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Varve, paleomagnetic, and ^{14}C Chronologies for late Pleistocene events in New Hampshire and Vermont (U.S.A.)

Chronologie de la déglaciation au Pléistocène supérieur, au New Hampshire et au Vermont (É.-U.A.) établie à partir des varves, du paléomagnétisme et des datations au 14C.

Warwe, Paläomagnetismus und 14C-Chronologien für Ereignisse im späten Pleistozän in New Hampshire und Vermont.

John C. Ridge, Mark R. Bensonen, Marc Brochu, Sarah L. Brown, Jamie W. Callahan, Glenn J. Cook, Robert S. Nicholson et Nathaniel J. Toll

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Résumé de l'article

La chronologie de la déglaciation du nord de la Nouvelle-Angleterre a été établie à l'aide de l'étalonnage de la New England Varve Chronology et des relevés du paléomagnétisme. Cette chronologie, fondée sur les datations au radiocarbone de macrofossiles et de plantes non aquatiques, est environ 1 550 ans plus jeu ne que les chronologies existantes en grande partie fondées sur les datations d'échantillons organiques et de macrofossiles aquatiques et non aquatiques. Les séquences de varves des vallées inférieure et supérieure du Connecticut de Ernst Antevs (varves 2 701-6 352 et 6 012-8 500) se superposent (6 012 de la vallée inférieure = 6 601 de la vallée supérieure). Trois dates au ^{14}C de Canoe Brook (Vermont) (varve 6150 = 12,3 ^{14}C ka) étalonnent la séquence de la vallée inférieure du Connecticut. De nouvelles datations au ^{14}C conventionnelles et par spectométrie de masse sur des brindilles en provenance de Newbury (Vermont) étalonnent a séquence du cours supérieur de 11,6 à 10,4 ^{14}C ka (varves 7 440-8 660) et concordent avec les relevés de varves chevauchantes et du paléomagnétisme et avec les datations au ^{14}C de Canoe Brook. La déglaciation de la vallée du Connecticut dans le sud du Vermont a commencé à 12,6 ^{14}C ka (15,2 ka étal.) et la récurrence de Littleton-Bethlehem dans le nord du New Hampshire et du Vermont était maximale à 11,9-11,8 ^{14}C ka (14,0-13,9 ka étal.) suivie du retrait de la glace au Québec vers 11,5 ^{14}C ka (13,4 ka étal.). Le lac qui a occupé la vallée supérieure du Connecticut jusqu'à environ 10,4 ^{14}C ka (12,3 ka étal.) a peut-être été aperçu par les premiers humains à fréquenter la région.

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VARVE, PALEOMAGNETIC, AND ^{14}C CHRONOLOGIES FOR LATE PLEISTOCENE EVENTS IN NEW HAMPSHIRE AND VERMONT (U.S.A.)

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ABSTRACT A deglacial chronology for northern New England has been formulated using an atmospheric ^{14}C calibration of the New England Varve Chronology and paleomagnetic records. This ^{14}C chronology is based on ^{14}C ages from macrofossils of non-aquatic plants and is about 1500 yr younger than existing chronologies that are based primarily on ^{14}C ages of bulk organic samples. The lower and upper Connecticut Valley varve sequences of Ernst Antevs (NE varves 2701-6352 and 6601-8500) overlap (lower 6012 = upper 6601) based on their crudely matching varve records and their similar paleomagnetic records. Three ^{14}C ages at Canoe Brook, Vermont (NE varve 6150 = 12.3 ^{14}C ka) calibrate the lower Connecticut Valley sequence. New AMS and conventional ^{14}C ages on woody twigs from Newbury, Vermont calibrate the upper sequence from 11.6-10.4 ^{14}C ka (NE varves 7440-8660) and are consistent with the overlapping varve and paleomagnetic records, and the Canoe Brook ^{14}C ages. Deglaciation of the Connecticut Valley in southern Vermont began at 12.6 ^{14}C ka (15.2 cal ka) and the Littleton-Bethlehem Readvance in northern New Hampshire and Vermont reached its maximum at 11.9-11.8 ^{14}C ka (14.0-13.9 cal ka) followed by recession of ice into Québec at about 11.5 ^{14}C ka (13.4 cal ka). A lake persisted in the upper Connecticut Valley until at least 10.4 ^{14}C ka (12.3 cal ka) and may have been seen by the first humans in the area.

RÉSUMÉ *Chronologie de la déglaciation au Pléistocène supérieur, au New Hampshire et au Vermont (É.-U.A.) établie à partir des varves, du paléomagnétisme et des datations au ^{14}C.* La chronologie de la déglaciation du nord de la Nouvelle-Angleterre a été établie à l'aide de l'étalonnage de la *New England Varve Chronology* et des relevés du paléomagnétisme. Cette chronologie, fondée sur les datations au radiocarbone de macrofossiles et de plantes non aquatiques, est environ 1550 ans plus jeune que les chronologies existantes en grande partie fondées sur les datations d'échantillons organiques et de macrofossiles aquatiques et non aquatiques. Les séquences de varves des vallées inférieure et supérieure du Connecticut de Ernst Antevs (varves 2701-6352 et 6012-8500) se superposent (6012 de la vallée inférieure = 6601 de la vallée supérieure). Trois dates au ^{14}C de Canoe Brook (Vermont) (varve 6150 = 12,3 ^{14}C ka) étalonnent la séquence de la vallée inférieure du Connecticut. De nouvelles datations au ^{14}C conventionnelles et par spectométrie de masse sur des brindilles en provenance de Newbury (Vermont) étalonnent la séquence du cours supérieur de 11,6 à 10,4 ^{14}C ka (varves 7440-8660) et concordent avec les relevés de varves chevauchantes et du paléomagnétisme et avec les datations au ^{14}C de Canoe Brook. La déglaciation de la vallée du Connecticut dans le sud du Vermont a commencé à 12,6 ^{14}C ka (15,2 ka étal.) et la récurrence de Littleton-Bethlehem dans le nord du New Hampshire et du Vermont était maximale à 11,9-11,8 ^{14}C ka (14,0-13,9 ka étal.) suivie du retrait de la glace au Québec vers 11,5 ^{14}C ka (13,4 ka étal.). Le lac qui a occupé la vallée supérieure du Connecticut jusqu'à environ 10,4 ^{14}C ka (12,3 ka étal.) a peut-être été aperçu par les premiers humains à fréquenter la région.

ZUSAMMENFASSUNG *Warwe, Paläomagnetismus und ^{14}C-Chronologien für Ereignisse im späten Pleistozän in New Hampshire und Vermont.* Man hat eine Enteisungs-Chronologie für den Norden Neu-Englands formuliert, indem man eine atmosphärische ^{14}C-Eichung der *New England Varve Chronology* und paläomagnetische Belege benutzt hat. Diese ^{14}C-Chronologie basiert auf ^{14}C-Datierungen von Makro-Fossilen nichtaquatischer Pflanzen und ist etwa 1500 Jahre jünger als schon bestehende Chronologien, die vorwiegend auf ^{14}C-Datierungen von organischen Proben sowohl aquatischer wie nichtaquatischer Makrofossile beruhen. Die Warwen-Sequenzen vom unteren und oberen Connecticut Valley von Ernst Antevs (NO-Warwen 2701-6352 und 6601-8500) überlappen sich (untere 6012 = obere 6601), sie haben grob übereinstimmende Warwen-Belege und ähnliche paläomagnetische Belege. Drei ^{14}C-Datierungen bei Canoe Brook, Vermont (NO-Warwe 6150 = 12.3 ^{14}C ka) kalibrieren die untere Connecticut Valley-Sequenz. Neue Massenspektrometrie- und konventionelle ^{14}C-Datierungen auf Zweigen von Newbury, Vermont, bemessen die obere Sequenz auf 11.6 bis 10.4 ^{14}C ka (NO-Warwen 7440-8660) und stimmen mit der überlappenden Warwe und paläomagnetischen Belegen sowie den ^{14}C-Datierungen von Canoe Brook überein. Die Enteisung des Connecticut Valley in Süd-Vermont begann um 12.6 ^{14}C ka (15.2 cal ka) und der Littleton-Bethlehem Rückvorstoβ in Nord-New Hampshire und Vermont erreichte sein Maximum um 11.9-11.8 ^{14}C ka (14.0-13.9 cal ka), gefolgt von einem Eisrückzug in Richtung Québec um etwa 11.5 ^{14}C ka (13.4 cal ka). Ein See existierte im oberen Connecticut Valley bis mindestens 10.4 ^{14}C ka (12.3 cal ka) und ist vielleicht noch von den ersten Menschen in diesem Gebiet gesehen worden.

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INTRODUCTION

Controversy over the style and chronology of deglaciation in northern New England has brewed for 60 years and has centered on whether the region was deglaciated by systematic ice recession from south to north (Lougee, 1935b, 1940) or by regional downwasting and stagnation (Flint, 1929, 1930, 1932, 1933; Goldthwait, 1938; Goldthwait *et al.*, 1951). At the heart of this conflict has been the analysis of varves (Antevs, 1922, 1928), which established a high-resolution chronology that was largely disregarded after the 1930's. Today disagreements center on the absolute ages of deglacial events, in particular the development of a ^{14}C chronology that will allow an accurate comparison to events in other regions of North America and the North Atlantic region.

This paper is the first comprehensive synthesis of the New England (NE) Varve Chronology in northern New England since the 1920's (Antevs, 1922, 1928). Because the varve chronology is anchored in work done at the beginning of this century we provide an historical analysis of the development of the chronology by Ernst Antevs in addition to recent developments and their implications. This historical presentation is critical because few glacial and Quaternary geologists working in New England over the last 50 years have been aware of the temporal and areal coverage of the New England Varve Chronology and the highly reproducible nature of its records in multiple drainage basins. Few studies in Quaternary geology from the early part of this century have had the scientific rigor that characterizes the varve chronology. At places in New England where varve thickness reflects the annual response of glacier melting to regional weather patterns, varve records represent a tremendous possibility for precise regional correlation. As with any Pleistocene chronology, varve records need to be tested with as many parallel techniques as possible. The addition of paleomagnetic secular variation records and AMS ^{14}C dating can make varve chronology in North America an extremely powerful correlation tool with unparalleled resolution. Based on multiple techniques we present a comprehensive late Pleistocene chronology for events that can be tied to the New England Varve Chronology, especially deglaciation in and around northwestern New England.

GLACIOLACUSTRINE SEDIMENTS AND VARVE CHRONOLOGY

EARLY VARVE INVESTIGATIONS

Silt and clay in the upper Connecticut Valley were first identified as lacustrine sediment in 1818 by Edward Hitchcock (Lougee, 1957). Warren Upham (1878) described the silt and clay as glacial flood deposits and it is not clear whether he recognized them as lacustrine sediment. Seasonal sedimentation patterns in the lacustrine sediment of the Connecticut Valley from Hanover to Woodsville and in the Ammonoosuc Valley were described in detail by Robert Sayles (1919) who may have been the first American to use the term 'varve' in connection with Connecticut Valley sediment. Sayles (1919) compared the Pleistocene varves with rhythmic units associated with the Squantum "tillite" Member of the Precambrian Roxbury Formation in Boston. Gerard De Geer visited the Champlain Valley as early as 1891 (De Geer, 1921) and later led a Swedish varve expedition in 1920 in which Ernst Antevs, Ebba Hult De Geer, and Ragnor Lidén accompanied him. This expedition introduced Ernst Antevs to the Connecticut Valley where he almost single handedly created the New England Varve Chronology. De Geer's goal was to create a varve chronology in North America that could be compared to varves in Sweden. De Geer (1921) found compelling year-to-year matches and inferred a correlation of varves between New England and Sweden. Varve sections at Woodsville, New Hampshire and Wells River, Vermont were the centerpieces of his interpretations. Antevs (1931, 1935, 1953, 1954) later dismissed De Geer's transatlantic correlations with claims of arbitrary correlations and inconsistencies with ^{14}C ages, an analysis that most modern geologists accept as correct.

THE NEW ENGLAND VARVE CHRONOLOGY — FIRST INSTALLMENT

In 1920 Ernst Antevs began assembling the New England Varve Chronology from varve sections in the Connecticut, Hudson, Ashuelot, and Merrimack Valleys (Figs. 1, 2). He compiled over 4000 consecutive years and published his work in 1922 (Antevs, 1922), an amazing accomplishment for less than two years work. To assemble the chronology Antevs created "normal" curves that are the averaged results from several outcrops and include matching sequences from different drainage basins. This matching or "connection" of individual varve records is necessary to eliminate errors resulting from missing couplets or single varves mistakenly counted as multiple years at one exposure. Except for the tail ends of his entire chronology and two short intervals represented by varves in Massachusetts (NE varves 4324-4341 and 4684-4702), Antevs constructed all his normal curves from varve records at two or more outcrops (Fig. 3). The interval of NE varves 4684-4702 has now been replicated in a core at Amherst, Massachusetts (T. Rittenour, pers. comm.). More than 80% of the normal curves are based on overlapping records from three or more outcrops and as many as 14 outcrops.

Antevs (1922) assembled a continuous lower Connecticut Valley sequence arbitrarily beginning with NE varve 3001 in southern Connecticut and ending just south of Claremont, New Hampshire with NE varve 6277 (Figs. 1, 2). He used varve sections measured by De Geer in the Hudson Valley that matched the Connecticut Valley records to span a gap in the lower Connecticut Valley sequence between NE varves 5600 and 5687 (Fig. 4a, 4b). This interval has now been covered by a measured varve sequence in a 40-m core taken from the Connecticut Valley at Amherst, Massachusetts. From this new core it appears that De Geer over counted his Hudson Valley sequence at one place by 10 years where flood events created a series of couplets that he mistook for annual layers (T. Rittenour and J. Brigham-Grette, pers. comm.). Antevs (1922) was able to match the lower Connecticut Valley sequence with varves in the Ashuelot Valley (NE varves 5687-5733 and 5804-5879, Fig. 4b) and the Merrimack Valley

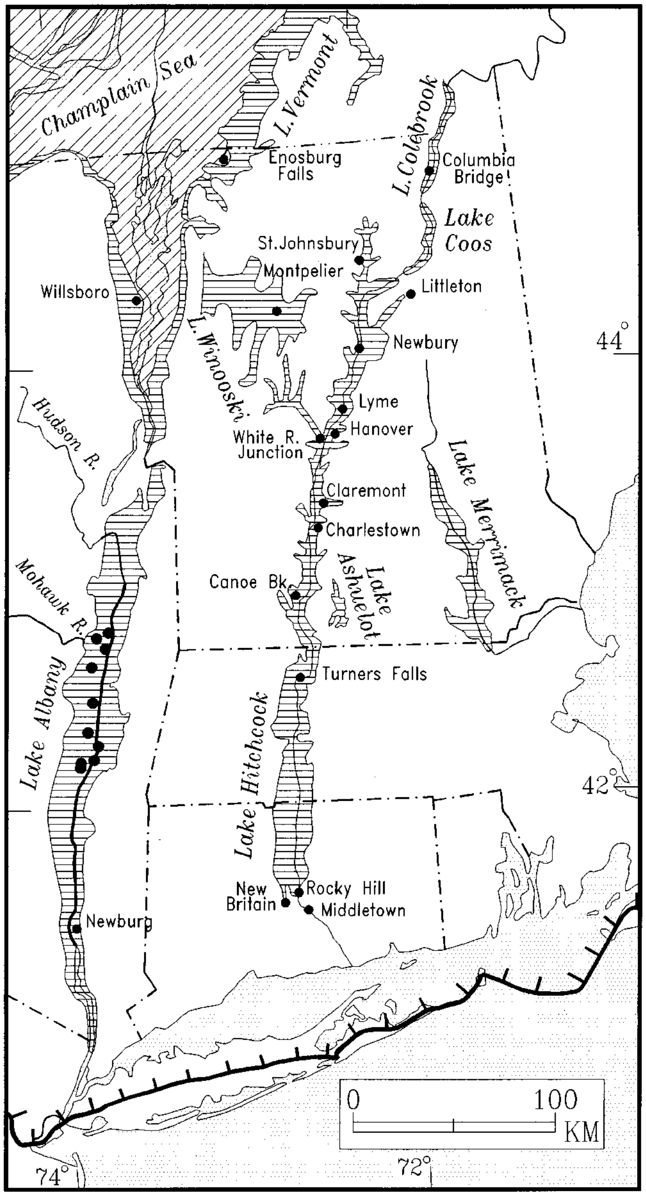

FIGURE 1. Location map of western New England and adjacent New York. The ice front position at the southern end of the map is the maximum extent of Late Wisconsinan ice advance. The Champlain Sea and major glacial lakes relevant to the New England Varve Chronology are shown. The mapped extent of Lake Winooski includes several lake levels in the Winooski Valley (Larsen, 1987b). Unlabeled sites in Lake Albany are locations of varve sections studied by Gerard De Geer (Antevs, 1922).

Carte de localisation de l'ouest de la Nouvelle-Angleterre et de l'état de New York adjacent. L'emplacement du front glaciaire à l'extrémité sud de la carte montre l'extension maximale de l'inlandsis au Wisconsinien supérieur. On montre la Mer de Champlain ainsi que les principaux lacs glaciaires en rapport avec la New England Varve Chronology. *Le Lac glaciaire Winooski cartographié (Vermont), comprend différents niveaux lacustres dans la vallée du Winooski (Larsen, 1987b). Les sites non identifiés dans le Lac glaciaire Albany montrent l'emplacement des coupes de varves étudiées par Gerard De Geer (Antevs, 1922).*

of eastern New Hampshire (NE varves 5709-5749, 5771-6352, Fig. 4c), which extended the lower Connecticut Valley sequence to NE varve 6352 (Fig. 2).

Beginning in Claremont, and continuing northward into the Passumpsic Valley to St. Johnsbury, Vermont, Antevs (1922) assembled an upper Connecticut Valley sequence (NE varves 6601-7400) that did not appear to overlap his lower Connecticut Valley sequence (Fig. 2). The apparent lack of a match between the upper and lower valley sequences prompted Antevs to create a gap between the two chronologies. The artificial gap (here called the Claremont Gap) was inferred to represent a 600-yr stillstand of the receding ice sheet despite a lack of any field evidence in the Connecticut Valley to suggest such an event. Creation of the Claremont Gap was stimulated by evidence of oscillating ice (till over varves) to the east in the Lake Winnipesaukee region (Antevs, 1922), which needs further investigation. At one locality near Newbury, Vermont Antevs (1922, site 73) counted an additional 1100 couplets (beyond NE varve 7400) that were too thin to measure with a ruler. This section would become the focus of later work in sedimentary paleomagnetism and is the site of new ^{14}C ages and paleomagnetic data discussed later in this paper.

NEW ENGLAND VARVE CHRONOLOGY — SECOND INSTALLMENT

After studying varves in Canada for a few years (Antevs, 1925) Antevs returned to the United States to complete the New England Varve Chronology. Antevs (1928) extended the lower Connecticut Valley sequence back to NE varve 2701 by measuring new sections in Connecticut and matching them with varves in the Hudson Valley at Newburg, New York (Figs. 1, 2). The last two years of his original upper Connecticut Valley sequence were revised and he extended that sequence to NE varve 7750. Antevs also compiled varve records from across northern Vermont and into Québec, which were too short and mostly too young to be matched to his sequence in the Connecticut Valley. However, varves from glacial Lake Winooski, resting directly on till at Montpelier (Fig. 1), matched the upper Connecticut Valley sequence (NE varves 7059-7288; Figs. 2, 4d) and provided a tie to glacial lakes in the Champlain–St. Lawrence drainage system. Other publications by Antevs (1925, 1931) in Canada provide additional chronologies that record deglaciation well into the Holocene.

In this volume in honor of Dick Goldthwait it is worth mentioning that Dick assisted Ernst Antevs in the construction of his varve chronology. Shortly after publishing a paper on varves in the Connecticut Valley (Ridge and Larsen, 1990), the first author received a letter from Dick Goldthwait revealing that his family hosted Ernst Antevs while he completed his work in the upper Connecticut Valley. Dick remembered as a teenager helping Antevs compile varve records on summer evenings in the attic of his family's home in Hanover, New Hampshire.

SYSTEMATIC ICE RECESSION IN NEW ENGLAND

Antevs (1922, 1928) was able to use his upper Connecticut Valley sequence to assemble a chronology of deglaciation for the upper valley. At fourteen localities along the axis of the Connecticut and Passumpsic Valleys from Claremont

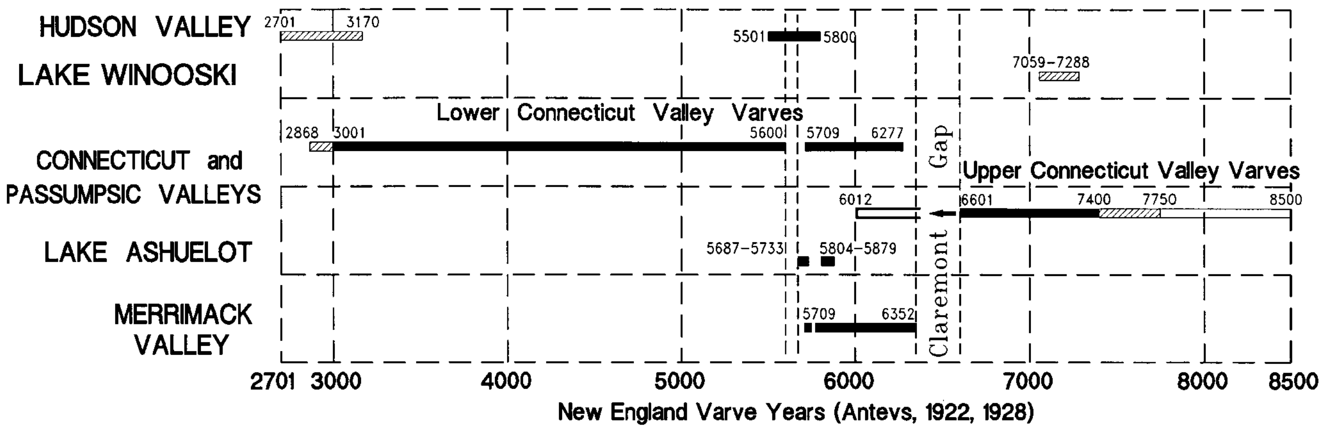

FIGURE 2. Time spans in arbitrary varve years (younger to the right) of overlapping sequences of the main part of the New England Varve Chronology (NE varves 2701-8500). Darkened spans (Antevs, 1922) and scribed spans (Antevs, 1928) are varve sequences that were counted, measured, and compiled into normal curves. The open span (NE varves 7750-8500) was counted but not measured (Antevs, 1922). The Claremont Gap was arbitrarily created by Antevs (1922) and separates the lower (NE varve 2701-6352) and upper (NE varve 6601-7750) Connecticut Valley sequences that overlap (lower NE varve 6012 = upper NE varve 6601) as indicated by the arrow and open box.

Durée en années varvaires arbitraires (plus récentes à droite) des séquences chevauchantes de la principale partie de la New England Varve Chronology *(varves 2701 à 8500). Les séquences en noir (Antevs, 1922) et hachurées (Antevs, 1928) ont été comptés, mesurées et compilées sous forme de courbes normales. La séquence (non tramée) à l'extrême droite (varves 7750-8500) a été comptée, mais non mesurée (Antevs, 1922). La lacune de Claremont (Claremont Gap) a été créée par Antevs (1922) afin de séparer les séquences de la vallée inférieure du Connecticut (2701-6352) de celle de la vallée supérieure (6601-7750), qui se chevauchent (la varve de la vallée inférieure 6012 = varve 6601 de la vallée supérieure) comme l'indiquent la flèche et la séquence non tramée.*

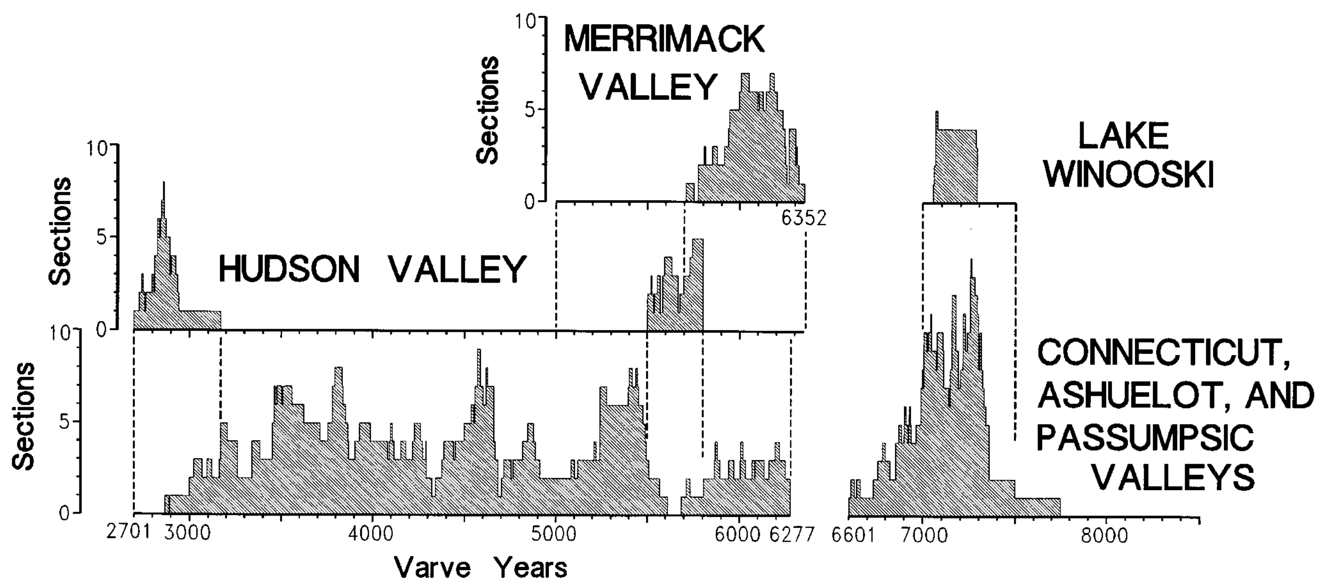

FIGURE 3. Number of sections matched by Antevs (1922, 1928) to construct the main part of the New England Varve Chronology (Fig. 2). A section constitutes one outcrop where Antevs may have measured one or several overlapping varve sequences.

Le nombre de coupes assorties par Antevs (1922, 1928) pour constituer la principale partie de la New England Varve Chronology *(fig. 2). Une coupe est composée d'un affleurement où Antevs a mesuré une ou plusieurs séquences de varves chevauchantes.*

to St. Johnsbury, and at five localities in the Merrimack Valley, Antevs found basal varves (Figs. 5, 6). Added to Antevs original basal varve sites are basal varve sites from Lougee (1935b) and our work. Couplets that are recognized as basal varves are found resting directly on till, bedrock, or gravel, and/or are thick and sandy varves (up to 396 cm) that were deposited in an ice-proximal environment within the first century after deglaciation. At a single location basal varves always become thinner upward and they become progressively younger or onlap to the north.

Basal varve localities in the Connecticut, Passumpsic, and Merrimack Valleys (Figs. 5, 6) are from the sides of the valleys and they should be viewed as indicators of a minimum ("youngest possible") age for deglaciation when they are used without additional information. Without knowledge

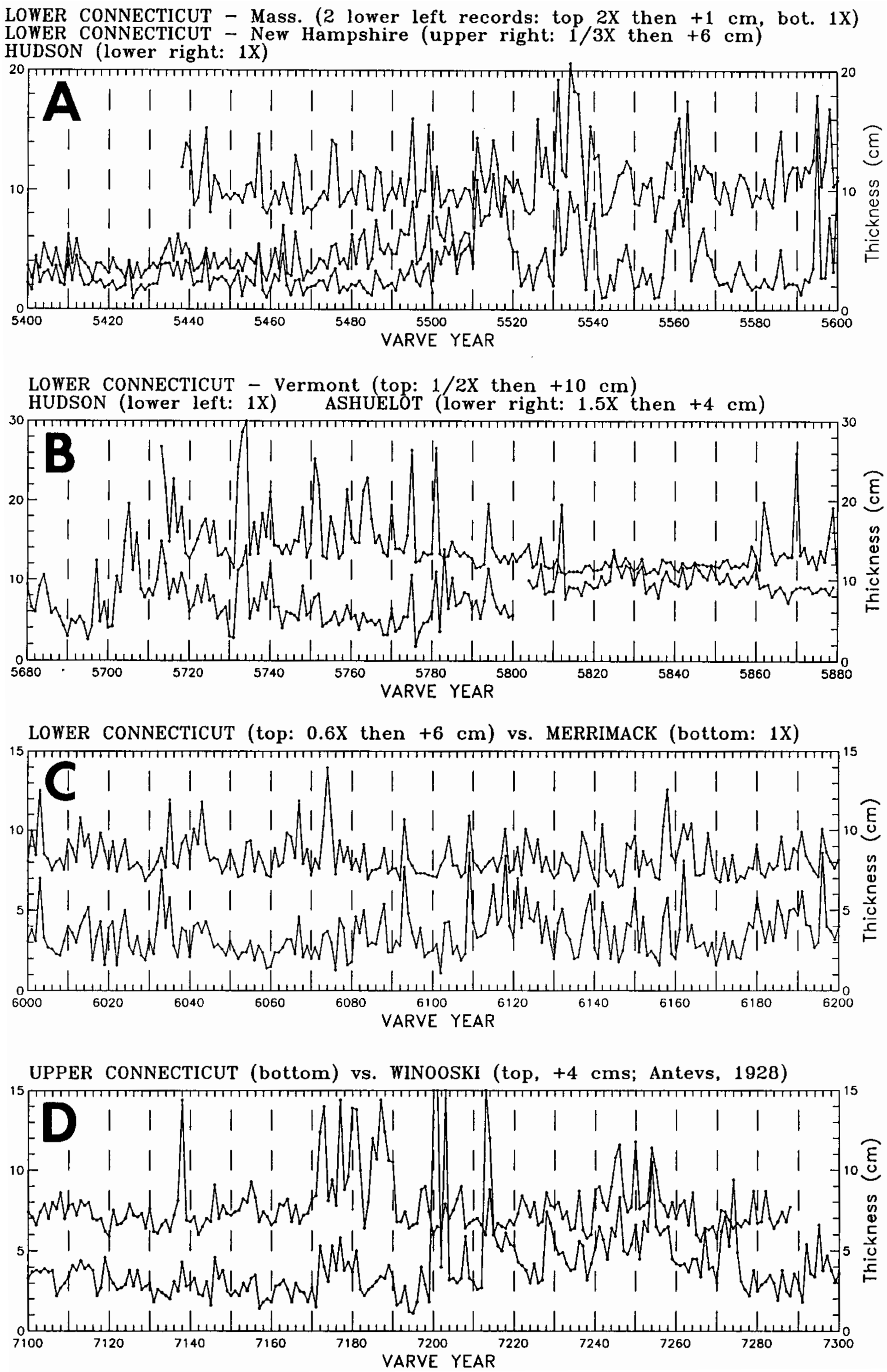

FIGURE 4. The overlap and match of normal curves (Antevs, 1922, 1928) from different drainage basins and glacial lakes. Included on the 200-year plots are normal curves from the Connecticut, Hudson, Ashuelot, and Merrimack Valleys. Many sequences are scaled to fit on the plots and then shifted an increment of the vertical axis (*e.g.* +6 cm) to allow easier comparison. Varves plotted on the top axis of a graph are excessively thick varves that actually plot well off the graph. Note**:** The best way to view the varve records is to hold the page at a low angle, looking across the page from bottom to top.

Le chevauchement et la concordance des courbes normales (Antevs, 1922, 1928) dans différents bassins de drainage et lacs glaciaires. Sont comprises dans la reconstitution de 200 ans les courbes normales des vallées du Connecticut, de l'Hudson, de l'Ashuelot et du Merrimack. Plusieurs séquences ont été ajustées puis décalées pour fins de comparaison. Les varves qui touchent la partie supérieure du graphique sont excessivement épaisses et excèdent largement le graphique. Note : la meilleure façon de consulter le relevé est de tenir la page à un angle faible, en la parcourant du bas vers le haut.

of the depth to till or bedrock in the center of a valley it is impossible to unequivocally deny the existence of deeper and older parts of the varve stratigraphy that lie in basins beneath the center of the valley. Antevs (1922) did not report the exact outcrop thickness of basal varves at every site but where he did report them (about half the basal sites) they reach a thickness of at least 37 cm and are up to 396 cm. These thick varves at basal sections are almost certainly ice-proximal and ice would probably have been within a few kilometers of the site at the time of deposition, thus making the ages of these varves very good approximations of the age of deglaciation.

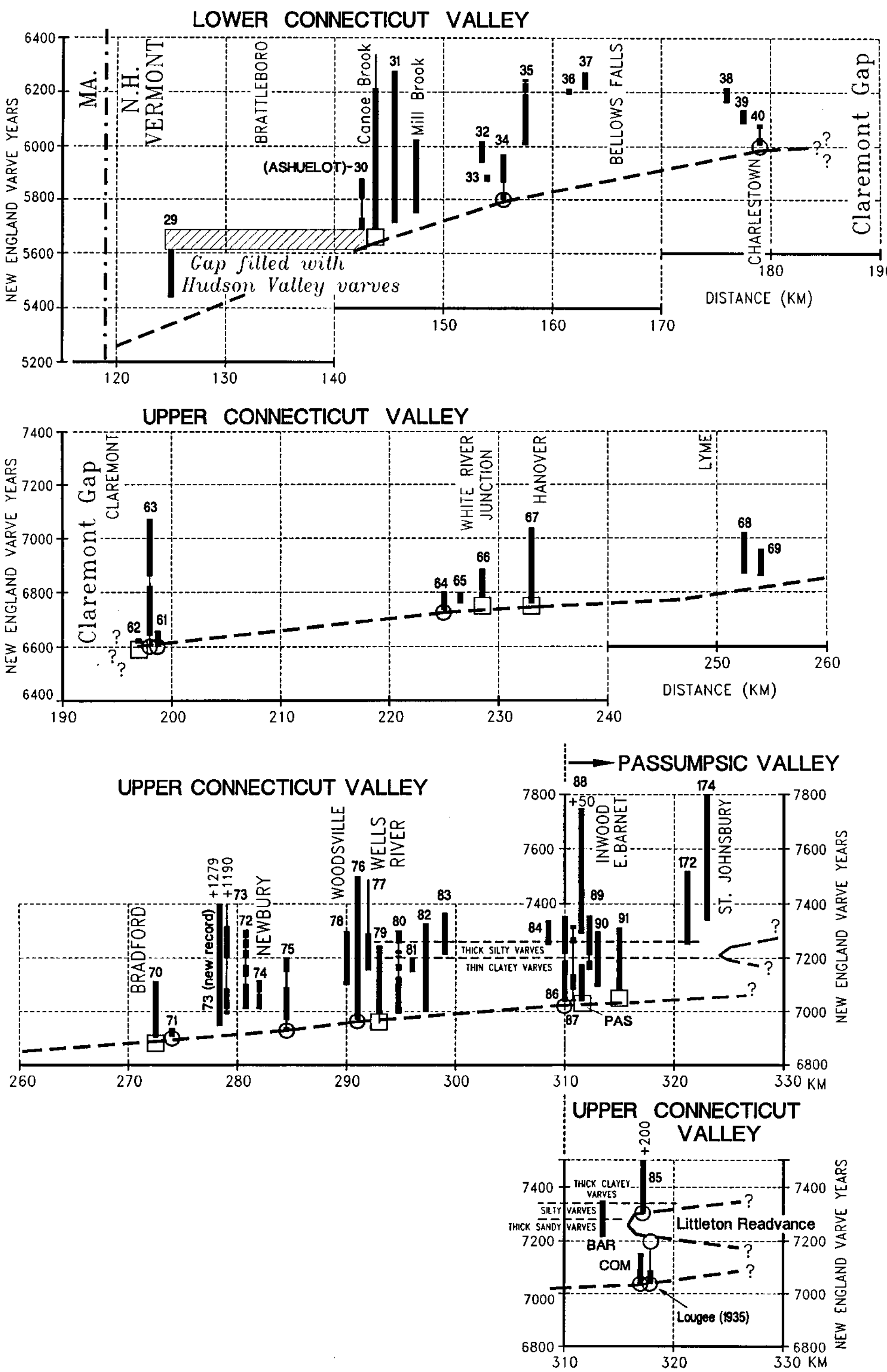

FIGURE 5. Time spans of varve sections in Vermont and New Hampshire along the axes of the Connecticut and Passumpsic Valleys from south (left, top) to north (right, bottom). Distances are from an arbitrary starting point south of Lake Hitchcock in Connecticut. The section of the valley marked Lower Connecticut Valley is the part of the valley covered by the Lower Connecticut Valley varve sequence (Antevs, 1922, 1928). The Upper Connecticut Valley plot from 310-330 km follows the valley eastward from its confluence with the Passumpsic Valley, the latter being the topographic extension of the south to north-trending Connecticut Valley. Thick varve columns are sequences measured and matched to other sections; thin columns were counted only. Numbered sections are from Antevs (1922, 1928) and other named sections are from later works (Lougee, 1935b; Ridge and Larsen, 1990; Ridge *et al.,* 1996; new data). Open circles at the bottoms of sections indicate outcrops where basal varves have been found overlying till, bedrock, or ice-proximal sand and gravel. Open squares indicate section bottoms with thick ice-proximal varves. The dashed line at the bottom of the profiles represents an interpretation of the age of deglaciation (see discussion in text).

Périodes couvertes par les séquences varvaires au Vermont et au New Hampshire le long des axes des vallées du Connecticut et du Passumpsic, du sud (en haut, à gauche) vers le nord (en bas, à droite). Les distances sont calculées à partir d'un point de départ arbitraire au sud du Lac glaciaire Hitchcock, dans le Connecticut. La partie identifiée comme étant la Lower Connecticut Valley est la partie comprise dans la séquence varvaire de la vallée inférieure du Connecticut (Antevs, 1922, 1928). Le relevé de la vallée supérieure du Connecticut de 310 à 330 km suit la vallée vers l'est à partir de la confluence avec la vallée du Passumpsic qui représente l'extension naturelle de la direction sud-nord de la vallée du Connecticut. Les colonnes plus larges de varves représentent des séquences mesurées et assorties à d'autres coupes ; les colonnes fines ne comprennent que des mesures. Les coupes numérotées sont de Antevs (1922, 1928) et les coupes nommées résultent de travaux ultérieurs (Lougee, 1935b ; Ridge et Larsen,1990 ; Ridge et al., *1996 ; données inédites). Les cercles non tramées à la base des colonnes identifient les coupes où les varves couvraient un till, le substratum ou des sables et des graviers proximaux. Les carrés non tramés identifient des coupes où la base comprend des varves épaisses proximales. Les tiretés à la base indiquent l'époque probable de la déglaciation.*

At most places where basal varves have been recorded in sections along the valley side there is very little or no opportunity for the accumulation of thick subsurface varve stratigraphy that could significantly predate valley side surface exposures. This is especially true in the upper Connecticut and Passumpsic Valleys. At Claremont (Fig. 5), where Antevs (1922) found

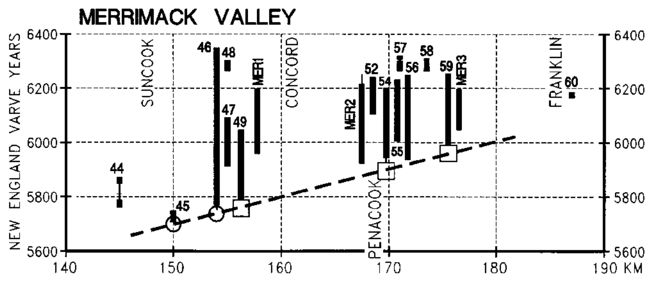

FIGURE 6. Time spans of varve sections along the axis of the Merrimack Valley from south (left) to north (right). Sites marked MER1-3 are new sections. Distance is from an arbitrary point south of the Merrimack Valley in Massachusetts. Symbols and plotting convention are the same as for Figure 5.

Périodes couvertes par les séquences de varves le long de l'axe de la vallée du Merrimack, du sud (à gauche) vers le nord. Les sites identifiés MER1-3 représentent de nouvelles coupes. Les distances sont calculées à partir d'un point arbitraire au sud de la vallée du Merrimack, au Massachusetts. Voir la figure 5 pour les symboles et la méthode utilisée.

his thickest basal varves (up to 396 cm, first 30 average >50 cm), bedrock and till are exposed along the banks of the Connecticut River. The center of the valley appears to be shallow and would have rapidly filled with fine sand, silt, and clay given the documented thickness of varves in surface exposures. At Wells River (Fig. 5) the bridge crossing the Connecticut River to Woodsville sits on bedrock outcrops and basal varve sections occur on till near river level. Basal varves in the Passumpsic Valley (Fig. 5) are exposed down to river level were the river runs across bedrock for 2 km.

In addition to areas of the upper Connecticut Valley where bedrock is shallow basal varves are also exposed above thick sequences of till and preglacial deposits that are now dissected by the Connecticut River. The till and preglacial deposits filled the valley above modern river level at the time of deglaciation and the Connecticut River has dissected the pre-varve deposits in postglacial time making the valley deeper today than during deglaciation. South of Hanover (Fig. 5) the Connecticut River is inset in a bluff that is composed of till and preglacial gravel totaling 22 m capped by basal varves (Larsen, 1987a). On the New Hampshire side of the Comerford Dam in the upper Connecticut Valley (located at about 318- 319 km on Fig. 5) over 50 m of till and preglacial gravel sit on bedrock and have been downcut by the modern Connecticut River that today runs on bedrock. Till on both sides of the valley is capped by varves deposited during deglaciation (Ridge *et al.*, 1996; Thompson *et al.*, 1999). During deglaciation the valley was filled with till and preglacial gravel and could not have been a location where a deep varve section accumulated significantly below the elevation of existing exposures along the river. Finally the Littleton-Bethlehem Readvance (discussed later) is recorded in the varve sequence fixing the age of deglaciation near the Comerford Dam and Littleton.

In situations where valley side exposures of basal varves occur next to subsurface basins in the center of the valley it is unlikely that significantly older varve sections reside in the basins. In situations where deposition along a valley side is delayed sediment is focused to deeper parts of a basin and varves lap up on the valley side. Varves in deep basins in the center of the valley should become thinner as they are traced outward and begin to lap up on till or bedrock on the sides of the valley. Using the bottom varves at Canoe Brook as an example (Figs. 1, 5; NE varve 5685 = 25.5 cm, 5686 = 23.0 cm, 5687 = 30.0 cm, and 5688 = 28.0 cm; Ridge and Larsen, 1990 and new data), valley-side basal varves conservatively have an average thickness of 20 cm. Thicker varves in the center of the valley would fill a 50-m basin in no more than 250 yr. The minimum thickness of basal varves in the center of the valley might better be represented by basal varves in parts of the valley where bedrock is shallow, such as Claremont (average of +50 cm for basal 30 varves, up to 396 cm, Antevs, 1922) or the Passumpsic Valley (45-180 cm; Antevs, 1922). Using these rates, valley filling would occur in 100 yr or less assuming that all valley filling was by varve deposition. However, subaqueous fan deposition at the receding ice front is likely to have filled some portion of the basin with sand and gravel in the first few years after deglaciation. Also, unless a cross-valley profile is very steep complete basin filling would not have to predate valley-side varve deposition and varves can drape the flanks of the basin. Differences in elevation of contemporaneous varves suggest that sedimentation did not closely follow a pattern dominated by the ponding of silt and clay in the center of the valley. All of these characteristics of valley filling during varve deposition suggest that there are not likely to be significant differences between the ages of valley-center and valley-side basal varves in the Connecticut and Passumpsic Valleys of New Hampshire and Vermont. Shallow bedrock in many places and rapid sedimentation rates for ice-proximal varves appear to make basal varves reliable recorders of the age of deglaciation in these valleys.

Critical data from areas with basal varve exposures in the Merrimack Valley do not exist to unequivocally make the same detailed arguments as in the Connecticut Valley. However, there seems to be no reason to expect the Merrimack Valley to behave differently than the upper Connecticut Valley. It has a lower relief than the upper Connecticut Valley, which would allow more draping of varves on valley sides, and basal varves at two sites reach a thickness of 75 cm (Antevs, 1922). In both the Connecticut and Merrimack Valleys basal varves always get younger to the north, a pattern that might not persist if there were differences in age for basal varves located at different cross-valley positions. The conclusion that we reach is that the existing data on basal varve ages in the upper Connecticut and Merrimack basins of New Hampshire and Vermont provide an estimate of the age of deglaciation that does not have significant errors. A similar situation might not exist in the lower Connecticut Valley of Massachusetts and Connecticut where basal varve localities are scarce and the valley is much wider and has larger and deeper subsurface basins. However, a 40-m core down to till taken on the floor of the Connecticut Valley at Amherst has a basal varve age in exact agreement with ages of basal varves found by Antevs (1922) in nearby valley-side surface exposures (T. Rittenour and J. Brigham-Grette, pers. comm.).

The onlapping varve sequences (Figs. 5, 6) record systematic recession of ice from south to north as did Antevs' original analysis that was in the form of a map showing the varve age of deglaciation across New England (Plate VI, Antevs, 1922, compiled with J.W. Goldthwait). However, within a decade of Antevs' original work, Richard Foster Flint (1929, 1930, 1932, 1933) denied systematic ice recession in favor of regional ice stagnation, and more importantly, he also created doubts as to the validity of the varve chronology (Flint, 1930). Flint's later publications (1932, 1933) were apologetic and supportive of the varve chronology as a dating tool, but varve chronology was not viewed with the credibility it had before Flint's criticism. In the 1950's some of the first ^{14}C ages obtained in New England were erroneously interpreted by Flint (1956) to constrain the age of Lake Hitchcock to about 2500 yr. Despite Antevs' (1962) objections these ^{14}C interpretations caused further erosion of confidence in the New England Varve Chronology. Although referenced in the first of Flint's (1947) textbooks on glacial geology, his later two textbooks (Flint, 1957, 1971), used by most students of glacial geology in North America for two decades, have no reference to Antevs' (1922, 1928) work on varves in New England. More recent studies of varves in New England have focused on the sedimentology of the varve sequence, in particular depositional processes and facies changes associated with the varves, and have not addressed issues of chronology (Ashley, 1972, 1975; Ashley *et al.*, 1982). While most glacial geologists working in New England over the last half century have ignored varve chronology as a viable chronologic tool, many investigators (Lougee, 1935b; McNish and Johnson, 1938; Johnson *et al.*, 1948; Verosub, 1979a, 1979b; Thomas, 1984; Ridge and Larsen, 1990, Ridge *et al.*, 1995, 1996; Levy, 1998; T. Rittenour, pers. comm.; A. Werner, pers. comm.) have been able to match new varve sections to Antevs' (1922, 1928) chronology.

OVERLAP OF THE LOWER AND UPPER CONNECTICUT VALLEY VARVE SEQUENCES

Attempts to match Antevs' (1922) lower and upper Connecticut Valley sequences, using visual inspection and mathematical correlation techniques with the aid of a computer, have revealed one potential correlation of the two sequences. With this overlap in place (lower NE varve 6012 = upper NE varve 6601) the two varve records have a greater visual resemblance in terms of relative peak heights and peak position than at any other overlap (Figs. 2, 7). This correlation is not represented by a match that is as compelling as any proposed by Antevs (1922, 1928) when he compiled his sequences in the Connecticut Valley. It is also less compelling than correlations between varves from different glacial lakes in New England (Fig. 4). New ^{14}C ages and paleomagnetic data are used later in this paper to support the correlation of the lower and upper Connecticut Valley sequences. The proposed correlation of the lower and upper valley sequences eliminates the necessity for a stillstand of the receding ice front near Claremont and creates a continuous rapid recession of ice from southern to northern Vermont and New Hampshire.

Three obstacles appear to have prevented a clear correlation of the lower and upper Connecticut Valley sequences. First, the two sequences have varves with greatly different couplet thickness. The first 30 couplets of the upper sequence average more than 50 cm and couplets in the second 100 yr still have an average of about 20 cm (Fig. 7). The corresponding part of the lower Connecticut Valley sequence has couplets with an average thickness of about 3 cm. Second, the thick varves in the beginning of the upper sequence are more likely to have a thickness that reflects local ice-proximal sedimentation (Ridge and Larsen, 1990), rather than regional weather patterns, making them less useful for regional correlation. The varve sections used to compile the first 275 varves of the upper Connecticut Valley sequence (Fig. 5) are all located close to the mouths of rivers near Claremont (Sugar River) and White River Junction, (White and Mas-

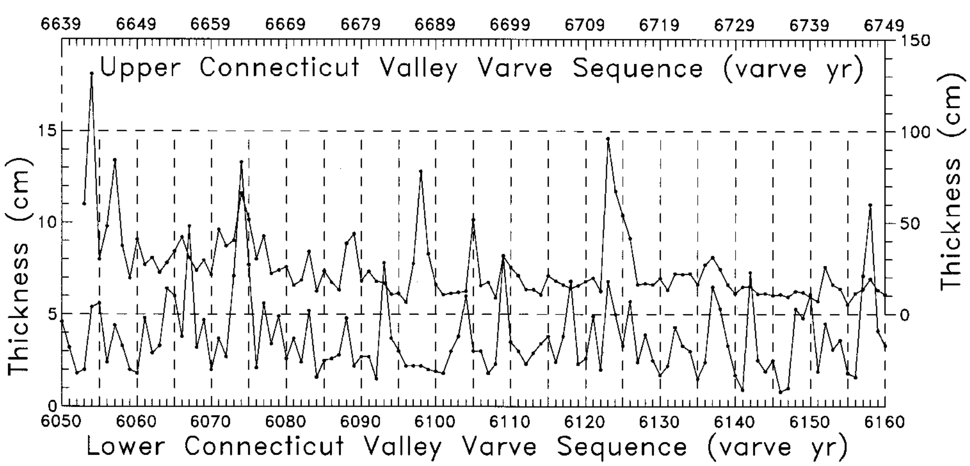

FIGURE 7. Correlation of the lower (bottom) and upper (top) Connecticut Valley normal curves of Antevs (1922). Lower NE varves 6053-6160 are correlated to upper NE varves 6642-6749. Note the different scales used to plot the sequences.

*Corrélations proposées entre les courbes normales des vallées inférieure et supérieure du Connecticut de Antevs (1922). Les varves NE (*New England*) 6053-6110 (vallée inférieure) correspondent aux varves 6642-6749 de la vallée supérieure. Noter les différentes échelles appliquées.*

coma Rivers). Varves deposited at these positions were influenced by large point source supplies of sediment and likely record floods dueto localized precipitation events or the release of water from ice-dammed lakes in tributaries. Varves near Claremont have the added complication of possibly being deposited by northward flowing bottom currents coming from the Sugar River and resulting in localized ponding of sediment. Finally, varves used to construct the last 50 years of the lower Connecticut Valley sequence in the Connecticut Valley and the last 50 years of the Merrimack Valley sequence (both overlap the upper Connecticut Valley varves) are varves influenced by deltaic sedimentation. Varve thickness in these sequences is probably dominated by local sedimentation processes and not regional weather patterns. Although couplets in both the upper and lower Connecticut Valley sequences are annual layers, couplet thickness that does not dominantly reflect a regional weather pattern will negate its easy use for regional correlation.

LAKE STAGES IN THE UPPER CONNECTICUT VALLEY

GLACIAL LAKE HITCHCOCK

The first compilation of glacial lake stages in the Connecticut Valley was by Richard Lougee (1935a), who named Lake Hitchcock after Prof. Edward Hitchcock of Amherst College. Lougee's Lake Hitchcock (1935a, 1939, 1957) extended from Middletown, Connecticut (Fig. 1) northward into New Hampshire. Lougee maintained that the spillway for the lake was near Middletown, despite recognition of another more viable spillway at New Britain (Loughlin, 1905; Flint, 1933; Jahns and Willard, 1942; Fig. 1). A drift dam for the lake was also identified at Rocky Hill, Connecticut (Flint, 1933, 1953), thus completely eliminating the need to extend the lake further south. Modern studies have confirmed and refined the early history of lake levels associated with the development of the New Britain spillway and the failure of the Rocky Hill dam (Hartshorn and Colton, 1967; Koteff *et al.*, 1987; Koteff and Larsen, 1989; Stone *et al.*, 1991; Stone and Ashley, 1992; Stone, 1995). Lougee recognized deltas from Lake Hitchcock as far north as Lyme, New Hampshire (Fig. 1), which he inferred to represent the northward extent of the lake when its dam was breached (Lougee, 1939, 1957).

LOUGEE'S LAKE UPHAM

Lougee's (1939, 1957) interpretation of terraces in the Connecticut Valley near Lyme and Hanover (Fig. 1), as remnants of lake floor from Lake Hitchcock, led him to conclude that the breaching of the Lake Hitchcock dam allowed water to fall 30 m giving way to Lake Upham. Lake Upham was named after Warren Upham who was an early investigator of Connecticut Valley terraces and eskers. Lougee (1957) inferred that Lake Upham drained by way of a channel that was cut across lake floor deposits south of Charlestown, New Hampshire and was graded to a bedrock ledge at Turners Falls, Massachusetts. Lougee extended Lake Upham northward to St. Johnsbury where he proposed a hinge line and an unrealistically steep water plane (>1.6 m/km) to intersect deltas at high elevations in the upper Connecticut and Ammonoosuc Valleys (Fig. 8). Lougee (1957) referred to precise survey data of strandline features collected in the 1920's to support his proposed lake levels, but these data were not published and have not been found in the archives at Dartmouth College (W. Thompson, pers. comm.).

MODERN STUDIES OF ISOSTASY AND LAKE HITCHCOCK DRAINAGE

Leveling surveys by Jahns and Willard (1942) in Massachusetts, that have been greatly refined and expanded to northern New Hampshire and Vermont (Koteff and Larsen, 1989), indicate that the level of Lake Hitchcock was controlled by the New Britain channel in Connecticut. Koteff and Larsen also identified deltas defining a flat, tilted (0.9 m/km, up at 339°) water plane for Lake Hitchcock that extends northward to at least Woodsville and Littleton (Fig. 1), thus refuting Lougee's (1939, 1957) formation of Lake Upham while the receding ice margin was at Lyme. Controversy still exists regarding when Lake Hitchcock abandoned the New Britain spillway and drained at a lower level. ^{14}C ages of plant debris from Connecticut in deposits that represent the drainage of Lake Hitchcock have been interpreted to indicate that drainage occurred at about 13.5 ^{14}C ka (Stone *et al.*, 1991; Stone and Ashley, 1992; Stone, 1995). It has been suggested that perhaps Lake Hitchcock completely drained at about 13.5 ^{14}C ka while the receding ice front was in central Massachusetts at the Holyoke Range (Ashley, 1995). The Holyoke Range is then thought to have served as a barrier allowing the continued impoundment of water to the north during subsequent ice recession. However, a thick package of varves immediately south of the Holyoke Range was deposited almost up to the water plane level of Lake Hitchcock (Werner, 1995). These varves indicate that Lake Hitchcock persisted long after recession of ice north of the Holyoke Range, which does not seem to have served as a dam or spillway.

Drainage of Lake Hitchcock while the receding ice front was in northern New Hampshire and Vermont has been inferred by the identification of Lake Hitchcock deltas as far north as Littleton and Woodsville (Larsen and Koteff, 1988; Koteff and Larsen, 1989). In central Vermont a late drainage for Lake Hitchcock is indicated by Lake Hitchcock deltas found from White River Junction (Fig. 1) northwest into the White River Valley that became a long embayment of Lake Hitchcock (Larsen, 1987a). Lake Hitchcock deltas in the upper White River Valley were dissected by spillway drainage from Lake Winooski (Larsen, 1987b) indicating that Lake Hitchcock drained while Lake Winooski was in existence (Larsen, 1984, 1987a). Antevs' (1928) varve record from Lake Winooski (Fig. 4d) matches the upper Connecticut Valley varve sequence (Antevs, 1922) and indicates that Lake Hitchcock may have drained sometime during the deposition of NE varves 7059-7288 (Fig. 2). By this time ice had receded to the vicinity of St. Johnsbury and Littleton (Fig. 5).

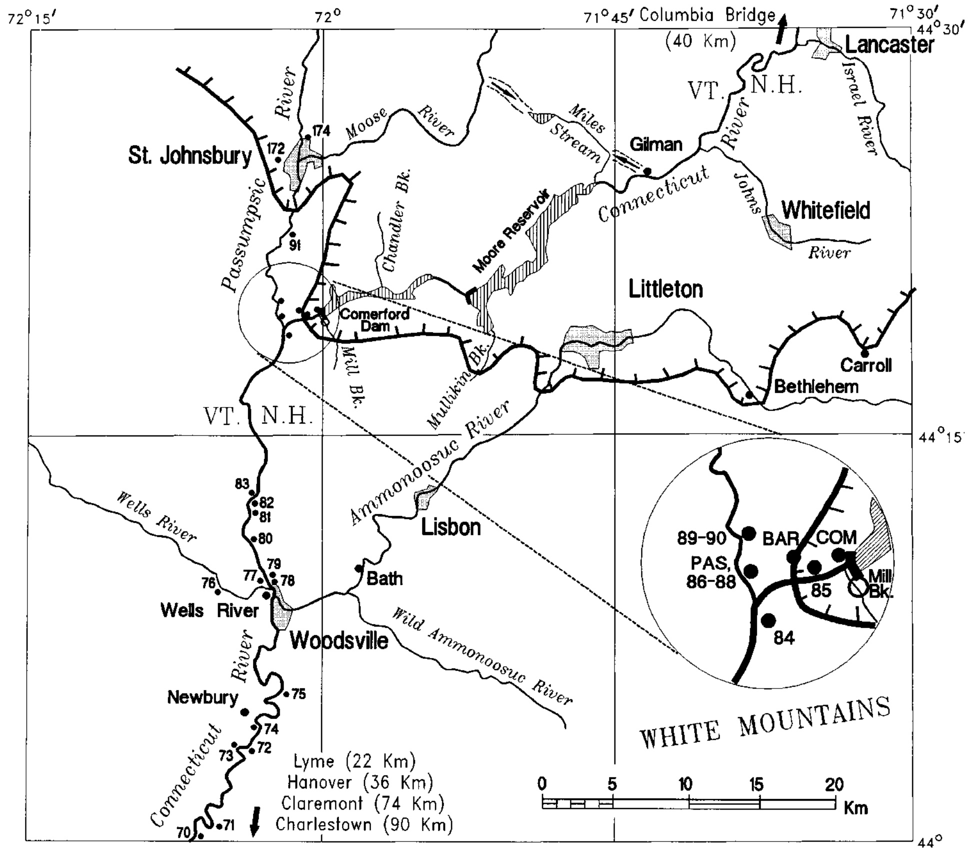

FIGURE 8. Location map of the upper Connecticut Valley near its confluence with the Passumpsic Valley northwest of the White Mountains. The numbered sites are varve sections studied by Antevs (1922, 1928). New sites are listed as BAR, COM, and PAS. The ice front position is the approximate limit of the Littleton-Bethlehem Readvance.

Carte de localisation de la vallée supérieure du Connecticut près de la confluence avec la vallée du Passumsic, au nord-ouest des White Mountains. Les sites de varves numérotés ont été étudiés par Antevs (1922, 1928). Les nouveaux sites sont identifiés par les lettres BAR, COM et PAS. Le front glaciaire donne la limite approximative de la récurrence de Littleton-Bethlehem.

The conflict between the drainage of Lake Hitchcock in Connecticut at 13.5 ^{14}C ka (Stone and Ashley, 1992; Stone, 1995) and younger ages for Lake Hitchcock in the upper Connecticut Valley (discussed later in this paper) has not yet been resolved. It is here suggested that perhaps the macrofossils dated at 13.5 ^{14}C ka used to infer the age of beds representing the drainage of Lake Hitchcock in Connecticut are from reworked older organic sediment. At the very least the upper Connecticut Valley appears to have had a lake in it during deglaciation that exactly coincides with the northward projection of the Lake Hitchcock water plane from Connecticut and Massachusetts (Koteff and Larsen, 1989). The exact position of the receding ice sheet when this lake in the upper valley drained has not yet been determined and has been difficult to study. Deltas from Lake Hitchcock are seldom preserved and they are mostly confined to tributary valleys as a result of rapid ice recession, the short life span of Lake Hitchcock in the upper Connecticut Valley, and the dissection and trimming of these features by later drainage.

POST-HITCHCOCK LAKES

Throughout the Connecticut Valley there is pervasive evidence for lake levels below the level of Lake Hitchcock. Drainage of Lake Hitchcock in Connecticut allowed a river to form high terraces on an exposed lake bed (Stone and Ashley, 1992), and when combined with isostatic depression at the time, would have allowed at least low level lakes to persist further north in the valley. The accordance of deltas in the valley on water planes approximately parallel to and about 8-10 m lower than the projected Lake Hitchcock water plane (Larsen and Koteff, 1987a; Koteff and Larsen, 1989) suggests that a discrete lower lake level formed prior to significant isostatic tilting in the area. This lake is well represented by meteoric deltas in southern New Hampshire and Vermont at the mouths of the Cold and Saxtons Rivers (Ridge, 1988). This lake level also appears to be represented by ice-contact deltas in the Chandler Brook and Ammonoosuc Valleys of the upper Connecticut Valley (Ridge *et al.*, 1996; Fig. 8). It is clear that Lougee (1939, 1957) did not recognize these deltas as representing a separate lake level. In some places Lougee tried to associate the deltas with Lake Hitchcock or created a hinge line and steep upper end of the Lake Upham water plane that intersects these features.

In the upper Connecticut Valley additional deltas record water levels that are 20 m or more below the level of Lake Hitchcock (Koteff and Larsen, 1989). Lake levels in this range are recorded by deltas and terraces near Hanover and Lyme (Fig. 1) that were used by Lougee, 1939, 1957 to define his Lake Upham. Evidence for low lake levels has been found further north (Koteff and Larsen, 1989) where they appear to be represented by terraces at Chandler Brook (Ridge *et al.*, 1996; Fig. 8). Perhaps these features represent Lougee's Lake Upham without its hinge line and steep profile to the north. Regardless, ice-contact deltas in the Chandler and Ammonoosuc Valleys at an elevation about 8 m below the projected Lake Hitchcock water plane indicate that lower lakes could not form until ice had receded north of St. Johnsbury and Littleton for the final time.

While postglacial lake levels in the upper Connecticut Valley have been difficult to document the persistence of lakes in the valley for at least 1600 yr after deglaciation is easily documented. Antevs counted about 1500 varves at Newbury that begin about 100 yr after deglaciation (Antevs, 1922, site 73; Fig. 8). A reexamination of this section (discussed later) reveals another 179 varve years that were not counted in the 1920's. There also appears to be a thick package of thin varves in the Ammonoosuc Valley that represents a long-lived lake (Sayles, 1919; Billings, 1935).

GLACIAL LAKES COOS AND COLEBROOK

North of Littleton in the Connecticut Valley Lougee (1939) found evidence for glacial lakes extending to Québec at higher levels than the modern projected water planes for Lake Hitchcock (Koteff and Larsen, 1989). The southern of these lakes, Lake Coos, and further north Lake Colebrook require blockage of the Connecticut Valley and diversion of spillway drainage. Lougee (undated) inferred that thick till at Fifteen Mile Falls (Comerford Dam, Fig. 8) provided a dam and stable spillway for lake Coos. However, till at this location is overlain by non-resistant silt and clay well below the projected level of even Lake Hitchcock thus eliminating it as a potential dam or spillway for Lake Coos. A better alternative is a channel at Gilman, Vermont (Ridge *et al.*, 1996) where water could have been diverted to Miles Stream before returning to the Connecticut Valley (Fig. 8). The Connecticut Valley at Gilman has a narrow constriction where till probably blocked its modern drainage path and diverted water into the Gilman channel. Lake Coos deltas identified by Lougee (undated) at the mouths of the Johns and Israel Rivers (Fig. 8) appear to be graded to a lake level compatible with the Gilman spillway. Lake Colebrook was a water body separate from Lake Coos because the floor of the Connecticut Valley and varves from Lake Colebrook at Columbia Bridge (Miller and Thompson, 1979) are above the projected water plane for Lake Coos, even with a steep isostatic tilt of 1.0 m/km.

VARVES AT NEWBURY, VERMONT: FLOOD EVENTS AND LAKE LEVEL CHANGE

In 1997 the first author and his students at Tufts University were able to locate a varve section about 50 m downstream from Antevs' original exposure of varves at Newbury (1922, site 73; Fig. 8) where Antevs counted 1500 couplets beginning at NE varve 6990. Antevs measured couplets up to NE varve 7316 but only counted the remaining couplets because they were too thin and indistinct to measure accurately in the field. We have collected samples of the entire section in two sets of overlapping PVC cores (7.6 cm id, 60 cm long) for measurement and analysis of the varve sequence. Our count was done on cores that were partially dried to improve the color contrast between clay and silt beds. Varve measurement was done with the aid of magnified video images and computer image software that allowed us to make measurements and assemble data files from the images. The new analysis of the section starts at NE varve 6944, 46 yr below Antevs' measured section. We have been able to match couplets at the exposure with NE varves 6944-7510 and have counted upward from that point to NE varve 8679 (+35/–20) after accounting for uncertainties in the interpretation of annual couplets (179 yr beyond Antevs' count).

In addition to providing an extension of the New England Varve chronology and new ^{14}C ages (discussed later) the Newbury section has a record of abrupt changes in varve thickness and lithology that appear to represent flood events and drops in lake level. Flood events are represented by the abrupt appearance of a few excessively thick couplets, but varve thickness returns to pre-flood thickness within a few years. Drops in lake level are also marked by the abrupt appearance of thick couplets, although usually not as extreme, but lake level drops create thickness and lithologic changes in the varve sequence that persist for many decades or centuries after the event. Persistent changes are caused by increased erosion as stream valleys and the glacial meltwater system adjust to falling base level and deltas and lake floor deposits are exposed to erosion. Also, increased sediment volumes delivered to the lake are distributed across a lake floor surface area that has decreased in size.

Beginning with NE varve 7200 at Newbury there is a 14-yr interval of varves with exceedingly thick couplets that can be found over a distance of 45 km (NE varves 7200, 7202, 7203, and 7213 on Figs. 9a, 9b). Varves in this interval separate thin varves (<1 cm) with silty summer partings below from thicker (2-3 cm) varves that have distinct silt and fine sand summer beds. The same pattern occurs in contemporaneous varves at Wells River near the mouth of the Ammonoosuc Valley where the extremely thick varves reach a thickness of 76 cm (Antevs, 1922). At Wells River the 14-yr varve package separates varves with an average thickness of 2 cm below from varves averaging 5 cm above the interval. This event was also found by Antevs (1922) further north in the Passumpsic Valley near St. Johnsbury (Fig. 8). The exceedingly thick varves occur at about the time that lakes in the upper Ammonoosuc Valley east of Littleton (Lougee, 1940; Thompson *et al*., 1996, 1999) catastrophically drained to the Connecticut Valley in response to the recession of ice from the Bethlehem Moraines. The Ammonoosuc Valley floods may represent the largest release of lake water impounded in a tributary during the recession of ice in the upper Connecticut Valley. The lithologic and thickness changes that persist after this event (after NE varve 7213, Fig. 9b) also indicate that a drop in lake level occurred in the Connecticut Valley. It is suggested here that, if Lake Hitchcock drained while receding ice was in the northern Connecticut Valley, this event may represent the initial drop in the level of Lake Hitchcock. More speculatively, the Ammonoosuc Valley floods may have provided a triggering mechanism that facilitated the initial failure of the Rocky Hill dam in Connecticut. Alternatively, the lowering of Lake Hitchcock in the lower Ammonoosuc Valley may have facilitated the catastrophic release of lake water in the upper Ammonoosuc Valley by suddenly increasing hydraulic gradients across an ice dam. A resolution of the problem of when Lake Hitchcock drained will be needed to confirm or deny these possibilities.

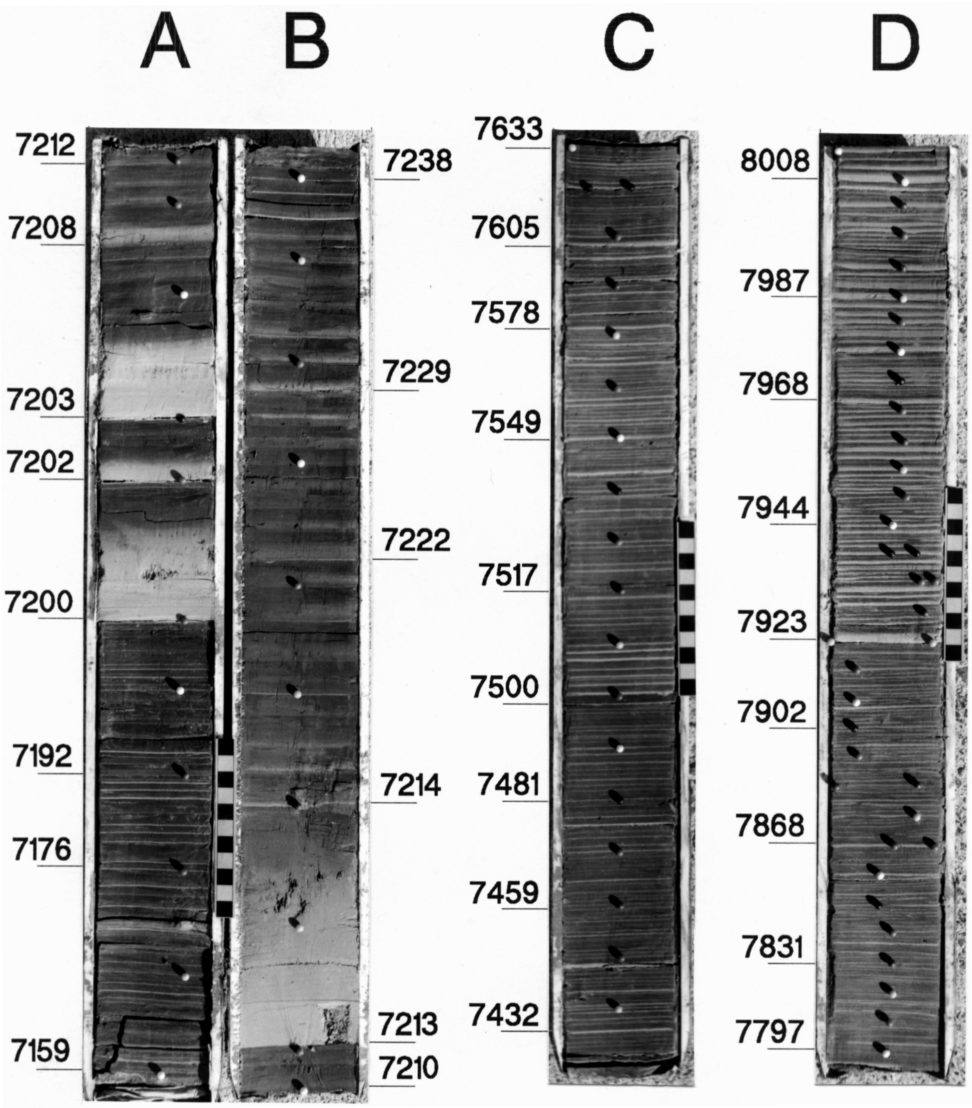

FIGURE 9. Flood and drainage events in varve cores (7.6-cm diameter) from Newbury, Vermont. Scales show centimeters. Pins in the core mark the boundaries of video images. All lines indicating NE varve numbers are positioned at the bottoms of numbered couplets that are either prominent varves or varves marked by pins. A and B) Varves 7159-7238 show a series of flood events in NE varves 7200, 7202, 7203, and 7213. Evidence for a simultaneous drop in lake level comes from the permanent 3 to 5-fold increase in couplet thickness that persists after the flood events and commences at NE varve 7214. C) NE varves 7428-7633 in which NE varve 7500 marks a drop in lake level. Note the sudden increase in thickness at NE varve 7500 and the more conspicuous summer silt beds that persist for decades after this event. D) NE varves 7797-8010 in which sudden and permanent increases in thickness and silt content at NE varve 7923 appear to represent a drop in lake level and possibly a flood event.

Les marques d'inondation et d'écoulement dans les carottes de varves (7,6 cm de diamètre) de Newbury, au Vermont (échelle en cm). Les repères dans les carottes donnent les limites des images vidéo. Toutes les lignes se rapportant aux numéros de varves sont situées à la base des doubles feuillets qui sont soit en saillie, soit identifiés par des repères. A et B) La séquence de 7159 à 7238 montre une série d'inondations dans les varves 7200, 7202, 7203 et 7213. La baisse simultanée des niveaux lacustres est signalée par l'augmentation de 3 à 5 fois l'épaisseur des feuillets qui persiste après les inondations et qui commence avec la varve 7214. C) Dans la séquence de 7228 à 7633, la varve 7500 montre une baisse du niveau lacustre. Noter la soudaine augmentation dans l'épaisseur à la varve 7500 et les feuillets d'été plus visibles même plusieurs décennies après l'événement. D) Dans la séquence 7797 à 8010, on observe une augmentation soudaine et permanente dans l'épaisseur et la teneur en silt à la varve 7923 qui semble traduire une baisse du niveau lacustre et peut-être une inondation.

Beginning at NE varve 7500 is another abrupt change in varve thickness and lithology that appears to represent another drop in lake level. At Newbury this event is marked by a sudden increase in average varve thickness from about 0.2-0.3 cm to 0.6 cm that persists for about 10-15 years (Fig. 9c). Varves below this interval have very thin silty summer partings and very clayey winter beds. Varves above eventually become slightly thinner, but have slightly thicker and sandier summer beds that are more conspicuous in a partially dried core than below NE varve 7500 (Fig. 9c). In the Passumpsic Valley 45 km to the north (Fig. 8) this event also occurs in the varve stratigraphy with NE varves 7500-7515 being about 5-10 cm thick and varves below less than 1 cm thick (Antevs, 1928). It is suggested that this event may represent the drop of water levels in the Connecticut Valley from 8-10 m below the water plane of Lake Hitchcock to about 20 m below. A similar more pronounced event occurs later in the Newbury section at NE varve 7923 (Fig. 9d) and may represent another drop in lake level, perhaps down to 30-40 m below the Lake Hitchcock water plane. It is not possible to unequivocally relate these events to specific lake levels and one must also consider flood events caused by the failure of dams for Lakes Coos and Colebrook. However, the events at Newbury do represent important marker horizons in the varve stratigraphy. If they can be related to specific lake levels or flood events they will provide an exact chronology for drainage events in the upper Connecticut Valley.

THE LITTLETON-BETHLEHEM READVANCE

THE BETHLEHEM MORAINES AND VARVE STRATIGRAPHY

Prior to 1910 morainic topography from Bethlehem to Littleton, New Hampshire was interpreted to be the result of northward flowing valley glaciers from the White Mountains at the end of the last glaciation (Agassiz, 1870; Hitchcock, 1878; Upham, 1904; see Thompson *et al.*, 1996, 1999; Thompson, 1999). James W. Goldthwait (1916) re-interpreted the Bethlehem Moraines as ice-marginal deposits built at the southern margin of a receding continental ice sheet. In the Connecticut Valley at the Comerford Dam site (Figs. 5, 8) Antevs (1922) found a basal varve resting on till (NE varve 7305, site 85) that was about 300 yr younger than basal varves resting on bedrock only 3 km to the west in the Passumpsic Valley (NE varve 7010, site 86). Antevs (1922) inferred that the apparent delay in deglaciation in the Connecticut Valley represented a stillstand of ice that was the westward equivalent of the Bethlehem Moraines. He also associated the stillstand with a moraine at St. Johnsbury in the Passumpsic Valley.

COMERFORD DAM CONSTRUCTION SITE

During construction and subsurface investigation for the Comerford Dam, Irving B. Crosby (1934a, 1934b) found pervasive two-till stratigraphy in borings and a large bluff exposure near the foot of the proposed Comerford Dam along Mill Brook (also called Smith Brook) in New Hampshire (Fig. 8). Crosby interpreted the upper of his two tills as representing a readvance. With additional fieldwork in the area he extended the Bethlehem Moraines to 7 km west of Littleton to include ice-marginal deposits in the Mullikin Brook valley. Careful reexamination of the sections on Mill Brook have revealed a more complete stratigraphy than seen by Crosby (Ridge *et al.*, 1996; Thompson *et al.*, 1999). On a higher bank about 250 m up stream from Crosby's section is an exposure of three till units. The basal till unit in this new exposure is also the basal unit seen by Crosby and except for a lack of any weathering it has all of the characteristics of a pre-late Wisconsinan 'lower' till unit seen across much of New England (Koteff and Pessl, 1985; Newman *et al.*, 1990; Oldale and Colman, 1992). The middle till unit in the new exposure appears to be the equivalent of Crosby's upper till which he found overlain by clay (Crosby, 1934b). Crosby did not see the upper till of the new exposure because the top of his section was eroded during the development of a stream terrace that caps his section (Ridge *et al.*, 1996; Thompson *et al.*, 1999). All till units at Mill Brook have the potential of being Late Wisconsinan but this seems especially true of the upper two tills. Stratified deposits separate the upper two till units and the tills represent separate ice sheet oscillations.

Varve sections stratigraphically above Crosby's (1934a, 1934b) upper till unit were exposed on both sides of the Connecticut Valley during the Comerford Dam construction and measured by J.W. Goldthwait and Dick Lougee. All of the sections were matched to the New England Varve Chronology (Antevs, 1922, 1928) and were reported by Lougee (1935b) to match varves at Antevs' site 85 (NE varves 7300-7400; Figs. 5, 8), thus postdating any proposed readvance in the area. Lougee did not publish the results or locations of these varve measurements. However, Lougee (1935b) did publish the results of varve measurements from a section in Vermont at the Comerford Dam (300 m east of site 85, Fig. 5) in which 119 varves were sandwiched between a lower stony till and an upper clayey "material resembling till". Despite minor deformation of the varves, which Lougee attributed to overriding ice, he measured and matched the bottom 52 varves with NE varves 7036-7087 of the Passumpsic Valley (Figs. 10a, 10b). This varve section appears to record the time between the initial recession of ice (NE varve yr 7036) and ice readvance (referred to by Thompson *et al.*, 1999 as the Littleton-Bethlehem Readvance) that arrived no earlier than NE varve yr 7154. Based on Antevs' (1922) earlier results final ice recession occurred no later than NE varve yr 7305 (site 85, Fig. 8).

J.W. GOLDTHWAIT'S GREAT RETRACTION

For reasons that today seem inexplicable, given his original vivid descriptions of the topography of the Bethlehem Moraines and recent field observations (Thompson *et al.*, 1996, 1999; Thompson, 1999), J.W. Goldthwait (1938) recanted his interpretations of the moraines as prominent ice-marginal features produced by an active ice sheet (Goldthwait, 1916). Seemingly under the influence of Flint (1929, 1930, 1932, 1933), and to the displeasure of Lougee (1940), Goldthwait reinterpreted the moraines as stratified deposits created by regional stagnation of the last ice sheet. Goldthwait's retraction, along with the support of Flint, and doubts created in the 1930's regarding the validity of the New England Varve Chronology, diminished the significance of the Bethlehem Moraines as ice-front positions.

NEW OBSERVATIONS NEAR THE COMERFORD DAM

We have been able to relocate Lougee's (1935b) Comerford Dam section, or more likely a very similar nearby outcrop (COM on Figs. 5, 8), and again matched the varves to Antevs' (1922) chronology (Ridge *et al.*, 1996; new data). The varve sequence begins with NE varve 7036 overlying till and continues to NE varve 7154 at the top of the section (Fig. 10b). Although our section ends at precisely the same couplet as the top of Lougee's (1935b) section we were unable to find the clayey till-like material visible on Lougee's (1935b) photograph of his exposure. Our exposure was truncated in the final stages of dam construction and NE varve 7154 is overlain by 0.5 m of sandy artificial fill. Varves at our section exhibit wavy bedding and are more compact than the varves in other sections in the area. However, it is not clear whether the deformation is due to overriding ice or mass movement and whether the compaction represents loading by ice.

Further support for the Littleton-Bethlehem Readvance was found in new varve sections about 1.5 km west of Lougee's Comerford Dam section along a small ravine draining south to the Connecticut River (Ridge *et al.*, 1996). Varves at the new site, which is here called the Barnet section (BAR on

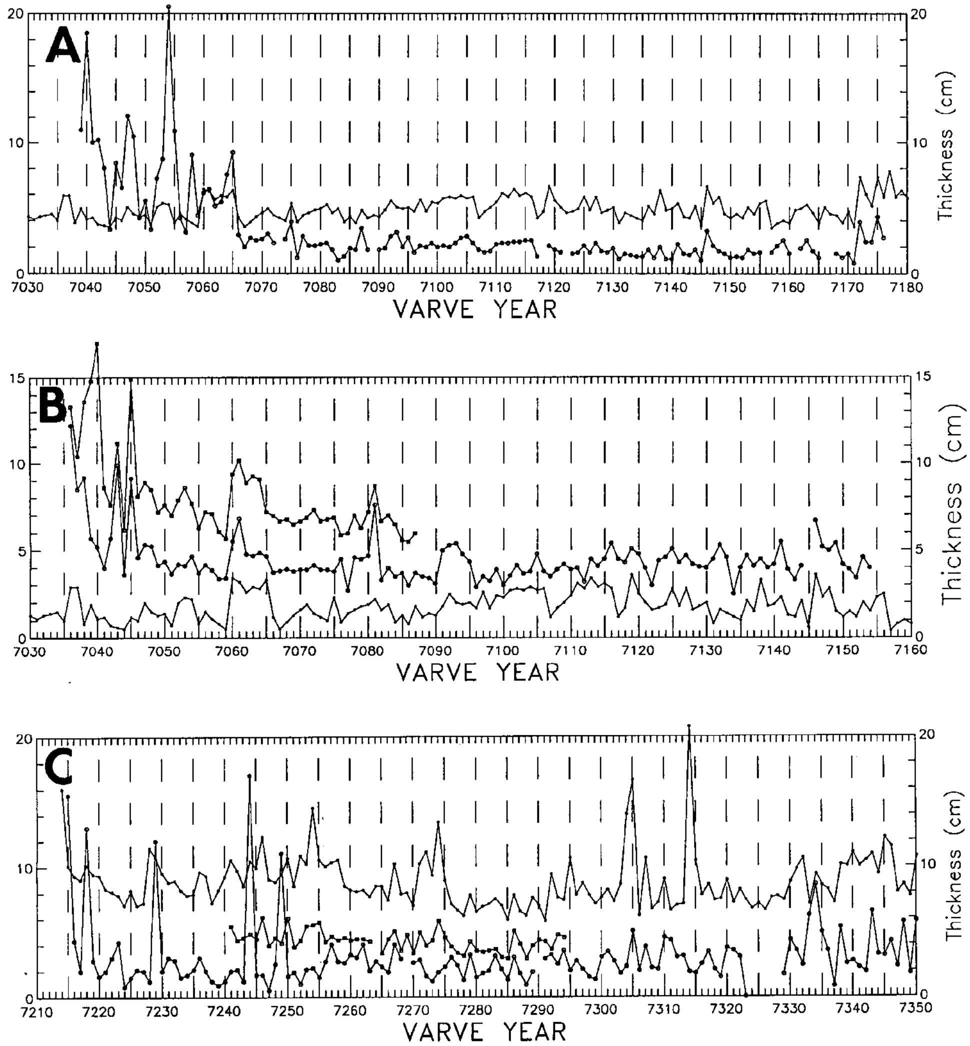

FIGURE 10. Correlation of varve measurements in the upper Connecticut and Passumpsic valleys (Figs. 5 and 8) with the New England Varve Chronology (Antevs, 1922). All plots are at the same scale but some have been shifted as indicated. A) Section PAS (bottom) vs. NE varves 7030-7180 (top, +2 cm). B) Comerford Dam sections in Vermont of Lougee (1935b; at COM on Fig. 8; top, +4 cm) and new composite section (COM on Fig. 8; middle, +2 cm) vs. NE varves 7030-7160 from the Passumpsic Valley (bottom, –1 cm). C) Barnet sections, BAR (bottom; middle, +2 cm) vs. NE varves 7210-7350 (top, +4 cm).

Correspondance entre les mesures des varves des vallées supérieures du Connecticut et du Passumpsic (fig. 5 et 8) et celles de la New England Varve Chronology *(Antevs, 1922). Toutes les données sont à la même échelle, mais certaines ont été décalées tel qu'indiqué. A) Coupe PAS (en bas) et varves (NE) 7030-7180 (en haut, +2 cm). B) coupes de Comerford Dam (Vermont) de Lougee (1935b; COM de la fig. 8 ; en haut, +4 cm) et nouvelle coupe composite (COM à la fig. 8 ; au centre, +2 cm) et varves (NE) 7030-7160 de la vallée du Passumpsic (en bas, –1 cm). C) Coupes Barnet, BAR (en bas ; au centre, +2 cm) et varves (NE) 7210-7350 (en haut, +4 cm).*

Figs. 5, 8), match varve sections in the Passumpsic Valley (Antevs, 1922, site 86) spanning NE varves 7215-7350 (Fig. 10c). If the Littleton-Bethlehem Readvance moved east of the Comerford Dam, it either did not quite reach the Barnet section or readvance deposits occur just below the exposed part of the section between NE varves 7154 and 7215. The lower 40 couplets of the Barnet section appear to be ice-proximal couplets that are up to 20 cm thick and contain rippled sand beds with current directions of 190-220°. These couplets are lithologically similar to basal or ice-proximal varves at other localities in this area (Antevs, 1922, sites 85 and 86; Lougee, 1935b; base of section PAS on Figs 5, 8, 10a) and are difficult to match with the New England Varve Chronology. Upward in the Barnet section varves become progressively thinner, lose the sandy character present lower in the section, and are more easily matched to the New England Varve Chronology. Overall the Barnet section appears to be consistent with varve deposition in an ice-proximal environment followed by increasingly more distal meltwater deposition during ice recession.

Higher in the varve sequence near the Comerford Dam Antevs (1922) recorded a transition over about 20 yr time marked by the upward thickening of varves combined with a pronounced increase in clay content (NE varves 7330-7500, sites 85 and BAR, Figs. 5, 8, 10c). The top of the Barnet section contains this transition zone in which the increasing clay content of summer beds makes the distinction of annual couplets and varve measurement difficult. This clayey interval appears to be a product of ice recession. Ice recession in the Passumpsic and Moose River Valleys allowed the Moose River Valley to freely drain to the Passumpsic Valley instead of being forced to overflow into the Connecticut Valley by way of Chandler Brook and Miles Stream (Fig. 8). Recession of ice north of the threshold at Gilman in the Connecticut Valley caused the formation of Lake Coos that served as a settling basin. The decanting of water from one glacial lake into another such as occurred at Gilman has been recognized as a significant factor in reducing the volume and grain size of sediment supplied to a down valley lake (Smith, 1981; Smith and Ashley, 1985). Lakes down valley are also likely to have lower underflow current velocities, which may allow more clay deposition. Ice recession in the Moose River Valley and in Lake Coos likely reduced the amount of silt and fine sand delivered to the Connecticut Valley immediately south of Lake Coos and may account for the clayey couplets beginning at NE varves 7330-7350.

PALEOMAGNETIC INVESTIGATIONS OF VARVES

PIONEERS IN SEDIMENTARY PALEOMAGNETISM

During the 1930's the New England Varve Chronology attracted the attention of geophysicists trying to document the secular variation of the geomagnetic field by studying sedimentary deposits (McNish and Johnson, 1938). The varve chronology provided an unparalleled time scale and the varves were composed of fine-grained sediment that was known to carry stable magnetic records. Using the varves in the Connecticut Valley Johnson *et al.* (1948) assembled a natural remanent magnetization record of declination (Fig. 11) for parts of both the lower and upper Connecticut Valley sequences of Antevs (1922, 1928). Johnson *et al.* (1948) took advantage of sites with long varve records, especially Antevs' (1922) Newbury section (site 73, Fig. 8), and at every section found an exact match between their varve measurements and Antevs' measured chronology. They did not create a complete inclination record because the results of laboratory sedimentation experiments reduced their confidence in the ability of sample inclination to faithfully record the geomagnetic field. In addition, their remanence results were never subjected to alternating field demagnetization (Zijderveld, 1967) in order to test the stability of samples. The removal of unstable components of magnetism with this technique is required in order to isolate detrital remanent magnetization as a record of the geomagnetic field.

REFINEMENT OF CONNECTICUT VALLEY PALEOMAGNETIC RECORDS

After the development of alternating field demagnetization, and statistical techniques for evaluating the precision of remanence data in the 1960's, Kenneth Verosub (1979a, 1979b) refined the work of Johnson *et al.* (1948) by formulating new detrital remanence records of declination and inclination for NE varves 3150-5500 (Figs. 11, 12). Using new exposures, and some originally studied by Antevs (1922), Verosub was able to match his varve records with the New England Varve Chronology. The first author and his students at Tufts University have been able to continue this work by collecting samples from varves at Canoe Brook and several exposures in the Connecticut, Passumpsic, and Merrimack Valleys (Figs. 11, 12, Appendix). At Newbury our reformulated declination and inclination records span NE varves 6963-8467. Paleomagnetic records for the entire New England Varve Chronology from NE varve 3150-8467 have now been reformulated except for results from NE varves 6601-6944. However, this interval partly overlaps the lower Connecticut Valley sequence leaving only NE varves 6850-6944 not covered by new results. Results obtained by Verosub (1979a, 1979b) and our new data are very similar to the results of Johnson *et al.* (1948). It is important to note that the magnetic records from the lower and upper Connecticut Valley are compatible with the overlapping correlation of the upper and lower Connecticut Valley varve sequences (Fig. 7).

REGIONAL PALEOMAGNETIC CORRELATIONS

Remanent declination and inclination results provide useful records for testing interregional chronologic correlations (Brennan *et al.*, 1984; Ridge *et al.*, 1990, 1991, 1995; Pair *et al.*, 1994; Ridge, 1997), even with varve or other bedded mud sequences where a varve correlation is not possible. For the purposes of correlation declination records appear to be more useful because they are a more faithful record of the geomagnetic field and declination tends to vary over a range of about 70°. Inclination can be subject to flattening by sediment compaction and other depositional processes (see review in Ridge *et al.*, 1990), and geomagnetic inclination generally varies over a range of only 40°.

The remanent declination record for lake sediment in the Connecticut and Merrimack Valleys can be correlated with a compilation of declination records from New York (Fig. 11). The lake sediments used to construct the New York record are tied to glacial events that can then be magnetically correlated to varve sequences in New England, allowing a regional correlation of glacial events across several drainage basins. The most striking feature on the paleomagnetic declination correlation is a prominent westward swing in declination to 35-60° West (325-300°). This event is unique on both declination records and is a feature that can be used as a reference interval for regional correlation.

The inclination records from New England and New York can only be matched for the time period representing the last 1900 varve yr of the paleomagnetic record in New England (Fig. 12). Paleomagnetic records from prior to this time in New York come from sections in the western Mohawk Valley (Ridge *et al.*, 1990) that have flattened inclinations which negates their use for stratigraphic correlation. The Mohawk Valley varve sections occur beneath a great thickness of overlying sediment (15 m or more) and in most cases were compacted by overriding ice. The remanent inclination results from New England do not appear to suffer the same problems and are a more faithful record of geomagnetic inclination than records from the western Mohawk Valley of New York.

RADIOCARBON CALIBRATION OF VARVES

CALIBRATION OF THE LOWER CONNECTICUT VALLEY VARVE SEQUENCE

Organic sediment recovered from varves at Canoe Brook, Vermont (Fig. 1; Ridge and Larsen, 1990) has provided the only ^{14}C calibration of the lower Connecticut and Merrimack Valley varve sequences of Antevs (1922). A cluster of three ^{14}C ages on plant macrofossils in NE varve 6150 provide a calibration of 12.3 ^{14}C ka (Fig. 13; Table I). However, there may have been some lag between when the plants died and lacustrine deposition in which case the ^{14}C ages represent a maximum ("oldest possible") age for NE varve 6150. AMS ^{14}C ages of terrestrial macrofossils from varves in Sweden have a

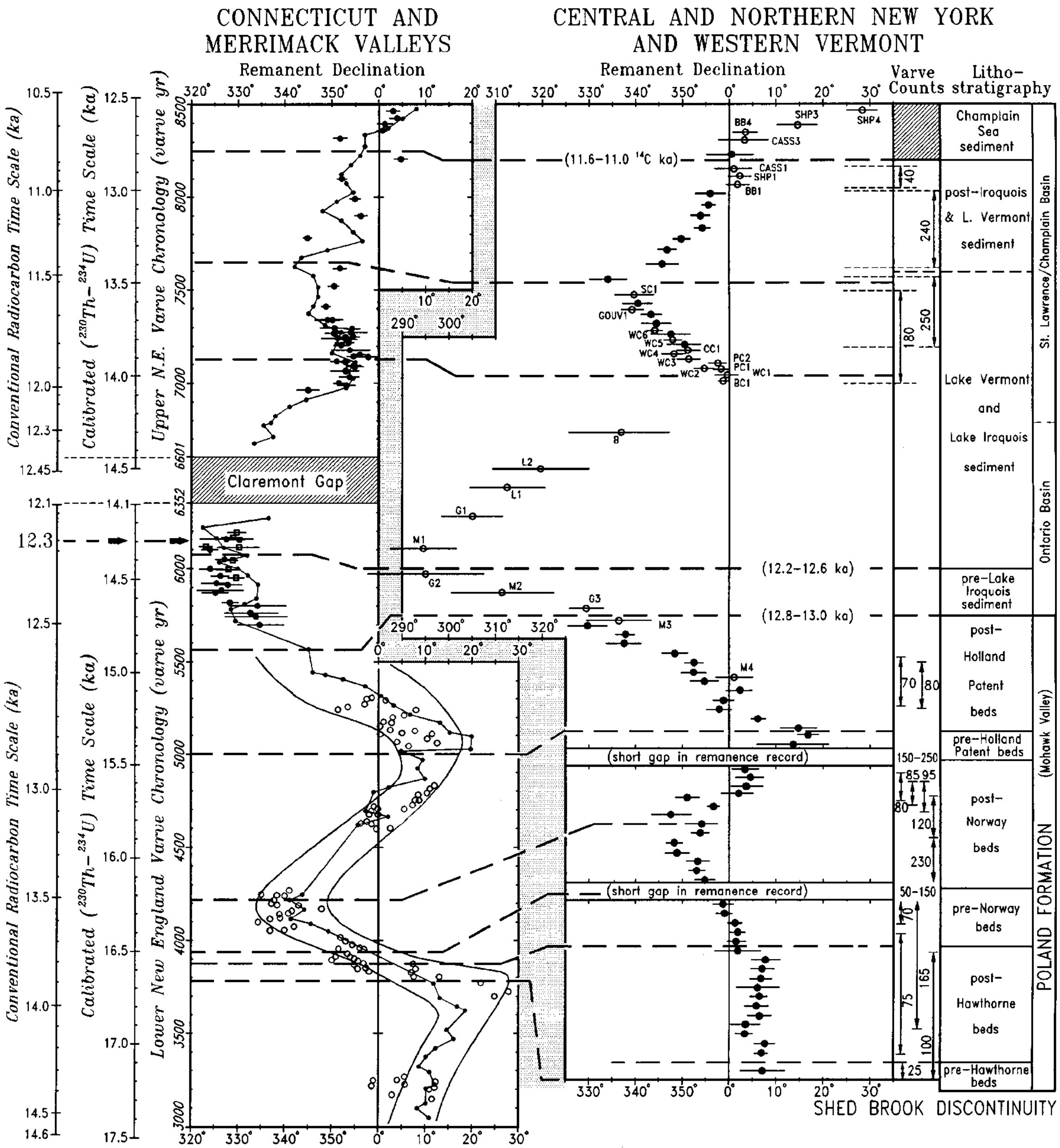

FIGURE 11. Correlation of Late Wisconsinan paleomagnetic declination records from New England and New York. All data except from Johnson *et al.* (1948) are alternating field demagnetized at 17.5-40 mT and error bars are α_{95} (precision parameter) values. The Connecticut and Merrimack Valley declination record is plotted using the New England Varve Chronology as a time scale. The New York and western Vermont records are plotted by age relative to lithostratigraphic units, superposition at individual exposures, and geomorphic relationships (Brennan *et al.*, 1984; Ridge *et al.*, 1990; Pair *et al.*, 1994). Data in New England are from Johnson *et al.* (1948; dots with tie line), Verosub (1979a; open circles and envelope), and new results (Appendix) in the Merrimack Valley (open squares) and Connecticut Valley (dark circles). Data in New York are from Ridge *et al.* (1990; dark circles, Mohawk Valley), Brennan *et al.* (1984; open circles, eastern Ontario Basin), and Pair *et al.* (1994; open circles, St. Lawrence Basin), and new results in the Champlain Valley (dark circles; Appendix). The age for the beginning of Lake Iroquois is from Muller and Prest (1985), Muller *et al.* (1986), and Muller and Calkin (1993). The age of the Champlain Sea invasion shown on the New York record is based on Anderson (1988) and Rodrigues (1988, 1992).

Corrélations entre les relevés de déclinaison paléomagnétique de la Nouvelle-Angleterre et de l'état de New York. Toutes les données, sauf celles de Jonhson et al.*, sont démagnétisées (champ magnétique alternatif) à 17,5-40 mT et les traits horizontaux montrent un intervalle de confiance à* α_{95}. *La* New England Varve Chronology *a servi d'échelle temporelle au relevé de déclinaison des vallées du Connecticut et du Merrimack. Les relevés de l'état de New York sont reportés chronologiquement d'après les unités lithostratigraphiques, les superpositions à certains sites et les liens géomorphologiques (Brennan* et al.*, 1984 ; Ridge* et al.*, 1990 ; Pair* et al.*, 1994). Les données sur la Nouvelle-Angleterre sont de Johnson* et al. *(1948 ; points reliés entre eux), Verosub (1979a ; cercles non tramés et bordés) ; les nouvelles données (Appendice) concernent la vallée du Merrimack (carrés non tramés) et la vallée du Connecticut (cercles noirs). Les données de l'état de New York sont de Ridge* et al. *(1990 ; cercles noirs, vallée du Mohawk), Brennan* et al. *(1984 ; cercles non tramés, bassin de l'ouest de l'Ontario), et de Pair* et al. *(1994 ; cercles non tramés, bassin du Saint-Laurent.) ; les nouveaux résultats concernent la vallée du lac Champlain (cercles noirs ; Appendice). La datation touchant le début du Lac Iroquois est de Muller et Prest (1985), Muller* et al. *(1986) et Muller et Calkin (1993). Le début de la Mer de Champlain a été daté par Anderson (1988) et Rodrigues (1988, 1992).*

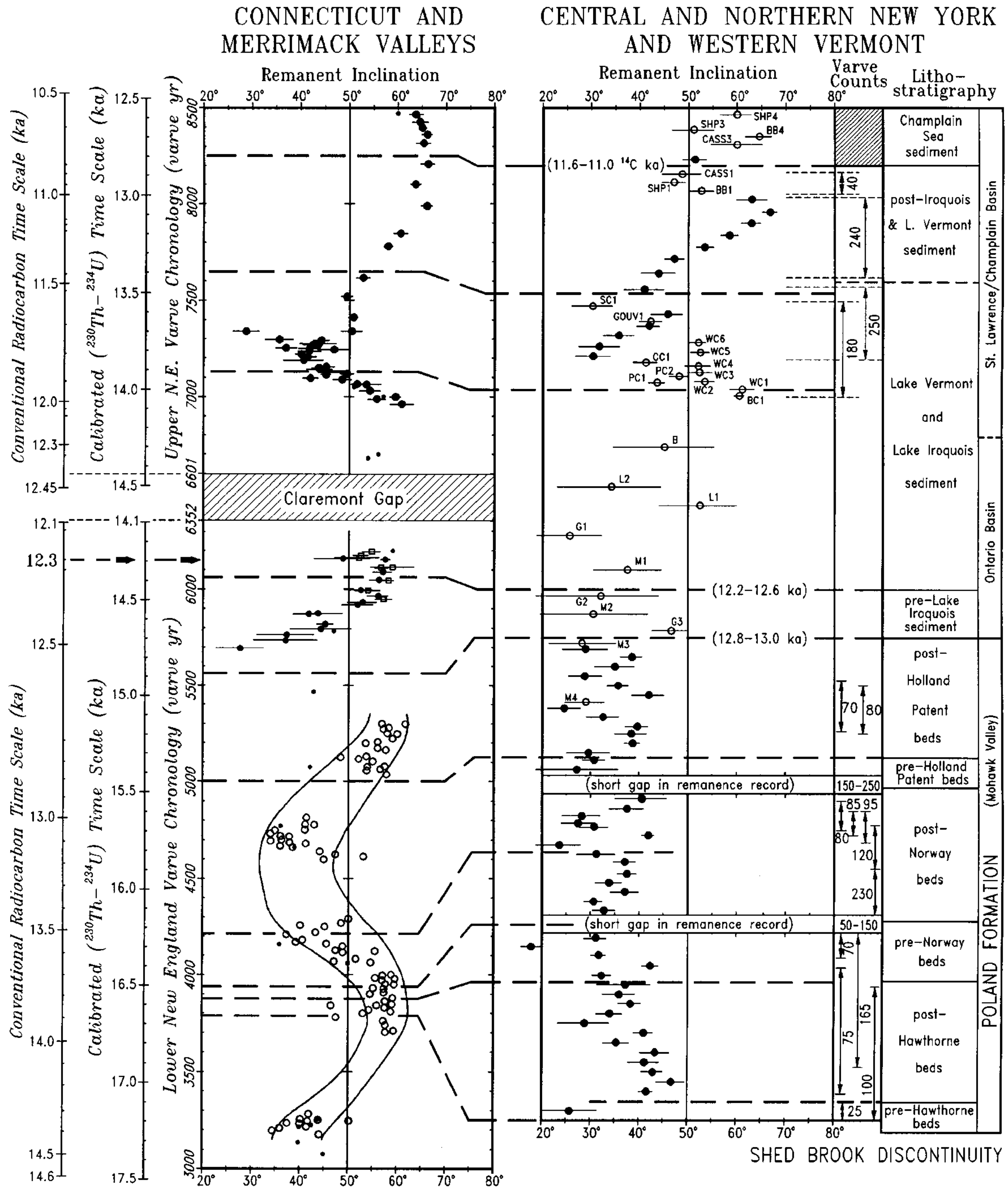

FIGURE 12. Correlation of Late Wisconsinan paleomagnetic inclination records from New England and New York. Correlation tie lines are based on declination results (Fig. 11). Data sources, plotting convention, and symbols are the same as for Figure 11.

Corrélation entre les relevés d'inclinaison paléomagnétique de la Nouvelle-Angleterre et de l'état de New York. Les lignes de lien corrélatif sont fondées sur les résultats de déclinaison (fig. 11). Se reporter à la figure 11 pour les sources des données, la méthode employée et les symboles utilisés.

scatter that reflects lags in deposition and the youngest ages appear to yield the most accurate estimate of true ^{14}C ages for the varves (Wohlfarth *et al.*, 1995). In previous publications (Ridge *et al.*, 1995, 1996; Ridge, 1997), the calibration of NE varve 6150 was recorded as 12.4 ^{14}C ka, the approximate average of the Canoe Brook ^{14}C ages. However, two of the ^{14}C ages at 12.35 ^{14}C ka are younger than 12.4 ^{14}C ka and there was likely some lag in deposition, even if for only a few years. Plant macrofossils from varve 6150 have been analyzed by species and did not contain any aquatic vascular plant remains (N. Miller, pers. comm.). The macrofossils do include a small percentage of wet-soil sedges, the only macrofossils identified that could potentially cause ^{14}C ages to be too old. The plant types indicated that they were carried into

Lake Hitchcock from an open tundra-like environment (Miller, 1995). A full calibration of the lower Connecticut Valley sequence to both ^{14}C and calibrated (U-Th or inferred calendar) years (Fig. 13) is inferred using the CALIB 4.0 computer program (Stuiver and Reimer, 1993; Stuiver *et al.*, 1998). This calibration program accounts for disparities between the ^{14}C and calibrated ages resulting from the secular variation of atmospheric ^{14}C. Several compressions of the ^{14}C time scale occur from 12.4 to 10.7 ^{14}C ka as well as a prominent ^{14}C plateau at 12.6-12.4 ^{14}C ka. Recognition of ^{14}C variations in these time spans is critical to formulating an accurate ^{14}C chronology for glacial events in New Hampshire and Vermont.

One additional Canoe Brook ^{14}C age of 12.9 ka was obtained on a bulk sample of silt and clay that contained peat and gyttja fragments from NE varve 6156 (Table I). The fragments are rip-up clasts composed of fine organic sediment and sieving a few of them did not yield any identifiable plant macrofossils. Instead of ruining the sample with further sieving the remaining fragments were submitted with their enclosing silt and clay as a bulk sample. This type of organic material is not considered reliable for determining an atmospheric ^{14}C calibration of a lacustrine sequence as compared to terrestrial plant macrofossils because it is sediment that was eroded from an older organic pond deposit and was later redeposited in Lake Hitchcock as ripped-up fragments. It may also contain the remains of aquatic species, especially algae that do not obtain their carbon directly from the atmosphere. The Connecticut Valley varves are calcareous due to marble and calcareous phyllite in Vermont. In addition to aged water from glacial melting, baseflow, and older organic sediment (Abbot and Stafford, 1996), the bedrock may have provided a source of carbon that could create anomalous ^{14}C ages for freshwater bodies. Bulk samples of organic lacustrine sediment, especially gyttja, have consistently yielded anomalous ages as compared to terrestrial plant macrofossils in attempts to calibrate the Swedish Varve Chronology (Wohlfarth *et al.*, 1993) and other lacustrine records (Oeschger *et al.*, 1985; Andrée *et al.*, 1986). The 12.9 ka ^{14}C age for varve 6156 is older than the three other ^{14}C ages from NE varve 6150 at Canoe Brook (Table I) by about 450-600 ^{14}C yr (about 1200 varve or calibrated yr, Fig. 13) and these other dates were determined on terrestrial macrofossils that are generally considered more reliable mate-

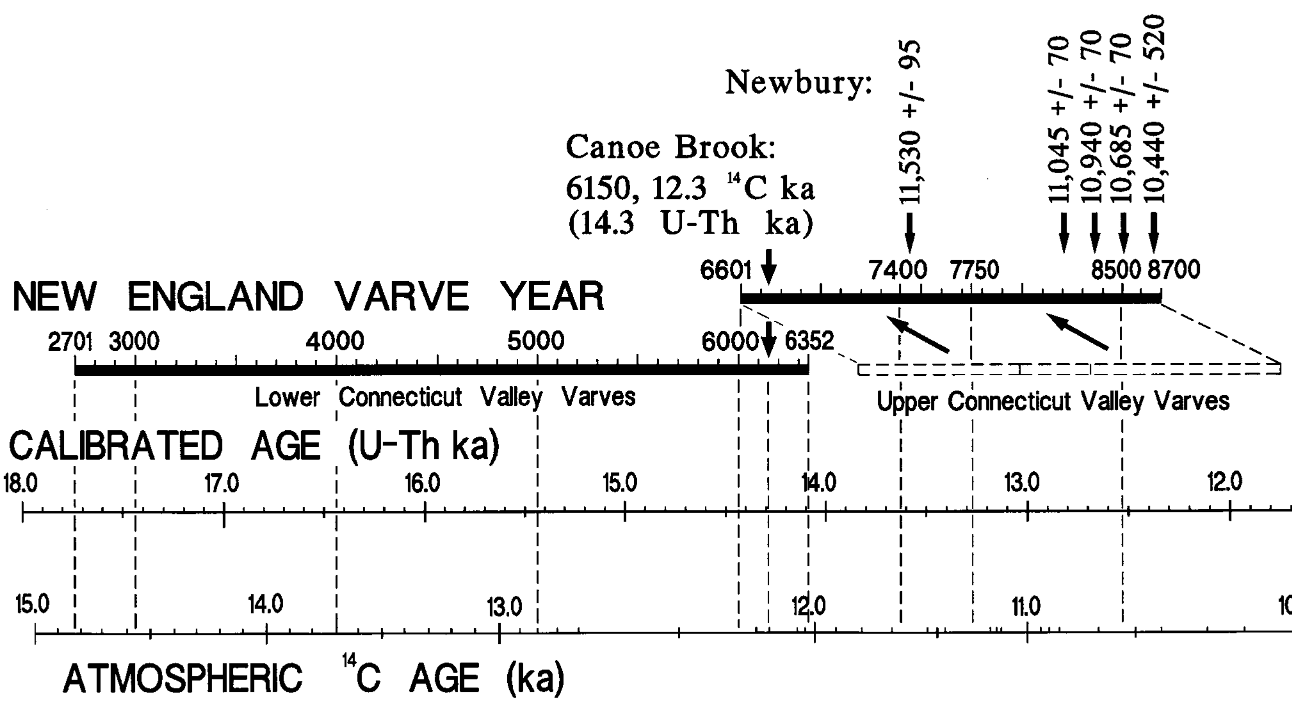

FIGURE 13. Calibration of the New England Varve Chronology. Time scales are based on a calibration point of 12.3 ^{14}C ka (14.3 cal. ka) for NE varve 6150 at Canoe Brook, Vermont (Table I). ^{14}C years were converted to calibrated (Th-U) years and the ^{14}C time scale was constructed using the CALIB 4.0 computer program (Stuiver and Reimer, 1993; Stuiver *et al.*, 1998). The CALIB program accounts for the disparity between ^{14}C and calibrated or calendar ages resulting from the secular variation of atmospheric ^{14}C. In the time span from 12.6 to10.7 ^{14}C ka the ^{14}C time scale is especially non-linear with significant compressions of the ^{14}C time scale from 12.4 to 10.7 ^{14}C ka and a ^{14}C plateau at 12.6-12.4 ^{14}C ka. Four AMS and one conventional ^{14}C age from varves at Newbury, Vermont (Table I) are plotted for comparison.

Étalonnage de la New England Varve Chronology. *Les échelles temporelles s'appuient sur le point d'étalonnage de 12,3 ^{14}C (14,3 ka étal.) de la varve (NE) 6150 de Canoe Brook, au Vermont (tabl. I). Les années au radiocarbone ont été converties en années étalonnées (Th-U) et l'échelle temporelle au ^{14}C a été établie avec le programme CALIB 4,0 (Stuiver et Reimer, 1993 ; Stuiver* et al.*, 1998). Le programme CALIB tient compte des divergences entre les datations au ^{14}C et les datations étalonnées résultant les variations séculaires du ^{14}C atmosphérique. Au cours de la période de 12,6 à 10,7 ^{14}C ka, l'échelle temporelle en ^{14}C est particulièrement non linéaire avec des compressions importantes de 1,4 à 10,7 ^{14}C ka et un plateau de12,6 à12,4 ^{14}C ka. Quatre datations par spectrométrie de masse et une datation au ^{14}C conventionnelle sur des varves à Newbury, au Vermont (tabl. I) sont montrées pour fins de comparaison.*

TABLE I

^{14}C ages from varves in the Connecticut Valley (locations on Fig. 1)

Laboratory number	Age (^{14}C yr BP)	$\delta^{13}C$ (‰)	NE varve number	Material dated	Reference
1. Canoe Brook, Vermont (Ridge and Larsen, 1990)					
GX-14231	12,355 ± 75	-27.2	6150	Bulk silt and clay with, non-aquatic twigs and leaves	Ridge and Larsen, 1990
GX-14780	12,455 ± 360	-27.6	6150	Handpicked non-aquatic leaves and twigs, mostly *Dryas* and *Salix*	Ridge and Larsen, 1990
CAMS-2667	12,350 ± 90	–	6150	one *Salix* twig (AMS)	Norton Miller, pers. comm.
GX-14781	12,915 ± 175	-27.1	6156	Peat and gyttja fragments	Ridge and Larsen, 1990
2. Newbury, Vermont (site 73 of Antevs, 1922)					
GX-23765	11,530 ± 95	-27.0	7435-7452	Woody twig (AMS)	New
GX-23766	11,045 ± 70	-27.5	8206	Woody twig (AMS)	New
GX-23640	10,940 ± 70	-26.8	8357	Woody twig (AMS)	New
GX-23641	10,080 ± 580	-26.7	8498-8500	Woody twig	New
GX-23767	10,685 ± 70	-26.3	8504	Woody twig (AMS)	New
GX-23642	10,040 ± 230	-26.5	8542-8544	Chunk of wood	New
GX-23643	10,440 ± 520	-26.8	8652-8662	2 woody twigs	New
3. Columbia Bridge, Vermont (Miller and Thompson, 1979)					
WIS-961	11,540 ± 110	-29.0	unknown (>7400)	Wood fragments	Miller and Thompson, 1979
WIS-919	11,390 ± 115	-27.5	unknown (>7400)	Wood fragments	Miller and Thompson, 1979
WIS-925	20,500 ± 250	–	unknown (>7400)	*Potamogeton* leaves and other plant remains	Miller and Thompson, 1979

Note: Blank spaces with hyphens indicate that information was not available from published source or was not obtained.

rials for ^{14}C dating. The 12.9 ^{14}C-ka age is also inconsistent with new ^{14}C ages from Newbury (discussed below) and paleomagnetic correlations between New England and New York.

The Canoe Brook calibration point (NE varve 6150 = 12.3 ^{14}C ka) can be tested using the paleomagnetic correlation between New England and New York. The Canoe Brook ^{14}C ages come from sediment that records the strong westward swing in declination that is a prominent part of both records (Fig. 11). Correlative sediment in New York represents the initiation of Lake Iroquois in the Ontario Basin at 12.6-12.2 ^{14}C ka (Muller and Prest, 1985; Muller *et al.*, 1986; Muller and Calkin, 1993) and has the same ^{14}C age as the sediment at Canoe Brook.

CALIBRATION OF THE UPPER CONNECTICUT VALLEY VARVE SEQUENCE

Until recently ^{14}C calibration of the upper Connecticut Valley varve sequence could only be inferred using three pieces of information: 1) the ^{14}C ages at Canoe Brook, 2) the correlation of the lower and upper Connecticut Valley sequences (Fig. 7), and 3) the CALIB program (Stuiver and Reimer, 1993). Four AMS ^{14}C ages and three conventional ^{14}C ages for woody twigs and wood from varves at Newbury, Vermont (Table I, Fig. 8; site 73 of Antevs, 1922) now provide a direct calibration of the upper Connecticut Valley varve sequence. The new AMS ^{14}C ages (Table I) are consistent with the ^{14}C calibration of the New England Varve Chronology (Figs. 13, 14) formulated from the Canoe Brook ^{14}C ages and the CALIB 4.0 program (Stuiver and Reimer, 1993; Stuiver *et al.*, 1998). Because of their large precision parameters the conventional ^{14}C ages are not as useful for precisely calibrating the varve chronology. It is important to emphasize again that it has not been possible to fully evaluate lags related to the erosion and redeposition of terrestrial plant macrofossils in the lake. A lag is suggested by some of the Newbury ^{14}C ages that are younger than the inferred ^{14}C age of the varve sequence based on the Canoe Brook ^{14}C data (Figs. 13, 14). Two AMS ^{14}C ages from Newbury are about 350 ^{14}C yr older than the ^{14}C calibration (Fig. 14) but this difference occurs at a time when there is compression of the ^{14}C time scale and 350 ^{14}C yr corresponds to about 200 varve or calibrated years.

CALIBRATED VARVE AND PALEOMAGNETIC CHRONOLOGIES: 13-10.5 ^{14}C KA

DEGLACIAL EVENTS

A model of deglaciation for New Hampshire, Vermont, and adjacent New York (Fig. 15) is given here based on the varve chronology (Figs. 2, 4), the ages of basal varve localities (Figs. 5, 6), paleomagnetic correlations (Figs. 11, 12),

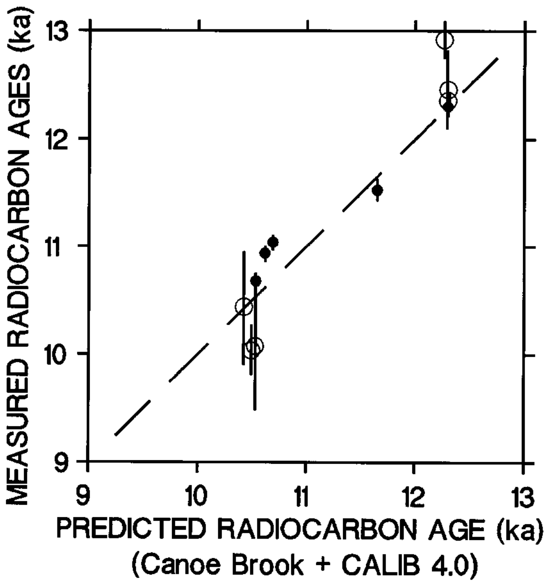

FIGURE 14. Plot of measured ^{14}C ages versus their predicted ^{14}C ages. Predicted ^{14}C ages are based on the positions of samples in the New England Varve Chronology and the ^{14}C calibration of the varves based on data at Canoe Brook (Fig. 13, Table I) and the CALIB 4.0 computer program (Stuiver and Reimer, 1993; Stuiver *et al.*, 1998). Open circles are conventional ^{14}C ages and smaller solid points are AMS ^{14}C ages. Error bars are ^{14}C age precision reported at $\pm$ 1σ. The ages from Canoe Brook are the data points prior to 12.0 ka. Points above the calibration line represent measured ^{14}C ages older than the ^{14}C calibration defined by the Canoe Brook data and points below represent measured ^{14}C ages younger than the Canoe Brook calibration.

Graphique des datations au ^{14}C mesurées par rapport aux datations escomptées. Les datations escomptées sont fondées sur l'emplacement des échantillons dans la New England Varve Chronology *et l'étalonnage des varves à partir des données du site de Canoe Brook (fig. 13, tabl. I) ainsi que le programme CALIB 4.0 (Stuiver et Reimer, 1993; Stuiver* et al.*, 1998). Les cercles non tramés représentent les datations au ^{14}C conventionnelles et les points noirs, les datations par spectométrie de masse. Les traits verticaux donnent la précision des datations au ^{14}C reportée à ±1σ. Les points avant 12,0 ka représentent les datations de Canoe Brook. Les points situés au-dessus de la ligne d'étalonnage représentent les datations au ^{14}C plus vieilles que les datations étalonnées à partir des données de Canoe Brook et les points sous la ligne d'étalonnage représentent des dates mesurées plus jeunes que les dates étalonnées de Canoe Brook.*

and the ^{14}C calibration of the varves (Fig. 13). According to these combined data sets deglaciation of the Connecticut Valley of New Hampshire and Vermont occurred between 12.6 and 11.5 ^{14}C ka (NE varve yr 5200-6000 plus 6612-7500). Disparities between varve and ^{14}C years during this period are a result of erratic changes in the atmospheric concentration of ^{14}C that have now been incorporated into a calibration of ^{14}C to calibrated or calendar years (Stuiver and Reimer, 1993; Stuiver *et al.*, 1998). Deglaciation of the Connecticut Valley (Figs. 5, 15) from Massachusetts to near Claremont, New Hampshire (12.6-12.45 ^{14}C ka, NE varve yr 5200-6000) occurred at a rate of 83.1 m/varve yr followed by a rate of 252 m/varve yr from Claremont to Littleton (12.45-12.0 ^{14}C ka, NE varve yr 6601-7000). Ice recession along a 30 km stretch of the central Merrimack Valley occurred at 12.5-12.45 ^{14}C ka (NE varve yr 5700-6000) at a rate of about 100 m/varve yr (Figs. 6, 15). The Littleton-Bethlehem Readvance reached its maximum extent at 11.9-11.8 ^{14}C ka at which time the ice front was just north of the White Mountains. The drainage and flood events at NE varves 7200-7213 (Figs. 9a, 9b), suggested earlier to possibly represent the initial lowering of Lake Hitchcock, occurred at about 11.8 ^{14}C ka. Later drainage events appear to have occurred at 11.6 ^{14}C ka (NE varve 7500, Fig. 9c) and 11.1 ^{14}C ka (NE varve 7923, Fig. 9d). Following the Littleton-Bethlehem Readvance, ice recession from Littleton to the Québec border was completed by about 11.5 ^{14}C ka to allow the burial of plant fossils in varves near Columbia Bridge (Miller and Thompson, 1979). The minimum rate of deglaciation for this 70-km stretch of the valley from 11.8 to 11.6 ^{14}C ka (NE varve yr 7200-7500) would have been about 230 m/varve yr. Also, 11.6-11.5 ^{14}C ka approximately represents the time that lakes in the upper Connecticut Valley became entirely non-glacial as ice receded into Québec.

It has been possible to infer the approximate ^{14}C age of deglaciation in two areas of northern Vermont west of the Connecticut Valley (Fig. 15). Near Montpelier Antevs (1928) found basal varves (about NE varve 7050) from glacial Lake Winooski overlying till indicating deglaciation from this area at about 12.0 ^{14}C ka. In northern Vermont at Enosburg Falls in the Missisquoi Valley a section of 300 varves from large glacial lakes in the Champlain Valley (Lakes Fort Ann and Candona of Parent and Occhietti, 1988; Lakes Fort Ann and St. Lawrence of Pair and Rodrigues, 1993) was found beneath glaciomarine mud of the Champlain Sea. The basal varve at this section was not exposed and varves in the exposed section were thin (<1 cm). The paleomagnetic stratigraphy of this section indicates that it is correlative with varves in the Connecticut Valley having a ^{14}C age of 11.3-10.7 ^{14}C ka. The thin varves exposed at Enosburg Falls are probably a hundred to a few hundred years above the bottom of the varve stratigraphy, which would give the basal varves and deglaciation at Enosburg Falls an estimated age of 11.7-11.4 ^{14}C ka.

In the Hudson and Champlain Valleys of New York two glacial readvances have been recognized that may be equivalent to events in the Connecticut Valley (Fig. 15). In the Hudson Valley the Luzerne Readvance (Connally and Sirkin, 1971, 1973) occurred prior to 12.5 ^{14}C ka to allow the deposition of varves that were measured by Gerard De Geer and matched to varves in the Connecticut Valley (Antevs, 1922; NE varves 5501-5800, Figs. 2, 4). This readvance has been assigned to the Pt. Huron Stadial of the eastern Great Lakes region (Connally and Sirkin, 1973). No readvance has been recognized in New England from this time. However, large ice-contact deltas and subaqueous fans that were deposited in Lake Hitchcock in southern most Vermont (Larsen and Koteff, 1988) at about 12.6-12.5 ^{14}C ka, may represent an equivalent ice front position. Further north in the Champlain Valley the Bridport Readvance (Connally and Sirkin, 1973) may be the equivalent of the Littleton-Bethlehem Readvance in the Connecticut Valley based on its geographic position.

POSTGLACIAL EVENTS

In the upper Connecticut Valley a lake persisted until at least 1780 yr after deglaciation. Varves at Newbury contain plant fossils dating from 10.7-10.45 ^{14}C ka that are in the 200 youngest varves at the exposure that are overlain by non-varved lacustrine sand. The lake represented by the youngest varves at Newbury appears to have persisted until at least 10.4 ^{14}C ka and may have been seen by the first humans to enter the region. Archaeologists working in this section of the Connecticut and Passumpsic Valleys between Lyme and St. Johnsbury should focus their search for evidence of the earliest humans along the shoreline of this lake. In sections of the valley to the south where lakes drained much sooner after deglaciation the earliest evidence of humans should be on stream terraces. In the northern Connecticut Valley near Newbury stream terraces postdate very young (latest Pleistocene) lacustrine sediment and might not be the locations of the earliest evidence of humans.

The inferred age of the transition from lacustrine to marine sediment, and thus the invasion of the Champlain Sea, at Enosburg Falls (Fig. 1) is 11.1-10.6 ^{14}C ka based on paleomagnetic correlations to varves in the Connecticut Valley (Fig. 11). The paleomagnetic data from this time in the Connecticut Valley are not very precise and do not allow a precise correlation. The lacustrine to marine transition at Enosburg Falls occurs at the same time as a paleomagnetic declination of 0° as it changed from a western to eastern direction. This paleomagnetic signature for the Champlain Sea invasion has also been found in the western St. Lawrence region (Pair *et al.*, 1994). Our estimated age of 11.1-10.6 ^{14}C ka overlaps the span of ^{14}C ages proposed for this event in the western St. Lawrence Lowland (11.6-11.0 ka). Ages from the St. Lawrence Valley are based on marine ^{14}C ages from deep water fossils (Rodrigues, 1988, 1992) and the ^{14}C time frame that has been applied to pollen stratigraphy in southern Ontario (Anderson, 1988).

DISCUSSION: AN ACCURATE TERRESTRIAL ^{14}C CHRONOLOGY

Until recently the terrestrial chronology of deglaciation and other late Pleistocene events in New England has relied on ^{14}C ages from lake-bottom bulk sediment samples. Bulk organic samples from the bottoms of lake cores avoid problems associated with marine samples such as marine reservoir variations (Mangerud, 1972; Hjort, 1973; Mangerud and Gullikson, 1975; Bard, 1988; Bard *et al.*, 1994; Birks *et al.*, 1996) and the influences of meltwater in the marine environment (Sutherland, 1986; Hillaire-Marcel, 1988; Rodrigues, 1992). However, lacustrine bulk sediment samples can also yield anomalous old ages for other reasons (Shotton, 1972; Oeschger *et al.*, 1985; Andrée *et al.*, 1986; Wohlfarth, 1996). Aquatic plants as well as other aquatic organisms, which are frequently a significant part of bulk organic samples from lake cores, acquire carbon from lake water in which the concentration of ^{14}C may be lower than the atmosphere. Dissolved carbon taken up by aquatic plants may be from the atmosphere and organic and inorganic sources, and deliv-

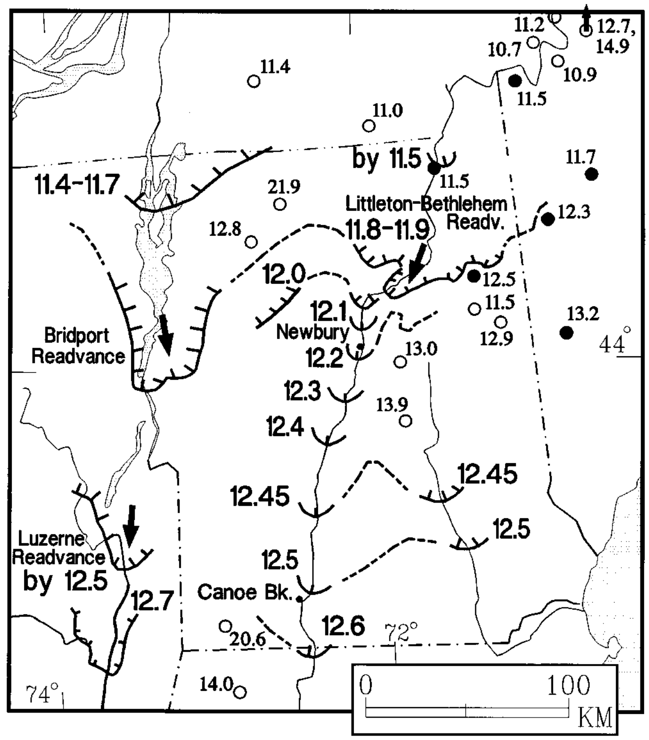

FIGURE 15. The deglaciation (dated ice front positions in ^{14}C ka) of New Hampshire, Vermont, and adjacent New York based on the combined ^{14}C calibration of the varve (Figs. 13, 14) and paleomagnetic declination chronologies (Fig. 11) and the varve ages for deglaciation in New England (Figs. 5, 6; see discussion in text). Arrows indicate glacial readvances. Both macrofossil (dark circles) and bulk sediment (open circles) lake-bottom ^{14}C ages (ka) relevant to the age of deglaciation are shown for comparison (Tables I and II). The apparently rapid deglaciation of southern New Hampshire and Vermont in ^{14}C years is an artifact of a ^{14}C plateau at 12.6-12.4 ^{14}C ka in which ^{14}C time changes very slowly as compared to varve or calibrated years (Fig. 13). Deglaciation of southern New Hampshire was actually slower than in northern New Hampshire, which is not apparent from the ^{14}C ages of ice front positions. As an example, deglaciation of southern New Hampshire at 12.6-12.4 ^{14}C ka represents 900 varve or calibrated yr while deglaciation of northern New Hampshire at 12.3-12.0 ^{14}C ka represents about 250 varve or calendar yr.

La déglaciation (fronts glaciaires en années ^{14}C ka) du New Hampshire, du Vermont et d'une partie de l'état de New York, reconstituée à partir de l'étalonnage combiné des chronologies établies pour les varves (fig. 13 et 14) et la déclinaison paléomagnétique (fig. 1) et de la déglaciation de la Nouvelle-Angleterre reconstituée à partir de l'âge des varves (fig. 5 et 6). Les flèches identifient les récurrences. Les datations au ^{14}C (ka) de macrofossiles (cercles noirs) et de sédiments (cercles non tramés) de fonds lacustres relatives à la déglaciation sont données pour fins de comparaison (tabl. I et II). La rapidité de la déglaciation au sud du New Hampshire n'est qu'apparente en raison de l'existence d'un plateau de 12,6 à 12,4 ^{14}C ka durant lequel le temps au ^{14}C n'a évolué que très lentement en comparaison des années varvaires ou étalonnées (fig. 13). La déglaciation du sud du New Hampshire a en fait été plus lente qu'au nord, fait qui ne ressort pas de l'emplacement des fronts glaciaires. Par exemple, la déglaciation du sud du New Hampshire de 12,6 à 12,4 ^{14}C ka représentent 900 années varvaires ou étalonnées, tandis que la déglaciation du nord du New Hampshire de 12,3 à 12,0 ^{14}C ka représentent 250 années varvaires ou étalonnées.

ered to the lake by runoff or baseflow or generated internally (Abbott and Stafford, 1996). Dissolved inorganic carbon is derived from bedrock sources while organic carbon comes from the organic decay of lake bottom sediment, organic matter in soils, or older organic deposits. Particulate organic carbon and macrofossils that are older than the lake bottom at the time of deposition can also be delivered to a lake by runoff and shoreline erosion.

There is clear evidence in New England indicating that bulk sediment and aquatic plants can produce significant ^{14}C errors. Aquatic plants that have anomalous ^{14}C ages have been found in varves in the upper Connecticut Valley near Columbia Bridge (Table I). Macrofossil debris of the plant *Potamogeton* has a ^{14}C age of 20.5 ka while non-aquatic plant macrofossils from horizons above and below it have ^{14}C ages of 11.5-11.4 ka. Bulk organic sediment from the bottoms of ponds in Vermont has yielded ^{14}C ages of 20.6 and 21.9-19.6 ka (Table II, Fig. 15). Basal sediment from Lower Togue Pond adjacent to Mt. Katahdin in Maine has yielded a basal ^{14}C age of 21.3 ka (Table II). Basal bulk sediment from Unknown Pond, Maine has yielded ^{14}C ages 1500-3700 yr older than similar materials from lakes to the south (Table II, Fig. 15). Anomalous old ages for bulk sediment have also been recognized further north in New Brunswick (Karrow and Anderson, 1975). These bulk sediment ^{14}C ages have extreme errors (>1000 yr) that are easily recognized because they clearly do not fit the younger lake-bottom chronology from surrounding areas. However, comparing bulk ^{14}C ages with an existing lake bottom chronology that is also based on bulk sediment ages does not allow us to recognize more subtle errors (<1000 yr) that may be pervasive. This can only be accomplished with a direct comparison of bulk sediment and plant macrofossil ages, which have systematically been different by 300-800 yr in European lake sediment studies (Oeschger *et al.,* 1985; Andrée *et al.,* 1986; Wohlfarth, 1996). Although it is possible for a bulk sediment sample to yield an accurate atmospheric ^{14}C age, systematic testing for subtle errors has not been incorporated into any chronology in New England. Until recently it has been customary to use the oldest lake bottom bulk sediment ages as minimum ("youngest possible") atmospheric ^{14}C ages for deglaciation but this ignores the errors that cause ^{14}C ages to be older than the actual atmospheric ^{14}C age of deglaciation. In general, lake bottom bulk sediment samples yield 'terrestrial ^{14}C ages' that do not meet the strict criteria necessary to consistently be used as atmospheric ^{14}C ages or to formulate an accurate glacial chronology.

One technique that should be applied to bulk sediment and macrofossil ^{14}C ages that can help to screen samples with anomalous ages is the analysis of ^{13}C. The measurement of $\delta^{13}C$ values represents not only a means of correcting for fractionation (Stuiver and Polach, 1977), but in some cases may indicate contamination or non-atmospheric sources of carbon. Non-aquatic plant leaves and wood, the best material for acquiring an atmospheric ^{14}C age, generally have $\delta^{13}C$ values of –28 to –26‰ (Stuiver and Polach, 1977; Lini *et al.*, 1995). $\delta^{13}C$ values outside of this range indicate that the associated ^{14}C age may be too old because of aquatic plants or contamination by 'old' carbon. Unfortunately, $\delta^{13}C$ values within the non-aquatic plant range do not provide unequivocal proof that a ^{14}C age is free of potential errors and other factors such as sample type must be evaluated as well.

The most accurate ages for determining an atmospheric ^{14}C chronology are those from non-aquatic plant macrofossils, which avoid problems with marine and freshwater aquatic organisms. In order to avoid potential errors inherent to aquatic fossils, non-aquatic samples should not be mixed with aquatic organisms. A high precision can be obtained with AMS ^{14}C ages on relatively small samples that allow the dating of specific plant species. However, non-aquatic plant macrofossils still present a potential problem when trying to interpret results. All plant macrofossils are potentially susceptible to the problem of a lag in erosion and redeposition after the plant dies on the land surface. Preservation of macrofossils in a frozen or very cold soil or anoxic wetland sediment may allow the survival of this material for millennia before it is eroded and transported to a lacustrine setting. Woody materials, but also leaves, may survive destruction during erosion and transport to become macrofossils that will produce a ^{14}C age that is significantly older than the clastic sediment in which it is found. A systematic scatter among macrofossil ages in contemporaneous varves in Sweden appears to be the result of lags in deposition and ages on the younger side of this scatter are now accepted as being more accurate representations of the ^{14}C age of enclosing sediment (Wohlfarth *et al.*, 1995). Unless the magnitude of depositional lags can be evaluated macrofossils should be treated as yielding maximum ("oldest possible") atmospheric ^{14}C ages for the enclosing lacustrine sediment. If possible multiple ^{14}C ages from a single horizon, or spread across a known number of varves, should be used to test the contemporaneity of the macrofossils and their enclosing sediment.

Another possible problem that may exist for macrofossils deposited in shallow ponds and lakes that have high organic productivity and low sedimentation rates is the coating of macrofossils by aquatic algae. If the algae are not removed by laboratory sample treatment it will cause the ^{14}C age for the macrofossil to be too old. This should not be a problem in large glacial or non-glacial lakes that are deep and retard the penetration of light to the floor of the lake. Also, if a lake has a relatively high clastic sedimentation rate the burial of macrofossils will occur before significant growth of algae.

EVALUATION: CALIBRATED VARVE AND PALEOMAGNETIC CHRONOLOGY

As indicated earlier our ^{14}C-calibrated varve and paleomagnetic chronology for New England appears to be consistent with the ^{14}C chronology of the western St. Lawrence Lowland (Anderson, 1988; Rodrigues, 1988, 1992). However, the new chronology is not consistent with existing chronologies for western New England (Davis and Jacobson, 1985; Hughes *et al.*, 1985; Stone and Borns, 1986; Dyke and Prest, 1987) based on bulk sediment ^{14}C ages from cores of small lakes

TABLE II

^{14}C ages from lakes in northern New England and adjacent Québec that are relevant to the age of deglaciation

Location	Laboratory	Age (^{14}C)	δ^{13}C (‰)	Material dated	Reference (‰)
A. Macrofossil samples from lake cores					
Pond of Safety, NH	OS-7125	12,450 ± 60	-18.2	*Dryas,* moss parts, *Carex* seeds, *Daphnia,* insect parts *Salix herbacea, Characea*	Thompson *et al.,* 1996
Cushman Pond, Me	OS-7122	13,150 ± 50	-23.5	*Salix herbacea* leaves plus insect parts, *Dryas,* moss parts, *Characeae, Daphnia,* and woody twigs.	Thompson *et al.,* 1996
Surplus Pond, Me	OS-7119	12,250 ± 55	-28.1	*Salix herbacea* leaves	Thompson *et al.,* 1996
Spencer Pond, Me	AA-9506	11,665 ± 85	-	(not reported)	C. Dorian, unpub. in Thompson *et al.,* 1996
Lower Black Pond, Me	OS-7123	11,500 ± 50	-28.1	Woody twigs plus other macrofossils	Thompson *et al.*, 1996
B. Bulk sediment or bulk organic sediment samples from lake cores					
Hawley Bog Pond, Ma	WIS-1122	14,000 ± 130	-	Basal organic silt	Bender *et al.*, 1981
Ritterbush Pond, Vt	CAMS-20197	21,860 ± 370	-24.8	Bulk sediment, 6 cm above base of pond sediment.	Lini *et al.*, 1995; Paul Bierman, pers. comm.
	CAMS-32852	20,740 ± 530	-25.8	Bulk sediment, 19 cm above	Lini *et al.*, 1995; Paul
	CAMS-33133	20,110 ± 170	-25.8	base of pond sediment.	Bierman, pers. comm.
	CAMS-33349	19,570 ± 170	-25.8	(3 replicates with additional acid wash)	
	CAMS-20902	11,940 ± 90	-34.6	Gyttja, 50 cm above base of pond sediment.	Bierman *et al.*, 1997
Woodford Bog, Vt	GX-16951	20,575 ± 1250	-	Bulk detrital organics	Davis *et al.*, 1995
Sterling Pond, Vt	CAMS-17895	12,760 ± 70	-	Basal gyttja	Lin *et al.*, 1995
Mirror Lake, NH	BX-5429	13,870 ± 560	-	Bulk sediment with *Dryas*	Davis *et al.,* 1980; Davis and Ford, 1982
Deer Lake Bog, NH	QL-1133	13,000 ± 400	-	Bulk sediment	Spear, 1989
Lost Pond, NH	QL-985	12,870 ± 370	-	Bulk sediment	Davis *et al.,* 1980
Lake of the Clouds, NH	I-10684	11,530 ± 420	-	Basal bulk sediment	Spear, 1989
Lower Togue Pd., Me (not on Fig. 14)	SI-2732	21,300 ± 1900	-	Bulk laminated sediment, basal 10 cm pond sediment	Davis and Davis, 1980
	SI-2992	11,630 ± 260		Bulk laminated sediment, 50 cm above base	
Unknown Pond, Me	GSC-1339	14,900 ± 240	-	Basal organic sediment	Mott, 1981
(2 ages)	GSC-1404	12,700 ± 280	-	Basal organic sediment above first sample	
Boundary Pond, Me	GSC-1248	11,200 ± 200	-	Basal organic sediment	Mott, 1981
Chain of Ponds, Me	-	10,860 ± 160	-	Bulk sediment	Borns and Calkin, 1977
Mount Shefford, Qc	-	11,400 ± 340	-	Basal bulk sediment	Richard, 1977 (as reported *in* Davis and Jacobson,1985)
Barnston Lake, Qc	GSC-420	11,020 ± 330	-	Bulk organic sediment	McDonald, 1968
Lac aux Araignees, Qc	GSC-1353	10,700 ± 310	-	Basal organic sediment	Mott, 1981

Notes: Locations listed by state/country and are shown on Figure 15. List partly compiled from Thompson *et al.,* 1996.
This list does not include ages from varve sections in the Connecticut Valley that are listed on Table I.
Blank spaces with hyphens indicate that information was not available from published source or was not obtained.

(Table II). Our atmospheric ^{14}C chronology indicates that deglaciation of New Hampshire and Vermont began at 12.6 ka in southern Vermont and ended with ice receding into Québec at about 11.5 ka (Fig. 15). The other models show deglaciation of this region completed before 13.5-13.0 ^{14}C ka. We interpret the bulk sediment ^{14}C ages used to construct the existing chronologies as maximum ages for deglaciation and not accurate representations of the atmospheric ^{14}C age of deglaciation for reasons discussed above. Deglaciation models formulated in the early 1980's used the only available data, which included no AMS ^{14}C ages and no samples composed of only non-aquatic plant macrofossils.

In general our chronology appears to be consistent with recently obtained ages for deglaciation based on non-aquatic plant macrofossils across northern-most New England (Fig. 15, Table II). In particular the proposed age of the Littleton-Bethlehem Readvance (11.9-11.8 ^{14}C ka) appears to be consistent with macrofossil and bulk sediment ^{14}C ages (Thompson *et al.*, 1996, 1999) north of this feature. The only

^{14}C ages that are inconsistent with the proposed chronology are from bulk samples and samples of mixed assemblages of aquatic and non-aquatic macrofossils from south of the Littleton-Bethlehem Readvance. Bulk sediment ages just south of this ice margin indicate a time of deglaciation that is up to 1500 yr older than predicted by our chronology. In front of the Bethlehem Moraines there are three macrofossil ages (Cushman Pond, Pond of Safety, and Surplus Pond, Table II), only one of which is in agreement with our age for the Bethlehem Moraines (11.9-11.8 ^{14}C ka). The ^{14}C age from Cushman Pond (12.9 ka) appears to differ by about 1000 yr from our model but this age has a $\delta^{13}C$ value of –23.5‰, somewhat lower than expected for non-aquatic plants that represent an accurate ^{14}C record. The ^{14}C age from Pond of Safety (12.5 ka) is about 400 yr older than expected from our chronology and has a suspect $\delta^{13}C$ value of –18.2‰. These two ^{14}C ages are from samples that contain non-aquatic plants but also aquatic organisms such as *Daphnia* (aquatic crustacean), *Characea* (aquatic algae), *Carex* (sedge) seeds, and moss parts. It should not be assumed that these fossils provide accurate atmospheric ^{14}C ages (N. Miller, pers. comm.). Also included in the apparently anomalous samples are insect parts that will have a ^{14}C age reflecting the diet of the insect. Depending on the insect species the diet may or may not include aquatic plants or other organisms that feed on aquatic plants. The only macrofossil ^{14}C age along the Bethlehem Moraines that is in agreement with our chronology is from Surplus Pond (12,250 ± 55, 12.3 ka on Fig. 15). This sample has a $\delta^{13}C$ value of –28.1‰ and is composed entirely of leaves from a non-aquatic scrub willow (*Salix herbacea*). It is our interpretation that many of the bulk sediment ages and some of the macrofossil ages may be in error because they were obtained on samples that did not exclusively contain fossils of non-aquatic plants. Only non-aquatic plant macrofossils (leaves and woody twigs) with $\delta^{13}C$ values of –26.3 to 27.6‰ have been used to calibrate the New England Varve Chronology (Fig. 13) and formulate our deglaciation chronology (Fig. 15).

CONCLUSIONS

Any formulation of a regional synthesis of deglaciation requires that events in different regions be compared with compatible time scales and that correlations be tested with as many techniques as possible. For the past 50 years a synthesis of deglacial events across New England has been plagued by a scarcity of numerical ages and inconsistencies between them. There was no alternative to accepting ^{14}C ages at face value from both marine and lake bottom environments and assuming they were roughly measurements of an atmospheric ^{14}C-time scale. An independent stratigraphic test of the contemporaneity of glacial events and accurate atmospheric ^{14}C ages have been needed, especially if accurate comparisons are to be made to climatic data from marine and ice core records. The New England Varve Chronology, despite its existence for more than 75 years, appears just now to be poised to fill this void, especially when combined with other lithostratigraphic data, paleomagnetic records, and AMS ^{14}C ages from macrofossils of non-aquatic plants. The ^{14}C-calibrated varve and paleomagnetic records for New England and New York (Figs. 11-13) have here been used to compile a comprehensive atmospheric ^{14}C chronology of deglaciation (Fig. 15) and postglacial events in northwestern New England and surrounding areas. At the very least, the combination of these techniques has established an independent test of other deglacial chronologies and an alternative to chronologies based on ^{14}C ages of marine fossils, aquatic plants, or bulk organic samples from lakes. The combined varve, paleomagnetic, and atmospheric ^{14}C chronologies hold the promise in the coming years of providing a correlation tool of unparalleled resolution.

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APPENDIX 1

PALEOMAGNETIC MEASUREMENTS

(All results are after alternating field demagnetization at 30 mT. Average sample volume is 7.0 cc. Samples are listed from bottom [first] to top [last] for each sample site. α_{95} is the 95% cone of confidence about the mean direction.)

Sample Name	Number of horizons / total specimens	Range of NE varve yr	Declination (°)	Inclination (°)	Intensity (mA/m)	α_{95} (°)
1. Canoe Brook, Dummerston, Vt.—lower Connecticut Valley (Ridge and Larsen, 1990)						
CAN1	5/14	5687-5702	334.8	27.7	33.8	4.9
CAN2	4/10	5732-5741	334.0	37.0	39.1	6.6
CAN3	4/18	5793-5803	334.4	44.3	54.3	6.3
CAN4	3/11	5867-5879	325.3	41.8	38.2	2.9
CAN5	4/11	5931-5941	325.7	52.9	47.2	3.0
CAN6	4/10	5990-6001	324.6	52.5	55.3	2.4
CAN7	5/12	6045-6056	327.2	56.2	65.3	2.1
CAN8	5/13	6086-6101	324.3	57.0	44.0	1.9
CAN9	5/9	6153-6165	327.8	48.8	69.9	5.8
CAN10	4/11	6169-6178	330.7	52.4	87.4	1.5
2. Mill Brook, Putney, Vt.—lower Connecticut Valley						
MIL1	6/12	5763-5770	333.1	37.3	82.5	5.8
MIL2	6/12	5815-5826	328.5	45.2	54.2	1.7
MIL3	5/9	5873-5883	326.6	43.7	68.3	5.0
MIL4	6/12	5916-5926	327.9	51.8	68.3	3.2
MIL5	6/12	5961-5973	326.6	56.1	88.7	2.1
3. Soucook, N.H.—east side of Merrimack Valley north of Soucook River						
MER1	6/12	6105-6118	330.5	59.0	81.6	4.5
4. Hayward Brook, Penacook, N.H.—east side of Merrimack Valley						
MER2-A	6/12	5939-5964	330.4	57.1	128.1	1.7
MER2-B	6/12	5986-6005	328.1	54.0	114.4	2.6
MER2-C	6/12	6032-6053	327.9	58.1	155.3	1.1
MER2-D	6/12	6105-6122	323.9	56.7	149.1	1.4
MER2-E	6/12	6148-6160	328.0	57.5	188.1	0.9
MER2-F	7/12	6186-6200	329.8	54.6	162.7	1.9
5. Bryant Brook, N.H.—7 km north of Penacook, east side of Merrimack Valley						
MER3	4/8	6159-6169	328.7	52.0	155.7	4.6
6. Newbury, Vt.—upper Connecticut Valley (site 73, Antevs, 1922)						
A1	1/8	6959-6960	344.9	60.9	62.4	2.4
A3	2/9	6986-6989	353.1	55.7	77.8	1.9
A4	3/12	6996-7008	351.5	59.5	101.9	1.1
A6	3/12	7029-7035	353.7	54.3	82.0	2.2
A7	4/12	7059-7075	352.9	51.6	67.2	1.1
A8	4/12	7082-7094	354.9	48.6	51.9	1.9
A9	4/12	7114-7126	352.9	45.2	44.3	1.0
A10	3/10	7141-7155	354.4	43.7	40.5	1.5
A11	3/10	7182-7199	353.8	40.6	30.4	4.1
A12	3/12	7203-7213	352.0	41.5	44.5	1.7
A13	3/12	7217-7222	353.7	40.1	37.7	1.2
A14	4/13	7229-7241	353.0	41.8	37.1	2.4
A15	3/12	7245-7252	352.9	41.9	42.1	2.2
A16	4/13	7264-7274	350.5	42.5	35.7	2.0
A17	4/12	7283-7303	354.3	44.3	27.0	1.6
A18	4/13	7330-7354	350.1	50.5	27.7	2.2
A19	4/12	7389-7455	348.7	50.9	40.9	1.0

Sample Name	Number of horizons / total specimens	Range of NE varve yr	Declination (°)	Inclination (°)	Intensity (mA/m)	α_{95} (°)
B1	4/12	7513-7540	350.4	49.5	56.5	1.2
B2	3/12	7595-7630	351.7	52.9	33.1	1.4
B3	2/12	7744-7780	344.8	58.0	29.5	0.9
C1	4/12	7850-7902	356.1	60.6	53.0	1.4
C2	3/13	7969-8000	354.9	66.0	74.9	1.2
C3	3/15	8070-8094	352.1	63.6	83.9	1.1
D1	4/12	8147-8217	4.7	66.2	88.4	1.4
D2	4/12	8284-8303	351.7	65.3	127.8	1.5
D3	2/12	8330-8348	0.8	66.0	130.5	1.1
E1	3/11	8365-8379	1.3	65.0	129.4	1.6
E2	4/12	8391-8410	3.9	64.6	135.6	1.7
E3	3/12	8431-8451	3.0	63.7	159.4	1.5
7. Barnet, Vt.—ravine 1 km west of Comerford Dam, upper Connecticut Valley (Ridge *et al.*, 1996)						
BAR1-B	6/12	7224-7259	351.1	46.9	41.7	3.3
BAR2-A	6/12	7246-7257	354.4	37.0	39.4	2.2
BAR2-B	6/12	7264-7286	353.9	43.7	50.5	3.8
BAR1-C	6/12	7289-7302	350.5	35.6	21.6	2.9
BAR1-A	6/12	7332-7344	349.0	28.8	24.5	2.7
8. Comerford Dam, Vt. – upper Connecticut Valley (Ridge *et al.*, 1996)						
DAM2	2/17	7093-7097	354.7	42.0	75.3	1.6
DAM3	6/12	7132-7147	357.8	44.0	79.4	2.6
9. East Barnet, Vt. – east side of Passumpsic River (Ridge *et al.*, 1996)						
PAS1-A	6/12	7060-7069	352.9	53.6	126.8	3.1
PAS1-B	6/12	7113-7124	351.1	49.5	76.1	1.4
PAS1-C	7/13	7146-7165	356.0	45.2	73.9	1.8
10. Willsboro, N.Y. – Bouquette River, Champlain Valley						
LV1-A	5/10	*2-10	350.6	30.4	50.9	3.6
LV1-F	6/10	*57-63	347.6	31.7	44.5	4.2
LV1-E	6/12	*92-98	344.6	35.7	41.0	3.2
LV1-B	5/10	*126-132	343.8	42.1	54.5	2.3
LV1-C	5/9	*187-193	340.6	45.8	50.1	3.2
LV1-D	5/7	*242-248	334.2	40.9	69.5	4.1
11. Enosburg Falls, Vt. – Missisquoi River, Champlain Valley						
LV2-1	5/12	*1-25	345.8	43.9	117.9	3.5
LV2-2	4/12	*25-50	346.7	47.1	139.6	2.0
LV2-3	3/12	*50-77	349.8	53.4	89.5	1.8
LV2-4	2/12	*80-100	354.4	58.4	95.4	1.8
LV2-5	2/12	*130-150	353.9	63.0	116.6	2.0
LV2-6	4/12	*175-190	355.5	66.8	136.2	1.5
LV2-7	4/12	*220-240	355.9	63.1	169.8	3.2
LV2-8	3/10	*marine beds	0.1	51.4	66.5	6.7

* Recorded as minimum number of varves above base of measured section (Champlain Valley sections).