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ON THE POSSIBILITY OF OBTAINING RELATIVE PALEOINTENSITIES FROM LAKE SEDIMENTS *

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Relative paleointensities are obtained from a 6-m sediment core from Lake St. Croix, Minnesota, spanning the time range from 445 to 1740 years B.P. To normalize the natural remanent magnetization (NRM) for variations in the magnetic content, a laboratory-induced remanence is chosen, whose alternating field (AF) demagnetization curves most closely resemble the NRM demagnetization curves. By plotting the ratio of the NRM to the normalizing remanence versus AF demagnetizing field, H_{AF}, for samples of the same sediment horizon, as well as for samples from different horizons, estimates are obtained for expected uncertainties in the relative paleointensities. For the Lake St. Croix sediments the anhysteretic remanence (ARM) demagnetization curves are very similar to those of the NRM's, and ARM is therefore used as the normalization parameter. Because the sediment exhibits homogeneous remanence properties throughout, and H_{AF} = 100 Oe is the optimum "cleaning" field for the entire core, NRM_{100}/ARM_{100} is evaluated to represent the fluctuations of the relative paleointensity. Our relative paleointensity data exhibit the same general features as obtained from archeomagnetic studies. The intensity increases as one goes back in time with a peak near 800 years B.P., representing an increase in the intensity of up to 60%. Apparent periodicities in the intensity of 300–400 years are observed.

1. Introduction

The last few years have seen a large increase in paleomagnetic studies of lake sediments. Often these sediments are characterized by continuous and rapid deposition, which, when combined with accurate dating, provide a potentially powerful medium for studying, in detail, the recorded spectrum of geomagnetic fluctuations. However, our understanding of the mechanisms for the acquisition of the natural remanent magnetization (NRM) in sediments is still lacking, compared, for example, with our knowledge of thermoremanent magnetization (TRM) in basalts. In particular, there is at present no paleointensity technique, analogous to the Thellier method for TRM-bearing rocks [1], for relating the magnetization intensity of a sedimentary rock to the absolute intensity of the geomagnetic field in whose presence the remanence was fixed. At best, one can obtain relative paleointensities by normalizing with respect to some magnetic property to compensate for depth variations in the samples' magnetic content and remanence potential of the sedimentary section. To the best of our knowledge this idea was first enunciated and used to obtain relative geomagnetic paleointensities from sediments by E.A. Johnson et al. [2], who used isothermal remanence (IRM, $H = 2000$ Oe) as the normalizing parameter to plot NRM/IRM versus time. More recently, Nakajima and Kawai [3] used NRM/SIRM (saturation IRM) for a similar purpose. Nesbitt [4] and Harrison [5] used initial susceptibility to normalize the NRM intensities. Opdyke et al. [6] compared the NRM fluctuations with fluctuations in IRM, anhysteretic remanence (ARM) and initial susceptibility (χ) to argue that geomagnetic intensity decreases during a field reversal. H.P. Johnson et al. [7] prefer using ARM rather than IRM or χ as a normalizing parameter, arguing that the latter two parameters probably over-emphasize the role of multidomain particles. Hence they normalized partially demagnetized NRM by undemagnetized ARM to obtain intensity trends in their cores.

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In this note we discuss further some of the possible magnetic parameters that can be used for normalization, and we suggest a method for discriminating among the various normalization parameters for use in relative paleointensity studies. We illustrate this method by applying it to sediments of two Minnesota lakes that we have been studying, and, finally, we present relative paleointensity data obtained from recent Minnesota lake sediments.

2. Sampling procedure and summary of the paleomagnetic results

The sediments studied in this paper are from Lake St. Croix, Minnesota (45°N, 93°W). A piston corer [8] was used to retrieve segments 1 m long and 5 cm in diameter. In total, 6 m (710–1350 cm from the water surface) were obtained; each segment was wrapped (in "saran wrap" and aluminum foil) to prevent drying. Two 2-cm cube samples were cored in the laboratory from a total of 72 horizons, separated by no more than 10 cm.

The paleomagnetic components (inclination (I), declination (D) and intensity (J)) were measured for both samples of each horizon. Although the core's paleomagnetic directions and rock magnetic properties will be discussed in detail elsewhere (Banerjee et al., in preparation) we shall summarize the results to provide the necessary foundation for our study of relative paleointensity.

(1) The samples are characterized by total NRM intensities usually varying between 1 and 2×10^{-4} emu.

(2) A total of 25 samples from 23 sediment horizons were stepwise demagnetized by alternating fields (AF demagnetization), and their NRM stabilities are characterized by median demagnetizing fields (MDF) varying from 330 to 370 Oe.

(3) The directions of magnetization of individual samples are well grouped upon AF demagnetization between 0 and 600 Oe. Fig. 1 shows typical behavior upon AF demagnetization of samples 1142/1 and 1205/2.

The MDF values for samples 1142/1 and 1205/2 are about 340 and 350 Oe, respectively, and the magnetic directions of each sample are characterized by α_{95} (95% cone of confidence) of 2.2° and 2.5°, respectively, for H_{AF} = 0–600 Oe.

(4) In addition to the high magnetic stability of individual samples there is high correlation in the values of I, D and J for samples of the same horizon. (Two examples will be given in the next section.)

(5) Thermomagnetic curves (J_s versus T) of bulk sediment and magnetic separates and thermal demagnetization experiments of dried samples suggest that the remanence is carried predominantly by magnetic particles.

(6) The average inclination (I) of the entire core is between 60° and 65°, whereas I due to an axial dipole at the sampling site is 63.5°.

(7) Laboratory resettling experiments (Levi and Banerjee, in preparation) of sediment material whose paleomagnetic components have been previously determined show that the NRM of the Lake St. Croix sediments is of depositional origin.

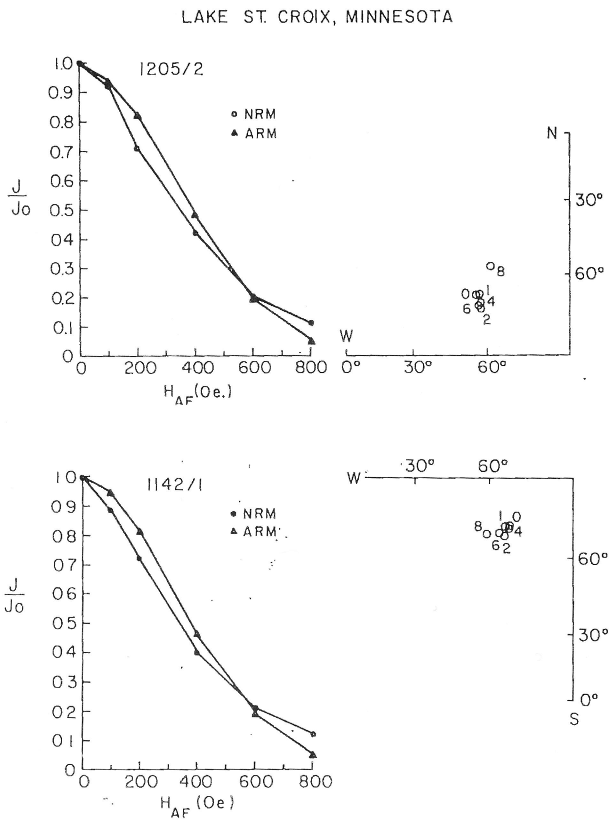
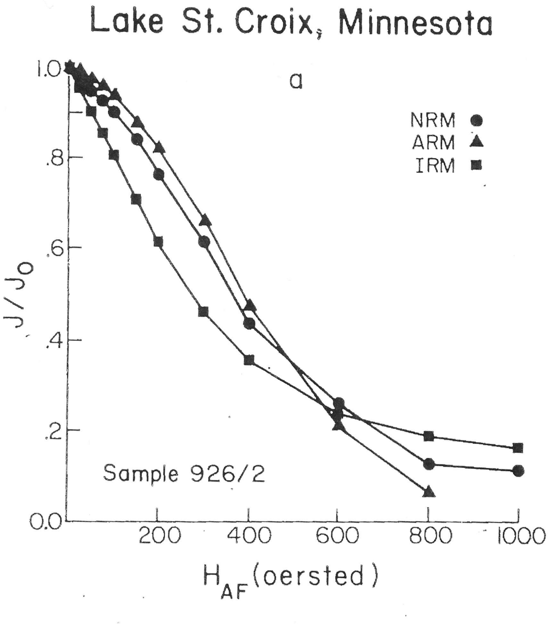


Fig. 1. Variations in the intensity (left) and the directions (right) of the NRM upon progressive AF demagnetization for two Lake St. Croix samples collected from 1142 cm and 1205 cm depths below the water surface. The triangles represent AF demagnetization of a 1-Oe ARM.

3. Normalization methods for relative paleointensities

To interpret fluctuations of the normalized remanence intensity (usually partially demagnetized NRM) as fluctuations of geomagnetic intensity, it is optimistically assumed that the remanence intensity of a particular sediment core is linearly related to the external field fixing the remanence and to the core's magnetic content. It is assumed that fluctuations of variables such as pressure, temperature, and water content during remanence acquisition are either very small or else they have a negligible effect on the remanence intensity. It is also required that the particular normalizing procedure chosen for the determination of the relative paleointensity activate the same relative spectrum of magnetic particles which are also responsible for the NRM.

Magnetic susceptibility [4,5] and saturation magnetization are not favored as normalizing parameters, because they are likely to activate a disproportionately large fraction of the superparamagnetic and multidomain particles; that is, particles which are relatively less important as stable NRM carriers. In addition, both susceptibility and saturation magnetization are dependent on the presence of an external field and are not easily related to remanence which is measured in zero field. More realistic normalization parameters can be found among processes that impart remanence at room temperature, such as viscous remanence (VRM), isothermal remanence (IRM) or anhysteretic remanence (ARM). Although none of the above processes duplicates the acquisition of the primary remanent magnetization of sediments, the resulting magnetizations (VRM, IRM, or ARM) can be demagnetized with alternating fields and their demagnetization curves can be compared with that of the NRM. One criterion for choosing the normalization parameter is to use the remanence whose demagnetization curve most closely approximates that of the NRM, because that process magnetizes particles with a stability (or coercivity) spectrum which most closely resembles the NRM.



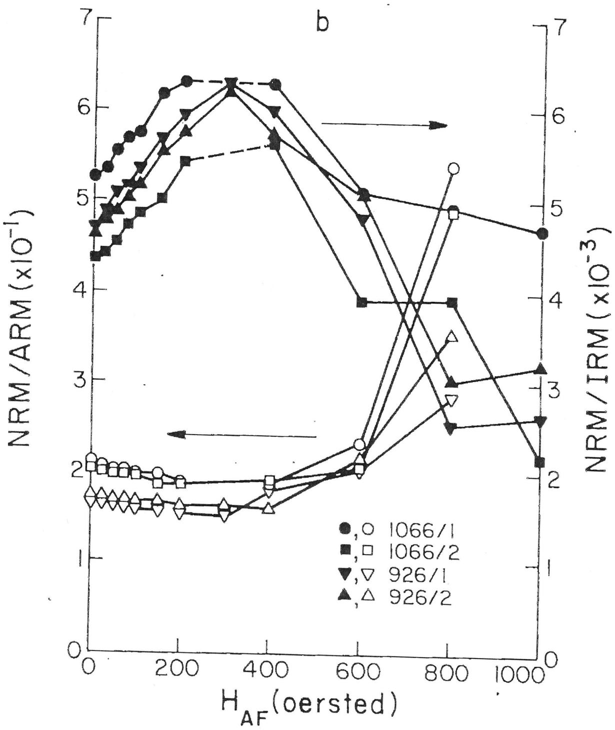


Fig. 2. (a) Normalized AF demagnetization curves of sample 926/2 of Lake St. Croix, Minnesota. Note the similarity of the NRM and ARM curves and the comparatively "softer" IRM curve. (b) Open symbols represent NRM/ARM (left ordinate) versus H_{AF}; solid symbols represent NRM/IRM (right ordinate) versus H_{AF} for samples from Lake St. Croix, Minnesota. The NRM/ARM curves are essentially flat up to 400 Oe, whereas the NRM/IRM is much more sensitive to variations in H_{AF}. Note the relatively greater internal consistency of the NRM/ARM plots for a given sample pair.

For sediments whose remanence can be shown to be of depositional origin (DRM), the best normalization procedure might be to redeposit the sediment in a known laboratory field. In practice, however, one must maintain the integrity of the samples' magnetic content as well as their shapes. This places substantial constraints on the deposition experiment, as the container's boundaries might cause adverse interference. In addition, difficulties with the precise duplication of the DRM process in nature and other unknowns about the nature of acquisition of DRM render the normalization procedure by laboratory redeposition less than practical.

Fig. 2a shows typical normalized AF demagnetization curves of NRM, ARM ($H = 1.0$ Oe, $H_{AF} = 1000$ Oe; H is applied parallel to H_{AF}) and saturation IRM ($H = 14.5$ kOe) for sample 926/2 from Lake St. Croix, Minnesota. The demagnetized magnetic directions of the NRM of sample 926/2 form an extremely tight cluster (α_{95} = 95% cone of confidence = 2.0°) for $H_{AF} = 0$–600 Oe. Also, the ARM and NRM have very similar demagnetization curves, both of which are distinct from the IRM curve, suggesting that the ARM would be a better choice for normalization parameter that the IRM. In addition, the ARM ($H = 1$ Oe; $H_{AF} = 1000$ Oe; $H \parallel H_{AF}$) is typically about 5–6 times more intense than the NRM, whereas the IRM ($H = 14.5$ kOe) is about 200 times as intense as the NRM.

The primary remanence is commonly superimposed by varying amounts of secondary magnetizations, which can often be removed by partial AF demagnetization. For Lake St. Croix the scatter of the magnetization directions of samples from the same horizon usually decreases after partial demagnetization to 100 Oe, and the directions remain well grouped up to $H_{AF} = 600$ Oe. For example, after AF demagnetization to 100 Oe, $\Delta I = 3°$ and $\Delta D = 3°$ for the sample pair at depth 926 cm, and, similarly, $\Delta I = 2°$ and $\Delta D = 2°$ for samples at 1066 cm. $H_{AF} = 100$ Oe was chosen as the peak alternating field to retrieve the "cleaned" magnetic directions [9]; however, any AF value between 50 and 400 Oe would have yielded substantially the same directions. It seems reasonable that a similar AF demagnetization level should be used to evaluate the relative paleointensities.

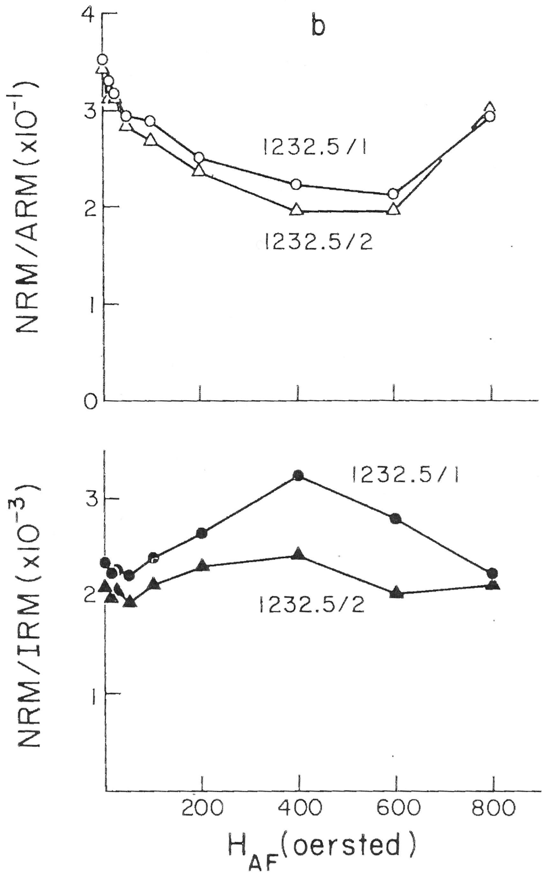
In Fig. 2b we plot NRM/ARM and NRM/IRM versus H_{AF} for four samples from two horizons. The NRM/ARM versus H_{AF} plots (left ordinate) are similar for all four samples and are substantially flat up to 400 Oe. For the individual samples at the horizon at 926 cm the ratio NRM/ARM decreases 7% between 50 and 300 Oe for sample 926/1 and 4% for sample 926/2; the difference between the two samples at $H_{AF} = 100$ Oe is 5%. For the individual samples at the horizon at 1066 cm the ratio NRM/ARM decreases 8% between 50 and 400 Oe for sample 1066/1 and 4% for sample 1066/2; the difference between the two samples at $H_{AF} = 100$ Oe is 1%. The difference in the means of the two sample pairs is 12% at $H_{AF} = 100$ Oe, and it can be seen in Fig. 2b that the difference in the means of the two sample pairs is substantially constant between $H_{AF} = 0$ and 300 Oe. To be consistent with the paleomagnetic direction data, we shall plot the relative paleointensities at $H_{AF} = 100$ Oe, however, substantially the same results would be obtained by choosing H_{AF} anywhere between 50 and 300 Oe. Normalized AF demagnetization curves of ARM acquired in a 0.50-Oe direct field and $H_{AF} = 1000$ Oe for the above 4 samples are indistinguishable from the 1.0-Oe curves, and consequently the NRM/ARM versus H_{AF} curves are also identical. The sharp increase in the NRM/ARM for high alternating field is due to the fact that the ARM is imparted with a peak alternating field of only 1000 Oe. This can also be seen from the intersection of NRM and ARM demagnetization curves in Fig. 2a.

The NRM/IRM versus H_{AF} (right ordinate) curves for samples 926/1 and 926/2 are also very similar up to $H_{AF} = 600$ Oe. However, for sample 926/1 the NRM/IRM increases by 24% between $H_{AF} = 50$ and 300 Oe, while for sample 926/2 there is a corresponding increase of 27%. At $H_{AF} = 100$ Oe there is only a 3% difference between the two 926-cm samples. For samples 1066 there is a similar increase in NRM/IRM between $H_{AF} = 50$ and 300 Oe; in addition, there is a large difference between the two curves: 19% at $H_{AF} = 100$ Oe. There is no significant difference in the means of the sample pairs from the two horizons, and this statement is equally true for all values of H_{AF}. Because of the rapid increase of NRM/IRM values between $H_{AF} = 50$ and 300 Oe, relative paleointensities using IRM as a normalizing parameter would be very sensitive to the choice of AF "cleaning" field, as opposed to the flatness of the NRM/ARM versus H_{AF} curve.

Thus it appears that for Lake St. Croix, ARM is a more useful normalizing parameter than IRM for obtaining relative paleointensities. This conclusion is reinforced by the additional 21 samples from this core for which stepwise AF demagnetization curves of both NRM and ARM were obtained. The ARM demagnetization curves are always similar to and slightly more stable than (for $H_{AF} < 400$ Oe) the NRM curves. This result has also been observed in 70 additional samples from other cores from Lake St. Croix. The demagnetization curves of SIRM (a total of 15 samples) are always considerably "softer" than the NRM's.

The relatively narrow range of the NRM intensities and of the ARM intensities (Fig. 4), the similarity of the NRM demagnetization curves and of the ARM demagnetization curves, and the constancy of the relative pattern of the normalized NRM and ARM demagnetized curves along the core suggest that the Lake St. Croix sediment core is magnetically homogeneous. In addition, $H_{AF} = 100$ Oe is an appropriate "cleaning" field for the entire sediment column. Therefore, the Lake St. Croix sediment core appears to be a good candidate for a relative paleointensity study.

In cases where the character of the demagnetization curves changes abruptly along the core length or where there is a change in the relative stabilities of the NRM with respect to the normalizing remanence, interpretation of the normalized remanence intensity data in terms of geomagnetic fluctuations becomes much more tenuous and may indeed not be possible. It might sometimes be useful to obtain separate relative intensity plots for different homogeneous sections of the core, utilizing, possibly, different normalization procedures for the different segments. Additional difficulties might arise, if various "cleaning" fields are required at different levels of the core. If the normalized intensity versus H_{AF} curve is flat in the region of the "cleaning" fields, the uncertainties need not be significant, but whenever the curve's slope is significant, substantial uncertainties may be introduced.



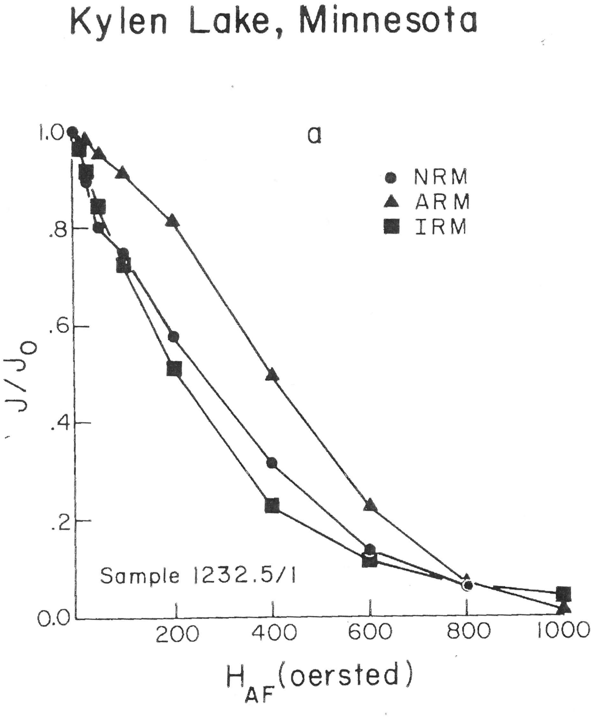


Fig. 3. (a) Normalized AF demagnetization curves of sample 1232.5/1 of Kylen Lake, Minnesota. Note the similarity of the NRM and IRM curves, both of which are substantially "softer" than the ARM. (b) Open symbols represent NRM/ARM versus H_{AF}. Solid symbols represent NRM/IRM versus H_{AF} for samples 1232.5/1 and 1232.5/2 of Kylen Lake, Minnesota. Note the greater internal consistency of NRM/ARM plots.

An instructive example is provided by the paleomagnetic study of Kylen Lake, Minnesota, where the NRM is typically much "softer" than the ARM and more closely resembles the IRM demagnetization plots, as in Fig. 3a. The NRM/IRM and NRM/ARM versus H_{AF} curves of the two Kylen Lake samples are similar in their general features to those of the St. Croix samples. Although the NRM/ARM curves are not as flat as for Lake St. Croix, the two NRM/ARM curves for the Kylen Lake samples are more similar to one another for all H_{AF} than the NRM/IRM curves. It is difficult to decide whether ARM or IRM would provide better normalization for Kylen Lake. Whichever the choice, however, the final relative intensities would have uncertainties exceeding those of Lake St. Croix.

Instead of the one-point normalization at a single H_{AF} value, one could also obtain an average relative intensity for each sample over a range of H_{AF} values for which the demagnetized directions are characterized by an α_{95} smaller than some predetermined value. Such an average value can be obtained from the NRM/ARM (NRM/IRM) versus H_{AF} curves such as in Figs. 2b and 3b. It is seen that for Lake St. Croix, using H_{AF} = 50–400 Oe, the standard deviation associated with the mean ratio NRM/ARM for each sample is substantially less than the standard deviation for the corresponding mean ratio NRM/ARM. For Kylen Lake, however, one obtains for each sample comparable standard deviations of the means for both NRM/IRM and NRM/ARM. The data can be cast differently – in a manner more common in paleointensity studies – by plotting NRM versus ARM (IRM) for different alternating field values. The average ratios NRM/ARM and NRM/IRM are then obtained from the slopes of the best fitting lines (in the least squares sense) through the points H_{AF} = 50–400 Oe. This was done for the sample pairs at 926 cm and 1066 cm of Lake St. Croix, and "better" lines, whose slopes are more self-consistent within a given horizon, are obtained for the NRM versus ARM plots than for the NRM versus IRM plots.

4. Results: relative paleointensities of the earth's field

In Fig. 4 we show results of relative paleointensities obtained from the sediments of Lake St. Croix, Minnesota. The vertical axes of Fig. 4 are determined from four ^{14}C dates from the following depths: 710–722 cm (445 ± 80 yr B.P.); 870–880 cm (645 ± 80 yr B.P.); 1078–1088 cm (740 ± 80 yr B.P.); 1350–1360 cm (1740 ± 85 yr B.P.). (The uncertainties in the ages are determined from counting the radioactive decay; "present" is defined at 1950 A.D.) The positions in the core of the ^{14}C age determinations are marked by asterisks in Fig. 4, constant sedimentation rates are assumed between dates. The core spans the time 445–1740 yr B.P. and its sedimentation rates vary from 0.27 to 2.2 cm/yr, and each sample con-

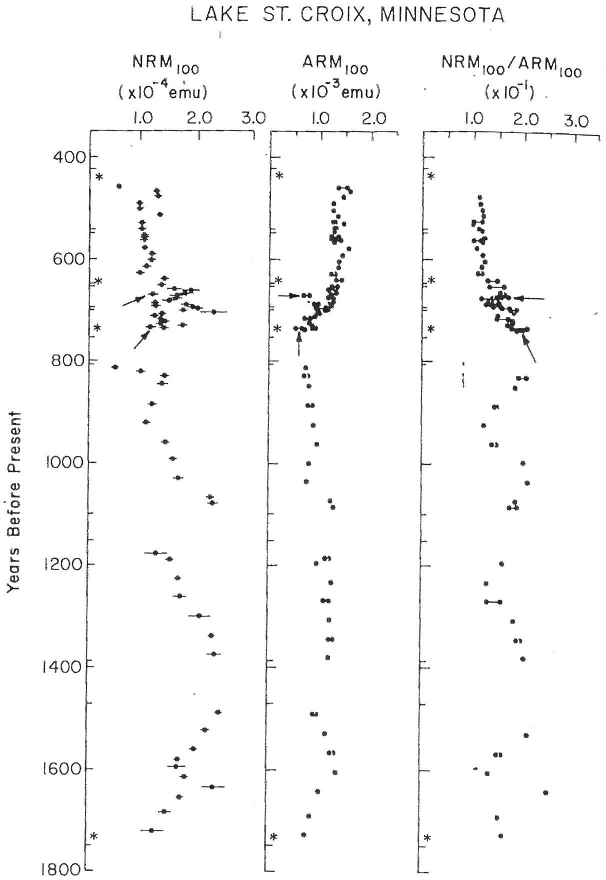


Fig. 4. From left to right, NRM intensity, ARM intensity and NRM/ARM as a function of time in years before present. All quantities are partially demagnetized to 100 Oe. Asterisks represent ^{14}C dates, which determine the time axes. Shorter horizontal marks on the time axes represent upper and lower boundaries of the core segments. Horizontal bars through the NRM data represent deviations from the mean of two samples at each horizon. Each point on the ARM and NRM/ARM plots represents one sample. The data from the top sample-pair of each core segment is omitted from the NRM/ARM plot. The NRM/ARM plot represents the relative paleointensities.

tains material deposited in no more than 8 years and in as short a time as 1 year.

The data in Fig. 4, from left to right, represent the NRM intensity, ARM intensity and the ratio NRM/ARM. All the intensity data are partially demagnetized to $H_{AF} = 100$ Oe. The shorter horizontal marks on the vertical time axes represent the boundaries of the core segments. Each point on the NRM intensity plot represents the mean of two samples at each horizon and the bars through each point represent the deviation from the mean of the two samples. On the ARM intensity plot and the relative paleointensity plot (NRM_{100}/ARM_{100}) each point represents a sample.

The top 5–10 cm of the core segments are usually disturbed, as judged from their different consistency (less compacted) compared to the remaining sediment in the segments. This disturbance is also exhibited by anomalous magnetic directions and intensities in the top-most sections of many core segments. For example, in four of the seven core segments the NRM intensity of the top sample-pair is anomalous, as seen in Fig. 4. Therefore, data from the top 10 cm of each core segment is omitted from the ARM intensity plot and the NRM/ARM plot. It is seen that the total dispersion as well as the dispersion within a given sediment horizon is usually less for the ARM data than for the NRM. (In the ARM and NRM/ARM plots the data of the two samples of a given horizon are connected with a bar.) There is a substantial decrease in the ARM intensity just prior to 800 years B.P., which is directly correlated with a sharp decrease in the sedimentation rate. The NRM/ARM plot represents the relative paleointensities at the sampling locality during the period spanned by our data. The NRM/ARM plot is defined by 84 samples from 60 horizons. Whenever the ratio NRM/ARM is determined for both samples of a given horizon, the observed dispersion is relatively small. The two sets of arrows show the data of the two sample pairs, whose behavior was discussed in the preceding section: the samples at 926 cm (668 yr B.P.) and the samples at 1066 cm (733 yr B.P.). (The samples at depths 1142 cm and 1205 cm have age assignments of 958 and 1191 yr B.P., respectively.) (The high significance of the listed dates is meaningful only for comparing the relative ages of different horizons.)

One of the fundamental problems in interpreting the magnetic fluctuations of lake sediments lies in determining the time at which the remanence was fixed. Assuming that the magnetic fluctuations are of geomagnetic origin, it is important to determine the lag between the time of deposition and the time at which the magnetization is fixed [10,11]. For the sediments of Lake St. Croix the magnetization seems to be fixed within 20 cm of the water-sediment interface, representing between 10 and 75 years of deposition (depending on the rate of sedimentation) which is within the reported uncertainty of each ^{14}C age determination of ± 80 years. Regardless of the possible lag between deposition and the fixing of the remanence, one of the chief advantages of working with sediments is that the relative chronology of the different horizons is usually known.

Going back in time from 450 years B.P., the relative intensity is observed to increase to a peak just prior to 800 years B.P., corresponding to approximately a 60% increase in the field intensity. This agrees well with worldwide archeomagnetic studies [1,12,13]. In particular, our data are in good agreement with the archeomagnetic data of Bucha et al. [14] for Arizona and Mexico, both with regard to the time and relative amplitude of the peak at about 800 years B.P. Our data, however, show much more structure on both sides of the maximum, which may be due in part to the continuous nature of the lake sediment record. It is premature to ascribe characteristic wavelengths to the intensity fluctuations, but rapid fluctuations with periods between 300 and 400 years are apparently present. In addition, the intensity can change by as much as 60% within 100–200 years. In principle, the relative paleointensity curve might sometimes be related to the absolute geomagnetic intensity, if there exists at least one independent absolute intensity determination of known age at the sampling location.

5. Conclusions

Clearly, the relative paleointensity results presented here from Lake St. Croix must be regarded as preliminary, and much more work in Minnesota and elsewhere is required to substantiate our results. We are, however, encouraged by the internal consistency of our data, their high resolution and the general agreement with the archeomagnetic data.

Before using a particular sediment core for a relative paleointensity study, the homogeneity of the sediment's remanence properties must be established, because only those sections with similar remanence properties can be compared for relative paleointensities. Homogeneity can be estimated from similarities in the NRM properties of the sediment and from similarities of properties of laboratory induced remanences such as ARM and IRM. Comparison of the relative stabilities of the NRM demagnetization curves with those of ARM and IRM provide a particularly useful method of judging whether a particular core might be suitable for a relative paleointensity study. Plotting the ratio of the NRM to the normalizing parameter as a function of demagnetizing field for samples of the same sediment horizon, as well as for samples from different horizons, provides a quantitative approach for evaluating the uncertainties expected from the study of the relative paleointensities of a particular core. These methods provide a framework for choosing certain sediment cores from which reliable relative paleointensities might be expected, while, more importantly, they also provide guidelines for discarding other cores from being used.

Acknowledgments

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