Timing and style of deposition on humid-temperate fans, Vermont, United States

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ABSTRACT

Fans in the once-glaciated, mountainous landscape of humid-temperate New England preserve a long and unique record of deposition and, thus, of hillslope erosion. By using multiple backhoe trenches and radiocarbon dating of wood and charcoal, we determined the history of five small fans (1900–14,850 m^3) that range in age from historic to ≥13,320 calibrated (cal.) ^{14}C yr B.P. Three fans located on river terraces have depositional records whose ages are limited by the age of the terrace on which they are situated. Two other fans, located in glacial valleys, preserve records that extend back nearly to deglaciation.

The stratigraphy of all five fans contains evidence suggesting episodic activity, including scoured surfaces and layers of gravel and cobbles. Periods of little or no activity are indicated by development of now-buried soils. Dated sand and gravel strata in several fans suggest correlative periods of increased sediment yield and by inference, runoff, at ca. 9650–9340 and 6900–6020 cal. ^{14}C yr B.P. Soils preserved within at least two of the five fans suggest lower sediment yield at ca. 12,900, ca. 5500, ca. 4300, and ca. 3200 cal. ^{14}C yr B.P. At least three of the fans aggraded rapidly during the past several hundred years in response to land clearance and disturbance; however, many aggradation and scour events in the Holocene cannot be correlated definitively between fans because of the discontinuous nature of gravel beds and the lack of radiocarbon-datable material in the coarsest strata.

Drainage-basin sediment yields implied by the fan volumes and integrated over the Holocene are quite low, ≥4–11 × 10^3 kg·km^{-2}·yr^{-1}. Sediment yields since settlement by European and other immigrants are several to hundreds of times higher, demonstrating the connections among forest clearance, agriculture, and increased erosion rates of New England hillslopes.

Keywords: erosion, fans, New England, radiocarbon dating, Vermont.

INTRODUCTION

Alluvial and debris fans are the products of geomorphic processes acting in drainage basins (Bull, 1991); thus, fans can be used to quantify rates and patterns of hillslope response to natural phenomena, such as large storms or forest fires (Meyer et al., 1992; Meyer and Wells, 1997), and to human-induced change, such as clear-cutting (Brazier et al., 1988; Macklin et al., 1992; Bierman et al., 1997). Arid-region fans have been studied extensively because they are large, highly visible landscape elements (Bull, 1964, 1977, 1991; Hooke, 1967; Beaty, 1970; Whipple and Dunne, 1992; Bierman et al., 1995; Zehfuss et al., 2001). Humid-region fans, because they are, in general, smaller, more heavily vegetated, and less prominent, have received less study (Pierson, 1980; Ballantyne and Whittington, 1999). Although southern Appalachian fans have been characterized (Kochel and Johnson, 1984; Mills, 1987; Eaton et al., 1997), the sedimentary record of fans in humid-temperate, northeastern North America has not been described, nor has it been used to quantify fluctuating rates of hillslope erosion through time.

During the last glacial maximum, New England was covered by the Laurentide ice sheet (Dyke and Prest, 1987). The ice margin retreated through northern Vermont ~12,000 radiocarbon years ago (14,000 cal. ^{14}C yr B.P., Ridge et al., 1999), leaving a landscape mantled with glacial sediment. As local base levels dropped, streams began to cut downward through the glacial debris, leaving terraces in many valleys (Whalen, 1998). As soon as drainages integrated on postglacial hillslopes, fans began to form. Mapping, trenching, and dating five such fans at Bristol, Hancock, Maidstone, Bridgewater Corners, and Eden Mills, Vermont (Fig. 1), provide the first detailed data on the location, stratigraphy, age, and behavior of these postglacial landforms in humid, northeastern North America. From these data, we calculate rates of fan aggradation and drainage-basin sediment yield, identify the timing of major scour and deposition events, determine the age of soil-forming intervals, and infer past periods of increased storminess. We compare our findings to other records used to infer changes in Holocene climate and paleostorm frequency in eastern North America (e.g. Davis et al. 1980; Noren et al., 2002).

Previous Research

In order for deposition to occur on fans, sediment must be eroded and transported from the drainage basin. Sediment erosion and transport require a reduction in forest cover, a lowering of effective soil cohesion originally provided by root networks (Ziemer, 1981; Meyer et al., 1992), or an increase in the

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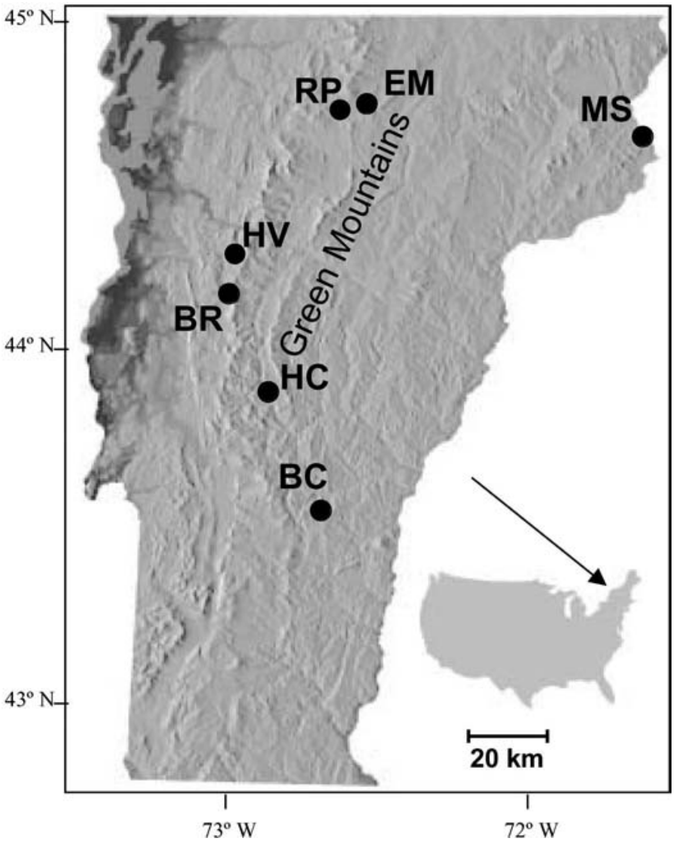


Figure 1. Digital topographic map of trenched fans and other pertinent sites in Vermont. Arrow toward inset shows location of Vermont in the United States. EM—Eden Mills, MS—Maidstone, BR—Bristol, HC—Hancock, BC—Bridgewater Corners, HV—Huntington Valley, RP—Ritterbush Pond.

amount or duration of local rainfall (Pierson, 1980; Kochel, 1987). Very large storm events are capable of triggering hillslope erosion and fan deposition even in fully forested regions (Kochel, 1990; Kochel and Johnson, 1984; Ratte and Rhodes, 1977; Wells and Harvey, 1987; Pierson, 1980; Orme, 1990; Wieczorek et al., 1996; Eaton et al., 1997). Thus, humid-temperate fans are likely to preserve, in their stratigraphy, a low-resolution record of runoff (storm) events and, possibly, climate change (Kochel, 1990; Bierman et al., 1997; Allen, 1999).

A variety of observations indicate that fan deposition occurs during major storms. Sedimentation on numerous, previously stable Virginia fan surfaces was triggered by Hurricane Camille (Williams and Guy, 1973). Buried soil horizons in Virginia fans demonstrate that the fans were constructed by infrequent deposition during large rainstorms having a 3000–6000 yr recurrence interval (Kochel and Johnson, 1984; Kochel, 1987). Rachocki's (1981) three-year study of small fans revealed that long, low-intensity precipitation events did not cause sediment deposition; only one high-intensity storm during the study period supplied material to the fan surface. Radiocarbon-dated peat layers from a 2000-yr-old fan in Scotland indicate that deposition occurred during exceptional storms (Ballantyne and Whittington, 1999), an inference supported by deposition on 13 fans during a 2.5 hour long intense storm in northwest England (Wells and Harvey, 1987). During one severe storm, sediment deposition on a New Zealand fan equaled thousands of years of sediment discharge by average fluvial processes (Pierson, 1980).

Observations of Modern Processes

Observations of contemporary deposition on Vermont fans suggest that aggradation occurs only during intense storms and runoff events. In 1998, northern Vermont had an anomalously wet early summer, which culminated in two intense storms that deposited 4.6 cm of rain on June 26 and 5.8 cm of rain on July 2 (National Oceanic and Atmospheric Administration data). The storms, each lasting several hours, caused widespread flooding along the western Green Mountains. During these storms, sand, gravel, and cobbles were deposited on at least 3 of 21 well-vegetated fans in the Huntington River Valley (Fig. 1). Over half a meter of sediment piled up against trees on the forested apex of one fan; isolated, thin lobes of sand and fine gravel were deposited distally on a grassy pasture. Deposition of sand and gravel also occurred on the otherwise stable Bristol fan. During a separate storm event in September 1998, sediment associated with gully incision of a Huntington River terrace blanketed a fan located on the terrace below (Fig. 2A). These observations suggest that changes in hillslope-erosion rates need not be driven by large, extended, regional shifts in climate (Bull, 1991); rather, it appears that individual drainage basins are differentially sensitive to rare, episodic meteorological events.

METHODS

We mapped 45 fans in Vermont and selected five widely separated fans for study on the basis of preservation and ease of access (Fig. 1). In order to understand better the stratigraphy of each fan and collect samples for dating, two intersecting backhoe trenches were dug into each fan, ranging from 0.5 to 2 m deep (Fig. 3). One wall of each trench was cleaned and gridded with string at meter intervals so that the stratigraphy could be diagrammed to scale in the field. Clasts were measured and mapped directly onto the stratigraphic logs. For each of the five fans, the top trench, oriented across the fan, is labeled A–A′ on the cross sections. The stem trench, oriented down fan, is labeled B–B′. The location of each trench intersection is labeled with an arrow on the A–A′ stratigraphic logs (Figs. 4–8). Because the trenches ranged from 1 to 2 m wide, strata mapped in the A–A′ and B–B′ sections may be offset at the trench intersection. Before leaving each site, we had the backhoe dig 1–3 m deeper at one location within each trench in order to determine the stratigraphy of the lower fan and underlying units. The base of the fan deposits was determined by considering sediment characteristics and extrapolated fan-toe elevation.

Over 300 samples of organic material were collected, and 48 were radiocarbon dated (Table 1); the dated samples included 35 discrete pieces of charcoal, 11 discrete pieces of wood, and 2 amalgamated soil samples. An additional 18 charcoal samples dissolved during preparation. Samples were prepared for radiocar-

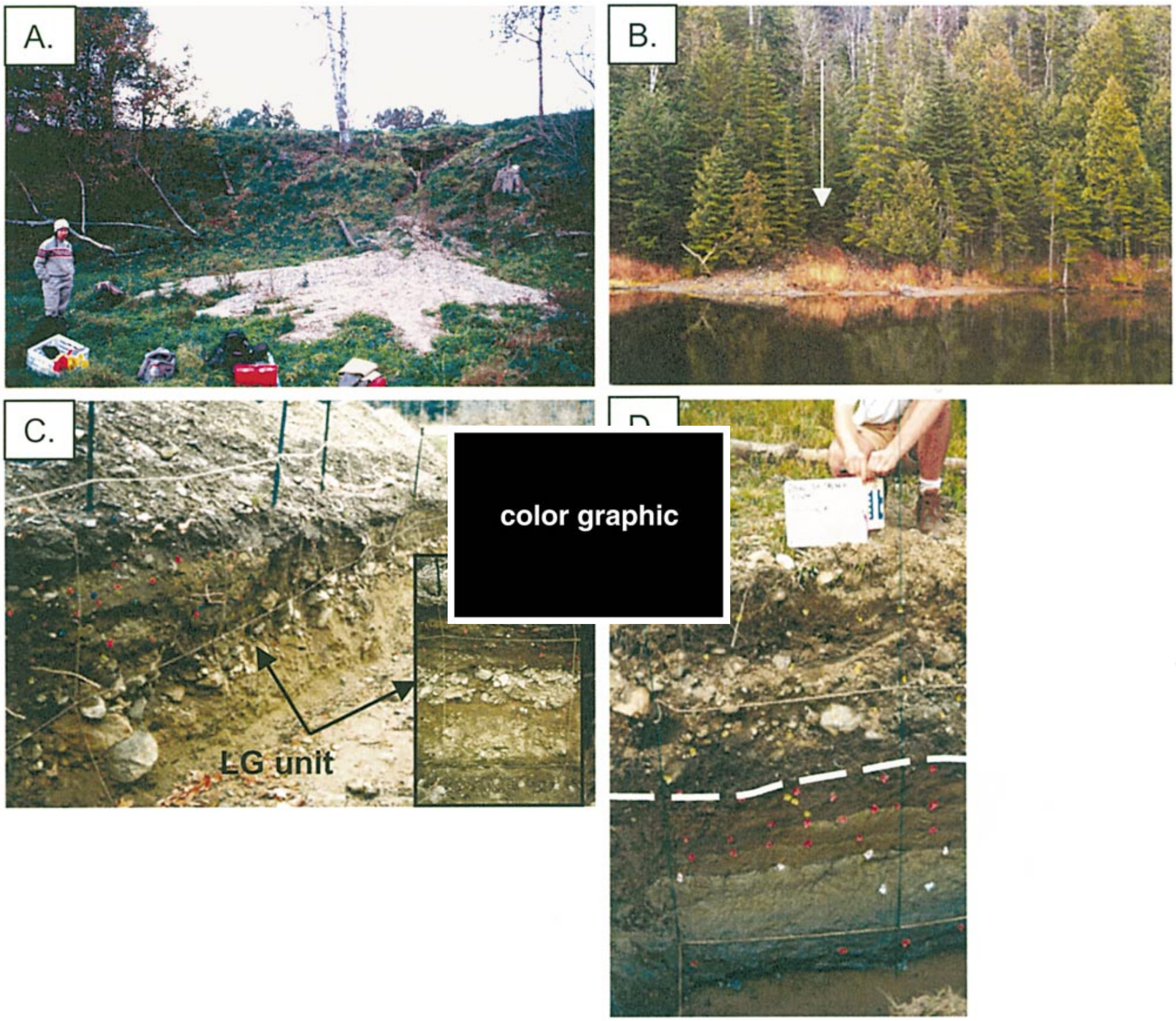


Figure 2. Photographs of Vermont fans. (A) Fan on terrace and covered in part by deposition of sand and gravel derived from gully above (Huntington, Vermont, September 1998); person provides scale. (B) Arrow indicates active fan-delta deposit in stream; sediments in this delta will not be preserved as a fan. (C) Coarse gravel unit representing a storm event in the Bristol fan (shown also in Fig. 5B, unit LG, 9340–4730 cal. ^{14}C yr B.P.). Trench is 1.5 m deep for scale. (D) Upward grain-size change from fine sand to coarse sand, gravel, and cobbles in the upper meter of the Eden Mills fan as the result of historic logging (shown in Fig. 4A, column 1); string grids are 1 m apart for scale. (E) Multiple buried A-horizons in the Eden Mills fan represent periods of fan stability (Fig. 4A, columns 2 and 3). Photograph shows 75 vertical centimeters of trench wall. (F) Laterally continuous, well-bedded sand and silt strata in the Maidstone fan (Fig. 8B). About 9 m of horizontal trench wall is shown. (G) Animal burrow in the Maidstone fan (Fig. 8B, column 7). Area of photograph ~1 m^2. (H) Paleostorm deposit represented by gravel, bracketed by two paleosols, Bridgewater Corners fan (Fig. 7B, unit Gr2). Photograph from wall of trench opposite that logged. GSA scale card has 10 cm bar scale.

bon analysis by accelerator mass spectrometry (AMS) at Lawrence Livermore National Laboratory using standard methods including acid and repeated base washes. Radiocarbon dates were calibrated by using the online version of CALIB 4.2 (Stuiver et al., 1998). Henceforth, we report all ages in calibrated radiocarbon years before present, abbreviated as cal. ^{14}C yr B.P.

The surface of each fan and the locations of trenches were surveyed from three benchmarks by using a combination of Trimble RTK (real time kinematic) differential GPS (Global Positioning System) (4400) and a Pentax total station. Aggradation rates were calculated on the basis of the radiocarbon ages, the sample depth below the fan surface, and the survey data, through the use of the assumption that fan geometry is reasonably modeled as a segment of a right circular cone. Detailed methods are provided in Jennings (2001).

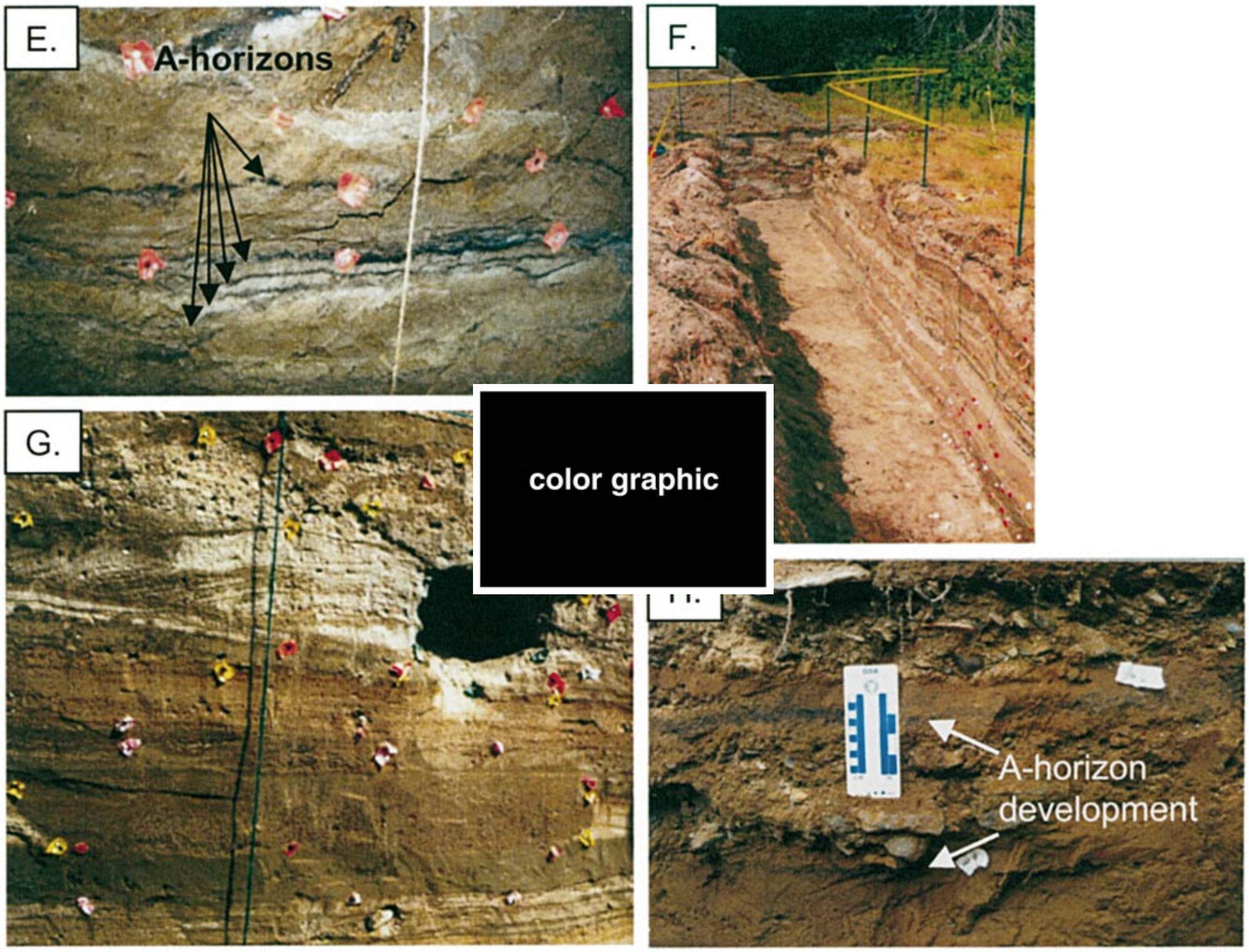


Figure 2. (*Continued*).

RESULTS

Fans we investigated in Vermont preserve subparallel depositional strata, erosional unconformities, and multiple buried soils that represent alternating periods of fan-surface stability and fan aggradation since late glacial time. With the exception of the Bridgewater Corners fan, which is partly truncated by Broad Brook (Data Repository Fig. DR4B)[1], the investigated fans approximate closed systems with little sediment loss downstream. The fans are not currently dissected, but instead have stream channels that extend only to the fan apex. The drainage basins at Eden Mills and Bridgewater Corners have perennial streams, which currently flow along the fan periphery before diffusing into the surface at Eden Mills and entering Broad Brook at Bridgewater Corners. The coarse-grained (sand and gravel) nature of most depositional units, along with observations of modern processes, suggest that these fans accumulated during a series of episodic events that interrupted stable, soil-forming intervals. Buried organic material in the fans allows dating of these events.

Fans directly record the timing of hillslope runoff events in both the depositional strata and the unconformities they preserve. Scouring of fan surfaces requires flowing water. Likewise, erosion, transport, and subsequent deposition of gravel on fan surfaces requires an increase in hillslope runoff. Because both fan-surface scour and deposition are indicative of significant flow, we suggest that both are directly related to runoff caused by storms. The fan record is low resolution, allowing identification of only the largest events, those capable of leaving an unconformity or a deposit of thickness and extent sufficient for identification and dating.

The New England landscape has been forested from the late Pleistocene (about a thousand radiocarbon years postdeglaciation, 11,000 ^{14}C yr B.P.) until colonization by European and other immigrants (Davis and Jacobson, 1985) with no evidence of widespread fires (Brown et al., 2000); thus, we interpret prehistoric fan deposition and scour events as the result of increased precipitation. An abrupt regional decline in the abundance of hemlock pollen has been noted at ca. 4600 ^{14}C yr B.P. in dated lake sediment cores throughout New England and attributed to a pathogen affecting only this species (Davis et al., 1969). Although hillslopes dominated by hemlock trees may have lost some tree cover at that time, there is no indication that the hemlock die-off caused increases in pond sedimentation rates

[1]GSA Data Repository item 2003030, site and locality maps for each alluvial fan, and detailed descriptions of the depositional strata, is available on the Web at http://www.geosociety.org/pubs/ft2003.htm. Requests may also be sent to editing@geosociety.org.

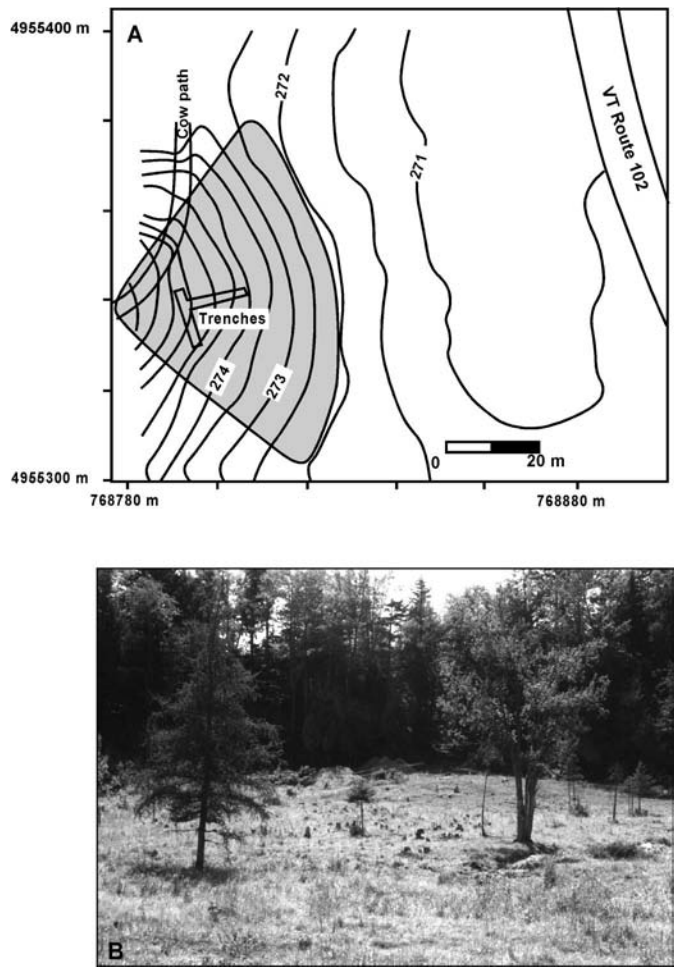


Figure 3. (A) Topographic map of the Maidstone fan, based on differential GPS and total station data. Top (i.e., on the left) trench runs across fan; stem trench runs down fan. Contour interval is 0.5 m. Scale in meters, UTM grid, North American Datum (NAD) 27. (B) Photograph of Maidstone fan. View from Vermont Route 102 toward the west. Field of view is ~20 m wide at front; trees for scale.

(Li, 1996) or fan aggradation. Human activity, primarily deforestation at the onset of settlement by European and other immigrants, caused large amounts of contemporary hillslope erosion and deposition on fans (Allen, 1999; Anderson et al., 2000), often on a much larger scale than natural phenomena (Costa, 1975; Bierman et al., 1997); thus, we interpret recent accelerated fan deposition as a result of human activity.

Fan Setting

We found fans in two settings, on river terraces and in underfit glacial valleys. We refer to fans on terraces as *terrace fans* and those in glacial valleys as *glacial valley fans.* The oldest fans (Bristol and Eden) are found in glacial valleys, deposited directly on proglacial and glacial sediments, respectively. Ages of the bases of these *glacial valley fans,* 12,980 (Bristol) and 13,320 (Eden Mills) cal. ^{14}C yr B.P., provide minimum limits for the timing of glacial lake drainage and glacial retreat and thus the initiation of postglacial hillslope processes.

Terrace fans, such as those at Maidstone, Hancock, and Bridgewater Corners, are found where drainages spill onto river terraces. Many of these terrace fans have lost part of their depositional record downstream as drainage-basin incision began before the fans could be preserved; i.e., sediment entered the trunk stream as a fan-delta and was washed away during high flows (Fig. 2B). Fans were preserved when the trunk stream migrated and incised, leaving terraces as sediment traps. The ages of the three fans on river terraces are historic (Maidstone), 10,030 cal. ^{14}C yr B.P. (Hancock), and 11,330 cal. ^{14}C yr B.P. (Bridgewater Corners). Basal dates for such fans represent a minimum age of terrace stabilization, not necessarily the onset of hillslope incision and fan deposition.

The fans we studied are small, 900–4990 m^2 in surface area and 1900–14,850 m^3 in volume (Table 2). Drainage basins range from 14,500 to 249,000 m^2 (Table 2), and all five basins have a history of logging and agricultural use during the past 250 yr. The five Vermont fans have coherent morphometric relationships. Fan volume and area are well and positively correlated (r^2 = .94). Fan volume/area ratios range from 1.7 to 3.5 m. Fan volume and drainage-basin area are also well and positively correlated (r^2 = .87). Fan apex height and fan length are similarly correlated (r^2 = .87), reflecting the observation that slopes of all five fans are grossly similar, ~0.1.

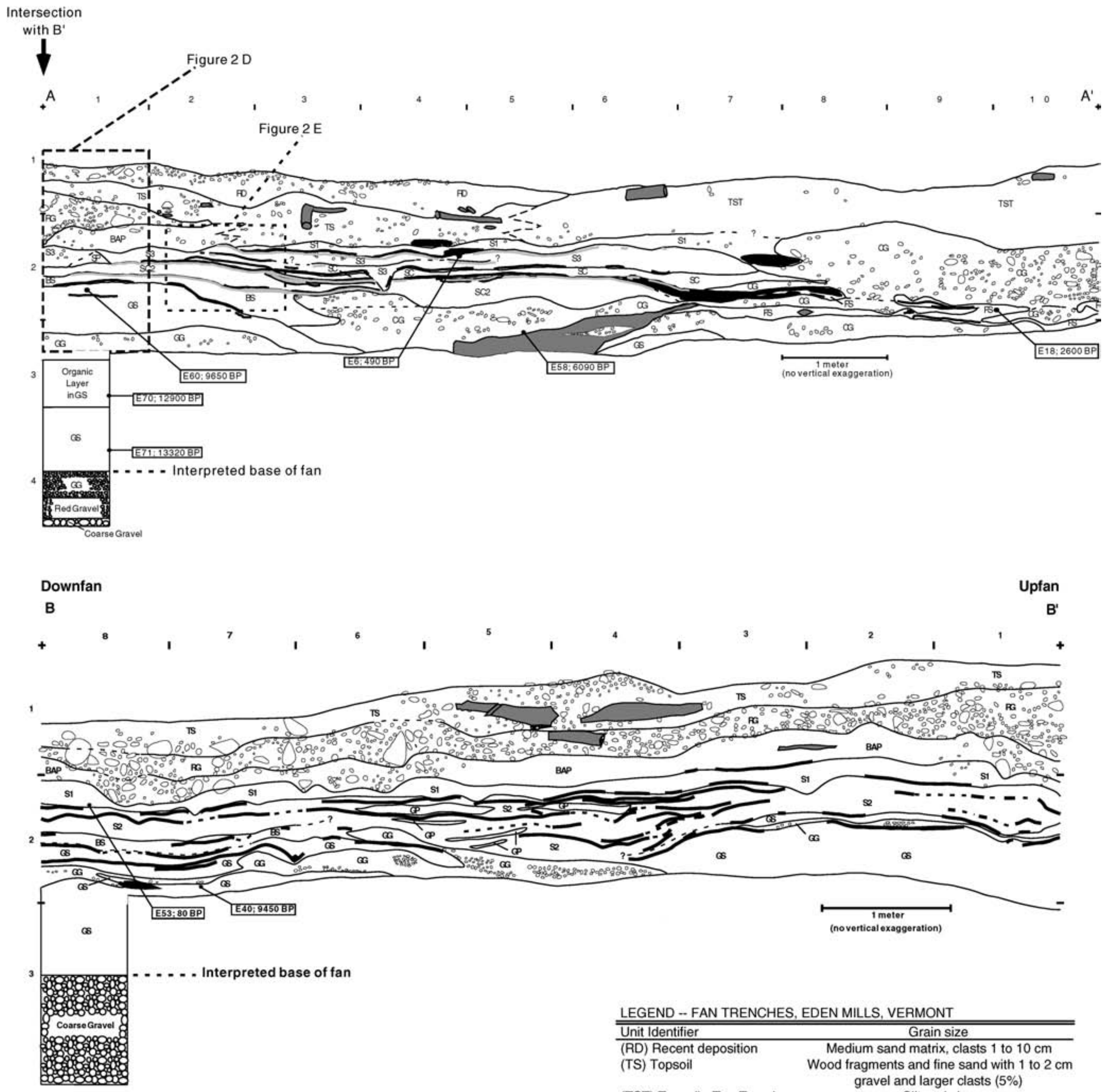
The Bristol, Hancock, and Eden Mills drainage basins are formed in thin mantles of till and colluvium overlying weathered bedrock. Drainage basins at Maidstone and Bridgewater Corners are formed in postglacial fluvial sediments at lower elevations and in glaciolacustrine sediments (Maidstone) and till (Bridgewater Corners), which crop out higher in the basins. In drainage basins supplying sediment to Vermont fans (this study; Bierman et al., 1997), we have observed stream-bank collapse, channel incision, and mass movements, all processes capable of mobilizing sediment.

Dating Fans

The five fans all contain significant but differing amounts of organic material, including wood, charcoal, and buried soil A-horizons. The Eden Mills fan preserved the most organic material; the Bridgewater Corners fan preserved the least. Organic material was more common in less permeable silt and sand and rare in gravel units and was better preserved in moist and less oxidized fine-grained units than in oxic gravel and sand.

Most of our AMS (accelerator mass spectrometry) dates are precise (1σ, ±50 ^{14}C yr); however, ages assigned to sedimentary units are less precise and less accurate than the dates for several reasons. Charcoal and wood can be reworked from colluvial and terrace deposits upstream, and inner rings of old-growth trees may be hundreds of years old when deposited. Calibration of ^{14}C ages further decreases precision, particularly in young samples.

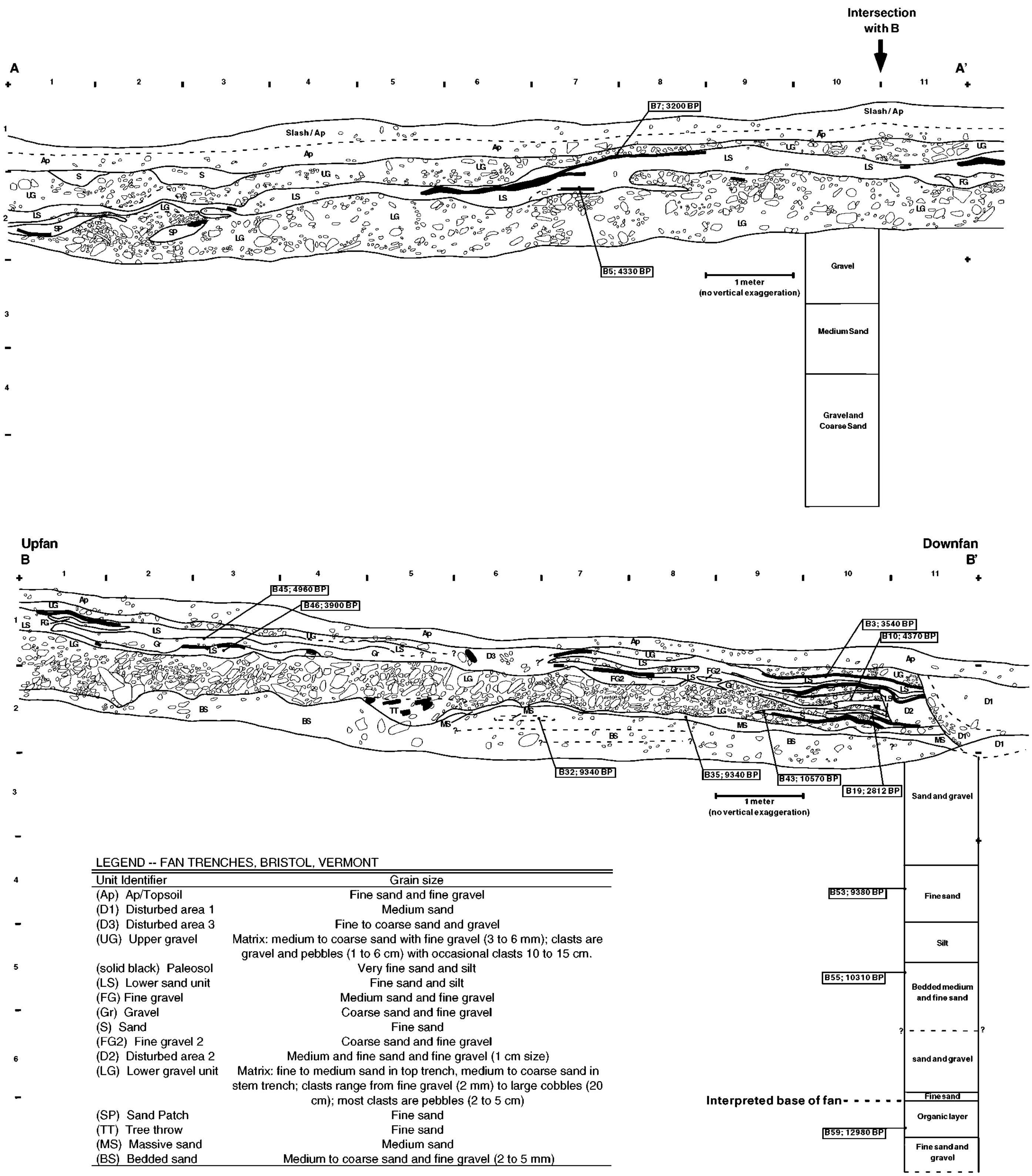
For example, we dated 10 samples from the Maidstone fan. Below the fan is a layer of wood, twigs, and grass (sample M52, Table 1; 170 ± 40 ^{14}C yr; 232–67 cal. ^{14}C yr B.P., 2σ) preserved by overbank deposition on the ter-



LEGEND -- FAN TRENCHES, EDEN MILLS, VERMONT

Unit Identifier	Grain size
(RD) Recent deposition	Medium sand matrix, clasts 1 to 10 cm
(TS) Topsoil	Wood fragments and fine sand with 1 to 2 cm gravel and larger clasts (5%)
(TST) Topsoil - Top Trench	Silt and clay
(RG) Recent Gravels	Fine sand (~15%) and medium to coarse sand matrix mixed with clasts 1 mm to 2 cm
(BAP) Buried, Ap-horizon	Fine sand and silt
(solid black) Paleosol	Silt and clay
(S1) Sand 1	Fine sand and silt
(S2) Sand 2	Fine sand and silt
(S3) Sand 3	Fine sand and silt
(SP) Sand Patch	Coarse sand matrix with clasts of fine gravel (2 mm) to pebbles (2 to 3 cm)
(SC and SC2) Silt - Clay	Silt and clay with little fine sand
(GP) Gravel Patch	Fine to medium sand matrix with fine gravel (2 to 10 mm)
(BS) Brown silt	Silt and clay
(CG) Channel Gravel	Fine sand and silt matrix mixed with coarse sand and fine gravel
(FS) Fine sand	N/A
(GS) Gley silt	Fine sand and silt
(GG) Gley gravel	Medium and coarse sand matrix with fine gravel (0.5 cm) to small pebbles (2-3 cm)

Figure 4. Stratigraphy of fan at Eden Mills, Vermont. Section A–A′ is top trench; section B–B′ is stem trench. Light gray is leached E-horizon; dark gray shading represents extensive wood fragments or logs. Rocks are outlined, and the location of dated samples (cal. ^{14}C yr B.P.) and their sample numbers and ages are shown. Interpreted base of fan indicated by dashed line.



LEGEND -- FAN TRENCHES, BRISTOL, VERMONT

Unit Identifier	Grain size
(Ap) Ap/Topsoil	Fine sand and fine gravel
(D1) Disturbed area 1	Medium sand
(D3) Disturbed area 3	Fine to coarse sand and gravel
(UG) Upper gravel	Matrix: medium to coarse sand with fine gravel (3 to 6 mm); clasts are gravel and pebbles (1 to 6 cm) with occasional clasts 10 to 15 cm.
(solid black) Paleosol	Very fine sand and silt
(LS) Lower sand unit	Fine sand and silt
(FG) Fine gravel	Medium sand and fine gravel
(Gr) Gravel	Coarse sand and fine gravel
(S) Sand	Fine sand
(FG2) Fine gravel 2	Coarse sand and fine gravel
(D2) Disturbed area 2	Medium and fine sand and fine gravel (1 cm size)
(LG) Lower gravel unit	Matrix: fine to medium sand in top trench, medium to coarse sand in stem trench; clasts range from fine gravel (2 mm) to large cobbles (20 cm); most clasts are pebbles (2 to 5 cm)
(SP) Sand Patch	Fine sand
(TT) Tree throw	Fine sand
(MS) Massive sand	Medium sand
(BS) Bedded sand	Medium to coarse sand and fine gravel (2 to 5 mm)

Figure 5. Stratigraphy of fan at Bristol, Vermont. A–A′ is top trench; B–B′ is stem trench. Rocks are outlined, and the location of dated samples (cal. ^{14}C yr B.P.) and their sample numbers and ages are shown. Interpreted base of fan indicated by dashed line (base of fan not reached in top trench, A–A′).

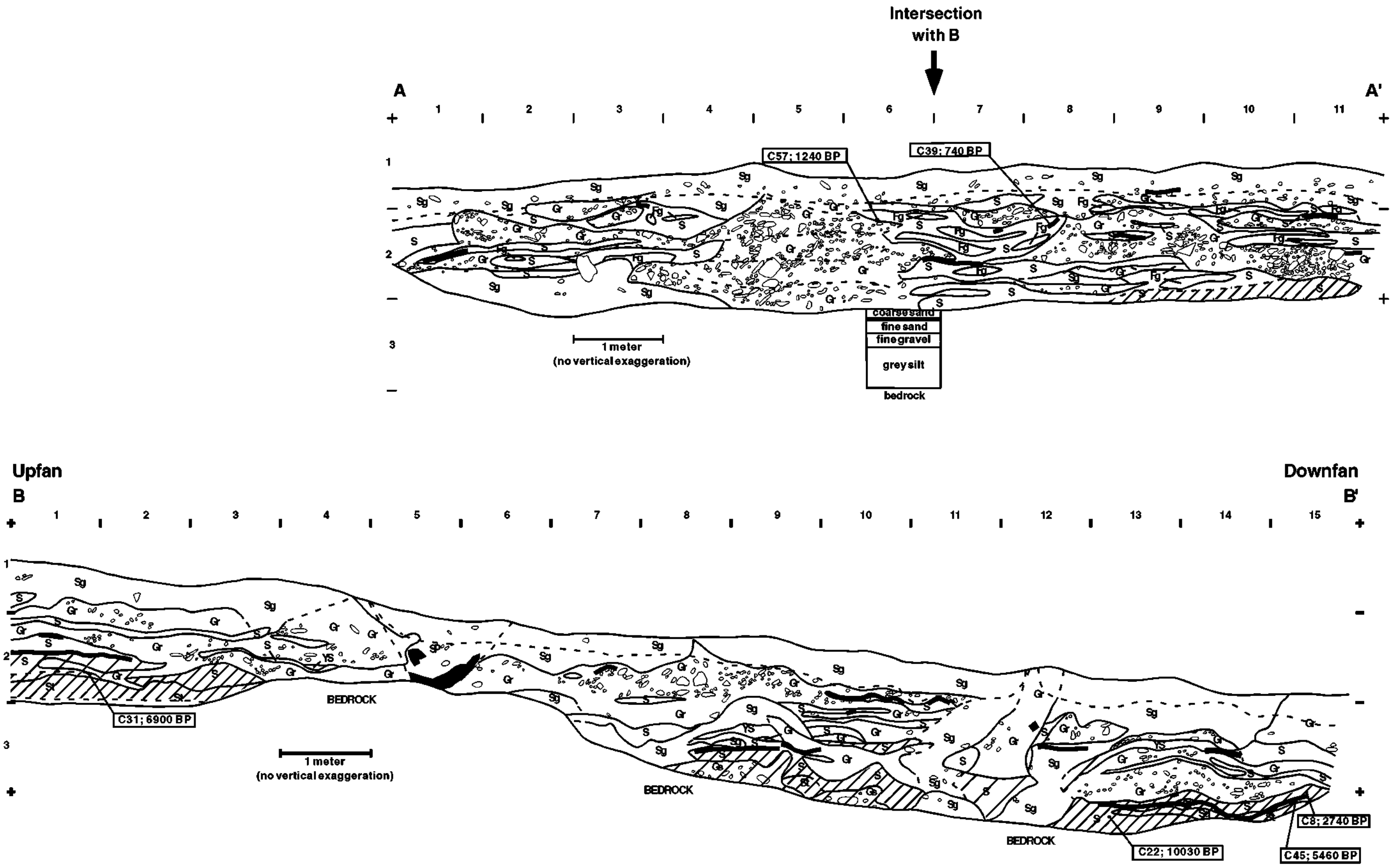


Figure 6. Stratigraphy of fan at Hancock, Vermont. A–A′ is top trench; B–B′ is stem trench. Top dashed line is bottom of topsoil coloring. Diagonal stripes indicate reddened soil color from B-horizon development. Rocks are outlined, and the location of dated samples (cal. ^{14}C yr B.P.) and their sample numbers and ages are shown. Base of fan is bedrock.

LEGEND -- FAN TRENCHES, HANCOCK, VERMONT

Unit Identifier	Grain size
(Sg) Sand and gravel	Fine sand matrix with fine gravel
(dashed line) Topsoil boundary	Fine sand
(S) Sand	Medium sand to silt
(Gr) Gravel	Medium sand to cobbles
(Fg) Fine gravel	Medium sand to gravel
(YS) Yellow sand	Medium and fine sand
(solid black) Paleosol	Fine sand
(SP) Slash pit	Fine sand matrix with gravel
(St) Silt	Silt and fine sand
(Gs) Gravel and silt	Silt matrix with cobbles

race underlying the fan. This date demonstrates that the fan is historic. Above the overbank sediments, nine charcoal and wood samples from the fan range in age from 8423 to 80 cal. ^{14}C yr B.P. and are not in stratigraphic order. Older samples (i.e., sample M1; 510–420 cal. ^{14}C yr B.P.) may be from the inner rings of old-growth trees cut and burned by settlers. Younger charcoal pieces may either be from younger trees or from the outer rings of old-growth trees. One sample of charcoal (sample M15, Table 1) has an age of 8420 cal. ^{14}C yr B.P. and is probably reworked from terrace sediment or colluvium upstream.

In order to test the utility of bulk soil ages, we extracted humic acids from two samples (W10 and W17, Table 1) and dated them separately (W10H and W17H) from the acid- and base-resistant soil organic material. Dates from acid- and base-resistant soil organic material and from humic extracts differed substantially. For example, sample W17 (organic) has an age of 6610 cal. ^{14}C yr B.P.; sample W17H (humic) is 3920 cal. ^{14}C yr B.P. Likewise, the acid- and base-resistant organic material in sample W10 is older (14,200 cal. ^{14}C yr B.P.) than the humic fraction (W10H, 6640 cal. ^{14}C yr B.P.).

The large differences between the age of the humic extracts and the resistant soil organic material indicates a substantial presence in the paleosol of migrating humic acids. The old age of acid- and base-resistant material from W10, which is out of stratigraphic order and older than the age of the base of the fan, suggests that reworked, older organic material is preserved in fan soils. Although the humic acid can be removed from bulk-soil organic material during sample preparation, the sources and history of the remaining mixture of organic material remain uncertain. For the purposes of dating fan stratigraphy, imprecise and possibly inaccurate mean residence times of soil horizons were not useful; hence, we relied only on dates from discrete wood and charcoal pieces.

Fan Sedimentology and Stratigraphy

Sediment in all five fans we studied was deposited by flowing water. Most fan units are

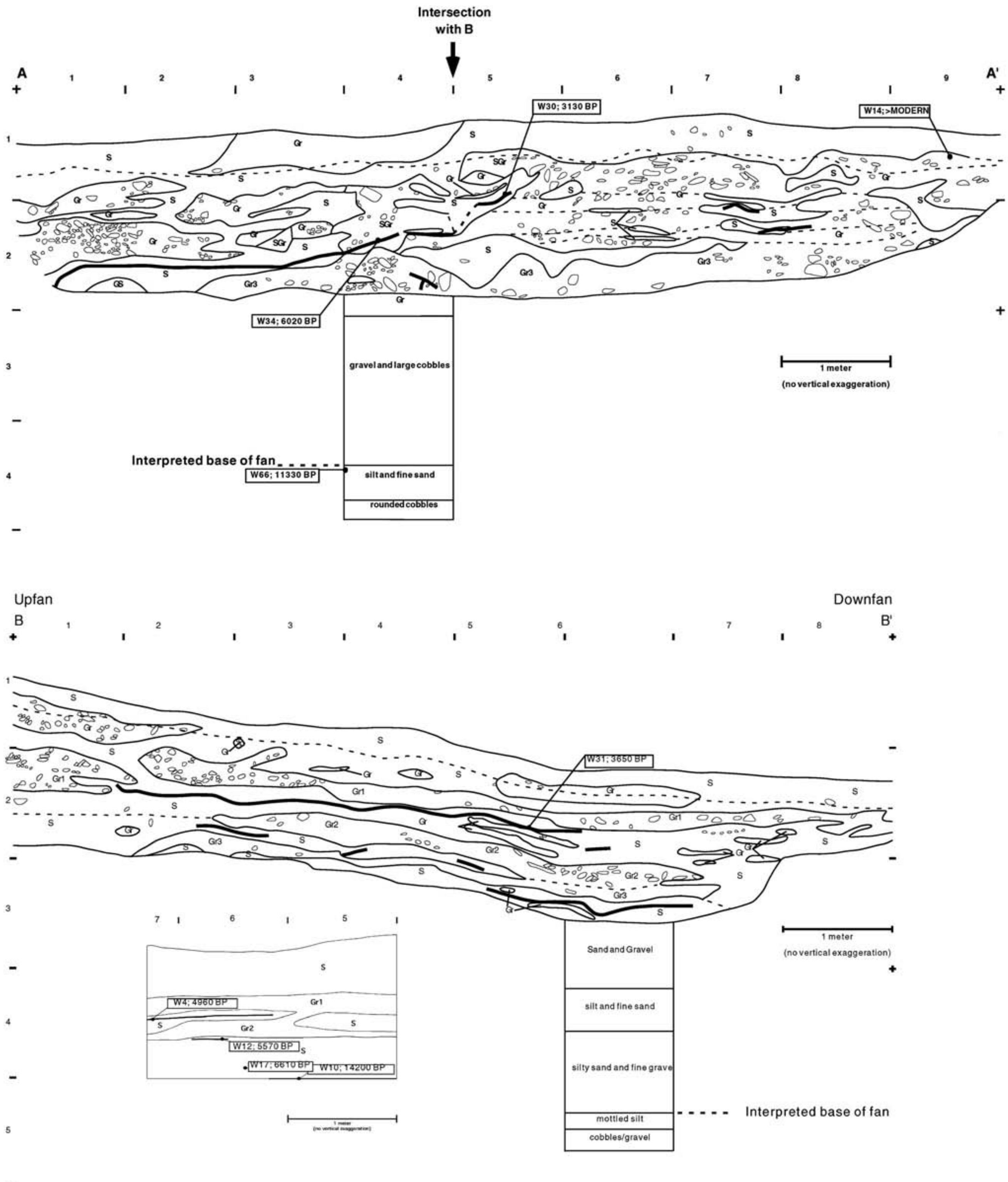


Figure 7. Stratigraphy of fan at Bridgewater Corners, Vermont. A–A′ is top trench; B–B′ is stem trench. Rocks are outlined, and the location of dated samples (cal. ^{14}C yr B.P.) and their sample numbers and ages are shown. Interpreted base of fan indicated by dashed line. Inset is section from opposite wall of the stem trench (B–B′).

LEGEND -- FAN TRENCHES, BRIDGEWATER CORNERS, VERMONT

Unit Identifier	Grain size
(above dashed line) Topsoil	N/A
(S) Sand	Fine sand and silt
(solid black) Paleosol	Very fine to coarse sand
(SGr) Sand and gravel	Fine sand and silt matrix with gravel clasts (20%)
(Gr, Gr1, Gr2, Gr3) Gravel	Gravel, medium sand and small cobbles
(GS) Grey silt	Silt and fine sand

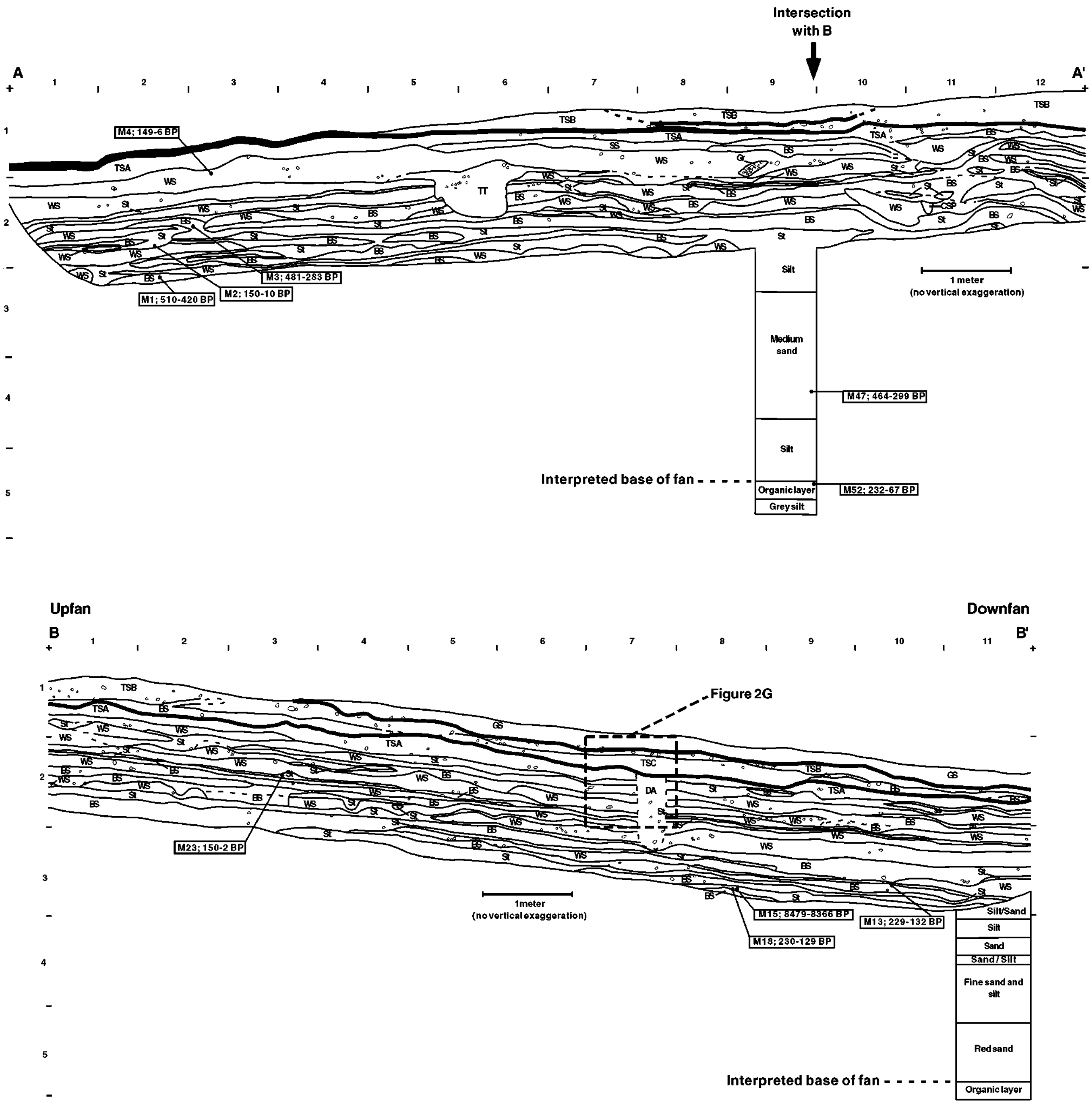


Figure 8. Stratigraphy of fan at Maidstone, Vermont. A–A′ is top trench; B–B′ is stem trench. Rocks are outlined, and the location of dated samples and their sample numbers and ages (2σ range, cal. ^{14}C yr B.P.) are shown. Interpreted base of fan indicated by dashed line.

LEGEND -- FAN TRENCHES, MAIDSTONE, VERMONT

Unit Identifier	Grain size
(GS) Gully sand	Fine to medium sand
(WS) White sand	Fine to medium sand
(St) Silt	Silt with little fine sand
(BS) Brown sand	Medium and fine sand
(CBS) Coarse brown sand	Medium sand and about 25% coarse sand
(TT) Tree throw area	Medium sand
(upper solid black) Upper buried soil	Fine sand
(lower solid black) Lower buried soil	Fine sand
(Gr) Gravel	Small cobbles in a medium sand matrix
(CSP) Coarse sand patch	Coarse sand
(TSA) Top sand A	Fine and medium sand
(TSB) Top sand B	Fine to medium sand
(DA) Disturbance area	Medium sand
(TSC) Top sand C	Medium sand with 30% fine gravel
(SS) Silt and Sand	Medium to coarse sand with 15% fine gravel

TABLE 1. RADIOCARBON AGES FOR ALLUVIAL FAN SAMPLES, VERMONT

Sample number	CAMS number†	Depth (m)	Material	Age (^{14}C yr BP)	1σ calibrated (yr BP)‡	2σ calibrated (yr BP)‡
B3	67867	0.32	Charcoal	3310 ± 50	3581–3471	3640–3442
B5	62297	0.32	Charcoal	3900 ± 40	4410–4341	4425–4230
B7	62296	0.40	Charcoal	3000 ± 40	3258–3154	3335–3069
B10	62450	0.60	Charcoal	3930 ± 60	4435–4282	4524–4224
B19	62451	0.77	Charcoal	2610 ± 660	3469–1896	4357–1267
B32	62295	0.92	Charcoal	8310 ± 40	9421–9338	9436–9243
B35	62294	0.85	Charcoal	8300 ± 40	9404–9339	9432–9240
B43	62293	0.70	Charcoal	9370 ± 60	10644–10502	10750–10395
B45	62291	0.40	Charcoal	4400 ± 40	4984–4875	5057–4857
B46	62292	0.55	Charcoal	3600 ± 40	3925–3842	3989–3823
B53	62449	2.60	Charcoal	8360 ± 40	9343–9303	9486–9270
B55	62290	3.45	Charcoal	9140 ± 40	10280–10225	10405–10214
B59	62289	5.20	Wood	10920 ± 40	13027–12876	13136–12829
C8	57769	1.08	Charcoal	2610 ± 190	2870–2439	3169–2304
C22	57767	1.51	Charcoal	8890 ± 50	10086–9922	10187–9865
C31	57766	1.15	Charcoal	6060 ± 50	6954–6854	7018–6776
C39	67868	0.60	Charcoal	860 ± 40	792–726	799–686
C45	57770	1.15	Charcoal	4730 ± 130	5590–5319	5722–5205
C57	67870	0.46	Charcoal	1320 ± 50	1290–1230	1312–1168
C83	57768	1.15–1.30	Charcoal	5550 ± 790	7266–5572	7954–4416
E6	62357	0.70	Wood	440 ± 40	518–477	539–437
E18	67873	1.19	Wood	2500 ± 40	2651–2488	2740–2451
E40	62287	1.28	Charcoal	8390 ± 60	9489–9400	9527–9266
E53	62288	0.66	Wood	90 ± 40	88–33	149–10
E58	62354	1.36	Wood	5320 ± 40	6082–5998	6196–5990
E60	67870	1.13	Charcoal	8640 ± 50	9604–9540	9759–9528
E70	62356	2.15	Wood	10820 ± 40	12982–12820	13013–12795
E71	62355	2.65	Wood	11400 ± 50	13441–13337	13488–13154
M1	62447	1.45	Wood	380 ± 40	501–433	510–420
M2	62346	1.10	Charcoal	110 ± 40	136–59	150–10
M3	62347	0.90	Charcoal	300 ± 50	433–353	481–283
M4	62348	0.30	Wood	110 ± 50	139–50	149–6
M13	62352	1.35	Charcoal	200 ± 40	209–147	229–132
M15	62353	1.57	Charcoal	7640 ± 40	8429–8385	8479–8366
M18	62448	1.57	Charcoal	220 ± 50	213–145	230–129
M23	62351	0.82	Charcoal	130 ± 40	144–66	150–2
M47	62349	3.25	Charcoal	310 ± 40	432–357	464–299
M52	62350	4.20	Wood	170 ± 40	219–165	232–67
W4	57765	0.75	Charcoal	4390 ± 80	5053–4850	5092–4834
W10	57785	1.35	Soil organic material§	12150 ± 50	14336–14058	14365–14041
W10	57788	1.35	Humic extract§	5850 ± 50	6730–6625	6755–6533
W12	57763	0.90	Charcoal	4960 ± 760	6551–4809	7324–3820
W14	67871	0.20	Wood	>MODERN	>MODERN	>MODERN
W17	57760	1.18	Soil organic material§	5810 ± 50	6668–6547	6734–6487
W17H	57787	1.18	Humic extract§	3620 ± 40	3978–3873	4007–3829
W17S	57786	1.18	Solids from humic extract§	4030 ± 50	4530–4424	4646–4405
W30	67872	0.67	Charcoal	2970 ± 50	3213–3074	3267–2985
W31	57762	0.57	Charcoal	3420 ± 40	3705–3632	3731–3569
W34	57764	0.95	Charcoal	5260 ± 130	6194–5909	6291–5743
W66	57761	2.75–3.25	Charcoal	9950 ± 50	11344–11235	11458–11208

†Center for Accelerator Mass Spectrometry, Lawrence Livermore Laboratory.
‡Calibrated using CALIB version 4.2 (Stuiver et al., 1998).
§The soil organic material (samples W10 and W17) was prepared with acid and base washes. The base washes from these two samples were retained and evaporated. The remaining humic acids were labeled W10H and W17H and dated. The base washes from soil sample W17 also contained a black, sludge-like material that had settled out of solution and was separated from the rest of the base wash before evaporating the solution to recover the humic acids. The sludge material was then dated separately as W17S and is assumed to be associated with the humic acids in the soil.

moderately well sorted, with the exception of the Maidstone fan, which has very well sorted strata. Grain size ranges from silt to cobbles. Sedimentary structures indicative of tractive load transport are best preserved in the Bridgewater Corners fan (cross-bedding and minor imbrication) and in Maidstone, the youngest fan (cross-bedding and soft-sediment deformation). The lack of sedimentary structures in the other fans is most likely the result of bioturbation; worm tracks and animal burrows are common. Numerous tree throws have mixed fan sediment and left distinct scars (e.g., unit TT in Fig. 8A), consistent with presettlement forest cover on fan surfaces.

All five fans we investigated appear to have been deposited by streamflow. None of the fans preserves characteristics indicative of debris-flow deposition; there are no matrix-supported clasts, reverse grading, levees, or matrix-dominated units (Blair and McPherson, 1994). The few poorly sorted units may be the result of hyperconcentrated flow; however, most deposition on the five fans is probably fluvial. We saw no evidence for debris flows in the 10 trenches we dug, nor did earlier studies of Vermont fans find evidence for debris-flow deposits (Bierman et al., 1997). There are debris-flow fans in Vermont (Ratte and Rhodes, 1977); those we know of are in deep mountain valleys and have very bouldery surfaces. We have not yet studied these debris fans because of access and trenching limitations.

Soil Development

All five fans preserve buried soil horizons that typically extend no more than a few meters along fan trench walls. This discontinuity likely reflects the removal of thin soils by erosion during the initial stages of fan-flooding events and the influence of dense presettlement forest vegetation. Soil development in buried profiles ranges from thin A-horizons, to reddened Bw-horizons, and the beginning of E-horizon development on the Eden Mills and Maidstone fans. Differences in soil-profile development represent relative amounts of time that the fan surfaces were stable and the

TABLE 2. DIMENSIONS OF VERMONT ALLUVIAL FANS AND DRAINAGE BASINS

Fan location	Fan-base age (ka)	Fan volume (m^3)	Fan surface area (m^2)	Length (m)	Apex height (m)	Sweep angle (°)	Drainage basin area (m^2)
Maidstone	0.25	3960	2260	52	5.3	95	14,500
Hancock	10.0	12,230	4390	87	8.0	70	225,000
Bristol	13.0	14,850	4990	87	9.0	75	249,000
Bridgewater Corners†	11.3	1900	900	44	4.5	75	77,000
Eden Mills	13.3	6850	1980	69	5.5	90	135,000

Notes: Sediment density of 2.0 g ● cm^{-3} was assumed.
†Not closed system.

acidity of the local weathering environments. Our data clearly show that soil profiles can develop quickly. The age of the Maidstone fan base, as well as eight overlying young ^{14}C ages, indicates that <250 yr were needed at this site to form the distinct buried A-, Bw-, and E-horizons observed on that fan as well as a second, less distinct A-horizon.

Fan Development

The five fans we examined have both similarities and differences. All preserve buried soil profiles, all are composed of gravel, sand, and silt, and all have coarse-grained units in erosional contact with finer-grained units below. Fans fed by perennial streams have large, infilled scour channels (Hancock, Bridgewater Corners, Eden Mills). Fans fed by ephemeral streams reveal aggraded contacts with only minor scoured surfaces (Maidstone and Bristol). Prehistoric fan deposition and soil development occurred in and around trees in forests and may have resulted from braided streams, thus causing laterally discontinuous fan stratigraphy.

Fans in separate basins have differing depositional patterns and histories. The Maidstone fan was deposited very rapidly in continuous strata. At Hancock, incision alternated with fill events, possibly the result of bedrock outcrops that concentrated flow. The Eden Mills and Bristol fans preserve most depositional events as continuous beds that cover the entire fan surface, in some cases scouring the underlying units. The Bridgewater fan does not appear to have any scouring, but contains patchy, discontinuous deposits of gravel.

DETAILED FAN STRATIGRAPHY

We examined each fan's stratigraphy on a unit-by-unit basis to identify coarse and extensive gravel units or areas of scour indicative of large runoff events (Fig. 2C). Detailed stratigraphic descriptions are provided for all fans in Data Repository Tables DR1A through DR5A (see footnote 1). Topographic maps of each fan are in Data Repository Figures DR1B through DR5B. Location maps are included as Figures DR1C through DR5C. Further information about each site can be found in Jennings (2001).

Eden Mills Fan

The Eden Mills fan, located in a glacial valley below till-mantled hillslopes, began to accumulate soon after ice-sheet retreat (Fig. 4). It is composed of bedded fine sand overlain in abrupt contact by coarse sand and gravel in the upper meter of the fan (Fig. 2D). The age of the base of the fan is 11,400 ^{14}C yr (E71, 13,320 cal. ^{14}C yr B.P.), only 540 ^{14}C yr after postglacial primary productivity was reestablished in Ritterbush Pond, 4 km to the west of Eden Mills (Fig. 1; elevation, 317 m above sea level; Bierman et al., 1997). This age also corresponds to the return of mixed woodland forests to northern Vermont (Davis and Jacobson, 1985). From 13,320 to 12,900 cal. ^{14}C yr B.P. (E71 and E70), 0.5 m of massive, well-sorted silt was deposited over coarse, well-sorted gravel that is likely glacial outwash. At 12,900 cal. ^{14}C yr B.P., a 0.5-m-thick organic unit developed (E70). This organic layer indicates surface stability sufficient for thick A-horizon development. The silt and organic layer is overlain by bedded gravel (GG unit, Fig. 4). The top trench of the Eden Mills fan contains a channel scour filled with gravel and a large, well-preserved log (E58) indicative of flooding and rapid burial at 6090 cal. ^{14}C yr B.P. (Fig. 4).

Above the GG gravel, multiple buried A-horizons (Fig. 2E) indicate that the fan was subject to cycles of fine-sand deposition followed by periods of fan-surface stability (buried soils) until 490 yr B.P., the date just beneath the lowest AP horizon (S1 unit, Fig. 4). The buried soils with sequences of A- E-, and B-horizons have much thicker sand units below them than between the multiple A-horizons. This disparity suggests that where more deposition occurs on the fan, such deposition is followed by a period of quiescence sufficient to develop thick soil profiles. The discontinuous nature of the paleosols is likely the result of discontinuous fan-surface scouring by channels during storms.

Two Ap horizons, a result of plowing for agricultural use, are preserved in the upper meter of the fan at the base of the BAP and S1 units. Above the two agricultural horizons, there is an abrupt change to coarse gravel and wood fragments. The topmost 50 cm of the fan are heavily laden with woody debris, including sawn logs ranging from 30 cm to 2 m in length (Fig. 4). Most likely this change in depositional style reflects the historical logging land use at this site and a resulting increase in hillslope-erosion rates. A piece of a metal horse bridle, an artifact that indicated a historic age for this unit, was found near the surface in the RG unit (Fig. 4). Large gravel lobes, high in the stratigraphy at the southern edge of the top trench, are likely stream-bed sediment deposited as the fan channel migrated southward to its current position.

Bristol Fan

The Bristol fan, fed by till-mantled bedrock hillslopes and overlying glacial-lake sediments, is composed of interbedded sand, gravel, and cobbles in laterally continuous and massive deposits (Fig. 5). Below the oldest fan deposits, at a depth of 4.9 m, is a thick layer of well-preserved organic material containing hemlock cones and large wood pieces, evidence of a moist, forested landscape at this location at 12,980 cal. ^{14}C yr B.P. (sample B59, Table 1 and Fig. 5B). The onset of fan aggradation filled and buried the moist area with well-sorted coarse sand and faceted 10–40-cm-diameter clasts grading upward into bedded fine and medium sand by 10,310 cal. ^{14}C yr B.P. (sample B55, Table 1 and Fig. 5).

At Bristol, the stem trench (Fig. 5) contains >1 m of sediment deposited between the fine sand of the trench extension (9380 cal. ^{14}C yr B.P., sample B53) and the MS unit (dated as 9340 cal. ^{14}C yr B.P., sample B35). This sediment represents a significant depositional event at ca. 9360 cal. ^{14}C yr B.P. The large gravel unit (unit LG, Figs. 5 and 2C) represents a high-energy deposit whose age is delimited by samples B10 (4370 cal. ^{14}C yr B.P.) and B5 (4330 cal. ^{14}C yr B.P.) above the unit and sample B35 (9340 cal. ^{14}C yr B.P.) below it. Samples B45 (4960 cal. ^{14}C yr B.P.) and B10 (4370 cal. ^{14}C yr B.P.) are from within the smaller Gr unit (Fig. 5) and represent an event at ca. 4500 cal. ^{14}C yr B.P. Above the LG unit, multiple, discontinuous A-horizons in both trenches indicate repeated short periods of fan stability, separated by scouring events. The thin, discontinuous sand and gravel units (units Gr, S, LS, and FG2) suggest that many small depositional events followed one another closely in time. On the basis of two dates from the LS unit (B7 and B46, Table 1, Fig. 5), we can infer that from ca. 4000 to 3000 yr B.P. the fan accumulated thin units of sand or fine gravel followed by periods of stability sufficient to develop A-horizons.

The interbedded, thin, patchy sand and gravel units of the Bristol fan are interrupted by at least three discontinuous buried A-horizon paleosols. A paleosol between the lowest two LG gravel lobes in sections 9 through 11 of the stem trench (Fig. 5) suggests that at least part of the LG unit be a relic of a previous depositional event, with a substantial period of stability before the rest of the unit was deposited. Samples B5 (4330 cal. ^{14}C yr B.P.) and B7 (3200 cal. ^{14}C yr B.P.) were collected near paleosol layers (Fig. 5) and indicate times of relative fan-surface stability. Across the top of both trenches, the fan has a clear Ap (plow) horizon indicated by dark color, platy structure, and an abrupt lower contact. Beneath the Ap horizon is light-colored gravel and coarse sand (UG, Fig. 5) that may reflect either a natural depositional event after 3200 cal. ^{14}C yr B.P., or a post-clear-cutting pulse of hillslope erosion and sediment deposition. Because the lower contact of the Ap horizon is close to the upper boundary of the 3200-yr-old unit, some record of prehistoric and perhaps historic deposition has likely been obscured by the more recent plowing.

Hancock Fan

The Hancock fan, located on a river terrace below colluvium-mantled bedrock slopes and fed by a perennial stream, is composed of interbedded sand, gravel, and silt that thinly blanket (1.5–2 m) the underlying bedrock topography (Fig. 6). This fan has a complex stratigraphy dominated by cut and fill (Blair and McPherson, 1994), probably caused by channel migration around bedrock outcrops. Overlapping gravel units in the top trench are most likely channel remnants; weak cross-bedding in the lower corner of section 6 in the top trench (Fig. 6) indicates fluvial activity. Discontinuity of most strata prevents detailed interpretation of the depositional history. Dated pieces of charcoal are not all in chronological order, indicating that the fan sediments were reworked from further upslope and that deposition was not occurring uniformly.

Thin, buried A-horizons were present in both trenches and were underlain by dark red Bw-horizons in places (Fig. 6). Soil development crosscuts stratigraphic units, indicating that soils formed after deposition and truncation of those layers. The Bw-horizon color was present at many locations where there was no paleo-A-horizon. In all cases where a buried cambic B-horizon was present with no overlying A-horizon, the buried soil was overlain by a coarse gravel deposit. This stratigraphy suggests that the fan was stable and that there was little or no deposition while the A and Bw horizons developed. The next depositional event on the fan was then large enough to scour the topsoil from the fan (what would have been the preserved A-horizon) and deposit the gravel. Buried A-horizons without the reddened Bw-horizon beneath indicate shorter periods of fan-surface stability.

Bridgewater Corners Fan

The Bridgewater Corners fan, deposited on a high terrace of Broad Brook, is composed of interbedded sand and gravel (Fig. 7) derived from the till-mantled drainage basin. The gravel units are clast supported and slightly imbricated within a fine-sand matrix. Units are continuous over 2–7 m in both trenches, indicating a patchy but consistent horizontal pattern of deposition. Sand units are massive and contain mostly fine sand with interbedded buried paleosol A-horizons. Sand units in the top trench (Fig. 7) are patchy and interrupted by large gravel lenses, but in the stem trench, sand units are continuous (Fig. 7). In the stem trench, there is a repeating depositional motif: Sand-gravel-sand-paleosol (Fig. 2H).

Fan sediments coarsen to large gravel and cobbles in the deeper parts of the top trench (Fig. 7). Just below 3.30 m depth, there is a deposit of Broad Brook stream-rounded cobbles. Silt and fine sand at a depth of 3 m represent river-channel overbank sediments from Broad Brook. Wood from the overbank layer (sample W66, Table 1) provides a maximum age for the fan (11,330 cal. ^{14}C yr B.P.). Dates on wood and charcoal associated with paleosols (Fig. 7; W4, W12, W30, W31) indicate times of fan stability at 5570, 4960–3650, and 3130 cal. ^{14}C yr B.P. Sample W34 indicates fan activity at 6020 cal. ^{14}C yr B.P. The lack of organic material preserved in sand layers suggests deposition slow enough to allow most organic material to decompose before being buried deeply enough to be seasonally saturated and preserved. It appears that thin patches of sand were laid down on the Bridgewater fan during many storms; only rare, intense precipitation events deposited gravel.

Maidstone Fan

Maidstone is the youngest fan we trenched. The calibrated basal radiocarbon age, measured on large, well-preserved chunks of wood, is consistent with historic deposition (232–67 cal. ^{14}C yr B.P.) as are most of the 10 dates within the fan. The Town of Maidstone was chartered in 1761, earlier than most towns in Vermont because it is located in the easily accessible Connecticut River Valley. On the basis of the 2σ lower limit of the age of the base of the fan and the settlement time of the town, we assign an age of $\leq$250 yr to the Maidstone fan and use that age for all calculations. All other Maidstone dates are reported as the 2σ calibrated age range (Fig. 8).

The Maidstone fan is located on a low terrace of the Connecticut River below a small, steep drainage basin, which appears to be a steep-walled gully eroded into an older, higher, river terrace. This young fan is probably the result of historic land disturbance. At 4.2 m depth, below the basal fan sediment, we found a continuous, 20-cm-thick layer of organic material including moss, leaves, and wood (Fig. 8). This layer represents deposition of organic material from Connecticut River floods and hence provides a reliable maximum age estimate for the Maidstone fan ($\leq$250 cal. ^{14}C yr B.P., sample M52, Table 1).

Only two buried soils appear in the stratigraphy. The higher buried soil, ~5–10 cm below the ground surface, is faintly colored and only appears in the top trench where it merges with the modern topsoil toward the fan margin (Fig. 8A). The lower buried soil is ~30 cm below the surface and has a black A-horizon, underlain by a pale E-horizon, with a reddened Bw-horizon beneath the E. This profile is typical of an acidic soil environment and probably developed under a pine or hemlock forest.

Except where the Maidstone fan has been bioturbated by animals (Fig. 2G) or tree throw (unit TT, Fig. 8A) and except close to the apex, where the fan stratigraphy has been disturbed by natural fan-head trenching, the fan consists of laterally continuous interbedded sand and silt (Fig. 2F). Light-colored sand units (WS) are well laminated. Interbedded with the WS units are massive, dark-colored sand units (BS), which have a higher silt content. Most sand units are separated by thin silt layers; silt layers are also found within some laminated sand units. The Maidstone fan preserves detailed sedimentary structures not observed in the four older fans where, over time, bioturbation by animals (Fig. 2G), worms, and root growth has probably mixed fan sediments and gradually blurred fan stratigraphy and structure.

DISCUSSION

Vermont fans are complex, long-lived landscape features that preserve a complicated history of incision and aggradation, punctuated by buried soils indicative of periods of fan-surface stability. Sediments within the fans range in age from just postglacial ($\geq$13,320 cal. ^{14}C yr B.P.) to historic. All fans aggraded episodically in the past, and several aggraded rapidly in historic times, presumably in response to recent, human-induced landscape changes.

Rates of Fan Aggradation and Drainage-Basin Sediment Yield

Aggradation rates of the five fans, determined through the use of radiocarbon-dated organic material, have changed over time and differ between fans (Fig. 9; 0.09–135 $m^3 \cdot yr^{-1}$).

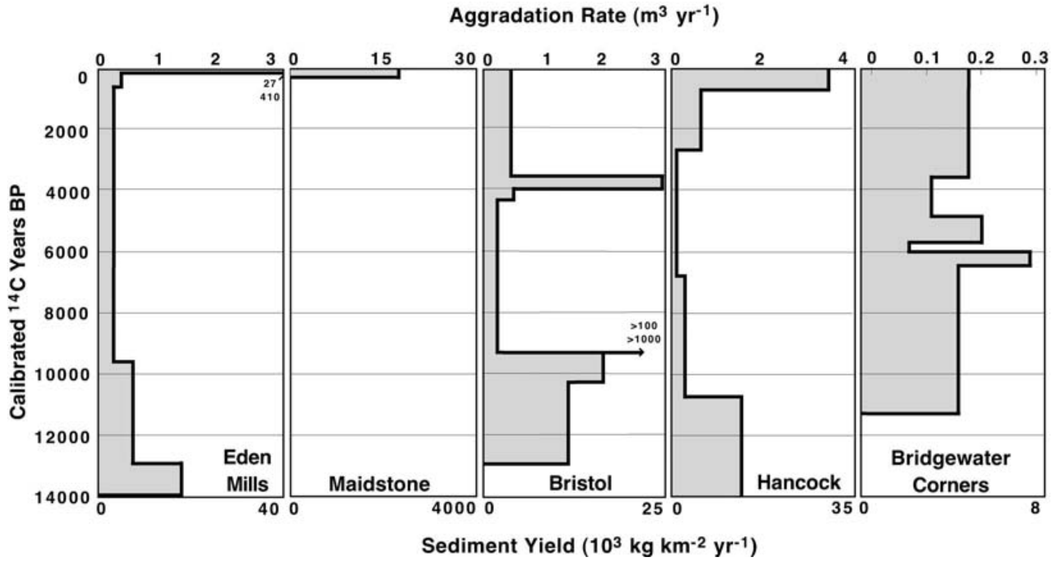


Figure 9. Comparison of aggradation rates and sediment yields on the five trenched and dated fans. Rates represented by shaded bar graphs; *x*-axis scales vary between fans. Upper axis is aggradation rate ($m^3 \cdot yr^{-1}$). Lower axis is sediment yield (10^3 kg·km^{-2}·yr^{-1}). Very high rates are not plotted but are indicated by number where the peak intersects the right side of the graph; aggradation rate ($m^3 \cdot yr^{-1}$) is first, and sediment yield is second (10^3 kg km^{-2} yr^{-1}).

TABLE 3. FAN-BASED SEDIMENT YIELD AND BASIN LOWERING RATES

Fan location	Integrated sediment yield (10^3kg ● km^{-2}yr^{-1})	Prehistoric sediment yield (10^3kg ● km^{-2}yr^{-1})	Historic sediment yield (10^3kg ● km^{-2}yr^{-1})	Basin average lowering (cm/k.y.)
Maidstone	NA	NA	2180‡	109
Hancock	11	9	>31	0.54
Bristol	9	≤9	NA	0.46
Bridgewater Corners†	≥4	≥4	NA	0.22
Eden Mills	8	5	410§	0.38

Note: Sediment density of 2.0 g cm^{-3} was assumed. NA—not applicable.
†Not closed system.
‡Calculated by assuming that historic sediment was delivered over the 250 yr since settlement.
§Calculated by assuming that historic sediment was delivered over 80 yr (uppermost cal^{14}C age).

High aggradation rates early in the Eden Mills fan's history (13,320–12,900 cal. ^{14}C yr B.P.) are consistent with sparsely vegetated hillslopes just after deglaciation (Davis and Jacobson, 1985) for which lesser amounts of precipitation would be needed to initiate sediment transport (Church and Ryder, 1972). We infer similar early pulses of aggradation for the Bristol and Hancock fans. However, the period of barren hillslopes was short. Wood dates of 13,320 and 12,980 cal. ^{14}C yr B.P., at Eden Mills and Bristol, respectively, suggest that woody vegetation regrew within 1000 yr after the ice melted off Vermont hillslopes (14,000 cal. ^{14}C yr B.P.; Ridge et al., 1999). During the Holocene, we detect little systematic change in time-integrated fan-aggradation rates with the exception of a well-dated pulse of sedimentation on the Bristol fan at ca. 9300 cal. ^{14}C yr B.P.

The Eden Mills fan, the Maidstone fan, and most probably the Hancock fan aggraded rapidly in historic time, responding, we presume, to land-use changes; the Eden Mills fan accumulated 2220 m^3 of sediment during historic time, about a third of its volume. The historic rate of sediment accumulation at Eden Mills (27 $m^3 \cdot yr^{-1}$) is 20–200 times higher than prehistoric, Holocene rates (0.13–1.4 $m^3 \cdot yr^{-1}$). The Maidstone fan is completely historic and represents nearly 4000 m^3 of aggradation over ≤250 yr at an average rate of nearly 16 $m^3 \cdot yr^{-1}$. Aggradation on the Hancock fan integrated since 740 yr B.P. (the uppermost date) exceeds Holocene aggradation rates by a factor of 10. The synchronous and significant response to historic deforestation that has affected sedimentation in the fans we investigated, as well as the fans investigated by Bierman et al. (1997), suggests the importance of woody vegetation in providing effective soil cohesion on basin hillslopes. Colonial and postcolonial clear cutting and agriculture increased fan-aggradation rates, and thus basin-erosion rates, significantly.

Fan volumes, drainage-basin areas, and fan ages can be used to calculate minimum rates of drainage-basin sediment yield and lowering integrated over various time periods (Tables 2 and 3). Such a calculation requires the assumption that the fans, since they began to form, functioned as effective sediment traps and that the conical approximation for fan shape is valid. These assumptions appear reasonable for all but the Bridgewater Corners fan, where it is clear that some mass has been lost as the feeder stream bypassed the fan and as the fan was eroded by adjacent Broad Brook.

Holocene average sediment yields for the four drainage basins are similar, very low (>4–11 × 10^3 kg·km^{-2}·yr^{-1}; Table 3), and comparable to rates measured by others in New England. For example, Ouimot and Dethier (2001) measured bed load transported by low-order streams in a forested northwestern Massachusetts catchment and determined that recent sediment yields from till-mantled uplands ranged from 2 to 10 $\times$ 10^3 kg·km^{-2}·yr^{-1}. Alluvial-fan–based sediment yields are equivalent to basin average-lowering rates of between 2 and 5 m/m.y., suggesting that the fan's drainage basins have lowered on average only centimeters to decimeters since deglaciation. To place these observations in context, consider that granitic rock surfaces and drainage basins in hyper-arid southern Africa (Namibia) erode at similarly low rates (Bierman and Caffee, 2001). Together, these data suggest that parts of the postglacial New England landscape are quite stable in the absence of disturbance, either natural or human-induced.

Fan data allow us to determine the variability in sediment yields over the Holocene; we find that such variability is significant. For example, at Eden Mills, prehistoric sediment yields, integrated over durations ranging from 9160 to 410 cal. ^{14}C yr, are 1.9–20.8 $\times$ 10^3 kg·km^{-2}·yr^{-1}. At Bristol, prehistoric sediment yields range from 1.7 to 1100 $\times$ 10^3 kg·km^{-2}·yr^{-1}, integrated over durations ranging 4960 to 10 cal. ^{14}C yr. If one considers sedimentation for only the historic period on the Eden Mills and Hancock fans, sediment yields are several to nearly 100 times higher than average Holocene background rates (Table 3). The sediment yield implied by the volume and age of the Maidstone fan is higher yet (2180 $\times$ 10^3 kg·km^{-2}·yr^{-1}), reflecting the rapid, historic incision of the deep gully, which feeds the fan and comprises almost the entire drainage basin. The historic sediment yield at Maidstone exceeds, by a factor of two, the highest prehistoric sediment yield (Bristol, 9380–9360 cal. ^{14}C yr, 1100 $\times$ 10^3 kg·km^{-2}·yr^{-1}), suggesting both the significance of human impact and the large magnitude of some prehistoric sediment-transport events.

Timing of Fan Deposition and Soil Formation

Despite the complexity of fan stratigraphy, the paucity of organic material in large gravel units indicative of significant prehistoric runoff, and the wide spatial distribution of the five fans we studied, three periods of increased aggradation and four periods of soil formation can be correlated between at least two of the fans (Table 4). Specifically, synchronous depositional pulses occurred on the Eden Mills and Bristol fans between 9650 and 9340 cal. ^{14}C yr B.P. We dated gravel deposition or scour on the Eden Mills, Hancock, and Bridgewater Corners fans between 6900 and 6020 cal. ^{14}C yr B.P.; the largest gravel layer at Bristol has only limiting ages (9340–4960 cal. ^{14}C yr B.P.) but could also correlate with this middle Holocene event. We found significant historic aggradation of three of the five fans; plowing has obscured the recent record of the other two fans.

In the four fans with Holocene records, we correlated four periods of relative fan-surface stability, as indicated by well-developed soils (Table 4). The two oldest fans, Eden Mills and Bristol, show correlative soil formation at ca. 13,000 cal. ^{14}C yr B.P. Hancock and Bridgewater have middle Holocene soils of similar age (5570 and 5460 cal. ^{14}C yr B.P.). Bridgewater and Bristol have two correlative later Holocene soils (ca. 4300 and ca. 3200 cal. ^{14}C yr B.P.). In general, it was easier to determine the age of soils than that of gravel layers because soils or the fine-grained units around them more often contained datable wood or charcoal.

Differences between fans in the timing of aggradation and soil formation also occur, and many depositional events remain undated despite the large number of radiocarbon dates we obtained. For example, a sediment pulse on the Bristol fan between 4960 and 4370 cal. ^{14}C yr B.P. is not reflected elsewhere. Rapid sedimentation at the Bridgewater Corners fan between 5570 and 4960 cal. ^{14}C yr B.P. coincides with soil formation on the Hancock fan. We identified late Holocene soils and events on the Eden and Hancock fans, but these events do not correlate between these or the other fans.

The limited temporal and spatial correlation of depositional periods and flow-related stratigraphic markers (gravel beds and scour) on Vermont fans is consistent with several plausible reasons for variable fan response to environmental triggers. Possible factors include (1) localized storm cells of great intensity but restricted size, (2) heterogeneous precipitation duration and intensity in large, regional storms, and (3) the stochastic nature of hillslope response to rainfall, including the difficult-to-quantify effects of antecedence on sediment availability and slope stability. Our observations of contemporary fan behavior—specifically, the spatial heterogeneity of deposition from one fan to the next during single storms—suggest the influence of all three factors. Thus, stable periods on the fans, and the lack of storminess such periods represent, may in fact be better temporal indicators of paleostorminess patterns than the storm deposits themselves. We conclude that the most robust records of paleostorminess will come from studying many fans and dating both stable soil-forming periods and the gravel deposits indicative of storms.

Comparison to Other Paleostorminess Records

Our estimates, both for periods of increased hillslope erosion and also for periods of fan-

TABLE 4. EVENT AND SOIL CORRELATION, VERMONT ALLUVIAL FANS

Eden	Age (cal ^{14}C yr B.P.)	Bristol	Age (cal ^{14}C yr B.P.)	Hancock	Age (cal ^{14}C yr B.P.)	Bridgewater	Age (cal ^{14}C yr B.P.)	Maidstone	Age (cal ^{14}C yr B.P.)
Basal age	13320	Basal age	12980	Basal age	10030	Basal age	11330		
Soil 1	<12900	Soil 1	<12980						
Soil 2	<9500								
Event 1	9450–9650	Event 1	9360						
Event 2	6090			Event 1	6900	Event 1	6020		
				Soil 1	5460	Soil 1	5570		
						Event 2	5570–4960		
		Event 2	4370, 4960						
		Soil 2	4330			Soil 2	4960–3650		
		Event 3	4330–3540						
		Soil 3	3200, 3540			Soil 3	3130		
						Event 3	<3130		
Soil 3	2600								
				Event 2	1240				
				Soil 2	740				
Soil 4	490-historic								
Event 3	Historic			Event 3	<740			Event 1	Historic

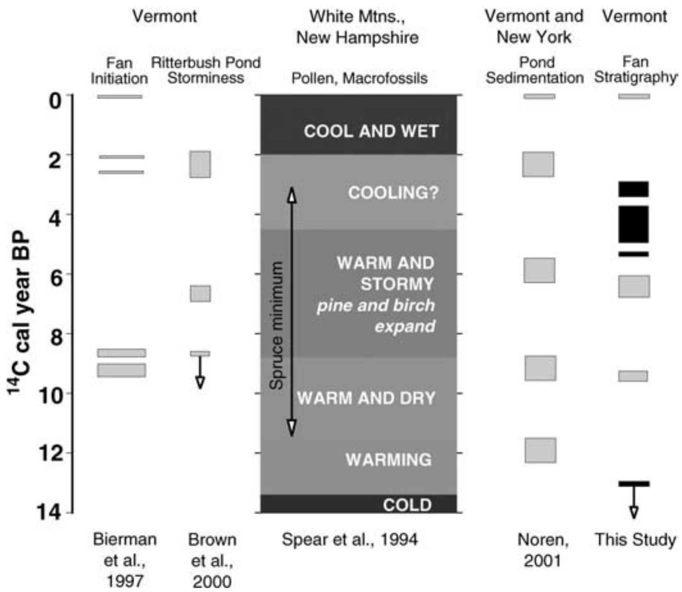


Figure 10. Summary diagram for New England climate and hillslope erosion studies. Ages of the bases of terrace fans (gray bars and boxes) reported by Bierman et al. (1997) indicate timing of terrace abandonment and initial fan aggradation. Periods of increased inorganic sediment accumulation in Ritterbush Pond, Vermont (Brown et al., 2000), suggest periods of increased storminess (gray boxes). Pollen and macrofossil data from the White Mountains (Spear et al., 1994) are indicative of regional climate trends. Amalgamation of inorganic sedimentation events detected in 13 lake cores from Vermont and New York (Noren, 2001) suggests four periods (gray boxes) of increased storminess spaced ~3000 yr apart. Data from this study show that soils (indicative of fan-surface stability and low storminess, black boxes) are interspersed with periods of fan aggradation and, by inference, greater storminess (gray boxes).

surface stability, are consistent with other records from New England derived from both fan histories (Bierman et al., 1997) and from lake deposits (Bierman et al., 1997; Brown et al., 2000; Noren, 2001; Noren et al., 2002), considering the uncertainty in dating (Fig. 10). There appears to be no direct relationship between periods of increased or decreased fan and pond sedimentation and generalized climate change as indicated by pollen and other terrestrial data (Bierman et al., 1997, and Fig. 10). This observation suggests that we are detecting, both in fans and in lakes, episodic events (storms or periods of storminess) to which large-scale vegetation assemblages and long-term lake levels are insensitive.

All studies, including this one, find early and middle Holocene (i.e., ca. 9000 and ca. 6000 cal. ^{14}C yr B.P.) sediment-yield maxima and thus paleostorminess maxima; some studies also find a late Holocene maximum at ca. 2500 cal. ^{14}C yr B.P. For example, Bierman et al. (1997) found that several fans in the Huntington River Valley of Vermont (Fig. 1) aggraded rapidly from 9600 to 8200 cal. ^{14}C yr B.P. and from 2500 to 2000 cal. ^{14}C yr B.P. These and our age ranges for increased fan activity (9650–9360 and 6900–6020 cal. ^{14}C yr B.P.) are consistent with the findings of Brown et al. (2000), Noren (2001), and Noren et al. (2002), who identified increased contributions of terrestrial sediment to New England ponds, the intensity of which peaked at ca. 11,900, 9100, 5800, and 2600 cal. ^{14}C yr B.P. Soils, indicative of landscape stability and correlated between several Vermont fans, date between these periods of increased sediment yield (i.e., at >12,900 and 5500–3100 cal. ^{14}C yr B.P.).

We calculated average recurrence intervals for depositional events and soil-forming periods for the Eden Mills, Bristol, and Bridgewater Corners fans by using the number of soils and discrete depositional events (gravel layers) or scour surfaces in each fan (whether dated or not). On average, soils formed every 1560 yr at Eden Mills, every 1450 yr at Bristol, and every 740 yr at Bridgewater Corners. Deposition events had a recurrence interval of 1330 yr at Eden Mills, 830 yr at Bristol, and 990 yr at Bridgewater Corners. In comparison, Kochel and Johnson (1984) and Kochel (1990) estimated that 3000–6000 yr passed between depositional events on fans in Virginia. It appears that Vermont fans are active more frequently than their southern counterparts, although this conclusion may be an artifact of better dating control for Vermont fan deposits.

Kochel (1987) suggested that the postglacial initiation of fan aggradation in humid-temperate, eastern North America depends on the return of tropical moisture necessary to generate rainfall sufficient to erode and move sediment. He postulated that ages of the bases of fans should decrease with increasing latitude, reflecting the gradual northward retreat of the polar front following deglaciation. Kochel (1990) suggested that debris flows began pouring onto Virginia fans after 11,000 ^{14}C yr B.P., coincident with the return of tropical air masses to the Mid-Atlantic region.

Fans in Vermont are older than those studied by Kochel (1990) and Kochel and Johnson (1984) in Virginia, suggesting that fan development began in Vermont as soon as there was a stable surface on which sediment could accumulate, regardless of polar-front position. We suspect that deglaciation, and the resultant unvegetated, unstable slopes, controlled the timing of fan initiation. Before the reestablishment of woody vegetation on Vermont hillslopes, even storms with more common rainfall intensity and duration significantly eroded hillslopes. Hence, we conclude that warm, tropical air was not initially necessary (before reforestation) to create storm events sufficiently intense to initiate slope failure and fan deposition in New England.

Utility of Fans as Recorders of Hillslope Erosion and Paleostorminess

Humid-region fans are direct, albeit low-resolution, recorders of hillslope erosion and, by inference, of paleostorminess and land-use change. Every fan we trenched revealed gravel beds indicative of discrete drainage-basin erosion events, presumably caused by storm-induced runoff. We can determine the average recurrence interval of such events, and we can determine their age, with varying levels of precision, by using radiocarbon dating of preserved wood and charcoal. However, the resolution of the fan record is limited by the paucity of preserved organic material in gravel beds, the discontinuous nature of both depositional strata and soil horizons, and the difficulty of identifying and dating every depositional event.

Fan-aggradation rates can be used to estimate basin-wide sediment yields integrated over different lengths of time, data useful for setting recent, human-influenced rates of hillslope erosion in their natural or background context. In general, even with the large number of radiocarbon dates we have obtained (an average of 10 per fan), aggradation rates are less useful for identifying periods of paleostorminess than are ages of gravel layers, soils, and scour features. However, aggradation rates clearly reveal the deglaciation sediment pulse, a period of rapid deposition at ca. 9300 yr B.P. on the Bristol fan, and the historic deforestation signature (Fig. 9).

Although the best fan-based record of paleostorminess—which is achieved by dating gravel beds either directly or by bracketing their ages using organic material above and below—is less detailed than records obtained from small, upland ponds (Brown et al., 2000; Noren, 2001; Noren et al., 2002), the fan record is critical for understanding Holocene landscape history in New England. The goodness of fit between the fan (this study; Bierman et al., 1997) and pond data sets (Brown et al., 2000; Noren, 2001; Noren et al., 2002) suggests that ponds, which record events dispersed over their drainage basins, are sensing the same general changes in Holocene paleostorminess as the fans, which are direct monitors of erosion on single hillslopes or in single drainage basins. Together, these two independent records suggest that the frequency of storms able to cause significant hillslope erosion has changed systematically during the Holocene.

CONCLUSIONS

Humid-temperate fans in Vermont preserve datable strata of gravel, sand, and silt deposited fluvially during storm events as well as buried paleosols formed during periods of fan-surface stability; thus, these fans are direct recorders of hillslope activity and by inference, paleostorminess and land-use change. Erosional contacts between units indicate scouring and reworking of fan sediments prior to or during depositional events. Buried wood and charcoal provide dating control that demonstrates that aggradation rates changed over time. Simultaneous periods of increased aggradation and dated depositional events on multiple fans suggest times of increased soil erosion just after glaciation, at 9650–9340 cal. yr. B.P., and at 6900–6020 cal. ^{14}C yr B.P., whereas periods of soil development suggest times when the landscape was more stable (before 12,900 and at ca. 5500, ca. 4300, and ca. 3200 cal. ^{14}C yr B.P.). The fan-based record of hillslope behavior is similar to that derived from the sediments of numerous New England ponds (Bierman et al., 1997; Brown et al., 2000; Noren, 2001; Noren et al., 2002), suggesting that both archives of landscape behavior are recording responses to similar forcing, presumably paleostorminess. The uniform response to land clearance during historical times (increased sedimentation) noted in most fan and pond records suggests the sensitivity of basin slopes to deforestation and agriculture.

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