

Paleoecology and high-resolution paleohydrology of a kettle peatland in upper Michigan

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Abstract

We investigated the developmental and hydrological history of a *Sphagnum*-dominated, kettle peatland in Upper Michigan using testate amoebae, plant macrofossils, and pollen. Our primary objective was to determine if the paleohydrological record of the peatland represents a record of past climate variability at subcentennial to millennial time scales. To assess the role of millennial-scale climate variability on peatland paleohydrology, we compared the timing of peatland and upland vegetation changes. To investigate the role of higher-frequency climate variability on peatland paleohydrology, we used testate amoebae to reconstruct a high-resolution, hydrologic history of the peatland for the past 5100 years, and compared this record to other regional records of paleoclimate and vegetation. Comparisons revealed coherent patterns of hydrological, vegetational, and climatic changes, suggesting that peatland paleohydrology responded to climate variability at millennial to sub-centennial time scales. Although ombrotrophic peatlands have been the focus of most high-resolution peatland paleoclimate research, paleohydrological records from *Sphagnum*-dominated, closed-basin peatlands record high-frequency and low-magnitude climatic changes and thus represent a significant source of unexplored paleoclimate data.

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Introduction

Holocene paleoclimate records with decadal to millennial-scale resolution have been extracted from a variety of sources in North America, including lake sediments (e.g., Baedke and Thompson, 2000; Dean, 2001; Laird et al., 1996), dunes (e.g., Forman et al., 2001; Loope and Arbogast, 2000), and speleothems (e.g., Denniston et al., 2001). Peatland archives have only recently been explored as a source of high-resolution paleoclimate records in North America (Booth and Jackson, 2003), although continuous, high-resolution records have been successfully extracted from peatlands in other regions (e.g., Barber et al., 2000; Chambers et al., 1997; Charman and Hendon, 2000; Mauquoy and Barber, 1999). A variety of proxies have been developed to infer past surface-moisture varia-

tions from peat stratigraphy, including plant macrofossils (Barber et al., 2000), peat humification (Blackford and Chambers, 1993), and testate amoebae (Woodland et al., 1998). Ombrotrophic peatlands (i.e., peatlands that receive all moisture inputs from precipitation) have been the primary source of peatland proxy-climate records, because surface-moisture conditions are directly coupled to the atmosphere.

Early paleoclimate work on ombrotrophic peatlands was focused on documenting high-magnitude hydrological changes, typically at millennial time scales. Concerns about the integrity of the stratigraphic record, the extent of autogenic (i.e., nonclimatic) influences, and a now-refuted theory of bog development (Backeus, 1990; Barber, 1981; Charman, 2002) hampered investigations of lower-magnitude and higher-frequency hydrologic changes until the late 1970s (e.g., Aaby, 1976). Research during the last decade has clearly shown that ombrotrophic peatlands contain reliable stratigraphic records with decadal to centennial temporal resolution and high sensitivity to moisture varia-

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tion (e.g., Barber et al., 2000; Booth and Jackson, 2003; Chambers et al., 1997; Mauquoy and Barber, 1999). Paleohydrologic records show similar temporal patterns within and among ombrotrophic peatlands (e.g., Barber et al., 1998, 2000; Hendon et al., 2001), and different moisture proxies covary in time (Booth and Jackson, 2003; Charman et al., 1999). Ombrotrophic peatland records also show good correspondence with other paleoclimate records (e.g., speleothems, lake-levels) (Booth and Jackson, 2003; Charman et al., 2001).

A few studies also suggest that sensitive, high-resolution paleoclimate records may be obtained from peatlands that are not truly ombrotrophic (Anderson, 1998; Hendon et al., 2001). Particularly promising in this regard are closed-basin, *Sphagnum*-dominated peatlands. *Sphagnum* is generally intolerant of strongly minerotrophic conditions, and the stems of *Sphagnum* are inhabited by testate amoebae, which are sensitive paleohydrological indicators (Charman, 2001). Closed-basin peatlands occupying ice-block depressions (kettle peatlands) are common in glaciated regions of North America, and are often dominated by *Sphagnum*. Climate change is important in controlling the long-term development of kettle peatlands through its effect on hydrology (Campbell et al., 1997; Futyma and Miller, 1986; Miller and Futyma, 1987; Winkler, 1988). Studies on the relationship between climate change and peatland development have focused on high-magnitude and low-frequency hydrologic changes, because these changes were usually sufficient to force a developmental response detectable by plant macrofossils and pollen. However, high-resolution stratigraphic analysis, especially using proxies particularly sensitive to moisture (e.g., testate amoebae, peat humification), can potentially yield records of higher frequency and lower magnitude hydrologic fluctuations.

In this study, we reconstruct the paleohydrology and developmental history of a *Sphagnum*-dominated, kettle peatland in Upper Michigan. We use pollen and plant macrofossils to infer the Holocene vegetation history of the peatland and surrounding uplands, and testate amoebae and plant macrofossils to develop a high-resolution record of moisture variability spanning the past 5100 years. We compare these records to each other and to regional proxy-climate records (e.g., vegetation, lake water-levels) to assess the relationship between peatland paleohydrology and paleoclimate at subcentennial to millennial time scales.

Study site

South Rhody peatland (unofficial name; 46°33'57" N, 86°43'0" W; ~285 m above sea level) is a small (~4.5 ha) kettle peatland located within the Lake Superior State Forest in Upper Michigan (Fig. 1). Sandy outwash and moraine deposits characterize the region, and upland soils are sandy

and relatively well-drained. The peatland is open, except for a few small *Pinus strobus* trees growing on hummocks, and vegetation is dominated by *Sphagnum* spp., *Carex oligosperma*, *C. limosa*, *Chamaedaphne calyculata*, and *Vaccinium oxycoccos*. In July 2000, water-table depths ranged from 2 to 25 cm below the peat surface and surface pH ranged from 3.7 to 4.2 (Booth, 2002). Second-growth forest dominated by *Pinus strobus*, *Acer saccharum*, *Tsuga canadensis*, *Picea mariana*, and *Fagus grandifolia* surrounds the peatland.

Methodology

Field methods

A sediment core was obtained from near the center of South Rhody peatland in July 2000 (Fig. 1). The top two meters were recovered using a 10.2-cm-diameter modified Livingstone piston corer (Wright et al., 1984), and lower sediments were collected using a 7.6-cm diameter square-rod piston corer. Core segments were extruded in the field.

Macrofossil analyses

Macrofossil samples from the 7.6- and 10.2-cm-diameter portions of the core spanned depth intervals of 2 cm and 1 cm, respectively. Macrofossils were isolated from the sediment using standard sieving methods (Jackson, 1999). Two size fractions were analyzed (>710 μm , 355–710 μm). Taxonomy follows Voss (1972, 1985, 1996). *Sphagnum* leaves were abundant in some samples, so we stopped counting after a total of 500 was reached. Numbers of each macrofossil morphotype were tallied and expressed as numbers per 70 cm^3 of sediment (average sample volume of all samples from the core). Macroscopic charcoal was also picked, dried, and weighed; concentrations were expressed as mg per 70 cm^3 of sediment.

Testate amoeba analyses and paleohydrological reconstruction

Samples for testate amoeba analysis were collected from approximately every other cm along the *Sphagnum*-dominated portion of the core (177 samples across 328 cm). Each sample spanned 1 cm and was 1 cm^3 in volume. Samples were processed using standard sieving procedures (Hendon and Charman, 1997), and the size fraction between 355 and 15 μm was analyzed. Slides were typically scanned until between 100 and 200 testate amoebae were identified and counted, although this count total was not always obtainable. The relative abundance of each taxon was calculated as a percentage of the total counted. Taxonomy followed Charman et al. (2000),

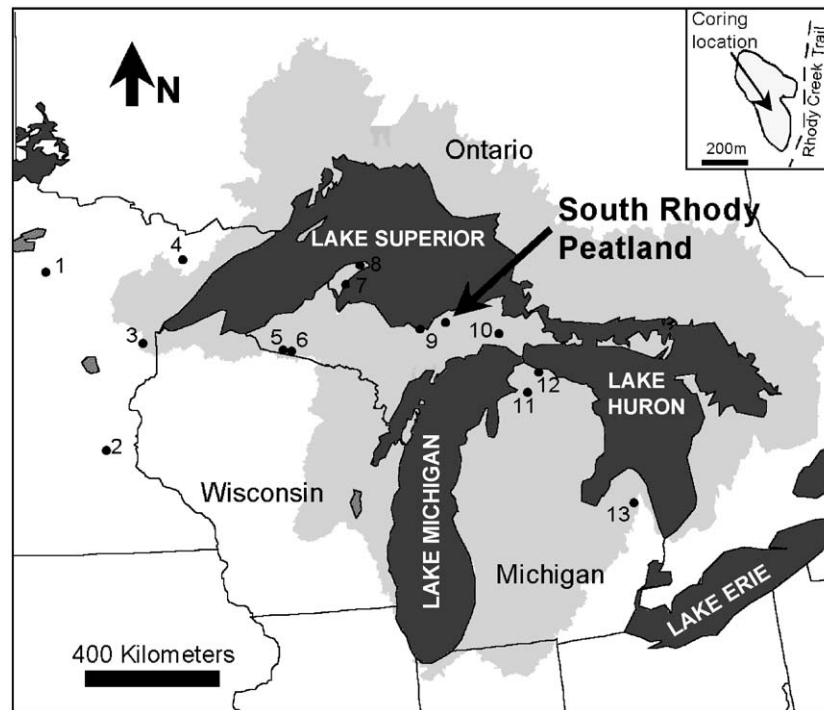


Fig. 1. Map showing the location of South Rhody peatland and other sites discussed in the text (1, Red Lake Peatland (Griffin, 1977); 2, Pogonia Bog (Brugam and Swain, 2000); 3, Jacobson Lake (Wright and Watts, 1969); 4, Third Lake (Swain, 1979); 5, Kerr Lake Peatland (Brugam and Johnson, 1997); 6, Crooked Lake (Brugam et al., 1998); 7, Mud Lake (Booth et al., 2002); 8, Partridge Lake Peatland (Booth and Jackson, unpublished data); 9, Au Train Peatland (Booth, 2003); 10, Trout Lake Peatland (Futyma, 1982); 11, Gates Bog (Miller and Futyma, 1987); 12, Lake Sixteen Peatland (Futyma and Miller, 1986); 13, Minden Bog (Booth and Jackson, 2003)). Gray area denotes the drainage basin of the western Great Lakes (Superior, Michigan, and Huron). Inset shows the approximate location of the core within the South Rhody peatland.

except as noted by Booth (2002). *Habrotrocha angusticollis*, a commonly fossilized rotifer, was included in the count total. Stratigraphically constrained cluster analysis (Grimm, 1987) was performed on the testate amoeba data to aid in zonation.

We modified the calibration dataset of Booth (2002) to infer the paleohydrology of the peatland. Several testate amoeba taxa were only present in the upper few centimeters of the core, so it is unclear whether these taxa were absent from the peatland in the past or were not preserved. Therefore, we standardized the calibration dataset and the downcore data by eliminating taxa in both datasets that were not present below the depth of the post-settlement *Ambrosia* pollen rise (29 cm depth). We then eliminated samples from the calibration dataset with count totals less than 150. The resulting calibration dataset consisted of 145 testate amoeba assemblages and associated water-table depths. Transfer functions were developed from this calibration dataset using several commonly used models (Birks, 1995). All models produced similar reconstructed water-table depths from the fossil data. Jack-knifing procedures suggested that tolerance downweighted averaging (WA-Tol) produced the most reliable reconstructions (Table 1), so we used this model to infer the paleohydrology of the peatland.

Pollen analyses

Because pollen grains were abundant and easily identifiable in the residues prepared for testate amoeba analysis, pollen analysis was performed on these samples (i.e., no chemical treatments were used to concentrate pollen from the peat). Total number of arboreal pollen grains identified per sample ranged from 200 to 261 (median = 206). Pollen percentages were calculated using an arboreal pollen sum for arboreal taxa, a total pollen sum for all other pollen taxa, and a total pollen and spore sum for spore taxa. Strati-

Table 1
Performance of transfer function models for water-table depth assessed by jack-knifed scores (RMSEP), correlation coefficients (r^2), and maximum bias (M-bias)

Model	RMSEP	r^2	M-bias
WA	7.88	0.71	12.06
WA-Tol	7.35	0.75	10.19
PLS (3 components)	7.96	0.71	11.38
WA-PLS (2 components)	7.68	0.73	10.45

Four commonly used models were explored, including weighted averaging (WA), tolerance downweighted averaging (WA-Tol), partial least squares (PLS), and weighted averaging partial least squares (WA-PLS) (Birks, 1995). The WA-Tol model was used for fossil reconstructions.

graphically constrained cluster analysis (Grimm, 1987), was performed on the arboreal pollen data to aid in zonation. Microscopic charcoal fragments were counted and assigned to size classes using an ocular grid (nine $50 \mu\text{m}^2$ size classes spanning 50 to $500 \mu\text{m}^2$), and data were expressed as μm^2 per 200 arboreal pollen grains.

Results and discussion

Chronology and sediment stratigraphy

Nine accelerator mass spectrometry (AMS) radiocarbon dates were obtained in the South Rhody peat core from *Sphagnum* moss or terrestrial plant material (Table 2). Radiocarbon ages were calibrated using CALIB 4.1 (Stuiver and Reimer, 1993; Stuiver et al., 1998). All dates discussed in this paper are in “calendar” years before present (cal yr B.P.) relative to the A.D. 1950 datum.

An age model was created using linear interpolation between median calibrated radiocarbon dates, the position of the post-settlement *Ambrosia*-pollen increase (~A.D. 1850), and the top of the core. All radiocarbon dates are progressively greater with depth. Average deposition times, indicating the relative degree of time-resolution per centi-

meter between dated horizons, varied from greater than 40 yr/cm in lower regions of the core to less than 6 yr/cm in the uppermost portion of the core (Fig. 2).

The sediment stratigraphy of the South Rhody core is characterized by several conspicuous changes (Figs. 2, 3). Basal sediments (dated to 10,500 cal yr B.P.) are composed of gyttja, which gradually becomes more fibrous upward. A variably fibrous mud occurs between 430 and 336 cm depth. The fibrous organic mud generally becomes more fibrous upward in the core, although between 386 and 376 cm this trend is interrupted by a very fibrous peat. This very fibrous peat stopped accumulating about 6800 cal yr B.P. At 328-cm depth (5050 cal yr B.P.), *Sphagnum* peat began accumulating in the basin.

Millennial-scale peatland and upland vegetation dynamics

Because of the limited number of radiocarbon dates before 5000 cal yr B.P., the timing of peatland and upland changes before this time is not well constrained. However, peatland and terrestrial vegetation changes are being inferred from the same core, so if there is temporal correspondence between upland and peatland vegetation changes, climate can be implicated as the likely cause (e.g., Campbell et al., 1997; Singer et al., 1996; Winkler, 1988).

A shallow lake with abundant *Najas flexilis*, *Potamogeton*, and *Cladium mariscoides* (Fig. 3) occupied the South Rhody site when sediment began accumulating 10,500 cal yr B.P. A transition from gyttja to fibrous mud indicates lowering of water levels in the basin, with floating-leaved aquatic plants (*Nuphar*, *Nymphaea*, *Scirpus subterminalis*) dominant in deeper areas of the basin and emergent aquatics (e.g., *Dulichium arundinaceum*) in shallower areas. The timing of the transition from abundant *Najas flexilis* to abundant *Nuphar* and the associated transition from gyttja to fibrous mud, are not well constrained. However, these peatland changes correspond temporally with a decrease in *Picea* and an increase in *Pinus* Subgenus *Pinus* on the uplands (Zone P-1). The correspondence between upland and peatland vegetation changes, along with the observation that local fires increased after *Pinus* Subgenus *Pinus* attained dominance (Fig. 4), suggests that both peatland and upland changes were forced by climate change.

The decline of *Picea* populations and replacement by *Pinus* Subgenus *Pinus* has been observed at other sites in the region during the early Holocene (e.g., Booth et al., 2002; Brubaker, 1975; Brugam et al., 1997; Davis et al., 2000; Webb, 1974), and has been attributed to replacement of late-glacial *Picea* forest by *Pinus banksiana* (Brugam et al., 1997; Wright, 1964). However, macrofossils of both *Pinus banksiana* and *Pinus resinosa* were recovered from the sediments of South Rhody (Fig. 4). Because of the dearth of macrofossil data from sites across the region, the spatial extent of *Pinus resinosa* populations during this time period is unclear.

Table 2
AMS radiocarbon dates obtained from the South Rhody peatland core

Depth (cm)	Material dated	Lab number	^{14}C yr B.P.	cal yr B.P. ^a
90–92	<i>Sphagnum</i> stems and leaves	GX-28713	970±40	921 (954–788)
128–130	<i>Pinus strobus</i> needles	CURL-5454	1520±50	1408 (1526–1306)
170–172	<i>Pinus</i> spp. needles	GX-28986	2210±40	2301, 2246, 2179, 2168, 2159 (2338–2118)
214–216	<i>Pinus</i> spp. needles	GX-28985	2670±40	2770 (2850–2744)
274–276	<i>Pinus</i> spp. needles	GX-28984	3640±40	3967, 3945, 3929 (4087–3833)
304–306	<i>Pinus strobus</i> bud scales	GX-28982	4230±40	4829 (4857–4646)
327–329	<i>Pinus</i> Subgenus <i>Pinus</i> needles	UGA-11023	4460±40	5046 (5295–4873)
374–376	<i>Pinus</i> Subgenus <i>Pinus</i> needles	GX-28983	6010±40	6853, 6836, 6830, 6822, 6802 (6946–6729)
464–466	<i>Picea</i> needles and seeds	CURL-5449	9350±55	10,559 (10,731–10,294)

^a Intercepts and 2σ ranges (in parentheses) are shown. Calculated using CALIB version 4.1 (Stuiver and Reimer, 1993; Stuiver et al., 1998).

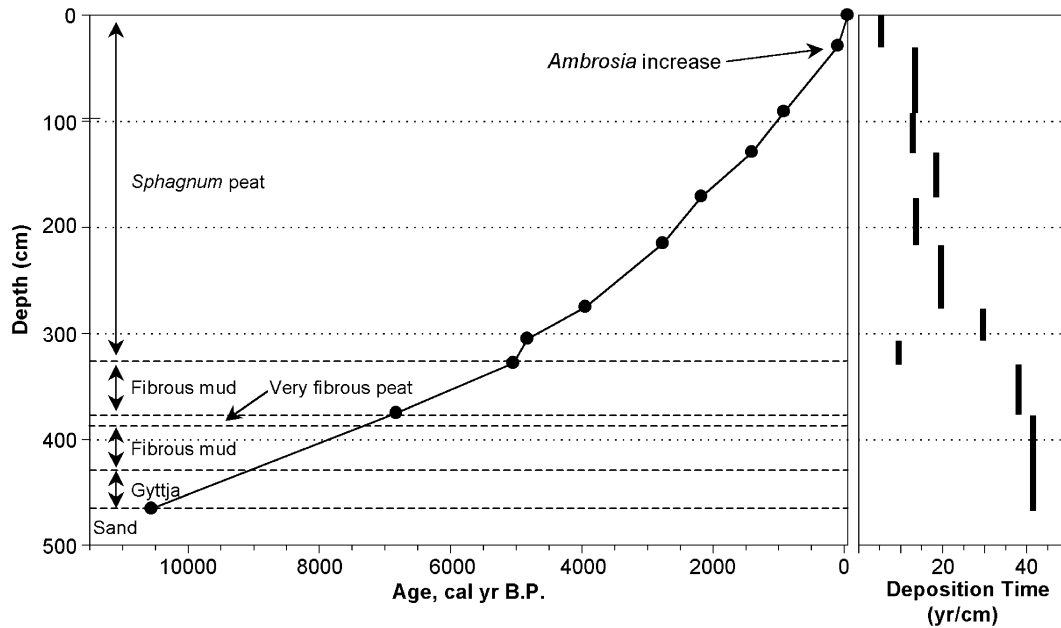


Fig. 2. Age–depth curve and average-deposition times for the South Rhody core.

The migration of *Pinus strobus* into the region marks the onset of Zone P-2 (~7800 to 4000 cal yr B.P.). *Pinus* Subgenus *Strobus* pollen, and needles and bud scales of *Pinus strobus* were abundant in sediments of this zone (Fig. 4). AMS radiocarbon dates from nearby sites suggest that *Pinus strobus* populations increased about 8300 cal yr B.P. (Booth et al., 2002; Booth and Jackson, unpublished data, 2003), but the event is poorly constrained in the South Rhody record. The expansion of *Pinus strobus* may have been related to drier and/or warmer conditions associated with the mid-Holocene dry period in the region (Booth et al., 2002; Brubaker, 1975). The *Pinus strobus* expansion occurred at South Rhody immediately before onset of deposition of the very fibrous peat (Fig. 4), suggesting that decreasing effective moisture caused water levels to drop in the peatland. Although *Nuphar*, *Nymphaea*, and *Dulichium arundinaceum* were present during deposition of both the fibrous mud and very fibrous peat, *Chamaedaphne calyculata* and *Sphagnum* occurred only in the very fibrous peat (Fig. 3), suggesting lower water levels. A similar, but more dramatic, wetland response to drier conditions at this time was recorded at Mud Lake on the Keweenaw Peninsula (Booth et al., 2002) and pollen-based climate reconstructions also suggest warmer and drier conditions throughout the region (Davis et al., 2000).

Immediately before *Sphagnum*-dominated peat began accumulating in the basin, the abundance of several poor to moderate fen species increased, including *Chamaedaphne calyculata*, *Vaccinium oxycoccus*, *Andromeda* or *Kalmia*, *Iris versicolor*, *Rhynchospora alba*, *Menyanthes trifoliata*, and *Viola* (Fig. 3). Aquatic plants like *Nuphar* and *Nymphaea* were also present, but disappeared along with

Dulichium arundinaceum as *Sphagnum* peat began to accumulate. Ericaceous shrubs remained abundant after the site became dominated by *Sphagnum*. It is unclear what hydrologic changes led to *Sphagnum* dominance, but an increase in the relative importance of meteoric water and a corresponding decrease in groundwater contribution may have been responsible. A transient increase in *Tsuga* pollen occurred at the transition to *Sphagnum* peat, suggesting climate change was responsible for the changes in peatland vegetation. Increases in *Tsuga* populations are documented earlier (6800–5800 cal yr B.P.) at more mesic sites in the region (e.g., Davis, 1987; Davis et al., 1986, 1994). However, *Tsuga* may have been unable to colonize sandy outwash soils like those around South Rhody until later (e.g., Brubaker, 1975; Ewing, 2002).

The *Betula* pollen increase marking the onset of Zone P-3 (4000–2100 cal yr B.P.) resulted from the expansion of *Betula alleghaniensis* into the region (Jackson and Booth, 2002). Peatland vegetation changes at South Rhody indicate major climate changes at this time. *Sphagnum* decreases in abundance early in this zone, between 3800 and 3400 cal yr B.P., probably because of increased groundwater influence. Aquatic plants (e.g., *Nuphar*, *Nymphaea*) also returned to the site between 3400 and 3000 cal yr B.P. After 3000 cal yr B.P., aquatic plants disappeared and *Sphagnum*-dominated peat accumulated to the present. Other mesic taxa (e.g., *Tsuga*, *Fagus*, *Picea*, *Abies*, *Acer saccharum*) increase in abundance during Zone P-3 and/or P-4 (2100 to -50 cal yr B.P.). A rise in *Ambrosia* pollen and decrease in *Pinus strobus* occurs at 29 cm depth and is associated with European land-clearance and logging.

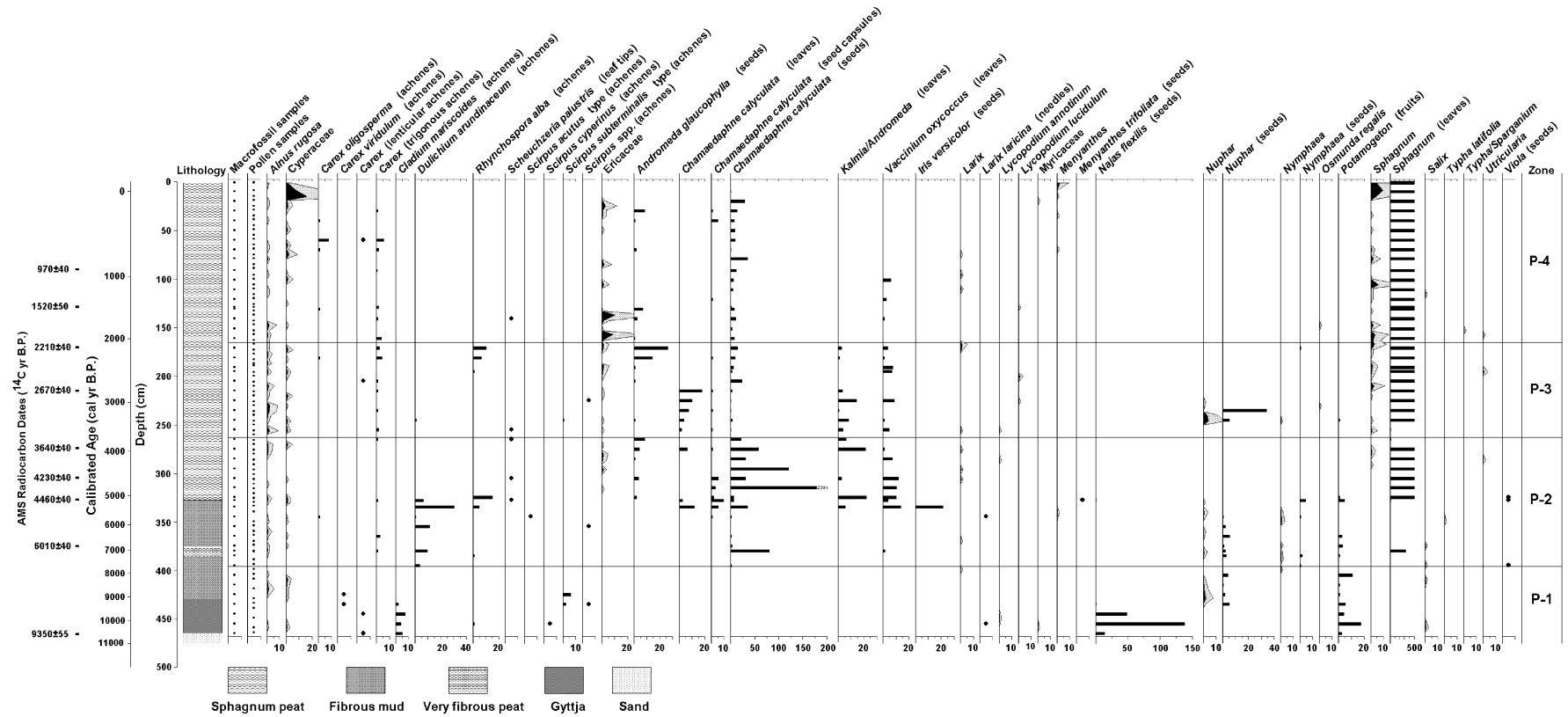


Fig. 3. Peatland plant macrofossil and pollen diagram from the South Rhody core. Accelerator mass spectrometry (AMS) dates, calibrated ages, depth, lithology, and location of pollen and macrofossil samples are shown on the left side of the diagram. Shaded silhouettes show pollen percentages, with the dotted area showing fourfold exaggeration for less frequent taxa. Histograms and closed circles show the abundance and presence/absence of macrofossil types. Arboreal pollen zones are on the right side of the diagram.

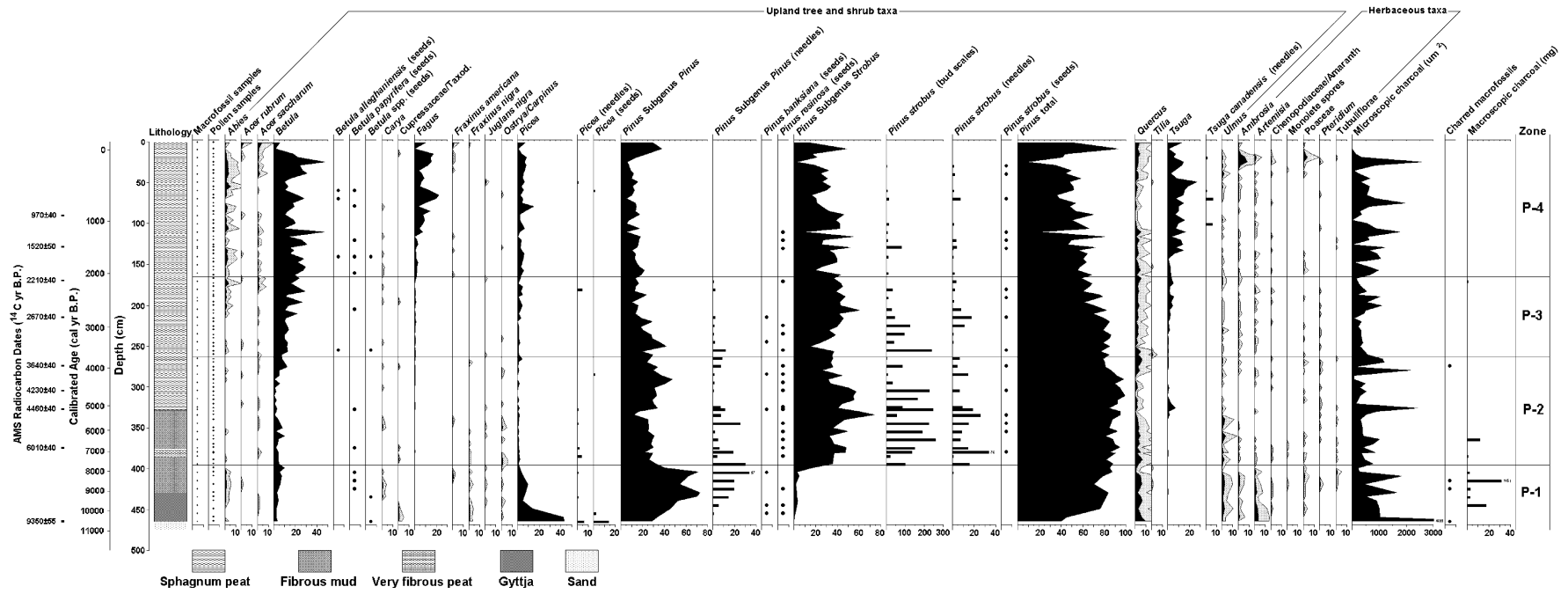


Fig. 4. Upland pollen and plant macrofossil diagram from the South Rhody core. Accelerator mass spectrometry (AMS) dates, calibrated ages, depth, lithology, and location of pollen and macrofossil samples are shown on the left side of the diagram. Shaded silhouettes show pollen percentages, with the dotted area showing fourfold exaggeration for less frequent taxa. Histograms and closed circles show the abundance and presence/absence of macrofossil types. Charcoal concentrations and arboreal pollen zones are on the right side of the diagram.

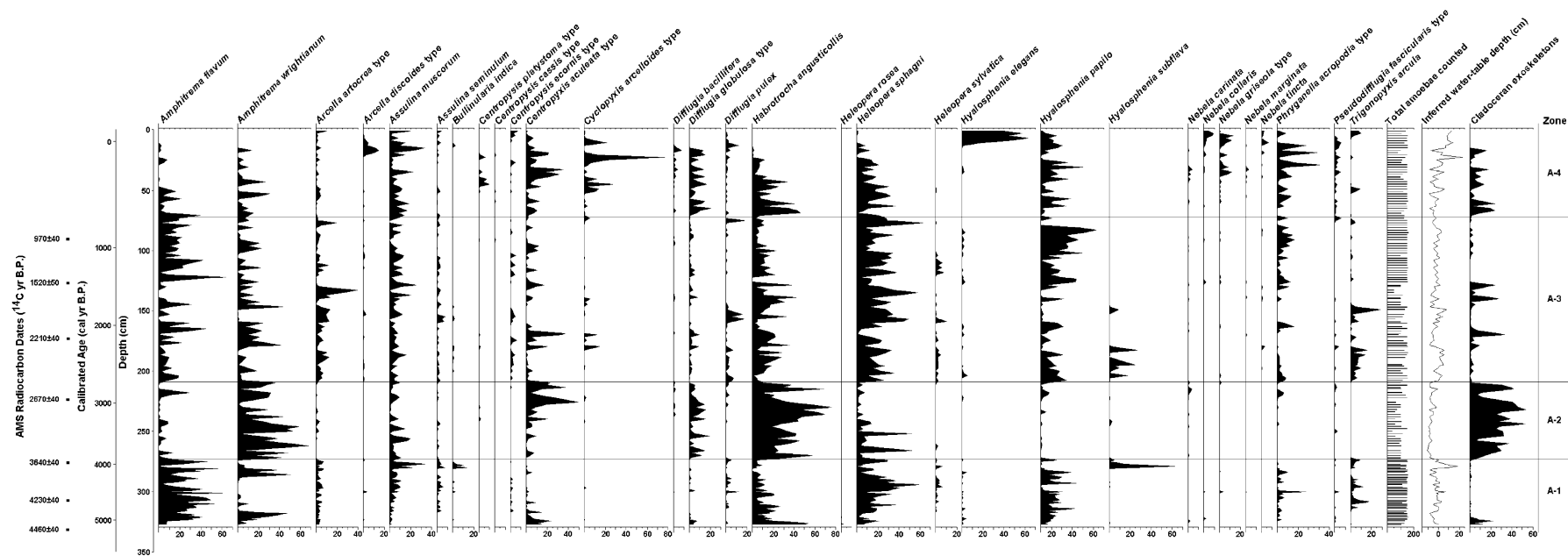


Fig. 5. Testate amoeba diagram from the South Rhody core. Accelerator mass spectrometry (AMS) dates, corresponding calibrated ages, and depth are shown on the left side of the diagram. Shaded silhouettes show testate amoeba percentages. The total number of testate amoebae counted, relative abundance of cladoceran exoskeletons, inferred water-table depths, and testate amoeba zones are on the right of the diagram.

High-resolution paleohydrology for the last 5100 years

Testate amoeba stratigraphy

We defined four zones to highlight long-term temporal patterns in the testate amoeba data (Fig. 5). Samples from Zone A-1 (5050 to 3900 cal B.P.) are generally characterized by taxa characteristic of moderately wet *Sphagnum*, including *Amphitrema flavum*, *Heleopera sphagni*, *Hyalosphenia papilio*, and *Habrotricha angusticollis*. However, testate amoeba taxa characteristic of both xerophytic (e.g., *Hyalosphenia subflava*, *Bulinularia indica*, *Trigonopyxis arcuata*) and very wet habitats (e.g., *Amphitrema wrightianum*) are also sporadically abundant (Fig. 5). The brief, high-magnitude dry event centered on 4050 cal B.P. (Fig. 5) is inferred from abundant *H. subflava* and *B. indica*, both reliable indicators of dry conditions (Booth, 2001, 2002). Zone A-2 (3900 to 2690 cal B.P.) is dominated by taxa that are most abundant in very wet habitats (i.e., standing water for at least a portion of the growing season) including *A. wrightianum*, *Centropyxis aculeata* type, *H. angusticollis*,

and *Diffflugia globulosa*. Very wet conditions are indicated also by abundant cladoceran exoskeletons in this zone (Fig. 5). Zone A-3 (2650 to 660 cal B.P.) is generally similar to Zone A-1, containing variable percentages of both xerophytic and hydrophytic taxa. Zone A-4 (660 to -50 cal B.P.) also shows relatively high temporal variability in xerophytic and hydrophytic taxa, although increased abundance of *D. globulosa* and *H. angusticollis* suggest conditions were wetter than Zone A-3, at least in the bottom half of Zone A-4.

Reconstruction of paleohydrology by testate amoebae and plant macrofossils

Temporal variability in the testate amoeba-inferred water-table depth profile (Fig. 5) is expected given the moisture-sensitivity and rapid response time of testate amoebae. However, the moisture sensitivity of testate amoebae probably varies under different long-term hydrologic regimes, and testate amoebae are probably relatively

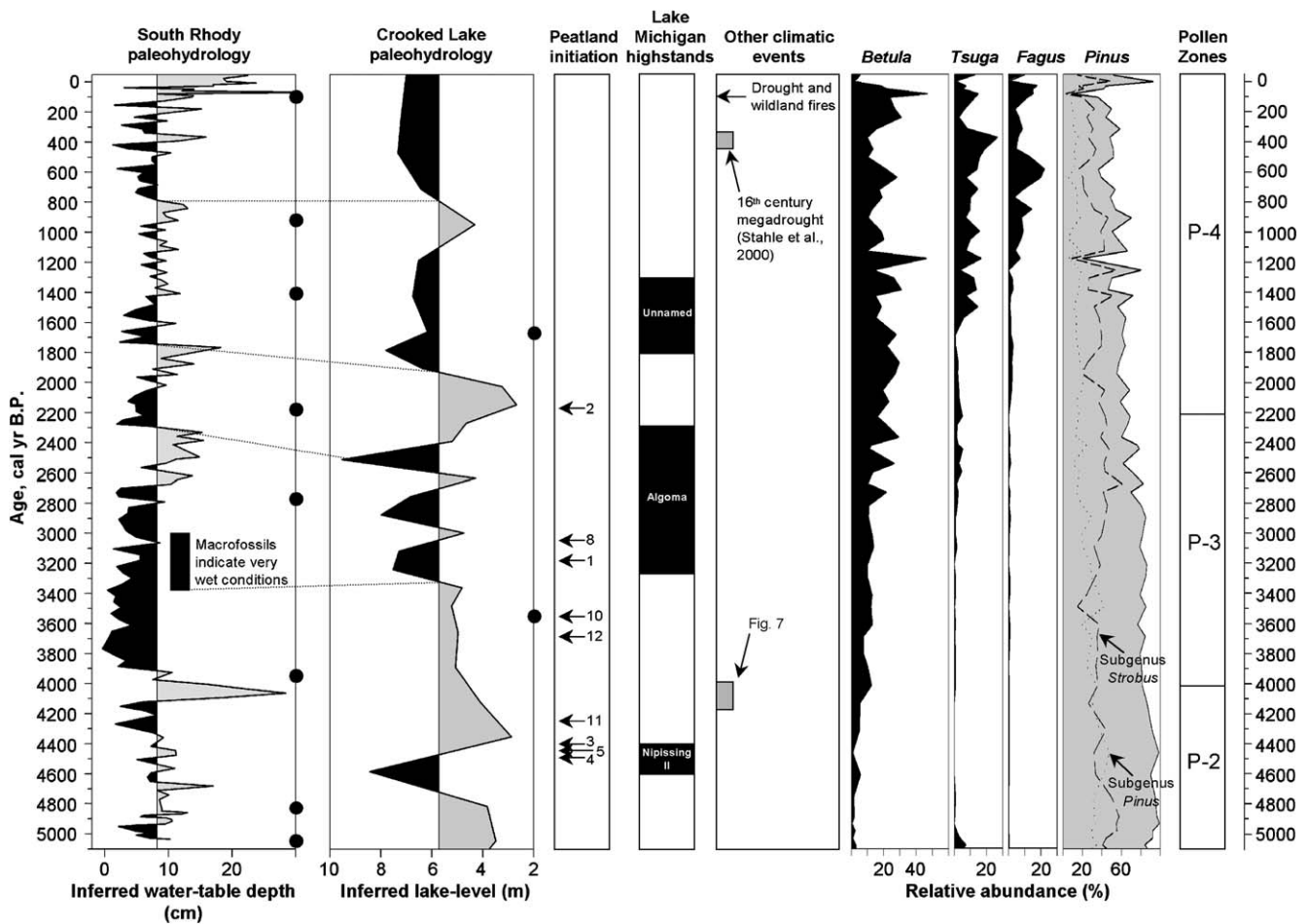


Fig. 6. Comparison of the South Rhody testate-amoeba-inferred paleohydrology to other regional records of paleohydrology (Crooked Lake (Brugam et al., 1998), the timing of peatland initiation (numbers refer to sites on Fig. 1); Lake Michigan highstands (Baedke and Thompson, 2000), and the profiles of selected upland pollen taxa at South Rhody. Gray and black areas of the South Rhody and Crooked Lake curves respectively indicate periods drier and wetter than the average for the last 5100 years. Circles indicate the position of radiocarbon dates in the Crooked Lake and South Rhody records.

insensitive to water-level variability at sites with an excess of moisture (i.e., sites with standing water for much of the year). For example, in very wet habitats without *Sphagnum*, factors other than substrate moisture (e.g., pH) are more important in controlling assemblage composition (Booth, 2001). Macrofossil evidence (i.e., abundant *Nuphar*) indicates standing water at South Rhody between 3400 and 3000 cal yr B.P., so the testate amoeba-inferred record during this time period may be relatively insensitive. Although testate amoeba assemblages indicate that conditions became very wet after 3900 cal yr B.P., they did not change substantially when *Nuphar* became abundant at the site. Interpretation of the testate amoeba-based moisture reconstruction along with the plant macrofossil record suggests major increases in surface moisture centered on both 3900 cal yr B.P. and 3200 cal yr B.P. (Fig. 6).

Climatic interpretation of high-resolution paleohydrology: low-frequency changes

Diatom-inferred water-level reconstructions at Crooked Lake in the Sylvania Wilderness Area (Fig. 1) suggest that the climate of Upper Michigan became progressively wetter after the mid-Holocene dry period, and lake-levels reached near-modern levels by about 3200 cal yr B.P. (Brugam et al., 1998). This pattern of increasing mid to late Holocene moisture is also generally supported by pollen-based climate reconstructions (Davis et al., 2000). Although the Crooked Lake chronology is not well constrained by radiocarbon dates at submillennial timescales (Fig. 6), the patterns of moisture fluctuations at Crooked Lake compare favorably with those at South Rhody peatland (Fig. 6). For example, both records indicate the onset of very wet conditions between 3200 and 3400 cal yr B.P., and alternating wet and dry multicentury intervals correspond between the two records for the past 2400 years. The correspondence between the two records is not as strong before 3400 cal yr B.P., perhaps attributable to inaccurate age models, differential sensitivities of the sites or proxies, the different temporal resolution of the records, nonclimatic influences on hydrology, or actual climatic differences between the sites. However, wet conditions prior to 3400 cal yr B.P. at South Rhody are supported by the timing of peatland initiation from sites in the region (Fig. 6). Although the timing of peatland initiation is partially controlled by local hydrologic conditions, and only a limited number of peatland initiation dates are available from the region, other periods of high moisture at South Rhody and Crooked Lake also are associated with the initiation of peatland development (Fig. 6).

Records of upland vegetation change provide additional evidence for the dominant role of climate in causing the changes in the paleohydrological record (Fig. 6). Rising *Betula* pollen is simultaneous with the large increase in moisture starting after 4000 cal yr B.P., and *Tsuga* pollen

occurs consistently after this time. The South Rhody basin flooded between 3400 and 3000 cal yr B.P., and although the terrestrial vegetation changes around South Rhody appear to have been relatively subtle (*Tsuga* pollen increases and *Pinus strobus* becomes more prevalent than *Pinus* Subgenus *Pinus*), more significant *Tsuga* population expansions are documented 3200 cal yr B.P. at more mesic sites in the region (e.g., Brugam et al., 1997, 1998; Davis et al., 1986). Another wet period was initiated 1850 cal yr B.P., and populations of *Tsuga* in the region around South Rhody expanded considerably during this wet period (Fig. 6). *Fagus* pollen consistently occurred after the wet period 2100 cal yr B.P., and populations expanded around 1200 cal yr B.P. Expansion of *Fagus* at 1200 cal yr B.P. may have been facilitated by disturbance, because it is preceded by a sharp spike in *Betula* pollen and a corresponding decrease in *Pinus* pollen (Fig. 6).

Lake Michigan water-level history can also be compared to the record from South Rhody to further assess the role of climate in controlling the paleohydrology of the peatland. Lake Michigan water-level history during the past 5000 years was characterized by several prolonged high-water events (i.e., highstands) (Baedke and Thompson, 2000). At least the most recent two highstands are attributable to climate variability (Booth and Jackson, 2003), and some evidence exists for climate's role in the Nipissing II highstand (4400–4600 cal yr B.P.) (Jackson and Booth, 2002). Lake Michigan water-levels respond to changes in the net

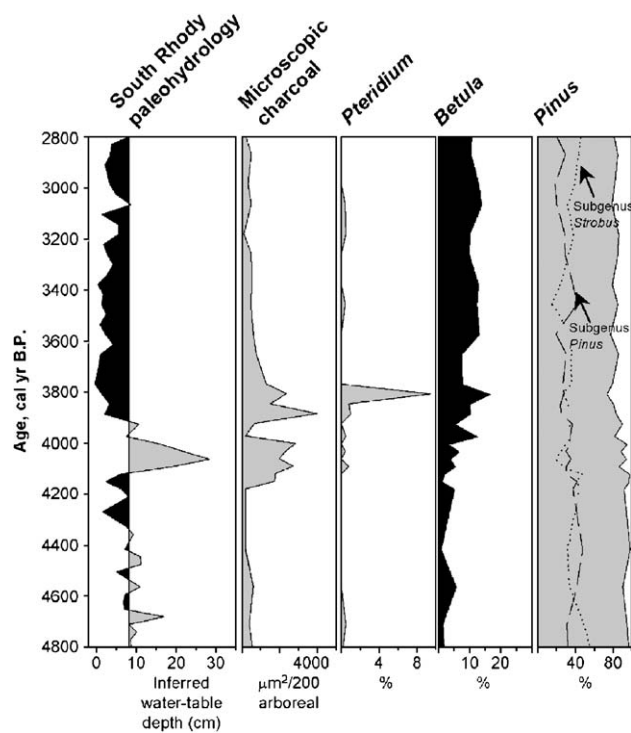


Fig. 7. Upland response to the dry period centered on 4050 cal yr B.P. from South Rhody sediments. The testate amoeba inferred paleohydrology is plotted next to microscopic charcoal and selected pollen/spore taxa.

water-budget of the entire western Great Lakes basin (Fig. 1), and thus represent a regionally integrated climate record. Even though the records from South Rhody and Crooked Lake are more localized, both document wetter conditions during the Algoma highstand (~3300 to 2300 cal yr B.P.) and a subsequent unnamed highstand (~1800 to 1300 cal yr B.P.) (Fig. 6). Although there is a greater amount of temporal uncertainty, the two sites may also document increased moisture during the Nipissing II highstand.

Climatic interpretation of high-resolution paleohydrology: high-frequency changes

One of these most conspicuous events in the South Rhody record is the brief (~100–200 year long), high-magnitude dry period centering on 4050 cal yr B.P. We examined this period more closely using high-resolution pollen and microscopic charcoal analysis. The dry period at South Rhody coincided with increased wildland fires (Fig. 7). The drought and/or fires may have resulted in extensive adult tree mortality. A brief expansion of *Pteridium* ferns occurred about 200 years after the onset of extremely dry conditions, indicating a more open forest or extensive disturbance patches at this time. The forest composition was considerably changed during the drought and subsequent wet period, with *Betula* expanding at the expense of *Pinus* (Fig. 7).

At least two other brief dry intervals recorded at South Rhody (centered on 360 and 80 cal yr B.P.) are temporally correlated with known climatic events (Fig. 6). The dry event centered on 360 cal yr B.P. at South Rhody corresponds to the 16th century megadrought (Stahle et al., 2000). Tree-ring records indicate that this event was the most severe and widespread drought in North America during the last 500 years (Stahle et al., 2000). However, the magnitude of this drought event in the Great Lakes region is somewhat unclear because of the small number of long tree-ring chronologies from the region (Stahle et al., 2000; Stahle, D.W., personal communication, 2002). The brief high-magnitude dry period centered on 80 cal yr B.P. in the South Rhody record, may be a response to climatic drought in the late 19th century. Extensive wildland fires occurred in the region during this time period (Sodders, 1997), and instrumental records also indicate unusually dry conditions in the 1870s and 1890s (Cook et al., 1999).

We have demonstrated that several short periods of peatland dryness (i.e., 4050, 360, 80 cal yr B.P.) appear to have been forced by climate; however, a comparison to another continuous high-resolution record is necessary to adequately assess the role of climate in high-frequency paleohydrological fluctuations. We compared the hydrologic history of South Rhody to another high-resolution, testate-amoeba-inferred record from a peatland located near Au Train Bay (Fig. 1). The Au Train peatland is located within a series of alternating sand ridges and inter-ridge wetlands that were created as a result of water-level

fluctuations of Lake Superior over the last several thousand years. The same transfer function was applied to the data (Booth, 2002), and details on the testate amoeba assemblages and chronology can be found in Booth (2003). A 550-year-long comparison of the South Rhody and Au Train records indicates a good correspondence for the last 200 years (Fig. 8a), the portion of the record that is best constrained (because the *Ambrosia*-pollen rise was identified to nearest centimeter). Modest errors in age models could be responsible for the poor correspondence before that time. To assess whether the errors in the age-models may have caused the poor correspondence between the two sites before 200 years ago, we modified the age-models using the assumption that both sites recorded the 16th century megadrought (Stahle et al., 2000). Because this drought event appears to have been most severe in the second half of the 16th century in the Great Lakes region, we assigned an age of 380 cal yr B.P. to the prominent dry event that occurs in both records between 300 and 400 cal yr B.P. and applied the age model using this benchmark. After modifying the age models, the two records show a much closer correspondence for the last 550 years (Fig. 8b), suggesting climate caused the hydrologic changes in both records.

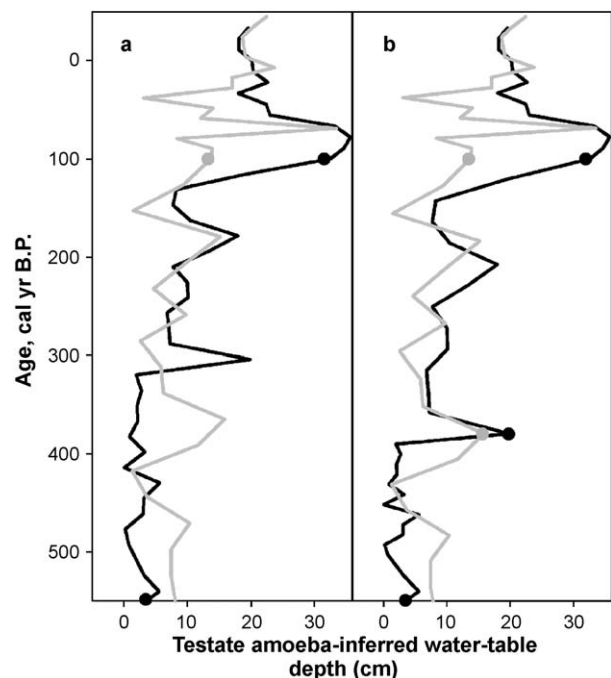


Fig. 8. Comparison of the testate-amoeba-inferred paleohydrologies of South Rhody (gray line) and Au Train Bay (swale 30) (black line) with (a) age-models using radiocarbon dates and the position of the *Ambrosia* pollen rise and (b) modified age-models using the assumption that both peatlands responded to the megadrought of the 16th century. Circles indicate locations of chronological benchmarks (radiocarbon dates, *Ambrosia*-rise). For the modified age-models (b), the lowest water-table depth between 300 and 400 cal yr B.P. was assigned an age of 380 cal yr B.P.

Conclusions

Climate was a dominant control on peatland hydrology and development at timescales ranging from multidecadal to millennial. At millennial timescales, the timing of major developmental changes in the peatland corresponds to times of upland vegetation change, supporting the primary role of climate in driving peatland vegetation changes (Campbell et al., 1997; Futyma and Miller, 1986; Miller and Futyma, 1987; Winkler, 1988). At higher frequencies (multidecadal and centennial), moisture variability at South Rhody corresponds well with independent records of paleoclimate and upland vegetation change (Figs. 6, 7, and 8).

Although high-resolution paleohydrological records from ombrotrophic peatlands should conceivably be more climate-sensitive than non-ombrotrophic peatlands, our study indicates that high-frequency paleohydrological variability in *Sphagnum*-dominated, closed-basin peatlands is driven primarily by climate. *Sphagnum*-dominated peatlands are geographically widespread in cool-temperate and boreal regions of North America and represent an important potential source of sensitive, high-resolution records of past climate variability.

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