This article was downloaded by: [Frederick Vollmer]
On: 02 July 2013, At: 13:34
Publisher: Taylor & Francis
Informa Ltd Registered in England and Wales Registered Number: 1072954 Registered office: Mortimer House, 37-41 Mortimer Street, London W1T 3JH, UK

GFF

Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/sgff20

ANTEVS: a quantitative varve sequence cross-correlation technique with examples from the Northeastern USA

John A. Rayburn [a] & Frederick W. Vollmer [a]

[a] Department of Geological Science , State University of New York at New Paltz , New Paltz , NY , 12561 , USA E-mail:

Published online: 01 Jul 2013.

To cite this article: GFF (2013): ANTEVS: a quantitative varve sequence cross-correlation technique with examples from the Northeastern USA, GFF, DOI: 10.1080/11035897.2013.801924

To link to this article: http://dx.doi.org/10.1080/11035897.2013.801924

PLEASE SCROLL DOWN FOR ARTICLE

Taylor & Francis makes every effort to ensure the accuracy of all the information (the "Content") contained in the publications on our platform. However, Taylor & Francis, our agents, and our licensors make no representations or warranties whatsoever as to the accuracy, completeness, or suitability for any purpose of the Content. Any opinions and views expressed in this publication are the opinions and views of the authors, and are not the views of or endorsed by Taylor & Francis. The accuracy of the Content should not be relied upon and should be independently verified with primary sources of information. Taylor and Francis shall not be liable for any losses, actions, claims, proceedings, demands, costs, expenses, damages, and other liabilities whatsoever or howsoever caused arising directly or indirectly in connection with, in relation to or arising out of the use of the Content.

This article may be used for research, teaching, and private study purposes. Any substantial or systematic reproduction, redistribution, reselling, loan, sub-licensing, systematic supply, or distribution in any form to anyone is expressly forbidden. Terms & Conditions of access and use can be found at http://www.tandfonline.com/page/terms-and-conditions

GFF 2013,
http://dx.doi.org/10.1080/11035897.2013.801924

ANTEVS: a quantitative varve sequence cross-correlation technique with examples from the Northeastern USA

JOHN A. RAYBURN and FREDERICK W. VOLLMER

Rayburn, J.A. & Vollmer, F.W., 2013: ANTEVS: a quantitative varve sequence cross-correlation technique with examples from the Northeastern USA. *GFF*, Vol. 00 (Pt. 1,), pp. 1–11. © Geologiska Föreningen. doi: http://dx.doi.org/10.1080/11035897.2013.801924.

Abstract: Varve correlation by hand was successfully applied by Ernst Antevs to establish the New England Varve Chronology, which has since been updated to form the North American Varve Chronology (NAVC). Although these methodologies are successful, numerical techniques can assist in finding and evaluating correlations. A quantitative numerical method for varve correlation using time-series Fourier analysis and cross-correlation is proposed and implemented in the computer program ANTEVS (Automatic Numerical Time-series Evaluation of Varve Sequences). The technique is demonstrated by correlating several varve sequences in the northeastern USA. Tests on NAVC data from the Hudson and Connecticut River Valleys show strong positive local and regional cross-correlations, confirming the method's validity. Guidelines for the evaluation of the correlation are determined by cross-testing NAVC sequences, suggesting minimum values for the cross-correlation statistic r, and z-score, a measure of its variation. Field relationships and careful examination of the data graphs and correlograms, however, must accompany numerical analysis. We then apply the method to previously uncorrelated sequences. A Champlain Valley varve sequence at Whallonsburg, NY, is compared with the NAVC, and to another Champlain Valley sequence at Keeseville, NY. No match is found with the NAVC, although none was expected as the sequences are of slightly different ages. A weak correlation is found between the two Champlain Valley sequences. This correlation is not significant and disagrees with the stratigraphic interpretation of the sites. We suggest that an overly strong local sedimentary signal at one of the sites masks the regional signal necessary for positive cross-correlation.

Keywords: varve chronology; Fourier analysis; time-series; glacial; Laurentide; ice retreat.

Department of Geological Science, State University of New York at New Paltz, New Paltz, NY 12561, USA; rayburnj@newpaltz.edu, vollmerf@newpaltz.edu

Manuscript received 29 October 2012. Revised manuscript accepted 30 April 2013.

Introduction

Antevs (1922) introduced North America to the Gerard De Geer method of varve chronology construction. Outcrops were cleaned and smoothed and varve measurements were made from the bottom up and recorded directly on long strips of paper. Field measurements were then transformed into a graphical representation by plotting curves on paper with lines set 5 mm apart. Matching of varve sequences from one location to another was accomplished by sliding one graph along another until a match was observed. Overlapping sequences were merged to build a long chronology. Antevs (1922, 1928) demonstrated this technique very successfully by constructing the New England Varve Chronology (NEVC) from lacustrine outcrops throughout the Connecticut River Valley and surrounding areas.

Originally, the NEVC was constructed as a floating chronology. Not anchored in calendar years, but rather in *varve years*, Antevs arbitrarily assigned his earliest varve from glacial Lake Hitchcock in the Lower Connecticut River Valley (Fig. 1) to New England (NE) varve year 3001. Through the comparison of 21 individual curves, Antevs (1922) created a 4400-year long chronology, although he was concerned about an apparent gap in his record from the area near Claremont, NH. To account for the "Claremont Gap", he arbitrarily added 249 years into his chronology which spanned NE varve years 3001–7400. Continued work in the region allowed Antevs (1928) to extend his chronology from varve years 2700–7750. Antevs' chronology was a powerful tool in the study of regional deglacial history allowing correlations of ice margin position and estimations of ice margin retreat rates in an age before radiocarbon dating.

A resurgence of study on the NEVC by Ridge & Larsen (1990), Rittenour (1999), Ridge (2004) and Balco et al. (2009) among others has refined the NEVC and attempted to make it an absolute chronology by the use of radiocarbon,

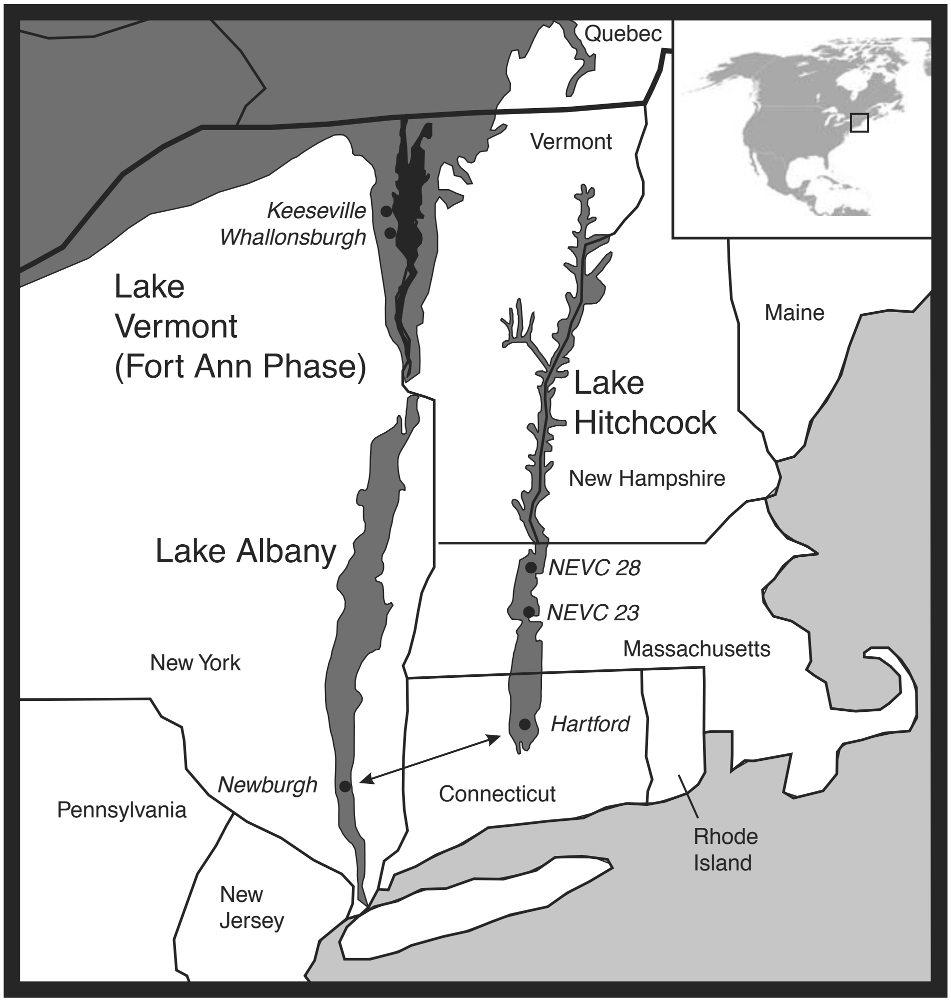

Fig. 1. Location of large proglacial lakes in the northeastern USA (after Ridge et al. 2012). The NE and North American varve chronologies were primarily developed in glacial Lake Hitchcock (Connecticut River Valley). Antevs' (1922) Sites 23 and 28 are 30 km apart and have a suggested overlap of 241 varves in the NAVC. A regionally correlative varve set exists in glacial Lake Albany (Hudson River Valley). Glacial Lake Vermont began in the Champlain Valley and extended into southern Quebec and Ontario (Canada). We begin the LVVC with cores from Whallonsburg and compare it with varves at Keeseville, New York.

paleomagnetic and cosmogenic-nuclide exposure dating techniques. These efforts identified errors in the NEVC, including a significant miscount in the Hudson Valley varve section of glacial Lake Albany (Fig. 1) by Rittenour (1999), and bracketed the age of the chronology between 18 050 and 12 410 calendar years before present (cal. yr. BP) (Balco et al. 2009). The most recent effort (Ridge et al. 2012) closed the Claremont Gap and recalibrated the chronology creating the new North American Varve Chronology (NAVC). This was accomplished through improved sediment coring techniques and digital varve measurement procedures. The NAVC also begins at varve year 2700 but is a continuous 5659-year record, which incorporates a total of 54 radiocarbon dates for age control (Ridge et al. 2012).

Although varves from glacial Lake Albany in the Hudson Valley of New York State have successfully been incorporated into the NAVC, varves from glacial Lake Vermont in the Lake Champlain Valley to the north (Fig. 1) have not (Rayburn 2004). Even positively correlating varve sequences within the Champlain basin has proven difficult (Rayburn 2004). We report here a new attempt through the incorporation of improved coring and digital measurement techniques similar to methods described by Ridge et al. (2012) as well as new quantitative techniques for sequence correlation.

Methods

Cores, counts and measurements

Two long (14.6 and 22.3 m) 6-cm diameter sediment cores were taken at Whallonsburg, NY (Fig. 1) above the bank of the Boquet River in proximity to a bank exposure of varved glacial lacustrine silts and clays. The deeper of the two coring drives refused on what we assume to be glacial till, based on hammer seismic surveys near the core site. The cores were taken in 1.5-m-long connected core tubes using a United States Geological Survey mobile drilling truck. There was a 1-m offset between tube breaks in the two cores so that a complete and uninterrupted varve sequence could be constructed. The cores were split, described, photographed and subsampled for microfossil and geochemical analyses (Rayburn et al. 2011). Varves were counted by hand in the archived half and pins were inserted into the core to mark decadal intervals (Fig. 2). Carefully scaled digital photographs were then taken and varve measurements to the nearest 0.1 cm were made on a computer display adjusted for higher contrast. Care was taken to measure each varve at or near the center of the photograph to avoid measurement error due to photographic parallax.

Comparative varve sequences were obtained from the North American Glacial Varve Project website (http://eos.tufts.edu/varves/; Ridge 2012).

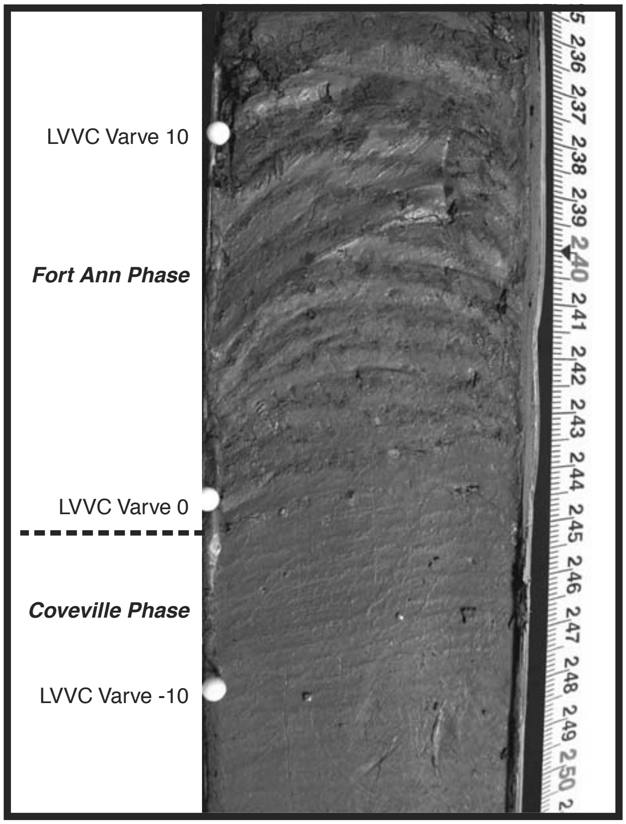

Fig. 2. Whallonsburg core varves at the transition from the Coveville phase to the Fort Ann phase of Lake Vermont. This transition began with a significant flood pulse from the northern end of the lake followed by a rapid lowering of lake level (Rayburn et al. 2005). The initial Fort Ann phase varves are manifested by significant increases in sedimentation rate, ice rafted debris and carbonate concentration (Rayburn et al. 2011). We designate the first Fort Ann phase varve as LVVC 0. Coveville varves are assigned negative numbers relative to varve 0 and Fort Ann varves positive numbers.

Quantitative varve sequence comparison

The inspiration for our quantitative method of varve sequence analysis came from coeval dendrochronology projects in our laboratory, our hypothesis being that the annual growth rings of temperate zone trees are much like varves. These annual rings contain two seasonal variations, early wood and late wood, with relative thicknesses that are often dependent on climatological variation (Fritts 1976). There is a vast literature on tree-ring analysis and well-established procedures for sequence-to-sequence comparison including visual verification, statistical validation and sequence normalization (e.g. Stokes & Smiley 1968; Cook & Kairiukstis 1990; Grissino-Mayer 2001).

Further inspiration for developing a quantitative varve analysis technique came from the realization that many of the considerations of varve sequencing have correlative scenarios in dendrochronology. For example, ice-proximal varves in proglacial lakes tend to be relatively thick due to their formation in proximity to the sediment source, the glacial ice margin. In the absence of other sediment sources, locations increasingly distant from the ice front have increasingly thinner varves. A varve sequence for a set location given a steadily receding ice margin in the local basin may contain a first-order (long-wavelength) nonlinear pattern of varve thinning, and an ice margin locally receding at irregular rates may contain a very complex first-order pattern of varve thinning. To make the varve sequence useful for regional cross-correlation, the effect of changing ice margin proximity in the record could be normalized, leaving only a shorter wavelength signal which should contain elements of higher frequency regional climatic variation. This same issue is present in dendrochronology since a young tree will generally grow thicker rings and an older tree will grow thinner rings, producing a long-frequency "growth curve" that must be normalized for comparative analysis (Stokes & Smiley 1968).

A varve sequence may be missing varves due to insufficient sedimentation, post-depositional deformation or erosion and sampling or counting errors. Conversely, there may be multiple couplets within a single year due to multiple sedimentation events, or warm or cool cycles within the year. Trees may also have missing or "false" multiple rings due to growth conditions, and tree-ring sequences are subject to the same sampling or counting errors as varves (Stokes & Smiley 1968). Given these similarities, we set out to develop a technique for varve sequence analysis using the dendrochronology literature as our guide, but with functionality tailored to lacustrine sedimentation. The result is automatic numerical time-series evaluation of varve sequences (ANTEVS; Vollmer 2013). The ANTEVS program is freely available at http://www.frederickvollmer.com/antevs/.

Automatic numerical time-series evaluation of varve sequences

The ANTEVS program reads and writes data files in various formats, including space, comma and tab-delimited files; however, the preferred format is a simple tab-separated value (TSV, see "Discussion" section) file that can be easily created and edited in a spreadsheet. ANTEVS includes an editing facility to allow entering or changing varve thicknesses, combining adjacent varves into a single varve, splitting existing varves and renumbering sequences.

For analysis, a known chronology file and an unknown varve sequence file are loaded and displayed. The raw data-sets can be graphed for direct comparison; however, long-term trends and variations in average varve thicknesses can make direct comparison difficult. Two procedures are used by ANTEVS to more easily compare the sequences, *detrending* and *normalizing*, before applying a cross-correlation procedure. Detrending removes longer term variations that may differ among data-sets, and normalizing rescales the data to a common range. ANTEVS includes a number of curve-fitting procedures, including linear, exponential and cubic splines, but adopts the default procedure of a low-pass Fourier filter.

Fourier, or harmonic, analysis allows the partitioning of a time-series into constituent components based on wavelength, by converting from a time domain to a frequency domain (e.g. Davis 1986; Press et al. 2007). Long wavelengths can then be removed, and the series transformed back into the time domain, giving the fitted curve as the sum of the remaining wavelengths. The resulting curve is subtracted from the raw data to give the residuals. The residuals have a mean of zero, but are scaled in the original measurement units. Therefore, the residuals are rescaled by normalizing, or standardizing, them by dividing by the standard deviation of errors to give dimensionless numbers.

In Fig. 3, we present an example of varve cross-correlation by this technique using two varve sections about 30 km apart which were described and sequenced by Antevs (1922). NEVC Site 23

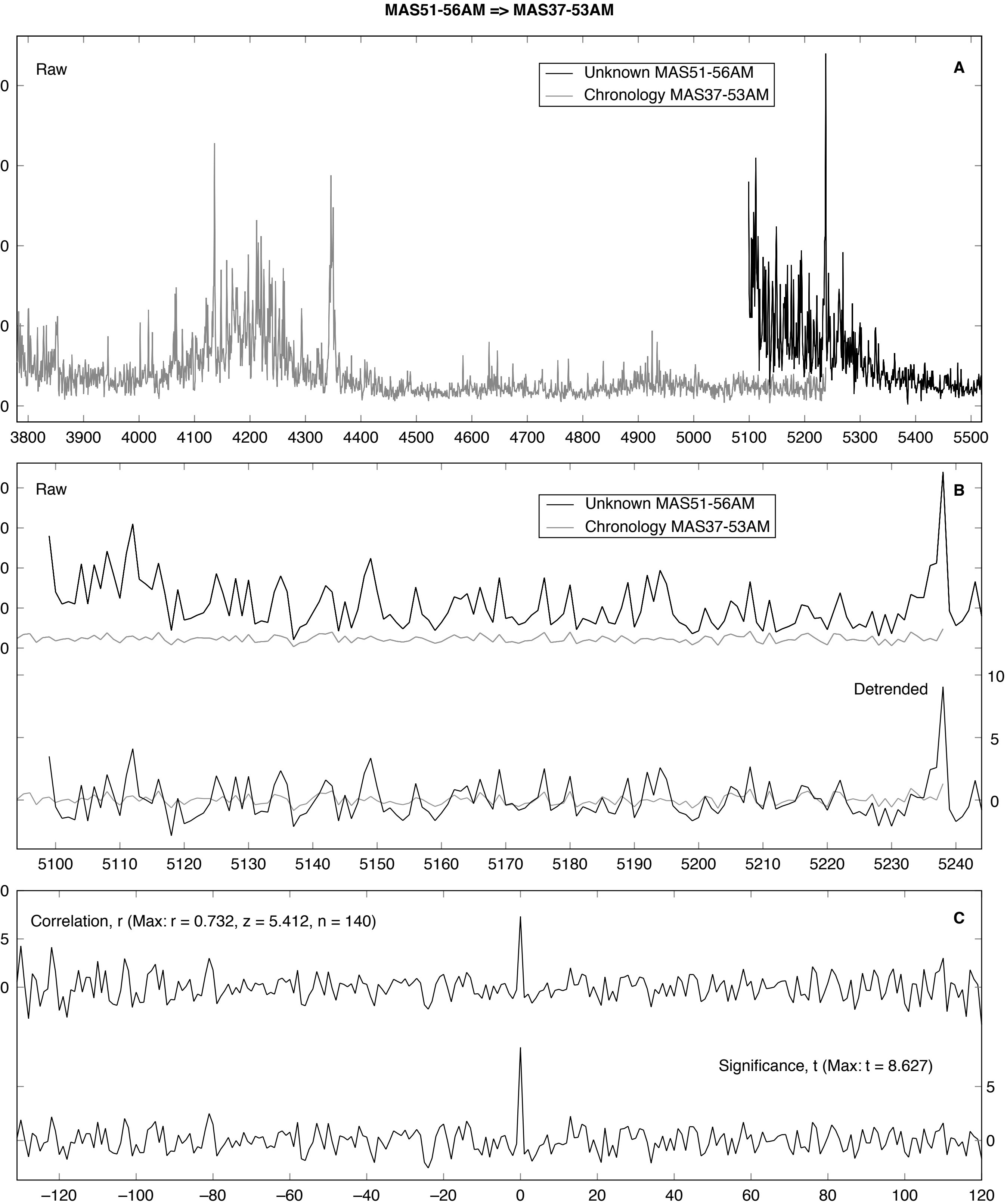

Fig. 3. ANTEVS correlation of NAVC varve data from Antevs' (1922) Sites 23 (MAS51-56AM) and 28 (MAS37-53AM) in the Connecticut River Valley. Data from Ridge (2012). **A**. Raw data with a suggested 141-varve overlap. **B**. Raw data zoomed to overlapping varves before (top) and after (bottom) detrending with a 16-term Fourier curve. **C**. Correlogram suggesting a correlation at 0 varve offset between the two sections with $r = 0.732$ (top) and $t = 8.627$ (bottom).

is in central Massachusetts on the eastern bank of the Connecticut River (Fig. 1). Here, Antevs (1922) measured a section of well-laminated clay varves that spanned NEVC 4845-5510. Although he extended his measurements down more than half a meter below river level, he did not observe the bottom of the sequence at this location (Antevs 1922). Thirty kilometers to the north at NEVC Site 28 (Fig. 1), Antevs (1922) measured a sequence of silty clay and thick sandy varves in a brickyard exposure. Although he again did not see the bottom of the sequence at this location, he interpreted the varve sequence as being deposited nearer the ice margin due to the thick coarse nature of the sediment and varves (Antevs 1922). After plotting the varves as curves, he cross-correlated this sequence to NEVC 5084-5500.

For the first example of our quantitative cross-correlation, we use the NAVC equivalent measurements for these two sections from the North American Glacial Varve Project (Ridge 2012). The NAVC versions add two varves to Antevs' (1922) original sequence resulting in a 241-varve overlap. Fig. 3A shows these two varve sequences plotted as raw data. The relatively thicker varves near the base of Site 28 (MAS51-56AM) become exponentially thinner up-section, probably in response to the receding ice margin. Fig. 3B at the top shows the raw data for the two sections zoomed into the area of overlap. This is similar to the plot that Antevs (1922) published as his "Massachusetts 11" curves and from which he made his cross-correlation. Although a visual cross-correlation is suggested, it becomes much clearer when both sequences are detrended using a 16-term Fourier smoothing function (bottom of Fig. 3B). To assess the cross-correlation quantitatively, we next generate a *correlogram* (e.g. Davis 1986; Press et al. 2007; Fig. 3C).

By default, a minimum overlap of 60 years is required for cross-correlation in the ANTEVS program; however, that value is adjustable. This gives cross-correlation, or Pearson's r values varying from 1 to -1, where 1 is a perfect positive correlation. The correlogram, showing r and significance, t, is plotted to locate potential matches. Fig 3C shows the strongest cross-correlation between Sites 23 and 28 at 0 varve offset between the two sequences with $r = 0.732$ and $t = 8.627$. This suggests that the current assignment of the varve sequence correlation between the two locations is correct.

As a second example of this technique, we use Antevs' (1928) Connecticut River Valley varve sequence (originally deposited in glacial Lake Hitchcock) and Hudson River Valley varve sequence (originally deposited in glacial Lake Albany) to demonstrate cross-correlation varve sequences from the same region, but deposited in separate pro-glacial lakes (Fig. 1). Again, we use the NAVC versions of these sequences (Ridge 2012).

Fig. 4A illustrates the effect of detrending on NAVC sequences from the Hudson River Valley (HUD29-32AM) and Connecticut River Valley (CON28-32AM; Antevs 1928; Ridge 2012). In this example, the Hudson River Valley varves are treated as unknowns to be correlated with the Connecticut River Valley varves. The raw data are shown with the fitted 16-term Fourier function. The raw data are detrended and standardized as described above, and displayed on the lower graph. At this point, the data have had long-term trends removed and have been rescaled to dimensionless numbers with a mean of zero. The low-pass Fourier filter is generally sufficient for the next step of cross-correlation; however, an additional filter may be applied to smooth short time-scale variations, which can enhance correlation. Numerous time-series filters are used for geological data (e.g. Davis 1986), and ANTEVS implements a number of such filters. However, a simple smoothing filter, referred to here as *delta bar*, has been found particularly effective for varve sequences. The delta bar filter subtracts the mean of n adjacent values from the central value, where n is an odd number ≥ 3. The three-term delta bar filter

$$y_i = \frac{y_i(y_{i-1} + y_i + y_{i+1})}{3}$$

has been found to be effective for enhancing correlation in some data-sets, particularly if there are occasional anomalously large or small varves created by local rather than regional events.

Fig. 4B is a correlogram for the Hudson River Valley and Connecticut River Valley data, showing a strong spike at 0 year offset with a maximum $r = 0.643$ and $t = 9.574$. Fig. 4C shows the same data with a three-term delta bar filter applied, with a maximum $r = 0.710$, $t = 10.581$. Note that in this case the z-score, discussed below, has decreased from 6.516 to 5.337, indicating an increase of the variation in r.

Finally, to examine the robustness of the match, a *bin test* can be carried out. The bin test sequentially groups the unknown data into bins, similar to bootstrapping and runs each against the selected chronology displaying the best correlations based on the maximum r value. The offset of each of the sequence matches is graphed along with r and t values. A robust match will have the same sequence match offset for all, or most, of the bins. Fig. 5 shows the bin test for a 16-term Fourier low-pass detrending, without additional filtering. The bins are 100 years wide, with a minimum overlap of 60 years. The offset of 0 for most values indicates a robust match. We have found that running this test with smaller bins is an effective way to isolate missing or false varves in an unknown data series. We use ANTEVS to attempt correlations between the Whallonsburg varve sequence and the NAVC, as well as other varve sequences in the Champlain Valley, but first consider the evaluation of correlations.

Evaluation of correlations

The primary statistic used by ANTEVS for correlating sequences is the correlation coefficient, r, which ranges from 1 for a perfect correlation to -1 for a perfect inverse correlation; a value of 0 indicates no correlation (Davis 1986). Critical correlation coefficients for given probability levels, p, can be determined from r and the overlapping segment length, n (Grissino-Mayer 2001). ANTEVS does a number of calculations to assist in evaluating correlations. A t-statistic and p for each value of r are calculated; these take into account the segment overlap. ANTEVS calculates and graphs a correlogram with r values for each possible segment match and reports the maximum r as the most likely match. A correlogram for a good match has a single strong spike at the maximum r; however, some correlograms have multiple spikes or a high degree of variability. ANTEVS, therefore, calculates the standard deviation for the r values and a z-score, the number of standard deviations from the mean. A high z indicates a strong maximum with low variability, a low z indicates a high degree of variability.

In order to determine guidelines for the evaluation of correlations, the 17 standard NAVC sequences (Ridge 2012) were cross-tested to give 136 tests. Two additional sequences

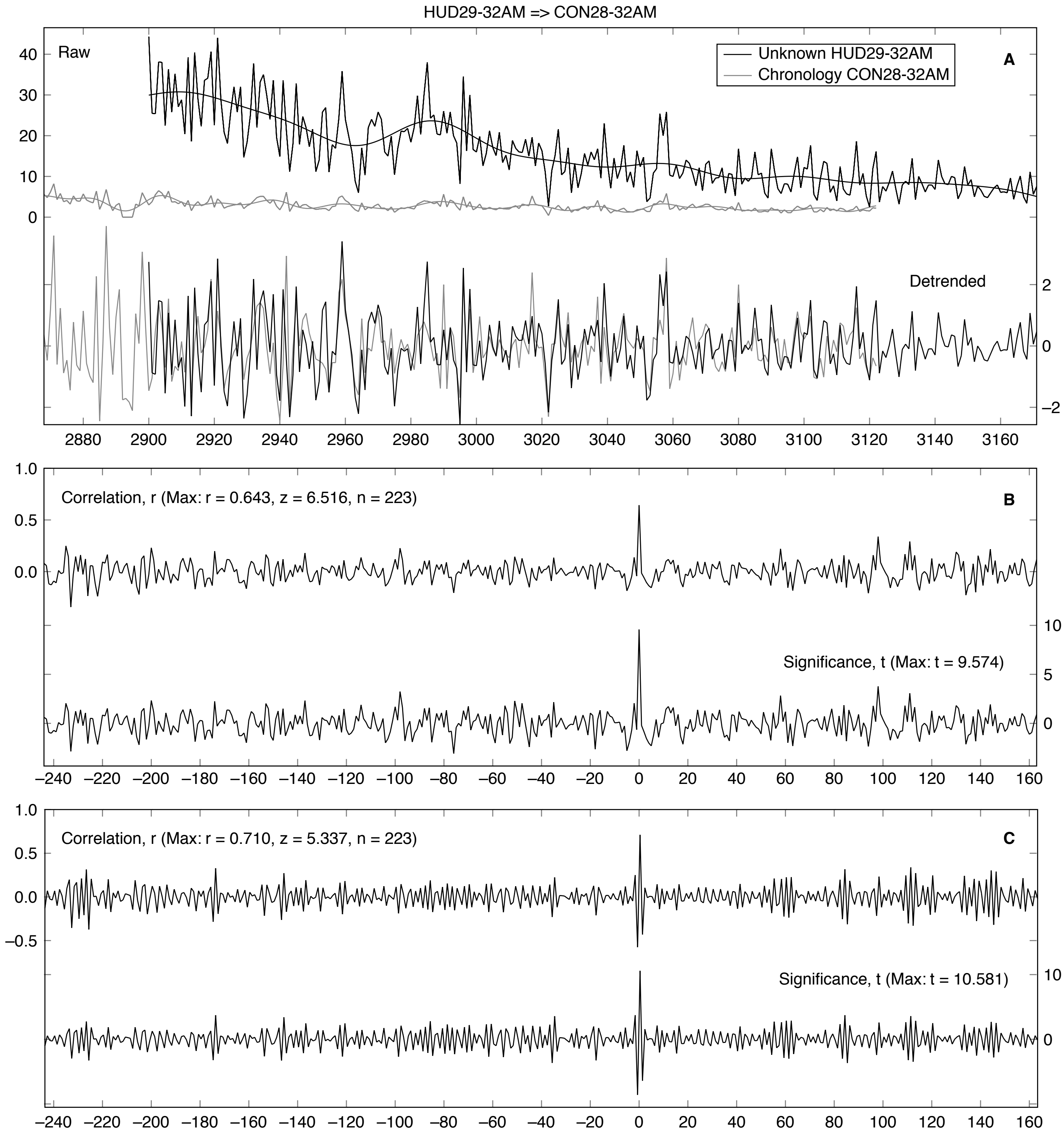

Fig. 4. ANTEVS correlation of NAVC varve data from the Hudson River Valley (HUD29-32AM) with the Connecticut River Valley (CON28-32AM) data (Antevs 1928; Ridge 2012). **A**. Raw data with a fitted 16-term Fourier sequence, and the detrended data normalized with the standard error to give a common scaling with a mean of zero. **B**. Cross-correlation correlogram of detrended data showing a strong match at 0 years offset, $r = 0.643$, $z = 6.516$ and $t = 9.574$. **C**. Correlogram as in **B**, with an additional three-term delta bar filter applied, giving a maximum $r = 0.710$, $z = 0.5337$ and $t = 10.581$.

previously correlated with the NAVC (KF-ABCD09-AM and MER3-AM) were used to give 34 additional tests. The data were detrended and standardized with a 16-term Fourier curve and a minimum offset of 60. The test statistics were sorted, and a cutoff of $r = 0.6$ was found to include the majority (15 of 17) of correct (previously accepted) correlations. A second cutoff was found at $z = 6$, also including the majority (16 of 17) of correct correlations. The tests with $r \geq 0.6$ are reported in Table 1. Evaluation of these shows that correlograms with multiple peaks or low z are likely to give false positives. Note that four of the

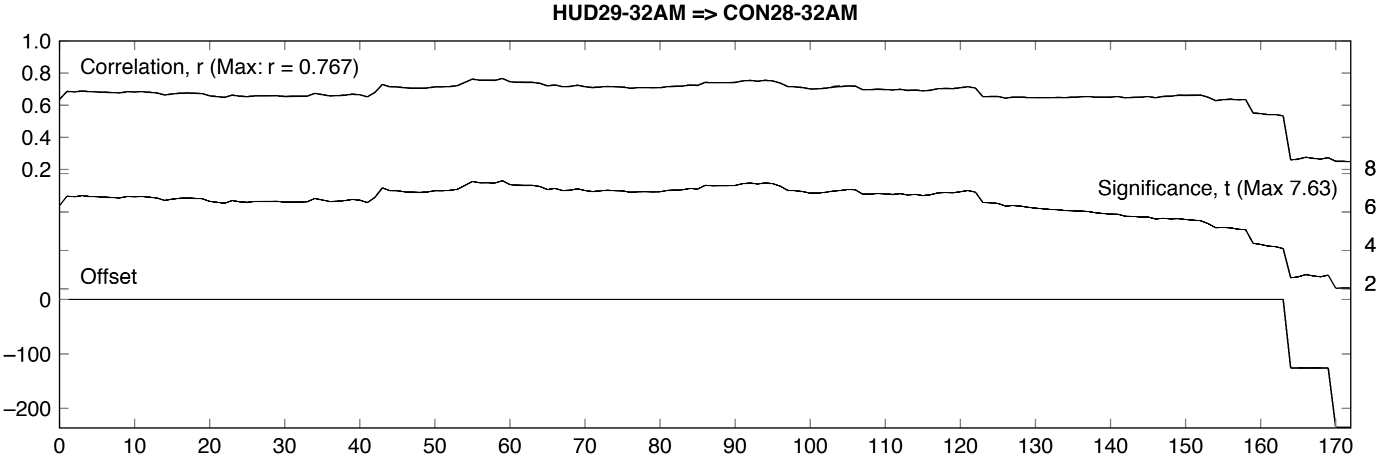

Fig. 5. Example ANTEVS bin test for the Hudson River Valley (HUD29-32AM) to Connecticut River Valley (CON28-32AM) correlation. Bins are 100 years wide with a 60-year minimum required overlap and show a consistent 0 year offset.

seven incorrectly correlated sequences are associated with HUD55-59AM, which contains an extremely thick varve deposited during a local flood event. This event varve was then manually reduced by an order of magnitude, and the tests were run again. The results in Table 2 show that these sequences are now all correctly correlated or rejected. These test calculations are not intended to be an exhaustive analysis, but to provide guidelines and a potential model for future analysis of varve correlation statistics.

Based on the evaluation of the NAVC data series, the following guidelines are suggested for correlating varve sequences. An initial baseline test with 16-term Fourier detrending and a minimum of 60-varve overlap should be done to determine the maximum correlation coefficient, r. Values below $r = 0.6$ are unlikely candidates, although cannot be discounted. Similarly, those with z-scores < 6 are suspect. A correlogram with a single spike with high r and z values is a good candidate for correlation, whereas a correlogram with multiple spikes indicates a potential false positive. Variation of test parameters, including the number of Fourier terms, the minimum offset, and a delta bar filter, can then be used to increase the maximum correlation coefficient. However, the correlogram should be examined for multiple peaks, and any increase in r should not be offset by a decrease in z, as this indicates that the relative r value has decreased.

Local anomalies, such as flood events (as in HUD55-59AM), can effect correlation, as can missing varves. The large number of possible influences on varve thickness makes definitive correlation acceptance criteria difficult to quantify, and ANTEVS does not attempt to supply precise criteria. Rather, ANTEVS provides statistical and graphical tools for the evaluation of sequences, recognizing that the ultimate decision for correlation lies with the researcher, similar to the evaluation of tree-ring cross-dating (Grissino-Mayer 2001).

Table 1. Correlation statistics using NAVC data and two additional sets previously correlated with NAVC (KF-ABCD09-AM and MER3-AM; Ridge 2012), combinations of these gave a total of 170 tests.

	Unknown	Chronology	r	z	n	t	Offset	Notes
1	KF-ABCD09-AM	CON30-39AM	0.927	14.069	588	22.453	0	
2	CON30-39AM	MAS37-53AM	0.846	14.658	105	8.631	0	
3	MER3-AM	MER77-64AM	0.803	8.903	145	9.640	0	
4	KF-ABCD09-AM	MAS37-53AM	0.772	14.053	402	15.457	0	
5	KF-ABCD09-AM	MAS34-37AM	0.764	8.666	177	10.132	0	
6	CON30-39AM	MAS34-37AM	0.752	8.466	177	9.981	0	
7	HUD55-59AM	LCB57-63AM	0.738	9.187	146	8.882	58	1, 4
8	HUD55-59AM	UCA63-75AM	0.735	11.794	296	12.620	1204	1, 3, 4
9	HUD55-59AM	UCC65-68AM	0.732	8.880	215	10.706	988	3, 4
10	HUD55-59AM	LCA54-57AM	0.727	7.883	99	7.202	0	4
11	LCA54-57AM	MAS52-56AM	0.716	6.571	73	6.079	0	
12	MAS37-53AM	MAS51-56AM	0.715	11.041	140	8.433	0	
13	CON28-32AM	CON30-39AM	0.695	8.226	121	7.611	0	
14	HUD55-59AM	ASH58-59AM	0.690	6.413	76	5.974	−136	3, 4
15	CON30-39AM	HUD29-32AM	0.689	9.040	170	8.960	0	
16	LCA54-57AM	MAS51-56AM	0.673	7.202	63	5.300	0	
17	ASH58-59AM	UCA63-75AM	0.667	6.945	76	5.779	862	1, 3
18	MAS51-56AM	MAS52-56AM	0.656	7.304	261	10.572	0	
19	CON28-32AM	HUD29-32AM	0.643	6.516	223	9.574	0	
20	LCB57-63AM	MER57-64AM	0.627	8.124	565	14.882	0	
21	ASH58-59AM	UCC65-68AM	0.615	5.033	76	5.326	852	2, 3
22	UCA63-75AM	UCC65-68AM	0.612	10.848	215	8.951	−216	1

Notes: Cross-correlation was done after detrending with a 16-term Fourier curve, using a minimum overlap of 60. The 22 listed are those with $r \geq 0.6$. An offset of 0 is correctly correlated. (1) Contains multiple correlation peaks. (2) Noisy correlogram indicated by $z < 6$. (3) Not correlated in NAVC. (4) Contains flood event anomaly, see text and Table 2.

Table 2. Correlations from Table 1 using modified HUD55-99AM which contains an anomalous flood event varve.

	Unknown	Chronology	*r*	*z*	*n*	*t*	Offset	Notes
7	HUD55-59AM*	LCB57-63AM	0.731	8.645	88	6.818	0	1
10	HUD55-59AM*	LCA54-57AM	0.722	7.935	99	7.144	0	
14	HUD55-59AM*	ASH58-59AM	0.536	5.002	76	4.642	214	2
9	HUD55-59AM*	UCC65-68AM	0.362	4.413	170	4.709	1066	2
8	HUD55-59AM*	UCA63-75AM	0.323	5.330	89	3.030	598	2

Notes: *Indicates the data set was modified from the NAVC HUD55-59AM by reducing the varve thickness for year 5691 by one order of magnitude, from 225.2 to 22.52. This modification allows HUD55-59AM to correlate correctly by discarding three false correlations and correcting one. (1) Corrected false correlation. (2) Discarded false correlation.

Results

NAVC correlation

Although we believe that we cored the Whallonsburg site to till at 22.3 m depth, the lowest 13.8 m appear as massive clay with occasional large dropstones and other nonlithified ice-rafted debris. Recognizable varves begin at 8.5 m depth and continue up until 6.9 m depth where they get too fine to measure with precision. Above 5.5 m depth the sediments become progressively siltier, and at the top 2 m the sediments are primarily sand. We may not have recognized large ice-proximal varves within the lower massive clay, so our varve measurements for this site may begin a decade or more after the site was deglaciated. The basal Whallonsburg varves should be only slightly younger than a 13 438–13 020 cal. yr. BP (2σ standard deviation) musk-ox vertebra recovered from ice-proximal sediments 10 km to the southwest (Fig. 6; Rayburn et al. 2007). This is in good agreement with radiocarbon age-controlled varve counts in the basin (Rayburn et al. 2011). The sequence of lacustrine and marine sedimentation in the basin begins with the deep-water Coveville phase of Lake Vermont which lasted until the receding ice margin exposed the northern flank of the Adirondack uplands (Rayburn et al. 2005). At that time a low northern threshold at Covey Hill, Quebec, was exposed in the higher level glacial Lake Iroquois west of the Adirondacks, and a catastrophic break-out flood discharged along the ice margin and entered the northern end of Lake Vermont (Rayburn et al. 2005). This event caused a breach of the Coveville level threshold and a subsequent drop to the Fort Ann level (Rayburn et al. 2005). The Fort Ann phase of Lake Vermont was stabilized on a bedrock threshold until ice margin retreat exposed a sea-level drainage route through the Gulf of St Lawrence. This ended glacial Lake Vermont, as marine water entered the basin and initiated the Champlain Sea. Radiocarbon dating of the freshwater–marine transition puts it around 13 124–12 853 cal. yr. BP (2σ standard deviation) (Rayburn et al. 2011).

There are an estimated minimum 216 varves in the Fort Ann phase lacustrine sediments in the Champlain Valley (Rayburn et al. 2011). The Whallonsburg cores contain a minimum of 185 Coveville phase varves beneath 48 coarse varves containing significant ice-rafted debris and high carbonate content (Fig. 2) (Rayburn et al. 2011). These varves are thought to represent the Lake Iroquois breakout flood event and therefore considered the basal Fort Ann phase varves. Above these flood varves are at least 20 significantly thinner Fort Ann phase varves. The top of the Whallonsburg sequence contains shallow marine silts and sands from the Champlain Sea. We have numbered the Whallonsburg varves to represent the lacustrine phase change by assigning the first flood varve to year 0, such that the Coveville phase varves are negatively numbered. We will refer to this as the Lake Vermont Varve Chronology (LVVC). We do this to keep close reference to the initial Fort Ann phase flood varves, since they represent an intra-basinal event and would therefore be unlikely to correlate regionally.

Since the currently estimated span of the NAVC is 18 200–12 500 cal. yr. BP, the Whallonsburg varves are too young to be correlated with any significance. Using the age calibration reported in Ridge et al. (2012), the Whallonsburg sequence would begin sometime in the NAVC range of 7437–7641. That range of the NAVC is represented by paraglacial varves (formed

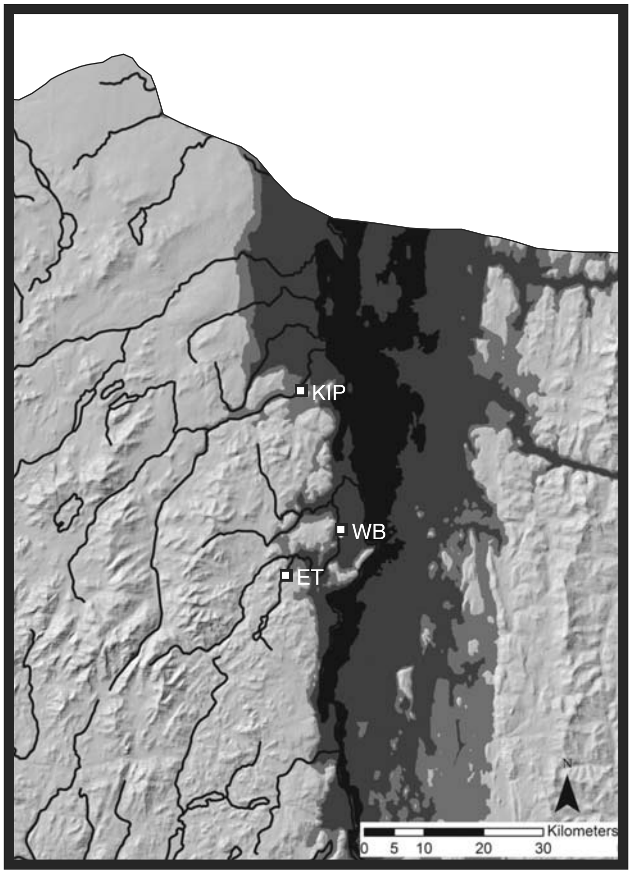

Fig. 6. Geographic Information System (GIS) digital elevation map of glacial Lake Vermont in the Champlain Valley (after Rayburn et al. 2005). The three lake levels shown are Coveville (highest), lower Fort Ann (middle) and modern Lake Champlain (lowest). The ice margin indicated here marks the position of the Laurentide Ice Sheet terminus at the transition from Coveville to Fort Ann phases (during deposition of LVVC 0). The locations of the Whallonsburg core (WB) and Keeseville core (KIP) are indicated, as well as the position of the 13 438–13 020 cal. yr. BP radiocarbon age (ET). Modern hydrography is shown for the New York side of the valley. The Boquet River which exposes the WB site and the Ausable River which exposes the KIP site both head on the eastern slope of the Adirondack High Peaks.

in a lake not in contact with active glacial ice) from Newbury, VT, which Ridge et al. (2012) suggest do not correlate beyond their basin. As expected, we were unable to find a significant correlation between the Whallonsburg and Newbury varves using ANTEVS.

LVVC correlation

The Keeseville Industrial Park (KIP) varve section is a sequence of 67 unpublished Lake Vermont varves cored by Jack Ridge in 1998 (personal communication.). The KIP site is a bluff above the Ausable River about 25 km north of Whallonsburg (Figs. 1 and 6). At this location, the river is deeply incised into a Fort Ann level delta terrace (Franzi et al. 2007). There is a diamicton exposed at the bottom of the section below approximately 2 m of varves. The varves are overlain by deltaic silt, sand and gravel. Since the basal varves at Keeseville formed in the Coveville phase glacial lake, there should be a correlation between the KIP varves and the Whallonsburg varves.

The raw and detrended (using a 16-term Fourier filter) KIP and Whallonsburg (WburgLV) data are shown in Fig. 7A. The KIP data are in local varve years and are not yet correlated. The correlogram for these data (Fig. 7B), although noisy, reveals a best potential match at KIP − 141 years = WburgLV, with $r = 0.468$ and significance $t = 3.801$. These values increase to $r = 0.596$ and $t = 4.844$ when the delta bar filter is applied, although z drops somewhat from 3.860 to 3.511. Fig. 7C shows the raw and detrended data after subtracting the 141-year offset from the KIP data using the renumbering feature in ANTEVS.

Discussion

Data formats

On testing the ANTEVS program, a number of varve data files were obtained from various sources, in a variety of text-based formats. Many of these formats are space delimited or TSVs, but lack column headers to identify the data types. This means that any program reading the data must rely on the assumed ordering of data columns. ANTEVS will read most of these files, but a standard, self-documenting format would make data sharing more reliable.

A simple modification is therefore suggested to standardize varve data file formats as TSV text files with column headers (e.g. "Year < tab > Raw < tab > Comment", for the varve year, thickness and a comment). The column header clearly identifies the data type and additional columns such as "Summer" and "Winter" can be included. This type of file can be read and written by most spreadsheet programs.

Second, it is important for self-documentation that data files contain relevant information such as location, date and researchers. ANTEVS therefore allows comments to be inserted as entire lines, by starting the line with two slashes ("//"). The first lines of a data file can, therefore, be used for documentation of the core or section data. We hope that such a standard format can be adopted by the varve community.

LVVC implications for ice margin retreat rates

A −141 correlation offset of the KIP varves to the LVVC results in an assignment to the time scale that is entirely within the Coveville phase. That generally agrees with the stratigraphic interpretation of the two sites; however, the expected offset was −68 based on the interpretation that the uppermost varve at the KIP site is the last in the Coveville phase (LVVC varve −1). That interpretation only results in $r = 0.161$. The ANTEVS best suggested offset would require a loss of the upper 73 Coveville varves from the KIP site; however, the KIP section appears to be conformable with the bottom set beds of the delta surface above it (Jack Ridge and David Franzi, personal communication.). Although there is some minor uncertainty in the KIP varve count – the possibility that varve 54 is actually two varves (Jack Ridge, personal communication.) – this variation was tested and only resulted in raising the r value for the −68 offset to 0.216, while reducing the r value of the −141 offset to 0.258. Given our standards for significance presented above, we have to reject both cross-correlations. How do we explain the failure of cross-correlation between these two sites in the Champlain Valley while we observe much better results in the prior two examples? A significant source of the problem may come from counting and measurement error. These varve sequences were constructed from only one site each rather than several well-exposed or multiply cored sites like the NEVC/NAVC. Similarly, the most robust dendro-chronologies are constructed from many trees per site (Cook & Kairiukstis 1990).

A second issue may be an overly strong local sedimentary influence drowning out the regional signal in the varve sequences. Although both the Whallonsburg and KIP sites are along bluffs of major rivers draining the Adirondack Mountains today (Fig. 6), during the time of varve deposition the Whallonsburg site would have been well out into the basin and sedimentation should have been primarily from the ice sheet. The KIP site, however, would have been just in front of a prograding delta and would have received a significant contribution of sedimentation from the fluvial source. This would result in very little of the regional signal in the varve sequence, and we should therefore not expect a cross-correlation.

Conclusions

Our results suggest that Antevs (1922, 1928) successfully cross-correlated local and regional varve sequences when he constructed his NEVC; however, there is no significant cross-correlation between the Whallonsburg site and the KIP sites, even though they should contain synchronously deposited varves. Although we believe the Whallonsburg site should be regionally correlative, and thus consider it an anchoring section for our LVVC, the KIP site is too strongly influenced by local sedimentation to include in a regional chronology. We need significantly more varve sequence sites to build a useful chronology in the Champlain Valley, and it would be optimal to look for sites farther south in the basin that would contain earlier varves and eventually allow us to tie in with the NAVC.

Although sampling and measurement techniques have greatly improved since Ernst Antevs compiled the NEVC, varve sequence cross-correlation techniques have remained essentially the same. We find our ANTEVS program to be an effective tool for varve sequence cross-correlation and quantitative evaluation. It has demonstrated and quantified accepted intra-basinal cross-correlation between sites in the Connecticut River Valley (Antevs 1922, Sites 23 and 28) as well as regional inter-basinal cross-correlation between the Lake Albany varve section at Newburgh, NY (HUD29-32AM) and the Lake Hitchcock varve section at Hartford, CT (CON28-32AM). The confirmation of

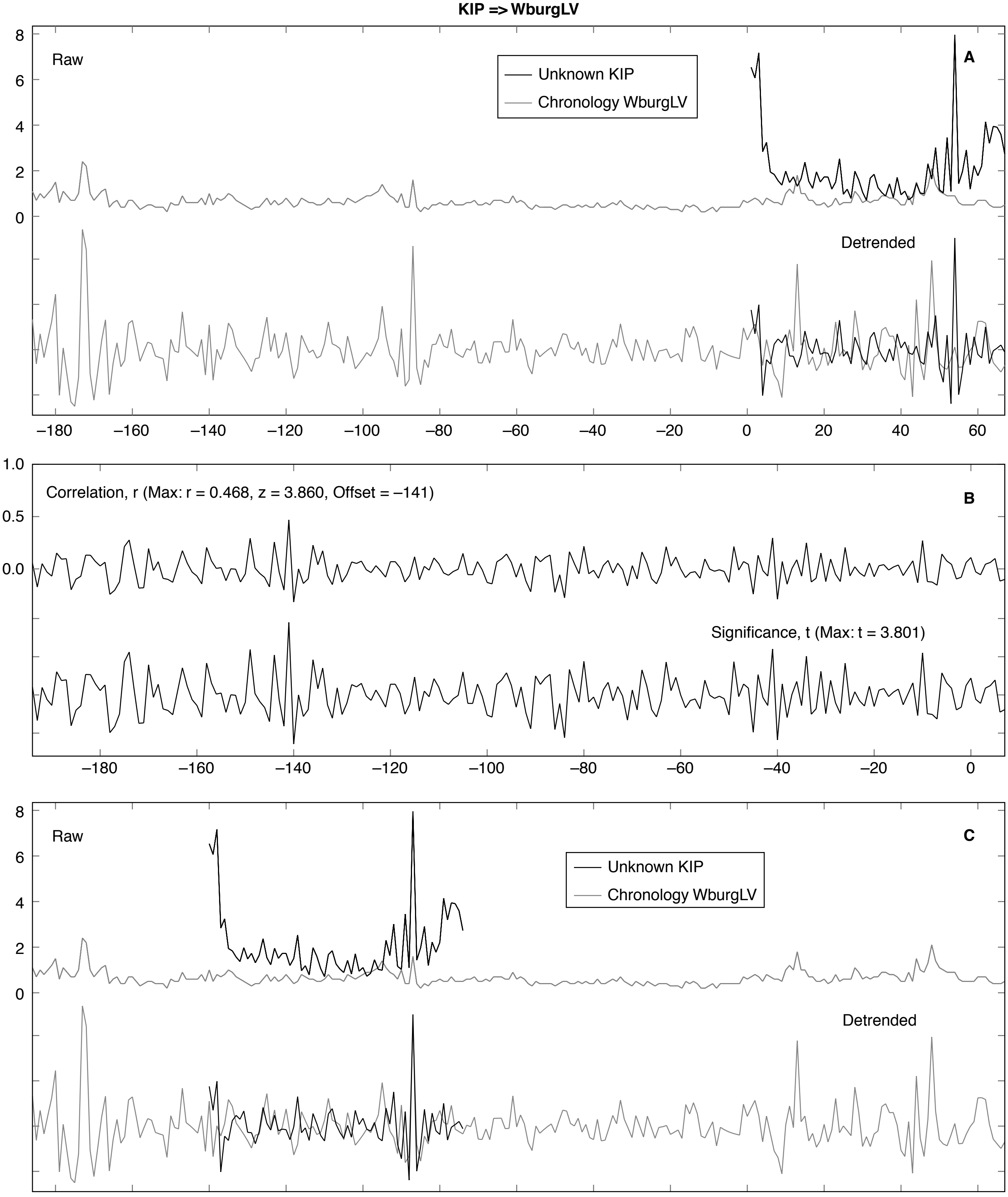

Fig. 7. ANTEVS correlation of KIP and LVVC Whallonsburg (WburgLV) varve data. **A**. Raw data and detrended data with a fitted 16-term Fourier sequence. The KIP data are in local varve years and are not yet correlated. **B**. Correlogram of detrended data showing match at − 141 years offset, $r = 0.468$, and $t = 3.801$. **C**. Raw and detrended data as correlated after subtracting the 141-year offset from the KIP data using the renumbering feature in ANTEVS.

numerous additional correlations among the NAVC sequences is presented in Tables 1 and 2. It is important to recognize that these cross-correlations were initially suggested based on visual inspection of the data plots. We believe that stratigraphic interpretation and visual data inspection are paramount to successful varve cross-correlation, just as it is in dendrochronology (Stokes & Smiley 1968). The ANTEVS program provides an effective way to plot, view and edit varve data while constructing chronologies, as well as evaluating significance of cross-correlation between chronologies. We hope that this program will be useful to other scientists building regional varve sequences.

Acknowledgements. — We would like to acknowledge and thank David Barclay (SUNY Cortland) for discussions on statistical methods of tree-ring analysis. We also thank the SUNY New Paltz students who helped test and improve ANTEVS: Alexis Wright, Christopher Callinan, Aileen Force and Mary Walsh. We especially thank Jack Ridge for his insightful advice and assistance. Thoughtful reviews of this manuscript were provided by Jack Ridge, David Franzi and Andrew Brekenridge. Comments and suggestions from Thomas Lowell are also greatly appreciated.

References

Antevs, E., 1922: The recession of the last ice sheet in New England. *American Geographical Society Research Series 11*. American Geographical Society, New York. 120 pp.

Antevs, E., 1928: The last glaciation, with special reference to the ice sheet in northeastern North America. *American Geographical Society Research Series 17*. American Geographical Society, New York. 292 pp.

Balco, G., Briner, J., Finkel, R.C., Rayburn, J.A., Ridge, J.C. & Schaefer, J.M., 2009: Regional beryllium-10 production rate calibration for late-glacial northeastern North America. *Quaternary Geochronology 4*, 93–107.

Cook, E.R. & Kairiutstis, L.A. (eds.), 1990: *Methods of dendrochronology – applications in the environmental sciences*. Kluwer Academic Publishers, Dordrecht, Netherlands. 394 pp.

Davis, J.C., 1986: *Statistics and data analysis in geology*. 2nd ed. Wiley, New York. 646 pp.

Franzi, D.A., Rayburn, J.A., Knuepfer, P.L.K. & Cronin, T.M., 2007: *Late Quaternary history of northeastern New York and adjacent parts of Vermont and Quebec*. 70th Annual northeast Friends of the Pleistocene Guidebook. Plattsburgh, New York. 70 pp.

Fritts, H.C., 1976: *Tree rings and climate*. Academic Press, London, New York and San Francisco. 567 pp.

Grissino-Mayer, H.D., 2001: Evaluating crossdating accuracy: a manual and tutorial for the computer program COFECHA. *Tree-Ring Research 57*, 205–221.

Press, W.H., Teukolsky, S.A., Vetterling, W.T. & Flannery, B.P., 2007: *Numerical recipes: the art of scientific computing*. 3rd ed. Cambridge University Press, Cambridge. 1235 pp.

Rayburn, J.A., 2004: *Deglaciation of the Champlain Valley New York and Vermont and its possible effects on North Atlantic climate change*, Ph.D. thesis. Binghamton University, Binghamton, NY. 158 pp.

Rayburn, J.A., Cronin, T.M., Franzi, D.A., Knuepfer, P.L.K. & Willard, D.A., 2011: Timing and duration of North American glacial lake discharges and the Younger Dryas climate reversal. *Quaternary Research 75*, 541–551.

Rayburn, J.A., Franzi, D.A. & Knuepfer, P.L.K., 2007: Evidence from the Lake Champlain Valley for a later onset of the Champlain Sea, and implications for late glacial meltwater routing to the North Atlantic. *Palaeogeography, Palaeoclimatology, Palaeoecology 246*, 62–74.

Rayburn, J.A., Knuepfer, P.L.K. & Franzi, D.A., 2005: A series of large late Wisconsianian meltwater floods through the Champlain and Hudson Valleys, New York State, USA. *Quaternary Science Reviews 24*, 2410–2419.

Ridge, J.C., 2004: The Quaternary glaciation of western New England with correlations to surrounding areas. *In* J. Ehlers & P.L. Gibbard (eds.): *Quaternary glaciations – extent and chronology, Part II: North America*, 163–193. Elsevier, Amsterdam. Developments in Quaternary Science 2B.

Ridge, J.C., 2012:, "The North American Glacial Varve Project", sponsored by The National Science Foundation and The Department of Earth and Ocean Sciences at Tufts University, Medford, Massachusetts. http://eos.tufts.edu/varves

Ridge, J.C., Balco, G., Bayless, R.L., Beck, C.C., Carter, L.B., Dean, J.L., Voytek, E.B. & Wei, J.H., 2012: The New North American Varve Chronology: a precise record of southeastern Laurentide ice sheet deglaciation and climate, 18.2–12.5 KYR BP, and correlations with Greenald ice core records. *American Journal of Science 312*, 685–722.

Ridge, J.C. & Larsen, F.D., 1990: Re-evaluation of Antevs' New England varve chronology and new radiocarbon dates of sediments from glacial Lake Hitchcock. *Geological Society of America Bulletin 102*, 889–899.

Rittenour, T.M., 1999: Drainage history of glacial Lake Hitchcock, northeastern USA., M.S. thesis. Department of Geology and Geography, University of Massachusetts, Amherst. 179 pp.

Stokes, M.A. & Smiley, T.L., 1968: *An introduction to tree-ring dating*. University of Chicago Press, Chicago, IL. 73 pp.

Vollmer, F.W., 2013: ANTEVS: automatic numerical time-series evaluation of varve sequences software. Retrieved from: http://www.frederickvollmer.com/antevs