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A new high-resolution geomagnetic relative paleointensity record for the North American Holocene: A comparison of sedimentary and absolute intensity data

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Abstract. A new high-resolution paleointensity record for North America has been constructed using Holocene sediments from Lake Pepin, Minnesota. Lake Pepin sediments yield the same Holocene paleosecular variation curve as nearby Lake St. Croix and satisfy all of the criteria recommended for paleointensity studies. Absolute paleointensity data for North America recorded by Holocene volcanic and archeomagnetic samples provide an independent record of geomagnetic field paleointensity against which the relative intensity records from Lake Pepin and Lake St. Croix can be compared. Since the absolute field paleointensity is known a priori, the effects of the magnetic recording assemblage can be isolated. Anhysteretic remanent magnetization (ARM) is the best choice among normalization parameters for the Lake Pepin sediments as the natural remanent magnetization (NRM) normalized by ARM shows no coherence with magnetic grain size proxies and yields a record of relative paleointensity peaks and troughs whose amplitudes are very similar to those in the archeomagnetic (ARCMAG) and Lake St. Croix data sets. Features with a wavelength of 1000 years are correlative between the three paleointensity records. NRM normalized by saturation isothermal remanent magnetization (SIRM) and by susceptibility (χ) shows grain-size dependences that cause errors in the amplitudes of paleointensity features. NRM/SIRM and NRM/χ are not coherent with their normalizers but are both strongly coherent with independent grain size proxies such as the median destructive field of the NRM and H_{CR}. We successfully removed the grain size dependences from NRM/SIRM by applying a correction function based on the linear relationship between normalized intensity and the median destructive field of the NRM.

1. Introduction

Sediments are attractive recorders of the geomagnetic field due to their continuity, high temporal resolution, and global availability. Studies of the directional recording abilities of sediments were conducted as early as the 1930s [e.g., *McNish and Johnson*, 1938; *Ising*, 1943; *Johnson et al.*, 1948]. Sedimentary records of geomagnetic field intensity are more difficult to interpret because the signal recorded in sediments is dependent on the concentration, grain size, and composition of the magnetic recording assemblage, in addition to dependences on bulk sedimentological parameters (see *Tauxe* [1993] for full discussion). Typically, the intensity of the "cleaned" natural remanent magnetization (NRM) at some demagnetization level is divided by the intensity of anhysteretic remanent magnetization (ARM), saturation isothermal remanent magnetization (SIRM), or susceptibility (χ) in order to correct or "normalize" for the variation in the amount of remanence carriers in the sediment. Ideally, the normalizer should activate the same grains that carry the NRM [Levi and Banerjee, 1976].

Studies based on marine cores have generated relative paleointensity records up to several millions of years long that can be used for testing geodynamo models and to constrain past radionuclide production rates. Several studies have suggested that geomagnetic field paleointensity has potential for use as a millennial-scale global correlation tool [e.g. *Meynadier et al.*, 1992; *Tric et al.*, 1992; *Guyodo and Valet*, 1996]. However, the intensity of the geomagnetic field is not known a priori; therefore it is not possible to assess the accuracy with which these normalized records reproduce the amplitudes of geomagnetic field features. It is commonly observed that NRM/ARM, NRM/SIRM, and NRM/χ curves from a given sediment core have similar profiles but varying amplitudes of peaks and troughs [e.g., *Schwartz et al.*, 1996]. This is problematic since, for example, the calculated intensity of phenomena such as reversals and excursions would depend upon the normalization method chosen.

Several studies have suggested that traditional normalization methods do not sufficiently correct for variations in magnetic grain size, lithology, or climatic effects [*Amerigian*, 1977; *Sprowl*, 1985; *Schwartz et al.*, 1996; *Brachfeld and Banerjee*, 1998; *Kok*, 1998; *Lehman et al.*, 1998; *Williams et al.*, 1998]. Attempts have been made to apply secondary normalizations based on the median destructive field (MDF) of the NRM [*Sprowl*, 1985; *Brachfeld and Banerjee*, 1998], H_C [*Lehman et al.*, 1998], and ARM/SIRM [*Williams et al.*, 1998]. These secondary normalizations successfully removed anomalous relative intensity features associated with diagenesis, abrupt lithology variations, and climate variations.

In this study we present a new high-resolution paleointensity record and associated rock magnetic data that allow us to assess

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the precision of traditional normalization methods. We then test a secondary normalization method that corrects for magnetic grain size variations in sediments that appear to contain only the desired pseudo-single-domain (PSD) grains. Our study area, Lake Pepin, Minnesota, is an ideal setting in which to assess the accuracy of normalization methods. The sediments accurately record the geomagnetic field, yielding the familiar Holocene paleosecular variation profile for North America. The sediments are magnetically and lithologically uniform, satisfying all of the criteria which have been recommended to determine the suitability of sediments for paleointensity studies [*King et al.*, 1983; *Tauxe*, 1993; *Lehman et al.*, 1994]. The availability of Holocene absolute paleointensity data from the western United States [*Bucha et al.*, 1970; *Champion*, 1980; *Sternberg*, 1989] provides a means of examining the accuracy of traditional and two-step relative paleointensity normalization methods. This approach has the distinct advantage that the geomagnetic field intensity is known and therefore the effects of the recording assemblage on the intensity of remanence can be isolated.

2. Geologic Setting

Lake Pepin is a natural impoundment of the upper Mississippi River (Figure 1). It formed ~9200 years B.P. when the outlet waters of Glacial Lake Agassiz were diverted northward, resulting in a lower carrying capacity for the Mississippi River, which could no longer transport the coarse sediment brought in by its steep-gradient tributaries. The tributary Chippewa River then deposited its coarse sediment in a fan delta that dammed the Mississippi, creating Lake Pepin. Lake Pepin is a long, flat-bottomed lake with a water depth of 8.5 m. Water quality is poor as a result of agricultural and urban developments upstream. The sediments are brown-black, massive, and consist of 10% organic matter, 5-10% carbonate, and the remainder is siliciclastics as determined by loss-on-ignition *analysis [Engstrom and Almendinger*, 1997; *Dean and Brachfeld*, 1999].

3. Experimental Methods

Sediment cores were collected during open-water season (using a pontoon boat) and during winter ice-over using piston corers operated from the lake surface by rigid drive rods. A corer equipped with 7-cm-diameter polycarbonate tubes was used to collect 1- and 2 m-long core sections. A 12-m core was collected from the center of the lake in the same region as a 16-m core collected in 1989 by *Wright et al.* [1998] and near transect III of *Engstrom and Almendinger* [1997]. A 1-m interval from 300 to 400 centimeters below lake floor was not recovered due to difficulties with the piston cable on that particular drive. This interval was recovered in another core and a composite was made using Analyseries software [*Paillard et al.*, 1996] to correlate the cores on the basis of rock-magnetic parameters and inclination.

The core was sampled via U channels, which were measured at the Laboratoire des Sciences du Climat et de l'Enviroment (LSCE) in Gif-sur-Yvette, France, on a 2G model 755-R cyrogenic magnetometer with DC SQUIDS and in-line alternating field (AF) demagnetization unit. ARM was acquired in a peak alternating field of 100 mT and a steady bias field of 50 μT at a translation speed of 1.0 cm/s. SIRM was acquired by passing the U channel between the pole pieces of an electromagnet, capable of peak fields of 0.55 T. Volume-normalized susceptibility was measured with a Bartington 45-mm-diameter susceptibility bridge.

Subsamples were collected every 5 cm for rock magnetic analyses. We used a combination of magnetic methods to characterize the magnetic mineral assemblage. Hysteresis parameters, Curie temperatures, and low-temperature remanence properties were measured at the Institute for Rock Magnetism at the University of Minnesota. Hysteresis loops and Curie temperatures were measured on a Princeton Measurements Corporation micro-Vibrating Sample Magnetometer (μVSM). Curie temperatures were determined from the temperature dependence of saturation magnetization (M_S). We also identified magnetic minerals via their low-temperature phase transitions

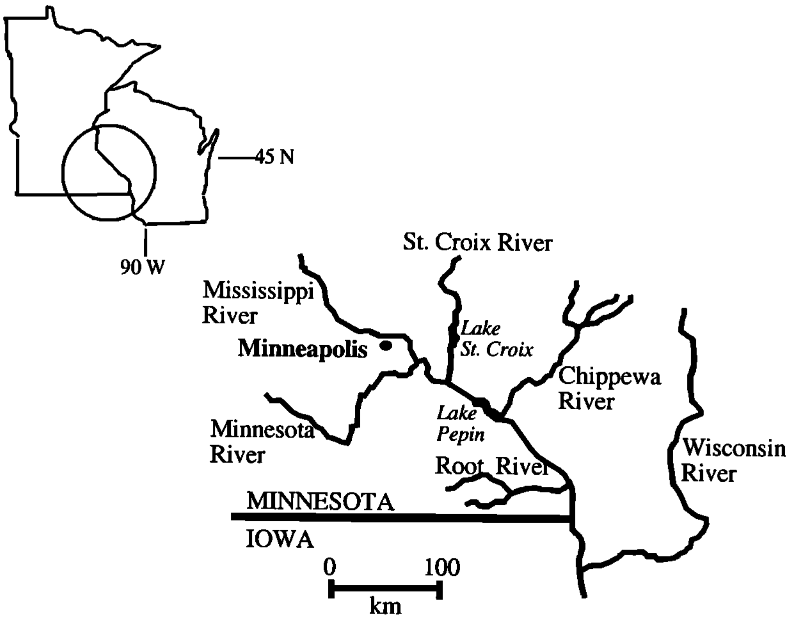

Figure 1. Location of Lake Pepin and Lake St. Croix in the upper Mississippi River watershed.

using a Quantum Design MPMS2 magnetic properties measurement system. Room temperature frequency dependence of susceptibility [$\chi_{FD} = 100^* (\chi_{400\ Hz} - \chi_{4000\ Hz})/(\chi_{400\ Hz})$] was measured on a Lakeshore 7000 AC Susceptometer. Susceptibility was measured at 18 frequencies between 40 Hz and 4000 Hz. Values for $\chi_{400\ Hz}$ and $\chi_{4000\ Hz}$ were obtained from a best fit line through the data points. Magnetic extracts were examined on a Philips 3100 X-ray diffractometer.

Spectral analysis and calculation of coherence spectra was performed using Analyseries software. Coherence tests were carried out according to methods described by *Tauxe and Wu* [1990].

4. Chronology

Several dating methods were applied to the upper 2 m of sediment deposited during the last 160 years. The results of these methods are described in detail by *Engstrom and Almendinger* [1997]. Peak concentrations of ^{137}Cs were used to identify sediments deposited during the 1963-1964 peak in atmospheric nuclear weapons testing. Lead 210 activity was measured to determine age and sediment accumulation rates for the past 130 years. Pollen samples were prepared to identify the change from the presettlement pine, oak, and birch assemblage to one with significantly increased ragweed (*Ambrosia*), the first appearance of cereal grains, and a reduction in pine pollen. This transition represents the spread of agriculture in Minnesota and Wisconsin and the logging of local pine forests and is dated at approximately 1860 A.D. The *Ambrosia* rise is preceded by a gradual increase in magnetic susceptibility that likely records the onset of settlement and land clearance in the upper Mississippi watershed, approximately 1830 A.D. for Minnesota [*Engstrom and Almendinger*, 1997]. *Wright et al.*, [1998] derived a presettlement sedimentation rate in Lake Pepin of 0.15 cm/yr based on carbon dating of one terrestrial macrofossil at the base of a 16-m core.

Lake Pepin is devoid of terrestrial macrofossils except near shore in shallower water. Bulk organic carbon and shells within the sediment are tainted by the "hard water effect" and therefore yield anomalously old ages. One terrestrial macrofossil was found in our core ~1 m below the settlement horizon and yielded a radiocarbon age of 290 ± 25 radiocarbon years B.P., from which we calculated a presettlement sedimentation rate of 0.149 cm/yr. This is in excellent agreement with the presettlement sedimentation rate of 0.15 cm/yr derived by *Wright et al.*, [1998] and 0.13 cm/yr determined by *Engstrom and Almendinger* [1997]. Our age model was obtained by applying a sedimentation rate of 0.15 cm/yr below the settlement horizon, further followed by tuning of the inclination record with that of Lake St. Croix [*Lund and Banerjee*, 1985], situated less than 100 km away. Several prominent inclination features are correlative between the two sites (Figure 2). The resulting depth-age model is shown in Figure 3.

5. Directional Record

Lake Pepin sediments record a strong, stable, single component of remanence with an easily isolated characteristic component of remanence. Representative "vector endpoint" diagrams are shown in Figure 4. Principal component analysis was performed using five steps from the 10–50 mT demagnetization levels. The maximum angular deviations (MAD angles) are generally < 1°. The highest MAD angles are only 2-3°, and these occur in the upper 2 m of sediment where the sedimentation rate and frequency dependence of susceptibility are both higher than average and the MDF of the NRM is lower than average. The inclinations in this upper interval agree well with site-specific International Geomagnetic Reference Field (IGRF) values and observations at the Toronto Geomagnetic Observatory, indicating that even this high deposition rate postsettlement interval reliably records the geomagnetic field.

6. Magnetic Mineral Assemblage

6.1. Composition

All normalization methods begin with the requirement that magnetite is the sole carrier of remanence and preferably the sole magnetic phase present. We have used high-temperature and low-temperature magnetic techniques and X-ray diffraction

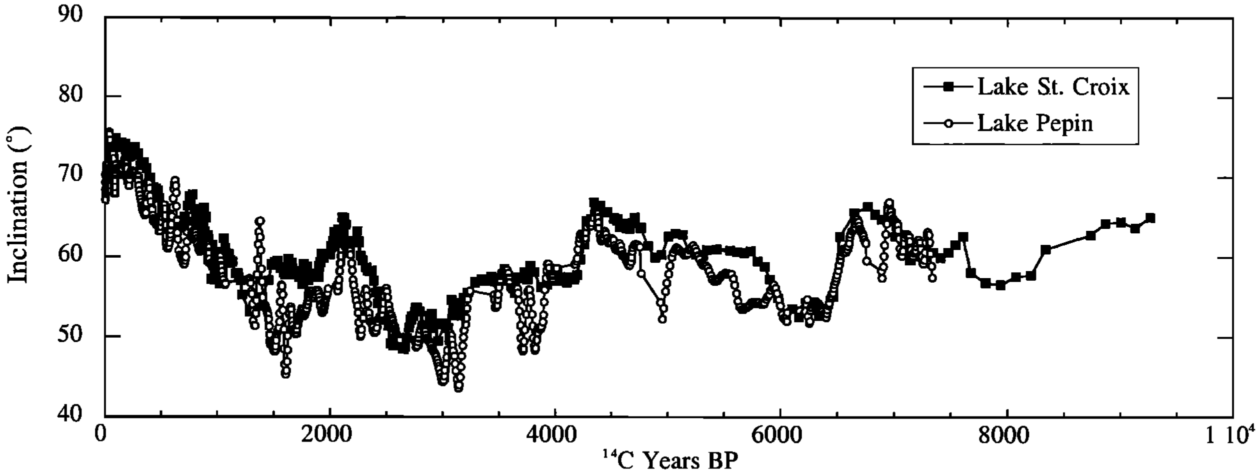

Figure 2. The Lake Pepin inclination record tuned to the Lake St. Croix record. The two curves are anchored at the European settlement horizon (1830). Analyseries software was used to adjust the Lake Pepin record with respect to Lake St. Croix until the highest correlation coefficient was achieved.

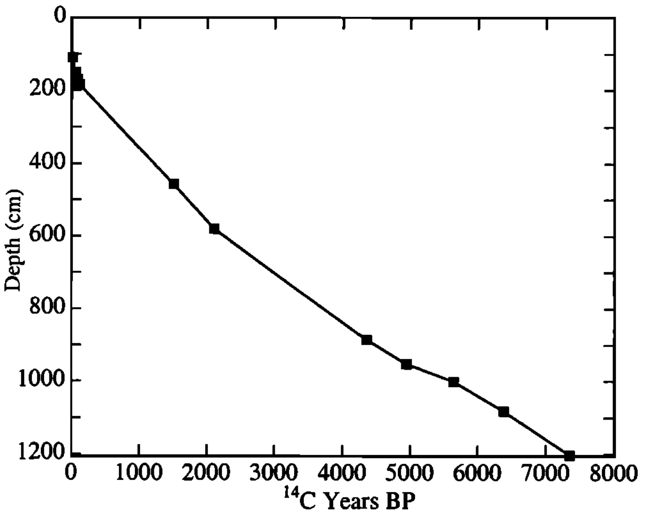

Figure 3. Depth-age model for Lake Pepin based on historical dating methods and tuning with inclination. A nearly threefold increase in sedimentation rate occurs at the European settlement horizon.

(XRD) to determine the composition of the magnetic mineral assemblage. Curie temperature measurements were performed on magnetic extracts using the temperature dependence of saturation magnetization (Figure 5a). The samples yielded nearly reversible, single-phase thermomagnetic curves, with Curie temperatures between 580 and 590°C, indicative of pure magnetite. This agrees well with our XRD data, from which an average cell parameter of 8.384 Å was determined from magnetic extracts.

Additional low-temperature methods were used to identify the magnetic mineralogy because the high sensitivity of the instrument allows bulk sediment to be used and alteration does not occur during the experiment. Several magnetic minerals undergo thermomagnetic or crystallographic phase transitions that can be used as indicators of the presence or absence of that mineral (for example pyrrhotite at 30-35K [*Rochette et al.*, 1990], magnetite at 90-120 K [*Özdemir et al.*, 1993], and siderite at 35-40 K [*Housen et al.*, 1996]). Samples were cooled to 20 K and given a remanence in a saturating field of 2.5 T. The total moment was measured as the sample was gradually heated to room temperature in zero field. In all samples a sharp decrease in intensity of remanence of 20-40% was observed over the range of

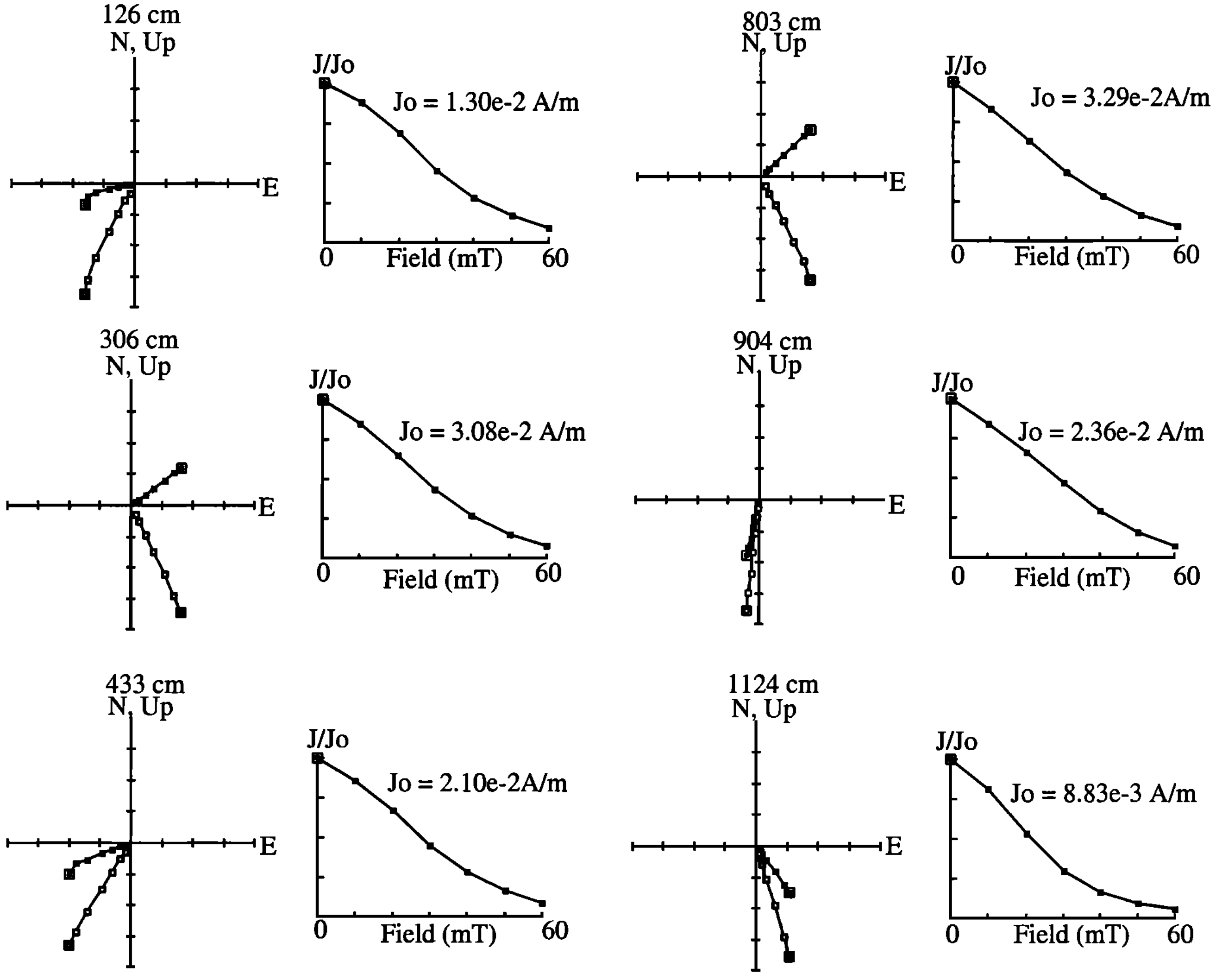

Figure 4. Vector endpoint diagrams and decay of J/J_0 during stepwise AF demagnetization of the NRM. Principal component analysis was performed using the 10, 20, 30, 40, and 50 mT steps.

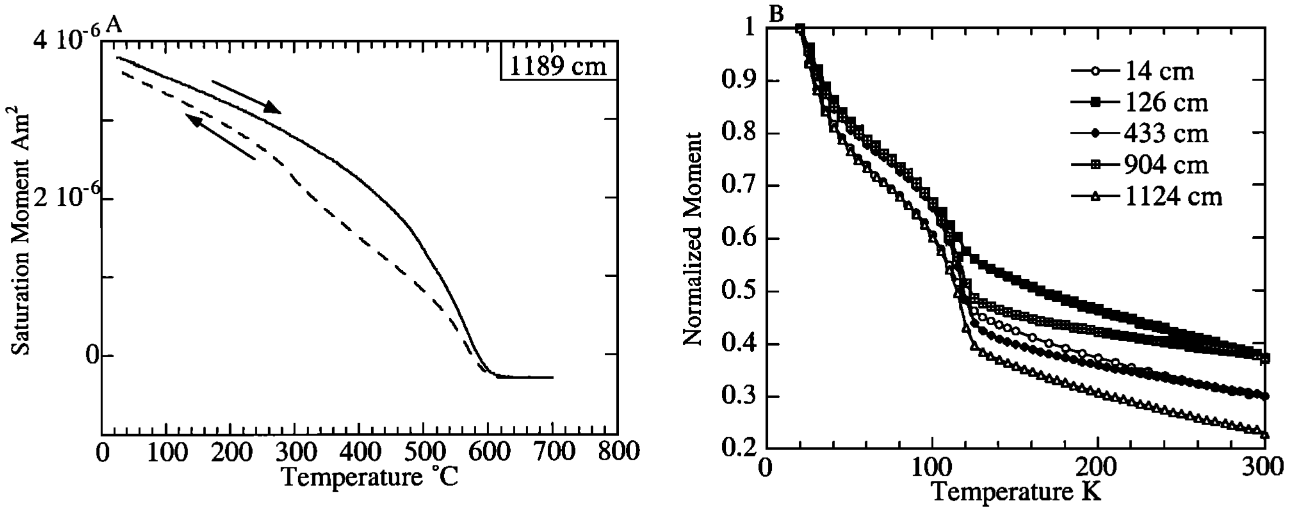

Figure 5. (a) A representative M_S-T curve (1189 cm) shows a magnetite Curie temperature of 585°C. (b) M_R-T from 20 to 300 K. All samples show a clear Verwey transition at 116 K.

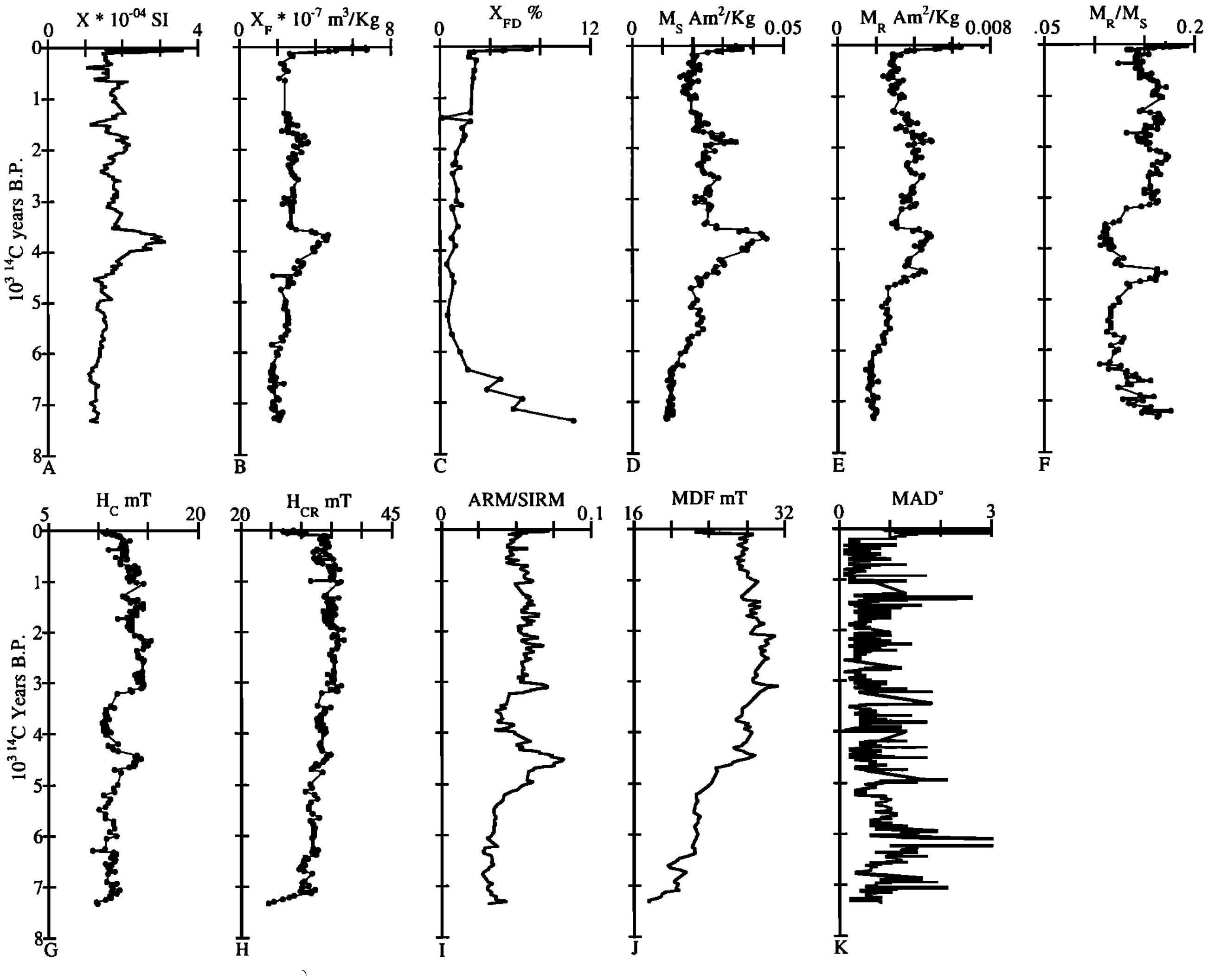

Figure 6. Rock magnetic properties of the Lake Pepin sediments. Solid lines denote U channel measurements. Solid circles denote subsample measurements. (a) Volume susceptibility, (b) ferromagnetic susceptibility (mass-normalized), (c) room temperature frequency dependence of susceptibility, (d) saturation magnetization, (e) saturation remanence, (f) M_R/M_S, (g) coercivity, (h) coercivity of remanence, (i) ARM/SIRM, (j) median destructive field of the NRM, and (k) maximum angular deviation.

110-116 K (Figure 5b). The Verwey temperature, T_V, was determined from the first derivative of the M_R-T curve, and was 116 K for all samples. This value of T_V is consistent with unoxidized, nearly stoichiometric magnetite [*Özdemir et al.*, 1993]. No other low-temperature phase transitions were observed, and it is likely that magnetite is the only remanence carrier and only ferromagnetic phase present in these sediments.

6.2. Concentration

In sediments that are suitable for paleointensity studies the concentration of magnetic material varies by no more than a factor of 10 [e.g., *Tauxe*, 1993]. This is typically monitored via low-field bulk magnetic susceptibility. In the Lake Pepin sediments the ratios of maximum to minimum values of bulk susceptibility and ferromagnetic susceptibility are 3.43 and 4.37, respectively (Figures 6a-6d). Ferromagnetic susceptibility is defined as the low-field magnetic susceptibility minus the high-field susceptibility ($\chi_{LF} - \chi_{HF}$), the latter determined from the high-field slope of a hysteresis loop. This parameter removes the paramagnetic and diamagnetic contributions from bulk susceptibility and isolates the contribution from phases likely to contribute to the remanence. However, in this case, χ_F does not solely reflect concentration variations but also changing superparamagnetic (SP) content. Saturation magnetization M_S is a better parameter to assess the concentration of ferromagnetic phases because it has no systematic grain size dependence. The saturation magnetization of the bulk sediment reported here is the induced magnetization, in a saturating field, which has had the paramagnetic contribution removed via correction with the high-field slope of the M-H loop (χ_{HF}, which is the paramagnetic susceptibility). The ratio $M_{S\text{-MAX}}/M_{S\text{-MIN}}$, 4.04 in these sediments, reflects the variation in the concentration of magnetite. By all previous criteria and additional criteria described here that more accurately target the ferromagnetic phases, the concentration variability in these sediments is approximately a factor of 4, well below the upper limit of 10 recommended by *Tauxe* [1993].

6.3. Magnetic "Grain Size"

The average magnetic domain state of these sediments was determined by measuring hysteresis loops. The sediments satisfy the qualitative "tight cluster" requirement in the pseudo-single-domain (PSD) region of a Day plot [*Day et al.*, 1977] at full scale (Figure 7), which is generally interpreted to mean that little variability exists in the overall assemblage [*King et al.*, 1983]. The sediments also satisfy the more quantitative requirements of *Lehman et al.* [1994] with ratios of maximum to minimum M_R/M_S and H_{CR}/H_C of 1.83 and 1.49, respectively. On an expanded-scale Day plot, four subclusters can be seen with a broad trend of coarsening with depth. The top 2 m and the basal 1.5 m of the core have higher than average values of χ_{FD}, suggesting that these parts of the core have higher than average SP content (Figure 6c). Variability in the relative contribution of stable single-domain (SSD) grains and small PSD grains is suggested by oscillations in both M_R/M_S and ARM/SIRM (Figures 6f and 6i). Even these small variations in magnetic grain-size that are not detected by the traditional Day plot test are sufficient to complicate the normalization process.

7. Relative Paleointensity Results

7.1. Traditional Normalization Methods

Relative paleointensity profiles are shown in Figure 8. For each normalization parameter we calculated the average ratio of NRM/normalizer at the 10, 20, 30, and 40 mT demagnetization

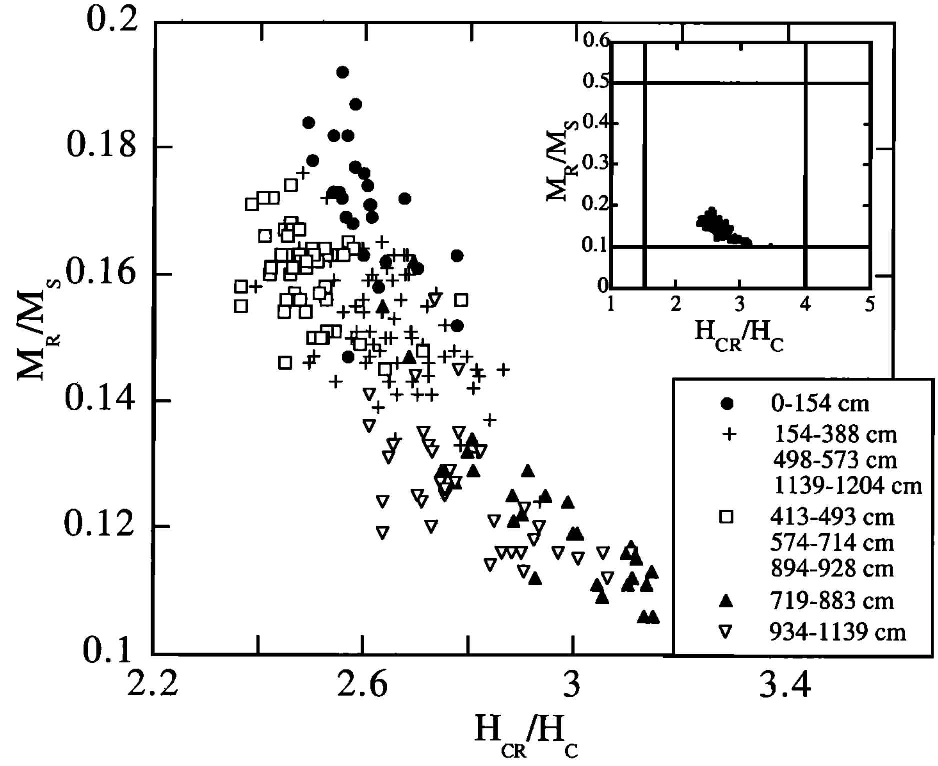

Figure 7. Lake Pepin hysteresis parameters. On a traditional Day plot (insert) the hysteresis parameters make a tight cluster in the pseudo-single domain field. On an expanded Day plot, several subclusters can be seen.

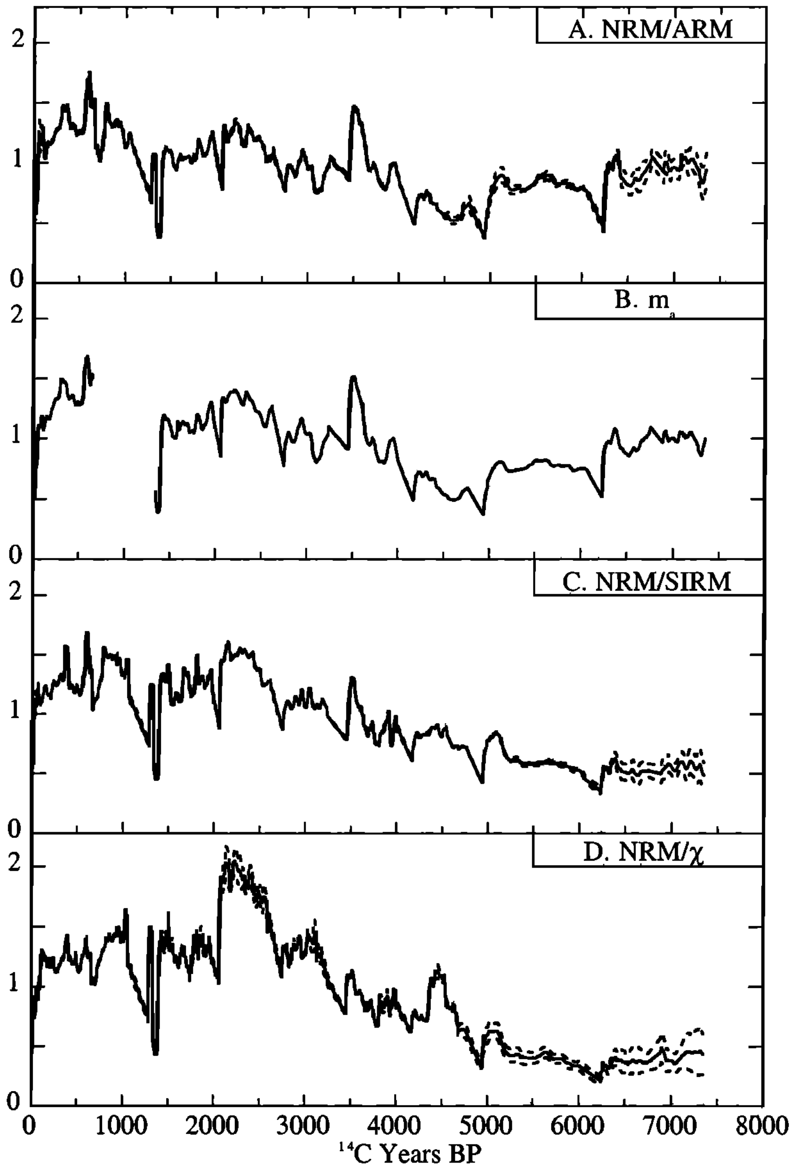

Figure 8. Normalized intensity records constructed from (a) NRM/ARM, (b) the pseudo-Thellier method (m_a), (c) NRM/SIRM, and (d) NRM/χ. The solid lines in Figures 8a, 8c, and 8d are the average ratio of NRM/normalizer at the 10, 20, 30, and 40 mT demagnetization levels. The pseudo-Thellier slope was determined from the 20, 30, 40, and 50 mT alternating field steps. The dotted lines denote the standard deviation.

levels. The pseudo-Thellier paleointensity m_a was determined from the slope of a line fit to the NRM lost versus partial ARM (pARM) gained over the 20-50 mT demagnetization steps [*Tauxe et al.*, 1995]. An unfortunate gap exists in the pseudo-Thellier record where one core segment was inadvertently given an SIRM prior to pARM acquisition. Each of the four data sets has been divided by its mean value. The pseudo-Thellier data are nearly identical to the average NRM/ARM profile, which is not surprising for young sediments unaffected by viscous overprints. The standard deviation is low for all normalization methods and particularly low for the pseudo-Thellier method. The four normalization methods yield profiles with broad similarities but differ in the amplitudes of peaks and troughs. Notable differences occur in features at 2000-2500 radiocarbon years B.P., 3300–3700 radiocarbon years B.P., 4300-4800 radiocarbon years B.P., and 5000–7000 radiocarbon years B.P., which coincide with maxima and minima in the four grain size proxies (Figure 6). It has been generally assumed that if the three traditional normalization parameters (ARM, SIRM, and χ) yield similar profiles of relative intensity, then any one of the three parameters is an adequate normalizer. However, even the very subtle grain size variations observed here show that this cannot be true. ARM is more sensitive to finer grains and SIRM and χ are more sensitive to the coarser grains, which makes ARM/SIRM and ARM/χ powerful grain size proxies in environmental magnetism studies. If, for example, there is an increase in the proportion of finer grains, the NRM/ARM will decrease but NRM/SIRM will increase, which is observed at 900 cm (4800 radiocarbon years B.P.).

Power spectra of normalized intensity, normalization parameters, and coherence tests of the two are shown in Figure 9. At the 95% confidence level the normalized intensity is not

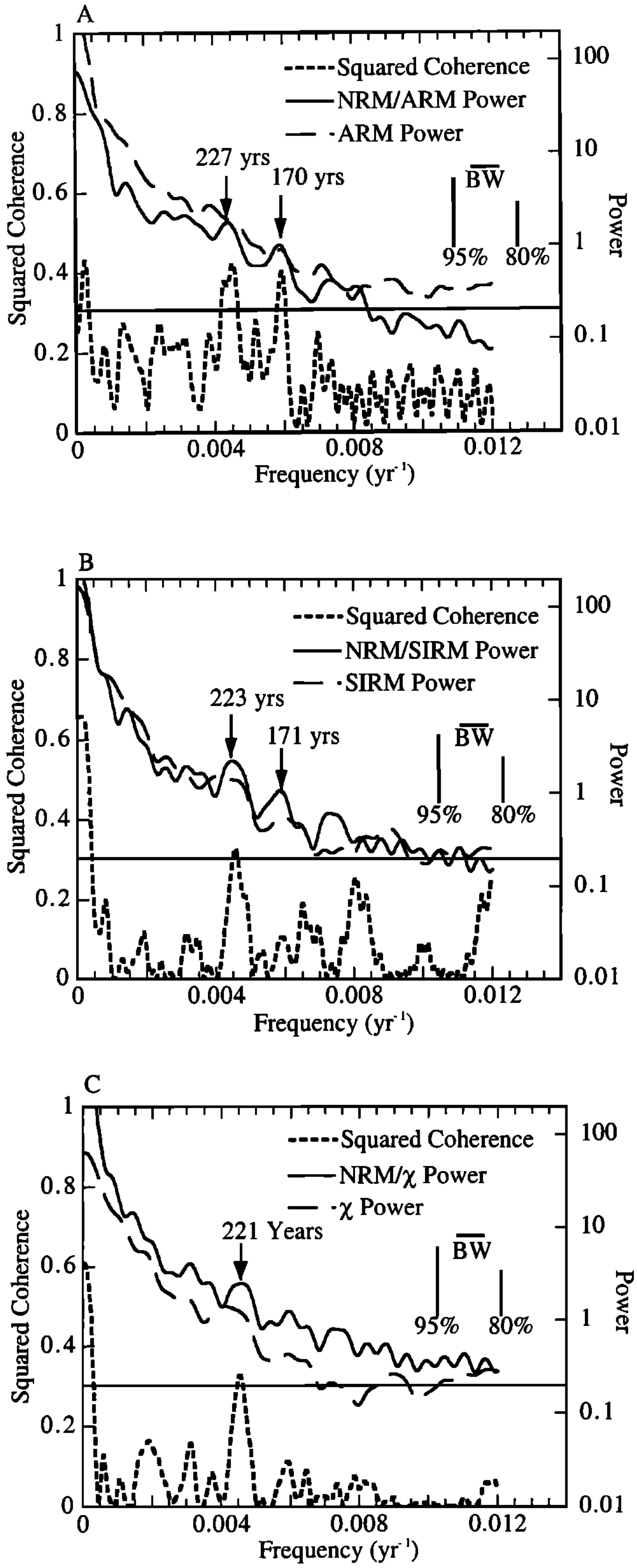

Figure 9. Coherence tests of normalized intensity with the normalization parameters. The solid horizontal line is the level above which coherence is considered significant at the 95% level. Vertical bars are significance levels for spectral power. BW is the bandwidth for 44 lags, or 30% of the series. (a) NRM/ARM and NRM, (b) NRM/SIRM and SIRM, and (c) NRM/χ and χ. In all cases, normalized intensity is not coherent with its normalization parameter. This test was not carried out for the pseudo-Thellier data due to a gap in the data set.

coherent with the normalizer except at periods of 170 years and 220-230 years. Normalized intensity spectra contain features at 200-230 years, but these only become significant below the 80% confidence level. There is a widespread geographic occurrence of 200-year cycles in a variety of terrestrial records such as ^{14}C anomalies in tree rings [*Stuiver and Braziunas*, 1993] and ^{10}Be concentrations in ice cores [*Raisbeck et al.*, 1990]. The 200-year cycles are well documented in Minnesota during the Holocene in varve thickness records from several lakes [*Anderson*, 1992; *Slawinski*, 1998]. The spectral feature at 200 years in the normalized intensity record is likely a climatic signal that has not been sufficiently removed by the normalization process.

Although these sediments are "uniform" and pass the coherence test described above, the significant differences between the four normalization methods suggest that some nonfield effects remain in the normalized intensity records. Coherence tests were repeated for normalized paleointensity and magnetic grain size proxies NRM MDF and H_{CR}. NRM/ARM is not coherent with any of the magnetic grain size proxies (Figure 10), but NRM/SIRM and NRM/χ are both strongly coherent with

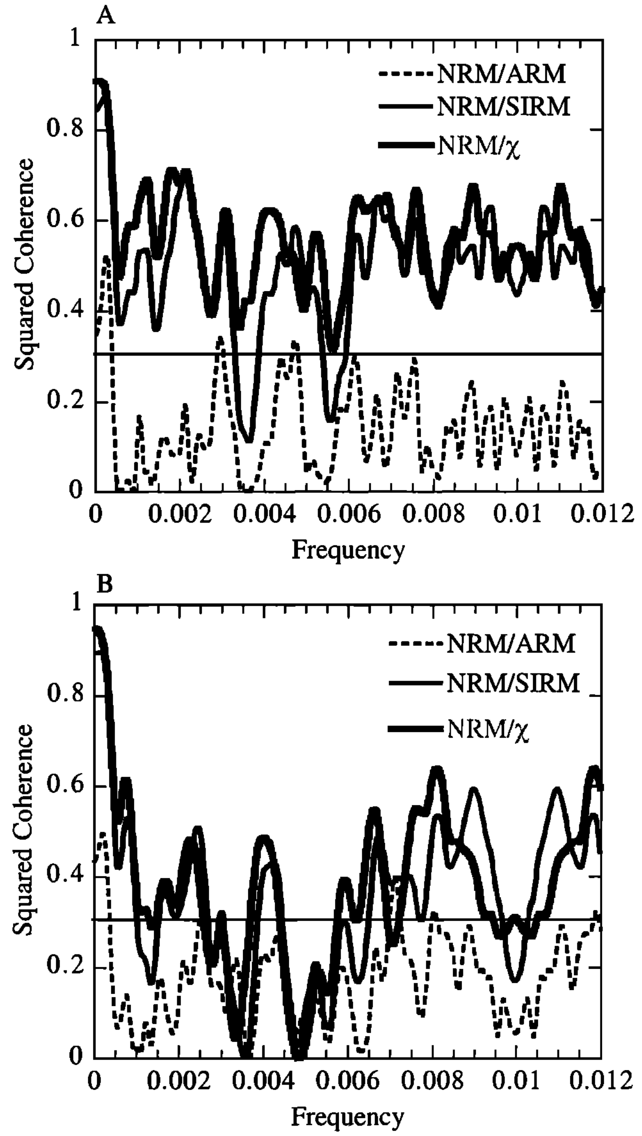

Figure 10. Tests of coherence between normalized intensity and (a) the NRM MDF and (b) H_{CR}.

both the NRM MDF and H_{CR}. This suggests that NRM/SIRM and NRM/χ have not been adequately normalized.

7.2. Comparison With ARCMAG and Lake St. Croix

We have compared our normalized intensity records with the relative paleointensity record from Lake St. Croix [*Lund and Schwartz*, 1999] and a compilation of absolute paleointensity measurements, termed ARCMAG by *Lund* [1996], obtained from Holocene archeological materials (bricks, ceramics) and basalts from the western United States [*Bucha et al.*, 1970; *Champion*, 1980; *Sternberg*, 1989]. The Lake St. Croix paleointensity curve is NRM_{20}/ARM_{20}, renormalized by dividing through by the trend in ARM coercivity [*Lund and Schwartz*, 1999].

ARCMAG chronology is based on radiometric dating and estimates of the timing of different cultures in the southwestern United States. We have placed the ARCMAG data in bins that are 50 to 250 years wide, as sample density and age uncertainty of the samples permit. The binned ARCMAG data set has been normalized to a mean of 1. The results are very encouraging. The NRM/ARM profile and the pseudo-Thellier profile are very similar to ARCMAG in both shape and amplitude over the interval 0-7000 radiocarbon years B.P. (Figures 11a and 11b). The standard deviation of the NRM/ARM is comparable with the intensity error bars for ARCMAG bins.

NRM/SIRM and NRM/χ show intervals of overcorrection and undercorrection (Figures 11c and 11d). NRM/SIRM is undercorrected over the interval 800 to 2500 radiocarbon years B.P. in which the magnetic mineral assemblage is dominated by finer grains. These grains are more efficient carriers of detrital remanent magnetization (DRM) and ARM than of SIRM and χ. The effect is even more pronounced in NRM/χ, which is undercorrected over the interval 800 to 3250 radiocarbon years

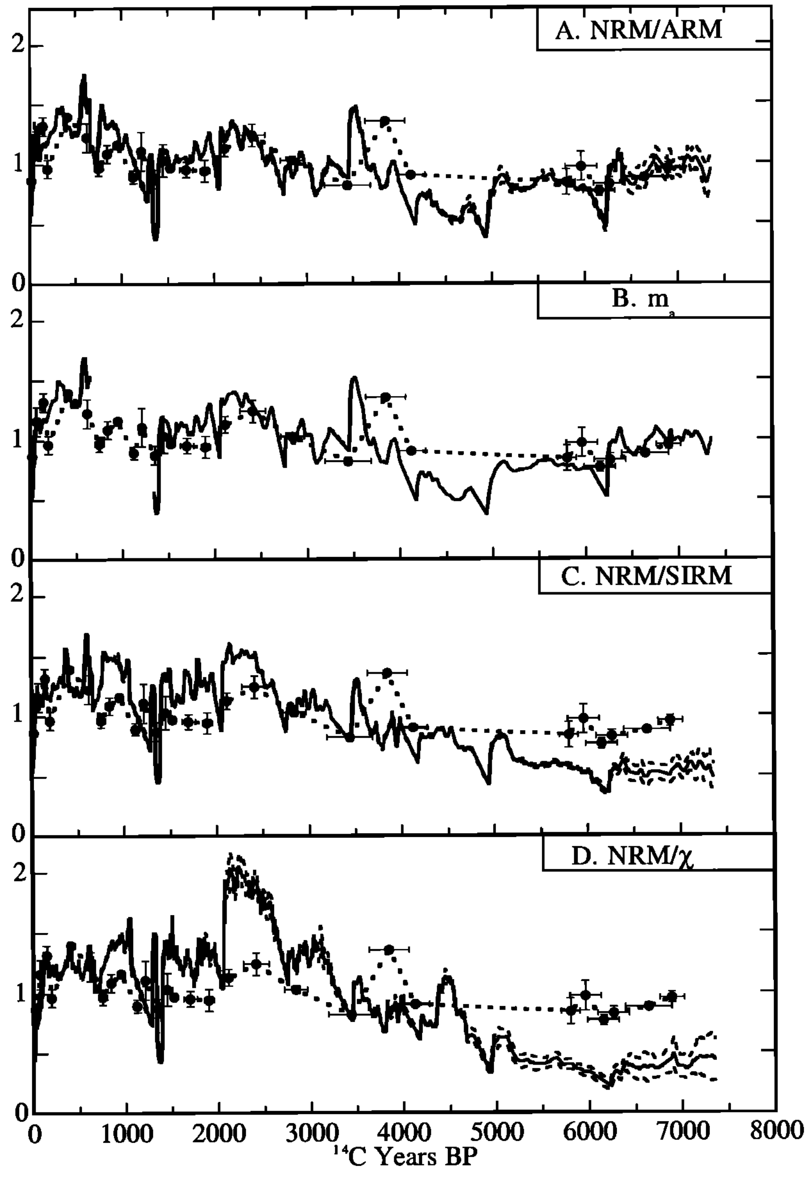

Figure 11. Normalized intensity (solid line) and absolute intensity (solid circles) for the past 8000 years in western United States. (a) NRM/ARM, (b) the pseudo-Thellier method, (c) NRM/SIRM, and (d) NRM/χ. ARCMAG data from *Bucha et al.* [1970] *Champion* [1980] and *Sternberg* [1989] have been binned. Bins are 50 to 250 years wide. Bins are narrowest over the last 1500 radiocarbon years B.P., where sample density is high and age uncertainty estimates are low.

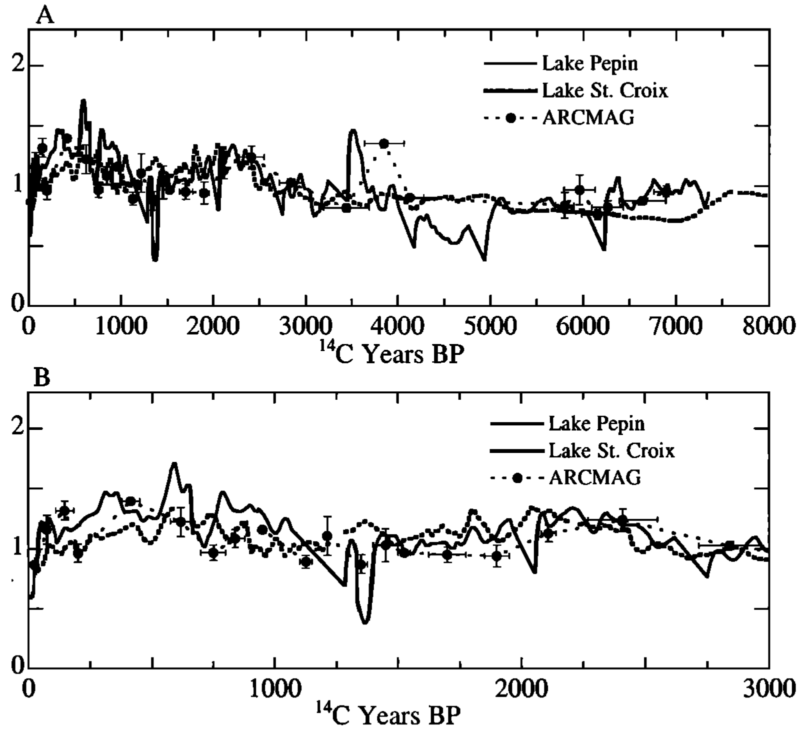

Figure 12. Paleointensity records from Lake Pepin (NRM/ARM), Lake St. Croix (NRM$_{20}$/ARM$_{20}$/ARM coercivity), and ARCMAG for (a) 0 to 8000 radiocarbon years B.P. and (b) 0 to 3000 radiocarbon years B.P. Features 1000 years long can be correlated between the three records.

B.P. NRM/SIRM and NRM/χ are both overcorrected over the interval 4000 to 7000 radiocarbon years B.P. Coarser grains that are more efficient carriers of SIRM and χ than of DRM dominate this interval. The relative paleointensity peak at 3750 radiocarbon years B.P. disappears entirely from the SIRM and χ-normalized records due to this overcorrection.

The Lake Pepin NRM/ARM record and the Lake St. Croix relative paleointensity record are very similar in shape and amplitude during the last 8000 radiocarbon years (Figure 12a). The most significant differences occur beyond 3000 radiocarbon years B.P., where the Lake St. Croix record is relatively flat but the Lake Pepin record continues to show variations. There is an

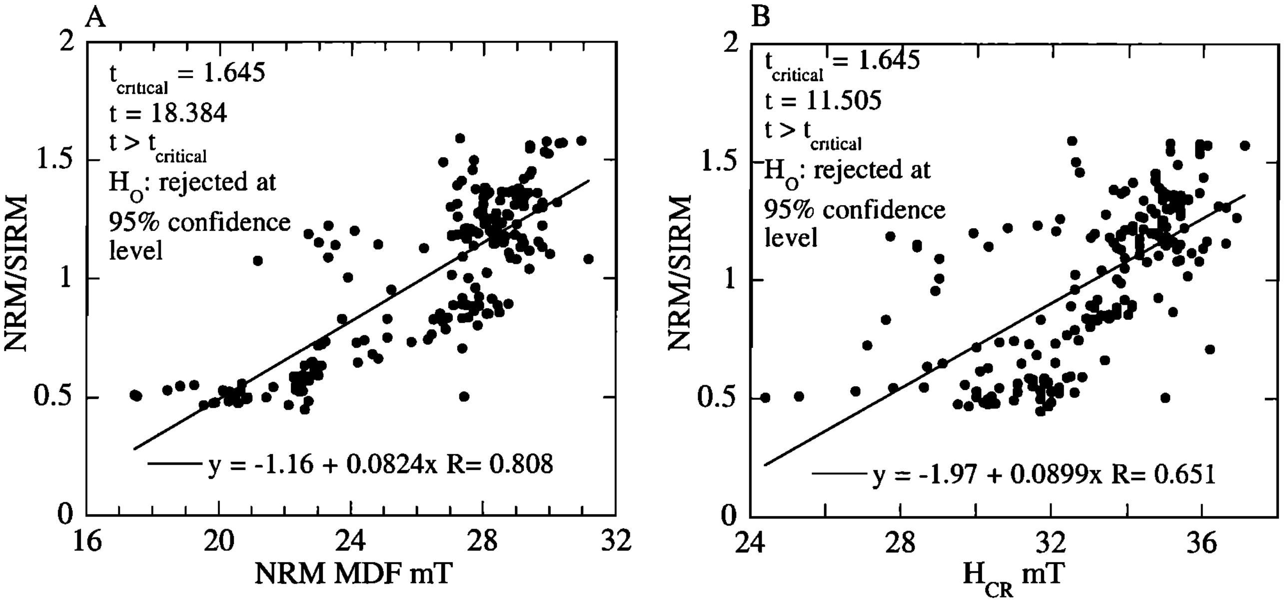

Figure 13. NRM/SIRM versus (a) NRM MDF and (b) H_{CR}. NRM/SIRM fails a test of independence with both magnetic grain size parameters. The regression line is used as a basis for a secondary normalization technique.

unfortunate gap in the ARCMAG data set between 4000 and 6000 radiocarbon years B.P., the interval of greatest discrepancy between the two lacustrine records. However, the two lacustrine records are quite similar over the last 3000 radiocarbon years B.P. (Figure 12b). Features with a wavelength of 1000 years are correlative between the Lake Pepin, Lake St. Croix, and ARCMAG records, suggesting that millennial-scale correlation based on paleointensity curves is indeed possible.

8. Grain Size Corrections

ARM is clearly the best choice of normalization parameters for the Lake Pepin sediments, which we can state with certainty since we have, by design, the benefit of the ARCMAG data set and the Lake St. Croix record for comparison. However, very long marine records, the current focus of relative paleointensity studies, do not yet have the benefit of a continuous volcanic sequence for comparison. In a scenario where all three normalized records show grain size contamination and the field is not known a piori, additional corrections would be required to extract reliable relative paleointensity data. We were interested in determining if grain size contamination could be removed from normalized intensity records. Of the available magnetic grain size proxies, the NRM MDF and H_{CR} are the best candidates for developing a grain size correction method. NRM MDF and H_{CR} are parameters that target the remanence stability of the recorders of DRM and the carriers of ARM and SIRM. H_C and M_R/M_S are determined by in-field measurements, and SP grains that do not contribute to DRM do influence both H_C and M_R/M_S. Further, NRM MDF and H_{CR} are both easily calculable from U channel data, which is becoming an increasingly popular sampling method for high-resolution, long-core sedimentary paleomagnetism and environmental magnetism studies [e.g. Weeks et al., 1993].

In designing a secondary correction we first investigated if there was a systematic relationship between normalized intensity and magnetic grain size. We focus here on NRM/SIRM in order to determine if a contaminated record can be improved. Clearly, NRM/ARM and the pseudo-Thellier method need no further correction. Figure 13 show plots of NRM/SIRM versus the MDF and versus H_{CR}. Lines fit to each data cloud have relatively high sample correlation coefficients (0.808 and 0.651, respectively). We used the correlation coefficients in order to carry out a test of independence between normalized intensity and magnetic grain size parameters [*Devore and Peck*, 1986]. The null hypothesis (H_O) is that normalized intensity and the magnetic grain size parameter are independent. The alternative hypothesis (H_a) is dependence. The test statistic is given by

$$t = \frac{r}{\sqrt{(1-r^2)/(n-2)}} \qquad (1)$$

where r is the sample correlation coefficient and n is the number of data points (n = 182 for the Lake Pepin data set). The t critical value is based on $n - 2$ degrees of freedom. The criterion for rejection of H_O is $t > t$ critical or $t < -t$ critical. H_O is rejected at the 95% confidence level for both magnetic grain size proxies.

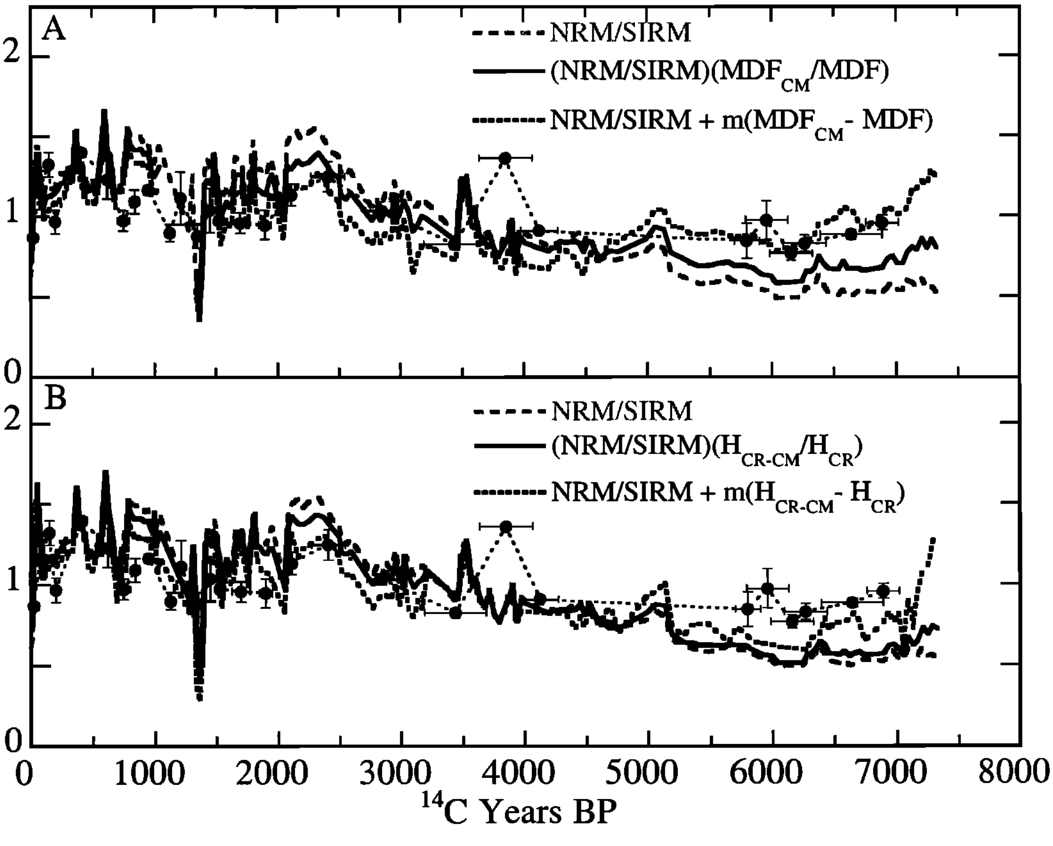

Figure 14. NRM/SIRM corrected using the ratio method and pivot method. (a) MDF_{CM} = 26 mT, m = 0.0824. (b) $H_{CR\text{-}CM}$ = 33 mT, m = 0.0899. NRM/SIRM corrected using the NRM MDF pivot method is significantly improved over the intervals 1500 to 3000 radiocarbon years B.P. and 5500 to 7000 radiocarbon years B.P.

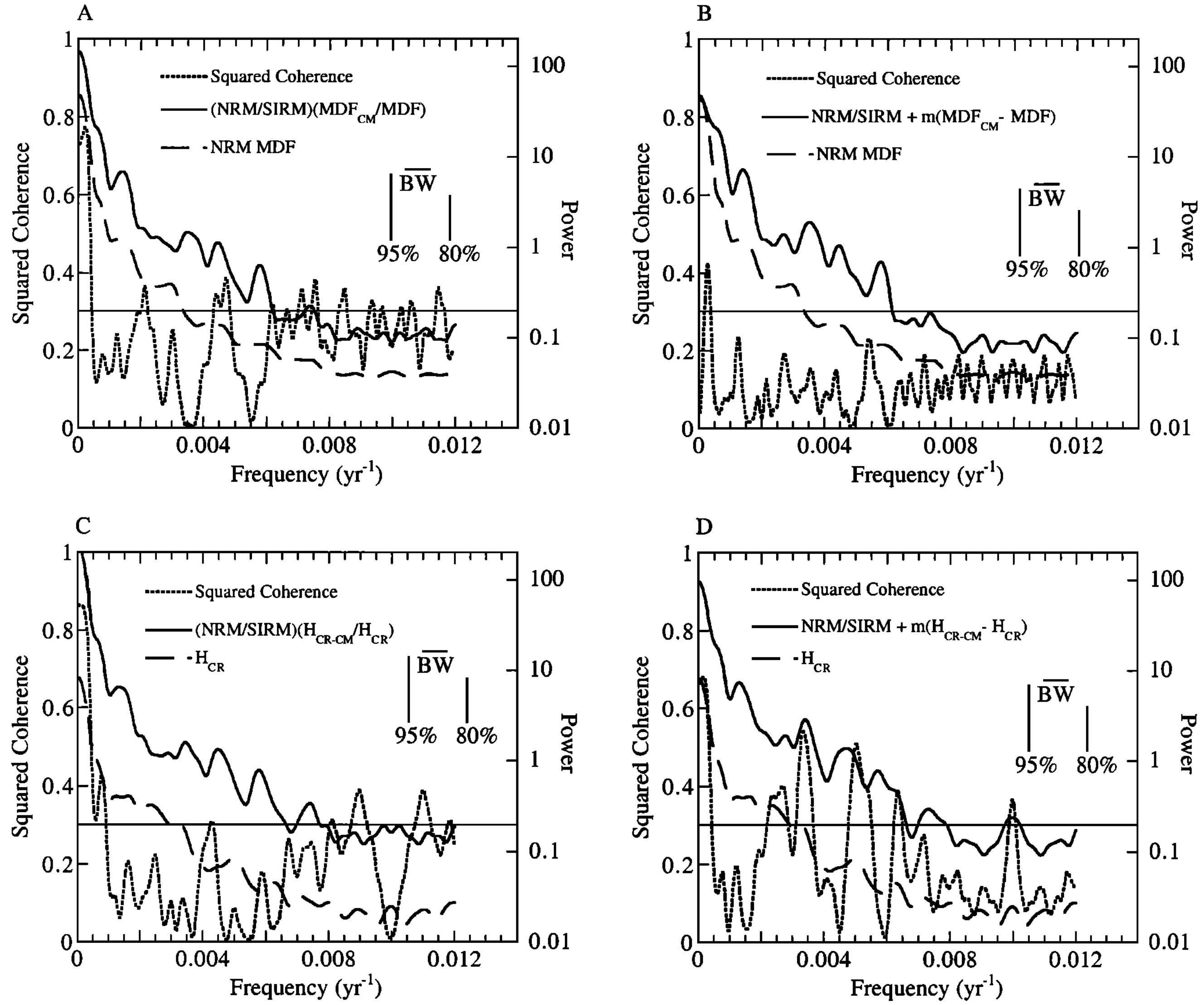

Figure 15. Coherence tests of corrected NRM/SIRM′ with MDF and H_{CR}. The solid horizontal line is the level above which coherence is considered significant at the 95% level. Vertical bars are significance levels for spectral power. BW is the bandwidth for 44 lags, or 30% of the series. (a) MDF ratio method, (b) MDF pivot method, (c) H_{CR} ratio method, and (d) H_{CR} pivot method. Only the NRM/SIRM′ corrected using the NRM MDF pivot method shows no coherence with magnetic grain size.

Therefore we feel that the simple linear relationship given by the regression line is a good starting point for developing a secondary correction.

We have tested two correction methods, one that revisits a technique proposed by *Sprowl* [1985] and one that uses the linear relationship discussed above. The first method uses a ratio of NRM MDFs and has the form

$$\mathrm{NRM/SIRM'} = (\mathrm{NRM/SIRM})(\mathrm{MDF_{CM}/MDF}) \qquad (2)$$

where $\mathrm{MDF_{CM}}$ is the value of the MDF at the center of mass of NRM/SIRM versus MDF cloud in Figure 13 and is 26 mT for these sediments. Points for which MDF < $\mathrm{MDF_{CM}}$ are those points that were overcorrected by SIRM and will have their relative intensity values increased. We have also applied this correction similarly using ratios of H_{CR}, where $H_{CR\text{-}CM}$ is 33 mT.

The second correction method uses the linear relationship between NRM/SIRM and MDF (and H_{CR}). This correction has the form

$$\mathrm{NRM/SIRM'} = \mathrm{NRM/SIRM} + m(\mathrm{MDF_{CM}} - \mathrm{MDF}) \qquad (3)$$

where m is the slope of the NRM/SIRM versus MDF line in Figure 13. We have also used this correction with H_{CR}. In this case $\mathrm{MDF_{CM}}$ (or $H_{CR\text{-}CM}$) is a pivot point about which the line in Figure 13 is rotated. Points to the left of $\mathrm{MDF_{CM}}$ or $H_{CR\text{-}CM}$ will have their relative intensity values increased, and points to the right will be decreased, both by an amount dependent upon their distance from the pivot point.

The results of both methods are shown in Figure 14. The pivot method based on MDF gives the best results. This method works particularly well at the base of the core in the coarse grain size intervals. However, the spectral feature at 200-230 years persists in all of the corrected NRM/SIRM′ spectra (Figure 15). NRM/SIRM′ corrected by the H_{CR} ratio method and by the H_{CR} pivot method both continue to be coherent with H_{CR}. NRM/SIRM′ corrected by the MDF ratio method continues to be coherent with the MDF. NRM/SIRM′ corrected by the MDF pivot method shows no coherence with MDF and is the best method of secondary correction for these sediments.

In any given sedimentary record the best choice of normalization parameter is the one that is free of magnetic mineral assemblage biases, and thus no further correction is needed. The correction discussed above should be reserved for the scenario where all traditionally normalized relative paleointensity profiles retain a grain size bias. In this situation a secondary correction such as the one described here could conceivably improve the relative paleointensity record.

9. Conclusions

Sediments from Lake Pepin that satisfy all current qualitative and quantitative tests for uniformity demonstrate that sedimentary records can yield geomagnetic relative paleointensity data with peak-to-trough amplitudes comparable to absolute intensity data sets. This is possible if the normalization method removes both concentration and grain size dependences from the NRM. ARM is clearly the best choice of normalization parameters for the Lake Pepin sediments, which are characterized by small PSD grains. NRM/ARM shows no coherence with magnetic grain size proxies and yields a record of normalized paleointensity that matches the shape and amplitude of both the ARCMAG absolute intensity record and the Lake St. Croix relative paleointensity record. Further, features with a wavelength of 1000 years are correlative between the three data sets. The Lake Pepin record provides new data that cover the gap in the ARCMAG dataset during the interval 4000–6000 radiocarbon years B.P., although there are discrepancies with the Lake St. Croix record. In Lake Pepin, NRM/SIRM and NRM/χ are affected by intervals of overcorrection and undercorrection, and both records show coherence with grain size proxies. A secondary correction to NRM/SIRM based on the linear dependence of NRM/SIRM on MDF greatly improved the correlation between NRM/SIRM′ and ARCMAG. Further, the MDF pivot method resulted in zero coherence between NRM/SIRM′ and MDF.

In view of our experience the selection process for the most appropriate normalization method for any sedimentary record should include a test of coherence of normalized intensity with a magnetic grain size proxy. We propose that MDF and H_{CR} are the best candidates for this test and subsequent corrections, as these parameters target the carriers of natural and induced remanences. Our observations in Lake Pepin suggest that ARM is an appropriate normalizer for sediments characterized by small PSD and SSD grains. Secondary corrections should be reserved for sediments characterized by larger PSD grains, or those for which all three normalization parameters yield relative paleointensity records that are coherent with magnetic grain size proxies.

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