Geomagnetic record in Minnesota lake sediments— Absence of the Gothenburg and Erieau excursions

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ABSTRACT

Several excursions of the geomagnetic field during the Brunhes epoch have been postulated on the basis of paleomagnetic data from sediments. It has further been suggested that these excursions may represent sudden fluctuations of the geomagnetic field, manifested especially in fluctuations of the local geomagnetic inclination. In this study we present high-resolution data of inclination variations recorded in the sediments of two Minnesota postglacial lakes. To the best of our knowledge, our data cover two overlapping time windows, 0 to 9600 B.P. and about 9000 to 16,000 B.P. The results strongly suggest that no excursions have occurred in Minnesota over the past 16,000 yr. Thus, it appears that the Gothenburg (Sweden) excursion at about 12,500 B.P. is not worldwide and that the regional Erieau (Lake Erie) excursion does not extend to Minnesota. We suggest that these two previously claimed excursions might not reflect geomagnetic field behavior but merely poor paleomagnetic "recording" within the sediments used for these studies.

INTRODUCTION

The first paleomagnetic study of North American lake sediments was made 41 yr ago (McNish and Johnson, 1938) using dry varved sediments from ancient glacial lakes in New England. Recent studies during the past eight years have shown that wet sediments cored from present-day lakes can also provide high-resolution records of past geomagnetic field variations (Mackereth, 1971; Creer and others, 1972; Dodson and others, 1977; Shuey and others, 1977; Vitorello and Van der Voo, 1977). Some of the potential problems associated with the dry, ancient lake sediments such as inclination errors (due possibly to mechanical stresses during the drying processes, Liddicoat, 1978, or to chemical remanence acquired during subaerial exposure) may be largely avoided in the wet sediments.

Even though wet lake sediments can provide an excellent record of geomagnetic field variations, other independent variables such as the sedimentation process itself can influence this record. If sedimentation varies significantly from "quiet sub-aqueous deposition" (which is the normal assumption for remanence acquisition in sediments), then serious angular deviations in the recorded magnetization away from the true magnetic field direction might occur. In addition, errors may be introduced during coring and recovery of lake sediments. Thus, for example, a column of sediment might become twisted within the core barrel, which could cause serious declination errors.

In order to investigate the fine-scale fluctuations in the geomagnetic field recorded in lake sediments, it is imperative to recognize and to circumvent the errors due to these nongeomagnetic variables. In our paleomagnetic studies we have tried to avoid them in the following ways. First, at least two independent and synchronous paleomagnetic records must be obtained from each lake. Second, each of these records must provide an estimate of the data variance as a function of depth (time). Third, lithologic control and radiometric dating must be used to determine accurately the age of the core, its sedimentation rates, and the possible presence of hiatuses. These three steps do not guarantee the realiability of the resultant paleomagnetic record, but, if there is disagreement between parallel records or if the inferred sedimentation process is abnormal, then the observed variations may be due to nongeomagnetic causes.

We present here the inclination results from a high-resolution paleomagnetic study of wet sediments using the above procedures from two postglacial lakes in Minnesota. We will compare these records with those from previous studies of the Great Lakes of central North America.

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The primary purpose of this comparison is to examine whether several "excursions" of stable remanence, which have been observed in Great Lakes sediments and attributed to geomagnetic origin, are observed in the Minnesota lake sediments. These and older "excursions" in the Brunhes normal polarity epoch have been reviewed by Verosub and Banerjee (1977), who concluded that the paleomagnetic records of excursions during the past 20,000 yr are often of poor quality but that either one or two of the reported excursions at about 10,000 and 15,000 B.P. may represent true field fluctuations. These excursions seem to last no longer than about 1,000 yr and are particularly striking in the inclination changes. Our data of detailed and reproducible records of inclination from two Minnesota lakes indicate that no excursions have occurred in Minnesota over the past 16,000 yr.

FIELD AND LABORATORY METHODS

Sediment cores were taken by means of a piston corer from Lake St. Croix in east-central Minnesota (lat 45.1°N, long 267.0°E) and from Kylen Lake in northeast Minnesota (lat 47.3°N, long 268.2°E). Two synchronous 19-m vertical cores, 5 cm in diameter, were obtained from Lake St. Croix, and three vertical cores, each between 3 and 5 m in length and 5 cm in diameter, were obtained from the bottommost sediments of Kylen Lake.

Each core was obtained by successive 1-m drives. The cores were taken in winter so that the frozen ice cover could provide a sturdy working surface. The individual coring locations at each lake were within 3 m of each other. While in the field, the cores were extruded smoothly with no visible distortions and wrapped first in a layer of thin plastic and then in aluminum foil. This type of double-wrapping prevented drying of the cores between the time of coring and later laboratory measurements.

The recovered sediments from Lake St. Croix, which extend from the sediment-water interface to the inferred bottom of the lake basin, are homogeneous and indistinguishable over their entire 19-m extent. The sediments are a silty mud throughout, with only a slight increase in the silt content in the top 1 m and in the bottom 1 m. Organic carbonaceous material is 10% ± 3% dry weight of the sediment at all depths. The recovered sediments of Kylen Lake, which are less homogeneous, represent only the bottommost portion of the entire sediment column. Core 75A begins 8 m below the sediment-water interface, whereas cores 75B and 75C begin 9 m below the same interface. In all three cores there is a basal silty sand (10 to 50 cm thick) that is overlain by dense muddy silt. The muddy silt changes gradually upward to a much finer grained, very organic-rich gyttja beginning 1.5 m above the basal sand in all three cores. This transition corresponds to the end of the Pleistocene in this region, based on ^{14}C (radiocarbon) ages and pollen analysis. All magnetic samples from the Kylen Lake cores were taken only from the fine-grained mud above the basal sand unit.

Samples from nine horizons from the 19-m-long St. Croix core 75B (Fig. 1) were dated using the radiocarbon method. In a similar manner, four radiocarbon ages were obtained from four horizons from the 4-m-long Kylen Lake core 75C

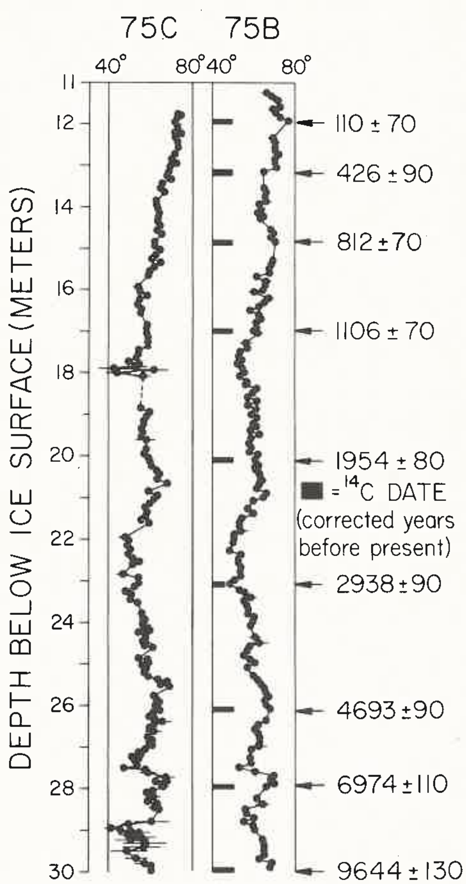

Figure 1. Paleomagnetic inclination for the past 9,600 yr from Lake St. Croix, Minnesota. Each dot represents the mean value of two subsamples taken at each sampling horizon. Error bars (±1σ) are shown only if they exceed the size of the dot (±2°). The two parallel but independent cores were obtained in winter, and the depth in each core was measured from the frozen lake surface. The sediment-water interface is at 11.2 m below ice surface.

(Fig. 2). On the basis of these ages, the sedimentation rate in the upper 12 m of St. Croix was very high, about 4 mm/yr; below 12 m the rate gradually decreases to about 1 mm/yr. Even at this lower rate, a 2-cm-thick sample contains material deposited, on average, in only 20 yr. The radiocarbon ages suggest that the 19-m sediment column from Lake St. Croix was deposited continuously between 9,600 B.P. and the present. This agrees with previous estimated based on geologic and pollen evidence (Wright, 1972; Eyster-Smith, 1978).

The average sedimentation rate in Kylen core 75C changes gradually from about 0.8 mm/yr at the top to about 0.3 mm/yr above the basal sand unit. With the exception of this basal sand unit, there is no evidence that hiatuses or abnormal fluctuations in the sedimentation rate of the Kylen cores occurred (H. E. Wright, Jr., 1979, personal commun.). On the basis of radiocarbon ages, the three cores from Kylen Lake cover at least the interval 9800 B.P. to 16,000 B.P. On the basis of the similar sedimentation rate in the basal 1.5 m (muddy silt) of all three cores, it is reasonable to expect that the upper 1 m of core 75A, which is the longest core, is less than 9,800 yr old, the age obtained from the top of core 75C.

In the laboratory, two 2-cm^3 subsamples

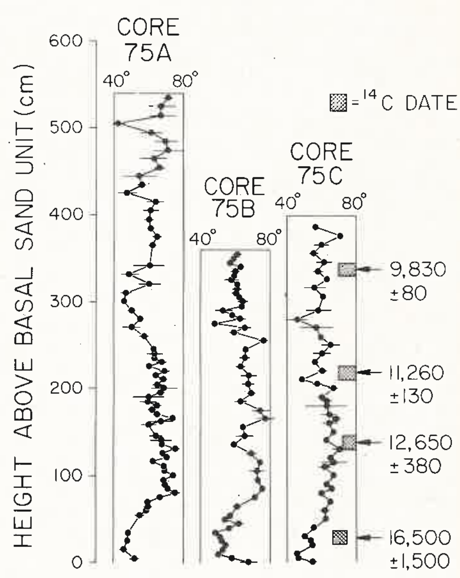

Figure 2. Paleomagnetic inclination for the period of about 16,000 to 9000 B.P. from Kylen Lake, Minnesota. Each dot represents the mean value of two subsamples taken from each sampling horizon. Error bars (±1σ) are shown only when they exceed the size of the dot (±2°). The heights of sample horizons are measured from a basal sand unit that is common to all three cores.

per horizon were collected from the cores at 5- to 10-cm intervals using a nonmagnetic mini-corer with a square cross section. The oriented subsamples were placed in tight-fitting plastic boxes of the same shape. Magnetic measurements were carried out in a two-axis superconducting rock magnetometer (SCT Corp.) whose noise per channel is about 1×10^{-8} emu. The signal from the empty plastic sample box is about 3×10^{-8} emu, and the intensity of the natural remanent magnetization (NRM) of the sediment samples ranges from 10^{-4} emu (St. Croix) to 10^{-5} emu (Kylen). For each sample, four independent measurements were made for each of the three axes of the sample.

Routine storage tests of a few days to several weeks in 0- ($\pm 5 \times 10^{-5}$ Oe) and 1-Oe magnetic fields were made on test samples from both lakes. It was found that the NRM of the Lake St. Croix samples contain essentially no secondary viscous remanent magnetization (VRM) but that as much as 20% of the NRM in Kylen Lake could be due to VRM. The NRM for selected samples from both lakes was demagnetized in progressively increasing peak alternating fields up to 1,000 Oe. The observed variations in intensity and direction of numerous samples were used to establish that 100 Oe was the optimum field for demagnetizing all the other samples for both lakes. After demagnetization at 100 Oe, the majority of the VRM in the Kylen Lake samples was eliminated.

Magnetite is the only magnetic material observed in Lakes St. Croix and Kylen, sediments as evidenced by X-ray diffraction and Curie point measurements.

St. Croix Results

Figure 1 shows the record of geomagnetic inclination obtained from the two independent, parallel St. Croix cores. Each point represents the average of two subsamples at each horizon after demagnetization at a peak field of 100 Oe. The variance (1σ) is signified by error bars; for most horizons the differences are less than 2°, and the error bars are included within the symbol. The two independent cores show excellent agreement with each other over their entire 19-m lengths. The data show that the geomagnetic inclination at St. Croix was of normal polarity over the past 9,600 yr; however, departures as high as ±15° from the axial dipole value of 63.5° can be observed at any one time. Semiperiodic features lasting for periods as short as 500 yr can be easily seen because of the detailed time resolution of the record and the reliable magnetic properties of the sediment.

The average inclinations for the 75B and 75C data sets are 61.2° ± 4.8° (1σ) and 60.3° ± 5.2°, respectively. These means are based on data averaged over 250-yr increments in the cores. They are both within 3° of the axial dipole inclination for this site. This 3° deviation is well within the limits of error expected for minor departures from a vertical coring direction or for minor sampling errors. We, therefore, see no a priori reason to postulate an inclination error for these data. This is further supported by laboratory redeposition experiments of natural sediments from Lake St. Croix (Levi and Banerjee, 1975).

Kylen Lake Results

Figure 2 shows the three independent inclination records from Kylen Lake, roughly 300 km north of the St. Croix site. The depth scale for the three Kylen cores, 75A, 75B, and 75C, is measured from above a basal sand unit that is common to all cores. As shown in Figure 2, four horizons from core 75C were dated by the radiocarbon method. The averages and error bars of the magnetic data were obtained from two subsamples per horizon as was done for the sediments of Lake St. Croix. The mean inclinations based on depth for these three cores are 62.3° ± 7.8° (A), 62.5° ± 7.4° (B), and 60.0° ± 6.1° (C). The average inclination for core C based on means of 250-yr intervals of the data is 60.1° ± 5.7°. Because the geocentric axial dipole inclination is 65.2°, we again see no need to postulate a primary depositional inclination error in the sediments. The dispersion of the inclinations at each horizon is greater for the Kylen Lake data (Fig. 2) than for the Lake St. Croix results (Fig. 1). One reason for this may be the persistence of some VRM in the "cleaned" magnetization. Nevertheless, the polarity is always normal, and the variation in inclination is similar to that observed in St. Croix. The visual agreement among the three cores is good, although not of the same quality as the intralake comparison in Lake St. Croix. Kylen cores 75B and 75C do not, unfortunately, overlap significantly in time with the St. Croix cores. However, Kylen core 75A may overlap, and the inclination variation seen between 400 and 500 cm appears to be repeated between 2,750 and 2,900 cm in Lake St. Croix (Fig. 1). Furthermore, the inferred age of this interval of Kylen sediment based on the radiocarbon ages is consistent with the comparable interval in the Lake St. Croix sediments (2,750 to 2,900 cm).

The declination was also measured in all these cores; however, azimuthal offsets between core segments produced discontinuities in declination at the core-sediment boundaries. Various methods are under study to "reorient" these sediments, and these results, together with a more detailed study of the rock magnetism and secular variation, will be presented in a future paper. Within each core segment, however, the declinations never vary by more than about 30° and provide no evidence for a large fluctuation in declination over the past 16,000 yr. Longer cores from Kylen Lake have now been obtained to provide a more complete overlap between the records of the two lakes.

DISCUSSION

The inclination data from Lakes St. Croix and Kylen, as shown in Figures 1 and 2, demonstrate two points. The first is that small postglacial lakes can provide high-quality, continuous geomagnetic records for the past 10,000 to 20,000 yr. This is shown by the reproducible paleomagnetic results from multiple cores in both lakes and by the smooth sedimentation rates implied by radiocarbon ages. Other studies of lake sediments, notably the Great Lakes studies of Creer and others (1976a, 1976b), Dodson and others (1977), Anderson and others (1976), and Vitorello and Van der Voo (1977), have been hampered by a lack of good radiometric time control and the possibility of sharp changes in sedimentation rates and/or local hiatuses in deposition.

The second point is that there is no evidence for abnormal behavior or excursions of the geomagnetic field over the past 16,000 yr in Minnesota. Several authors have claimed that, in addition to secular variation of the geomagnetic field, there have also been sharp excursions in the field direction. These excursions, lasting only about 1,000 yr, are characterized by virtual geomagnetic poles with equatorial or even reversed positions. If real, these excursions would be of great use for magnetostratigraphy and for theoretical studies into the origin of the geomagnetic field. After reviewing the existing paleomagnetic data, Verosub and Banerjee

(1977) concluded, however, that only a few of these proposed excursions might represent real geomagnetic fluctuations; the rest, especially those recorded in sediments, are probably caused by disturbance of the sediment during its recovery or by imperfect recording of the geomagnetic field during deposition.

The most notable of these excursions is the Gothenburg (Sweden) event of Mörner and Lanser (1974) at about 12,000 B.P., which, they suggest, was worldwide in extent. The validity of this fluctuation was seriously questioned, however, by Thompson and Berglund (1976), who failed to observe the Gothenburg event in two parallel cores from southern Sweden that spanned the period 13,000 to 11,000 B.P. Our data further confirm the observations of Thompson and Berglund, because our data also provide no evidence for an excursion of the geomagnetic field around 12,000 B.P. in Minnesota.

A regional excursion (the Erieau excursion) has been proposed by Creer and others (1976b) on the basis of their study of Lake Erie sediments. This excursion was dated indirectly as starting at about 14,000 B.P. and ending at a horizon whose age is somewhere between 10,500 and 7,600 B.P. The excursion manifests itself as a change in inclination from about $-90°$ to $+90°$ recorded in a glacial clay horizon sandwiched between a basal till and an upper, lithologically more uniform postglacial mud.

The records from Minnesota span continuously this entire time range and show no inclination below 45°. The sampling interval at Kylen Lake was typically 75 yr and never more than 200 yr; thus, at least 17 sampling horizons from Kylen Lake should have had similar low inclinations if the Erieau excursion of 3,500+ yr is to be observed in Minnesota. Because the core recovery of the Lake Erie glacial clays containing the excursion was poor (about 75%) and because its expression is strongest at the upper and lower lithologic boundaries, it is possible that the Erieau excursion is an artifact of either poor magnetic recording or disturbance of sediment during coring.

Finally, several other anomalous inclination records are known from the Great Lakes in this general time span from 0 to 16,000 B.P. (Dodson and others, 1977; Anderson and others, 1976; Vitorello and Van der Voo, 1977). However, only the Lake Michigan records of Vitorello and Van der Voo showed results that are reproducible in more than one core. They show two short swings in inclination to about $+10°$. The first was in the Winnetka bed, and the second was in the lower lying Carmi bed. Both of these features are potentially correlatable in time to the Erieau excursion; however, neither shows the extent or degree of inclination change that the Lake Erie sediments show. Although these two short features do contain lower inclinations than are seen in our Minnesota lakes, we see no reason at present to deny their existence.

CONCLUSIONS

The inclination results that we have presented here provide clear evidence for the reproducibility of paleomagnetic records recovered from small postglacial lakes. The use of several radiocarbon ages from each core has provided important proof of the smoothly varying sedimentation history for both lakes, which argues forcefully against any significant hiatus in sedimentation. Finally, our observations of the magnetic inclination over the past 16,000 yr suggest that neither the Gothenburg event nor the Erieau excursion was recorded in Minnesota. We feel that the Erieau excursion is more likely a result of either poor magnetic recording or disturbance of the sediment during coring.

REFERENCES CITED

Anderson, T. W., Richardson, R. J., and Foster, J. H., 1976, Late Quaternary paleomagnetic stratigraphy from east-central Lake Ontario: Geological Survey of Canada Paper 76-1C, p. 203–205.

Creer, K. M., Thompson, R., and Molyneaux, L., 1972, Geomagnetic secular variation recorded in the stable remanence of recent sediments: Earth and Planetary Science Letters, v. 14, p. 115–127.

Creer, K. M., Anderson, T. W., and Lewis, C.F.M., 1976a, Quaternary geomagnetic stratigraphy recorded in Lake Erie sediments: Earth and Planetary Science Letters, v. 31, p. 37–47.

Creer, K. M., Gross, D. L., and Lineback, J. A., 1976b, Origin of regional geomagnetic variations recorded by Wisconsinan and Holocene sediments from Lake Michigan, U.S.A., and Lake Windermere, England: Geological Society of America Bulletin, v. 87, p. 531–540.

Dodson, R. E., Fuller, M. D., and Kean, W. F., 1977, Paleomagnetic records of secular variation from Lake Michigan sediment cores: Earth and Planetary Science Letters, v. 34, p. 387–395.

Eyster-Smith, N., 1978, Holocene pollen stratigraphy of Lake St. Croix, Minnesotate-Wisconsin, and some aspects of the depositional history [M.S. thesis]: Minneapolis, University of Minnesota, 128 p.

Levi, S., and Banerjee, S. K., 1975, Redeposition of, and DRM experiments using lake sediments [abs.]: EOS (American Geophysical Union Transactions), v. 56, p. 977.

Liddicoat, J., 1978, A paleomagnetic study of late Quaternary dry-lake deposits from the western United States and basin of Mexico [Ph.D. thesis]: Santa Cruz, University of California, 465 p.

Mackereth, F.J.H., 1971, On the variation in direction of the horizontal component of remanent magnetization in lake sediments: Earth and Planetary Science Letters, v. 12, p. 332–338.

McNish, A. G., and Johnson, E. A., 1938, Magnetization of unmetamorphosed varves and marine sediments: Terrestrial Magnetism, v. 43, p. 401–407.

Mörner, N. A., and Lanser, J. P., 1974, Gothenburg magnetic 'flip': Nature, v. 251, p. 408–409.

Shuey, R. T., Ugland, R. O., and Schmit, C. R., 1977, Magnetic properties and secular variation in cores from Yellowstone and Jackson Lakes, Wyoming: Journal of Geophysical Research, v. 82, p. 3739–3746.

Thompson, R., and Berglund, B., 1976, Late Weichselian goemagnetic 'reversal' as a possible example of the reinforcement syndrome: Nature, v. 263, p. 490–491.

Verosub, K. L., and Banerjee, S. K., 1977, Geomagnetic excursions and their paleomagnetic records: Reviews of Geophysics and Space Physics, v. 15, p. 145–155.

Vitorello, I., and Van der Voo, R., 1977, Magnetic stratigraphy of Lake Michigan sediments obtained from cores of lacustrine clay: Quaternary Research, v. 7, p. 398–412.

Wright, H. E., Jr., 1972, Glacial geology of Minnesota, *in* Sims, P. K., and Morey, G. B., eds., Geology of Minnesota: Minnesota Geological Survey, p. 515–548.

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