1988

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Citation/Publisher Attribution:
Wilcox, D.A. and H.A. Simonin. 1988. The stratigraphy and development of a floating peatland, Pinhook Bog, Indiana. Wetlands 8:75-91.

THE STRATIGRAPHY AND DEVELOPMENT OF A FLOATING PEATLAND, PINHOOK BOG, INDIANA

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Abstract. Pinhook Bog is an acidic, weakly-minerotrophic peatland that occupies an ice-block depression in the Valparaiso Moraine in northwest Indiana. It has a floating mat approximately 22 ha in area but no central pond. Detailed stratigraphic descriptions of the peatland were made to analyze its developmental history and determine what factors may be responsible for mat formation. Stratigraphic data along four transects identified a clay-lined basin with three major sub-basins 18, 14, and 14 m deep. The deeper parts of the sub-basins contain fibrous limnic peats with some intermixed lacustrine sediments deposited between 12000 and 4200 years ago. The younger, upper peat layers are composed primarily of *Sphagnum* and consist of the fibrous surface peat and two underlying layers of fluid, fibrous peat separated by a water layer about one meter thick. Peat materials from above the water layer have fallen through the water to form the lower layer of detritus peat.

In addition to the obvious factors of climate and presence of mat-forming species, the development of extensive floating peatland mats is considered to be largely a function of deep, steep-sided basins that allow horizontal mat growth to exceed vertical peat accumulation. Other important contributing factors are clay-lined basins and the lack of inlets or outlets. These factors may result in water-level changes in the basin and weakly-minerotrophic waters conducive to *Sphagnum* growth.

Keywords: peatland, stratigraphy, bog development, *schwingmoor*, floating bog mat

INTRODUCTION

Processes causing formation of peatlands sometimes lead to the development of extensive floating mats, although the necessary conditions have not been thoroughly investigated. Detailed stratigraphic descriptions of one peatland with an extensive floating mat suggest some of the factors responsible for mat development there and elsewhere.

Most peatland basins that have been studied stratigraphically contain solid deposits of peat (e.g., Rigg and Richardson 1934, 1938, Rigg 1940a, Tolonen 1966,

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Mörnsjö 1968, Moore 1977, Overpeck 1985). A floating mat or *schwingmoor* structure (Moore and Bellamy 1974, Gore 1983) is a generally well-accepted phenomenon, but it is usually found only near the edge of an open-water pond, where it represents the final stage of peat-filling. Extensive floating mats have been cited, but detailed stratigraphic and developmental studies of them have been few in number, and some may represent specialized cases (Swan and Gill 1970, Green and Pearson 1977). Most references to floating mats are casual observations with little reported stratigraphic data (Conway 1949, Osvald 1970, Vitt and Slack 1975, Schwintzer 1978a, Sjörs 1983).

Previous work in Pinhook Bog, Indiana (Wilcox 1982) identified the presence of a peat mat floating over a layer of trapped water that seemed to extend over a large area of the peatland. This finding corroborated the observation of Guennel (1950) that a fluid layer was present in the 18 m peat core from Pinhook Bog that he used for pollen analyses. We undertook the current study to investigate further the nature of the floating mat and to gain greater knowledge of peat stratigraphy throughout the basin, thereby providing a better understanding of the sequential development of the peatland.

In this paper, we present stratigraphic data from Pinhook Bog, formulate the developmental history of the peatland and its floating mat, and compare this information with that published for other floating peatlands. Despite the existence of numerous lengthy publications on bog development (e.g., Gorham 1957, Heinselman 1970, Clymo 1984), we rely heavily on Kratz (1981) and Kratz and DeWitt (1986) for interpretation of our data because their concepts, developed in Wisconsin, seem to apply most closely to our data.

STUDY AREA

Pinhook Bog, in northwest Indiana about 12 km southwest of Lake Michigan, occupies an ice-block depression in the Valparaiso moraine that was deposited by the retreating Wisconsin ice sheet (Figure 1). The entire wetland is 44 ha in area (Wilcox 1986a), but the main body of the peatland studied here has an area of 36 ha. It is surrounded by a shallow, narrow moat and has no remaining central open-water area. The bog has no surficial inlets or outlets and is effectively isolated from regional ground-water flow by the sandy-clay glacial till of the moraine that bounds its entire basin (Wilcox 1982). The bog is characterized by acidic, weakly-minerotrophic waters: mean pH, 3.68; mean specific conductance, 64 μS; mean Ca, 2.7 mg l^{-1}; mean Mg, 1.6 mg l^{-1} (Wilcox 1986a). The characteristic vegetation of the bog surface includes *Sphagnum* mosses, *Drosera intermedia, Sarracenia purpurea, Vaccinium oxycoccos, Chamaedaphne calyculata angustifolia, Vaccinium corymbosum,* and *Larix laricina* (Wilcox 1986b). The bog and most of its 215 ha watershed were included within the boundaries of Indiana Dunes National Lakeshore by the U.S. Congress as part of the 1966 and 1976 authorization bills. The bog was also designated as a National Natural Landmark in 1966.

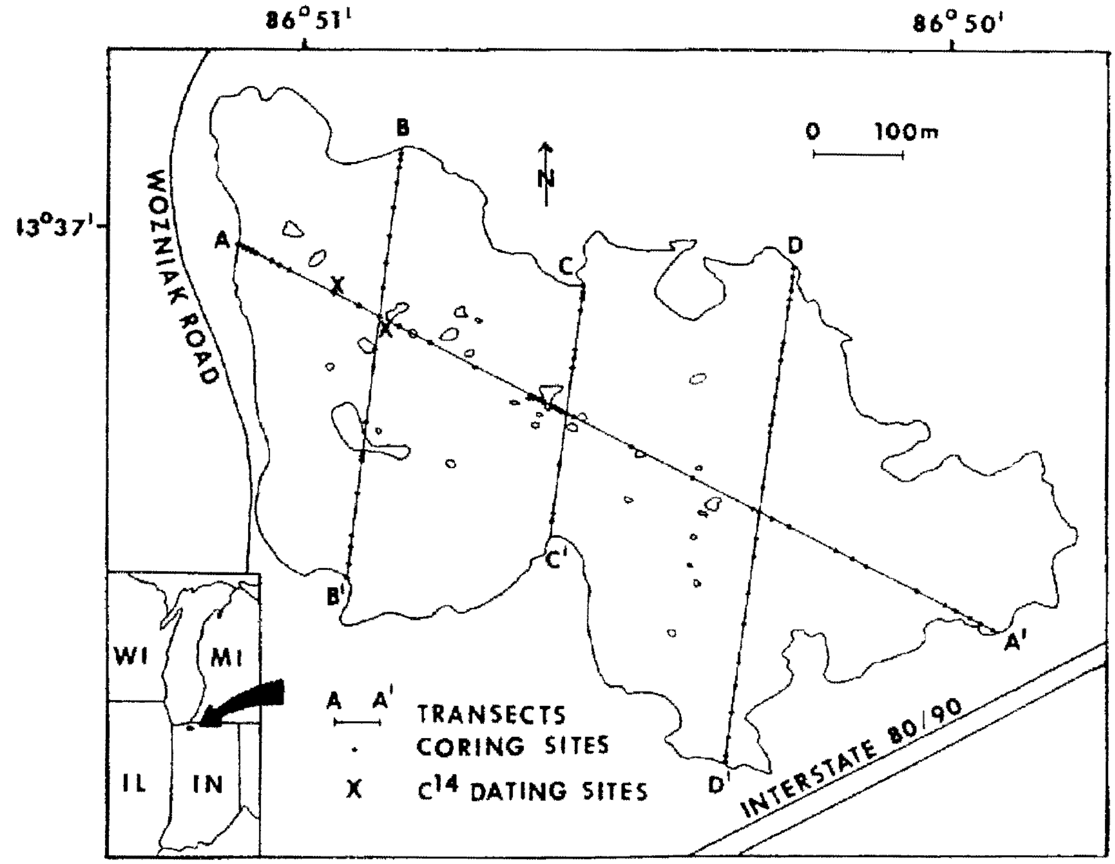

Figure 1. Map of Pinhook Bog showing coring transects, coring sites, radiocarbon dating sites, and surface ponds.

METHODS

The stratigraphy of Pinhook Bog was determined by extensive coring of the peatland and identification of gross peat types. The initial coring effort resulted in 39 cores taken along a 955-m transect (A-A') that followed the long axis of the bog (Figure 1). The distance between core sites ranged from 5 to 80 m, depending on the basin slope. Coring was conducted with a combination of soil augers and a modified Livingstone piston corer (Brown 1956) at depth intervals that ranged from 0.25 to 1.0 m, depending on the stratigraphic changes encountered. In addition, a mat-depth sampler was devised (Figure 2) that could be inserted into the core hole, opened into an inverted T, and lifted until resistance was met. This device provided improved accuracy in determining the thickness of the peat mat. Coring in a similar manner was also conducted along 3 additional transects (B-B': 19 cores, 485 m; C-C': 11 cores, 285 m; D-D': 23 cores, 565 m) that crossed the 3 major sub-basins of the bog identified along transect A-A' (Figure 1). The surface topography along each transect was determined at 20 m intervals and at each core site with a transit, avoiding measurements from hummocks. The relative depths of horizon interfaces were then adjusted to compensate for variations in surface topography, and all measurements were corrected to an arbitrary benchmark set at the water level in the moat.

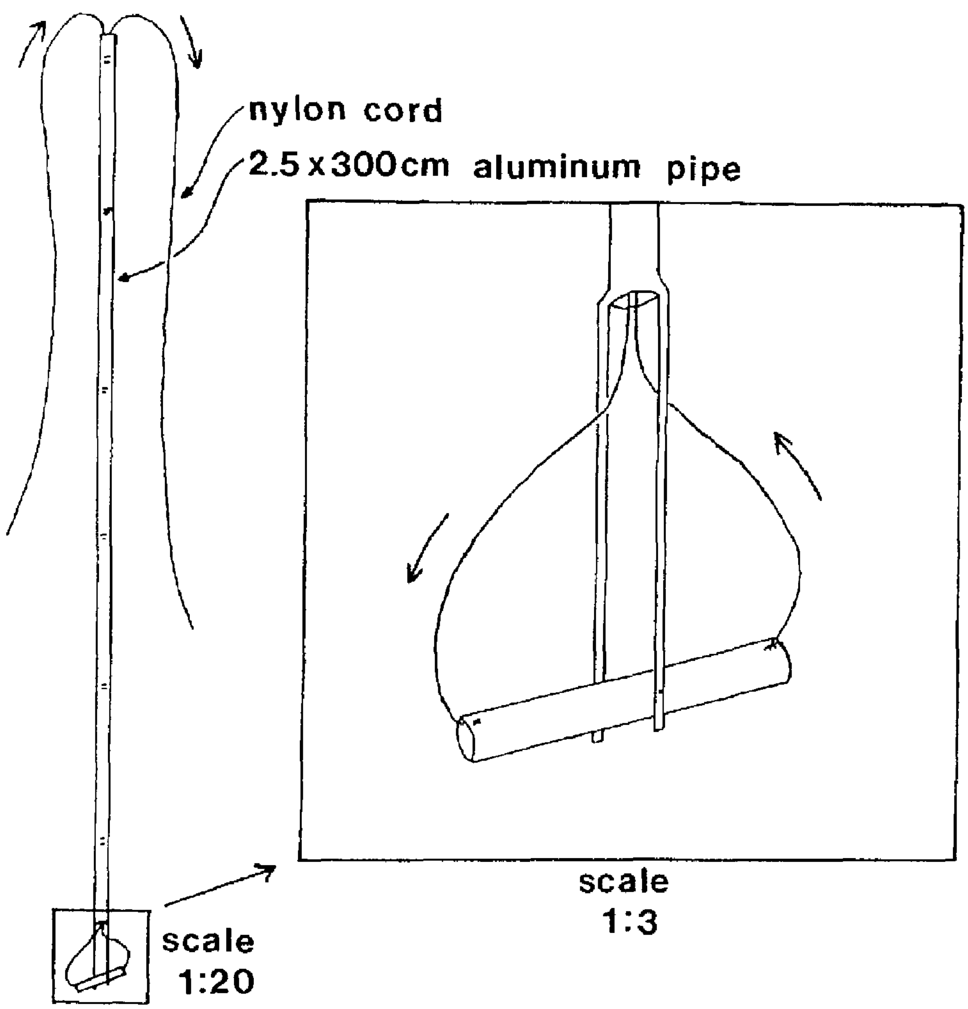

Figure 2. Bog mat depth sampler, which is inserted into core hole, opened into an inverted T, and lifted until resistance is met.

Cross-sections of each transect were drawn by plotting the depth of each horizon interface against transect distance. Contour maps of each horizon interface were then derived by transferring this information to base maps drawn from direct aerial photographs and connecting equal depth points. Three-dimensional contour maps of the bog stratigraphy were made with the SurfaceII contouring program.

Six samples of peat from the lower portions of the basin near the intersection of transects A-A' and B-B' were radiocarbon-dated. The fibrous nature of the poorly-decomposed surface peats at the site made it difficult to obtain good cores from which samples of the upper peats could be dated reliably. Therefore, a site 60 m nearer the edge of the bog on transect A-A' was used for dating the upper peat materials (3 samples). The 6 samples at the first site were collected with a modified Livingstone corer; the 3 samples at the second site were collected with a Jowsey corer (Jowsey 1966).

RESULTS

Bog basin

Coring along the four transects identified three major sub-basins in Pinhook Bog (Figure 3). The central sub-basin is approximately 18 m deep. The east and west sub-basins have maximum depths of approximately 14 m, and each has a second lobe about 13 m deep. The slope of the bog basin at its perimeter is about 4 to 6 percent except on the north side of each sub-basin, where it ranges from 16 to 48 percent. The slope in the deeper parts of the sub-basins ranges from 8 to 18 percent. A slightly-sandy clay glacial till was found at the bottom of nearly all of the 92 core holes, indicating that the ice block responsible for creating the bog was nestled in glacial till. The remaining core holes, in deeper portions of each sub-basin, contained a reworked lacustrine clay as the bottom material.

Peat deposits

A compact limnic peat fills nearly all of the lower lobes of the 3 sub-basins and their sloping edges (Figure 4). This layer is composed of a moderately fibrous, brown peat primarily of sedge and aquatic macrophyte origin. The deepest parts of the bog also contain some lake sediments mixed with the limnic peat. The limnic peat layer began to accumulate over 12,000 years ago, as indicated by the radiocarbon date of the deepest peat sample tested. It became less-influenced by lake sediments about 8300 years before present (B.P.) and continued deposition until about 4200 years B.P.

Upward in the profile, the next peat layer is a fibrous detritus peat, primarily of *Sphagnum* origin, that is poorly-compacted and thus quite fluid. There are actually two layers of this fluid, fibrous peat separated by a narrow zone of trapped water. The upper layer ranges in thickness from about 1 to 3 m. Debris from its underside has sedimented through the water zone to form the lower layer, which ranges from about 1 to 5 m in thickness. The two layers are connected at the bog perimeter. The trapped water layer is as thick as 2.5 m at places along transect D-D' and as thin as 0.3 m at one location on transect B-B', with an average thickness of about 1 m. The water layer (22 ha area) was found across nearly the entire expanse of the bog on all transects, with the exception of the perimeter area (usually less than 50 m from the bog edge). It was generally 2 to 5 m below the surface of the bog. Samples of this horizon taken with the transparent plexiglass Livingstone corer confirmed its composition as being a stained, yet transparent, layer of water containing very small suspended particles of peat.

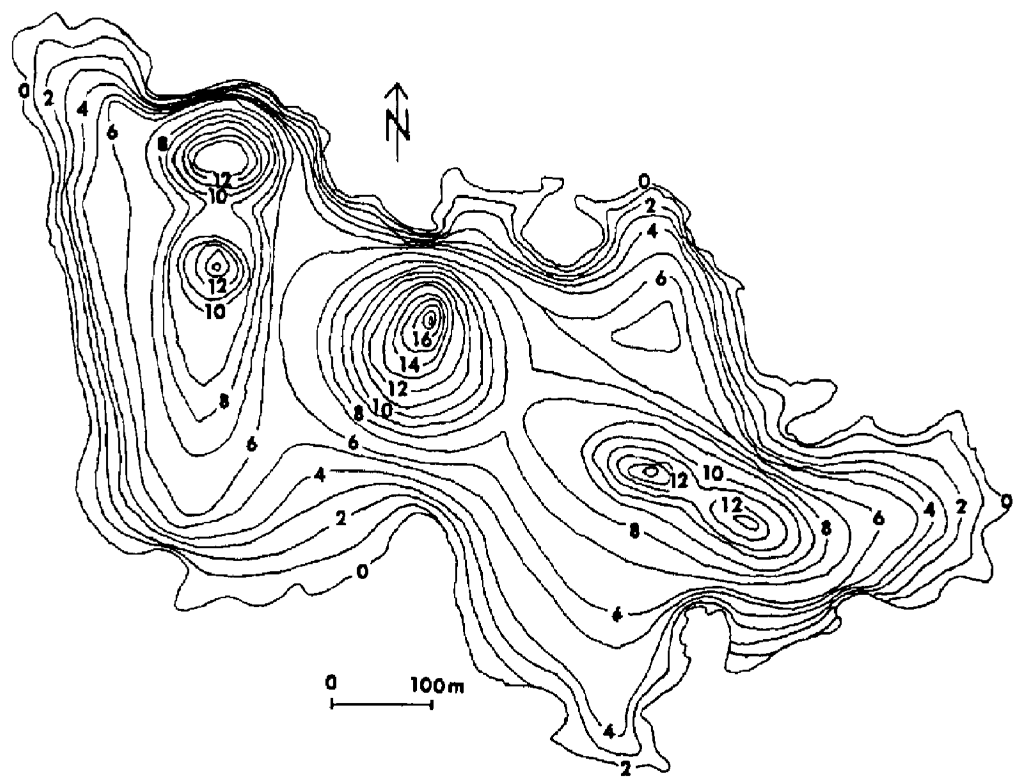

Figure 3. Topographic map of Pinhook Bog basin, the surface of the glacial till (clay). Contour interval is 1 m. The clay does not come to the surface at some locations along the southern boundary of the bog.

The uppermost peat layer is composed of very fibrous, dark brown *Sphagnum* peat with abundant shrub rootlets. The layer is generally about 2 m thick but is thinner at some locations, especially near the edges of the 30 small ponds that are dispersed across the surface of the bog (see Figure 1). Its surface is also depressed at the perimeter of the bog, where a moat 10 to 50 m wide is present. The bog surface gives the appearance of being raised by as much as 1 m at several points in Figure 4, but some of the relief is probably due to localized topographic differences that are not representative of the entire bog surface. The upper fibrous peat layer was formed during the past 2000 years. There is probably a lot of variation in the age of the bottom of this layer and of the fluid, fibrous peat layers because the upper layers are the source of *Sphagnum* materials for the lower layers. Detritus peat at the center of the bog may be of more recent origin, but at greater depth, than floating peat closer to shore. This apparent discrepancy (see Figure 4) may be due to radial mat growth that forms peat near the shoreline before a mat exists at the center of the bog.

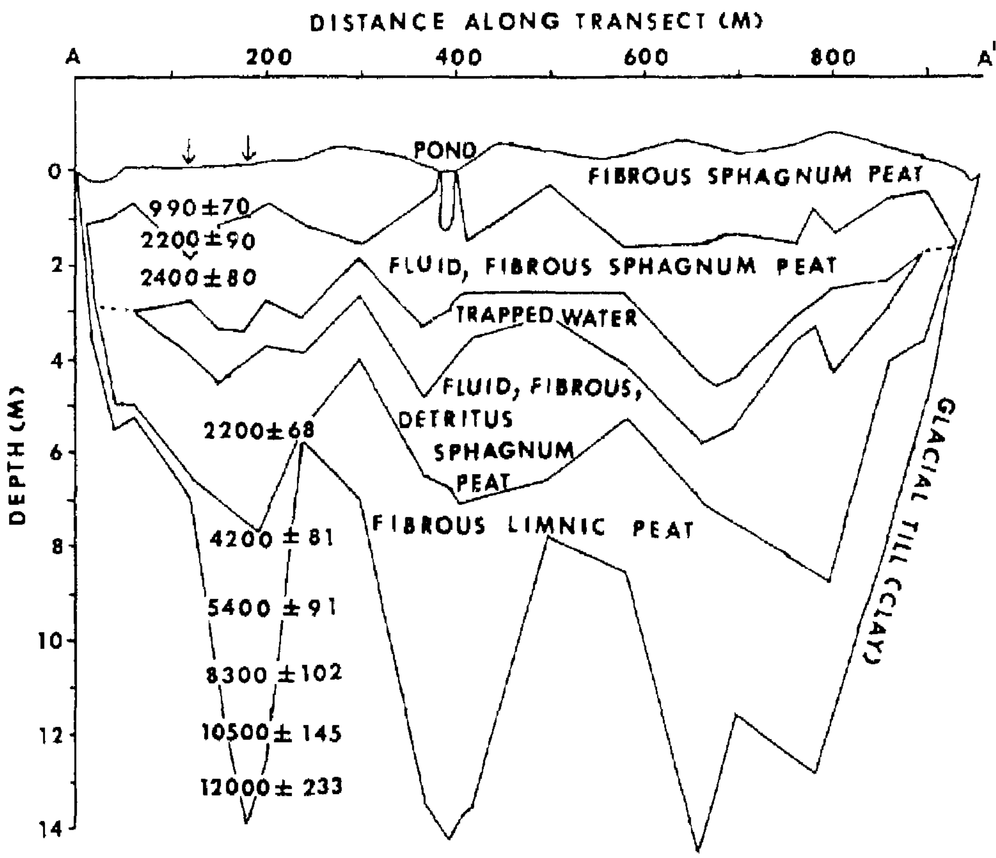

Figure 4. Stratigraphic cross-section of Pinhook Bog along transect A-A' (see Figure 1) with radiocarbon dates at sites 120 m and 180 m. The vertical exaggeration is X 50.

Three-dimensional maps

Three-dimensional mapping gives a better appreciation for bog morphometry than a plane view. There is also less distortion caused by vertical exaggeration. When the horizon interfaces are mapped in three dimensions, the clay-lined bottom of the bog appears as a multi-lobed structure similar in shape to the bottom of the ice block left by the retreating Wisconsin glacier (Figure 5). Three major sub-basins are discernible, with the east and west basins having two lobes each. Three distinct sub-basins are still recognizable for the interface between the limnic peat and the layer of detritus peat, but since the limnic peat almost completely fills the deeper lobes of the bog, the sub-basins do not appear in the upper horizons shown in Figure 5. The fibrous peat surface shown for the bog does not truly represent all the surface topography because it does not depict the complex hummock/hollow relationships common throughout the bog. However, a general increase in altitude from water level at the moat to +0.2 m above water level approximately 75 m in from the bog edge does occur. With the exception of a few locally-higher areas, the +0.2 m altitude is the mean level of the ground surface throughout much of the bog.

DISCUSSION

Bog developmental history

The Wisconsin ice sheet retreated from northwest Indiana about 14-15,000 years ago (Johnson 1976) and deposited an end moraine that stretches around the entire southern end of present-day Lake Michigan at a distance of about 10-30 km from the lake. Numerous large blocks of ice remained in the moraine and gave rise to several groups of kettle-hole lakes. The basin of one of these lakes (Pinhook Bog) was isolated from regional ground-water flow by sandy-clay glacial till that bounded the entire underside of the original ice block. This lake developed into a bog because the precipitation and local runoff waters supplying it were poorly buffered (Wilcox 1986a). The other lakes were fed by very calcereous regional ground waters (Wilcox *et al.* 1986, Wilcox and Simonin 1987), did not provide habitat suitable for the growth of *Sphagnum* and hence for bog development, and therefore remained open-water lakes.

During the early Holocene boreal forest period that marked its early years (Guennel 1950, Bailey 1972, Futyma 1985), the Pinhook Bog basin was an open lake colonized by various aquatic plants, with some sedges growing at the perimeter. The remains of these plants were transported from the steep slopes of the basin to the lower parts of the deep lobes of the bog by sediment focusing, thus forming the fibrous, limnic peat layer. The climate became warmer about 8300 years B.P. (Futyma 1985), corresponding to the mid-Holocene of central North America (Wright 1983). Also at that time, Lake Michigan entered the Chippewa low stage

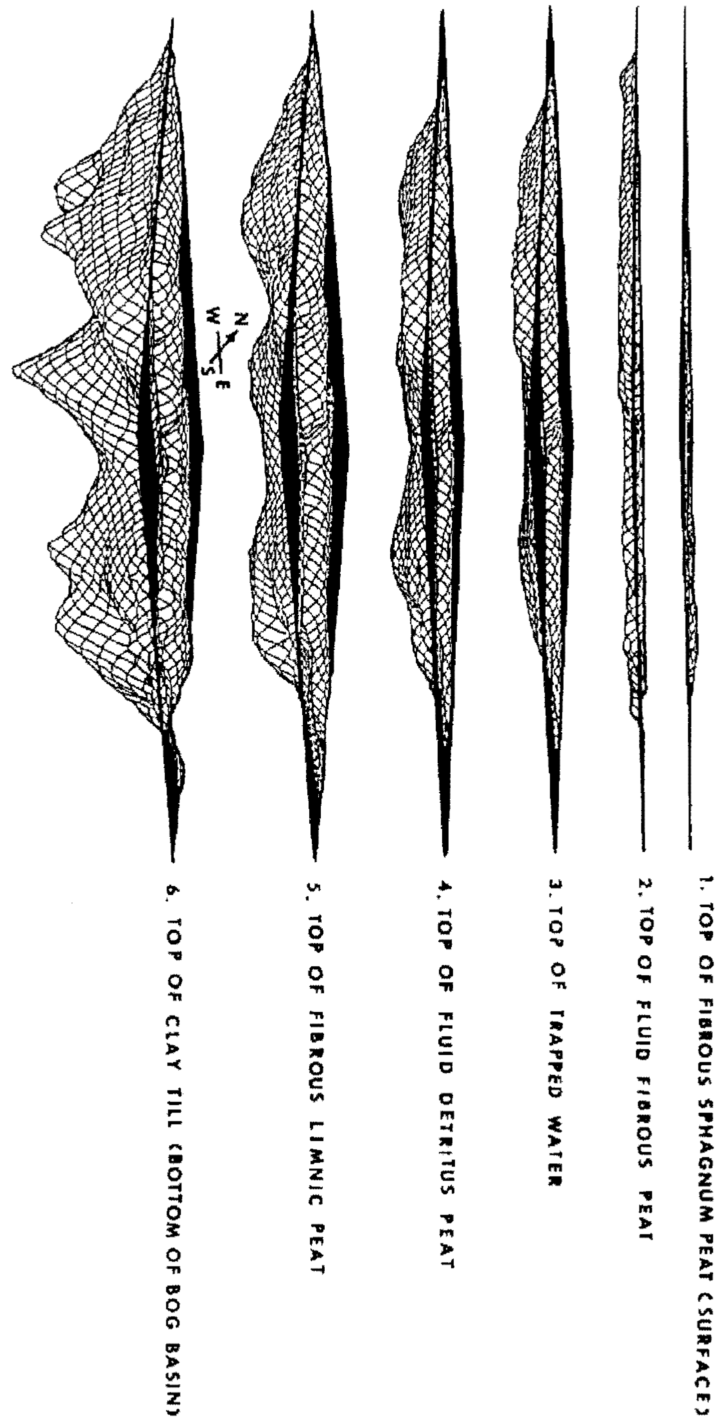

Figure 5. Computer-generated, three-dimensional contour maps of Pinhook Bog stratigraphy. Each mapped surface represents the upper surface of the peat layer indicated at the right (shown as boundary lines in Figure 4). The vertical exaggeration is X 13.

(116 m above sea level) (Hansel *et al.* 1985), and the increased distance of Lake Michigan from the Pinhook basin may have coupled with the dominance of zonal airflow from west to east at this time (Wells 1983) to reduce lake-effect precipitation and lower the water levels in the bog basin. Emergent sedges then increased in the more gently sloping shallows at the lake edge, and a floating *Carex lasiocarpa* mat may have formed around the perimeter of the lake (Gates 1942, Conway 1949, Vitt and Slack 1975, Schwintzer 1978a, Tallis 1983). Sedge remains from the lake edge and detritus peat from the bottom of the mat (Gates 1942, Kratz and DeWitt 1986) continued to accumulate in the deep lobes of the basin and were poorly humified because of the lack of oxygen in deep waters (Walker 1970).

Sphagnum mosses then became prominent on the mat about 4200 years B.P. during a cooler period that was also associated with the rise in Lake Michigan levels to the Nipissing I stage (184 m) (Hansel *et al.* 1985). A shift in dominant airflow to northwest-southeast accompanying the climatic change would also have produced increased lake-effect precipitation in the vicinity of Pinhook Bog, as has been reported in modern times (Harman and Elton 1971, Changnon 1980). Such cooler and locally-wetter conditions may have raised water levels in the bog basin, and they were also conducive to bog formation and growth of ericads such as *Chamaedaphne calyculata*. This common plant of Pinhook Bog (Wilcox 1986b) provides the framework for horizontal mat growth in many peatlands of North America (Swan and Gill 1970, Kratz and DeWitt 1986). It is therefore probable that, along with *Sphagnum*, it was involved in closure of the mat over the entire surface of Pinhook Bog, an event that took place when the waters overlying the limnic peat in the basin were still 7-8 m deep (see Figure 4). The outer edges of the mat were grounded by detritus peat (Kratz and DeWitt 1986), but the horizontal growth of the mat exceeded the production of enough detritus peat to fill the deep basin. The irregular shoreline of the bog would also allow the mat to close over the surface faster than if the lake were circular in outline (Kratz 1981). As a result, an extensive floating mat was formed that trapped a broad layer of water beneath it.

The buoyant mat continued to grow vertically, but since only part of its mass could remain above the water surface, the lower part of the mat was forced deeper into the trapped water zone (Kratz 1981). The fluid nature of this peat layer suspended over the water facilitated deposition of its lower materials through the water column and into repose over the limnic peat. Continuation of this process has built a 1-5 m layer of detritus peat and narrowed the zone of trapped water. In future centuries, the entire mat will likely become grounded, the peat will compact until its maximum average density is reached (Kratz and DeWitt 1986), and peat will no longer accumulate.

Formation of ponds and moat

The numerous ponds in Pinhook Bog do not represent remnants of the original central open water lake. Rather, they are areas where the peat mat was flooded

(Boatman and Armstrong 1968, Foster *et al.* 1983, Engstrom 1984). Three of the larger ponds or groups of ponds are centered over or near the deeper lobes of the bog basin. These surface features may be a reflection of variations in the underlying peat deposits, as suggested by Moore and Bellamy (1974). The tendency for ponds to form at these locations may be due to a younger, weaker peat mat that is more prone to depression from flooding. A dead trunk of *Larix laricina* stands in the center of one pond, indicating that the pond is a secondary feature, formed after the establishment of the peat mat. Strong evidence for secondary succession, in the form of zonation patterns, can be observed around these ponds. This evidence, coupled with personal observations of changes in pond size and depth over a period of 8 years, leads us to believe that the ponds are not permanent, but are periodically formed and filled in again.

Moats are commonly found around the perimeter of flat bogs in North America (Rigg 1940b). The waters of the moat that surrounds Pinhook Bog are more mineralized (mean pH, 5.45; mean specific conductance, 115 μS; mean Ca, 3.8 mg l^{-1}; mean Mg, 1.6 mg l^{-1}) than the interstitial waters of the bog mat (Wilcox 1982) because the moat is adjacent to uplands with overlying mineral soils. The moat is also subject to fluctuations in water levels because the peat is grounded and cannot float when flooding occurs. Both of these conditions would result in the establishment of vegetation that differed from that of the mat, and both have been suggested as causes for moat development (Moore and Bellamy 1974, Buell and Buell 1975). The floating nature of the bog mat that prevents flooding (except for the small ponds), is also the major reason that much of the bog is forested by *Larix laricina* (Buell and Buell 1941, Schwintzer 1978b, Kratz 1981).

Comparison with other floating peatlands

A review of peatland literature reveals many cases where small areas of floating bog mat are reported. Large areas of floating mat are less-commonly reported, especially those mats that have been verified as floating by stratigraphic analyses. The most prominent feature of an extensive floating peatland is a basin that is deep and steep-sided, thus allowing a mat to grow horizontally across the surface without becoming grounded by vertical accumulation of detritus peat. Two other prominent features are records of water-level changes and weakly-minerotrophic waters. These two features are, at least in part, due to such common factors as the lack of an inlet or outlet and isolation from ground-water flow by a clay-lined basin. They are also partly responsible for the common occurrence of sedge peats overlain by *Sphagnum* peats in these basins, the sedge peats forming during low-water periods and *Sphagnum* peats forming after a rise in water levels and under less-mineralized conditions.

In addition to Pinhook Bog, documented examples of floating bogs include (Table 1): Bryants Bog in northern Lower Michigan (Coburn *et al.* 1932, Gates 1942, Schwintzer and Williams 1974, Schwintzer 1978b), which occupies a steep-sided ice-block depression that may be as deep as 22 m; Tyee Bog on Vancouver Island, British Columbia (Rigg and Richardson 1934, 1938), which is 10.5 m deep and has a steep, clay-lined basin; Clear Lake Bog in west-central Oregon (Rigg and Richardson 1938), which is a steep-sided, lake-edge peatland 8.3 m deep; Flaxmere in North Cheshire, U.K. (Tallis 1973), which is in a clay-lined, ice-block depression that is not extremely deep (5.45 m) but is steep on one side; Llyn Mire in Radnorshire, U.K. (Moore and Beckett 1971), where a floating *Sphagnum* mat developed over part of the 9 m deep basin following flooding of a reedswamp; and Wybunbury Moss is Cheshire, U.K. (Green and Pearson 1977), which has a basin 17 m deep, portions of which are steep-sided, and a closed, floating mat over as much as 13 m of water. Subsidence caused by dissolution of an underground salt deposit is believed to have also contributed to development of the mat at Wybunbury Moss.

TABLE 1. Prominent characteristics of peatlands with extensive floating mats.

Peatland	Pinhook Bog	Bryant's Bog	Tyee Bog	Clear Lake Bog	Flax-mere	Wybunbury Moss	Llyn Mire
Basin depth (m)	18	22	10.5	8.3	5.45	17	9
Max. basin slope(%)	48	150	45	49	21	65	11
Basin material	clay	sand	clay	sand & clay	clay	sand	clay
Inlet/outlet	no/no	no/no	no/no	yes/yes	no/no	no/no	no/yes
Water-level change	yes	yes	?	?	yes	yes	yes
Water chemistry	weakly minero.	weakly minero.	weakly minero.	?	weakly minero.	weakly minero.	?

Other peatlands with some of these features are Chartley Moss in Staffordshire, U.K. (Moore and Bellamy 1974), which has a floating mat over more than 10 m of water at some places, and County Line Bog in Ohio (Rigg 1940a), with a 1-2 m thick mat overlying 13 m of water in a clay-lined basin. In contrast, still other peatlands have been reported that have floating mats but shallow basins. The clay-lined basin of Helmetta Bog in New Jersey (Rigg 1940a) is slightly over 2 m deep; however, it has a water layer more than 1 m thick that is overlain by a thin mat formed by sedges and *Chamaedaphne*. Harvard Pond in Massachusetts (Swan and Gill 1970) has a 400 m x 400 m floating mat at one end. Most of this small man-made lake is only 1 m deep, but a floating *Chamaedaphne* mat was able to form, supported at the surface by tree stumps.

Clearly, not all of the floating-mat peatlands described have the same set of characteristics responsible for their development, and all peatlands that have these characteristics do not form floating mats. However, as shown in the example of Pinhook Bog, basins that 1) are deep, steep-sided, clay-lined, 2) lack surface inlets or outlets, 3) have encountered water-level changes, 4) have weakly-minerotrophic waters and mat-forming plant species, and 5) are located where the climate is suitable for peat formation have a very strong chance of developing an extensive *schwingmoor* structure.

ACKNOWLEDGMENTS

We thank Jon Alden for assistance in peat coring, Richard Futyma and Robert Shedlock for help in collecting and arranging for radiocarbon dating of peat samples, Harvey Fleet for preparing the computer-generated, 3-dimensional stratigraphy figure, and Keith Edwards for preparing the other figures. We also thank Timothy Kratz, Paul Glaser, and Richard Futyma for their helpful reviews of the manuscript.

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