COLLABORATIVE RESEARCH: SYNCHRONIZING THE NORTH AMERICAN VARVE CHRONOLOGY AND THE GREENLAND ICE CORE RECORD USING METEORIC ^{10}Be FLUX

The purpose of this proposal is to use measurements of atmospherically-produced ^{10}Be to synchronize the North American Varve Chronology with the Greenland ice core record.

Several decades of research on the Greenland ice cores has shown that they contain an extraordinary record of regional climate, atmospheric composition, and some aspects of global climate during the last glaciation and deglaciation (Alley, 2001). The Greenland ice core timescale and climate records are a primary template for our current understanding of northern hemisphere climate change during the Last Glacial Maximum (LGM) and deglaciation. The North American Varve Chronology (NAVC) is a 5659-year sequence of annually laminated lacustrine sediment deposited in lakes at and near the margin of the retreating Laurentide Ice Sheet (LIS) in the northeastern United States, between approximately 18,000 and 12,500 years ago (Figure 1). The NAVC records events taking place at the ice sheet margin, including ice margin position, meltwater and sediment production, and proglacial lake outburst floods. Because some of these events are related to climate, the NAVC is also a climate proxy record with annual resolution.

Our goal in this proposal is to synchronize these two records with decadal precision. This goal is important because it would enable a high-temporal-resolution comparison between climate events recorded in Greenland and events at the margin of the LIS, which would advance understanding of the existence, importance, and time-dependence of ice sheet-climate interactions and feedback processes. We believe that we can achieve this goal by measuring atmospherically-produced ^{10}Be in NAVC sediments. ^{10}Be is produced by cosmic-ray bombardment of atmospheric constituents (primarily N and O) and delivered to the Earth's surface by precipitation or dry fallout. The ^{10}Be production rate and, in turn, the fallout rate at the surface, vary significantly with changes in solar activity and geomagnetic field properties. These variations are global in nature, so variations in the ^{10}Be fallout rate are, in general, globally synchronous. Thus, comparing measurements of ^{10}Be fallout flux in different sedimentary records can be used to synchronize those records. There already exists a record of ^{10}Be flux to the Greenland ice cores that, during the period recorded by the NAVC, is sampled at decadal to multidecadal resolution and displays significant centennial-scale variability. We propose to generate a record of ^{10}Be fallout from the NAVC with a time resolution appropriate for matching this centennial-scale variability, thus synchronizing ice-core and NAVC proxy records with decadal precision.

In the rest of this proposal we will: i) show examples in which high-resolution correlation of specific ice-marginal events recorded in the NAVC with ice-core climate records would lead to new understanding of ice sheet-climate interactions; ii) summarize existing ice-core ^{10}Be records and correlation studies to support our argument that if we can generate a ^{10}Be fallout record from the NAVC, we can correlate NAVC and ice-core records at decadal precision, and iii) show that first principles and available observations strongly indicate that we can successfully generate a ^{10}Be fallout record from the NAVC.

This proposal includes a significant degree of risk, because it is possible that the ^{10}Be concentration of NAVC sediments might not reflect changes in ^{10}Be fallout. Although first-principles reasoning and all relevant observations indicate to us that there is a high likelihood of success, our overall strategy has not been applied before and our measurements may reveal new complications that we have not recognized in advance. We argue, however, that the potential return – in the form of entirely new and potentially very significant insights into ice sheet-climate interactions during the last deglaciation – justifies the risk.

I. THE NORTH AMERICAN VARVE CHRONOLOGY: WHAT IS IT AND WHY IS IT IMPORTANT?

History of the NAVC. The core of the NAVC is a series of stratigraphic sections in the Connecticut River Valley of the northeastern United States that expose annually laminated ("varved") sediment deposited in glacial Lake Hitchcock and its successors (Figure 1). Lake Hitchcock initially formed when the LIS retreated from a moraine dam in central Connecticut. Although the lake's outline varied due to breach of the dam, isostatic rebound, and ice retreat, it occupied some part of the Connecticut Valley for at least 5700 years and was in contact with the retreating ice margin for at least 4600 years.

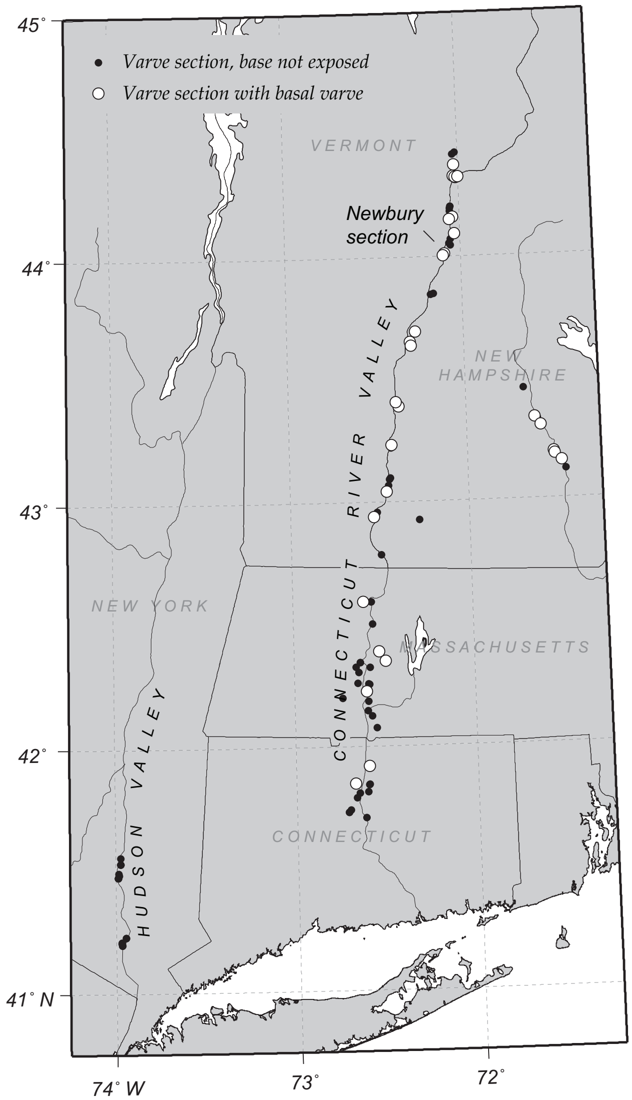

Figure 1: *Varve sections linked to the NAVC. Circles show exposures and boreholes of varved sediment, deposited in a variety of proglacial lakes impounded by the retreating Laurentide Ice Sheet, that are correlated to the NAVC (see Ridge, 2010, for a full catalog).*

During that time, the ice margin retreated ~350 km from central Connecticut to northern Vermont and New Hampshire (Figure 1). Ernst Antevs (1922, 1928) showed that varved sediments throughout the Connecticut Valley could be correlated into two long composite sequences from the lower (southern) and upper (northern) valley, which together spanned arbitrarily numbered varve years 2701 to 7750 (the numbering scheme runs forward, so that younger varves have higher numbers). Antevs also matched these to other, shorter, varve sequences in the Hudson (NY), Merrimack (NH), and Winooski (VT) Valleys to extend and bridge gaps in the Connecticut Valley sequences. Later work by Ridge and co-workers (Ridge and Larsen, 1990; Ridge et al., 2001; Ridge, 2003, 2004; Ridge and Toll, 1999; Rittenour, 2000) extended the youngest end of the varve chronology by ca. 1000 years and correlated it to additional lacustrine sequences in Maine and New York. Finally, recent work (see Results of Prior Research below) has matched the upper and lower Connecticut Valley sequences, resulting in a single long sequence. This match, as well as the discovery of several varves either improperly counted or not counted by Antevs, created conflicts in Antevs' original numbering system. Thus, Antevs' enumeration has been replaced with a revised numbering system, now called the North American Varve Chronology (documented in detail in Ridge, 2010). The NAVC extends between varve years 2700-8358, a duration of 5659 yr.

Varve year - calendar year calibration. The NAVC is a floating chronology, but it can be anchored to the absolute time scale by radiocarbon dating of organic material found within particular varves. Currently there exist 54 radiocarbon dates on detrital plant material found within varved sediments that are correlated to the NAVC (Ridge 2003, 2004, 2010). 13 of these fail quality control tests, mostly because the origin of the sample material is uncertain. The remaining 41 span NAVC years 3513-8186. One can find a best-fitting offset between NAVC years and calendar years (specifically, the offset is the calendar year before 1950 age of the varve with NAVC year zero) by fitting these radiocarbon dates to the INTCAL09 radiocarbon calibration curve (formally, by minimizing the error-weighted sum of squared deviations between observed radiocarbon ages and those predicted by INTCAL09). This yields a best-fitting offset of 20,810 years. With this offset, the NAVC spans the time period between 18,110-12,450 years before 1950 (Figure 2). The formal uncertainty in this value of the offset is $\pm$ 100 yr, but the fitting exercise shows that the scatter of the radiocarbon data set with respect to the INTCAL09 calibration curve is greater than expected from measurement uncertainty alone (a reduced chi-squared value of 3.3 for 40 DOF; $p < 10^{-7}$). Thus, the true uncertainty in this estimate is larger, most likely near $\pm$ 200-250 yr.

Events recorded in the NAVC. Varved sediments of the NAVC record a variety of information about conditions at the ice margin (discussion in this section relies on: Antevs, 1922; Ashley, 1975, Ridge and Larsen, 1990; Ridge and Toll, 1999; Rittenour et al., 2000; Ridge et al., 2001; Ridge, 2003, 2004, 2010). First, these conditions control varve thickness. The majority of the NAVC consists of glacial varves, that is, varves deposited in a lake that directly received glacial meltwater. For glacial varves, varve thickness reflects primarily distance to the ice margin, and secondarily the rate of sediment supply and transport, which is controlled by meltwater delivery to the lake. Thus, varve thickness records display i) gradual upsection thinning as the ice margin retreats, with ii) much larger superimposed variability due to changes in meltwater production. Meltwater production depends on climate, primarily summer temperature in the ablation zone of the ice sheet. This dependence of glacial varve thickness on climate is why it is possible to correlate varve sections between glacial lakes across a region, even if they are not confluent. Second, varve sections also record the position of the ice margin in a particular varve year: not only does the presence of a varve show that a site was ice-free in the year represented by that varve, but many varves can be traced to their northern termination in ice-proximal sediments, thus showing the precise position of the ice margin in a given year. Finally, glacial-lake outburst floods are commonly recorded in varve sequences. For example, sections in the Hudson Valley that are correlated to the NAVC display a series of graded beds (first incorrectly interpreted as varves) that record the drainage of a glacial lake in the Mohawk Valley of New York, and (as further discussed below), the catastrophic drainage of Glacial Lake Iroquois in central New York into the Champlain Valley is recorded in varved sediments.

The youngest portion of the NAVC (the uppermost ca. 1200 varves at the Newbury, Vermont section; Figures 1, 4, and 5) consists of nonglacial varves. At the time these varves were deposited, this portion of Lake Hitchcock was no longer receiving direct meltwater discharge. These varves are thinner, because their sediment source consisted only of runoff from the recently deglaciated landscape, and the relationship between varve thickness and climate appears to be different than for glacial varves (Figure 4): cold periods (which would result in decreased ablation and thus thinner glacial varves) are associated with thicker nonglacial varves, pehaps because of increased sediment yield from the land surface due to reduced vegetation or the formation of seasonally active permafrost.

Apparent relations between Greenland climate and events in the NAVC. Comparing the NAVC with Greenland ice-core records based on the radiocarbon dates described above suggests a relationship between Greenland climate and events at the LIS margin. Three examples follow. First, the retreat rate of the LIS margin up the Connecticut Valley reconstructed from the location of ice-proximal varves (Figure 3) approximately tripled ca. 14,700 years ago. This is close to the time of the abrupt Bolling warming recorded in Greenland, suggesting a causal relation. Similarly, a readvance of the ice margin near 14,000 years ago (Figure 3, also recorded by abrupt changes in varve thickness in the glacial part of the Newbury section (Figure 4) is close in age to the Older Dryas cold period recorded in Greenland (see Ridge and Toll, 1999). Third, the NAVC appears to record a large (3000 km^3) outburst flood in which glacial Lake Iroquois, which occupied much of central New York State 13,500 years ago, drained into the Champlain Valley and thence down the Hudson River into the Atlantic (Rayburn et al., 2005, 2007). Donnelly et al. (2005) suggested that suppression of North Atlantic thermohaline circulation due to this outburst flood may have caused the Intra-Allerod Cold Period (IACP) recorded in Greenland (Figures 2, 4). Chronological evidence is ambiguous as to this conclusion (Figure 2). Limiting terrestrial radiocarbon ages (Rayburn, 2005; also see summary in Balco et al., 2009) as well as a compilation of limiting marine and terrestrial ages (Donnelly, 2005) permit this flood either to pre- or postdate the onset of the IACP. However, Rayburn et al. (2008) suggested a correlation between varves in glacial Lake Vermont and the NAVC that places the flood at NAVC varve year 7480, which, given the radiocarbon calibration discussed above, is close to the onset of the IACP (Figure 2).

There are also some notable differences between Greenland climate recorded in the ice cores and events recorded by the NAVC, the most striking of which is the contrast between i) the apparent coupling between ice margin retreat rate and Greenland climate at the onset of the Bolling warm period (discussed above) and ii) the lack of such a relationship before that time. This in fact is one reason that Denton et al. (2006) and subsequent work have called the period between 17,500 and 14,500 years ago the "Mystery Interval": significant retreat of ice sheet margins occurred during a period of sustained cold climate recorded in the

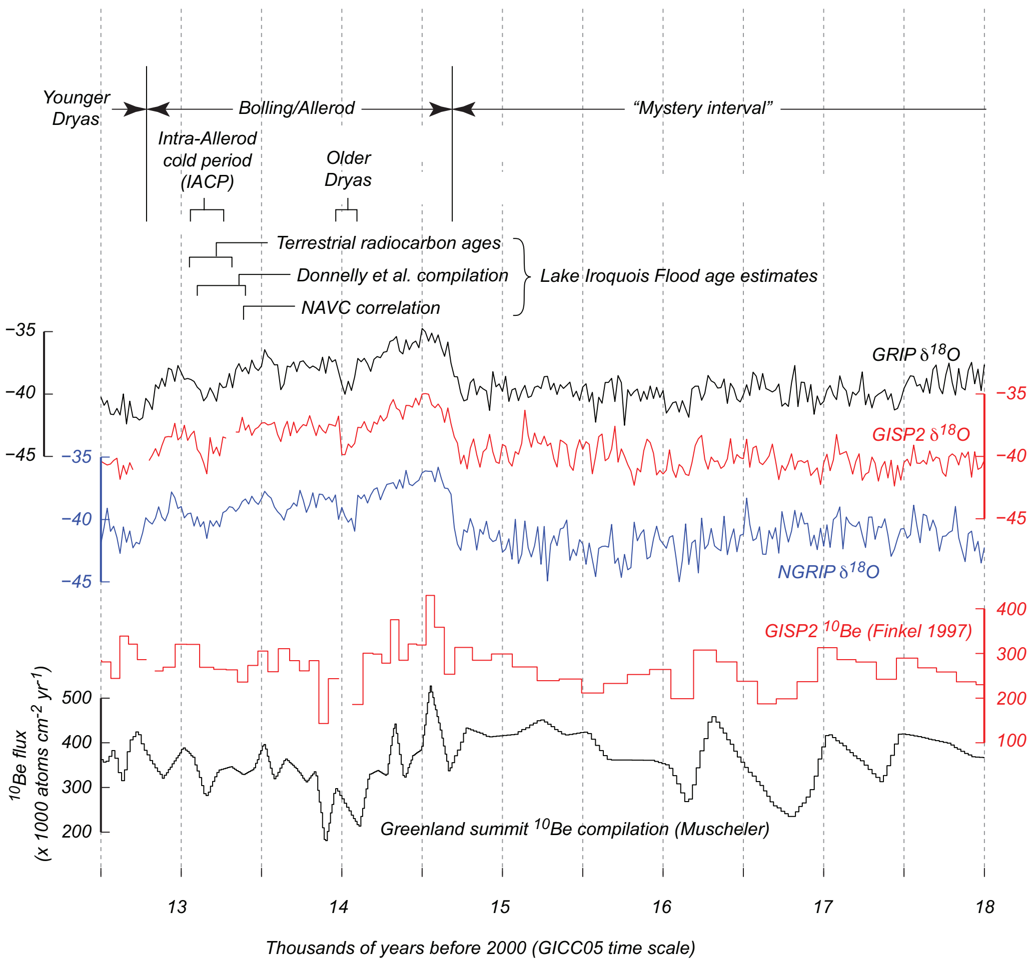

Figure 2: *Climate events and ^{10}Be flux recorded in the Greenland ice cores during the period spanned by the NAVC. Varve years are mapped to the GICC05 time scale using the best-fit offset of 20,810 $\pm$ 250 yr derived from the radiocarbon data set of Ridge (2003, 2004, 2010) as described in the text.Suggested correlations between the outburst flood caused by the drainage of Glacial Lake Iroquois and the Greenland climate record, based on a variety of data sets as described in the text, are also shown. Greenland $\delta^{18}O$ records and their synchronization to the GICC05 time scale are described in Rasmussen et al. (2006), Andersen et al. (2005), Svensson et al. (2006), and Rasmussen et al. (2008). Two ^{10}Be flux records are shown: that of Finkel and Nishiizumi (1997) from the GISP2 ice core and a composite smoothed record from multiple Greenland Summit cores from Muscheler et al. (2004). We thank Raimund Muscheler for providing these data on the GICC05 timescale.*

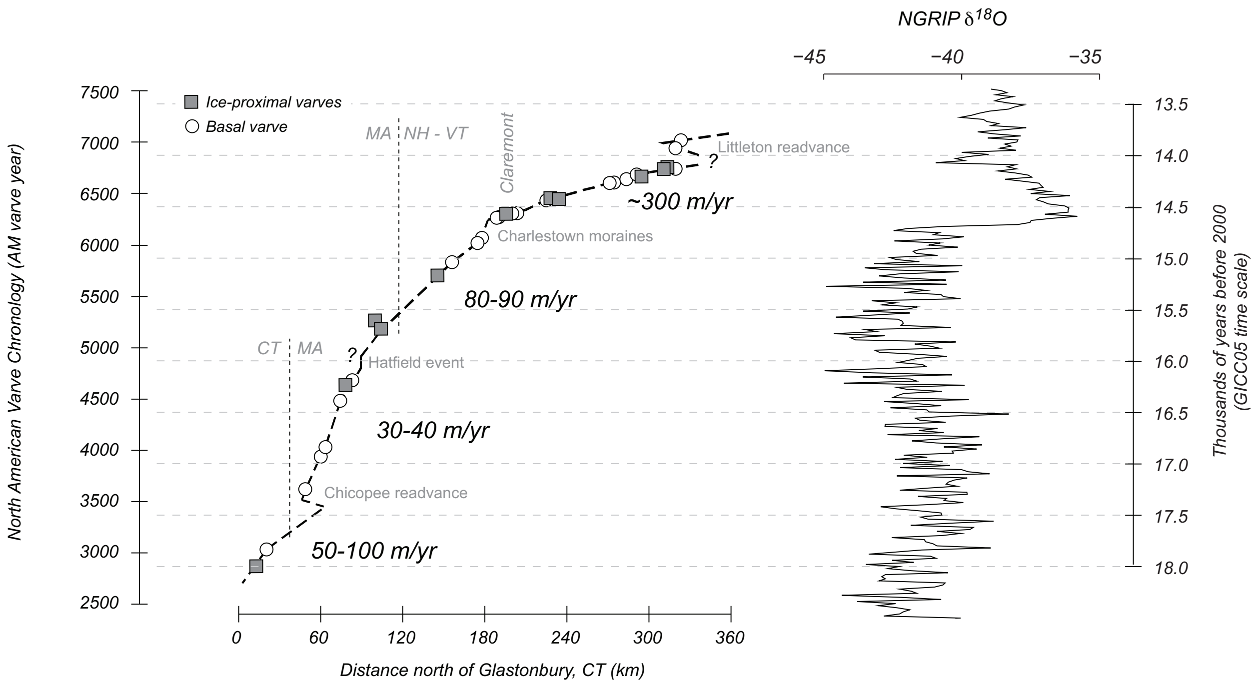

Figure 3: *Relationship between Greenland ice core climate record (see Figure 1 caption for references) and retreat of the Laurentide Ice Sheet through central New England inferred from the NAVC. Varve years are mapped to the GICC05 time scale using the best-fit offset of 20,810 ± 250 yr derived from the radiocarbon data set of Ridge (2003, 2004, 2010) as described in the text. "Basal varves" and "ice-proximal varves" are sedimentologically and stratigraphically distinct, but both record the position of the ice margin in a particular varve year. Prominent stillstands or readvances of the ice margin, as well as average retreat rates between these events, are noted. Data used to make this figure are tabulated in Ridge (2010).*

Greenland ice cores. For example, a doubling of the ice-margin retreat rate recorded by the NAVC near 16,000 years ago appears to have occurred during a relatively cold period in Greenland (Figure 3). We offer no explanation for this phenomenon, but we propose that high-resolution correlation of the Greenland climate record (which appears to record winter temperature; e.g., Denton et al., 2005) with the NAVC (which is sensitive to summer temperature) would provide insight into climate-ice sheet interactions during this period.

Value of high-resolution correlation between ice-core records and the NAVC. The discussion above shows that our current best estimate of the calendar year age for the NAVC leads to a number of apparent correlations between the NAVC and the Greenland ice-core records. Our goal is to correlate these two records with decadal precision in a way that i) is independent of the absolute dating of either one, and ii) does not rely on "wiggle-matching" based on preconceptions about the expected relationship between the records. If we achieved this, we could rigorously and quantitatively evaluate these possible correlations, examine the temporal relationships between Greenland climate changes and ice-marginal events, and shed light on the processes responsible for these relationships. Here we suggest some results that could be achieved by precise correlation of the two records. First, it would be possible to establish the temporal relationship between the winter temperature recorded in the ice core records and the melt-season temperature recorded by the NAVC varve thickness record. This might shed light on i) the climate dynamics active during the "Mystery Interval," and ii) the relative timing of climate warmings recorded in the ice core records during the Bolling-Allerod-Younger Dryas period and the ablation response (or lack thereof) at the ice margin. Second, one could establish the relationship between Greenland climate changes and changes in the location of the LIS margin, which would shed light on the relative importance of ablation forcing and internal ice dynamics in controlling ice margin retreat. Third, by relating Greenland climate records to sediment fluxes and, perhaps, other climate proxies such as pollen or plant macrofossils in the uppermost nonglacial portion of the NAVC, one could establish how fast vegetation and landscape processes responded to rapid climate changes before and during abrupt late-glacial climate changes. Finally, if ongoing work on correlating Champlain Valley varve sequences to the NAVC supports the correlation of the Lake Iroquois outburst flood to the NAVC discussed above, correlating the NAVC and Greenland records at decadal precision would allow rigorous testing of the hypothesis that this outburst flood caused the IACP by disrupting north Atlantic thermohaline circulation.

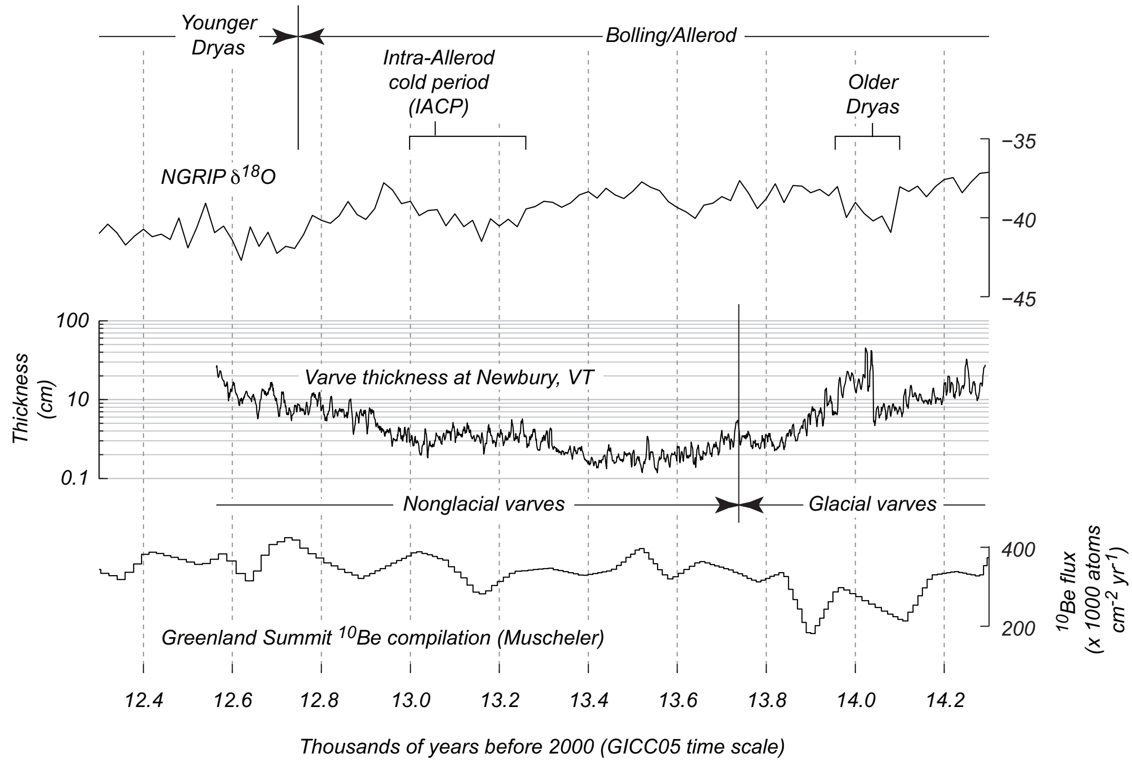

Figure 4: *This figure shows: i) the relationship between Greenland ice core climate record and varve thickness record from glacial and nonglacial varves at Newbury, VT (see Figure 1 for location), and ii)* ^{10}*Be flux variations at the Greenland ice core sites during the same time period (from Muscheler et al., 2004, as described in the caption to Figure 2) The varve thickness record shows a 5-year running mean thickness and is reproduced from Ridge and Toll (1999). Varve years are mapped to the GICC05 time scale using the best-fit offset of 20,810* $\pm$ *250 yr derived from the radiocarbon data set of Ridge (2003, 2004, 2010) as described in the text. The apparent relationship between Greenland climate and varve thickness differs over time and between glacial and nonglacial varves. In the glacial varve sequence, warming in Greenland (for example, at the end of the Older Dryas ca. 13,900 years ago) is associated with increased varve thicknesses, presumably because of increased meltwater production as ablation increased with temperature. In the nonglacial varve sequence, however, thicker varves (e.g., between 13,000-13,200 years ago) appear to be associated with cool conditions in Greenland. Our goal in synchronzing these two records more accurately is to better understand the precise time relationship between these events. The lower plot shows centennial variation in* ^{10}*Be flux to the Greenland ice cores during this time period: this is the record we seek to match using* ^{10}*Be measurements in the Newbury varve section.*

II. ICE CORE AND SEDIMENTARY ARCHIVES OF ^{10}Be FLUX

Causes of variability in ^{10}*Be fallout flux.* ^{10}Be is produced in the atmosphere by cosmic-ray bombardment of atomic nuclei, primarily N and O. Being strongly particle-reactive, ^{10}Be adsorbs to atmospheric aerosol particles and is eventually delivered to the Earth's surface either as dry deposition or in precipitation (for reviews of ^{10}Be production, transport, and fate, see Lal and Peters, 1967; Brown, 1987; Beer et al., 1994; and Beer, 2000). ^{10}Be produced and deposited in this way is variously referred to as 'atmospheric,' 'meteoric,' or 'garden-variety,' and is distinguished from so-called 'in-situ-produced' ^{10}Be formed within rock and mineral grains exposed at the Earth's surface. The deposition rate of atmospheric ^{10}Be (on a per-surface-area basis) is several orders of magnitude greater than the rate of in-situ production, so in-situ-produced ^{10}Be is generally a negligible fraction of the ^{10}Be inventory in surface materials. The production rate of ^{10}Be in the atmosphere varies with the intensity of the cosmic-ray flux in the upper atmosphere, which in turn depends on solar activity and changes in the Earth's magnetic field. The residence time of ^{10}Be in the atmosphere is of order 1 year, so production rate changes on timescales longer than 2-3 years are reflected in changes in the ^{10}Be fallout flux to the surface.

^{10}Be flux variations recorded in sedimentary records. Many studies have measured ^{10}Be concentrations at monthly to millenial resolution in sedimentary records including ice cores, lake sediments, and marine sediments. Of these, ice core ^{10}Be records are the most straightforward to interpret because the majority of ^{10}Be found in polar ice is derived from direct deposition of recently produced atmospheric ^{10}Be, and only a minority is derived from recycled dust. Numerous studies of ice cores from Greenland and Antarctica have shown that the ^{10}Be flux to the ice cores (that is, the ^{10}Be concentration divided by the accumulation rate) faithfully records solar variability at multiannual to centennial time scales (Raisbeck and Yiou, 1985; Beer et al., 1994; Beer, 2000). Beer et al. (1994 and references therein) and Steig et al. (1996, 1998) showed that the 11-year Schwabe cycle in solar activity is present in ice core ^{10}Be records from Greenland and Antarctica. At these sites the amplitude of the 11-year cycle is 20-40% of the average ^{10}Be concentration or flux. Solar variability on centennial time scales is also recorded in ice core ^{10}Be records (Beer et al., 1994; Wagner et al., 2001). At longer time scales (i.e. the Holocene and longer), variations in ^{10}Be flux to ice cores record both solar and geomagnetic field variability (e.g., Yiou et al., 1997; Finkel and Nishiizumi, 1997; Vonmoos et al., 2006). Agreement between ^{10}Be fluxes inferred from ice cores and variations in atmospheric radiocarbon concentration reinforces the conclusion that ice core ^{10}Be records in fact record variations in atmospheric cosmogenic nuclide production (Muscheler et al., 2004 and references therein).

^{10}Be concentrations in marine and lacustrine sedimentary records are potentially more complicated to interpret than ice core records because a significant fraction of the ^{10}Be in the sediment may be derived from recycling of already ^{10}Be-enriched sediment, rather than from ^{10}Be fallout at the time of sediment deposition. Regardless, it is well established that ^{10}Be concentrations in deep-sea sediments, once properly normalized to changes in particle scavenging and sediment accumulation rates, record changes in ^{10}Be production due to geomagnetic field intensity variations (Frank, 2000 and references therein). There exist relatively few ^{10}Be records from lake sediments, but they lead to the same conclusion. ^{10}Be concentrations measured at millenial resolution at Lake Baikal (Aldahan et al., 1999) agree with ^{10}Be fallout variations inferred from marine and ice-core ^{10}Be records. Belmaker et al. (2008) considered the more complicated example of the former Lake Lisan in the Dead Sea Rift, where recycled ^{10}Be-enriched dust provides a significant fraction of the ^{10}Be input to the lake. They concluded that one could discern variations in ^{10}Be production in these sediments regardless of this background input. An example that is particularly relevant to this proposal is that of Ljung et al. (2007), who measured ^{10}Be concentrations at $\sim$40-year resolution in a lake sediment sequence spanning the last 650 years from Tristan da Cunha Island (37°S), and showed that they were well correlated with centennial-scale variations in ^{10}Be flux measured in the Greenland ice cores. This example is also important because it lies at a latitude similar to the NAVC: despite a theoretical expectation that fallout rate variability should be greatest at the poles and suppressed at lower latitudes, relative variations in fallout rate at this site are similar to those in ice cores.

To summarize, it is well established from many ice-core studies that ^{10}Be concentrations in ice cores record globally synchronous variations in atmospheric ^{10}Be production. It is likewise clear that ^{10}Be concentrations in at least some marine and lacustrine sediments also record variations in ^{10}Be production. However, first principles as well as measurements (Aldahan et al., 1999; Belmaker et al., 2008) show that ^{10}Be concentrations in sedimentary sections can be significantly affected by recycling of ^{10}Be-enriched sediment. For clarity in the subsequent discussion, we will refer to ^{10}Be that is already adsorbed to detrital sediment at its point of origin, and is carried with that sediment to the depositional site of interest, as 'recycled' ^{10}Be.

We will refer to ^{10}Be that is derived from atmospheric production at or immediately before the time of sediment deposition as 'fallout' ^{10}Be. If variability in the recycled ^{10}Be concentration in sediment supplied to a depositional basin outweighs the fallout ^{10}Be flux, then total ^{10}Be fluxes recorded in sediment will reflect source variability rather than fallout rate variability. In the opposite situation, where the concentration of recycled ^{10}Be in sediment is either relatively low or relatively constant, variations in total ^{10}Be flux to the sediment will reflect changes in ^{10}Be fallout rate and thus production. We will argue in the next section that available evidence indicates that NAVC sediments are likely to fall into this second category.

Correlation of sedimentary records using ^{10}Be flux. The importance of ^{10}Be fallout for the present proposal is that because changes in ^{10}Be production are global in nature, changes in ^{10}Be fallout flux are likewise globally synchronous. Thus one can use ^{10}Be flux variations to align the time scale of two sedimentary records. For example, Yiou et al. (1997) used a prominent ^{10}Be flux peak at 40 ka to synchronize the age models for Greenland and Antarctic ice cores with approximately 100 year precision. Muscheler et al. (2008) matched the ^{10}Be flux record from the Greenland ice cores to record of atmospheric radiocarbon concentration derived from a late-glacial floating tree-ring chronology, thus fixing the absolute age of the tree-ring chronology. Because one must account for the differing atmospheric residence times of ^{14}C and ^{10}Be, this was somewhat more complex than simply comparing two ^{10}Be records. However, this work is important for the present proposal because it relied on centennial-scale variations in ^{10}Be production between 12,500 and 14,000 years BP (see Figures 2 and 4) to synchronize two records at a precision of approximately $\pm$ 40 years. As discussed below, this is the same time period for which we believe the NAVC is most likely to yield a reliable ^{10}Be flux record. This in turn shows that, if we can generate a ^{10}Be flux record from the NAVC with the same or better resolution as the ^{10}Be flux record from the Greenland ice cores, we can expect to synchronize the two records with precision similar to that attained in the Muscheler study. In the next section we will consider whether or not it is possible to derive such a ^{10}Be flux record from the NAVC.

III. DO ^{10}Be CONCENTRATIONS IN NAVC SEDIMENTS RECORD FALLOUT VARIATIONS?

Basic approach. The ^{10}Be concentration in a lake sediment sample is related to the sediment accumulation rate and to the ^{10}Be fallout flux as follows:

$$C_i = C_b + \frac{Q_{0,i} f}{b_i} \quad (1)$$

where C_i is the ^{10}Be concentration in sample i, (atoms g^{-1}), C_b is a background concentration of recycled ^{10}Be in the sediment (atoms g^{-1}), b_i is the sediment accumulation rate (g cm^{-2} yr^{-1}) during the time sample i accumulated, $Q_{0,i}$ is the ^{10}Be fallout flux normalized to unit area (atoms cm^{-2} yr^{-1}) during the time in which sample i accumulated, and f is a focusing factor (nondimensional).

The focusing factor f describes the fact that ^{10}Be deposition occurs throughout the area of the lake and its watershed, but lake sediment is only accumulating in a fraction of that area. Thus, the deposition rate of ^{10}Be in the lake sediment (on a per-area basis) is greater than the average deposition rate in the watershed. This focusing factor depends on the geometry and hydrology of the lake and its watershed; Ljung et al. (2007) estimated $f \simeq 20$, Belmaker et al. (2008) estimated $f \simeq 15$ for Lake Lisan, and the results of Aldahan et al. implied $f \simeq 3$ for Lake Baikal. In the absence of significant changes in the geometry of the lake and watershed, however, f is expected to be constant. Thus, because we are interested in the variability of the fallout flux rather than its absolute value, it is sufficient for our purposes to determine the total fallout flux to the sediment $Q_{0,i}f$.

In this project we will measure the ^{10}Be concentration C_i and seek to reconstruct the time-dependent fallout flux $Q_{0,i}f$ using Equation 1. A significant advantage of working with annually laminated sediments is that varve thickness directly records the sediment accumulation rate b, which leaves the background concentration C_b as the only other unknown.

Varved sediments in the NAVC are derived from two sources of sediment: first, direct subglacial and supraglacial discharge of englacial and subglacial sediment, and second, runoff of previously deposited glacial sediment from the recently deglaciated landscape. Both of these sources, however, are essentially sampling the same thing: englacial and subglacial sediment carried by the Laurentide Ice Sheet. There exists relatively little information about the expected ^{10}Be concentration of sediment carried within and beneath the LIS. Balco (2004) made numerous measurements of the ^{10}Be concentration in unweathered Wisconsinan glacial sediment, also deposited by the Laurentide Ice Sheet, in Minnesota and adjacent states, and found that i) ^{10}Be concentrations were $\sim 1 \times 10^7$ atoms g^{-1}, and ii) ^{10}Be concentrations were quite constant both laterally within a single glacial till and vertically within multiple sedimentary units deposited in the same glacial advance-retreat cycle. This uniformity of ^{10}Be concentrations indicates, in agreement with many lithologic studies (e.g., Goldthwait, 1969), that glacial sedimentary systems are very effective at homogenizing sediment over large areas. Although there is no reason to assume that the ^{10}Be concentration in sediment within the New England sector of the LIS will be the same as that within the Minnesota sector, the conclusion that the ^{10}Be concentration of contemporaneous glacial sediment is geographically homogeneous should hold true in both situations. This is important for the present study because the fact that NAVC sediments are all sourced from recently deposited subglacial and englacial LIS sediment implies that the background concentration C_b is not likely to display short-timescale variability (also see further discussion below). This in turn is important because the assumption of constant Q_b, combined with the fact that we can measure b from varve thicknesses, makes it quite straightforward to estimate fallout fluxes from a time series of ^{10}Be concentrations and varve thicknesses (specifically, by i) a direct inversion of the underdetermined system of equations defined by the measurements and Equation 1, or ii) choosing the value of C_b that minimizes the correlation between b_i and $Q_{0,i}f$).

Potential complicating factors. Although, as discussed above, first-principles arguments and available observations indicate that it should be feasible to reconstruct ^{10}Be fallout variations from NAVC sediments, there are several complicating factors that could make it difficult or impossible. Here we discuss several of these potential complications that we are aware of and argue that available data indicate that they will not present fatal obstacles.

Background concentration might outweigh fallout variability. If the background ^{10}Be concentration in NAVC sediments was very high, even large variations in the fallout rate would result in only small changes to the total ^{10}Be concentration. Because ^{10}Be measurements are subject to some analytical uncertainty, fallout-related variation might become too small to be detectable. Evaluating this possibility requires some knowledge of the background ^{10}Be concentration as well as the total ^{10}Be concentration (which determines the measurement precision) in NAVC sediments. To investigate this, we carried out trial ^{10}Be measurements on one glacial varve

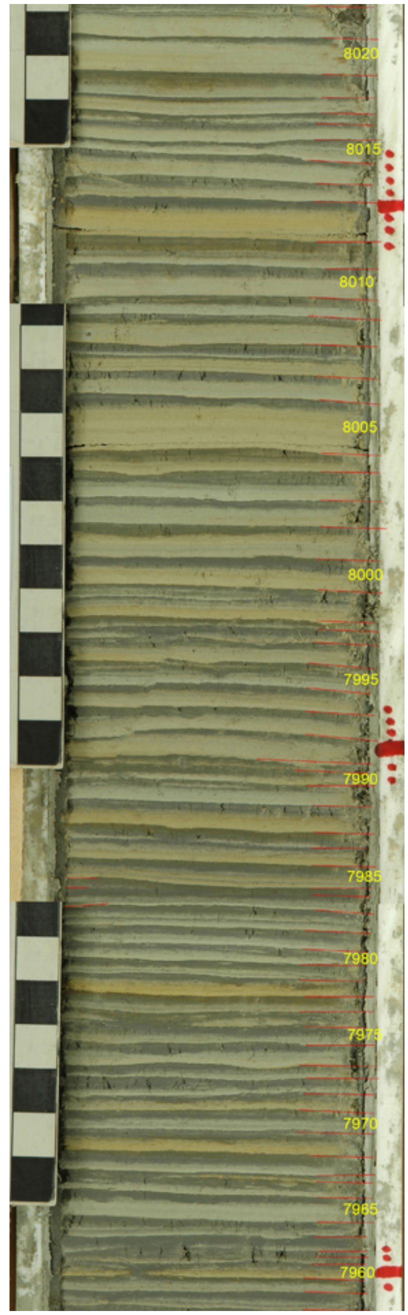

Figure 5: *Nonglacial varves at the Newbury section. The increase in varve thickness beginning approximately at varve 7985 (12,900 years ago with the best-fitting offset) appears to correspond to the beginning of the Younger Dryas cold period.*

and one nonglacial varve (from the Newbury section shown in Figures 4 and 5). These had 5.5×10^7 and 1.1×10^8 atoms g^{-1} ^{10}Be respectively. First, these concentrations permit measurement precision (also see discussion below) of 1-2%. Second, we can use this information to estimate the ^{10}Be balance in NAVC sediments. Assuming an average ^{10}Be concentration of 7.5×10^7, an average fallout flux of 1.5×10^6 atoms cm^{-2} yr^{-1} (Monaghan et al., 1985), $f = 15$ (see discussion above), and an average varve thickness of 0.25 cm (e.g., Figure 4), Equation 1 implies a background ^{10}Be concentration of 3.4×10^7 atoms g^{-1}. Variability in the fallout flux of 30% (Ljung et al., 2007) would then imply variations in total ^{10}Be concentrations of $\sim$15%, well in excess of analytical uncertainty. We then carried out a Monte Carlo simulation in which we simulated expected ^{10}Be concentrations in a sequence of varves assuming a constant background ^{10}Be concentration, centennial-scale periodic variation in fallout rate, random variation in varve thicknesses within the range observed in the Newbury section, random measurement uncertainty, and the estimated parameter values above. We found that we could successfully recover fallout rate variations from the simulated concentrations using Equation (1). We conclude that background ^{10}Be concentrations will most likely be low enough to permit reconstructing fallout variability.

Background concentration might vary on short time scales. As discussed above, it would not be possible to reconstruct variability in ^{10}Be fallout if variability in the background ^{10}Be concentration on the same time scale was also present. Here we argue that this is unlikely. Abrupt variability in background ^{10}Be concentration in lake sediments requires two conditions. First, the lake watershed must include sedimentary reservoirs that display large differences in ^{10}Be concentration. For example, in unglaciated landscapes, sediment derived from river cutbank erosion (which would sample from well below the soil surface where the ^{10}Be concentration is low) and from surface runoff (which would sample from surface soils with relatively high ^{10}Be concentration) would comprise two such reservoirs.

Second, a rapid change in erosional or sediment transport processes, that drastically changes the proportion of sediment derived from each of these reservoirs, is required. We are aware of one such example from the literature: Valette-Silver et al. (1986) observed large and abrupt changes in recycled ^{10}Be flux to Chesapeake Bay sediments at the time of deforestation and the establishment of large-scale agriculture after European colonization (prior to colonization, recycled ^{10}Be flux was nearly constant). Although the second condition could hold for the NAVC (because drainage or lake-level changes could potentially abruptly change sediment sources), the first condition is unlikely to. Because all sediment sources for the NAVC consist of active or recently deposited glacial sediment, the entire landscape would essentially act as a single sedimentary reservoir with, as we have argued above, a well-mixed ^{10}Be concentration. No ^{10}Be-enriched soil reservoirs could be present.

This reasoning leads us to conclude that rapid changes in recycled ^{10}Be concentrations, that might obscure centennial-scale variations in ^{10}Be fallout, are unlikely for NAVC sediments. This does not necessarily mean that the background ^{10}Be concentration will be strictly constant. For example, because a significant proportion of fallout ^{10}Be accumulates in soils, the recently deglaciated landscape will gradually develop a ^{10}Be-enriched soil profile. Thus, we hypothesize that the background ^{10}Be concentration in ice-distal or nonglacial NAVC sediments, whose source is predominantly runoff from the deglaciated landscape rather than direct ice sheet discharge, will gradually increase. We can test this hypothesis with the data we propose to collect, and in any case a gradual and monotonic increase of this sort would not affect our ability to reconstruct centennial-scale variation in ^{10}Be fallout flux.

Unrecognized aspects of ^{10}Be systematics in varved sediments. Although some studies (e.g., Belmaker, 2008) have investigated ^{10}Be systematics in nonglacial varved sediments, we are unaware of any ^{10}Be measurements either on glacial varves or nonglacial varves from recently deglaciated environments. Thus, it is possible that effects such as interruption of ^{10}Be transport to the lake by winter lake ice, variations in ^{10}Be concentration attributable to sedimentary grain-size variations (e.g., Brown et al., 1987), a mixing time of ^{10}Be in the lake watershed that is long enough to suppress high-frequency variability, or other effects that we are not yet aware of, will complicate the interpretation of ^{10}Be concentrations in NAVC sediments. The fact that we will, for the most part, be analysing bulk samples composed of many individual varves (because our ultimate goal is to create a ^{10}Be fallout record with decadal resolution) should serve to mitigate seasonal or grain-size effects. However, as discussed below at more length, our research plan includes measurements designed to learn more about each of these potential complications and better evaluate their importance.

IV. RESEARCH PLAN

This project will proceed as follows. First, we will investigate the systematics of ^{10}Be concentrations in glacial and nonglacial varved sediments from the NAVC, with the goal of determining how best to extract a record of ^{10}Be fallout variations. Second, we will use the information gained in this first part of the project to plan and carry out a sampling and measurement scheme most likely to yield a record of centennial variability in ^{10}Be fallout flux that can be matched to the ^{10}Be flux record from the Greenland ice cores. This section describes these two parts of the project as well as the analytical methods we will use and the division of work among PIs and students.

Measurement of bulk ^{10}Be in NAVC sediments. The specific analytical tasks in this project include locating and obtaining samples of NAVC sediments, subsampling them for ^{10}Be analysis, and measuring ^{10}Be concentrations by accelerator mass spectrometry (AMS). Our primary source of samples will be an extensive archive of cores of NAVC sediments that PI Ridge has collected over many years and that are stored at Tufts University. One important aspect of this part of the project, however, is to ensure that subsamples are not cross-contaminated, or contaminated with modern ^{10}Be, during collection. This requirement may restrict use of archived cores that are highly fractured or otherwise difficult to sample cleanly. If we can not obtain the samples we need from this archive, we will revisit source outcrops and collect new samples, typically by collecting short cores from outcrops using a hammered-PVC-pipe procedure that Ridge has employed for many years. Ridge will have primary responsibility for locating archived and new sample material and correlating it to the NAVC, although students will also be closely involved in this process and all project personnel will participate.

^{10}Be concentrations are measured by an isotope dilution method in which a ^{9}Be carrier is added to the sample, the entire sample is digested and the Be extracted, and the Be isotope ratio is measured by accelerator mass spectrometry (AMS). All aspects of this process are proven, reliable, and efficient. We will carry out Be extraction from sediments in a purpose-built chemistry laboratory at the University of Vermont (see Facilities and Resources), using a total-fusion method described by Stone (1996) and further refined during the past few years by Balco, Bierman, and Bierman's students. This work will be carried out by the graduate and undergraduate students, supervised by Bierman. This method permits analysis of approximately 30 sediment samples in a normal work week. We will carry out AMS measurements at the Center for Accelerator Mass Spectrometry, Lawrence Livermore National Laboratory (LLNL-CAMS). PI Rood will have primary responsibility for AMS measurements. At the ^{10}Be concentrations we expect to measure in this project ($> 10^7$ atoms g^{-1}), AMS measurement is rapid (a few minutes per sample) and precise ($\sim$1-2% analytical uncertainty). High measurement efficiency at this range of ^{10}Be concentrations also reduces the cost of AMS measurement (to $200/sample).

Research focus 1: systematics of ^{10}Be deposition in varved sediments. We will use several strategies in the first part of the project. First, we will investigate how ^{10}Be is delivered to glacial and nonglacial varved sediments. We hypothesize that ^{10}Be deposition is seasonally focused due to effects such as more effective scavenging by fine sediment during winter, suppression of fallout ^{10}Be delivery to the lake during winter due to snow and ice cover, and the strong overall seasonality of sediment transport and deposition. We will investigate this by characterizing ^{10}Be concentrations and their variability within both summer and winter layers to investigate seasonal effects, as well as laterally within a single varve to investigate the effect of sediment source variation between direct glacial sediment and runoff from the landscape. Understanding which, if any, of these processes are important may suggest means to preferentially sample fallout ^{10}Be rather than recycled ^{10}Be. Second, we will determine whether or not short-period solar variability, in particular the diagnostic 11-year Schwabe cycle, is present. As noted in many ice-core studies (Beer et al., 1994; Yiou et al., 1997; Steig et al., 1998), observing the 11-year cycle in a ^{10}Be concentration record clearly shows that ^{10}Be fallout variations are recorded (the reverse is not necessarily true: if we did not observe the 11-year cycle, it could signal only that it was suppressed by a multi-year residence time for fallout ^{10}Be in the lake and catchment, which would not affect recording of centennial-scale variability). Analytical work for this part of the project will require approximately 90 ^{10}Be measurements, including paired summer and winter analyses on a number of glacial and nonglacial sections (approx. 40 analyses) and analyses of at least two short continuous sections at a resolution adequate to observe the 11-year period (e.g., two-year spacing over a 50-year period; 50 samples). Research projects for the two undergraduate students will be drawn from this part of the project, and will be designed to apply a relatively small number of ^{10}Be measurements to address one of the sedimentological questions discussed above.

Research focus 2: generating a long ^{10}Be flux record suitable for correlation. In the second part of the project we will choose a section of the NAVC from which to generate a long ^{10}Be record with resolution appropriate to matching the centennial-scale variations in ^{10}Be flux observed in the Greenland ice cores, and then generate this record. At present, absent any new information we may gain from the first part of the project described above, we think the nonglacial varve section at Newbury is the most likely section of the NAVC to yield such a record, for three reasons. First, varves are relatively thin, which limits dilution of the fallout signal. Second, centennial-scale variations in ^{10}Be flux during this time interval are suitable for correlation at the needed precision, as demonstrated by Muscheler et al. (2008). Third, this section is one of the longest continuous sections in the NAVC, which permits us to generate as long a record as possible from a single site: this avoids any potential complications related to patching together ^{10}Be records from multiple locations within the lake system. The Newbury section includes 1700 varves, so sampling at 15-year resolution would require 113 samples. Thus, the total number of ^{10}Be measurements required in this project, and for which we have budgeted, is 200. The analytical work needed to generate this long record and the subsequent data-reduction and correlation will form the core of the graduate student's work on this project.

Division of responsibility. Although all project personnel will participate to some extent in field work, analytical work, data reduction and interpretation, and student instruction and mentoring, the focus of responsibilities will be as follows. Ridge will have primary responsibility for sample selection and will supervise two undergraduate students at Tufts; Bierman and the M.S. student at the University of Vermont will have primary responsibility for the analytical work; Rood and to a lesser extent Balco will supervise and mentor the graduate student in AMS measurements; and Balco will work with the graduate and undergraduate students to accomplish data reduction and analysis, including inversion of ^{10}Be concentrations to determine fallout flux variations, correlation of varve and ice core records, and uncertainty estimation. All budgets include travel funds sufficient for all PIs to participate in field work and sample collection and all students to participate in all phases of the project.

V. BROADER IMPACTS.

Broader impacts of this project are i) educational, including the direct involvement of undergraduate and graduate students; and ii) scientific, in that the results of this project are likely to provide a platform for future advances in Earth science research.

Our goal for the educational impacts of this proposal is to develop a collaboration between research scientists (Balco and Rood), faculty at research universities (Bierman) and at undergraduate-focused universities (Ridge) that will result in i) the richest possible exposure to Earth science research for the undergraduate and graduate students engaged in this project, and ii) exposure to educational ideas and practice for the PIs who are primarily researchers. This project will continue and expand the research program at Tufts in which 21 undergraduates since 1990 have undertaken research projects on varve stratigraphy or its related paleomagnetism. 15 of those students have continued on to graduate school in geology or are currently applying (9 for M.S., 6 for Ph.D.). Bierman also has a successful record of training graduate and undergraduate students who themselves have been successful in educational careers at all levels. In this project, we will focus on training students in field work, laboratory work, and data analysis in an integrated fashion; Ridge will supervise each undergraduate student through a start to finish research project directed at testing a well constructed hypothesis and yielding a senior thesis.

The potential scientific impact of this proposal is that, if this project is successful, the high-resolution link between Greenland climate and ice-marginal processes of the Laurentide Ice Sheet will provide a platform for glaciologists, climate dynamicists, and paleoclimatologists to develop and test hypotheses about ice sheet-climate interactions during the last deglaciation. Glacial varve chronologies are an extraordinary detailed record of ice-marginal dynamics, climate, and environment, and the NAVC already provides a chronological platform for precise internal correlation of late-glacial events throughout lake systems surrounding the existing core area of the NAVC. As glacial lakes were continually present along the margin of the Laurentide Ice Sheet throughout deglaciation, it is in principle possible to link nearly the entire sedimentary record of deglaciation to the NAVC. Also synchronizing this chronology to the regional and global climate records derived from Greenland ice cores will permit rigorous and quantitative testing of a wide variety of existing and not-yet-formulated hypotheses regarding climate-ice sheet interactions, as well as providing a rich set of observational constraints for model simulations of late-glacial climate and environment.

VI. RELATION TO P2C2 OBJECTIVES

This project addresses P2C2 primary objectives 2 (*How does the geological record inform us about past climate sensitivity and the impact of past abrupt changes in climate under a variety of different boundary conditions, past climate states, or during periods of large and rapid changes in forcing?*) and 3 (*How sensitive was ice to rapid changes in climate?*).

Our focus on a 5700-year, annually resolved record of ice marginal events addresses the overall issue that *"the observational record of ice sheet behavior is both sparse and short relative to the timescales at which ice sheets will adjust to climate change,"* as well as specific P2C2 objectives 3b (*What was the rate of change in sea ice distribution and land ice in the past and what were the dominant controls on the rates of change?*) and 3c (*What were the climatic impacts of ice dynamics, such as melting, during periods of past climatic variability?*).

VII. DATA DISTRIBUTION AND ARCHIVING

The data generated by this project will consist of a large number of measurements of ^{10}Be concentrations in varved sediments, as well as information about the sedimentology and age of the samples. As soon as these data have been generated and subjected to adequate quality control, they will be freely available upon request from the project PIs. Once the data set is complete, it will be placed in a publicly accessible online repository incorporated in the North American Varve Chronology Project website currently maintained by PI Ridge at Tufts University (*http://ase.tufts.edu/geology/varves*). All PIs of this project have a demonstrated record of making data generated in NSF-funded projects publicly accessible, in many cases in advance of formal publication.

VIII. RESULTS FROM PRIOR NSF SUPPORT

Collaborative Research: Detrital cosmochronology of the Greenland Ice Sheet (Bierman, ARC-0713956, 9/15/2007-8/14/2011, $273,052)

PI Bierman's research and students have been supported continuously by NSF since 1993. Bierman and his cosmogenic nuclide laboratory (uvm.edu/cosmolab) have received funding from NSF Hydrologic Sciences, Geomorphology, Geography, Polar Programs, and Arctic Sciences for both research and graduate student research training. Much of the work done in the lab involves the estimation of erosion rates and sediment sources using both in situ and meteoric ^{10}Be as tracers – work directly germane to this project. Together, these grants have supported 24 graduate students at the MS and PhD levels, resulted in $\sim$50 referred publications and $>$100 abstracts, and supported the creation of heavily used geo-education and dissemination web sites.

This most recent related NSF award supported the analysis of material from within the Greenland Ice Sheet in order to determine periods of prior exposure and rates of subglacial erosion. It supported two MS students and the analysis of over 250 samples. Four publications (all student authored) to date include Corbett et al. (in review), Graly et al. (in review), Graly et al. (2010), and Reusser et al. (2010).

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 (Ridge, EAR-0639830, 4/1/2007-3/31-2010, $338,752)

Activities of this award focused on completing, revising, and calibrating Antevs' New England Varve Chronology and relating it to deglaciation, climate, and environment at the southern margin of the Laurentide Ice Sheet. Scientific accomplishments include:

1. A major gap (Claremont Gap) in the NEVC was closed with new overlapping varve sections.
2. Errors in the old chronology were identified from new cores and the varve chronology was reformulated as the NAVC with a new numbering system spanning 5659 years (2700-8358).
3. The NAVC was calibrated to the calendar year time scale with 37 new radiocarbon ages spanning 4700 varve years.
4. As discussed above, glacial events in New England have been dated and compared to records of climate from the north Atlantic region, especially from Greenland ice cores. Features in the varve record and Greenland ice cores strongly resemble each other at the scale of a decade or two, which in part inspires the present proposal.
5. We developed models to relate ice surface profiles and recession rates to varve deposition and thickness changes.
6. We have identified major meltwater flood and lake level change events in the varve records.

Education and outreach accomplishments include completion of research projects by several undergraduate students as well as the creation and development of the North American Glacial Varve Project web site (*http://ase.tufts.edu/geology/varves*). This web site contains extensive data holdings, including varve thickness records for all sections linked to the NAVC, radiocarbon calibration data, and NAVC-NEVC intercomparison data. It also contains extensive educational material, including i) an introduction to glacial varves, varve chronology, and the history of scientific research into them; ii) information about absolute calibration of varve chronologies; iii) background information on the original formulation of the NEVC, Claremont Gap closure, and the NEVC-NAVC relationship; iv) a guide to varve collection, analysis, and correlation; and v) software for this purpose.

Products resulting from this award include two abstracts (Ridge et al., 2009; Stone and Ridge, 2009), four papers (Balco et al., 2009; Knecht et al., 2009; Benner et al., 2009; Benner et al., 2008) and the website described above.

Extending the record of Antarctic landscape evolution into the Pliocene with Ne-21 measurements (Balco and D. Shuster, ANT-0838958, 6/1/2009-5/31/2010, $47,265; Systematic analysis of landscape evolution and surface ages in the southern Transantarctic Mountains (J. Putkonen, Balco, and Shuster, ANT-0838968, 9/01/2009-present, $247,684).

These related projects as well as their predecessor (ANT-0338224 to Putkonen) comprise a research program focused on understanding current and former landscape-forming processes in the Transantarctic Mountains using a combination of geomorphic observations, sediment-transport measurements, and cosmogenic-nuclide measurements. This environment is of interest because, largely due to the lack of free water and geomorphically active biota, landscape-forming processes here are fundamentally different from those elsewhere on Earth. Key findings of this research include:

1. We have quantified both present and geologic-term rates of sediment transport and surface degradation. This shows a striking, and surprising, contrast between relatively active sediment transport processes at the surface and extremely slow rates of long-term landform degradation.

2. The common landscape-forming process of penetrative creep is largely absent here. Geomorphic activity is very much confined to the very surface of landforms.

3. Rates of erosion and sediment transport processes are extremely patchy in this environment, resulting in the close juxtaposition of relatively active surfaces with surfaces that have been stable for millions of years. The overall landscape appearance strongly reflects these extreme contrasts in the rates of erosion and surface modification.

4. Rates of landscape-forming processes were different during the relatively warm climate of the Pliocene: in most cases faster and more active, but in some cases slower. Despite this, however, rates of geomorphic processes remained extremely low relative to other environments.

Publications related to these awards on which Balco is a co-author include Morgan et al., (2010a, 2010b); Balco and Shuster (2009a, 2009b) and Putkonen et al., (2008).