10 000 yr record of extreme hydrologic events

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ABSTRACT

Well-dated lacustrine sediments provide a hydrologic record indicating that the frequency and magnitude of runoff events, and by inference, storms, have varied over the past 10 k.y. in northern New England. We used five sediment cores and radiocarbon dating to develop a chronology of Holocene hydrologic events for the Ritterbush Pond basin, northern Vermont. Chemical and physical analyses allow us to identify 52 distinct layers of predominately inorganic sediment that represent terrestrially derived material delivered to the pond by runoff events. The thickness of some layers suggests hydrologic events at least equal in size to, and probably much larger than, any storm or flood recorded during nearly 300 yr of written regional history. Layer thickness and frequency and, by analogy, storm size and recurrence, change through the Holocene. The largest events occurred 2620, 6840, and 9440 calibrated ^{14}C years before present (cal ^{14}C yr B.P.). The most frequent hydrologic events occurred in three periods: 1750 to 2620, 6330 to 6840, and >8600 cal yr B.P. The recurrence interval of layer deposition during stormy periods averages 130 ± 100 cal yr, whereas the recurrence interval during less stormy periods is longer, 270 ±170 cal yr. The Ritterbush Pond event record illustrates the potential of inorganic lacustrine sediment to serve as a proxy record for estimating paleoflood frequency and deciphering climate change.

Keywords: hydrology, storms, lake cores, floods.

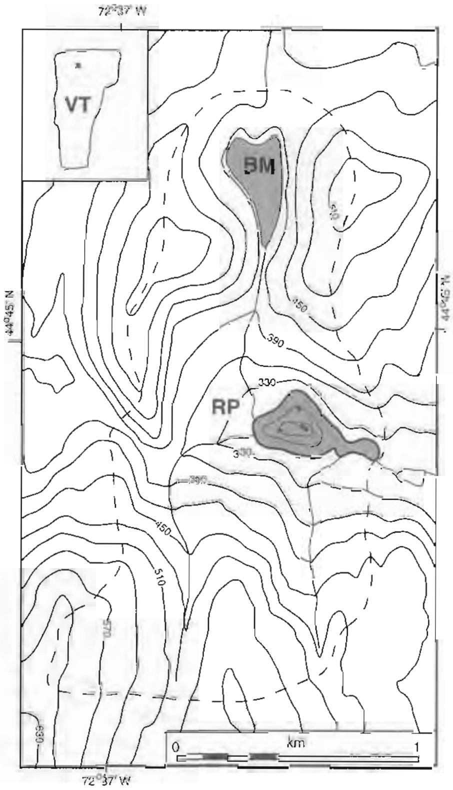

Figure 1. Ritterbush Pond watershed, Eden, Vermont (VT): pond elevation, 317 m; surface area, 0.07 km^2; maximum depth, 13.6 m. Stars indicate core locations. Dashed line is watershed boundary. Bathymetric contour interval, 6 m; topographic contour interval, 30 m; contour values are in meters. Adapted from U.S. Geological Survey quadrangle maps. RP = Ritterbush Pond, BM = Big Muddy Pond.

INTRODUCTION

Quantitative measures of extreme hydrologic events, in the form of precipitation intensity and duration records, exist for little more than 100 yr of New England's history (Ludlam, 1996). Newspaper accounts and diaries extend this record back more than 300 yr since European settlement began. Together, these records define the magnitude of extreme events and provide the design basis for local infrastructure. This paper demonstrates that ponds in mountainous New England, just as in similar landscapes around the world (e.g., Eden and Page, 1998), have the potential to provide an even longer record that could reveal high-magnitude, hydrologic events as far back as deglaciation, more than 13 000 ^{14}C yr ago.

Lake sediments preserve a record of surface processes and, by inference, the geomorphic effects of past climates and hydrologic events (Campbell, 1998; Eden and Page, 1998; Rodbell et al., 1999). In particular, terrestrially derived, inorganic layers in otherwise organic-rich lake sediment provide a record of basin-scale runoff and sedimentation events. In one northern Vermont water body, Ritterbush Pond, we find 52 such layers, many of which are considerably thicker than sediment layers deposited during the past 300 yr, for which we know at least relative storm intensity.

This new record of extreme hydrologic events suggests that New England is unprepared for the magnitude, and thus destructive potential, of future storms. Our approach provides a complementary alternative to the paleoflood methods developed for rivers (e.g., Kochel and Baker, 1982; Knox, 1993) and estuaries (Liu and Fearn, 1993) and is more applicable in regions where base levels have changed systematically since deglaciation (Brackenridge et al., 1988; Whalen and Bierman, 1996; Wright et al., 1997).

METHODS

Ritterbush Pond, a small postglacial lake, is located in the Green Mountains of northern Vermont; its level is controlled by a shallow bedrock spillway (Fig. 1). Several streams drain the steeply sloping forested hillsides, which expose metamorphic rocks overlain by a thin layer of glacial till and soil. We retrieved 3, 4.5–6-m-long continuous cores using a modified Reasoner coring device fitted with a piston (Reasoner, 1993). Two overlapping cores were recovered previously with a Livingston corer (Lin et al., 1995). In order to characterize the location, source, and extent of terrestrial sediment within the pond, three cores were located in the deepest part of the pond and two were taken near small deltas. Three of the cores bottomed in sand and till deposited just after deglaciation.

We used 10 analytical techniques to characterize the sediments, in particular, the discrete inorganic deposits that punctuate otherwise organic-rich sediments (Brown, 1999). Each core was analyzed at centimeter intervals for magnetic susceptibility, loss on ignition (LOI), and/or total organic carbon (TOC), and X-ray radiograph density (Fig. 2). Lithologic, bulk-density, grain-size, carbon:nitrogen ratio (C/N), stable carbon isotope, and charcoal analyses focused on determining the origin, sedimentology, and depositional processes of individual inorganic layers.

We developed a detailed record of 52 discrete inorganic layers; we use the stratigraphy of a core (C2) from the center of the pond as an example of the results; data for the four other cores were provided in Brown (1999) and Lin et al. (1995). Accelerator mass spectrometer (AMS) radiocarbon dates (on both gyttja and macrofossils) from each core were calibrated to calendar years with CALIB v 3.0a (Stuiver and Reimer, 1993) and used to confirm the stratigraphic correlation among cores (Table 1).[1] These radiocarbon dates provide age control on individual depositional events and the intervals of increased inorganic

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[1] Data Repository item 200037 contains additional material related to this article.

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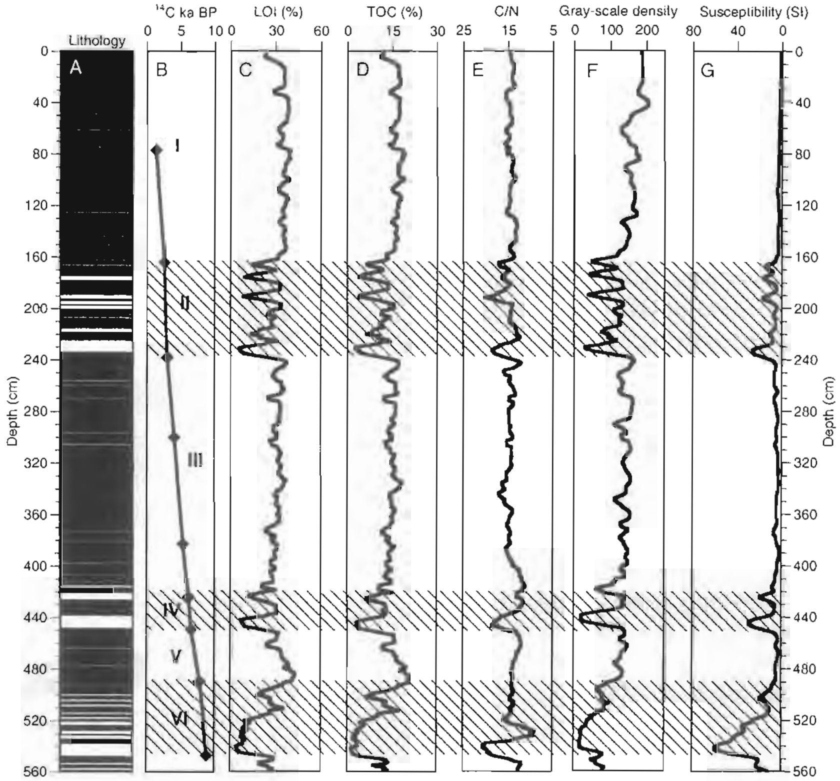

Figure 2. Comparison of high-resolution (centimeter by centimeter), whole-core data sets on Ritterbush Pond core C-2 indicates location of inorganic layers (white in A). Horizontal shaded bars demark clusters of inorganic layers interpreted as times of larger and more frequent storms (intervals II, IV, and VI). A: Lithology; black indicates predominately gyttja; white indicates terrestrially derived, predominately inorganic sediment. B: Radiocarbon ages on core C2 plotted as diamonds. C: Loss on ignition (LOI) determined by combustion at 450 °C for 2 hr and smoothed with five-point running average. D: Total organic carbon (TOC) determined by using CE NC 2500 Elemental Analyzer on samples pretreated with dilute HCl and smoothed with five-point running average. E: Carbon:nitrogen ratio (C/N) determined by using elemental analyzer on samples pretreated with dilute HCl and smoothed with five-point running average. F: X-ray radiograph gray-scale density, measured at 72 dpi, averaged and plotted at 1 cm intervals. G: Magnetic susceptibility (measured by using Bartington MS2 at 1 cm stepping resolution).

deposition. Samples of gyttja were dated above and below three of the thickest inorganic layers (Bierman et al., 1997) and support instantaneous layer deposition. Because the inorganic layers do not represent significant time within the chronology, but do represent a significant thickness, their thickness was removed prior to age modeling (Eden and Page, 1998). Dates at interval boundaries were used to model linearly the deposition of gyttja and inorganic material within each interval and thus provide a radiocarbon and calibrated model age for each of the 52 events in Ritterbush Pond (Fig. 3).

RESULTS

The Ritterbush Pond cores are composed primarily of lacustrine organic sediment (gyttja) punctuated by inorganic layers of varying thickness (1 mm to 10 cm). Magnetic susceptibility, X-ray gray-scale density, LOI, TOC, and C/N data exhibit coincident, distinct variations that correspond to lithologic changes with depth (Fig. 2). The thicker (>1 cm), sandier layers cluster in three distinct intervals within the cores, identified as the even-numbered intervals (II, IV, VI) (Figs. 2 and 3). The odd-numbered intervals (I, III, V) are characterized by fewer and thinner laminations of fine silt. These six intervals, and the majority of the layers within them, are correlatable among all five cores (Brown, 1999). The thickest inorganic layers are normally graded from medium sand to fine silt, and are in sharp contact with the surrounding gyttja. Both the thickness and mean grain size of the layers correlated between cores decrease toward the center of the pond (Brown, 1999).

The sediment in the layers must have originated from the surrounding watershed or the shallow pond margins. The inorganic layers include macrofossils, such as wood and leaves, that are clearly of terrestrial origin. Relatively high C/N ratios (15–20) and the $\delta^{13}C$ values of included organic matter indicate that a mixture of terrestrial and vascular aquatic plants make up the organic fraction of the predominantly inorganic sediment layers (Bierman et al., 1997; Lini, 1997; Lini et al., 1998). Together with lithologic, grain-size, and radiocarbon data, the organic matter characterization indicates interruption of quiet-water gyttja deposition by episodic terrestrial sediment influxes perhaps carried to the center of the pond by density currents (Bierman et al., 1997; Brown, 1999).

The radiocarbon-based age model places the clusters of depositional events at 1800–2540 (1750–2620), 5525–5980 (6330–6840), and >7730 (>8600) ^{14}C yr B.P. (cal yr B.P.) (Fig. 3). The average event recurrence interval for odd intervals (I, III, V), in which the layers are as thick as 1 cm, is 270 ± 170 cal yr; the average event recurrence for the even intervals (II, IV, VI), in which layer thickness ranges from 0.1 to 10 cm, is 130 ± 100 cal yr.

DISCUSSION

The 52 discrete inorganic layers each represent an individual erosional event in the watershed that caused an episode of terrestrial sediment delivery to Ritterbush Pond. What caused the hydrologic and/or geomorphic conditions that repeatedly allowed sediment transport to Ritterbush Pond? We consider three possibilities: very large hydrologic events (storms), removal of vegetation by

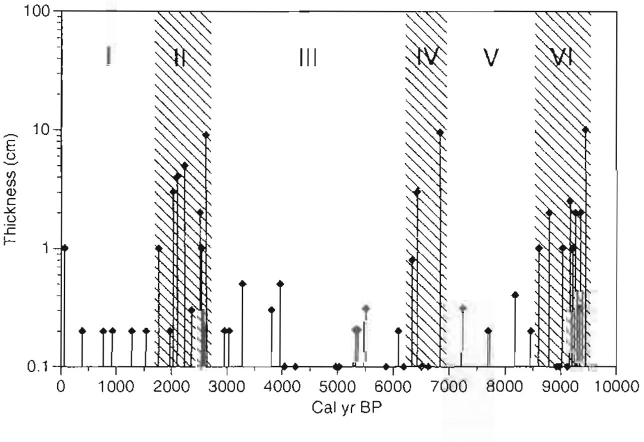

Figure 3. Event chronology based on calibrated ^{14}C ages for organic material from Ritterbush Pond. Individual layer ages based on age model that linearly interpolates organic sediment deposition rate between bracketing radiocarbon ages for each interval. Thickest and most frequent layer deposition is clustered in three shaded intervals (II, IV, VI) during late, middle, and early Holocene.

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[1] GSA Data Repository item 200037, Table 1, Radiocarbon dates for Ritterbush Pond, is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/drpint.htm.

blight or fire, and earthquakes triggering mass movement. We discount the latter, because of New England's relative tectonic stability (Ouellet, 1997; Ebel et al., 1995). Pollen data from all of New England (Jackson and Whitehead, 1991; Spear et al., 1994) do not indicate extensive deforestation at any time during the Holocene. A blight-induced hemlock decline at 4800 ^{14}C yr B.P. may have partially deforested some slopes at Ritterbush Pond (Lin et al., 1995), but there is no evidence for inorganic layer deposition at this time.

Because hillslope-clearing fires are often linked to slope failure and sediment transport (e.g., Clark, 1988; Meyer and Wells, 1997; Whitlock and Millspaugh, 1996), we analyzed sections of the core for charcoal content by using a nitric acid digestion method (Winkler, 1985). The data show that charcoal abundance is low throughout the core and does not increase within or around the thickest layers, suggesting that fires are rare in the basin and that layer deposition is apparently not coincident with fires (Fig. 4).

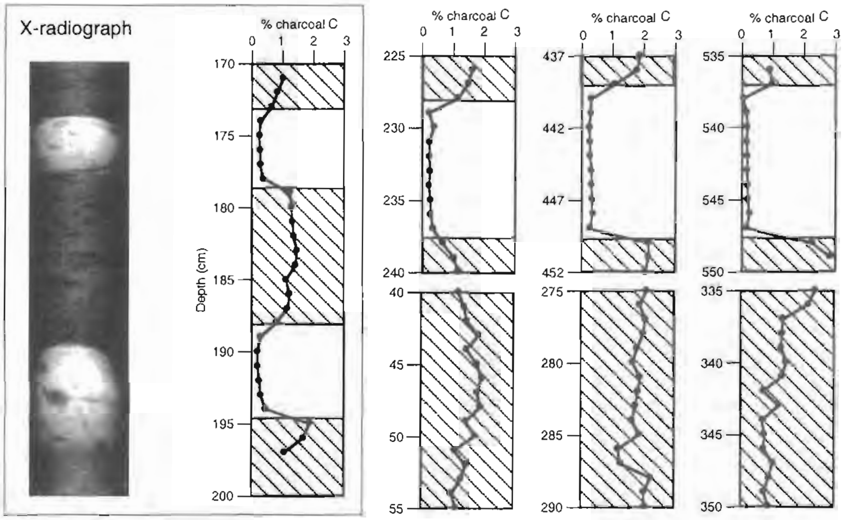

Figure 4. Percent charcoal carbon in seven subsections of core C2 from center of Ritterbush Pond as measured by nitric acid digestion (Winkler, 1985) modified so that material remaining after digestion was analyzed for total organic carbon by elemental analysis. Four subsections contain sedimentation events; three subsections are controls from parts of core containing only gyttja. X-radiographic image of corresponding portion part of core C2 (depth 170–200 cm) illustrates events.

The most likely trigger for the deposition of coarser, terrestrial sediment layers is runoff triggered by hydrologic events. Inorganic layer deposition in Ritterbush Pond is most likely the result of storms, including rain-on-snow events, which increase rates of hillslope erosion, stream-channel scouring, and pond-marginal sediment reworking. Specifically, we suggest that terrestrial sediment stored in the watershed and at the pond margins is transported toward the center during storm events that significantly increase stream discharge and erosion (Eden and Page, 1998; Campbell, 1998). The range in layer thickness from 1 mm to 10 cm within core C2 implies variation in the energy or size of density currents causing sediment transport and layer deposition. Such variation suggests time-dependent changes in storm size.

Storm Magnitude

We can make rough estimates of storm magnitudes represented by the layers deposited in Ritterbush Pond by using historic weather data, the modeled age of events, and the thickness of the inorganic deposits. Ritterbush Pond core C2 reveals only a single, 1-cm-thick layer within deposits of the past 300 yr; the modeled age of this layer is consistent with the date of the largest storm in Vermont's written history, the flood of record, 1927 (Ludlam, 1996; Kinnison, 1929). If layer thickness is a proxy for storm magnitude, then 18 of the 52 events we identify in the Ritterbush Pond cores were larger than the 1927 flood. The 9, 9.5, and 10 cm layers deposited at 2600, 6840, and 9440 cal yr B.P. are particularly striking and imply hydrologic events much larger than any witnessed during 300 yr of western settlement.

We used an intensity vs. duration model for hillslope failure in the forested Appalachians (Kochel, 1990) to constrain the meteorological conditions represented by inorganic layers in the Ritterbush Pond cores. Probabilistic approaches (Dunne and Leopold, 1978) allowed us to estimate the 100-yr-return storm for the 1 hr and 24 hr cases; we present these along with data from the 1927 storm on Kochel's diagram (Fig. 5). These three extreme scenarios plot on the lower boundary of the envelope, suggesting that they are barely capable of inducing slope failure—a conclusion consistent with the single historical event preserved in the sediments of Ritterbush Pond.

How large are the hydrologic events at 2600, 6840, and 9440 cal yr B.P. represented by 9–10-cm-thick layers in the cores? If our meteorological inferences are correct, then these events are larger than the 100 yr storms at various durations as well as the flood of record. An upper bound for events recorded by Ritterbush Pond sediments is provided by the U.S. Weather Bureau (1961) estimate of probable maximum precipitation (PMP). PMP values, based on observations and atmospheric models, suggest that northern New England could receive as much as 48 cm of precipitation in 6 hr, sufficient to trigger hillslope failure in forested terrain (Williams and Guy, 1973). The PMP plots well within Kochel's envelope for slope failure.

Although the interpretation of layer thickness in terms of rainfall magnitude is imprecise, the thickness and extent of an event recorded in the pond cores are direct proxies for the magnitude of slope and channel instability in the basin. Sediment transport to the pond likely requires that a threshold be crossed; perhaps a delta front oversteepens or a previously weakened hillslope collapses. Landscape conditioning must also be important; high ground-water tables would allow smaller rainfall events to destabilize slopes and erode channels more effectively.

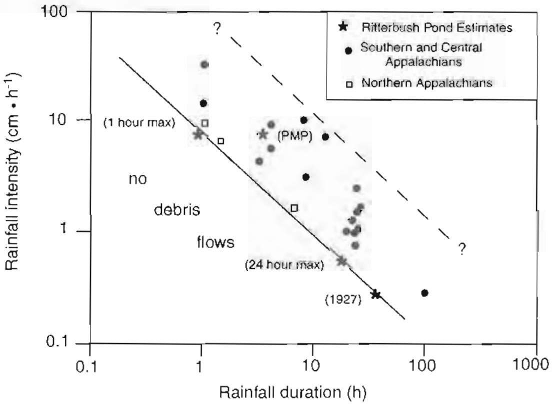

Figure 5. Intensity vs. duration relationships for major debris-flow–producing storms in Appalachians (from Kochel, 1990). Storms capable of causing debris flows are plotted with circles and squares. We interpret this envelope to show range of meteorological conditions needed to trigger hillslope instability and subsequently initiate inorganic sediment deposition in Ritterbush Pond. Estimates of maximum-intensity storms at Ritterbush Pond are plotted as stars: 100 yr, 1 and 24 h maximum precipitation estimated from National Weather Service data for Burlington, Vermont, scaled to elevation of Ritterbush Pond using multiplier established empirically from relationship for 31 Vermont weather stations between elevation and average precipitation (7.5 cm precipitation per 100 m elevation based on 30 yr normal values); probable maximum precipitation (PMP) from U.S. Weather Bureau (1961) isohyetal maps; flood of 1927 from isohyetal maps (Kinnison, 1929). Only PMP plots well within shaded envelope in which precipitation duration and intensity are sufficient to generate slope failure on steep, forested hillsides.

Event Timing

The frequency of inorganic layer deposition and the thickness of the layers fluctuate nonrandomly through the Holocene (Fig. 3). During at least three intervals (II, IV, VI), lasting from 500 to >900 yr, thicker layers were deposited more frequently. For example, the past 1750 yr (interval I) record fewer depositional events than the preceding 870 yr (interval II). Thus, the recurrence interval (RI) for events capable of triggering inorganic deposition in Ritterbush Pond is not uniform. Events occur more frequently (RI = 130 ± 100 cal yr) during stormier, even-numbered intervals than during calmer, odd-numbered intervals (RI = 270 ± 170 cal yr).

The alternation between intervals of increased terrestrial sediment deposition and quieter periods, at least three times in the past 10 k.y., suggests longer term forcing than seasonal or decadal cycling. However, we can deduce no temporal or causal relationship between the event clusters (intervals II, IV, and VI) and other, more general paleoclimate records for New England including pollen, ice-core, and lake-level records (Bierman et al., 1997).

Pollen chronologies for Ritterbush Pond (Lin et al., 1995) and northeastern North America (Spear et al., 1994; Webb et al., 1993) indicate a threefold division of postglacial time: gradual warming after deglaciation, increased warmth and moisture in the middle Holocene, and cooler, wetter conditions in the past few thousand years. The intervals of increased inorganic layer deposition appear unrelated to these long-term climate changes; interval VI occurred during a warm and dry climate and interval II occurred during a cool, wet period. Layers were not deposited in Ritterbush Pond during the Little Ice Age, the Medieval Warm Period, or the 8200 cal yr B.P. drying event identified in the Greenland ice cores (Alley et al., 1997), suggesting no clear correlation with widespread climate events. The frequency of geomorphically effective storms is apparently decoupled from longer and larger scale climate change as reflected by vegetation or ice-core records.

Ritterbush Pond data reflect the occurrence and effects of rare, extreme hydrologic events. Coring lakes throughout the Appalachians will reveal the temporal and spatial coherence of paleostorms in this, the most populous region of North America. Such data will suggest what proportion of the hillslope instability we infer is regional in nature and what proportion reflects local, noncorrelatable events. Additional paleohydrologic data, such as we report here for New England, will be of significant utility to planners. The data will allow more accurate hazard assessments in regard to flooding, runoff generation, and slope instability triggered by extreme, long-recurrence-interval storms. The long-term perspective provided by geologic investigations is particularly important given the extensive damage and flooding caused by recent hurricanes, including Andrew and Floyd.

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TABLE 1. RADIOCARBON DATES FOR RITTERBUSH POND

CAMS number	Core	Depth (cm)	Correlation depth in C2[*]	Material	$\delta^{13}C$[†]	^{14}C age	Adjusted ^{14}C age[§]	Calibrated Age[#] (cal yr B.P.)	Best age estimate[**]
33132	RT-2	96	164	gyttja	-31.7	2570 ± 60	2120	2146 (2093) 1993	2090
33135	RT-2	142	228	gyttja	-31.5	3170 ± 60	2720	2855 (2787) 2767	2790
33352	RT-2	154	238	gyttja	-29.5	2940 ± 70	2490	2717 (2707, 2629, 2499) 2475	2610
22993	RT-2	220	300	gyttja	-30.6	3960 ± 60	3510	3843 (3817, 3782, 3732) 3700	3780
33351	RT-2	339	439	gyttja	-32.0	6540 ± 60	6090	7014 (6915) 6871	6920
20195	RT-2	348	448	gyttja	-32.4	6430 ± 70	5980	6884 (6833, 6826, 6799) 6742	6820
32856	RT-2	416	537	gyttja	-32.7	9140 ± 60	8690	9666 (9638) 9533	9640
32854	RT-2	426	547	gyttja	-31.8	8870 ± 60	8420	9469 (9434) 9374	9430
33134	RT-2	426	547	gyttja	-31.8	8950 ± 50	8500	9469 (9467) 9444	9470
33350	RT-2	426	547	gyttja	-31.8	8890 ± 60	8440	9471 (9440) 9385	9440
32855	RT-2	426	547	seed	-28	8450 ± 60	8450	9475 (9442) 9389	9440
46942	C2	77	77	gyttja	-31	1290 ± 40	840	771 (733) 699	730
46943	C2	383	383	gyttja	-31	5240 ± 40	4790	5587 (5578) 5566 5540 (5510, 5505) 5473	5520
46944	C2	424	424	gyttja	-31	6080 ± 40	5630	6456 (6412) 6394	6410
40775	C2	440	440	twig	-28	6020 ± 70	6020	6932 (6866) 6767	6870
46945	C2	489	489	gyttja	-31	7720 ± 40	7270	8081 (8060, 8039) 8021 8017 (8001) 7981	8030
40776	C2	548	548	gyttja	-31	9030 ± 60	8580	9571 (9505) 9459	9510
44693	C3	64	164	wood	-26.5	2050 ± 50	2050	2060 (1990) 1931	1990
44695	C3	144	238	wood	-27.6	2550 ± 50	2550	2751 (2726) 2709 2622 - 2502	2610
44697	C3	375	432	wood	-28	5790 ± 70	5790	6677 (6626) 6504	6630
44699	C3	444	510	bark	-32.0	7880 ± 50	7880	8718 (8582) 8540	8580
44694	C4	81	164	leaves	-28.0	2040 ± 50	2040	2042 (1980) 1916	1980
44696	C4	132	238	gyttja, leaves	-29.5	2570 ± 60	2570 [††]	2761 (2734) 2709 2623 - 2502	2630
44698	C4	311	448	gyttja, leaves	-23.3	6430 ± 40	5980	6860 (6833, 6826, 6799) 6774	6820
44700	C4	380	547	wood	-30.6	8450 ± 50	8450	9473 (9442) 9399	9440

[*] All ages are stratigraphically correlated to depth in core 2 (C2).

[†] Measured acid-base-acid-washed samples reported to one decimal place. Estimated values (no decimal) are average for all measured samples.

[§] ^{14}C ages were adjusted for measured gyttja-macrofossil offset by subtracting 450 ^{14}C yr from each gyttja age. For explanation and justification see Bierman et al (1997).

[#] Adjusted ^{14}C ages calibrated with CALIB rev 3.0.3A (Stuiver and Reimer, 1993). A 1σ range encloses reported intercepts in ().

[**] Intercept or average of intercepts where one range is reported, weighted average of intercepts (or midpoint of range where no intercept is reported) where two ranges are reported. Ages rounded to nearest decade.

[††] Sample not adjusted for gyttja-macrofossil offset because of ambiguity of material dated.