4

Geology, Vegetation, and Hydrology of the S2 Bog at the MEF: 12,000 Years in Northern Minnesota

Elon S. Verry and Joannes Janssens

CONTENTS

Introduction

A clear understanding of geology and landscape setting is fundamental to the interpretation of water and solute movement among landscape forms. This understanding allows us to assess how land use affects water, soils, and vegetation as well as assess the fate of acids, nutrients, trace metals, and organic compounds deposited from the atmosphere. Pleistocene Glaciation and the Holocene accumulation of peat in ice-block depressions are two primary determinants of the landscape in the recessional moraine area of north-central Minnesota, which is the setting of the Marcell Experimental Forest (MEF). We examine these two processes using studies of lacustrine and peat sediment accumulation, ice-block paleobotany, mineral-soil development, and a review of Wisconsin Glaciation at the MEF.

An understanding of geology and soil development illuminates the physical link between water in "pothole" bogs and recharge of water in the lagg at their perimeter to groundwater aquifers. Regional paleobotany patterns reveal broad climate change as a third driver of landscape development, imposing its control on water levels, plant migration, interspecies competition, and the vegetation community—in short, a 12,000 year interpretation of Earth processes since a great ice sheet.

This chapter is an account of geologic, hydrologic, paleobotanical, and current botanical development in and around a single ice-block depression now occupied by a black spruce (*Picea mariana*)-*Sphagnum* bog on deep peat (Figure 4.1). Included with interpretations of the published literature are previously unpublished soil, water chemistry, piezometer and well records, topographic surveys, rigorous peat-core dating and pollen analysis, and a critical, regionally specific application of recent interpretations of Wisconsin Glaciation and climate change. The insights into environmental change over 26 millennia place our current evaluations of anthropogenic environmental change in perspective. In particular, the last 20,000 years, including Late-Wisconsin Glaciation and the Holocene (the last 12,000 years at this site), encompass fundamental geologic events that drive today's ecosystems and our interpretation of their function.

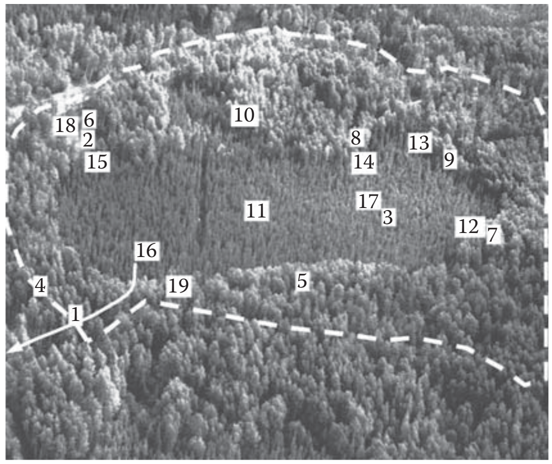

FIGURE 4.1
Oblique view of S2 bog on June 11, 1964 (photo by Bluford Muir, USDA Forest Service). The central peatland filling an ice block depression is forested with black spruce and the uplands with aspen and birch. The view is looking NNE. Numbers locate instrumentation: weir (1), weather station (2), bog well (3), upland wells (4–6), upland runoff plots (7, 8), soil pit A (9), soil pit B (10), piezometer nests (11–16), soil temperature stack (17), and neutron soil moisture tubes (18, 19). The arrow identifies the exit stream and the dashed line shows a picture-truncated watershed boundary.

General Setting and Contemporary Climate

The MEF is located in north central Itasca County, Minnesota (Lat. 47:31:52N, Long. 93:28:07W) at about 430 m above sea level (NAVD 1929). The Marcell Hills are in the Humid Temperate Domain (200), Warm Continental Division (210), Laurentian Mixed Forest Province (212), Northern Minnesota Drift and Lake Plains Section (212), and St. Louis Moraines Subsection (212Nb) of terrestrial ecoregions in North America (Keys and Carpenter, 1995).

In the North American aquatic classification (Maxwell et al., 1995), it is in the Nearctic Zone (North America), the Arctic-Atlantic Subzone (A), the Mississippi Region (A2), and at the very northern tip of the Upper Mississippi Subregion (A2a), several kilometers west of the tricontinental divide point for the Upper Mississippi, St. Lawrence, and Hudson Bay watersheds.

The climate is strongly continental (Chapter 2). The mean annual precipitation from 1961 to 2000 was 78 cm, and the annual temperature 3.3°C. Monthly precipitation ranges from 4 cm in February to 33 cm in August (Figure 4.2) and annual precipitation ranges from 412 to 946 mm. Monthly average temperatures are 16°C, 19°C, and 15°C in June, July, and August, and –12°C, –16°C, and –11°C in December, January, and February (Figure 4.3).

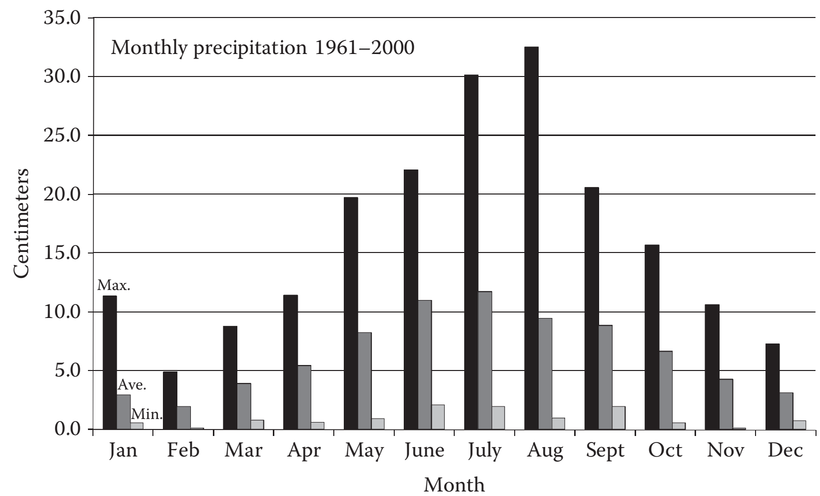

FIGURE 4.2
Monthly maximum, average, and minimum precipitation for the S2 meteorological station.

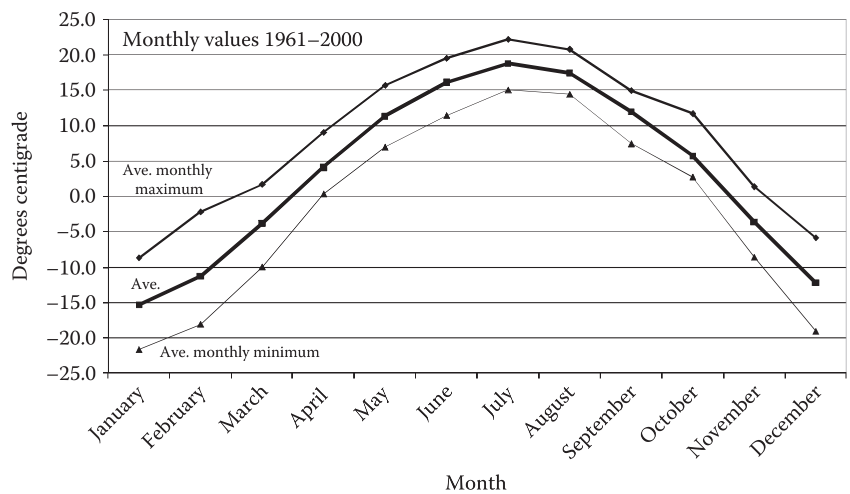

FIGURE 4.3
Monthly maximum, average, and minimum temperature for the S2 meteorological station.

Bedrock Setting

The MEF site is underlain by the Giants Range Batholith, a large complex of intrusions formed about 2.7 Ga before present (BP) (Figure 4.4). The bedrock lies some 40–50 m under late Wisconsin glacial drift (Oakes and Bidwell, 1968). The MEF and S2 bog lie in a recessional moraine complex (the Marcell

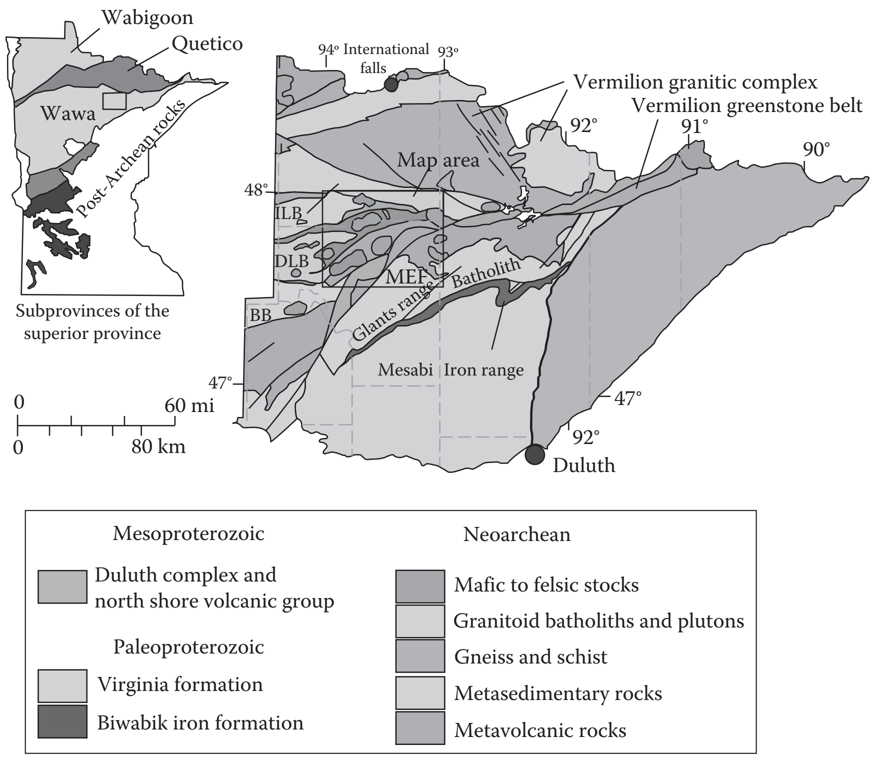

FIGURE 4.4
The MEF lies within the Bigfork USGS quadrangle (black rectangle) above the Giants Ridge, granitoid, batholith composed of tonalite to granodiorite, part of the Wawa subprovince of the Superior bedrock province (from Jirsa and Chandler, 2007). Black lines are major faults or NW trending dikes. ILB is Island Lake batholith, DLB is Dora Lake batholith, and BB is Bemidji batholith.

Hills) formed by Late-Wisconsin glaciation (26–12 ka BP), with elevation ranges of 10–30 m, mineral soil side slopes of 5%–40%, flat-topped hills, and peat- or lake-filled, ice-block depressions (Figure 4.5). Because this location is within 3 km of the Hudson Bay-Mississippi Continental Divide, we speculate that the bedrock surface may also be a topographic high.

Methods

Mapping

In 1966, Mark Hurd Aerial Surveys (Minneapolis, Minnesota) produced topographic maps with 4 ft contours for the MEF. We interpolated contour lines by hand at 1 m intervals. In 1982, we recorded a hollow and a hummock

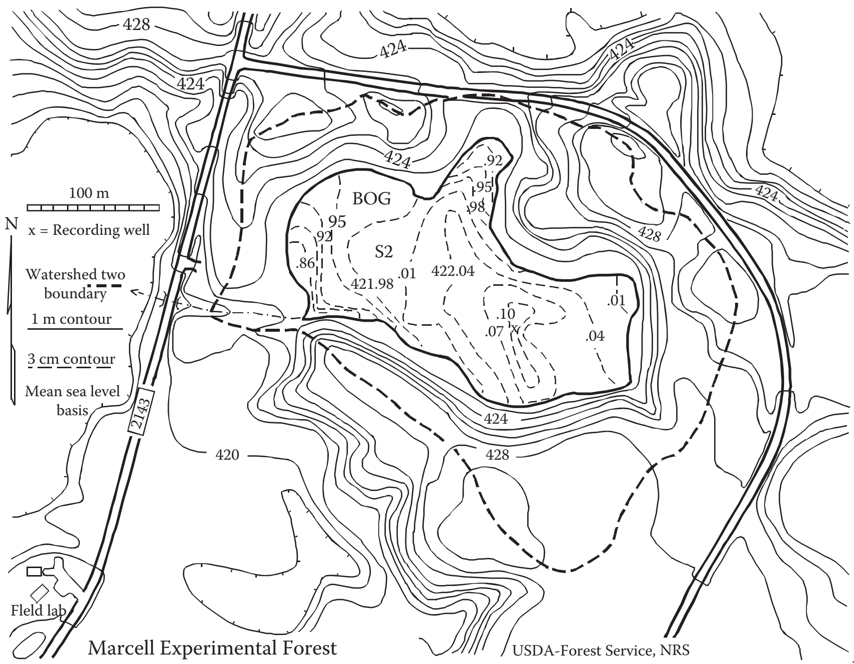

FIGURE 4.5
Surface contours of the uplands (1 m interval) and peatland (3 cm interval) in the S2 watershed. A surface stream drains from the southwest tip of the bog.

surface elevation near each point on a 30.5 m grid over the S2 peatland (Verry, 1984). In 1988, we sounded the same grid for depth to the Koochiching till the surface lying below the peat deposit and mapped 1 m contours of the ice-block depression. We mapped only the hollow elevation of the peat surface and interpolated a series of 3 cm contour intervals. Detailed metric maps for watershed S2 were drawn and digitized in December 1994.

Peat Coring

On November 20, 1983, Herb Wright Jr. (emeritus professor, University of Minnesota) extracted a 782 cm-long peat core (MR2-8307) using a 10 cm-diameter piston corer at a site near the middle of bog S2 located 80° east of north and 33 m from the recording well. On April 20, 1994 at the same location, Janssens, Paul H. Glaser (senior research associate, University of Minnesota), Howard D. Mooers (professor, University of Minnesota), and Verry collected a 106 cm-long core (MR2-9401) using a Waadenaar corer. In addition, Janssens collected several short cores in S2 bog in July 1986. Data composites from the short cores were useful in documenting the post settlement peat horizon developing after about 1865.

Weather, Water, Soil, and Geologic Studies

Weather records were summarized for 1961–2000 at a weather station on the upland, 20 m north of bog S2. At the MEF technicians measured streamflow, bog and regional water table elevations continuously, and took soil moisture and water-chemistry samples periodically from 1966 to 2001 (Chapter 2). We derived the elevation, referenced to U.S. Geological Survey quad map elevations and benchmarks, of soil and peat horizons from logs for wells, piezometers, soil pits, and surface topography.

Soil descriptions are detailed in Paulson (1968) and Nyberg (1987). Detailed mineral- and organic-soil physical properties (including bulk density, carbonate content, hydraulic conductivity, color, texture, and degree of decomposition) were determined in two large, soil pits (about 3 m deep) in contiguous mineral and peat soils at two locations on the edge of the S2 bog (Brooks and Kreft, 1991; Tracy, 1997). Hydraulic conductivity was measured in the peat (Boelter, 1965; Gafni and Brooks, 1986, 1990) and in the A/E and Bt upland soil horizons of S2 (Tracy, 1997).

Sander (1971) carried out a local groundwater geology study from 1967 to 1969, which included a fully penetrating well for an aquifer pumping test (water transmissivity) and descriptions of geologic material, seismic refraction, resistivity, and residual Bouger gravity anomalies. Samples of surface and deep sand were collected in late September 2004 at 11 locations surrounding the S2 watershed to help differentiate between Rainy and Des Moines drift; both wet and dry soil color chips and hand textures were used.

Late Wisconsin Glaciation

Glacial Advances, Stable Margins, and Meltout over Stagnant Ice

Rainy/Itasca Lobe ice (from the north and northeast) stagnated north of the Itasca Moraine (lying along an east-west band near the southern shore of Leech Lake in north-central Minnesota; 100 km SW of MEF) after 18,000 calibrated years (cal y) BP. However, the Rainy/Itasca ice established stable margins northeast of Leech Lake about 3 km east of S2 bog (a north-south-oriented margin of the Rainy Lobe), and about 15 km to the north (an east-west-oriented margin of the Itasca Lobe). The ice sheet terminated at this stable margin for several thousand years. Meltwater and sediment released from the ice accumulated on the stagnant ice surface north and east of S2 bog, forming a large outwash fan.

Stagnant ice to the west and south of S2 bog melted over several thousand years, forming a topographic low. About 14,000 cal y BP, ice of the Des Moines Lobe advanced through this low from east to west along an axis extending through Grand Rapids, Minnesota and the large Lake Winnibigoshish

WSW of MEF. The northern margin of this advance, the St. Louis Sublobe, abutted against the Rainy/Itasca Lobe outwash fan about 15 km southwest of the S2 bog.

Meltwater and sediment then poured onto stagnant ice in the triangle-shaped, topographically low area bounded by the Itasca Lobe to the north, the Rainy Lobe to the east, and the St. Louis sublobe to the southwest. Meltwater escaped from the low area by means of a subglacial drainage channel passing through the Giant's Range near present-day Taconite, Minnesota. While the advance of the St. Louis Sublobe was short-lived, and its ice rapidly stagnated and melted, its advance allowed about 15 m of glaciofluvial and glaciolacustrine sediment to accumulate over stagnant ice at the S2 bog site.

After 13,000 cal y BP, the Rainy and Itasca Lobes retreated further to the north. Glaciofluvial sediment no longer accumulated at the S2 site but stagnant ice cored the topography (lay buried in the sediment) for thousands of years (to as late as about 11,000 cal y BP). As the buried ice melted gradually the overlying sediment slowly collapsed. Sediment slumped from high areas, accumulating in low areas. As the last ice melted, the sediment-filled areas remained as hills, while the relatively sediment-poor formerly high areas had collapsed to form depressions (kettles), one of which was the precursor to S2.

Concurrent with meltout of the last buried ice, large glacial lakes formed to the west and north of S2, most notably Lake Agassiz and its precursor Lake Koochiching. As the levels of these lakes fluctuated and finally drained, large areas of unvegetated lake bottom were exposed to wind erosion. Silt and very fine sand sediment eroded from the lake bottom and entrained by the prevailing westerly winds was deposited as a blanket of loess on the landscape to the south and east, including S2.

Sander (1971) describes sands beneath the till cap at S2 as brown. In addition, Rainy (reddish brown) and St. Louis Sublobe (yellowish brown) drifts are in the MEF area. The younger St. Louis Sublobe drift overlies the older Rainy drift in much of north-central Minnesota. Although the S2 watershed is overlain by a till cap of Koochiching drift origin, 11 samples of sand drift around the S2 watershed show a tongue of Rainy drift with no St. Louis drift. Sample sites with Rainy drift extend from at least 2.4 km north-northeast of the S2 watershed to 0.6 km south-southwest in a tongue about 0.6 km wide. The Rainy drift is overlain by St. Louis Sublobe drift in areas to the north, west, and south. The Rainy drift samples have a soil color description of 5YR 6/6 (dry) and 5YR 5/8 (wet) while the St. Louis Sublobe drift samples have a soil color description of 10YR 7/2 (dry and wet). The Rainy drift color is described as orange to bright reddish brown, while the St. Louis Sublobe drift is described as dull yellow orange. The Rainy sands are coarse, medium, and fine textured with few small-gravel pebbles while the Des Moines sands are coarse, medium to fine with a wide range of gravel and small cobble.

Table 4.1 lists the geologic materials documented at the MEF (Sander, 1971) and two possible interpretations of their drift origin (Meyer, 1986; Mooers,

TABLE 4.1

Geologic Materials Documented at the MEF (Shaded), Others in the Region, and Alternative Interpretations of Wisconsin Glaciation using Information from Mooers and Lehr (1997) or Meyer et al. (1986)

Geologic Material at the MEF or Near the S2 Bog	Elevation (m)	Mooers et al. Interpretation of Source Area	Mooers et al. Interpretation of Dates BP (ka)	Meyer et al. Interpretation of Source Area	Meyer et al. Interpretation of Dates BP (ka)
No Vermillion Phase drift at MEF		Rainy Lobe	12.3		
		Vermillion Phase			
		Labrador Center	13.7		
Brown till, clay loam, with rock, and few slightly calcareous Cretaceous shale fragments	429	Red R.-Kooch. Lobe	11.9	Koochiching Lobe	
		Riding Mtn. Prov.		Riding Mtn. Prov.	
	424	Keewatin Center	12.2	Keewatin Center	
Brown Sand, fine to medium sands, with slight streaks of clay near the top, and some coarse sand with up to 13-mm pebbles near the bottom; noncalcareous	424	Rainy Lobe	13.2	Rainy Lobe	
		Bemis Phase		Labrador Center	
		Labrador Center			
		North-central Ontario			
	395		14		
Brown sand, medium to coarse sand with few pebbles up to 13 mm in top 1.0 m and bottom 1.2 m; noncalcareous	395	Rainy Lobe	15	Rainy Lobe	
		St. Croix Phase		Labrador Center	
		Labrador Center			
	391	West of James Bay	17.5		
Gray sand, with pebbles and limestone fragments up to 6 mm in diameter	391	Itasca Lobe Outwash	18	Rainy Lobe	
		Hudson Provenance		Labrador Center	
		Labrador Center			
		West Hudson Bay			
	387				

(continued)

TABLE 4.1 (continued)

Geologic Materials Documented at the MEF (Shaded), Others in the Region, and Alternative Interpretations of Wisconsin Glaciation using Information from Mooers and Lehr (1997) or Meyer et al. (1986)

Geologic Material at the MEF or Near the S2 Bog	Elevation (m)	Mooers et al. Interpretation of Source Area	Mooers et al. Interpretation of Dates BP (ka)	Meyer et al. Interpretation of Source Area	Meyer et al. Interpretation of Dates BP (ka)
Gray till, compacted clay, sand, silt, pebbles and limestone fragments up to 13 mm in diameter	387	Itasca Lobe	20	Winnipeg Lobe	26
		Hudson Provenance		Browerville Phase	
		Labrador Center		Keewatin Center from the NNW	
		West Hudson Bay from the NNE			
	380			(Pre-Late Wisc.)	30?
Greenstone and granite bedrock	380				
Other early Late-Wisconsin and pre Late-Wisconsin glacial drifts were not documented at the MEF					
Carbonate (<25%) and graywacke clasts called "Omars" (Mooers and Lehr, 1997)		Rainy Lobe	21 ka	Rainy Lobe	
		Hewitt Phase		Hewitt Phase	
		Labrador Center		Labrador Center	
(Late Wisconsin)		East Hudson Bay	23 ka		>30
Carbonate (25%–40%), Cretaceous shale (Mooers and Lehr, 1997). Loamy-clay loam, pre-Cambrian pebbles (Meyer, 1986)		Winnipeg Lobe		Winnipeg Lobe	
		Browerville Phase		Browerville Phase	
		Keewatin Center		Keewatin Center	
Silty clay, silty fine sand, coarse sand at base; gravel, cobbles and boulders, greenish gray, clay noncalcareous to moderately calcareous; rocky, hard, and compact. Alternates with Winnipeg Lobe (Meyer et al., 1986)				Old Rainy Lobe	
				Various Phases	
				Labrador Center	

Note: Elevations and dates are listed for the top and bottom of each major material described.

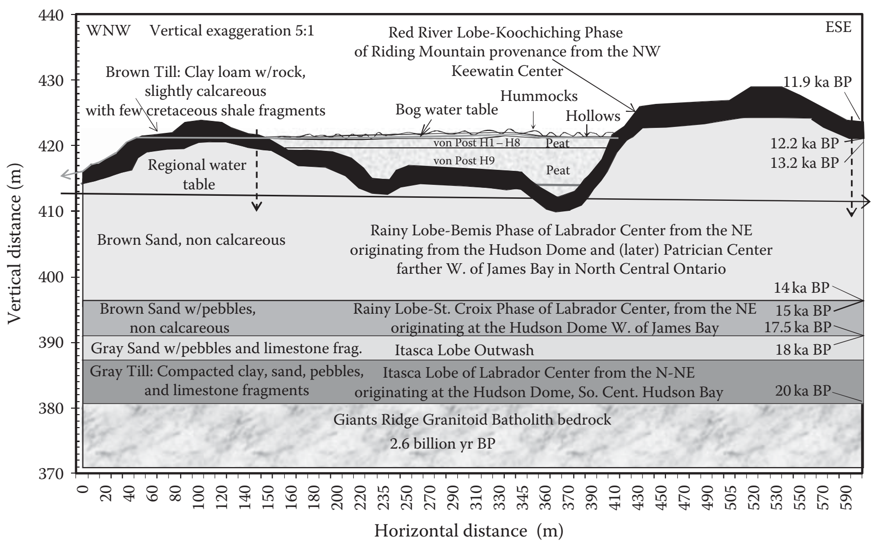

FIGURE 4.6
Longitudinal cross section of the S2 watershed (WNW to ESE) showing age and depth of major geologic and soil materials and the position of the bog and regional water tables during contemporary times. Note the slightly domed peat surface and parallel peatland water table. Vertical arrows are deep well locations.

1990; Mooers and Dobbs, 1993; Meyer, 1997; Mooers and Lehr, 1997; Mooers and Norton, 1997; Meyer et al., 1998). Figure 4.6 is a descriptive cross section drawn longitudinally through S2 bog and the entire S2 watershed using our interpretations based on various works of Mooers. It includes a surface deposit of loess and glacial flour at the bottom of the ice-block depression.

Beneath S2 Bog

The limestone fragments in the Itasca Lobe drift are the source of high calcium concentrations in groundwater (>20 mg L^{-1}) discharging from aquifers in the overlying Rainy Lobe sand into area streams and lakes. Rainy Lobe sands are brown and lack calcium carbonate except near the upper boundary where more recent slightly calcareous till overlies it.

Koochiching till caps the deep sandy drift of the Rainy Lobe, covering more than 75% of the MEF and ranging in thickness from 3 to 5 m; it was not covered with glacial meltwater or ice. An additional 20–30 cm of eolian loess was deposited over both the till cap and sandy drift. The loess is fine sandy loam in texture. It blew from the dry hills exposed after meltback of the ice (Nyberg, 1987). Beneath the bog peat the Koochiching till surface is mostly glacial flour formed directly beneath the grinding ice sheet, or washed into the tundra pond, beginning about 11,900 years ago.

Ice-Block Depression

The surface below the S2 bog is a muted contour of the original ice-block depression and hides much of the detail needed to explain the sequence of events resulting in the basin's current shape (Figure 4.7). The bottom contour is not the original ice-block depression, but the contour of the Koochiching till collapsed into an ice-block cavity in the underlying Rainy outwash. Nevertheless, it reveals the track of the original ice block (from the Rainy ice sheet) being dragged, pushed, and finally over-ridden by its mother sheet into the Rainy sands below.

It began when a wedge of ice broke from the leading edge of the Rainy Lobe glacier and rested near the outlet of S2, where the stream is today. It was perhaps 50 m wide at its base, 100 m wide at its top, and at least 20 m tall. We estimated its size from the width of the depression in the Rainy Lobe drift (Figure 4.6). It was a small block of ice compared to the enormous Laurentide ice sheet that rose 2,200 m into the air at maximum development some 18,000 years ago near its eastern Hudson Bay maximum. However, when the block broke away, perhaps 13,200 years ago, the ice was much thinner. There were tens of thousands of these ice-block depressions across the Lake States, New England, and the Canadian Provinces, giving rise to kettle (pothole) topography throughout.

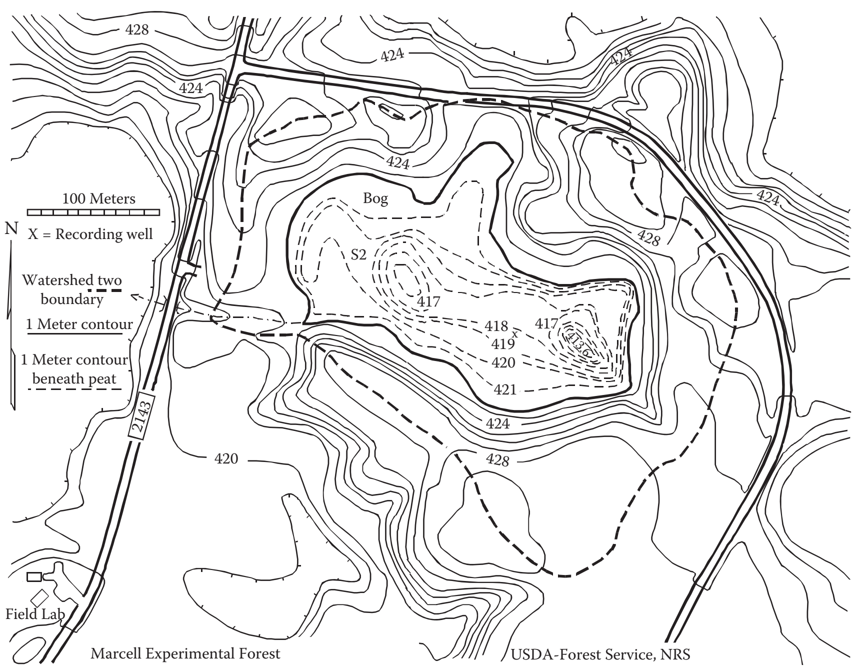

FIGURE 4.7
Contours at 1 m intervals of the uplands surface and the Koochiching drift that lies below the peatland in the S2 watershed.

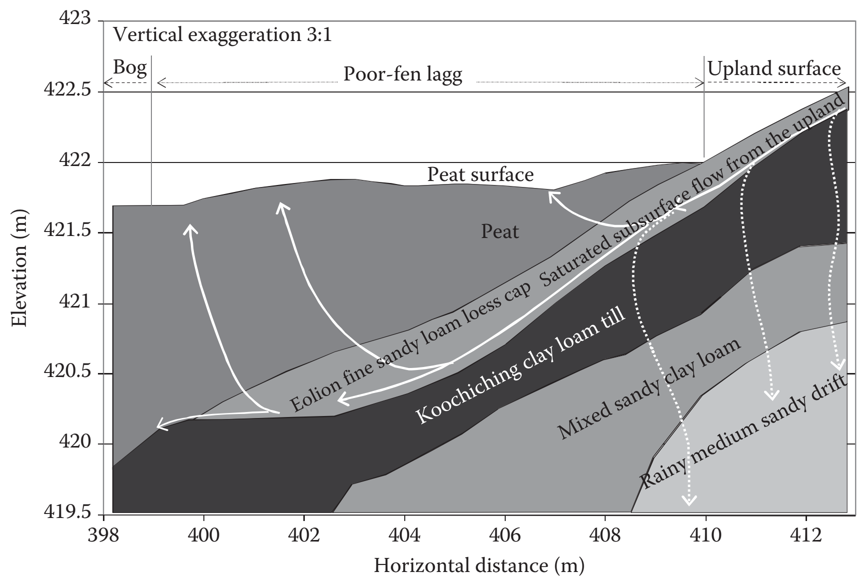

FIGURE 4.8
Soil boundaries and textures at the edge of the S2 bog near its eastern end. Arrows show saturated subsurface flow from the mineral soil upland flowing below the peat and exiting upward to the peat surface or downward as unsaturated flow into the Rainy Drift sands. Also, there is unsaturated flow through the Rainy sands directly beneath the uplands when the surface mineral soils saturate from snowmelt or large summer rains. The peat surface reflects hollow elevations only.

Revealing Sequence of Soil Horizons at Lagg Edge

A physical basis for chemical, hydrologic, and plant-biodiversity characteristics in the lagg is revealed when we interpret the story of horizons in a large soil pit near the east (or right) side of bog S2 (Figure 4.8). A deeper section showing the entire bog (see Figure 4.10) also uses our local climate interpretations to explain the accumulations of peat types within the S2 peatland.

Holocene Vegetation

Gross Composition of Core Segments

Figure 4.9 shows the gross composition of the long core from the S2 bog and indicates the slices examined for pollen and macrofossils. Relatively high bulk densities at the bottom reflect mineral entrainment in the algal gyttja on the now-filled lake bottom; low bulk densities at the top reflect the uncompacted *Sphagnum*, *Ericaceae* shrubs stems, and *Carex* roots in the acrotelm (active surface layer).

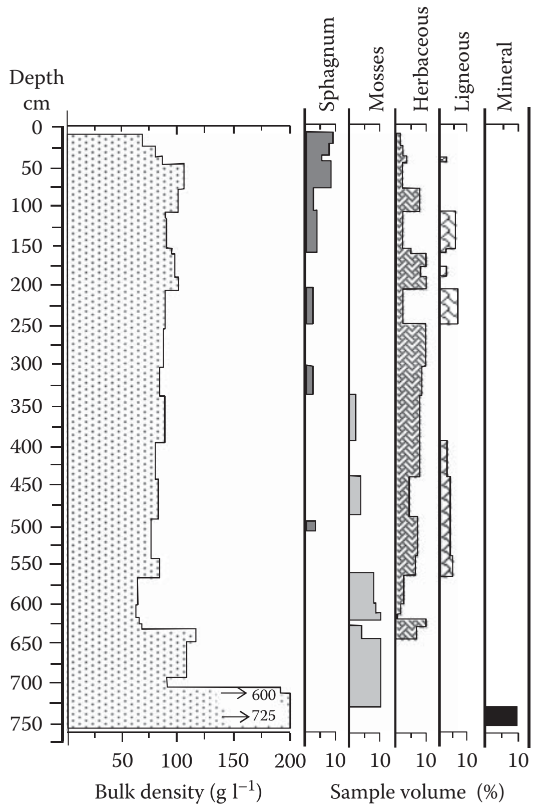

FIGURE 4.9
The gross composition of peat cores in the S2 bog: bulk density, *Sphagna*, other mosses, herbaceous, ligneous, and mineral composition values calculated as a percent of core volume within each visibly differentiated peat zone.

Dating of Core Segments and Peat Accumulation Rates

Eight 5 cm segments of the long core (MR28307) and one segment of the short core (MR29401) were radiocarbon dated and calibrated (Table 4.2). Calibrated year dates BP are plotted in Figure 4.10. The charcoal layer signifying post-fire establishment of the existing black spruce stand is dated at 1865 calendar year using tree rings.

Calendar years 1864 and 1610 are shown at a depth of 75 cm at the strong charcoal layer located there. The divergence between the long and short core also may reflect the loss of peat in fires (Figure 4.10). Prescribed fire in other peatlands at MEF have consumed 6–10 cm of peat; it is likely that hot fires during droughts can consume at least 15 cm of peat. The years 1863 and 1864 were two of the driest on record at St. Paul, MN; only 400 mm of annual precipitation fell in each year (Meyer, 1944). Fire likely burned the surface of the

TABLE 4.2

Calibrated Dates for Long-Core and Short-Core Samples at the S2 Bog

Sample	Lab No.	Depth of Top (cm)	Depth of Bottom (cm)	Radiocarbon Date (y BP)	Radiocarbon Error (y BP)	Calibrated Date, -2s (y BP)	Calibrated Date, Intercept (y BP)	Calibrated Date, -2s (y BP)
MR29401A	BEATA 72327	–95	–100	930	60	671	782	931
MR28307A	SI 6,481	–100	3	1,860	80	1,567	1,809	1,952
MR28307B	SI 6,482	–200	–205	3,475	70	3,564	3,699	3,900
MR28307C	SI 6,483	–300	–305	4,710	60	5,302	5,357	5,590
MR28307D	SI 6,506	–400	–405	5,265	55	5,917	6,016	6,186
MR28307E	SI 6,484	–500	–505	6,455	80	7,204	7,330	7,512
MR28307F	SI 6,485	–600	–605	8,265	85	8,986	9,245	9,441
MR28307G	SI 6,507	–645	–650	8,735	65	9,497	9,767	9,903
MR28307H	SI 6,486	–713	–718	9,675	90	10,474	10,931	11,001

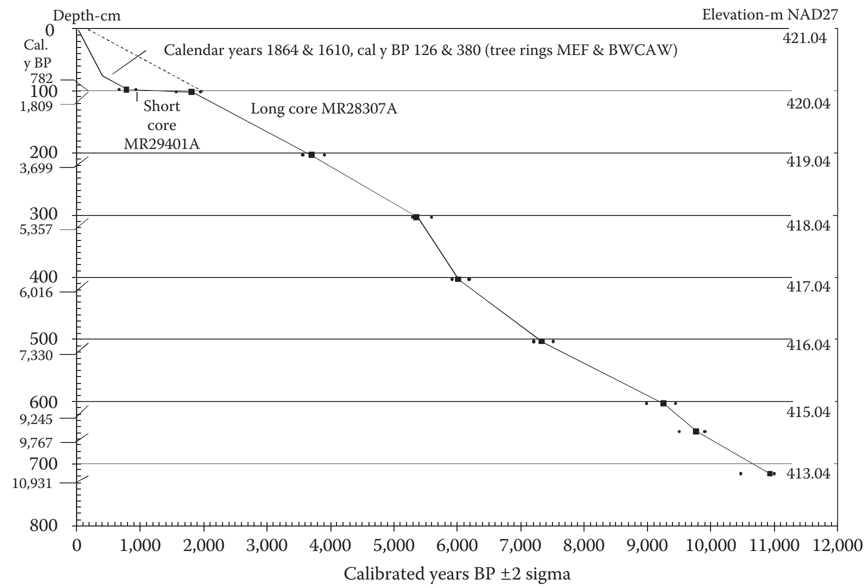

FIGURE 4.10
Calibrated y BP (and their ±2 sigma values) on the *x*-axis. Depth (cm) is on the left *y*-axis and the location of specific cores slices with cal y BP. Elevation (m NVGD 1929) is on the right *y*-axis.

S2 bog in the autumn of 1864. Seed within the surface peat or from surrounding unburned or standing burned black spruce on the peatland germinated in 1865. Tree cores on S2 show a 20 year range in dominant tree ages, suggesting a fully stocked stand by 1885.

The mass of peat accumulated (above the algal gyttja at a date of 9245 cal y BP) to the surface is 56.2 g m^{-2} y^{-1} (29.2 g C m^{-2} y^{-1}) is close to the overall rate for northern peatlands of 29 g C m^{-2} y^{-1} as calculated by Gorham (1991) (Figure 4.11). Accumulation rates from 18 cores in northern North America range from 16 to 80 g m^{-2} y^{-1} (8–41 g C cm^{-2} y^{-1}), and 12 sites within the Red Lake Peatland located 160 km northwest of the MEF are relatively high at 50–100 g m^{-2} y^{-1} (26–52 g C cm^{-2} y^{-1}). The Red Lake peatland sites developed over upwelling groundwater (Siegel and Glasser, 1987). Accumulation rates at the S2 bog are similar for all of the periods between dating ages except for the period 6000–7300 cal y BP, which accumulated carbon at the rate of 67 g C m^{-2} y^{-1}.

Major Changes in Upland Trees

Figure 4.12 shows pollen occurrence for upland trees and shrubs, upland herbs and ferns, wetland trees and shrubs, and aquatic plants. Four major

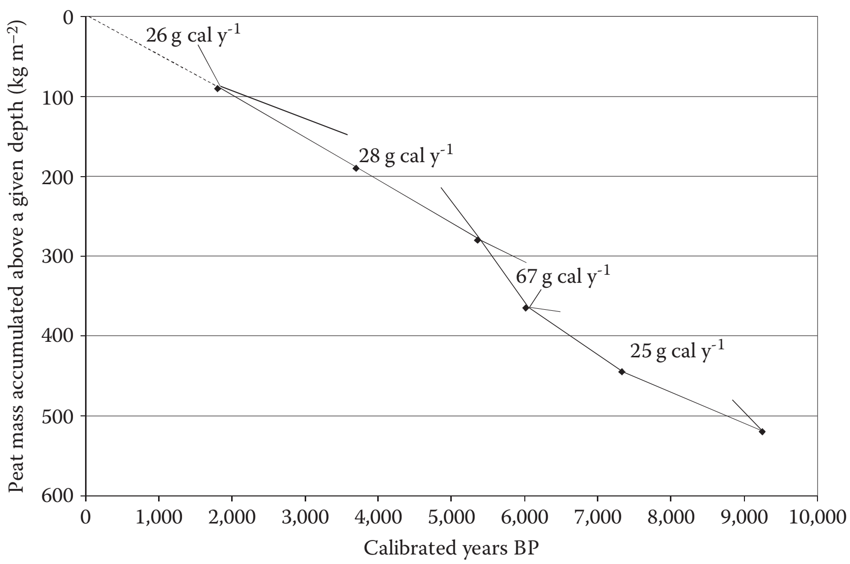

FIGURE 4.11
Accumulative mass of peat above a given depth in the S2 bog over the post-glacial period. Rates of carbon accumulation are shown for four periods.

vegetation associations are shown based on upland trees. The first association, 11,000–9,500 cal y BP, is dominated by *Picea*, which makes up 75%–30% of the segment volume. At the same time, *Pinus resinosa*/*Pinus banksiana* (red and jack pine) increases from 15% to 35% of the segment volume. A similar tree mixture at Steel Lake 106 km southwest of the MEF began its decline of *Picea* in favor of *P. resinosa*/*P. banksiana* at 11,200 and made the transition to *P. resinosa*/*P. banksiana* by 11,000 cal y BP as the climate became too warm and dry for *Picea* (Wright et al., 2004). At the MEF, the beginning of this decline is beyond the core depth, but the transition to the period dominated by *P. resinosa*/*P. banksiana* did not occur until 9500 cal y BP, some 1500 years later.

Between 9500 and 6500 cal y BP, *P. resinosa*/*P. banksiana* dominates the segment volumes (~40%) for 3000 years. Beginning at 6500 cal y BP, *Pinus strobus* (white pine) rises and dominates the pollen volume at 40% while *P. resinosa*/*P. baksiana* recedes to about 20% of the segment volume.

Major Changes in Wetland Vegetation

An examination of macrofossils with depth in the peat-core segments suggest seven vegetation phases in the S2 wetland (Figures 4.13 and 4.14). Changes in wetland vegetation occur more frequently and do not coincide with changes in upland vegetation (Figure 4.12).

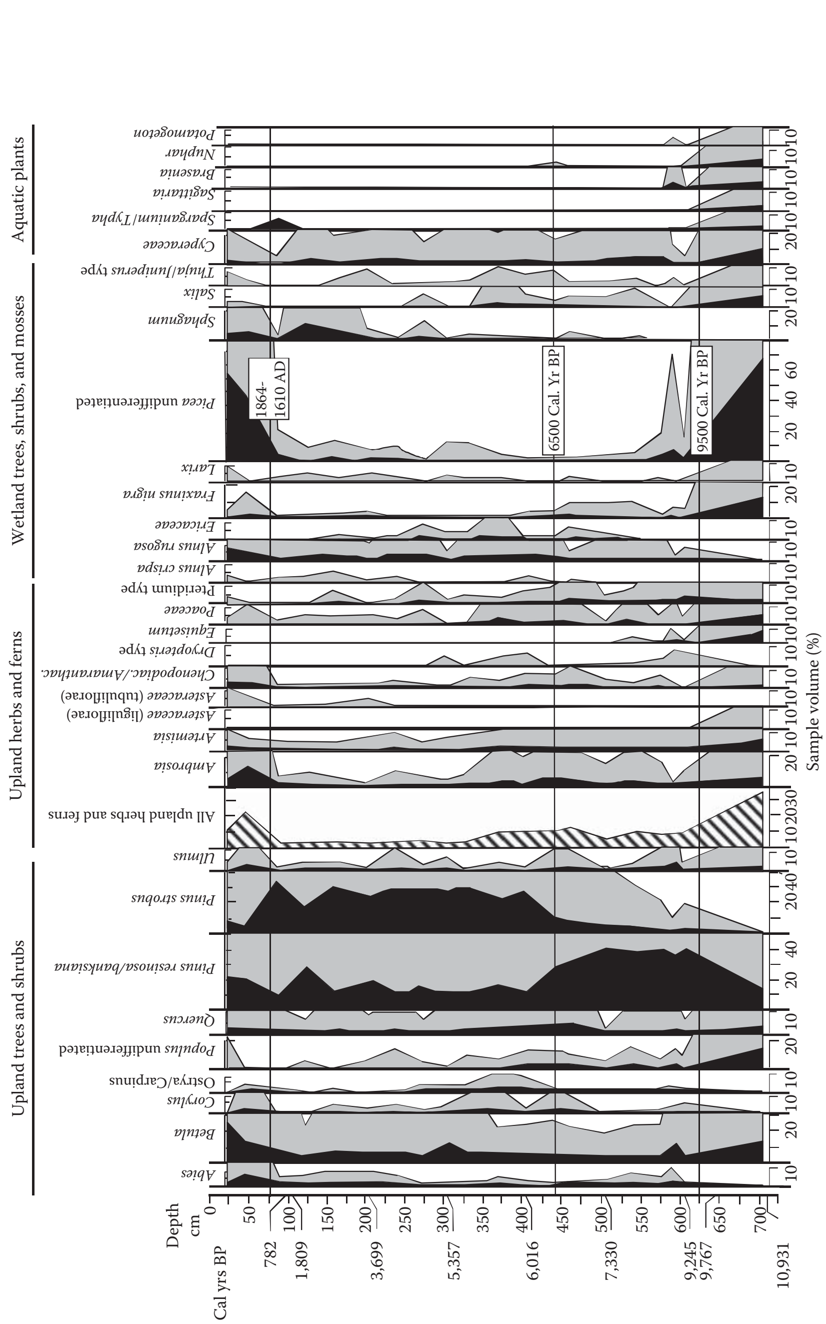

FIGURE 4.12
Pollen occurrence (percent of sample volume) in the long core from the S2 bog. Location of radiocarbon-dated (calibrated) core slices are shown on the *y*-axis.

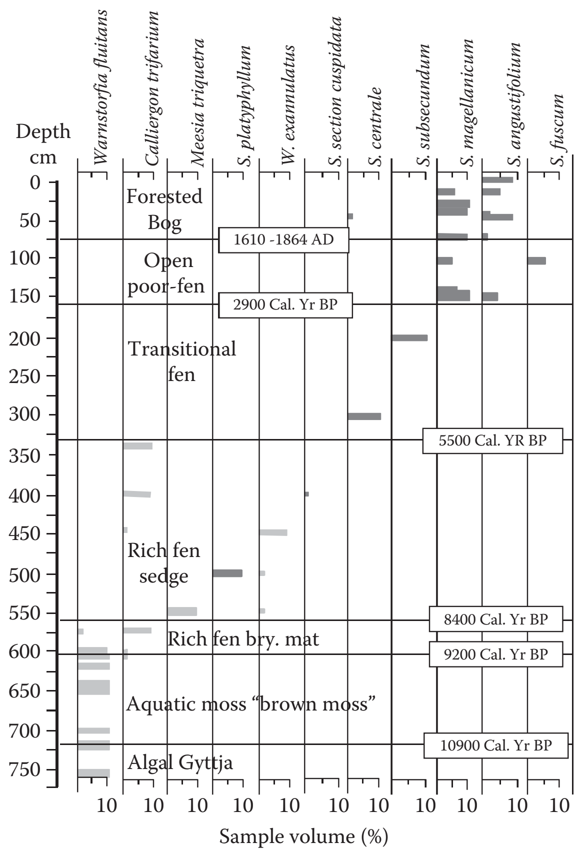

FIGURE 4.13
Sphagna and other mosses in the peat core of the S2 bog.

Discussion of Findings

11,900–11,800 Years BP

During the initial formation of a shallow pond, the Koochiching drift sank into the water-filled ice-block depression that eventually would become a small lake at the S2 bog site. The water level in the small lake began this period at an elevation of 422 m (near the top of the Koochiching till on the upland) and then dropped as the till sank to 420.2 m (see Figure 4.8 at the extent of the eolian deposit). Above the till, sediment of glacial flour and algal remains were slowly deposited. Algae are the only plant residues represented in both the bottom gyttja of the long core (MR2-8307) and in the

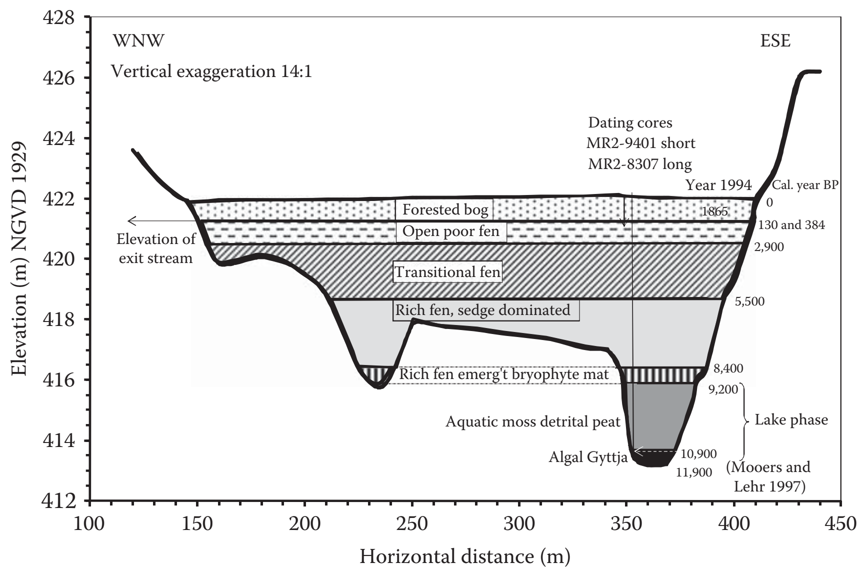

FIGURE 4.14
Major vegetation phases in the ice-block depression of S2 that filled with water and peat.

TABLE 4.3

Texture at the Organic-Mineral Interface at the Deepest Location in the S2 Depression

Elevation in (m)	Material Description	OM (%)	Sand (%)	Silt (%)	Clay (%)
416.7–416.5	Sapric peat and coprogenous gyttja	38	–	–	–
416.5–415.8	Silty clay loam	18	4	60	36
415.8–415.5	Silt loam	3	17	59	25
415.5–414.7	Loam	8	45	35	20
414.7–414.4	Loam	2	42	40	18
414.4–414.3	Clay loam	2	33	37	30

Source: Tracy, D.R., Hydrologic linkages between uplands and peatlands, PhD dissertation, University of Minnesota, St. Paul, MN, 1997.

Note: This bucket auger hole is deeper than the length of the long core shown in Figure 4.10.

auger hole sampled in the deepest part of the depression (Brooks and Kreft, 1991). Below the gyttja, the first 2.2 m into the Koochiching till, at the deepest part of the depression, averages 2% organic matter, 34% sand, 42% silt, and 23% clay (Table 4.3). Diameters in the sand fraction are fine to very fine (0.12–0.06 mm in diameter) and sand-particle edges under magnification are rounded indicating an eolian origin.

11,800–9,200 Years BP

The sedimentary profiles illustrate this period as a major zone of brown moss (*Warnstorfia fluitans*) near the base of the peat core, corresponding to Lacustrine Period II (10,900–9,200 cal y BP; Figures 4.13 and 4.14). The water level in the small lake dropped during this period as successively lower outlets to Lake Superior developed (Teller and Leverington, 2004). Perhaps the drop was slow at first as Figure 4.8 shows a possible wave-cut shelf in the Koochiching till at an elevation of 420.2 m. At 9200 y BP, the water level in the S2 depression had dropped a total of 6 m to the 416 m elevation. The southeast shore of glacial Lake Agassiz was 135 km north of S2 at 10,000 cal y BP, and 4,500 km north of S2 at 9,000 cal y BP (Viau et al., 2006).

Schwalb and Dean (2002) showed a drop in water levels at Williams and Shingobee Lakes 120 km SE of the MEF near the prairie boundary beginning at 9800 and extending to 7700 y BP (further lowering of lake levels occurred up to 5000 y BP). Donovan et al. (2002) showed that even in the droughts of the twentieth century, groundwater levels could drop by as much as 5 m in west-central Minnesota. Digerfeldt et al. (1992) reconstructed a drop in lake levels of 3–6 m at the Parkers Prairie sandplain in west-central Minnesota and Filby et al. (2002) reconstructed a drop in water level of 3.5 m in Williams Lake. The S2 bog is located only 3 km from the subcontinental divide (Hudson Bay, Mississippi Basins), so a drop in water level of 6 m from 11,000 to 9,200 cal y BP was possible (Figure 4.14).

The aquatic moss *W. fluitans* flourished during the end of this period (several centuries) when the water level was near 416 m. This species is the most acidophilous among its cogeners (Hedenäs, 2003; Hedenäs and Kooijman, 1996) and among most of the "brown mosses" typically found in more minerotrophic peatland mesohabitats. The water chemistry of the lake likely was more akin to today's upland subsurface or surface runoff than to the groundwater chemistry (Table 4.4) during this early period when the elevation of regional water tables ranged from 420 to 416 m.

The Lacustrine Period (11,900–9,200 y BP) included the aquatic mosses (Figure 4.13) but also floating-leaved and emergent aquatic plants: *Nuphar*, *Potamogeton*, *Brasenia*, *Sagittaria*, *Sparganium*, and *Typha* (Figure 4.12). Black ash (*Fraxinus nigra*) in shallow depressions and swales were at their Holocene climax during this initial tundra setting; their pollen accounted for 14% of the pollen sum. *Salix* (willow) also reached its Holocene maximum (6%) in this early lake period, as did *Larix* (eastern larch), but it accounted for less than 2% of the pollen sum. Two members of the Cupressaceae family, *Thuja* and *Juniperus*, represent less than 1% of the pollen but they too were at their Holocene maximum. *Thuja* likely is *Thuja occidentalis* (northern white cedar), which is well suited to wet and calcareous habitats. *Juniperus* probably is the shrubby, circumpolar *Juniperus communis* (common juniper) now common in northeastern and northwestern United States and Canada, and/or *Juniperus virginiana* (*eastern redcedar*) growing on cold dry ridge tops.

TABLE 4.4

Water Chemistry at Major Locations in the S2 Watershed on the MEF

Parameter	Units	Deep Groundwater, Number of Samples	Deep Groundwater, Mean	Deep Groundwater, Standard Deviation	Upland Subsurface Runoff, Number of Samples	Upland Subsurface Runoff, Mean
pH		76	7.43	0.29	496	6.28
Alkalinity	μeq/L	73	3144	314	484	62
Calcium	mg/L	74	41.60	2.65	486	3.44
Magnesium	mg/L	74	7.62	0.70	486	1.04
Sodium	mg/L	74	3.62	0.75	485	1.15
Potassium	mg/L	74	1.31	0.21	486	0.89
Ammonium-N	mg/L	69	0.08	0.07	418	0.05
Nitrate-N	mg/L	44	0.06	0.04	351	0.12
Sulfate	mg/L	73	3.13	1.03	485	2.56
Chloride	mg/L	73	1.03	0.47	467	0.49
Total phosphorus	mg/L	45	0.04	0.01	355	0.06
Phosphate-P	mg/L	54	0.017	0.006	395	0.042
Total organic carbon	mg/L	36	6.20	3.38	416	22.45
Total Kjeldahl nitrogen	mg/L	56	0.27	0.11	393	0.58
Carbon:nitrogen	Ratio	Ave.	23.0	—	—	38.7
Aluminum	mg/L	28	0.18	0.01	245	0.77
Iron	mg/L	61	3.12	4.77	412	0.60
Manganese	mg/L	25	1.38	0.01	234	0.03
Copper	mg/L	1	0.03	—	17	0.06
Zinc	mg/L	25	13.21[b]	2.87	234	0.29

[a] 1978–2001 National Atmospheric Deposition Program (access nadp.sws.uiuc.edu for complete weekly dataset).

[b] Zinc levels are elevated by galvanized plot borders or galvanized well pipe.

Upland Subsurface Runoff, Standard Deviation	Upland Surface Runoff, Number of Samples	Upland Surface Runoff, Mean	Upland Surface Runoff, Standard Deviation	Streamflow, Number of Samples	Streamflow, Mean	Streamflow, Standard Deviation	Mean Precipitation[a]
0.45	376	6.64	0.35	118	4.07	0.22	5.06
70	376	222	191	14	−73	54	—
1.00	366	5.56	2.24	116	2.32	0.87	0.20
0.29	366	1.27	0.54	116	0.83	0.31	0.03
0.52	365	0.38	0.29	115	0.53	0.21	0.07
0.74	366	4.92	3.61	116	0.92	0.64	0.04
0.10	349	0.30	0.58	109	0.14	0.21	0.33
0.21	364	1.14	2.47	96	0.13	0.28	1.05
2.43	367	2.04	2.03	114	1.22	2.41	1.03
4.07	361	0.93	1.43	111	0.41	0.26	0.08
0.14	285	0.41	0.85	85	0.08	0.10	—
0.12	308	0.343	0.264	89	0.035	0.074	—
13.35	296	23.07	32.98	99	49.83	22.47	—
0.26	290	1.86	235	95	1.15	0.81	—
—	—	12.4	—	—	43.3	—	—
0.29	137	0.3	0.19	50	0.64	0.31	—
0.42	296	0.21	0.25	98	1.14	0.71	—
0.28	127	0.03	0.02	46	0.05	0.03	—
0.05	7	0.09	0.13	11	0.05	0.03	—
1.08	127	4.89[b]	3.46	46	0.13	0.66	

Betula (birch) and undifferentiated *Populus* then, as now, were early invaders of disturbed landscapes (about 15% of the pollen sum). Oak (*Quercus*) and elm (*Ulmus*) were earlier invaders in smaller numbers (5% of the pollen sum). These may be associated with broad glacial river corridors assuming that the *Quercus* had a greater representation of white oaks (*Quercus alba* and *Quercus macrocarpa*) typical today on bottomlands and deep, well-drained, moist sites (Harlow and Harrar, 1958). The more abundant northern red oak (*Quercus rubra*), found today in association with sugar maple and white pine (and moister red pine sites), is typical of temperate forests on sandy loams and silty clay loams. The common upland trees were red and jack pine (*P. resinosa*/*P. banksiana*) beginning with pollen in 15% of the core volume and expanding rapidly to 42% of core volume by 9200 y BP.

Immediately after icemelt spruce (*Picea*), presumably both black (*P. mariana*) and white (*Picea glauca*), dominated the area with pollen in 75% of the pollen sum. This was reduced to 10% at the end of Lacustrine Period I (9200 BP) and remained below 2% until an intense fire in 1864 burned the peatland and, following harvest of white pine, *P. mariana* once again exceeded over 50%.

Balsam fir (*Abies balsamea*) was a minor component of the upland forest during the early lake period and remained under 5% of the pollen sum until immigrant harvest of the white pine in the late 1800s. The upland hazel shrubs (*Corylus americana* and *Corylus rostrata*) were early and persistent forest components, always occurring at 1%–2%. At the wet edges of the lake and shallow depressions within the upland, speckled alder (*Alnus rugosa*) was the only wetland shrub.

The upland was not a continuous forest as evidenced by the grass (*Poaceae*) and horsetail (*Equisetum*) pollen, which accounted for more than 10% of the core volume. Other upland herbs invading the glacial melt exposures included goosefoot (*Chenopodiacea*), aster (Asteraceae), ragweed (*Ambrosia*), amaranth (*Amaranthaceae*), and wormwood (*Artemisia*).

The entire Lacustrine Phase shown in the pollen record (Figure 4.14) suggests a widespread, large, and presumably gradual decline in the regional water table from 11,000 to 9,200 y BP. This is evidenced by decreases in tree pollen characteristic of wetter sites: *Picea*, *Thuja*, *Fraxinus*, and *Abies*, and increases in drier-site pines: *P. resinosa*/*P. banksiana* in particular but also small increases in the temperate and mesic *P. strobus*. Concomitant decreases in *Betula* and *Populus* may record early colonization by species adapted to a wide range of moisture regimes followed by declines owing to competition from the invading pines. Reductions in upland herb and fern pollen are strong and may reflect large forest areas nearing crown closure.

9200–8400 5Years BP

Water levels during this period remained at a pond-surface elevation of about 416 m. *Calliergon trifarium*, another aquatic brown moss, joined and succeeded by *W. fluitans* in what now were two small ponds, perhaps thinly joined, and then smothered by an emergent bryophyte mat at the water surface (see 416 and 417 contours in Figures 4.13 and 4.14). Pollen of submerged aquatics declined (*Brasenia* 4.9%–0%, *Nuphar* 4.9%–0.2%, *Potamogeton* 2.4%–0%), as did that of emergent aquatics (*Cyperaceae* 12.2%–0.6%, *Sagittaria* 2.4%–0%, *Sparganium/Typha angustifolium* 2.4%–0%).

The Rich-Fen Bryophyte Mat period is the shortest, only 800 years, *C. trifarium* peaked about 300 years into the period and appeared late in the Rich-Fen Phase. Sedges flourished in the next 500 years, poking through the bryophyte mat reaching their Holocene maximum. They persisted at 5%–10% of the pollen count for millennia until the latter part of the poor-fen period.

Wetlands with trees have sufficient drainage to a surface outlet to provide both air and water for growth in the near surface pore space. Wetlands without surface outlets collect water and retain it, giving rise to higher water levels and either sedge or shrub habitats (Verry, 2000). In the landlocked ponds at the bottom of S2, the floating plants *Brasenia* (water-shield) and *Potamogeton* (pondweed), increased. Most characteristically for the pond gyttja, *C. trifarium* smothered the surface and formed peat (Figure 4.13).

The bryophyte mat period reveals a landscape with dry uplands, aquatic moss, and sedge wetlands (mildly calcareous) with little drainage, and minor increases in treed wetlands with sufficient surface drainage to a small stream. The next major pollen reconstruction period (rich-fen sedge 8400–5500 cal y BP) reveals a drier period with longer summers when the local region reached its climatic optimum.

8400–5500 Years BP

A rich-fen sedge peat characterized this period. The peatland had a water pH of about 8 and associated calcium and magnesium values were near the high end of the groundwater chemistry dataset in Table 4.4 as inferred from plant species (Vitt et al., 1995). Early in the Rich-Fen period, the first identifiable *Sphagnum* species, the aquatic *Sphagnum platyphyllum* (an alkaline species), appeared (Figure 4.13). Sometimes known as *Sphagnum subsecundum* var. *platyphyllum* it grows in mineral-rich, open habitats in sedge mats marginal to eutrophic lakes and in the hollows of sedge fens (Crum, 1988). Also consistent with a calcium-rich environment is the first appearance of *Warnstorfia exannulatus* and additional mats of *C. trifarium* late in the period (Figure 4.13.). Toward and beyond the end of the rich-fen period, the pollen of *Ambrosia*, *Artemisia*, and *Chenopodiacea/Amaranthaceae* peaked between 7000 and 6000 y BP.

The MEF pollen record reveals an apparent warming and drying period during this transition from the Pleistocene to the Holocene. Over this early Aquatic Moss Phase there is a major reduction in the *Picea* pollen count representing cool/wet sites from 11,000 to 9,300 y BP (75%–5%, Figure 4.13). By contrast, *P. resinosa/P. banksiana* pollen count representative of warm/dry sites rises from 15% to 40% (Figure 4.14). Upland herbs and ferns also significantly decrease during this period (35%–15%) suggesting a forest succession explanation as well as an increasing amount of *P. resinosa/P. banksiana* invading the eolian and outwash sands on uplands.

The *P. resinosa/banksiana* pollen data at the MEF suggest that a warm/dry period achieved by 9200 cal y BP lasted until 6500 cal y BP. The next 500 years saw a transition to a cooler/wetter climate favoring *P. strobus* with pollen counts rising from 2% to 30%) over the warmer/drier climate that favors *P. resinosa/P. banksiana* when pollen counts fell from 40% to 12% (Figure 4.12).

There is an "acid anomaly" during this high pH period: *Sphagnum* section *Cuspidata sp*. occurs in 1.5% of the core pollen/spore count at a depth of 400 cm (Figure 4.13) and an elevation of 418.5 m. *Sphagnum* section *Cuspidata sp*. is rare in the Great Lakes Region, where it occurs as a submerged moss growing at the margins of acid lakes (Crum, 1988). The occurrence of this acidiphilous, aquatic *Sphagnum* with the alkaliphilous aquatic moss *C. trifarium* is curious. The 400 cm depth corresponds to 6000 cal y BP. The occurrence of *Sphagnum* section *Cuspidata sp*. is sandwiched in a bulk core description showing ligneous peat below it and aquatic mosses above it (Figure 4.13). Though relatively rare, thin acid bands of peat (pH 2.7–3.5) have been reported within alkaline peat profiles in Minnesota (Always, 1920), Michigan (Davis and Lucas, 1959), and Poland (Okruskzko, 1960). Acidity in organic soils is accounted for by the presence of organic compounds, exchangeable H, iron sulfide, and silicic acid. It is believed that these thin acid layers are formed under conditions similar to "cat clays" (cation clays) found in brackish coastal waters (Davis and Lucas, 1959). In these instances, the roots of reeds may contain as much as 3% sulfur in the form of bisulfides. When oxidized sulfuric acid is formed along with scattered crystals of calcium sulfate. The acid layer at the S2 peatland occurs at an elevation of 418.5 m, just about half meter above two deep pools in the bottom of S2 (Figure 4.14). It may be that the high lignin sedges accumulated on the shelf between the two pools (roughly the area between the 418 and 419 m contour lines in Figure 4.7). They also may be high in sulfur and during a period of high summer temperatures, relatively low rainfall, and low lake levels in the northern hemisphere oxidized to produce a thin acid layer in the otherwise alkaline peat.

How did calcium-rich groundwater rise into the S2 depression during the rich-fen, sedge-dominated period? First, the hydraulic conductivity of the Koochiching till, though extremely low (5×10^{-7} cm s^{-1}), is sufficient to allow regional groundwater to enter and exit the peat depression slowly over long periods. The hydraulic conductivity of the unweathered, silty clay layer (glacial flour) is even lower (1×10^{-8} cm s^{-1}), but over centuries can pass small amounts of water. Second, the hydraulic head on the regional water table at the S2 depression derives from the subcontinental divide 3 km north, where the contemporary water table elevation peaks near 418 m and fluctuates down to 417 m. The same regional water table range at the S2 depression is 414.8–413.8 m. In other words, the 4 m head drop over 3 km allows groundwater in the depression to rise to an elevation approaching 418 m. This elevation is just shy of the upper boundary of the Rich-Fen, Sedge-Dominated Peat Sediment Phase. Perhaps in the long Holocene after 9000 y BP water table elevations fluctuated through a range of 1.5 m as opposed to the contemporary 50 year record of 1 m.

Cyperaceae dominate the aquatic and wetland species in the peat sediment record. There also is one calciphile *Sphagnum* (*Sphagnum platyphylum*) and two calciphile aquatic mosses (*C. trifarium* and *W. fluitans*). *Salix* spp., *A. rugosa*, and *Alnus crispa* (its first occurrence) dominate the tall wetland shrubs. Short ericaceous shrubs also are strong in the peat record. Wetland trees strong in the record are *Fraxinus* and *Larix* with a notable near-absence of *Picea*. This is not a pond or lake environment, but a wet sedge meadow with ericaceous shrubs underlain by aquatic mosses and a calciphile *Sphagnum*. The sedge-shrub meadow is surrounded by alder and willow shrubs with sparse ash and tamarack trees, sitting in a landscape first dominated by dry site red and jack pine and then mixed with the temperate, moister, and dominant-crowned white pine.

Paludification is the process allowing the wet sedge meadow to accumulate peat. It occurs when there is a hydrostatic head (pressure field) above the meadow surface. Centuries of peat accumulation fill this energy field with pore space (about 8 cm per century), allowing groundwater under pressure to fill the pores at progressively higher elevations. The growth of sedge, *Ericaceae*, and moss continues upward. Hence, the peatland is a feature of the landscape that grows upward (and outward where the hills allow) on the death of its own vegetation and the pore structure that it creates in the organic soil.

5600–3000 Years BP

The overall picture of sediment during the Transitional-Fen Phase is nearly identical with that during the Rich-Fen Phase. The difference is the occurrence of circumneutral *Sphagnum* mosses, both *Sphagnum centrale* and *S. subsecundum. S. centrale* is typical of *Thuja* swamps (treed fens) where it occurs frequently today. It has been observed in a contemporary ice-block depression in outwash sands only 0.5 km distant and 7.5 m lower at an elevation of 414.5 m (Bay, 1967). The 414.5 m elevation at the S3 fen is coincident with the algal gyttja at the deepest part of S2 bog (Lacustrine, Calcareous Lake Phase) and also coincides with the contemporary upper limit of regional water table fluctuation beneath the S2 bog.

Groundwater in the S3 fen has a contemporary pH of 6.9–7.4, calcium of 17–20 mg L^{-1}, and magnesium of 3–4 mg L^{-1}. Groundwater beneath S2 bog has a contemporary pH of 6.8–8.0, calcium ranges from 37 to 47 mg L^{-1}, and magnesium ranges from 6 to 9 mg L^{-1} (Table 4.4). *S. subsecundum* grows in mineral-rich mats in open habitats, and in the hollows of poor-sedge fens (Crum, 1988). Thus, the Transitional-Fen Phase marks a subtle change in water chemistry from alkaline pH values near 8 to circumneutral values slipping below 7 (Vitt et al., 1995).

The hydraulic head arising at the subcontinental divide enables strong groundwater control on peatland water chemistry and water table elevation. Downward flowing groundwater flow lines begin at the divide and then flow deep through the Rainy sands into the Itasca Lobe ground moraine above the bedrock. There it dissolves the limestone fragments, pushed 20,000 years ago from south-central Hudson Bay. The flow lines then curve upward and fill the aquifer sands with water rich in calcium bicarbonate. This is the water flowing under S2 bog and discharging in large amounts to the surface at S3 fen. The groundwater control weakened when the peat surface in the S2 sedge meadow rose above the water table at the subcontinental divide (417.5 m) about 5500 cal y BP.

The paludification process continues upward and the surface water draining to the depression from the upland increases in importance relative to the slow lateral and upward seep of deep groundwater. The paludification process (about 6 cm per century during the Transitional-Fen Phase) accumulates an additional 1.6 m of peat, such that the peat surface rises above the subcontinental water table but retains (by chemical diffusion) a chemical groundwater memory during the process.

Annual peatland water table fluctuations (0.5 m) and severe drought fluctuations (1.2 m) (Verry, 1980) repeatedly mix the water in the undecomposed to moderately decomposed active peat layer (acrotelm) with water in the well-decomposed catotelm (Verry, 1984). During the Transitional-Fen Phase, groundwater still controlled the peat development through the power of a constant hydraulic head. This power gradually gave way to periodic processes including water table fluctuation, biologic mixing (vegetation growth, decay, and gas exchange), and deep frost penetration (0.1–0.5 m) that preferentially drives fine organic matter and elements to the bottom of freezing ice. Thus, frost formation fosters the transfer of material from the acrotelm to the catotelm (Verry, 1991).

At the end of the Transitional Fen Phase there is a clearer break with groundwater chronicled by new *Sphagna* such as *Sphagna magillanicum*, *Sphagna angustifolium*, and *Sphagna fuscum*, changes in water chemistry, and transition to a warmer continental climate.

2900–390 Years BP

There was a severe fire (a distinct charcoal layer) at the upper boundary in 1864, 130 years BP, but the layer may contain charcoal from an earlier fire documented north of Grand Marais, MN, in 1610 AD (384 y BP). An analysis of peat accumulation rates suggests how many years and how many centimeters of peat accumulation were consumed by the 1864 fire.

The amount of catotelm peat consumed by the 1864 fire are estimated by subtracting the years to reach the projected open poor-fen surface (413) from the middle of the last dated core slice (782). This yields a 369 y BP. A more reliable date estimated from St. Paul, MN, weather records and tree-ring cores from 1994 in the spruce at S2 bog is 1864 or 130 y BP. Thus, 369–130 suggests that the fire burned 239 years of catotelm peat. The lost years multiplied by the accumulation rate suggests the fire consumed 14 cm of catotelm peat. Because another severe fire occurred in 1610, the charcoal layer may represent two fires.

We derived our open poor-fen upper date of 390 y BP from peat accumulation rates extrapolated above the fire horizon depth of 75 cm (421.25 m elevation). The peat accumulation rate averaged over the last three dating slices is 0.55 mm y^{-1}. This rate applied to 22.5 cm of projected peat accumulation (decomposed and relatively dense catotelm peat) suggests that peat accumulated up to the pre-fire surface of the Open Poor-Fen Phase over a 413 year period beyond the center of the previous dating slice (782 y BP). This accumulation of catotelm peat extends from the middle of the last dating slice (421.07 m elevation, 97.5 cm depth) to just below the elevation of the contemporary stream outlet (421.29 m elevation, 75 cm depth). A less dense acrotelm peat of about 20 cm occurs above the catotelm boundary (Verry, 1984). Accordingly, we project the actual peat hollow surface at the end of the Open Poor-Fen Phase at virtually the stream-outlet elevation (421.5 m). This is deduced from the continued occurrence of *S. magellanicum* throughout the Open Poor-Fen Phase, the frequent occurrence of *S. angustifolium* above the 75 cm depth (Figure 4.12), and the peat humification values of 8 and 9 (on the von Post scale of 1:10; see Malterer et al., 1992) immediately below the charcoal horizon.

Characteristic of this Open Poor-Fen Phase is the occurrence (dominance) of acid *Sphagnum* species, particularly *S. magellanicum*, which first appeared about 2900 cal y BP and heralded the initiation of the Open Poor-Fen period. It was accompanied by *Sphagna recurvum* agg., identifiable as *S. angustifolium* at the top of the peat core (Figure 4.13) along with some transitional *S. fuscum*.

130/390–0 Years BP

Picea pollen rose sharply, from 2% to 60% of the upland pollen sum, as a forest of black spruce developed on the bog. Pollen of *Betula* also increased from 7% to 24%, presumably owing to the logging of pine and subsequent slash fires. White-pine pollen declined from 35% to 5%. The pollen of weedy invaders of open spaces, *Ambrosia sp.*, *Artemisia sp.*, and *Chenopodiaceae/Amaranthaceae* sp. increased by 5%–15% for the same reason. Fire history documents initiation of the aspen forest (*Populus tremuloides*) in 1917 and 1918 in the MEF.

The intense fire in 1864 probably burned peat accumulated in the narrow surface outlet on the southwest side of the S2 bog, and effectively lowered the water table at least 5 cm. This was sufficient to establish and grow a poor- to medium-site stand of black spruce (Verry, 1982, 2000). Bog development began immediately after the fire, fostered by unobstructed streamflow drainage, colonization by acidiophile *Sphagnum* species, decomposition of acid-producing *Sphagnum* moss (Gorham et al., 1985), minimal availability of bicarbonates from the deep peat (and little from the upland), and continuation of a wetter climate.

Since 1865, the S2 peatland has developed an *S. angustifolium/S. magellanicum* dome rising 18 cm from its edge to a high near the existing recording well (Figure 4.5). A small dome may have existed before the 1864 fire as well. This dome, built by *Sphagnum* accumulation above the elevation of the outlet stream, developed a localized groundwater flow net above the much deeper regional groundwater flow net (Ingram, 1978). Even before the acid, ombrotrophic peat in the Forested-Bog Phase rose an additional meter above the stream elevation, paludification had reversed the flow of water deep in the depression from vertically upward to vertically downward. Today the water table of the bog (422.2 m) is 4–5 m higher than that at the subcontinental divide (417.5 m).

Contemporary Water Chemistry in S2 Peatland

Extensive data on water chemistry for regional groundwater, upland, bog, streamflow, and precipitation show strong site differences (Table 4.4). Precipitation at the MEF is moderately impacted by industrial emissions. Sulfate concentration is slightly elevated (1.03 mg L^{-1}) and nitrate (1.05 mg L^{-1}) and ammonium (0.33 mg L^{-1}) more so. However, alkaline dust from the prairies yields high calcium (0.20 mg L^{-1}) and magnesium (0.03 mg/L) concentrations. Thus, pH is within the normal range for precipitation (5.06) as is chloride (0.08 mg L^{-1}) for midcontinental sites.

Although S2 streamflow pH reflects a mixing of the interior bog dome and the poor-fen lagg, it is acid (4.07) while calcium (2.3 mg L^{-1}) and magnesium (0.8 mg L^{-1}) are slightly elevated above bog waters in other cool and humid areas with no influence from windborne dust. Organic matter dissolved and suspended in the bog water yields high total phosphorus (TP) values (0.08 mg L^{-1}) and high total organic carbon (49.8 mg L^{-1}). Total Keljdahl nitrogen (TKN) also is high (1.15 mg L^{-1}), but the carbon to nitrogen ratio (C/N) of 43 is still very high compared with many natural systems.

The two components of upland water are surface and subsurface flow (Chapter 7). Upland surface water flows through the forest floor, whereas the subsurface component is water collected from the saturated A horizon of the mineral soil. Verry and Timmons (1982) described the chemical analyses and physical collection methods. Concentrations of calcium, magnesium, and alkalinity are higher in the surface flow than in the subsurface flow (Table 4.4). Uptake of these elements from the mineral-soil horizons by trees (*P. tremuloides*) and their subsequent release from decaying leaves is the source of elevated calcium and magnesium in the upland surface flow. Similarly, potassium, TKN, ammonium, TP, and phosphate-phosphorus (phosphate-P) are high in leaves and higher in upland surface flow than subsurface flow (Table 4.4). By contrast, sodium is higher in the subsurface flow, reflecting the quick release and leaching from leaves to the saturated A horizon. Total organic carbon and pH concentrations are similar between subsurface and surface flows. However, the C/N for subsurface flow is more than three times that in the surface flow. Aluminum is high in the subsurface flow and the peatland streamflow, reflecting acid leaching in both locations.

Regional groundwater (drawn from 3.2 cm diameter galvanized pipe, screened for 1 m, 15 m beneath the surface) is high in pH, alkalinity, calcium, magnesium, sodium, potassium, iron, and manganese relative to all other sites (Table 4.4) and provides the alkaline environment for the early lake and rich-fen environments deep in the S2 depression. These same concentrations are typical of the S3 fen 2 km north of the S2 bog. Phosphorous and nitrogen values are low as is TOC (6 mg L^{-1}), but the C/N of 23 is midway among all sites.

Contemporary Vegetation in the S2 Peatland

Tables 4.5 and 4.6 show the species present in single relevés ($10 \times 10\,m^2$) from both the bog dome and the marginal fen lagg. The bog relevé contains 19 species while the relevé from the lagg contains 35 species. Nomenclature follows Ownbey and Morley (1991) for vascular plants, Anderson (1990) for *Sphagnum*, Anderson et al. (1990) for other mosses, and Stotler and Crandall-Stotler (1977) for liverworts.

The overstory vegetation of the bog was almost entirely black spruce with some birches (*Betula papyrifera*) and tamarack (*Larix laricina*). *Ledum groenlandicum* was the dominant broad-leaved, evergreen woody shrub with five other ericaceous heaths present. *Carex trisperma* dominated the graminiods and *Smilacina trifolia* is the only common forb. Among the bryophytes, *S. magellanicum* and *S. angustifolium*—characteristic of low hummocks and cushions—had high cover values with another 14 species present (Table 4.6). Also common was *Pleurozium schreberi*, a feather moss usually found on taller, drier hummocks. The shrubby overstory of the lagg was dominated by *Alnus incana* with five other deciduous, broadleaf woody species. *C. trisperma* and *Carex disperma* were most common of the six graminiods, whereas *Calla palustris* was the chief forb among the 13 species present. *S. centrale* and *S. russowii* were the most common bryophytes in the relevé. When bryophyte species were enumerated during quantitative collections from the lagg, *Callicladium haldanianum* was the most frequent of the species collected followed by *Tetraphis pellucida*, *S. magellanicum*, *S. angustifolium*, and *S. centrale*. The bog plant list comprised 17 taxa on 2.8 ha while the lagg list comprised 55 taxa on just 0.4 ha (Table 4.6). The relative area-weighted species ratio (lagg:bog) is 23:1 and plant diversity in the lagg is three times greater than that in the bog.

TABLE 4.5

Vegetation of the S2 Bog and Lagg

Life Form	Species	Cover Scales[a] Bog	Cover Scales[a] Lagg
Needleleaf evergreen			
	Abies balsamea (<2 m)		+
	Picea mariana (10–35 m)	3	
	Picea mariana (<2 m)	+	+
Broadleaf deciduous			
	Acer rubrum (<2 m)	+	
	Alnus incana (<2 m)	1	
	Alnus incana (2–10 m)		1
	Amelanchier intermedia		+
	Betula papyrifera (2–10 m)	+	1
	Cornus stolonifera	+	
	Ribes glandulosum	1	
Broadleaf evergreen			
	Chamaedaphne calyculata	1	
	Gaultheria hispidula	1	+
	Kalmia polifolia	1	
	Ledum groenlandicum	3	+
	Vaccinium angustifolium	+	+
	Vaccinium oxycoccus	+	
Forbs			
	Aster puniceus	+	
	Calla palustris	2	
	Clintonia borealis		+
	Cornus canadensis		+
	Drosera rotundifolia	+	
	Dryopteris carthusiana		1
	Equisetum sylvaticum	+	
	Lycopus uniflorus	+	
	Lysimachia thyrsiflora		+
	Osmunda cinnamomea		+
	Rubus pubescens	1	
	Sarracenia purpurea	+	
	Smilacina trifolia	2	+
	Trientalis borealis		+
	Viola incognita		1
Graminoids			
	Calamagrostis canadensis		+
	Carex brunnescens	+	
	Carex disperma	1	
	Carex intumescens	+	
	Carex oligosperma	1	
	Carex pauciflora	1	
	Carex projecta		+
	Carex trisperma	2	1
	Eriophorum spissum	+	

TABLE 4.5 (continued)

Vegetation of the S2 Bog and Lagg

Life Form	Species	Cover Scales[a] Bog	Cover Scales[a] Lagg
Bryophytes			
	Calliergon giganteum		1
	Pleurozium schreberi	2	
	Polytrichum commune		1
	Sphagna angustifolium	3	
	Sphagnum centrale	2	
	Sphagnum magellanicum	3	
	Sphagnum russowii	2	

Note: The cover scores are those of the Braun-Blanquet scale.

[a] + = 5%, several individuals; 1 = 5%, many individuals; 2 = 5%–25%; 3 = 25%–50%.

TABLE 4.6

Additional Bryophyte Species Found in the Bog and Poor-Fen Lagg Habitats in the S2 Peatland, in Order of Frequency

Bog	Lagg	Lagg
Sphagnum magellanicum	*C. haldanianum*	*Campylium hispidulum*
Sphagna angustifolium	*Tetraphis pellucida*	*Climacium dendroides*
Pleurozium schreberi	*Sphagnum magellanicum*	*Dicranum polysetum*
Ptilidium pulcherrimum	*Sphagna angustifolium*	*Oncophorus wahlenbergii*
C. haldanianum	*Sphagnum centrale*	*Plagiomnium cuspidatum*
Dicranum polysetum	*Pleurozium schreberi*	*Plagiomnium ellipticum*
Dicranum undulatum	*Ptilium crista-castrensis*	*Pseudobryum cinclidioides*
Ptilium crista-castrensis	*Dicranum flagellare*	*Amblystegium serpens*
Aulacomnium palustre	*Brachythecium oedipodium*	*A. serpens* var. *juratzkanum*
Brotherella recurvans	*Thuidium recognitum*	*Anastrophyllum hellerianum*
Dicranum ontariense	*Plagiomnium ciliare*	*Brachythecium rivulare*
Lophocolea heterophylla	*Brachythecium salebrosum*	*Brachythecium velutinum*
Sphagna fuscum	*Calliergon cordifolium*	*Brotherella recurvans*
Pohlia sphagnicola	*Plagiomnium medium*	*Calliergon giganteum*
Cephalozia pleniceps subsp. *sphagnorum*	*Polytrichum commune*	*Dicranum undulatum*
Polytrichum strictum	*Sphagnum wulfianum*	*Hylocomium splendens*
Dicranum fuscescens	*Aulacomnium palustre*	*Hypnum pallescens*
	Jamesoniella autumnalis	*Orthotrichum speciosum*
	Lophocolea heterophylla	*Plagiothecium cavifolium*
	Plagiothecium denticulatum	*Polytrichum longisetum*
	Pohlia nutans	*Pylaisiella selwynii*
	Ptilidium pulcherrimum	*Rhytidiadelphus triquetrus*
	Brachythecium erythrorrhizon	*Sanionia unciata*
	Bryohaplocladium microphyllum	*Sphagnum russowii*
	Plagiothecium laetum	*Sphagnum subnitens*
	Platygyrium repens	*Sphagnum warnstorfii*
	Sphagnum teres	*Warnstorfia fluitans*
	Brachythecium reflexum	

The greater plant diversity in the lagg is driven by the chemistry of water upwelling from the underlying A horizon of eolian loess beneath the peatland (Figure 4.8). At the time the relevés were established, pH was 4.03 in the bog and 5.28 in the marginal poor-fen lagg (compare to upland runoff pH of 6.5, Table 4.4). Specific conductivity ($K_{25°Ccorr}$) reduced by the conductivity attributable to H^+ ions indicated that both waters were dilute, the bog 17 and the lagg 23 µS cm^{-1}. The bog water is tea colored with an absorbance value ($Abs_{350nm\ 1cm}$) of 0.77; the lagg water less so with a value of 0.31, reflecting the admixture of bog water and less colored water from the surrounding upland. Both the floristic and the water-chemistry data characterize the central peatland as a bog and the lagg as a poor fen according to the widely accepted classification of DuRietz (1949); see also Vitt et al. (1995).

Summary and Discussion

Accumulation of Peat Sediment

Dates in a long peat core (^{14}C dates) stretched over 610 cm and ranged from 783 y BP to 10,900 cal y BP. Simple division yielded an annual peat accumulation rate of 0.06 m $century^{-1}$. Overall, this was 56 g m^{-2} y^{-1} equivalent to 29 g C m^{-2} y^{-1} and similar to the North America average (Gorham, 1991).

Dates and pollen identification in the long core from the S2 bog identified seven peat sediment phases. The first was Lake Phase I (11,900–10,900 cal y BP), characterized by algal gyttja in the first 900 years. Lake Phase II (10,900–9,200 cal y BP) accumulated the remains of aquatic mosses (Amblystegiaceae, principally *W. fluitans*). Also prevalent were emergent lake aquatics (e.g., *Nuphar*, *Potamogeton*, *Brasenia*, *Sagittaria*, *Sparganium*, and *Typha*). During Lake Phase II, the water level in the ice-block dropped from an elevation of 420–416 m.

The Rich-Fen/Emergent-Bryophyte Mat Phase spanned only 800 years (9200–8400 cal y BP). A bryophyte mat smothered two small ponds near the bottom of the ice-block depression. The aquatic mosses *W. fluitans* and *C. trifarium* formed the mat. The water had high concentrations of calcium and magnesium and pH values around 8 (in both the Lake and Rich-Fen/Bryophyte Mat Phases). It occurred when the ice front was 390–470 km north fronted by the large glacial Lake Agassiz (Via et al., 2006).

The Rich-Fen/Sedge Phase encompassed 2900 years (8400–5500 cal y BP). *S. platyphyllum* (an alkaline *Sphagna* species), *C. trifarium*, the appearance of *W. exannulatus*, and abundant Cyperaceae characterize this long period of peat accumulation. Between 6300 and 5700 y BP there was a single 5–10 cm slice representing about a 75–150 year period containing *Sphagnum* section *Cuspidata* sp., an acid anomaly in a long period of alkaline water conditions caused by the oxidation of reed roots containing high concentrations of sulfide when water levels dropped to the level of the central flat in the bottom of S2 bog. Peat accumulation during this phase (2.4 m) responded to a piezometric water elevation set by a water table high at the subcontinental divide 3 km north of the S2 peatland. Limestone fragments in the mixed-texture Itasca ground moraine derived from the west side of Hudson Bay. Regional groundwater flowing in the deep sands above this layer dissolved the limestone and brought water into the S2 depression at pH values near 8.

The Transitional-Fen Phase encompassed 2600 years (5500–2900 cal y BP). Pollen of peatland origin during the Transitional-Fen Phase was virtually identical with that of the Rich-Fen/Sedge Phase, marked only by additions of the circumneutral *Sphagna*—*S. cenrale* and *S. subsecundum*. At the beginning of the Transitional-Fen Phase, the peatland was still under the influence of groundwater, but as further paludification occurred (accumulations of another 1.6 m), the groundwater influence waned and water pH values shifted from above 8 to just below 7. At the end of the phase, peat had risen to an elevation of 420.39 m and the depression began to drain to a stream. In the beginning of the phase, the pressure of constant, upwelling groundwater was a dominant force for peat accumulation. During this period, when the peat rose above the subcontinental divide water table at 418 m, the flow of water within the peat mass reversed from upward to downward. Flow reversals and the concurrent existence of local and regional groundwater flow systems are common in peatlands and paramount in understanding hydrology and biogeochemistry in peatlands (Devito et al., 1997). At the end of the Phase, the constant influence of regional, circumneutral, groundwater gave way to periodic processes controlling the chemistry of peat formation. These included water table fluctuation, biologic mixing (vegetation growth, decay, and gas exchange between soils and the atmosphere), and deep frost penetration. Frost penetration preferentially moves colloidal organic matter to the bottom of the frost layers, reaching as much a 45 cm below the surface hollows. At the end of the Transition-Fen Phase, there was a clear break with high-calcium, regional groundwater.

The Open Poor-Fen Phase (2900-130/390 y BP) is marked by the arrival of acid *Sphagna* species—*S. magellanicum*, *S. angustifolium*, and *S. fuscum*. This period accumulated peat (about 1.1 m), but intense fire during 1864 (based on St. Paul, MN weather records) burned 14 cm of peat. Heinselman (1973, 1996) also documented nearly a half million acres of fire-origin pine dating from 1863 and 1864 in the Boundary Waters Canoe Area Wilderness. He documented an earlier fire in 1610 north of Grand Marais, MN. Surface drainage to the stream was well established with no groundwater upwelling.

The Forested-Bog Phase (1864–2001) accumulated 70 cm of peat, including the construction of an 18 cm-high dome near the recording well toward the east end of bog S2. Built by *Sphagnum* mosses and *Ericaceae* roots, the dome rises above the stream elevation. Bog water acid derives from H-ion generation during organic-matter decomposition in the absence of significant bicarbonate ions (Gorham et al., 1985). The bog dome also contains its own shallow groundwater flow system on top of the 7.7 m of fen and algal gyttja once influenced by the flow strength and alkaline chemistry of the regional groundwater system. The additional 70 cm of hydraulic head induces minute amounts of vertically downward seepage through the bog bottom. However, much larger amounts of water leave the bog above the von Post H9 peat layer in the lagg as unsaturated flow through the thin Koochiching till and the Rainy River sands to the regional water table that is 7 m below.

Climate Change

The occurrence of upland pollen in the long peat core allowed us to interpret major changes in the regional climate at the MEF over the last 12,000 years. First is a transition-climate period (12,000–9,300 y BP). Its definition is hampered by the inability to slice algal gyttja, but change from the bottom of the core to the top of the Aquatic Moss Sediment Phase suggests an average annual temperature rising from −1°C to +5°C, and 1,000 mm of annual precipitation at 12,000 y BP dropping to 700 mm at 9,300 y BP.

A dry and warm phase persisted for 2700 years (9300–7400 y BP). During this period, *P. resinosa/P. banksiana* from the uplands dominated the long core with pollen counts that were 40% of the total pollen sum, the highest of any species in the Holocene. The local pollen record, other pollen work (Kutzbach et al., 1993), and CCM modeling suggest annual temperatures at 4°C–5°C and annual precipitation at 700 mm.

A transition climate from 7400 to 6100 y BP cooled from 4°C to 2°C and became wetter with 700–800 mm of annual precipitation. There was a major shift in upland tree pollen. The *P. resinosa/P. banksiana* component decreased from 40% to 15% and the *P. strobus* component increased from 8% to 35%. Then, the relative distribution of pines persisted through a stable period of nearly 3000 years from 6100 to 3200 y BP. A slight cooling period for 800 years from 3200 to 2400 y BP followed, with a subsequent shift to a short (200 year) warmer and drier period from 2000 to 1800 y BP. Changes in *P. resinosa/P. banksiana* and *P. strobus* pollen of 10%–20% followed suit.

The Little Ice Age from 600 to 150 y BP or about 1370–1840 saw the maximum amount of *P. strobus* pollen (40%). Average annual temperature cooled to 1°C and precipitation increased to 800 mm. For a brief period of 75–150 years, the acidiphilous aquatic *Sphagnum* section *Cuspidata* sp. occurred in the S2 bog pond-waters. In, 6000 y BP, significant remnants of the Keewatin and Labrador Ice Centers remained (Hamblin, 1989) but large expanses of ice in western and eastern Canada had melted, releasing enormous stress on the crust of North America and initiating rebound of the Earth's surface.

Peatland Ecology Perspective

Moore and Bellamy (1974) reviewed the evolution of mire ecology; treatises by Weber (1908) and Potonie (1908) conceptualize how peatlands develop from groundwater-fed basins that accumulate peat until the elevation exceeds the height of a surface outlet. Then the peat mass in the center is fed only by rainwater. Weber (1909) developed the hypothesis of terrestrialization based on a natural history of developing peat masses (ontogeny) near Hanover, Germany. The terms used to describe the three stages of mire development were: niedermoore or flachmoore (rich-fen), ubergangsmoore or zwischenmoore (poor fen), and hochmoore (moss or bog) for both Weber and Potonie. These terms simply mean low, medium, and high moors, referring to their elevation as they develop low to high. Mellin (1917) used a similar division for Swedish mires as riekarr, karr, and moss.

Kivinen (1935) summarized all the early chemistry of lake and moorwässer that laid a phytosociological foundation for the work of Witting (1947, 1949) to explain the occurrence of mire vegetation. It was accepted by DuRietz (1949) that water in the peat mass was distinctly different among the three mire types. Early work in Sweden by Sjörs (1948) followed, but he used the terms rich fen, poor fen, and moss. Later Sjörs (1950) made a direct correlation between water chemistry and vegetation in Swedish mires, but considered the change in mires and their vegetation as they built from low to high elevations as gradual rather than three distinct types.

Kulczynski (1949) also used three divisions for Polish mires—rehophilous or neidermoore, transition or ubergangsmoore, and ombrophilous or hochmoore. This was the first use of the term "transition." Earlier work was autecological in nature, while Kulczynski's work, which linked the terminology and classification of mires using the ontogenic, phytosociologic, and chemical approaches, was synecological in nature. Thunmark (1942) classified mire types in Sweden by pH and calcium concentrations, which Vitt et al. (1995) in Canada and Bridgham et al. (1996) in the United States further defined. In Europe, subsequent correlations between water chemistry and mire vegetation were made for England (Pearsall and Lind, 1941; Gorham, 1956a,b), Poland (Tolpa et al., 1967) and Ireland (Bellamy and Bellamy, 1967).

The work reported here for the S2 bog supports the three class divisions (i.e., rich fen, poor fen, and bog). However, it extends previous investigations to show how ice-block, watershed, and regional hydrology influence the amount and chemistry of water and eventually yield a peat mass based on peat phase development. It also considers not only the waning influence of groundwater under constant piezometric pressure but also the importance of a variety of periodic processes that wean dependence of the developing peat mass from alkaline groundwater to rainwater at the top of the bog dome. Although the water-flow and water-chemistry drivers of peat development gradually change as peat develops (Sjörs, 1950), the phytosociological character of rich fen, poor fen, and bog yield distinct phases of peat development interpreted in the study of paleobotany in peat cores.

In Fennoscandia mire terminology, lagg refers to the plant-rich peatland edge (Cajander, 1913; Sjörs, 1948; Kulczynski, 1949). Lagg always is described in terms of plant diversity. However, the detail of geologic and soil lithology at the edge of the S2 bog functionally defines a lagg that results from the movement of upland water through mineral soil horizons beneath the peat and upwelling to the lagg surface. It also shows and quantifies water movement at the lagg in three directions (Chapter 7). Water upwells to the lagg when upslope mineral soil horizons are saturated. Water seeps downward beneath the lagg to the regional water table daily. And, water forms surface flow (water tracks) originating from both the bog dome and the upland and sends it around the lagg to form first order streams leaving the peatland (Figures 4.7 and 4.8).

Lessons Learned

1. *Pleistocene, Wisconsin glaciation*. Matching glacial drift lithology to dates and regions of origin is a continuing process improved with new chemistry, cores, and insight. It includes details of contemporary soil surveys (e.g., shale fragments in the Koochiching till) and accounts for both regional (western Great Lakes) and distant geology.
2. *Topography*. Detailed maps of surface topography, soil horizons, ice-block bathymetry, and water table elevations that are tied to the same elevation datum greatly improve our ability to interpret Pleistocene and Holocene materials, dating, and climate.
3. *Core dating*. The precision of peat or lake sediment cores is derived from the thickness and cleanness of the slice, in our case 5–10 cm representing about 75–150 years; however, accuracy is a function of carbon dating with a variety of adjustments (± 250 years), tree rings (± 5 years), and climate or historic records (± 1 year).
4. Interpreting sediment cores. Records of moss and aquatic pollen preserved in the peat sediment core provide an insight to plant environmental conditions in the ice-block depression, suggesting identification of major peat sediment phases. Tree, shrub, and herbaceous pollen from the uplands provide an insight into major climate periods of transition or stability.
5. *Landscape hydrology*. Water table position, whether within the ice block depression or in the region, helps differentiate between environmental conditions within the depression giving rise to peat phases and climate periods within the region.
6. Hemisphere or regional? Local pollen records representing the regional climate temper our application of climate based on CCM models or interpreted between century and millennial periods in regional cores not subjected to inferences related to watershed hydrology.

7. *Linkages*. Linkages among the upland, lagg, bog, stream, and the regional water table define how a given watershed ecosystem functions. Topography, soil and glacial lithology, climate periods, peat phases, water chemistry, vegetation autecology and synecology, and hydrology refine our deductions of watershed and ecosystem function.

References

Always, F.J. 1920. Agricultural value and reclamation of Minnesota peat soils. Bulletin 188. St. Paul, MN: University of Minnesota Agricultural Experiment Station.

Anderson, L.E. 1990. A checklist of *Sphagnum* in North America north of Mexico. *The Bryologist* 93:500–501.

Anderson, L.E, H.A. Crum, and W.R. Buck. 1990. List of mosses of North America north of Mexico. *The Bryologist* 93:448–499.

Bay, R.R. 1967. Factors influencing soil moisture relationships in undrained forested bogs. In: *International Symposium on Forest Hydrology*, pp. 335–343. Pennsylvania State University, University Park, PA, Aug. 29–Sept. 10, 1965. Oxford: Pergamon Press.

Bellamy, D.J. and S.R. Bellamy. 1967. An ecological approach to the classification of the lowland mires of Ireland. *Proceedings of the Royal Irish Academy* 65B(6):237–251.

Boelter, D.H. 1965. Hydraulic conductivity of peats. *Soil Science* 100(4):227–231.

Bridgham, D.D., J. Pastor, J.A. Janssens, C. Chapin, and T.J. Malterer. 1996. Multiple limiting gradients in peatlands: A call for a new paradigm. *Wetlands* 16:45–65.

Brooks, K.N. and D.A. Kreft. 1991. Hydrologic Linkages between Uplands and Peatlands. Final Report. St. Paul, MN: Department of Forest Resources, University of Minnesota.

Cajander, A.K. 1913. Studien uber die Moore Finnlands. *Acta Forestalia Fennica* 2(3):1–208.

Crum, H. 1988. *A Focus on Peatlands and Peat Mosses*. Ann Arbor, MI: University of Michigan Press.

Davis, J.F. and R.E. Lucas. 1959. Organic soils, their formation, distribution, utilization and management. Special Bulletin 425. East Lansing, MI: Department of Soil Sciences and Agricultural Experiment Station, Michigan State University.

Devito, K.J., J.M. Waddington, and B.A. Branfireun. 1997. Flow reversals in peatlands influenced by local groundwater systems. *Hydrological Processes* 11:103–110.

Digerfeldt, G., J.E. Almendinger, and S. Björck. 1992. Reconstruction of past lake levels and their relation to groundwater hydrology in the Parkers Prairie sandplain, west-central Minnesota. *Palaeogeography, Palaeoclimatology, Palaeoecology* 94(104):99–118.

Donovan, J.J., A.J. Smith, V.A. Panek, D. Engstrom, and E. Ito. 2002. Climate-driven hydrologic transients in lake sediment records: calibration of groundwater conditions using 20th Century drought. *Quaternary Science Reviews* 21:605–624.

DuRietz, G.E. 1949. Huvudenheter och huvudgränser i Svensk myrvegetation. *Svensk Botanisk Tidskrift* 43:274–309.

Filby, S.K., S.M. Locke, M.A. Person, T.A. Winter, D.O. Rosenberry, J.L. Nieber, W.J. Gutowski, and E. Ito. 2002. Mid-Holocene hydrologic model of the Shingobee Watershed, Minnesota. *Quaternary Research* 58(3):246–254.

Gafni, A. and K.N. Brooks. 1986. Tracing approach to determine groundwater velocity in peatlands. *Hydrological Science and Technology* 2(4):17–25.

Gafni, A. and K.N. Brooks. 1990. Hydraulic characteristics of four peatlands in Minnesota. *Canadian Journal of Soil Science* 70:239–253.

Gorham, E. 1956a. The ionic composition of some bog and fen waters in the English lake district. *Journal of Ecology* 44:142–152.

Gorham, E. 1956b. On the chemical composition of some waters form the Moor House Nature Reserve. *Journal of Ecology* 44:377–384.

Gorham, E. 1991. Northern peatlands: Role in the carbon cycle and probable responses to climatic warming. *Ecological Applications* 1:182–195.

Gorham, E., S.J. Eisenreich, J. Ford, and M.V. Santelmann. 1985. The chemistry of bog waters. In: *Chemical Processes in Lakes*, ed. W. Stumm, pp. 339–363. New York: Wiley.

Hamblin, W.K. 1989. *The Earth's Dynamic Systems*, 5th edn. New York: Macmillan Publishing Co.

Harlow, W.M. and E.S. Harrar. 1958. *Textbook of Dendrology*, 4th edn. New York: McGraw-Hill Book Co.

Hedenäs, L. 2003. The European species of the *Calliergon–Scorpidium–Drepanocladus* complex, including some related or similar species. *Meylania* 28:1–117.

Hedenäs, L. and A. Kooijman. 1996. Phylogeny and habitat adaptations within a monophyletic group of wetland moss genera (Amblystegiaceae). *Plant Systematics and Evolution* 199:33–52.

Heinselman, M.L. 1973. Fire in the virgin forests of the Boundary Waters Canoe Area, Minnesota. *Quaternary Research* 3:329–82.

Heinselman, M.L. 1996. *The Boundary Waters Wilderness Ecosystem*. Minneapolis, MN: University of Minnesota Press.

Ingram, H.A.P. 1978. Soil layers in mires: function and terminology. *Journal of Soil Science* 29:224–227.

Jirsa, M.A. and V.W. Chandler. 2007 Bedrock geology of the Bigfork 30′ × 60′ quadrangle, northern Minnesota. Misc. Map Series Map M-176. Minneapolis, MN: University of Minnesota, Minnesota Geological Survey.

Keys, J.E. Jr. and C.A. Carpenter. 1995. *Ecological Units of the Eastern United States: First Approximation*. Atlanta, GA: USDA Forest Service.

Kivenen, E. 1935. Über electolytegehalt und reaction der moorwässer. *Maatouskoelatioksen Maatutkimusosasto Agrogeol. Julkaisuja*. 38. Helsingfors.

Kulczynski, S. 1949. Peat bogs of Polesie. *Memoirs Academy of Cracovie* 315:1–356.

Kutzbach, J.E., P.J. Bartlein, I.C. Prentice, W.F. Ruddiman, F.A. Street-Perrott, T. Webb III, and H.R. Wright Jr. 1993. Epilogue. In: *Global Climates Since the Last Glacial Maximum*, eds., H.W. Wright Jr., J.E. Kutzbach, T. Webb III, W.F. Ruddiman, F.A. Street-Perrott, and P.J. Bartlein, Chap. 20, pp. 536–542. Minneapolis, MN: University of Minnesota Press.

Malterer, T.J., E.S. Verry, and J. Erjavec. 1992. Fiber content and degree of decomposition in peats. *Soil Science Society of America Journal* 56(6):1200–1211.

Maxwell, J.R., C.J. Edwards, M.R. Jensen, S.J. Paustion, H. Parrott, and D.M. Hill. 1995. A hierarchical framework of aquatic ecological units in North America (Nearctic Zone). Gen. Tech. Report NC-176. St. Paul, MN: USDA Forest Service.

Mellin, E. 1917. Studier Över de noorlandska Handbibl, 7. Uppsala, Sweden.
Meyer, A.F. 1944. *The Elements of Hydrology*, 2nd edn, fifth printing, pp. 522. London: John Wiley & Sons.
Meyer, G.N. 1986. Subsurface till stratigraphy of the Todd County area, central Minnesota. Report of Investigations 34. St. Paul, MN: Minnesota Geological Survey.
Meyer, G.N. 1997. Pre-Late Wisconsinan till stratigraphy of north-central Minnesota. Report of Investigations 48. St. Paul, MN: Minnesota Geological Survey.
Meyer, G.N., C.J. Patterson, H.C. Hobbs, M.D. Johnson, and J.F.P. Cotter. 1998. Terrestrial record of Laurentide Ice Sheet reorganization during Heinrich events: Comments and Reply. *Geology* 26:667–668.
Moore, P.D. and D.J. Bellamy. 1974. *Peatlands*. New York: Springer-Verlag.
Mooers, H.D. 1990. Discriminating texturally-similar glacial tills in central Minnesota with graphical and multivariate techniques. *Quaternary Research* 34(2):133–147.
Mooers, H.D. and C.A. Dobbs. 1993. Holocene landscape evolution and the development of models for human interaction with the environment: An example from the Mississippi Headwaters region. *Geoarchaeology* 8(6):475–492.
Mooers, H.D. and J.D. Lehr. 1997. Terrestrial record of Laurentide Ice Sheet reorganization during Heinrich events. *Geology* 25(11):987–990.
Mooers, H.D. and A.R. Norton. 1997. Glacial landscape evolution of the Itasca/St. Croix moraine interlobate area including the Shingobee River headwaters area. In: *Hydrological and Biogeochemical Research in the Shingobee River Headwaters Area, North-central Minnesota*, ed., T.C. Winter, pp. 3–10. Water Resources Investigation Report 96-4215. Denver, CO: U.S. Geological Survey.
Nyberg, P.R. 1987. *Soil Survey of Itasca County, Minnesota*. 1987 0-493-527. QL3USDA-Soil Conservation Service. St. Paul, MN.
Oakes, E.L. and L.W. Bidwell. 1968. Water resources of the Mississippi headwaters watershed, north central Minnesota. USDI—Geological Survey. Hydrologic Atlas. HA-278.
Okruszko, H. 1960. Muck soils of the valley peat bogs and the chemical and physical properties. *Roczniki Nauk Rolniczych* 74-F1:5–89. Translation from U.S. Department of Commerce, Clearinghouse for Federal Scientific and Technical Information. 11 67-56119. Springfield, VA.
Ownbey, G.B. and T. Morley. 1991. *Vascular Plants of Minnesota. A Checklist and Atlas*. Minneapolis, MN: University of Minnesota Press.
Paulson, R.O. 1968. A soil survey: Marcell Experimental Forest. Itasca Co. Minnesota. Grand Rapids, MN: USDA Soil Conservation Service.
Pearsall, W.H. and E. Lind. 1941. A note on a Connemara bog type. *Journal of Ecology* 29:62–68.
Potonie, R. 1908. Aufbau und vegetation der norddeutschlands. *Engler. Bot. Jahrb*. 90, Leipzig, Germany.
Sander, J.E. 1971. Bog-watershed relationships utilizing electric analog modeling. PhD dissertation. East Lansing, MI: Michigan State University.
Schwalb, A. and W.E. Dean. 2002. Reconstruction of hydrological changes and response to effective moisture variations from North-Central USA lake sediments. *Quaternary Science Reviews* 21(202):1541–1554.
Siegel, D. and P. Glaser. 1987. Groundwater flow in a bog-fen complex, Lost River Peatland, northern Minnesota. *Journal of Ecology* 75:743–754.

Sjors, H. 1948. Myrvegetation i Bergslagen (Mire vegetation in Bergslagen). *Acta Phytogeographica Suecica* 21:1–299.

Sjors, H. 1950. On the relation between vegetation and electrolytes in north Swedish mires. *Oikos* 2:241–258.

Stotler, R. and B. Crandall-Stotler. 1997. A checklist of the liverworts and hornworts of North America. *The Bryologist* 80:405–428.

Teller, J.T. and D.W. Leverington. 2004. Glacial Lake Agassiz: A 5000 year history of change and its relationship to the $\delta^{18}O$ record of Greenland. *Bulletin of the Geological Society of America* 116:729–742.

Thunmark, S. 1942. Über rezente eisenocker und ihre mikroorganismengeme in-Schaften. *Bulletin of the Geological Institute of Uppsala.* Uppsala, 29:1–285.

Tolpa, S., M. Jasnowski, and A. Palczynski. 1967. System der genetischen klassifizierung der torfe mitteluropas. NO 76. Warsaw: Zesz. Probl. Post. Navk. Roln.

Tracy, D.R. 1997. Hydrologic linkages between uplands and peatlands. PhD dissertation. St. Paul, MN: University of Minnesota.

Verry, E.S. 1980. Streamflow and water table changes following stripcutting and clearcutting in an undrained black spruce bog. In: *Proceedings of the 6th International Peat Congress*, pp. 493–498, August 17–23, 1980. Duluth, MN. Helsinki: International Peat Society.

Verry, E.S. 1984. Microtopography and water table fluctuation in a *Sphagnum* mire. In: *7th International Peat Congress,* June 18–23, 1984, Dublin, Ireland. Helsinki: International Peat Society, Vol. 2, pp. 11–31.

Verry, E.S. 1991. Concrete frost in peatland and mineral soils: Northern Minnesota. In: *Proceedings of the International Peat Symposium Peat and Peatlands: The Resource and Its Utilization*, eds., D.N. Grubich and T.J. Malterer, August 19–22, 1991, Duluth, MN. Helsinki, Finland: International Peat Society, pp. 121–141.

Verry, E.S. 2000. Water flow in soils and streams: sustaining hydrologic function. In: *Riparian Management in Forests*, eds., E.S. Verry, J.W. Hornbeck, and C.A. Dolloff, pp. 99–125. Boca Raton, FL: Lewis Publishers.

Verry, E.S. and T.R. Timmons. 1982. Waterborne nutrient flow through an upland-peatland watershed in Minnesota. *Ecology* 63(5):1456–1467.

Viau, A.E., K. Gajewski, M.C. Sawada, and P. Fines. 2006. Millennial-scale temperature variations in North America during the Holocene. *Journal of Geophysical Research, D, Atmospheres* 111(D09102):1–12.

Vitt, D.H., S.E. Bayley, and T.L. Jin. 1995. Seasonal variations in water chemistry over a bog-rich fen gradient in Continental Western Canada. *Canadian Journal of Fisheries and Aquatic Sciences* 52:587–606.

Weber, C.A. 1908. Aufbau und vegetation der moore norddeutschlands. *Englers. Bot. Jahrb*. 90. Leipzig, Germany.

Weber, C.A. 1909. Das moor hanoverishce geschict blätter.

Witting, M. 1947. Katjonbestämningar I myrvatten. *Botaniska Notiser*. 287–311.

Witting, M. 1949. Kalsiumhalten I nagra nordsvenska myrvatten. *Svensk Botanisk Tidskrift* 43:715–739.

Wright, H.E., I. Stefanova, J. Tian, T.A. Brown, and F.S. Hu. 2004. A chronological framework for the Holocene vegetational history of central Minnesota: The Steel Lake pollen record. *Quaternary Science Reviews* 23(2004):611–626.