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THE POTENTIAL ROLE OF LAKE BASIN MORPHOMETRY IN THE FORMATION AND DEVELOPMENT OF PEATLANDS IN INDIANA

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ABSTRACT. Numerical support for generalizations about factors favoring peat formation in kettles is scant. Kettle morphometry was examined on the basis of fetch orientation, shoreline development, surface area, maximum depth, mean depth, and relative depth. The only significant feature separating peat-forming kettles from non-peat-forming kettles was surface area. Small basins seemed most likely to become peat-forming due to reduced wind and wave-induced erosion. Protected shores were more likely to develop a floating mat that favored the genesis and build-up of peat. The chemistry and ecology of the successive stands of vegetation that eventually colonized the peat was most affected by watershed area and hardpan permeability (which ultimately determined the degree of minerotrophy).

Keywords: Bog, fen, glacial geology, Indiana, kettle, lake, morphometry, peatland, wetland

Although most of the peatlands in the southern Great Lakes region are associated with glacial kettle depressions, an equal or greater number of such depressions never develop into peatlands. This indicates that some basin-specific factor or factors must determine whether or not a particular lake or pond will develop into a peatland rather than a more common marsh, swamp, or slough.

Many investigators have considered the effects of basin morphometry on the ontogeny and senescence of lakes. Taylor (1907) suggests that *small* glacial lakes and ponds were the most favorable geographic features for peat formation due to reduced wave action. Similarly, Gates (1942) states that bogs [in the sense of *Sphagnum*-dominated peatlands] may develop in any open-water depression (shallow or deep) or small embayment of a larger waterbody that is small enough to prevent significant wave action. Both Taylor and Gates view wave action as destructive to the marginal mat of vegetation and thus, a hinderance to the establishment of peat-forming plant communities. Although Crum (1988) also recognizes the negative impact of wave action in the stability of peat-forming marginal mats, he points out that wave action also positively influences the magnitude of seasonal overturn (and thus nutrient cycling) in a basin, which may reduce the likelihood of peat formation.

Crum characterizes "kettlehole" lakes that are commonly occupied by peat as having a small surface area, cold water, and an abrupt drop-off. Transeau (1905) and Davis (1907) also discuss the magnitude of drop-off. Both authors associate the slope of the basin walls with the coverage of littoral vegetation and the dynamics and source of vegetable detritus. However, they do not elaborate on whether steep slopes might favor peat formation as opposed to the formation of more common, humified sediments. While Ruttner (1953) remarks that the development of a floating mat, typical of "quaking bogs," is likely only over shallow benches and in protected bays, Wilcox & Simonin (1988) conclude that classic floating-mat peatlands are largely a function of deep, steep-sided basins that allow horizontal mat growth to exceed vertical peat accumulation.

Although general summaries outlining the proposed importance of basin morphometry on peatland formation have been presented, no known comparisons between the morphometry of these depressions and non-peat-forming depressions have ever been made.

The present study examines how certain morphometric qualities of some basins made them predisposed toward peatland development. Northern Indiana was the focus of the

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study because the regional climate and topography are unfavorable for the development of blanket mires, thus restricting peatlands to small, isolated depressions. Because the regional climate is not optimal for extensive peat formation over large areas of the landscape, these Indiana peatlands may facilitate the study of the specific qualities of lake basins that favor peatland formation. The objectives of the study were to examine and characterize the morphometric qualities of peat-filled depressions and compare them to non-peat-filled lake basins.

STUDY AREA

Northeast and north-central Indiana is characterized by hundreds of lakes that stretch from the Huron River Valley of Michigan (see Transeau 1905) through the northeast corner of Indiana to a point nearly 160 km southwest. These lake basins consist of kettle holes, irregularities in moraines, and channel lakes, created in the interlobate region of the former Saginaw and Erie Lobes of Wisconsin age (Scott 1916). The lakes occurring west of the interlobate area (north-central Indiana) are a result of the stagnation and deterioration of the Saginaw Lobe *circa* 15,000 ybp (years before present) (Wayne 1966).

While examples of several types of lake basins have been identified in Indiana by Scott (1916), most would be best classified as kettle lakes. Lakes resulting from the scouring of rock or the damming of pre-glacial valleys are absent in Indiana (Scott 1916). Other types of basins, such as those resulting from irregularities in ground moraine are most common in areas where pre-glacial relief strongly influenced glacial and post-glacial topography and drainage. This situation was probably not present in Indiana at the onset of Wisconsin glaciation, due to the presence of significant, pre-Wisconsin glacial deposits already in place over the bedrock topography. Hutchinson (1975) reports that in the glaciated parts of North America east of the Rocky Mountains, the number of kettle basins is likely far greater than that of all other types of basins considered together.

STUDY SITES

The 10 basins that were selected for detailed morphometric analysis occur mainly in northeast Indiana (Kosciusko, Lagrange, Noble, and Steuben Counties) with the exception of Shoemaker Bog in northwest Indiana (La Porte County). All have developed typical peatland plant communities. Burket, Dutch Street, Leatherleaf, Shoemaker, and Yost Bogs are *Sphagnum*-dominated leatherleaf (*Chamedaphne calyculata*) bogs. Little Chapman and Hickory bogs are *Sphagnum*-dominated, but lack a significant low shrub component. Binkley and Svoboda Fens are non-*Sphagnum*-dominated peatlands with bush-cinquefoil and sedges as dominant vascular plants. Tamarack Bog is a non-*Sphagnum*-dominated peatland with a dense tree canopy dominated by red maple (previously dominated by tamarack).

All of the sites, given their relative depth, are probably kettles. While the large area collectively called Chapman Lake (formerly Little Eagle Lake) may be the result of irregularities in the ground moraine, as proposed by Scott (1916), the associated sub-basin occupied by Little Chapman Bog, due to its depth and shape, is probably of ice-block origin.

Hutchinson (1975) recognizes five types of kettles based on how they were formed: 1) kettles or cavities left by melting of ice-blocks in outwash discharged into a pre-existing valley, 2) kettles in drift-filled valleys, the drainage having no relationship to the pre-existing hydrography, 3) kettles in pitted outwash plains, 4) kettles in till of continental ice sheets, and 5) kettles in eskers. Most of the sites conform to types 3 and 4. Hickory Bog is a classic example of type 5, resulting from linear strips of ice from the lower parts of the side walls of sub-glacial streams becoming embedded in the sides of an esker (Hutchinson 1975), and is probably the first record of this type of kettle in Indiana.

METHODS

Morphometry.—Depth of the basins was determined by systematic soundings with metal rods. Soundings were made at 25 m intervals (arranged in a grid) on small basins ($\leq$ 10 ha) and 50 m intervals on larger basins ($<$ 10 ha). The bottom of the basin was defined as the depth at which sand or gravel was reached; overlaying clays and silts were penetrated by the probe and were included in the total depth. Bathymetric maps were constructed by transferring the data to maps drawn from aerial photos and connecting equal depth points (see Swinehart 1997).

Definitions for and calculation of fetch (F) (or maximum effective length; the shoreline was defined as the point where the surface of organic wetland sediments interfaced with inorganic glacial drift), maximum breadth (b_m), shoreline length (L), shoreline development (D_L), surface area (A), maximum depth (Z_m), mean depth (Z), volume (V), and relative depth (Z_r) follow Hutchinson (1975). Values for F, b_m, L, and A were determined cartographically.

Stratigraphy.—A modified Hiller-type corer was used to retrieve sediment samples for stratigraphic analysis of six peatlands. A single core was taken from the deepest known point in each peatland. While sediment layers can be unevenly distributed throughout a basin (see Rigg & Richardson 1938), most basins have relatively horizontal layers of sediment (see Rigg & Richardson 1938; Scott & Miner 1936; Wilson 1938), especially kettles lacking distinct sub-basins which may have different sediment accumulation rates. In the present study, it was assumed that the stratigraphy of the various sediment layers was relatively uniform across the basin.

Sediment-type was determined by microscopic analysis. Three major stratigraphic units were identified. Lake sediments were usually highly decomposed (sapric) but contained subfossils of submergent and emergent aquatic macrophytes such as *Ceratophyllum demersum*, *Najas flexilis*, *Potamogeton* spp., *Nymphaea tuberosa*, *Nuphar advena*, and *Brasenia schreberi*. Fen sediments were less humified (hemic) and were dominated by brown moss subfossils, primarily *Drepanocladus aduncus*. *Sphagnum*-peat was composed almost entirely of well-preserved (fibric) remains of *Sphagnum* spp., with lesser amounts of wood and leaves of ericaceous shrubs.

Radiocarbon dating was conducted by Mass Accelerator Spectrometry at the Purdue Rare Isotope Measurement Laboratory.

RESULTS & DISCUSSION

Although the concentration of peat-forming wetlands and non-peat-forming wetlands may vary between different glacial regions and different drift types, peatlands and other wetlands are, more often than not, found in close proximity. So, there must be some more specific qualities of individual basins that favor the development of peatlands over other types of wetlands.

Surface area, fetch, and orientation of the long axis: The surface area of 25 peatlands listed in Table 1 ranged from 0.6–39 ha, with a mean area of about 19 ha (SD = 11.2). The areas of these peatlands are similar to those of peat-filled kettles described by other investigators (Coburn et al. 1932; Rigg & Richardson 1934, 1938; Welch 1936, 1938a, 1939; Karlin & Lynn 1988; Andreas & Bryan 1990). While many investigators observe that peat-filled kettles in the southern Great Lakes region are small, none have presented numerical comparisons with the average area of water-filled kettles as a whole. To support the conclusion that peat-filled kettles are characteristically small, some comparison must be made with non peat-forming kettles.

The surface area of 248 glacial lakes in Indiana (data from Sanderlin 1984), ranged from 0.8–1239 ha with a mean of 59 ha (SD = 114.19). These data suggest that most kettles occupied by peat are much smaller than non-peat-filled kettles in Indiana. Large peatlands, some over several hundred hectares in area, have been reported in the southern Great Lakes region (Andreas & Knoop 1992); but they are extremely rare.

The influence of area, like most morphometric parameters, on peatland formation is limnological in nature and affects the ontogeny of a lake long before it becomes a bog or a fen. The significance of surface area to the biological, chemical, and physical characteristics of lakes has been discussed by many authors (see Welch 1952; Ruttner 1953; Lerman 1978; Cole 1983; Wetzel 1983). Its effects on wind and wave action are of primary consideration because agitation of the water-surface influences shoreline erosion as well as the chemical and thermal characteristics of the water. Given the variation in the chemical and thermal characteristics of both bog-lakes and other types of lakes, it appears that shoreline erosion is the most significant factor in the formation of lake-fill peatlands.

Length and orientation of the fetch also influence the magnitude of shoreline erosion. The longer the uninterrupted distance of open water, the greater is the potential amplitude (and thus erosive force) of waves (Wetzel 1983). The fetch of peat-filled kettles in Indiana ranged from 115–1370 m (Table 1) with a mean of 615 m (SD = 294.6). Intuitively, the relatively small area of the peatlands will result in a relatively short fetch, unless a particular basin is unusually oblong or linear. While all of the kettles had sparsely developed shorelines (Table 1), most were slightly oblong rather than truly circular. Only four (16%) of the kettles approached the shape of a circle, therefore the orientation of the long axis becomes important in terms of potential wave generation and erosion. Examination of the fetch orientation yielded no consistency among the peat-filled kettles. The importance of fetch orientation may be difficult to ascertain because prevailing winds may have changed throughout the late-Pleistocene and Holocene.

Smaller basins with a short fetch, or with a fetch oriented perpendicular to prevailing winds, are most likely to be sheltered from erosive waves, favoring accumulation of a "false-bottom" of organic material (Welch 1936, 1938a, 1939). Although wind-swept lakes can develop a false bottom due to erosion by waves (Welch 1938b), flocculent sediments rarely accumulate around the margins. The presence of marginal accumulations of flocculent organic material, favored by shelter from wind initiates the formation of a peat-forming mat. This observation is supported by the presence of many kettles with peat mats developed exclusively or primarily on the windward side of the lake rather than on the wave-battered shore (Crum 1988).

When undisturbed organic sediments along the shoreline build up to the point where they approach the water surface, they become a substrate for sedges and mosses. In times of low water, these colonies consolidate, develop a matrix of stems and roots, and become a floating fen mat. With a hinged substrate free from flooding and standing water, horizontal mat growth can far exceed vertical sediment accumulation. What may result is a major change in the ecology of a lake simply because the mat further reduces area, and the area that the mat now occupies is no longer open to free diffusion of oxygen into the water. Consequently, the chemistry and productivity of the oxygen-poor mat, also poor in plant-available macro-nutrients, may deviate drastically from what would be expected based on the chemistry of the open lake water. Reduced contact with groundwater as a result of semi-impermeable organic sediments, along with cation exchange by brown mosses (Glime et al. 1982), and eventually by *Sphagnum*, can form an acid-forming mat on an extremely alkaline lake. Examples of such conditions include Egg Lake, Beaver Island, Michigan (Swinehart 1996a) and Inverness Mud Lake, Cheboygan County, Michigan (Welch 1936). However, even in these lakes, the open water is likely altered because the mat affects the flow of nutrients by catching and holding allochthonous litter and nutrients.

Because small lakes are protected from wind and waves, the magnitude of seasonal overturn may be reduced (Wetzel 1983; Crum 1988). Whether this factor truly favors peatland formation is questionable since most peat production is restricted to the margins of the lake at the interface between air and water. This location would seem to be exempt from any unique thermal/hydrodynamic qualities of the rest of the water volume. Only nutrient availability and primary productivity should be affected by reduced seasonal overturn. Recharge of oxygen to anoxic sediments would be reduced, transport of nutrients from the hypolimnion to the epilimnion would be reduced, and consequently, nutrient availability would be reduced due to permanent incorporation in the sediments of the hypolimnion. While a cold, proportionally large hypolimnion that is subjected to little mixing could accelerate in-filling by limiting reduction of organic detritus during settling, the resulting sediments never approach the fibric character of peat formed at the margins of the lake.

Productivity of a lake, as a whole, need not affect peatland development. Peatlands may form on either eutrophic or oligotrophic lakes as long as local decomposition is significantly less than local productivity. This condition occurs where the mat occupies the air-water interface, thus reducing oxygen saturation, decreasing temperature of the substrate as a result of evapotranspiration, and consequently reducing bacterial decomposition.

Depth: Kettle lakes are not characteristically deep in comparison to other types of lake basins (glacial or otherwise). They are relatively shallow inclusions in the glacial drift, and they vary in maximum depth from less than a meter to over 45 m (see Coburn et al. 1932; Wilson 1938; Scott & Minor 1938;

Table 1.—Morphometric data for 25 peatlands in Indiana: Fetch, maximum breadth (b_m), surface area (A), maximum depth (Z_m), mean depth (Z_{mean}), ratio of mean depth to maximum depth ($Z_{mean}:Z_m$), relative depth (Z_r), volume (V), shoreline length (L), and shoreline development (D_L). * Orientation of the long axis given in parentheses. [1] Smith (1937), [2] Prettyman (1937), [3] Howell (1938), [4] Lindsey (1932), [5] Swickard (1941), [6] Wilcox & Simonin (1988), [7] Richards (1938), [8] Otto (1938), [9] Keller (1943), [10] Hamp (1940) [Data obtained from these sources restricted to depth. All other values were obtained cartographically by the author.]

Peatland	*Fetch (m) & orientation	b_m (m)	A (m^2)	Z_m (m)	Z_{mean} (m)	$Z_{mean}:Z_m$	Z_r (%)	V (m^3)	L (m)	D_L
Little Chapman Bog	305 (circular)	305	90000	15	3.9	0.26	4.43	232710	1100	1.03
Burket Bog	990 (N-S)	395	250000	15	7.2	0.48	2.66	1187050	3050	1.72
Shoemaker Bog	685 (N-S)	610	150000	8	2.9	0.36	1.83	284770	2135	1.55
Yost Bog	380 (NS-SW)	100	80000	12	6.5	0.54	3.76	339890	915	1.0
Dutch Street Bog	685 (N-S)	75	160000	15	6.3	0.42	3.32	669232	2135	1.51
Svoboda Fen	460 (circular)	460	250000	14	6.6	0.47	1.59	1086360	1950	1.10
Leatherleaf Bog	305 (N-S)	230	40000	9	2.3	0.26	3.99	62215	1525	2.15
Tamarack Bog	760 (N-S)	380	140000	10	3.0	0.30	2.37	278200	2135	1.61
Hickory Bog	115 (NE-SW)	65	6000	4.5	3.2	0.72	5.15	12995	365	1.33
Binkley Fen	760 (W-E)	610	310000	10	4.9	0.49	1.59	998995	2315	1.17
Lake Cicott Bog[1]	1800 (W-E)	300	300000	15	—	—	—	—	1525	1.0
Fox Prairie Bog[2]	530 (W-E)	460	220000	12	—	—	—	—	1465	1.0
Kokomo Bog[3]	1370 (NE-SW)	380	300000	10	—	—	—	—	3050	1.57
Little Arethusa Bog	800 (NE-SW)	300	150000	17	—	—	—	—	2440	1.78
Merrillville White Pine Bog[4]	685 (W-E)	460	300000	12	—	—	—	—	2440	1.26
Mill Creek Fen[5]	600 (N-S)	300	170000	18	—	—	—	—	2135	1.46
Mt. Pleasant Bog	760 (NE-SW)	380	180000	12	—	—	—	—	2440	1.62
Pinhook Bog[6]	1140 (NW-SE)	533	380000	18	—	—	—	—	3170	1.45
Thompson Bog	305 (W-E)	230	60000	11	—	—	—	—	915	1.05
Otterbein Bog[7]	700 (circular)	700	380000	10	—	—	—	—	2135	1.0
Bacon's Swamp (bog)[8]	265 (NE-SW)	75	125000	10	—	—	—	—	—	—
Culver Bog[9]	610 (N-S)	380	170000	13	—	—	—	—	1830	1.25
Round Lake Bog[10]	760 (circular)	760	390000	10	—	—	—	—	2440	1.10
Ropchan Memorial Bog	610 (W-E)	425	140000	9	—	—	—	—	1525	1.15
Jeff Bog[9]	265 (NW-SE)	150	40000	16	—	—	—	—	609	1.0

Kratz & DeWitt 1986; Miller & Futyma 1987; Wilcox & Simonin 1988). It is often implied and sometimes explicitly proposed (see Wilcox & Simonin 1988) that kettles most favorable to peatland or floating mat development are "deep." To support such an observation, measurements of peat-filled kettles and non-peat-filled kettles are needed to place the parameter of depth into a relative context.

Maximum depth of peat-forming kettles in Indiana ranged from 4.5–18 m (Table 1) with a mean of 12.2 m (SD = 3.36). Unfortunately, very little data exists on the original depths of non-peat-forming kettle lakes, as only a few have been probed beyond the surface of the sediments (Scott & Miner 1936; Wilson 1938). For general comparison purposes, the maximum water depth (not inclusive of accumulated sediments) of 248 glacial lakes in Indiana was compiled. Maximum depths ranged from 2.4–37 m with a mean of 12.4 m (SD = 6.37). This mean is nearly equivalent to that determined for the peat-forming kettles, even though the total maximum depth of the non-peat-forming kettles was not available. Consequently, it must be assumed that their true maximum depth is much greater. Over 15 m of sediment has been found beneath the water column in some Indiana lakes (Scott & Miner 1936; Wilson 1938). With these points considered, it is very likely that peat-forming kettles are shallower on average than non-peat-forming kettles, at least in terms of maximum depth.

Mean depth, the ratio of mean to maximum depth, and relative depth probably depend mostly on the position of the original ice block in the till and the amount of debris in the ice block. Masses largely exposed at the surface would likely retain much steepness and depth, whereas masses buried with appreciable overburden would likely be shallower and have gradual slopes due to slumping (Fig. 1).

Mean depth of Indiana peatlands ranged from 2.3–7.2 m (Table 1) with a mean of 4.7 m (SD = 1.84). The ratio of mean to maximum depth ranged from 0.26–0.54 with a mean of 0.43 (SD = 0.14). Mean relative depth averaged 3.07% (SD = 1.25), ranging from 1.59–5.15%. Hutchinson (1975, pp. 168–169) summarizes the morphometric parameters from lakes that are especially deep (mainly grabens, calderas, and fjords), and those that have particularly large surface areas (primarily lakes formed from glacial corrasion). These summaries serve as examples of relatively deep and relatively shallow lake basins, respectively. The ratio of mean depth to maximum depth averaged 0.44 in relatively deep lakes and 0.35 in relatively shallow lakes. Relative depth averaged 3.13% in relatively deep lakes and 0.065% in relatively shallow lakes. Comparing these values to the data given in the present study (Table 1) suggests that the kettles examined are "relatively deep" (deep for their size), even though paludification of surrounding upland can create shallow rims causing underestimation of the original relative depth of the lake before infilling.

Whether the relative depth of kettles favorable to the formation of floating mats and peat is greater than that for other kettles is doubtful, even though there is insufficient morphometric data to allow a definitive conclusion. It is likely, however, based on what is known of current hydrography, that if the original morphometry of non-peat-forming kettles was measured, as it was for Winona and Tippecanoe Lakes (Scott & Miner 1936; Wilson 1938), no significant differences in relative depth would be observed. Thus, it seems that the importance of great depth in peat and mat formation is not well supported.

Wilcox & Simonin (1988) suggest that deep basins allow a mat to grow horizontally across the surface without becoming grounded by vertical accumulation of detritus peat. The primary argument against this theory is that horizontal mat growth can far exceed vertical sediment accumulation. Even if the detritus peat in a shallow basin was accumulating at an extremely fast rate of 3 cm per year, a floating mat of leatherleaf (*Chamaedaphne calyculata*) can advance as much as 6.3 cm per year (Swan & Gill 1970) and likely much faster for sedge mats. Another problem is that the theory does not take into account rising water tables during the Holocene (see Miller & Futyma 1987) that would progressively increase distance between the mat and the detritus peat.

While Wilcox & Simonin (1988) conclude that deep, steep-sided basins are most favorable to peat formation, Ruttner (1953) states that development of a floating mat is favored only over shallow benches and in protected bays. It seems clear that such formations can

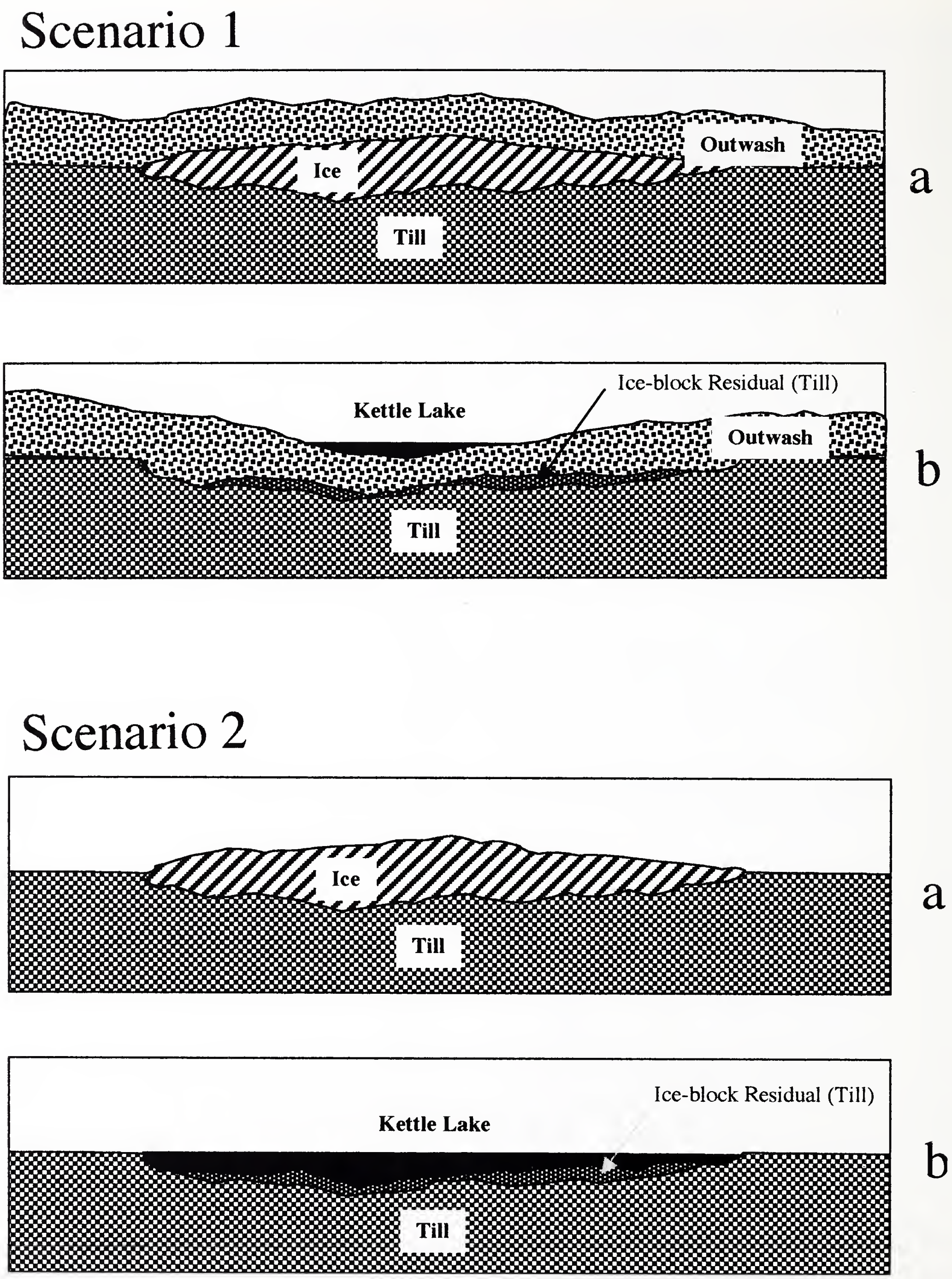

Figure 1.—Conceptual model of kettle lake formation. In Scenario 1 the glacial ice block is covered with overburden (a), and the resulting kettle (b) has gently sloping margins due to slumping. In Scenario 2, the ice block is exposed at the surface (a), and the resulting kettle (b) has steeply sloping margins.

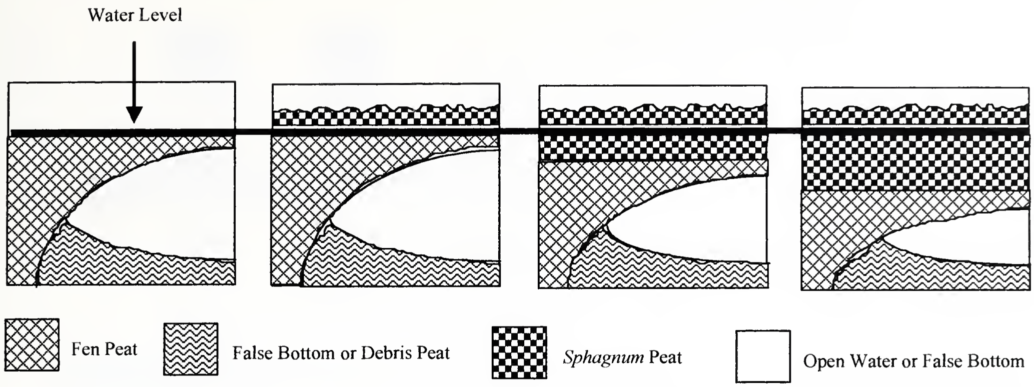

Figure 2.—Conceptual model of the compaction of a floating mat and underlying sediments after successive build-up of peat. Eventually, the mat becomes grounded, compaction is significantly reduced, and decomposition increases significantly at the surface. Note that the interface between *Sphagnum* peat and fen peat that was initially formed at or above the water surface is pushed below the water level over time.

occur over both shallow and deep water. The tendency for floating mats to be found more commonly over deep water is likely due to longevity. Most floating mats that developed over shallow water have long ago grounded and developed vegetation that would no longer characterize them as classic peatlands, and therefore they have not attracted the attention of peatland investigators.

Prevalence and importance of floating mats: Mat formation, favored by shelter from waves, is considered to be essential to the development of peatlands in Indiana. This is supported by the stratigraphic and macrofossil data presented by Swinehart & Parker (2000). Significant lenses of open water were found buried within the strata of nearly all 12 peatlands cored (Swinehart & Parker 2000). Although most Indiana peatlands have no lakes remaining, the few that actually exhibit open water are surrounded by a floating mat. Additionally, Lindsey (1932), Smith (1937), Moss (1940), Keller (1943), and Wilcox & Simonin (1988), present evidence of lenses of open water in stratigraphic profiles of other Indiana peatlands. With careful analysis of peatlands exhibiting solid profiles, evidence of a distinction between mat-peat and debris-peat (see Kratz & DeWitt 1986) might indicate the previous presence of a floating mat that has been entirely grounded (hence no lens of open water remains). Some peatlands, however, especially those that develop over marl flats, appear to lack evidence of a previous floating mat (Swinehart 1996b).

Because the development of a floating mat seems to be so important to the establishment and persistence of typical peatland plants in the southern Great Lakes region, some comparisons need to be made between the potential physical and hydrological characteristics of the mat versus the typical littoral situation. Kratz & DeWitt (1986) provide a useful model illustrating the factors controlling mat development on small peatlands. At the oldest (shoreward) portions of the bogs that they studied, where the peat was grounded and all compaction had ceased due to peak density, a state of "equilibrium" occurred in which no net accumulations of peat were noted (productivity was equal to decomposition). In the zones of compaction and thickening (closer to the open water), accumulations of peat at the surface pushed the mat further below the surface of the water table. In this case, biomass produced at the surface would be continually submersed into the inundated, oxygen-poor portion of the mat, preventing complete decomposition and thus creating an increasingly nutrient-poor substrate (see Fig. 2).

If the margins of a lake are disturbed to a considerable extent by waves, flocculent organic detritus will be transported to deeper portions of the basin and will never accumulate about the margins (Fig. 3). Only the more solid or dense sedimentary debris would be deposited, leaving no room for compaction. The organic sediments would eventually exceed the limit of the ground water to harbor sufficient oxygen to allow the rate of decom-

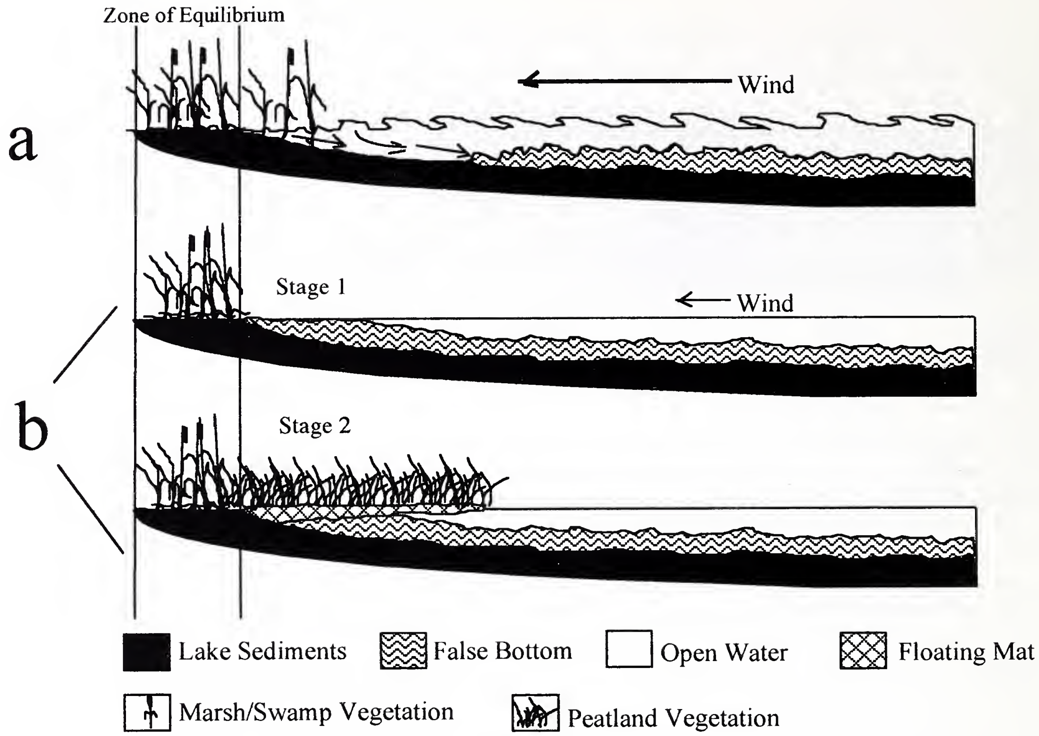

Figure 3.—Conceptual model showing a) wave-battered shore where consolidated lake sediments dominate and flocculent false bottom sediments are transported to deeper water, and b) protected shoreline where flocculent sediments accumulate near shore and provide a treacherous, water-logged substrate where mat-forming plants take hold. The oxygenated "zone of equilibrium" (after Kratz & DeWitt 1986) is where productivity is nearly equal to decomposition; and, consequently, plant available nutrients are more prevalent there.

position to approach the rate of productivity. Since the margins would be fully "grounded," fluctuation of the water table above or below the surface of the sediments would favor oxidation and decomposition. Or, if standing water persisted over the littoral zone, a similar "equilibrium" might occur due to higher oxygen diffusion.

In the case of a protected shore that accumulates appreciable amounts of unconsolidated organic material, enough support is provided for rhizomitous plants to take hold and eventually form a floating matrix or mat (Fig. 3). Once the mat is formed, any seasonal or regional water fluctuations would have little or no effect on the mat. The mat and its associated flora would rise and fall with the water. In this situation, most of the mat is continually inundated, oxygen-poor, and thus exhibits productivity which greatly exceeds decomposition. Only when the mat is grounded to the point where compaction no longer occurs does the productivity at the surface begin to equal decomposition (Kratz & DeWitt 1986).

While the vegetation of a pioneering mat often supports characteristic peatland plants, it may harbor just as many typical marsh species, such as *Thelypterus palustris*, *Typha* spp., *Scirpus validus*, and *S. acutus* (Swinehart & Parker 2001). Only after the chemistry of the substrate has been altered sufficiently via anoxia, cation exchange, and loss of plant-available nutrients does the mat take on a unique or characteristic peatland flora.

Drainage, mineral richness, stratigraphy, and vegetation: Peatlands do not develop at the same rate in all basins that happen to be favorable to peat formation. Lake, fen, and bog sediments occupy varying proportions of the total volume of a given basin. However, based on stratigraphy and radiocarbon dating,

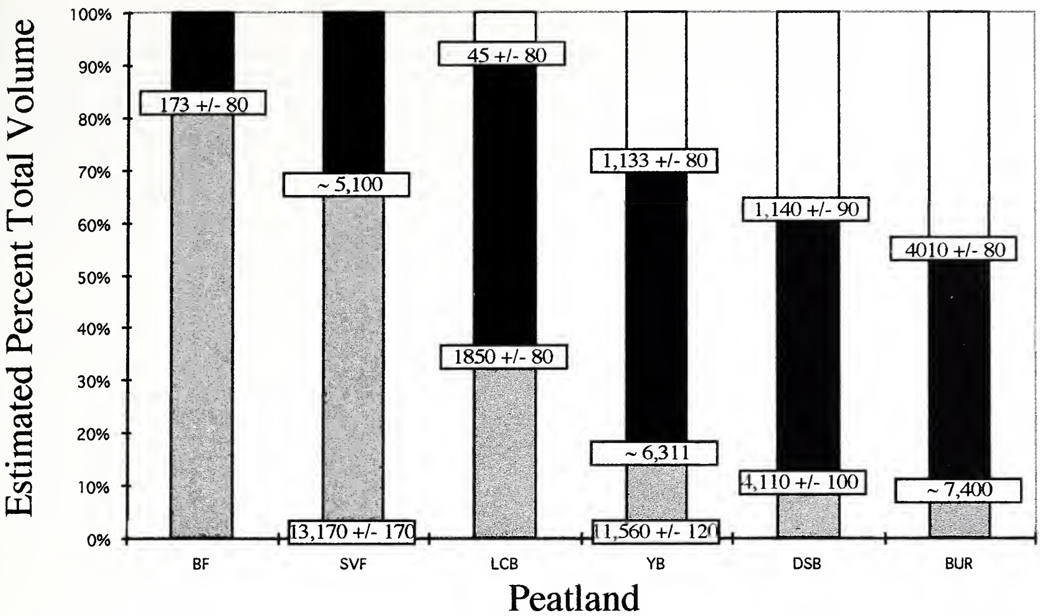

Figure 4.—Stratigraphy and associated radiocarbon (^{14}C) dates of six kettles in relation to percent total volume. BF = Binkley Fen, SVF = Svoboda Fen, LCB = Little Chapman Bog, YB = Yost Bog, DSB = Dutch Street Bog, BUR = Burket Bog. BF and SVF are alkaline fens, LCB is a transitional peatland; and YB, DSB, and BUR are leatherleaf bogs. Radiocarbon dates preceded by "~" are estimated. White bar is sphagnum peat, black bar is fen peat, and gray bar is lake sediment.

leatherleaf (*Chamaedaphne calyculata*) dominated peatlands made the transition from lake to peatland between 2250–5550 ^{14}C ybp earlier than other types of peatlands, both *Sphagnum*-dominated and non-*Sphagnum*-dominated (Fig. 4). Estimated percent total volume of lake sediments in three leatherleaf bogs ranged from 15–17%. Lake sediments were superceded by fen peat, which occupied from 40–55% of the total volume of the basins of leatherleaf bogs. *Sphagnum*-peat in the leatherleaf bogs occupied from 28–45% of the total volume of the basins. The basin occupied by Little Chapman Bog, a transitional peatland (between fen and bog), was composed of 37% lake sediments, 53% fen sediments, and 10% *Sphagnum*-peat. Two fens, Binkley and Svoboda, lacked a layer of *Sphagnum*-peat. The total in their basins (given respectively) included 82% and 66% lake sediments and 18% and 34% fen sediments.

If all of the basins, regardless of size or depth, began with their water-level at the same elevation as it is today, and all of them were proportionally equal in terms of watershed size, productivity, hydrology, and mineral richness, it could be expected that the proportion of the volume where transition from lake to peatland occurred would be equal among the basins. Since this is not the case, several external factors must be examined.

Because peat has its origins at the interface between air and the water surface, it can be deduced that the transition from sediments to peat coincides with the accumulation of lake sediments to the surface of the water, at least around the margins. Although some peat will be transported by currents from the margins to the deeper areas (where coring is conducted), the transition point in the profile is likely to be relatively close to where the water surface was at the time of peat initiation. This may explain why so little volume is occupied by lake sediments in the leatherleaf bogs. At the time of their formation (probably as a result of the nature of the substrate and hydrology), the water level in the basins was much shallower than at present, and the majority of their volume began to fill with lake sediments at an earlier time. As these sediments accumulated, drainage was further impeded (see Crum 1988), and water-levels slowly rose. Instead of sprawling over a shallow bench, steep upland slopes of the local watershed confined the growing peatland to a small, deep area.

The fens, on the other hand, appear to have begun with more water occupying their basins. More time was required for the sediments to accumulate to the point where they reached the surface; and hence the point at which peat began to form was delayed, and most of the basin filled with lake sediments. Three qualities distinguished the two basin-type fens from the *Sphagnum*-bogs: 1) fen basins were not lined with continuous, appreciable amounts of clay, 2) the watersheds of fens were hundreds of times greater than the area of the respective wetland, and 3) the fens possessed inlets and/or outlets. In contrast, bogs had significant and nearly continuous deposits of silt and clay (up to 4 m in Dutch Street Bog) lining the basin, their watersheds ranged from only 2–4 times the area of the respective wetland, and none possessed inlets or outlets.

Morphometry of the basin itself seems to have little effect on the vegetation that eventually develops on the peat. While it has been demonstrated that most peatlands in Indiana senesce into red maple-dominated lowland forests (Swinehart & Parker 2000, 2001), the pathway to that end is not the same for all peatlands. Palaeoecological evidence shows that in some extremely mineral-rich fens, the open mat is invaded simultaneously by trees and *Sphagnum* hummocks such that an open *Sphagnum* bog never develops (Swinehart & Parker 2000). This is already apparent at Svoboda Fen. Binkley Fen, although mineral-rich, is developing areas on the open mat that are becoming *Sphagnum*-dominated while there is no immediate evidence or threat of forest encroachment. Little Chapman Bog, which in recent times has developed an open, *Sphagnum*-dominated condition (with no low shrub component), is quickly succumbing to tall shrubs and wetland trees.

At the mineral-poor end of the spectrum are the leatherleaf bogs. None in the present study show any evidence, palaeoecological or otherwise, of having harbored typical bog conifers such as tamarack (Swinehart & Parker 2000). They simply succeed from low shrub bogs to tall shrub bogs (dominated by *Vaccinium corymbosum*) and finally to red maple-dominated forests (Swinehart & Parker 2001). Whether or not alkaliphobic species such as *Sphagnum* ever develop is dependent on the resistance of the ecosystem to the influence of mineral-rich groundwater. While the morphometric qualities that favor the simple genesis of peat seem to be the same for all basins, factors such as hardpan permeability, watershed area, and hydrologic history most likely determine the composition and structure of the successive stands of vegetation.

CONCLUSIONS

The factors affecting the formation and distribution of peatlands in the southern Great Lakes region are clearly hierarchical. At the coarsest level, glacial processes such as the stagnation of entire lobes of ice facilitated the formation of kettles. The local processes that determined the texture and composition of the drift affected drainage. Size, shape, and position of individual ice masses greatly affected the limnology of resulting lakes. And, at the finest level, biological responses to these abiotic factors resulted in variation in the composition, structure, and succession of the vegetation that eventually colonized the glacial lakes.

The only significant feature separating peat-forming kettles from non-peat-forming kettles was surface area. Small basins seemed most likely to become peat-forming due to reduced wind and wave-induced erosion. Protected shores were more likely to develop a floating mat that favored the genesis and build-up of peat. The chemistry and ecology of the successive stands of vegetation that eventually colonized the peat were most affected by watershed area and hardpan permeability (which ultimately determined the degree of minerotrophy).

Experimental research is needed to further investigate the role of waves and basin morphometry on littoral ecology and peatland formation.

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