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Title:

Consolidation and Calibration of the New England Varve Chronology (NEVC): An Annual Continental Record of Ice Dynamics and Terrestrial Change, 18-11.5 kyr BP

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1. Project Summary

Intellectual merit. Rapid climate change events during deglaciation are closely linked to ice sheet, ocean, and atmosphere interactions. Understanding these interactions requires ***high resolution*** comparisons of climate and continental ice dynamics. Although general patterns of Laurentide Ice Sheet (LIS) variation have been discerned, they are not continuously resolved at a sub-century scale. This lack of continuous, high-resolution terrestrial glacial chronologies with accurate radiometric controls continues to be a limiting factor in understanding deglacial climate. Such records, especially from the southeastern sector of the LIS, can provide critical comparisons to N. Atlantic climate records (marine and ice core) and a rigorous test of hypotheses linking glacial activity to climate change.

Consolidation of the New England Varve Chronology (NEVC), and development of its records of glacier dynamics and terrestrial change, is a rare opportunity to formulate a complete, annual-scale terrestrial chronology from 18-11.5 kyr BP. Glacial varve deposition, which is linked to glacial meltwater discharge, can be used to monitor ice sheet ablation and has a direct tie to glacier mass balance and climate. Complete records of readvances (not just maximum positions and times), ice recession rates, and annual meltwater discharge of the southeastern LIS could be compared to climatic events in the N. Atlantic region to determine whether the ice sheet was in lock-step with climate and ice rafting events, whether it was a driver or responder, or whether it behaved independently or with time lags. Even as a non-calibrated floating time scale the NEVC is an unprecedented annual window on overall patterns of climate and deglaciation. The NEVC's use as a precise regional chronology of glacial events, including floods that may have been triggers for rapid climate change, would be critical to evaluating climate models and the thresholds necessary for individual floods to influence ocean circulation and climate.

Objectives of the project will be to join sequences of the NEVC, forming a single sequence spanning over 6000 years (18.0-11.5 kyr BP). This will be the longest continuous, high resolution record of terrestrial ice front changes, ice recession rates, and glacial lake history in North America. Cores will be collected in critical areas to join sequences of the NEVC and new ^{14}C ages will be used to improve its calendar-yr calibration. The new NEVC will serve as a precise chronology of glacial and non-glacial events and climate in the northeastern U.S. and adjacent Canada and should provide the detailed chronology, as well as relationships to climate of glacial readvances, ice recession, and lake level history in western New England.

Broader impacts of this study are:

1) Stimulation of North America varve chronology. The exceptional accuracy and precision of the NEVC will demonstrate the potential usefulness of glacial varve chronology in other regions of North America where glacial varve sequences have not been studied for either their glacial chronologies or climate records. This project will serve as a stepping stone to an expansion of the NEVC to cover the entire last deglaciation (~24-11.5 kyr BP) and is likely to stimulate varve studies in many other regions of the U.S. and Canada.

2) Varve chronology will serve as a calibration or consistency test of other dating techniques. The NEVC represents the most precise and accurate opportunity for comparison of cosmogenic-nuclide ages for deglaciation with an independently-calibrated deglacial chronology. Refinement of the NEVC will dramatically improve the accuracy and confidence in this geological calibration.

3) Varve chronology research resource. Dissemination of results, in addition to normal publication in scientific journals, will include internet availability of: a) a library of varve records and images for other researchers; b) instructional presentations on how to collect, formulate, and match varve records; and c) an image glossary of varve characteristics and features as a reference for students and instructors.

4) Educational benefits. This project will expand the research program at Tufts Univ. that since 1990 has had 17 undergraduates undertake research projects on varve stratigraphy and related paleomagnetism with 12 of those students so far having continued on to graduate school in geology (4 for PhD). Undergraduates (2 per summer for 3 yr), will be active research participants in field and laboratory phases of the project. Each student will be supervised through a start-to-finish analysis of a complete varve section leading to a year-long thesis or research project. Over three years the project will effectively double the number of people in the U.S. trained in the analysis of glacial varve cores.

2. Project Description

2.1 Results of Prior NSF Projects

None in last 5 years.

2.2 Introduction and Significance

A fundamental problem in understanding deglaciation is accurately defining the ages of glacial events leading to a better understanding of the interaction of glaciers and climate. Hypotheses of how the Laurentide Ice Sheet (LIS) responded to climate or how glacial activity influenced climate may be tested with comparisons of high resolution records of LIS behavior with climate records in the N. Atlantic region. Although the general pattern of southern LIS variation has been discerned it is not resolved at the sub-century scale, a situation that continues to be a limiting factor in understanding interactions of ice sheets and climate. Varve chronology has been underutilized in this regard but has the potential of providing complete and accurate terrestrial chronologies with annual resolution.

New England is the only region of North America (Fig. 1) where a calibrated varve chronology is tied to a significant portion of the last deglaciation (Fig. 2). This project will expand this tie and further establish the NEVC (Antevs 1922, 1928) as a key chronologic template of late Pleistocene events in the northeastern U.S. and as a record of Lateglacial change by obtaining cores of new varve stratigraphy in critical areas and refining varve calibration. Specifically this project will: 1) fill a major gap between the two NEVC sequences, and 2) obtain new ^{14}C ages for calibration from a wider span of time.

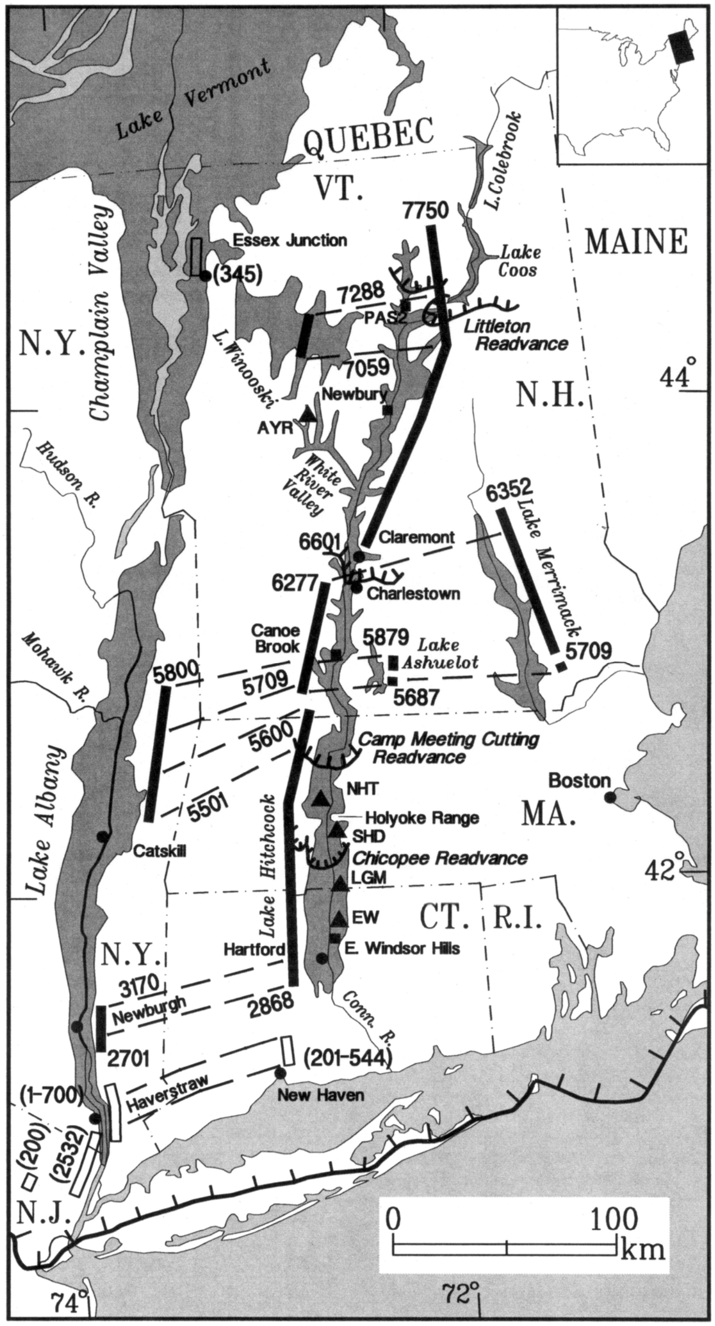


Figure 1. Glacial lakes and associated varve sequences in the northeastern U.S. NEVC sequences (solid columns; Antevs, 1922, 1928) are labeled with varve yr numbers: lower Connecticut varves, 2701-6352; upper Connecticut varves, 6601-7750. Other varve sequences not attached to NEVC (open columns, numbers in parentheses; Reeds, 1926; Antevs, 1928) are in New Jersey and the Hudson (Haverstraw), Quinnipiac (New Haven), and Champlain valleys.

The power of varve chronology to date and resolve Lateglacial events has been demonstrated in Scandinavia where a revised Swedish Time Scale covers the last ~14.0 kyr (Strömberg, 1985, 1990; Cato, 1987; Björck et al., 1995; Wohlfarth et al., 1997; Wohlfarth and Possnert, 2000; Lundqvist and Wohlfarth, 2001). As a result Fennoscandian glacial events have been precisely and accurately compared to well-dated climate records. Varves provide the framework for assembling high-resolution records of environmental change (Andrén et al., 1999, 2002; Björck and Digerfeldt, 1989; Björck et al., 2001, 2002). With refinement of the NEVC a similar scenario could exist in North America with an *even longer record* of late Pleistocene ice recession (prior to Heinrich Event 1 to end of Younger Dryas, 11.5-18.0 kyr BP).

A continuous and calibrated NEVC that: 1) can be used as an ***annual*** time scale for terrestrial ice front activity and ice recession rates, 2) has an associated record of glacial meltwater discharge, and 3) is calibrated with sub-century accuracy, has many benefits. The resulting Lateglacial chronology will be the only ***continuous, high precision (annual) terrestrial*** record of deglaciation and Lateglacial change in North America. It will allow accurate and detailed comparisons to independently-dated records of climate in the N. Atlantic region (Lowe et al., 1994, 2001; Björck et al., 1998), especially from Greenland ice cores (Dansgaard, 1989, 1993; Alley et al., 1993; Cuffey et al., 1995; Stuiver et al., 1995; Walker et al., 1999). Recent attempts to relate the glacial record of the southeastern LIS to ice core stratigraphy (Boothroyd et al., 1998; Ridge, 2003, 2004) have had limited certainty. Precise and continuous terrestrial records are difficult to assemble and yet critical to formulating the cause and effect relationships between climate change and glacier dynamics (McCabe and Clark, 1998). Glacial varve records are a unique window on this problem since they provide a continuous annual record of ice recession rates and readvances, not just an assessment of the times and positions of the maximum extents of readvances. Varves also have the advantage of recording glacial meltwater discharge, therefore having a direct tie to mass balance, glaciological responses, and climate. Even as a non-calibrated floating time scale the NEVC provides an unprecedented annual window on overall climate patterns (Rittenour et al, 2000).

A consolidated and calibrated NEVC will create a template for correlation and dating of varve sequences in areas adjacent to New England. This is a two step process that first involves the development of an accurately calibrated varve template in New England. The second step will be to create and correlate varve sequences in areas such as the Mohawk, Hudson, and Champlain valleys of New York to the NEVC. With existing paleomagnetic correlations, and the future development of varve records in New York, a comprehensive and highly detailed chronology of floods from glacial lake discharge events from 18-11.5 kyr BP (Parent and Occhietti, 1988, 1999; Ridge et al., 1991; Ridge and Franzi, 1992; Hand, 1992; Ridge, 1997; Liccardi et al., 1999; Marshall and Clarke, 1999; Clark et al., 2001, 2002; Connally and Cadwell, 2002, 2004; Franzi et al., 2002; Rayburn, 2004; Donnelly et al., 2005; Rayburn et al., 2005, 2006) can then be

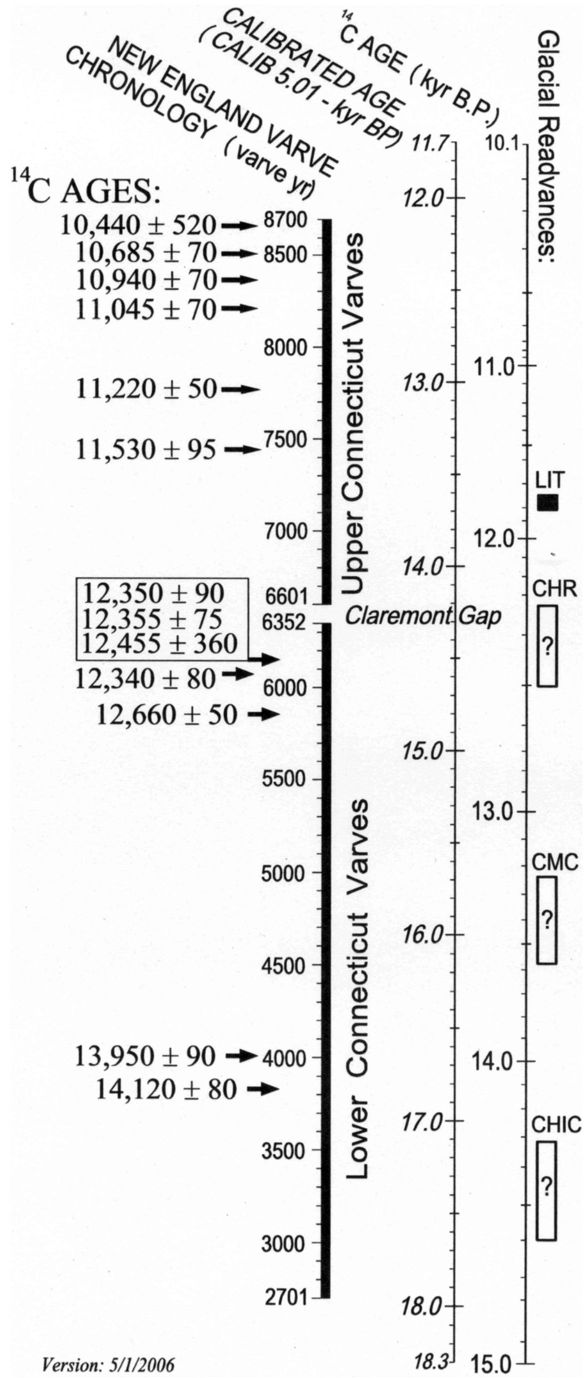


Figure 2. NEVC vs. ^{14}C and calibrated years (Ridge, 2003, 2004) updated using CALIB 5.01 (Stuiver et al., 2005), INTCAL04 data (Reimer et al., 2004), and new ^{14}C ages. ^{14}C ages critical to calibration are shown. Age constraints for Littleton (LIT), Charlestown (CHR), Camp Meeting Cutting (CMC), and Chicopee (CHIC) readvances are shown.

assembled. Development of correlative varve records in these areas began over 80 years ago with varves from Lake Albany in the Hudson Valley (Antevs, 1922, Fig. 1), Mohawk Valley lakes (Ridge and others, 1990, 1991; Ridge and Franzi, 1992), and the Champlain Valley (Rayburn, 2004; Rayburn et al., 2005, 2006) representing an untapped resource of flood events within varve sequences. As an example Hudson Valley varve records near Catskill, NY (Fig. 1, NE 5500-5800), originally measured by Gerard De Geer and used by Antevs (1922) to fill a gap in the Connecticut Valley sequences, contain a flood event (Fig. 3A). Ten consecutive, exceedingly thick rhythmites were interpreted by De Geer as separate varves. Rittenour (1999) first measured this time period in the Connecticut Valley where the ten Hudson Valley rhythmites are missing, indicating that they are local, non-annual flood layers in the Hudson Valley. The flood beds represent the release of water from a lake in the Mohawk Valley as an impounding Hudson ice lobe receded (Ridge and Franzi, 1992; Ridge, 2003). Future compilations of varves and their included flood events in the Hudson and Champlain valleys, along with correlation to the NEVC, will provide a means of defining accurate and precise time constraints for flood *events* (i.e. clusters of floods, R3-R8 of Clark et al., 2001) thought to be triggers for abrupt climate change. It will also allow the investigation of individual floods of many different magnitudes within the clustered events to establish thresholds for their specific impacts on N. Atlantic thermohaline circulation and climate (Clark et al., 2002).

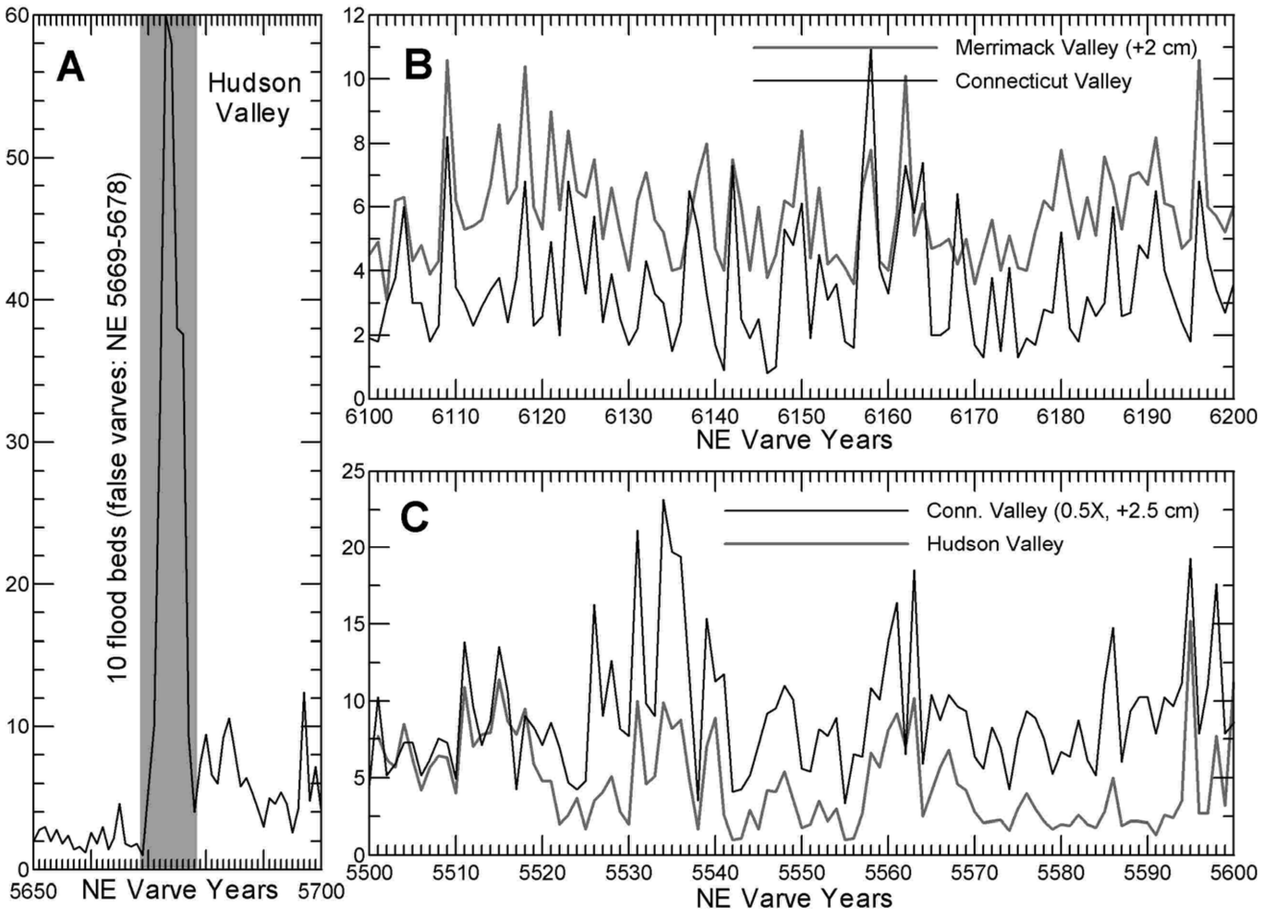


Figure 3. NEVC varve records (Antevs, 1922). **A.** Flood layers (false varves) from the upper Hudson Valley missing from correlative Connecticut Valley sequence (Rittenour, 1999). **B.** Correlation of varves in the Connecticut and Merrimack valleys. **C.** Correlation of varves in the upper Hudson and Connecticut valleys.

2.3 Broader Impacts of the Research

1. Stimulating North American varve chronology. The project will demonstrate the extraordinary resolution and accuracy of varve chronology as a tool for establishing Lateglacial chronologies and records of climate and glacial activity. There is an untapped potential for glacial varves to serve as the basis for constructing continuous deglacial sequences in other parts of North America. Studies of this type over the last decade are few in number outside New England (Johnson and Hemstad, 1998; Johnson et al., 1999; Breckenridge et al., 2004; Rayburn et al., 2005, 2006). Calibrated varve sequences have the ability to establish exact ages of events recorded in varve sequences or in sequences that can be correlated to established varve chronologies. Chronologies for glacial readvances, ice recession, flood events, and lake level histories are more easily, and usually more cheaply, established using varve sequences than by trying to assemble the ^{14}C ages necessary to specifically assemble all these records. An additional advantage of varves is that even non-calibrated varves can be used to establish rates well beyond precision of constraining radiometric ages. Examples are the development of rates of ice advance, ice recession, biologic change, and lake level lowering. Studies of this type may be applied to many regions of the U.S. and Canada where there were persistent glacial lakes during deglaciation.

As explained in the "Long Term Research Goals" section of this proposal the project will lay the groundwork for expanding varve chronology in the northeastern U.S. It will also set the stage for connecting the NEVC to Holocene glacial varves in eastern Canada (Antevs, 1925, 1928; Hughes, 1955, 1956, 1965). In New England varve stratigraphy is perhaps our best opportunity to establish a high resolution record and chronology of New England's Lateglacial climate and geomorphic activity involving deglacial, lacustrine, periglacial, eolian, and paraglacial processes (Stone et al., 1992; Ashley and Stone, 1995; Thorson and Schile, 1995; Ashley et al., 1999; Wetzel et al., 1999). The NEVC has served and will continue to serve as a chronology for establishing records of biotic and ecological change (e.g. trace fossils, Benner and Ridge, 2004; pollen and plant macrofossils, Miller and Thompson, 1979 and Miller and Spear, 1999).

2. Geological Calibration of Cosmogenic-Nuclide Dating. An improved and expanded NEVC will be an invaluable chronology for calibrating other dating techniques in the northeastern U.S. The calibrated NEVC currently represents our best opportunity for comparison of cosmogenic-nuclide ages for deglaciation (Larsen et al., 1995a, 1995b; Balco et al., 2002) with ^{14}C ages tied to a detailed deglacial chronology. Currently Balco and Schaefer (in review) identify an offset of about 1700 years between calibrated varve ages and cosmogenic ages. The NEVC represents a superb geological calibration of cosmogenic dating defined as by NSF's CRONUS-Earth Project (www.physics.purdue.edu/cronus).

3. National Research/Educational Resource. Several of the deliverable products of this project will be unique high school to university-level resources in the field of varve chronology. In addition to the publication of results in scientific journals, a public archive of annotated high-resolution digital varve images and records that will serve as a research and teaching resource will be created. Internet access of the results of this project will include the following data sets: 1) successive high resolution images of each section of each core showing posted measurements, 2) composite varve records (data files with varve yr and summer-, winter-, and total thicknesses) for each core, 3) PDF files of plotted matches of all core records with existing varve records, 4) all varve records from New England and Quebec measured by Antevs (1922, 1928) or the PI and his co-investigators (Ridge and Larsen, 1990; Ridge and Toll, 1999a; Ridge et al., 1996, 1999, 2001; Wilson, 2000; Nichols, 2004) in digital format, and 5) a set of annotated images showing the range of varve types and representative characteristics that may serve as an educational image glossary. Internet access will also include software used at Tufts to measure varves, presentations on varve chronology including how to collect, record, and match varve sequences, the history of varve chronology in the northeastern U.S., and varve deposition. These presentations have been a part of seminars and workshops given by the PI over the last four years and are not yet available via the internet.

4. Educational Benefits. This project will expand the research program at Tufts that since 1990 has had 17 undergraduates undertake research projects on varve stratigraphy or its related paleomagnetism with 11 of those students continuing on to graduate school in geology (4 for PhD). Undergraduate students (2 students/summer) will be active research participants, benefiting from training in field and laboratory phases of the project. Each student will be supervised through a start to finish analysis of a complete varve section leading to a year-long thesis or research project. Over three years the project will effectively double the number of people in the U.S. trained in core analysis of glacial varves.

2.4 Background/Previous Work

The following sections have detailed information regarding the NEVC, its history, and its relationship to deglaciation. The detail is included because over the last 20 years, other than by the PI, there have been few references to the NEVC. Until recently it was neglected as a mainstream part of the glacial history of the northeastern U.S. and greatly underutilized. For decades, as explained below, glacial varve chronology in the U.S. had an unwarranted poor reputation. Although not as common as 20 years ago there are lingering unfounded reservations about the NEVC's accuracy and validity.

2.4.1. Varve deposition and correlation

Glacial meltwater and sediment discharge are the key variables controlling annual changes in sediment input and glacial varve thickness. These variables have a direct tie to melting and ablation. As ice sheets recede varve thickness generally decreases as the glacial sediment source becomes more distal. During ice recession varve deposition is increasingly influenced by non-glacial drainage basin erosion processes that are a complex function of climate, runoff, and erosion on a paraglacial landscape. The complete removal of a glacial meltwater source when glaciers finally recede completely out of a drainage basin, marking the beginning of strictly *non-glacial* varve deposition, is often marked by a dramatic decrease in sedimentation rates (Ridge and Toll, 1999a, 1999b).

A model of glacial varve deposition in the lower Connecticut Valley, highlighting summer underflow deposition, has been developed along with a varve classification (Ashley, 1972, 1975; Ashley et al., 1985). This model clearly defines the annual characteristics of varves in the Connecticut Valley and elsewhere. However, the model does not fully address many minor bedding characteristics and secondary sediment dispersal patterns seen in the upper Connecticut Valley and glacial lakes of New York (Ridge, 1985; Ridge et al., 1990, 1991; Ridge and Toll, 1999b; Ridge, 2001a). Although these varves are clearly annual questions remain about: 1) the down valley persistence of underflow currents and their height in the water column, 2) diurnal cycling, 3) shallow basin-side vs. deeper basin-center deposition patterns, 4) seasonal overturning, and 5) flocculation as a mechanism for winter clay deposition (O'Brien and Pietraszek-Mattner, 1998) and the secondary effects of 1) sediment contributions from glacial meltwater vs. land surface runoff, 2) the effects of ice recession, glacial readvances, and sublacustrine valley bottom thresholds, and 3) contributions by ice-rafting. Although the current proposal is not designed to specifically address these issues, assembling long varve sequences will undoubtedly have an impact by expanding observations of varve types over a wider array of glacial to non-glacial settings that have few if any modern analogues at the scale being studied.

In varves of glaciated terranes annual thickness is measured from the base of the summer (melt season) layer to the top of the winter (non-melt season) layer. Varve records from glacial or non-glacial lakes that receive high volumes of clastic sediment are correlated based on similar patterns of annual thickness variation and unique marker beds created by such things as flood events and abrupt bathymetric changes resulting from drops in lake level. When regional conditions controlling varve thickness are relatively uniform, varve records from separate lake basins can be matched at an annual scale. The regional matching of *glacial* varve records over distances of 200 km and through hundreds of years (Figs. 3B and 3C) has been demonstrated with the NEVC (Antevs, 1922, 1928).

2.4.2. Ernst Antevs' NEVC and others

The NEVC was assembled by Ernst Antevs (1922, 1928) from matched varve records in New England and New York (Fig. 1). The NEVC is composed of two non-connected sequences, informally called the lower and upper Connecticut varves (Fig. 1). The lower Connecticut varves, arbitrarily numbered NE 2701-6352 (Fig. 1), were largely compiled from records of Lake Hitchcock in the

Connecticut Valley (Hartford, CT to Charlestown, NH). Matching records from the Merrimack, Hudson, and Ashuelot valleys were used to fill gaps and extend the record.

North of Claremont, NH Antevs (1922) could not find an overlap with sections to the south or with varves from surrounding regions and thus postulated the 'Claremont Gap' between the lower and upper Connecticut varves (Fig. 2). The Connecticut Valley is constricted in this area and this promoted fluvial dissection of lacustrine deposits (Ridge, 1999, 2001b). There are also several tributaries and ice-front positions from which sand and gravel deposition rapidly filled parts of the valley before varves could accumulate.

The upper Connecticut varves, which include a correlation to varve sections in the Winooski Valley, were arbitrarily numbered NE 6601-7750 with an additional 750 younger varves counted but not measured at Newbury, VT (Antevs, 1922; Johnson et al., 1948). Reinvestigation of the Newbury section using outcrop core samples, magnified digital images, and computerized measurement has extended the measured upper Connecticut varves to NE 8679 (Ridge and Toll, 1999a, 1999b; Ridge et al., 1999).

Using ice-proximal varve sections resting on till or bedrock, Antevs (1922) related the age of deglaciation to the NEVC in the Connecticut and Merrimack Valleys from central Massachusetts northward through Vermont and New Hampshire. Antevs documented a systematic south to north ice recession by showing the onlapping relationship of varves to sub-varve units and established the groundwork for determining precise rates of ice recession.

In addition to the formally numbered NEVC, older and younger varve sequences were assembled (Antevs, 1922, 1928; Reeds, 1926). The four longest of these sequences (Fig. 1) do not match the NEVC, have their own independent numbering systems, and internally include some regional correlations. Included are a 200-yr sequence from Lake Passaic in New Jersey, 2532 years from Lake Hackensack in New Jersey, a 700-yr sequence from Haverstraw, NY (Lake Albany) and the Quinnipiac Valley north of New Haven, CT, and a 345-yr sequence from Lake Vermont (Essex Junction, VT). These varve records, and many additional shorter varve records measured by Antevs (1928) in Connecticut, Rhode Island, southeastern Massachusetts, northern Vermont, and Quebec (see also Parent and Occhietti, 1999), may eventually be tied to the NEVC if its glacial varve record is expanded. The isolated sections provide a foundation for expanding the NEVC to cover the entire period of deglaciation (~24-11 kyr BP) in the northeastern U.S. and adjacent Quebec, and establishing precise regional correlations.

2.4.3 The NEVC: Initially Maligned to Rebirth

Although today the construction of varve sequences seems straight forward and an exceptionally precise tool it struggled for acceptance in North America. Beginning in the 1930's, Antevs' (1922) systematic northward ice recession did not fit emerging ideas of regional glacial stagnation as a model of ice recession (Flint, 1929, 1930, 1932, 1933; Goldthwait, 1938). It was also during this time that Gerard De Geer (1921, 1927, 1929, 1940) proposed annual transatlantic and inter-hemispheric correlations based on the matching of individual varve records. Most geologists then and today, including Antevs (1935), considered global correlations of this type impossible, leading to further erosion of the perceived accuracy of varve chronology. The misinterpretation of stratigraphy associated with the first ^{14}C ages in New England also led to incorrect ideas of varve counts being inconsistent with ^{14}C ages (Flint, 1956). As a result the NEVC was omitted from the later editions of R.F. Flint's (1957, 1971) textbooks on glacial and Quaternary geology and starting in the late 1930's many U.S. geologists ignored varve chronology as a viable dating tool.

Surficial mapping by the USGS (Jahns, 1941, 1953; Koteff, 1974; Koteff and Pessl, 1981; Shafer and Stone, 1983) later verified Antevs' systematic south to north ice recession. Newly discovered basal varve sections also conform to this systematic deglaciation (Ridge and Larsen, 1990; Ridge et al., 1996, 1999, 2001; Ridge, 2003, 2004). Despite early obstacles many researchers documented precise annual correlations of new varve records and the fidelity of the NEVC while creating other records of secular variation, most notably of paleomagnetic declination (McNish and Johnson, 1938; Johnson et al., 1948; Verosub, 1977a, 1977b; Thomas, 1984; Ridge and Larsen, 1990; Ridge and Toll, 1999a; Ridge et al., 1996; Levy, 1998; Rittenour, 1999; Ridge et al., 1999, 2001; Wilson, 2000; Ridge, 2003). Paleomagnetic records have allowed a wider correlation of glacial lake sediments from across the northeastern U.S. (Brennan et al., 1984; Ridge et al., 1990; Pair et al., 1994) and the application of the NEVC time scale to a regional chronology of the later stages of deglaciation (Ridge, 2003, 2004).

2.5 Improvements to Antevs' Varve Chronology

2.5.1. Calibration of the NEVC

It is only with the application of radiometric and calibrated time scales that links between the NEVC and continental and global records can be established. NEVC varve years have been calibrated using ^{14}C ages from terrestrial plant macrofossils (Ridge and Larsen, 1990; Ridge et al., 1999, 2001; Ridge 2003, 2004) here updated using some new ^{14}C ages, the CALIB 5.01 program (Stuiver et al., 2005), and the INTCAL04 data set (Reimer et al., 2004).

Despite some persistent uncertainties calibration of the NEVC has prompted a significant rethinking of the New England deglacial chronology in two ways:

1) The age of deglaciation in western New England, previously based on ^{14}C ages of bulk lake-bottom sediment, has been revised to a chronology about 1.5-2 kyr younger (Ridge et al., 1999; Ridge, 2003, 2004) than in previous models (Davis et al., 1980; Davis and Jacobson, 1985; Stone and Borns, 1986; Dyke and Prest, 1987). AMS ^{14}C ages from terrestrial plant macrofossils, and a precise knowledge of the location of ^{14}C samples in the NEVC have improved the accuracy and precision of deglacial chronology.

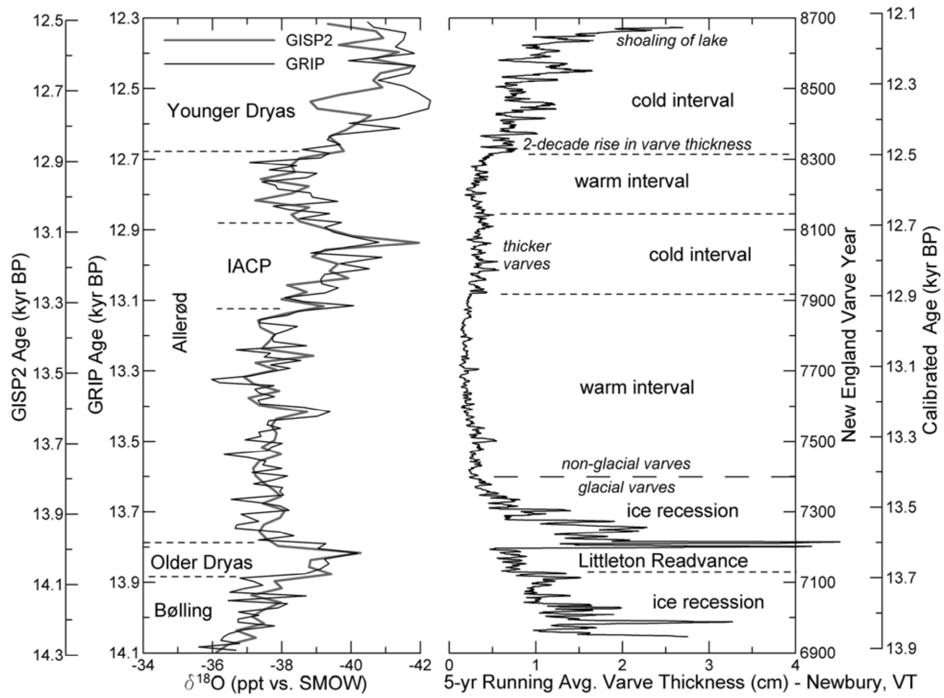
2) A comparison of the terrestrial, varve-based ^{14}C chronology of deglaciation for the Merrimack Valley with the uncorrected marine ^{14}C chronology of deglaciation for coastal eastern New England (Hughes et al., 1985; Smith, 1985; Thompson and Borns, 1985; Koteff et al., 1993) indicates a significant age difference (Ridge et al., 2001). This age difference is interpreted to represent a marine reservoir correction on the order of 0.8-1.0 kyr (Ridge et al., 2001 refined by Ridge, 2003, 2004 and CALIB 5.01). Recently, a correction of 600-700 yr has been used to formulate the deglaciation chronology of coastal Maine (Dorian et al., 2001; Borns et al., 2004; Weddle et al., 2004), still leaving a disparity of a few centuries between the terrestrial and corrected marine chronologies. Calibration of the NEVC is in agreement with revised chronologies of the Champlain Sea (Anderson, 1988; Rodrigues, 1988, 1992; Richard and Occhietti, 2005). Subtraction of a reservoir correction from marine ^{14}C ages is critical to formulating accurate correlations with other regions and climate records, but estimating an appropriate correction has been difficult because it varies both spatially and temporally. Improved accuracy of the NEVC calibration, especially an accurate calibration for the NEVC spanning Lake Merrimack (Fig. 1), should lead to improved marine ^{14}C corrections in adjacent areas where they have been elusive.

2.5.2. Climatic Interpretations

Analysis of varves at Newbury, VT and further north (Ridge and Toll, 1999a, 1999b; Ridge et al., 1999; Wilson, 2000) has revealed a transition in NE 7300-7470 from thicker (>4 cm) varves dominated by summer layers to much thinner (< 0.5 cm) varves dominated by winter layers that have conspicuous plant and mollusk fossils and a variety of trace fossils (Ridge and Toll 1999a; Smith and Ridge, 2001; Benner and Ridge, 2004). The transition is interpreted to represent a change from glacially-dominated (glacial) to non-glacial varves brought on by ice recession out of the basin or behind barriers (for Lakes Coos and Colebrook, Fig. 1) that impeded continuous down valley sediment transport. Currently there is no match of NEVC non-glacial varves with contemporaneous glacial varves of the Champlain Valley.

Non-glacial varves in the Connecticut Valley above NE 7470 appear to record abrupt changes in Lateglacial climate. When a calibrated time scale has been applied to varves NE 7470-8679 and compared to Greenland ice core records (Dansgaard et al., 1989, 1993; Cuffey et al., 1995; Stuiver et al., 1995) both the Killarney Oscillation (Intra-Allerød Cold Pulse, IACP) and the beginning of the Younger Dryas (YD) correspond to increased varve thickness and summer layer grain size (Fig. 4; Ridge and Toll, 1999a, 1999b). Preliminary pollen analysis of varves at Newbury that span the beginning of the YD show a distinct shift in pollen types reflective of cooling corresponding to increased varve thickness (Andrew Stern and Zicheng Yu, Lehigh University, pers. comm.). It appears that increased erosion and higher clastic sediment input to Connecticut Valley lakes may be associated with the cold events, as in smaller

Figure 4. Tentative correlation of varve stratigraphy and GISP2 (Stuiver et al., 1995) and GRIP (Dansgaard et al., 1989, 1993) ice core oxygen isotope records. Correlation based on alignment of Littleton Readv. with Older Dryas. Modified from Ridge and Toll (1999a).



lakes across the northeastern U.S. and maritime Canada (Peteet, 1992; Levesque et al., 1993a, 1993b; Mayle et al., 1993; Wilson et al., 1993; Cwynar and Levesque, 1995; Thompson et al., 1996; Borns et al., 2004).

2.6 Long Term Research Goals

Over the last 25 years, the PI has devoted most of his research to understanding the glacial chronology of the northeastern U.S., in particular the glacial lake stratigraphy of the Mohawk, Champlain, Connecticut, and Merrimack Valleys. Before coming to Tufts most of this work focused on traditional glacial stratigraphy. Work in the late 1980s on varves in southern Vermont made the PI realize that the NEVC was not only a viable correlation and dating tool but that it was greatly underutilized. Since then it has become apparent that an expanded NEVC could cover the whole period of late Wisconsinan glaciation (~24-11.5 kyr BP) while establishing a precise chronology worthy of solving global issues related to the interaction of glaciers and climate.

The current proposal will consolidate the two major NEVC sequences and establish a sub-century scale calibration. Once in place a unified NEVC can be expanded on both ends taking advantage of many unconnected sequences. Future projects will include:

1. Expansion of the NEVC's glacial sequence at its younger (northern) end above NE 7300, which is currently non-glacial, to allow a correlation with glacial varves in the Champlain Valley, northern NH and VT, and southern Quebec leading up to the YD. This will involve investigation of subsurface sequences from deglaciation in Lakes Coos and Colebrook in northern NH and VT (Fig. 1).
2. Expansion of the NEVC at its older (southern) end creating a complete sequence extending across southern New England, down the Hudson Valley and into New Jersey (Lakes Passaic, Hackensack, and Hudson; Stanford and Harper, 1991; Stone et al., 2002). While most research has focused on rapid climate change events after H1 (after 17 kyr BP) this southern chronology would be an unusually detailed terrestrial chronology of poorly understood climatic events from prior to H1 (~24-17 kyr BP) and the only continuous deglacial record from this time in North America.
3. Correlation of varve sequences in the Mohawk and upper Hudson Valleys (north of Haverstraw, NY) to the NEVC. This will provide a tie to events in the eastern Great Lakes region and the exact ages of flood events from the Ontario Basin and Mohawk Valley. It will allow a detailed comparison of deglacial chronologies in the eastern Great Lakes region and western New England, two areas with contrasting ice margins (calving deepwater lacustrine vs. terrestrial).

4. Collaboration with other investigators to use varve stratigraphy to establish high-resolution records of ecological/biological change during rapid climate change events. Currently fish traces in varves are being investigated using the NEVC as a chronology (Benner and Ridge, 2004). Future projects are likely to include the development of records of pollen and ostracode isotopic signatures ($\delta^{13}C$, $\delta^{18}O$) when their feasibility has been fully established, especially from 14-11.5 kyr BP.

2.7 Remaining NEVC Improvement with Planned Activities

The main objective of this proposal will be to create a master varve chronology (new NEVC) that can serve as a template for regional correlation by closing the Claremont Gap (Fig. 1; Aim 1 below) between the existing NEVC sequences (lower and upper Connecticut varves) and creating a more accurate calibration (Aim 2). This will lead to a revised and unified numbering system that also corrects the error discovered by Rittenour (1999) in the lower Connecticut varves (Fig. 3A). The revised NEVC will be used to formulate an improved chronology of ice recession (especially rates) for different segments of western New England (~17.5-13.5 kyr BP) and establish the relationship of individual readvances to glacial melting and N. Atlantic climate (Aim 3). The NEVC will also be used to test hypotheses regarding the influences of climate on non-glacial varve deposition centuries after ice recession (14-11.5 kyr BP) in the northern Connecticut Valley (Aim 4) and to formulate a chronology of lake level change in the Connecticut Valley (Aim 5).

This project focuses on the analysis of long varve cores to be collected in successive field seasons (2007-2009, Table 1). Over the last decade the PI has exhausted surface exposures of varves in areas critical to NEVC improvement. Solving the remaining problems requires measurement of varves preserved in specific subsurface basins. High quality cores are specialized and expensive to obtain. Drill sites have been carefully chosen to maximize results by solving multiple problems. Characteristics of the core sites are: 1) long continuous sequences identified by detailed surficial mapping and well records (Table 1), 2) locations away from steep slopes where sub-lacustrine mass movement may have been persistent, and 3) north-south positions that will produce overlapping records, which are necessary for establishing new varve sequences and studying ice-proximal to distal relationships. Repetitiveness in cores targeting new varve stratigraphy will be necessary to cover core breaks between 5-ft core sections and to guarantee the elimination of errors that may occur in individual sections from occasional uncertainties in defining annual layering or because of subaqueous mass movement.

2.7.1 Aim 1: Filling the Claremont Gap

The Claremont Gap, as formulated by Antevs (1922), is an arbitrary break of 248 yr in the NEVC (NE 6352-6601), and a gap of 312 years in the Connecticut Valley (NE6277-6601; Fig. 1), that until recently remained untested by independent numerical ages. The current calibration indicates a 100-yr gap in the whole NEVC and a gap of 170 yr in the Connecticut Valley (Fig. 2).

Closure of the Claremont Gap is a critical part of establishing a template varve chronology for the region, the importance of which is discussed in the introduction of this proposal. In addition to allowing a unified numbering system, filling the gap will allow the application of all ^{14}C ages to a single NEVC sequence, thus improving the accuracy of calibration. Currently the length of the gap changes as new ^{14}C ages are obtained and new CALIB versions are released. A consolidated NEVC will provide greater certainty when trying to correlate to other records or when using the NEVC as a standard time line. Filling the gap also fulfills the objectives of establishing the pattern of deglaciation, timing of readvances and end moraines, and lake level history in the Charlestown/Claremont area of the Connecticut Valley.

Before requesting funding for expensive cores to fill the Claremont Gap the PI tried to solve this problem from surface exposures. While preparing detailed (1:24,000) surficial geologic maps for the State of New Hampshire (Ridge, 1990, 1999, 2001b) the PI spent six summers trying to locate varve sections that could be used to fill the gap. Eight exposures were discovered in the gap area but they were too short (21-91 years each) to compile overlapping records. Some of the exposures adjacent to steep valley sides also had deformed units created by syndepositional mass movement. Antevs (1922) found three short sections exposed at the land surface in the gap area (Fig. 5, sections 41-43) but he could not match them

Table 1: Proposed cores with supporting geologic information			
Core Sites	**Setting & Geology**	**Planned Cores**	**References: geology, well/varve records**
Summer 1: 2007 - Claremont Gap (Fig. 5), 4 sites, 6 long cores			
PHN and PHS: Perry Hill basin (N & S), N. Charlestown, NH	Deep basin - preserved lake floor underlain by 32 m (105 ft) of clay and silt in well record, top exposed in gully. Duplicate cores at both sites fill gaps between core sections.	4 cores: 2/site -34 m (110 ft)/core	Surficial map: Ridge (2001b). Well data: Moore et al. (1994)
CB: Clay Bk., Charlestown, NH	Preserved lake floor in front of Black R. delta, 31.4 m (103 ft) "stiff blue clay" beneath alluvium in well record.	34 m (110 ft)	Well data: Moore et al. (1994). Surficial maps: Ridge (1999, 2001b)
AL: Aldrich Bk., Walpole, NH	Preserved lake floor of L. Hitchcock. Records ice recession and lake level and drainage.	30 m (100 ft)	Surficial map: Ridge (1990). Varves: Antevs (1922), Ridge et al. (1999).
Summer 2: 2008 - Claremont Gap (Fig. 5) and Randolph, VT (Fig. 1), 4 sites, 5 long cores			
AYR: Ayers Bk., Randolph, VT **(Fig. 1)**	Tributary arm of L. Hitchcock, maintained impounded water after glacial lake drainage into Holocene. Deglaciation, lake level change, climate change.	2 cores: 34 m (110 ft) each	Geology: Larsen et al. (2003); Well data: VT Nat. Res., Water Sup Div.
CL: Calavant Mtn. N. Charlestown, NH	Preserved lake floor along Connecticut River. Top to bottom varve section	40 m (130 ft)	Surficial map: Ridge (2001b) Varves: Antevs (unpub.)
CJ: Claremont Junction, NH	Preserved prodeltaic lake floor - 9 m sandy varves over 21 m of silt and clay varves.	30 m (100 ft)	Surficial map: Ridge (2001b)
WB: Weathersfield Bow, Vt.	Lower and middle varve stratigraphy preserved beneath stream terrace. Small outcrops along Conn. R.	50 m (165 ft)	Surficial map: Ridge (2001b); Well data: VT Nat. Res., Water Sup Div.
Summer 3: 2009 – Massachusetts and Connecticut (Fig. 1), 4 sites, 4 long cores			
NHT: N. Hatfield, MA	Preserved lake floor, complete L. Hitchcock varve section. Top: abrupt upward change from varves to micro-varves, then sand. Deglaciation, lake level history and drainage. Proximal varves of Camp Meeting Cutting Readvance.	30 m (100 ft)	Surficial geology: Jahns (1951, 1967) Varves: Antevs (1922)
SHD: S. Hadley, MA	Preserved lake floor, full L. Hitchcock varve section. Top has abrupt change to sand. Deglaciation, lake level history and drainage. Distal varves of Camp Meeting Cutting Readvance.	40 m (130 ft)	Geology and well data: Werner (1995), Garabedian & Stone (2003). Field recon.
LGM: Longmeadow, MA	Complete section of L. Hitchcock varves, southern MA. Deglaciation chronology, proximal varves of Chicopee Readvance, L. Hitchcock drainage.	40 m (130 ft)	Surficial maps: Colton (1965a), Hartshorn and Koteff (1967).Varves: Antevs (1922).
EW: near Rice Road, East Windsor, CT	Near top to bottom section L. Hitchcock varves. Deglaciation chronology, distal varves of Chicopee Readvance	37 m (120 ft)	Geology: Colton (1965a, 1965b), Stone et al. (2005a). Varves: Antevs (1922)

to his other sections. Antevs did not report these measurements but the PI has received copies of Antevs' original plots of these sites from the archives of the Antevs Library at the Univ. of Arizona. The PI was also not able to match Antevs' unpublished records to either the NEVC's lower or upper Connecticut varves or to any of the PI's new sections.

Detailed mapping identified areas of preserved lake floors, away from valley sides, where subsurface varve sections include the oldest varves deposited immediately after ice recession and complete sequences up to the youngest varves in the entire basin that have not been trimmed or capped by later fluvial deposits (Table 1, Fig. 5). These sections survived erosion in basins separated from the main valley by bedrock ridges. The occurrence of thick undisturbed sections of clay and silt in these areas was confirmed from small surface exposures and well records (Table 1). The depths and progressive south to north positions of core sites between Charlestown and Claremont will provide an overlapping assemblage that bridges the Claremont Gap. An additional site at Aldrich Brook (Table 1; Fig. 5) has been targeted because it preserves a lake floor south of the Claremont area and will give a complete extension of the top of the lower Connecticut varves, something not record by Antevs.

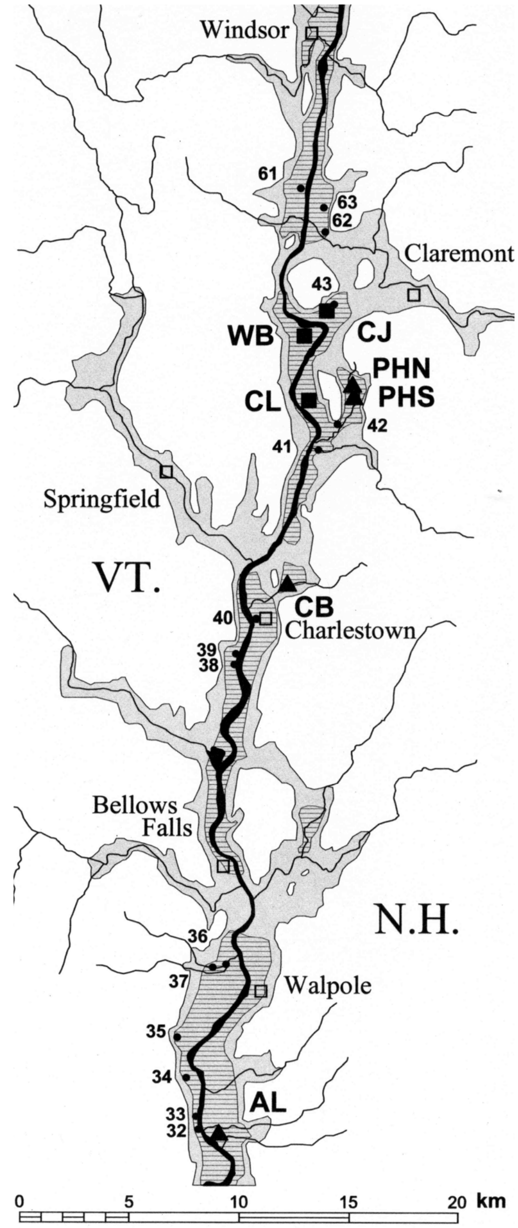


Figure 5. Claremont Gap area of the Connecticut Valley showing Lake Hitchcock. Scribed areas indicate thick subsurface clay and silt varve stratigraphy, in some cases having preserved lake floor at the land surface. Numbered sites: Antevs' (1922) varve sections. Core sites for 2007 (triangles) and 2008 (squares) are listed on Table 1.

2.7.2 Aim 2: Improving the NEVC Calibration

^{14}C ages used to calibrate the NEVC are in general agreement with each other (Fig. 2), but two major uncertainties still limit the accuracy of calibration. First, plant macrofossils used to obtain ^{14}C ages resided on land prior to lacustrine deposition. There may have been lags in transport to the lake so that ^{14}C ages significantly pre-date the actual age of the varve in which they occur, providing only maximum ages. This is likely more of a problem with wood and twigs than more delicate leaves. Regional consistency and fossils taken from varves that post-date deglaciation by only a few centuries suggest that lags in deposition of this type are relatively small (< 3 centuries).

A second uncertainty involves using ^{14}C ages from ^{14}C plateaus to calibrate varves. Very similar ^{14}C ages can be obtained over a couple of centuries of varves. In particular there is a plateau in ^{14}C time at 12.6-12.3 ^{14}C ka (Fig. 2) which corresponds to about 750 calibrated years (14.9-14.15 kyr BP). This allows small precision values (<100 yr), and small errors in individual samples, to balloon into uncertainties of several centuries. The collection of ^{14}C samples from a wider range of varve years, and outside of ^{14}C plateaus, will improve the calibration of the NEVC.

Parts of this project, intended to improve the varve stratigraphy, can also improve the calibration of the NEVC. Closure of the Claremont Gap will allow the application of all new and existing ^{14}C ages to a single continuous sequence and provide a rigorous consistency test of the calibration over a longer time span. Because all of the ^{14}C ages will be linked to a single sequence, and separated by a known number of years, uncertainty will be reduced for the overall calibration. As a minimum expectation the plan described below will increase the span of ^{14}C samples from NE 3600 in Connecticut to NE 8660 at Newbury, VT and add many additional intermediate points.

Four previously studied exposures will be sampled in new intervals for AMS ^{14}C dating that include:

1) An interval beneath previous samples at Canoe Brook, VT (NE 5700-5900; Ridge and Larsen, 1990; Ridge et al., 2001) where scattered plant fossils were found while looking for trace fossils in 2005.

2) The bottom- and top-most parts of the Newbury, VT section (NE 7300-7600 and 8500-8700) where varves older and younger than those previously dated contain plant fossils or previous conventional ^{14}C ages had poor precision values (Ridge and Toll, 1999a; Ridge et al., 1999).

3) A varve section in the Passumpsic Valley (PAS2 on Fig. 1), where a ^{14}C age was obtained high in the section (NE 7754, Wilson, 2000; Ridge, 2003, 2004). An additional sample lower in this section (NE 7265) was accidentally ruined at a radiocarbon laboratory. This lower section will be a sampling target.

4) A section at East Windsor Hills, CT (Redlands Brick Co.) where a study of trace fossils during the summers of 2004 and 2005 revealed abundant leaves of tundra plants on several horizons in NE 3617-4168 (Stone et al., 2005b). Two horizons are now dated (NE 3826 and 4113, Fig. 2) but plant material has been found lower in the section.

^{14}C sample collection will include several precautions and the parallel collection of outcrop cores for placing samples in the NEVC. Outcrop core collection and identification of precise varve numbers for each sample will employ the sampling techniques developed by the PI for studying varves from surface exposures (Ridge and Toll, 1999a; Ridge et al., 1996, 1999; Wilson, 2000; Nichols, 2004; Benner and Ridge, 2004). Only terrestrial plant macrofossil leaves of known genus will be submitted for age determination. Both *Dryas* and *Salix* leaves have been dated in the past. Samples will not be stored for more than a few days and then in aluminum foil under refrigerated or freezing conditions to retard decay and contamination. After identification, samples will be thoroughly dried and immediately sent to a lab for AMS ^{14}C age and $\delta^{13}C$ determinations.

2.7.3 Aim 3: The Dynamics of Glacial Readvances and Ice Recession.

A. Timing of Readvances, Ice Recession, Recession Rates. A consolidated and well calibrated NEVC will provide the precise chronology for determining the exact ages of four glacial readvances in the Connecticut Valley (Fig. 1): the Chicopee and Camp Meeting Cutting readvances in Massachusetts (Larsen and Hartshorn, 1982), and the Charlestown (Ridge, 2001b, 2003, 2004) and Littleton (see Ridge et al., 1999; Thompson et al., 1999; Ridge, 2003) readvances in New Hampshire (Fig. 1). The age of the Littleton Readvance is known very precisely relative to the upper Connecticut varves (Lougee, 1935; Ridge et al., 1996, 1999a) while long cores will be acquired (at least one proximal and one distal to each readvance limit) to precisely bracket the ages of the other readvances relative to varve years (Table 1). The long cores planned in this proposal will also extend the record of the precise timing of ice recession to prior to Heinrich Event 1 and into Connecticut for the first time. All of the readvances have been tentatively assigned to known climatic events (see Ridge, 2003, 2004 for summary) but the new chronology would allow a precise comparison of these events with N.Atlantic climate records to determine their relationship to climate change and also whether they are exactly synchronous with events in adjacent areas. The chronologic correlation of varve and deglaciation records to ice core records will not simply be an alignment of their independent time scales because of an uncertainty of several centuries in absolute ice core ages (Alley et al., 1993) and differences between ^{14}C calibration programs (OxCal: Bronk Ramsey, 1995, 2001; Fairbanks0805: Fairbanks et al., 2005; CALIB 5.01: Stuiver et al., 2005) during the period of analysis. *As a starting point* the Littleton Readvance, which appears to exactly match the pattern of the Older Dryas (Fig. 4; Ridge and Toll, 1999a), will be used to correlate ice core and varve records. Other readvances will be investigated using this correlation anchor in addition to the climate patterns during readvances depicted by varve thickness (meltwater production, see below).

B. Readvance Mechanisms vs. Meltwater. As important as the timing of readvances is the assessment of meltwater production during readvance events. Glacial varve thickness, primarily a function of meltwater delivery of sediment to a lake, will be used to gage meltwater production, which has a direct tie to glacial ablation and mass balance. Antevs' (1922) records cannot be used for this purpose because they do not exist in the Charlestown Readvance area and Antevs' published records in the other areas are composite normalized records from multiple exposures. The normalized records do not give accurate records of long-term varve trends at one section. Varves in the new cores will be used to determine whether times of readvance were periods of lower meltwater production (thinner varves), implying a time of lower ablation brought on by cooling climate (Lowell et al., 1999). Alternatively, readvances may be periods of thicker varve deposition implying that they are periods of high meltwater production, and thus high ablation, that elevated basal water pressure and accelerated basal ice flow processes. Although the hypothesis that readvances are a reaction to climatic cooling seems reasonable the exact relationship has not been established with a precise chronology and lags and response times are not presently known. Analysis of the Littleton Readvance (Ridge et al., 1999a) suggests that during ice advance varve thickness diminished along with the disappearance of occasionally thick varves representing flood events (Fig. 4). Disappearance of flood events would result from the readvance of an ice front that prevented the release of water from small lakes impounded in tributary valleys being overrun by ice. As ice recession began varve thickness abruptly increased by ~ 5 times with increased melting. Flood events again became a conspicuous part of the varve stratigraphy as ice recession released water from ice-marginal lakes. In the Littleton Readvance analysis, as will be the case with the others, it is important to look at varve sections that are sufficiently distal to the ice front in order to avoid local changes in sedimentation associated with the close approach of an ice front advancing over lacustrine mud. At least two core sites in front of each readvance, one more distal than the other, will be used to characterize overall meltwater activity.

C. The Chicopee Readvance vs. Heinrich Event 1 (H1). Varves overlying till deposited by the Chicopee Readvance near its limit (Antevs, 1922 and new data of J. Ridge) indicate that the readvance fits into the time frame of H1 (no younger than NE 3550 or ~ 17 kyr BP, Fig. 2). The maximum age of this event will be precisely constrained by the long cores collected at Longmeadow, MA and East Windsor, CT (LGM and EW on Fig. 1, Table 1). Both the precise timing of the readvance and its relationship to meltwater discharge will help address the important questions of how the readvance is related to climate at the time of H1. Several scenarios are possible with a test of hypotheses that readvance of the southeastern LIS at this time was: 1) a response to cooling that also lead to H1 (Bond and Lotti, 1995); 2) the result of ice sheet instability independent of climatic cooling, which came later with H1 (MacAyeal, 1993; Alley and MacAyeal, 1994); or 3) a rapid response to cooling brought on by H1's influence on ocean circulation and climate (McCabe and Clark, 1998).

2.7.4 Aim 4: Lateglacial Climate Change (14-11.5 kyr BP).

In varves at Newbury, VT in the upper Connecticut Valley (Fig. 1) a relationship was found between rapid climate change events and varve lithology and thickness. Within the potential errors of the Greenland ice core chronology and varve measurement the Older Dryas (OD) event appeared to be represented by glacial varves recording the Littleton Readvance while the thickness and sandiness of non-glacial varves increased during the IACP and YD (Fig. 4; Ridge and Toll, 1999a). Cores at Ayers Brook (White River Valley, Randolph, VT; Fig. 1 and Table 1) along with the NEVC's calibration will be used to further test this relationship by comparison to the previous results at Newbury and N. Atlantic climate records. Varves in the Ayers Brook cores will be measured and their lithology changes recorded to determine if they show similar variations at the times of the OD, IACP, and YD with the advantage of also being able to investigate the YD/Preboreal transition, which was not available at Newbury.

The Ayers Brook site represents a unique situation for studying Lateglacial climate. While the valley was occupied immediately after deglaciation by a White River embayment of Lake Hitchcock (Fig. 1) a large glacial subaqueous fan was deposited at the mouth of Ayers Brook. With falling glacial lake level this obstruction maintained impounded water in the Ayers Brook valley long after glacial lake drainage. The varve stratigraphy along Ayers Brook begins with deglaciation in a deep glacial lake but continued with non-glacial varves and finally non-varved pond sediment that is exposed at the land surface and the bottom of which has been dated at 10.0-8.7 ^{14}C ka (Larsen et al., 2003). This section provides a rare opportunity to study continuous varve deposition from ~14.0-11.5 kyr BP (~12.2-10.0 ^{14}C ka), culminating with the end of the YD. Because of their unique setting and continuous high resolution stratigraphy Ayers Brook cores will also be evaluated to determine whether it is feasible to obtain pollen and ostracode isotope ($\delta^{13}C$, $\delta^{18}O$) records. The cores may provide the materials for these later studies if ostracodes are preserved and pollen concentrations are sufficient.

2.7.5 Aim 5: Lake Level History

A pervasive idea for the last 50 years has been that Lake Hitchcock (Fig. 1) existed as a long continuous lake that expanded northward from its southern end near Hartford, CT as ice receded and that it remained a single long water body until ice receded to northern Vermont. This “long single lake” hypothesis has been used to formulate a controversial model of delayed isostatic recovery in New England (Koteff and Larsen, 1989; Koteff et al., 1993). Recently the lake level history of Lake Hitchcock has been revised with its southern–most basin (south of Holyoke Range, Fig. 1) draining much earlier than basins to the north by at least 1600 years. This early drainage of the southern basin has been documented by ^{14}C ages and varve stratigraphy in the southern basin (Stone et al., 1992, 2005b; McWeeney, 1995; Stone and Ashley, 1995; Stone, 1999). Precise constraints for this drainage event using varve stratigraphy are being pursued outside of this proposal with short vibra-cores of preserved lake floor in the southern Hitchcock basin near Hartford, CT. Long cores collected at East Windsor, South Hadley, and Longmeadow (EW, SHD, LGM on Fig. 1, Table 1) could have an impact on this problem.

Further north in New Hampshire and Vermont, a similar pattern of progressive south to north drainage of separate basins also may have occurred as indicated by the apparent termination of varve sequences beneath preserved lake floors in basins south of Charlestown relative to basins further north. Basins north of Charlestown appear to have much longer varve sequences than basins to the south despite northward onlap of the varve stratigraphy. It is clear that the lake level history of the basin demands a reinvestigation if not a complete overhaul.

Long cores of preserved lake floors at several sites in Massachusetts and at Aldrich Brook (Fig. 5), southern NH will be used to define the complete varve stratigraphy of the basins south of the Charlestown area and document their drainage times. Of particular interest is the core at North Hatfield (NHT, Fig. 1, Table 1) in an area where the top of the varve stratigraphy shows an abrupt upward change from normal Lake Hitchcock varves to “microvarves” followed by another abrupt change to sand (Jahns, 1967). The cores in the Claremont Gap area and also at Ayers Brook (Randolph, VT) will be used to augment existing data from the Newbury, VT section (Ridge and Toll, 1999a, 1999b) to evaluate the drainage of lakes in the Claremont Gap area and northward. The cores will help identify the potential relationship of lake drainage in these basins to isostatic recovery, addressing the issue of whether changes in varve facies depict abrupt drops in lake level, as would be the case with the failure of a dam, or whether lowering of water was gradual, perhaps due to decanting during isostatic tilting. A chronologically consistent, abrupt, basin-wide change in varve thickness and lithology is the earmark of an abrupt drop in lake level while isostatic tilting would trigger slower, more subtle changes over centuries. At the very least the entire array of cores will be a more than adequate test of the “long single lake” hypothesis that is the pinning concept of delayed isostatic rebound in New England (Koteff and Larsen, 1989; Koteff et al., 1993).

2.8 Specialized Methodology

2.8.1. Long Core Collection

This project will contract drilling services of the USGS Water Science Center (Pembroke, NH) for the collection of cores of thick (up to 50 m) varve sections (Table 1). The contractor was carefully selected to collect high-quality, large diameter cores as in a study by researchers at the University of Massachusetts (Rittenour, 1999; J. Brigham Grette, pers. comm.). Cores with 7.6 to 10.2-cm (3 to 4-in) diameter in 1.52-m (5-ft) long plastic liners will be collected utilizing a continuous sample tube system or a bearing head continuous sampling system in conjunction with hollow stem auger drilling. This technique will yield cores of a quality and completeness necessary for measuring and analyzing varve stratigraphy including: 1) core samples that have deformation of bedding in only their outer 1-3 mm, and 2) gaps of no more than 10 cm between successive core sections. The proposed coring technique eliminates problems with cores of smaller diameter or that are hammered. In some places complete subsurface stratigraphy will be necessary to create new parts of the NEVC. At selected sites two parallel long cores will be taken in which the 1.52-m core sections in adjacent holes will be offset by 0.76 m to span core breaks, or a cluster of sites will be used to capture the whole stratigraphy. Unfortunately, paleomagnetic measurements, a consistent part of the PI's studies of surface varve exposures, will not be possible in very deep auger-driven cores. Paleomagnetic sampling was attempted by the University of Massachusetts researchers in similar cores but remanence directions proved to be inconsistent within core sections and of very limited accuracy not solely because of difficulties with core orientation (Rittenour, pers. comm.). High coring stresses necessary to penetrate very silty, and sometimes sandy, sediment may create conditions that disturb magnetic signals.

2.8.2. Core Preparation, Analysis, and Storage

After cores are collected they will be split and one core half will be archived in a moist environment (heat-sealed, 6-mil plastic core bag) with an anti-fungal agent, while the other half will be used for varve analysis. Both core halves can later serve as samples for analysis of climate proxies. The Geology Dept. at Tufts has both a large space for storage at room temperature and a walk-in refrigerator for special samples. Core halves used for varve measurement will be scraped with a razor and slowly dried to develop a significant contrast between clayey and silty layers, a technique that the PI has perfected in previous studies. Sequential high-resolution digital images of each varve core will be collected for computer measurement of summer and winter layer and total varve thickness using Script plug-in software especially written by the PI and his former students for UTHSCA Image Tool 3.0. This will create a digital image archive of all measurements.

2.9 Research Time Table

Table 2. Time table of research activities, Spring 2007 to Spring 2010.

Sp 07	**Early - Late Summer 07**	**Fall 07**	**Winter 2007-2008**	**Sp 08**
Property permission	^{14}C sampling – Newbury/PAS2 Core processing/measurement – Claremont Gap & south. NH	Varve record construction and matching. Lake level analysis - Aldrich Bk. vs. Claremont Gap.		
	Core collection Summer 1 (Table 1)	Begin Charlestown Readvance/end moraine analysis. Web construction: varve techniques, NEVC history, and northeast U.S. records.	^{14}C results from Newbury/PAS2. Prop. permission for Summer 08. Web posting: new varve records.	
Sp 08	**Early to Late Summer 08**	**Fall 08**	**Winter 2008-2009**	**Sp 09**
Student reports	^{14}C sampling – Canoe Bk., VT Core processing/measurement – Claremont Gap/ Ayers Bk., VT	Varve record construction and matching. Lake level analysis - Claremont Gap vs. northern NH/VT and Ayers Bk., VT		Complete NEVC consolidation.
Core collection Summer 2 (Table 1) – Claremont Gap/ Ayers Bk., VT		Finish Charlestown Readvance & end moraine analysis. Analysis and compilation of climate in Ayers Bk. cores.	^{14}C results from Canoe Brook, VT. Prop. permission for Summer 09. Web posting: new varve records and new NEVC number system.	
Sp 09	**Early to Late Summer 09**	**Fall 09**	**Winter 2009-2010**	**Sp 10**
Student reports	^{14}C sampling – East Windsor, CT. Core processing & measurement – Mass. & Conn.	Varve record construction and matching. Lake level analysis in Mass.		Compilation: Conn. Valley lake level. Student reports.
Core collection Summer 3 (Table 1) – Massachusetts & Connecticut.		Camp Meeting Cutting/Chicopee Readvance analyses. Compilation: Readvance chronology vs. N.Atlantic climate.	^{14}C results from E. Windsor, CT. New NEVC calibration. Web posting: new NEVC calibration.	

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Biographical Sketch

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Professional Preparation

Lehigh University	Geological Sciences	BS 1977
Lehigh University	Geological Sciences	MS 1983
Syracuse University	Geology	PhD 1985

Appointments

Tufts University, Dept. of Geology, Professor, 2002-present
New Hampshire Geological Survey (summers), Field Geologist, 1998-2001
Tufts University, Dept. of Geology, Associate Professor, 1991-2002
Tufts University, Dept. of Geology, Assistant Professor, 1986-1991
New Hampshire Geological Survey (summers), Field Geologist, 1985-1992
Tufts University, Dept. of Geology, Instructor, 1985
University College of Syracuse University, Graduate Lecturer, 1983-1985

Five Related Publications

Ridge, J.C., 2003, The last deglaciation of the northeastern United States: A combined varve, paleomagnetic, and calibrated ^{14}C chronology, *in* Hart, J.P. and Cremeens D.L., eds., Geoarchaeology of Landscapes in the Glaciated Northeast U.S.: New York State Museum Bulletin 497, p. 15-45.

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Five Other Significant Publications

Ridge, J.C., 2004, The Quaternary glaciation of western New England with correlations to surrounding areas, *in* Ehlers, J. & Gibbard, P.L. (eds.), Quaternary Glaciations – Extent and Chronology, Part II: North America. Developments in Quaternary Science, vol. 2b, Amsterdam, Elsevier, p. 163-193.

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<u>Synergistic Activities</u>

Invited Full-day Workshops: "Varve Chronology – Methodology and Results"
Dept. of Earth and Environmental Sciences, Lehigh University, Bethlehem, Pa. November 21, 2003.
Annual Meeting of the Vermont Geological Society, Norwich Univ., Northfield, VT, Feb. 16, 2002.
(example instructional images can be seen at: http://ase.tufts.edu/geology/VarveIL.pdf)

Director, Archaeology Program, Tufts University, 1996-1999, 2002-2004.

Lecturer and Resource, Science Teaching Professional Development Program, Medford Public Schools, Medford, Massachusetts.

School of Engineering Curriculum Task Force, redesign of core curriculum (introductory science courses and science requirements), School of Engineering, Tufts University, 2005-present.

Tufts Representative to Center for Materials Research in Archaeology and Ethnology (CMRAE) at MIT, a consortium of local universities (MIT, Harvard, Boston Univ., Brandeis, UMass Boston, Tufts, Wellesley, Boston Museum of Fine Arts) that teaches analytical techniques in science and technology to archaeology students. 1991-present.

<u>Collaborators and Other Affiliations</u>

A) Collaborators:
Mr. Jacob S. Benner, Tufts University; Dr. Duane Braun, Bloomsburg (Pa.) University; Dr. William J. Brennan, SUNY Geneseo; Dr. Edward B. Evenson, Lehigh University; Dr. David A. Franzi, SUNY Plattsburgh; Dr. Meredith A. Kelly, post-doc at Lamont-Doherty Geological Observatory of Columbia University; Mr. Carl Koteff, USGS; Dr. Fred D. Larsen, Norwich University (VT); Janet R. Stone, USGS; Mr. Woodrow B. Thompson, Maine Geological Survey; Dr. Zicheng Yu, Lehigh University.

B) Graduate Advisors:
MS: Dr. Edward B. Evenson, Lehigh University; PhD: Dr. Ernst H. Muller (deceased), Syracuse University.

C) Thesis Advisor and Postgraduate-Scholar Sponsor: N/A, the Tufts University Geology Dept. currently offers only undergraduate degrees.

Facilities, Equipment, and Resources

The Geology Department at Tufts University is well-equipped for an undergraduate department with a wide array of laboratory/analytical equipment and computer capabilities.

The Geology Department has several important facilities and devices that are relevant to this proposal. In the basement of Lane Hall, which houses the Geology Department, is a 20 x 20 ft space that will have core racks (purchased each year) for core storage. There is also a walk-in refrigerator for storing special samples at low temperature. In addition to a computer equipped class room during the summer, a wet-sediment laboratory will serve as a room for analysis for both the summer and academic year. The lab is equipped with a drying oven, loss-on-ignition furnace, fume hood, full array of sieves, a table saw outfitted for core liner splitting, binocular and petrographic microscopes, and a refrigerator and freezer.

Several computers will be available for the project equipped with software for varve analysis and plotting of results. All computers have access to the internet and have Adobe Photoshop and Illustrator, Microsoft Word and Excel, ArcGIS, and UTHSCA ImageTool 3.0 installed. In addition the PI has AutoCAD 2000, Absoft FORTRAN, and Golden Software Grapher on his office computer. Several in-house Script programs have been written by the PI and his former students for UTHSCA ImageTool 3.0 (free software) and will be used for computerized measurement of varve sequences and gray scale image analysis of varves along transects of chosen length and pixel width.

Image capture will be accomplished with a core imaging box that employs indirect full spectrum lighting and the Geology Department’s several digital cameras including a Nikon Coolpix 995 and a Nikon D70.

The PI has a lab with the following paleomagnetic equipment should new outcrops in the study area become available for sampling: 1) Molspin Minispin magnetometer, 2) Molspin Minisep anisotropy of magnetic susceptibility device, 3) Molspin bulk (Z-axis) susceptibility device, 4) Sapphire Instruments single axis alternating field demagnetizer with a DC field generator for IRM acquisition and a biasing field utility for creating ARMs between specified alternating field values, and 5) Bartington MS2C 125 cm diameter core logging magnetic susceptibility device.

Should a detailed look at microfossils in the varves or chemical or mineralogical analyses of varve sediment prove useful the Geology Dept. has a fully computerized JEOL 6300 Scanning Electron Microscope with an Energy Dispersive Spectrometer for X-ray elemental analysis and an automated Phillips 3100 XRG X-ray diffraction device. There is also a fully equipped rock prep room with several rock saws.