FAN DEPOSITS IN NORTHWESTERN VERMONT: DEPOSITIONAL ACTIVITY AND AGGRADATION RATES OVER THE LAST 9,500 YEARS

A Thesis Presented

by

Amy Beth Church

to

The Faculty of the Graduate College

of

The University of Vermont

In Partial Fulfillment of the Requirements
for the Degree of Master of Science
Specializing in Geology

May, 1997

Accepted by the Faculty of the Graduate College, The University of Vermont, in partial fulfillment of the requirements for the degree of Master of Science, specializing in Geology.

Thesis Examination Committee:

Paul R. Bierman _________________ Advisor
Paul R. Bierman, Ph.D.

Charlotte Mehrtens _________________
Charlotte Mehrtens, Ph.D.

David R. Hemenway _________________ Chairperson
David R. Hemenway, Ph.D.

Delcie R Durham _________________ Dean,
Delcie R. Durham, Ph.D. Graduate College

Date: December 2, 1996

Abstract

This thesis presents the first detailed description of post-glacial, humid-temperate fan deposits in northwestern Vermont, including data characterizing fan sedimentology and aggradation rates during the past 9,500 sidereal years. The studied fans contain abundant organic material suitable for radiocarbon dating. Fan aggradation rates were constrained using calibrated radiocarbon dates obtained from wood and charcoal exposed within three trenches and from estimated volumes of sediment deposited on each fan during specific time periods. Colonial land use resulted in deforestation of hillslopes and increased rates of fan aggradation. On one fan, aggradation increased >10 times over past rates due to land use practices. In addition to radiocarbon dates and volumetric information used to calculate rates of fan aggradation, northwestern Vermont fans provide information about fan depositional processes through the Holocene. Two fan deposits were carefully documented using back-hoe trenches and stratigraphic logging of fan profiles. Grain size analyses of stratigraphic units within the fans were used to determine the depositional processes resulting in fan formation.

The fans described in this thesis are both located in the Huntington River valley (207 km^2) in northwestern Vermont. These fans are small, four to six meters at the apex with 50 to 62 meter radii, and generally fed by ephemeral streams. The fans are located on Huntington River cobble-strath terraces at the break in slope between the terrace and adjacent hillslope. Sediment deposited on the fans originates from small (<0.5 km^2) drainage basins located above the fans on the hillslopes. The sediment found in the fans was eroded from glacial till or glaciolacustrine deposits found on the metamorphic bedrock uplands. The fans are experiencing little aggradation today; one fan deposit is currently being dissected by the stream that feeds it.

Excavation of the two fans (Moultroup and Audubon) revealed a complex stratigraphy in the Moultroup fan, and a relatively simple stratigraphy in the Audubon fan. Trenches in the Moultroup and Audubon fans revealed sediment interbedded with organic layers and cross-cut by a distinct buried soil horizon. The Moultroup fan had interbedded units of sand and silt, and gravel. The Audubon fan was massive and lacked sedimentary structures.

Samples of wood and charcoal were removed from trench walls and radiocarbon dated in order to constrain ages of discreet volumes of sediment in the fan. Four samples, two wood and two charcoal, were dated from the Moultroup fan, and three samples, one wood and two charcoal, were dated from the Audubon fan.

The Moultroup fan records an episodic depositional history. In the early Holocene, aggradation occurred at a rate of 3.7 $m^3 y^{-1}$. The rate slowed to 0.1 $m^3 y^{-1}$ over the next 4,000 years. From 4,000 years ago to pre-settlement, the rate of aggradation on the fan increased to 0.3 $m^3 y^{-1}$. Since settlement, aggradation has increased to a rate of 7.0 $m^3 y^{-1}$, coinciding with a period of colonial land use for agriculture. Aggradation rates calculated for the Audubon fan indicate a low rate of aggradation for the early Holocene (1.1 $m^3 y^{-1}$), and an even lower rate for the next 8,600 years (0.1 $m^3 y^{-1}$). The rate of aggradation on the fan increased in the last 180 years to 2.3 $m^3 y^{-1}$.

The results of this study provide a better understanding of rates of hillslope erosion in Vermont. Specifically, stratigraphic, sedimentologic, and chronological data obtained from fan deposits were used to characterize the morphometry and rates of development of humid region fans. Establishing rates of fan aggradation throughout the Holocene, specifically during a period of extensive colonial land use, quantifies the hillslope-fan response to external forcings, such as deforestation.

Acknowledgments

The author wishes to express her appreciation to Professor P. R. Bierman and Professor C. Mehrtens for guidance, advice and encouragement given during the course of this investigation, to Henry Moultroup and the Huntington Audubon Society for support of this research, and to the students of the UVM Geology Department for their help in the field. My deepest gratitude goes to my family and my fiancé, King, for unfailing support throughout the preparation and writing of this thesis. ^{14}C dating was supported by start-up funds to Bierman by UVM and Milan Pavich of the United States Geological Survey. Grants and awards, the J. Hoover/Mackin Award from the Geomorphology and Quaternary Geology Division of the Geological Society of America, a Sigma-Xi Grant-in-Aid of Research from the Sigma-Xi Foundation, a Research Grant from the Burlington Gem and Mineral Club, and a Vermont Geological Society Research Grant, were all deeply appreciated during the course of this study.

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Chapter 1

Introduction

1.1 Statement of Problem

Fan deposits are an important but often overlooked feature of the Vermont Green Mountains which have received little study in humid-temperate regions (Ryder, 1971). Humid-temperate fans are more likely than arid fans to contain organic material necessary for dating depositional events, establishing chronology, and constraining rates of hillslope denudation throughout the Holocene (Lecce, 1990). In Vermont, processes transporting sediment to fans have not been characterized, fan stratigraphy has never been described in detail, and fans have not been dated. Moreover, response of the hillslope-fan system to climatic, ecological, and land-use changes is not understood. This study incorporated excavation, grain size analyses and radiocarbon dating to better understand fan deposits in Vermont.

1.2 Overview of Thesis

This thesis presents the results of field observations and laboratory analyses of two inactive fan deposits in northwestern Vermont. I present, in the following order, the methodology used to study fan deposits, the data obtained from each fan, and a discussion of the history and processes of fan deposition in northeastern Vermont. This study suggests that deposition on the fans has been episodic, and offers three hypotheses of how hillslope erosion could have resulted in fan aggradation over the last 9,000 years:

1) hillslope erosion and fan aggradation occur when hillslopes are clear of vegetation, 2) hillslope erosion and fan aggradation are triggered by infrequent catastrophic storms events regardless of the presence of vegetation on the hillsides, and 3) continual soil creep fills basin channels with colluvium which is flushed to the fan episodically during large, infrequent storm events.

1.3 Geographic and Geologic Setting

The Huntington River Valley (207 km^2) is located in northwestern Vermont, approximately 20 km southeast of Burlington, Vermont (Figure 1). The Huntington Valley is located on the Richmond, Vermont and Huntington, Vermont USGS topographic quadrangles. The total relief of the valley is 1,153 m (3,783 ft), and the highest peak is Camels Hump, 1,245 m (4,083 ft). The area is drained by the Huntington River which is a tributary of the Winooski River. The bedrock is predominately chlorite schist of the Underhill Formation, Camels Hump group, structurally dominated by the arch of the Green Mountain Anticlinorium (Doll, 1961). The valley was glaciated repeatedly during the Pleistocene. The Huntington River area was selected for study because of the frequency and accessibility of identifiable fan deposits due to farming on the floodplain and adjacent terraces.

The Huntington River basin was occupied by glacial lakes, including Lake Vermont between 13-12k ^{14}C years ago as the Laurentide ice sheet retreated north, damming north-flowing drainage (Stewart and MacClintock, 1969). On the valley floor, bedrock is discontinuously covered by a layer of glacial till and glaciolacustrine fine-grained sediments. Above the lacustrine deposits, lie sand and gravel deposited by drainage through the Huntington basin as the lake levels receded and the ice margin continued its northward retreat. The Huntington River has incised the lacustrine deposits and reworked the sand and gravel to form distinct cobble-strath terraces. A layer of glacial till still covers the hillslopes except where schistose bedrock crops out. Isolated deltaic and fill terrace deposits, composed of silt, sand and gravel, and deposited during Lake Vermont occur within the valley. Glaciolacustrine fill terraces (T. Whalen, pers. comm.) are located within the catchments that supply sediment to both of the fans studied. Figure 2 presents a schematic diagram of the region's post-glacial evolution with fan chronology.

1.4 Literature Review

Much of the study of surficial deposits in New England has been directed towards mapping glacial sediments in order to determine the timing of glacial events and distribution of glacial sediments (e.g. Koteff and Pessel, 1981, Connally, 1982, DeSimone and Dethier, 1992). It is established that the Laurentide ice sheet repeatedly advanced and retreated over the mountains of New England, scouring their surfaces and leaving behind a blanket of glacial till and sorted sediments (Koteff and Pessel, 1981). In many areas of the Green Mountains, the till cover still remains, while in the valleys the sediment has been reworked by outwash rivers and streams forming glaciofluvial deposits (Chapman, 1937). During the final glacial retreat glacially dammed lakes filled the valleys abutted by the retreating ice masses (Connally, 1982). Glaciolacustrine deposits such as terraces and deltas record the levels of lake stands during this period (Flint, 1971). Although studies have been devoted to deciphering the implications of the glaciofluvial and glaciolacustrine deposits in Vermont (Chapman, 1937, Stewart and MacClintock, 1969), very little attention has been paid to the post-glacial evolution of the landscape. Geomorphologic studies of post-glacial landscape development in northern New England have been limited to landslide studies (e.g. Cleland, 1902, Flaccus, 1958, Bogucki, 1977, Eschner et al., 1982) and the study of landslides and debris torrents occurring in response to severe storm events (Ratte and Rhodes, 1977, Renwick, 1977, Pomeroy, 1980). Little attention has been paid to the rates and types of hillslope processes shaping today's landscape. In short, scant information is available describing the post-glacial geomorphic response of the northern New England landscape.

1.4.1 Humid Region Fans

Although New England fan deposits have received little study, humid region fans have been investigated in other areas (Ryder, 1971, Kochel and Johnson, 1984, Wells and Harvey, 1987, Kochel, 1990). In her paper defining para-glacial sedimentation, Ryder (1971) describes two areas subject to para-glacial denudation, central Baffin Island and south-central British Columbia. Ryder identified three non-glacial deposits: alluvial fans, fluvial sediments and lacustrine sediments. The para-glacial alluvial fans formed on surfaces as soon as they became ice-free. The fans are generally in contact with glacial till at their apexes, and the deposits are comprised of reworked till. As base-levels lowered and/or source material was depleted, fan aggradation ceased and fan-head trenching commenced.

Ryder points out that as long as glacially derived sediment is unstable, transfer of readily erodable sediment will occur. The alluvial fan deposits exhibited little evidence of current fan aggradation, and in fact in some areas land forms were degrading. A more detailed investigation of the British Columbia fan deposits (Ryder, 1971) revealed evidence of rapid rates of surface denudation after glacial retreat. Rates of denudation on British Columbia fans were estimated by determining volumes of sediment deposited between approximately known time periods. In British Columbia, rates of hillslope denudation were found to be highest during and immediately after deglaciation in this area (Ryder, 1971; Church and Ryder, 1972). Erosion rates lessened as the sediment source was depleted. Evidence of increased landscape erosion due to deglaciation has been recorded in New England. Freeman-Lynd et al. (1980) found that sedimentation rates in southern Lake Champlain were higher during the late Pleistocene and decreased steadily through the early Holocene.

1.4.2 Northeastern Climate and Post-glacial Revegetation

In order to develop an understanding of landscape change since deglaciation in Vermont, it is necessary to establish a climate and post-glacial revegetation history. A continental ice sheet covered almost all of Maine and the lower elevations of northern Vermont and New Hampshire at 14 ^{14}C ky BP (Davis and Jacobson, 1982). Eustatic sea level rise caused an incursion of sea water through the St. Lawrence seaway. The Champlain Sea was formed at or shortly after 11.7 ^{14}C ky BP from the influx of sea water (Parent and Occhietti, 1988), filling the Champlain lowlands and the foothill valleys of the Green Mountains, reaching elevations of 114 meters (375 feet) in Vermont (Stewart and MacClintock, 1969). Vegetation in northern Vermont at this point was extremely sparse, consisting of tundra (Spear, 1981), while in southern Vermont taxa including poplar and spruce where invading indicating that over a thousand-year period (14-13 ^{14}C ky BP), the climate had notably warmed (Davis and Jacobson, 1982). Watts (1979) attributed an increase in species diversity in sections of Pennsylvania at 13 ^{14}C ky BP to climatic warming as well.

Climatic warming continued through 12 ^{14}C ky BP, as indicated by the further advancement of woodland flora into northern Vermont and into Canada. From 11-10 ^{14}C ky BP a rapid development from woodland to forest cover (Delcourt and Delcourt, 1981, Davis and Jacobson, 1982) has been tentatively attributed to a rapid warming of the area (Davis and Jacobson, 1982).

At 5 ^{14}C ky BP, the forest cover described by Davis and Jacobson (1982) was still present, although the taxa had changed from mixed hardwood to mixed hardwood and white pine. The modern climatic regime had yet to be fully established in the northeastern states (Davis and Jacobson, 1982). A cooling trend with increased precipitation is recognized for the period of 5,000-200 ^{14}C yrs BP, as the northern forest extended southward (Delcourt and Delcourt, 1981). In a later paper by Delcourt and Delcourt (1984), palynological data were used to interpret paleoclimatic changes in eastern North America in order to establish a paleoclimate model since deglaciation. In the northeast, temperatures were cooler from 10-8 ^{14}C ky BP, warmer from 8-4 ^{14}C ky BP with increased aridity, and cooler during the last 4 ^{14}C ky BP with the establishment of the modern climatic regime.

1.4.3 Land Use in Vermont

Colonial settlement in Vermont drastically changed the landscape from primarily forest cover to vast regions of deforested terrain. By the mid-1800's, 75% of Vermont had been cleared of its forests to be used for lumber and populated by livestock (Severson, 1991). In 1840 Vermont was second in America in wool production with a sheep population of 1,700,000, a ratio of six sheep to every person (Maunsell, 1966). In 1850, 29% of Vermonters were employed in the lumber and wood manufacturing, while 66% devoted their time to raising sheep and producing wool (Meeks, 1986).

When hillslopes are cleared, soil erosion is accelerated for a number of reasons. The loss of vegetation, root systems, and surface litter decreases soil water retention capacity and increases surface runoff, causing the exposed topsoil to be eroded more easily (Dunne and Leopold, 1978). The sedimentological effects on a river of clear-cutting Vermont hillslopes were quantified by the findings of an archaeological and geomorphological study of historical Winooski River floodplain deposits (Thomas, 1993). From 1802 to 1869, a time period encompassing the mass deforestation of Vermont, average point bar accretion on a bend in the Winooski River averaged 2.7 to 3.5 meters per year, a high average likely due to the influx of large amounts of sediment to the hydraulic system (Thomas, 1993). During the period of 1894 to 1972, point bar accretion slowed to 0.8 meters per year, translating to a 350% decrease in channel migration during the late nineteenth and twentieth centuries (Thomas, 1993), coinciding with the restabilization of vegetation in the area.

1.4.4 Effects of Land Use in Other Regions

The effects of historical land use have been documented in other regions. In their paper on rates of surface processes and denudation in various climates, Young and Saunders (1986) stated that land-use practices can accelerate hillslope denudation up to 20 times that of non-cultivated land degradation, depending land use methods. Heede (1985) studied two watersheds before and after timber harvesting. The primary stream in the deforested drainage enlarged, on average 5.6%, more than the stream in the undisturbed watershed, and knickpoints in the stream in the deforested watershed advanced 21 cm farther upstream.

Local forest clearing and an increase in plowed land, combined with an increase in annual precipitation, caused accelerated soil erosion and floodplain deposition on the upper Thames in England (Hazelden and Jarvis, 1979). A relationship between variations in climate and Anglo-American settlement was established by Miller et al. (1993) for a watershed in southern Illinois. At least two meters of fine-grained alluvium was deposited historically on valley floors, at a rate of 2.11 cm per year between the years of 1890-1988. This rate is one to two orders of magnitude larger than pre-settlement values calculated for other areas in the mid-west. In a side valley in Adair County, Iowa, Ruhe and Daniels (1965) determined volumes of sediment eroded from the valley side-walls and deposited on the valley bottom. Using radiocarbon dates from sediment deposited in the valley, they calculated that post-settlement hillside erosion and alluvial filling has occurred at rates three and ten times, respectively, that of pre-settlement times. Settlement occurred extensively in Maury County, Tennessee, between 1800 and 1900 AD. The settled land was cleared and plowed and used for row cropping or agricultural grazing. Brakenridge (1984) proposed a causal relationship between these land-use changes and increased local floodplain sedimentation. The sedimentary response to land use changes in Tennessee, hillslope erosion and alluvial filling, was greater than that occurring over the last 10k years.

1.4.5 Effects of Fire on Hillslope Stability

Clear-cutting is not the only method employed to clear hillslopes. Although even less information is available on the effects of fire on hillslope stability, the few studies completed show fires leave the hillslopes severely susceptible to erosion. In the Hawea Flat district of New Zealand, a radiocarbon date from a coalesced alluvial fan deposit was used to calculate historical sedimentation rates (Leamy, 1969). The catchments supplying debris to the fans total approximately 20 km^2, and their average surface lowering by erosion over the last 200 years is approximately 0.3 m (Leamy, 1969). Pollen records showed a deforestation event occurred that caused the beech and conifer forest to be replaced by non-forest flora. Charcoal was identified that post-dated the flora transition, and the investigators inferred that forest fires, whether human induced or natural, were the immediate cause of the deforestation and subsequent erosion.

In Yellowstone National Park, evidence of forest fires causing sedimentation events has been found in alluvial fan deposits. Meyer et al. (1992) studied the geomorphological response of alluvial systems to fires occurring in the park in 1988. As a result of the fires, sediment transport was accelerated and alluvial fan aggradation resulted. Older deposits, identified within the alluvial systems, revealed a chronology of fire-related sedimentation over the last 3,500 years, attributed to periods of drought or high climatic variability. The authors found that approximately 30% of the late Holocene fan deposits were probably a result of fire-induced hillslope instability.

1.4.6 Hillslope Response to Severe Storm Events

Fan aggradation has occurred as a result of severe storm events. Pierson (1980) summarized recent erosion and deposition on an alluvial fan at least 20k years old resulting from a catastrophic storm event in New Zealand. The fan was built by episodic debris-flow events. In one catastrophic storm event, with a return period in excess of 20 years, 130,000 m^3 of sediment were deposited onto the fan. This volume of sediment is equivalent to thousands of years of erosion by mass wasting and gully erosion at normal rates for the area. Pierson noted in this study that large, active fan deposits in this area are present only in grass-covered watersheds that were deforested over 100 years ago. Nearby forested catchments are not experiencing gully erosion and active fan development. Pierson attributes accelerated rates of mass wasting in the drainage above the fans to forest clearing in the catchments.

In northwest England, Wells and Harvey (1987) describe sedimentologic variations in thirteen alluvial fan deposits, all deposited as a result of a single severe storm event. Wells and Harvey described six facies types that occurred within the storm-generated deposits, and categorized them into three groups; 1) stream-flow facies 2) transitional-flow facies and 3) debris-flow facies. Deposits were divided into facies groups based on surficial expression, vertical sequences, depositional morphology and relief, the presence and type of stratification and clast orientation. In the field, units of varying facies type were found stacked on top one another and attributed to varying sediment:water ratios during deposition. By using discriminate analyses, Wells and Harvey determined that catchment size, channel gradient, and percentage of area eroded during the storm event determined which facies dominated the fan deposit.

Alluvial fan deposits along the east coast of the United States have been documented from North Carolina to New Hampshire. For the most part, alluvial fan aggradation has been attributed to debris flow deposition caused by storms. In Virginia, Kochel and Johnson (1984) identified two major types of fan deposits; 1) large (2-18 km^2) prograding, probably Pleistocene-age deposits formed by water-flood processes that coalesce into an alluvial apron along the western flank of the Blue Ridge and 2) smaller (0.5 km^2) Holocene-age deposits formed exclusively by debris flow activity east of the Blue Ridge. Kochel and Johnson assert the fans of the second type are formed by episodic deposition as a result of precipitation-induced debris flows. After depositional events, the fans are often re-worked by streams emerging from the tributary basins. Wilson and Kochel (1983) describe the morphology and sedimentology of small fan deposits created by debris flow events in several Appalachian states (Tennessee, Virginia, West Virginia, New York and New Hampshire). All the fans studied exhibit sedimentological characteristics of extremely poor sorting, angular clasts and the absence of sedimentary structures. The fan deposits form at the base of steep, low-order tributaries. Wilson and Kochel (1983) noted the abundance of clast-supported sediment at some sites, indicating a transition from sediment-rich debris flows to diluted hyperconcentrated flows down-fan.

Debris fans in North Carolina have been sites of active deposition in the recent past (Neary et al., 1986). When shallow soils in steep, upland slopes became saturated, debris avalanches resulted in rapid mass-movement of sediment downslope. The debris avalanches incorporated considerable amounts of woody material that was deposited on older debris fans.

Landsliding has been attributed to catastrophic storm events in the northeastern United States often resulting in fan deposition. Eschner and Patric (1982) describe the occurrence of landslides in response to heavy rains throughout the Appalachians. Landsliding is most probable when rainfall exceeds 12 cm in 24 hours on steep (25-40°) slopes where soils are less than 90 cm deep (Eschner and Patric, 1982). In 1977, a storm system reached North Carolina and dumped 30-120 mm of rain per hour in the region, triggering landslides on forested slopes (Neary et al., 1986). The majority of slides occurred on slopes with gradients of 60-80% and followed paths along ephemeral stream channels or old landslide scars.

Debris flows created by intense storm events are not restricted to the southern Appalachian states. Pomeroy (1980) reports debris flows occurring in central Pennsylvania as a result of storm events. Detheir et al. (1992) describe a similar flow in Massachusetts. Indeed, rainfall induced debris flow events in the northeast have received much attention in the last 70 years (New Hampshire; Flaccus, 1958, Vermont; Ratte and Rhodes, 1977, New York; Bogucki, 1977, Massachusetts; Cleland, 1902).

Catastrophic storm events resulting in debris flows may be recorded in Appalachian alluvial fan deposits and can be used to estimate event return periods (Kochel, 1987). In 1969, during Hurricane Camille, more than 75 cm of rainfall fell overnight in Virginia causing extensive debris flow activity along the east side of the Blue Ridge Mountains. Debris avalanching occurred in first-order channels, preceded by slides initiated most commonly at the colluvium/bedrock interface where pore pressure reached a maximum. The avalanches traveled downslope to the debris fan deposits, with the coarsest clasts accumulating at the fan apex. The resultant deposits are small (<1 km^2), elongate, have steep, segmented profiles and dips of >10°. Debris flow deposits resulting from individual storm events can be recognized by the presence of paleosols, abrupt changes in sediment texture, and abrupt changes in matrix composition at suspected event boundaries. Using the debris flow deposits caused by Hurricane Camille as a modern analogue, Kochel determined that there have been three or four other debris flow events in the last 11k years on other, older alluvial fan deposits. He proposes a model of fan aggradation caused by warm, moist tropical air masses with the retreat of polar front at the end of the Pleistocene (Delcourt and Delcourt, 1981).

1.4.7 Alluvial Fan Sedimentation

Alluvial fan deposits are comprised of discontinuous units of debris and streamflow deposits (Ritter et al., 1995). Hyperconcentrated flow (Keaton, 1988), transitional flow (Wells and Harvey, 1987), and mudflow deposits have also been identified in alluvial fan deposits (Ryder, 1971). Each of these flow types are components of a continuous spectrum of sediment-water mixtures that range from 100 percent water to 100 percent sediment. Pierson and Costa (1987) proposed a more quantitative classification of flow types based on velocity and sediment concentration of flowing sediment-water mixtures (Figure 3). They define the ability of a sediment-water mixture to liquefy as the threshold between granular flow and slurry flow. In granular flow, grain support is provided by grain-to-grain contact, while in slurry flow grain support is provided by pore fluid pressure. Slurry flow and hyperconcentrated streamflow are differentiated by an abrupt decrease in yield strength as the Newtonian Fluid Threshold is crossed (Figure 3). Newtonian fluids have no strength and do not undergo a change in viscosity as shear rate increases through flow. Non-Newtonian behave as Bingham plastics; that is, they have a yield strength that must be overcome before flow is initiated. Once flowing, non-Newtonian fluids have no strength, but show variable viscosity with changes in shear during flow. Grain support in hyperconcentrated streamflows is provided by dispersive pressure, in the form of grain-to-grain collisions and close encounters as the flow moves downslope.

Distinctions can be made between flow deposit types based on morphology and sedimentology. Streamflow deposits can contain any of the following sedimentary structures: ripple marks, cross-lamination, cross-bedding, and/or planar lamination. Bottom contacts of streamflow deposits are often erosional, and regular or irregular well-defined stratification are common. Waning and waxing flow can cause regular or inverse grading in a deposit. Particle fabrics; e. g. imbrication of pebbles and parallel alignment of the long axes of clasts, are common, but not always evident in streamflow deposits. Hyperconcentrated flow deposits generally result from extreme flood conditions (Lewis and McConchie, 1994). They are generally clast supported, but can be partially matrix supported and contain outsize clasts. Hyperconcentrated flow deposits often have erosional contacts, and can exhibit graded bedding and clast imbrication (Keaton, 1988).

Gravity flow deposits (formed from debris and mudflows) occur in environments where there is a slope, an unstable accumulation of sediment, and a trigger mechanism. Debris flow deposits generally show poor sorting with large outsize clasts and matrix support, but may be well-sorted fine to very fine sands with up to 20% mud matrix (Lewis and McConchie, 1994). Ungraded debris flow deposits are typical, but normal and inverse grading can occur. In contrast, mudflow deposits are commonly massive, poorly sorted, with a high silt and clay content. Basal contacts are usually non-erosive.

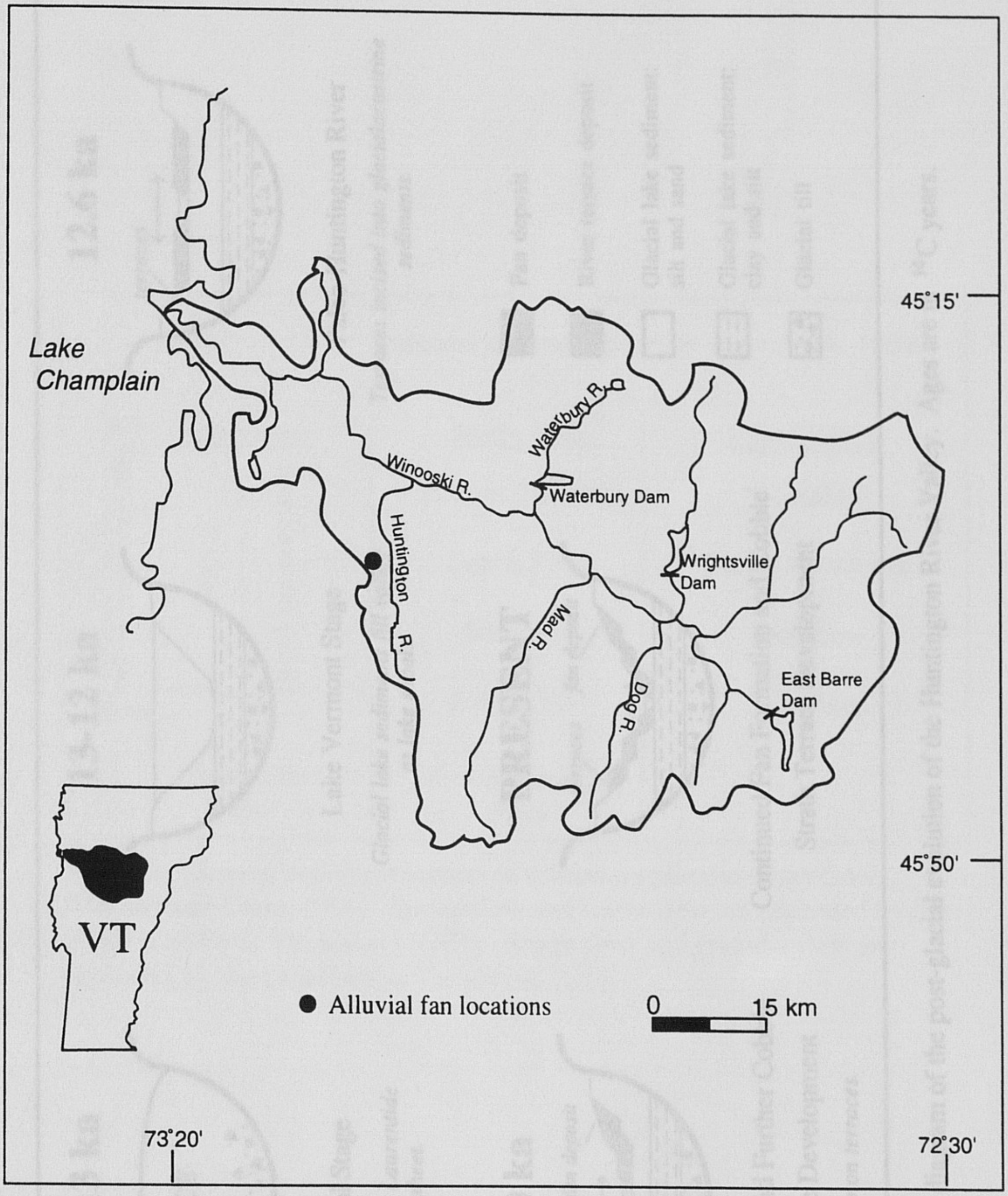

Figure 1. The Winooski River watershed showing major tributaries and location of study site.

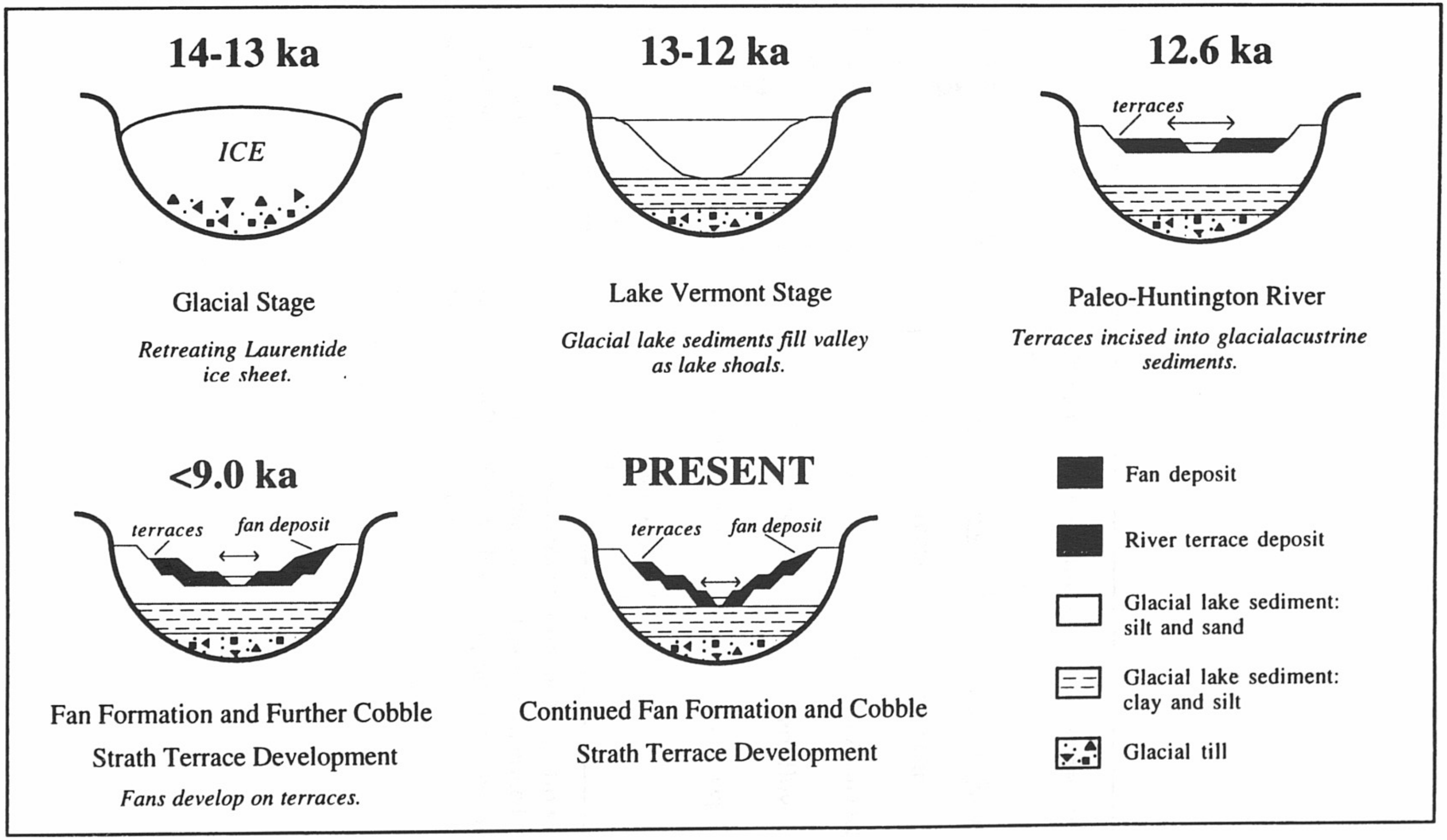

Figure 2. Schematic diagram of the post-glacial evolution of the Huntington River Valley. Ages are in ^{14}C years.

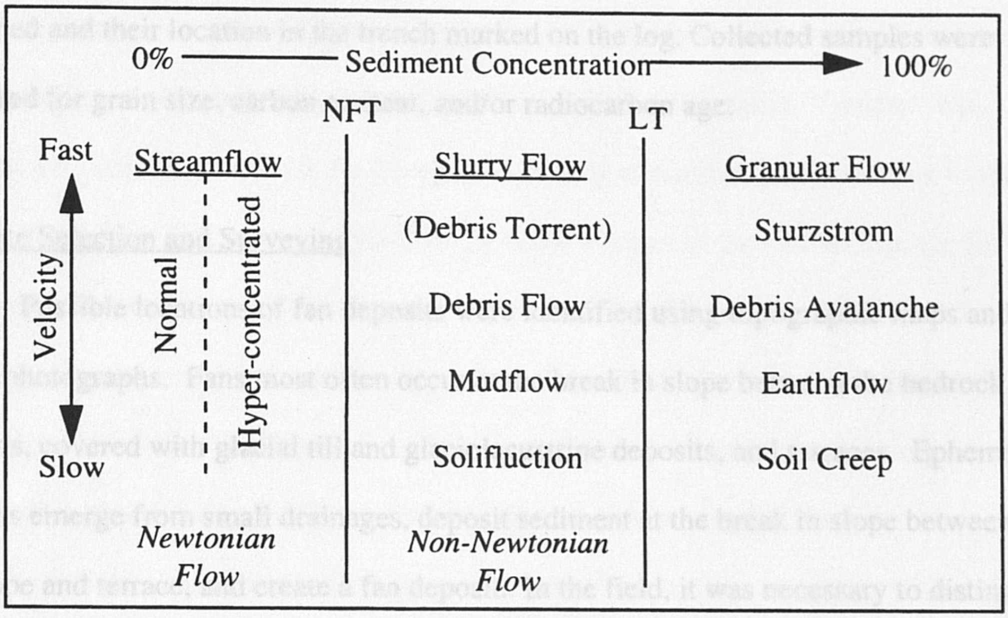

Figure 3. Generalized classification of subaerial sediment-water flows (Pierson and Costa, 1984). Streamflow and slurry flow are seperated by the Newtonian Fluid Threshhold (NFT). Slurry flow and granular flow are seperated by the Liquifaction Threshhold (LT).

Chapter 2

Methodology

During the summers of 1994 and 1995, two fans were studied in the Huntington River Valley (Figure 4). A backhoe was used to dig trenches in the fans, some of which were kept open for a week. Each trench was stratigraphically logged and samples were collected and their location in the trench marked on the log. Collected samples were analyzed for grain size, carbon content, and/or radiocarbon age.

2.1 Site Selection and Surveying

Possible locations of fan deposits were identified using topographic maps and aerial photographs. Fans most often occur at the break in slope between the bedrock uplands, covered with glacial till and glaciolacustrine deposits, and terraces. Ephemeral streams emerge from small drainages, deposit sediment at the break in slope between hillslope and terrace, and create a fan deposit. In the field, it was necessary to distinguish between dissected terraces and fan deposits. Dissected terraces tended to be larger than typical fan deposits in this area, with no identifiable drainage upstream from the junction of the terrace and the hillslope. The Moultroup and Audubon fans were chosen for detailed study because of their accessibility and permission gained from the owners.

The Audubon fan and associated drainage basin were surveyed using Pentax Total Station laser surveying equipment. The survey was used to construct a detailed contour map of the fan and its drainage, needed to compute fan aggradation rates (Figure 5 and Table 1, Appendix D). The Moultroup fan and associated drainage basin were surveyed using a Sokia autolevel. The data from the survey was used to create a detailed contour map of the fan, depicting the location of the trenches (Figure 6), and to compute fan aggradation rates (Table 1, Appendix D).

2.2 Trenching

Using a backhoe, 2 trenches and 3 pits were excavated in the Moultroup fan during the summer of 1994 (Figure 6, Appendix A). Trench locations were determined considering the water table and the probable stability of trench walls. Trench 1 was excavated on a radial line from the fan apex beginning at mid-fan and extending to the fan toe (Figure 7). Pit 3 was excavated in the distal portion of the fan, pit 2 in the field adjacent to the fan, and pit 5 was dug mid-fan (Figure 8). Trench 4 was excavated cross-fan, perpendicular to trench 1, in the upper half of the fan (Figure 9). Stratigraphic logs were compiled of all pits and trenches. Excavation with the backhoe could only be completed safely to a depth of approximately two meters because of the water table. If trenches were excavated more than two meters below fan surface, the water table caused trench walls to cave in. In order to determine the stratigraphy of the fans below two meters depth, the backhoe was used to dig quickly to 4 meters depth (the length of the backhoe arm), and a generalized stratigraphy was determined from sub-surface inspection and sediment brought up in the backhoe bucket.

During the summer of 1995, a backhoe was used to excavate one trench in a fan located on property owned by The Green Mountain Audubon Center (Figures 4 and 5). Only one trench was dug in this fan in order to comply with the wishes of the Audubon Society to disturb as little land as possible. The trench was dug through the mid-fan region on a radial line from the apex (Figure 10). The water table was lower at this site than at the Moultroup fan. Before closing trench 4 in the Moultroup fan and trench A in the Audubon fan, the backhoe was used to excavate another two meters below the trench floor to determine the underlying stratigraphy (Figures 11 and 12).

2.3 Stratigraphic Descriptions

Five detailed stratigraphic logs with strata descriptions were compiled from the Moultroup fan excavations (Figures 7, 8 and 9; Tables 3, 4, 5, 6, and 7). The stratigraphy within pits 2, 3 and 5 in the Moultroup fan was drawn using a tape measure dropped from ground surface (Figure 8 and Tables 3, 4 and 5). These pits were dug in order to determine the stratigraphy below the fan, and for safety reasons no one entered them. Trenches 1 and 4 in the Moultroup fan and trench A in the Audubon fan were kept open for a week each, while the stratigraphy was mapped (Figures 7 and 10; Tables 3 and 7). Water was pumped from the trench and the walls were cleaned using trowels. Contacts between units were marked with flags, as were soil horizons and organic-rich lenses (Appendix A). Units were delineated based on clast size and distribution, matrix grain size, and estimated matrix percentage.

2.4 Sampling

In Moultroup trench 4 and Audubon trench A, a total of six vertical sample sets were taken, three from each trench. A sample set was obtained from each end and the middle of each trench. The vertical samples in each set were taken approximately 3-5 cm apart, or closer if needed to characterize adequately the soil horizons present. These samples were analyzed for carbon content by LOI, to confirm the presence of a visually identified soil horizon (Figures 13 and 14). In the Moultroup trench 4 only, the same samples were also analyzed for iron content.

Samples for grain size analysis were taken from 15 units within trench 4 in the Moultroup fan. Due to the homogeneity of sediment deposited on the Audubon fan, the trench revealed no clear contacts between sedimentary units. For this reason, 8 samples for grain size analyses were taken from a single vertical column, each sample 10 centimeters apart.

Organic matter in the form of wood, charcoal and organic-rich lenses was sampled throughout trenches 1, 4 and pit 5 in the Moultroup fan and trench A in the Audubon fan. After organic samples were identified and their location marked with a flag, they were collected for radiocarbon dating.

2.5 Grain Size Analysis

Grain size analyses were accomplished by dry sieving disaggregated samples with sieves ranging from 0.0ϕ to 4.0ϕ in half phi increments (Folk, 1980). Samples were disaggregated by crushing sediments between sheets of waxed paper. The fine fraction (<4 ϕ) was wet sieved and dried, the sand fraction (>4 and <-1) was washed for fines and dry sieved. Any fines from washing the sand fraction were added to the fines collected previously. The dried sand sample was placed in the Ro-Tap sieve shaker and shaken for 15 minutes. The sediment remaining on each sieve was weighed and the weight was recorded. The silt and clay fraction (<4.0ϕ-14.0ϕ) of each sample was determined through pipette analysis (Folk, 1980). The dispersed sample was agitated and withdrawals were made at the appropriate time intervals. The samples were dried and weighed, and their weights recorded.

2.6 Loss On Ignition

Loss on ignition (LOI) analysis was used to determine the vertical differences in organic content within the trench walls, as well as the relative changes in water content (Bengsston and Magnus, 1986). Sample were collected every 10 cm, from fan surface to trench bottom, but sample location varied by up to 5 cm to coincide with what appeared to be organic-rich layers.

Approximately one gram of soil was removed from each sample and placed in a pre-weighed crucible and weighed. The wet weight of the sample was recorded prior to drying overnight at 90° C, in order to determine the percent water in the sediment. After the sediment had dried, the sample weight was recorded again. The sample was then combusted for two hours at 450° C to ash any organic material. The final weight of the sample after ignition was recorded to determine the percent organic matter in the sediment.

2.7 Radiocarbon Analysis

Two large wood samples from the Moultroup fan were sent to Geochron Laboratory and analyzed for ^{14}C content. Two samples of charcoal from the Moultroup fan were analyzed by accelerator mass spectrometry (AMS) at Lawrence Livermore National Laboratory after being prepared at the USGS laboratory in Reston, Virginia (Table 2). Two samples of charcoal as well as one sample of wood from the Audubon fan were prepared and analyzed at Lawrence Livermore National Laboratory. The resulting ^{14}C ages were calibrated for temporal variation in atmospheric ^{14}C using the CALIB 3.0 ^{14}C calibration program and calibration data set one, based on bidecadel age averages of dendrochronological data (Stuiver and Reimer, 1993).

2.8 Calculation of Aggradation Rates

Aggradation rates were calculated using calibrated ages and estimated volumes of sediment in the fan. The sediment volume deposited before or after each date was calculated by assuming a geometric relationship of fan length and depth. For both fan deposits, it was assumed that the fan was a portion of a right circular cone. It was also assumed sediment deposition on the fan has occurred evenly over the fan surface, and that the sample height from fan base was the surface of the fan at the time of sample deposition. Finally, it was assumed that the hillslope and fan were a closed system, and no erosion took place on the fan between depositional events. Making these assumptions, the method of like triangles was used to compute a total volume of sediment deposited on the fan between the times the dated samples were deposited. Volumes of sediment were subtracted from one another to calculate the volume of sediment between two dated samples. The volume of sediment deposited in a specific interval was then divided by the calibrated age range of the unit to determine an aggradation rate for that period (Appendixes D, E and F).

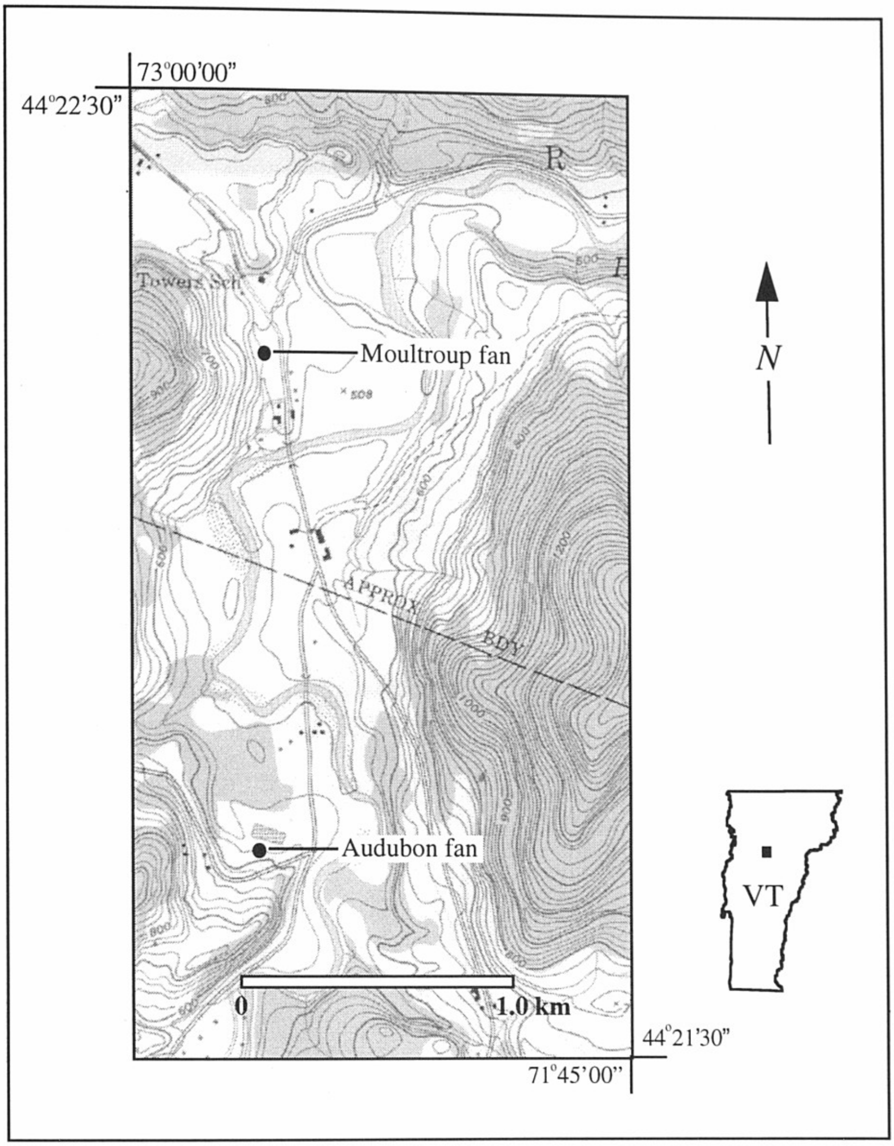

Figure 4. Location of studied fans. Portion of 1972 USGS Huntington quadrangle topographic map.

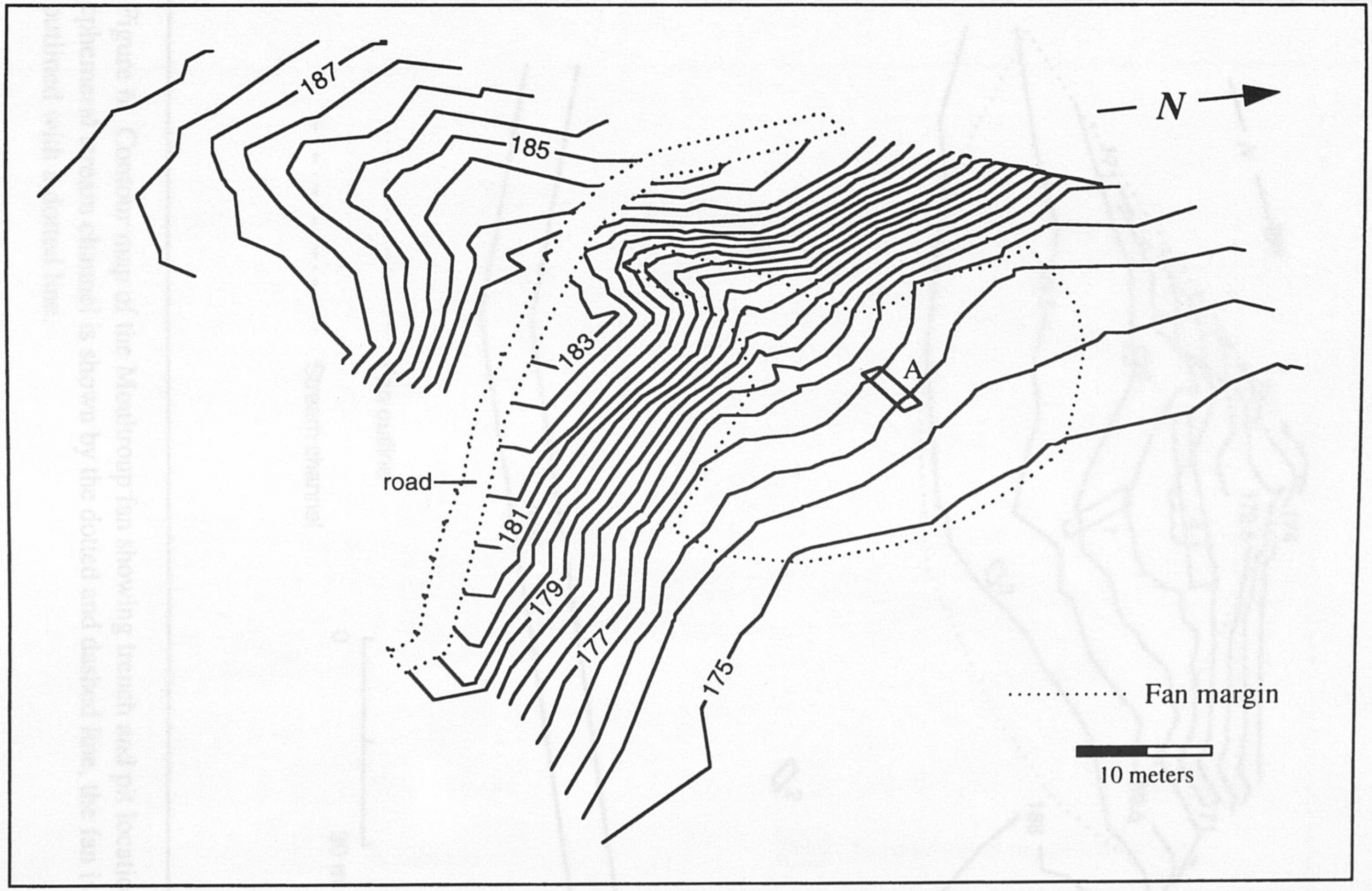

Figure 5. Contour map of the Audubon fan and drainage basin. Trench A is labeled and dotted line outlines fan. Contour interval is 0.5 m, relative to sea level.

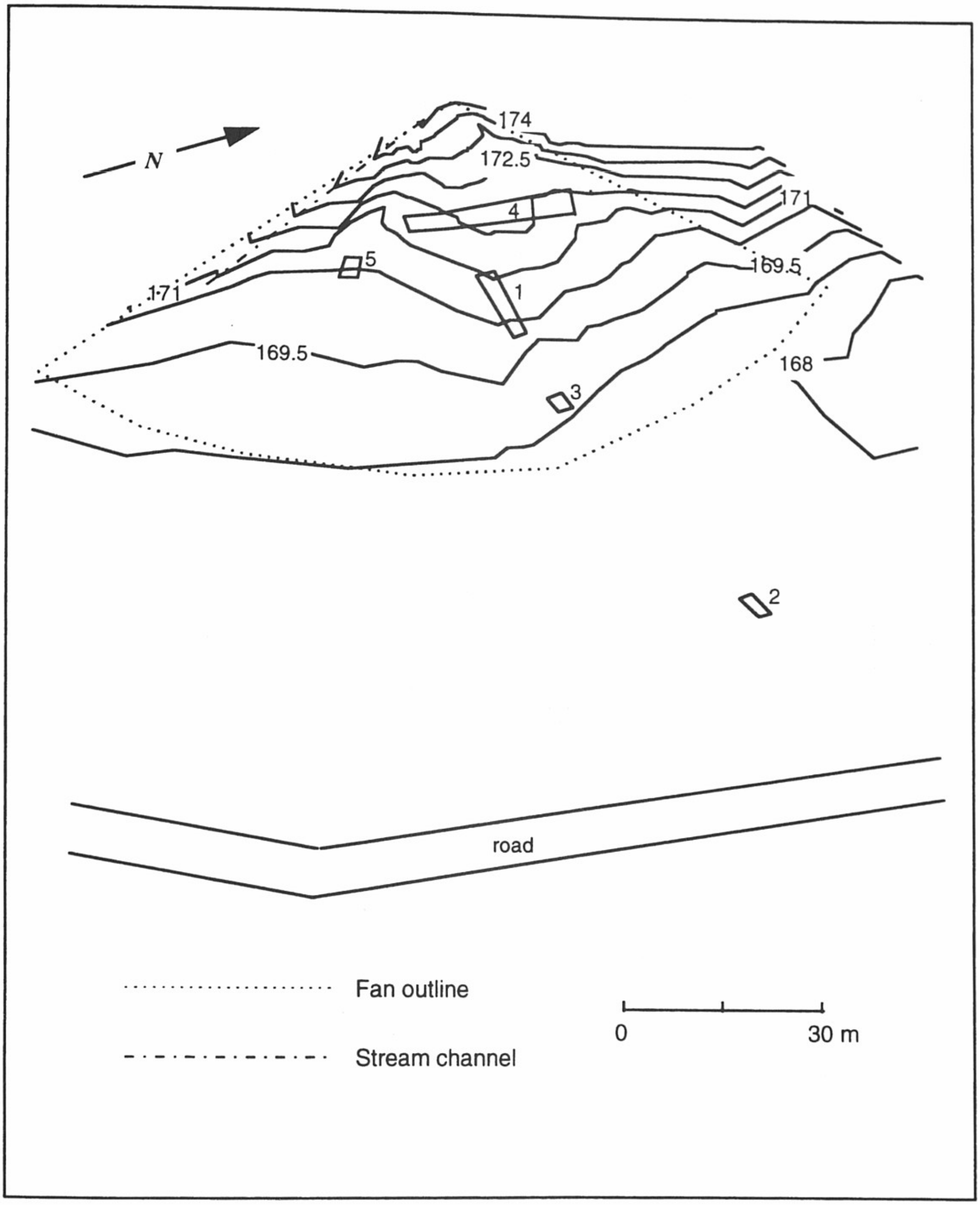

Figure 6. Contour map of the Moultroup fan showing trench and pit locations. An ephemeral stream channel is shown by the dotted and dashed line, the fan is outlined with a dotted line.

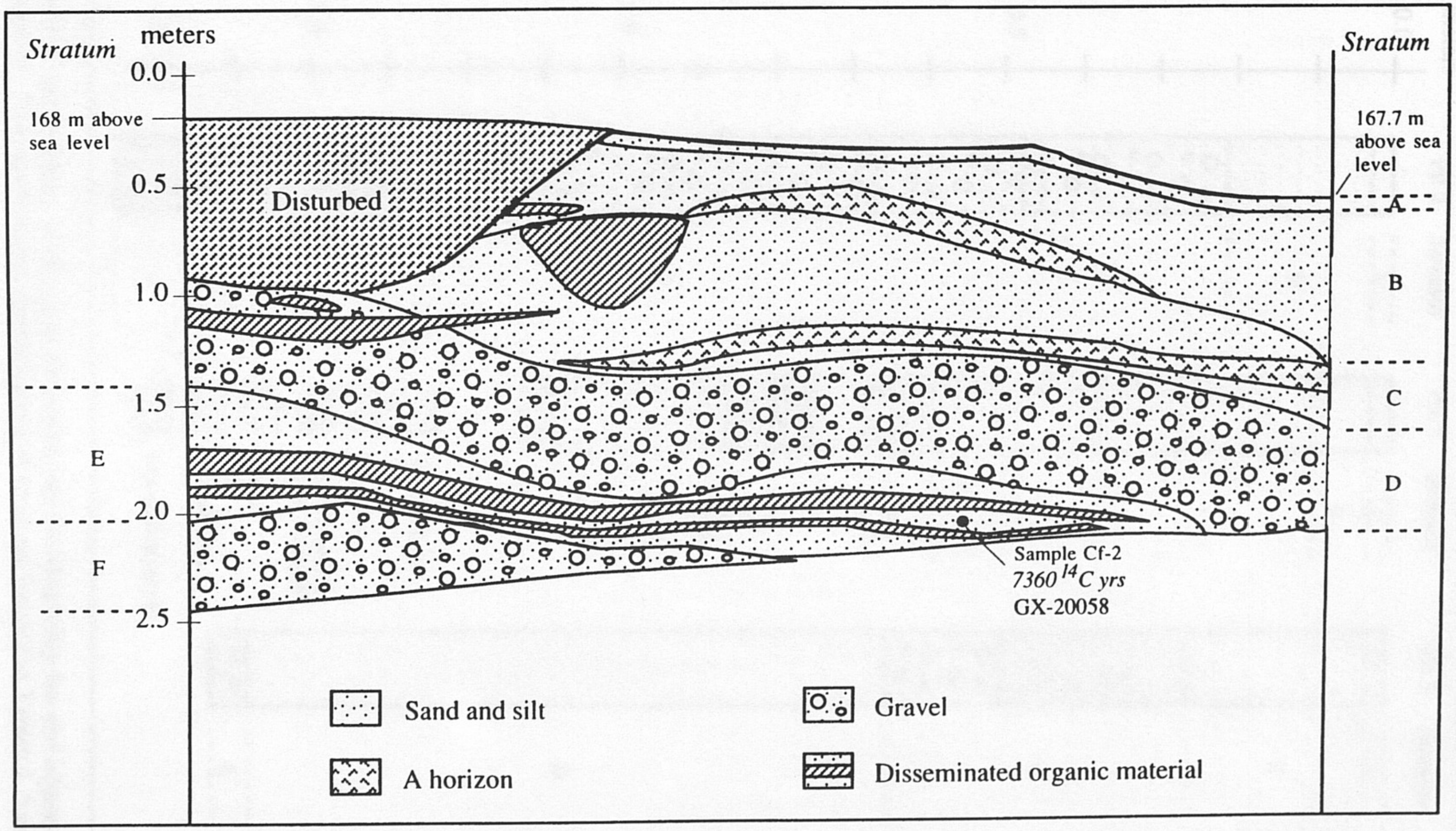

Figure 7. Stratigraphic log of Moultroup trench 1 showing strata as interpreted in the field. The top of the trench is at an elevation of 169 m relative to sea level. Description and interpretations of strata are located in Table 3.

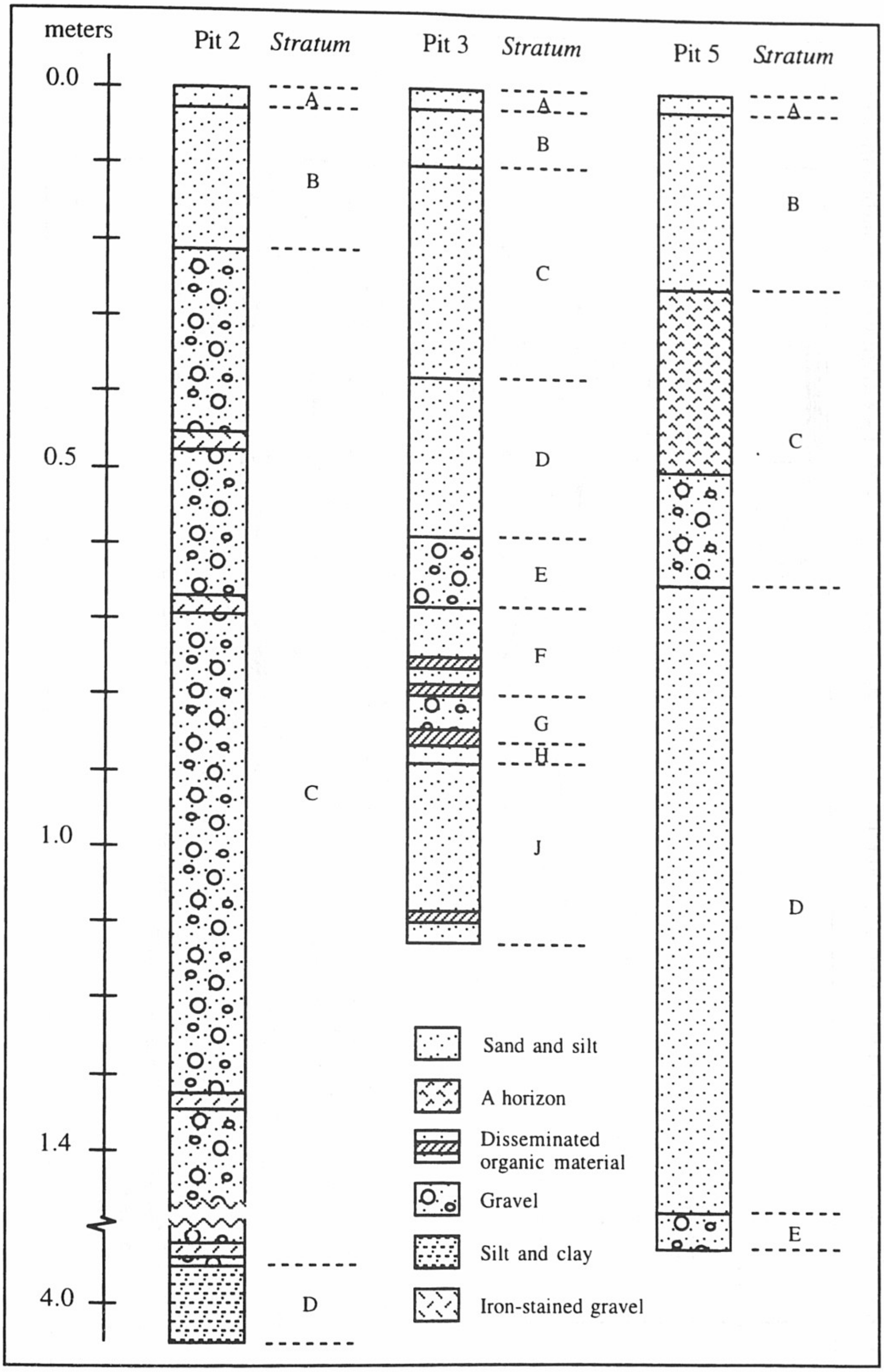

Figure 8. Stratigraphy of three pits excavated into the Moultroup fan and adjacent field (Figure 6). Descriptions and interpretations of strata are located in Tables 4, 5 and 7.

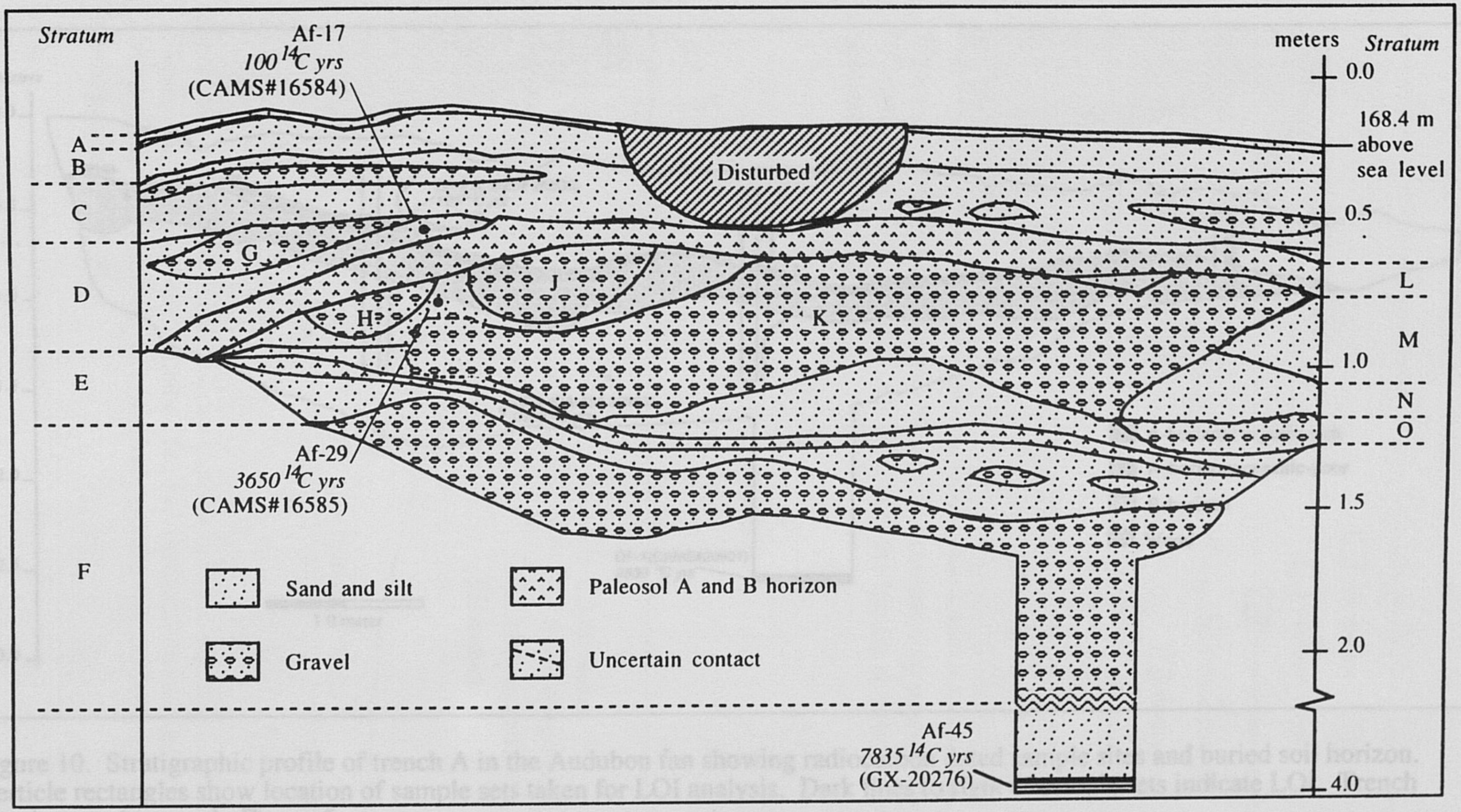

Figure 9. Stratigraphic log of Moultroup trench 4 showing strata as interpretted in the field. Descriptions and interpretations of strata are located in Table 6.

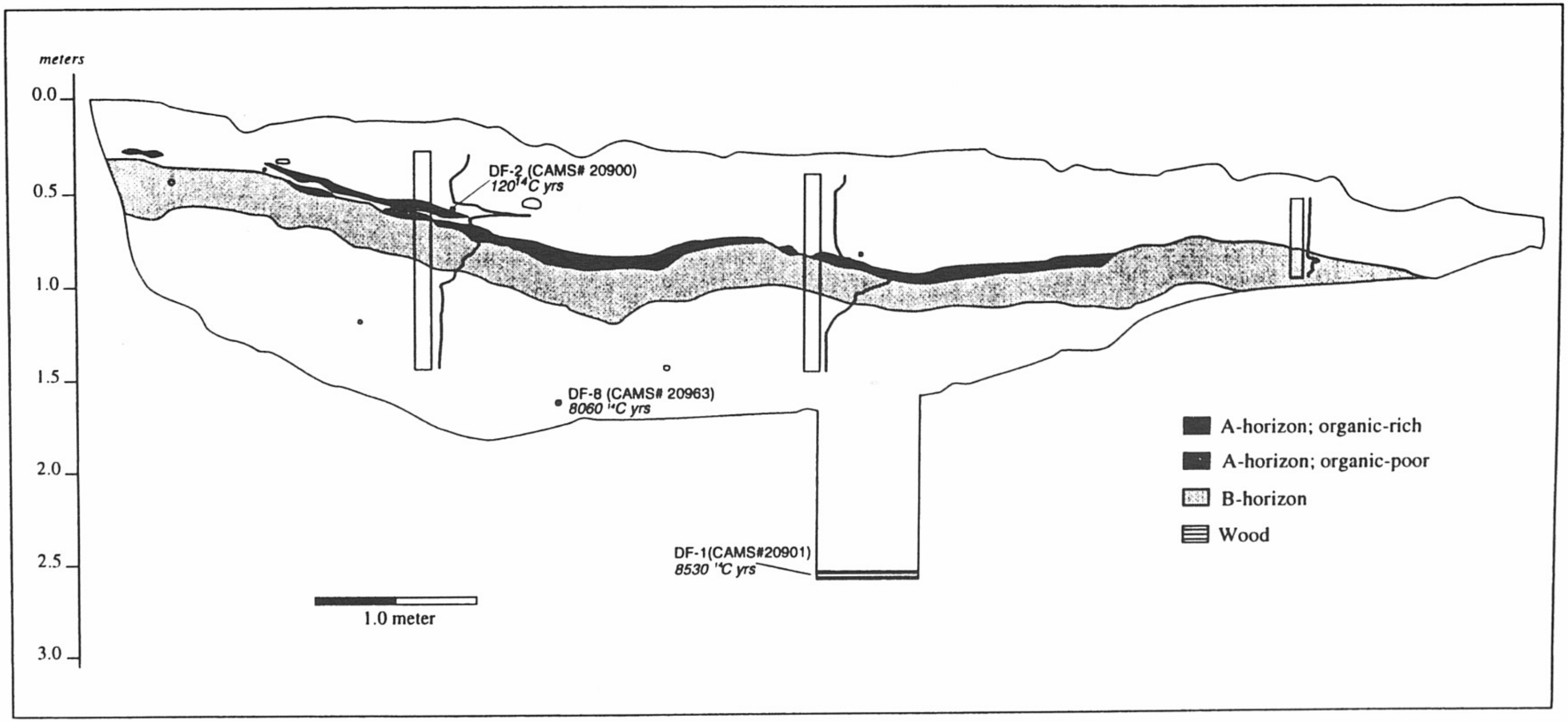

Figure 10. Stratigraphic profile of trench A in the Audubon fan showing radiocarbon dated sample sites and buried soil horizon. Verticle rectangles show location of sample sets taken for LOI analysis. Dark lines to right of sample sets indicate LOI. Trench location can be seen in Figure 5.

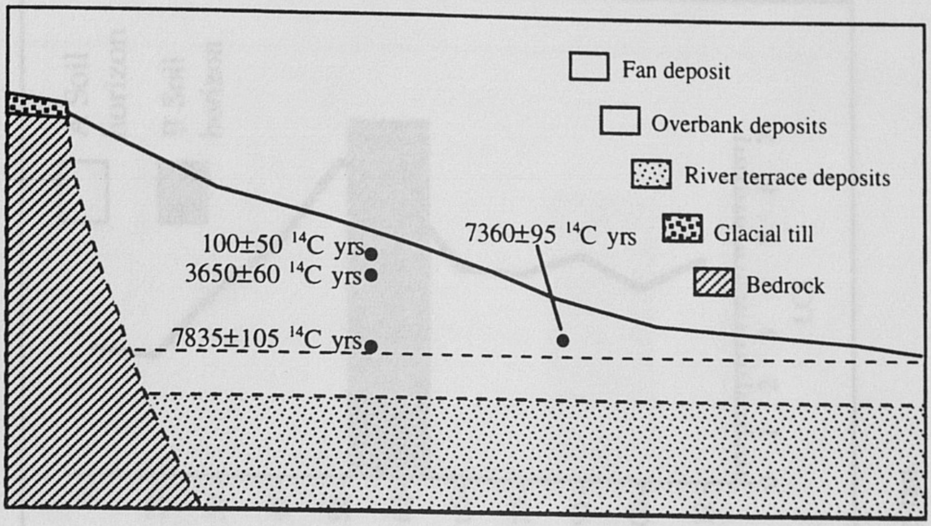

Figure 11. Profile of the Moultroup fan and surrounding stratigraphy. ^{14}C dates in years of samples collected from the fan are shown in their stratigraphic position.

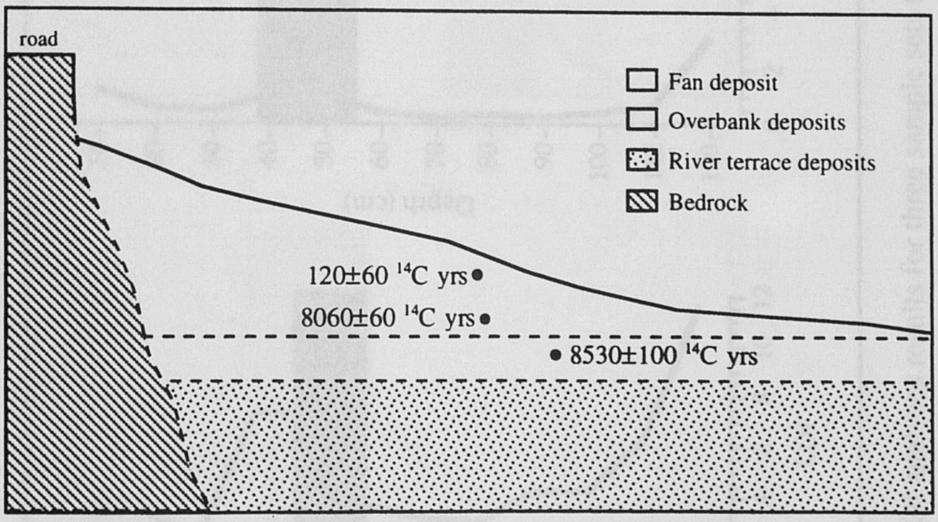

Figure 12. Profile of the Audubon fan and surrounding stratigraphy. ^{14}C dates in years of samples collected from the fan are shown in their stratigraphic position.

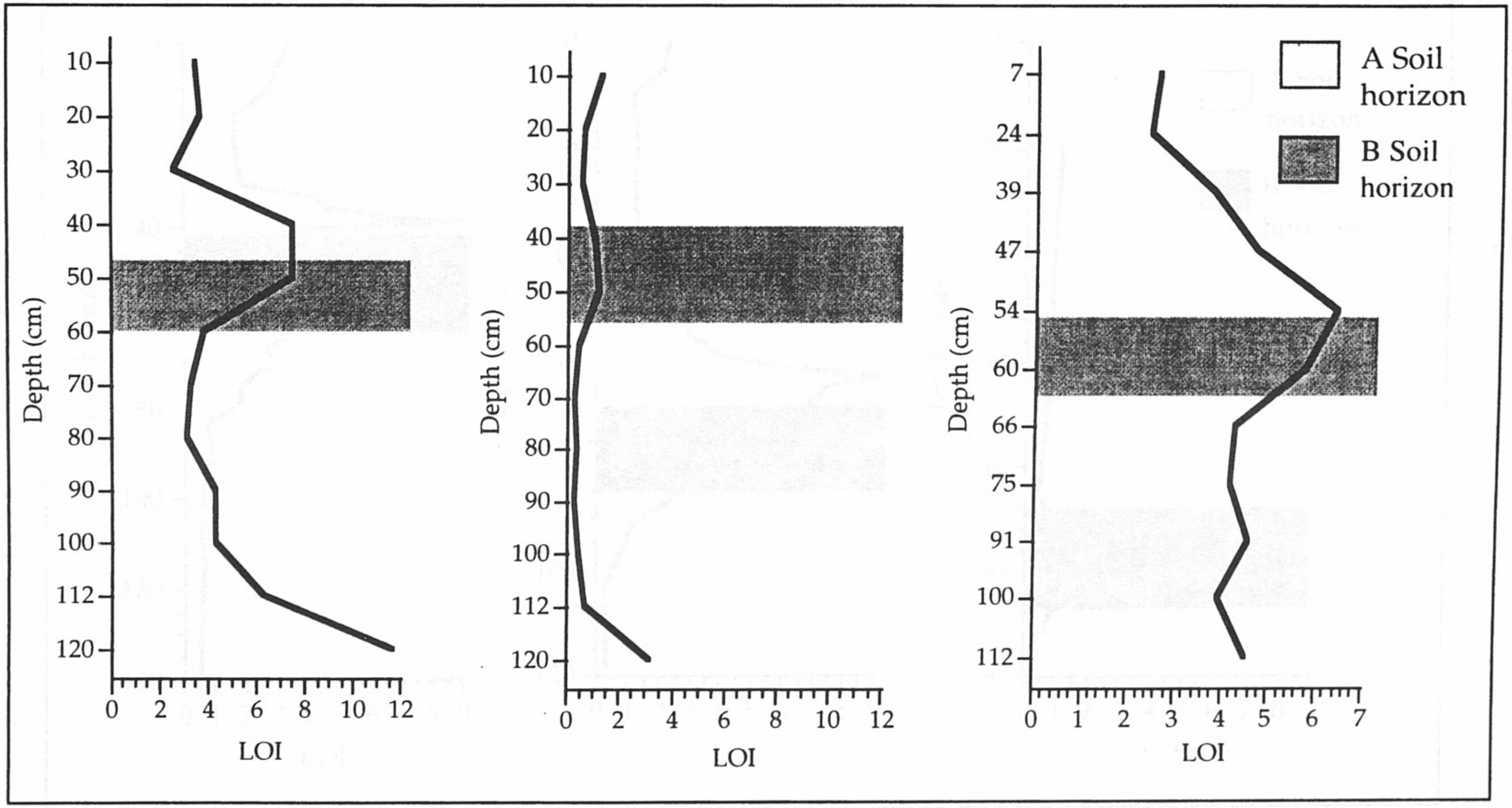

Figure 13. LOI analyses results for three sample sets taken from the Moultroup fan.

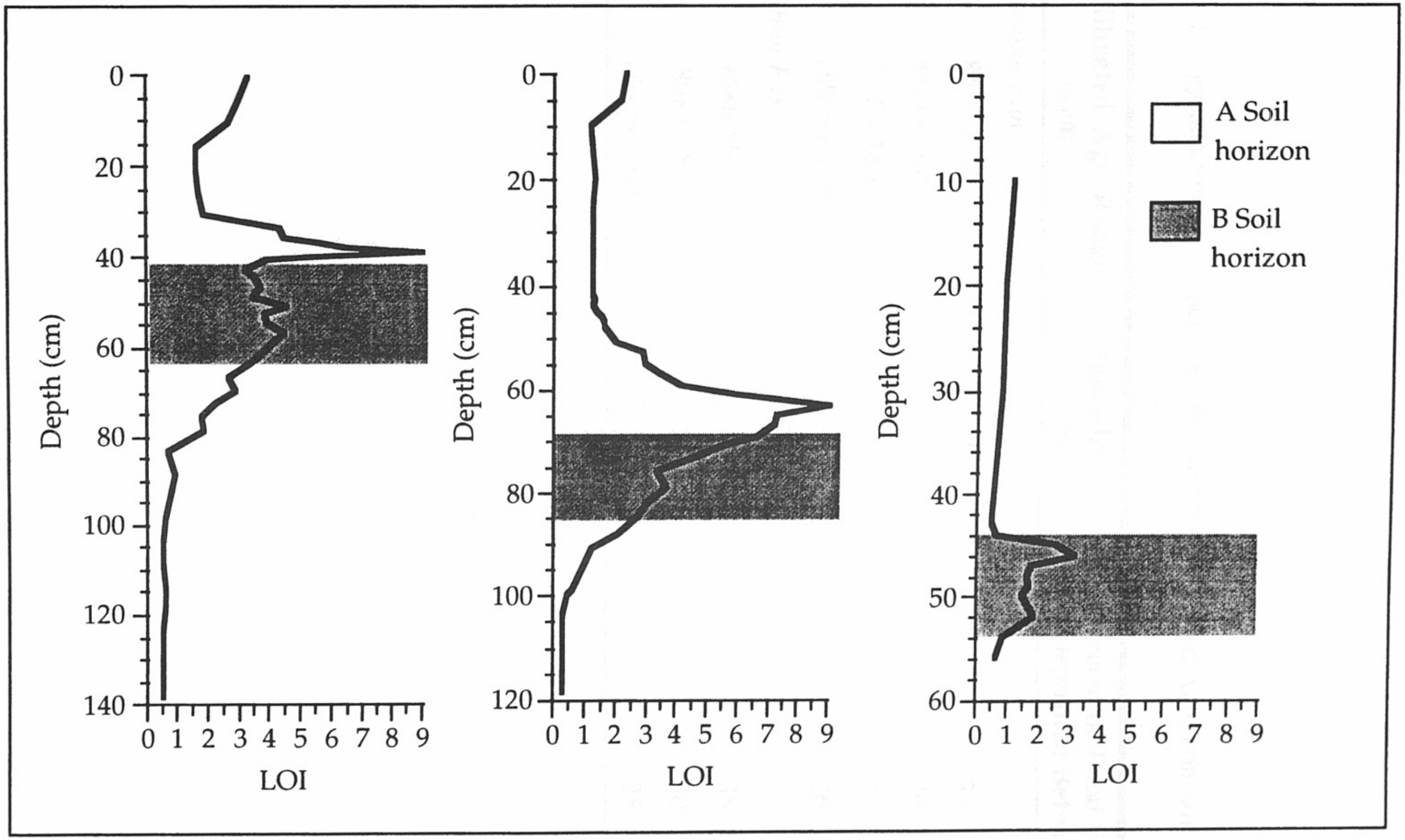

Figure 14. LOI anlyses results for three sample sets collected from the Audubon fan.

Table 1. Aggradation rates calculated for the Moultroup and Audubon fans over the last 9,500 years.

Calibrated Age Range (years)	Aggradation Rate ($m^3\ y^{-1}$)	Percent of Total Fan Volume Deposited Between Dates
Moultroup Fan		
8555-8126	3.7	33
8126-3968	0.1	30
3968-180	0.3	11
180-present	7.0	26
Audubon Fan		
9486-8981	1.1	35
8981-180	0.1	40
180-present	2.3	25

Table 2. Radiocarbon analysis results of samples taken from the Moultroup and Audubon fans.

Sample	Laboratory ID	Material Dated	Depth Below Fan Surface (m)	^{14}C Date (yrs)	Calibrated Date (yrs)*	1σ Range (yrs)	2σ Range (yrs)
Moultroup fan							
Af-45	GX-20276	wood	4.0	7835±105	8555	8713-8430	8981-8375
Cf-2	GX-20058	wood	2.1	7360±95	8126	8240-7998	8336-7934
Af-29	CAMS #16585	charcoal	0.9	3650±60	3968-3930	4079-3874	4140-3739
Af-17	CAMS #16584	charcoal	0.6	100±50	61-0	264-0	278-0
Audubon fan							
Df-1	CAMS #20901	wood	2.5	8530±100	9486	9531-9436	9819-9275
Df-8	CAMS #20963	charcoal	1.3	8060±60	8981	8993-8764	9194-8662
Df-2	CAMS #20900	charcoal	0.4	120±60	248-0	272-0	290-0

*Calibrated ages were calculated using the CALIB 3.0 calibration program (Stuiver and Reimer, 1993).

Table 3. Moultroup trench 1 stratum descriptions and interpretations.

Stratum	Description	Interpretation
A	Dark, organic-rich soil. Rootlets and worm burrows.	Topsoil in plowzone, post-settlement deposition.
B	Dark olive-brown sand and silt with rounded pebbles from 0.5 to 4 cm, average pebble size is 1 cm. Rootlets.	Plowzone, post-settlement deposition.
C	Olive brown sand and silt with gravel lens. Pebbles in gravel range from 0.5 to 3 cm, average pebble size is 1 cm. Red stained bands and lens of organic material within black bands.	Paleosol cross-cuts, pre-settlement deposition.
D	Gravel and sand with rounded clasts 1 to 6 cm. Stratum grades upwards from gravel to sand. Reddish-brown bands in upper 20 cm, organic matter in lens in upper 20 cm. Same depositional unit as stratum K in trench 4.	Hyperconcentrated flow deposit.
E	Brown sand and silt with thin organic lens. Rootlets and small gravel lens.	Streamflow deposition.
F	Gravel and sand with rounded pebbles to 3 cm. Red staining throughout, areas of clast cementation.	Streamflow deposition.
G	Olive gray gravel and sand, rounded pebbles to 2 cm. Red bands throughout, organic lens and rootlets.	Streamflow deposition.

Table 4. Moultroup pit 2 stratum descriptions and interpretations.

Stratum	Description	Interpretation
A	Dark, organic-rich soil with rootlets.	Topsoil in plowzone, post-settlement deposition.
B	Silt and sand with rounded pebbles to 2 cm. Rootlets.	Pre-settlement overbank deposits, probably disturbed by plowing.
C	Rounded to well-rounded gravel with tan sand. Cobbles up to 20 cm. Water present at 3.4 m.	Huntington River terrace gravel, pre-settlement deposition.
D	Blue gray silt and clay.	Glaciolacustrine sediment.

Table 5. Moultroup pit 3 stratum descriptions and interpretations.

Stratum	Description	Interpretation
A	Dark, organic-rich soil. Rootlets and worm burrows.	Topsoil in plowzone, post-settlement deposition.
B	Dark gray sand and silt with 1 to 2 cm pebbles. Rootlets and organic matter.	Post-settlement fan deposition, depth of plowzone.
C	Dark gray fine sand and silt with few 1 to 2 cm pebbles. Rootlets and disseminated organic material.	Distal fan deposits, post-settlement deposition.
D	Light gray sand and silt. Dark red and brown staining in sandier lens. Fewer rootlets and less organic matter than stratum B.	Distal fan deposits, post-settlement deposition.
E	Green-gray fine sand and silt with disseminated organic matter. Contains two thin (1 cm and 1.5 cm) black layers of silty organic matter.	Distal fan deposits, pre-settlement deposition.
F	Green-gray fine sand and silt with disseminated organic matter. Contains 2 thin (1 and 1.5 cm) black layers of silty organic matter.	Distal fan deposits, pre-settlement deposition.
G	Dark gray-green sand and silt with well-rounded clasts up to 6 cm. Matrix coarsens upwards and contains organic matter. Black layer (2 cm) of silty organic matter.	Distal fan deposits, pre-settlement deposition.
H	Light brown silt and sand with dark brown mottling.	Distal fan deposits, pre-settlement deposition. Mottling suggests seasonal saturation.
J	Gray silt with occasional pebbles to 1.0 cm and rootlets. 1 cm black layer of silt and organic matter at base of stratum. Water flowing out of pit wall at base.	Distal fan deposits, pre-settlement deposition.

Table 6. Moultroup trench 4 stratum descriptions and interpretations.

Stratum	Description	Interpretation
A	Dark, organic-rich soil. Rootlets and worm burrows.	Topsoil in plowzone, post-settlement deposition.
B	Gray-brown sand and silt with rootlets. Rounded pebbles to 2 cm, one clast 5 cm.	Plowzone, post-settlement deposition.
C	Tan sand and silt with a yellow-brown gravel lens. Lens is primarily rounded pebbles to 2 cm and sand. Some scattered clasts to 5 cm.	Streamflow deposit, post-settlement deposition.
D	Dark yellow-orange sand and silt with pebbles from 1 to 3 cm.	Streamflow deposit, post-settlement deposition.
E	Very dark grayish-brown sand and silt that turns to olive-brown below abundant bands of organic matter.	Streamflow deposit, pre-settlement deposition.
F	Yellow-brown gravel and sand with sub-angular clasts from 3 to 6 cm. Clasts imbricated in bottom half of the stratum.	Streamflow deposit, pre-settlement deposition.
G	Dark yellow-brown gravel with sand and silt. Pebbles to 3 cm, average pebble size 1.5 cm.	Possibly hyperconcentrated flow. Pre-settlement deposition.
H	Yellow-brown gravel with 1 to 3 cm clasts grading up to dark brown sand with some pebbles to 1.5 cm.	Streamflow deposit, pre-settlement deposition.
J	Dark yellow-brown gravel with sub-angular to rounded clasts from 2 to 6 cm (average: 3 cm) and sand. Faint imbrication of clasts at base of stratum.	Streamflow deposit, pre-settlement deposition.

K	Gravel with dark grayish-brown sand. Largest cobble 35 cm, average cobble size 7 cm. Larger cobbles >4 cm are sub-angular, <4 cm are rounded.	Hyperconcentrated flow deposit, pre-settlement deposition.
L	Distinct black layer averaging 10 cm thick with an orange layer averaging 12 cm thickness below. Charcoal concentrated in and above these bands.	Buried soil horizon. Developed over at least 1000 years. Pre-settlement deposition.
M	Yellowish-brown gravel with sand and silt. Rounded pebbles from 1 to 4 cm. Imbrication of pebbles less than 2 cm.	Streamflow deposit, pre-settlement deposition.
N	Gray-brown sand grading upwards into fine sand and silt. Red patches of staining and bands of organic matter.	Streamflow deposit. pre-settlement deposition.
O	Red-brown gravel. Red-stained sub-rounded pebbles from 1 to 5 cm. Red-brown coarse sand.	Streamflow deposit, pre-settlement deposition.

Table 7. Moultroup pit 5 stratum descriptions and interpretations.

Stratum	Description	Interpretation
A	Dark brown sand and silt. Rootlets and burrows.	Plowzone, post-settlement fan deposition.
B	Dark brown sand and silt with few pebbles to 1 cm.	Contains plowzone, post-settlement deposition.
C	Clast supported gravel, clasts up to 8 cm. Black in upper 24 cm, red brown in lower 20 cm.	Streamflow deposit. Contains A and B horizon of paleosol, pre-settlement deposition.
D	Blue gray sand and silt.	Streamflow deposit, pre-settlement deposition.
E	Clast supported gravel, with clasts to 12 cm.	Streamflow deposit, pre-settlement deposition.

Chapter 3

Results

Data from the Moultroup fan are presented in section 3.1. Audubon fan study results are presented in section 3.2. Discussion of the data from both fans will follow in Chapter 4.

3.1 The Moultroup Fan

The Moultroup fan is a small (1,300 m^2), but distinct fan located on the western side of the Huntington Valley (Figures 4 and 6). The fan was designated the Moultroup fan for the owner of the property, Henry Moultroup. The fan is presently cleared of woody vegetation, and the fan and adjacent field are used as a cow pasture. At the toe of the fan, in an area of tall grass and pitted soil, is a seasonally wet zone. Mr. Moultroup provided information about the historic use of his property, including disturbance of the fan to less than a meter depth along its southeastern edge where a ditch for a water line was dug. According to Mr. Moultroup, the hillslopes above the fan, now forested, were cleared for grazing until the late 1940's.

Two ephemeral streambeds join just above the apex of the fan and channel water and sediment to the fan apex. One of these streams is fed by a bedrock spring, and has an average gradient of 25°. The second stream is shallow and has an average gradient of 23°. A small linear depression, littered with leaves and woody debris, extends three meters down-fan and is located at the edge of the fan abutting the hillslope (Figure 6). During storm events, discharge temporarily flows through this channel, filtering into the fan surface about half-way down the length of the fan where the streambed becomes indistinct. A glaciolacustrine deposit is located north of the Moultroup fan deposit, partly within the drainage area of the fan (Figure 4). The glaciolacustrine sediment was deposited 13-12 ^{14}C ky BP as Lake Vermont waters receded from the valley (Figure 2).

3.1.1 Geographic Setting

The Moultroup fan contains approximately 4,600 m^3 of sediment and has an average surface slope of 7° (Figures 11 and 15). The height of the fan at the apex is 6.8 m. The fan drainage basin is approximately 0.27 km^2, and contains the two ephemeral streams which feed the fan. The relief ratio, which is the maximum relief divided by the maximum length of the catchment is 0.33.

The catchment contains three sources of sediment: 1) bedrock 2) glacial till and 3) glaciolacustrine deposits. The primary ephemeral channel is armored with boulders (>60 cm) of chlorite schist, although only one boulder this large was found in the fan. The majority of the sediment in the fan was eroded from the glaciolacustrine deposits and the thin till cover which mantle the hillslopes. The majority of clasts found in the fan were well-rounded, of varying lithologies, and in various stages of weathering, not angular clasts of chlorite schist as would be expected if they had been derived from a near-by bedrock source. Approximately one meter of overbank deposits underlies the fan deposit, and is underlain by cobble gravel deposited by the Huntington River (Figure 11).

3.1.2 Trenching

Pits 2, 3 and 5 were reconnaissance pits, dug to determine the stratigraphy below the fan (Figure 8; Tables 4, 5 and 7). The pits were rapidly excavated straight down to a maximum depth of 4 meters from fan surface, in order to view the stratigraphy before the water table rose. Trenches 1 and 4 were excavated so that stratigraphic units and soil horizons within the trenches could be carefully mapped (Figures 7 and 9; Tables 3 and 6). A mud pump was used to pump standing water from trench 4. Figure 16 is a photograph of trench 4, with units and soil horizons outlined with colored flags. Stratigraphic profiles for trenches 1 and 4 in the Moultroup fan can be seen in Figures 7 and 9, respectively.

3.1.3 Stratigraphy

Exposures in the Moultroup fan trench walls show a complex internal stratigraphy (Figures 7 and 9; Tables 3 and 6). Distinct sedimentary structures are absent in the fan deposit, although in one area weak clast imbrication was noted. Strata identified as channel fill (Units H, and J, Figure 9) based on geometry and texture have erosional contacts. These deposits are clast supported and have high angle, erosional contacts with adjacent units. Assuming the top of the channel fill units was the fan surface at the time of stream incision, the channels eroded approximately 0.3 m into the fan.

In the Moultroup fan, the largest clasts are deposited at the at the apex of the fan, and the deposit fines towards the fan toe. A distally fining-out stratigraphy is typical for fan deposits (Bull, 1964). Boundaries between units are sharp in some areas and faint in others. The sharp contacts are more easily identified due to distinct differences in the sediment sizes of adjacent units. Approximately 2 m below the surface of the fan, a highly hydrologically conductive gravel unit marks the base of a perched water table, underlain by a unit of fine silt and sand which acts as an aquatard. Water from the perched water table emerges at the intersection of the fan and the terrace in a seasonally wet area. The location of the perched water table limited the depth to which trenches 1 and 4 could be excavated and examined. Organic matter in the form of wood, charcoal, and organic-rich lenses was abundant within the fan.

Organic-rich lenses are very fine-grained, black deposits, which combustion indicates contain >15% organic carbon (Figure 17). Organic lenses may represent decomposed leaf mats. A buried soil horizon is clearly visible in the upper half of trench 4, with distinguishable A and B horizons (Figures 9 and 18). The buried soil arcs through the profile of trench 4, and was present in every trench excavated. A lower, possible buried soil horizon in the lower half of trench 4 contains "stringers" (discontinuous undulating bands of dark colored sediment rich in organic material); (Figure 17). The stringers often are surrounded by a margin of olive green to gray fine sediment 4 to 5 cm thick. Some wood samples were found in trench 1 clustered in a gravel unit located 2 meters below the mid-fan surface. Pieces of wood were also found in the fan at depths of 4 to 5 meters below the mid-fan surface in trench 4. These were large, well-preserved chunks of wood identified by a University of Vermont forestry professor, Dr. Peter Hannah, as hardwood, possibly maple. Charcoal was found throughout the fan, but was concentrated in and above the buried soil horizon identified in trench 4.

3.1.4 Grain Size Analysis

The Moultroup fan is composed of interbedded units of sand and gravel. Units in the exposed walls of trench 4 were defined based on clast size and distribution, matrix grain size, and estimated matrix percentage. Grain size analyses on 12 samples showed that clay content ranged from 0.3% to 10.7% with an average of 3.0%. Silt content ranged from 6.9% to 26.7% with an average of 17.7%. Sand content ranged from 68.4% to 92.2% with an average of 79.3% (Table 8 and Figure 19). Strata G, H and N are clast supported with fine to medium sand, silt, and clay (<0.9%) matrices. The average pebble size for strata G, H and N is 1.5 cm. Strata J and M are clast-supported units with matrices of sand, silt and clay (<3%). Clasts range from 1 to 6 cm in these units. Units C and E both lack any clasts. Figure 20 shows the percent coarser plots (-1.5 to 10 ¢) of samples from strata within the Moultroup trench 4. A detailed description of the units in trench 4 is located in Table 6.

3.1.5 Loss On Ignition

Loss on ignition was performed in order to confirm the presence of the buried soil, in particular, the organic rich A-horizon. Figure 21 shows the locations of the three vertical sample sets taken for LOI with relative LOI curves, and Figure 13 is a graphical presentation of the LOI results. LOI is low (0.2 to 0.5%) where no soil horizon was identified in the field, and increases (1.1 to 1.4%) when the sample taken from the buried soil horizon. A small organic lens was analyzed by LOI and lost 3.1% of its weight on ignition. Appendix B contains the data from the LOI from the three sample sets.

3.1.6 Radiocarbon Analysis

Samples from the Moultroup fan were dated by ^{14}C analysis (Figure 7 and 9, Table 2). Sample Af-45 (Figure 9), a sample of wood and the lowest sample obtained from the base of the fan deposit (4.0 meters below fan surface), was dated at 7,835±105 (GX-20276) ^{14}C years (1σ calibrated age range 8,713-8,430 ybp). Sample Cf-2 (Figure 7), also a wood sample, was found 2.1 m below the fan surface and showed evidence of charring (an uncharred portion of the sample was dated); it had a date of 7,360±95 (GX-20058) ^{14}C years (1σ calibrated age range 8,240-7,998 ybp). A sample of charcoal (Af-

20058) ^{14}C years (1σ calibrated age range 8,240-7,998 ybp). A sample of charcoal (Af-29) obtained from below the soil horizon (0.9 meters below fan surface; Figure 9) was dated at 3,650±60 (CAMS# 16585) ^{14}C years (1σ calibrated age range 4,079-3,874 ybp). The youngest sample dated from the Moultroup fan, Af-17, was collected just above the buried soil horizon, 0.6 meters below fan surface (Figure 9). Sample Af-17, a piece of charcoal, was dated at 100±50 (CAMS #16584) ^{14}C years (1σ calibrated age range 264-0 ybp).

3.1.7 Aggradation Rates for the Moultroup Fan

Using the method of like triangles described earlier, aggradation rates were calculated for the Moultroup fan. For dates with more than one calibrated age intercept, the oldest intercept value was used to calculate minimum fan aggradation rates. A radiocarbon dated sample taken from the base of the fan suggests that fan aggradation began almost 8,600 calibrated ^{14}C years ago. Other radiocarbon dated samples of wood and charcoal within the fans show that aggradation rates varied during the fan's existence (Figure 22, Table 1). Fan aggradation rates calculated for the Moultroup fan show active sedimentation through the early Holocene, when pollen data suggest the climate was warmer and dryer (Delcourt and Delcourt, 1984). Aggradation rates are lower in what has been interpreted as the colder and wetter late Holocene (Delcourt and Delcourt, 1984). Aggradation rates were high during the early Holocene (8,555-8,126 ybp; 3.7 $m^3 y^{-1}$), lower (0.1 m^3y^{-1}) for the next 4 ky and slightly higher (0.3 m^3y^{-1}) during for the following 4 ky. During the last 180 years, coinciding with the time of colonial settlement and land use changes in Vermont, the fan aggradation rate increased to 7.0 m^3y^{-1} (Figure 22, Table 1).

Combustion of fossil fuels since ~1850 has contaminated the atmosphere with ^{14}C-free CO_2, resulting in a negative departure from the long-term average of ^{14}C in the atmosphere (Bradley, 1990). This variation of ^{14}C in the atmosphere can cause difficulty in interpreting historical radiocarbon dates. The rate of aggradation, 7.0 $m^3\ y^{-1}$, of the historic sediment on the Moultroup fan was calculated using a value of 180 years. The calibrated age range for the radiocarbon date of 100±50 (CAMS #16584) is 61-0 yrs, and the 1σ calibrated age range is 264-0 yrs. Calculating an aggradation rate for the historic sediments on the fan using an age of 61 yrs misrepresents the rate of aggradation for the period of historic land use. The town of Huntington was settled in the 1780's, and widespread deforestation was occurring by 1810 (P. Thomas, pers. comm.). By 1880, 80% of Vermont was cleared of forest cover (Severson, 1991). Calculation of fan aggradation using a date of 1810, gives a rate of 7.0 $m^3\ y^{-1}$, a 70 fold increase in the rate of aggradation from the previous rate (0.1 $m^3\ y^{-1}$).

3.2 The Audubon Fan

The Audubon fan is located on property owned by the Green Mountain Audubon Nature Center (Figure 23). The 131 acre property was originally owned by the Stevens family who kept it cleared for pasture land until the mid-1940's (Beal et al., 1974). When the property was sold in the 1940's, the new owner allowed natural regrowth of forest in all open pastures. The Audubon Center acquired the land in 1964, and in the next 5 years, an additional 78 acres to the north. The Audubon Center also allows natural cover to grow (Beal et al., 1974).

3.2.1 Geographic Setting

The Audubon fan covers approximately 1,800 m^3, has an average surface slope of 8° and a radius of 50 meters (Figures 5 and 23). The height of the fan at the apex is 4.0 meters. The surface of the fan is covered with vegetation, mainly grass and some shrubs. The apex of the fan is choked with large woody debris, and shrubs. The fan is currently being entrenched by the stream that feeds it. Figures 4 and 5 show a dirt road that crosses the drainage of the fan. Just below the road is a culvert that drains the fan's watershed under the road to the fan apex. The culvert also collects water that runs off the road to a ditch along the side of the road. The addition of the road and culvert may have increased the size of the fan's drainage basin slightly and increased incision into the fan, but because they are recent additions, have probably only marginally affected the sediment transfer in the fan-drainage system.

The fan drainage basin is approximately 0.19 km^2, and contains the single ephemeral stream which feeds the fan. The relief ratio, which is the maximum relief divided by the maximum length of the catchment is 0.1. A single stream discharges onto the fan; this stream has an average gradient of 11° (Figure 5).

The catchment contains one primary source of sediment, glaciolacustrine sand, deposited during the existence and recession of Lake Vermont from the valley. The ephemeral streambed is littered with leaves and small (<0.5 m) pieces of woody debris. The drainage is forested, comprised mainly of sugar maple, red oak and pine trees. There are no clasts visible on the drainage basin floor.

3.2.2 Stratigraphy

The Audubon fan trench revealed a very simple stratigraphy. The most distinct feature visible in the trench walls was a buried soil horizon that extended the length of the trench (Figures 10 and 24). A small gravel lens was identified in the lower portion of the trench wall and few organic samples were found suitable for radiocarbon dating.

Although presumed to be present because of the size of the deposit and the dated samples, no contacts between strata could be identified, due to the homogeneous nature of the sediment in the fan. The walls of the trench were a single color, except where the soil horizon or organic deposits were present, and where the sediment was darkened because of moisture. This homogeneity implies a single source of sediment for the fan.

3.2.3 Grain Size Analysis

Samples were collected for grain size analysis at uniform intervals. Eight samples were collected and analyzed for clay and silt, sand, and gravel content. The results of the analyses are presented in Table 9 and Figure 19, a ternary plot of clay, silt and sand percentages. Figure 20 is a percent coarser plot of these samples. Using Folk's classification (Folk, 1980) of grain sizes, the samples had between 1.99% and 7.34% very coarse sand and larger grains, with an average of 3.9%. The samples contained between 66.6% and 78.3% sand, with an average sand content of 74.0%. Silt content ranged from 16.4% to 22.0% with an average of 18.2%. Clay content in the samples was between 5.0% and 12.8%, with an average of 7.8% (Table 9, Figure 19).

3.2.4 Loss On Ignition

LOI was measured in order to confirm the presence of a buried soil horizon in the Audubon fan (Figures 10 and 14). In the Audubon fan, LOI is low (0.1-3.0%) where no soil horizon is present, and increases (3.0-8.6%) in samples taken from the buried soil horizon. Appendix C includes the data for the LOI from the three sample sets at the Audubon fan.

3.2.5 Radiocarbon Analysis

Three samples from the Audubon fan were radiocarbon dated (Figure 10, Table 2). Sample DF-1 (Figure 25), a sample of wood and the lowest sample obtained from the fan deposit (2.5 meters below fan surface) was dated at 8,530±100 (CAMS# 20901) ^{14}C years (1σ calibrated age range 9,531-9,436 ybp). Sample DF-8, a charcoal sample found 1.3 meters below the fan surface had a date of 8,060±60 (CAMS# 20963) ^{14}C years (1σ calibrated age range 8,993-8,764 ybp). A sample of charcoal (DF-2) obtained from above the soil horizon (0.4 meters below fan surface) was dated at 120±60 ^{14}C years (CAMS# 20900) ^{14}C years (1σ calibrated age range 272-0 ybp).

3.2.6 Aggradation Rates for the Audubon Fan

Using the method of like triangles described earlier, aggradation rates were calculated for the Audubon fan (Table 1, Figure 26). The aggradation rate on the Audubon fan for the early Holocene was 1.1 m^3y^{-1} (9,500 ybp) (Figure 26). From 8,981 ybp to 248 ybp the aggradation rate dropped to 0.1 m^3y^{-1}. During the period of historic settlement in Vermont, aggradation on the Audubon fan increased to 2.3 $m^3 y^{-1}$ (180 ybp to present).

Figure 15. Photograph of the Moultroup fan. Dashed line indicates toe of fan. Trees behind fan show scale.

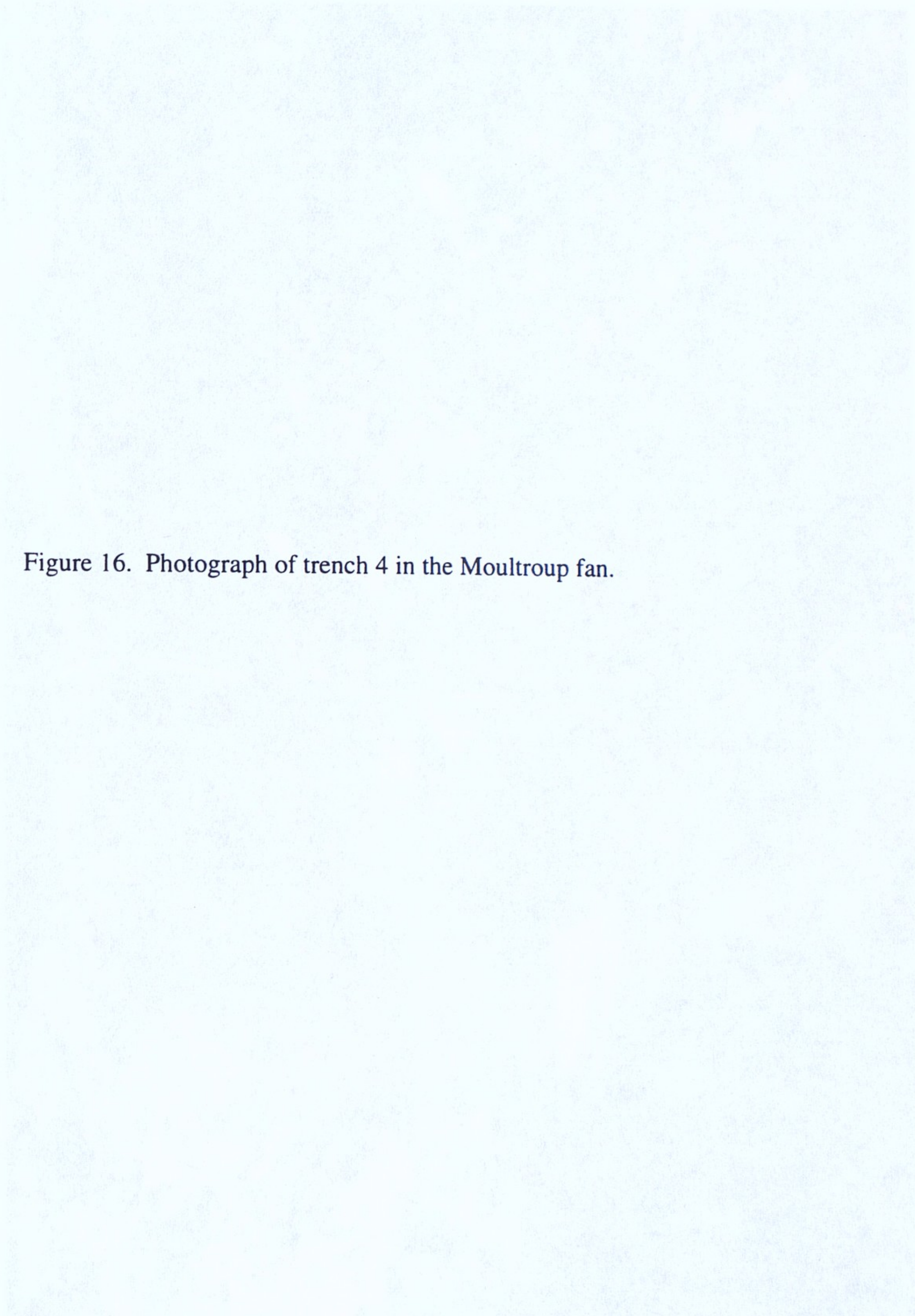

Figure 16. Photograph of trench 4 in the Moultroup fan.

Figure 17. Close-up of organic lenses in Moultroup fan trench 4 (Figure 9). The tape measure is 1 cm wide.

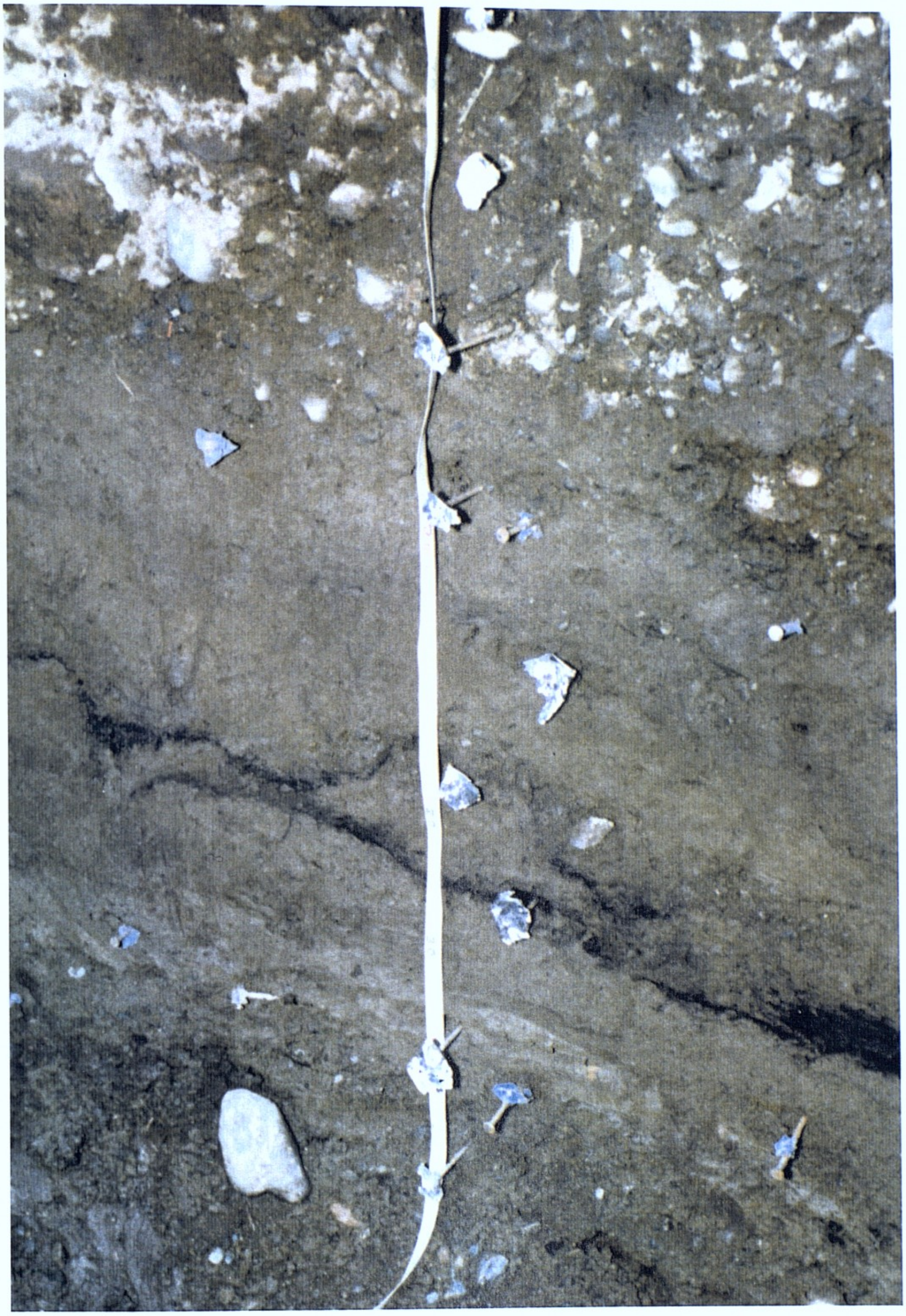

Figure 18. Close-up of soil horizon in Moultroup trench 4. The flag is pegged in the A-horizon, and the orange band below is the B-horizon. The flag on the nail is 2 cm long.

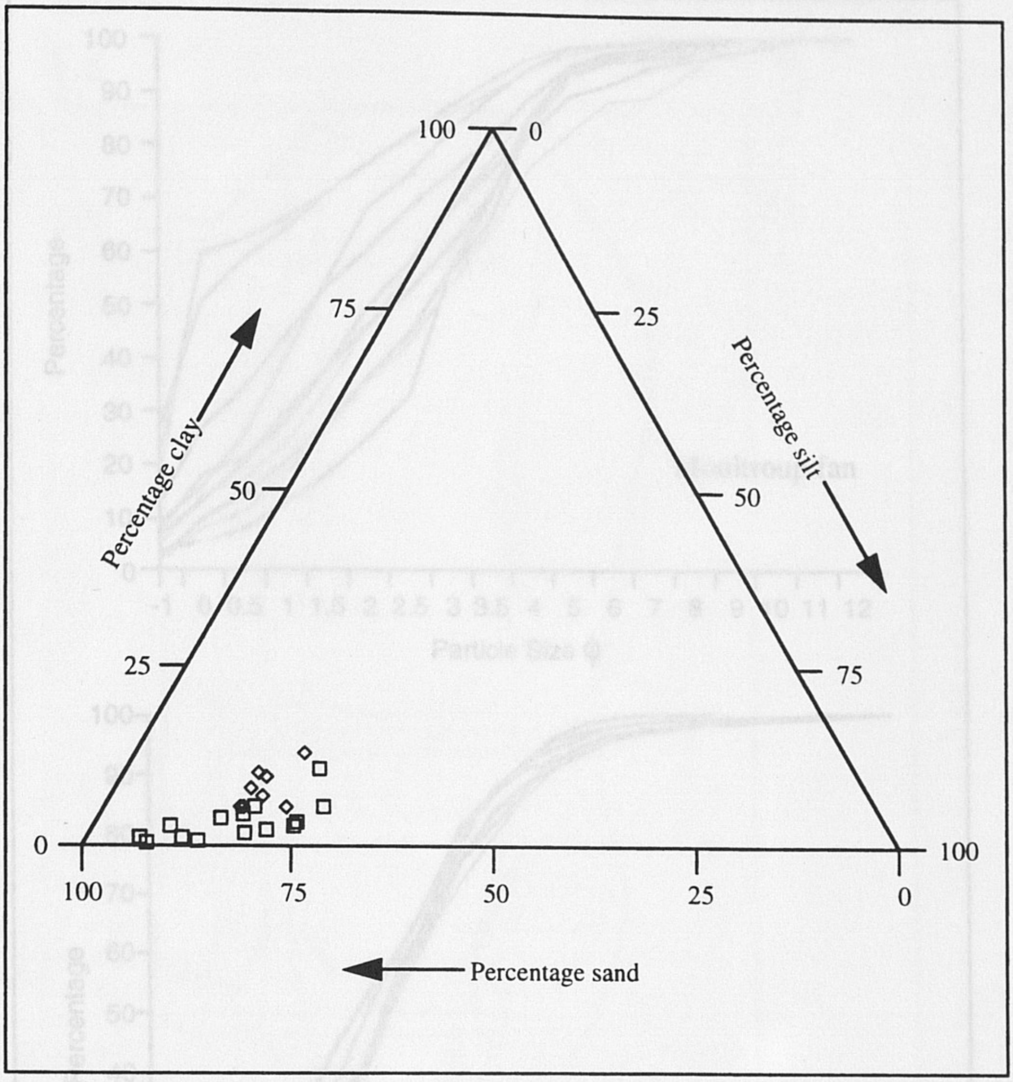

Figure 19. Ternary plot of sand, silt and clay percentages in grain size samples collected from the Moultroup and Audubon fans. The Audubon samples are represented by diamonds, Moultroup samples by squares.

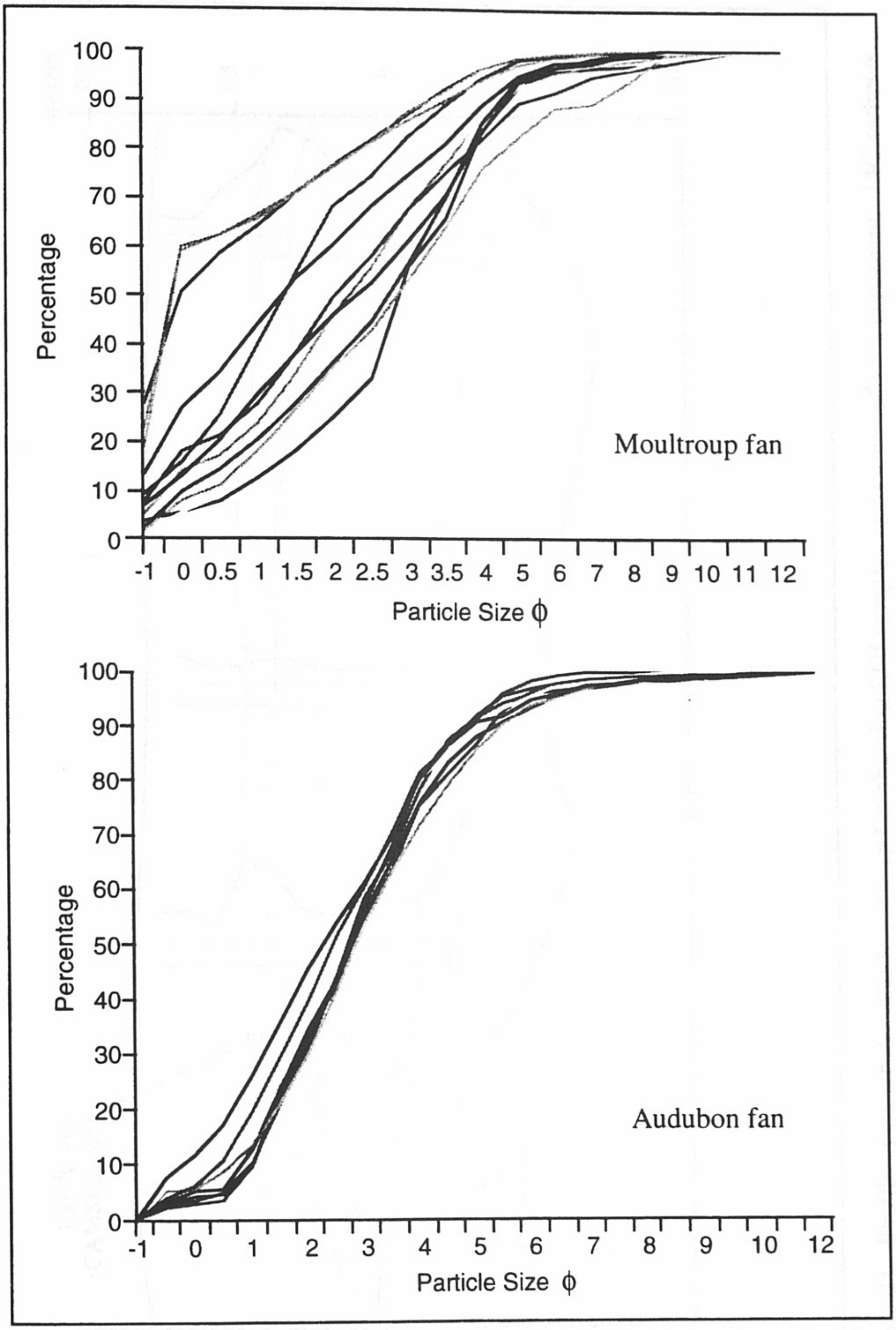

Figure 20. Representative grain size distributions of fine-grained fraction of Moultroup and Audubon fan samples.

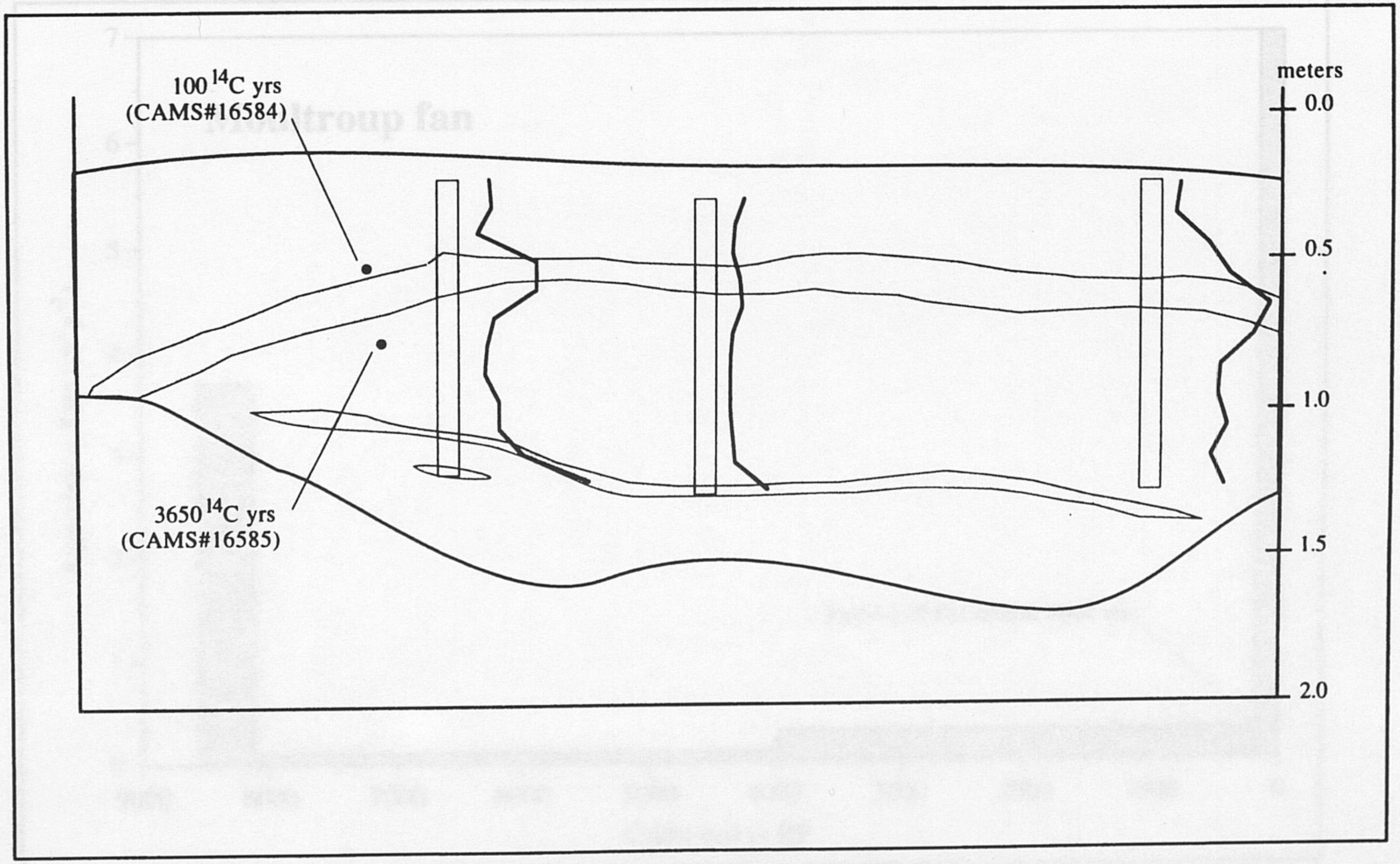

Figure 21. Profile of trench 4 in the Moultroup fan showing LOI samples and curves of carbon percent. 14C samples and dates are also shown.

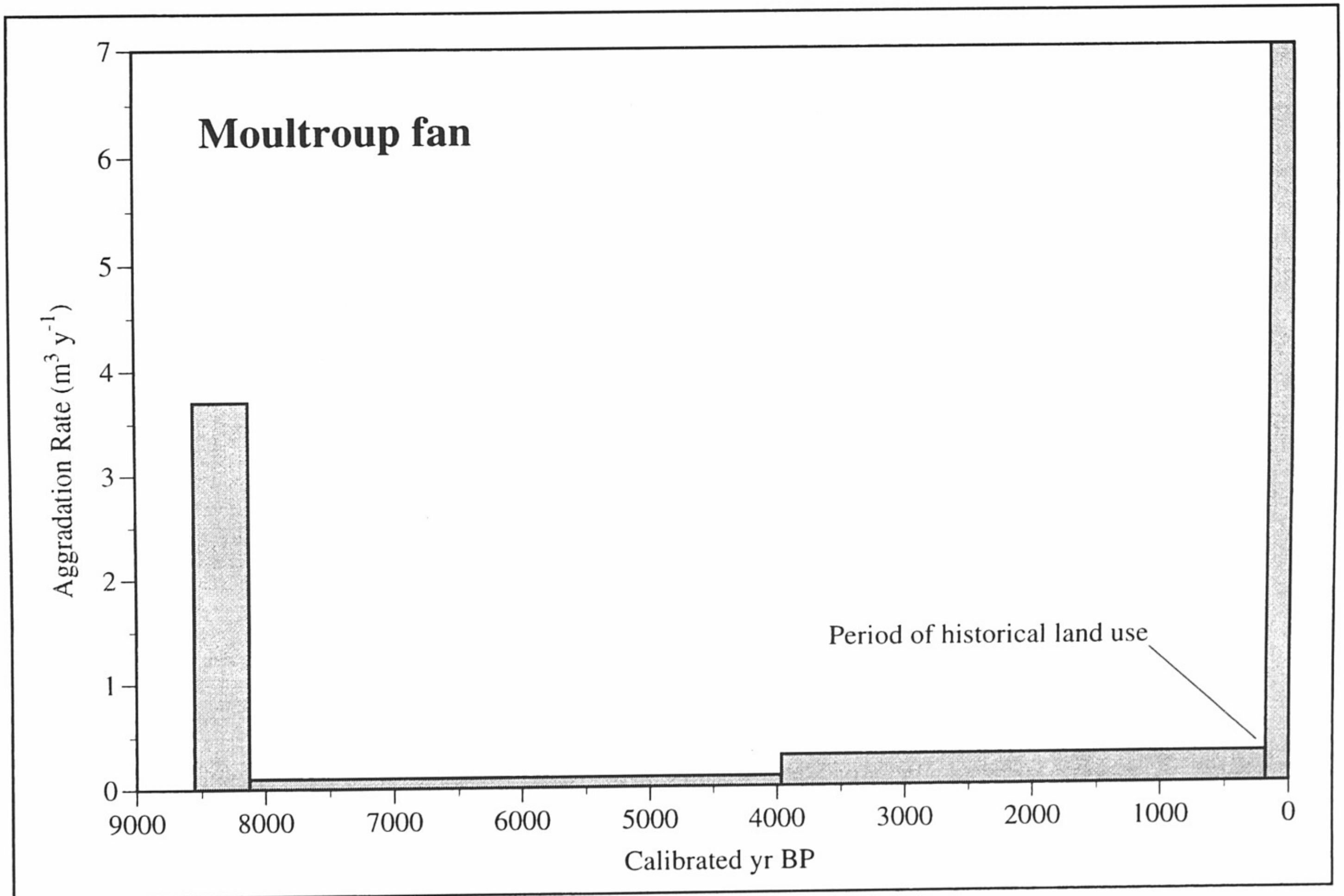

Figure 22. Rates of aggradation on the Moultroup fan over the last 8,600 calibrated years. The aggradation rate increased to 7.0 m^3 y^{-1} in the last 180 years, coinciding with the period of historical land use in the Huntington Valley.

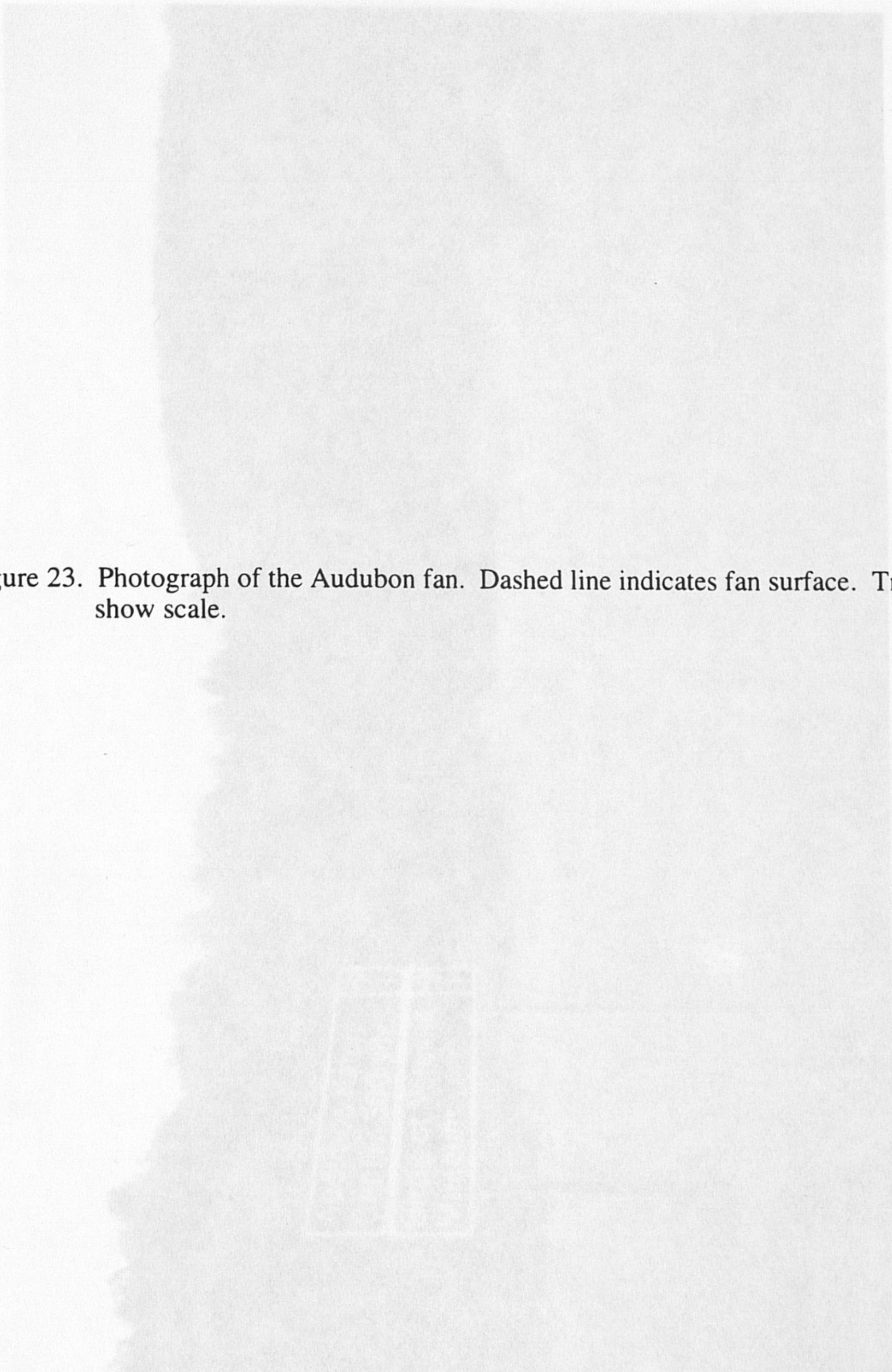

Figure 23. Photograph of the Audubon fan. Dashed line indicates fan surface. Trees show scale.


Audubon Nature
Center 300 yds.
Birds of Vermont
Museum
1

Figure 24. Photograph of trench A in Audubon fan. The gray and orange bands are the buried soil horizon. The gray band is the A-horizon, and the orange band is the B-horizon.

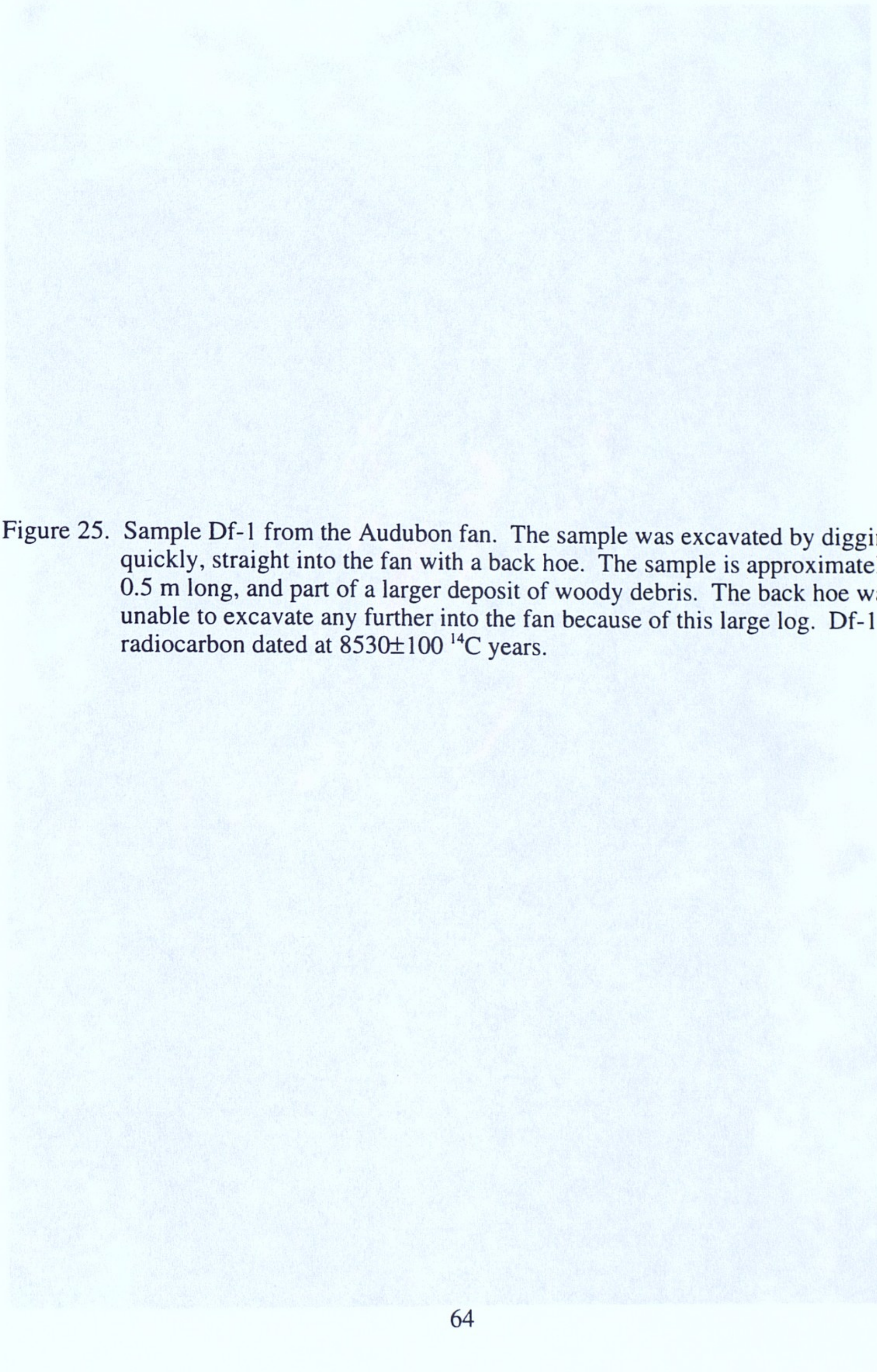

Figure 25. Sample Df-1 from the Audubon fan. The sample was excavated by digging quickly, straight into the fan with a back hoe. The sample is approximately 0.5 m long, and part of a larger deposit of woody debris. The back hoe was unable to excavate any further into the fan because of this large log. Df-1 was radiocarbon dated at 8530±100 ^{14}C years.

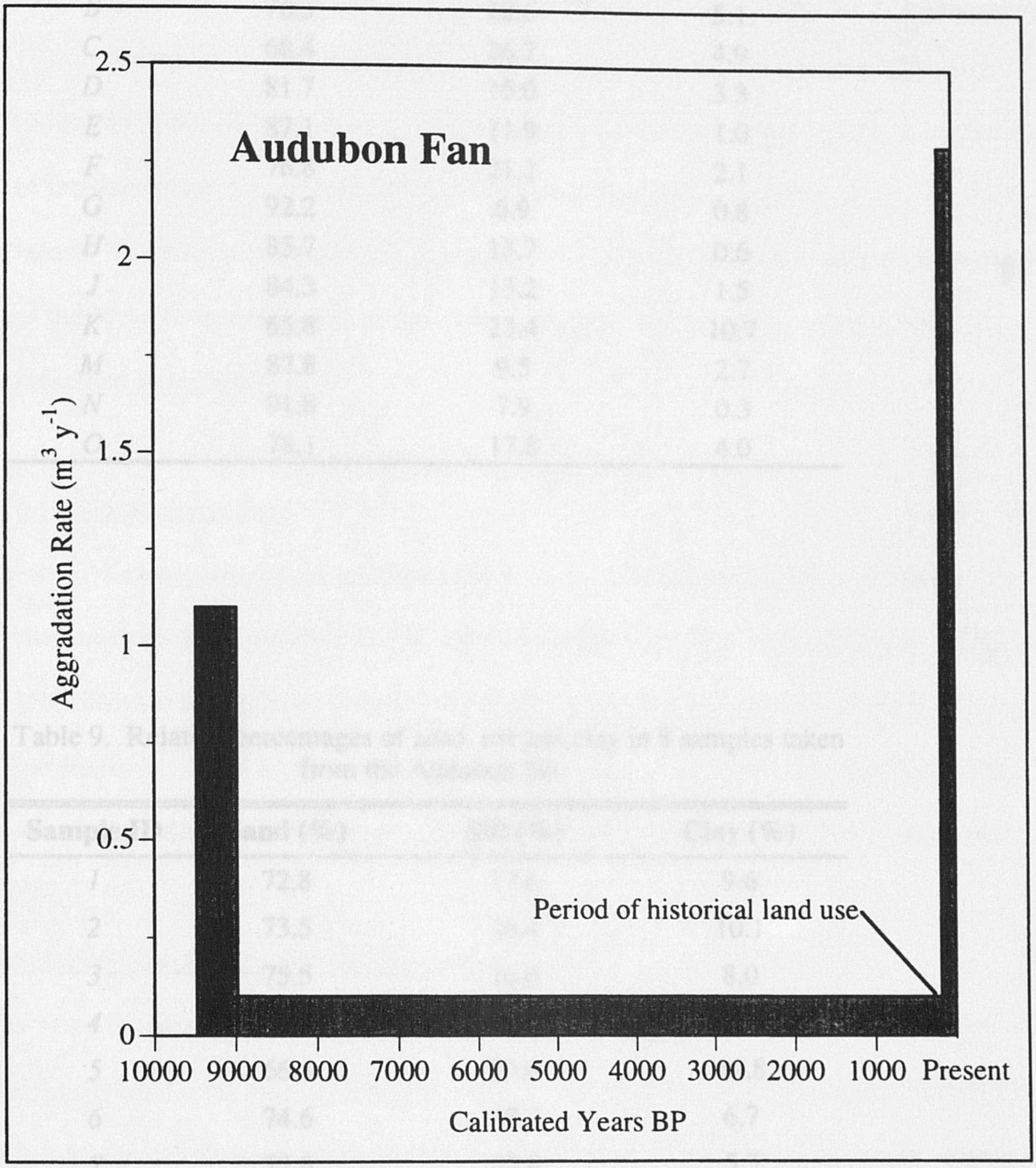

Figure 26. Rates of aggradation on the Audubon fan over the last 9,500 years. The highest agradation rate coincides with the onset of historical land use in northwestern Vermont.

Table 8. Relative percentages of sand, silt and clay in 15 units identified in trench 4, Moultroup fan.

Sample ID	Sand (%)	Silt (%)	Clay (%)
B	76.3	18.6	5.1
C	68.4	26.7	4.9
D	81.7	15.0	3.3
E	87.1	11.9	1.0
F	76.8	21.2	2.1
G	92.2	6.9	0.8
H	85.7	13.7	0.6
J	84.3	13.2	1.5
K	65.8	23.4	10.7
M	87.8	9.5	2.7
N	91.8	7.9	0.3
O	78.1	17.8	4.0

Table 9. Relative percentages of sand, silt and clay in 8 samples taken from the Audubon fan.

Sample ID	Sand (%)	Silt (%)	Clay (%)
1	72.8	17.6	9.6
2	73.5	16.4	10.1
3	75.5	16.6	8.0
4	78.4	16.4	5.2
5	66.3	20.6	12.8
6	74.6	18.7	6.7
7	72.6	22.0	5.3
8	77.7	17.3	5.0

Chapter 4

Discussion

A discussion of the geography, morphology, stratigraphy, sedimentology and formation of the Moultroup and Audubon fans follows in sections 4.1-4.6. A comparison of fan deposits in Vermont to fan deposits in the southern Appalachians, and to a study of fans in Howgill Fells, England is presented in section 4.7. The depositional chronology of the Moultroup and Audubon fans and a comparison with paleoclimate models is presented in section 4.8.

4.1 Geography of Fans

Fan deposits occur on older river terraces in the Huntington River Valley. The river terraces are above flood level and located adjacent to the valley hillsides, or large glaciolacustrine deposits. Fan formation occurs at either the junction of the hillslope and terrace, or on top of a younger terrace, at the base of an older terrace. Fan formation occurs regardless of forest cover, but fans are more readily identified on cleared land.

4.2 Fan Morphology and Recent Activity

Fan deposits in the Huntington Valley are subtle geomorphic features. The deposits tend to be small (<2,500 m^2) and fed by ephemeral streams from similarly small (<3,500 m^2) drainage basins. Fans vary in slope from 7-10°, and range in radius from less than 10 m to more than 80 m.

Fan formation occurs where sediment is carried downslope to a level or gently sloping surface, usually an old river terrace. The decrease in slope encountered when the stream reaches the terrace results in sediment deposition at that point. The deposited sediment builds over time, upward and outward, forming a fan-shaped deposit. When a stream encounters the decrease in slope at the fan apex, coarse sand, pebbles and clasts drop out of the flow. Further down-fan, continued decreasing slope, and therefore velocity, causes the same stream flow to deposit relatively finer-grained sediment on the fan surface. The finest sediments entrained by streamflow are deposited on the fan toe. Not all streams flow down the hillslope and across the fan. Field observations suggest that some streams infiltrate the fan surface, which causes sediment deposition at that point.

The drainage basins that feed the two studied fans are small (<3,500m^2), and contain one to three streams. The streams are ephemeral, one originates from a bedrock spring. The ephemeral stream beds are wide and shallow, and lack clear channel boundaries. One is lined with boulders, because there is a bedrock source nearby. Twigs, soil and leaves accumulate on and between the boulders. The streambeds with continuous flow are narrower and incise the hillslope.

Fan deposits in the Huntington Valley are currently experiencing little aggradation, although, my data show that fan aggradation occurred at an accelerated rate within the past 180 years. In July 1995, a day after a storm event in the Huntington Valley occurred, a layer of small pebbles (1-2 cm) and sand was observed at the apex of the Moultroup fan. The sediment appeared to be an over-bank deposit. It was created when the small stream, that runs along the hillslope and edge of the fan, exceeded channel capacity. Although a small amount of deposition occurred on the fan, the well-established vegetation on the fans suggests there has been little modification of the fan surface from aggradation in the recent past.

The Audubon fan is experiencing re-working of sediments from the upper portion of the fan. A stream fed to the fan apex through a culvert is dissecting the fan, moving sediment from the fan apex to mid-fan section, where the stream infiltrates into the fan surface. This fan-head trenching could eventually decrease the slope of the fan surface.

4.3 Fan Stratigraphy

The Moultroup fan stratigraphy reveals repeated episodes of Holocene fan aggradation. Episodes of fan aggradation are recognized by changes in sediment type and texture, and the presence of paleosols. In general, the composition of the strata in Huntington Valley fan deposits is dependent on the type of sediment supplied from the fan drainage basin. The Moultroup fan has three sediment sources: glacial till, glaciolacustrine deposits, and bedrock. The Audubon fan has two sediment sources: glacial till and glaciolacustrine deposits.

The Moultroup fan consists of alternating beds of gravel, sand, and silt that dip gently from the apex at a slope of between 3° and 9°, approximating the slope of the fan surface. Trench 1 revealed strata that decreased in thickness towards the toe of the fan. Two strata in trench 4 were identified as channel fills (Strata H and J, Figure 9) based on the U-shaped erosional contacts with adjacent strata and the presence of well sorted, slightly imbricated clasts. The height of the structures indicate the channel eroded 0.3 m into the fan surface, implying the calculated aggradation rates are a minimum. Fan trenching has been attributed to numerous factors, such as a decrease in sediment supply (Ryder, 1971), changes in stream flow velocity, and reaching a fan slope threshold (Weaver and Schumm, 1974). Erosional contacts were identified below other strata in the Moultroup fan, mostly the gravel-dominated beds. The large lens shape of the beds, prohibited accurate estimation of the amount of scour that took place when the beds were deposited.

Changes in sediment type in the Moultroup fan could be easily identified in the fan trenches and pits (Figures 7, 8 and 9). The strata alternated between sand and silt and gravel. Both types of strata, gravel or sand and silt, occurred in large deposits and small, lens-shaped deposits.

The sand and silt dominated strata showed no internal structure, except thin organic layers (Figures 8 and 9). The organic layers occurred in isolated lenses and in long thin "stringers". One large sand and silt bed (Strata E, Figures 9 and 17) has a layer of organic stringers that extends through the deposit. A pit dug into an active fan in Stowe, Vermont (latitude: 73°45'00", longitude: 44°25'45"), revealed leaf mats located 0.25-0.5 meters below the fan surface. The leaves were still intact and could be peeled apart. The organic stringers in the Huntington Valley fans could represent leaves that were buried by sand and silt. Whatever the organic material, the presence of such a layer suggests a period of subaerial exposure of the fan surface. The stringers could also represent the remains of a soil horizon, of which the B-horizon is no longer identifiable.

The gravel layers are imbricated in places, with the long axes of elongated pebbles aligned indicating down-fan stream flow. The gravel units are clast supported, and the clasts were moderately to well-sorted within sand matrixes. One large gravel bed, stratum K (Figures 9 and 27), had sections of imbrication of small pebbles (2-4 cm) at the base of the stratum. The clasts were rounded to well rounded and poorly sorted overall (2-35 cm). However, the unit had areas of like clast size, with some faint lateral and vertical grading. The textures observed in the gravel units indicate deposition by fluvial processes.

A well-developed buried soil, present in both the Audubon and Moultroup trenches, indicates a regional period of stability (Figures 9 and 10). Farming practices truncated the top of the soil horizon in the Moultroup fan (Figure 9). The soil formed over at least 1,000 years (M. Pavich, pers. comm.). A sample of charcoal, dated 100 ^{14}C ybp, was taken from 3 cm above the soil horizon and indicates the soil formed under the last pre-settlement forest to exist in this area. Another charcoal sample, taken from 8 cm below the buried soil, was dated at 3,650 ^{14}C. The ≥1,000 years estimated for soil formation and the proximity of the two radiocarbon dates, 3,500 years apart, indicate a period of stability on the fan surface.

Charcoal was also found throughout the fan deposits, with a concentration in and above the youngest soil horizon (Figure 9). In a study of semi-arid coniferous forests in Yellowstone National Park, Meyer et al., (1992) noted an increase in fan sedimentation after forest fires, which were indicated by increased amounts of charcoal in fan sediments. Concentrations of charcoal found in alluvial deposits along Allen Brook in Vermont have been attributed to slash and burn practices (P. Thomas, pers. comm.), when forest undergrowth was cut and hauled to piles which were then burned. The abundance of charcoal in and above the soil horizon is evidence that fires occurred. Because of the wet climate, naturally occurring forest fires are infrequent events in Vermont (D. Bergdahl, pers. comm.). The coincidence of the timing and methods of historical land use, abundant charcoal in the buried soil and overlying sediments, and the incidence of few forest fires in this area, indicates human land use practices may be the primary cause of the charcoal concentration in recent sediments.

4.4 Sedimentology of the Moultroup fan

The Moultroup fan is comprised of alternating gravel and sand and silt units, deposited by streamflow. Unit C in the Moultroup fan trench 4 is comprised of sand (68%), silt (26%), and clay (4.9%), with small clasts (up to 5 cm in length) (Figure 9, Table 6 and Table 8). The clasts are supported by the matrix of fine-grained sediments. The unit is massive with no internal structures and poorly sorted. A gravel lens with pebbles to 2 cm is located near the top of the unit. This unit could have been deposited by a hyperconcentrated streamflow or mudflow. A distinction between the two types of flow is not possible with the available data; however, based on comparison with other units in trench 4, this unit was most likely deposited by streamflow.

The stratigraphic characteristics observed in the Moultroup fan trench 1 and in trench 4 are very similar, alternating from gravel- to sand- and silt-dominated units (Figures 7 and 9). The upper soil horizon and stringers are also in the same stratigraphic position in both trenches. Unit K in trench 4 and unit D in trench 1 have the same textural characteristics, and are believed to be the same deposit (Figures 7 and 9). The thickness of this deposit does not decrease down fan, as seen in trench 1 (Figure 7), although clast size does decrease (unit D has clasts 2-8 cm in length). Unit D in trench 1 grades upward from gravel to sand. Unit K in trench 4 is an extensive deposit that is poorly sorted (Figure 27). The unit is predominantly clast supported, with clasts ranging from 2-35 cm in length on the long axis. The matrix is comprised of 65% sand, 23% silt, and 10% clay. Imbrication of small clasts (2-4 cm) was noted at the base of the deposit. The long axes of some larger clasts (up to 35 cm) were aligned in the down-fan direction, indicating a down-fan flow direction. The fluvial structures in this deposit, clast-support, upward grading, and imbrication, all indicate bedload transport and deposition by streamflow. However, the percentage of clay in the matrix, poor sorting, and the extent and thickness of the deposit indicate a higher sediment concentration than that of bedload dominated streamflow. For these reasons, I believe this unit was deposited by a hyperconcentrated flow, that had higher suspended load concentrations than streamflow, but remained non-Newtonian in its characteristics (Pierson and Costa, 1984).

Field evidence indicates that all the other units in trench 4 were deposited by streamflow (Units D, E, F, G, H, J, M, N and O; Figure 9 and Table 6). This classification is based on the presence of sedimentary structures; imbrication, alignment of long axes of clasts with flow direction, upward grading of sand beds (Unit N), and low clay content. Not all of these structures appeared in each unit (Table 6). Unit B is not classified by depositional process because it lies within the plowzone, and has been disturbed.

4.5 Sedimentology of the Audubon fan

The Audubon fan is comprised of massive deposits containing varying amounts of sand, silt and clay. No contacts or structures were visible in the walls of trench A (Figure 10), although mottling was present. The fan has one sediment source; a glaciolacustrine deposit adjacent to the fan. Grain size samples were taken in a column at intervals of 10 cm, and were analyzed for clay, silt, and sand content. The percentage of fine-grained sediment varied from sample to sample, and may indicate several depositional events, although this conclusion is tentative. Percentages of sand (66%-78%) and silt (16%-22%) did not vary much from sample to sample (Table 9). The percentage of clay in the samples analyzed ranged from 5% to 12.8%. On the basis of the massive texture, the clay content of the samples analyzed, and the lack of contacts, it is possible the Audubon fan was deposited by mudflows. Alternatively, the Audubon fan could represent hyperconcentrated streamflow deposition. Primary stratification, such as sorted beds resulting from streamflow deposition, could have been altered by bioturbation. The mottled sediment seen in the Audubon fan, may result from the activity of animals or root growth, and supports the bioturbation hypothesis. Two studies, one of younger fans (<2,500 ^{14}C years old), and the other of river terraces in the Huntington Valley, revealed stratigraphy that was altered by bioturbation (Zehfuss, 1996; T. Whalen, pers. comm.). Trenches revealed root casts, worm tracks and animal burrows that had disturbed the stratification in the deposits, displacing sediment. With the available data, it is difficult to discern whether streamflow or gravity flow was the mechanism of deposition on the Audubon fan. However, an active fan deposit in Stowe, Vermont (32 km to the northeast of Audubon fan) may provide information as to which flow type was the more likely method of deposition on the Audubon fan.

The Audubon fan is small (~1,150 m^2), formed by gully erosion into a large glaciolacustrine deposit that serves as its sediment source. The Audubon fan is fed by a small stream, and currently is experiencing fan-head entrenchment. Radiocarbon dating suggests the fan is approximately 9,500 years old, and that deposition on the fan has been episodic. The Audubon fan has a massive stratigraphy of sand, silt and clay, with a well-developed soil horizon is its most visible feature. The Audubon fan is currently experiencing fan-head dissection, and a redistribution of sediment on the mid-fan section by streamflow.

The Stowe fan is also small (~900 m^2) and is actively forming from gully erosion into glaciolacustrine deposits. A small stream, possibly originating from a spring, feeds the fan, and is dissecting the fan at its apex. A pit dug into the Stowe fan revealed a stratigraphy of well-sorted sand, silts and clays in beds. During a recent storm event, active streamflow deposition was observed on the distal portion of the fan. Figure 28 presents a comparison of the characteristics of the Stowe and Audubon fans.

The fans are similar in the climate regime in which they formed, their method of formation, sediment source, and geologic history. Both are currently being reworked by streamflow. The primary difference between the fans is the structure of the deposits; the Stowe fan is stratified and the Audubon fan is massive. Of the two interpretations of flow deposition on the Audubon fan, streamflow or gravity flow, streamflow is thought to be more likely. Because the two fans are otherwise similar, and because bioturbation is common in other, local fans, it is possible that the massive nature of the Audubon fan is due to soil stirring by roots and animals.

4.6 Audubon Fan Formation

The Stowe fan study site also provides a probable explanation for how the Audubon fan formed. The Audubon fan has back-filled the gully from which it formed. The gully has steep sides (25°) with established vegetation. At the Stowe fan site, the active fan deposit is fed by a spring that originates from a hydraulically conductive sediment layer within a glaciolacustrine terrace. The spring has eroded a gully into the terrace. The gully has steep, almost vertical sides into which sediment caves. An older, relict gully and fan are located 100 m south of the active fan. The relict gully walls are steep (~25°) and also have established vegetation. It is very likely the relict and the active Stowe fans formed in same manner, by gullying into glaciolacustrine sediments. It is likely the Audubon fan also formed by gullying, due to the similarity of the Audubon fan and Stowe fan sites (Figure 28). The formation of gullies is dependent on sediment type. The appear to form preferentially in glaciolacustrine sediments, but not in glacial till.

4.7 Hillslope Erosion and Fan Aggradation

Little evidence is available to determine the causes or processes of hillslope erosion which resulted in aggradation on the Moultroup and Audubon fans. However, based on the evidence available, I present three different potential driving forces for hillslope erosion and fan formation in this area: 1) forest clearance 2) catastrophic storm events and 3) cyclic sediment movement. Current data are insufficient to choose with certainty which driving force most dramatically influences sediment delivery to the fans.

Hillslope erosion and fan deposition may occur when the hillslopes are cleared, whether by human land-use changes, forest fires, or vegetation removal by blight or severe storm events. If hillslopes are cleared by any one or a combination of these processes, storm events can more easily destabilize sediment on the hillslopes, transporting it by stream- and transitional-flow processes. Wells and Harvey (1987) stated that stream-flow deposition could result from overland flow occurring on the unvegetated contributing hillslopes. The basin feeding the Moultroup fan contains abundant sand and little fine sediment, reducing the likelihood of overland flow occurring. However, wet conditions prevailing over a period of time could create the necessary antecedent conditions to cause saturated overland flow. The well-developed, buried soil horizon identified in every trench and the sediments immediately above the soil horizon were littered with pieces of charcoal. This indicates that the settlers must have removed the forest cover by burning. Fan aggradation rates increased after the soil horizon formed, coincident with colonial clearance of the hillslopes.

Many studies have shown that catastrophic storm events can induce hillslope erosion and sediment transport downslope even while full tree cover is present. Kochel (1990), Kochel and Johnson (1984), Mills (1982), and Orme (1990) all discuss the impact of catastrophic storm events on debris production and fan aggradation. In these studies, fan formation occurred at the base of forested slopes when the antecedent and precipitation conditions were such that mass-wasting occurred. Sediment and trees were carried down hill and deposited on fans. Large and small pieces of wood were found throughout the Moultroup fan, possibly deposited as a result of large storms which mobilized sediment and debris downstream to the fan. When catastrophic storms occur in forested areas in the eastern states, Kochel (1987), Kochel and Johnson (1984) and Pomeroy (1980), suggest the dominant form of sediment transport is debris flow. Mass-wasting due to saturated soil slipping on bedrock surface can create debris flows which are then routed by high-gradient, steep-sided stream channels to the fan surface (L. Benda, pers. comm.). In the Moultroup fan catchment, the ephemeral stream channels that feed the fan are presently wide and shallow. Broad, shallow channels are not conducive to debris flow movement because the unconfined debris flow will spread out and stop as the shear stress drops below the yield strength. Because field evidence suggests that deposition on the Moultroup fan has been primarily by stream-flow and transitional-flow processes, antecedent and catastrophic storm conditions must have been such that fluvial deposition occurred on the fan.

The last hypothesis addresses cyclic hillslope erosion and fan aggradation. In this scenario, sediment accumulates in ephemeral stream channels over a period of time until a storm event produces sufficient precipitation to move accumulated material down channel to the fan surface. Beaty (1990) discusses this scenario occurring on fans in the

White Mountains of California. O'Connor (pers. comm.) found first and second order streams in the western Cascades of Washington unload sediment in a cyclic pattern. The streams would fill with sediment and debris until a precipitation event created enough flow in the channel to evacuate the accumulated sediment and debris. O'Connor also found that the sediment and debris were transported primarily by fluvial processes. The same processes could have deposited sediment on the Moultroup fan. Today the ephemeral channels feeding the fan are armored with large boulders and the spaces between the boulders are filled with loose sediment. The sediment may continue to accumulate in the channels by soil creep until a storm event occurs which generates enough precipitation to transport sediment to the fan below.

4.8 Comparison of Huntington Valley Fans With Other Fan Studies

The results of the sedimentological analyses were compared with a studies by Kochel (1990), Kochel and Johnson (1984), and Wells and Harvey (1987). Kochel and Johnson (1984) compared fans formed in a variety of climates, and hypothesized that the dominant depositional processes occurring on a fan are controlled by climate and lithology. In a study of humid fans in the central Appalachians, Kochel (1990) proposed a model of fan formation by debris flow events triggered by intense rainfall events. Central Appalachian debris flow fans have been forming throughout the Holocene, commencing in the Late Pleistocene, about 11,000 yrs ago (Kochel, 1990). This date coincides with the possible retreat of the polar front, which enabled an influx of warm, moist tropical air, resulting in weather conditions capable of producing precipitation heavy enough to trigger debris flows.

Hurricanes and extreme storm events affect New England as well as the central Appalachians (Coch, 1994). Rainfall-induced debris flow events have been documented in northeast New England as well: in Massachusetts (Cleland, 1902), New Hampshire (Flaccus, 1958), New York (Bogucki, 1977), Pennsylvania (Pomeroy, 1980) and Vermont (Ratte and Rhodes, 1977). If Kochel's model is correct, extreme storm events may have been the cause of sedimentation events on the Moultroup and Audubon fans. However, the distinct difference between Kochel's rainfall-induced fans and Huntington Valley fans is the type of flow shown to dominate fan building processes. Huntington Valley fans have been built primarily by streamflow processes, while the Holocene fans in central Appalachians (studied by Kochel) were built by debris flow.

Wells and Harvey studied modern storm-generated alluvial fans in England and found that storm-generated deposits occurred in six facies types, of which they identified three groups; 1) stream-flow facies 2) transitional-flow facies and 3) debris-flow facies. Wells and Harvey divided deposits into facies groups based on surficial expression, vertical sequences, depositional morphology and relief, the presence and type of stratification and clast orientation.

Grain size analyses of samples taken from the Huntington Valley fans determined percentages of clay, silt and sand, that were plotted on ternary diagrams (Figure 29). The location of the data points on the ternary plots were compared to similar plots produced by Wells and Harvey (1987). Wells and Harvey designated areas of their ternary diagrams to correspond to the clay, silt and sand percentages of stream-flow, transitional flow and debris flow facies identified in the field. When plotted over Wells and Harvey's areas of streamflow, transitional and debris flow, of 12 units in trench 4 in the Moultroup fan, 6 plot in the deposition by streamflow area, 3 in the transitional flow area, and none in debris flow area. Three units did not fall into areas designated stream-, transitional, or debris flow plots (Figure 29).

It is difficult to draw conclusions from a comparison between Huntington Fans and Wells and Harvey's (1987) fans, because of differences in sediment source.

4.9 Chronology of Deposition

Radiocarbon dating organic samples allowed for the establishment of a chronology of fan deposition. In the following discussion of fan depositional chronology, the calibrated ages of the radiocarbon samples will be used, except where otherwise noted. Refer to Table 2 for ^{14}C dates and 1σ and 2σ calibrated age ranges.

A dated sample of wood from the Moultroup fan (8,555 yrs), identified as sugar maple, indicates the fan began to aggrade about 8,500 years ago. A second radiocarbon date from another piece of wood (8,126 yrs) indicates that in the interval between the dates, almost 1,600 m^3, or 33% of today's fan volume, was deposited at a rate of 3.7 m^3 y^{-1} (Table 1). The next stratigraphically higher sample (charcoal) has a calibrated ^{14}C age of 3,968 yrs. The sample was taken 0.9 m below the surface of the fan, and approximately 15 cm below the buried soil horizon. Between the ages of 8,126 and 3,968 yrs, 30% of the total fan volume was deposited. The aggradation rate calculated for the same period is 0.1 m^3 y^{-1} (Table 1).

The uppermost sample dated from the Moultroup fan was collected from 2 to 3 cm above the A-horizon of the paleosol. A ^{14}C age of 100±50 yrs constrains the youngest age possible for the soil horizon. The Huntington basin was originally settled around 1780, by two families. Widespread-spread deforestation probably began in the Huntington Valley around 1810 (P. Thomas, pers. comm.). The aggradation rate calculated using a historical age based on town settlement of 180 years is 7.0 m^3 y^{-1}. Eleven percent of the fan's volume was deposited between the historically dated sample and the sample calibrated to 3,968 yrs. Twenty-six percent of the fan's volume was deposited during the estimated historical period (180-present; Table 1).

Three samples were taken from the Audubon fan and radiocarbon dated. The stratigraphically lowest sample, a 0.5 m sample of wood, was taken from what is estimated to be approximately 50 cm below the base of the fan. This estimation was made by assuming the fan formed on a level surface, and extending a line from the fan toe to the base of the fan below the apex. The calibrated age of 9,486 yrs provides a limiting age for fan formation. The next stratigraphically higher radiocarbon date came from a sample of charcoal (8,981 yrs). The volume of sediment deposited between the dates of 9,486 yrs and 8,981 yrs is 35% of the total sediment deposited on the fan (Table 1). The aggradation rate calculated between the dates of 9,486 yrs and 8,981 yrs is 1.1 m^3 y^{-1}. A sample of charcoal taken from 6 cm above the buried soil horizon dated at 248 yrs. Forty percent of the fan volume was deposited between the samples dated at 8,981 and 268 yrs (Table 1). The aggradation rate on the fan between the dates of 8,981 and 180 yrs is 0.1 m^3 y^{-1}. From the time of the advent of wide-spread clear cutting (180 yrs) to the present, 407 m^3 of sediment has been deposited on the fan, at a rate of 2.3 m^3 y^{-1}. This sediment comprises 25% of the total fan volume (Table 1).

A climatic model over the 12k years was established in a study of the timing of deglaciation and revegetation in northeastern Vermont (Lin, 1996). Lin identified pollen grains and radiocarbon dated samples from two pond cores taken from ponds in the Green Mountains. Pollen influx rates and pollen percentage of taxa were correlated with the radiocarbon dates to establish the climate model. Lin's and other palynological studies (Brackenridge et al., 1984, Watts, 1979) indicate the climate during the early Holocene may have been warmer and less wet. Forest fires were more likely during this period (Jacobson et al., 1987). Lin (1996), however, did not find evidence that supports increased forest fires in northeastern Vermont. This time period (8,500-8,100 yrs ago) coincides with a period of aggradation, at a rate of 3.7 $m^3\ y^{-1}$, on the Moultroup fan (Figure 22). Over the next 8,000 years, until the period of historical land use, fan aggradation rates dropped to 0.1 $m^3\ y^{-1}$ (8,100-3,968 yrs ago) and increased to 0.3 $m^3\ y^{-1}$ (3,968-180 yrs ago). The buried soil horizon seen in the Moultroup and Audubon fans developed during this period of decreased sedimentation and increased fan surface stability. The low rates of aggradation on the Moultroup and Audubon fans coincide with a period in which New England climate is believed to have increased in temperature and humidity (Brackenridge, et al., 1984, Watts, 1979).

Extensive deforestation in the 1800's resulted in nearly 80% of Vermont forests being cleared (Severson, 1991). In the Huntington Valley, deforested land was used for agricultural purposes, until the 1930's and '40's when hillslopes began to be re-forested. Since the formation of the buried soil, 50 cm of sediment has been deposited on the Moultroup fan, 26% of the total fan volume. The removal of the tree cover and underbrush on the hillslopes above Green Mountain Audubon Center accelerated fan sedimentation on the Audubon fan and resulted in 25% of the total fan volume being deposited during historic time. The aggradation rates of 7.0 $m^3\ y^{-1}$ and 2.3 $m^3\ y^{-1}$ for the Moultroup and Audubon fans, respectively, are higher than the fans experienced during the any other period since their formation. A study in the northwestern Vermont recorded a noticeable increase in floodplain aggradation coinciding with the advent of land use by settlers in this area (P. Thomas, pers. com.). An increase in hillslope erosion attributed to changes in land use practices. It is clear the removal of vegetation in this area impacted the hillslopes by causing increased erosion, and increased aggradation on fan surfaces.

Figure 27. Close-up of Moultroup fan trench 4. Large unit with coarse clasts is stratum K (Figure 9, Table 6). Field assistant shows scale.

Fan deposit / Fan characteristics	Stowe Fan	Audubon Fan
Climate	humid-temperate	humid-temperate
Sediment source	glaciolacustrine sediments	glaciolacustrine sediments
Area	~900 m^2	~1,150 m^2
Age	Currently aggrading	9,500 yrs old
Stream activity	Fed by small, low-flow stream	Fed by small, low-flow stream
Fan activity	Fan-head disection	Fan-head disection
Source erosion	gullying	gullying
Deposit structure	Stratified sand, silt and clay	Massive sand, silt and clay. Bioturbation?
Depositional process	Observed streamflow	Hypothesized streamflow or gravity flow

Figure 28. Comparison of fan characteristics between the Stowe and Audubon fans.

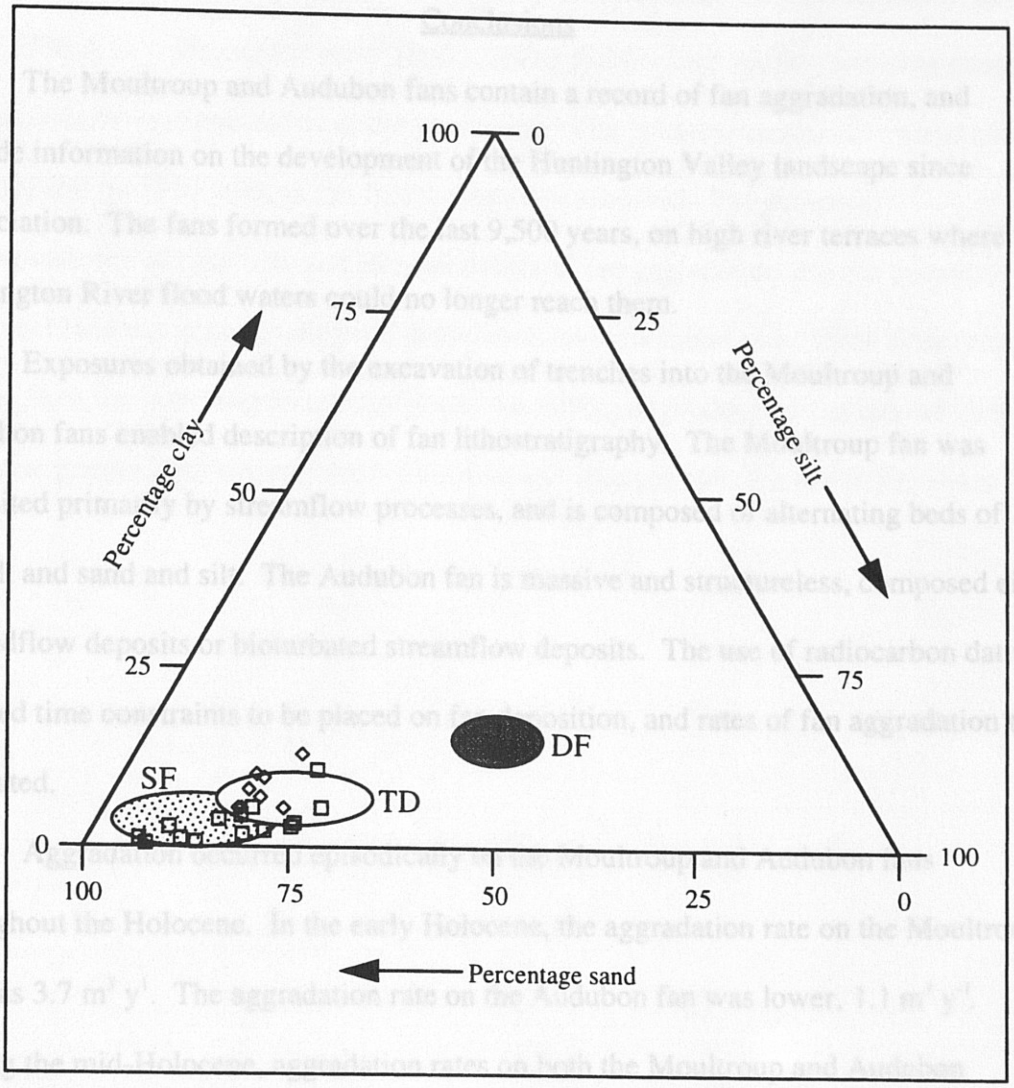

Figure 29. Ternary plot of sand, silt and clay percentages in grain size samples collected from the Moultroup and Audubon fans. The Audubon samples are represented by diamonds, Moultroup samples by squares. Shaded areas represent Wells and Harvey's debris flow (DF), transitional (TD) and streamflow deposit (SF) plots for comparison.

Chapter 5

Conclusions

The Moultroup and Audubon fans contain a record of fan aggradation, and provide information on the development of the Huntington Valley landscape since deglaciation. The fans formed over the last 9,500 years, on high river terraces where Huntington River flood waters could no longer reach them.

Exposures obtained by the excavation of trenches into the Moultroup and Audubon fans enabled description of fan lithostratigraphy. The Moultroup fan was deposited primarily by streamflow processes, and is composed of alternating beds of gravel, and sand and silt. The Audubon fan is massive and structureless, composed either of mudflow deposits or bioturbated streamflow deposits. The use of radiocarbon dating allowed time constraints to be placed on fan deposition, and rates of fan aggradation to be estimated.

Aggradation occurred episodically on the Moultroup and Audubon fans throughout the Holocene. In the early Holocene, the aggradation rate on the Moultroup fan was 3.7 m^3 y^1. The aggradation rate on the Audubon fan was lower, 1.1 m^3 y^{-1}. During the mid-Holocene, aggradation rates on both the Moultroup and Audubon dropped to below 0.2 m^3 y^{-1}. Both fans showed an increase in aggradation rate in the last 180 years, coinciding with the period of extensive clearcutting and agriculture in the Huntington Valley. The historical aggradation rates on both the Moultroup and Audubon fans are 7.0 m^3 y^{-1} and 2.3 m^3 y^{-1}, respectively. During the last 180 years, 26% of the Moultroup fan's total volume, and 25% of the Audubon fan's total volume, were deposited.

The most recent aggradation rates on the fans reflect a period of enhanced hillslope erosion in the Huntington River Valley that coincides with settlement in this area (1780 A.D.). During the early 1800's, sheep farming and milling were the primary occupations of over two-thirds of the population. The land was cleared for wood and pasture, and by 1880, 80% of the forest cover was removed. The temporal correspondence of time between increased rates of fan aggradation and the advent of historical land use strongly suggests the relationship is a causal one. If the relationship is causal, then the human-induced changes to the hillslopes produced a fan aggradation response greater than any previous environmental changes over the last 9,500 years.

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Appendix A

Trenching Methods

1. One wall of the trench is kept vertical from the surface of the fan to the base of the trench. This is the wall from which samples are collected and a profile is drawn. Available light and trench stability are considered when deciding which wall to profile. The opposite wall is stepped so the possibility of the walls caving in is diminished. Also, the floor of the trench at one or both ends, when possible, is sloped for entering and exiting easily.

2. The wall of the trench is cleaned with trowels so that unit contacts and changes in color are well exposed. From this point on, if samples of wood, charcoal or organic-rich layers are taken, they are flagged and locations labeled on the trench wall with labeled pins. Throughout the time the trench is open, the walls are constantly being troweled and inspected. The majority of charcoal and wood samples are found through cleaning. All sample locations are labeled and drawn on the trench profile.

3. Textural units within the trench are determined and outlined with colored flags, to aid in drawing the trench profile.

4. A detailed trench profile is drawn using a tape measure which lays on the surface of the fan next to the trench. Vertical measurements are made from measuring tapes which hang from the horizontal tape on the fan surface. Once a vertical and horizontal scale are plotted on graph paper, on person calls out the depths of the unit boundaries, flagged samples and larger rock locations while another person plots the

points on graph paper. The points which outline units are then connected and each sample point is double-checked to confirm accurate position on the profile.

5. Soil horizons, based on color, are outlined with colored flags and drawn on the cross-section using the same method as described in step (4).

6. Three sets of samples are taken in vertical columns located at either end of the trench and in the center. In each column block soil samples are taken approximately every 5 - 10 cm for LOI.

7. Samples for grain size analysis are taken from each textural unit and each unit is described in the field based on color, approximate grain sizes and sediment maturity.

8. Layers and lenses of organic-rich layers are sampled for radiocarbon dating.

9. Before filling in the trench, the cross section is double-checked for accuracy. Areas in the profile devoid of datable samples are checked again with the intent of finding samples suitable for dating.

Appendix B

LOI analyses, Moultroup fan samples

Sample ID: TOC-1 Trench 4/ Moultroup Fan	Crucible Wt. (g)	Wet Sample & Crucible Wt. (g)	Sample Wt. (g)	Dry Sample + Crucible Wt. (g)	Combusted Sample + Crucible Wt. (g)	% Water	% LOI
10	4.616	5.89	1.274	5.683	5.612	3.51	1.25
20	4.664	5.97	1.306	5.753	5.722	3.63	0.54
30	4.514	5.977	1.463	5.825	5.798	2.54	0.46
40	4.609	6.281	1.672	5.813	5.756	7.45	0.98
50	4.686	6.274	1.588	5.808	5.742	7.43	1.14
60	4.49	7.273	2.783	6.991	6.961	3.88	0.43
70	4.657	6.281	1.624	6.073	6.057	3.31	0.26
80	4.42	6.075	1.655	5.884	5.867	3.14	0.29
90	4.899	7.364	2.465	7.049	7.035	4.28	0.20
100	4.538	6.495	1.957	6.218	6.193	4.26	0.40
112	4.682	5.911	1.229	5.539	5.503	6.29	0.65
120	5.038	6.123	1.085	5.414	5.246	11.58	3.10

Sample ID: TOC-2 Trench 4/ Moultroup Fan	Crucible Wt. (g)	Wet Sample & Crucible Wt. (g)	Sample Wt. (g)	Dry Sample + Crucible Wt. (g)	Combusted Sample + Crucible Wt. (g)	% Water	% LOI
10	4.617	6.949	2.332	6.643	6.57	4.40	1.10
20	4.678	6.38	1.702	6.03	5.956	5.49	1.23
30	4.899	7.258	2.359	6.788	6.69	6.48	1.44
40	5.083	7.347	2.264	6.991	6.925	4.85	0.94
50	4.539	7.273	2.734	7.018	6.961	3.51	0.81
60	4.656	6.638	1.982	6.616	6.583	0.33	0.50
70	4.611	7.164	2.553	7.06	7.038	1.45	0.31
80	4.423	6.89	2.467	6.569	6.527	4.66	0.64
90	4.686	7.355	2.669	6.656	6.601	9.50	0.83
100	4.663	8.017	3.354	7.498	7.45	6.47	0.64
110	4.492	6.311	1.819	5.621	5.528	10.93	1.65
120	4.515	6.926	2.411	6.551	6.52	5.41	0.47

Sample ID: TOC-3 Trench 4/ Moultroup Fan	Crucible Wt. (g)	Wet Sample & Crucible Wt. (g)	Sample Wt. (g)	Dry Sample + Crucible Wt. (g)	Combusted Sample + Crucible Wt. (g)	% Water	% LOI
1-16	4.276	5.605	1.329	5.459	5.44	2.60	0.35
20-28	4.593	5.638	1.045	5.502	5.488	2.41	0.25
36-42	4.671	6.015	1.344	5.79	5.756	3.74	0.59
44-50	4.703	6.022	1.319	5.742	5.693	4.65	0.85
51-57	4.582	5.898	1.316	5.523	5.478	6.36	0.81
57-64	4.609	5.916	1.307	5.577	5.536	5.73	0.74
64-68	4.684	5.885	1.201	5.635	5.61	4.25	0.44
71-78	4.329	5.442	1.113	5.215	5.194	4.17	0.40
86-96	4.595	5.826	1.231	5.56	5.541	4.57	0.34
96-104	4.453	6.128	1.675	5.889	5.876	3.90	0.22
108-116	4.702	5.833	1.131	5.558	5.546	4.71	0.22
R57-64	4.623	6.105	1.482	5.712	5.664	6.44	0.84

Appendix C

LOI analyses, Audubon fan samples

Sample ID	Crucible Wt. (g)	Crucible w/ Sample (g)	Sample Wt. (g)	Wt. After 90 C (g)	Present Samp. Wt. (g)	Wt. After 450 C (g)	Present Samp. Wt (g)	% LOI
0	4.542	5.798	1.256	5.527	0.985	5.491	0.949	2.87
5	4.661	5.978	1.317	5.676	1.015	5.643	0.982	2.51
10	4.668	5.979	1.311	5.676	1.008	5.647	0.979	2.21
15	4.658	6.009	1.351	5.821	1.163	5.805	1.147	1.18
20	4.887	5.961	1.074	5.825	0.938	5.812	0.925	1.21
25	4.637	5.752	1.115	5.472	0.835	5.458	0.821	1.26
30	4.580	6.169	1.589	5.786	1.206	5.763	1.183	1.45
33	4.669	5.901	1.232	5.787	1.118	5.739	1.070	3.90
35	4.687	5.826	1.139	5.528	0.841	5.482	0.795	4.04
36	4.618	5.921	1.303	5.567	0.949	5.500	0.882	5.14
37	4.686	5.931	1.245	5.534	0.848	5.459	0.773	6.02
38	4.517	5.815	1.298	5.377	0.860	5.266	0.749	8.55

39	4.612	6.072	1.460	5.654	1.042	5.584	0.972	4.79
40	4.453	5.504	1.051	5.209	0.756	5.172	0.719	3.52
42	4.619	5.699	1.080	5.392	0.773	5.362	0.743	2.78
44	4.595	6.034	1.439	5.648	1.053	5.604	1.009	3.06
46	4.513	5.609	1.096	5.240	0.727	5.204	0.691	3.28
48	4.709	5.774	1.065	5.451	0.742	5.419	0.710	3.00
50	4.602	5.759	1.157	5.489	0.887	5.441	0.839	4.15
52	4.608	6.334	1.726	5.774	1.166	5.715	1.107	3.42
54	5.085	6.305	1.220	5.874	0.789	5.831	0.746	3.52
56	4.539	5.576	1.037	5.139	0.600	5.097	0.558	4.05
58	4.682	5.782	1.100	5.370	0.688	5.329	0.647	3.73
60	4.606	5.624	1.018	5.259	0.653	5.224	0.618	3.44
63	4.596	5.625	1.029	5.305	0.709	5.275	0.679	2.92
66	4.492	5.639	1.147	5.258	0.766	5.232	0.740	2.27
69	4.610	5.674	1.064	5.298	0.688	5.272	0.662	2.44
72	4.327	5.649	1.322	5.277	0.950	5.253	0.926	1.82
75	4.532	5.554	1.022	5.304	0.772	5.290	0.758	1.37
78	4.901	5.930	1.029	5.666	0.765	5.651	0.750	1.46

83	4.706	6.044	1.338	5.942	1.236	5.938	1.232	0.30
88	4.423	5.625	1.202	5.412	0.989	5.406	0.983	0.50
98	4.792	6.450	1.658	6.225	1.433	6.222	1.430	0.18
103	4.556	5.591	1.035	5.435	0.879	5.434	0.878	0.10
108	4.571	5.782	1.211	5.601	1.030	5.600	1.029	0.08
113	4.754	5.882	1.128	5.741	0.987	5.739	0.985	0.18
118	4.668	6.065	1.397	5.432	0.764	5.429	0.761	0.21
123	4.600	6.653	2.053	5.518	0.918	5.516	0.916	0.10
128	4.280	5.935	1.655	5.197	0.917	5.195	0.915	0.12
138	4.478	5.601	1.123	5.254	0.776	5.253	0.775	0.09

Sample ID	Crucible Wt. (g)	Crucible w/ Sample (g)	Sample Wt. (g)	Wt. After 90 C (g)	Present Samp. Wt. (g)	Wt. After 450 C (g)	Present Samp. Wt (g)	% LOI
0	4.498	5.532	1.034	5.258	0.760	5.234	0.736	2.32
5	4.684	6.080	1.396	5.759	1.075	5.729	1.045	2.15
10	4.655	5.723	1.068	5.410	0.755	5.398	0.743	1.12
15	4.634	5.764	1.130	5.495	0.861	5.481	0.847	1.24
20	4.555	5.761	1.206	5.458	0.903	5.442	0.887	1.33
25	4.755	6.080	1.325	5.847	1.092	5.831	1.076	1.21
30	4.794	6.064	1.270	5.785	0.991	5.769	0.975	1.26
35	4.666	5.803	1.137	5.665	0.999	5.651	0.985	1.23
40	4.577	5.628	1.051	5.447	0.870	5.434	0.857	1.24
42	4.721	5.864	1.143	5.264	0.543	5.250	0.529	1.22
43	4.602	5.690	1.088	5.461	0.859	5.447	0.845	1.29
44	4.788	5.809	1.021	5.395	0.607	5.382	0.594	1.27
45	4.568	5.790	1.222	5.148	0.580	5.131	0.563	1.39
46	4.595	6.047	1.452	5.328	0.733	5.306	0.711	1.52
47	4.681	5.815	1.134	5.687	1.006	5.669	0.988	1.59
48	4.664	5.725	1.061	5.491	0.827	5.474	0.810	1.60

49	4.539	5.726	1.187	5.394	0.855	5.373	0.834	1.77
51	4.514	5.927	1.413	5.502	0.988	5.474	0.960	1.98
53	5.593	5.698	0.105	5.663	0.070	5.660	0.067	2.86
55	4.898	5.915	1.017	5.691	0.793	5.661	0.763	2.95
57	4.705	5.825	1.120	5.557	0.852	5.519	0.814	3.39
59	4.489	5.513	1.024	5.354	0.865	5.312	0.823	4.10
61	4.702	6.023	1.321	5.286	0.584	5.209	0.507	5.83
63	5.082	6.166	1.084	5.845	0.763	5.748	0.666	8.95
65	4.883	5.966	1.083	5.415	0.532	5.336	0.453	7.29
67	4.595	5.668	1.073	5.335	0.740	5.258	0.663	7.18
69	4.449	5.488	1.039	5.298	0.849	5.229	0.780	6.64
71	4.657	5.692	1.035	5.589	0.932	5.532	0.875	5.51
73	4.364	5.368	1.004	5.218	0.854	5.172	0.808	4.58
76	4.325	5.586	1.261	5.197	0.872	5.155	0.830	3.33
79	4.608	5.816	1.208	5.219	0.611	5.175	0.567	3.64
82	4.597	5.672	1.075	5.492	0.895	5.459	0.862	3.07
85	4.683	6.287	1.604	5.998	1.315	5.954	1.271	2.74
88	4.618	5.927	1.309	5.164	0.546	5.137	0.519	2.06

91	4.597	5.672	1.075	5.492	0.895	5.479	0.882	1.21
94	4.683	6.287	1.604	5.998	1.315	5.982	1.299	1.00
99	4.618	5.927	1.309	5.164	0.546	5.156	0.538	0.61
100	4.532	5.621	1.089	5.016	0.484	5.011	0.479	0.46
104	4.610	6.432	1.822	6.129	1.519	6.123	1.513	0.33
109	4.535	5.668	1.133	5.490	0.955	5.487	0.952	0.26
119	4.607	6.159	1.552	5.685	1.078	5.680	1.073	0.32

Sample ID	Crucible Wt. (g)	Crucible w/ Sample (g)	Sample Wt. (g)	Wt. After 90 C (g)	Present Samp. Wt. (g)	Wt. After 450 C (g)	Present Samp. Wt (g)	% LOI
10	4.797	6.161	1.364	5.861	1.064	5.846	1.049	1.10
20	4.669	5.713	1.044	5.507	0.838	5.498	0.829	0.86
30	4.693	5.933	1.240	5.607	0.914	5.598	0.905	0.73
43	4.502	5.834	1.332	5.520	1.018	5.514	1.012	0.45
44	4.693	6.090	1.397	5.771	1.078	5.762	1.069	0.64
45	4.313	5.389	1.076	5.005	0.692	4.978	0.665	2.51
46	4.562	5.646	1.084	5.258	0.696	5.224	0.662	3.14
47	4.649	5.789	1.140	5.465	0.816	5.445	0.796	1.75
48	4.997	5.998	1.001	5.720	0.723	5.704	0.707	1.60
49	4.845	5.867	1.022	5.590	0.745	5.573	0.728	1.66
50	4.733	5.750	1.017	5.478	0.745	5.463	0.730	1.47
52	4.729	5.769	1.040	5.429	0.700	5.410	0.681	1.83
54	4.605	5.773	1.168	5.399	0.794	5.389	0.784	0.86
56	4.735	5.777	1.042	4.993	0.258	4.987	0.252	0.58

Appendix D

Fan Geometry and Aggradation Rate Calculations

Moultroup Fan Geometry

Radius (m)	Relief at Apex (m)
62	6.8
Fan Volume (m^3)	**Sweep Angle (°)**
4790	63

Moultroup Fan Aggradation Rate Calculations

Calibrated Age Range (yrs)	Volume of Fan Between Samples (m^3)	Aggradation Rate (m^3 y^{-1})
8555-8126	1592	3.7
8126-3968	1432	0.3
3968-180	512	0.1
180-present	1254	7.0

Audubon Fan Geometry

Radius (m)	Relief at Apex (m)
50	4.0
Fan Volume (m^3)	**Sweep Angle (°)**
1599	55

Audubon Fan Aggradation Rate Calculations

Calibrated Age Range (yrs)	Volume of Fan Between Samples (m^3)	Aggradation Rate (m^3 y^{-1})
9486-8981	560	1.1
8981-180	632	0.1
180-present	407	2.3

Appendix E

Explanation of Fan Volume and Aggradation Rate Calculations

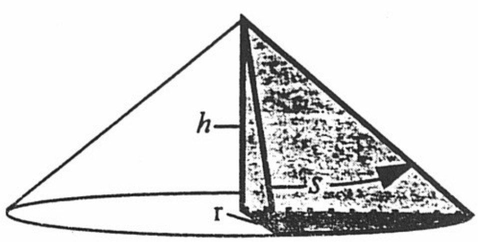
The equations used to calculate fan volumes and aggradation rates for the Moultroup and Audubon fans are outlined in this appendix, listed by order of operation. Fan volumes and aggradation rates are listed in table form in Appendix D.

Fan Volume

1. The relief of the fan at the apex (h) and the average radius of the fan (r) are used to calculate the volume of a right circular cone (V) using the following equation:

$$V = \tfrac{1}{3}\pi r^2 h$$

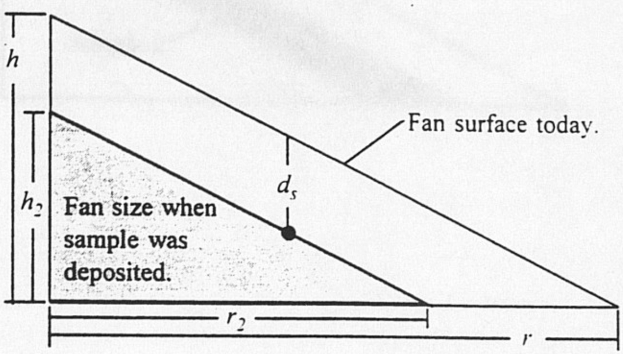
2. The volume of the fan (V_f) is determined by the sweep angle (s) of the fan deposit. V_f is a percentage of the right circular cone:



$$V = (\tfrac{1}{3}\pi r^2 h) \times (s/360)$$

Aggradation Rates

1. To calculate the aggradation rates, the volume of the fan at the time of sample deposition (V_2) must be determined. The sample depth (d_s) and location within the fan are used to determine the height (h_2) and radius (r_2) of the fan at the time of sample deposition. The sweep angle at the time of sample deposition (s_2) is assumed to be the same as the sweep angle today:



$$V_2 = (\tfrac{1}{3}\pi (r_2)^2 h_2) \times (s_2/360)$$

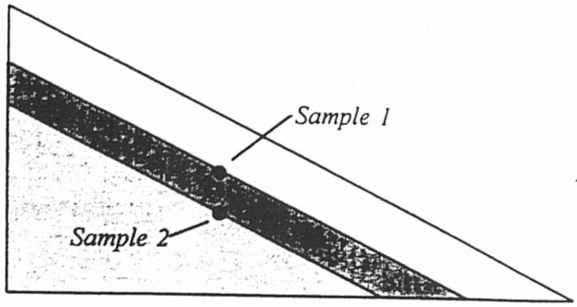
This calculation is based on the assumption that the fan surface had the same slope at the time of sample deposition as it does today. The calculation is completed for each sample (V_2, V_3, V_4...).

2. The volume of the fan deposited between each sample (V_d), or the surface of the fan today, is calculated by subtracting the volume calculated for the samples deposited prior to the sample in question:

$$V_d = V_3 - V_2$$

3. To determine the aggradation rate (A), the volume of sediment deposited before the

sample was deposited, and after the last sample was deposited, is divided by the numbers of years occurring between each depositional event. The depositional events are marked by the calibrated ^{14}C age of each sample:

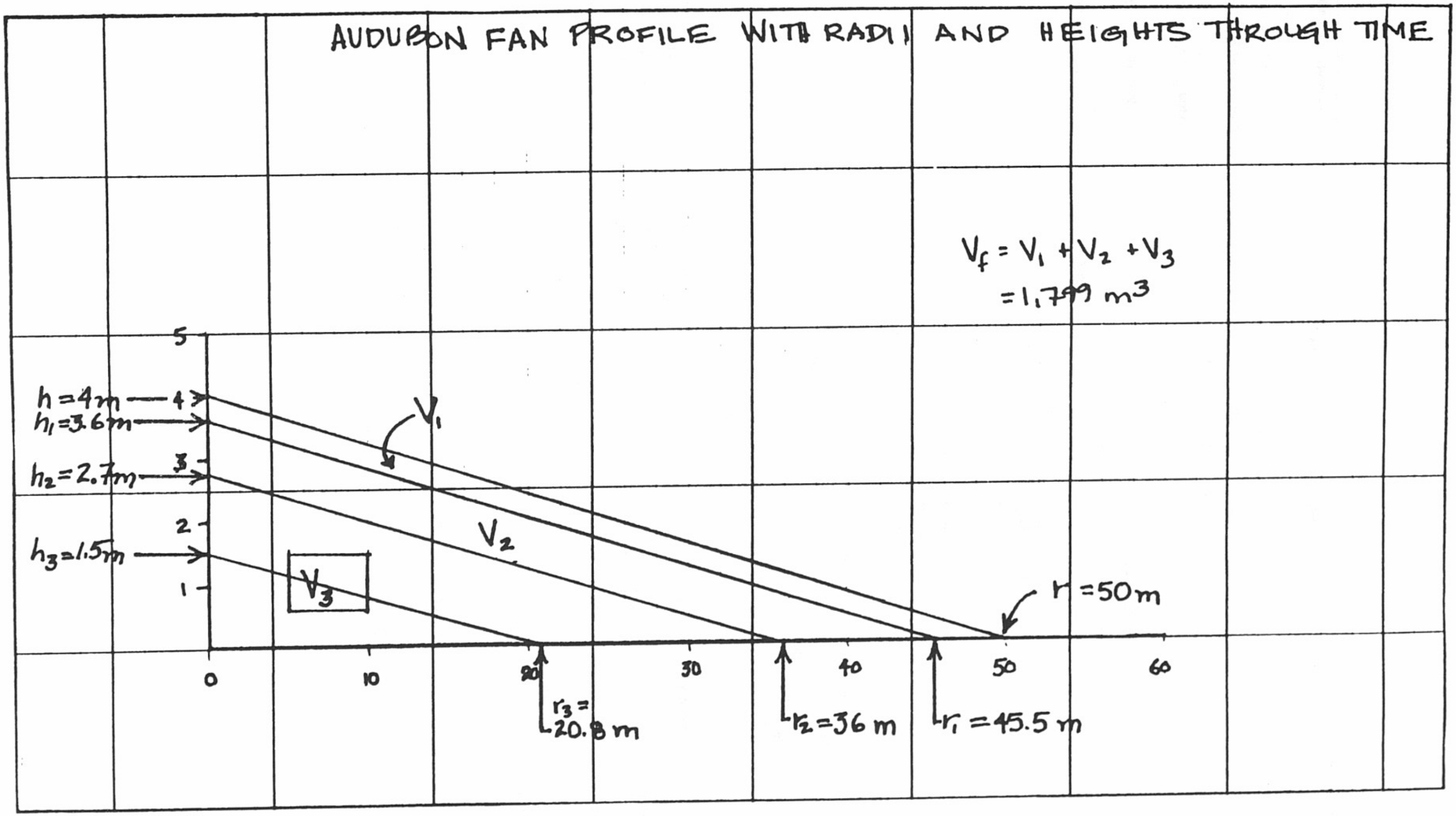


$A = V_d/(\text{age of Sample 2} - \text{age of Sample 1})$

Appendix F

Fan Geometry and Aggradation Rate Calculations

Fan Volume Calculations		**Aggradation Rate Calculations**	
Moultroup Fan			
Height at Apex *(h)* (m)=	6.8	Sample 1 Depth *(d_1,* (m) =	0.6
Average Fan Radius *(r)* (m)=	62	Sample 2 Depth *(d_2)* (m) =	0.9
		Sample 3 Depth *(d_3)* (m) =	2.1
Volume (of right circle cone) *(V)* (m3) =	27372	Sample 4 Depth *(d_4)* (m) =	4
Sweep Angle *(s)* (degrees) =	63	Fan Height at Time of Sample 1 Deposition *(h_2)* =	6.2
		Fan Height at Time of Sample 2 Deposition *(h_3)* =	5.9
Fan Volume *(Vf)* (m3) =	4790	Fan Height at Time of Sample 3 Deposition *(h_4)* =	4.7
		Fan Height at Time of Sample 4 Deposition *(h_5)* =	2.8
		Fan Radius at Time of Sample 1 Deposition *(r_2)* =	56
		Fan Radius at Time of Sample 1 Deposition *(r_3)* =	52.9
		Fan Radius at Time of Sample 1 Deposition *(r_4)* =	43
		Fan Radius at Time of Sample 1 Deposition *(r_5)* =	26.1
		Fan Volume at Time of Sample 1 Deposition *(V_2)* =	3536
		Fan Volume at Time of Sample 2 Deposition *(V_3)* =	3024
		Fan Volume at Time of Sample 3 Deposition *(V_4)* =	1592
		Fan Volume at Time of Sample 4 Deposition *(V_5)* =	349
		Volume of Sediment Deposited Between Sample1 and present *(Vd_1)* =	1254
		Volume of Sediment Deposited Between Sample 2 and Sample 1 *(Vd_2)* =	512
		Volume of Sediment Deposited Between Sample 3 and Sample 2 *(Vd_3)* =	1432
		Volume of Sediment Deposited Between Sample 4 and Sample 3 *(Vd_4)* =	1592
		Total Volume=	4790
		Age Range for *Vd_1* =	180 - present
		Age Range for *Vd_2* =	3968 - 180
		Age Range for *Vd_3* =	8126 - 3968
		Age Range for *Vd_4* =	8555 -8126
		Years of Deposition *Vd_1* =	180
		Years of Deposition *Vd_2* =	3788
		Years of Deposition *Vd_3* =	4158
		Years of Deposition *Vd_4* =	429
		Aggradation Rate *Vd_1* (m^3 yr^{-1}) =	7.0
		Aggradation Rate *Vd_2* (m^3 yr^{-1}) =	0.1
		Aggradation Rate *Vd_3* (m^3 yr^{-1}) =	0.3
		Aggradation Rate *Vd_4* (m^3 yr^{-1}) =	3.7


AUDUBON FAN PROFILE WITH RADII AND HEIGHTS THROUGH TIME
$V_f = V_1 + V_2 + V_3$
$= 1,799\ m^3$
$h = 4m$
$h_1 = 3.6m$
$h_2 = 2.7m$
$h_3 = 1.5m$
V_1
V_2
V_3
$r = 50m$
$r_3 = 20.8\ m$
$r_2 = 36\ m$
$r_1 = 45.5\ m$
0
10
20
30
40
50
60
1
2
3
4
5

Fan Volume Calculations		**Aggradation Rate Calculations**	
Audubon Fan			
Height at Apex *(h)* (m)=	4	Sample 1 Depth *(d_1)* (m) =	0.4
Average Fan Radius *(r)* (m)=	50	Sample 2 Depth *(d_2)* (m) =	1.3
		Sample 3 Depth *(d_3)* (m) =	2.5
Volume (of right circle cone) *(V)* (m3) =	10467		
		Fan Height at Time of Sample 1 Deposition *(h_2)* =	3.6
Sweep Angle *(s)* (degrees) =	55	Fan Height at Time of Sample 2 Deposition *(h_3)* =	2.7
		*Fan Height at Time of Sample 3 Deposition *(h_4)* =	1
Fan Volume *(Vf)* (m3) =	1599		
		Fan Radius at Time of Sample 1 Deposition *(r_2)* =	45.5
		Fan Radius at Time of Sample 2 Deposition *(r_3)* =	36
		Fan Radius at Time of Sample 3 Deposition *(r_4)* =	20.8
		Fan Volume at Time of Sample 1 Deposition *(V_2)* =	1192
		Fan Volume at Time of Sample 2 Deposition *(V_3)* =	560
		Fan Volume at Time of Sample 3 Deposition *(V_4)* =	69
		Volume of Sediment Deposited Between Sample1 and present *(Vd_1)* =	407
		Volume of Sediment Deposited Between Sample 2 and Sample 1 *(Vd_2)* =	632
		Volume of Sediment Deposited Between Sample 3 and Sample 2 *(Vd_3)* =	560
		Total Volume=	1599
		Age Range for *Vd_1* =	180 - present
		Age Range for *Vd_2* =	8981 - 180
		Age Range for *Vd_3* =	9486 - 8981
		Years of Deposition *Vd_1* =	180
		Years of Deposition *Vd_2* =	8801
		Years of Deposition *Vd_3* =	505
		Aggradation Rate *Vd_1* ($m^3 yr^{-1}$) =	2.3
		Aggradation Rate *Vd_2* ($m^3 yr^{-1}$) =	0.1
		Aggradation Rate *Vd_3* ($m^3 yr^{-1}$) =	1.1

*This sample was collected from 0.5 m below the base of the fan, in a river terrace. The fan height (h3) reflects the actual height of the fan, not where the sample was collected.

MOULTROUP FAN PROFILE WITH RADII AND HEIGHTS THROUGH TIME