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INSIDE

Postglacial Ponds and Alluvial Fans: Recorders of Holocene Landscape History

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ABSTRACT

Little is known about rates and patterns of Holocene hillslope erosion in areas once covered by Pleistocene ice sheets and now heavily populated. Yet, understanding past landscape behavior is prerequisite to predicting and mitigating future impacts of human-induced disturbance and climate change. Using northern Vermont as an example, we demonstrate that the sedimentary record preserved in humid-region ponds and alluvial fans can be dated, deciphered isotopically and stratigraphically, and used to understand the history of hillslope erosion. Our data suggest that erosion rates were higher in the early and late Holocene than in the mid-Holocene, perhaps the result of changing climate and the frequency of severe storms. In Vermont, dated alluvial fan sediments reveal that the highest rates of hillslope erosion occurred as a consequence of European settlement. The geologic record of colonial deforestation is clear, revealing significant human impact and suggesting that past landscape response is a meaningful basis for guiding future land management practices.

INTRODUCTION

Geologists have studied mountainous landscapes in western New England for over 150 years (Hitchcock, 1833). Major landscape features are controlled by Appalachian structure and lithology; there is a

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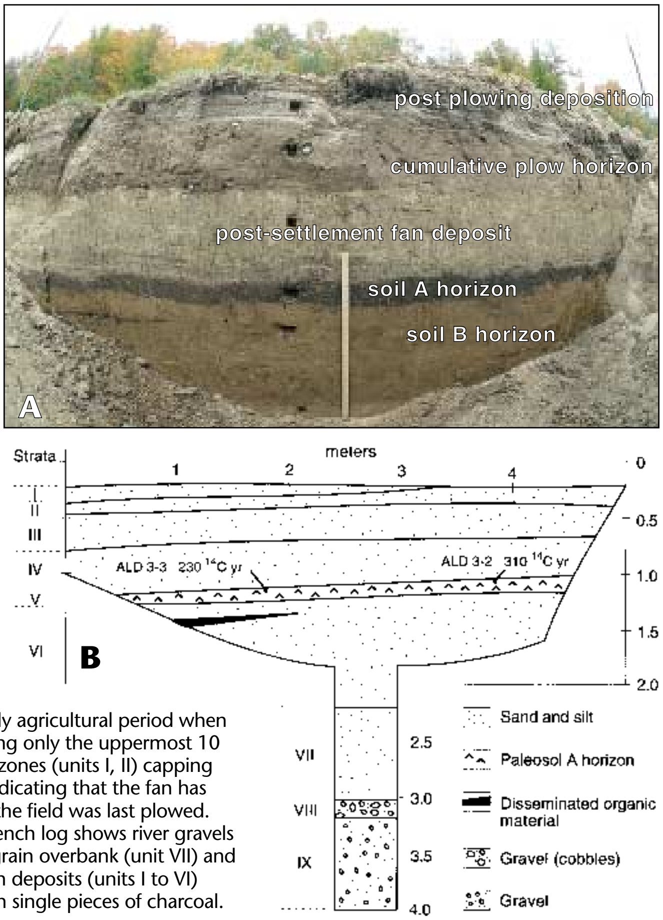

Figure 1. Fish-eye view (A) and interpretive log (B) for a backhoe trench cut into the toe of a fine-grained Vermont alluvial fan and oriented perpendicular to fan axis (trench ALD-3, fan ALD-B). The exposure shows a dark brown soil buried by sand and silt eroded from adjacent hillslopes during and after European settlement and land clearance. Worm burrows filled with material of contrasting color are evident in and near the soil horizon. A: The reddened B horizon in the distal fan deposits (unit VI) is capped by well-developed, dark brown paleo–A horizon (unit V). The chaotic light tan zone (unit IV) above the paleosol represents first deposits after hillslope clearance but before the fan surface was plowed. Overlying darker zone (unit III) is a well-mixed, cumulative plow horizon, the thickness (35 cm) of which demonstrates that the fan remained active during the early agricultural period when plows were capable of disturbing only the uppermost 10 to 15 cm of soil. Light-colored zones (units I, II) capping the section remain stratified, indicating that the fan has been active since 1960, when the field was last plowed. The stick is 1 m long. B: The trench log shows river gravels (units VIII, IX) underlying fine-grain overbank (unit VII) and post- and prehistoric alluvial fan deposits (units I to VI) along with radiocarbon ages on single pieces of charcoal.

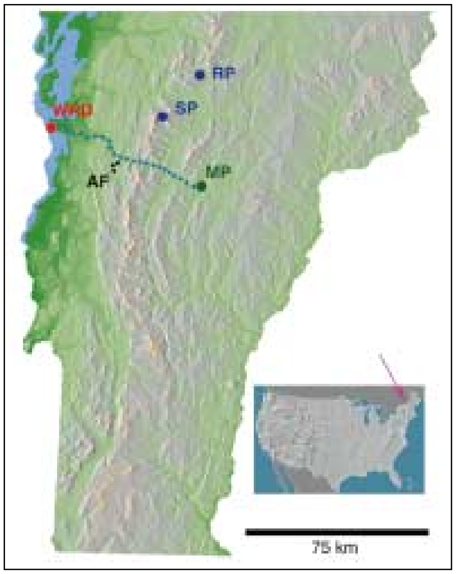

Figure 2. Shaded relief map of Vermont. RP = Ritterbush Pond, SP = Sterling Pond, WRD = Winooski River delta in Lake Champlain, AF = Aldrich, Moultroup, and Audubon alluvial fans, MP = Montpelier. Dotted line indicates the main stem of the Winooski River. Inset map courtesy of R. Sterner.

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relatively thin cover of Pleistocene and Holocene sediment. Although geomorphologists have mapped the distribution of glacial sediments and determined the pattern and timing of glacier retreat (e.g., Flint, 1971; Koteff and Pessl, 1981), little is known about the rate and distribution of surface processes affecting New England hillslopes during the Holocene.

Hillslope erosion in New England was probably most rapid immediately after deglaciation when vegetation was sparse (Waitt and Davis, 1988). As forests spread over the region 11,000–12,000 ^{14}C yr B.P. (Davis and Jacobson, 1985), erosion rates declined, as indicated by decreasing late Pleistocene and early Holocene sedimentation rates in the Champlain Basin (Freeman-Lynde et al., 1980). Until the late 1700s, much of New England remained forested, although some forests may have been open woodlands with understory vegetation kept in check by Native American fires (Pyne, 1982).

During the past 200 years, humans have changed the New England landscape. Settlers cleared trees from over 80% of northwestern Vermont prior to the Civil War, using deforested hillslopes for farming and grazing livestock. Forests below 600 m elevation were almost completely removed by the early 1800s (Meeks, 1986). In response to deforestation, hillslopes eroded and rivers aggraded (Figs. 1, 2, 3, and 4). In Vermont, the transitory expansion of the Winooski River delta into Lake Champlain during the mid-1800s testifies to the amount of sediment rapidly mobilized from uplands as a result of colonial deforestation (Figs. 2 and 3). Following the opening of the American mid-continent to settlement (1850s and 1860s), 200,000 people emigrated from Vermont, abandoning marginal farmland (Severson, 1991). Since then, forests have again cloaked Vermont hillslopes, and rivers have incised their floodplains (Brakenridge et al., 1988), similar to landscape response

Holocene Landscape *continued on p. 3*

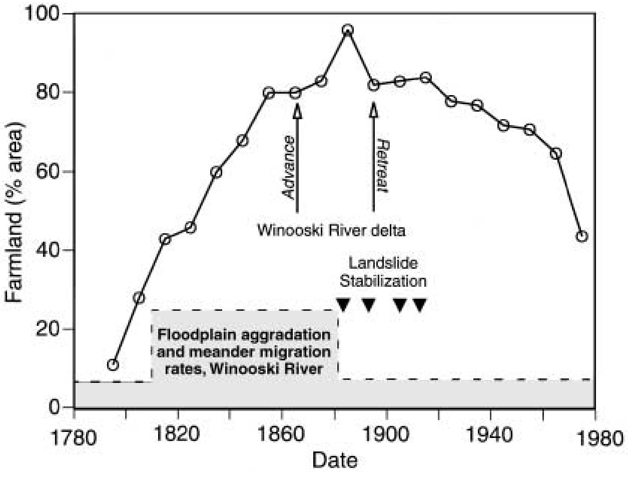

Figure 3. Historic landscape response in Chittenden County, northwestern Vermont. Open circles represent the percentage of land area in the county occupied by cultivated land, pastures, overgrown fields, orchards, and farm woodlots. Clearance before 1830 was for farming; later clearance was for lumber (U.S. Bureau of the Census, in Severson, 1991). The arrows mark major expansion and contraction of the Winooski River delta in Lake Champlain as deduced from historic maps (Severson, 1991). Winooski River's 2900 km^2 watershed represents 13% of the drainage area for Lake Champlain. Triangles indicate the maximum age of trees growing in fossil landslide scars on a tributary of the Winooski River, indicating when slides stabilized. The period of increased meander migration and floodplain aggradation in the lower Winooski River flood plain is shown schematically (Thomas, 1985).

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Help Celebrate the Memory of Laurence L. Sloss

Sunday, October 19, 2–5 p.m., Room 251AB, Salt Lake City Convention Center
Sponsored by the GSA History of Geology Division

Distinguished stratigrapher, former GSA president, Penrose Medalist, and geological statesman L. L. Sloss died just a few days after the 1996 GSA Annual Meeting. Join Larry's many friends, students, and admirers in celebrating a remarkable career. R. H. Dott, Jr. (University of Wisconsin) will moderate the session, which will feature memories shared by close Sloss associates, such as Edward C. Dapples and Peter Vail, followed by comments from the audience. All are welcome, particularly students, who should profit especially from learning about an exceptional person whose contributions, most notably the concept of sequence stratigraphy, form an important part of their professional legacy.

In Memoriam

Thomas Henry Clark
Canada
April 28, 1996

Robert M. Dreyer
San Francisco, California

John E. Nafe
Canada
April 7, 1996

Vincent D. Perry
New York, New York
August 1997

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noted in the mid-Atlantic States (Costa, 1975).

METHODS

In order to infer the Holocene history of hillslope behavior, we excavated shovel and backhoe trenches (1 to 4.5 m deep, 5 to 14 m long) in 23 alluvial fans in northwestern Vermont and collected continuous sediment cores from two ponds. Organic material including charcoal, wood, and gyttja (lake mud rich in organic carbon) was dated at Livermore Laboratory; ^{14}C was used according to standard protocols. In order to make our data comparable to existing literature, we report all ages in ^{14}C years corrected for ^{13}C/^{12}C, but not calibrated for changing initial ^{14}C abundance. The stable carbon isotope composition of the total organic carbon (TOC) fraction of acid-treated sediment was determined at the University of Vermont by combusting the samples in sealed quartz tubes, analysis on a VG SIRA II mass spectrometer, and comparison to standards (values reported relative to VPDB). Replicate analyses reproduce to better than 0.1‰. Loss on ignition (LOI) was measured as a proxy for organic carbon content by burning dried samples at 450 °C for 2 h; samples for LOI were taken contiguously every 2 cm.

ALLUVIAL FANS

The fans we investigated are very small (<2500 m^2), subtle landforms found on flat, permeable river terraces below higher terraces or hillslopes covered by till or glacial lake sediments. All but one of the fans are grass-covered and show little recent activity. In northern New England, such small fans have not been well studied, although elsewhere workers have investigated humid-region fans (e.g.,

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TABLE 1. RADIOCARBON AND AGGRADATION DATA FOR ALLUVIAL FANS, HUNTINGTON RIVER VALLEY, VERMONT

Trench	Fan*	Sediment deposited in time interval (m)	Time of deposition[†] (^{14}C yr B.P.)	Laboratory number	Context of sample	Time Period
ALD-2	ALD-A	4	<100	GX-21329	Basal age	Historic
ALD-3	ALD-B	1	<230 ± 60, 310 ± 60	CAMS-26105 and 26106	Above buried soil	
ALD-5	ALD-C	0.9	<100	CAMS-26108	Above buried soil	
MUL-4	MUL	0.6	<100	CAMS-16584	Above buried soil	
AUD-1	AUD	0.4	<125	CAMS-20900	Above buried soil	
ALD-4	ALD-B	1.3	1850 ± 80 to 1900 ± 50	CAMS-30358 and 30359	Basal interval	Late Holocene
ALD-5	ALD-C	2.1	840 ± 60 to 2500 ± 60	CAMS-22994 and 22995	Basal interval	
MUL-1 and 4X	MUL	Basal age	between 7360 ± 95 and 7835 ± 105	GX-20058 and 20276	Basal interval, underlying terrace	Early Holocene
AUD-1	AUD	Basal age	between 8060 ± 60 and 8530 ± 100	CAMS-20901 and 20963	Basal interval, underlying terrace	

*UTM locations for the sampled fans: MUL (659680E, 4913800N), AUD (659730E, 4912150N), ALD (660740E, 4914110N).
[†]Dates bound sedimentary units.

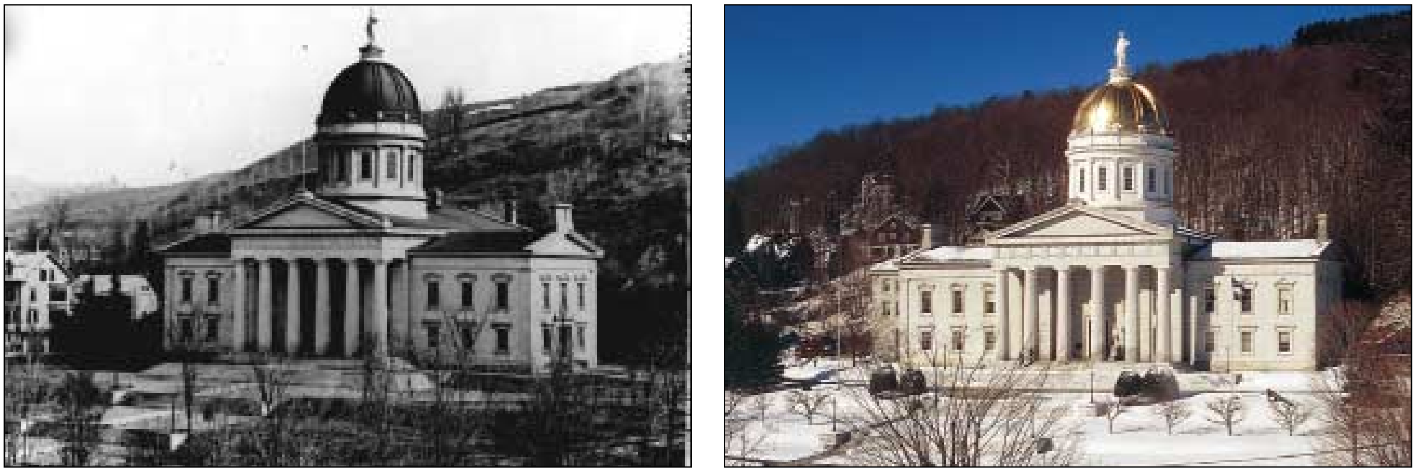

Figure 4. These photographs of the Vermont State House, Montpelier, Vermont, demonstrate the dramatic deforestation of hillslopes behind the building by the late 19th century (left—May, 1874, photo VHS-96, courtesy of the Vermont Historical Society) and subsequent reforestation (right—April, 1995).

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Kochel, 1990; Mills, 1982; Church and Ryder, 1972; Wells and Harvey, 1987; Patton, 1988).

The 23 fans examined so far in Vermont are finer grained, better sorted, and much more intricately stratified than those in the southern Appalachians, the result of differing parent material and different sediment transport mechanisms. Grain size analyses, sedimentary structures, observations of an active fan, and comparison to the data of Wells and Harvey (1987) suggest that stream flows, not debris flows, transported most of the sediment to the fans we studied. None of the fans are confined on their sides, and all are fed only by ephemeral streams. To a first approximation, the fans and their drainage basins can be considered closed systems. Sediment, once it leaves the steep hillslopes (>30°) and is deposited on the low-gradient fans (<7°), does not appear to be removed by subsequent flows, although small amounts may be reworked by shallow (<20 cm deep) fan-head trenching and redeposited at the toe of the fan. The closed-system assumption allows us to infer rates of hillslope erosion from rates of fan deposition (Fig. 5).

Unlike fans in arid regions, fan deposition in northern Vermont can be dated directly because the fans preserve abundant wood and charcoal within a distinct stratigraphy of silt, sand, gravel, and cobbles (Figs. 1 and 6). Most beds are poorly sorted, although there are occasional thin (~10 cm) beds of well-sorted, clast-supported gravel, as well as black laminae that may represent decomposed leaf mats or concentrations of finely disseminated charcoal (>15% organic carbon). We have radiocarbon dated 14 samples of wood and charcoal from five alluvial fans in order to determine the timing of aggradation (Table 1). These data show that two fans began to aggrade in the early Holocene (between 8530 and 8060 ^{14}C yr B.P., and between 7835 and 7360 ^{14}C yr B.P.), two in the late Holocene (2500 and 1900 ^{14}C yr B.P.), and one fan aggraded over 4 m during historic time (<100 ^{14}C yr B.P.).

On one fan, we have sufficient radiocarbon and stratigraphic data to estimate sediment accumulation rates over much of the Holocene. Rapid early Holocene aggradation was followed in the mid-Holocene by relative quiescence and soil formation (Fig. 5). In this and all other fans we trenched, there is a distinct soil profile near the fan surface buried by 0.5 to 4 m of poorly sorted sediment (Fig. 1). In each case, charcoal dates just above the buried soil and the presence of cumulative plow horizons indicate that the overlying sediment postdates European settlement and is likely related to land clearance and agricultural practices (Table 1 and Fig. 1). Changes in atmospheric ^{14}C over the past several hundred years preclude more precise radiocarbon dating of this young sediment.

POND SEDIMENTS

In order to reconstruct the history of pond sedimentation, we recovered and analyzed cores from the depocenters of

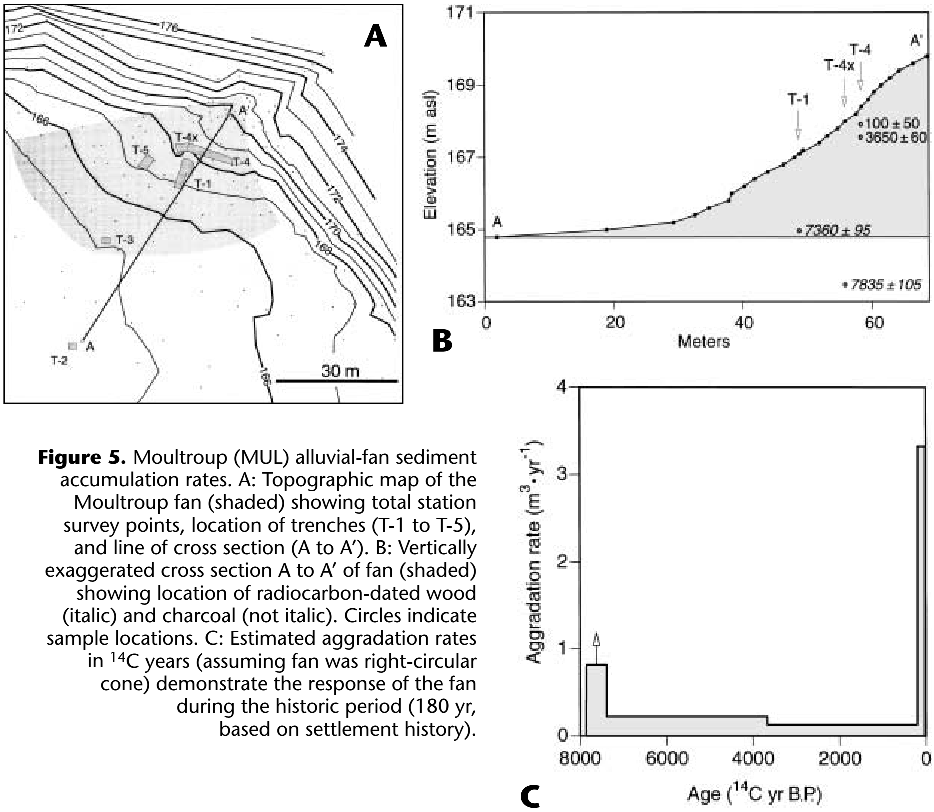

Figure 5. Moultroup (MUL) alluvial-fan sediment accumulation rates. A: Topographic map of the Moultroup fan (shaded) showing total station survey points, location of trenches (T-1 to T-5), and line of cross section (A to A'). B: Vertically exaggerated cross section A to A' of fan (shaded) showing location of radiocarbon-dated wood (italic) and charcoal (not italic). Circles indicate sample locations. C: Estimated aggradation rates in ^{14}C years (assuming fan was right-circular cone) demonstrate the response of the fan during the historic period (180 yr, based on settlement history).

two Vermont ponds. Sterling Pond (0.03 km^2; 917 m above sea level [asl]; 9 m maximum depth) has a small (0.3 km^2), low-relief (40 m) drainage basin and is predominantly spring fed. Ritterbush Pond (0.07 km^2; 317 m asl; 14 m max. depth) has a larger (2.2 km^2), higher relief (>200 m) drainage basin and is fed by several streams; the coring site at Ritterbush is located >75 m from the nearest stream. Both ponds are located in drainage basins underlain by schist; however, till at both sites contains disseminated carbonate.

The cores contain organic and inorganic sediment in varying proportions. The inorganic material is derived from the eroding drainage basins. The organic material is a mixture resulting from primary productivity in the ponds and terrestrial plant debris from the surrounding watersheds. Stable carbon isotope analysis of present-day terrestrial and aquatic plants (macrophytes and algae), collected from Sterling and Ritterbush Ponds and their watersheds, indicates that these two sources of sedimentary organic matter have distinctive isotopic signatures. Terrestrial plants yield δ^{13}C values ranging from –25‰ to –30‰, whereas aquatic plants yield values between –29‰ and –34‰. Thus, we can use stable carbon isotope analyses to determine whether organic material in our cores has a predominantly terrestrial or aquatic source. The difference in δ^{13}C between terrestrial and aquatic plants reflects differing δ^{13}C in their carbon sources, atmosphere and inorganic carbon dissolved in the lake water, respectively.

The two ponds have contrasting sedimentation histories reflecting differences in the hydrology of their watersheds. The Holocene part of the Sterling Pond core is relatively homogeneous gyttja with little change in LOI and δ^{13}C. The small, gently sloping, high-elevation watershed appears unable to generate sufficient episodic runoff to transport significant amounts of terrestrial sediment to the pond. In contrast, cores from Ritterbush Pond show significant stratification and distinct, correlated changes in LOI and δ^{13}C that we interpret as episodic inputs of terrestrial sediment derived from the large, steeply sloping watershed that surrounds the pond (Fig. 7).


Figure 6. Trench 4 of the Moultroup fan contains a variety of grain sizes, from silt to cobbles, reflecting different sediment sources, till and glacial lacustrine sediments. The prehistoric soil horizon and overlying postsettlement alluvium are just above the large cobble beyond the tape.

In the Ritterbush Pond cores, we recognize five major intervals of terrestrial sedimentation based on low LOI and less depleted δ^{13}C values (I, 470 to 448 cm; II, 426 to 400 cm; III, 348 to 339 cm; IV, 154 to 142 cm; V, 120 to 96 cm; Table 2, Fig. 7). The intervals are characterized by numerous millimeter- to centimeter-thick layers of gray silt and sand alternating with brown gyttja. Silt and sand layers are coincident with a drop in LOI and less negative δ^{13}C values (–26‰ to –28‰—terrestrial carbon) in comparison to the adjacent gyttja (–30‰ to –35‰—aquatic carbon). The sand and silt layers have sharp basal contacts and diffuse or sharp tops. The thicker inorganic layers are graded, suggesting that they are turbidite deposits. At the bottom of the core (495 to 479 cm), the isotopic and LOI data clearly show when aquatic primary productivity first became the dominant carbon source in the pond as LOI rises above 1% and there is a remarkable negative shift (more than –10‰) in the δ^{13}C values.

Fourteen radiocarbon ages of pond sediments, including three replicates, allow us to estimate the onset of the five intervals during which detrital sediment influx increased. At three levels in the cores, we have sampled directly below and above what we interpret as the first discrete clastic sedimentation event within an interval of increased terrestrially derived sediment (426 and 416 cm; 348 and 339 cm; 154 and 142 cm). In each case, sediment above the inorganic horizon yields greater ^{14}C ages than sediment below the horizon (offsets are 240, 110, and 230 ^{14}C yr, respectively). This systematic age inversion is consistent with erosion and resuspension of older gyttja from the basin margin or incorporation of older soil carbon from the basin by the flows that deposited the inorganic sediments.

Dating gyttja introduces additional systematic uncertainty. In cores from both Sterling and Ritterbush Ponds, we dated both a terrestrial macrofossil and the enclosing gyttja. In Ritterbush core RT-2, only several millimeters below interval II, a maple seed pod (426 cm; 8470 ± 60 ^{14}C yr B.P.) was 430 ^{14}C yr younger than the average of three replicates of the surrounding gyttja (426 cm; 8900 ± 40 ^{14}C yr B.P.). In the Sterling Pond core ST-1, a twig (260 cm, 3900 ± 60 ^{14}C yr B.P.) was 280 ^{14}C yr younger than the surrounding gyttja (4180 ± 50 ^{14}C yr B.P.). These age discrepancies could result from the uptake of "old" carbon by the aquatic plants (from dissolution of carbonate-bearing till) or from sinking of younger terrestrial macrofossils through older, soft, pond-bottom sediments. If the macrofossils are sinking, then the event that began interval II must have eroded about 22 cm of gyttja (430 ^{14}C yr, assuming a sedimentation rate of 0.5 mm/yr) that was once above the maple seed pod. In either case, the ^{14}C

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TABLE 2. AGE AND DEPTH DATA FOR INTERVALS OF INCREASED TERRESTRIAL DEPOSITION, RITTERBUSH POND, VERMONT

Interval no.	Initiation depth core RT-2 (cm)	Initiation age (^{14}C yr B.P.)	Best initiation age estimate[*] (^{14}C yr B.P.)	Time period
V	120	2570[†]	>1950[††]	Late Holocene
IV	154	<2940[§]	2510	
III	348	<6430[§]	6000	Early Holocene
II	426	<8470#	8470	Early Holocene
I	470	<11,940**	<11,510	Late Glacial

*Subtracts 430 ^{14}C yr offset for gyttja samples based on offset between gyttja and terrestrial macrofossil measured at 426 cm.

[†] Gyttja age just above last laminae in interval V.

[§] Gyttja age just below first laminae in interval.

#Age of maple schizocarp at 426 cm directly below laminae initiating interval II.

**Gyttja age at 479 cm 9 cm below beginning of interval I.

[††] Subtracts additional 190 ^{14}C yr based on the observation that the age of sediment just above interpreted events averages 193 ± 72 ^{14}C yr (n = 3) greater than sediment just below.

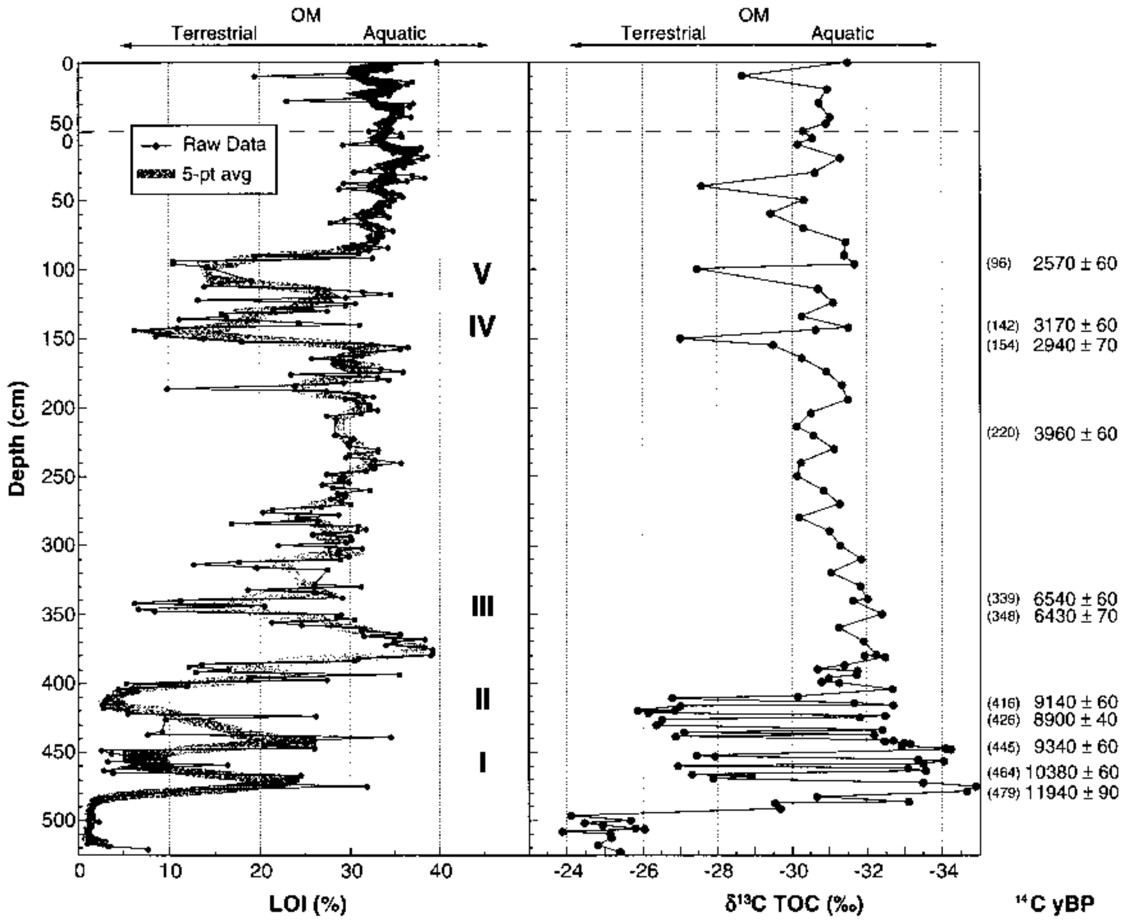

Figure 7. Loss on ignition (LOI) and total organic carbon (TOC) $\delta^{13}C$ for Ritterbush Pond. The results are a combination of two overlapping sequences of Livingston cores with a total length of 575 cm. Roman numerals indicate inorganic deposition intervals. Radiocarbon ages with 1σ counting uncertainties are shown, except for the gyttja at 426 cm, which is an average, ±1σ, of three measurements. Samples used for dating were acid- and base-washed repeatedly prior to combustion. OM = organic matter.

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ages of gyttja below inorganic sediment layers overestimate the age of the terrestrial input events by several hundred ^{14}C yr. We have used the measured gyttja—macrofossil age offset (430 ^{14}C yr for Ritterbush Pond) as an arbitrary correction for the interval initiation ages shown in Table 2 and Figure 8.

DISCUSSION

Alluvial fan trenches and pond sediment cores show that New England's Holocene history is every bit as dynamic and interesting as the preceding and well-studied deglaciation. Pond sediments are a continuous, integrated record of a drainage basin; small alluvial fans directly record discreet events from single hillslopes. Although these two geologic archives are strikingly different, the initial conclusions we draw from both records are remarkably similar. Hillslopes were more active during the early and late Holocene than during the middle Holocene. This case study not only suggests that it will be worthwhile to examine similar archives elsewhere, but also illustrates the challenges facing those trying to interpret these complex and integrative records of surface processes in terms of climate change and process-response models.

The similarity between fan and pond records suggests that different hillslopes respond to the same large-scale forcing, probably climate (Fig. 8). In the early Holocene (>6000 ^{14}C yr B.P.), sediment eroded off hillsides onto alluvial fans and into ponds. High rates of deposition on two fans (MUL and AUD, <8530 to 7360 ^{14}C yr B.P.) are coincident with the time during which clastic sedimentation intervals II and III occurred at Ritterbush Pond (8470 and 6000 ^{14}C yr B.P.). Pollen data, lake level histories, and global circulation models suggest that in general, climate was warmer, drier, and stormier than today, although a short-lived cool, dry, and dusty episode (ca. 7500 ^{14}C yr B.P.) has been identified by Alley et al. (1997) in a variety of records (Fig. 8), and Dywer et al. (1996) reported a highstand in Owasco Lake (western New York) at 6900 ^{14}C yr B.P.

The landscape was more stable during the middle Holocene (6000 to 2500 ^{14}C yr B.P.), when pollen, lake level histories, and climate models suggest that northeastern North America was slowly cooling and becoming moister. Ritterbush Pond cores contain less terrestrially derived sediment (340 to 155 cm, 6000 to 2510 ^{14}C yr B.P.), and soil profiles developed on what appear to have been relatively stable alluvial fan surfaces. About 2500 ^{14}C yr ago, environmental conditions began to change; an increase in spruce pollen suggests that eastern North America was significantly cooler and moister, an inference strongly supported by rising lake levels. High rates of deposition on two fans (ALD-C and ALD-B, 2500 to 1850 ^{14}C yr B.P.) are coincident with the period when inorganic deposition in Ritterbush Pond again increased (2510 to 1940 ^{14}C yr B.P.; clastic intervals IV and V).

Our data are consistent with gross climatic controls on hillslope activity. However, climate does not move sediment and erode hillslopes, water does, and water comes from distinct and episodic hydrologic events. There are numerous historical accounts in New England and elsewhere of both high-intensity and long-duration storm events triggering hillslope erosion (Flaccus, 1958; Bogucki, 1977; Ratte and Rhodes, 1977; Dethier et al., 1992). We believe that the record of such events is preserved as inorganic layers in the pond sediments and as discrete beds in the alluvial fans. Hurricanes and other moisture-laden storms of tropical and/or Atlantic origin do influence interior New England (Coch, 1994). These storms cause landslides and gullying as ground-water tables rise, soil pore pressures increase, and saturated overland flow runs over the landscape. If the paleoclimatic proxy data

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are correctly interpreted, early Holocene hillslope erosion may have been driven by episodic large storms in a drier climate than today. Late Holocene erosion and aggradation were also event driven, but greater ambient levels of soil saturation may have allowed smaller storms to trigger similar landscape responses. It appears that the middle Holocene was less stormy.

Vegetation affects hillslope stability. For example, European settlement, clear-cutting, and agricultural practices removed the heavy forest cover and triggered massive aggradation on valley-bottom alluvial fans. Presumably, landsliding and gullying increased as soils were compacted, tree roots rotted, and the effective cohesion that those roots provided was lost. Was the New England landscape cleared of trees at any other time during the Holocene? Pollen data are definitive. New England was generally tree-covered from shortly after deglaciation until European settlement. The pathogen-induced hemlock decline at 4800 ^{14}C yr B.P. may have cleared some slopes, and pollen spectra can be interpreted to indicate increased fire frequency during the drier early Holocene (Jacobson et al., 1987), an observation supported by charcoal abundance data from several New England ponds (e.g., Anderson et al., 1986; Davis, 1985). However, we lack a record of small-scale forest disturbance from blowdown, fire, and disease, all capable of clearing vegetation from hillslopes and making small drainage basins more sensitive to hydrologic events.

Our geologic data have implications for land management practices and reinforce the conclusion that humans are significant geomorphic agents (Hooke, 1994). In Vermont, extensive colonial land clearance and agriculture dramatically increased sediment yield from some hillslopes. The fans that we have investigated aggraded more quickly during the past 200 yr than at any time during the past 8000 ^{14}C yr (Fig. 5). Transitory expansion of the Winooski River delta into Lake Champlain, rapid meander migration, and the volume of historic alluvium in the Winooski River flood plain testify to the massive amount of sediment removed from the uplands, transported, and deposited by this river during the early and mid-1800s (Fig. 3; Severson, 1991; Thomas, 1985). The retreat of the Winooski River delta, the incision of this and other rivers into historic alluvium, and tree-core data gathered from fossil landslide scars suggest that hillslopes stabilized and sediment supply to the river decreased quickly as reforestation began to occur in the 1880s (Fig. 3). Curiously, the steep, rocky, uncultivated, and till-covered slopes around Ritterbush Pond barely responded to European deforestation, yet repeatedly and distinctly responded to events, presumably hydrologic, through the Holocene.

Hillslopes are sensitive, diverse, and dynamic systems that respond measurably to climate and land-use change. For example, fluvial terraces underlain by glacial lake sediments appear to be more sensitive to clear-cutting than are till-mantled upland basins; yet, our data show that both terrace and upland hillslopes erode in response to long-term climate change and short-term hydrologic events. As development clears slopes in New England and around the world, further work is needed to identify which parts of the landscape are most sensitive to deforestation and whether the temporal records of episodic hillslope activity we infer from northern Vermont fans and ponds are regionally coherent and represent the record of a potentially significant natural hazard.

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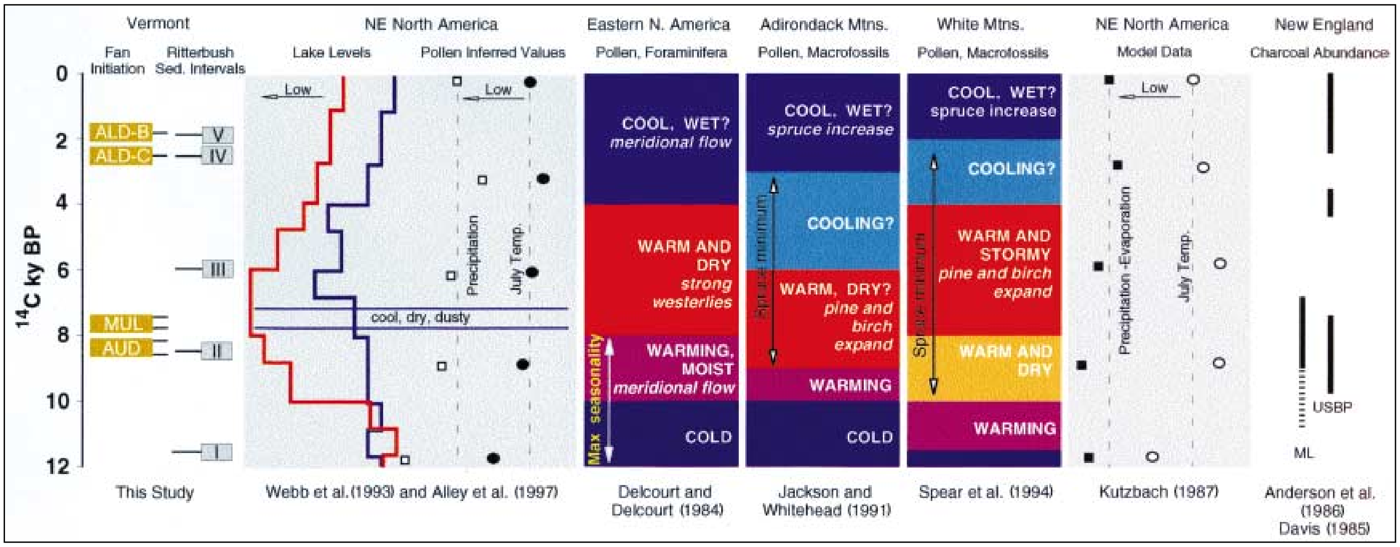

Figure 8. A compilation of selected climate-change records for eastern North America and New England. Horizontal lines indicate the best age estimates (including gyttja age-offset) for initiation of deposition of the alluvial fan and Ritterbush Pond inorganic sediment. Lake levels are a summary of Webb et al.'s (1993) compilation. The red line is a temporal histogram of lakes having lowstands. The blue line is an inverse histogram of lakes having highstands. Webb et al.'s (1993) pollen-inferred values for precipitation and July temperatures are averages derived from pollen response surfaces incorporating numerous sites in eastern North America. Horizontal lines indicate the cooling event of Alley et al. (1997). The Delcourt and Delcourt (1984) compilation is based on foraminifera from North Atlantic cores and pollen from lakes in northeastern North America. Jackson and Whitehead (1991) and Spear et al. (1994) reported data from the Adirondack Mountains of New York and the White Mountains of New Hampshire, mountain ranges immediately west and east of Vermont's Green Mountains, respectively. The Kutzbach (1987) record is a result of global climate modeling. Charcoal abundance is from Upper South Branch Pond (USBP), Maine (Anderson et al., 1986) and from Mirror Lake (ML), New Hampshire (Davis, 1985).

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