.5	bark	-23.7 o/oo	6860+/-40	7676
171689	MPB	825-830	gyttja	-25.0 o/oo*	8430+/-160	9472
168756	MPB	870-875	gyttja	-25.0 o/oo*	11010+/-130	13002
171691	MPD	447-452	gyttja	-25.0 o/oo*	1730+/-100	1644
168750	MPD	510-515	gyttja	-25.0 o/oo*	3050+/-70	3296
168751	MPD	560-565	gyttja	-25.0 o/oo*	4910+/-70	5627
168752	MPD	625	seeds	-22.5 o/oo	5890+/-40	6745
168753	MPD	683-688	gyttja	-25.0 o/oo*	9420+/-160	10635
168754	MPD	690-695	gyttja	-25.0 o/oo*	10180+/-100	11830
168755	MPD	695-700	gyttja	-25.0 o/oo*	11470+/-150	13444
171692	MPE	355-360	sedge gyttja	-25.0 o/oo*	1260+/-90	1205
171693	MPE	458-467	gyttja	-25.0 o/oo*	3020+/-70	3226
171694	MPE	533-542	gyttja	-25.0 o/oo*	4000+/-70	4477
171695	MPE	620-625	gyttja	-25.0 o/oo*	6160+/-120	7091
171696	MPE	700-705	gyttja	-25.0 o/oo*	9160+/-110	10316
173757	MPC	167-172	charcoal	-26.2 o/oo	5140+/-50	5911
173758	MPC	200-205	gyttja	-25.0 o/oo*	7280+/-70	8104
173759	MPC	238-243	gyttja	-25.0 o/oo*	8340+/-70	9380
173760	MPC	293-298	gyttja	-25.0 o/oo*	10050+/-100	11490
173755	MPF	27	wood	-27.1 o/oo	270+/-40	305
177871	MPF	40	seeds	-26.4 o/oo	4380+/-40	4950
173756	MPF	60	wood	-28.8 o/oo	5430+/-50	6235
165213**	MPF	73	sedge, grass	-27.0 o/oo	2170+/-40**	

* Estimated $^{13}C/^{12}C$ values based on values typical for gyttja.

** AMS Radiocarbon date disregarded as too young for statigraphic position.

Beta Analytic Inc. reported all dates as radiocarbon years before 1950 A.D. Modern reference standard was 95% of the ^{14}C content of the National Bureau of Standards's oxalic acid, and was calculated using the Libby 14C half life of 5568 years. Quoted errors represent 1 standard deviation (68% probability) and are based on combined measurements of the sample, background, and modern reference standards. Measured 13C/12C ratios were calculated relative to the PDB-1 international standard and radiocarbon ages normalized to -25 per mil. Radiocarbon ages (14C yr) were converted to calendar year (cal yr) notation with Calib 4.3 computer programming (Stuiver and Braziunas 1993, Stuiver et al. 1998a, Stuiver et al. 1998b).

Table 2 Radiocarbon dates for cores MPA, MPB, MPD, MPE, MPC, and MPF from Mathews Pond.

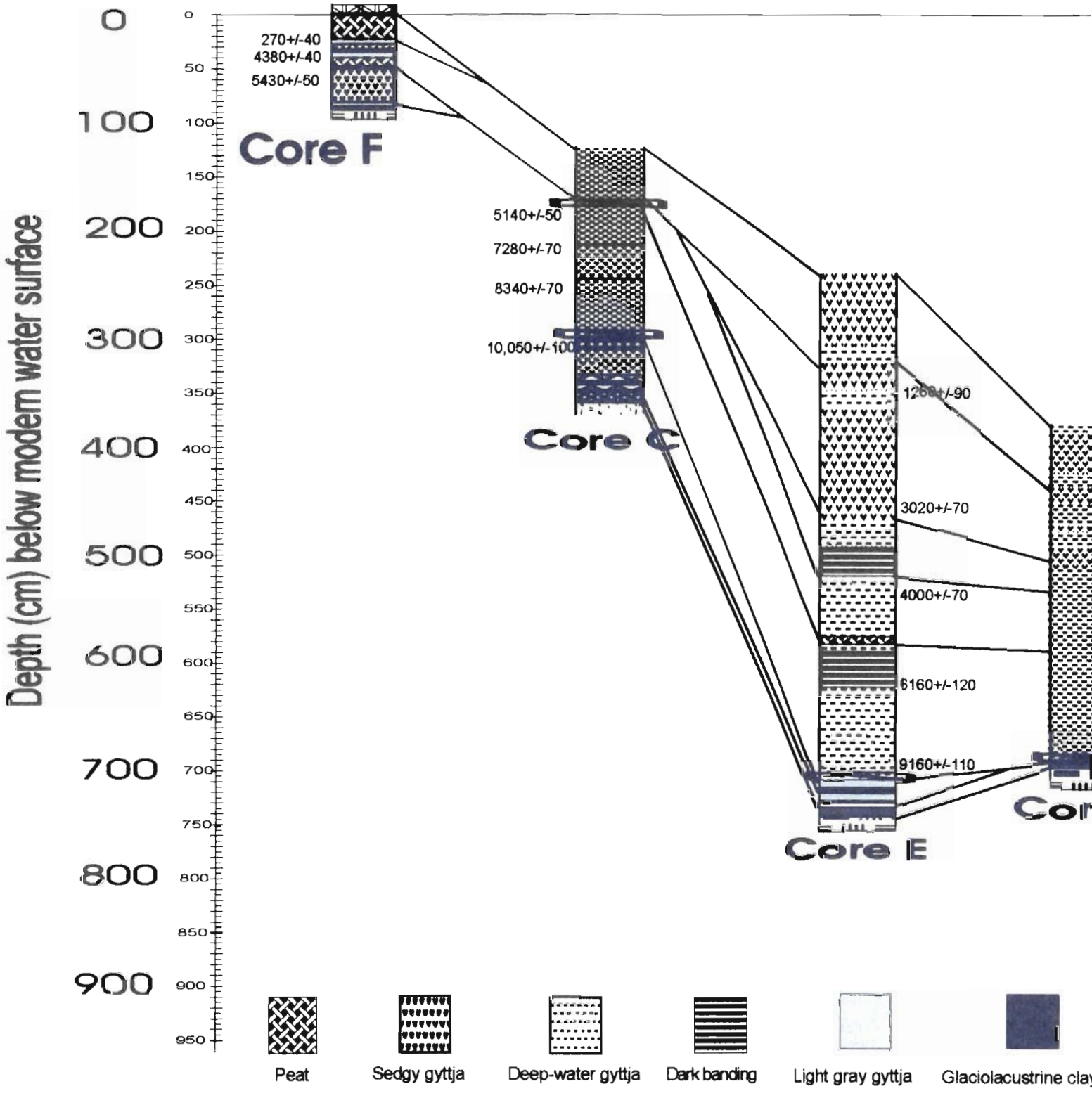
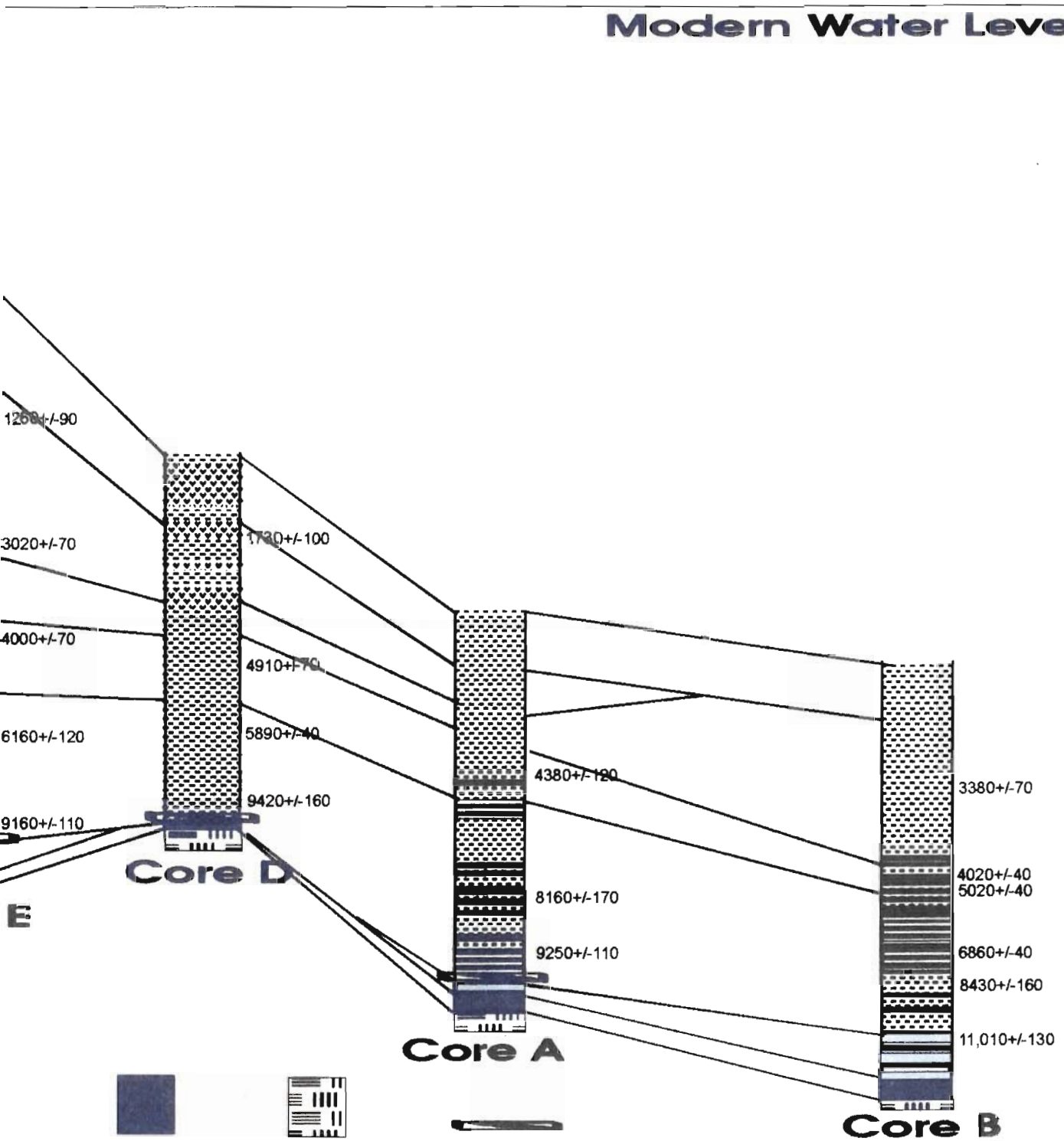


Figure 6 Lithic fence diagram of Mathews Pond sediment distribution. Y-
water surface. Inferred core positions indicated by layout along X-axis. Fe



t distribution. Y-axis marks core depth below modern
along X-axis. Fence diagram connects contiguous sediment layers.

Sediment analysis

Clastic grain size provided the strongest indication of lake-level change. Changes in grain size for cores MPF, MPE, MPD, MPA, and MPB are summarized in Figure 7. Inorganic content, clastic grain size, carbonate content, and macrofossils for core MPA are diagramed in Figure 9. Figures 8, 10, 11, and 13 diagram inorganic content, clastic grain size, and macrofossils for cores MPB, MPD, MPE, and MPF respectively. Inorganic content in core MPC is shown in Figure 12.

Macrofossil analysis

Although Mathews Pond displayed distinct *Chara* and *Nitella* oospore and *Najas* seed peaks, except for the shoreline core MPF, no cores displayed a clear relationship between aquatic seed deposition and water depth. Heavy, terrestrial macrofossils, such as *Pinus* and *Picea* needles, sink rapidly and tend to collect in shallower water along shorelines (Hannon and Gaillard 1997). Terrestrial macrofossils were present in all cores, but quantities did not fluctuate to a degree that suggested shoreline advancement or regression. Sedge-filled layers of macrofossil-poor gyttja provided the most direct evidence of lake-level low stands. Full macrofossil diagrams for each core are presented in Appendix A.

Sample resolution of charcoal particles larger than 250 μm identified millennial-scale periods of fire activity in the Mathews Pond region. Charcoal particle deposition is included in the stratigraphic interpretation, because increased charcoal deposition suggests a drier environment.

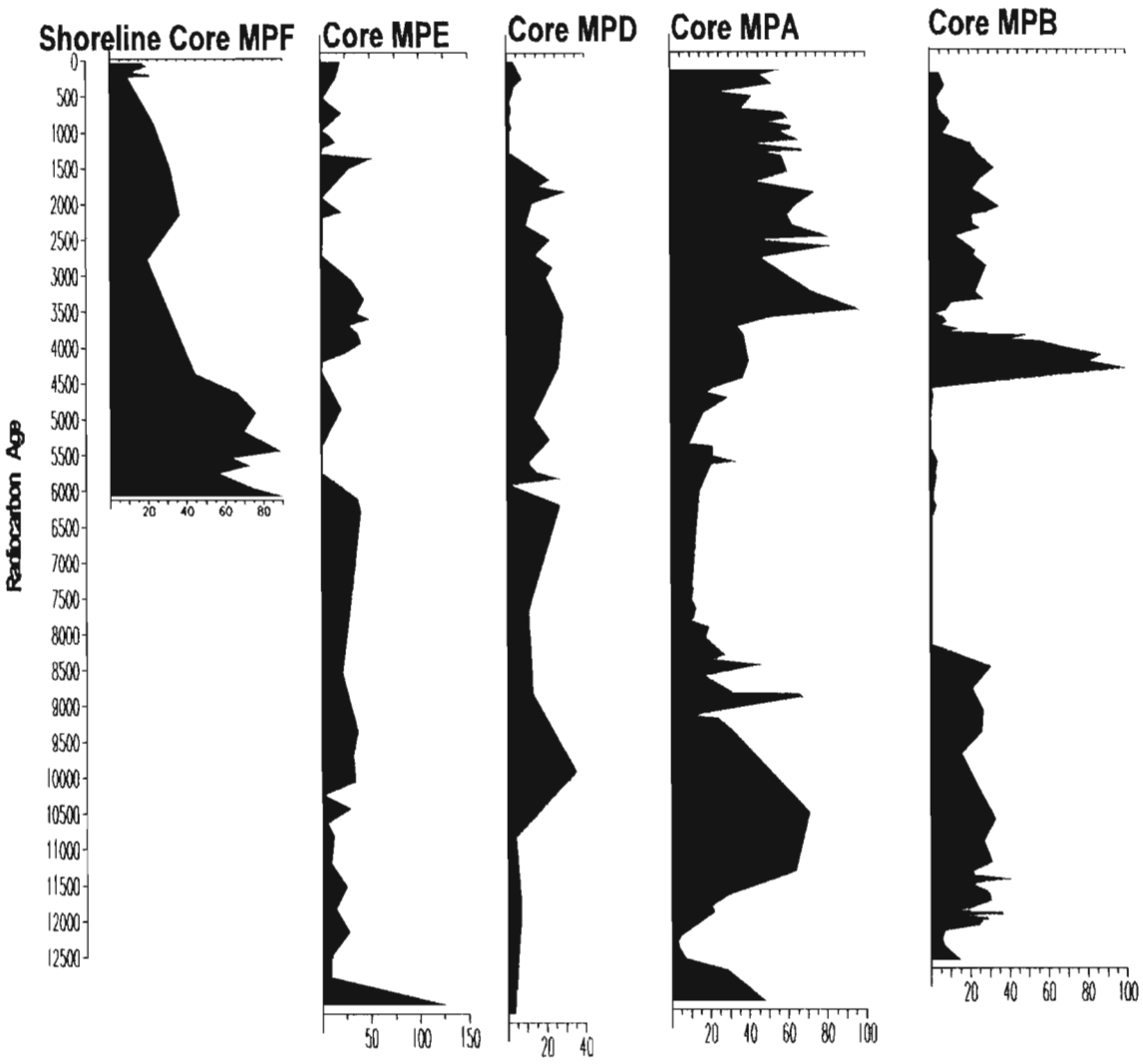


Figure 7 Comparison of changes in clastic grain size in Mathews Pond cores. X-axes represent percent of total solids by weight larger than .63 mm. Cores are arranged in order of water depth left to right. Y-axes are scaled to radiocarbon age.

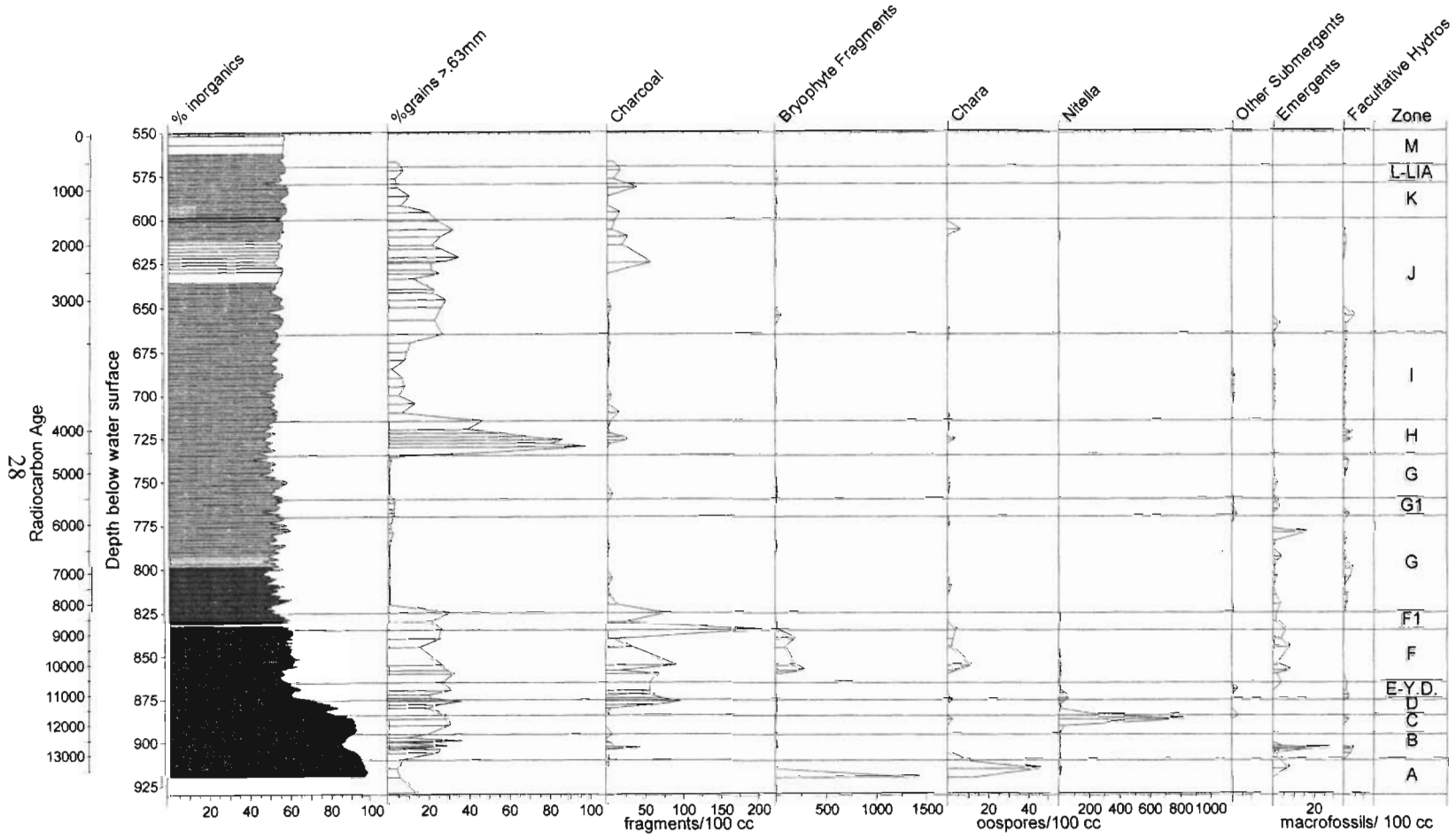
Chapter 4

STRATIGRAPHIC INTERPRETATION

Because MPB was the deepest and only continuous core, sediment zones indicating changes in water level were established in MPB and applied to cores MPA, MPD, and MPE. All cores bottomed in blue-gray, glaciolacustrine clay underlain by sand and gravel. These layers of glacial till and silty outwash draped the entire basin and are designated Zone A. Sediment draping compressed stratigraphic units as the basin floor rose into the littoral zone. Imperfect age-depth correlation between cores complicated zone correlation.

Disconformities in core stratigraphy formed during periods of non-deposition or from rapid sediment decomposition, when the sediment surface was exposed to the air. Surface erosion during periods of rising water levels could also create sediment disconformities. In either case, disconformities were associated with low-water periods. Conversely, rhythmic banding may represent periods when the lake was deep enough to experience thermal stratification and seasonal turnover.

Figure 8 Core MPB summary of lithic and macrofossil analyses: inorganic content, grain size, charcoal, and macrofossils. Zones A-M indicate changes in sediment composition related to changes in water depth.



Core MPB (modern water depth 547 cm; Figures 8 and A.1)

Zone A: Proglacial outwash of medium to coarse sand and small pebbles is overlain by silt and clay with <5% organic material. A macrofossil assemblage dominated by *Chara* and emergent species suggests a shallow pond surrounded by sedge wetlands. The peak in bryophyte fragments, along with an increase in clastic grain size, may signal a period of high-energy terrestrial runoff, perhaps from snow melt or heavy storms.

Zone B: Ten percent increase in organic content, an increase in macrofossil emergent species, and rhythmic banding indicate deeper, quieter water. Large charcoal particles from 13.0 ka to 12.0 ka indicate fire activity.

Zone C: Increased inorganics, increased clastic grain size, and low abundance of aquatic, emergent, and facultative hydrophile macrofossils suggest a period of low water.

Zone D: Decrease in inorganics, decrease in clastic grain size, and rhythmic banding suggest an increased lake level.

Zone E: A radiocarbon date of 11,010 +/-130 years identified the lower boundary of Zone E as the start of the Younger Dryas chronozone. Increase in inorganics, increase in clastic grain size, high charcoal levels, and low sedimentation rate suggest a dry environment and low water level in the pond.

Zone F: Percent inorganics and clastic grain size remain high for most of this period, indicating a low lake level for at least the first Holocene millennium. Increased macrofossils of emergent species also suggest a wide littoral zone. Charcoal levels remain high, with a distinct peak corresponding to a dark band in the core at 837 cm.

Zone G (8.3 ka to 4.8 ka): Increased sedimentation rate, stable inorganic content, fine-

grained clastic sediments, and rhythmic banding indicate deep water. Decline in grain size at 820 cm and increase in grain size at 730 cm are clear transitions into and out of this period. Marked decline in charcoal suggests a more humid environment. Slight increase in inorganic content and clastic grain size signal a decrease in water level between 6.5 ka and 7.6 ka (Zone G_1, Figure 8). An increase in terrestrial macrofossils in Zone G_1 (Figure A.1) suggests shoreline encroachment of trees and shrubs.

Zone H (4.8 ka to 4.0 ka): Clear transitional increase in clastic grain size, thin coarse organic layers, and low sedimentation rates indicate low water level. Lack of aquatic macrofossils, increased facultative hydrophile and terrestrial macrofossils, and increased charcoal deposition all suggest a drier environment.

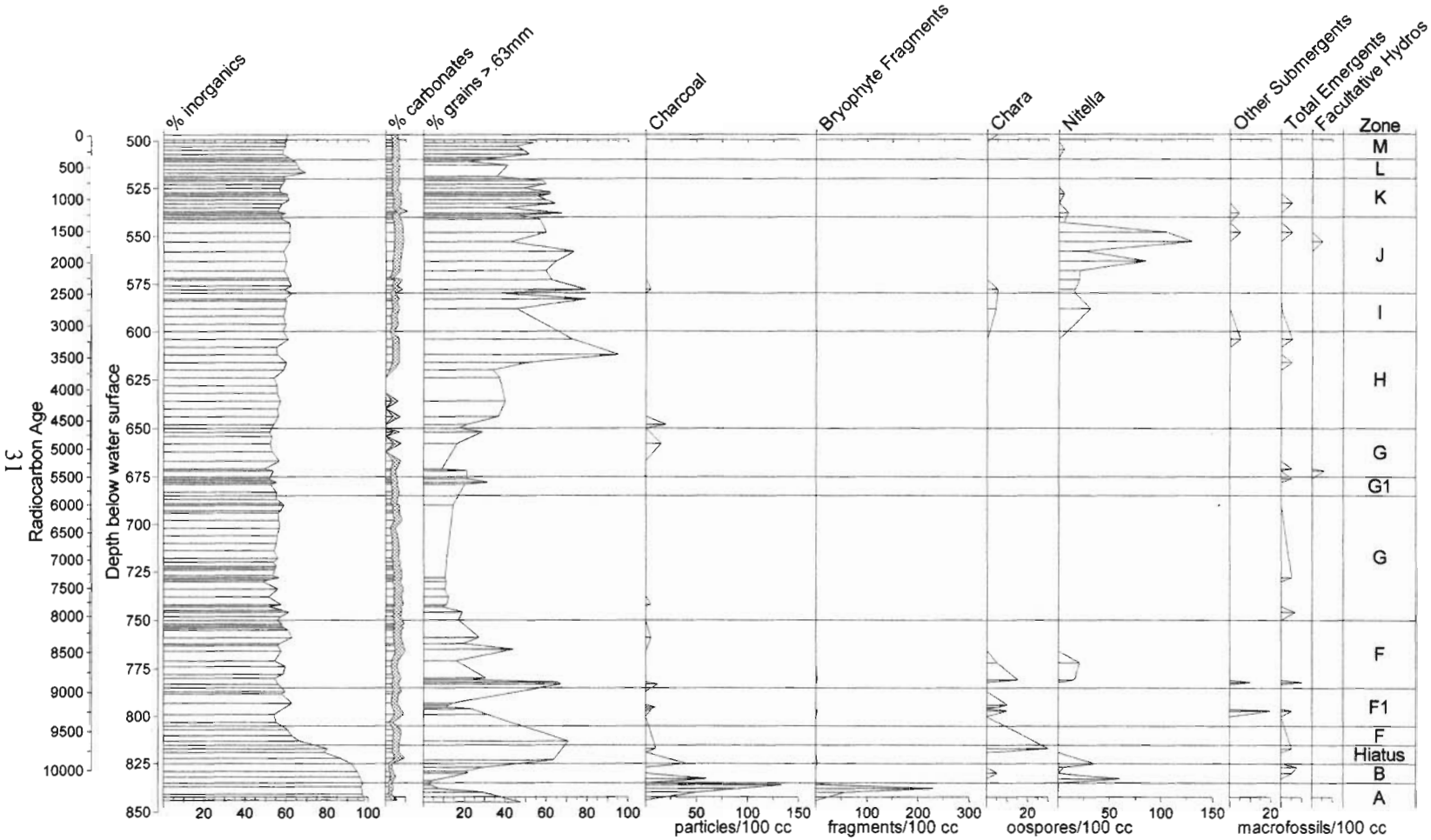
Zone I (4.0 ka to 3.5 ka): Decreased clastic grain size, increased aquatic macrofossils, and rapid sedimentation rates indicate a period of rising water levels.

Zone J: Increased clastic grain size and decreased aquatic macrofossils suggest lower water levels. Charcoal particle deposition increases in the latter half of this zone.

Zone K: Decreased clastic grain size indicates rising water levels.

Zones L and M: Surface sediments contain minimal stratigraphic changes.

Figure 9 Core MPA summary of lithic and macrofossil analyses: inorganic content, carbonate content, grain size, charcoal, and macrofossils. Zones A-M indicate changes in sediment composition related to changes in water depth.



Core MPA (modern water depth 497 cm, Figures 9 and A.2)

Despite low sample resolution, grain-size, macrofossil, and charcoal results substantiate inferences based on MPB. Because carbonate content of < 4.0% is too low to provide evidence of lake-level change, low carbonate values in MPA justified not performing the analysis on additional cores.

Zone A: Proglacial outwash of medium to coarse sand and small pebbles are overlain by silt and clay. This zone is macrofossil-poor and has <5% organic material.

Zone B: Seven percent increase in organic content and decreased clastic grain size indicates deeper, quieter water. Peak in charcoal particles corresponds to12.5 ka charcoal peak in MPB.

Zones C, D, & E are not evident: Disconformity. The current sediment/water interface of MPA is 0.5 m above that of MPB. An erosional disconformity immediately above post-glacial lacustrine sediment suggests that the water surface lowered by 0.5 m between 12.5 ka and 9.3 ka.

Zone F (Disconformity to ~8.0 ka): High inorganic content and increased clastic grain size indicate a period of low water interrupted by a brief high-water flux at 9.2 ka (Zone F_1, Figure 9) evidenced by an abrupt decline in clastic grain size.

Zone G (~8.0 ka to 4.5 ka): Increase in organic content and decrease in clastic grain size indicate deep water. This high water period is interrupted by a brief low water period ~5.5 ka (Zone G_1, Figure 9) indicated by an abrupt increase in clastic grain size.

Zone H (4.5 ka to 3.1 ka): Increased clastic grain size indicates low water. Charcoal peaks between 4.5 ka and 4.3 ka suggest drier conditions.

Zone I: A brief high water period is indicated by decreased clastic grain size.

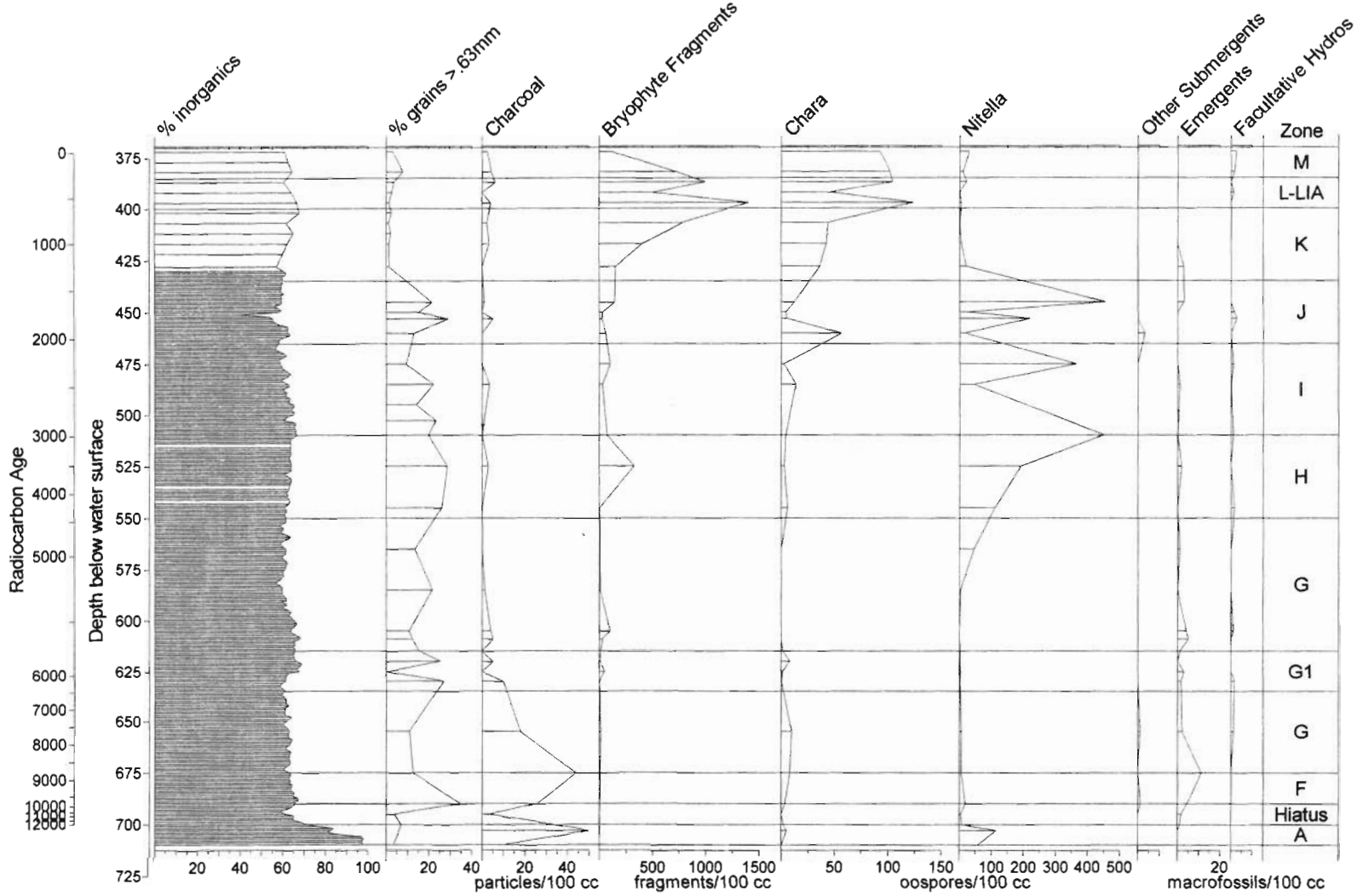
Zone J: Increased clastic grain size suggests low water levels.

Zone K: Consistent inorganic content with slightly smaller clastic grain sizes suggests rising water levels.

Zone L (0.25 ka (~300 cal yrs BP)): High inorganic content and decreased clastic grain size suggest a cold, wet environment and high lake levels.

Zone M: Modern surface sediments contain minimal stratigraphic changes.

Figure 10 Core MPD summary of lithic and macrofossil analyses: inorganic content, grain size, charcoal, and macrofossils. Zones A-M indicate changes in sediment composition related to changes in water depth.



Core MPD (modern water depth 361 cm, Figures 10 and A.3)

MPD demonstrates a visual disconformity just above the lacustrine clay layer. Radiocarbon dating indicates the disconformity to be of Younger Dryas age.

Zone A: Proglacial outwash of medium to coarse sand and small pebbles is overlain by silt and clay. Sediment is macrofossil-poor with <5% organic material.

Zones B, C, D, & E are not evident: Disconformity. Erosional disconformities immediately above post-glacial lacustrine sediment and again between 11.5 ka and 10.2 ka suggest that water receded into the deep area of the basin.

Zone F (Disconformity to ~8.2 ka): Increased inorganics, increased clastic grain size, and increased emergent macrofossil species indicate low water levels. Charcoal peak at start of deposition zone suggests drier environment.

Zone G (~8.2 ka to 4.9 ka): Decreased clastic grain size and higher sedimentation rate indicate a period of high water. A brief water level decline ~5.9 ka (Zone G_1, Figure 10) is evidenced by increased inorganic content, increased terrestrial macrofossils, and increased clastic grain size.

Zone H (4.9 ka to 3.0 ka): This low water period is characterized by low sedimentation rates, increased clastic grain size, and an undifferentiated bryophyte peak.

Zone I (3.0 ka to 2.0 ka): Increased sedimentation rate and decreased clastic grain size suggest higher water levels.

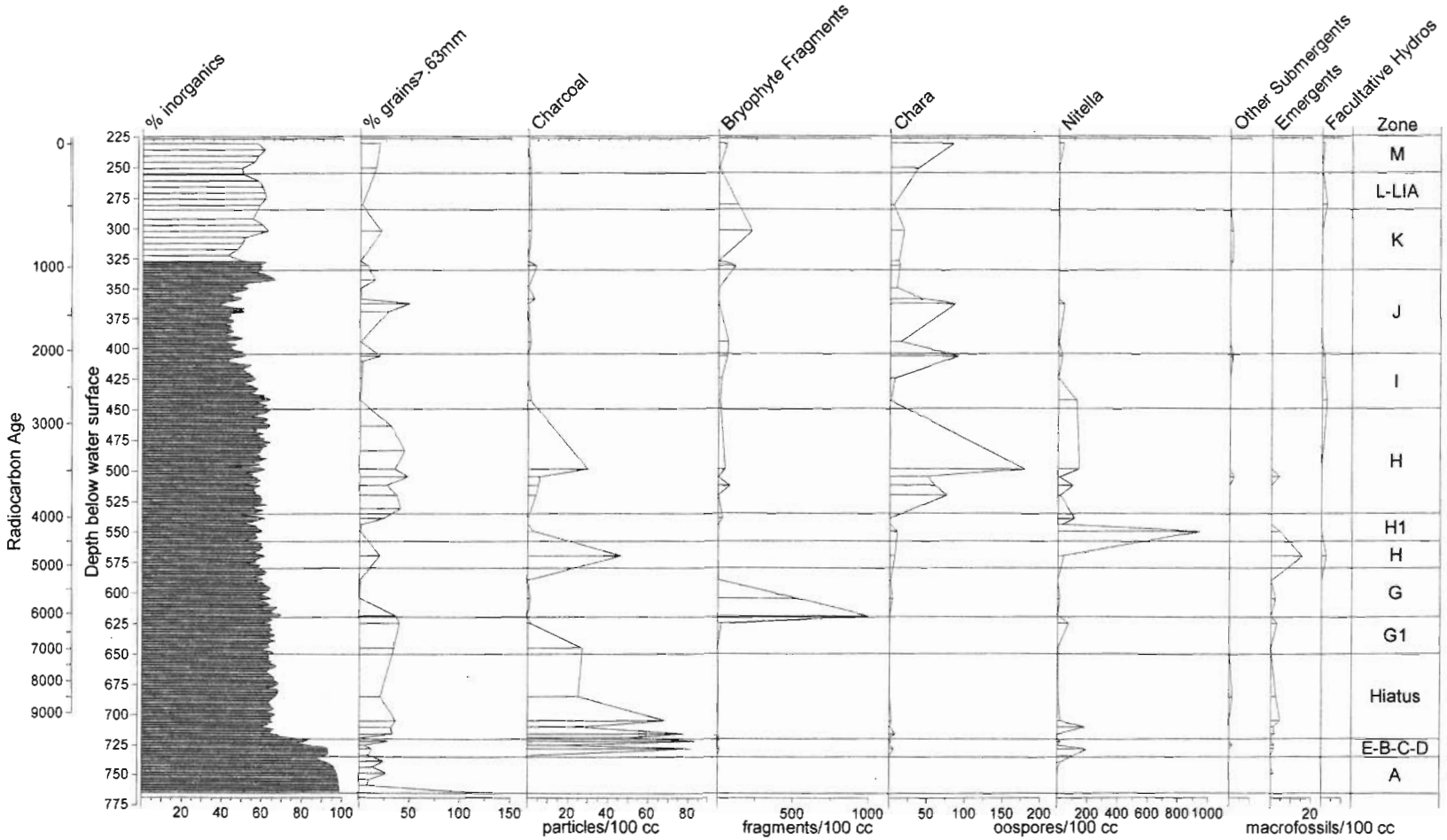
Zone J (2.0 ka to 1.4 ka): Increase in clastic grain size and increase in emergent macrofossils suggests lower water levels.

Zone K: Rising water levels are indicated by decrease in clastic grain size and *Nitella* oospore peak.

Zone L: High inorganic content and fine-grained clastics suggest a cold, wet environment. Peaks in bryophyte fragments may indicate increased terrestrial runoff.

Zone M (0.27 ka to present): High water at start of zone is suggested by a brief decline in inorganic content. Slight increases in inorganic content and clastic grain size following the initial high-water flux suggest that water levels briefly declined and are now increasing.

Figure 11 Core MPE summary of lithic and macrofossil analyses: inorganic content, grain size, charcoal, and macrofossils. Zones A-M indicate changes in sediment composition related to changes in water depth.



Core MPE (modern water depth 226 cm, Figures 11 and A.4)

Disconformity in MPE occurred during the early Holocene, when water was confined to the deepest portion of the basin. A narrow band of peat at ~ 4.7 ka indicates that the core site was above water for a brief period. High sedimentation rates after ~ 4.0 ka may be the result of sediment trapping by littoral flora.

Zone A: Proglacial outwash of medium to coarse sand and small cobbles are overlain by narrow band of silt and clay. The sediment is macrofossil-poor and contains <5% organic material.

Zones B, C, and D: These zones appear as narrow bands of lacustrine deposition.

Zones E, F, and early-G are not evident: Erosional disconformities between 9.2 ka and 6.2 ka suggest that water receded into the deep portion of the basin. Early Holocene deposition may have eroded as waters rose between 9.2 ka and 8.4 ka.

Zone late-G: Sedimentation resumed in MPE following the Zone G_1 dry interval (~6.2 ka to 5.7 ka) evident in the deeper cores. Rhythmic banding, *Nitella* oospore peak, and low clastic grain size identify this zone as a high water period.

Zone H (~4.7 ka to 3.0 ka): This is low-water period is characterized by high inorganic content, increased clastic grain size, increased terrestrial macrofossils, and stratified sedgy gyttja layers. A significant charcoal peak at ~ 4.5 ka indicates local fire activity. A high-water interlude, characterized by decreased grain size, follows the charcoal peak (Zone H_1, Figure 11).

Zone I (3.0 ka to ~1.8 ka): High organic content, low clastic grain size, and decreased terrestrial macrofossils indicate high water levels.

Zone J (~1.8 ka to ~1.1 ka): Multiple sedge layers and intermittent increases in clastic grain size indicate lowered water depth.

Zone K (~1.1 ka to 0.5 ka): Except for a brief decline in water depth between 0.7 and 0.6 ka evidenced by an abrupt increase in inorganic content and clastic grain size, decreased inorganics and clastic grain size indicate rising water levels.

Zone L (500 to 130 cal yrs BP): High inorganic content and low clastic grain size suggest the cold, wet environment. Decreased clastic grain size at 270 cm suggests a high water flux.

Zone M: Modern surface sediments characterized by increased clastic grain size suggest a decline in water depth during uppermost sediment deposition.

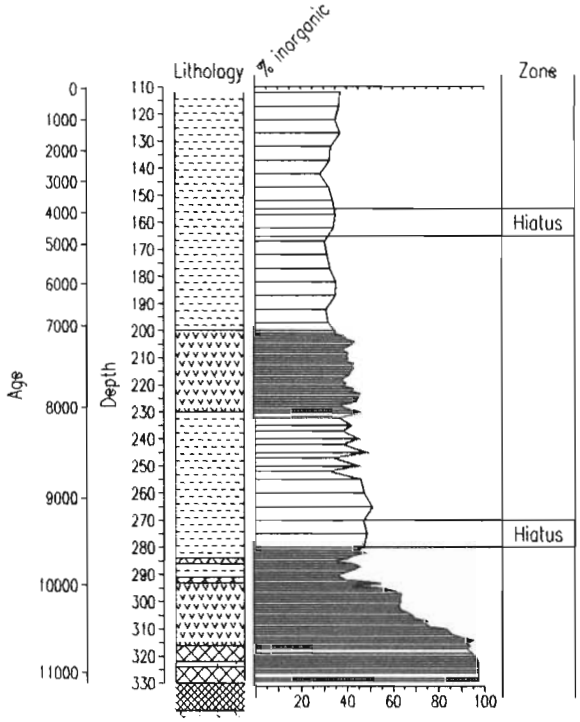


Figure 12 Core MPC sediment stratigraphy with inferred disconformities, inorganic content, and age in radiocarbon years.

Core MPC (modern water depth 107 cm; Figures 12 and A.5)

Disconformities at both top and bottom of this core complicate an already confusing stratigraphy. Loss-on-ignition (LOI) analysis for inorganic content conforms to patterns established with deeper cores and the observed core stratigraphy. Radiocarbon dates are in sequence, and match core stratigraphy and LOI results. Post-glacial MPC stood well above the water line. The thick layer of coarse sedge material below gyttja dated to 10.0 ka (295-315 cm) indicates a sedge-filled, marshy shoreline during the Younger Dryas chronozone. The 5.1 ka date just 55 cm below the sediment/water interface precedes the 1000+ year mid-Holocene dry period, and probably marks the lower limit of an erosional disconformity. Due to laboratory error, clastic grain size, charcoal, and macrofossil analyses were not used to assess lake-level change.

Core MPF (modern water depth -6.0 cm; Figures 13 and A.6)

MPF was collected from the sphagnum heath shore approximately 10 m from the shoreline and 6 cm above the current water level. The Russian corer refused in gravel till at 73 cm. Sediment progression from compacted dark brown mud, to compacted coarse organics, to loosely compacted peat represents natural wetlands in-filling by surrounding forest and shrubs. This premise is supported by large numbers of aquatic seeds and oospores in the lower portion of the core. Two bands of light gray, fine-grained clastics at 25-28 cm and at 32-35 cm dated 0.5 ka - 0.27 ka and 2.5 ka - 2.0 ka respectively and may represent brief high-water events.

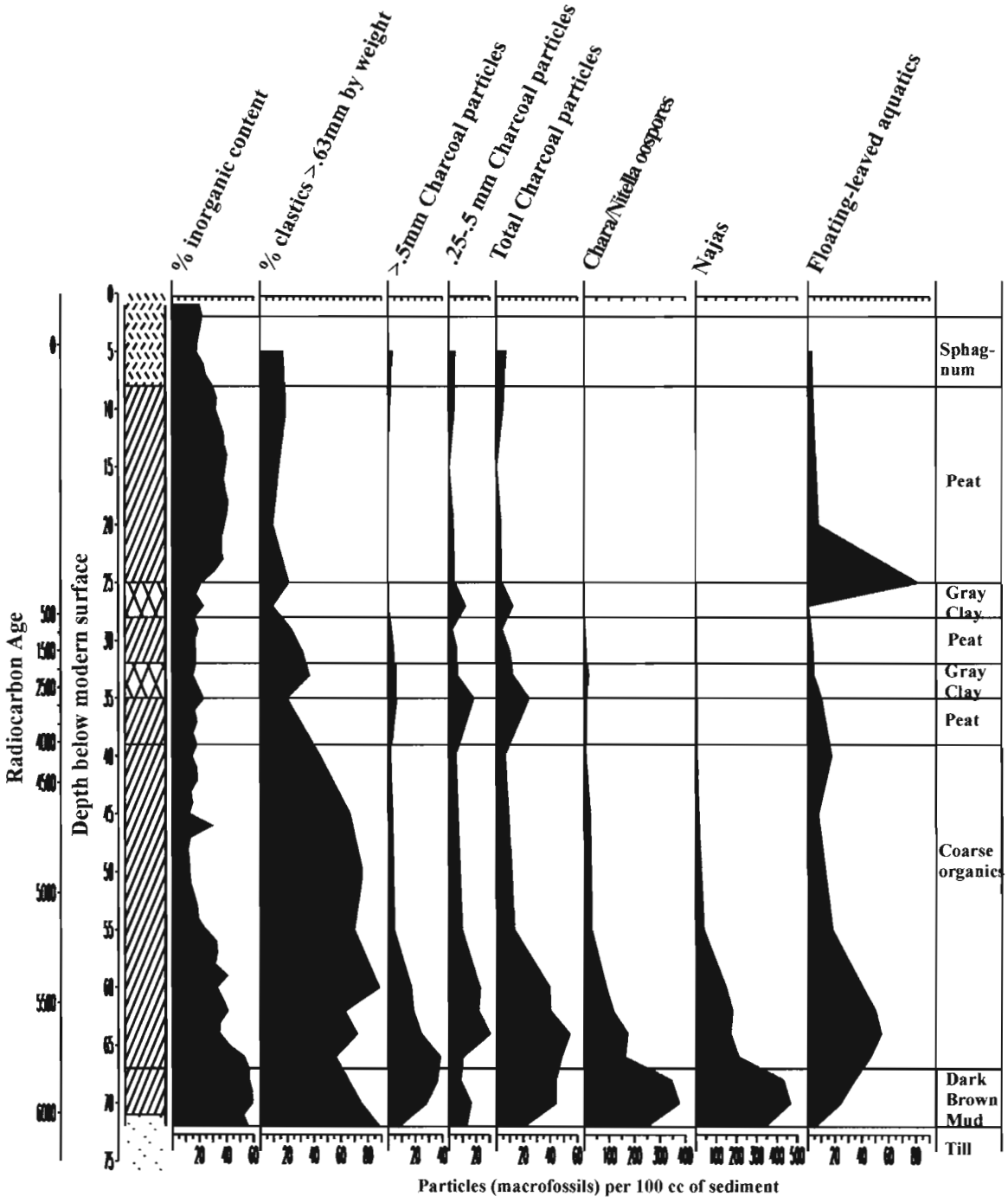


Figure 13 Core MPF summary of lithic and macrofossil analyses: sediment stratigraphy, inorganic content, grain size, and age in radiocarbon years.

Pollen stratigraphy

Stratigraphically constrained cluster analysis (CONISS) (Grimm 1987) designated eleven local pollen assemblage zones (PAZ) in core MPB (Figure 17). Variations in pollen concentration relate to vegetation cover-type and to lake sedimentation rates. Grass and shrub-covered tundra and open, *Pinus-Picea* parklands produced low pollen concentrations prior to11.5 ka. Periodic declines in pollen concentration since 11.5 ka correspond to increased sedimentation rates during periods of high or rising water levels (*i.e.*, 820-725 cm and 690-670 cm, Figure 14). While *Betula* has undoubtedly been a dominant forest component throughout the Holocene, pollen levels greater than 40% probably overstate species significance. Only selected pollen taxa are shown in the percentage pollen diagram (Figure 14).

PAZ-I (*Pinus-Picea-Populus-Ostrya-Salix*-herbaceous basal layer (915-885 cm; *c.* 13.5-11.4 ka)): Low pollen concentrations suggest a tundra landscape gradually grading into open *Pinus-Picea* taiga forests. Resurgence of *Picea* and Cyperaceae, along with increased minerogenics between 895-885 cm (Figure 14), may signal the brief Older Dryas cold period.

PAZ-II (*Pinus-Picea-Quercus-Betula*-shrub *Betula* (885-860 cm; 11.0-10.0 ka)): Except for a subtle increase in inorganic content, an increase in *Picea* pollen (40% of tree and shrub pollen) provides the strongest indication of Younger Dryas cooling at Mathews Pond. *Pinus strobus* and *Picea glauca* are the predominant conifer pollen types.

PAZ-III (*Pinus-Betula-Alnus* (860-835 cm; c. 10.0-9.0 ka)): Decline in *Picea* pollen to less than 10% of the tree and shrub total is accompanied by an increase in *Betula* and

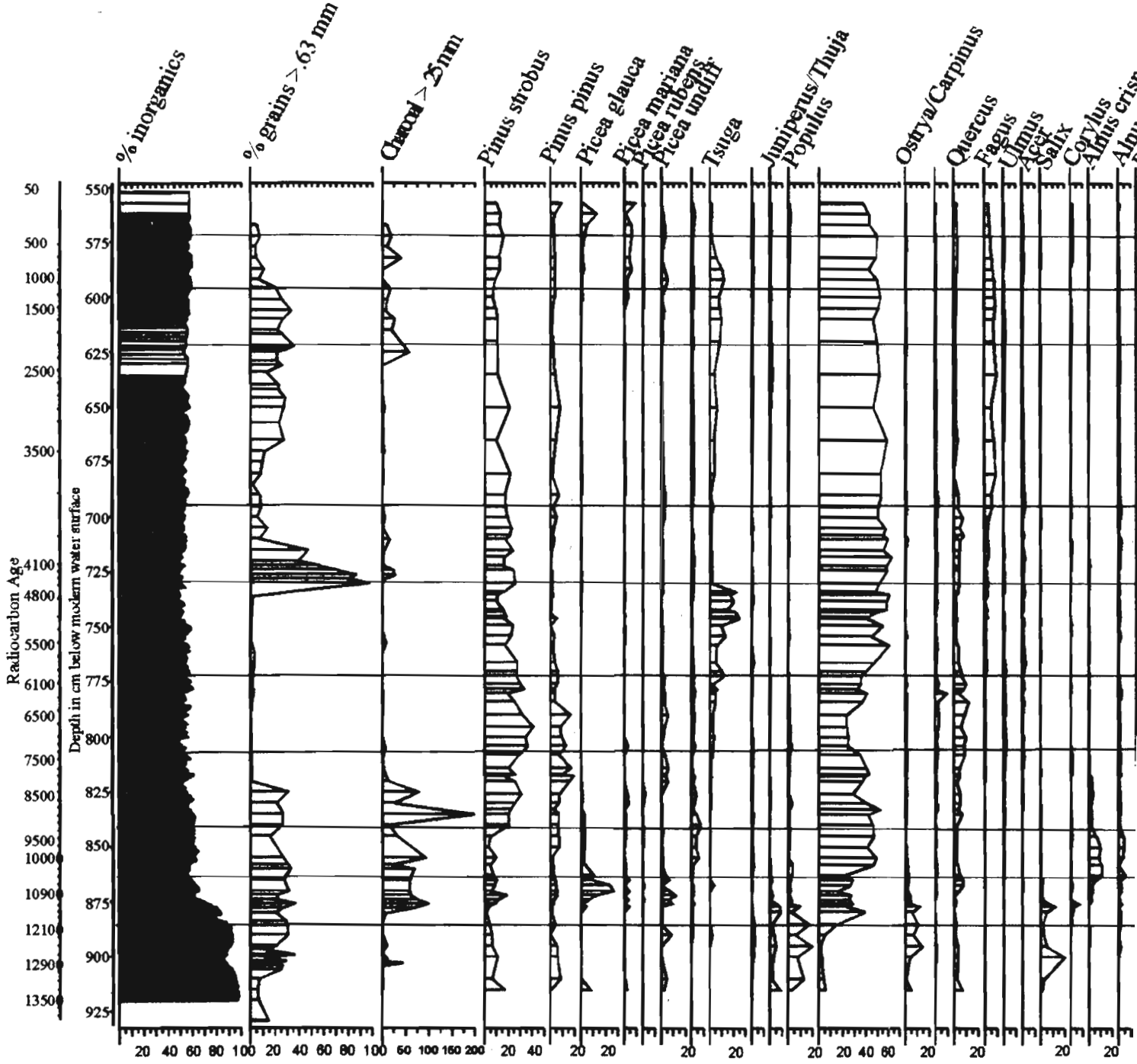
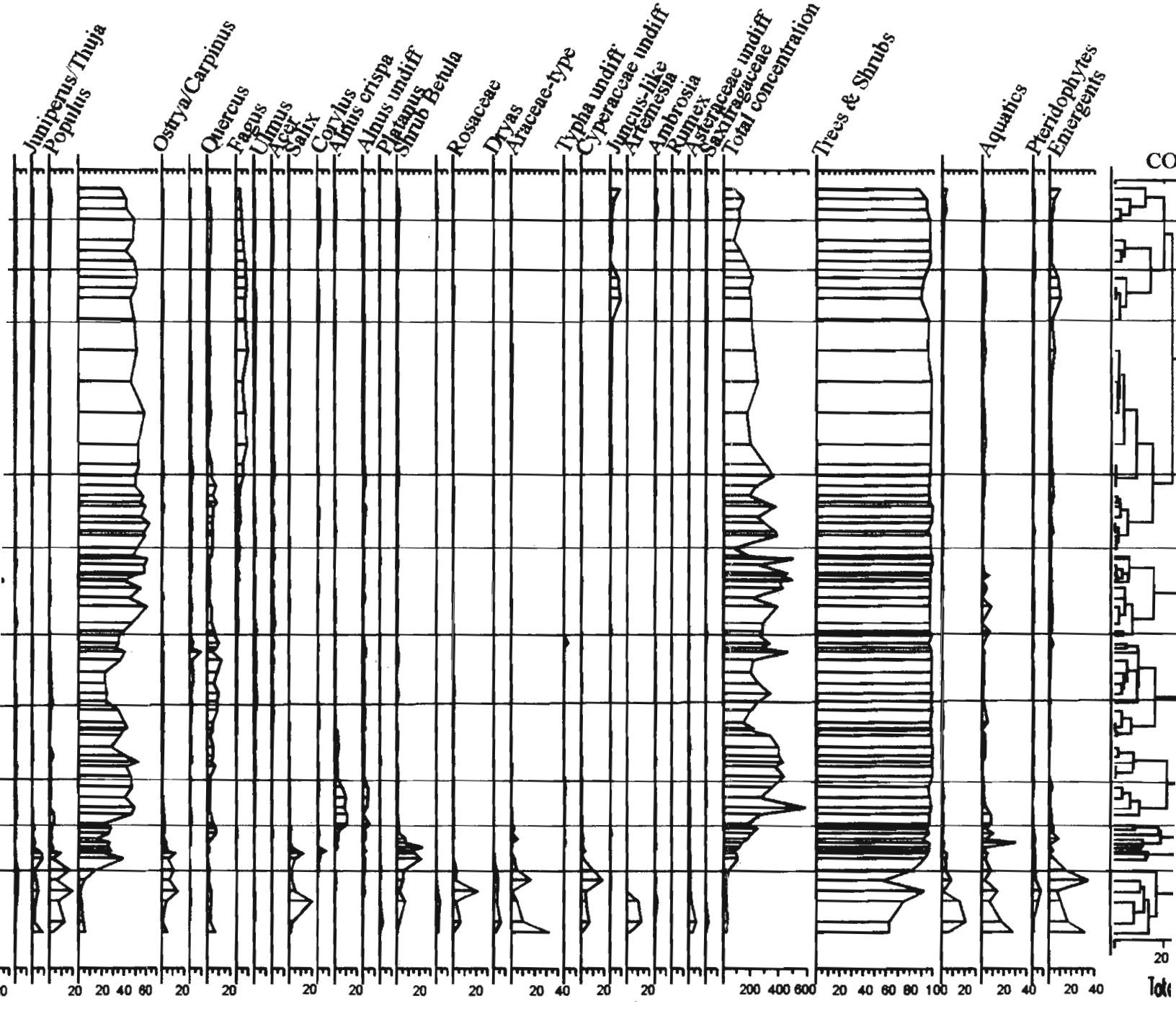
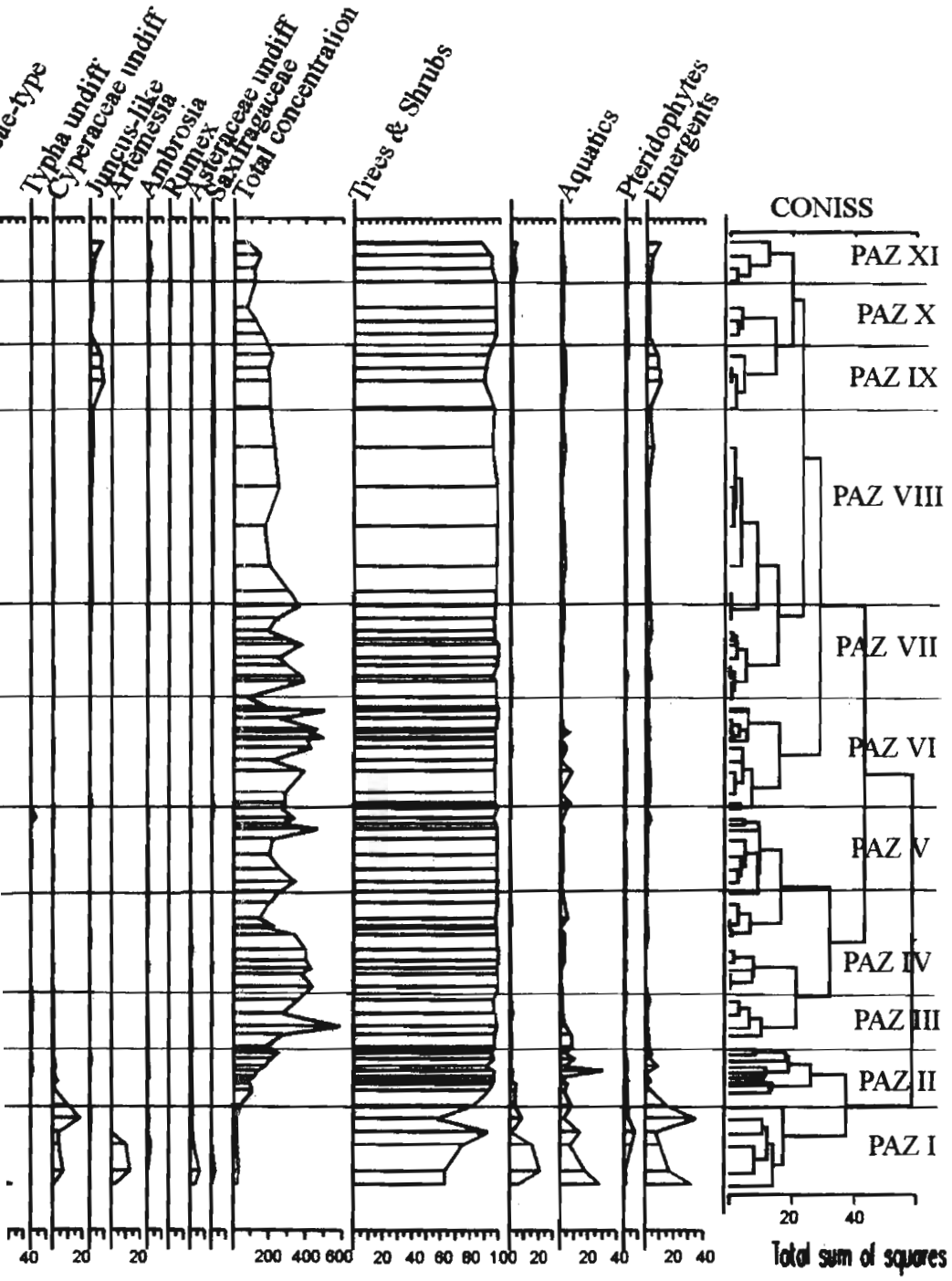


Figure 14 Full-core summary for Core MPB: Percent inorganic content, % clastic grains >.63mm by d
dendrogram was constructed with CONISS square root transformation analysis (Grimm 1987).



content, % clastic grains >.63mm by dry weight, charcoal particles/100cc, and pollen percentages. Pollen assemblage
nation analysis (Grimm 1987).



al particles/100cc, and pollen percentages. Pollen assemblage zone (PAZ)

Alnus pollen, with *Alnus crispa* the dominant *Alnus* species.

PAZ-IV (*Pinus-Betula-Quercus* (835-805 cm; c. 9.0-6.7 ka)): Decline in *Alnus* to less than 10% is accompanied by increases in *Pinus* and in *Quercus* pollen.

PAZ-V (*Pinus-Betula-Quercus* (805-770 cm; 6.7-5.9 ka)): Decrease in *Betula* and increase in *Pinus strobus* is concurrent with decline in charcoal deposition.

PAZ-VI *(Pinus-Tsuga-Betula-Quercus* (770-735 cm; 5.9-4.8 ka)): *Quercus* pollen declines as *Tsuga* becomes more prominent.

PAZ-VII (*Pinus-Betula-Quercus-Fagus* (735-700 cm ; 4.8 ka-3.8 ka)): Abrupt *Tsuga* decline at 4.8 ka is followed by a gradual increase in *Fagus* and *Quercus* pollen.

PAZ-VIII (*Pinus-Betula-Fagus* (700-625 cm; 3.8-2.2 ka)): Pollen taxa suggest an open hardwood forest with scattered Pine.

PAZ-IX (*Pinus-Tsuga-Betula-Fagus-Juncus* (625-595 cm; 2.2-1.2 ka)): Increased emergent species (*Juncus*) suggest that the lake-level at Mathews Pond declined and the wet, sedge-covered shore zone expanded. Return of Tsuga indicates a more closed-canopy forest.

PAZ-X (*Pinus-Picea-Tsuga-Betula-Quercus-Fagus* (595-570 cm; 1.2-.3 ka)): *Picea* pollen increases, and *Picea glauca* re-appears in the pollen record.

PAZ-XI (*Pinus-Picea-Tsuga-Betula-Quercus-Fagus-Ambrosia-Rumex* (570-560 cm; .3 ka to present)): *Ambrosia* and *Rumex* pollen appears in the pollen record.

Chapter 5

PALEOENVIRONMENTAL SYNTHESIS OF CORE DATA

Integration of lake-level, charcoal, and pollen data at Mathews Pond tracked broad, climate-related changes in vegetation, as well as subtle groundwater increases in response to decreased forest transpiration following forest fire. Fine-resolution analyses identified subtle increases in lake level and in *Betula* pollen following peaks in early-Holocene charcoal deposition (Zone F1, Figure 8 and PAZ IV, Figure 14). Mathews Pond contained 16 sediment units related to changes in water level, and nine lake-level stands (Figures 8 and 15, Table 3).

Before 11.8 ka: high lake level

Ice-recession isobars from Davis and Jacobson (1985) and Borns *et al.* (2003) along with linear age-depth interpretation of core MPB radiocarbon dates indicate that the region was ice-free by 13.5 ka. Pro-glacial deposits of sand and gravel abruptly grading into minerogenic, macrofossil-poor glaciolacustrine clay underlie the entire basin at Mathews Pond. Organic sedimentation began 13.0-12.5 ka with deposition of silty, banded gyttja. Pollen and macrofossil assemblages indicate an open landscape dominated by cold-tolerant *Picea, Pinus*, *Populus, Salix*, shrub *Betula, Dryas* and other Rosaceae, Cyperaceae, and *Artemisia.* Pollen assemblages in Figure 14 suggest that the landscape evolved from grass and shrub-covered tundra to spruce and pine-dotted parkland to mixed boreal forest by 11.8 ka.

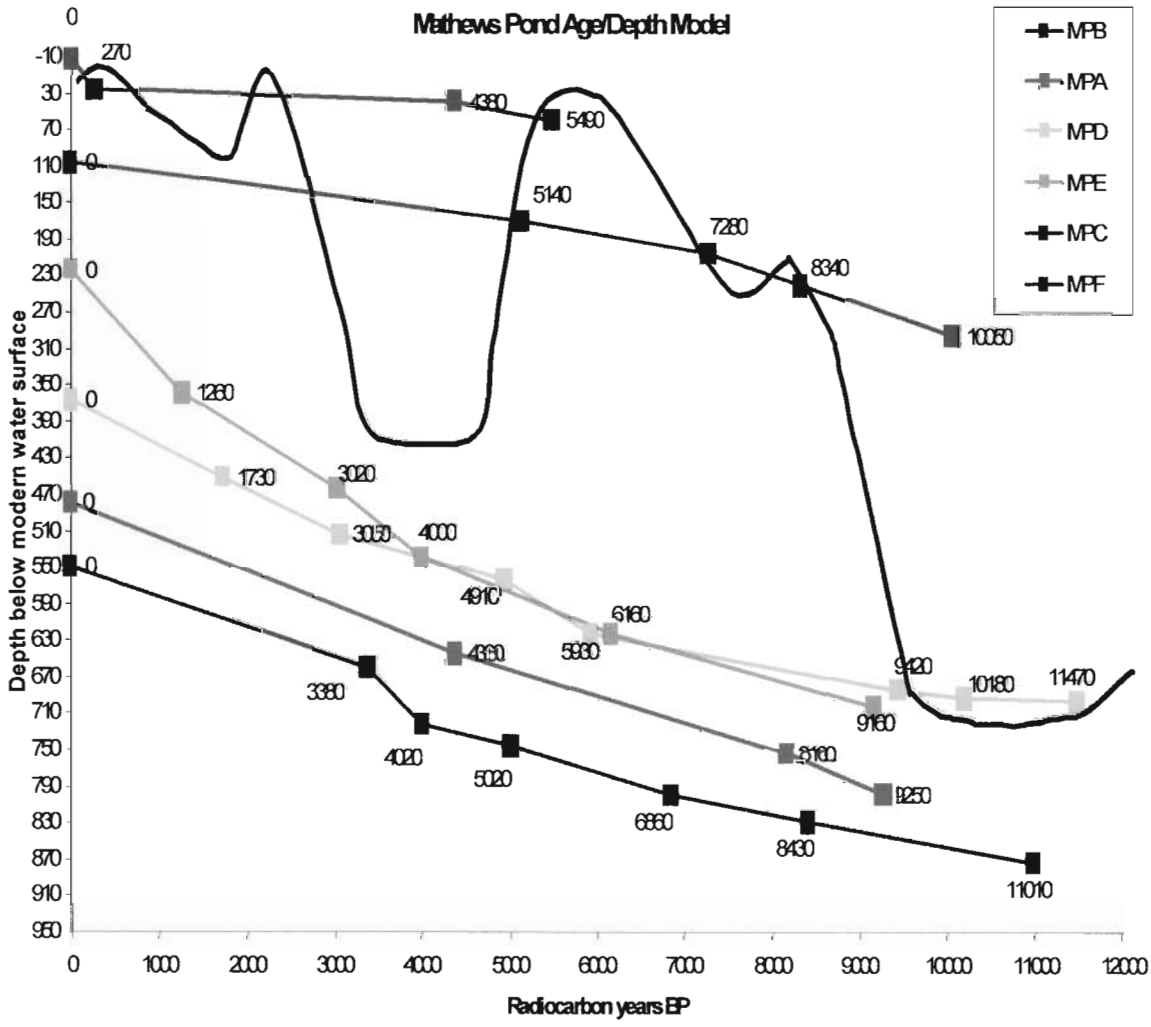


Figure 15 Inferred lake-level change curve for Mathews Pond. 12,000-year inferred lake-level curve is superimposed on age-depth curve for each core. Radiocarbon years before present are charted against depth below modern water surface for six cores. Inferred lake-level change curve, shown here as the solid black line, is based on core characteristics.

11.8 ka to 9.4 ka: low lake level

Except for brief water influxes coincident with the cold Killarney Oscillation observed in New Brunswick, Canada (Levesque *et al.* 1993) (Zone D, Figure 8 and Figure14) and following local forest fires (Zone F1, Figure 8), water level was low throughout this period. Sediment disconformities in cores MPA, MPD, MPE, and MPC suggest that water persisted only in the deepest section of the basin. Abundant *Pinus strobus* (>6% of total pollen) and elevated charcoal levels between 11.2 ka and 8.2 ka further imply a dry environment.

Changes in water balance between 10.0 ka and 8.2 ka may have been influenced by the effects of isostatic tilt and forebulge migration on groundwater hydraulics. If the Aroostook River and Allagash River recharge boundaries are far enough apart, isostatic tilt could affect groundwater distribution (Appendix B). Major evapotranspiration (ET) shifts from changing forest cover could also alter groundwater recharge. By 11.7 ka, high-ET forests, dominated by *Picea, Pinus,* and *Betula*, had replaced low-ET shrub grasslands. As the Bølling-Allerød warm period came to an end, a forest of pine and mixed northern hardwoods (*Juniperus/Thula, Populus, Betula* and *Ostrya*) covered the local landscape. A subtle increase in sediment inorganics and a resurgence of *Picea glauca* (white spruce) pollen between 11.0 and 10.0 ka (Figure 14) mark the cool, Younger Dryas chronozone.

Paleoamericans at Munsungun quarry sites (Jacobson *et al.* 1987, Pollock *et al.* 1999) apparently worked in a mixed boreal forest dotted with sedge-covered wetlands where shallow ponds occur today. Based on the inferred lake level at Mathews Pond

(Figure 15), the water level at Munsungun Lake could have been as much as five meters lower than its present level.

9.4 ka to 8.2 ka: abrupt increase in water level

Water level in Mathews Pond rose as much as five meters during the millennium (Figure 18). While increased water levels were reported from other northeastern North American lakes (Table 3), rising water levels at other sites began earlier and were not as abrupt. If tilting of the Aroostook and Allagash watershed recharge boundaries are sufficiently far apart to effect groundwater distribution, isostatic crustal adjustment could have masked surficial expression of increased groundwater recharge at Mathews Pond (see Appendix B.1).

Spruce forests rapidly declined as the climate warmed after the Younger Dryas chronozone. *Pinus strobus* and *Betula* became abundant early in this period. *Abies* and *Quercus* also increased, and the landscape returned to a more open forest of pine and mixed northern hardwoods.

Charcoal deposition was high at Mathews Pond from 11.25 ka to 8.2 ka (Figures 8 and 14). Mathews Pond charcoal deposition patterns are supported by a study of charcoal deposition in lake sediments at 30 sites in eastern Canada (Carcaillet and Richard 2000). While water levels in groundwater seepage lakes are controlled by winter precipitation, fire occurrence is typically controlled by summer precipitation (Carcaillet and Richard 2000). The combination of increased wild fire and rising lake levels between 9.0 and 8.2 ka required heavy winter snow fall and dry summer seasonality. MPB charcoal peaks at

876 cm (c.11.2 ka), at 835 cm (c.8.8 ka), and at 625 cm (c. 2.5 ka) are followed by subtle increases in lake-level and *Betula* pollen spikes succeeded by increases in *Pinus* pollen (Zone D/E transition and Zone F1, Figure 8 and PAZ II, IV, and IX, Figure 14).

8.2 ka to 4.8 ka: high lake level

By 8.2 ka water level had risen to approximately modern levels, and charcoal deposition markedly declined. The slight water-level decline (Zone G_1) centered around 7.5 ka (8,200 cal yrs BP) (Figure 15, Table 3) was consistent with the cool, dry period described by Alley *et al.* (1997) and Bond *et al.* (1997). Persistence of submergent and floating-leaved aquatic macrofossils (*Chara, Najas, Potamogeton, and Sparganium*) in the bottom of shoreline core MPF suggested that the lake rose to within 67 cm of its current level, and maintained that depth until *c.* 5.3 ka (Figures 13 and A.6).

As *Picea* species declined to <10% of the pollen rain, *Picea glauca* disappeared from the pollen record to be replaced by moisture-tolerant *P. marianna* and *P. rubens*. *Pinus, Betula alleghaniensis* (species identification from fossil seeds), and *Quercus* characterized the mixed hardwood forest. Between *c.*5.2 and 4.8 ka, *Tsuga canadensis* (eastern hemlock) replaced *Pinus strobus* (white pine) as the dominant conifer species. Charcoal abundances indicate that local fire was minimal during this period.

4.8 ka to 3.0 ka: low lake level

Water level fell sufficiently to create a sediment disconformity in MPC (Figure 12), and sedgy gyttja deposition in MPE (Figure A.4). A brief rise in water level followed a

charcoal peak *c.* 4.7-4.3 ka (Zone H_1, Figure 11). This mid-Holocene, low-water period coincides with the cool, dry 1500-year cyclical events described as Holocene expressions of Dansgaard/Oeschger ^{18}O shifts (Dansgaard *et al.* 1984, Bond *et al.* 1997).

The 4.8 ka *Tsuga* decline recorded across northeastern North America (Allison *et al.* 1986) coincidentally occurred at the same time as the abrupt, 4.8 ka lake-level decline at Mathews Pond. Mixed, open hardwood forests of *Pinus, Betula, Quercus*, and *Fagus* replaced dense hemlock stands.

3.0 ka to 2.0 ka: rising lake level

Rising lake levels are inferred from decreasing clastic grain size and decreased inorganic content. Charcoal abundances indicate that local fire activity increased after 2.5 ka. Carcaillet and Richard (2000) also reported increased fire activity after 2.5 ka in the mixed boreal forests of southern Quebec. Rising lake levels and increased fire frequency suggests warm, dry summers and heavy winter snowfall.

2.0 ka to 1.5 ka: declining lake level

Coarse, sedgy gyttja sandwiched between layers of deep-water gyttja in MPE (Figure 11) confirmed the lake-level low stand subtly evident in MPB, MPA, and MPD. Submergent and floating-leaved macrofossils in MPFdeclined during this period, suggesting a prograding shoreline and natural lake in-filling. An increase in emergent taxa in the pollen record provides additional evidence of an expanded, marshy shore.

1.5 ka to present: rising lake level

The lake level rose approximately 70 cm during this period. An apparent flooding event indicated by an inorganic layer in MPF and centered around 0.4 ka (Figures 13 and A.6) suggests that the lake level fluctuated during this period. Increased inorganics and clastic grain size in the top of MPE suggest that water level may have declined over the past 50-100 years.

The percent of *Picea* pollen increased after 1.5 ka, evidence of a cooler climate. *Tsuga* pollen peaked c. 1.1 ka, and then declined after 0.8 ka. Conifers dominated the mixed, pre-boreal forest.

Chapter 6

CONCLUSIONS

Figure 15 summarizes lake-level change at Mathews Pond over the past 12,000 years. Table 3 compares synchrony of lake-level change at seven sites in northeastern North America. Although Almquist *et al* (2001) listed 17 paleohydrological study sites in northeastern North America, only the seven sites presented in Table 3 adhered to the guidelines for identifying lake-level fluctuations established by Digerfeldt (1986).

Low lake levels at adjacent sites in Massachusetts (Shuman *et al.*2001, Newby *et al.* 2000), at Mathews Pond, and at Whited Lake in Aroostook County, Maine (Dieffenbacher-Krall 2003) (Table 3) suggest that the climate in Acadia was relatively dry throughout the late-glacial period and the Younger Dryas chronozone. Low lake levels, combined with high fire activity, during the early Holocene at Mathews Pond coincide with low lake levels and high fire activity in southwestern Quebec (Carcaillet and Richard 2000). Dry climatic conditions in the early Holocene could have resulted from a combination of high summer solar radiation, Arctic Oscillation low-phase, and adiabatic winds from the remnant Laurentide ice sheet (Carcaillet and Richard 2000).

Mathews Pond water levels rose to near-modern levels by 8.4 ka, and, except for a slight decline centered around 7.5 ka (8200 cal yr BP), remained high until ~4.8 ka. All three Maine ponds listed in Table 3 exhibited lake-level decline coincident with the 8200-year event (Alley *et al.* 1997, Bond *et al.*1997). The mid-Holocene dry period, evident at all sites summarized in Table 3 and lasting from 1,500 to 2,000 years, exhibited

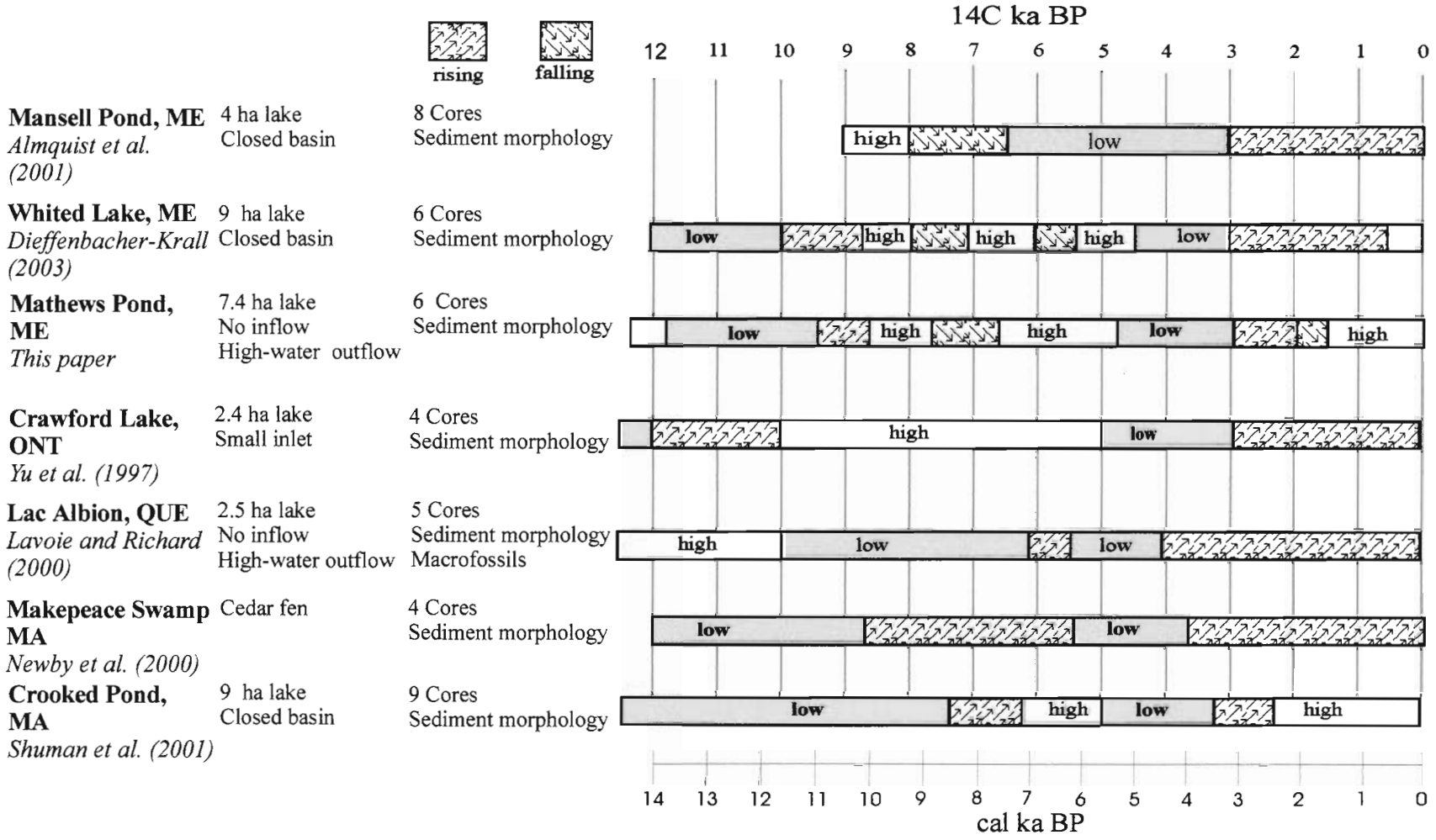


Table 3 Comparison of lake-level change at selected sites in northeastern North America (based on Almquist et al. 2001). Site locations are shown in Figure 1.

west-to-east, time-transgressive onset: Minnesota prairie-forest border moved eastward and Parker's Prairie lake levels declined from 8.0 to 5.0 ka (Baker *et al.* 1992, Digerfeldt *et al.* 1992); southern Wisconsin prairie-forest border moved eastward 5.5 to 3.0 ka (Baker *et al.* 1992); southern Ontario lake-levels declined 5.0 to 3.0 ka (Yu *et al.* 1997); Maine lake-levels declined 4.8 to 3.0 ka (this study, Dieffenbacher-Krall 2003). The time-transgressive nature of the mid-Holocene dry period provides additional evidence that changing air-mass distribution patterns controlled mid-Holocene climate (Yu *et al.* 1997).

With intermittent low and high fluctuations lasting from 200-500 years, Mathews Pond lake level rose to modern levels after 3.0 ka. This lake-level rise was accompanied by increased charcoal deposition, an indication of heavy winter precipitation accompanied by dry summers. Late-Holocene periods of high fire activity and rising lake levels may be associated with millennial shifts in storminess (increased fall and winter storms) associated with the low-phase, atmospheric Arctic Oscillation (Thompson and Wallace 2001, Noren *et al.* 2002). Southward-dipping Arctic air masses could increase winter snow pack, while blocking humid Maritime Tropical air masses (Carcaillet and Richard 2000) to produce dry summer conditions. Synchrony of lake-level changes between Mathews Pond and Whited Lake (Dieffenbacher-Krall 2003), a groundwater seepage lake in an adjacent watershed, and with additional sites across northeastern North America (Figure 1, Table 3) provides strong evidence that atmospheric circulation shifts drive periodic, short-term climate changes.

A number of catchment experiments and ET models demonstrated the direct relationship between vegetation change and groundwater recharge rates (Bosch and

Hewlett 1982, Alley 1984, Whitehead and Robinson 1993, Sahin and Hall 1996, Stednick 1996, Disse 1999, Abbott *et al.* 2000, Rosenmeier *et al.* 2002). Conifer forests have the greatest evapotranspiration rates, followed by deciduous hardwood forests, with scrub and grasslands having the lowest ET rates (Bosch and Hewlett 1982). Figure 14 demonstrates that marked changes in vegetation in response to changing climate or to fire influence groundwater recharge. Lake-level low-stands beginning before the Younger Dryas chronozone and extending into the early Holocene may have been prolongd by increased ET accompanying the sift from shrub-dominated, *Picea* parklands to *Pinus/Picea/Betula* forests. As the Acadia landscape continues to revert to mixed hardwood and conifer forests from the open agricultural and grazing lands of 200 years ago, increased forest transpiration may further lower overtaxed groundwater aquifers.

Synchrony of lake-level behavior depicted in Table 3 suggests that moisture balance during much of the Holocene may have been similar to current levels. While decline in non-coastal *Picea* populations has been linked to warmer, drier climates (Schauffler and Jacobson 2002), the *Picea glauca*-dominated spruce populations at Mathews Pond declined during the early-Holocene lake-level rise. This implies that temperature rather than general moisture balance may be the limiting factor, at least for white spruce. Because groundwater recharge in forested regions occurs during late fall and early spring (Abbott *et al.* 2000), lake levels in heavily forested regions are controlled by winter precipitation, and may be stronger indications of seasonality than of annual P-E ratios. This recharge pattern could compromise moisture balance assessments and paleotemperature estimates based on ^{18}O values.

While most pollen preserved in lake sediments came from a broad geographic area, pollen from small forest hollows originated within 20-30 m of the hollow (Jacobson and Bradshaw 1981, Schauffler and Jacobson 2002). In an effort to separate regional and local components of the pollen rain, a companion study will examine pollen stratigraphies from forest hollows within BRFR. Pollen diagrams from paired sites that share a common regional component, but where vegetation varies as a result of local differences in soil and relief, define fine-scale changes in past vegetation (Jacobson 1979, Schauffler and Jacobson 2002).

Research at Mathews Pond met the following established project objectives:

1. The 10,000-year record of lake-level change at Mathews Pond indicated a dry early-Holocene, increased moisture balance 8.2 ka to 4.8 ka, pronounced dry periods from 4.8 ka to 3.0 and from 2.0 ka to 1.5 ka, and general increase in moisture balance after 1.5 ka. In addition to long-term hydrologic trends, lake-level responses to short-term climate events were recorded at 7.5 ka (8,200 cal yr), 2.5 ka, 2.0 ka, and 0.4 ka.

2. High-resolution sampling for lake-level, charcoal, and pollen analyses demonstrated that changes in regional vegetation interrelate with changes in regional hydrology and with periods of high fire activity. Mathews Pond sediments held evidence of both millennial-scale and short-term changes in hydrology and vegetation across the landscape surrounding BRFR.

3. Lake-level change at Mathews Pond exhibited a high degree of synchrony with lake-level change at Whited Lake, a groundwater-fed lake in an adjacent watershed. Synchrony of groundwater response between watersheds and across broad geographic regions

suggests that changes in moisture balance are driven by external influences such as shifts in solar insolation or in atmospheric circulation. Disparity of lake-level change data may be related to the water-balance regime of the lake (i.e., atmosphere controlled versus groundwater controlled).

REFERENCES

Abbott, M.D., Lini, A., Bierman, P.R. 2000: ^{18}O, D, and ^{3}H measurements constrain groundwater recharge pattern in an upland fractured bedrock aquifer, Vermont, USA. *Journal of Hydrology* 288, 101-12.

Alley, R.B., Mayewski, P.A., Sowers, T., Stuiver, M., Taylor, K.C., Clark, P.U. 1997: Holocene climatic instability: A prominent, widespread event 8200 yr ago. *Geology* 25, No. 6, 483-86.

Alley, W.M. 1984: On the treatment of evapotranspiration, soil moisture accounting and aquifer recharge in monthly water balance models. *Water Resources Research* 20, 1137-49.

Allison, T.D., Moeller, R.E., Davis, M.B. 1986: Pollen in laminated sediments provides evidence for a mid-Holocene forest pathogen outbreak. *Ecology* 67, 1101-05.

Almendinger, J.E. 1990: Groundwater control of closed-basin lake levels under steady-state conditions. *Journal of Hydrology* 112, 293-318.

Almquist, H., Dieffenbacher-Krall, A.C., Flanagan-Brown, R., Sanger, D. 2001: The Holocene record of lake levels of Mansell Pond, central Maine, USA. *The Holocene* 11, 189-201.

Almquist-Jacobson, H. and Sanger, D. 1995: Holocene climate and vegetation in the Milford drainage basin, Maine, USA, and their implications for human history. *Vegetation History and Archaeobotany* 4, 211-22.

Baker, R.G., Maher, L.J., Chumbley, C.A., Van Zant, K.L. 1992: Patterns of Holocene environmental changes in the midwestern United States. *Quaternary Research* 37, 379-389.

Bengtsson, L. and Enell, M. 1986: Chemical Analysis. In Berglund, B.E., editor, *Handbook of Holocene Palaeoecology and Palaeohydrology*, Chichester, John Wiley, 423-54.

Birks, H.H. 1980: Plant macrofossils in Quaternary lake sediments. *Archives of Hydrobiology* 15, 60.

Bond, G., Shower, W., Cheseby, M., Lotti, R., Almasi, P., deMenocal, P., Priore, P., Cullen, H., Hajdas, I., Bonani, G. 1997: A pervasive millennial-scale cycle in North Atlantic Holocene and Glacial Climates. *Science* 278, 1257-66.

Born, S.M., Smith, S.A., Stephenson, D.A. 1979: Hydrogeology of glacial-terrain lakes with management and planning applications. *Journal of Hydrology* 43, 7-43.

Borns, H.W. Jr., Doner, L.A., Dorian, C.C., Jacobson, G.L.Jr., Kaplan, M.R., Kreutz, K.J., Lowell, T.V., Thompson, W.B., Weddle, T.K. 2003: The Deglaciation of Maine, USA. In Ellers, J. and Gibbard, T.L., editors, *Quaternary Glaciations - Extent and Chronology, Part II: North America*, Elsevier, Amsterdam, in press.

Bosch, J.M. and Hewlett, J.D. 1982: A Review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* 55, 3-23.

Bryson, R.A. 1966: Air masses, streamlines, and the boreal forest. *Geographic Bulletin* 8, 228-69.

Bryson, R.A. and Hare, F.K. 1974: Climates of North America. In Bryson, R.A. and Hare, F.K., editors, *Climates of North America*, Elsevier, New York, 1-47.

Carcaillet, C. and Richard, P.J.H. 2000: Holocine changes in seasonal precipitation highlighted by fire incidence in eastern Canada. *Climate Dynamics* 16, 549-59.

Dansgaard, W., Johnsen, S.J., Clausen, H.B., Dahl-Jensen, D., Gundestrup, N., Hammer, C.U., Oeschger, H. 1984: North Atlantic climatic oscillations revealed by deep Greenland ice cores. In Hansen, J.E. and Takahashi, T, editors, *Climate processes and climate sensitivity*. American Geophysical Union, Washington, D.C., 288-98.

Davis, R.B. and Jacobson, G.L.,Jr. 1985: Late glacial and early Holocene landscapes in northern New England and adjacent areas of Canada. *Quaternary Research* 23, 341-68.

Dearing, J.A. 1997: Sedimentary indicators of lake-level changes in the humid temperate zone: a critical review. *Journal of Paleolimnology* 18, 1-14.

Dieffenbacher-Krall, A.C. and Halteman, W.A. 2000: The relationship of modern plant remains to water depth in alkaline lakes in New England, USA. *Journal of Paleolimnology* 24, 213-29.

Dieffenbacher-Krall, A.C. 2003: Late-glacial and Holocene hydrology of Whited Lake, northern Maine. *Palaeogeography, Palaeoclimatology, Palaeoecology,* submitted.

Digerfeldt, G. 1986: Studies on past lake-level fluctuations. In Berglund, B.E., editor, *Handbook of Holocene palaeoecology and palaeohydrology*. John Wiley and Sons, Chichester, UK, 127-43.

Digerfeldt, G., Almendinger, J.E., Björck, S. 1992: Reconstruction of past lake levels and their relation to groundwater hydrology in the Parkers Prairie sandplain, west-central Minnesota. *Palaeogeography, Palaeoclimatology, Palaeoecology* 94, 99-118.

Disse, M. 1999: Validation of a simple model to determine regional evapotranspiration and groundwater recharge rates. *Physical Chemical Earth* 24 (4), 325-30.

Faegri, K., Iversen, J., Krzywinski, K. 1989: *Textbook of Pollen Analysis IV Edition.* John Wiley & Sons, Chichester.

Foster, D.R., Orwig, D.A., McLachlan, J.S. 1996: Ecological and conservation insights from reconstructive studies of temperate old-growth forests. *Trends in Ecology and Evolution* 11: 419-24.

Gleason, H.A. and Cronquist, A. 1991: *Manual of Vascular Plants of Northeastern United States and Adjacent Canada.* New York Botanical Garden, New York.

Grimm, E.C. 1994: TILIA and TILIAGRAPH pollen diagramming program. Illinois State Museum, Springfield, IL.

Grimm, E.C. 1987: CONISS: a FORTRAN 77 program for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers & Geosciences* 13, 13-35.

Håkanson, L. and Jansson, M. 2002: *Principles of Lake Sedimentology*: *Second Edition.* Blackburn Press, Caldwell, NJ.

Hall, B.A. 1970: *Stratigraphy of the Southern End of the Munsungun Anticlinorium, Maine*. Maine Geological Survey Bulletin 22, Augusta, Maine, 23-29.

Hannon, G.E. and Gaillard, M.J. 1997: The plant-macrofossil record of past lake-level changes. *Journal of Paleolimnology* 18, 15-28.

Harrison, S.P. 1989: Lake levels and climatic change in eastern North America. *Climate Dynamics* 3, 157-67.

Holmgren, N.H. 1998: Illustrated Companion to Gleason and Cronquist's Manual: *Illustrations of the Vascular Plants of Northeastern United States and Adjacent Canada*. New York Botanical Garden, New York.

Jacobson, G.L., Jr. 1979: The paleoecology of white pine (Pinus strobus) in Minnesota. *Journal of Ecology* 67, 697-726.

Jacobson, G.L. and Bradshaw, R.H. 1981: The selection of sites for paleovegetational studies. *Quaternary Research* 16, 80-96.

Jacobson, G.L.,Jr., Webb, T. III, Grimm, E.C. 1987: Patterns and rates of vegetation change during the deglaciation of eastern North America. In: Ruddiman, W.F. and Wright, H.E.,Jr., editors, *North America during deglaciation. The Geology of North America.*, DNAG V.K3, Geological Society of America, Boulder, CO, 277-88.

Kutzbach, J.E. 1987: Model simulations of the climatic patterns during the deglaciation of North America. In Ruddiman, W.F. and Wright, H.E. Jr., editors, *North America and adjacent oceans during the last deglaciation. The geology of North America* Volume K-3. Geological Society of America, Boulder, Colorado, 425-46.

Lavoie, M. and Richard, P.J.H. 2000: Postglacial water-level changes of a small lake in southern Quebec, Canada. *The Holocene* 10, 621-34.

Leverett, R. 1996: Definitions and History. In Davis, M.B., editor, *Eastern Old-Growth Forests*. Island Press, Washington, D.C., 3-17.

Lévesque, A.J., Mayle, F.E., Walker, I.R., Cwyner, L.C. 1993: A previously unrecognized late-glacial cold event in eastern North America. *Nature* 361, 623-26.

Lévesque, P.E., Dinel, M.H., Larouche, A. 1988: *Guide to the Identification of Plant Macrofossils in Canadian Peatlands*. Publication 1817, Land Resource Research Centre, Agriculture Canada, Ottawa, Canada.

Lindbladh, M., O'Connor, R., Jacobson, G.L. 2002: Morphometric analysis of pollen grains for paleoecological studies: Classification of *Picea* from eastern North America. *American Journal of Botany* 89 (9), 1459-67.

Martin, A.C. and Barkley, W.D. 1961: *Seed Identification Manual*. University of California Press, Berkeley, CA.

McAndrews, J.H., Berti, A.A., Norris, G. 1973: *Key to the Quaternary Pollen and Spores of the Great Lakes Region*, Royal Ontario Museum Life Sciences Misc. Publication, Toronto, Canada.

McBride, M.S. and Pfannkuch, H.O. 1975: The distribution of seepage within lake beds. *Journal of Research* U.S. Geologic Survey 3 (5), 505-12.

Montgomery, F.H. 1977: *Seeds and Fruits of Plants of Eastern Canada and Northeastern United States*. University of Toronto Press, Toronto, Canada.

Moore, P.D., Webb, J.A., Collinson, M.E. 1991: *Pollen Analysis Second Edition*, Blackwell Science Ltd., Malden, MA.

Moorman, B.J. 2001: Ground Penetrating Radar Applications in Paleolimnology. In Last, W.M. and Smol, J.P., editors, *Tracking Environmental Change Using Lake Sediments, Volume 1, Basin Analysis, Coring, and Chronological Techniques.* Kluwer Academic Publishers, Dordrecht, The Netherlands, 23-47.

Newby, P.E., Killoran, P., Waldorf, M.R., Shuman, B.N., Webb, R.S., Webb, T. 2000: 14,000 years of sediment, vegetation, and water-level changes at the Makepeace Cedar Swamp, southeastern Massachusetts. *Quaternary Research* 53, 352-68.

Nichols, G. 1999: Sedimentology and Stratigraphy, Blackwell Science Ltd., Oxford, UK, 129-32.

Noren, A.J., Bierman, P.R., Steig, E.J., Lini, A., Southon, J. 2002: Millennial-scale storminess variability in the northeastern United States during the Holocene epoch. *Nature* 419, 821-23.

Pollock, S.G., Hamilton, N.D., Bonnichsen, R. 1999: Chert from the Munsungun Lake formation (Maine) in Palaeoamerican archaeological sites in northeastern North America: Recognition of its occurrence and distribution. *Journal of Archaeological Science* 26, 269-93.

Pulse EKKO 100 Run User's Guide Version 1.2 1996: Technical Manual 25, Sensors & Software Inc., Mississauga, Ontario, Canada.

Rosenmeier, M.F., Hodell, D.A., Brenner, M., Curtis, J.H., Martin, J.B., Anselmetti, F.S., Ariztegui, D., Guilderson, T.P. 2002: Influence of vegetation change on watershed hydrology: implications for paleoclimatic interpretation of lacustrine ^{18}O records. *Journal of Paleolimnology* 27, 117-31.

Sahin, V. and Hall, M.J. 1996: The effects of afforestation and deforestation on water yields. *Journal of Hydrology* 178, 294-309.

Schauffler, M. and Jacobson, G.L. 2002: Persistence of coastal spruce refugia during the Holocene in northern New England, USA, detected by stand-scale pollen stratigraphies. *Journal of Ecology* 90, 235-50.

Shuman, B., Bravo, J., Kaye, J., Lynch, J.A., Newby, P., Webb, T. 2001: Late Quaternary water-level variations and vegetation history at Crooked Pond, southeastern Massachusetts. *Quaternary Research* 56, 401-10.

Stednick, J.D. 1996: Monitoring the effects of timber harvest on annual water yield. *Journal of Hydrology* 176, 79-95.

Street-Perrott, F.A. and Roberts, N. 1983: Fluctuations in closed-basin lakes as an indicator of past atmospheric circulation patterns. In Street-Perrott, A., Beran, M., Ratcliffe, R., editors, *Variations in the Global Water Budget.* D. Reidel Publishing, Dordrecht, The Netherlands, 331-45.

Street-Perrott, F.A. and Harrison, S.P. 1985: Lake levels and climate reconstruction. In Hecht, A.D., editor, *Palaeoclimate Analysis and Modeling.* John Wiley, New York, 291-340.

Stuiver, M. and Braziunas, T.F. 1993: *The Holocene* 3, 289-305.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, F.G., v.d. Plight, J., Spurk, M. 1998a: INTCA L98 Radiocarbon Age Calibration. *Radiocarbon* 40, 1041-83.

Stuiver, M., Reimer, P.J., Braziunas, T.F. 1998b: *Radiocarbon* 40, 1127-51.

Thompson, D.W.J. and Wallace, J.M. 2001: Regional climate impacts of the northern hemisphere annular mode. *Science* 293, 85-89.

Vickery, B. 1999: Official communication to TNC Ecosystem Research Program Review Team, The Nature Conservancy, Arlington, Virginia.

Whitehead, P.G. and Robinson, M. 1993: Experimental basin studies - an international and historical perspective of forest impacts. Journal of Hydrology 145, 217-230.

Williams, J.W., Post, D.M., Cwynar, L.C., Lotter, A.J. 2002: Rapid and widespread vegetation responses to past climate change in the North Atantic region. *Geology* 30 (11), 971-74.

Wright, H.E. 1967: A square-rod piston sampler for lake sediments. *Journal of Sediment Petrology* 37, 975-76.

Wright, H.E., Jr. 1992: Patterns of Holocene climate change in the midwestern United States. *Quaternary Research* 38, 129-134.

Yu, Z., McAndrews, J.H., Eicher, U. 1997: Middle Holocene dry climate caused by change in atmospheric circulation patterns: Evidence from lake levels and stable isotopes. *Geology* 25 (3), 251-54.

APPENDIX A

MACROFOSSILS

Plant Macrofossils

Mathews Pond, with its high transparency, lack of algal blooms, and trout population, is presently an oligotrophic lake. Littoral plants, both submergent aquatics and emergent plant species that root in shallow waters, enhance sediment accumulation in water < 2 m deep through wave velocity reduction, increased sediment trapping, and localized organic loading (Anderson 1990, Dearing 1997). Littoral macrophytes are particularly important in stabilizing erosional shorelines. Organic accumulation and littoral zone progradation are precursors to natural in-filling of the lake basin. When assessing lake-level change, natural shoreline progradation must be differentiated from shoreline expansion due to lake lowering.

Because the distribution of submerged, floating-leaved, and emergent plant species are related to water depth, macrofossil associations of these species can be used as one of several independent lines of evidence to infer lake-level change (Digerfeldt 1986, Harrison and Digerfeldt 1993, Hannon and Gaillard 1997, Dieffenbacher-Krall and Halteman 2000). Traditional macrofossil analysis assumed obligate aquatic plants had short seed-dispersal distances, while emergent and shoreline species had longer dispersal distances (Birks 1980). Several studies found little correlation between vegetation cover and the aquatic seed bank (Greatrex 1983, Haag 1983, Kautsky 1990, Dieffenbacher-Krall and Halteman 2000). In an extensive study of plant remains in alkaline, New England lakes

Dieffenbacher-Krall and Halteman (2000) concluded that the key issue is water depth at which the seeds settle, rather than proximity of seed deposition to the source plant. The most useful types of macrofossils are those from plants with the narrowest depth ranges, and whose seeds fall to the sediment quickly (Hannon and Gaillard 1997). While Dieffenbacher-Krall and Halteman (2000) identified several indicator species for alkaline lakes, this calibration can not automatically be extended to non-alkaline lakes. Alkalinity is a major factor in determining distribution of many aquatic plant species (Hellquist 1980), with species assemblages differing significantly between alkaline and non-alkaline lakes (Dieffenbacher-Krall and Halteman 2000). Dieffenbacher-Krall and Halteman (2000) also concluded that the presence of a species within the macrofossil assemblage was a more useful indicator of lake-level change than was the relative abundance of a species within the macrofossil assemblage.

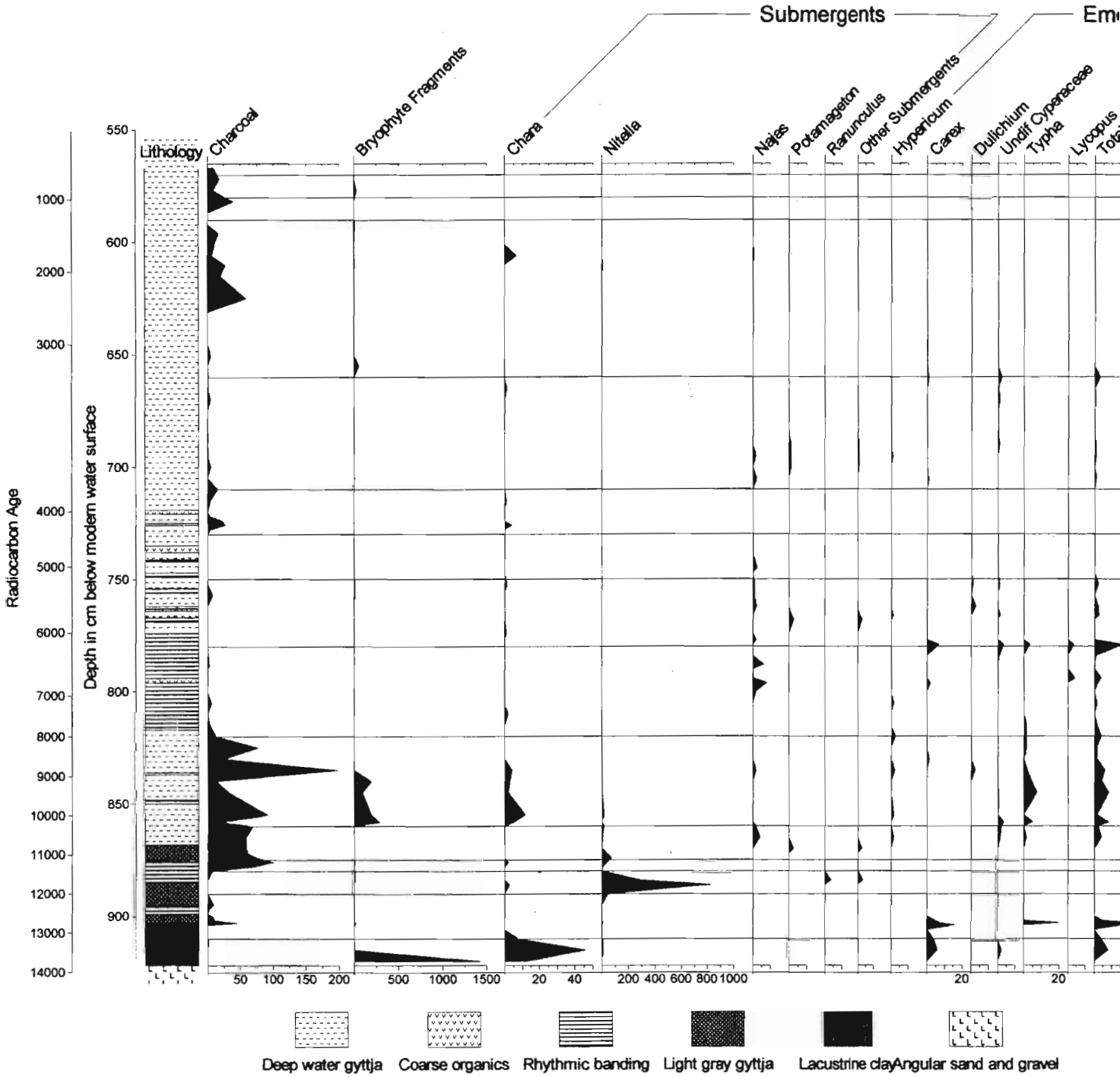
Charcoal

Charcoal analyses of sediment cores are biased by the distance between the collecting basin and the charcoal source (Clark 1988a, 1990). During a fire, charcoal particles of all size ranges are lifted into the atmosphere by thermal convection plumes. Charcoal particles ranging in size from 0.1 μm to 10,000 μm are lifted above the forest canopy by turbulent in-drafts and convection winds (Clark 1988a). Fragments differentially fall out of suspension. Charcoal particles >130 μm fall close to the fire zone, while smaller, dust-sized particles spread out into continental and even global distribution (Clark 1988a, 1988b, 1990, Clark and Royall 1995). Because this project targeted the fire

history of the Mathews Pond catchment region, charcoal particles >250 μm were identified and counted.

Charcoal analyses of sediment cores are spatially and temporally imprecise (Clark 1990). To delineate fire frequency, the quantitative sampling technique must be at a scale fine enough to resolve individual fires while spanning extended time periods (Clark 1988b). Sample resolution at Mathews Pond identified millennial-scale periods of fire activity.

Figure A.1 Summary of core MPB macrofossil analysis. Charcoal particles and macrofossils calculated to 100 cc of sediment. Zones indicate changes in sediment composition related to changes in water depth.



o 100 cc of sediment.

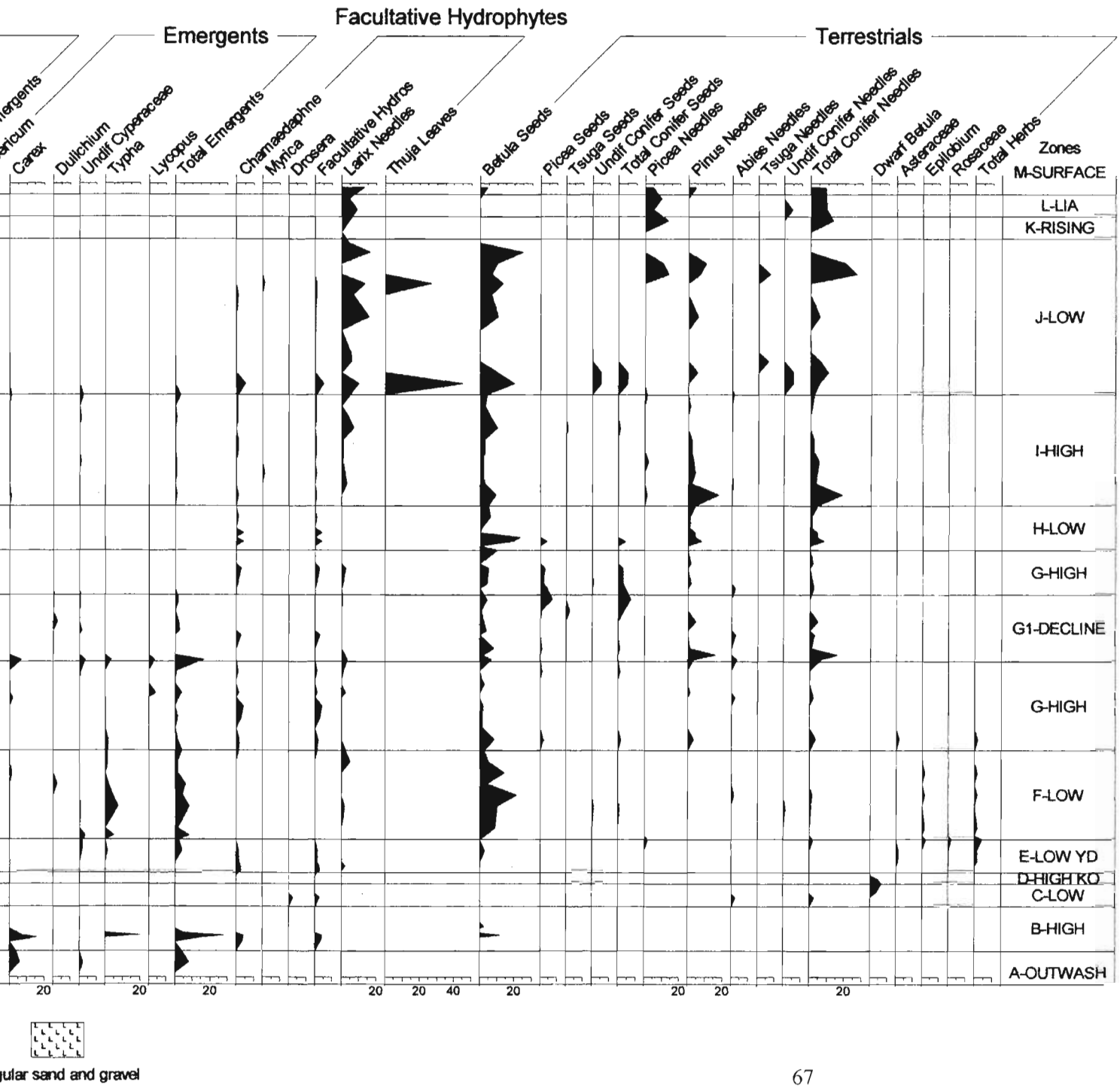
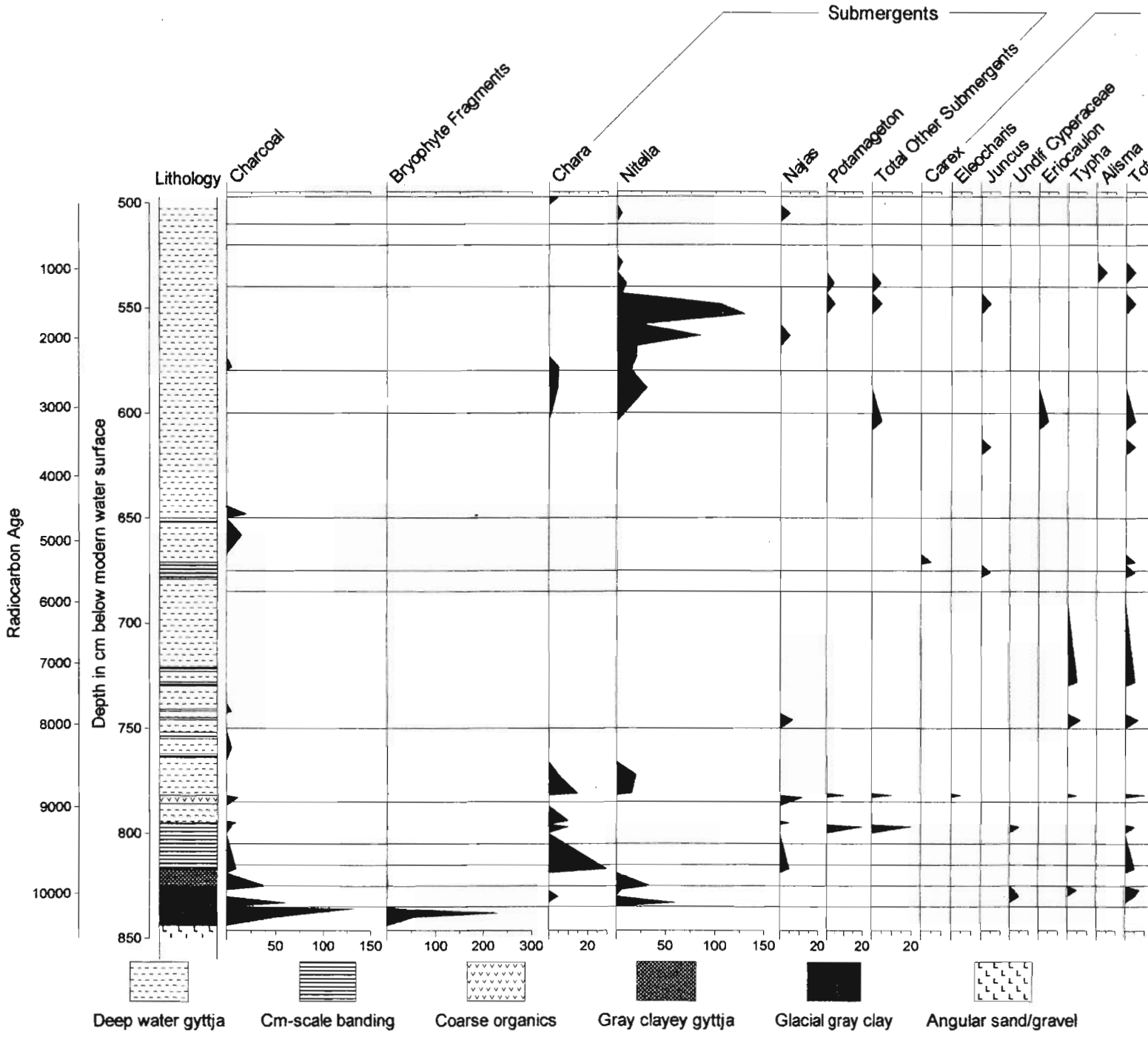


Figure A.2 Summary of core MPA macrofossil analysis. Charcoal and macrofossil values adjusted to 100 cc of sedi
Zones indicate changes in sediment composition related to changes in water depth.



values adjusted to 100 cc of sediment.

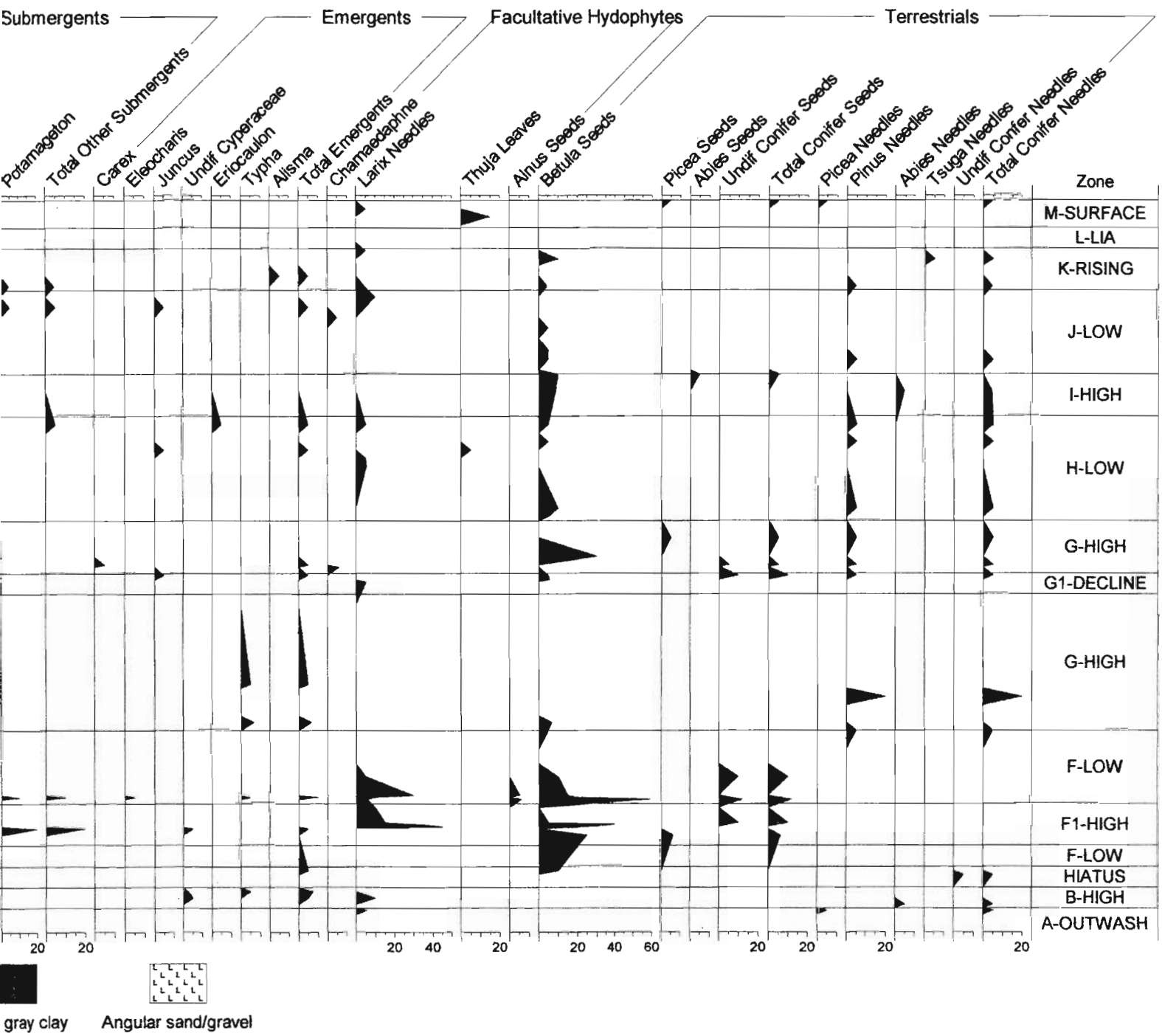
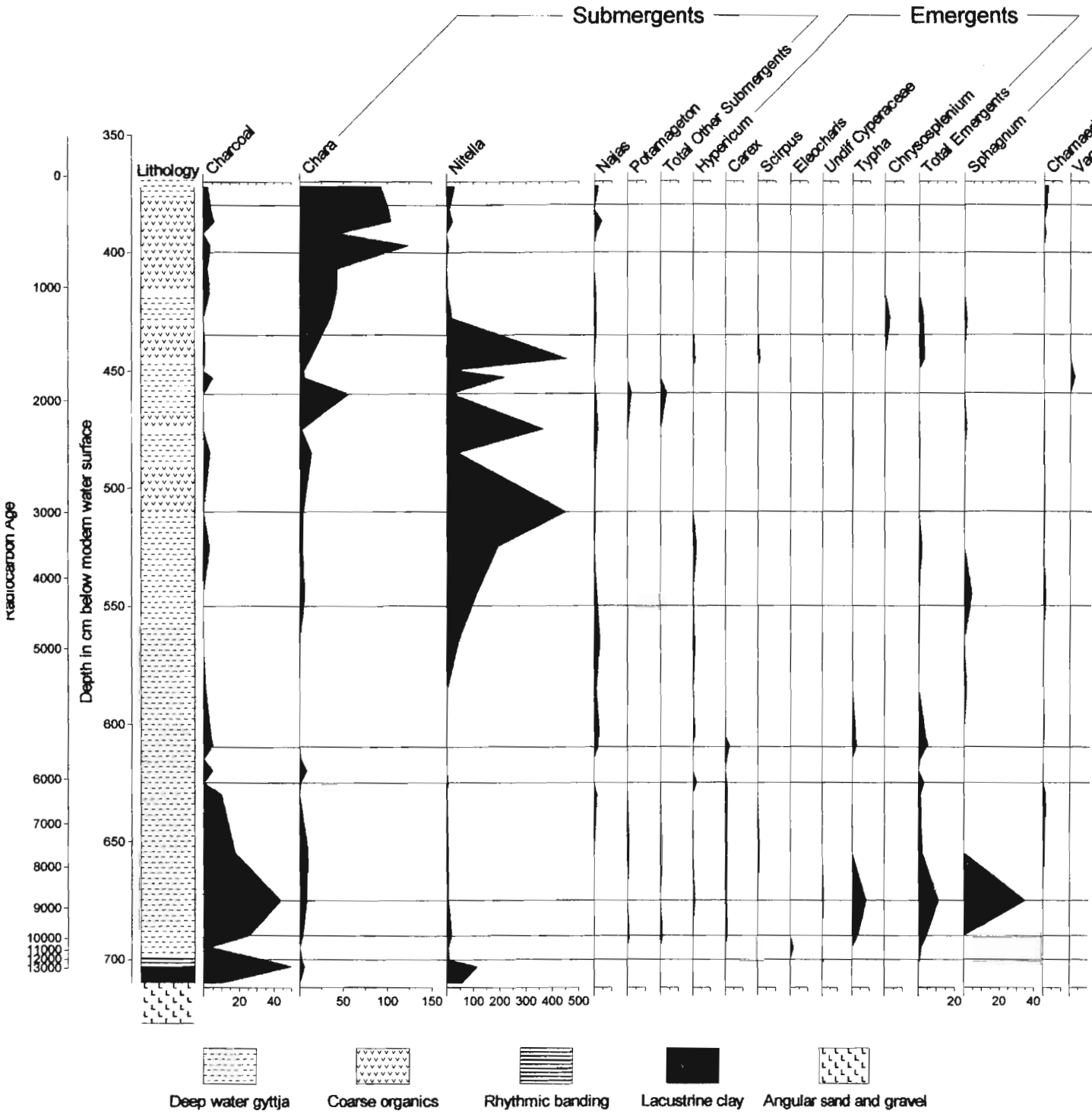
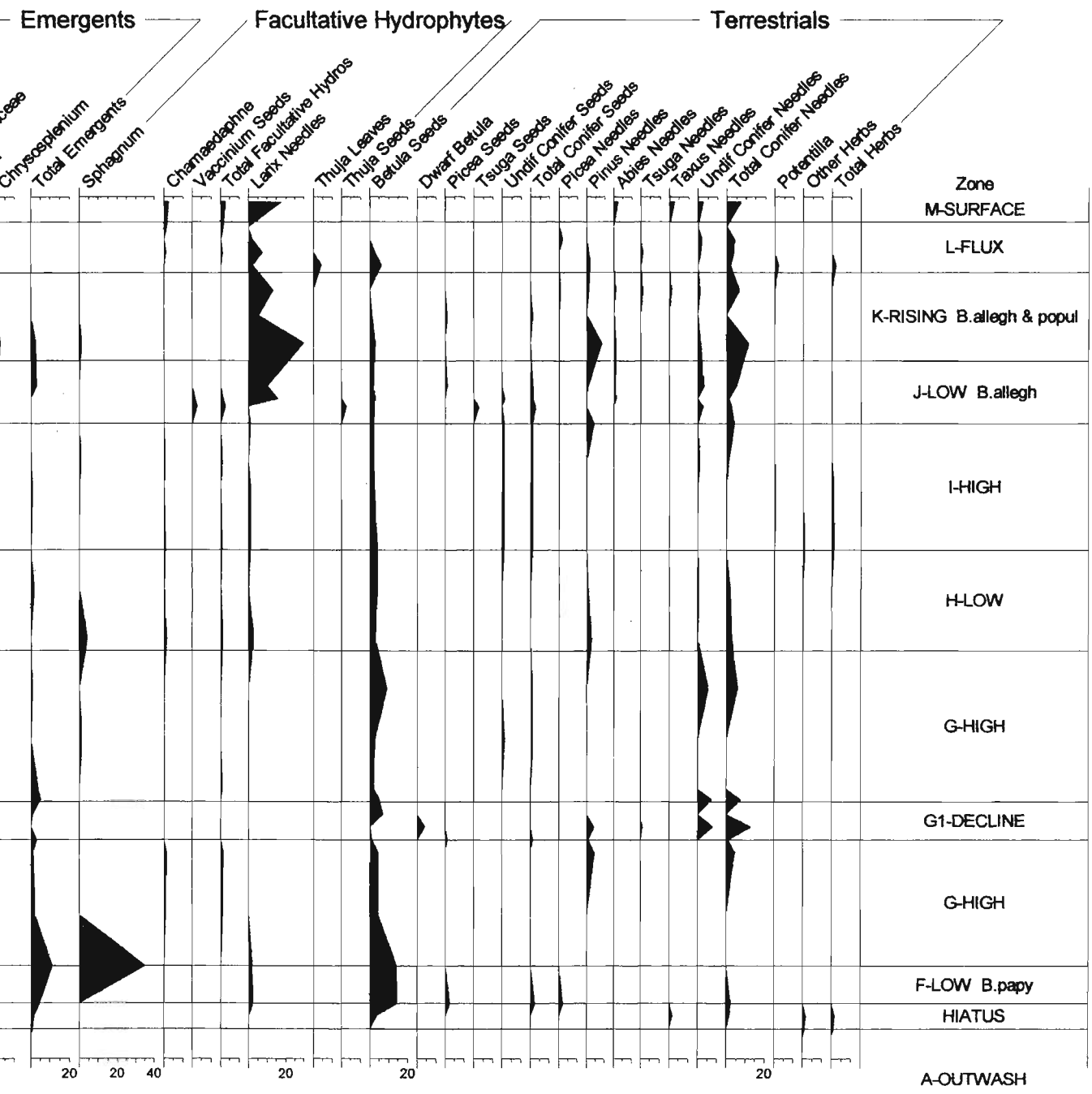


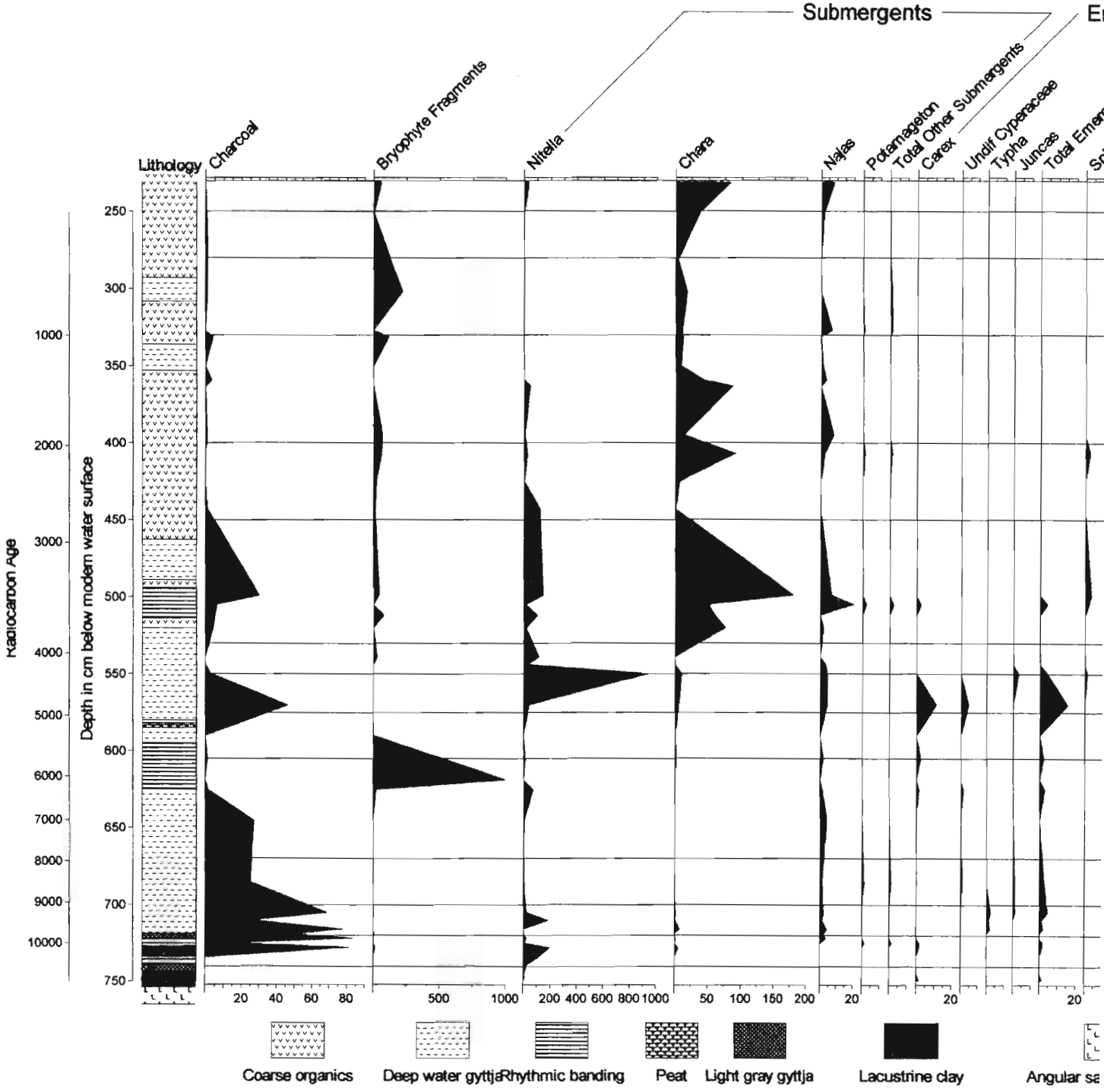
Figure A.3 Summary of core MPD macrofossil analysis.
Zones indicate changes in sediment composition related to changes in water depth.




Emergents
Facultative Hydrophytes
Terrestrials
Chnysosplenium
Total Emergents
Sphagnum
Chamaedaphne
Vaccinium Seeds
Total Facultative Hydros
Larix Needles
Thuja Leaves
Thuja Seeds
Betula Seeds
Dwarf Betula
Picea Seeds
Tsuga Seeds
Undif Conifer Seeds
Total Conifer Seeds
Picea Needles
Pinus Needles
Abies Needles
Tsuga Needles
Taxus Needles
Undif Conifer Needles
Total Conifer Needles
Potentilla
Other Herbs
Total Herbs
Zone
M-SURFACE
L-FLUX
K-RISING B.allegh & popul
J-LOW B.allegh
I-HIGH
H-LOW
G-HIGH
G1-DECLINE
G-HIGH
F-LOW B.papy
HIATUS
A-OUTWASH
20
20
40
20
20
20

gravel

Figure A.4 Summary of core MPE macrofossil analysis.
Zones indicate changes in sediment composition related to changes in water depth.



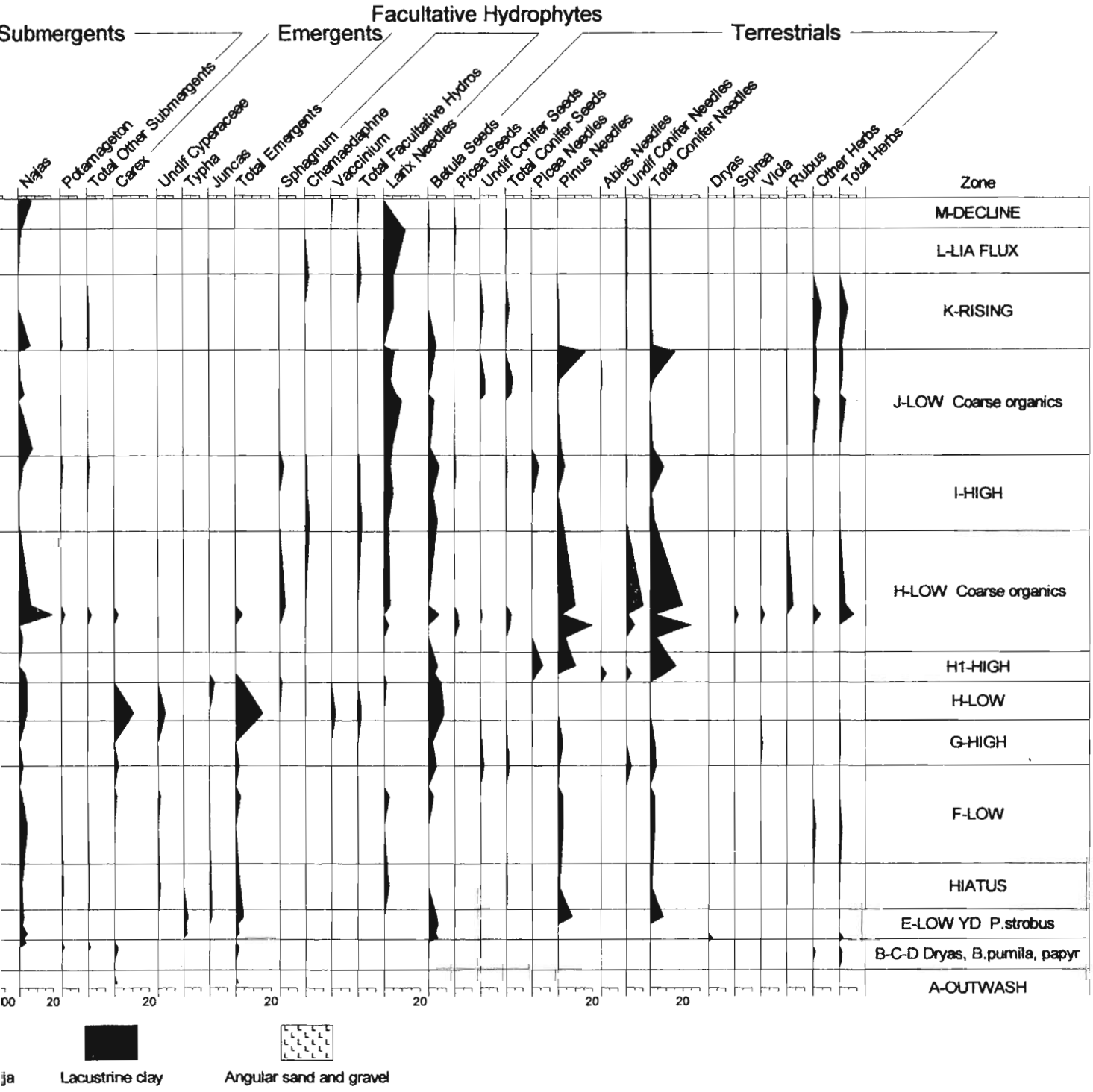
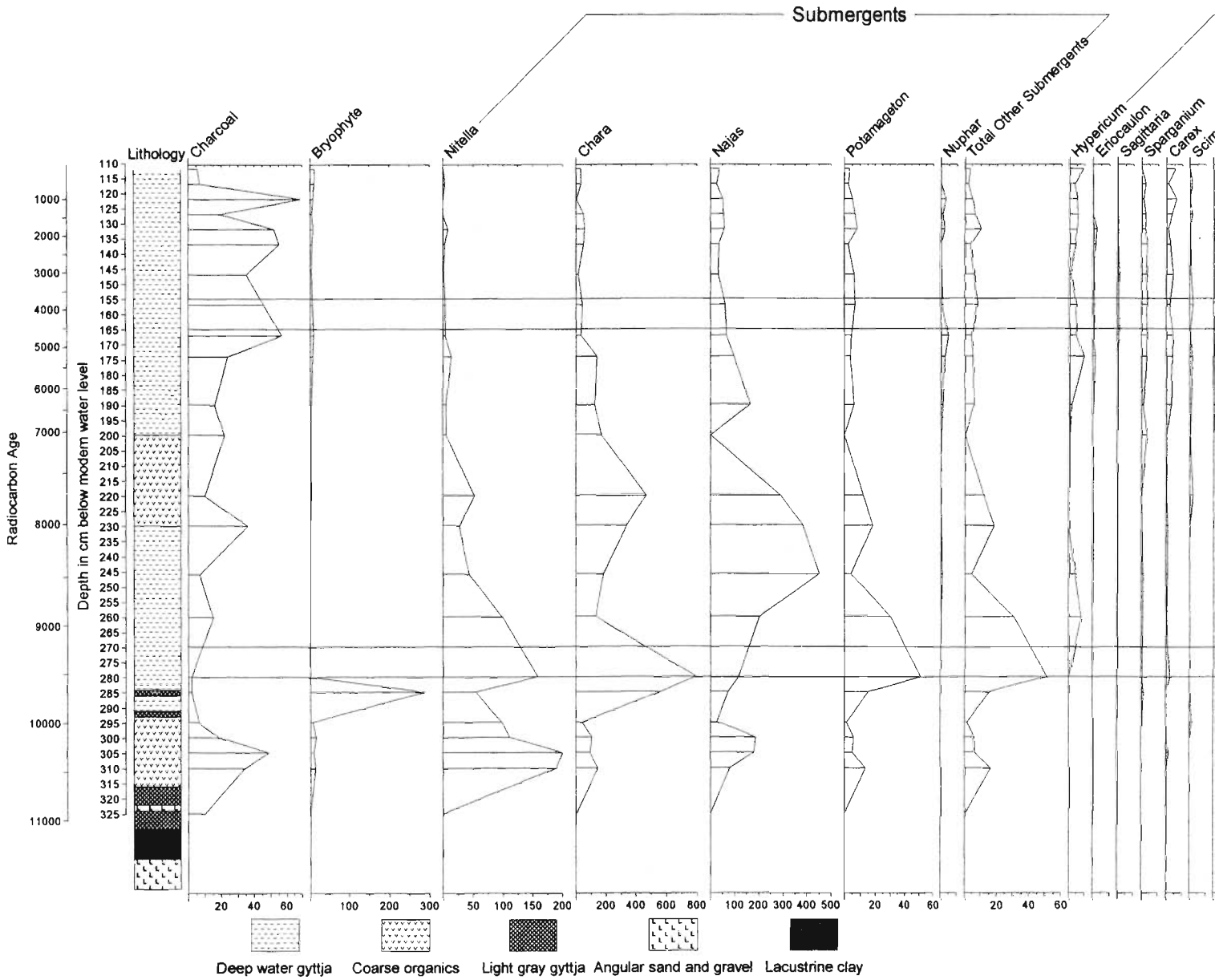

Submergents
Emergents
Facultative Hydrophytes
Terrestrials
Najas
Potamageton
Total Other Submergents
Carex
Undif Cyperaceae
Typha
Juncas
Total Emergents
Sphagnum
Charnaedaphne
Vaccinium
Total Facultative Hydros
Larix Needles
Betula Seeds
Picea Seeds
Undif Conifer Seeds
Total Conifer Seeds
Picea Needles
Pinus Needles
Abies Needles
Undif Conifer Needles
Total Conifer Needles
Dryas
Spirea
Vicia
Rubus
Other Herbs
Total Herbs
Zone
M-DECLINE
L-LIA FLUX
K-RISING
J-LOW Coarse organics
I-HIGH
H-LOW Coarse organics
H1-HIGH
H-LOW
G-HIGH
F-LOW
HIATUS
E-LOW YD P.strobus
B-C-D Dryas, B.pumila, papyr
A-OUTWASH
00
20
20
20
20
20
20
ja
Lacustrine clay
Angular sand and gravel

Figure A.5 Summary of core MPC macrofossil analysis. Charcoal and macrofossil values adjusted to 100 cc of sediment.
Charcoal and macrofossil analyses were not considered in lake-level calculations, because of questions regarding the orientation of core segment 210-310 cm



c of sediment.
ling the orientation of core segment 210-310 cm.

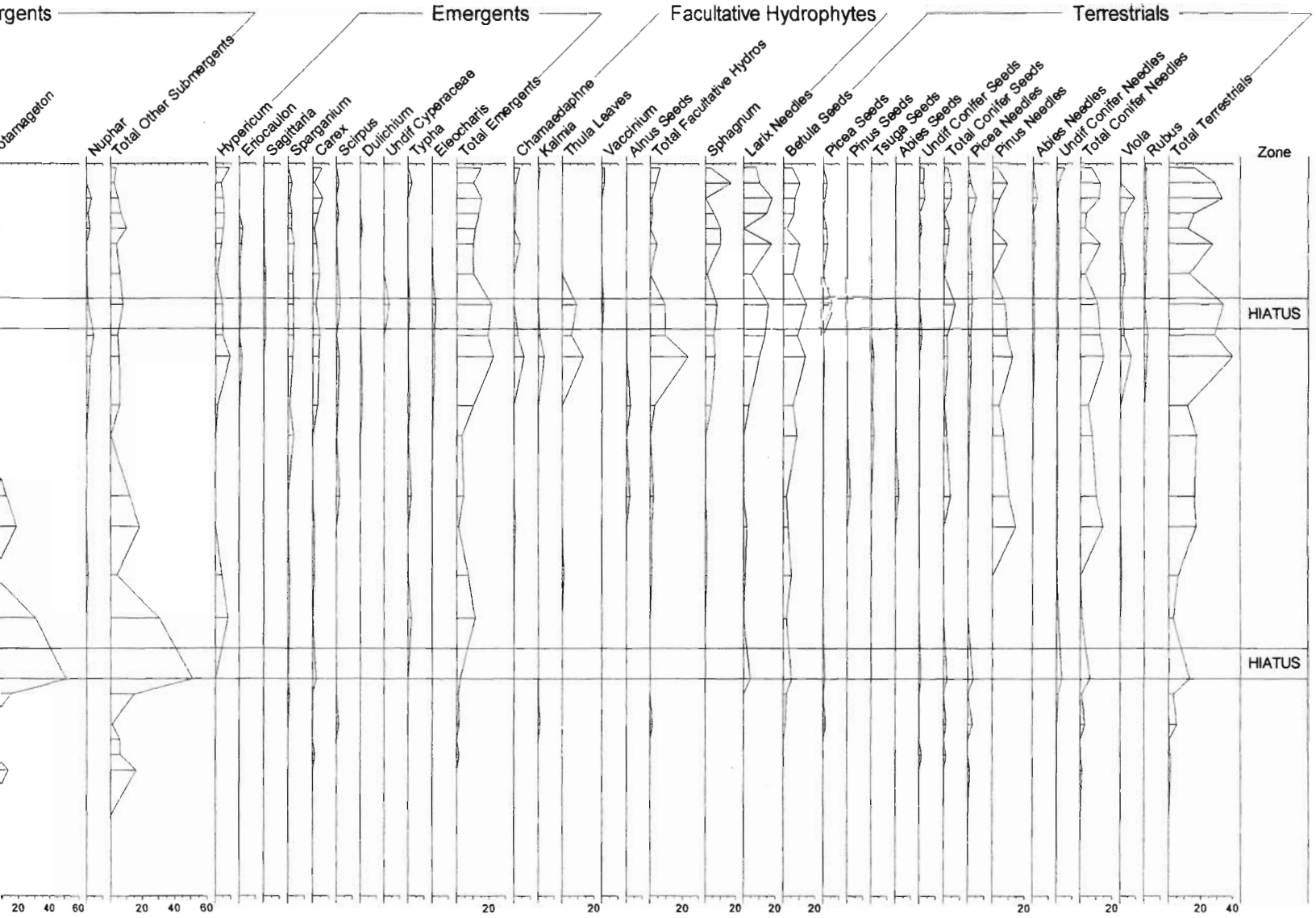
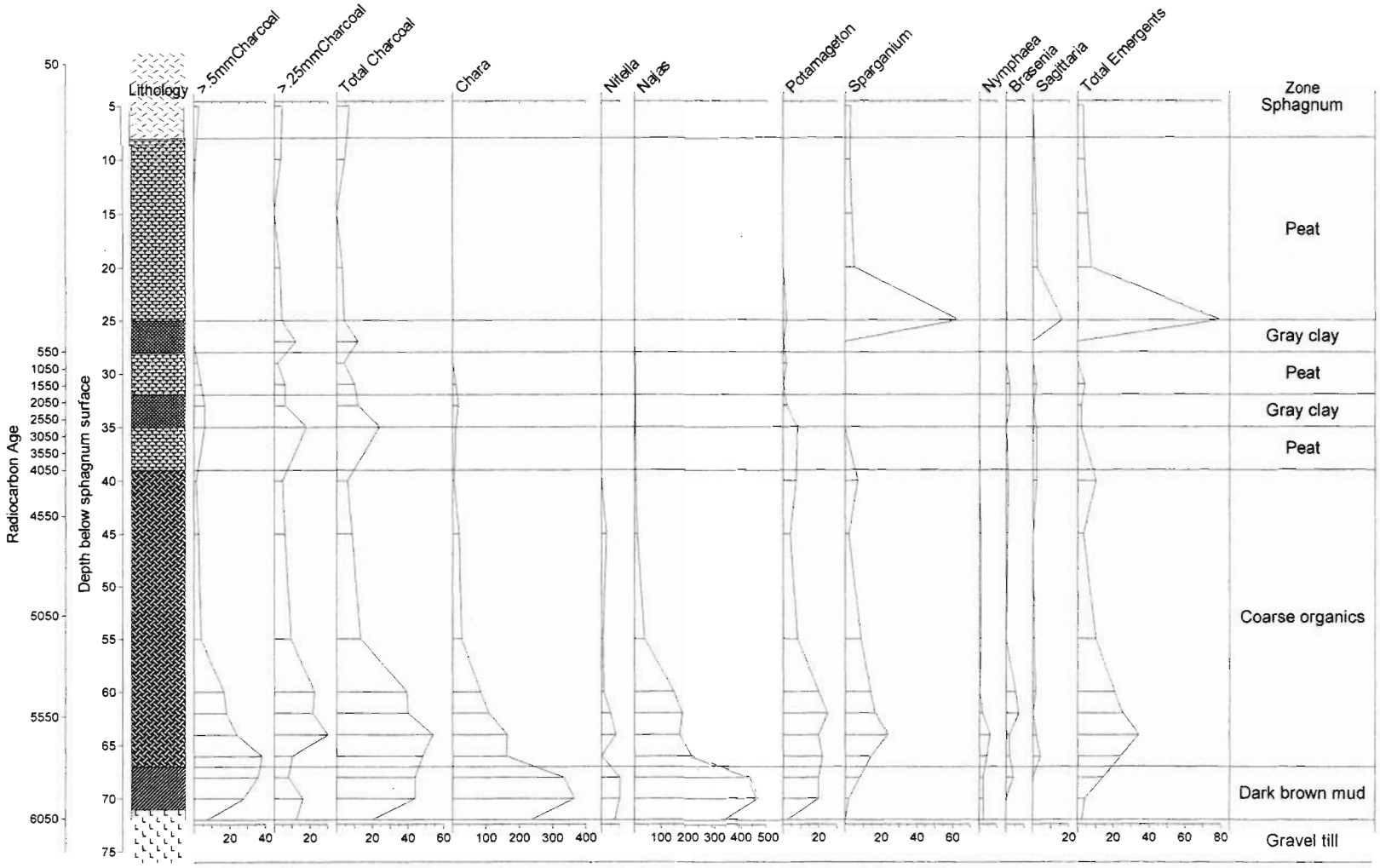


Figure A.6 Summary of shoreline core MPF macrofossil analysis includes lithic stratigraphy, charcoal, submergent species, and floating-leaved emergent species. Zones indicate lithic horizons.



Family	Genus	Classification	Comments
Characeae	Chara spp.	Submergent aquatic	less abundant than Nitella
Characeae	Nitella spp.	Submergent aquatic	
Haloragaceae	Myriophyllum farwellii Morong	Submergent aquatic	fairly abundant
Isoetaceae	Isoetes echinospora Durieu	Submergent aquatic	
Nymphaeaceae	Nuphar variegata Dur.	Submergent aquatic	abundant
Potamogetonaceae	Potamogeton amplifolius Tuckerman	Submergent aquatic	sporadic
Potamogetonaceae	Potamogeton epihydrus Raf.	Submergent aquatic	abundant
Potamogetonaceae	Potamogeton spirillus Tuckerman	Submergent aquatic	present
Ranunculaceae	Ranunculus aquatilis L. var. diffusus Withering	Submergent aquatic	
Apiacaee	Sium suave Walt.	Emergent	rare
Clusiaceae	Triadenum virginicum (L.) Raf.	Emergent	
Cyperaceae	Carex spp.	Emergent	
Eriocaulaceae	Eriocaulon aquaticum (Hill) Druce	Emergent	abundant
Juncaceae	Juncus spp.	Emergent	
Menthaceae	Lycopus uniflorus Michx.	Emergent	
Poaceae	Miscellaneous	Emergent	
Sparganiaceae	Sparganium angustifolium Michx.	Emergent	
Veronicaceae	cf. Gratiola	Emergent	
Cupressaceae	Thuja occidentalis L.	Facultative hydrophyte	on shore
Droseraceae	Drosera rotundifolia L.	Facultative hydrophyte	on log
Ericaceae	Chamaedaphne calyculata (L.) Moench	Facultative hydrophyte	abundant
Ericaceae	Gaultheria hispidula (L.) Muhl. ex Bigelow	Facultative hydrophyte	
Ericaceae	Kalmia angustifolia L.	Facultative hydrophyte	
Iridaceae	Iris versicolor L.	Facultative hydrophyte	
Myricaceae	Myrica gale L.	Facultative hydrophyte	abundant
Pinaceae	Picea mariana (P. Mill.) B.S.P.	Facultative hydrophyte	on shore
Asteraceae	Hieracium sp.	Terrestrial	on shore
Betulaceae	Betula alleghaniensis Britt.	Terrestrial	
Betulaceae	Betula papyrifera Marsh.	Terrestrial	
Ericaceae	Rhododendron canadense (L.) Torr.	Terrestrial	
Ericaceae	Rhododendron groenlandicum (Oeder) Kron & Judd	Terrestrial	present
Fagaceae	Fagus grandifolia Ehrh.	Terrestrial	
Pinaceae	Abies balsamea (L.) P. Mill.	Terrestrial	on shore
Pinaceae	Picea rubens Sarg.	Terrestrial	on shore
Pinaceae	Pinus resinosa Ait.	Terrestrial	on shore
Pinaceae	Pinus strobus L.	Terrestrial	on shore
Pinaceae	Tsuga canadensis (L.) Carr.	Terrestrial	on shore
Rubiaceae	Galium sp.	Terrestrial	
Sapindaceae	Acer pensylvanicum L.	Terrestrial	
Sapindaceae	Acer rubrum L.	Terrestrial	
Sapindaceae	Acer saccharum Marsh.	Terrestrial	
Violaceae	Viola sp.	Terrestrial	on shore

Table A.1 Terrestrial and aquatic plant survey for Mathews Pond, Piscataquis County, Maine, USA. Aquatic plants surveyed 30-July-02 by Ann Dieffenbacher-Krall. Trees and surveyed 04-October-00 by Andrea Nurse. Taxonomy follows Haines and Vining (1998).

Appendix A. References

Anderson, N.J. 1990: Spatial pattern of recent sediment and diatom accumulation in a small, monomictic, eutrophic lake. Journal of Paleolimnology 3, 143-60.

Birks, H.H. 1980: Plant macrofossils in Quaternary lake sediments. *Archives of Hydrobiology* 15, 60.

Clark, J.S. 1988a: Particle motion and the theory of charcoal analysis: Source area, transport, deposition, and sampling. *Quaternary Research* 30, 67-80.

Clark, J.S. 1988b: Stratigraphic charcoal analysis on petrographic thin sections: Application to fire history in northwestern Minnesota. *Quaternary Research* 30, 81-91.

Clark, J.S. 1990: Fire and climate change during th last 750 yr in northwestern Minnesota. *Ecological Monographs* 60, 135-59.

Clark, J.S. and Royall, P.D. 1995: Particle-size evidence for source areas of charcoal accumulation in late Holocene sediments of eastern North American lakes. *Quaternary Research* 43, 80-9.

Dearing, J.A. 1997: Sedimentary indicators of lake-level changes in the humid temperate zone: a critical review. *Journal of Paleolimnology* 18, 1-14.

Dieffenbacher-Krall, A.C. and Halteman, W.A. 2000: The relationship of modern plant remains to water depth in alkaline lakes in New England, USA. *Journal of Paleolimnology* 24: 213-29.

Digerfeldt, G. 1986: Studies on past lake-level fluctuations. In Berglund, B.E., editor, *Handbook of Holocene palaeoecology and palaeohydrology*. John Wiley and Sons, Chichester, UK, 127-43.

Greatrex, P.A. 1983: Interpretation of macrofossil assemblages from surface sampling of macroscopic plant remains in mire communities. *Journal of Ecology* 71, 773-91.

Haag, R.W. 1983: Emergence of seedlings of aquatic macrophytes from lake sediments. *Canadian Journal of Botany* 61, 148-56.

Haines, A. and Vining, T.F. 1998: *Flora of Maine: A Manual for Identification of Native and Naturalized Vascular Plants of Maine*. V.F. Vining Company, Bar Harbor, Maine.

Hannon, G.E. and Gaillard, M.J. 1997: The plant-macrofossil record of past lake-level changes. *Journal of Paleolimnology* 18: 15-28.

Harrison, S.P. and Digerfeldt, G. 1993: European lakes as palaeohydrological and palaeoclimatic indicators. *Quaternary Science Review* 12, 233-48.

Hellquist, C.B. 1980: Correlation of alkalinity and the distribution of Potamogeton in New England. *Rhodora* 82: 331-44.

Kautsky, L. 1990: Seed and tuber banks of aquatic macrophytes in the Askö area, northern Baltic proper. *Holarctic Ecology* 13, 143-148.

APPENDIX B

INFLUENCE OF ISOSTACY ON GROUNDWATER MOUND

Groundwater response to forebulge migration

Because Mathews Pond is a groundwater seepage lake, changes in lake-level at Mathews Pond more strongly reflect changes in the height and shape of the underlying groundwater aquifer than changes in P_L-E_L over the lake surface. If the groundwater aquifer sustaining Mathews Pond is hinged between the Allagash River in the

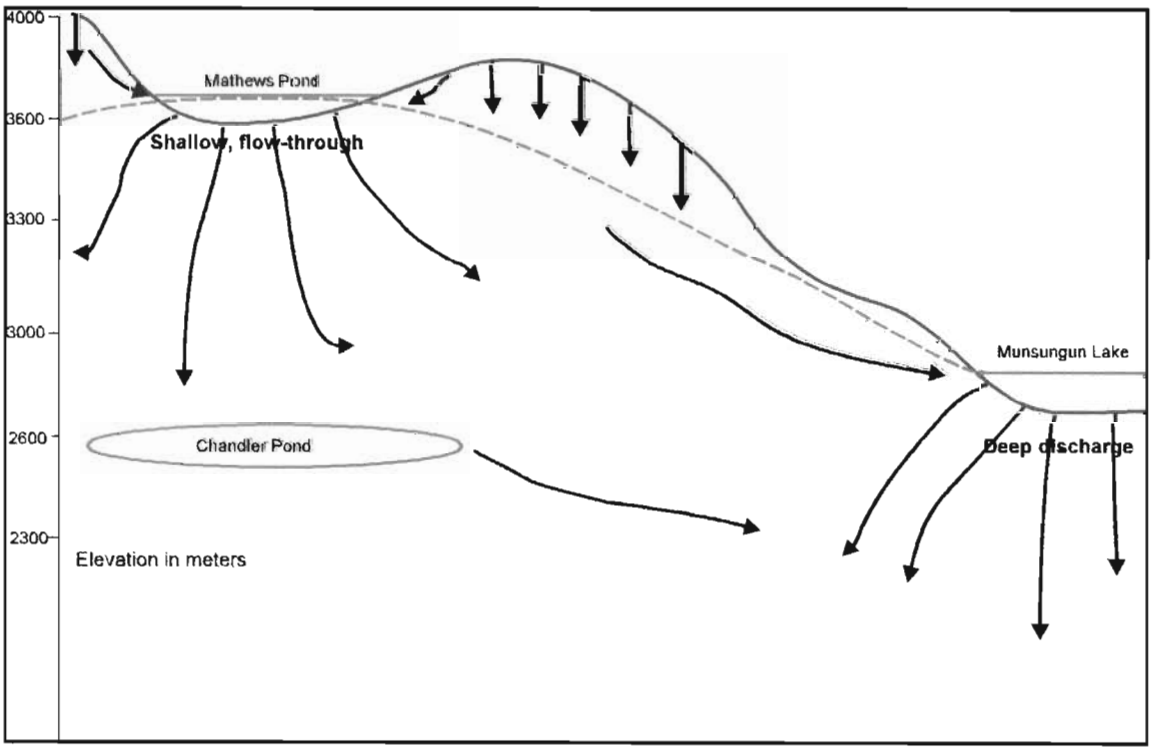


Figure B.1 Schematic representation of groundwater mound and flow-through groundwater system underlying Mathews Pond. Adapted from Born *et al.* (1979).

northwest and Aroostook River drainage system in the southeast (Figures B.1 and B.3), the aquifer encompasses a geographic region large enough for the shape of the aquifer (i.e., groundwater hydraulic pore pressure) to be influenced by isostatic depression and subsequent forebulge migration.

Timing and magnitude of sea-level lowstands in Massachusetts (-43 m at 12 cal yr BP (Oldale *et al.* 1993)), off the Maine coast (-65 m at 11.65-11.25 cal yr BP (Stea *et al.* 1994)), and in Quebec (-5 m at 7-6 cal yr BP (Dionne 1988)) suggest that a crustal forebulge of 20-25 m in amplitude migrated across Acadia at a rate of 7-11 km/100 years (Barnhardt *et al.* 1995). Mathews Pond is located northeast and along roughly the same glaciostatic rebound contour as the north end of Moosehead Lake (Balco *et al.* 1998). Forebulge migration rates from Balco *et al.* (1998)(Figure B.2) predicted that the aquifer was tilted to the northwest, and that water levels in the southeast sector of the aquifer

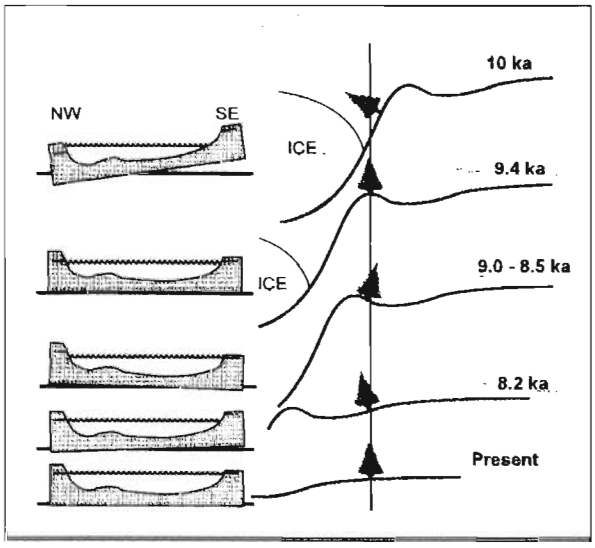


Figure B.2 Ice proximal depression and forebulge migration across Moosehead Lake basin. From Balco *et al.* (1998).

were low 12.0 ka to 10.0 ka. The forebulge passed through the region c. 9.4 ka, leveling, but elevating, the underlying bedrock basement. Between 9.0 ka and 8.5 ka the region tilled toward the southeast, implying high groundwater levels in the southeast and low groundwater levels in the northwest sector. By 8.2 ka tilt rebounded slightly back to the northwest, and then gradually decreased to the present inclination (Balco *et al.* 1998).

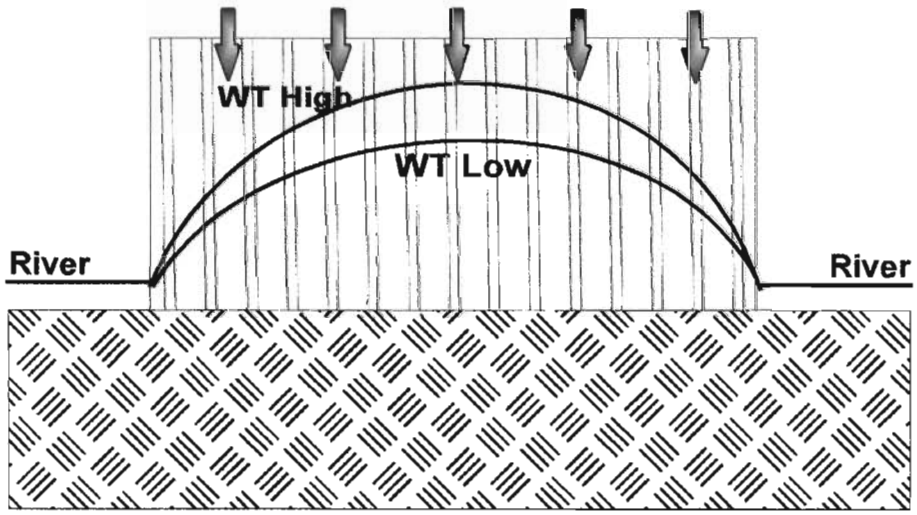


Figure B.3 Schematic representation of an inter-fluvial watertable (WT) hydraulic pressure mound. From Almendinger (1990) and Digerfeldt *et al.* (1992).

In response to effective moisture over the land surface (groundwater recharge), hydraulic pore pressure creates a water table mound, with mound elevation greatest midway between two parallel rivers (Figure B.3)(Almendinger 1990, Digerfeldt *et al.* 1992). When groundwater recharge is reduced, the water table mound elevation lowers, lowering more in the center of the mound than near the rivers (Almendinger 1990). Lakes near the center of the aquifer experience greater decrease in water level than do lakes

nearer the draining river systems. If isostatic tilt and forebulge migration changed surficial aquifer drainage patterns or altered the shape of the interfluvial, water-table mound, aquifer hydraulics could influence lake levels.

Without knowing the effects on groundwater mound shape and elevation, or knowledge of the geographic extent and orientation of the groundwater aquifer, it is impossible to predict exact timing of surficial groundwater response to ice-proximal tilt and forebulge migration. However, groundwater response to isostatic rebound could account for at least part of the pronounced increase in water level at Mathews Pond following the extended early-Holocene low stand.

Appendix B. References

Almendinger, J.E. 1990: Groundwater control of closed-basin lake levels under steady-state conditions. *Journal of Hydrology* 112: 293-318.

Balco, G., Belknap, D.F., Kelley, J.T. 1998: Glacioistasy and lake-level change at Moosehead Lake, Maine. *Quaternary Research* 49, 157-70.

Barnhardt, W.A., Gehrels, W.R., Belknap, D.F., Kelley, J.T. 1995: Late Quaternary relative sea-level change in the western Gulf of Maine: Evidence for a migrating glacial forebulge. *Geology* 23 (4), 317-20.

Born, S.M., Smith, S.A., Stephenson, D.A. 1979: Hydrogeology of glacial-terrain lakes with management and planning applications. *Journal of Hydrology* 43, 7-43.

Digerfeldt, G., Almendinger, J.E., Björck, S. 1992: Reconstruction of past lake levels and their relation to groundwater hydrology in the Parkers Prairie sandplain, west-central Minnesota. *Palaeogeography, Palaeoclimatology, Palaeoecology* 94, 99-118.

Dionne, J.C, 1988: Holocene relative sea-level fluctuations in the St. Lawrence estuary, Quebec, Canada. *Quaternary Research* 29, 233-44.

Oldale, R.N., Coleman, S.M., Jones, G.A. 1993: Radiocarbon ages from two submerged strandline features in the western Gulf of Maine and a sea-level curve for the northeastern Massachusetts coastal region. *Quaternary Research* 40, 38-45.

Stea, R.R., Boyd, R., Fader, G.B.J., Courtney, R.C., Scott, D.B., Pecore, S.S. 1994: Morphology and seismic stratigraphy of the inner continental shelf off Nova Scotia, Canada: Evidence for a -65 m low-standbetween 11,650 and 11,250 ^{14}C yr B.P. *Marine Geology* 117, 135-54.

BIOGRAPHY OF THE AUTHOR

Andrea Masterman Nurse was born in Farmington, Maine on October 30, 1948. She grew up on a third-generation, family dairy farm in Avon, Maine, and graduated from Phillips High School in 1967.

Andrea entered Springfield College in 1967 and obtained a degree in Biology in 1971. In 1972 she completed a Medical Technology internship through the University of Texas Medical School at the Bexar County Hospital, San Antonio, Texas. After returning to Maine with her husband and daughters, Andrea worked as a clinical microbiologist and laboratory manager for 13 years. She left the hospital laboratory to earn a Master in Business Administration degree in 1991 from Thomas College, Waterville, Maine. From 1986 to 2001 she worked in administrative positions in group health insurance, non-profit organization management, and physician recruitment. Andrea raises organically-grown, commercial highbush blueberries.

Prompted by a desire to return to scientific research, in June, 1997 Andrea enrolled for graduate study at the University of Maine. Andrea is a candidate for the Master of Science degree in Quaternary Studies from the University of Maine in August, 2003.