

AN IMPROVED CROSS-CORRELATION TECHNIQUE
FOR CROSS-DATING VARVE
SERIES TAKEN FROM DIFFERENT SEDIMENT CORING
SITES WITHIN A SMALL STUDY AREA

by

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ABSTRACT.

Modern varved sediments (those which display annual laminae) from certain lake and coastal marine environments are natural repositories of climatic and ecological information where the original signal is unusually well preserved as a serial record of the interacting physical, chemical, biological and geological phenomena which control deposition within the environment. The value of these sediments as sources of modern eco-climatic histories (through the past several centuries) depends on the quality of the natural chronology preserved as the annually laminated structure. This natural chronology must first be carefully reconstructed in order that the eco-climatic information be interpreted in its true historical context and that all real signals with periods longer than one year may be observed. The technique described in this paper has been developed to achieve a high level of confidence in cross-dating among individual sample coring sites. This should in turn provide a precise composite varve chronology for areas over which depositional controls are considered reasonably uniform. This technique is an extension of the cross-correlation between two time series. Its purpose is to detect missing or false varves within individual cores in an attempt to establish each as a proper chronographic series.

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RESUMEN.

Sedimentos varvados modernos (aquellos que muestran láminas anuales) de ciertos lagos y medios ambientes costeros marinos son repositorios de información climática y ecológica donde la señal original es bien preservada como un registro seriado de los fenómenos de interacción físicos, químicos, biológicos y geológicos, los cuales controlan la depositación dentro del medio ambiente. El valor de estos sedimentos como fuente de historias modernas eco-climáticas (a través de los últimos siglos) depende en la calidad de la cronología natural preservada como estructura laminar anual. Esta cronología natural deberá primeramente reconstruirse cuidadosamente para que la información eco-climática sea interpretada en su contexto histórico verdadero y permita observar todas las señales reales con períodos más largos que un año. La técnica descrita en este reporte ha sido desarrollada para alcanzar un alto nivel de confianza en el fechamiento-cruz entre los diferentes muestreos de núcleos individuales. En su oportunidad esto proveerá una cronología de varves precisa, compuesta del conjunto de las muestras, para áreas donde el control deposicional está razonablemente considerado uniforme. Esta técnica es una extensión de correlación-cruz entre dos series de tiempo. El propósito es el detectar varves falsos o ausentes dentro de núcleos individuales en un atentado para establecer cada uno como una serie cronográfica correcta.

INTRODUCTION

This paper contains the results of efforts undertaken to achieve a numerical methodology for the cross-dating of laminae preserved in anaerobic sediments on the continental slopes of the Gulf of California. Each pair of sequentially contrasting (light vs. dark) laminae formed there represents a single year of deposition and thus can be called a varve (Calvert, 1966).

This work is part of an investigation of the bio-sedimentological response to "short period" (interannual to decadal) climatic variations which have affected the Gulf of California and northwestern Mexico during the past two centuries. The larger problem requires that a record of the precise chronological order of varve characteristics be initially developed for a geographically limited area of study. The area should be small enough so

that sedimentation throughout may be considered reasonably representative of a uniform response to a given set of climatic variables. A chronological record must be derived from enough samples within the study area to suppress the contribution of variation to the data from sources other than climate fluctuations which are the principal interest of this study. Thus the characteristics of varves from equivalent years are averaged across an appropriate number of sample sites (for a description of equipment and procedures employed in obtaining samples, see Bruland, 1974, p. 19-22). This "average varve chronology" provides an areal chronographic index which can be used as the time framework for the serial analysis of annual data retrieved from the sediments.

The sum of all steps taken to ensure that indeed only the characteristics of equivalent varves (those found at different sites but formed during the same year) are averaged is called cross-dating. Most of the effort towards developing adequate schemes of cross-dating has been put forth by workers in dendrochronology. Fritts (1976, p.20 and 1971 p.249) describes what he calls the "principle of cross-dating" which he maintains is the "most unique and important principle for tree ring analysis". We suggest that cross dating will achieve similar status in the study of modern varved sediments whenever sampling techniques routinely permit the retrieval of varved sediment cores which are amenable to this analysis.

The methodology of cross-dating given here is developed by way of "ideal" examples to facilitate the presentation. No real examples of cross-dating among different cores are shown, although the method has been tested on three box cores of varved sediments from the Santa Barbara Basin off California and found to yield substantially improved results over visual cross-dating. During the summer of 1978, we hope to retrieve between four and six well preserved varved cores from the continental slope near Guaymas, Sonora. The results obtained from the cross-dating of these samples will be reported in a later paper devoted to the establishment of an areal varve chronology for that study area.

DESCRIPTION OF VARVE CHRONOLOGIES AND SOURCES OF ERROR IN CROSS-DATING.

Readers who are not familiar with the characteristics and origins of varved sediments are referred to earlier papers by Anderson (1961), Calvert (1966), Soutar and Crill (1977) and references therein. Figure 1 exhibits the obvious

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structural and stratigraphic characteristics of a box core taken from the Guaymas Slope in the Gulf of California. To the right in this figure is a template drawn from the X-radiograph of a 1.5 cm thick slab cut from the box core. The radiograph displays regular interlayered dark and light laminations from the top to beyond 3/4 of the total core length. Each pair of light and dark laminae was counted as a total varve and traced onto the template. No attempt was made to resolve the varves beyond number 145 due to an apparent structural disturbance which causes the varves to pinch out across the core in the subjacent area, and because of the diminished clarity of the varves in the lower 1/4 of the core. The bars of the histogram to the left of the template represent the areas of each total varve measured by planimetry. No corrections were made to the areas for variation down-core in water and salt content. Below varve number 4 this does not appear to significantly affect the relative differences among the measured varve areas. Analyses of % dry weight for this core by Bruland (1974) show that between 2.4 cm and 23.4 cm the % dry weight only varies between 12.0 and 15.4. Area then is an obvious characteristic of the varve unit which can be easily measured and should be sensitive to climatic fluctuations as well (Soutar and Crill, 1977). Thus an individual varve chronology is usually constructed from serially indexed values of thickness or in this instance, area which may be considered equivalent to unit volume. In this sense a chronographic unit may be defined as the volume of sediment deposited per unit area during a single year.

Before describing the method by which the quality of an individual varve chronology is to be determined, it will be helpful to identify the factors which may result in error to the chronological indexing of varve sequences. In the simplest terms a chronological discrepancy or mismatch between two core site chronologies must be due to either the occurrence of a false varve (i.e. one too many in a sequence) or a missing varve in one or both of the two varve sequences. This is of course analagous to the problem of missing and false rings which cross-dating must detect in dendrochronological analyses. One possible way to generate such a discrepancy between varve records is by simple misinterpretation of the data. The raw varve record consists of a varve template heretofore prepared by visually tracing the varved structure from an X-radiograph of a core slab. This step in the preparation of the chronology is subject to human biases, the quality of resolution of the radiograph, and the level of preservation of the original structures in the core slab. (This is a step from which at least human

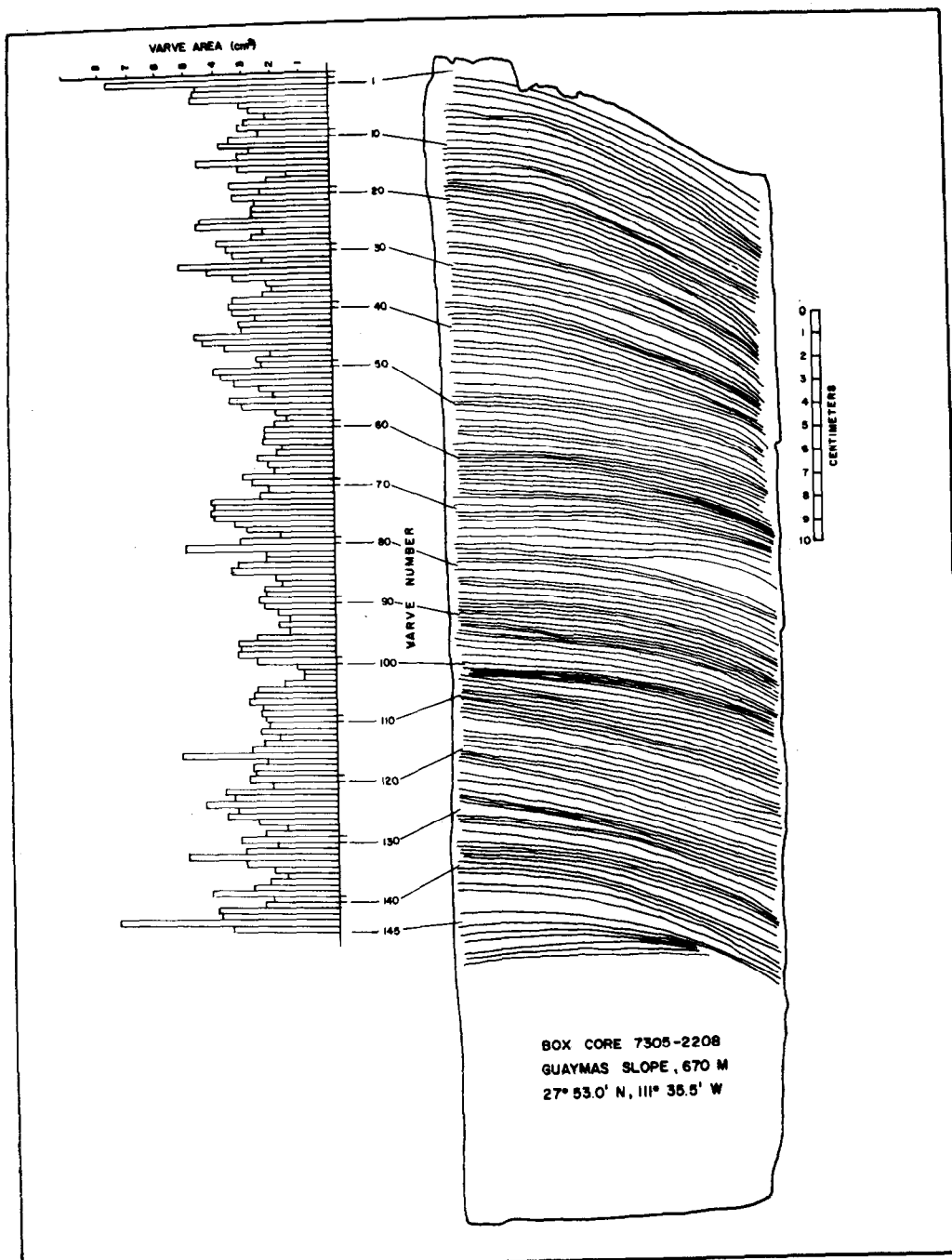


Figure 1. At right, template of varve structure drawn from x-radiograph of 1.5 cm thick slab of a box core taken from Guaymas Slope in Gulf of California. Each layer represents a total varve, or one year of deposition. At left, histogram of varve areas.

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bias may be removed by scanning the radiograph with an optical densitometer now under development by Soutar and Crill (oral communication)). It is probably safe to assume that many or perhaps all of the errors result from this step in the procedure. A more fundamental way to create discrepancies in the chronologies however may be the result of natural processes. That is for a year of extremely low river discharge and terrigenous influx it is easy to imagine that at some or perhaps all of the core sites no varve is produced. Conversely there may occur on occasion more than one pulse of terrigenous sediments during a single year. The latter possibility for the study area selected in the Gulf of California is supported by the occurrence of severe winter storms over Sonora during the years 1931 and 1949 which produced river flooding. Presumably an influx of terrigenous detritus could have reached the continental slope sandwiched between the normal summer-fall periods of river discharge and create an additional lamina which if it occurs in the middle of the production of a contrasting light lamina would result in a false varve. If all varve sequences throughout the study area exhibit the same missing or false varve there is obviously no way to detect the absolute error by cross-dating among sites. Then the chronological indexing of the averaged varve record would be in error by some percentage corresponding to the number of missing or false varves which had escaped detection. In order to detect such an event which affects all core sites the average chronology can be cross-dated and matched with available historical records of river discharge as well as other climatic variables. Therefore the one remaining problem is the detection of natural false and missing varves which encompass the entire study area and lie in the past beyond the period of historical records. Comparison of the averaged chronology to the period of observed climatic records will indicate the frequency of such events if they are present, and hopefully will provide a guide for their identification in the earlier portion of the varve record.

METHOD OF CROSS-DATING BETWEEN CHRONOGRAPHIC RECORDS,

The technique for cross-dating among varve series described here is an extension of the normal cross-correlation procedure for two different time series which is described in Davis (1973, p.239). This method has been developed to overcome the lack of information provided by the normal procedure. The shortcomings of cross-correlation as applied to most stratigraphic sequences is well summarized by Davis as follows:

"In a time series, the interval between successive observations is assumed to be constant through the sequence. This means we must assume that the spacing between observations is the same in two different series if we are to compare them. These assumptions are seriously violated in typical stratigraphic sequences. Almost inevitably, one section is 'stretched' with respect to the other, and often parts of one section are stretched and other parts are compressed. Because of this, it is impossible to move all equivalent parts of two series into correspondence at the same lag. Rather than peaks of high correlation, the correlogram will show broad regions of weak positive correlation."

Varve series are stratigraphic sequences which because of their regularity, do the least violence of stratigraphic data to the assumptions of time series analysis. The method developed here uses the same calculation techniques as ordinary cross-correlation but is designed to identify the portion of a series which is stretched (occurrence of a false varve) or compressed (occurrence of a missing varve). Rather than compare the entire length of both series which renders the method helpless to align all equivalent portions of the sequences if one or both series are stretched or compressed, the series are simply divided into short sequences which are more likely to be equivalent over their reduced length. This is accomplished by a sliding "correlation window" which compares the two series over a much shorter length than their total. First of all the two total series are made to be the same length. The correlation window is then centered at each position down the entire length of both series, and for each position correlation coefficients are calculated for a specified number of shifts of the sequences which fall within the window. The value of using a sliding correlation window was recognized by Wendland (1975) in a similar effort. However, he only calculated a single correlation coefficient for each position of the window and thus did not use the full potential of cross-correlation. It will be shown that combination of the techniques described by Wendland (1975) and Davis (1973, for cross-correlation) provides a greatly improved method for detection of imperfections in the chronological indexing of varve and tree-ring records.

Let us ignore for the moment the total series length and consider what is happening within the window. Here we proceed as in any cross-correlation. The two series consist of a set of data points $\{(x_i, y_i), i=1, 2, \dots, n\}$ which are compared at successive "lagged" positions. That is while one series remains situated the other series is moved passed it

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first in one direction then in the opposite direction. This is called "lagging" the moving series. Positive and negative senses are assigned to each lag direction. For each lag position a correlation coefficient is computed. The 0 lag is the non-shifted position. This is easily seen graphically. If the window contains 7 positions then at 0 lag the two series are positioned as:

X₁ X₂ X₃ X₄ X₅ X₆ X₇

Y₁ Y₂ Y₃ Y₄ Y₅ Y₆ Y₇

If y_i is chosen as the lagged series then at +2 lag the series are positioned thusly:

X₁ X₂ X₃ X₄ X₅ X₆ X₇.

Y₁ Y₂ Y₃ Y₄ Y₅ Y₆ Y₇

At -1 lag the series are:

X₁ X₂ X₃ X₄ X₅ X₆ X₇

Y₁ Y₂ Y₃ Y₄ Y₅ Y₆ Y₇

The correlation coefficients computed for each lag position of course only consider the overlapped portions of the two series, e.g. x₂ through x₇ and y₁ through y₆ at -1 lag. The cross-correlation for a lag position is:

$$\text{LAGR}(\tau) = \frac{N \sum X_i Y_{i+\tau} - \sum X_i \sum Y_{i+\tau}}{\sqrt{[N \sum X_i^2 - (\sum X_i)^2] [N \sum Y_{i+\tau}^2 - (\sum Y_{i+\tau})^2]}}$$

where N is the number of overlapped positions and (x_i, y_{i+τ}) are the matched pairs between the two sequences and τ is the lag position. The results may be displayed in the form of a correlogram shown in figure 2. In this correlogram the highest correlation and the best match position is at 0 lag. Here LAGR=0.75, and the other correlations fall off rapidly to either side of 0 lag. This indicates "equivalency" of the two time series at this best match position of 0 lag.

Now let us return to the full length of the time series to see how the method of the sliding window, or the "incremented cross-correlation" as we shall call it, works. For reference the lagged series will always be the second series as found in the parentheses (A₁, A₂), and the convention of positive and negative lags agrees with the description above. The parameter of window length is

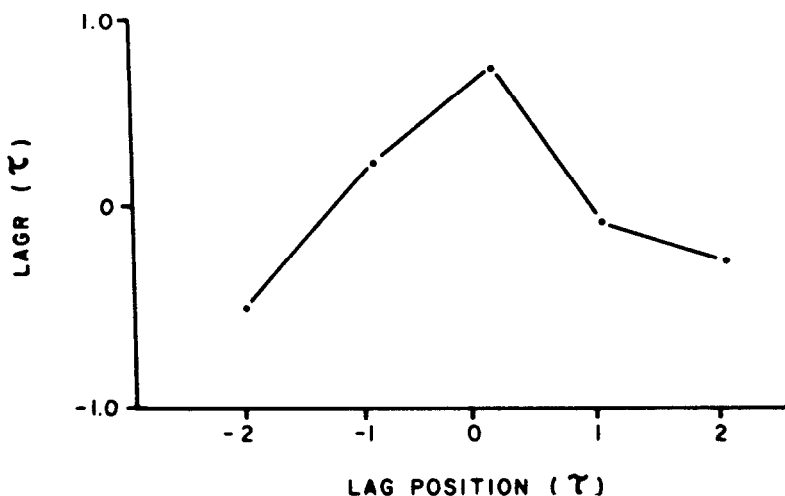


Figure 2. Example of hypothetical correlogram produced by cross-correlation explained in text.

designated IWIND, and the number of positive and /or negative lags is ILAG. To implement the method, IWIND which must be an odd number, is centered over each possible successive position along the two series in order to compare just those matched pairs of the total series which now lie within the window. Note that the central positions of IWIND do not extend to either end of the paired time series. The incremented cross-correlations are begun at $n = \{(IWIND-1)/2\} + 1$ and end at $n = N - \{(IWIND-1)/2\}$ where n is the common position between the two series, and N is the final position of the two series. This assures that the window always contains the same number of positions; that it does not run off either edge of the series. So the window is successively centered over a total of $N - (IWIND - 1)$ positions, and a correlogram is computed and plotted for each of these positions.

As the simplest example consider the incremented cross-correlation of two identical time series: (A,A) where IWIND=15 and ILAG=3. Series A is an actual varved core from the Santa Barbara Basin off Southern California. The serial observations are measured varve thicknesses adjusted to 60% water content. The results are displayed in Figure 3.

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The "raw data" plot consists of two identical curves of varve thicknesses for series A for which the incremented cross-correlations are computed and displayed in the two plots below. Note that the vertical axis of varve thickness corresponds to the upper-most of the two series A curves within the raw data plot. The middle plot in this figure is a series of incremented correlograms, each one corresponding to a successive position along the two series. The lag position axes are vertical here with the positive sense directed upwards. The successive LAGR axes are overlapped in the horizontal direction. The single LAGR axis present on the figure corresponds to the top correlogram in the series. The successive down-series positions at which the window is centered, are printed at regular intervals just below the correlograms beginning with varve number 8 and ending with 92. At the upper edge of this plot each trace is identified by again printing the central position of the window. The lower plot displays the same information in different graphical form in order to assist in the interpretations. Here each value of the correlation coefficient LAGR is plotted on a vertical axis at each central position of the window. This plot is called "Ranked LAGR". The LAGR for each lagged position is designated by an inverted numeral for the positive lags, and an upright numeral for negative lags; 0 identifies the plotted value of the 0 lag. It is immediately obvious from these two plots that because of its redundancy, this method of incremented cross-correlation supplies many times the amount of information as one simple cross-correlation over the entire length of two series. But what does it mean?

First of all we note that the maximum LAGR (designated $LAGR_{max}$) remains at 0 lag throughout the entire series, and that $LAGR_{max}$ at 0=1 at every position. This never changes since we are comparing two identical series. Another constant factor in this comparison shown by both plots is that the correlations are symmetrical around 0 lag. That is at each position, the value of each positive lag is equal to that of the corresponding negative lag, i.e. we have performed a series of autocorrelations. A striking variability however is shown by the undulations down-series of these auto-correlations which is best observed on the lower plot. These undulations of LAGR reveal the statistical structure of the two series. They are chiefly due to the size of the variances of the series whose product is found in the denominator of the LAGR formula. A good illustration is the high autocorrelations which peak at position 26. The window

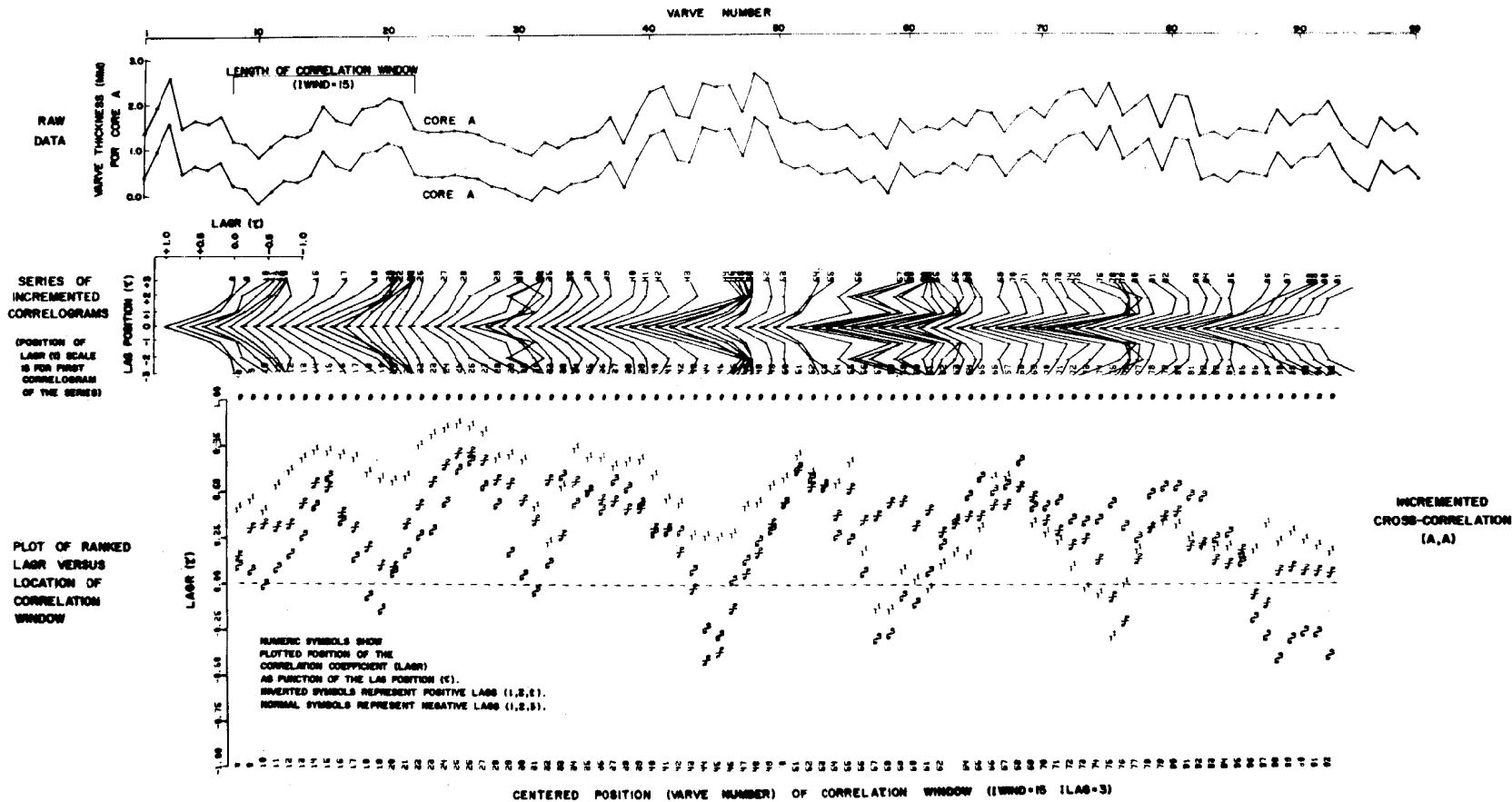


Figure 3. Results of incremented cross-correlations for two identical series of varve thicknesses. Explanation of plots in text.

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here is centered over the smoothest and flattest portion of the series. In this region of the duplicate series LAGR at ± 1 reaches approximately 0.8 and LAGR at ± 3 is near 0.7. These are extremely high autocorrelations and are due simply to the changing structure of the time series. It is worth mentioning here that this is a potential problem in the interpretations when applied to real data series. It would be much better if the variance of the series remained stable through all over-lapping positions of IWIND. This autocorrelation effect could interfere with the principal information which we are seeking, therefore it must be recognized and taken into account. In the future we are planning to design weights for the correlation coefficients within the window which will help cope with this problem.

Now let us consider an example which illustrates the value of this method for locating chronological error due to discrepancies in the spacing of observations between two time series. We will use the same two identical series, but in one we will introduce some hypothetically erroneous observations. Again IWIND=15 and ILAG=3. The incremented cross-correlations are to be performed on the series (A_1, A_2) where A_2 has been altered so that: 1) a false varve is inserted between positions 21 and 22; 2) varve 34 is missing; 3) varve 59 is missing; and 4) a false varve is inserted between 76 and 77. The results of the incremented cross-correlations along with the plot of the series A_1 and A_2 are shown in figure 4. The effects of the discrepancies are quite obvious. Starting from the top of the series and proceeding through $n=14$, the window perceives no discrepancies, and $LAGR_{max}$ persists at 0 lag and is equal to 1.0. However as soon as the first discrepancy (which lies at varve 22 and beyond) falls within the window, the value of $LAGR_{max}$ is lowered and LAGR at + 1 lag is raised. Here the discrepancy begins to inhibit the correlation within the window, and as the window passes over $n=22$ the best match position for the two series changes from $LAGR_{max}$ at 0 lag to $LAGR_{max}$ at + 1. By position 25, $LAGR_{max}$ has completed its shift to + 1 lag. The location of this discrepancy is easy to find by noting at what position the window initially moved over the mismatched observations. This occurred at $n=15$. Therefore the discrepancy must lie at: $15 + \{(IWIND-1)/2\} = 22$. The exact location of the next discrepancy requires a somewhat more subtle search. If we used the same criterion as just given, we might say that the discrepancy occurred at $30 + \{(IWIND-1)/2\} = 37$, but we know that it is at 34 because we put it there. Why is there this apparent inconsistency? It seems to result from the proximity of the two errors; they lie a distance

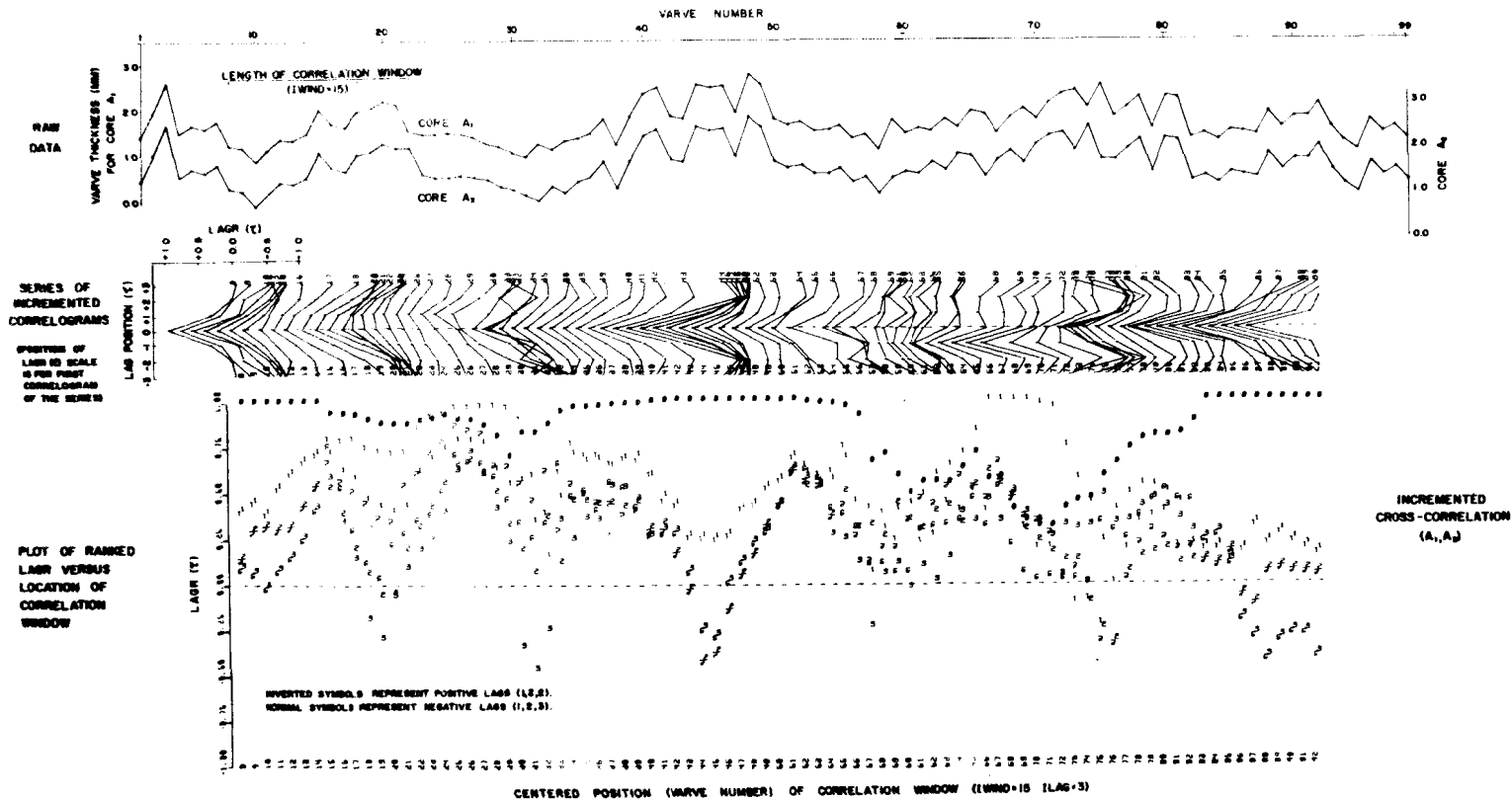


Figure 4. Results of incremented cross-correlation for series A_1 and series A_2 . Series A_2 obtained by altering A_1 to produce two missing varves and two false varves. See explanation of results in the text.

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of 12 positions from one another and thus both fall within the window from positions 27 through 29. It is not until after position 29 that the influence of the second error at 34 becomes obvious. I assume that the tardiness of the effect of the second error is due to the "residual" effect of the first. This discrepancy can only be located by observing where $LAGR_{max}$ at 0 lag again reaches the value of 1.0 at $n=42$. Accordingly the mismatch must lie at $42 - \{(IWIND+1)/2\} = 34$. However in a real situation this latter criterion may not always be applicable. To locate the error at 34 in such a case it would be better to reduce the size of the window to $IWIND=11$. It should be noted that as $IWIND$ is reduced the correlations become less meaningful. Locations of the third and fourth discrepancies are clearly marked: the influence of the third error extends from position 52 through 66, and for the fourth, from 70 through 84, each interval consisting of 15 observations.

DISCUSSION.

It is necessary to point out here a fundamental aspect of the interpretation of the results. The solutions which the incremented cross-correlations provide are non-unique. If we suppose to have correctly located the four discrepancies between the two series, we still could not identify which of the two series contained the error. However it is possible to classify the errors based upon the direction of shift of $LAGR_{max}$ as shown below:

Positive shift of $LAGR_{max}$ { False varve in 2d series (lagged series)
OR
Missing varve in 1st series

Negative shift of $LAGR_{max}$ { False varve in 1st series
OR
Missing varve in 2d series (lagged series)

In the example just discussed (A_1, A_2), all errors were in the second series and the shifts of the $LAGR_{max}$ peak are consistent with the above classification of errors. We can check this by noting, for example, that between $n=52$ and $n=68$, the shift of the correlograms' peak is from 0 lag to -1 which indicates a false varve in series A_1 or a missing varve in A_2 . We know that A_2 has a missing varve at $n=59$.

We are now faced with finding a solution to this problem of non-uniqueness. This can only be overcome by considering combinations of three or more time series whereby a discrepancy will occur in some but not all of the combinations. As an illustration we consider four imaginary varve chronologies from a small study area, series A, B, C, and D. There are six combinations which provide us with a three dimensional correlation matrix pictured in figure 5. Within this matrix are shown the hypothetical results of lag positions of $LAGR_{max}$. The matrix only indicates that the errors occur somewhere before $n=15$ which is the length of IWIND. To simplify things assume that all chronological discrepancies occur at a common varve position, say $n=5$. The identification of the classes of the discrepancies among the combinations is straightforward in this case. Results are compiled in figure 6.

The solution falls out of the summary of possible errors present among the combinations. Note that the errors indicated for A are inconsistent-- results show that A must have both a missing and a false varve within the window-- while for B, C, and D the results are consistent. The correct conclusion is that only core A is without a chronological error, that C lacks one varve, and that B and D each contain a false varve.

Naturally we have given an example which worked here in providing a non-obvious but unique solution to our problem. We would like to end the discussion here, but must admit to situations where the identity of the problem series must remain non-unique and even to cases where the incorrect solution would logically be favored over the correct one. Such situations could have occurred above under two sets of circumstances illustrated by the following examples:

- | | | | |
|-----|---|-----|---|
| (1) | $\left\{ \begin{array}{l} \text{A is OK} \\ \text{B has false varve} \\ \text{C is OK} \\ \text{D has false varve} \end{array} \right.$ | (2) | $\left\{ \begin{array}{l} \text{A is OK} \\ \text{B has missing varve} \\ \text{C has missing varve} \\ \text{D has missing varve} \end{array} \right.$ |
|-----|---|-----|---|

In the first case, we could not discriminate between the possibilities of A and C being correct, with B and D containing false varves, or whether A and C are lacking a varve apiece while B and D are without error. Here we could do as well by flipping a coin. There is a way however to avoid the first situation. The problem of nonuniqueness stems from there being an even number of

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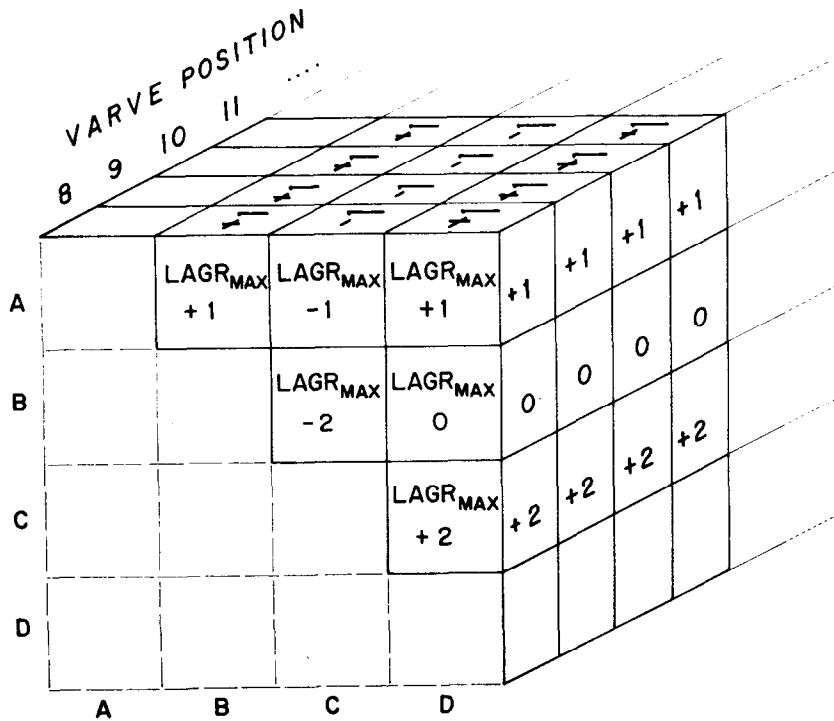


Figure 5. Three dimensional matrix for lag position (τ) of LAGR_{max} among four imaginary cores: A, B, C, D. (IWIND = 15).

combinations (6) for the comparison of four cores. If the number of cores we compare provides an odd number of combinations, defined by $\binom{k}{r} = \frac{k!}{r!(k-r)!}$, where k is the number of cores and $r=2$, this problem does not arise. Odd numbers of combinations result from using 3, 6, and 10 cores.

In the second case set out above, where all cores have the same error except A, the results would indicate that either A has a false varve, or that B, C, and D each has a missing varve. This evidence weighs most heavily against core A as being the correct series, and using only our method in the absence of any other information, we would logically assume that B, C, and D were the correct series. There is no way to compensate for this situation, however it seems unlikely that it should arise. Indeed we must assume that the more cores which exhibit a given characteristic, the greater likelihood that the feature represents a real event.

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CORRELATION PAIR	(A,B)	(A,C)	(A,D)	(B,C)	(B,D)	(C,D)
LAG POSITION (τ) OF LAGR _{MAX}	+1	-1	+1	-2	0	+2
POSSIBLE MISMATCH	FALSE:B OR MISS:A	FALSE:A OR MISS:C	FALSE:D OR MISS:A	FALSE:B AND/OR MISS:C	NONE	FALSE:D AND/OR MISS:C
SUMMARY OF CHRONOLOGICAL DISCREPANCIES INDICATED FOR EACH SERIES BETWEEN VARVES N° 1 AND N° 10	<ul style="list-style-type: none"> A : MISSING, FALSE, MISSING (INCONSISTENT) B : FALSE, FALSE, O.K. (CONSISTENT) C : MISSING, MISSING, MISSING (CONSISTENT) D : FALSE, FALSE, O.K. (CONSISTENT) 					
CONCLUSIONS	<ul style="list-style-type: none"> A : NO CHRONOLOGICAL DISCREPANCY WITHIN INTERVAL B : ONE FALSE VARVE WITHIN INTERVAL C : ONE MISSING VARVE WITHIN INTERVAL D : ONE FALSE VARVE WITHIN INTERVAL 					

Figure 6. Tabulation and summary of results for all correlation pairs among four imaginary cores A, B, C, D, for the varve No. Interval N=1 to N=10 illustrated on matrix. (IWIND =15).

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