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Timing and style of deposition on humid-temperate fans, Vermont, U.S.A.

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ABSTRACT

Fans in the once-glaciated, mountainous landscape of humid-temperate New England preserve a long record of deposition and thus, hillslope erosion. Using multiple backhoe trenches and radiocarbon dating of wood and charcoal, we determined the history of five small fans (1,300 to 14,500 m^3) that range in age from 150 to 13,320 calibrated ^{14}C years BP. Three fans located on river terraces have depositional records

constrained 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.

All five fans contain 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. Simultaneous increases in aggradation on multiple fans indicate periods of increased sediment yield and by inference, run off, >12,900, 10,000 to 9,300, 6,000 to 4,500, and about 3500 calibrated ^{14}C years BP. Synchronous soil surfaces on several fans suggest lower sediment yield c. 12,900, 9,300 to 6,500, and 4,200 to 3,500 calibrated ^{14}C years BP. Although all five fans aggraded rapidly during the past 200 years in response to land clearance, most episodes of aggradation or scour in the Holocene cannot be correlated between fans.

INTRODUCTION

Alluvial and debris fans are the product 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, accessible, and highly visible landscape elements (Bull, 1964, 1977, 1991; Hooke, 1967; Beatty, 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 neither been described, nor has it been used to quantify fluctuating rates of hillslope erosion throughout time.

During the last glacial maximum, New England was covered by the Laurentide icesheet (Dyke and Prest, 1987). The ice margin retreated through northern Vermont about 13,000 radiocarbon years ago (15,000 calibrated years BP, 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). Immediately, fans began to form. Mapping, trenching, and dating five such fans at Bristol, Hancock, Maidstone, Bridgewater Corners, and Eden Mills, Vermont (Figure 1) provide the first detailed data on the location, stratigraphy, age, and behavior of these post-glacial landforms in humid, northeastern North America. From these data, we calculate rates of fan aggradation, identify the timing of major scour and deposition events, constrain the age of soil-forming intervals, and infer changes in Holocene paleostorm frequency.

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 either a reduction in forest cover, lowering effective soil cohesion originally provided by root networks (Ziemer, 1981; Meyer et al., 1992), or an increase in the 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 to 6000 year recurrence interval (Kochel and Johnson, 1984). 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 year old fan in Scotland indicate that deposition occurred during intense storms (Ballantyne and Whittington, 1999), an inference supported by the development of thirteen fans during a 2.5 hour intense storm in northwest England (Wells and Harvey, 1987). During an intense 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 similarly that aggradation occurs only during intense storms and runoff events. In 1998, northern Vermont experienced 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 (Figure 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 (Figure 2A). 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 (Figure 2B). 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 based on preservation and access (Figure 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 (Figure 3, Data Repository File DR1).. The *top trench,* oriented across the fan is labeled A-A' on the cross-sections. The *stem trench*, oriented downfan, is labeled B-B'. Before leaving each site, we dug one to three meters deeper in each trench in order to determine the stratigraphy of lower fan and underlying units. The deep sediment was described and the base of the fan was determined considering sediment characteristics and extrapolated fan-toe elevation.

Over 300 samples of organic material were collected; fifty were radiocarbon dated (Table 1): 35 discrete pieces of charcoal, 11 discrete pieces of wood, and 4 amalgamated soil samples. An additional 18 charcoal samples dissolved during preparation. Samples were prepared for accelerator mass spectrometric radiocarbon analysis at Lawrence Livermore National Laboratory using standard methods including acid and repeated base washes. Radiocarbon dates were calibrated using the online version of CALIB 4.2 (Stuiver et al., 1998).

The surface of each fan and location of trenches were surveyed from three benchmarks using a combination of Trimble RTK (real time kinematic) differential GPS

(4400) and a Pentax total station. Aggradation rates based on radiocarbon ages and the survey data were calculated assuming that fan geometry is reasonably modeled as a portion of a right circular cone (Data Repository Figure DR2).

RESULTS

Fans in Vermont preserve sub-parallel depositional strata, erosional unconformities, and multiple buried soils that represent alternating periods of fan surface stability and fan aggradation since late glacial times. The abundance of buried organic material in the fans allows dating; the coarse-grained (sand and gravel) nature of most depositional units, along with observations of modern processes, suggest that these fans accumulated through a series of episodic events that disrupted stable, soil-forming intervals.

Fans directly record the timing of hillslope runoff events in both the depositional strata and the unconformities they preserve. Scouring of fan surfaces requires an increase in runoff. Likewise, deposition, especially of gravel and cobbles, requires an increase in sediment transport capacity over normal processes. Because both scour and deposition are indicative of significant flow on fan surfaces, 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 a deposit or unconformity of thickness and extent sufficient for identification and dating.

The New England landscape has been heavily forested from deglaciation until Western colonization (Davis and Jacobson, 1985) with no evidence of widespread fires or blight (Brown et al., 2000); thus, we interpret pre-historic fan deposition and scour events as the result of increased precipitation. Human activity, primarily deforestation at the onset of Western settlement, 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 accelerated recent fan deposition as the result of human activity.

Fan Setting

We found fans in one of 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) were found in glacial valleys, deposited directly on proglacial and glacial sediments, respectively. Basal ages of these *glacial valley fans*, 12,980 (Bristol) and 13,320 (Eden Mills) calibrated ^{14}C years BP, provide minimum limits for the timing of glacial lake and glacial retreat and thus the initiation of post-glacial hillslope processes.

Terrace fans, such as those at Maidstone, Hancock and Bridgewater Corners, are found where drainages dispatch onto river terraces. Many of these *terrace fans* have lost part of their depositional history downstream as drainage basin incision began before fans could be preserved; i.e. sediment entered the trunk stream as a delta, and was washed away during high flows (Figure 2B). When the trunk stream migrated and incised, leaving terraces as sediment traps, fans were preserved. The three fans on river terraces are 150 (Maidstone), 10,030 (Hancock), and 11,330 (Bridgewater Corners) calibrated ^{14}C years old. Basal dates for such fans represent the age of terrace stabilization, not necessarily the onset of hillslope incision and fan deposition.

The fans we studied are small, 200 to 3,600 m^2 and 1,300 to 14,500 m^3 (Figure 1; Table 2). Drainage basins range from 3,000 to 250,000 m^2 (Table 2) and all five basins have a history of logging and agricultural use during the past 100 to 200 years. Morphometric analysis shows good and positive correlation between fan volume, fan surface area, and drainage basin area, particularly if the Maidstone fan is excluded because it is so young and likely retains only a portion of the sediment eroded form its drainage basin.

The Maidstone and Bristol fans are fed by ephemeral streams; the other three fans are fed by small perennial streams. The Bristol, Hancock, and Eden Mills drainage basins are formed in thin mantles of till and colluvium overlying weathered bedrock. Drainages at Maidstone and Bridgewater Corners are formed in postglacial fluvial sediments at lower elevations, with glaciolacustrine sediments (Maidstone) and till (Bridgewater Corners) cropping out higher in the basins.

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 frequent in less permeable silt and sand, rare in gravel or cobble units. Organic material was better preserved in moist and less oxic fine-grained units.

Most of our AMS dates are very precise (1σ, ± 50 ^{14}C years); however, ages assigned to sedimentary units are less precise and less accurate for several reasons. Charcoal and wood can be reworked from 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 ten samples from the Maidstone fan. Below the fan is a layer of twigs and grass (sample M52, Table 1; 170 ± 40 ^{14}C years; 150 calibrated ^{14}C years BP) preserved by overbank deposition on the terrace underlying the fan. This date demonstrates that the fan is historic. Above the overbank sediments, eight charcoal and wood samples from the fan range in age from 80 to 470 calibrated ^{14}C years BP and are not in stratigraphic order. Older samples (i.e. sample M1; 470 calibrated ^{14}C years old) were probably 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 8,420 calibrated ^{14}C years BP and is probably reworked from terrace sediment upstream.

In order to test the utility of 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 soil organic material and from humic extracts differed substantially. For example, sample W17 (organic) has an age of 6,610 calibrated ^{14}C years BP; sample W17H (humic) is 4,520 calibrated ^{14}C years old. Likewise, the acid- and base-resistant organic material in sample W10 is older (14,200 calibrated ^{14}C years BP) than the humic fraction (W10H, 6,640 calibrated ^{14}C years BP).

The large and systematic differences between the age of the humic extracts and the resistant soil organic material indicates substantial contamination of the paleosol from migrating humic acids. The very old age of W10, which is out of stratigraphic order and older than the basal fan age, indicates 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 ambiguous. 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 discreet wood and charcoal pieces.

FAN STRATIGRAPHY

We examined each fan's stratigraphy on a unit by unit basis to identify large gravel units or areas of scour indicative of large runoff events (Figure 2C). Detailed stratigraphic descriptions are provided for all fans in data repository files (A) and tables

(B) DR3A-B, DR4A-B, DR5A-B, DR6A-B, and DR7A-B. Topographic maps of each fan are in data repository figures DR3C, DR4C, DR5C, DR6C, and DR7C. Location maps are included as figures DR3D, DR4D, DR5D, DR6D, and DR7D.

Eden Mills Fan

The Eden Mills fan, located in a glacial valley below till-mantled hillslopes, began to accumulate immediately after icesheet retreat (Figure 4 and Table 3). It is composed of bedded fine sand in abrupt contact with coarse sand and gravel in the upper meter of the fan (Figure 2D). The fan's basal age is 11,400 ^{14}C years (E71, 13,320 calibrated ^{14}C years BP), only 540 ^{14}C years after post-glacial primary productivity was re-established in Ritterbush Pond, 4 km to the west of Eden Mills (elevation 317 m asl; Bierman et al., 1997). From 13,320 to 12,900 calibrated ^{14}C years BP (E71 and E70), half a meter of massive, well-sorted silt was deposited over large, well-sorted gravel that is likely glacial outwash. At 12,900 calibrated ^{14}C years BP, a 0.5 meter-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, fluvial gravel (GG unit, Figure 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, 6,090 calibrated ^{14}C years BP (Figure 4A),

Above the GG gravel, multiple buried A-horizons indicate that the fan experienced cycles of fine sand deposition followed by periods of fan surface stability (buried soils) until 490 years BP, the date just beneath the lowest AP horizon (S1 unit, Figures 4B and 2E). The buried soils with A/E/B-horizon sequences have much thicker sand units below them than between the multiple A-horizons. This disparity suggests that where more deposition occurs on the fan, it is followed by a longer period of quiescence sufficient to develop thicker soil profiles. The discontinuous nature of the paleosols is likely the result of fan surface scouring during large 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 large 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 meters in length (Figure 4). Most likely this change in depositional style reflects large-scale clear cutting and the resulting increase in hillslope erosion rates. A piece of a metal horse bridal, an artifact that allowed definitive dating of this unit, was found near the surface in the RG unit (Figure 4B). Large gravel lobes, high in the stratigraphy at the southern edge of the top trench, are likely remnant stream channel sediment deposited as the channel migrated southward to its current position.

Maidstone Fan

The Maidstone fan is located on a low terrace of the Connecticut River below a drainage basin eroded into an older, higher terrace. This is a young fan, the result of historic land disturbance. At 4.2 meters depth, below the basal fan sediment, we found a continuous, 20 cm-thick layer of organic material including moss, leaves, and wood (Figure 5 and Table 4). This layer represents deposition of organic material from Connecticut River floods and hence provides a reliable maximum age estimate for the Maidstone fan (150 calibrated ^{14}C years old, sample M52, Table 1).

Only two buried soils appear in the stratigraphy. The higher buried soil is faintly colored, about 5 to 10 cm below the ground surface, and only appears in the top trench where it merges with the modern topsoil towards the fan margin (Figure 5A). The lower buried soil is about 30 cm below the surface and has a black A-horizon, underlain by a leached E-horizon, with a reddened B-horizon beneath the E. This spodosol 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 (Figure 2G) or tree throw (unit TT, Figure 5A) and except close to the apex, where the fan stratigraphy has been disturbed by fan-head trenching, the fan consists of laterally continuous interbedded sand and silt (Figure 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 from animals, worms, and root growth has mixed fan sediments and gradually blurred fan stratigraphy and structure (Figure 2G).

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 (Figure 6 and Table 5). Below the earliest 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 12,980 calibrated years ago (sample B59, Table 1 and Figure 6B). The onset of fan aggradation infilled and buried the moist area with well-sorted coarse sand and faceted 10 to 40 cm clasts grading upward into bedded fine and medium sand by 10,310 calibrated ^{14}C years BP (sample B55, Table 1 and Figure 6B).

At Bristol, the stem trench (Figure 6B) contains over a meter of sediment deposited between the fine sand of the trench extension (9,380 calibrated ^{14}C years BP, sample B53) and the MS unit (dated as 9,340 calibrated ^{14}C years BP, sample B35). This sediment represents a significant depositional event around 9,360 calibrated ^{14}C years BP. The large gravel unit (unit LG, Figures 6 and 2C) represents a high energy deposit constrained by samples B10 (4,370 calibrated ^{14}C years BP) and B5 (4,330 calibrated ^{14}C years BP) above the unit, and sample B35 (9,340 calibrated ^{14}C years BP) below it. Samples B45 (4,960 calibrated ^{14}C years BP) and B10 (4,370 calibrated ^{14}C years BP) are from within the smaller Gr unit (Figure 6) and represent an event around 4,500 calibrated ^{14}C years BP. Above the LG unit, multiple, discontinuous A-horizons in both trenches indicate repeated short periods of fan stability, followed by scouring events. The thin, discontinuous sand and gravel units (units G, S, LS, and FG2) indicate many small depositional events that closely followed one another in time. Based on two dates from the LS unit (B7 and B46, Table 1, Figure 6), we can infer that from about 4,000 to 3,000 years BP the fan was accumulating 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 (Figure 6B) suggests that at least part of the LG unit may remain from a previous depositional event, with a substantial period of stability before the rest of the unit was deposited. Samples B5 (4,330 calibrated ^{14}C years BP) and B7 (3,200 calibrated ^{14}C years BP) are taken very close to paleosol layers (Figure 6A) 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) that likely reflects a post-clear-cutting pulse of hillslope erosion and sediment deposition (Figure 6B).

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 mantle (1.5 to 2 meters) the underlying bedrock topography (Figure 7 and Table 6). This fan has a complex, cut and fill dominated stratigraphy (Blair and McPherson, 1994), probably caused by channel migration around bedrock outcrops. Overlapping gravel units in the top trench are most likely channel remnants, with weak cross-bedding in the lower corner of section 6 in the top trench (Figure 7A) indicating fluvial activity. Discontinuity of most strata prevents reliable interpretation of the depositional history. Dated pieces of charcoal are not all in chronological order, indicating that the fan sediments were reworked from further upfan and that deposition was not occurring uniformly.

Thin, buried A-horizons were present in both trenches, and were underlain by dark red B-horizons in places (Figure 7). Soil development cross-cuts stratigraphic units, indicating that soils formed after deposition and truncation of those layers. Often the B-horizon color was present when 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 quiet, with little or no deposition, while the A and B horizons developed (probably 300 to 400 years, based on soil profile development at the Maidstone fan). 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 B-horizon beneath indicate shorter periods of fan surface stability (150 to 200 years based on the Maidstone fan).

Bridgewater Corners Fan

The Bridgewater Corners fan, deposited on a high terrace of Broad Brook, is composed of interbedded sand and gravel (Figure 8) 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 to 7 meters 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 are patchy and interrupted by large gravel lenses in the top trench (Figure 8A), but are continuous in the stem trench (Figure 8B). In the stem trench, there is a repeating motif: sand-gravel-sand-paleosol (Figure 2H).

Fan sediments coarsen to large gravel and cobbles in the deeper portions of the top trench (Figure 8A). Silt and fine sand at a depth of 3 meters represent river channel overbank sediments from Broad Brook. Just below 3.30 meters depth, there is a deposit of Broad Brook stream-rounded cobbles. Wood from the overbank layer (sample W66, Table 1) provides a maximum age for the fan (11,330 calibrated ^{14}C years BP). Dates on wood and charcoal associated with paleosols indicate times of fan stability (Figure 8). Samples W30 and W31 are 3,130 calibrated ^{14}C years and 3,650 calibrated ^{14}C years old respectively, indicating fan stability at about 3,300 calibrated ^{14}C years BP. Samples W4 and W34 indicate fan stability at 4,960 and 6,020 calibrated ^{14}C years BP, respectively. 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.

Integrated Aggradation Rates

Aggradation rates of the five fans, constrained by radiocarbon-dated organic material, change over time and differ between fans (0.001 to 80 m^3/yr). High aggradation rates early in the Eden Mills fan's history (13,320 to 12,900 cal ^{14}C years BP) 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). However, wood dates of 13,300 and 12,980 calibrated ^{14}C years BP, at Eden Mills and Bristol, respectively, suggest that vegetation re-established rapidly after the ice melted off Vermont hillslopes. After vegetation was reestablished, subsequent periods of aggradation and fan surface stability likely indicate times of greater and lesser hillslope erosion and by inference, storminess.

There are several periods of synchronous aggradation (Figure 9). Rapid aggradation characterized the Bristol, Eden Mills, and Hancock fans 10,000 to 9,300 calibrated ^{14}C years ago. The Bristol, Bridgewater Corners, and Hancock fans aggraded rapidly 3,650 to 3,540 calibrated ^{14}C years ago. The Hancock and Eden Mills fans also aggraded rapidly in historic time, responding to land use changes; the Eden Mills fan accumulated 3000 m^3 of sediment during the past 100 years, 46% of its volume. The Maidstone fan is completely historic and represents 4770 m^3 of aggradation over 150 years or less. The synchronous and significant response to historic deforestation of the fans we investigated demonstrates the importance of woody vegetation in providing effective soil cohesion on basin hillslopes.

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 immediately post-glacial (13,320 calibrated ^{14}C years BP) to historic. Most fans aggraded rapidly in response to recent, human-induced landscape changes.

Fan Sedimentology and Stratigraphy

Sediment in all five fans was deposited by flowing water. Most fan units were moderately well sorted, with the exception of the Maidstone fan which had very well sorted strata. Grain size ranged from silt to cobbles. Sedimentary structures were best preserved in Maidstone, the youngest fan (cross-bedding and soft-sediment faulting) and the Bridgewater Corners fan (cross-bedding and minor imbrication). The lack of sedimentary structures in the other fans is the result of bioturbation; worm tracks and animal burrows are common. Numerous tree throws turbate fan sediment and leave distinct scars (e.g., unit TT in Figure 5A), consistent with pre-settlement forest cover on fan surfaces. 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). Poorly sorted units may be the result of hyperconcentrated flow; however, most deposition on the five fans is probably fluvial.

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 course-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 occurred in and around trees in forests, resulting in 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 very patchy, discontinuous deposits of gravel.

Soil Development

All five fans preserve buried soil horizons that typically expend 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. Soil development ranges from thin Ab-horizons, to reddened Bb-horizons, and the beginning of leached Eb-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 acidity of the leaching environments. The basal age of the Maidstone fan indicates that less than 200 years were needed to form the sequence of buried A-, B- and E-horizons observed in the stratigraphy of that fan.

Timing of Fan Deposition and Periods of Increased Storminess

Neither periods of increased aggradation nor individual dated storm deposits correlate extensively between the five fans we studied (Figure 9). The only synchronous depositional pulses occurred on the Eden Mills, Hancock, and Bristol fans c. 9,300 years BP, at Eden Mills and Bridgewater Corners c. 6000 year BP, and during historic times on all five fans. Differences between fans in the timing and rate of aggradation occur at most other times. For example, a sediment pulse on the Bristol fan 4,500 years BP is not reflected elsewhere. Rapid sedimentation at the Bridgewater Corners fan c. 5,500 years BP coincides with soil formation on the Hancock fan and low aggradation rates at Eden Mills and Bristol.

The limited temporal and spatial correlation of aggradation rate increases and flow-related stratigraphic markers (gravel beds and scour) is consistent with several different scenarios triggering fan deposition including: localized storm cells of great intensity but restricted size, heterogeneous precipitation duration and intensity in large, regional storms, and/or 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. Because fan deposition is dependent on the many factors cited above, stable periods on the fans may in fact be better temporal indicators of paleostorminess patterns than storm deposits themselves.

Indeed, periods of relative fan surface stability, as indicated by low aggradation rates or well developed soils, are better correlated than periods of aggradation in the four fans with Holocene records. From 9300 to 6500 cal years BP, all four fans have low aggradation rates, indicating drainage basin slope stability. Soil profiles developed c. 3,500 cal years BP on the Bristol and Bridgewater Corners fans coincide with slow aggradation on the Eden Mills fan. Likewise, soil development on the Bristol fan 4,200 years BP coincides with slow aggradation on the other three fans. Any two of several undated paleosols in the Eden Mills fan between the ages of 6,000 and 490 cal years BP could coincide with these 3,500 and 4,200 cal year old paleosols in the Bristol fan. The two oldest fans, Eden Mills and Bristol, show correlative soil formation around 13,000 cal years BP. In summary, data suggest significant fan aggradation 13,300 to 12,900, 10,000 to 9,300, 6,000 to 4,500, around 3,500 cal ^{14}C yr BP, and during historic times interspersed with stable intervals c. 12,900, 9,300 to 6,500, and 4,200 to 3,500 cal ^{14}C yr BP.

Comparison to Other Paleostorm Records

Considering the uncertainty in dating fan deposits, our estimates for periods of increased hillslope erosion are consistent with other records of New England paleostorminess derived from fan histories (Bierman et al., 1997) and the analysis of lake deposits (Brown et al., 2000, Noren et al., in review, and Bierman et al., 1997). All studies find early and mid Holocene storminess maxima, but agree less well on the timing of later Holocene activity. For example, Bierman et al. (1997) found that three fans in the Huntington River Valley of Vermont (Figure 1) aggraded rapidly from 9,590 to 8,180 calibrated ^{14}C years BP, and 2,590 to 1,770 calibrated ^{14}C years BP. These and our age ranges for increased fan activity are consistent with the findings of Brown et al. (2000) and Noren et al. (in review) who identified increased contributions of terrestrial sediment to New England ponds as periods of paleostorminess, the intensity of which peaked around 2,600, 5,800, 9,100, and 11,900 calibrated ^{14}C years BP. There appears to be no robust relation between increased fan and pond sedimentation and generalized climate as indicated by pollen and other data (Bierman et al., 1997 and Table 8).

Kochel (1990) suggested that the post-glacial 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 basal fan ages should decrease with increasing latitude reflecting the gradual northward retreat of the polar front following deglaciation. Kochel and Johnson (1984) dated Virginia fan initiation at 11,000 calibrated ^{14}C years BP, coincident with the return of tropical air masses to the mid-Atlantic region (Kochel, 1990). Fans in Vermont are older than those Virginia, suggesting that fan development may begin as soon as there is a stable surface on which sediment can accumulate, regardless of polar front position. Hence, we conclude that warm, tropical air is not necessary to create storm events sufficiently intense to initiate slope failure and fan deposition in New England.

CONCLUSIONS

Humid-temperate fans 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, albeit low-resolution, recorders of hillslope activity. 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 aggradation rates changed over time. Simultaneous periods of increased aggradation on multiple fans suggest times of increased slope erosion (storminess) from >12,900, 10,000 to 9,300 and 6,000 to 4,500, and about 3500 cal ^{14}C years BP, whereas periods of soil development suggest times when storms were less frequent (<12,900, 9,300 to 6,500, and 4,200 to 3,500 cal ^{14}C years BP). The uniform response of most fans to land clearance in the past 200 years suggests the sensitivity of basin slopes to deforestation.

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Figure Captions

Figure 1. Location map of trenched fans and other pertinent sites in Vermont. Inset shows location of Vermont with arrow. EM = Eden Mills, MS = Maidstone, BR = Bristol, HC = Hancock, BC = Bridgewater Corners, HV = Huntington Valley, RP = Ritterbush Pond.

Figure 2. Photographs of Vermont fans. A) Fan-covering deposition of sand and gravel in Huntington, Vermont, September, 1998; people for scale. B) Active fan-delta deposit in stream, sediments will not be preserved. C) Large gravel unit representing a storm event in the Bristol fan (Figure 7B, unit LG, 9340 to 4730 cal ^{14}C years BP). Trench is 1.5 m deep. D) 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 (Figure 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 (Figure 4A columns 2 and 3). F) Continuous, well-bedded sand and silt strata in the Maidstone fan (Figure 5B) G) Animal burrow in the Maidstone fan (Figure 5B, column 7) H) Paleostorm deposit represented by gravel, bracketed by two paleosols, Bridgewater Corners fan (Figure 8B, unit Gr2). Photo from wall of trench opposite that logged.

Figure 3. A) Topographic map of the Maidstone fan, based on differential GPS and total station data. A-A’ is top trench, B-B’ is stem trench Contour interval is 0.5 meters. Scale in meters, UTM grid, NAD 27. B) Photograph of Maidstone fan. Trench locations indicated by white outline. View from Vermont Route 102 towards the west.

Figure 4. Stratigraphy of fan at Eden Mills, Vermont. A-A' is top trench; B-B' is stem trench. Thick, black lines or solid black shading represent buried paleosol A-horizons; light gray is leached E-horizon; dark gray shading represents wood fragments. Rocks are outlined and the location of dated samples (cal ^{14}C years BP) indicated. Units described in Table 3. Interpreted base of fan indicated by dashed line.

Figure 5. Stratigraphy of fan at Maidstone, Vermont. A-A' is top trench; B-B' is stem trench. Thick, black lines represent buried paleosol A-horizons. Rocks are outlined and the location of dated samples (cal ^{14}C years BP) indicated. Units described in Table 4. Interpreted base of fan indicated by dashed line.

Figure 6. Stratigraphy of fan at Bristol, Vermont. A-A' is top trench; B-B' is stem trench. Thick, black lines represent buried paleosol A-horizons. Rocks are outlined and the location of dated samples (cal ^{14}C years BP) indicated. Units described in Table 5. Interpreted base of fan indicated by dashed line (base of fan not reached in top trench, A-A’).

Figure 7. 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 indicates reddened soil color from B-horizon development; closer stripes are a redder soil color.

Rocks are outlined and the location of dated samples (cal ^{14}C years BP) indicated. Units described in Table 6. Base of fan is bedrock. Black shading represents paleosols.

Figure 8. Stratigraphy of fan at Bridgewater Corners, Vermont. A-A' is top trench; B-B' is stem trench. Thick, black lines represent buried paleosol A-horizons. Rocks are outlined and the location of dated samples (cal ^{14}C years BP) indicated. Units described in Table 7. Interpreted base of fan indicated by dashed line. Inset is section from opposite wall of the stem trench (B-B').

Figure 9. Comparison of aggradation rates, gravel deposition, and soil formation on the five trenched and dated fans. Aggradation rates represented by shaded bar graphs; x-axis scales vary between fans. Individual, dated depositional events, as indicated by the fan stratigraphy, are shown by a row of crosses (XXXX). A line between two rows of crosses brackets deposit age. Thick, black horizontal lines indicate dated paleosols. The vertical line between 2 solid horizontal black lines brackets the paleosol age. The depositional events and paleosols are not associated with any aggradation (x-axis) rate value. Very high aggradation rates are not plotted but are indicated by number where the peak intersects the right side of the graph..

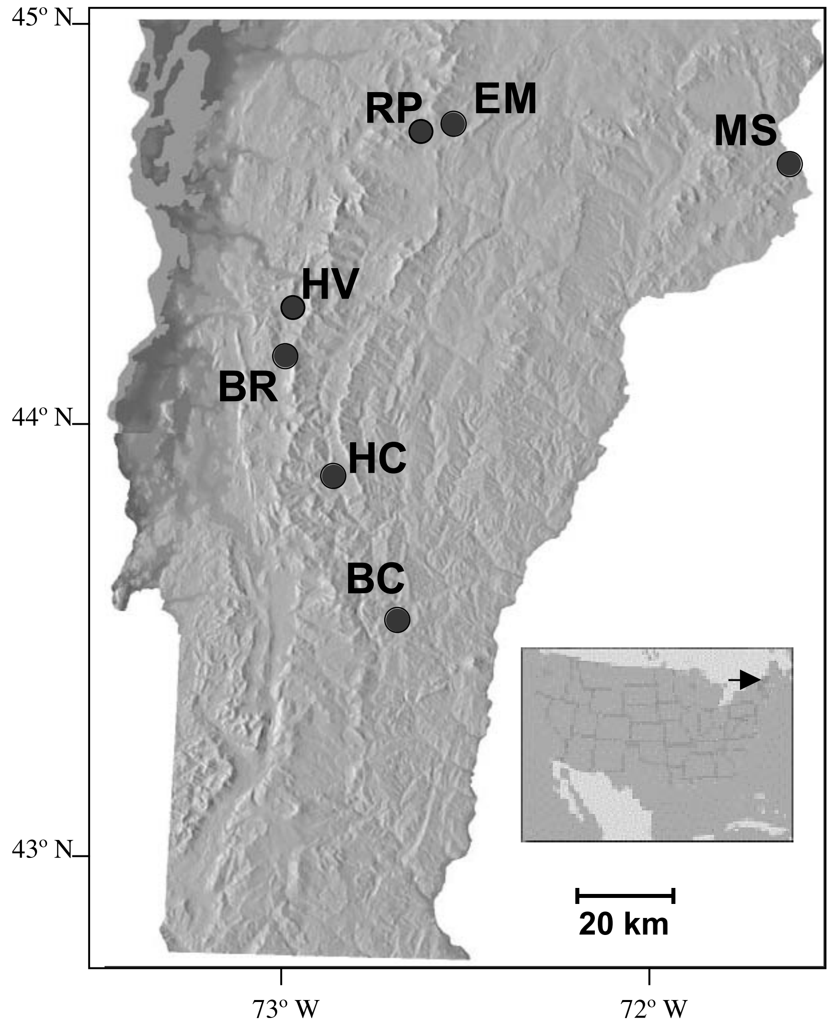


Figure 1. Jennings et al.

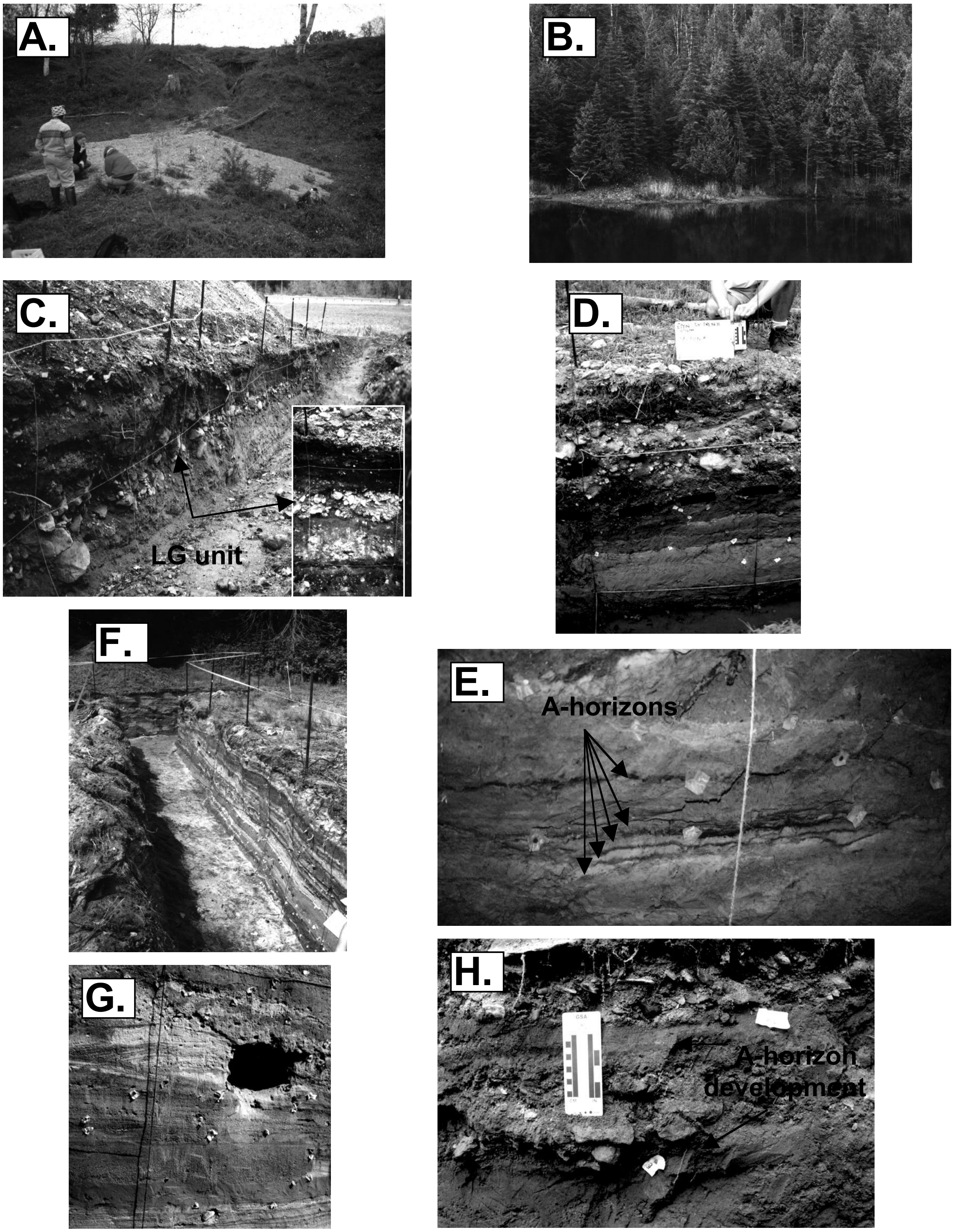


Figure 2 Jennings et al.

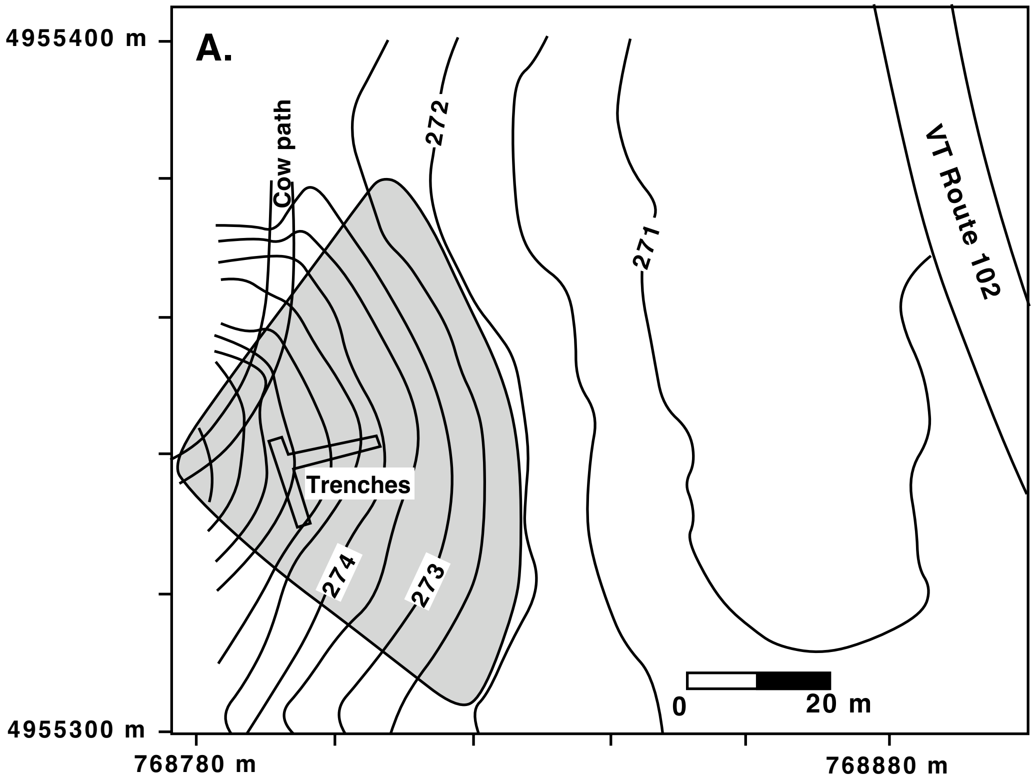
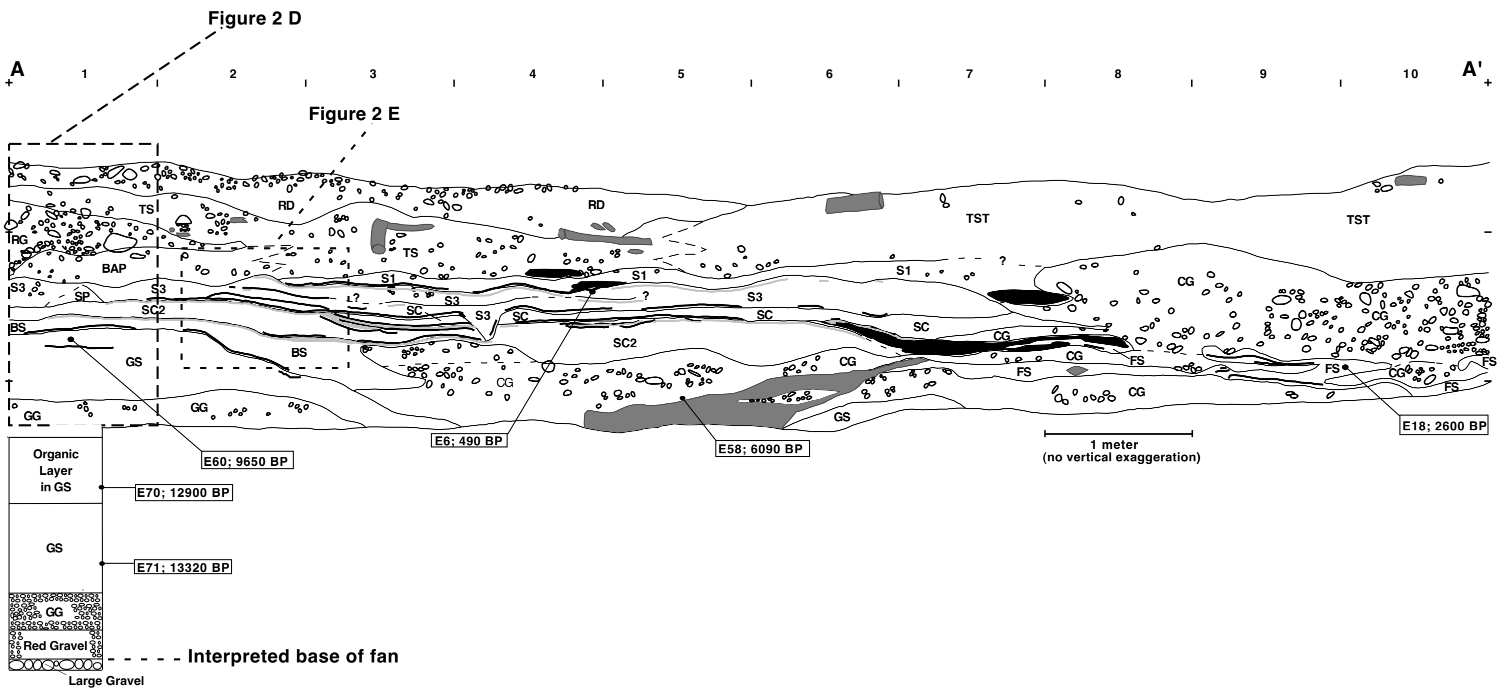


Figure 3A. Jennings et al.

Figure 3B. Jennings et al.



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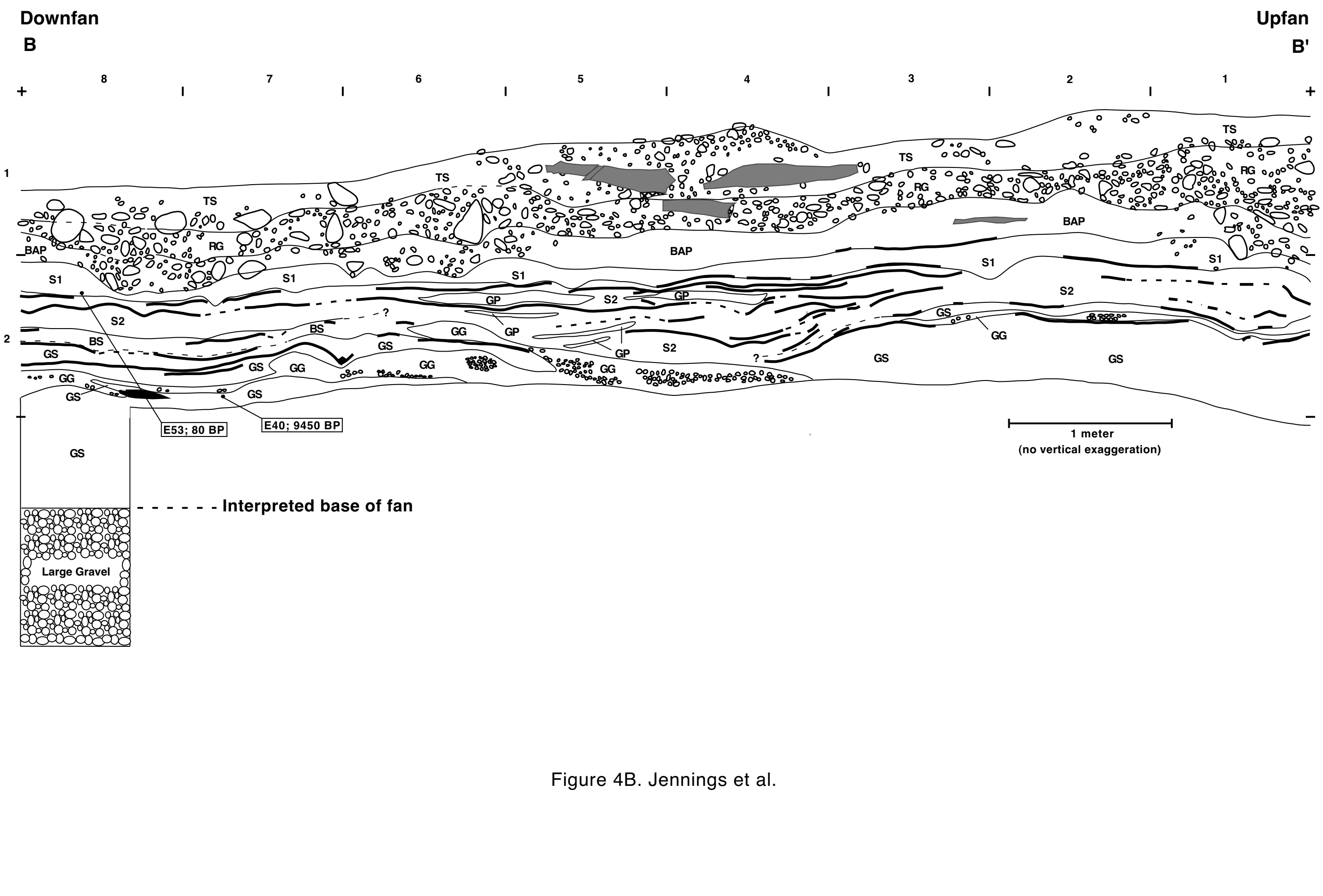

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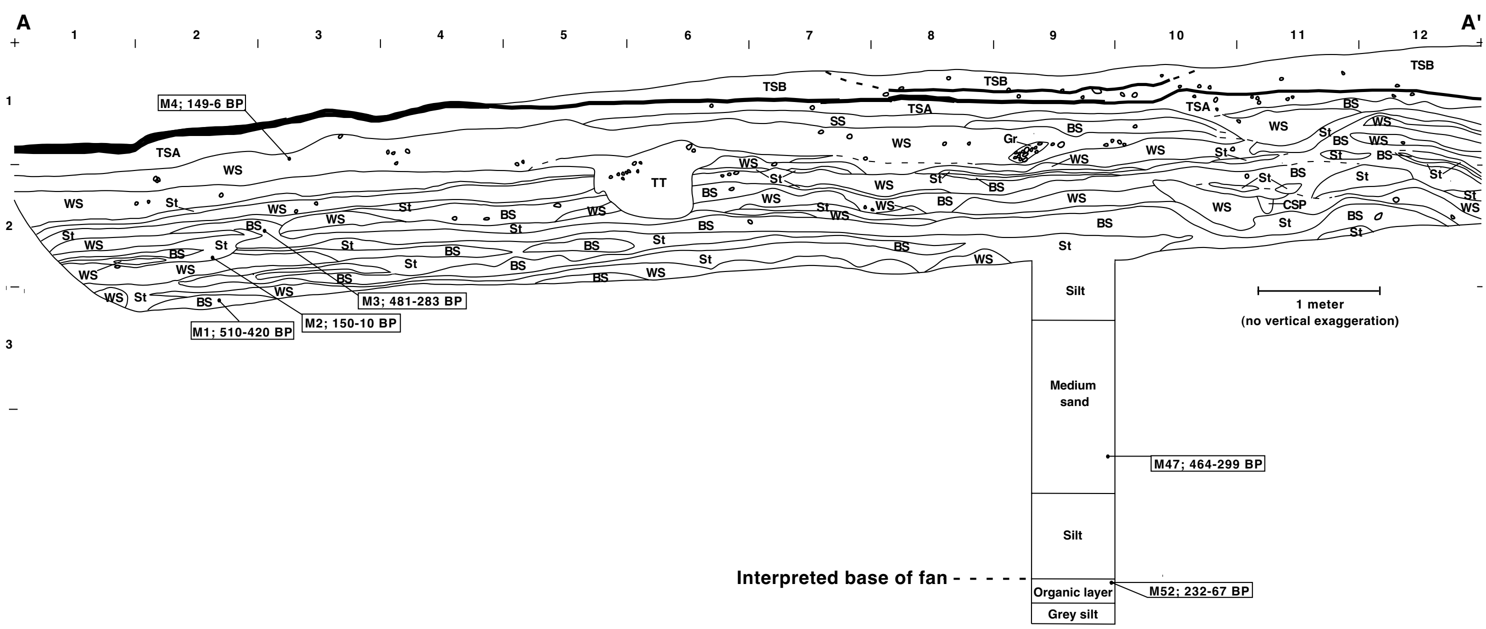

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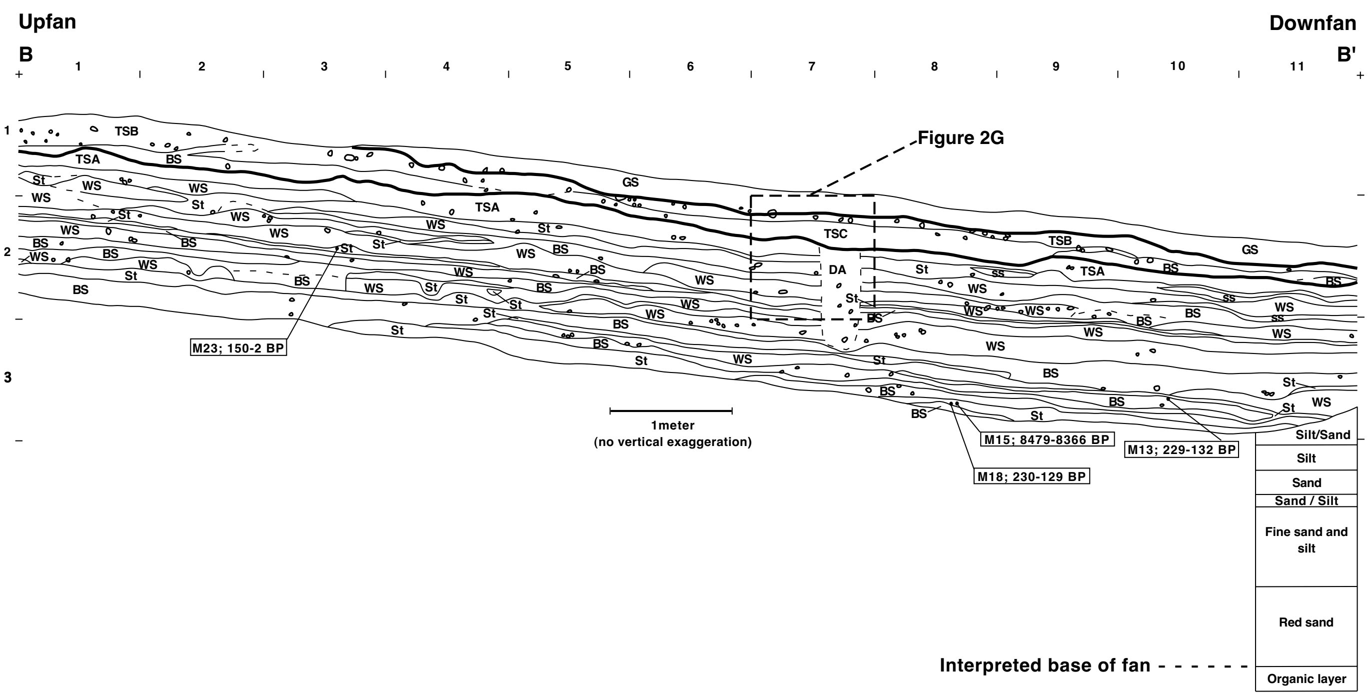

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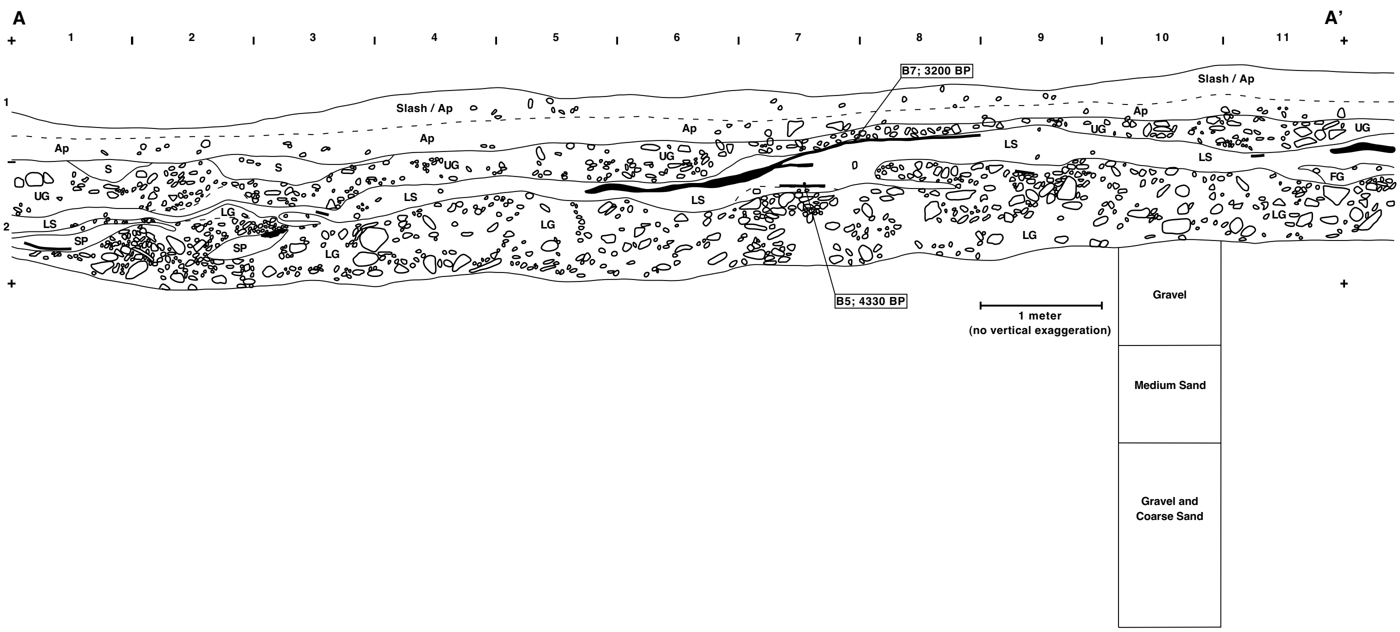
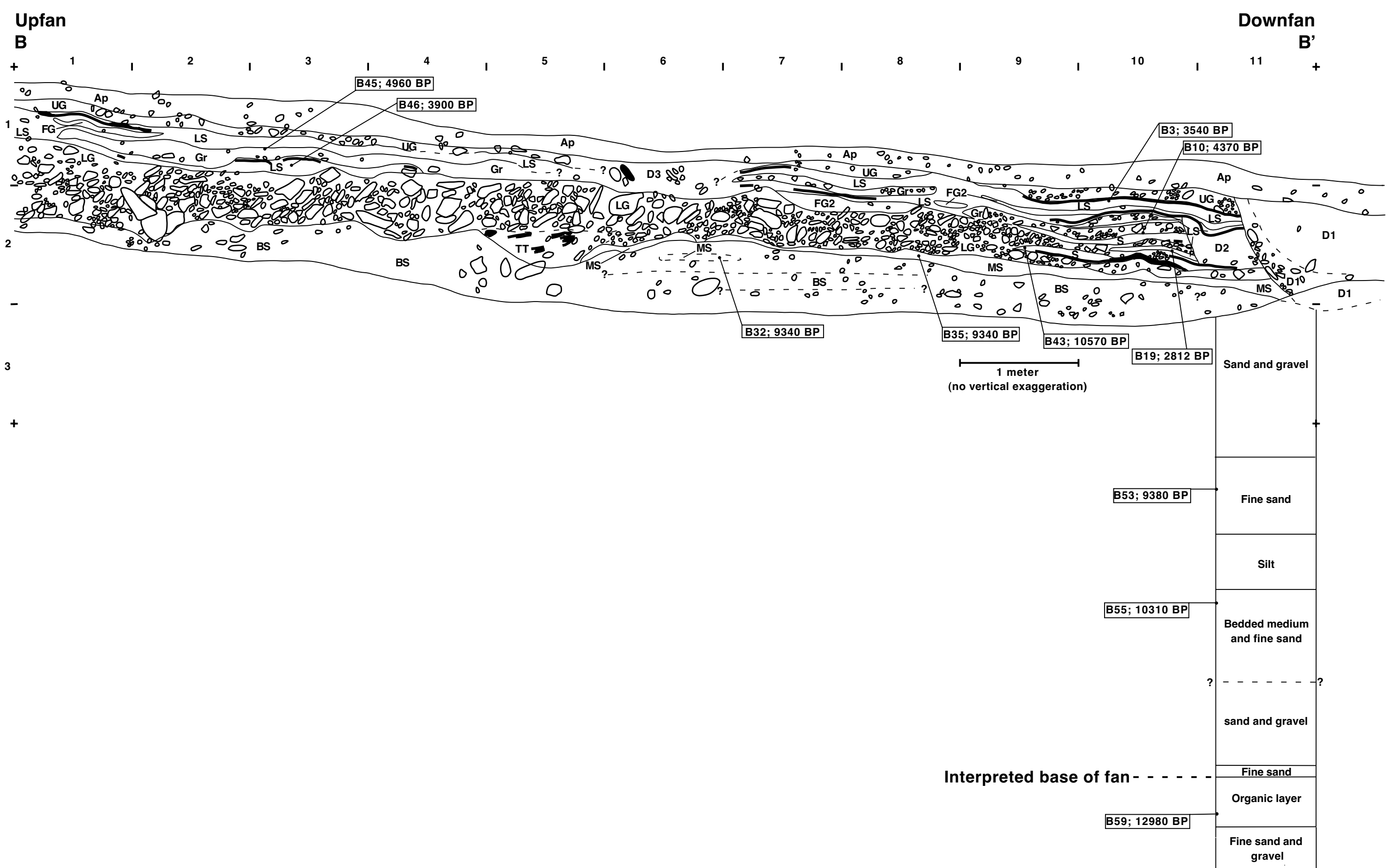


Figure 6A. Jennings et al.



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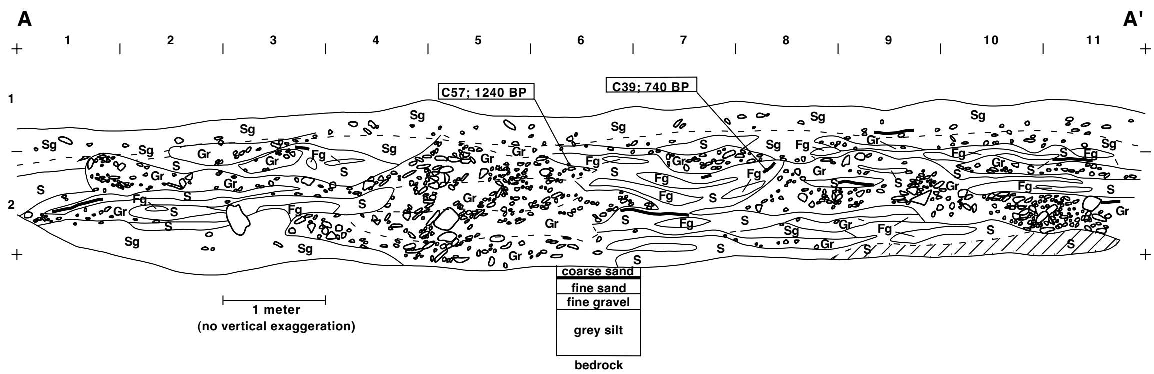

Figure 7A. Jennings et al.

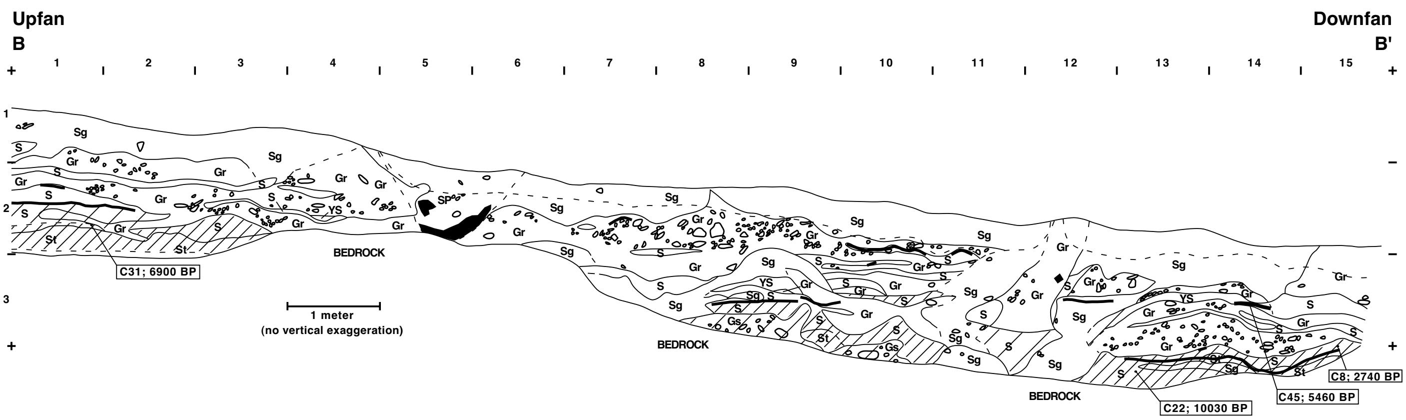

Figure 7B. Jennings et al.

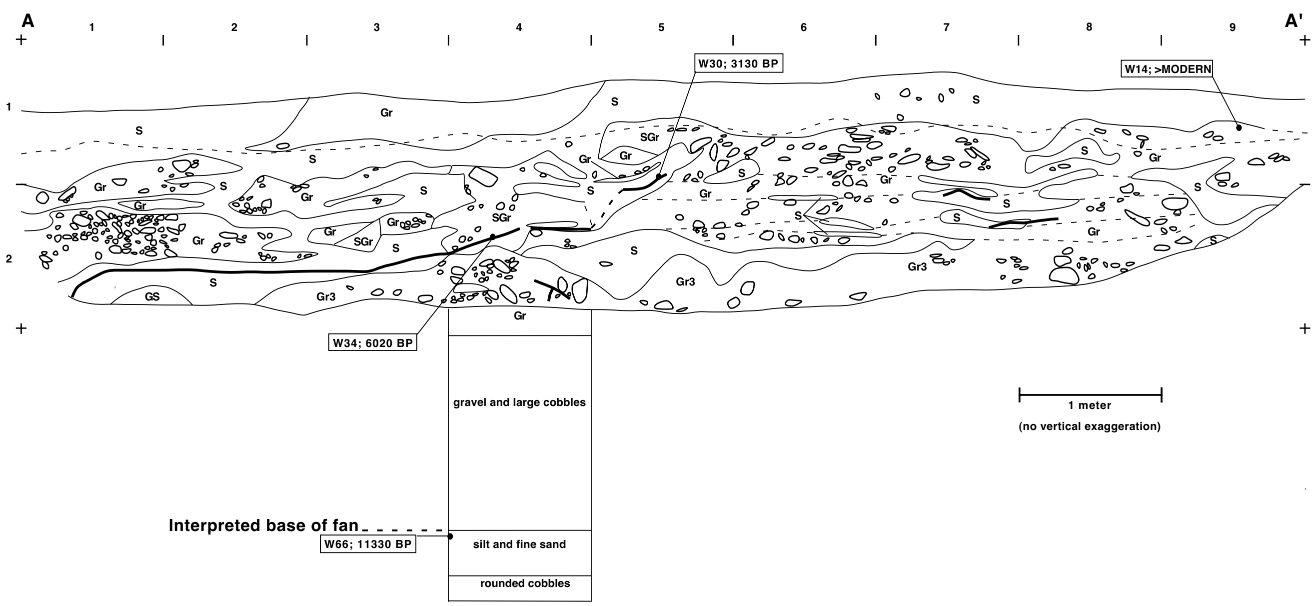

Figure 8A. Jennings et al

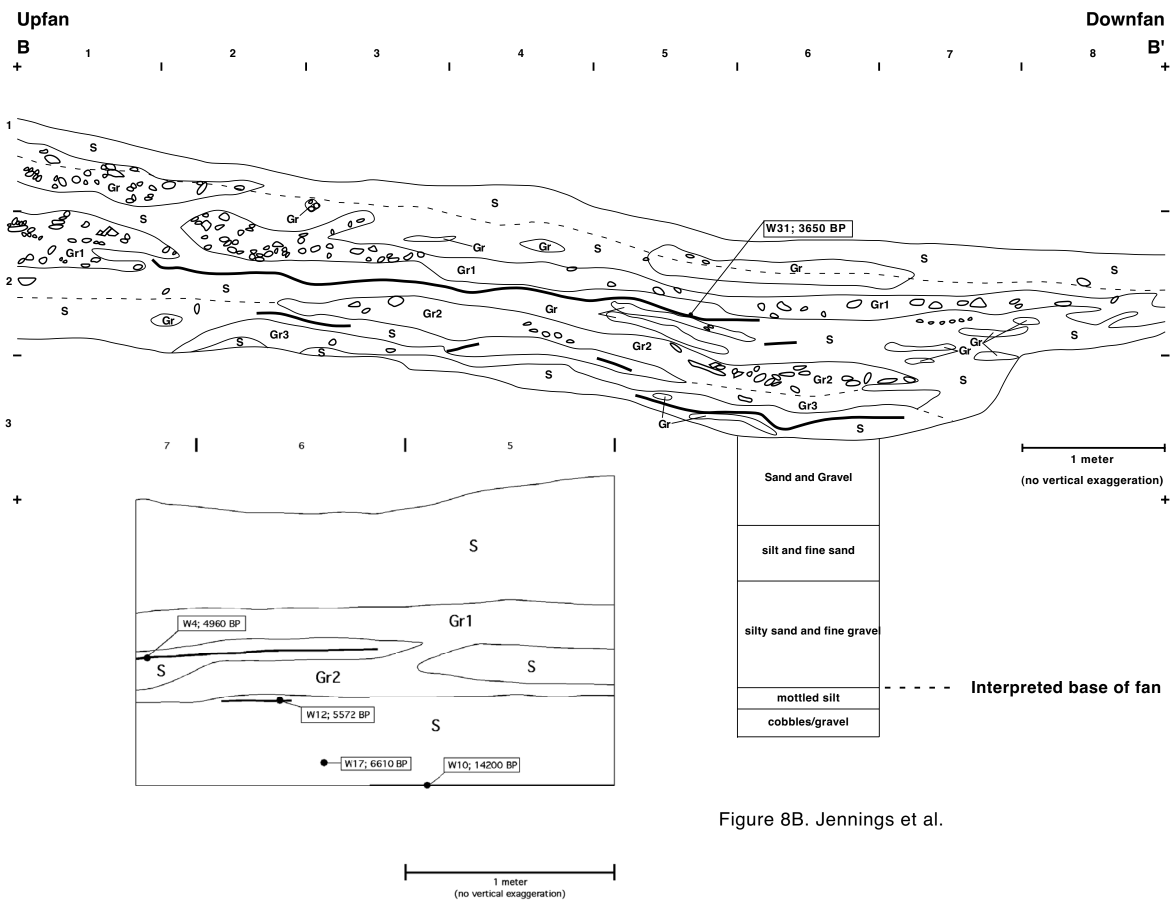

Figure 8B. Jennings et al.

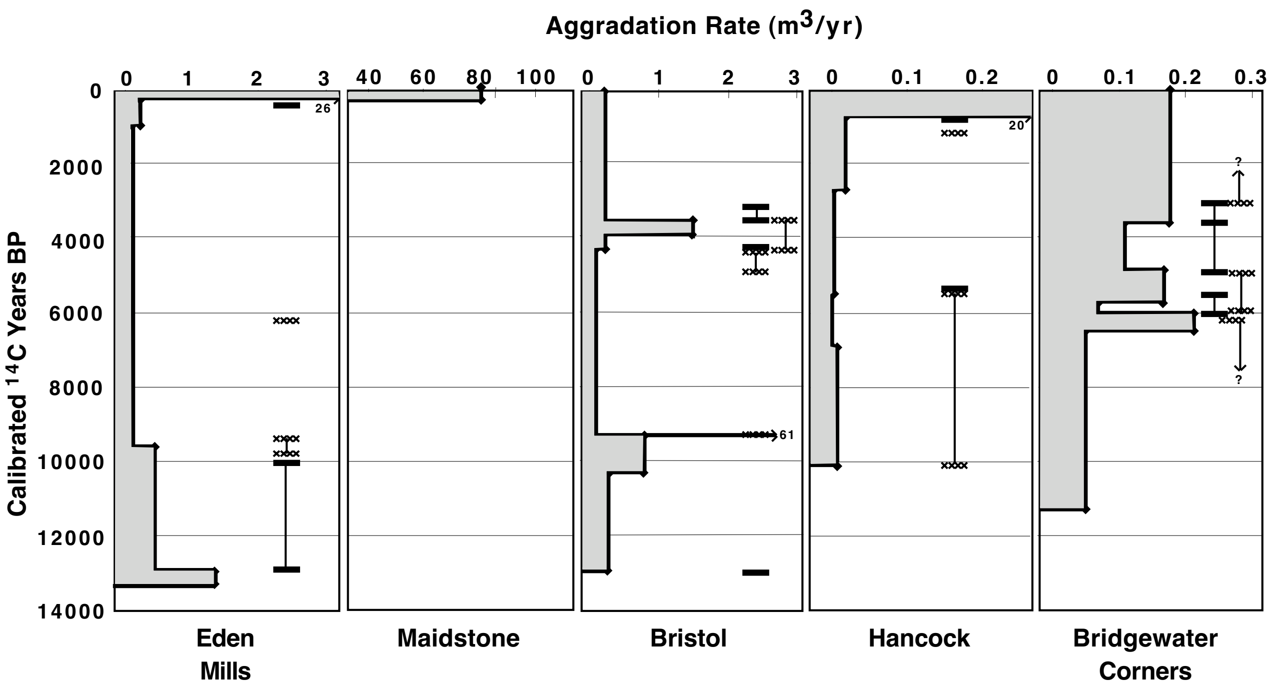

Figure 9 Jennings et al.

TABLE 1. RADIOCARBON AGES FOR ALLUVIAL FAN SAMPLES, VERMONT

Sample Number	CAMS Number*	Depth (m)	Material	Age (^{14}C years BP)	1 sigma calibrated (BP)†	2 sigma calibrated (BP)†
E53	62288	0.66	wood	90 ± 40	88 - 33	149 - 10
E6	62357	0.70	wood	440 ± 40	518 - 477	539 - 437
E18	67873	1.19	wood	2500 ± 40	2651 - 2488	2740 - 2451
E58	62354	1.36	wood	5320 ± 40	6082 - 5998	6196 - 5990
E40	62287	1.28	charcoal	8390 ± 60	9489 - 9400	9527 - 9266
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
M2	62346	1.10	charcoal	110 ± 40	136 - 59	150 - 10
M4	62348	0.30	wood	110 ± 50	139 - 50	149 - 6
M23	62351	0.82	charcoal	130 ± 40	144 - 66	150 - 2
M52	62350	4.20	wood	170 ± 40	219 - 165	232 - 67
M13	62352	1.35	charcoal	200 ± 40	209 - 147	229 - 132
M18	62448	1.57	charcoal	220 ± 50	213 - 145	230 - 129
M3	62347	0.90	charcoal	300 ± 50	433 - 353	481 - 283
M 47	62349	3.25	charcoal	310 ± 40	432 - 357	464 - 299
M1	62447	1.45	wood	380 ± 40	501 - 433	510 - 420
M15	62353	1.57	charcoal	7640 ± 40	8429 - 8385	8479 - 8366
W14	67871	0.20	wood	>MODERN	>MODERN	>MODERN
W30	67872	0.67	charcoal	2970 ± 50	3213 - 3074	3267 - 2985
W31	57762	0.57	charcoal	3420 ± 40	3705 - 3632	3731 - 3569
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
W4	57765	0.75	charcoal	4390 ± 80	5053 - 4850	5092 - 4834
W12	57763	0.90	charcoal	4960 ± 760	6551 - 4809	7324 - 3820
W34	57764	0.95	charcoal	5260 ± 130	6194 - 5909	6291 - 5743
W17	57760	1.18	soil organic material§	5810 ± 50	6668 - 6547	6734 - 6487
W10 H	57788	1.35	humic extract§	5850 ± 50	6730 - 6625	6755 - 6533
W66	57761	2.75 - 3.25	charcoal	9950 ± 50	11344 - 11235	11458 - 11208
W10	57785	1.35	soil organic material§	12150 ± 50	14336 - 14058	14365 - 14041
B7	62296	0.40	charcoal	3000 ± 40	3258 - 3154	3335 - 3069
B3	67867	0.32	charcoal	3310 ± 50	3581 - 3471	3640 - 3442
B19	62451	0.77	charcoal	2610 ± 660	3469 - 1896	4357 - 1267
B46	62292	0.55	charcoal	3600 ± 40	3925 - 3842	3989 - 3823
B5	62297	0.32	charcoal	3900 ± 40	4410 - 4341	4425 - 4230
B10	62450	0.60	charcoal	3930 ± 60	4435 - 4282	4524 - 4224
B45	62291	0.40	charcoal	4400 ± 40	4984 - 4875	5057 - 4857
B53	62449	2.60	charcoal	8360 ± 40	9343 - 9303	9486 - 9270
B35	62294	0.85	charcoal	8300 ± 40	9404 - 9339	9432 - 9240
B32	62295	0.92	charcoal	8310 ± 40	9421 - 9338	9436 - 9243
B55	62290	3.45	charcoal	9140 ± 40	10280 - 10225	10405 - 10214
B43	62293	0.70	charcoal	9370 ± 60	10644 - 10502	10750 - 10395
B59	62289	5.20	wood	10920 ± 40	13027 - 12876	13136 - 12829
C39	67868	0.60	charcoal	860 ± 40	792 - 726	799 - 686
C57	67870	0.46	charcoal	1320 ± 50	1290 - 1230	1312 - 1168
C8	57769	1.08	charcoal	2610 ± 190	2870 - 2439	3169 - 2304
C45	57770	1.15	charcoal	4730 ± 130	5590 - 5319	5722 - 5205
C31	57766	1.15	charcoal	6060 ± 50	6954 - 6854	7018 - 6776
C83	57768	1.15 - 1.30	charcoal	5550 ± 790	7266 - 5572	7954 - 4416
C22	57767	1.51	charcoal	8890 ± 50	10086 - 9922	10187 - 9865

*Center for Accelerator Mass Spectrometry, Lawrence Livermore Laboratory.

†Calibrated using CALIB version 4.2 (Stuiver et al., 1998).

§The soil organics (Samples W10 and W17) were 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 out 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.

TABLE 2. DIMENSIONS OF ALLUVIAL FANS AND DRAINAGE BASINS

Fan Location	Volume (m^3)	Surface Area (m^2)	Drainage Basin Area (m^2)
Maidstone	12,200	1,300	2,800
Hancock	14,500	3,600	225,000
Bristol	6,300	2,600	249,000
Bridgewater Corners	1,300	200	41,600
Eden Mills	6,500	1,600	135,000

TABLE 3. UNIT DESCRIPTIONS, ALLUVIAL FAN TRENCHES, EDEN MILLS, VERMONT

Unit Identifier	Grain size	Soil color	Notes
(RD) Recent deposition	Medium sand matrix, clasts 1 to 10 cm	2.5Y 4/2	Result of logging road incision and gullying
(TS) Topsoil	Wood fragments and fine sand with 1 to 2 cm gravel and larger clasts (5%)	10YR 3/1	Modern topsoil layer; sediment from post-clearing deposition
(TST) Topsoil - Top Trench	Silt and clay	10YR 3/1	Modern topsoil; sediment from overbank deposition
(RG) Recent Gravels	Fine sand (~15%) and medium to coarse sand matrix mixed with clasts 1 mm to 2 cm	2.5Y 4/2	Layer of historic gravel deposition on the surface of the alluvial fan resulting from increased erosion and runoff during historical logging of hillslope
(BAP) Buried, Ap-horizon	Fine sand and silt	10YR 3/1	Represents plowing of the fan surface prior or concurrent to hillslope clearance
(solid black) Paleosol	Silt and clay	5Y 2.5/1	Buried soil A-horizon (topsoil)
(S1) Sand 1	Fine sand and silt	2.5Y 3/2	Massive sand; also buried Ap-horizon
(S2) Sand 2	Fine sand and silt	2.5Y 4/2	Massive sand with discontinuous buried paleosols
(S3) Sand 3	Fine sand and silt	2.5Y 4/2	Massive sand capped by leached E-horizon
(SP) Sand Patch	Coarse sand matrix with clasts of fine gravel (2 mm) to pebbles (2 to 3 cm)	7.5YR 3/2	Discontinuous unit; grades into S3 unit
(SC and SC2) Silt - Clay	Silt and clay with little fine sand	2.5Y 4/2; E-hor. 5Y 5/2	Massive units separated by thin paleosol layer
(GP) Gravel Patch	Fine to medium sand matrix with fine gravel (2 to 10 mm)	N/A	Discontinuous unit within the S2 unit
(BS) Brown silt	Silt and clay	2.5Y 5/2; E-horizon 5Y 6/2	Massive unit capped with paleosol overtopping a leached E-horizon
(CG) Channel Gravel	Fine sand and silt matrix mixed with coarse sand and fine gravel	10YR 3/1	Represents migrating channel of the feeder stream
(FS) Fine sand	N/A	N/A	Discontinuous unit within the CG unit; similar to SC unit
(GS) Gley silt	Fine sand and silt	6/10 Y Gley	Massive silt unit
(GG) Gley gravel	Medium and coarse sand matrix with fine gravel (0.5 cm) to small pebbles (2-3 cm)	6/5 GY Gley	Lowest unit in the trenches; bedded gravel

TABLE 4. UNIT DESCRIPTIONS, ALLUVIAL FAN TRENCHES, MAIDSTONE, VERMONT

Unit Identifier	Grain size	Soil color	Notes
(GS) Gully sand	Fine to medium sand	2.5Y 5/3	Sediment washed downfan from dirt road in gully
(WS) White sand	Fine to medium sand	2.5Y 6/3	Very clean, sheetflow deposit; cross-bedded, braided structures; wavy laminations and unit boundaries
(St) Silt	Silt with little fine sand	Top: 5Y 4/2 Stem: 2.5Y 4/1	Massive unit that separates sand units
(BS) Brown sand	Medium and fine sand	Top: 2.5 Y 4/2 Stem: 2.5Y 5/3	Massive layer with patchy, faint bedding; higher silt content than white sand
(CBS) Coarse brown sand	Medium sand and about 25% coarse sand	2.5Y4/2	Same as (BS) but coarser
(TT) Tree throw area	Medium sand	2.5Y 5/3	Disturbed area where tree fell over
(upper solid black) Upper buried soil	Fine sand	Top: 10 YR 3/2 Stem: 10YR 2/1	Buried soil, poorly developed
(lower solid black) Lower buried soil	Fine sand	A: 2.5 Y 3/1 E:7N gley B:10YR 4/3	Buried soil sequence; becomes topsoil in sections 1-4 of A-A'
(Gr) Gravel	Small cobbles in a medium sand matrix	N/A	Small patch of gravel
(CSP) Coarse sand patch	Coarse sand	N/A	Similar to (CBS)
(TSA) Top sand A	Fine and medium sand	2.5 Y 4/4	Poorly sorted sand unit
(TSB) Top sand B	Fine to medium sand	2.5 Y 5/3	Poorly sorted sand unit; very densely packed from farm animal grazing
(DA) Disturbance area	Medium sand	2.5Y 4/3	Disturbed areas from either tree root growth or bioturbation
(TSC) Top sand C	Medium sand with 30% fine gravel	2.5Y 4/3	Discontinuous unit; grades into silt
(SS) Silt and Sand	Medium to coarse sand with 15% fine gravel	2.5 Y 5/3	Similar to (BS) unit; no bedding

TABLE 5. UNIT DESCRIPTIONS, ALLUVIAL FAN TRENCHES, BRISTOL, VERMONT

Unit Identifier	Grain size	Soil color	Notes
(Ap) Ap/Topsoil	Fine sand and fine gravel	10YR 3/2	Plowed A-horizon; top 10-25 cm is slash (pieces of bark, wood and leaves)
(D1) Disturbed area 1	Medium sand	10YR 4/3	Appears to be dug pit, possibly by backhoe
(D3) Disturbed area 3	Fine to coarse sand and gravel	10YR 3/3	Possibly a pit or tree throw
(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.	2.5Y 5/4	Large depositional event, possibly induced by clear-cutting of hillslope
(solid black) Paleosol	Very fine sand and silt	7.5YR 2.5/1	Buried A-horizon
(LS) Lower sand unit	Fine sand and silt	10YR 3/2	Massive sand unit interrupted by three paleosol layers
(FG) Fine gravel	Medium sand and fine gravel	10YR 4/4	Discontinuous; possibly part of a larger gravel unit
(Gr) Gravel	Coarse sand and fine gravel	2.5Y 4/4	Discontinuous unit with weak bedding
(S) Sand	Fine sand	10YR 3/2	Contains about 10% gravel clasts
(FG2) Fine gravel 2	Coarse sand and fine gravel	10YR 4/3	Possibly part of a larger gravel unit
(D2) Disturbed area 2	Medium and fine sand and fine gravel (1 cm size)	2.5Y 3/3	Another area disturbed by a tree throw
(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)	Top:10YR 4/4 Stem: 2.5Y 5/4	Represents a large depositional event; can be subdivided into three sub-units
(SP) Sand Patch	Fine sand	2.5Y 3/2	Only in top trench
(TT) Tree throw	Fine sand	2.5Y 3/3	Location of a tree that fell over
(MS) Massive sand	Medium sand	2.5Y 4/4	Homogeneous sand that caps BS unit
(BS) Bedded sand	Medium to coarse sand and fine gravel (2 to 5 mm)	2.5Y 4/4	Can be divided into sub-units as indicated on the cross-section

TABLE 6. UNIT DESCRIPTIONS, ALLUVIAL FAN TRENCHES, HANCOCK, VERMONT

Unit Identifier	Grain size	Soil color	Notes
(Sg) Sand and gravel	Fine sand matrix with fine gravel	Top: 10YR 3/3 Stem: 2.5Y 3/3	Matrix supported, 15% coarse fragments
(dashed line) Topsoil boundary		2.5Y 3/2	Color change due to modern soil development at the fan surface
(S) Sand	Medium sand to silt	Top: 2.5Y 3/3 Stem: 10YR 4/3	Massive, semi-continuous unit
(Gr) Gravel	Medium sand to cobbles	Top: 2.5Y 3/2 Stem:10YR 4/3	Clast supported, some faint bedding
(Fg) Fine gravel	Medium sand to gravel	10YR 4/3	Discontinuous, poorly-sorted; may be part of a larger gravel unit
(YS) Yellow sand	Medium and fine sand	2.5Y 4/4	Light-colored, homogeneous unit with weak cross-bedding
(solid black) Paleosol	Fine sand	2.5Y 2.5/1	Buried A-horizon
(SP) Slash pit	Fine sand matrix with gravel	10YR 3/1	Disturbed area that was dug as a pit and filled with organic material
(St) Silt	Silt and fine sand	2.5Y 4/3	Discontinuous unit, shows B-horizon development
(Gs) Gravel and silt	Silt matrix with cobbles	10YR 4/3	Clast supported cobble unit

TABLE 7. UNIT DESCRIPTIONS, ALLUVIAL FAN TRENCHES, BRIDGEWATER CORNERS, VERMONT

Unit Identifier	Grain size	Soil color	Notes
(above dashed line) Topsoil	N/A	10YR 3/2	Faint coloration due to recent soil profile development, cuts across stratigraphic units.
(S) Sand	Fine sand and silt	10YR 3/4	Mostly massive, although bedding in localized areas; pockets of stratified coarse sand and fine gravel.
(solid black) Paleosol	Very fine to coarse sand	2.5Y 2.5/1	Buried A-horizon.
(SGr) Sand and gravel	Fine sand and silt matrix with gravel clasts (20%)	10YR 3/4	Transitional unit between sand and gravel units; matrix supported; poorly sorted.
(Gr, Gr1, Gr2, Gr3) Gravel	Gravel, medium sand and small cobbles	10YR 4/4	Weakly imbricated; clast supported; clasts from 3 mm to 10 cm.
(GS) Grey silt	Silt and fine sand	2.5Y 5/3	Massive; isolated gravel (<1%); high moisture content.

Table 8. Comparison to New England Records

Other studies	Climate	Timing (^{14}C years BP)	This study
Davis et al., 1980; Spear et al., 1994; Li, 1996	cool and moist	2000-0	Increased agg. at EM, HC, and BC (may be historic)
Dwyer et al., 1996; Li, 1996	warm and dry	5000-3000	Low agg. at EM and HC; high agg. at BC and BR.
Spear et al., 1994	warmer with more frequent storms	7000-4000	Low agg. at EM, HC, and BR; storms at EM, BR and BC
Davis et al., 1980; Dwyer et al., 1996	warm and wet	9000-7000	Low agg. at all fans
Davis et al., 1980; Dwyer et al., 1996	cool and dry	11000-9000	Moderate agg. at EM and BR; low agg. at BC
Davis et al., 1980; Dwyer et al., 1996	cool and wet	13000-11000	Moderate agg. at EM and BR; low agg. at BC