Integrating Lateral Expansion into Models of Peatland Development in Temperate New England

A thesis presented

by

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to

The Department of Forestry

in partial fulfillment of the requirements
for the degree of

Master in Forest Science

November 2001

Harvard University
Cambridge, Massachusetts

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ACKNOWLEDGEMENTS

I would like to thank David Foster, Glenn Motzkin, and Paul Barten for their guidance and support. Special thanks are due to Erin Largey, Morgan Tingley, and Scott Demers for providing patient field assistance. Mindy Syfert, Audrey Barker Plotkin, Sylvia Barry Musielewicz, Stephanie Pellerin, Kris Verheyen, Tim Parshall, Felicia Frizell, Kate Capecelatro, Matt Kirwan, Erin McCarty, Eric Huber, and Laurie Miskimins and provided additional help with fieldwork. Matt Kizlinksi and Jesse Bellemare provided feedback on all stages of the project. Lucinda McWeeney and Donna Francis assisted by examining sediments and Julie Pallant helped with computer support. Sylvia Barry Musielewicz assisted with the pollen diagram. The staff and woods crew at Harvard Forest provided creative assistance with field work challenges.

I'd especially like to thank some of the many people who helped me stay focused: Christine Muth, Sebastian Catovsky, Mindy Syfert, Eric Huber, Matt Kizlinski, Jesse Bellemare, and Audrey Barker Plotkin. Richard and Valerie Anderson supported my enthusiasm and delighted in stories of my excursions.

Thanks to the landowners for providing permission to sample on their sites. NSF Arizona AMS Laboratory provided radiocarbon dates. Funding for radiocarbon dates was supported by NSF Division of Environmental Biology Grant no: DEB 94/00-08056 and the Richard T. Fisher Fund at Harvard Forest. This study is a contribution to the Harvard Forest Longterm Ecological Research Program.

ABSTRACT

As peatlands form they create a temporal archive of community development, allowing the reconstruction of vegetation dynamics through the analysis of sediments and development of detailed chronologies of successional changes. Peatland formation occurs through two mechanisms: (*i*) terrestrialization, when a water body fills with sediments and peat and (*ii*) paludification, the gradual conversion of uplands to wetlands. General models of peatland development suggest that high rates of evapotranspiration limit peat accumulation in the temperate zone, and that the terrestrialization is the primary model for peatland formation in the temperate northeastern United States. This study evaluates these models by comparing the stratigraphies of three peatlands within the same climate region in order to (*i*) describe the developmental pathways and timing of successional events among the peatlands, (*ii*) document the relative role of paludification and terrestrialization as developmental mechanisms, and (*iii*) investigate the sensitivity of peatland development to regional climate change.

At three 10-ha forested peatlands in central New England a 25-m sampling grid was installed. Basin morphometery was mapped, sediment stratigraphies were described, and chronologies of community change were determined through radiocarbon dating. The results indicate that peatland development involved both terrestrialization and paludification, with no apparent influence of climate change on the process or timing of these developmental processes at the scale investigated. Successional changes followed the same patterns at all three sites, with lake sedimentation and terrestrialization followed by paludification. Paludification was initiated coincident with the consolidation of a shrub mat across the basin, and was controlled by the topography of the adjoining upland.

Notably, the timing of successional changes varied at each site, suggesting that autogenic factors rather than environmental changes controlled development.

INTRODUCTION

As substantial reservoirs of organic carbon, peatlands are a significant component of global carbon dynamics (Gorham 1991, Warner et al. 1993, Gignac and Vitt 1994). According to current models, climatic warming and ensuing worldwide water level fluctuations may fundamentally alter organic sequestration dynamics. In some areas large amounts of carbon may be released into the atmosphere as peat decomposes, while peat accumulation may actually increase in other locations (Gorham 1991, Mäkilä 2001). Yet, fundamental questions persist concerning the developmental dynamics of peatland ecosystems. How much regional variation exists in peatland development and what controls these differences and the timing of successional changes? It is possible to address such issues by studying the temporal archive of community development preserved in the accumulation of partially decomposed plant material in peatlands.

Peatland vegetation dynamics may be reconstructed by characterizing sediments and by developing detailed chronologies of successional changes. Peatland formation occurs through two mechanisms: terrestrialization, when a water body fills with sediments and peat, and paludification, when upland is converted to wetland (Figure 1). Terrestrialization is identified by the presence of open-water sediments, such as silt or lake mud underlying peat, while paludification may be identified by the presence of peat deposits directly over basal mineral materials (Solem 1986, Foster et al. 1988, Foster and Wright 1990, Korhola 1992 1994 1995, Mäkilä 1997). Following paludification, basal peat deposits are younger towards the wetland margin.

General models of wetland formation for temperate regions such as central New England suggest that high temperatures limit peat accumulation (Transeau 1903,

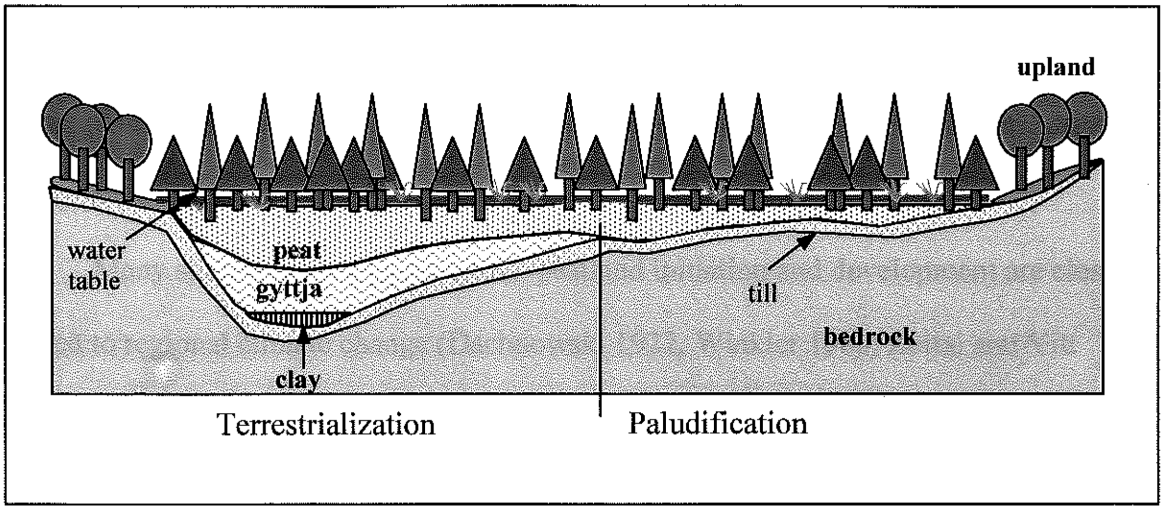

Figure 1. Mechanisms of peatland formation. Terrestrialization (lake-infilling) is indicated by the presence of aquatic sediments (gyttja) under peat. Paludification (lateral spread) is indicated by the presence of mineral material without underlying gyttja.

Damman 1979), and that terrestrialization is the primary mechanism of peatland development. Although incompletely documented, a few studies suggest that paludification also may be important in the development of peatlands in this area (Zebryk 1991, Thorson and Webb 1991). Identifying the relative importance of terrestrialization versus paludification in New England is critical for understanding the factors that drive the dynamics of the ecosystem.

Many studies have suggested that peatland initiation and development are closely related to regional climate change (Dachnowski 1922, Winkler 1988, Zoltai and Vitt 1990, Hansen and Engstrom 1996). If climate change drives peatland development within a region, major successional changes might be expected to occur synchronously across a region and coincident with known climatic shifts. Sorting out the relative role of autogenic versus allogenic factors is important in order to understand what controls community dynamics and formation. For example, in the deep basins of some New England peatlands, alternating layers of peat and aquatic sediments (gyttja) indicate multiple water table fluctuations of several meters, presumably in response to climate change (Thorson and Webb 1991, Newby et al. 2000, Almquist et al. 2001).

Alternatively, numerous studies have documented that autogenic processes are important drivers of peatland development in many regions (Clymo 1984, Foster et al. 1988, Foster and Jacobson 1990, Almquist-Jacobson and Foster 1995, Bunting and Warner 1998, Bunting, Warner, and Aravena 1996). For example, lateral expansion may be initiated when the water table rises due to the accumulation of partially decomposed peat with low hydrological conductivity (Ivanov 1981, Clymo 1984, Futyma and Miller 1986, Johnson, Damman, and Malmer 1990, Nobel 1990).

In the current study, we compare the developmental histories of three sites within the same climate zone in order to: (*i*) investigate similarities of developmental pathways and timing of successional events among peatlands, (*ii*) document the relative importance of paludification as a developmental mechanism in the study region, and (*iii*) investigate the sensitivity of peatland development to regional climate change.

STUDY AREA

The study focused on three approximately 10-ha peatlands in central New England that currently support similar forest communities dominated by red spruce (*Picea rubens*), Eastern hemlock (*Tsuga canadensis*), and red maple (*Acer rubrum*; Figure 2). Located in the Central Uplands physiographic region of New England (Motts and O'Brien 1981), this moderately rugged area is characterized by north-south oriented ridges and valleys and Paleozoic bedrock of granite, gneiss, and schist. Upland soils are moderate to well drained, acidic, sandy-loams formed in glacial till, with poorly to excessively drained soils in glacial outwash in some valleys and basins. Elevation ranges from 220 m to 410 m a.s.l. and regional deglaciation occurred approximately 14,500 cal YBP (Ridge et al. 1999). The regional climate is cool temperate and humid, with a mean July temperature of 20° C and a mean January temperature of –7 ° C. The annual precipitation of 110 cm is evenly distributed throughout the year (Rasche 1953). The regional upland vegetation is characteristic of the transition hardwood-hemlock-white pine forest region (Westveld 1956).

Sites were selected due to similarities in vegetation and isolation from other wetlands and waterbodies. Black Gum Swamp at an elevation of 365 m a.s.l. at Harvard Forest in Petersham, Massachusetts occupies an irregularly shaped basin. The

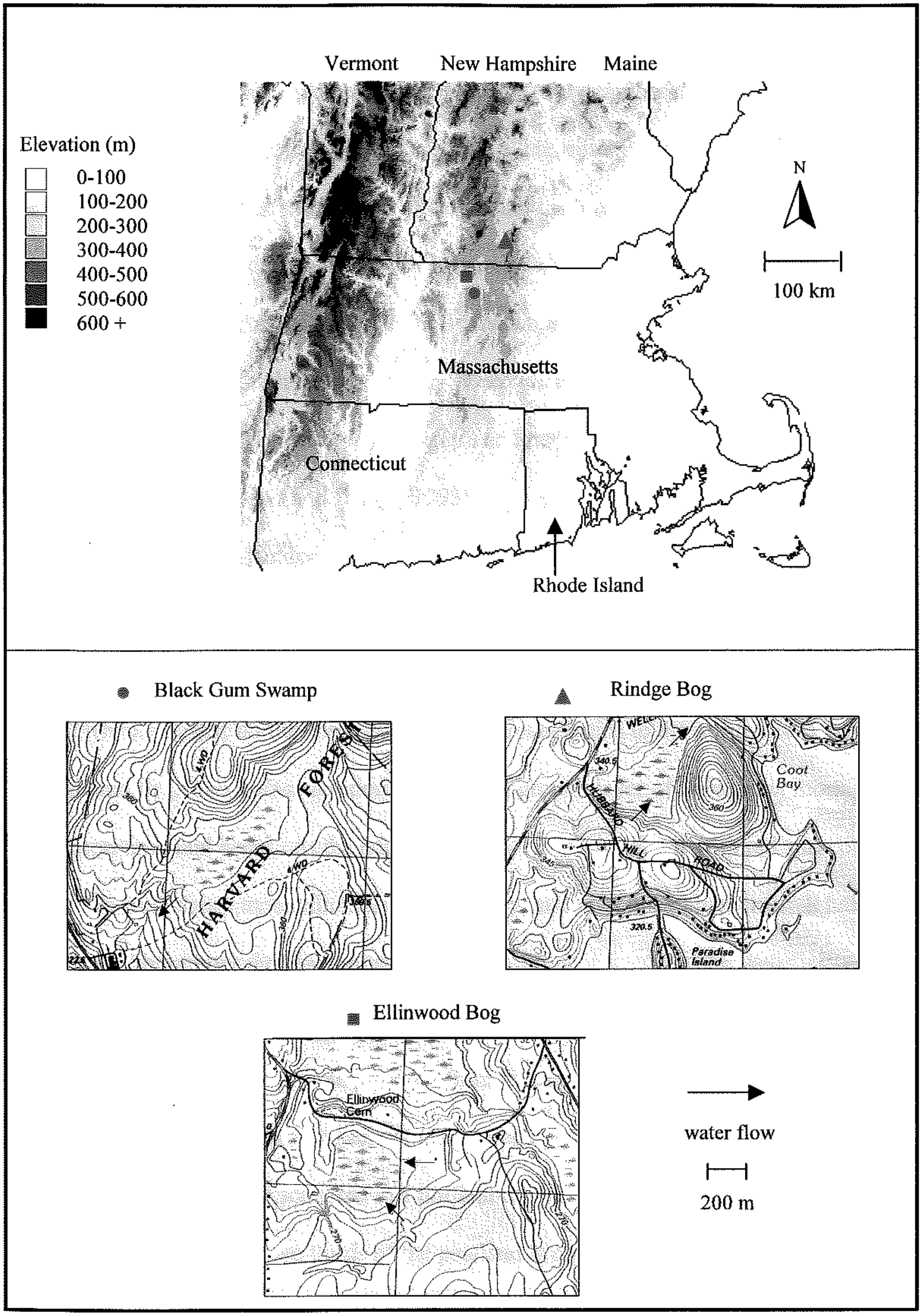

Figure 2. Study site locations in New England, USA.
Top panel: Study site locations on elevation map of southern New England states.
Bottom Panel: USGS 1:25,000 topographic maps of sites. Contour intervals 3m.

surrounding upland has gentle to steep slopes on the northern and northeastern sides and supports a mixed hardwood forest (*Quercus* spp.), American beech (*Fagus grandifolia*), red maple, hemlock, and birch (*Betula* spp.). An intermittent stream drains from the peatland to the southwest and a small mineral island is located in the north-central section. Vegetation is dominated by red spruce, black gum (*Nyssa sylvatica*), and red maple, with an understory of mountain holly (*Nemopanthus mucronata*), winterberry (*Ilex verticillata*), and high-bush blueberry (*Vaccinium corymbosum*) over *Sphagnum* spp., cinnamon fern (*Osmunda cinnamomea*), and herbs. It has pronounced hummock-hollow topography (Foster and Zebryk 1993).

Rindge Bog in Rindge, New Hampshire at an elevation of 335 m a.s.l., is a roughly triangular basin. Steep hills border the peatland to the south and east, with a gentler slope to the northwest. A small intermittent stream feeds the peatland from the south, while a larger, northeastern intermittent stream drains to the north. Red spruce and balsam fir (*Abies balsamea*) dominate over a ground layer of *Sphagnum* moss, cinnamon fern, and herbs. At the edges, red maple is co-dominant with red spruce and balsam fir over dense mountain holly, winterberry, and high bush blueberry. It has pronounced hummock-hollow topography.

Ellinwood Bog in Athol, Massachusetts at an elevation of 258 m a.s.l. is a roughly circular basin. Streams enter the peatland from the south and the southeast, but there is no visible drainage stream. The surrounding upland is steepest to the north and south. Small mineral islands are scattered in a north-south band from the inlet stream to the north edge. The eastern two thirds of the peatland is dominated by red spruce over *Sphagnum*, cinnamon fern, and herbs. Scattered shrubs grow on pronounced hummock-hollow topography. The western third and the southern edge are dominated by hemlock, red maple, yellow birch (*Betula alleghaniensis*), and scattered red spruce over a dense understory of mountain holly, winterberry, and high bush blueberry.

METHODS

Basin morphometery and stratigraphy

At each peatland, north-south and east-west transects were established at 25-m intervals. Grid points were installed with an accuracy of +/- 1 m and marked for the duration of the study. Peatland margins, defined by the horizontal limit of organic deposits, were determined by probing with a thin metal rod and mapped relative to adjacent grid points. Sediment depth was probed at each grid point. As the hummock-hollow topography produces height variation up to 75 cm, measurements were consistently measured from a topographically low area close to the sample point. From these data, basin morphometery was interpolated using SURFER (Golden Software 1994).

Peatland stratigraphy was described for every sample point at Black Gum Swamp (n= 146) and Ellinwood Bog (n=139) and for all but 17 points (n=142) at Rindge Bog. Sediments were extracted using a Russian corer with a 50 x 5 cm chamber. Two parallel holes were alternately used to minimize disturbance from the 6 cm tip. Boundaries between different sediment types were rounded to the nearest 5 cm.

In the field, sediments were assigned into major types characterized by dominant matrix, macrofossils, and color. As the purpose of the study was to determine broad patterns of peatland development, minor variations, such as degree of decomposition or minor macrofossil composition, within discrete zones were not recorded. Although transitions among sediment types were often clear and abrupt, when the transitions were gradual, the length of the transition was recorded. Representative samples of the major sediment types were washed, sieved, and examined under a light microscope (up to 3x) to identify major macrofossil constituents (Levesque et al. 1988).

Radiocarbon dating

Basin morphometery and stratigraphies were used to select samples for radiocarbon dating. At each peatland, basal samples were taken along two perpendicular transects running from the deepest portion of the basin to the upland (Figure 3). Transects were located on gentle slopes and points were distributed to sample both basal peat and gyttja. At Rindge Bog and Ellinwood Bog, samples of each sediment type were also taken along the length of a core from a deep basin. At Black Gum Swamp, a comparable long core had been previously collected and radiocarbon dated (Figure 3a; Zebryk 1991).

A total of 41 20-50 cm cores were sampled in the field, extruded, and wrapped in plastic film wrap and aluminum foil. In the lab, each sample was scraped to expose uncontaminated sediments and 2-5 g subsamples were removed. Samples were dried for 6-12 hours at 105° C, wrapped in aluminum foil, and sealed in plastic bags for AMS radiocarbon dating at the Radiocarbon Lab at the University of Arizona. Results were calibrated using Calib version 4.1 (Stuiver and Reimer 1993). Results are reported as calibrated years before present (cal YBP) where present is 1950.

RESULTS

Basin morphometry and stratigraphy

Basin depth is defined as the depth of organic sediments (peat or gyttja) to till or clay. Basin morphometry is consistent with surrounding topography and varies gradually

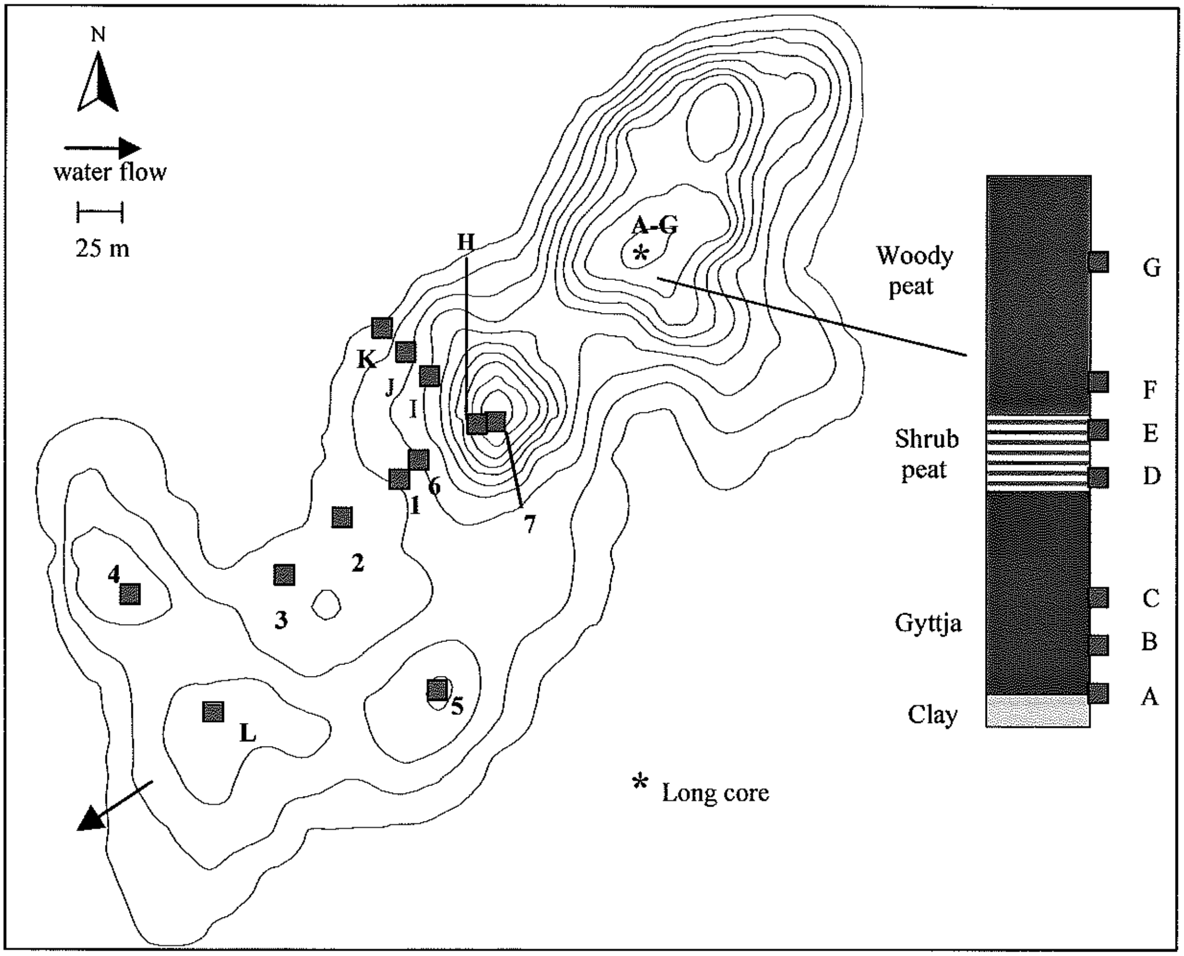

Figure 3a. Location of radiocarbon dated samples from basal sediments and one long core collected from Black Gum Swamp. Contour interval 50 cm. Lettered sample points are from Zebryk (1991).

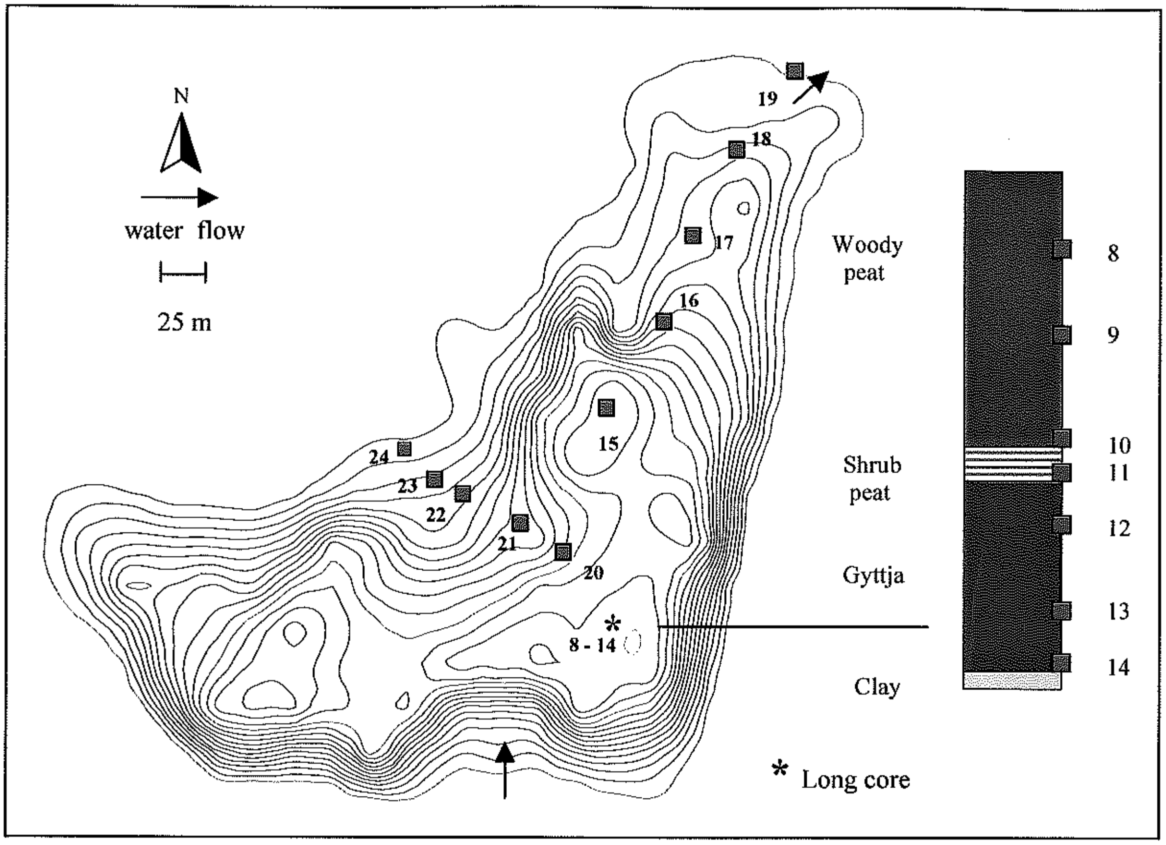

Figure 3b. Location of radiocarbon dated samples from basal sediments and one long core collected at Rindge Bog. Contour interval 50 cm.

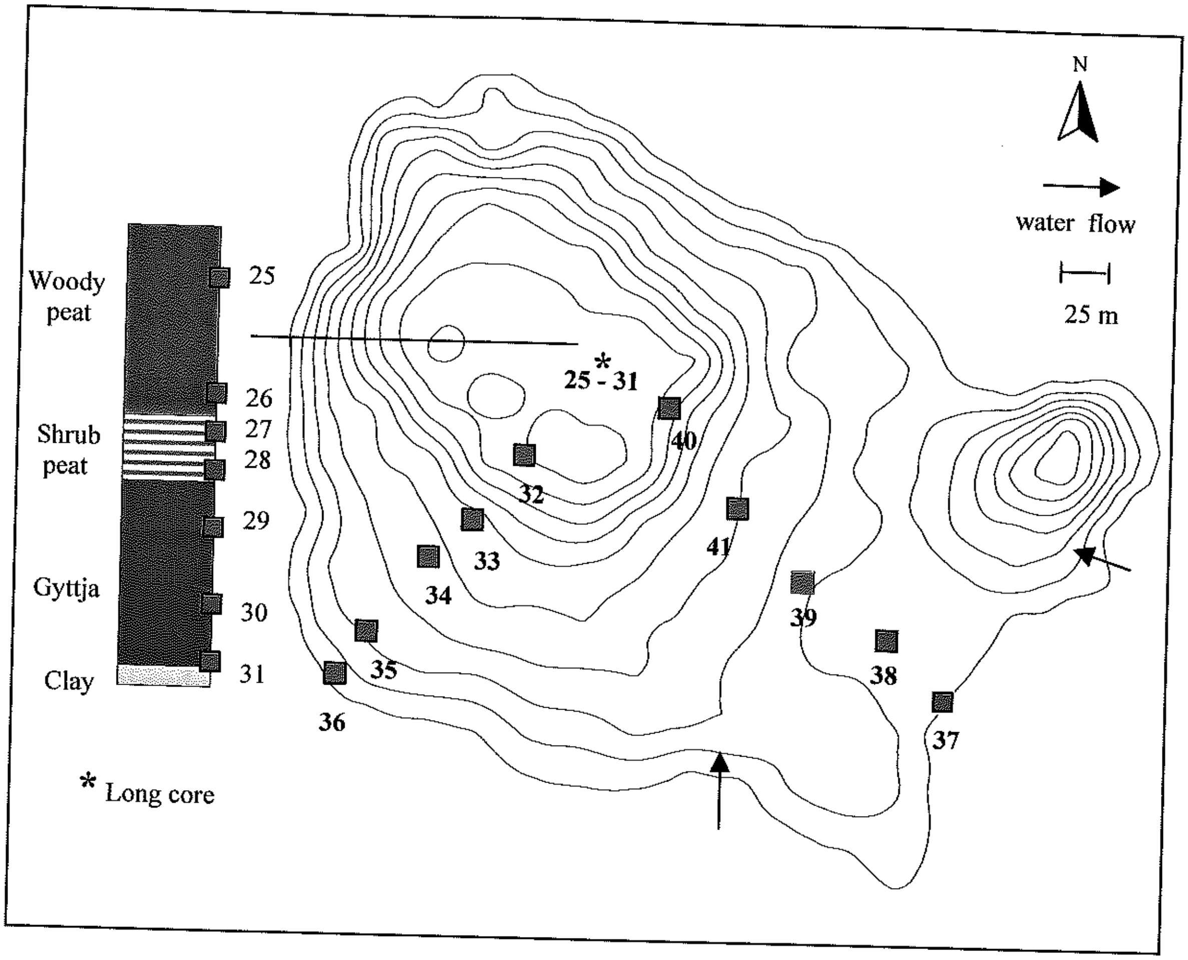

Figure 3c. Location of radiocarbon dated samples from basal sediments and one long core collected at Ellinwood Bog. Contour intervals 50 cm.

with few abrupt changes. Black Gum Swamp (Figure 4a) has a deep basin in the northeastern corner with a maximum depth of 6.5 m. Scattered small, shallow basins less than 2 m deep are found throughout the southwestern lobe. Much of the southern half of the site is less than 1 m in depth. Rindge Bog is dominated by a large steep-sided central basin with a maximum depth of 7.5 m (Figure 4b). The northern lobe has a shallower slope. Ellinwood Bog is dominated by a large basin on the western side (Figure 4c). A shallow north-south oriented bench less than 0.5 m deep separates the deep basin from a small, steep-sided basin 5.7 m deep in the northeastern corner.

Four stratigraphies were observed: woody peat on till, woody peat over shrub peat, woody peat over gyttja, and woody peat and shrub peat over gyttja. Two dominant peat types were identified. Woody peat occasionally contained large wood fragments with small twig and sedge fragments. Shrub peat contained abundant small diameter (up to 1 cm) ericaceous wood fragments within a matrix of decomposed *Sphagnum* and fern rhizomes. This material was very coarse, medium brown, better preserved than the woody peat, and consistently found under woody peat above aquatic sediments (gyttja) in deep basins. The transition from woody to shrub peat was often gradual, occurring over 25-35 cm. Gyttja varied considerably in color and texture. It was always found below peat and was typically medium brown with abundant macrofossil fragments near the boundary with the overlying peat. At increasing depth it was gray/green with no visible macrofossils. Light to dark gray clay lined the deepest basins.

At Black Gum Swamp woody peat forms the surface sediment (Figure 4a). In areas up to 100 cm deep and in one case to a maximum depth of 165 cm, woody peat occurs directly on mineral soil. Aquatic sediments occur in the small, shallow basins of

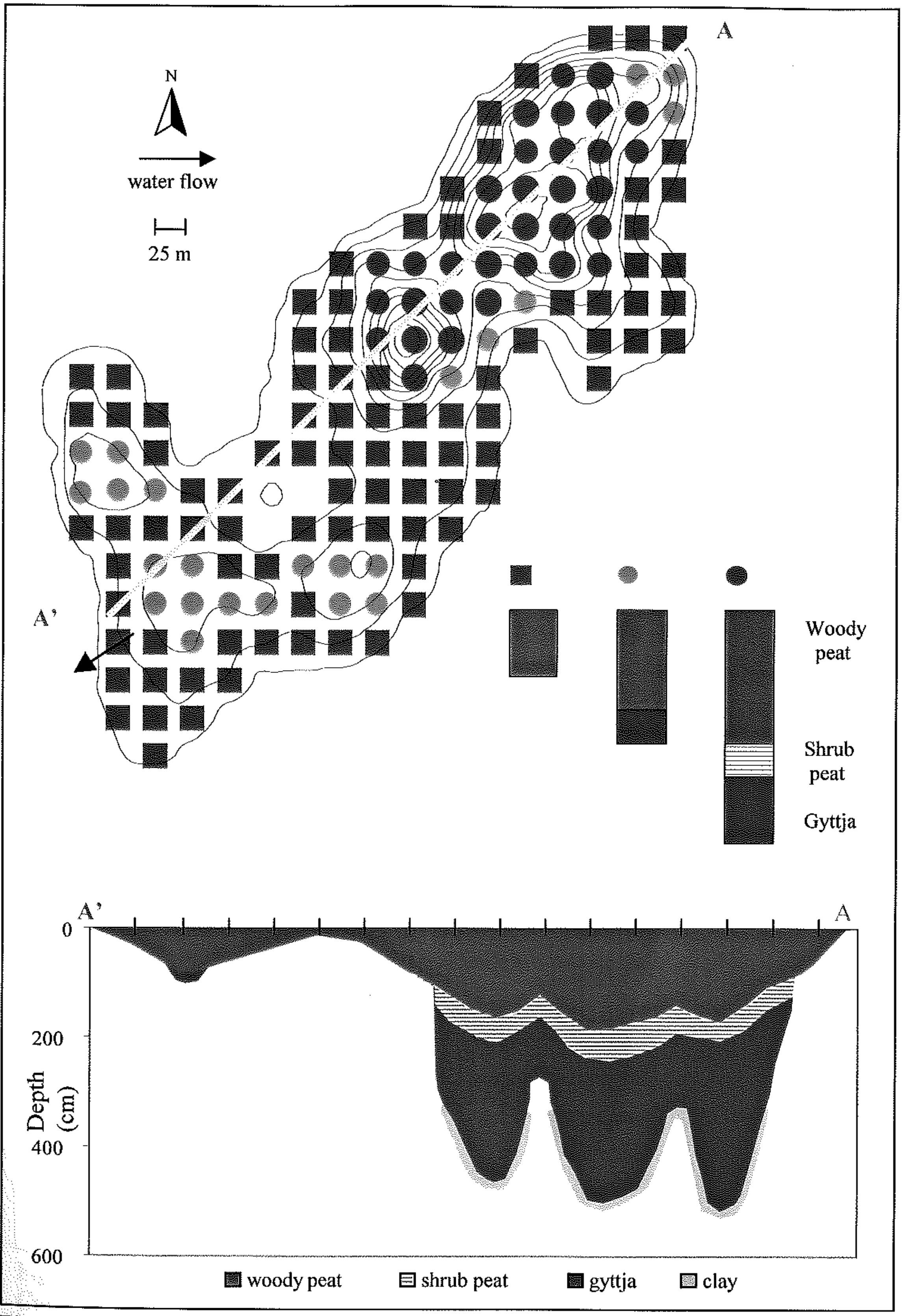

Figure 4a. Stratigraphy of each cored sample point and cross-section of Black Gum Swamp. Contour intervals 50 cm.

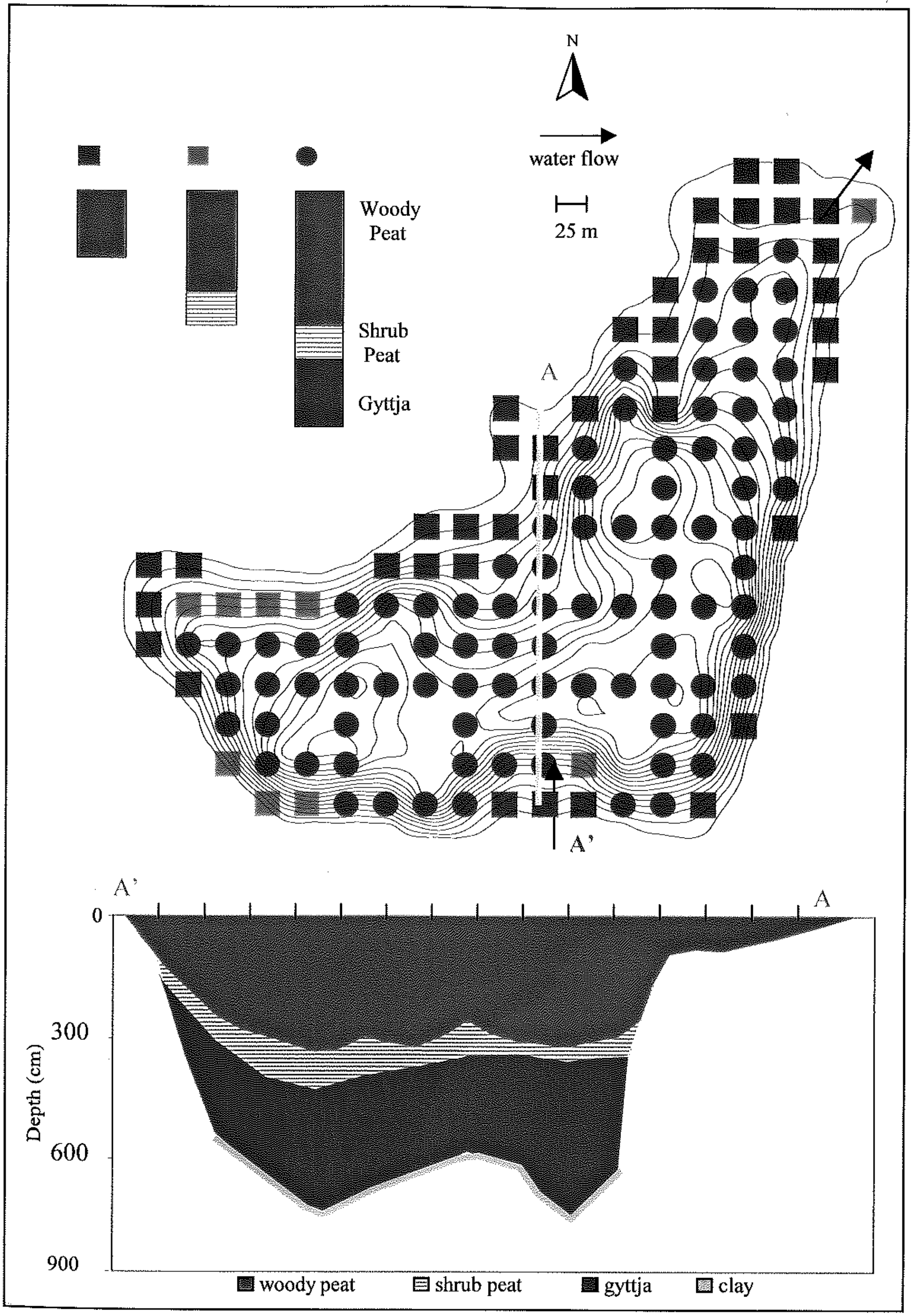

Figure 4b. Stratigraphy of each cored sample point and cross-section of Rindge Bog. Contour intervals 50 cm.

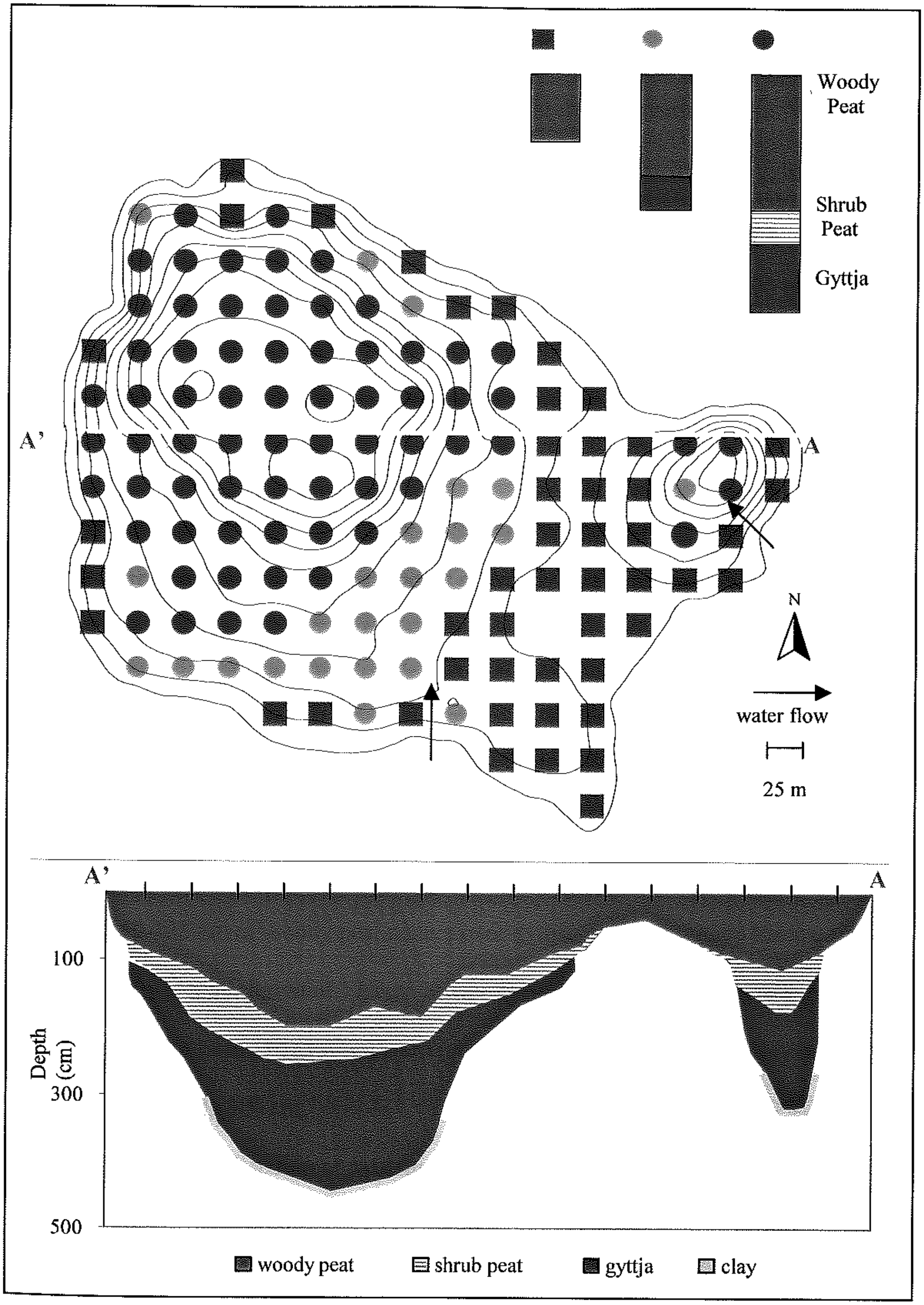

Figure 4c. Stratigraphy of each cored sample point and cross-section of Ellinwood Bog. Contour intervals 50 cm.

the southern lobe and in the deeper northern basin. In the southern basins, the typical stratigraphy is 85-100 cm of woody peat over macrofossil-rich gyttja. In the deep northern basin, woody peat or woody peat and shrub peat overlay gyttja. With increasing basin depth, the amount of woody peat increases and the transition to gyttja occurs at correspondingly greater depths. Shrub peat is found only in the deep northern basin. Clay occurs beneath the gyttja where the basin depth is greater than 300 cm.

At Rindge Bog (Figure 4b) woody peat and shrub peat form basal peat deposits. There is a range of 15-165 cm of woody peat deposited on mineral soil, with a typical depth of 80 cm. Basal shrub peat 23-110 cm deep occurs under woody peat. The deep central basin has a consistent pattern of woody peat, shrub peat, and gyttja over clay. With increasing basin depth, the amount of woody peat increases and the transition to gyttja deposits occurs at correspondingly deeper levels. Clay occurs beneath the gyttja where the basin depth is greater than 500 cm.

At Ellinwood Bog (Figure 4c) woody peat up to 140 cm deep forms the basal deposit in a shallow zone around the perimeter of the site and along the north-south oriented bench. South-west of the shallow bench in the vicinity of the intermittent in-flow stream, 60-135 cm of woody peat occurs over gyttja. In the two deep basins, the typical stratigraphy is a minimum of 110 cm of woody peat and shrub peat over gyttja. In the smaller eastern basin, macrofossils are present throughout the gyttja. Clay occurs where the depth exceeds 300 cm.

In summary, sediment patterns are highly consistent across and within sites, with an overall pattern from the bottom of the peatland to the top of mineral soil-gyttja-shrub peat-woody peat. The amount of peat preserved increases with basin depth; woody peat is the surface deposit at all sites and is highly decomposed near the surface. Shrub peat is found only in deep basins. Sediment patterns are consistent with the overall basin depth and morphometery and there are no "reversals" in stratigraphy. The shallowest areas have basal deposits of woody peat directly on till while intermediate depths have woody peat over gyttja with abundant macrofossils. In deep basins, woody and shrub peat overlie gyttja. Clay occurs at the bottom of only the deepest basins.

The quantity of macrofossils in the gyttja is consistently related to basin depth. In shallow areas, typically less than 2 m in depth, the gyttja contains abundant macrofossils. In deep basins, there are abundant macrofossils in the aquatic sediments directly beneath peat deposits but fewer macrofossils with increasing depth. In locally deep areas in an otherwise shallow basin, macrofossils are present throughout the gyttja sediments.

Radiocarbon dating

Black Gum Swamp (Figure 5a, Table 1) has basal gyttja sediments ranging in age from 14,590 cal YBP to 9,510 cal YBP. In the center of the deep northern basin, gyttja deposited until at least 9,600 cal YBP. A sharp transition occurred to shrub peat approximately 9,500-9,600 cal YBP, and then woody peat developed. At the same time period, woody peat formed on mineral soil in the 50-100 cm contour interval. Woody peat accumulated on mineral soil in the 0-50 cm contour interval from at least 5,590 cal YBP until approximately 4,000 cal YBP and continued to accumulate in the deep basin until at least 3,620 cal YBP.

Rindge Bog (Figure 5b, Table 1) has basal gyttja dates ranging from 14,080 cal YBP until 9,360 cal YBP. In the core from the deep basin, gyttja accumulated until at

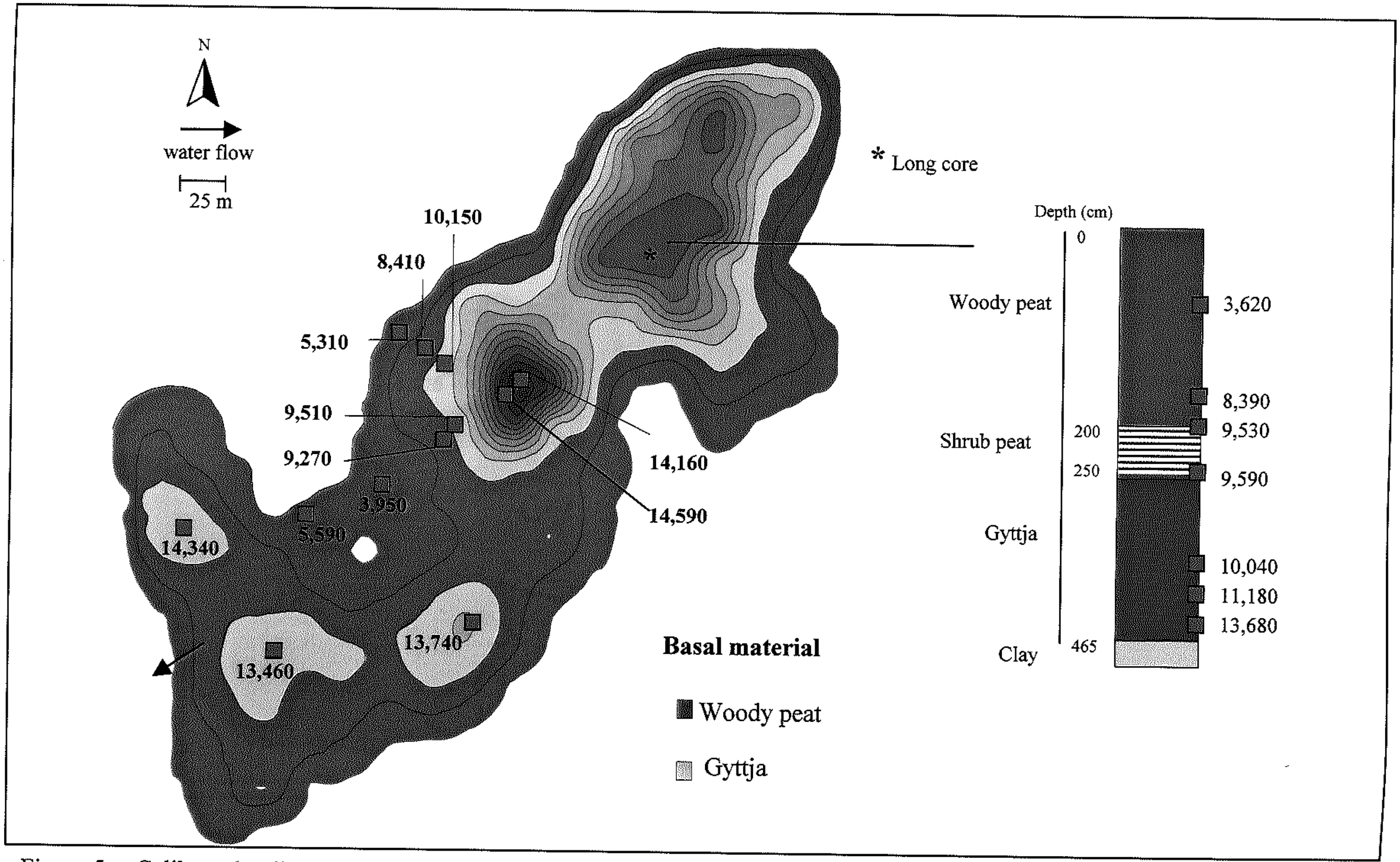

Figure 5a. Calibrated radiocarbon dates for Black Gum Swamp rounded to the nearest decade. Contour intervals 50 cm.

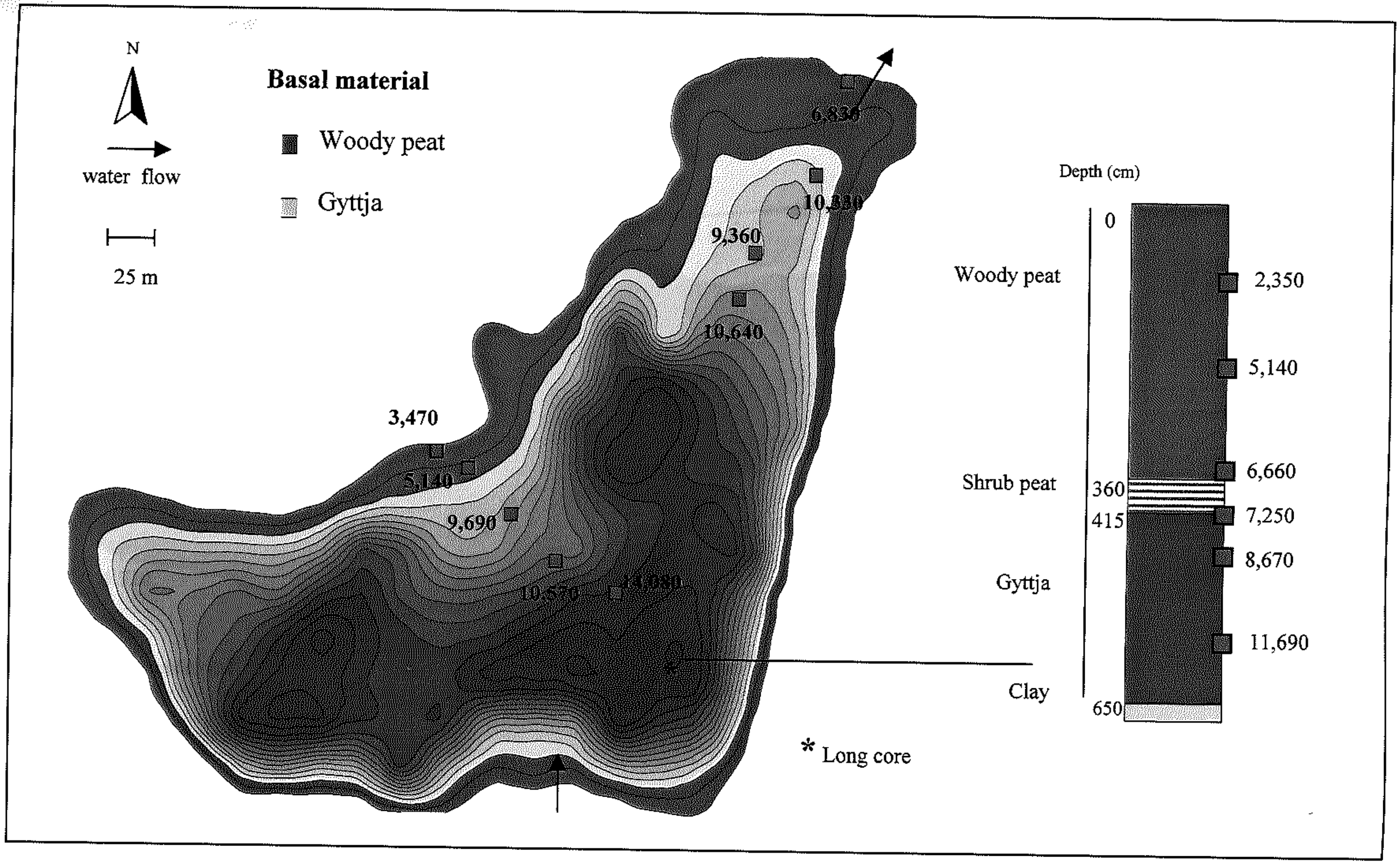

Figure 5b. Calibrated radiocarbon dates for Rindge Bog rounded to the nearest decade. Contour intervals 50 cm.

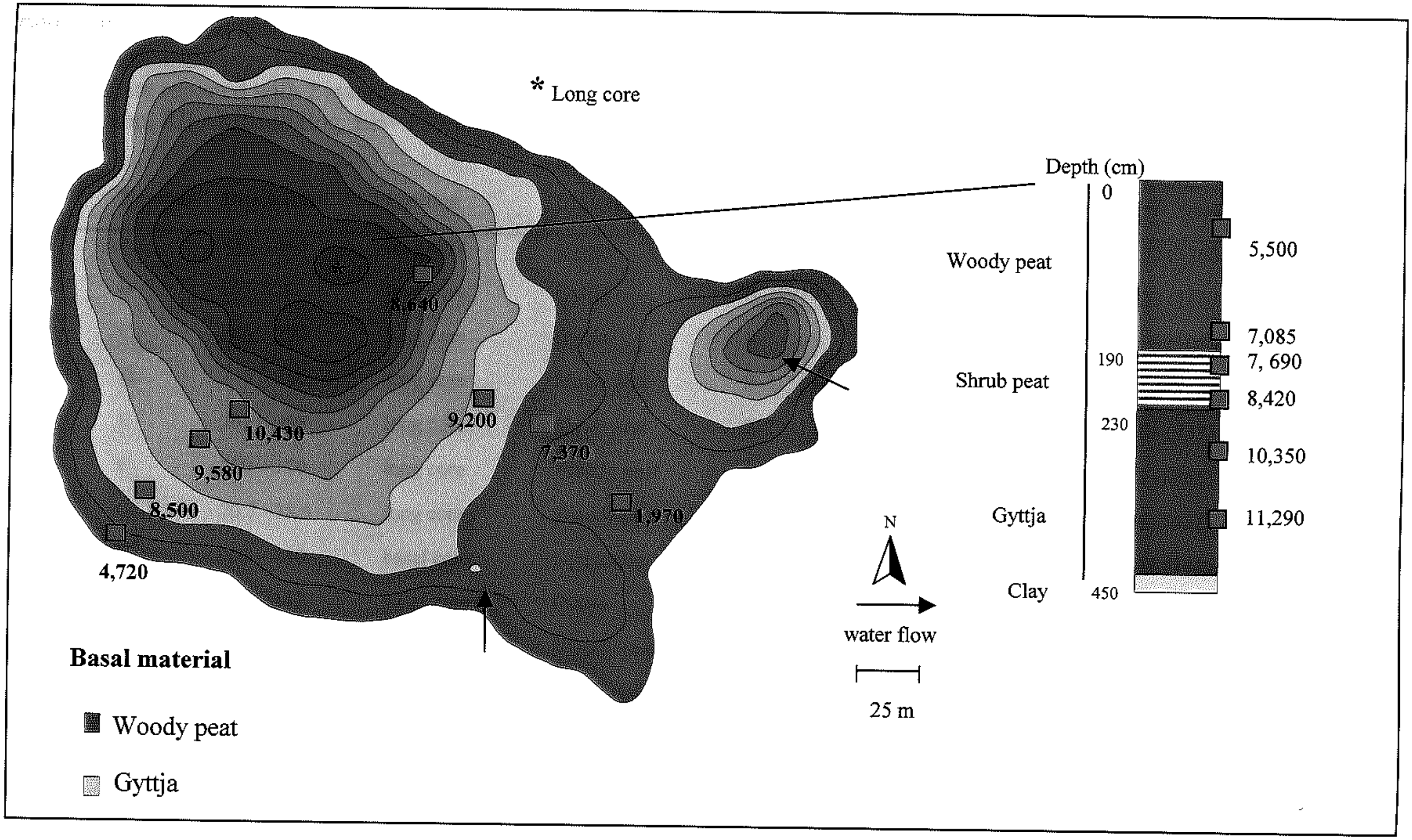

Figure 5c. Calibrated radiocarbon dates for Ellinwood Bog rounded to the nearest decade. Contour intervals 50 cm.

Table 1 Radiocarbon dates from sediment samples. Lettered samples A-L are results from Black Gum Swamp from Zebryk (1991). Numbered samples were from this study. AMS dates were calibrated to calendar years before present (cal YBP, where 'present' is 1950) and are reported with 2 standard deviations above and below the median calibrated age (Stuiver et al. 1998a). BGS= Black Gum Swamp, RB= Rindge Bog, EB= Ellinwood Bog. Italicized dates were not used in analysis because they predate deglaciation.

Site	**Number**	**Depth (cm)**	**Position**	**Material**	**Lab ID**	**C14 age BP**	**2 σ +/- (median cal YBP)**
BGS	A	450 – 465	long core	Gyttja	B-31366	11690 +/- 140	15132 (13680) 13198
BGS	B	371-378	long core	Gyttja	B-29919	9750 +/-450	12832 (11176) 9915
BGS	C	280 – 290	long core	Gyttja	B-31365	8910 +/-120	10356 (10038) 9558
BGS	D	240 – 250	long core	Shrub peat	B-31364	8680 +/-120	10152 (9586) 9473
BGS	E	202 – 208	long core	Shrub peat	B-29917	8560 +/-140	10106 (9533) 9164
BGS	F	160 – 170	long core	Woody peat	B-31363	7580 +/-90	8541 (8386) 8181
BGS	G	70.5 –75.5	long core	Woody peat	B-29916	3340 +/-110	3838 (3622) 3356
BGS	H	400 – 410	basal core	Gyttja/clay	B-42117	12240 +/-110	15448 (14156) 13839
BGS	I	134 – 142	basal core	Gyttja	B-42118	8940 +/- 110	10357 (10154) 9634
BGS	J	74 – 82	basal core	Woody peat	B-43786	7630 +/-80	8589 (8407) 8218
BGS	K	64 – 72	basal core	Woody peat	B-42119	4580 +/- 90	5578 (5307) 4970
BGS	L	117 – 125	basal core	Gyttja	B-42120	11520 +/-100	13834 (13463) 13161
BGS	1	78 – 80	basal core	Woody peat	AA40806	8,476 +/- 63	9548 (9513) 9329
BGS	2	42 – 44	basal core	Woody peat	AA40807	3,624 +/- 61	4140 (3950) 3727
BGS	3	33 – 35	basal core	Woody peat	AA40808	4,855 +/- 54	5661 (5594) 5474
BGS	4	178 –180	basal core	Gyttja	AA40809	12,399 +/- 80	15511 (14336) 14119

Table 1 (cont.)

Site	Number	Depth (cm)	Position	Material	Lab ID	C14 age BP	2σ +/- (median cal YBP)
BGS	5	178 – 180	basal core	Gyttja	AA40810	11,617+-85	13878 (13737) 13317
BGS	6	110 – 115	basal core	Woody peat	AA40811	8,266+-66	9470 (9271) 9029
BGS	7	480 – 483	basal core	Gyttja/ mineral	AA40812	12,612 +/- 82	15648 (14590) 14219
BGS	8	104-108	long core	Woody peat	AA40813	2,350 +/- 45	2467 (2349) 2212
RB	9	239-243	long core	Woody peat	AA40814	4,509 +/- 64	5439 (5135) 4875
RB	10	358-366	long core	Shrub peat	AA40815	5,847 +/- 50	6781 (6664) 6500
RB	11	409-416	long core	Shrub/ gyttja	AA40816	6,311 +/- 67	7418 (7250) 7025
RB	12	485-490	long core	Gyttja	AA40817	7,899 +/- 82	9009 (8674) 8458
RB	13	579-581	long core	Gyttja	AA40818	10,120 +/- 66	12294 (11692) 11265
RB	14	644-647	long /basal	Gyttja / mineral	AA40819	12,710 +/- 96	*15782 (15352) 14299*
RB	15	705-707	basal core	Gyttja/mineral	AA40820	13,340 +/- 110	*17442 (16883) 16369*
RB	16	343-345	basal core	Gyttja/ sand	AA40821	9,4320 +/- 72	11068 (10641) 10430
RB	17	180-185	basal core	Gyttja	AA40822	8,303 +/- 70	9488 (9359) 9033
RB	18	158-160	basal core	Gyttja	AA40823	9,216 +/- 71	10578 (10333) 10221
RB	19	43-45	basal core	Woody peat	AA40824	6,005 +/- 50	6986 (6827) 6685
RB	20	498-500	basal core	Gyttja	AA40825	12,031 +/- 74	15333 (14076) 13660
RB	21	381-385	basal core	Gyttja	AA40826	9,359 +/- 67	10741 (10570) 10291
RB	22	180-185	basal core	Gyttja	AA40827	8721 +/- 56	10106 (9694) 9547
RB	23	92-95	basal core	Woody peat	AA40828	4,525 +/-58	5309 (5143) 5048

Table 1 (cont.)

Site	Number	Depth (cm)	Position	Material	Lab ID	C14 age BP	2σ +/- (median cal YBP)
RB	24	48-50	basal core	Woody peat	AA40829	3,263 +/-51	3633 (3470) 3378
EB	25	95-99	long core	Woody peat	AA40830	4799 +/- 45	5606 (5498) 5477
EB	26	159-165	long core	Woody peat	AA40831	6164 +/- 62	7248 (7085) 6808
EB	27	184-188	long core	Shrub peat	AA40832	6900 +/- 52	7834 (7690) 7614
EB	28	229-233	long core	Shrub peat	AA40833	7684 +/- 64	8593 (8423) 8372
EB	29	319-322	long core	Gyttja	AA40834	9163 +/- 60	10496 (10352) 10214
EB	30	384-386	long core	Gyttja	AA40835	9939 +/- 76	11904 (11287) 11196
EB	31	448-450	long/basal	Gyttja/mineral	AA40836	14,320+/-140	*17766 (17158) 16599*
EB	33	228-230	basal core	Gyttja	AA40838	9309 +/- 66	10689 (10434) 10245
EB	34	182-184	basal core	Gyttja	AA40839	8444 +/- 57	9535 (9479) 9303
EB	35	96-100	basal core	Gyttja	AA40840	7735 +/- 58	8627 (8498) 8394
EB	36	48-50	basal core	Woody peat	AA40841	4185 +/- 44	4840 (4716) 4549
EB	37	37-40	basal core	Woody peat	AA40842	10740 +/- 100	*13000 (12868) 12373*
EB	38	17-20	basal core	Woody peat	AA40843	2015 +/- 45	2109 (1969) 1872
EB	39	38-40	basal core	Woody peat	AA40844	6470 +/-52	7462 (7374) 7270
EB	40	137-140	basal core	Gyttja	AA40845	8216 +/- 40	9398 (9201) 9028
EB	41	175-180	basal core	Gyttja	AA40846	7885 +/- 55	8988 (8639) 8543

least 7,250 cal YBP, when there was a distinct transition to shrub peat. Shrub peat accumulated until 6,660 cal YBP, and graded into woody peat which accumulated in the deep basin until at least 2,350 cal YBP. By 6,830 cal YBP woody peat formed on mineral soil at the edge of the shallow northern lobe. On the steeper northwestern edge woody peat accumulated on mineral soil until at least 3,470 cal YBP.

Ellinwood Bog (Figure 5c, Table 1) has basal gyttja dates up to 8,500 cal YBP. One central basal gyttja date predated deglaciation and was presumably contaminated with older carbon. In the center of the western basin, open water conditions persisted until at least approximately 8,420 cal YBP, when there was a sharp transition to shrub peat. Shrub peat accumulated until at least 7,690 cal YBP and graded into woody peat which accumulated until at least 5,500 cal YBP. On the south-western edge, woody peat was deposited on mineral soil until at least 4,720 cal YBP, while on the shallow eastern bench woody peat was deposited on mineral soil until 1,970 cal YBP. On the edge of the site, there is a woody basal peat date of 12, 870 cal YBP. This date is not included in analysis, as the late date is likely due to contamination of the sample. No result was available for sample RA-32.

Accumulation rates, shown as the age/depth curve for the vertical core from the deep basin of each site (Figure 6a), vary by site. At Black Gum Swamp accumulation rates may slowed during the formation of the bog mat, but with the large error bars for these samples this interpretation is not conclusive. At Rindge Bog and Ellinwood Bog there was little variation in the accumulation rates. These results do not appear to reflect general climate trends shown in the pollen diagram taken from the long core at Black Gum Swamp (Zebryk 1991; Figure 6b).

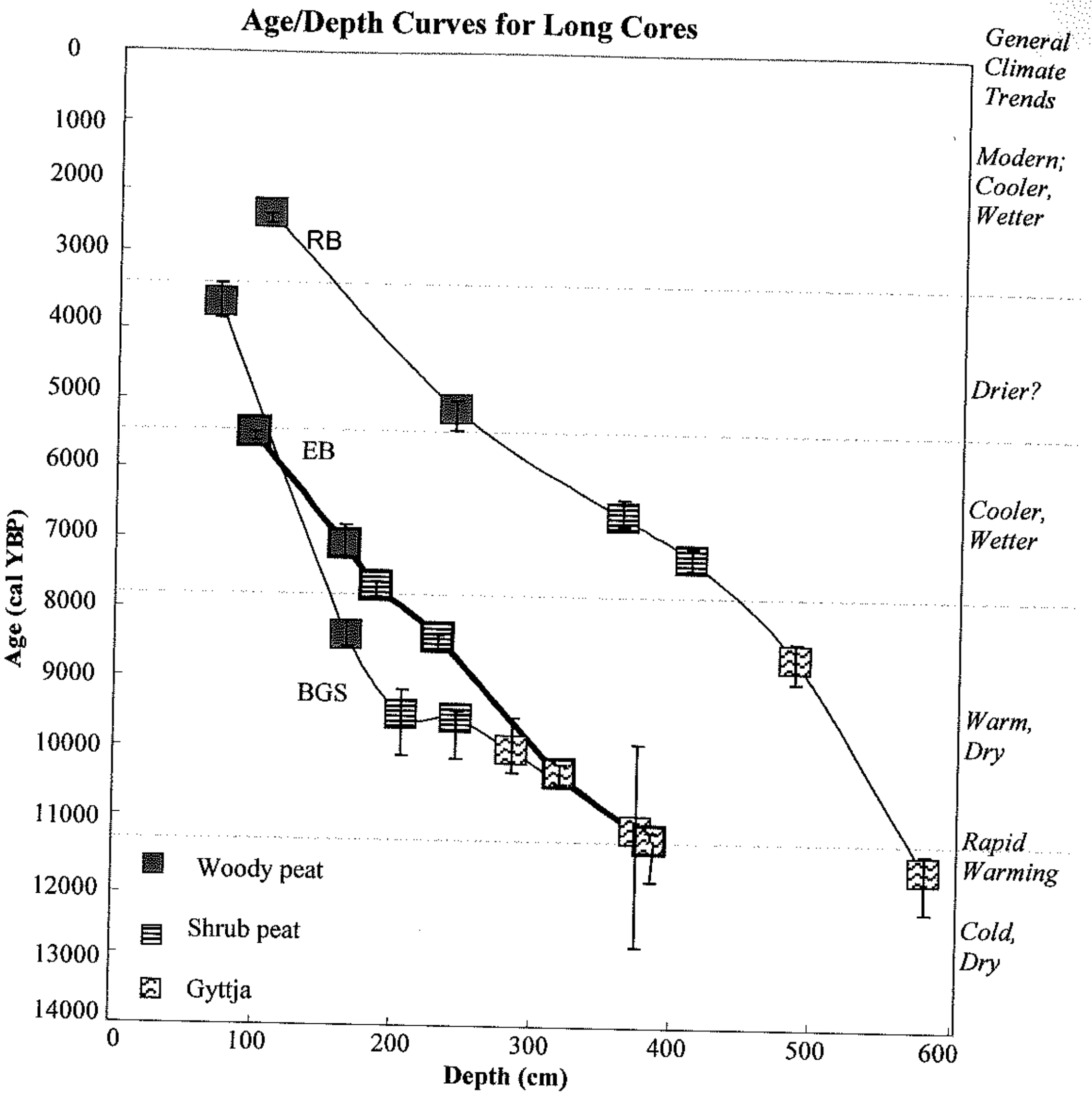

Figure 6a. Age/depth curves for long cores from each site. BGS= Black Gum Swamp, RB= Rindge Bog, EB=Ellinwood Bog. EB samples are outlined in black and connected by a heavier black line. Error bars = +/- 2 standard deviations from the median calibrated age. Lowest gyttja samples from each core are not included. General climate trends are based on Newby et al. (2000).

Pollen Diagram for Black Gum Swamp

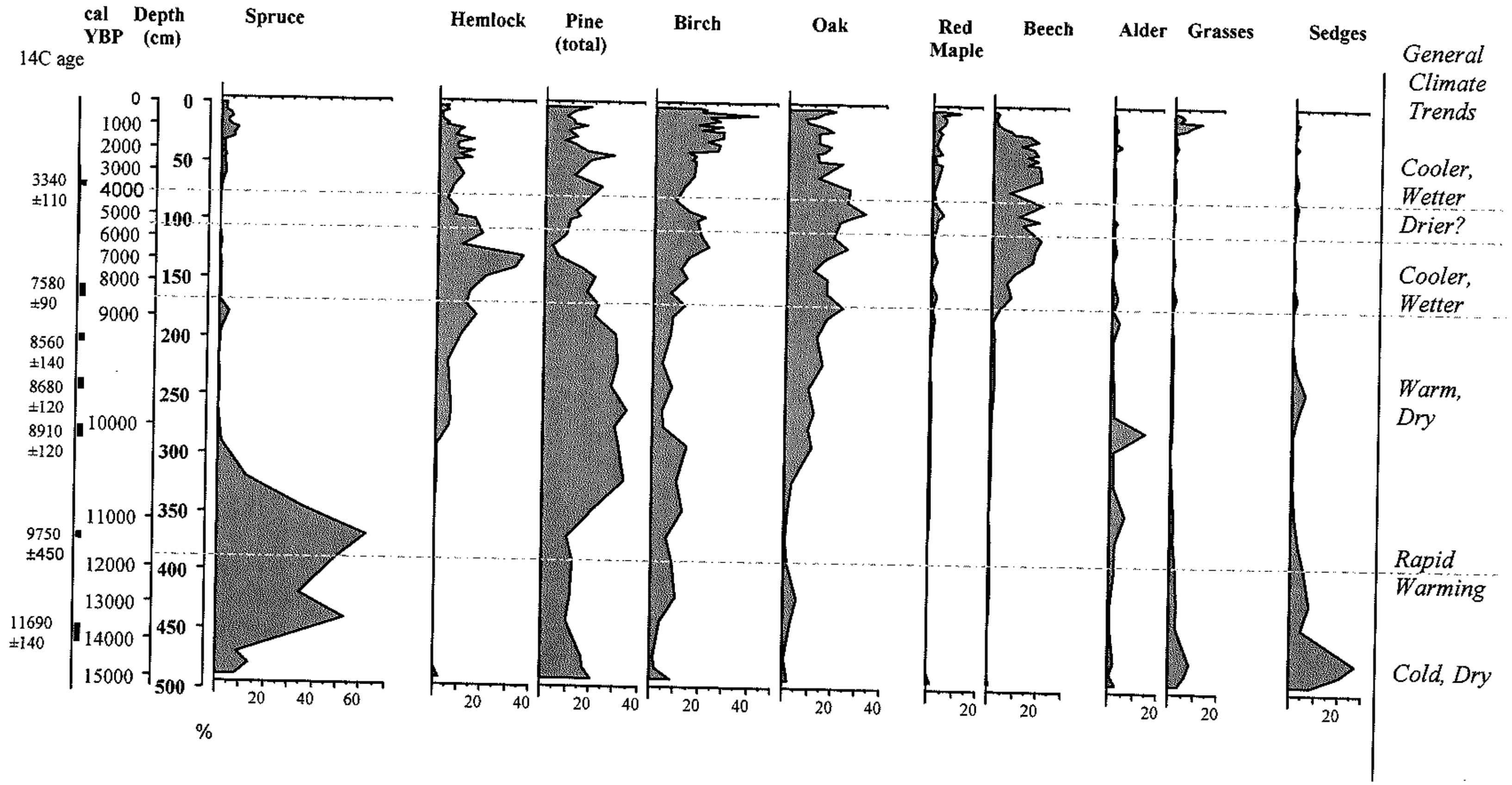

Figure 6b. Pollen diagram for Black Gum Swamp from the long core (Zebryk 1991) and general climate trends from Newby et al. (2000).

DISCUSSION

Although paludification is a major mechanism of peatland formation worldwide (Heinselman 1970, Frenzel 1983, Gore 1983, Johnson 1985, Glaser 1987), it has not been included in models of peatland development in temperate areas. By comparing the developmental histories and timing of successional events at multiple peatlands within the same climatic region, this study addresses the timing and relative importance of terrestrialization versus paludification and factors that influence peatland development in central New England. Results indicate that both terrestrialization and paludification were involved in the development of these peatlands although different rates and timing of developmental events among the sites suggest that autogenic processes and local topography exert greater control over development than regional climate change. Close similarities in the pattern of development among these sites provides the basis for a general model of temperate wetland development.

Deposit and sediment interpretations

Peat deposits are identified in this study as representing broad vegetation types, with woody peat developing from swamp forest vegetation and shrub peat resulting from an ericaceous bog mat and related shrub vegetation. The transition from shrub peat to gyttja was consistently sharp, supporting the interpretation that the shrub peat represents the expansion of shrub vegetation over shallow water and lake sediments. The transition from woody peat to shrub peat was typically gradual, suggesting a lengthy successional process involving a range of shrub and forested communities. These interpretations are consistent with macrofossil studies of nearby wetlands as well as models of bog mat formation (Swan and Gill 1970, Kratz and DeWitt 1986, Zebryk 1991). Gyttja is interpreted as resulting from algal and aquatic plant material collecting in permanent water bodies.

Developmental histories and driving forces

While overall developmental patterns were consistent at the three sites, the timing of successional events varied substantially. Lake-infilling and terrestrialization were the initial mechanisms of peatland formation. Limnic clay was deposited in the deepest basins, presumably coincident with ice melting in an open late-glacial landscape. This clay grades upward into more organic-rich sediments representing an open-water environment in a stabilized landscape. Accurate determination of the onset of gyttja deposition is hampered by extremely old basal dates from Rindge Bog and Ellinwood Bog. These anomalous dates may be due to contamination by older carbon from organic matter in soils or by the incorporation of non-atmospheric carbon in aquatic organisms (Olsson 1979, Ridge et al.1999). Over time, classic terrestrialization occurred: lake sediments accumulated, a marginal shrub mat encroached across the sediments and shallow water, and a swamp forest ultimately developed on the stabilized peat surface. At all three sites, the open shrub mat lasted less than a thousand years before the swamp forest became dominant. The low estimate of 53 years of shrub peat accumulation at Black Gum Swamp may be due to the bulk radiocarbon dating (Zebryk 1991), which is less precise than AMS dating, used on the samples. A more conservative estimate of 988 years is provided by the difference between the younger standard deviation of the upper shrub sample (BGS- E, 9164 cal YBP) and the older standard deviation of the lower shrub peat sample (BGS- D, 10152 cal YBP) of the calibrated bulk dates. As the transition from shrub peat to forest peat in the sediment cores was very gradual, the succession from a bog mat to a closed canopy forested swamp was likely very slow. Moderately deep basins with standing water filled in with gyttja and eventually developed into swamp forest without any evidence of an intermediate bog mat stage.

Basin depth and size appear to be major factors in determining the timing of sediment changes during terrestrialization. Terrestrialization occurred a thousand years earlier in the smaller basin at Black Gum Swamp than at a larger basin of similar depth at Ellinwood Bog. Rindge Bog, with the deepest and largest basin, was covered by a floating mat two thousand years after Black Gum Swamp. Overall, the three age/depth curves are relatively smooth with no synchronous changes in peat stratigraphy or accumulation rates during terrestrialization that might indicate regional climatic control over accumulation rates (Figure 6a). The pollen record for the site (Zebryk 1991) indicates these climate variations were influencing plants in the vicinity (Figure 6b).

Paludification is indicated at all three sites by the presence of up to a meter of woody peat deposited directly on mineral soil without a layer of intermediate gyttja, and by the sequence of radiocarbon dates indicating progressively younger basal peat samples away from the lake basins. Lateral expansion of the peatland appears to have initiated at different times at the three sites subsequent to terrestrialization. This suggests that lateral expansion was primarily influenced by autogenic factors, not a regional climate signal. The extent of peatland expansion varied substantially in this topographically complex landscape. Due to steep adjoining uplands, peatland expansion through paludification at Rindge Bog accounts for approximately 25% of the current peatland extent. In contrast, at Black Gum Swamp, with its shallow slopes and multiple basins, paludification increased the size of the peatland approximately 40% and joined several smaller basins into one extensive wetland. While steep surrounding topography appears to limit further expansion, it may still be occurring in the southeastern shallow lobe of Ellinwood Bog where the youngest basal sample is found.

Model for forested peatland development

Figure 7 presents a model for forested peatland development in temperate New England. After deglaciation, lakes occupy depressions in glacial till and clay is focused into deeper basins (A). With time, lake sediments (gyttja) become increasingly organic and are focused into the deeper section of the larger basins. In smaller basins, gyttja mixes with macrofossils from emergent and adjoining vegetation, forming a layer of macrofossil rich gyttja. Marginal shrub mats form on the edge of the larger basins (B). Organic matter falling from the bottom of the mat mixes with the gyttja and is deposited as gyttja with abundant macrofossils. At the edges of deeper basins, the shrub mat becomes grounded and a swamp forest slowly establishes (C). Woody peat begins to accumulate under the swamp forest as the shrub mat grows and continues to expand and solidify (D). As the smaller basins become shallower due to sedimentation, the swamp forest covers the basins and woody peat begins to accumulate (C-D). The complete transition from shrub mat to closed swamp forest canopy is slow and gradual.

The swamp forest laterally expands across the shallow slope outside the original lake basin at approximately the end of terrestrialization (D). As the woody peat continues to accumulate, it pushes the shrub peat further down into the basin (E) resulting in more woody peat accumulating in deeper sections of the basins. Lateral expansion continues until there is a limitation in the rise of the water table water due to factors such as a climate change, a steep slope, or reaching an outlet.

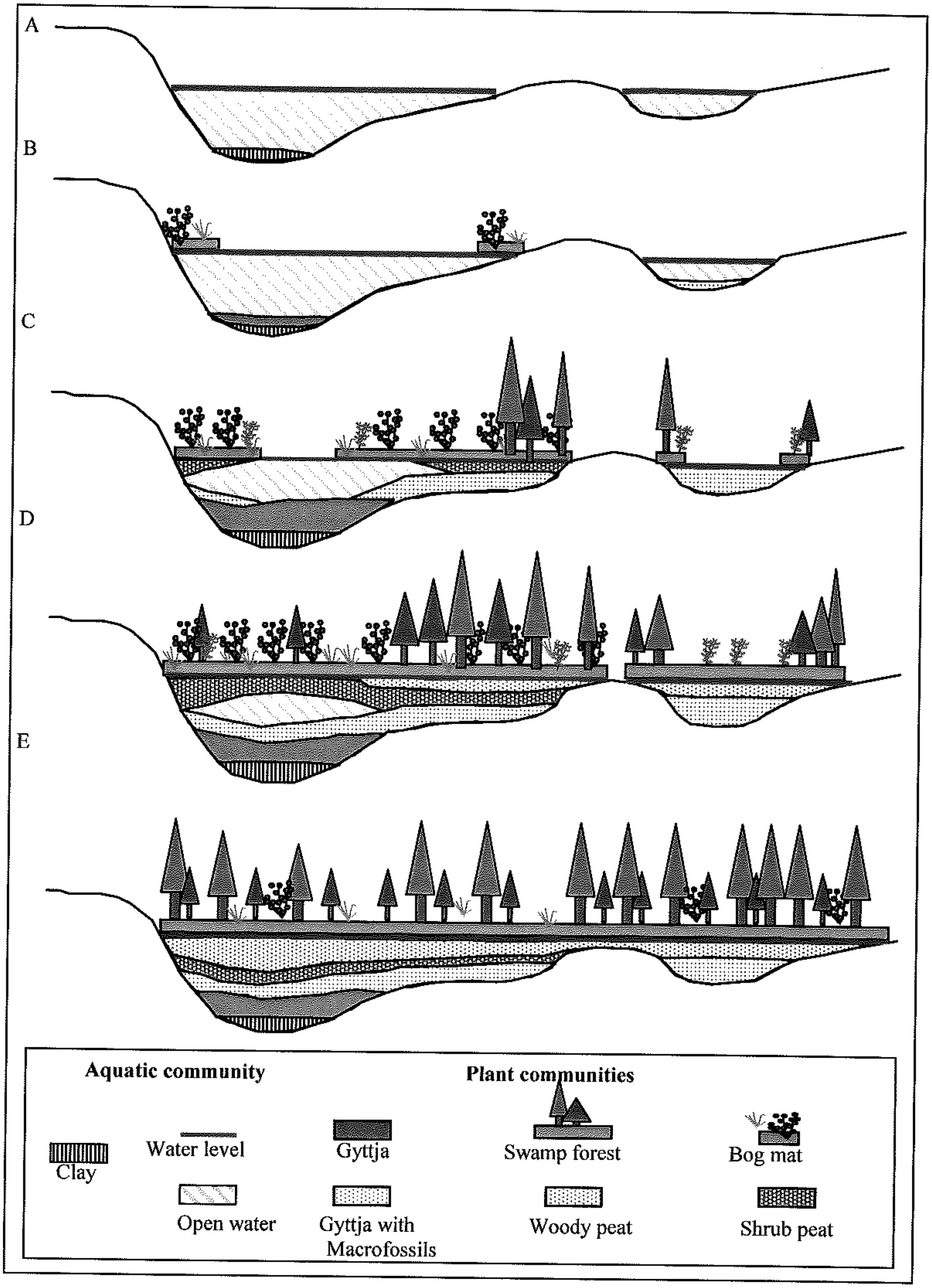

Figure 7. Model for forested peatland development in central New England. The events in the two basins are not assumed to be synchronous. Letter C is based on Kratz and DeWitt (1986).

CONCLUSIONS

This study presents documentation of the lateral expansion of peatlands as a result of paludification in temperate New England and demonstrates that terrestrialization alone is not an adequate model for peatland development in the region. The sites followed similar developmental pathways, with lake sedimentation and terrestrialization followed by paludification once the floating mat and associated shrub vegetation covered the basin. The extent of paludification at each site was determined by topographical constraints. As these events occurred at different times at each site, peatland development appears to be driven largely by autogenic factors, with little evidence for synchronous shifts in peat stratigraphy or rates of accumulation in association with major climatic shifts.

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