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THE NEW NORTH AMERICAN VARVE CHRONOLOGY: A PRECISE RECORD OF SOUTHEASTERN LAURENTIDE ICE SHEET DEGLACIATION AND CLIMATE, 18.2–12.5 KYR BP, AND CORRELATIONS WITH GREENLAND ICE CORE RECORDS

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ABSTRACT. **New glacial varve records from long cores combined with records from key surface exposures and new radiocarbon ages have allowed the correction, consolidation, expansion, and calibration of Ernst Antevs' original New England Varve Chronology (NEVC) in the Connecticut Valley of New England, U.S.A. The varve records have been reformulated, with corrections and a new numbering system, as the new North American Varve Chronology (NAVC), which is a continuous 5659-yr varve sequence that spans most of the last deglaciation (18,200-12,500 yr BP) in the northeastern United States. Rates of ice recession for separate intervals terminated by abrupt glacial stillstands and readvances have been determined for western New England. Ice recession history is coupled to varve thickness changes that depict changes in meltwater production in the Connecticut Valley and show the relationship of changes in ablation rate (summer climate variation) to glacial readvances and periods of halted and rapid ice recession (up to 300 m/yr). Comparison of varve thickness records to Greenland ice-core climate records show that after 15,000 yr BP, climate changes of sub-century and longer scales recorded in both records appear identical and synchronous. After 15,000 yr BP, therefore, there was a link between North Atlantic climate and marginal processes of the southeastern sector of the Laurentide Ice Sheet (LIS). Prior to 15,000 yr BP, when the LIS was closer to an equilibrium condition, retreat rates were generally lower and changes in varve thickness and ablation were more subtle, but can still be linked to ice sheet activity. Only weak relationships between varve thickness changes and Greenland climate are evident suggesting that changes in the southeastern LIS during this time may have been significantly influenced by climate patterns unique to the North American continent or ice dynamics.**

Key words: Glacial varves, varve chronology, radiocarbon chronology, deglaciation, late Wisconsinan, glacial climate

INTRODUCTION

Glacial varves are annually layered sediments found in lakes fed by glacial meltwater where the seasonal cycle of glacial melting leads to a strong variation in the type of sediment accumulation during the year. There exist a number of correlated sequences of varved sediments deposited in glacial lakes at the margin of former ice

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sheets that provide extraordinary records of ice sheet dynamics and ice-marginal processes at annual resolution for thousands of years. Such a record exists in Scandinavia in the form of the Swedish Varve Chronology that covers the last ~14,000 yr with only minor gaps (Cato, 1985; Stromberg, 1989; Wohlfarth and others, 1997), in the Lake Superior region of the northern United States (Breckenridge, 2007), and in southern Canada (Antevs, 1925, 1928; Hughes, ms 1955, 1965; Breckenridge and others, 2012). A similar long chronology in eastern North America, the New England Varve Chronology (NEVC) developed by Ernst Antevs (1922, 1928), is the subject of this paper.

Glacial varve records are unique among terrestrial glacial records in that they record annual and in some cases sub-annual resolution of glacial events and they are also tied to climate through their record of meltwater production. Thickness changes in glacial varves provide a high resolution (annual) record of the transitions between climate episodes (stadial and interstadial events) as well as non-climatic events. Varves can be used to determine rates of terrestrial ice recession and the timing of glacial readvances. Varve chronologies have the ability to test the internal consistency of existing radiocarbon-based chronologies by extending correlations and providing precise and accurate annual counts between radiocarbon ages used to calibrate varve sequences. On a larger scale the correlation of varve records, with their related glacial and climatic events, and other chronologies in the North Atlantic region can provide clues to mechanisms of deglacial climate change by helping to investigate the consistency of terrestrial glacial activity at the southeastern margin of the Laurentide Ice Sheet (LIS) and events documented in marine and ice cores in the North Atlantic region. In addition to acting as high-resolution chronologies and records of meltwater production, varves provide an important framework for understanding postglacial isostatic rebound and the reinhabitation of waterways following glaciation (Benner and others, 2008, 2009; Knecht and others, 2009) and a calibrated varve chronology has provided a means of calibrating ^{10}Be production rates in eastern North America (Balco and others, 2009).

Antevs' (1922, 1928) original NEVC (tabulated in arbitrary New England or NE varve years; fig. 1A) was formulated in New England and adjacent eastern New York State. A revised NEVC is here reformulated as the North American Varve Chronology (NAVC; fig. 1B), based on the measurement of varves in long cores that provide new varve records that were not previously available (figs. 1B-C). The new varve sequences provide links between old NEVC sequences, and they have allowed us to make corrections. The main products of our research are: (1) a consolidated NAVC (tabulated in American, or AM varve years) with a closure of the main gap between existing varve sequences of the old NEVC; the NAVC is a single chronology of 5659 varve years that incorporates additions and corrections to the original NEVC with a unified and revised numbering system (fig. 1B); (2) a calibration of the NAVC based on ^{14}C ages from mostly terrestrial plant fossils in varves matched to the chronology (~18.2-12.5 cal kyr BP[1]) and a best fit of radiocarbon ages from the varves to the most recent IntCal09 calibration data set (Reimer and others, 2009); (3) an updated deglacial chronology for western New England with precise ages of deglacial events and rates of deglaciation; and (4) a detailed high-resolution comparison of climate change events depicted in New England varves and in Greenland ice cores. The current chronology provides a starting point for an expansion to the whole period of

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[1] Ages given in this paper in [cal yr BP], or calibrated radiocarbon years before present (relative to 1950 AD), are determined using the CALIB 6 program and Intcal09 data set (Stuiver and others, 2005; Reimer and others, 2009). Later in this paper, when comparing varve records and deglaciation with ice core chronologies, ages will be given in [b2k], or years before 2000 AD, which is the current standard for ice core chronology.

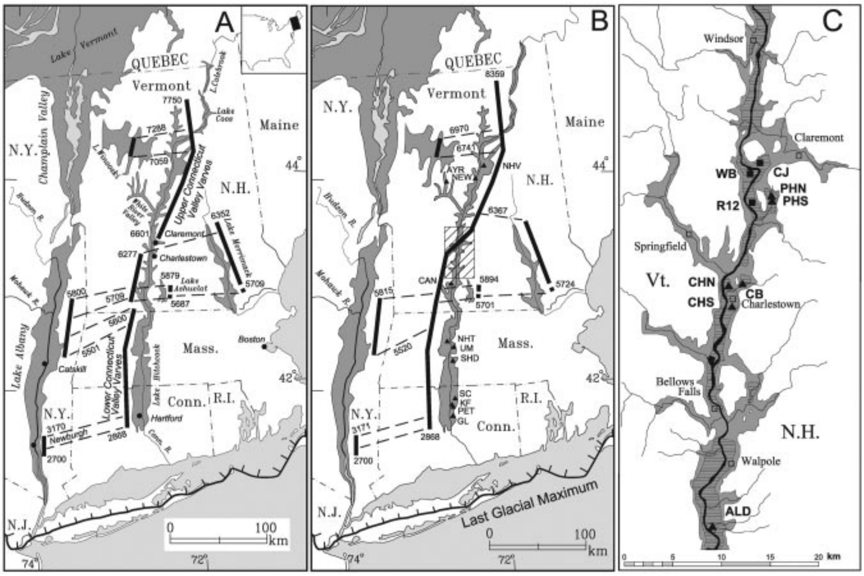

Fig. 1. (A) Varve sequences of Ernst Antevs' (1922, 1928) original New England Varve Chronology (NEVC) and their correlations. The locations of varve sequences show the approximate geographic areas and lakes in which they were measured. Numbers at ends of varve sequences are New England (NE) varve years. (B) Varve sequences of the new North American Varve Chronology (NAVC). The varve sequences show the renumbering, consolidation, and extension of Antevs' original chronology in North American (AM) varve years. Also shown are the core sites and outcrops used to revise the original NEVC or that are otherwise mentioned in the text (south to north): GL—Glastonbury, Conn.; PET—Petersen Farm, South Windsor, Conn.; KF—Kelsey Ferguson Brick Yard (Redlands Brick Co.), South Windsor, Conn.; SC—Scantic, East Windsor, Conn.; SHD—South Hadley, Mass.; UM—University of Massachusetts, Amherst (Rittenour, 1999); NHT—North Hatfield, Mass.; CAN—Canoe Brook, Dummerston, Vermont (Ridge and Larsen, 1990); NEW—Newbury, Vermont (Ridge and Toll, 1999); AYR—Ayers Brook, Randolph, Vermont; NHV—North Haverhill, N.H. Scribed box is area shown in figure 1C. (C) Core sites in the Connecticut Valley of southern New Hampshire and Vermont (south to north): ALD—Aldrich Brook, Westmoreland, N.H.; CHN and CHS—Charlestown (north and south sites), N.H.; CB—Clay Brook, Charlestown, N.H.; R12—Rt. 12A, North Charlestown, N.H.; PHS and PHN—Perry Hill Basin (south and north sites), North Charlestown, N.H.; WB—Weathersfield Bow, Vt.; CJ—Claremont Junction, N.H. Shaded region is area covered by Lake Hitchcock and scribed areas are where the valley is today floored by thick lake bottom silt and clay.

deglaciation and also to other parts of North America. The NAVC record and its calibration defined by this study allow for the varve numbering system to be continually updated and revised as additional varve records, new radiocarbon ages, and updated calibration data sets become available.

ANTEVS' NEW ENGLAND VARVE CHRONOLOGY (NEVC)

Ernst Antevs (1922, 1928) constructed the original NEVC as two major varve sequences (with separate NE varve year numbering systems), mostly compiled from the varve records of glacial Lake Hitchcock in the Connecticut Valley of western New England (fig. 1A). Antevs' older varve sequence (NE 2700-6352) was based on the correlation of varve records in the Hudson (Lake Albany), Connecticut (Lake Hitchcock), Ashuelot (Lake Ashuelot), and Merrimack (Lake Merrimack) valleys and has become known as the "lower Connecticut Valley varves" (Ridge and others, 1999; Ridge, 2003, 2004). Antevs began this sequence at NE 2700 to eventually incorporate older varves in New York, New Jersey, and southern Connecticut that he could not connect to varves from Lake Hitchcock. The younger sequence (NE 6601-7750), referred to as the "the upper Connecticut Valley varves," represents a correlation of varves in the upper Connecticut (Lake Hitchcock) and Winooski (Lake Winooski) valleys of northwestern New England. Here, "lower" and "upper" refer to the sequences' stratigraphic positions, but they were also formulated in the lower and upper Connecticut Valleys, along with their correlative sections in adjacent valleys. Antevs was not able to link the two sequences as a single chronology and inferred a gap between them, informally known as the "Claremont gap," which he estimated to be ~250 years. Attempts to close the gap based on less than satisfactory varve matching (Ridge and others, 1996, 1999) are now known to be incompatible with new radiocarbon ages and the present work replaces these earlier interpretations. Difficulty in finding varve exposures in the Charlestown to Claremont area of southwest-central New Hampshire was an obstacle to closing the Claremont gap. In addition, the upper century of the lower Connecticut Valley sequence was measured on sandy pro-deltaic varves, while the lower part of the upper Connecticut Valley sequence was composed of extremely thick (up to 200 cm) sandy ice-proximal varves. Both of these varve types may be influenced by local sedimentation processes and can be difficult to match with varves that record regional trends in varve thickness. Charlestown is also an area of delayed ice recession and end moraine building (Ridge, 2000) that interrupted the onlapping pattern of glacial varve deposition in the Connecticut Valley.

The NEVC was a significant leap forward in our understanding of the last glaciation because of several important attributes that allowed it to be used as a record for correlation and deglaciation chronology. First, varves from many different basins, which were not hydrologically connected, match each other very precisely and allowed Antevs (1922, 1928) to fill gaps in the records from the Connecticut Valley (fig. 2). These correlations demonstrate that deglacial weather patterns, which controlled varve thickness from year to year, were relatively consistent across New England and eastern New York State. Second, the matching of varves could be accomplished regardless of the thickness of individual records, with the relative thickness patterns of ice-proximal sequences composed of thick (10's of cm) varves matching distal sequences composed of much thinner (<1 cm) varves. Thick, sandy, ice-proximal varves as well as basal varves resting on till, outwash, or bedrock show the position of the ice margin in a given varve year. These varves could be matched to the NEVC and were used by Antevs (1922) as a means of reconstructing the pattern and rates of deglaciation from central Massachusetts to northern New Hampshire and Vermont.

Beginning in the 1930's, the validity of the NEVC as an accurate chronology, and its use for determining the history of deglaciation, was challenged. Richard Foster Flint (1929, 1930, 1932, 1933) interpreted the deglaciation of southern New England as having occurred by vertical "downwasting" of the ice sheet (also called regional stagnation) over a large region. In the minds of many geologists, Antevs' mode of deglaciation by "recession" (Antevs, 1922, 1939; today called "systematic ice recession" or "stagnation-zone retreat") was replaced by Flint's concept of regional stagnation. The idea of regional stagnation challenged the systematic south to north ice margin recession depicted by the NEVC and more importantly challenged the validity of the varve chronology for determining the pattern and rate of deglaciation. Although Flint recanted his criticisms of varve chronology in later publications, inferring that the NEVC was compatible with regional stagnation (Flint, 1932, 1933), and treating the subject in detail in the first edition of his textbook, *Glacial Geology and the Pleistocene Epoch* (Flint, 1947), the doubts he created in earlier publications never completely disappeared. Later work in New England on stratified deposits associated with ice recession, primarily by the U.S. Geological Survey employing the morphosequence concept (Jahns and Willard, 1942a, 1942b; Koteff, 1974; Koteff and Pessl, 1981), has confirmed a systematic south to north ice recession by an active glacier with a stagnant marginal zone and has confirmed Antevs' (1922) systematic ice recession model.

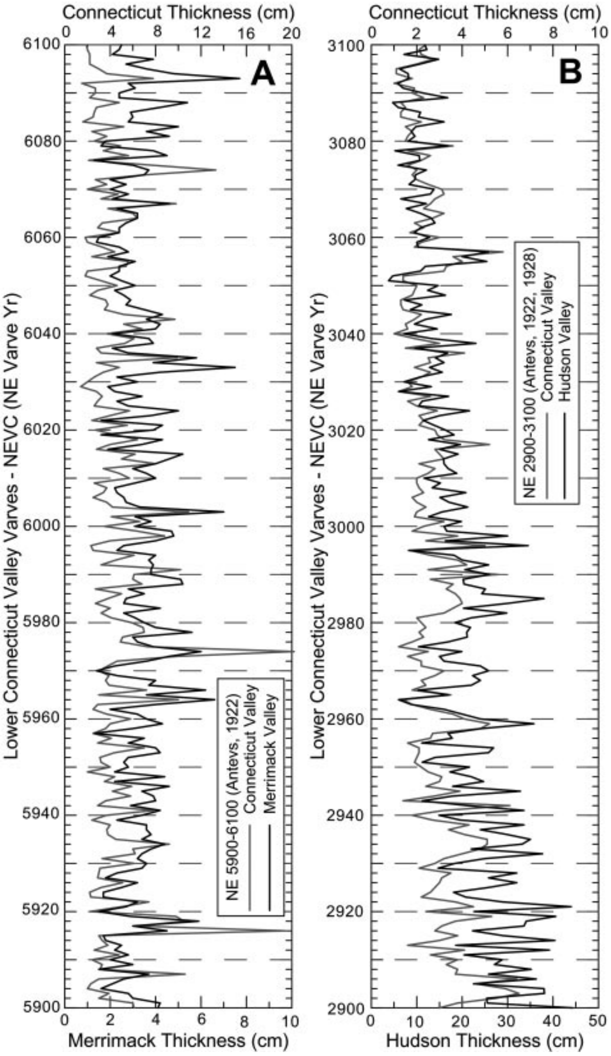

Fig. 2. Correlation of varve sequences based on annual matches between separate glacial lake basins across New England and New York State in Antevs' (1922, 1928) original New England Varve Chronology. (A) Match of varves in the Merrimack Valley near Concord, New Hampshire and the Connecticut Valley of southern New Hampshire and Vermont. (B) Match of varves in the Hudson Valley near Newburgh, New York and the Connecticut Valley near Hartford, Connecticut.

Another source of skepticism regarding varve chronology in North America were emerging global and trans-Atlantic connections or "teleconnections" of De Geer (1940) based on the matching of annual layers from varve sequences around the world. By the mid-1930's teleconnections were proposed between Scandinavia and North America (De Geer, 1921, 1926, 1929, 1930, 1934b), South America (De Geer, 1927, 1929, 1930, 1934b), and Africa (De Geer, 1934a, 1934b). Today it seems that exact annual correlation of varve records between widely-spaced continents, some in different hemispheres, cannot be supported given the very different behavior of annual weather patterns world-wide and also the quality of the matches. Antevs did not attempt such correlations and he sharply criticized De Geer's inter-hemispheric and trans-Atlantic varve connections (Antevs, 1931b, 1935, 1954).

Further skepticism of varve chronology in North America occurred with the first application of radiocarbon ages to the chronology of deglaciation in New England. Flint (1956) interpreted two sets of radiocarbon ages as bracketing the age of Lake Hitchcock between 12,700 and 10,700 ^{14}C yr BP. At the time this seemed to dispute the over 4000 years of varves thought to represent this lake in Antevs' NEVC. Flint's interpretations are today known to be incorrect based on detailed study of the annual nature of sediment and its distribution in Lake Hitchcock (Ashley, 1972, 1975), more recent studies of the drainage of Lake Hitchcock (Stone and others, 2005a, 2005b), new radiocarbon ages from fossils within varves of the NEVC (Ridge and Larsen, 1990; Ridge, 2004; Stone and Ridge, 2009), and the calibration of the radiocarbon time scale (Stuiver and others, 2005; Reimer and others, 2009). Unfortunately, Flint's interpretations of radiocarbon ages in New England were disastrous for varve chronology in North America. Not only did the radiocarbon ages apparently invalidate the varve count, but it prompted Flint to omit any reference to the NEVC from the later two editions of his widely-used textbook on glacial and Quaternary geology (Flint, 1957, 1971). Meanwhile, pioneering studies of the secular variation of paleomagnetism (McNish and Johnson, 1938; Johnson and others, 1948; Verosub, 1979a, 1979b) were performed on varves from sections that always seemed to match Antevs' chronology but these studies got little attention from glacial and Quaternary geologists. Spectral analysis of the NEVC has since been used to document El Niño-like cycles in the late glacial climate of New England (Rittenour and others, 2000).

METHODS

New long cores (up to 46 m) of varve sequences were collected in the Connecticut Valley for improving the NEVC (figs. 1B and 1C). Targets of the drilling were varve sections that might provide closure of the Claremont gap, refinement of the varve record relative to deglaciation, and repetition of the NEVC for making corrections and evaluating the record of climate in the varves. Antevs faced difficulties in achieving many of these goals because surface exposures of varves were not available to him in critical areas where we drilled many of our cores. We have also been able to apply digital imagery to the measurement and analysis of varves. The methods we applied to core collection, core preparation, capture of digital images, and computer measurement, as well as the computer software we use to measure varves, are available in the supplementary data (http://earth.geology.yale.edu/~ajs/SupplementaryData/2012/Ridge) for this paper and at Ridge (2012).

Long cores were collected by the drilling services of the U.S. Geological Survey using a Central Mining Equipment hollow-stem auger continuous sampling system. At each drill site, core samples in plastic liners [7.6-cm (3-in) inside diameter] were collected in 152-cm (5-ft) core drive segments from two side by side holes vertically offset by 61 cm (2 ft). The duplicate drill holes were necessary to capture complete sections that were sometimes disturbed by drilling in one drill hole or otherwise incomplete near the top and bottom of each core drive segment.

Cores were drained and split into working and archived halves. Archived halves were stored while the working half was scraped with a razor blade and partially dried in preparation for the collection of successive digital images along the axis of each core segment. High-resolution (2000 × 3008 pixels, 2.33 MB) images were collected in a specially designed box illuminated with full spectrum fluorescent bulbs and using a Nikon D-50 digital camera with a USB connection to a computer equipped with Nikon Capture Control 4 and Nikon Capture Editor software. Varve measurements were made with a script program written to operate with UTHSCSA Image Tool 3.0 freeware (Wilcox and others, 2002).

CRITERIA FOR VARVE RECOGNITION AND MEASUREMENT

The collection of magnified digital images of partially dried cores has allowed a more accurate and consistent identification of varve boundaries than is possible in the field and the digital images have allowed us to delineate the details of intra-annual varve stratigraphy (figs. 3A to 3D) as well as develop our own criteria for varve recognition. A foundation to sound glacial varve measurement is the accurate identification of winter layers[2] without which an accurate varve count is not likely. At some of our core sites, varves with well-defined winter layers pass upwards at the top of the section into units with winter layers that are silty or split by many partings (figs. 3E and 3F), making their consistent identification essentially impossible. This problem is usually the result of decreasing water depth (to less than 10-15 m) during sediment accumulation or a gradual fall in lake level due to postglacial isostatic adjustment. Inconsistent varve identification can also be caused by the interfingering of sandy deltaic bottomset beds with varve stratigraphy during delta progradation.

Several fundamental characteristics are common to all glacial varves that we have confidently measured and were recognized by Ashley (1972, 1975), including: (1) winter layers composed of nearly pure clay; (2) winter layers that are sharply truncated above, while below winter layers have a diffuse or gradational boundary with the underlying summer layer; and (3) summer layers that are internally complex with at least a few separate micrograded units composed of fine sand to silty clay indicating that summer layers are not the result of single events (figs. 3A to 3D). We have measured the boundary of winter layers overlain by summer layers as the first silty or sandy layer that interrupts the nearly pure clay of the winter layer. Without exception this boundary is a sharp contact. However, the upper boundaries of summer layers, where they are overlain by winter layers, may be diffuse or gradational and are placed where nearly pure clay settles above clayey silt or fine sand. The total thickness of a varve is measured from the bottom of its summer layer to the top of its overlying winter layer.

In addition to the fundamental characteristics outlined above, which apply to all glacial varves, the internal stratigraphy of thicker glacial varves that were deposited relatively close to a receding ice front, or within a century or two after deglaciation, follows a pattern that lends itself to greater consistency while counting. Summer sediment deposition in these varves (fig. 4) can be subdivided into three units: (1) an early melt season layer, (2) a main melt season layer, and (3) a late melt season layer. These distinctions are based on grain size, as reflected by color upon partial drying of the core with clayey units being darker because of higher moisture content. At the base of summer deposition, early melt season layers are composed of darker and more clayey silt than the main melt season layer above and frequently display highly rhythmic micrograded units (figs. 4A-4B). These rhythmic units appear to represent diurnal meltwater pulses introduced to the lake at a time of the year when weak, daytime melting pulses largely dissipated during nighttime when temperatures dropped. The main melt season layer that makes up most of the summer layer is coarser and lighter in color than the other summer units and is composed of many graded fine sand to coarse silt units of irregular thickness. The first graded unit of the main melt season layer is commonly the coarsest sediment in the entire summer layer and may

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[2] Although not strictly true it has become customary in glacial varve studies to refer to the relatively coarse part of a varve couplet that has fine silt to sand, and was produced during the melt season, as the "summer" layer. The melt season is when meltwater and sediment were added to the lake and bottom currents transported silt and sand across the lake floor. Likewise, the clay bed of the couplet, which is produced during the non-melt season, is referred to as the "winter" layer. The non-melt season is when little or no meltwater and sediment enter the lake, bottom currents are not active enough to prevent clay deposition, and the lake surface is usually frozen.

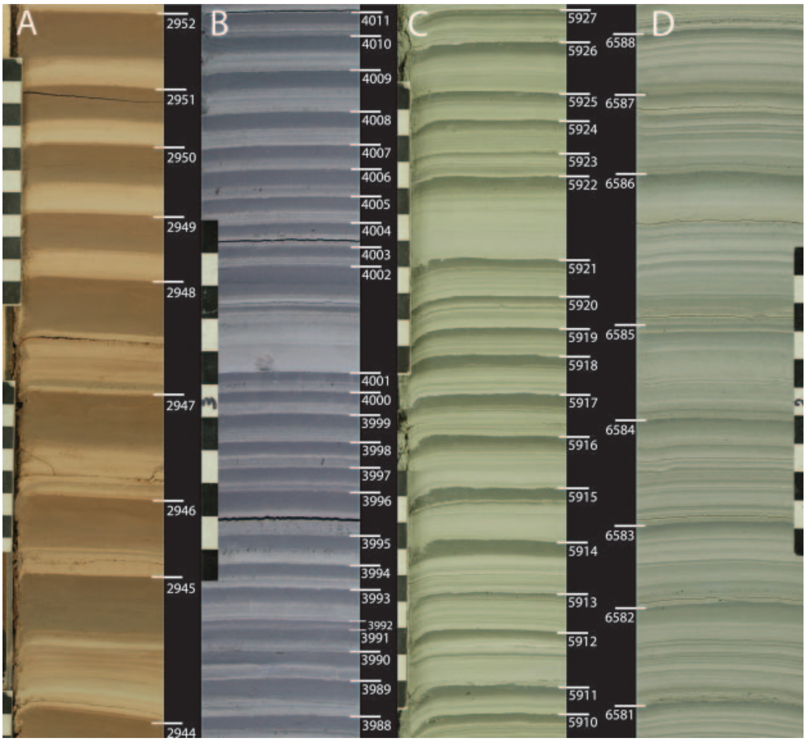

Fig. 3. Glacial varves and other laminated sediment in cores from the Connecticut Valley. All scales are in centimeters. Locations of core sites are in figures 1B and 1C. (A) Varves (AM 2944-2952) from the southern end of Lake Hitchcock at Glastonbury, Conn. Reddish brown color is from the glacial erosion of red sedimentary rock in the Mesozoic Hartford Basin. (B) Thin and clayey ice-distal varves (AM 3988-4011) from the Kelsey Ferguson Brick Yard in South Windsor, Conn. There is a strong positive correlation in this sequence between coupled summer and winter layer thicknesses. The thick varve in the middle of this sequence (AM 4002) represents a flood from a tributary valley in central Massachusetts. The dark bed in its upper summer layer is too silty to be counted as a separate winter layer. AM 3992 is an abnormally thin varve in this sequence. (C) Ice-distal varves (AM 5910-5927) from North Hatfield, Mass. that display multiple micrograded beds throughout each summer layer. Some of the winter layers in this sequence (AM 5913, 5915, and 5918) have thin silt and sand partings in their lower parts that may represent sand and silt deposited during storm or melting events near the end of the summer and after the initiation of winter clay and fine silt deposition (Shaw and others, 1978). AM 5912 has a dark bed in the upper part of its summer layer that is too silty to be counted as a separate winter layer. Also, the light unit above this dark bed has too few intra-summer units as compared to summer layers in this sequence to be counted as a separate summer layer. (D) Thick ice-distal varves (AM 6581-6588) from the southern core site in Perry Hill Basin, North Charlestown, N.H. that are sandy with many intra-summer micrograded laminations and a highly gradational transition from summer to winter layers. Although several of the winter layers are split by thin silt and fine sand partings it is still possible to consistently discern individual winter layers composed of nearly pure clay.

represent a nival flood early in the summer. Some of the individual graded units in the main melt season layer may be thicker than the winter layer or other parts of the summer layer. These units represent a very active meltwater system at a time when subglacial drainage paths are adjusted to their maximum efficiency by high meltwater discharges and they are fed by mid-summer melting, the release of meltwater stored from earlier in the summer (Elliston, 1973; Jansson and others, 2003; Bennett and Glasser, 2009), and large summer rainfall events (Chutko and Lamoureux, 2008). At the top of the summer layer the late melt season layer is darker and more clayey than the unit below and may display the same rhythmic micrograded units found in the early melt season layer, although these units tend to be less well organized and less

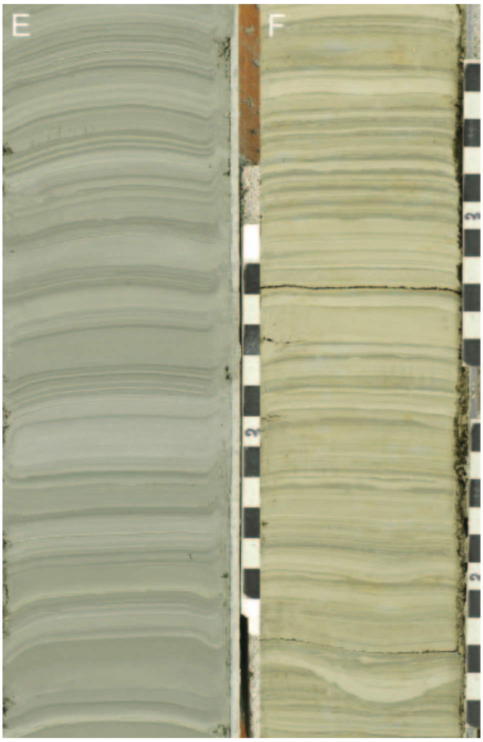

Fig. 3 (continued). (E-F) Laminated glacial lake sediment with indistinct winter layers from the top of the core at the southern core site in Perry Hill Basin, North Charlestown, New Hampshire. The laminated beds in these images were likely deposited over years, but clear pure-clay winter layers are lacking, and this part of the section cannot be used for correlation. Varves transition upward into this type of sediment as a lake becomes shallow from sediment infilling or decanting of water during isostatic rebound. A critical water depth at which this begins to happen in the upper Connecticut Valley appears to be about 10–15 m. (E) Beds in this image have well defined laminations but appear to be missing distinct winter beds composed of nearly pure clay. (F) Higher in the section than shown in figure 3E, clay beds are sometimes apparent but are frequently split by silt laminae or disturbed by erosional surfaces created by organisms on the lake floor. Disturbances, such as the large dish-like feature at the bottom of the image, are associated with the swimming, resting, or nesting traces of fish and other organisms when seen in outcrops (Benner and others, 2008, 2009; Knecht and others, 2009).

conspicuous. The late melt season unit represents a waning meltwater discharge and commonly fines upward. This unit grades into the winter layer above with occasional interruptions by silt or fine sand partings that may represent late summer to early fall runoff or melting events that briefly reinvigorate bottom currents after clay deposition has begun. In much thinner ice-distal varves, the main melt season unit dominates the summer layer and the early and late melt season units may be extremely thin or absent.

FORMULATING THE NAVC

After its initial formulation the NEVC did not have any revision or modification of its numbering system (Antevs, 1922, 1928; fig. 1; NE 2700-6352, 6601-7750). Modifications are warranted with the documentation of errors and the discovery of a link between the lower and upper Connecticut Valley varves, which allows a unified numbering system for all NEVC varves. The revised numbering system for varves in the northeastern United States, or the new NAVC (tabulated in American or AM years), begins at AM 2700, the same beginning number of the old NEVC. The NAVC numbers

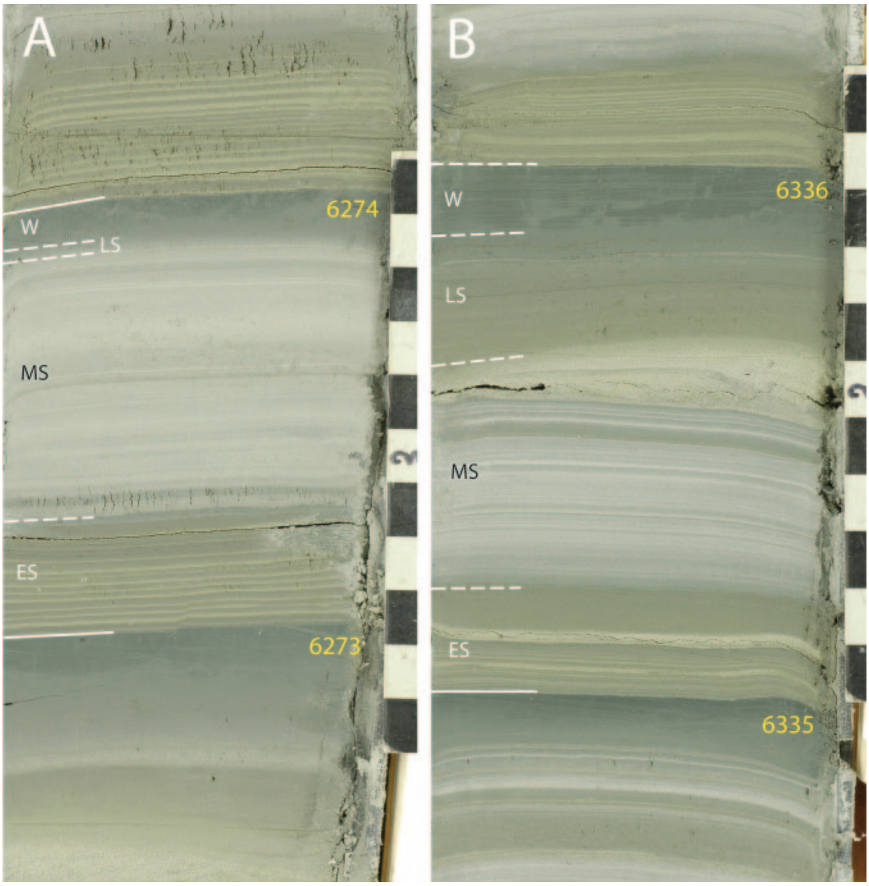

Fig. 4. Anatomy of ice-proximal varves at the Perry Hill South core site, North Charlestown, N.H. (fig. 1C) showing subdivisions of the summer layer into early (ES), main (MS), and late (LS) melt season (summer) units. Numbers on winter clay units (W) indicate NAVC (AM) varve years. Early and late melt season units are darker than the main melt season unit because of higher clay content and they often have highly rhythmic (diurnal?) units in them. The lighter main melt season unit has a higher silt and fine-sand content. Winter units are composed of nearly pure clay and have a dark greenish gray color. (A) Varve AM 6274 shows a highly rhythmic early melt season unit (also seen above in AM 6275) while its late melt season unit is very thin and not very distinct. The rhythmic, probably diurnal, beds in the early melt season unit were likely deposited when nighttime temperatures dropped to near or below freezing prior to the nival flood event that marks the beginning of the main melt season layer. Varve AM 6273 shows a highly gradational contact between its summer and winter layers. (B) Varve AM 6336 shows rhythmic beds in its early melt season unit (also seen above in AM 6337) and very faint rhythmic layers in its late melt season unit. The main melt season unit in varve AM 6336 has a high fine-sand content with a ripple preserved near the top of the unit as well as many sandy micrograded units that may represent diurnal pulses of sediment.

were then adjusted to incorporate all corrections and consolidations of the varve chronology (fig. 1B). A translation table and programs for conversion between NEVC (NE) and NAVC (AM) varve years as well as all applicable varve records in the northeastern United States and century plots of the NAVC are available in the supplementary data (http://earth.geology.yale.edu/~ajs/SupplementaryData/2012/Ridge) and at Ridge (2012). Renaming the varve sequence to the NAVC is a more accurate reflection of the inclusion of sequences in New York State and anticipates a connection to sequences in New Jersey, New York State, Pennsylvania, and Canada.

Corrections to the NEVC

The matching of new cores (figs. 1B and 1C) to NEVC sequences (Antevs, 1922, 1928) revealed an almost exact replication of Antevs' chronology, but also what we interpret to be infrequent errors in the NEVC between NE 2700 of the lower Connecticut Valley varves and NE 7000 of the upper Connecticut Valley varves. Altogether there are 14 more varves in the NAVC than in the original NEVC. A complete listing of corrections and images of cores showing the areas of correction or unusual varves in our new cores is available in the supplementary data (http://earth.geology.yale.edu/~ajs/SupplementaryData/2012/Ridge) and at Ridge (2012). The most common errors are 23 very thin varves that were missed in the original NEVC chronology (figs. 5A-5C). Most of the missing varves were found in the lowest 1500 years of the old chronology where Antevs compiled records from moist clayey outcrops of thin varves in Connecticut and Massachusetts that can be difficult to visually separate in the field but are clearly visible using magnified digital images of partially dried sediment. We have found almost all the missing varves in cores from at least two sites and have also seen the missing varves in deep subsurface cores of ice-proximal varves where they are much thicker and easier to identify than in near surface outcrops of thin clayey varves. In figure 5, missing varves from outcrops of thin varves are shown to display more of the sequences in which they occur. In our correction of the original NEVC varve records, we have split couplets that Antevs counted as one varve, and which we now recognize as two varves, using the same proportions found in our cores. This process does not destroy the integrity of the original NEVC sequences because these already consist of "normalized" thicknesses (Antevs, 1922, 1928) from more than one measurement and outcrop. At five positions in the old chronology we interpreted two original NEVC couplets to be a single couplet where a dark clayey silt unit in a summer layer appears to have been mistaken for a winter layer (figs. 5D-5E). We interpreted these dark silty units to be too silty or sandy to be true winter clay beds.

At one position we interpreted five exceedingly thick couplets in a Hudson Valley record of the NEVC to represent instead exceedingly thick units within a single couplet (total thickness 225 cm). When the Hudson Valley records are matched to new Connecticut Valley core records (fig. 6), the thick intra-varve units appear to represent individual intra-annual flood events. The thick Hudson Valley couplets were measured by Gerard De Geer and published and used by Antevs (1922) to fill a gap in Connecticut Valley records. This error was first recognized by Rittenour (ms, 1999) in a long core collected at Amherst, Massachusetts (UM on fig. 1B) and is here further refined with an additional Connecticut Valley core at North Hatfield, Massachusetts (NHT, fig. 1B). The match of the Hudson and Connecticut Valley varves indicates the timing and character of the drainage of a glacial lake in the Mohawk Valley of eastern New York into the Hudson Valley. The drainage event occurred over the course of just one summer either as five distinct successive floods into the Hudson Valley and perhaps with partial refilling of the Mohawk Valley lake prior to each flood. The Mohawk Valley lake that drained was probably a stage of what has been called Lake Amsterdam (Fairchild, 1912; LaFleur, 1979, 1983).

In addition to the errors outlined above, we also identified nine varves prior to NE 7000 that were unusual in either color or relative thicknesses of winter and summer layers as compared to surrounding varves. These couplets did not violate our varve recognition criteria and we have interpreted these occurrences as varves, as did Antevs (1922, 1928).

Consolidation and Extension of the NEVC

The main obstacle to creating a unified varve chronology in New England, and also to obtaining an accurate calibration, has been the Claremont gap. Previous

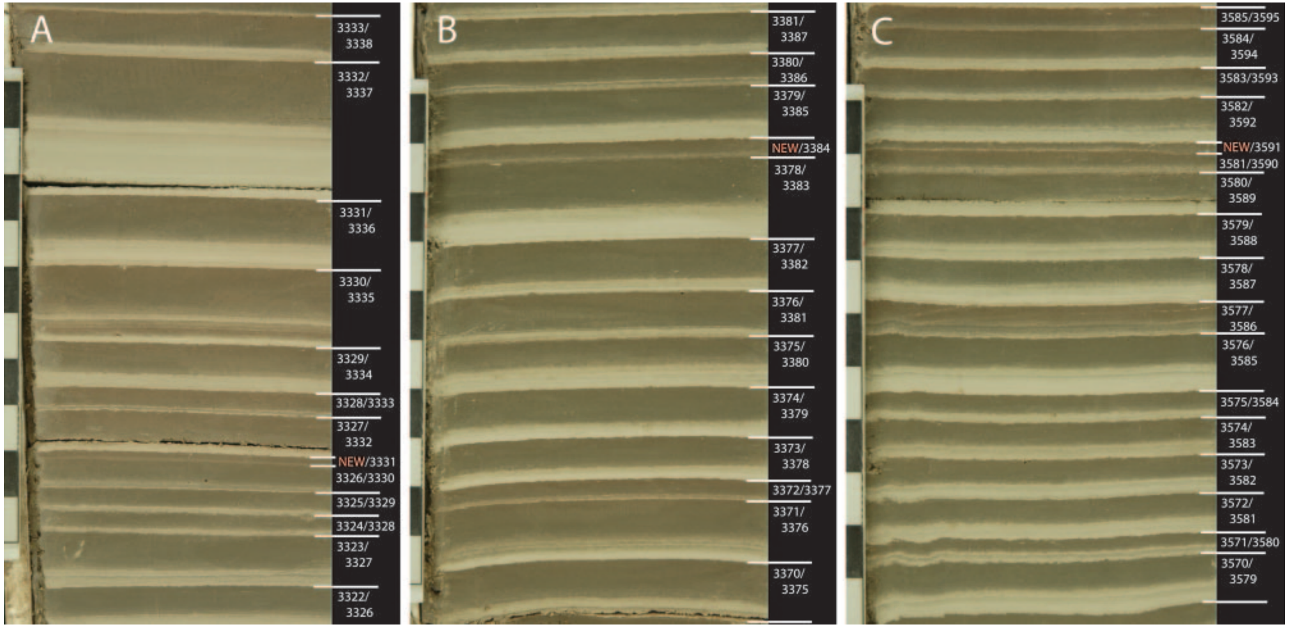

Fig. 5. Examples of corrections to Antevs' (1922) original NEVC based on detailed images of new varve cores in the Connecticut Valley (figs. 1B-C). Numbers on the images represent both the NEVC—NE years and the NAVC—AM years with the NE years shown over the AM years for each varve. Numbers in red show positions of errors in the NEVC. (A-C) New thin varves found in cores from the Kelsey Ferguson Brickyard. The clayey varves found here that have winter layers thicker than summer layers are difficult to accurately measure in the field. (A) Varve AM 3331 is a new very thin varve overlooked by Antevs and included as part of his NE 3326. We interpreted the clayey unit in the summer layer of NE 3330/AM 3335 to be too silty to be a winter layer, which was also the interpretation of Antevs. (B) AM 3384 is a new thin varve overlooked by Antevs as a part of NE 3378. A thin varve at NE 3372/AM 3377 was not missed by Antevs. (C) Varve AM 3591 is a new thin varve overlooked by Antevs as part of NE 3581. We interpreted the dark unit in the summer layer of NE 3577/AM 3586 as too silty to be a winter layer, which was also the interpretation of Antevs.

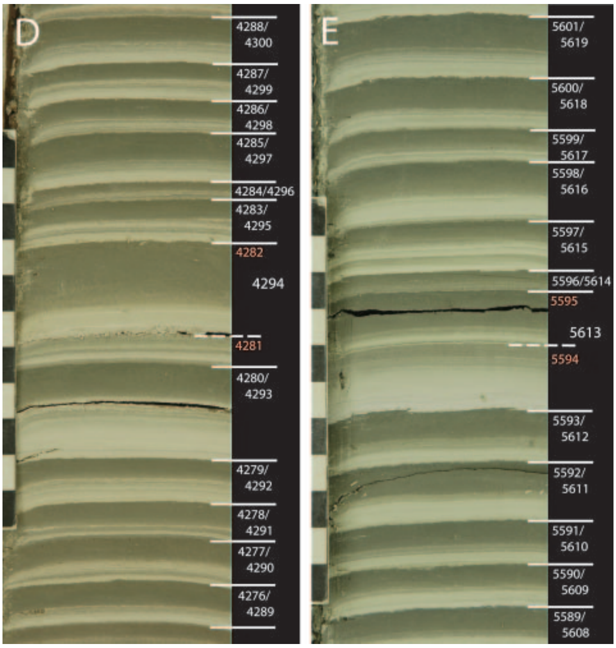

Fig. 5 (continued). (D-E) Locations where two varves were joined to form one varve. In each case the lower of the two joined couplets from the original NEVC (NE 4281 and 5594) is a false varve that has a dark upper unit that is too silty to be a winter clay bed. (D) Varves from Glastonbury, Connecticut. (E) Varves from North Hatfield, Massachusetts.

attempts to infer the precise duration of the gap, or the overlap of the lower and upper Connecticut Valley varves, relied on weak matches between the two sequences (Ridge and others, 1996, 1999, 2001), possible time relations inferred from surficial mapping in the Charlestown/Claremont area (Ridge, 2000), and sparse radiocarbon ages (Ridge, 2003, 2004). Cores of preserved lake floor surfaces near Aldrich Brook (ALD) in Westmoreland, New Hampshire, and in the Perry Hill Basin (PHN and PHS) in North Charlestown, New Hampshire (fig. 1C) provide the overlapping matched records that show a definitive link of the lower and upper Connecticut Valley varves that spans the Claremont gap (fig. 7). The Aldrich Brook record extends the lower Connecticut Valley varves by 177 years in the Connecticut Valley and ties them to the upper Connecticut Valley varves. The Perry Hill Basin cores in Charlestown, New Hampshire extended the upper Connecticut Valley varves further back in time by 32 years and helped facilitate the match of the upper Connecticut Valley varves to the older sequence. The correlation of the two NEVC varve sequences (NE lower Conn 6268 = NE upper Conn 6600), which now overlap by 219 years, shows that Antevs' original records in the Connecticut Valley overlapped by 10 years, which was not long enough to recognize a correlation. Also, the last ~45 varves of the lower Connecticut sequence (fig. 1A) are represented by shallow water and pro-deltaic environments along the side of the basin in which sandy varves did not record regional trends. The record in the Merrimack Valley overlaps with the upper Connecticut Valley varves by 85 years, but the last ~130 yr of the Merrimack Valley record (fig. 1A) were measured on sandy prodeltaic varves that do not correlate regionally.

The upper end of the NEVC has been extended beyond Antevs' original records with the complete measurement of a varve section at Newbury, Vermont (Ridge and Toll, 1999). Although Antevs measured varves in the base of this outcrop, it was not

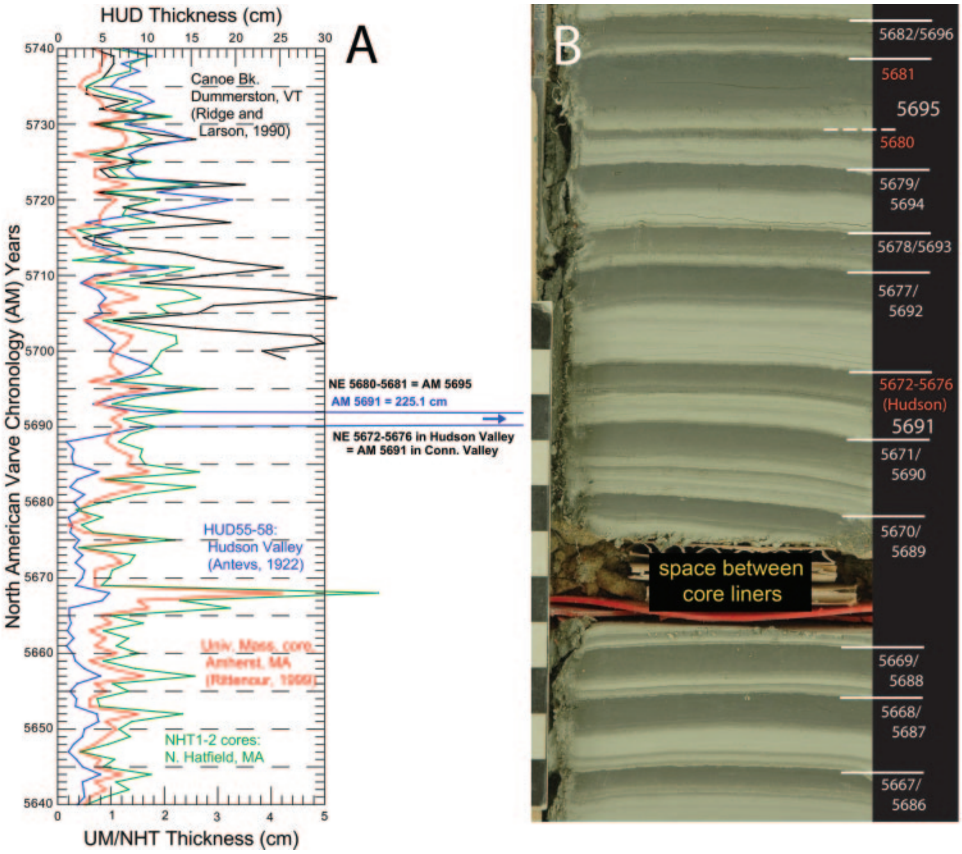

Fig. 6. Correction of Hudson Valley flood events from Antevs (1922). (A) Plot of AM 5640–5740 with corrected varve records spanning the interval of flood events in the Hudson Valley. When matched to new core records in the Connecticut Valley (North Hatfield and Amherst, Mass.; fig. 1B) five extremely thick couplets (totaling 225 cm), counted as individual varves in the old Hudson Valley record of Antevs (1922), correlate to one varve in the new Connecticut Valley cores. The five couplets measured in the original NEVC have been joined to form one varve (AM 5691) in the corrected Hudson Valley record. An additional correction was also made where varves NE 5680–5681 were joined to form AM 5695. (B) Varves in the North Hatfield core that span the period of Hudson Valley flood events. Numbers on the images show both NEVC—NE years and NAVC—AM years with the NE years shown over the AM years for each varve. Numbers in red show positions of NEVC corrections as outlined on the plot. AM 5691 represents the position of five thick couplets (NE 5672-5676), originally counted as separate varves in the Hudson Valley. NE 5680 is a false varve in which the dark upper unit is too silty to be a winter layer. The core space is between two 76-cm (2.5-ft) core liners that house the sample of a single core drive.

possible, using his field methods, to measure the very thin (mm-scale) varves that make up the upper part of the section. The entire Newbury outcrop was measured in duplicate sets of overlapping outcrop cores using magnified digital images. These measurements extended the NEVC over 900 years (to NE 8676 or AM 8358) into paraglacial varves[3] (fig. 8) that were deposited after ice receded from the Connecticut

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[3] The definition of *glacial varves* used here is varves that are deposited by currents generated by glacial meltwater inflow to the lake. Sediment in glacial varves can have a glacial source or it can be introduced to the lake by meteoric stream runoff. Sediment from meteoric sources is entrained by the relatively energetic currents generated by glacial meltwater inflow. *Paraglacial varves* are deposited in a glacial or postglacial lake in areas where sediment transport and accumulation are not controlled by currents generated by the

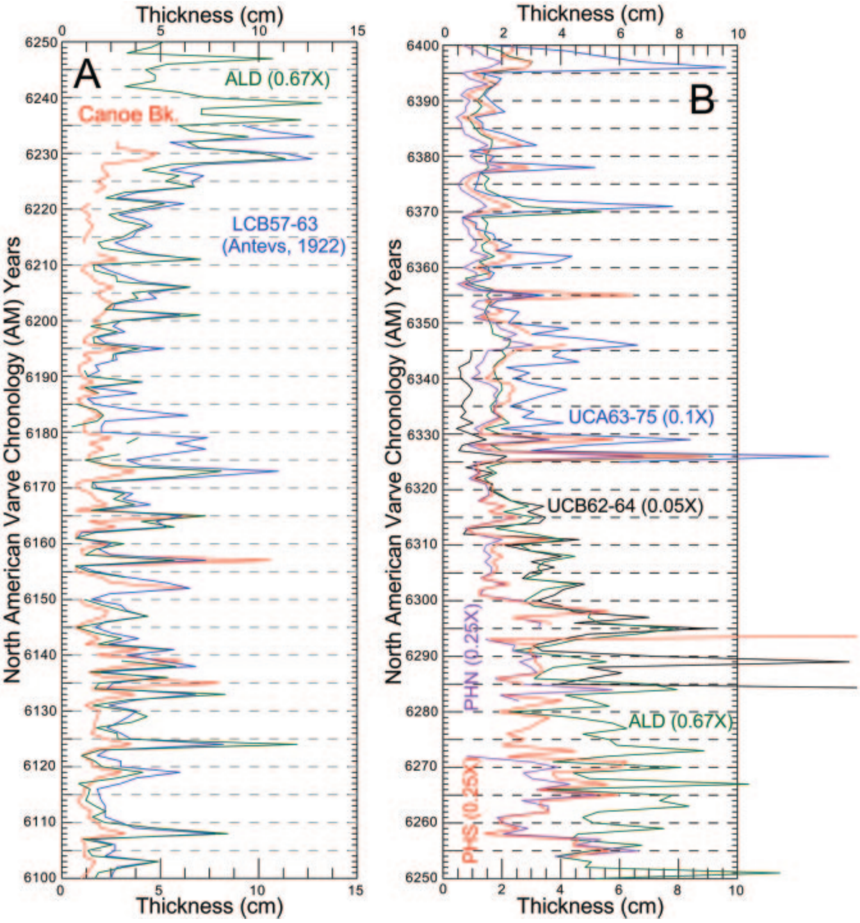

Fig. 7. Plot of varve records (A: AM 6100-6250; B: AM 6250-6400) showing the closure of the Claremont Gap. A critical record is the Aldrich Brook (ALD; fig. 1C) sequence, which spans the entire interval. Other records plotted are the Perry Hill Basin (south and north) core sites (figs. 1C), as well as varve records from Canoe Brook (Ridge and Larsen, 1990; fig. 1B) and the lower (LCB) and upper (UCA, UCB) Connecticut Valley records (fig. 1A) from Antevs (1922). Very sandy varves from the top of the LCB and Canoe Brook records, which do not match other records in the region, and exceedingly thick (up to 2 m) ice-proximal varves at the beginnings of some of the varve sequences (UCA, UCB, PHS, PHN) have been omitted for clarity. Some varve plots have been scaled down for comparison on the same graph as indicated by the thickness multipliers.

River drainage basin. Thin paraglacial varves have a larger counting uncertainty than glacial varves, which above NE 7200 (AM 6882-8358) was defined in duplicate core measurements as +35/−20 years.

CALIBRATION OF THE NAVC

Prior to 2008, 16 radiocarbon ages had been obtained on plant fossils from varves matched to the NEVC (Ridge and Larsen, 1990; Ridge, 2004; Stone and Ridge, 2009).

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introduction of glacial meltwater to the lake. Instead paraglacial varves are deposited by water and sediment from a paraglacial landscape, or a landscape that was previously glaciated but was not experiencing glaciation at the time of varve deposition. Paraglacial sediment delivery to a lake is highly influenced by past glacial modification of the land surface and varve thickness is controlled by meteoric runoff to the lake, which has a complex relationship to weather, geomorphic factors, and vegetation.

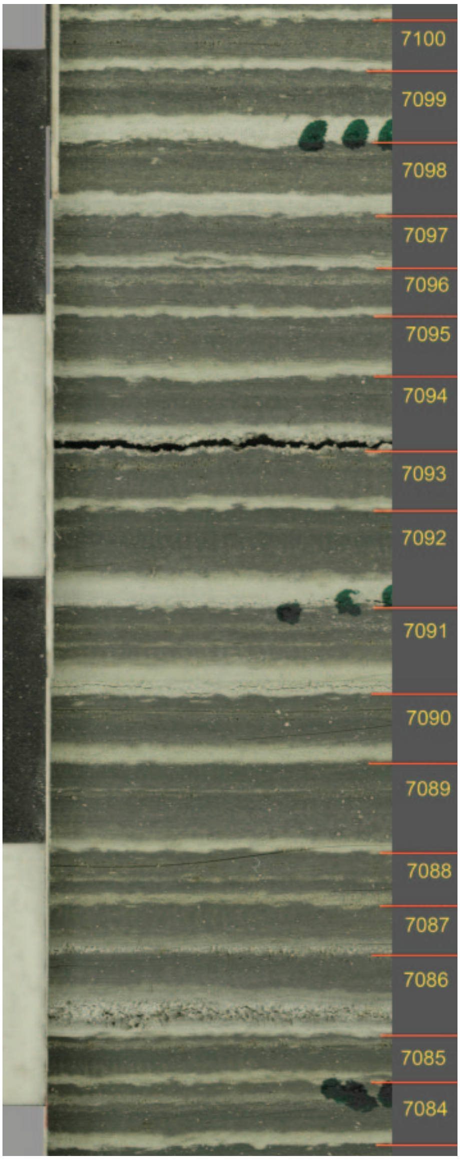

Fig. 8. Paraglacial varves from the northern Connecticut Valley at North Haverhill, New Hampshire. Numbers indicate NAVC (AM) varve years. Scale is in centimeters. Paraglacial varves are generally very thin, here averaging about 4 varves per cm. The tops of winter clay layers are disturbed by bioturbation (for example 7088, 7092, and 7100) and most winter layers contain fine sand and silt partings. Faint silt partings consistently near the tops of most winter clay units may be the result of late fall or early winter overturning. Occasional summer fine sand units that are thicker and coarser than in other varves (for example 7086 and 7094) are likely related to large precipitation or snowmelt events that washed sediment onto the lake floor from a local tributary stream.

We have added 38 radiocarbon ages measured on plant fossils and one fossil snail shell from varves matched to the NAVC in the Connecticut Valley and that span about 4800 varve years (see Appendix). Unfortunately, it was not possible to obtain radiocarbon ages from all parts of the NAVC or produce an even distribution across the whole

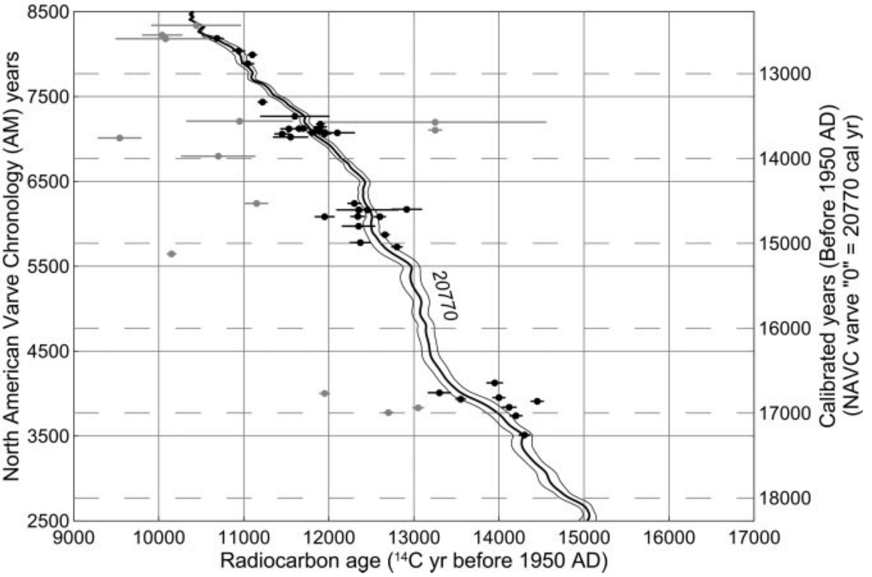

Fig. 9. Calibration of the NAVC using all available radiocarbon ages (see Appendix for list). Ages are plotted with 1-σ laboratory uncertainties as error bars. Using all the radiocarbon ages gives a best-fit (lowest mean square of weighted deviations, fig. 10A) offset of 20,770 cal yr BP between IntCal09 calibrated years (Reimer and others, 2009; thick line with 1-σ uncertainties shown as thin lines) and NAVC years. This is also the calibrated age of the NAVC "0" varve. Fourteen of the radiocarbon ages have poor laboratory precision values or may be outliers (gray, two of these points plot on top of other points). If only the remaining 40 radiocarbon ages (black, five of these points plot on top of other points) are used to calibrate the NAVC the offset is 20,810 cal yr BP (fig. 10A).

chronology because of the rarity of fossils in the varves. Finding numerous fossils for radiocarbon dating required searching in key outcrops, since most of the new sections we have studied are in cores that have only rarely yielded fossils.

Calibration of the NAVC (fig. 9) is based on the best fit of the varve year—radiocarbon age relationship of Connecticut Valley samples to the calibrated year—radiocarbon age relationship defined by the IntCal09 data (Reimer and others, 2009). This alignment assumes that the calibrated and varve year time scales record the same number of years and are only different by a consistent offset. This assumption would only be violated if there were a significant number of missing or spurious varves in the NAVC. Because the majority of the NAVC is covered by multiple varve sections and because we have replicated Antevs' work and corrected errors therein, such violation appears unlikely. We accomplish our calibration by choosing the value of the calibrated year minus varve year offset that minimizes the mean square of weighted deviations (M) between measured radiocarbon ages and those predicted by the IntCal09 data (fig. 10A). Numerically the offset is also the calibrated year age of the "0" varve year of the NAVC.

For each tested offset:

$$M = 1/n \sum_{i=1}^{n} [(({}^{14}C_p - {}^{14}C_m)/(\sigma_p{}^2 + \sigma_m{}^2)^{1/2})^2],$$

where ${}^{14}C_m$ = a measured ${}^{14}C$ age, σ_m = the reported 1-sigma lab uncertainty of a measured ${}^{14}C$ age, ${}^{14}C_p$ = an IntCal09 predicted ${}^{14}C$ age for the NAVC yr using a

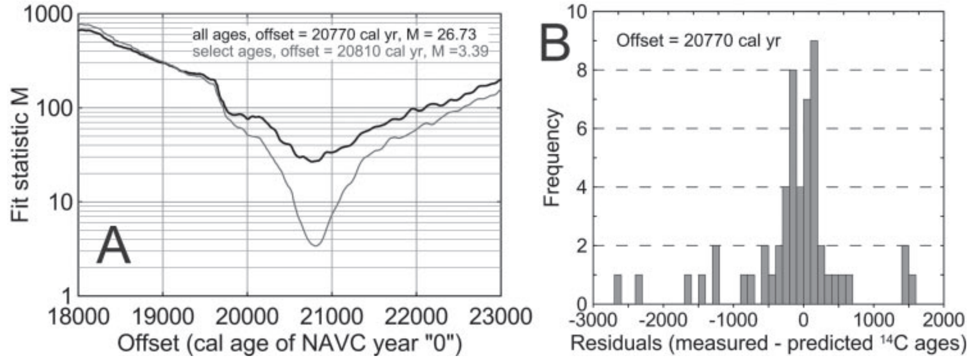

Fig. 10. NAVC calibration statistics. (A) Plot of M, mean square of weighted deviations between measured radiocarbon ages and corresponding radiocarbon ages predicted by a chosen offset value, for trial offsets (every 5 yr) from 18,000–23,000 cal yr BP. Shown here are results: 1) for all the radiocarbon ages (black), which is used to calibrate the NAVC, and 2) after removing 14 radiocarbon ages (gray). Removal of possible outliers and radiocarbon ages with poor precision better defines the best-fit (lowest M value) but does not significantly change the offset value given the uncertainties associated with the radiocarbon ages. (B) Histogram plot of residuals (actual minus predicted radiocarbon ages) for best-fit offset using all the radiocarbon ages.

chosen offset, σ_p = the reported 1-sigma uncertainty of an IntCal09 predicted ^{14}C age, and n = number of NAVC ^{14}C ages used for the calibration. This method allows us to avoid the rather messy translation of individual radiocarbon ages to calibrated ages along with their statistical distributions. Analysis of M was done every 5 years for offsets from 18,000 to 23,000 yr. If we use all of the radiocarbon ages without regard for quality, the best-fitting offset (lowest M = 26.73) is 20,770 years before 1950 AD (cal yr BP) or 20,820 years before 2000 AD (b2k). Formulas for converting NAVC years to calendar year estimates are:

$$\text{Calibrated year age [cal yr BP]} = 20{,}770 \text{ yr} - \text{AM yr},$$

and

$$\text{Age before 2000 AD [b2k]} = 20{,}820 \text{ yr} - \text{AM yr}.$$

It is clear from the plot of radiocarbon ages (fig. 9) that there are some outliers and ages with poor precision (>400 yr, mostly because of small sample sizes). If we eliminate these fourteen radiocarbon ages from the analysis (see Appendix), the fit of the radiocarbon ages from the varves to the Intcal09 data set better defines the best-fit offset (M = 3.39; fig. 10A) but this selective analysis changes the best-fit offset position by only 40 years (20,810 yr before 1950 AD) from the result we obtained using all the radiocarbon ages. It appears that selecting radiocarbon ages does not significantly improve the calibration. Regardless of which offset is used, it is important to note that the NAVC varve count is entirely compatible with the radiocarbon ages given their uncertainties.

The residual scatter between our radiocarbon ages and the IntCal09 calibration curve (actual minus predicted radiocarbon ages at the best-fit offset; fig. 10B) is inconsistent with measurement uncertainty alone in these two data sets because: (1) the minimum value of M, even after apparent outliers have been removed, is 3.39 ($p \ll 0.001$), and (2) the residuals display negative skewness as well as a scatter of ages that are "too old." This observation is consistent with the geological processes that are expected to disturb radiocarbon ages. Although we sought to minimize the possibility

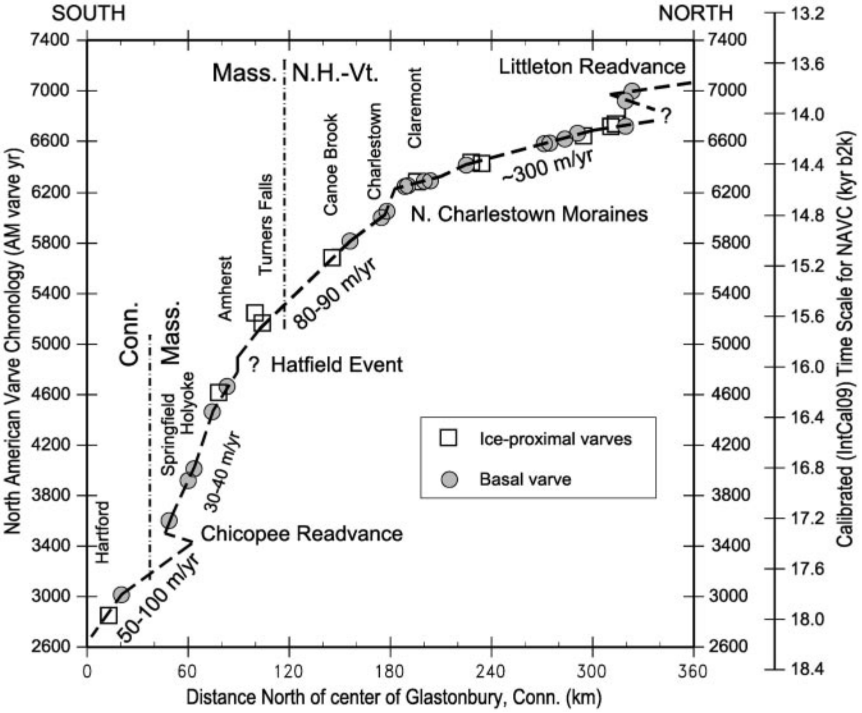

Fig. 11. Time-distance plot of Laurentide Ice Sheet recession along the axis of the Connecticut Valley. Shown is ice recession from central Connecticut to northern New Hampshire and Vermont. Data points are either sites with basal varves, where varves rest on till, ice-proximal sand and gravel, or bedrock, or thick sandy ice-proximal varves deposited within a few decades of deglaciation. Calibration of the NAVC (AM) years is shown in kyr b2k. Also indicated are average rates of ice recession in m/yr for different intervals of ice recession.

of recycling of older organic material into younger varves by sampling plant fossils in many varves that formed as soon as possible after deglaciation of a site, several old outliers may be the result of this process. The negative skewness of residuals is most likely the result of small degrees of sample contamination by post-depositional carbon due to decomposition and exchange with groundwater. For these reasons, one cannot compute the uncertainty of the best-fitting offset on the basis that the scatter is normally distributed and due only to measurement uncertainty (±80 yr). Negative skewness of residuals, which is probably caused by low levels of sample contamination, and sixteen positive residuals within 200 years of our best-fit offset suggest that the true offset could be older than the best-fit value by one to two centuries and our best-fit offset has an uncertainty of up to about 200 yr. A more precise estimate of the offset from radiocarbon data will most likely only be possible with a better quantitative understanding of the geological processes responsible for the observed scatter.

NEW ENGLAND'S DEGLACIATION CHRONOLOGY VS. THE NAVC

The NAVC spans the time intervals of several glacial events in the Connecticut Valley separated by intervals with very different ice recession rates. In order to investigate the timing of glacial events and rates of ice recession we have constructed a time-distance diagram of ice margin retreat from basal and ice-proximal varves (fig. 11). Basal varves occur at the bottoms of sediment sections resting on either bedrock, till, or ice-contact sand and gravel deposits and at a particular site represent the first varves deposited (first year) following ice recession. Ice-proximal varves are very thick and sandy couplets that indicate deposition within no more than a few decades of ice recession. The rate of onlap of glacial varves from south to north indicates the rate of ice recession with a ~10-yr resolution and allows us to determine the position and duration of major glacial stillstands and readvances in the Connecticut Valley. These data allow the construction of a map showing the ages of ice margin positions from south to north during the last deglaciation in western New England (fig. 12). In the Connecticut Valley there was a generally increasing rate of ice recession with the later periods of deglaciation showing very high rates of ice margin retreat (up to 300 m/yr). This fast retreat is indicated by the progressively gentler slope of the line indicating the age of deglaciation on figure 11 and the relatively rapid deglaciation of New Hampshire and Vermont (220 km in ~2000 yr, or average of ~110 m/yr) as compared to central Connecticut through Massachusetts (125 km in 2800 yr, or average of ~45 m/yr) on figure 12.

Glacial events such as stillstands of the receding ice front or readvances, known from previous studies, interrupt distinct periods of ice recession at four places in the NAVC record, and each lasted up to two centuries. The oldest of these events is the Chicopee Readvance in southern Massachusetts (Larsen and Hartshorn, 1982). In northern Massachusetts the Hatfield event represents a period of slow ice recession or a brief stillstand that occurred during ice retreat from Amherst to Sunderland, Massachusetts. After the Hatfield event, ice recession was more rapid than in previous intervals until the receding ice front reached the area of Charlestown, New Hampshire. The North Charlestown moraines represent another delay in ice recession (Ridge, 2000, 2004). Because there does not appear to be any evidence of a major readvance at this time, it is possible that the ice sheet merely receded to a position of stability or equilibrium. Following deposition of the North Charlestown moraines, ice recession into northern New Hampshire and Vermont was extremely fast (300 m/yr) for about five centuries before being interrupted by the Littleton Readvance and its equivalents (Antevs, 1922; Lougee, 1935; Ridge and others, 1999; Thompson and others, 1999; Larsen, 2001; Balco and others, 2009), which again demonstrates that the ice sheet remained active and did not simply stagnate. Ice recession north of the Littleton Readvance position was again very rapid (>150 m/yr).

THE NAVC AS A CLIMATE RECORD

In addition to spanning the time of several glacial events in the Connecticut Valley (figs. 11 and 12), the NAVC spans an interval with abrupt and extreme changes in climate (Greenland Event Stratigraphy units GS-2a to GS-1; Lowe and others, 2008) that are also recorded in the varves. Under late Pleistocene temperate glacial conditions, varve thickness in the Connecticut Valley would have been dominated by ablation and the introduction of large volumes of glacial meltwater and sediment to Lake Hitchcock during the summer. Meltwater discharge varied from year to year, and also between longer climatic events, allowing the varves to serve as a record of climate. There have been many studies of varves and their relationship to climate in small glacial lakes in the arctic and in alpine environments (for example Leemann and Niessen, 1994; Hardy and others, 1996; Lamoureux and Bradley, 1996; Leonard, 1997; Hughen and others, 2000; Moore and others, 2001; Lamoureux and others, 2002; Lamoureux and Gilbert, 2004; Hambley and Lamoureux, 2006; Chutko and Lamoureux, 2008; Bird and others, 2009; Thomas and Briner, 2009; Larsen and others, 2011). However, none of these lakes, because of their small size, their relatively small glacial runoff, significant biological and chemical changes that occur annually in some cases, and the overall complexity of processes controlling sedimentation in them (Menounos and others, 2005; Hodder and others, 2007), can serve as adequate analogs for Lake

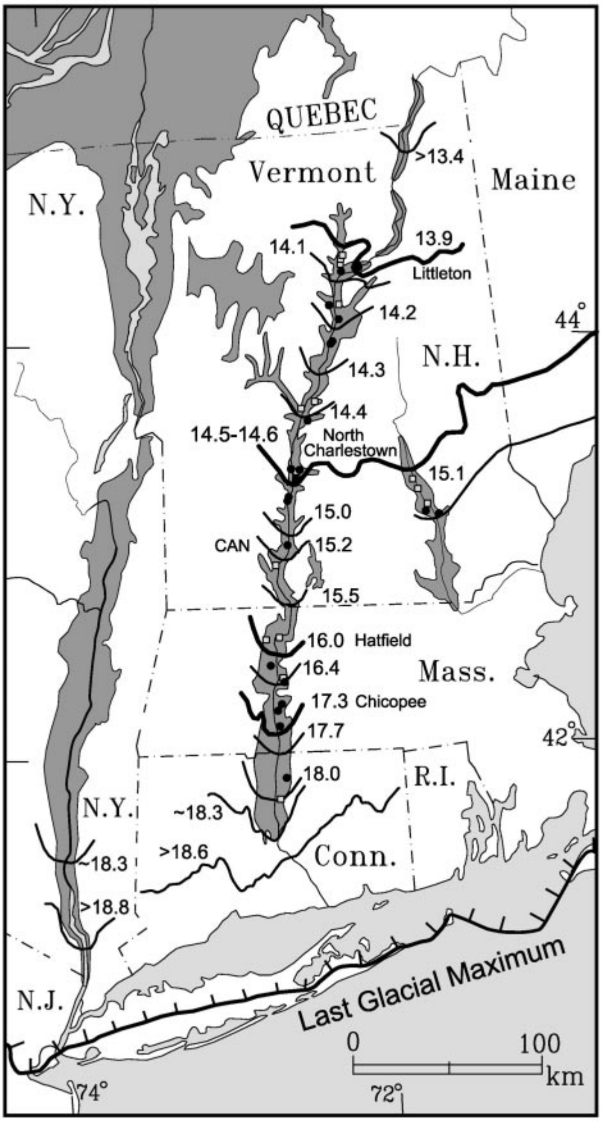

Fig. 12. Ages in years b2k of approximate reconstructed ice recession positions of the last deglaciation in western New England. The locations of basal and ice-proximal varve sections are shown in Lakes Hitchcock (Connecticut Valley) and Merrimack with the same symbols as on figure 11. The names of physiographic features and glacial lakes are given on figure 1A. Major delays in deglaciation and readvances (heavy lines) are labeled as discussed in the text. In the southern Hudson Valley and across southern Connecticut minimum ages of ice front positions are determined from the minimum number of varves deposited after these events that pre-date the formation of Lake Hitchcock. In southern New Hampshire are ice front positions that extend into Maine as compiled from Ridge and others (2001).

Hitchcock. Although there are no large modern glacial lakes that could serve as exact analogs for Lake Hitchcock, modern glacial lakes associated with temperate glaciers and that are dominated by glacial meltwater discharges produce varves similar to those in Lake Hitchcock (Gustavson, 1975; Loso and others, 2004; Loso and others, 2006). The key parameter in evaluating climate change in Connecticut Valley varve records is varve thickness (bottom of summer to top of overlying winter layer). The relatively thick silt to medium sand summer layers of Lake Hitchcock varves, which sometimes contain ripples, indicate strong bottom currents sweeping the floor of the lake, especially during years with the highest meltwater discharge. Varve thickness may be a proxy for mean annual temperature but more likely summer positive degree days, which are a function of summer length and temperature. Summer and winter layers are composed of sediment introduced to a lake during the melt season. Winter layers, which are composed of clay that is left in the water column at the end of the melt season, settle during the non-melt season when meltwater-driven lake bottom currents diminish. Thus, total varve, summer, and winter layer thicknesses, like ablation, are not significantly influenced by winter temperature.

Glacial varve thickness records (AM 2700-7050) at specific sites in the Connecticut Valley display overall up section thinning as distance to the ice margin increases during ice recession. Variations superimposed on that overall trend, in addition to reflecting climate-related changes in meltwater production, show non-climatic variations caused by lake-level changes or outburst floods from ice-marginal lakes. Events caused by these non-climatic stimuli must be identified to separate them from climatic variations if glacial varves are to be properly interpreted for their climate record. Flood events produce single year spikes in varve thickness that do not persist in the varve record and can be associated with the release of water from specific tributaries. Several abrupt and persistent decreases in glacial varve thickness in the NAVC correspond to periods of glacial readvance and moraine building, while sharp and persistent increases in varve thickness correspond to the initiation of rapid ice recession. The changes in varve thickness reflect changes in meltwater production that appear to be brought on by abrupt climate change events that influenced ice sheet ablation. A similar interpretation of varve thickness and climate was formulated by Andrén and others (1999) and Ringberg and others (2003) in trying to correlate glacial varve sequences in Sweden with Greenland ice core records. Paraglacial varves above AM 7050 (fig. 8) are generally much thinner than the glacial varves but also display sub-century and longer term variations. The thickness patterns of paraglacial varves, relative to climate, are the opposite of glacial varves with thinning during warm events, perhaps as a result of denser vegetation, and thickening during cold events when landscape erosion was more active (Ridge and Toll, 1999).

THE NAVC-GREENLAND COMPARISON

This paper compares NAVC varve records, calibrated to the IntCal09 time scale (converted to yr b2k), and the GISP2 Greenland oxygen isotope record matched to the GICC05 time scale (yr b2k) of the NGRIP ice core (figs. 13 and 14). It must be emphasized that in figures 13 and 14 the calibrated time scales of the varve and ice core records were formulated differently and have different uncertainties, one being a varve count calibrated with radiocarbon ages and the other being a count of ice core layers back from the present. Uncertainties in the varve count and its radiocarbon calibration were discussed above. Ice core layers were counted conservatively as a minimum number of annual layers with uncertain annual layers not included in the layer count and tabulated as an accumulated positive uncertainty (Andersen and others, 2006; Rasmussen and others, 2006; Svensson and others, 2006). The true ice core time scale can therefore only be older than the GICC05 time scale. We do not expect the varve and ice core calibrations to match each other exactly at the true time correlation of the records. We have chosen not to precisely align the two independent time scales as a starting point, but rather we align the records where features on both records appear to be similar in spacing and magnitude from decadal to stadial scales. This approach better displays the proposed coupling of the two records, especially the fine details at the sub-century scale. The uncertainties of both the varve and ice core time scales do

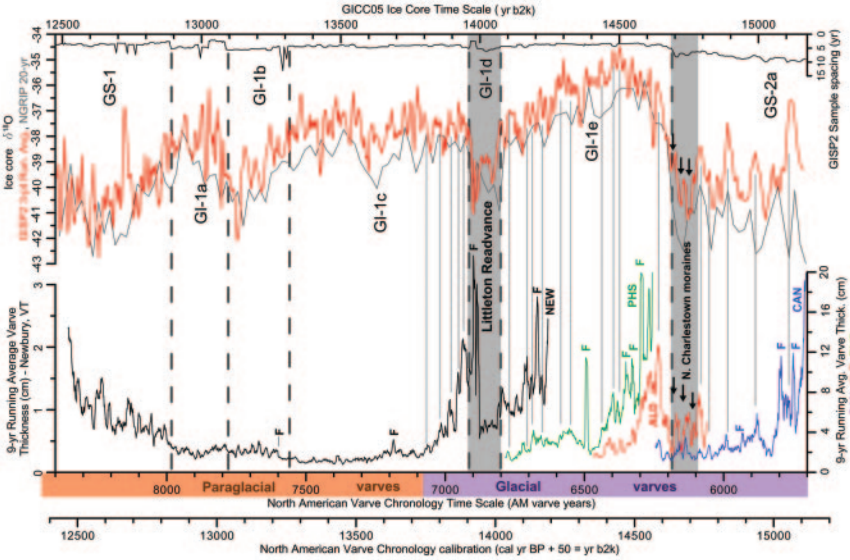

Fig. 13. A comparison of NAVC varve records and oxygen isotope records from the Greenland Ice Sheet from 15,100 to 12,500 yr b2k. Connecticut Valley NAVC records (9-yr running averages) AM 5700–8400 (bottom) are from Canoe Brook (CAN; Ridge and Larsen, 1990) and Newbury (NEW; Ridge and Toll, 1999), Vt. and Westmoreland (ALD) and North Charlestown (PHS), N.H. (Figs. 1B-C). The calibrated time scale applied to the NAVC (fig. 9) is here converted to yr b2k to match the standard for ice cores. Greenland ice core oxygen isotope records (top, calibrated to the GICC05 ice core time scale; Andersen and others, 2006; Rasmussen and others, 2006, 2008; Svensson and others, 2006) are the GISP2 continuous non-averaged original measurements (red, 3-pt running average; Stuiver and others, 1995; Stuiver and Grootes, 2000) with sample spacing in GICC05 years and the NGRIP 20-yr averaged record (gray; Rasmussen and others, 2006). The NGRIP record has only been plotted for comparison since it does not have the resolution of the GISP2 record. Varve and GISP2 data files used here are available in the Supplementary Data (http://earth.geology.yale.edu/~ajs/SupplementaryData/2012/Ridge). Uncertainty of ice core layer counts used to formulate the GICC05 time scale is +125 to +197 yr in the 15,000–12,500 yr b2k interval (Andersen and others, 2006; Rasmussen and others, 2006). With the proposed exact alignment of sub-century-scale and stadial-scale events in the two records for 15,000–13,800 yr b2k the independent calibrated time scales of the ice core and varve plots are different by only +55 yr (ice core age minus varve age) as discussed in the text. Prominent spikes in varve thickness due to non-climatic events (marked F), such as floods produced by the release of local ice-marginal lakes and lake level changes, cannot be correlated to the Greenland record. Shading of the NAVC varve year axis indicates records from glacial (purple) and paraglacial (orange) varves. Dark gray swaths show stadial-scale delayed ice recession events in the Connecticut Valley represented by the North Charlestown moraines (Ridge, 2000, 2004) and Littleton Readvance (Antevs, 1922; Lougee, 1935; Ridge and others, 1999; Thompson and others, 1999) aligned to ice core events. Bold dark gray dashed lines are Greenland stadial (S) and interstadial (I) event boundaries of the ice core record (Lowe and others, 2008). Thin gray tie lines indicate the coupling of sub-century warming events between the varve and ice core records (intervening cold events also match). Black arrows indicate coupled drops in varve thickness and cold events on the ice core record during deposition of the North Charlestown moraines. After 13,800 yr b2k the boundaries of events in the paraglacial varve record are not as precisely defined and may lag behind the ice core record by up to 50 yr.

not allow us to use them to prove that aligned features are synchronous or to measure a lag between the records. However, as will be discussed below, the consistent offset alone between multiple major event pairs as well as many smaller sub-century-scale events extending across a 1200-year period (15,000-13,800 yr b2k) can only be explained if either the time lag between them was precisely constant or the events were in fact synchronous. We conclude below that the latter possibility is most likely and that both records are simultaneously recording the same regional climate changes. Aligning events between 15,000 to 12,500 b2k and adopting the GICC05 time scale of the ice cores implies a NAVC offset of 20825 cal yr (or 20875 yr b2k), which is 55 yr older than

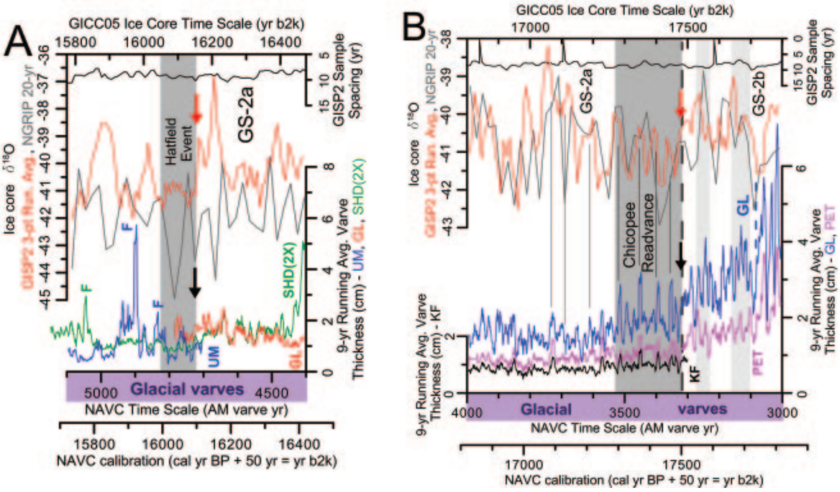

Fig. 14. A comparison of NAVC varve records and oxygen isotope records from the Greenland Ice Sheet at two intervals prior to 15,000 yr b2k: the Hatfield event (A) and Chicopee Readvance (B; Larsen and Hartshorn, 1982). Note that the time scales are offset from each other to better show the proposed coupling of events as discussed in the text. All time scale, ice core, and symbolic information are the same as on figure 13. Varve and GISP2 data files are available in the Supplementary Data (http://earth.geology.yale.edu/~ajs/SupplementaryData/2012/Ridge). (A) NAVC varve records (AM 4400-5100) from Glastonbury (GL), Conn., and South Hadley (SHD, expanded 2X) and Amherst (UM; Rittenour, 1999), Mass. Dark gray swath is the time of the Hatfield Event. The black arrow marks the decrease in varve thickness at the beginning of this event seen in the SHD core that may be coupled to a cool interval in GS-2a of the GISP2 ice core record (red arrow). With the proposed alignment of events on the two records the independent calibrated time scales on this plot are different by +55 yr (ice core age minus varve age; same as fig. 13). (B) NAVC varve records (AM 3000-4000) from sites at Glastonbury (GL), Conn. and Petersen Farm (PET) and Kelsey Ferguson Brickyard (KF) in South Windsor, Conn. Dark gray swath is the time of the Chicopee Readvance. Black arrow shows a prominent decrease in varve thickness marking the beginning of the readvance interval that may be coupled with a cold interval on the GISP2 ice core record (red arrow). Thin gray lines and light gray swaths show the coupling of sub-century-scale events in the two records. With the proposed alignment of events on the two records the independent calibrated time scales on this plot are different by −20 yr (ice core age minus varve age; different by 75 yr from figs. 13 and 14A).

the NAVC offset inferred from radiocarbon calibration and indistinguishable from it given its uncertainty.

Overlapping individual NAVC varve records provide a better record of varve variability resulting from climate change than Antevs' (1922, 1928) original "normal curves" in which extra-annual trends were suppressed or removed by his "normalization" of varve thickness (see Supplementary Data—http://earth.geology.yale.edu/~ajs/SupplementaryData/2012/Ridge—or Ridge, 2012 for varve data files). The specific Greenland ice core data set we use for comparison is the GISP2 continuous non-averaged original oxygen isotope measurements (Stuiver and others, 1995; Grootes and Stuiver, 1997; Stuiver and Grootes, 2000). This GISP2 $\delta^{18}O$ record was used because it has the highest resolution of any publically available ice core record and allows an analysis of events down to the decade scale over some parts of the record. We have averaged duplicate oxygen isotope measurements at single depths that are occasionally found in the GISP2 ice core dataset (see Supplementary Data—http://earth.geology.yale.edu/~ajs/SupplementaryData/2012/Ridge—for GISP2 data used here). The GISP2 data have been synchronized to the NGRIP ice core (Andersen and others, 2004) and GICC05 time scale (Andersen and others, 2006; Rasmussen and others, 2006) using interpolations between matched ice core signatures of chemical and volcanic events as employed by Rasmussen and others (2008).

Comparison—15,000 to 12,500 yr b2k

Figure 13 shows the ice core/varve comparison for 15,100 to 12,500 yr b2k with the alignment of their almost identical patterns in terms of relative positions and magnitudes of major changes in varve thickness related to climate and ice core oxygen isotope trends. Prior to 14.7 kyr b2k, when ice receded at 80 to 90 m/yr, $\delta^{18}O$ values averaged about -39 to -40 permil. From 14.7 to 14.1 kyr b2k, when ice receded at 300 m/yr, $\delta^{18}O$ values average about -36 to -37 permil. An abrupt varve thickness increase (following North Charlestown moraine deposition) is aligned with the GS-2a/GI-1e boundary and the start and end of the Littleton Readvance are aligned with the start and end of GI-1d. With this alignment the two independently calibrated time scales nearly coincide with each other, being different by only 55 years (ice core age minus varve age), which is well within the uncertainties of both calibrated time scales. In the interval of coupled major events (14,700-13,900 yr b2k), errors in varve counting are negligible as discussed earlier. There are probably also negligible errors in ice core layer counting in this interval (max. underestimate for interval = 22 yr; Rasmussen and others, 2006).

In addition to the correspondence of major ice core and varve events, the records also align with each other on a sub-century scale in the 15,000 to 13,800 yr b2k interval (fig. 13). The North Charlestown moraines are three ice-marginal positions at which stillstands or small readvances took place (Ridge, 2000). Equivalent NAVC records show three 20 to 35 year periods of reduced varve thickness (fig. 15), which appear to match cooling events in the GISP2 record (fig. 13). The abrupt 3-fold increase in varve thickness (figs. 13 and 15), and beginning of rapid ice recession (300 m/yr), after North Charlestown moraine deposition matches warming to near modern conditions in the ice cores (GI-1e) and is the most extreme event depicted on both records. The varve record, when not interrupted by flood events, depicts the same sub-century warming events from 14,700 yr b2k until the Littleton Readvance as in the ice core records. The Littleton Readvance interval begins with an abrupt decrease in varve thickness as glacial melting and meltwater delivery to the Connecticut Valley decreased during climatic cooling that reduced ice sheet ablation. The Littleton Readvance ends with an abrupt increase in varve thickness (after AM 6900, following a 14-yr interval of flood events) as glacial melting abruptly increased again. After the Littleton Readvance, an interval of rapid ice recession (>150 m/yr), characterized by coupled sub-century oscillations on both records, led to removal of ice to northern-most New Hampshire and Vermont in a few centuries and paraglacial varve deposition in the north-central Connecticut Valley (Newbury, Vt. and North Haverhill, N.H., figs. 1B and 8).

Because of the uncertainties in both calibrated time scales one cannot prove that matched events in both records were synchronous or not, but the consistent offset between multiple major event pairs as well as many smaller sub-century-scale events extending across a 1200-year period (15,000-13,800 yr b2k) can only be explained if the time lag between them was precisely constant or if the events were in fact synchronous. We conclude that the latter possibility is most likely and that both records are simultaneously recording the same regional climate changes. For this climate response to be true, the varve and ice layer counts must be consistent as they apparently are from 15,000 to 13,800 yr b2k. The clear coupling and apparent synchroneity of events between 15,000 to 13,800 yr b2k in the NAVC with Greenland events calibrated to the GICC05 time scale (Rasmussen and others, 2006) also suggests that a true varve calibration is older than our best-fit calibration (using all radiocarbon ages) given that the GICC05 time scale is based on conservative ice core layer counting. If the varve and ice core records are synchronous, the varve time scale must be at least 55 yr older than

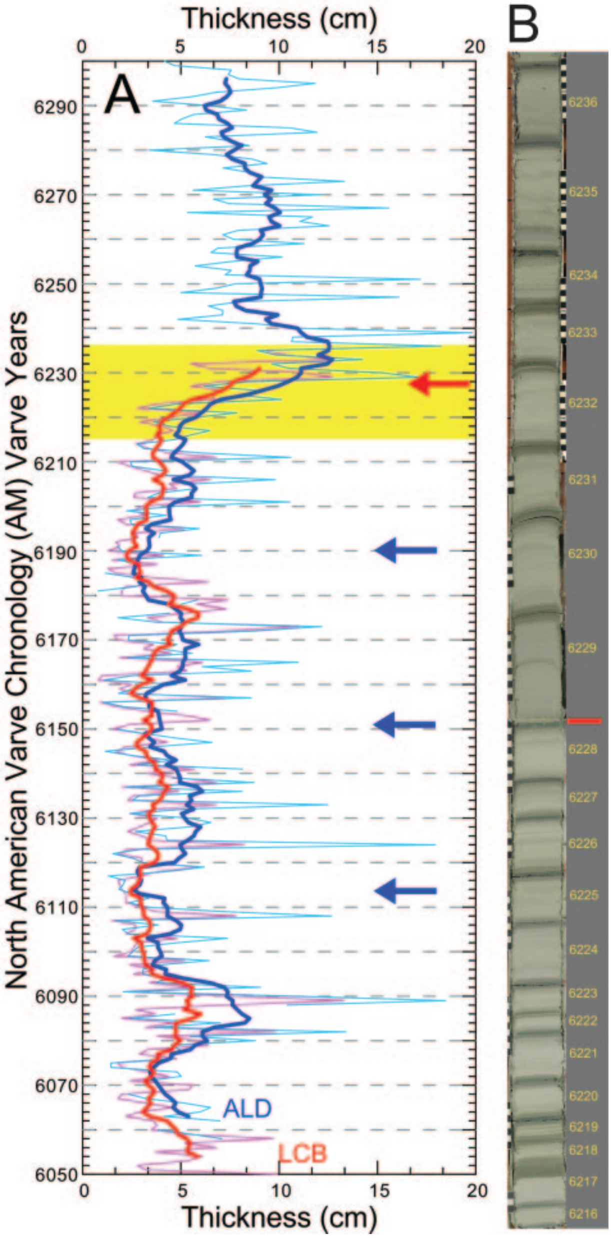

Fig. 15. (A) Plot of varve years AM 6050–6300 (thin lines) for varve records in the Connecticut Valley from Antevs (1922; LCB) and at the Aldrich Brook (ALD) core site. Antevs' LCB record is a "normalized" record with some of the regional variability in varve thickness removed. The LCB record is shown only to demonstrate that single outcrop records like at ALD better capture the regional variability of varve thickness related to climate. Accompanying each graph are 9-yr running average plots (thick lines). Blue arrows indicate dips in varve thickness that correspond to periods of slowed ice recession during end moraine development or minor glacial readvances as depicted on figure 13. The red arrow indicates a sudden increase (by ~3X) in varve thickness at AM 6229 that coincides with the beginning of very rapid ice recession (300 m/yr) and also an extreme warming event (GS-2a/GI-1e boundary) that appears on Greenland oxygen isotope records (fig. 13). (B) Stitched images of varves (yellow swath on fig. 15A) showing the sudden change in varve thickness at AM 6229 (red bar).

our best-fit calibration, and older by more than 55 yr if there is any undercounting of annual layers in the ice core record after 15,000 yr b2k.

In the paraglacial varve section at Newbury (fig. 13), events GS-1b and GS-1 are correlated with sections of relatively thick varves and GI-1c and GI-1a with thinner varves. However, the boundaries between events in the paraglacial varve record are not precisely defined and lags with event boundaries in the Greenland records may be as much as 50 years. This imprecision is systematically greater than the offsets between ice core climate events and thickness changes in the glacial varves discussed above. No more than 20 years of this difference can be caused by counting uncertainty in thin paraglacial varves. Most of the difference is likely due to climatic effects on paraglacial varve thickness that are mediated by changes in vegetation cover and subsequent geomorphic responses on a paraglacial landscape. This mediation takes decades and unlike in the glacial part of the varve record climate changes will likely not be recorded instantly by varve thickness in paraglacial varves.

Comparison—Prior to 15,000 yr b2k

In the 18,200 to 15,000 yr b2k interval, both the Hatfield event and Chicopee Readvance (figs. 11 and 12) begin with 20 to 40 percent decreases in average varve thickness, which indicates reduced meltwater production and thus cooling that retarded ice recession in the Connecticut Valley (fig. 14). These events are less conspicuous in the varve record than events after 15,000 yr b2k. The Hatfield event may correspond to a cooling event in stadial GS-2a of the ice core record (arrows on fig. 14A), but this ice core event is less distinct than younger events discussed above. To clearly display our interpreted coupling of the ice core and varve records at the time of the Hatfield event, features on both records have been aligned, which means that the independent calibrations of the two records are offset, but again as on figure 13 by only 55 years (ice core age minus varve age). Aligning events between 16,400 to 15,800 b2k and adopting the GICC05 time scale of the ice cores implies an NAVC offset of 20825 cal yr (or 20875 yr b2k), which is 55 years older than the NAVC offset inferred from radiocarbon calibration and indistinguishable from it given its uncertainty. In the interval ~16,400 to 15,800 yr b2k, errors in varve counting are negligible as discussed earlier. There are probably also negligible errors in ice core layer counting in this interval (max. underestimate for interval = 34 yr; Andersen and others, 2008).

The Chicopee Readvance and its associated drop in varve thickness may correspond to a cold interval in the ice core (arrows on fig. 14B), which is supported by the matching of sub-century-scale events. To clearly display the proposed coupling of the ice core and varve records, events on both records are aligned but the time scales of both records are not aligned as is the case with the other plots (figs. 13 and 14A). However, this time the varve and ice core calibrations are off by −20 years (ice core age minus varve age), a 75 year difference from the other plots that is still well within the uncertainties of both calibrations. Aligning events between 17,800 to 16,800 b2k (fig. 14B) and adopting the GICC05 time scale of the ice cores implies an NAVC offset of 20750 cal yr (or 20800 yr b2k), which is 20 years younger than the NAVC offset inferred from radiocarbon calibration and indistinguishable from it given its uncertainty. It is not possible to determine independently whether this alignment is a valid coupling of varve and ice core events or whether there is a time lag between coupled events because: (1) ice core events are weakly (GISP2) or not (NGRIP) defined in the Chicopee interval; (2) there are not very many GISP2-NGRIP (GICC05) match points in this interval (Rasmussen and others, 2008) that allow a more precise synchronization of the GISP2 record to the GICC05 time scale; and (3) the ≥8-yr ice core sample spacing prior to 15,000 yr b2k reduces ice core resolution. If the coupling of events shown on figure 14B is correct and the events are synchronous, a possible explanation for the difference in time scale offset as compared to later in time may be either missing or undercounted ice core layers. We cannot eliminate this possibility in this interval because: (1) in the interval of 18,296 to 16,333 yr b2k there is a reported ice layer undercount uncertainty of 100 years (Andersen and others, 2006), and (2) the interval of 18,296 to 16,469 yr b2k has also been identified by Rasmussen and others (2008) as having an unusual GISP2 vs. NGRIP core depth offset. We must also consider the possibility of an overcount of varves as a possible explanation. However, the counting and measurement of varves in the interval of 17,800 to 16,200 yr b2k (~AM 3000-4600) has been replicated at several of our core sites and in Antevs' (1922) records. Varve counting and measurement in this interval is not ambiguous, with 22 varves in this interval of the old NEVC requiring correction or being unusual as compared to surrounding varves (see Corrections to NEVC in Supplementary Data—http://earth.geology.yale.edu/~ajs/SupplementaryData/2012/Ridge—or at Ridge, 2012). The possibility also remains that our coupling of the varve and ice core records is not correct and during the time of the Chicopee Readvance the records are not coupled and do not have synchronous features. This last possibility is very real given that changes in both the varve and ice core records are subtle in this interval as compared to after 15,000 yr b2k.

DISCUSSION

After 15,000 yr b2k the NAVC and Greenland ice core records appear to be closely coupled and to represent synchronous climate change across the North Atlantic region. Below we discuss what elements of regional climate change are depicted in each record and the implications of their relationships for climate, seasonality, and ice-marginal events during deglaciation.

The close coupling of Greenland temperature, summer conditions at the LIS margin as reflected by varve thickness, and LIS retreat rate from 15,000 to 13,800 yr b2k (figs. 11, 12, 13, and 15) suggests that surface ablation exerted a strong control on southeastern LIS retreat. Large and abrupt changes in retreat rate during this time period are associated with large changes in LIS meltwater production, which is a record of ablation and therefore summer climate. This type of rapid response of glaciers to climate as a result of changing summer ablation conditions has been hypothesized as a control on ice margin oscillations for glaciers over many time intervals and scales (Lowell and others, 1999; Lowell, 2000). Changes in winter snow accumulation, which may have also occurred, would not be linked to changes in meltwater production coupled with changes in ice margin recession. Changes in accumulation would likely provoke ice sheet responses that lagged behind ablation by hundreds of years given the size of the LIS.

From 18,200 to 15,000 yr b2k (the so called "mystery interval" of Denton and others, 2006), the relationships between ice core temperature and varve thickness are weaker than after 15,000 yr b2k. However, a relationship between changes in southeast LIS recession rate and changes in varve thickness are still evident. LIS recession rates during this time were generally lower and ice recession may have occurred under overall cooler conditions (as is also depicted by lower ice core δ^{18}O values) in a state much closer to equilibrium than after 15,000 yr b2k. Prior to 15,000 yr b2k, episodes of southeast LIS readvance and changes in the retreat rate are not as clearly coupled to the Greenland climate record, which shows smaller variations in climate than after 15,000 yr b2k. Evidence that climate changes were synchronous across the North Atlantic and that a North Atlantic climate regime controlled surface ablation and ice-marginal position of the southeastern LIS prior to 15,000 yr b2k is weak. Thus, southeast LIS advance and recession prior to 15,000 yr b2k may have been more influenced by a continental climate regime or ice dynamics as compared to after this time when a North Atlantic climate regime appears to have controlled LIS ablation and recession.

A comparison of ice core and varve records provides some information about the seasonality of temperature change across the North Atlantic region. Temperature changes reconstructed from Greenland ice cores appear to be dominated by changes in winter temperature (Denton and others, 2005; Kelly and others, 2008). Varve thickness, on the other hand, records meltwater production, a summer phenomenon that cannot be directly calibrated to temperature (because temperature and melt season length are both important) and most likely reflects total summer positive degree days. Therefore, varve thickness has no direct relation to winter temperature, except that the presence of a winter layer indicates that a period of negligible meltwater input and lake bottom current activity did occur. As expected from the fact that both summer and winter layers in varves are composed of sediment introduced to the lake during the summer melt season, variability in winter layer thickness in NAVC varves, when present, is positively correlated with summer layer thickness. The seasonal contrast between ice core and varve records is important because examples of apparent synchroneity between increases in varve thickness and warm events recorded in Greenland ice cores are present throughout a large interval at both sub-century to millennial scales. This synchroneity implies either: (1) a persistent correlation between Greenland winter temperature and LIS summer ablation, perhaps because warmer winters in Greenland correspond to shorter winters and longer melt seasons in the North Atlantic region in general; or (2) small summer temperature changes coincident with large changes in winter temperature occurred in both Greenland and at the LIS margin but summer temperature varied enough to generate the changes recorded in varve thickness; or (3) summer temperature changes in Greenland may have been muted as compared to summer temperature changes at the southeastern LIS margin that are recorded in varves.

CONCLUSIONS

Varves have the ability to delineate not only the timing of glacial events with unprecedented resolution, but also to provide a record of climate by tracking changes in meltwater production and glacial ablation. The coupling of varve thickness to recession events and rates clearly shows the response of the southeastern margin of the LIS to ablation and climate. In New England the NAVC documents separate episodes of relatively uniform ice recession that are abruptly terminated by delays in recession marked by glacial stillstands and readvances, lasting only a century or two. These events are clearly manifested in the varve record with the more extreme changes in glacier recession being recorded as more extreme changes in varve thickness. The general trend is for more rapid deglaciation over time from 18,200 to 13,800 yr b2k, with the later stages of ice recession in northern New England being at the very high rate of up to 300 m/yr, and all while the glacier continued its forward movement as an active ice sheet.

We propose that the systematic coupling of event pairs with decadal precision in the NAVC and in Greenland ice cores during the later stages of the glacial varve record (15,000-13,800 yr b2k) is difficult to explain unless the two records are in fact simultaneously recording regional North Atlantic climate events. This correlation of varve and ice core records implies that North Atlantic climate, as recorded in Greenland, controlled marginal conditions and position of the southeastern LIS through ablation. In the paraglacial part of the NAVC after 13,800 yr b2k, it is most likely that varve and ice core records continue to record the same regional climate changes, but the signal in the varve records is delayed and attenuated because of its mediation through landscape-forming processes.

From 18,200 to 15,000 yr b2k, climate change events were not as extreme and climate was generally cooler both at the southeastern margin of the LIS and in Greenland than at later times. Further, lack of clear evidence of the coupling of varve and ice core records during this time implies that prior to 15,000 yr b2k either (1) there is very weak coupling of the two records because there are some differences in response to climate, or (2) there is no coupling between the two records because climate variations at the southeastern LIS margin were not the same as those in Greenland. It also remains possible that the records do not contain events distinct enough for a comparison at the available time resolution prior to 15,000 yr b2k.

ACKNOWLEDGMENTS

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Dedication

With great respect and admiration the authors would like to recognize Ernst Antevs by dedicating this paper to him, not only for his pioneering work in varve chronology in North America but also for the high quality of his work on glacial varves. Without Antevs' early development of the New England Varve Chronology this paper would not have been possible. Antevs' work not only encompassed the northeastern U.S. and adjacent Canada (Antevs, 1922, 1928) but included areas of southern Ontario, Quebec, and Manitoba (Antevs, 1925, 1931a, 1951). Almost all of Antevs' work on glacial varves was completed between 1920, when Antevs first arrived in North America on an expedition led by Gerard De Geer, and 1931 with Antevs' last major publication of varve records in Canada. Although Antevs worked on glacial varves for only a brief interval, many of the concepts he introduced regarding the analysis of glacial history and modes of deglaciation in North American (Antevs, 1957) are valid today and were far ahead of their time.

APPENDIX

^{14}*C ages from varves in New England by location from south to north*

Laboratory Number	Age (^{14}C yr BP)	δ^{13}C PDB (‰)	NEVC/ ***NAVC*** yr	Material dated	Reference
				East Windsor Hills, South Windsor, Connecticut (outcrop - Kelsey Ferguson Plant, Redlands Brick Co.)	
OS-77140	14,300 ± 60	-26.23	3505/***3513***	Terrestrial plant leaves, mostly *Dryas integrifolia* (split with below)	Unpublished
OS-77141	14,300 ± 70	-27.79	3505/***3513***	Terrestrial plant leaves, mostly *Dryas integrifolia* (split with above)	Unpublished
OS-76979	14,200 ± 70	-27.24	3726/***3739***	Terrestrial plant leaves, includes *Dryas integrifolia, Salix, Populus*	Unpublished
OS-77139	12,700 ± 50	-26.19	3763/***3776***	Terrestrial plant leaves, includes *Dryas integrifolia, Salix, Populus*	Unpublished
	(Younger than contemporaneous samples by ~1500 yr)				
OS-76978	13,050 ± 60	-27.29	3820/***3833***	Terrestrial plant leaves, includes *Dryas integrifolia, Salix, Populus*	Unpublished
	(Younger than contemporaneous samples by ~1000 yr)				
GX-32114	14,120 ± 80	-27.5	3826/***3839***	Terrestrial plant leaves, mostly *Salix* and *Dryas integrifolia* (20%)	Unpublished
OS-76905	14,450 ± 70	-27.57	3896/***3909***	Terrestrial plant leaves, includes *Dryas integrifolia, Salix, Populus*	Unpublished
OS-76904	13,550 ± 55	-25.65	3922/***3935***	Terrestrial plant leaves, includes *Dryas integrifolia, Salix, Populus*	Unpublished
OS-76903	14,000 ± 70	-27.44	3969/***3982***	Terrestrial plant leaves, 10% *Dryas Integrifolia* with *Salix* and *Populus*	Unpublished
OS-76902	11,950 ± 55	-27.22	3989/***4002***	Terrestrial plant leaves and stems, includes *Salix* and *Populus*	Unpublished
	(Younger than contemporaneous samples by ~1500 yr, low sample mass)				
OS-77228	13,300 ± 130	-27.45	3997/***4010***	Terrestrial plant leaves and stems, includes *Salix* and *Populus*	Unpublished
GX-32113	13,950 ± 90	-28.5	4113/***4126***	Terrestrial plant leaves, mostly *Salix* and *Dryas integrifolia* (33%)	Unpublished
				Amherst, Massachusetts (UMass campus long core)	
Beta-124780	12,370 ± 120	-27.1	5761-5768/***5776-5783***	Plant fragments from core	Rittenour, ms, 1999
				North Hatfield, Massachusetts (long core)	
OS-77149	10,150 ± 50	-27.13	5627/***5646***	Plant fragments from core, includes *Dryas integrifolia, Salix* and mosses	Unpublished
	(Younger than contemporaneous samples by >2500 yr)				
OS-77150	12,800 ± 60	-25.26	5713/***5728***	Plant fragments from core, includes *Dryas integrifolia, Salix* and mosses	Unpublished
				Aldrich Brook, Westmoreland, New Hampshire (long core)	
OS-64787	11,950 ± 110	-28.55	6069/***6084***	10 *Salix* and *Populus* leaves	Unpublished
OS-65821	12,600 ± 65	-28.00	6069/***6084***	2 *Dryas* receptacles, 10 full *Dryas integrifolia* leaves and mixture of other leaves including *Populus, Salix,* and *Dryas* leaf fragments	Unpublished
OS-65780	12,300 ± 75	-26.74	6226/***6241***	~40 *Dryas integrifolia* leaves with additional *Dryas* fragments	Unpublished
OS-66121	11,150 ± 130	-28.29	6226/***6241***	~40 *Dryas integrifolia* leaves with additional *Dryas* fragments (other half of sample above)	Unpublished
	(Younger than contemporaneous samples by >1100 yr, small sample mass)				
				Walpole, New Hampshire (outcrop)	
OS-64811	12,350 ± 190	-26.85	5958/***5973***	*Dryas integrifolia* leaves with two *Salix* and one *Populus* leaf	Unpublished

APPENDIX
(continued)

Laboratory Number	Age (^{14}C yr BP)	δ^{13}C PDB (‰)	NEVC/ ***NAVC*** yr	Material dated	Reference
				Canoe Brook, Dummerston, Vermont (outcrop)	
GX-25735	12,660 ± 50	-28.9	5858/***5873***	Woody twigs and *Dryas* leaves	Ridge and others, 2001
GX-32115	12,340 ± 80	-29.0	6072/***6087***	Terrestrial plant leaves, mostly *Salix* and *Dryas integrifolia* (10%)	Unpublished
GX-14231	12,355 ± 75	-27.2	6150/***6165***	Bulk sample of silt and clay with non-aquatic leaves and twigs (beta count)	Ridge and Larsen, 1990
GX-14780	12,455 ± 360	-27.6	6150/***6165***	Handpicked non-aquatic leaves and twigs, mostly *Dryas* and *Salix* beta count)	Ridge and Larsen, 1990
CAMS-2667	12,350 ± 90	---	6150/***6165***	*Salix* twig	N. Miller, per. com., 1993
GX-14781	12,915 ± 175	-27.1	6156/***6171***	Bulk sample of silt and clay with fragments of peat and gyttja, likely contains aquatic plant material (beta count)	Ridge and Larsen, 1990
				Newbury, Vermont (outcrop)	
OS-64816	10700 ± 430	-25.35	7115/***6797***	Single *Dryas integrifolia* leaf	Unpublished
	(Younger than contemporaneous samples by >1500 yr, precision uncertainty high, small sample size)				
OS-64812	11,550 ± 200	-27.75	7340/***7022***	*Populus balsamifera* leaf	Unpublished
OS-65777	11,450 ± 85	-26.80	7378/***7060***	*Dryas drummondii* leaf and many *Dryas integrifolia* leaves	Unpublished
OS-64466	11,950 ± 70	-19.39	7379/***7061***	*Populus balsamifera* leaf	Unpublished
OS-64461	13,250 ± 75	-24.45	7423/***7105***	*Populus balsamifera* leaf (re-dated as OS-65420)	Unpublished
	(Older than contemporaneous samples from same section by~1300 yr)				
OS-65420	13,250 ± 65	-25.84	7423/***7105***	*Populus balsamifera* leaf (OS-64461 re-dated)	Unpublished
	(Older than contemporaneous samples from same section by ~1300 yr)				
GX-23765	11,530 ± 95	-27.0	7435-7452/***7117-7134***	Woody twig	Ridge and others, 1999
OS-64086	11,650 ± 50	-26.32	7441/***7123***	Woody stem	Unpublished
OS-65783	11,700 ± 55	-28.22	7442/***7124***	*Vaccinium* leaf and *Dryas integrifolia* leaves	Unpublished
OS-64463	11,900 ± 70	-26.84	7461-7462/***7143-7144***	*Populus balsamifera* leaf	Unpublished
OS-64818	13,250 ± 1300	-25.00	7516/***7198***	Single *Salix* leaf	Unpublished
	(Older than contemporaneous samples by >1200 yr, large precision uncertainty, small sample size)				
GX-23766	11,045 ± 70	-27.5	8206/***7888***	Woody twig	Ridge and others, 1999
OS-77142	11,100 ± 50	-26.38	8310/***7992***	Chunk of wood	Unpublished
GX-23640	10,940 ± 70	-26.8	8357/***8039***	Woody twig	Ridge and others, 1999
GX-23641	10,080 ± 580	-26.7	8498-8500/***8180-8182***	Woody twig (beta count)	Ridge and others, 1999
	(Precision uncertainty high, younger than contemporaneous samples by ~700 yr)				
GX-23767	10,685 ± 70	-26.3	8504/***8186***	Woody twig	Ridge and others, 1999
GX-23642	10,040 ± 230	-26.5	8542-8544/***8224-8226***	Chunk of wood (beta count)	Ridge and others, 1999
	(Younger than contemporaneous samples by ~700 yr)				
GX-23643	10,440 ± 520	-26.8	8652-8662/***8334-8344***	Two woody twigs (beta count)	Ridge and others, 1999
	(Large precision uncertainty)				

APPENDIX

(continued)

Laboratory Number	Age (^{14}C yr BP)	δ^{13}C PDB (‰)	NEVC/ ***NAVC*** yr	Material dated	Reference
				Wells River, Vermont (outcrop)	
OS-66132	12,100 ± 200	-26.05	7391/***7073***	*Dryas drummondii* leaf	Unpublished
OS-64475	11,950 ± 65	-27.22	7396/***7078***	Woody twig	Unpublished
OS-65809	11,950 ± 50	-27.77	7396/***7078***	Thin woody twig	Unpublished
OS-65810	11,800 ± 50	-27.25	7396/***7078***	Thin twigs and twig fragments	Unpublished
OS-64474	11,850 ± 70	-26.78	7414/***7096***	Two woody twigs	Unpublished
OS-65620	11,900 ± 45	-3.61	7494/***7176***	Snail, genus *Fossaria* in family *Lymnaeidae* (Note: this age may have a reservoir error but is essentially the same as ages for twig samples that may have a lag time error.)	Unpublished
OS-64814	9,540 ± 250	-27.51	7330/***7012***	Two leaves: *Dryas integrifolia* and *Dryas drummondii*	Unpublished
	(Small sample size, younger than contemporaneous samples by ~2500 yr)				
OS-64817	10,950 ± 620	-25.00	7528/***7210***	*Salix* leaf	Unpublished
	(Precision uncertainty high, small sample size, younger than contemporaneous samples by >700 yr)				
OS-64815	11,600 ± 400	-28.64	7585/***7267***	*Salix* leaf fragments	Unpublished
GX-26456	11,220 ± 50	-27.1	7754/***7436***	Woody twig	Unpublished
				Columbia Bridge, Vermont (outcrop)	
WIS-961	11,540 ± 110	-29.0	(>7400)/***(>7082)***	Wood fragments (beta count)	Miller and Thompson, 1979
	(Sample not matched to varve chronologies)				
WIS-919	11,390 ± 115	-27.5	(>7400)/***(>7082)***	Wood fragments (beta count)	Miller and Thompson, 1979
	(Sample not matched to varve chronologies)				
WIS-925	20,500 ± 250		(>7400)/***(>7082)***	bulk sediment w *Potamogeton* leaves (beta count)	Miller and Thompson, 1979
	(Sample not matched to varve chronologies, *Potamogeton* is aquatic and acquires carbon from non-atmospheric sources)				

Possible problems with fourteen individual ages, as discussed in the text, are indicated below some age listings in parentheses. Missing δ^{13}C values are ages for which no value was recorded. All dates are AMS ^{14}C ages unless specified as beta counting dates.

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