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PALAEOMAGNETIC SECULAR VARIATION STUDIES OF FINNISH LAKE SEDIMENT AND THE CARRIERS OF REMANENCE

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Palaeomagnetic and mineral magnetism measurements have been carried out on two cores from Lake Vuokonjarvi in Finnish Karelia. The sediment probably covers 5000 years of continuous deposition at a mean sedimentation rate of about 0.8 mm/yr.

The magnetic declination exhibits fluctuations of similar amplitude (~20°) and character to those recorded in northern England and northern Ireland. Magnetic inclination variations are of higher amplitude (~15°) than those found in Britain. Matching the palaeomagnetic patterns with the dated British master curves permits an estimate of the rate of deposition of the Finnish sediments, which is suggested to be more reliable than estimates from radiocarbon dating of the Vuokonjarvi sediment.

The stable natural remanence is shown to be carried by fine-grained magnetite and titanomagnetite grains and to have grown by post-depositional alignment during a period of the order of 100 years. Laboratory dehydration of the sediment results in loss of around 40% of the stable natural remanence. Such behaviour is also found in lake sediments from central and southern Europe and should be considered in interpreting palaeomagnetic data from dried out lake sections and ocean cores.

1. Introduction

Historic documentation of the geomagnetic field permits spatial and temporal analyses over the last 400 years (e.g. [1]). Remanent magnetism in post-Glacial organic limnic sediments extends the records of relative declination and inclination to 10,000 years B.P. in northern Britain 54°N, 5°W (e.g. [2,3]). The variations in declination and inclination found in the limnic cores are of similar amplitude to those of the historic records. Post-Glacial sediments were collected in eastern Finland (64°N, 30°E) in order to investigate the spatial change of the long-period geomagnetic variations and hence investigate their generation.

The carrier and origin of the stable natural remanent magnetization (NRM) was investigated in detail, as the mode and length of time of stabilization of the remanence will largely determine the resolution of geomagnetic fluctuations preserved in the sediments.

2. Collection and sampling

The most recent deglaciation of eastern Fennoscandia proceeded from east to west [4]. Sediment was collected from the east of Finland in order to obtain as long a record as possible and to increase the geographic coverage of secular variation changes. Lake Vuokonjarvi was one of four chosen in Finnish Karelia as being of sufficient depth for coring, of palaeobotanical interest to the Ecology Section of the Karelian Institute of Joensuu University and suitable for ^{14}C dating.

Mackereth [5] 6-m corers were used to collect a continuous sequence of sediment from Vuokonjarvi. Two cores were taken from the flattest and deepest central section of the lake in 8 m of water. Core 1 was rather short (4.5 m) and a longer core 2 (5.9 m) was obtained from an anchored buoy at the same locality as core 1 after replacing the Kullenburg seals of the corer. The sediment cores were transported to

Edinburgh unopened in their UPVC liners.

After measurement of horizontal remanence and susceptibility had been made on the whole cores, the core tubes were cut into 1.5-m lengths, slotted on a circular saw and opened using a sharp knife. Plastic sample holders of 20 mm square section and 17 mm height were inserted into one half of the split core sections. The other halves were preserved for ^{14}C and later analyses.

3. Palaeomagnetic measurements

Preliminary investigations of the NRM carried by the two sediment cores were made using a Digico long core spinner magnetometer [6] and long core susceptibility bridge [7]. After opening and subsampling of the cores, the NRM of the individual subsamples was measured on a Digico balanced fluxgate spinner (modified from Molyneux [8]) with a noise level of 0.1×10^{-6} G. The initial, reversible susceptibility of the subsamples was measured on an air cored bridge (modified from Molyneux and Thompson [7]) with a noise level about 0.2×10^{-6} G/Oe.

Alternating field cleaning up to peak fields of 800 Oe was performed with an electronically ramped 304 c/s oscillator circuit [9]. The coil was enclosed in a 0.6 m wide cylindrical triple mu-metal shield in order to reduce the ambient field and field gradients.

Continuous low-temperature demagnetization was carried out in a Dewar surrounded by a Digico balanced fluxgate system. Liquid nitrogen was used for cooling in the Dewar. The declination and intensity of NRM of the sample could be monitored continuously as the temperature (measured by a copper constanan thermocouple inserted into the sediment) decreased.

4. Sedimentary and magnetic stratigraphy

The sediment in the two cores is composed of gyttja (organic mud) and clay. A narrow layer of stiff grey clay at the top of the cores, corresponding to the higher magnetic intensity and susceptibility values found in this part of core 2 (Fig. 2), grades down into brownish grey gyttja which in turn passes into a banded clay section at about 3 m. This change does not appear as a significant feature in the intensity and susceptibility records which both continue to increase gradually, although there is a decrease in the rate at which this occurs. There is no visible layer in the sediment corresponding to the anomalously low intensity and susceptibility measurements made at around 3.7 m in core 2. The bands in this section are green and black and up to 1 cm in width with the black bands tending to be narrower than the green. The bands are too wide to represent any annual variations in deposition. Beneath the banded section the sediment again changes character, becoming light grey clay at 4.5 m which is very stiff near the base of the core. This sedimentological change is represented by increased intensity and susceptibility values, with the Q-ratio becoming more constant (Fig. 2). Anomalous intensity measurements are found for the two samples between 4.12 and 4.17 m depth (Fig. 2) associated with aberrant directional data (which have not been included in Fig. 1 or Fig. 3).

The results of X-ray fluorescence analyses on sediment taken at intervals from core 2 show a gradual increase down the core for K (2–3.5%), Fe (6–9.5%), Al (11–16%) and Mg (2.3–4%). There are no significant peaks in these elements, taken to be indicators of erosion by Mackereth [10]. Slightly higher percentages of these minerals were found in a sample taken from a depth of 2.78 m but the susceptibility record does not show increased values near this depth. The organic carbon content of these samples was also investigated and revealed an overall decrease down the core from 6% near the top to 1% near the base.

5. Palaeomagnetic direction variations

Vuokonjarvi declination logs of both NRM and partially demagnetized remanence are shown in Fig. 1. Well-defined swings can be seen in both the centred declination and inclination records (Fig. 3). The character of all the records changes at 4.5 m depth. Below 4.5 m the scatter of directions is greater but the overall variation rate is lower, reflecting a faster rate of deposition in the lowermost sediments. The uppermost declination swings have a similar character to oscillations recorded in British lakes (e.g. Lake Windermere, Fig. 1) and Lake Lojarvi [11] in

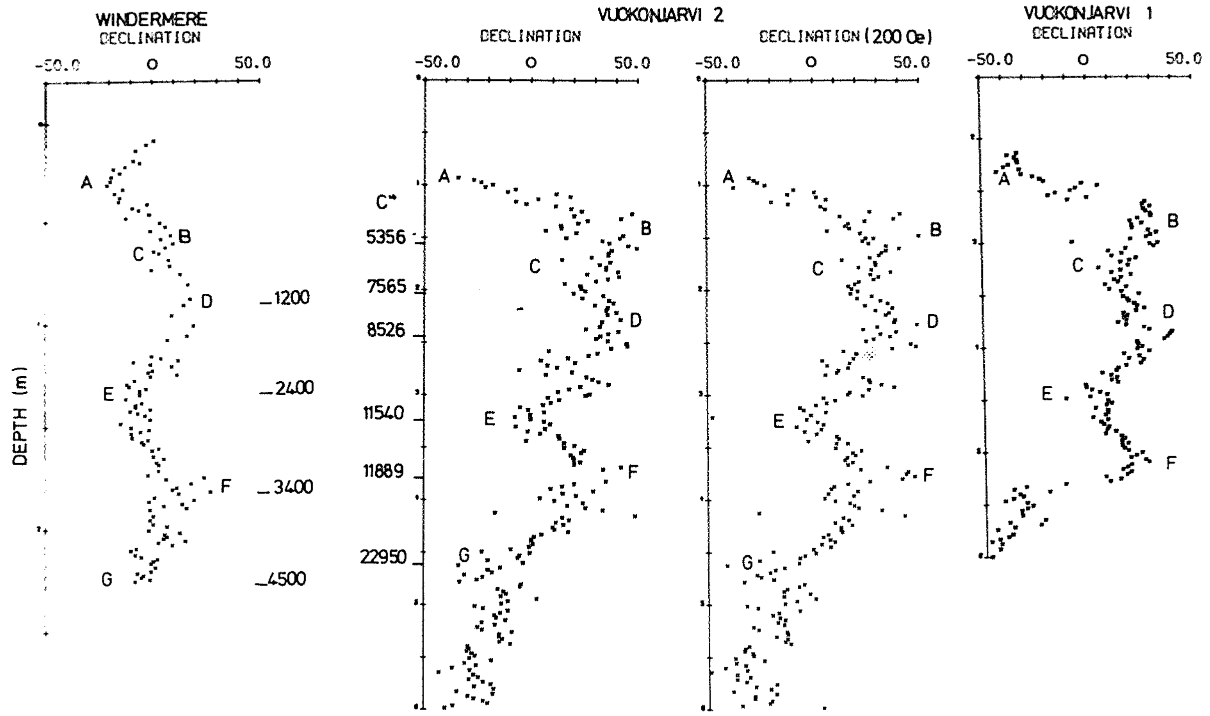

Fig. 1. Palaeomagnetic relative declination logs for Vuokonjarvi core 2 (NRM and partially demagnetized at 200 Oe), Vuokonjarvi core 1 (200 Oe), and Lake Windermere. Conventional radiocarbon age determinations (Windermere data from Mackereth [2]).

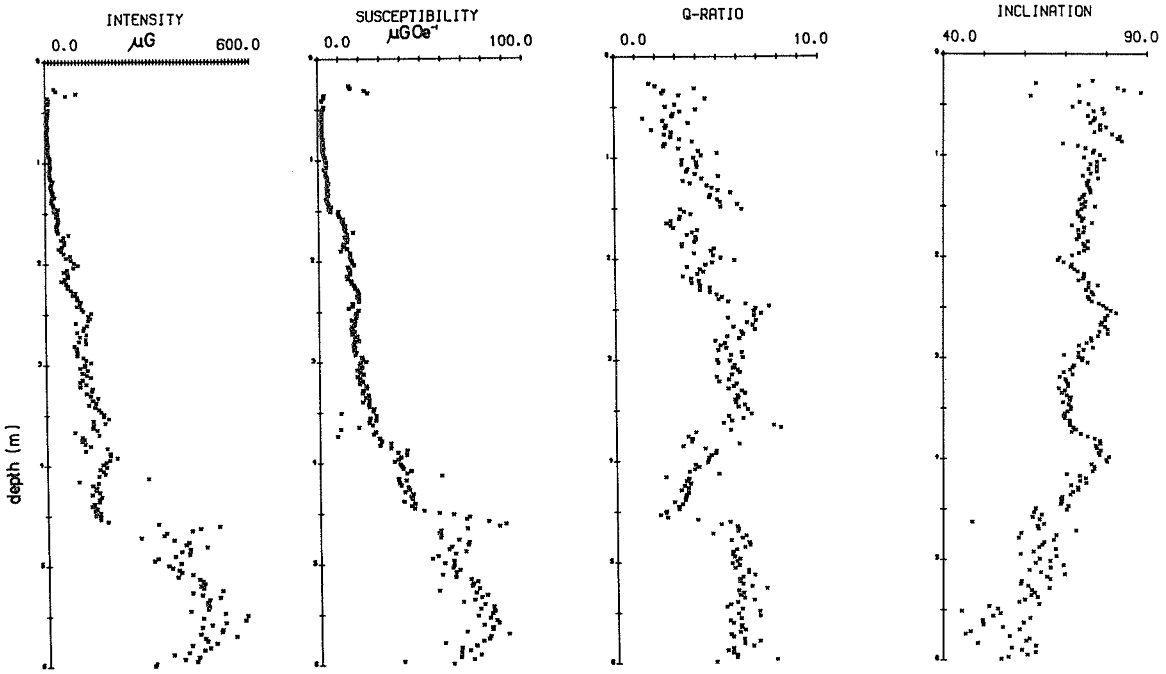

Fig. 2. Natural magnetic remanence (J), initial reversible susceptibility (χ) and modified Koenigsberger ratio (Q) and inclination logs for Vuokonjarvi core 2.

southern Finland. In contrast the inclination oscillations (Figs. 3 and 4) are of larger amplitude than those recorded in Lake Windermere [3] and more closely resemble results from the eastern Mediterranean [12,13].

In order to compare the variations of declination and inclination between cores 1 and 2, we have stretched the depth scale of core 1 to fit the scale of core 2 by matching 13 characteristic features of the magnetic susceptibility records. The stretching was achieved by fitting a cubic spline through the 13 depth pairs (Fig. 4). New stretched depth values for all the old depth values of core 1 were obtained from the cubic spline of Fig. 4. Stretching was carried out for the longest undisturbed section of core 1 which corresponds to depth values between 1.2 m and

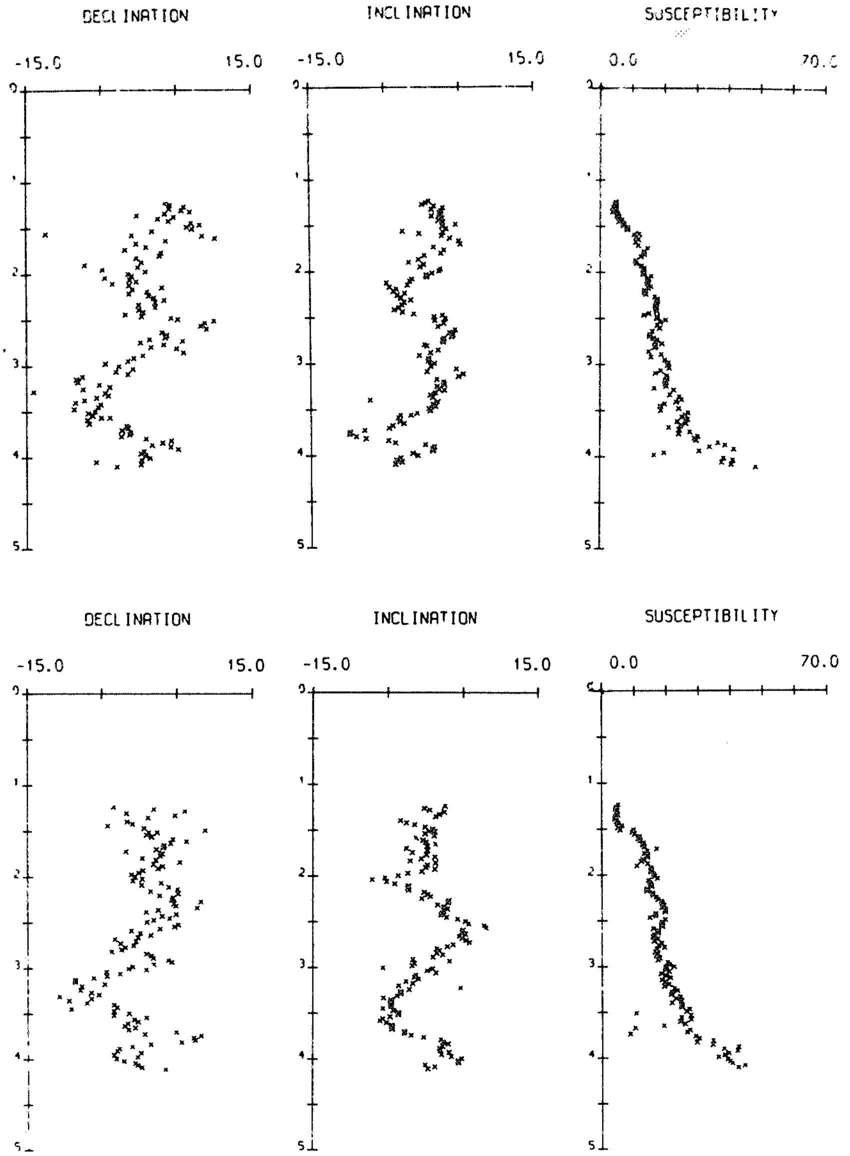

Fig. 3. Rotated declination and inclination for Vuokonjarvi cores 1 (top) and 2 (bottom). Core 1 stretched to match depth scale of core 2 using susceptibility features (see Fig. 4).

4.2 m in core 2. The depth pairs of Fig. 2 lie very close to a straight line of gradient 0.92 which suggests that linear stretching could have alternatively been applied. Other objective stretching methods are under investigation in conjunction with R.M. Clark and will be reported in a later paper.

To improve further the comparison of the paired declination and inclination values, the directions were rotated firstly so that the mean declination was centred to zero and secondly so that the mean inclination was zero. The resulting stretched and rotated declination and inclination logs are shown in Fig. 3.

In previous studies of palaeomagnetic direction logs, the above procedure has not been considered. However, plots of natural declination and inclination can be misleading and the above method of presentation is useful when (1) the natural inclination is high, and (2) the rotated inclination variations are equivalent in amplitude to rotated declination variations. The above procedure could not be adopted for the Lake Windermere results of Fig. 1 as the declination values of Mackereth [2] were not paired with inclination values.

Inspection of Fig. 3 shows a reasonably clear similarity in rotated declination between V1 and V2 over the whole depth range, and in inclination between 1.2 and 3.0 m. However, between 3.0 and 3.7 m there is a discrepancy of over 5° in rotated inclination. Techniques for assessing correlations between declination and inclination pair logs are being developed in collaboration with R.M. Clark as an extension to the cross validation method adapted by Clark [14]. Without such statistical methods it is difficult to judge the correlation of the direction pairs in Fig. 3. However, we feel the close similarity of the declination logs lends support to the remanence directions of core 2 being a reliable representation of past geomagnetic field changes in eastern Finland.

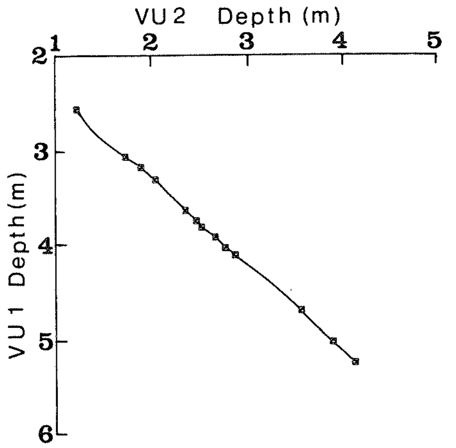

Fig. 4. Vuokonjarvi core 1 vs. core 2, depth scales matched using 13 susceptibility features and cubic spline interpolation.

The general sense of motion of the magnetic vector, between 3.0 and 1.2 m, is anticlockwise (i.e. opposite to that in observatory records) and in character more resembles that of European archaeomagnetic records [15], thus lending further support to suggestions that westward drift of the geomagnetic field has not been a continuously dominant phenomena over the last 10^4 years.

Radiocarbon age determinations of Vuokonjarvi sediment (Fig. 1) are almost certainly erroneous, producing ages in excess of the age of deposition of the sediment. The close similarity of the declination records of Windermere and Vuokonjarvi suggests they are magnetic signatures of synchronous geomagnetic fluctuations and that more realistic age determinations can be obtained by matching the declination features. Because of the apparent cyclic nature of the declination fluctuations, firm correlations cannot be established until the fine structure of individual cycles is recognisable. Thus a less likely, but possible, correlation is that the uppermost Windermere oscillation is absent at the top of Vuokonjarvi core 2 and the westerly swing at 3.2 m corresponds to the 4500-year swing in Windermere and the break in rate of deposition at 4.5 m depth reflects the facies change from late-Glacial to post-Glacial sedimentary environments. Pollen assemblage zonation of the Vuokonjarvi material would enable dating by comparison with local peat profiles (in which the ^{14}C dating problems are reduced because of the minimal allochthonous input) and hence a more detailed assessment of Finnish geomagnetic secular variation.

6. Identification of remanence carriers

The sediment thus appears to carry a record of past geomagnetic field variations over the time during which it accumulated. It is of interest to know which mineral or minerals carry the stable NRM in order to gain insight into the mode of origin, and hence length of time of stabilization of remanence, and to determine which lakes will be amenable to future palaeomagnetic investigations. Also to know the total magnetic mineralogy which carries the susceptibility and isothermal magnetic remanence (IRM) is of importance for correlating sequences and for tracing erosion and environmental changes in the drainage basin [16,17].

6.1. Coercivities

Partial step alternating field (AF) demagnetization of pilot samples from core 2 showed the NRM to be stable with a median destructive field (MDF) between 300 and 400 Oe. The detailed behaviour of AF demagnetization of NRM is illustrated in Fig. 5.

When samples were given an IRM in steps up to 10 kOe, the majority saturated at about 2 kOe. The exceptions to this were samples from the uppermost part of the sequence where the magnetization continued to rise as the applied field was increased to the maximum of 10 kOe. The coercivity of remanence (HCR) for these samples was about 550 Oe compared with values between 300 and 400 Oe for most of the lower sediments. The IRM acquired above 2 kOe is most likely to be carried by fine-grained haematite, but this is evidently not a major carrier of NRM since it would give rise to a much higher coercivity of NRM than is observed.

6.2. Dehydration

It was found that when samples were dried in air they lost between 30 and 40% of their NRM. The loss of remanence was proportional to the decrease in weight (Fig. 6). In order to investigate the role of water in the samples more closely, a series of experiments was carried out on samples in different physical states.

One experiment involved three adjacent samples which possessed very similar NRM intensities (~25 μG). Two were dried in air and then all three were demagnetized before being placed in a field of 10 Oe. Distilled water was added to one of the dried samples. The remanence grown was measured at intervals and then the field was reversed. All three samples showed the same shape of curve of acquisition of remanence (Fig. 7), but the dry sample gained only 63% of that of the fresh sample, while the wetted gained 85% of the remanence of the fresh one. On reversing the field direction after $4\frac{1}{4}$ hours the direction of remanence in all three samples also reversed (Fig. 7).

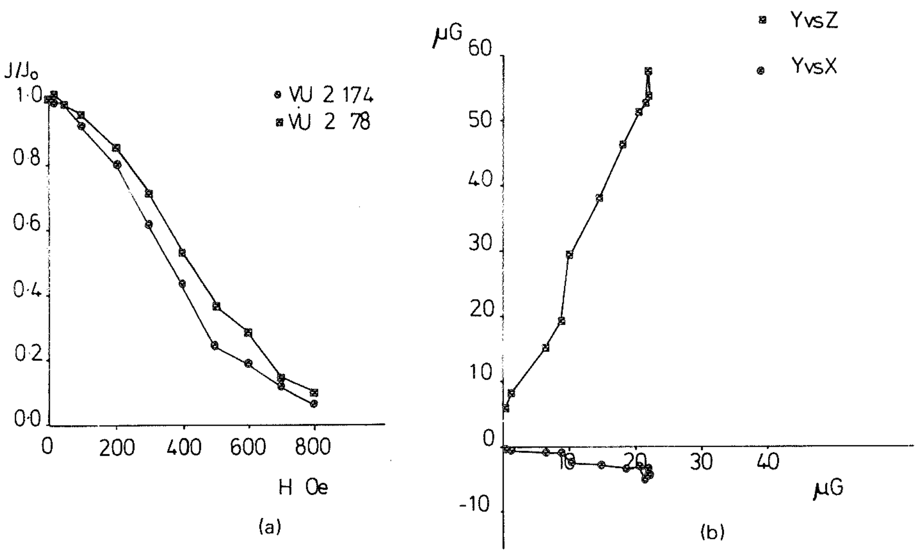

Fig. 5. Typical step AF demagnetization curves of pilot specimens from Vuokonjarvi core 2. (a) Total intensity decrease. (b) Decrease of components: Z direction perpendicular to sediment stratification, X and Y in horizontal plane.

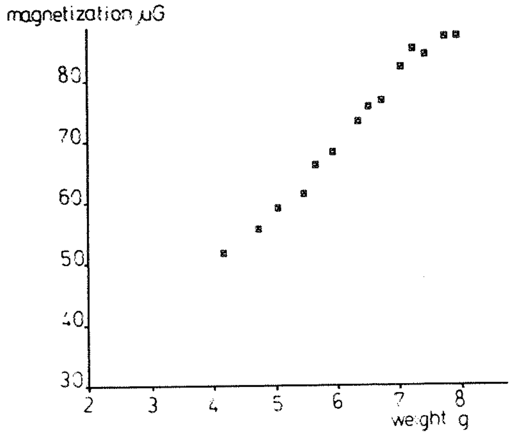

Fig. 6. Loss of NRM vs. weight during drying of a 20 mm × 20 mm × 17 mm sample.

In another experiment two similar adjacent samples were used. One was impregnated with Polyethylene Glycol 6000 [18]. Water in the sample was thus replaced by wax with little distortion of microstructure and little alteration of NRM. Both were placed in a 10-Oe field in such an orientation that the field direction was perpendicular to the main component of NRM. Again the remanence was measured at intervals and over a period of 24 hours the fresh sample gained 41% more remanence than the impregnated sample, while the NRM component remained unaltered.

In the above experiments a remanence over and above the VRM and IRM of the dried and impregnated samples was acquired by the samples which contained water. This can be explained if fine magnetic grains in the fresh and wetted sediment were free to rotate into the ambient field. Since the NRM component in the second experiment did not alter, the grains affected by the applied field must have been other than those carrying the NRM. The loss of NRM with dehydration is most simply explained by magnetic grains which were in physical equilibrium with their wet surroundings being misaligned, with evaporation of the interstitial water, by stresses such as the surface tension of the water molecules and electrostatic attractions of clay minerals.

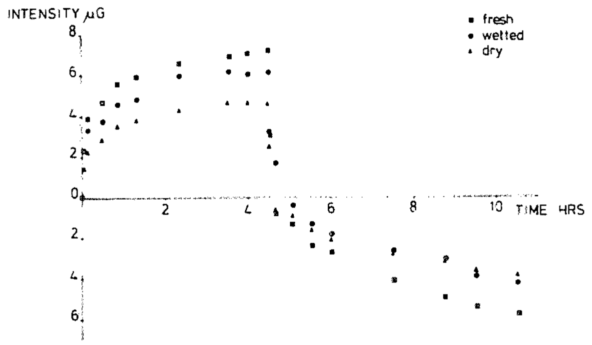

Fig. 7. Acquisition of remanence before and after reversal (at t = 4.25 hours) of 10 Oe magnetic field for fresh, dried and wetted samples.

The possibility of an hydrated iron mineral (e.g. [19]) carrying part of the NRM was considered, since in this case loss of water might be expected to alter the structure of the mineral and so result in loss of remanence. However, if the remanence were carried by an hydrated mineral it is unlikely that the mineral could be easily reconstituted by the addition of water after the sample had dried. Furthermore, in the experiment described above, the mineral would have grown through a blocking volume before the applied field was reversed and the remanence would have remained in the original direction. The possibility of NRM loss during dehydration being due to oxidation in air of magnetic minerals can also be discounted because losses were also found when samples were dried in an inert atmosphere (carbon dioxide at 40°C).

6.3. Low-temperature demagnetization

Pure magnetite and coarse-grained haematite both have magnetic transitions at specific temperatures so that

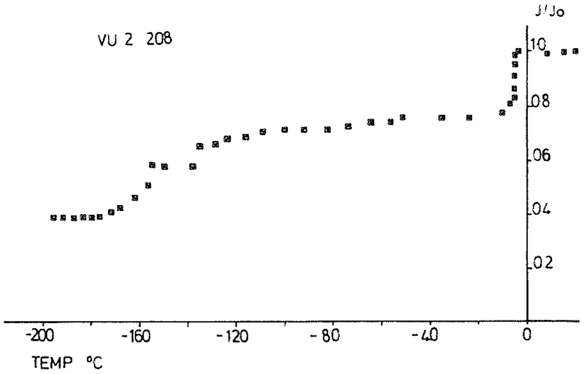

Fig. 8. Low-temperature demagnetization of NRM. Lower transition (−140°C) due to magnetite K_1 anisotropy transition, upper transition (−10°C) due to reorientation of fine particles.

TABLE 1

NRM, ARM and IRM total intensity and percentage of remanences lost at upper transition (U), lower transition (L) and remaining (R) after cooling in zero field to liquid nitrogen temperature, for a suite of 24 samples from core 2

No.	Depth (cm)	NRM (μG)	NRM (%)			ARM (μG)	ARM (%)			IRM (μG)	IRM (%)		
			U	L	R		U	L	R		U	L	R
1	10	7	34	12	54	19	11	11	78	420	12	7	81
2	37	2	28	17	55	7	13	18	69	140	17	10	73
3	51	4	37	9	54	8	23	1	76	190	14	17	69
4	85	8	37	9	54	9	9	16	75	230	12	14	74
5	106	12	36	13	51	13	35	0	65	320	13	14	73
6	141	15	29	11	60	23	8	8	84	1040	7	23	70
7	157	26	33	12	55	30	10	10	80	1140	11	22	67
8	191	20	34	8	58	28	10	7	83	1340	9	22	69
9	210	48	32	9	59	57	10	12	78	2460	8	24	68
10	229	89	34	7	59	61	8	9	83	2570	8	23	59
11	248	76	42	18	40	76	10	10	80	2590	12	21	67
12	277	75	30	13	57	71	7	12	81	3060	8	28	64
13	311	115	30	14	56	86	10	14	76	3870	12	29	59
14	329	137	32	20	48	86	12	10	78	4090	10	26	64
15	347	93	34	15	51	85	9	13	78	4010	9	28	63
16	343	126	36	21	43	122	12	17	71	5810	10	26	64
17	391	88	35	16	49	121	12	10	78	5890	8	28	64
18	421	101	34	14	52	150	13	8	79	7010	8	29	63
19	445	241	26	15	59	244	18	11	71	11020	12	31	57
20	473	208	25	26	49	239	11	9	80	12330	9	32	59
21	493	278	26	21	53	268	15	13	72	14360	10	32	58
22	509	311	22	26	52	253	16	11	73	15830	11	33	56
23	531	407	20	18	62	285	12	10	78	19370	10	34	56
24	558	286	23	16	61	266	3	8	89	17450	4	30	66

by cooling samples the presence of these minerals as remanence carriers can be detected [20]. Fig. 8 is a typical plot of magnetization against temperature. In every sample cooled, a sharp decrease in intensity was observed at around −10°C and in most cases there was a further less well-defined decrease at −140°C. No memory effects were observed during warming in zero field.

In the above method, the magnetization could only be measured in one plane and the noise level of the magnetometer ($\sim 1 \times 10^{-6}$ G) was such that satisfactory measurements could not be obtained for sediments with a remanence weaker than about ten times the noise level. It was also very time consuming to investigate the low temperature behaviour in a suite of samples.

These drawbacks were overcome by performing step bulk low-temperature demagnetization in a commercial deep-freeze at −40°C and then in liquid nitrogen. Zero field ($<20\ \gamma$) was provided by a triple mu-metal shield and the remanence measured on a standard magnetometer. The permeability of the mu-metal was not reduced by cooling. Tens of specimens could be cooled within a few hours or more conveniently overnight. We chose simply to use two steps to characterize the remanence, and measured the remanence at 20°C, −40°C and −196°C. In this way the magnetic remanence lost during each transition was quickly estimated for twenty-four samples from core 2 (Table 1). The proportions of remanence lost varied through the core. Typically between 30 and 40% of NRM was lost at −10°C in the higher muds compared with 20–25% in the basal clay, whereas the proportion lost at the magnetite transition (−140°C) increased from 10% to 25% down the core.

When dried samples were cooled to −40°C no further reduction in magnetization was found. Drying a cooled sample, however, produced a further decrease in intensity. The decrease in remanence observed at −10°C in fresh samples cannot therefore be due to the Morin transition in haematite as originally suggested for Lake Windermere [21] as loss of water would not affect haematite carrying a remanence. The decrease seen at −10°C can be most simply explained by the growth of ice crystals, from the interstitial water, misaligning small magnetic grains. When the ice melts, with warming, the particles will be able physically to relax but will remain randomized. Following iron and magnetic analyses, including Mössbauer spectra, Readman et al. [22] concluded that haematite made up 2% of the total iron content and carried roughly half the remanence in three Greek lakes. Our results suggest that the remanence in these Greek lakes is also most unlikely to be carried by haematite.

6.4. *Thermal demagnetization*

A proportion of the NRM (40–60%) was always left after cooling in zero field to −196°C. Stepwise thermal demagnetization was carried out on a set of samples and a range of blocking temperatures found with the remanence becoming negligible at 600°C. This indicates that the NRM left below −196°C is probably due to titanomagnetite in which the magnetite transition is suppressed by the titanium content.

6.5. *Anhysteretic and isothermal remanent magnetization*

In subjecting samples to an applied field of sufficient magnitude to cause saturation, the fine magnetic particles in the sediment will be physically forced into the field direction and this will combine with the movement of domain walls in large grains to give the observed IRM intensity.

When a sample is given an ARM (with a DC field or 0.4 Oe) the small grains will not be significantly rotated, since they are not rotated by the earth's field. Domain wall movement in large grains will take place to contribute to the ARM intensity, but if the small grains are single domain then only those which are in the direction of the applied DC field will acquire a remanence.

The proportions of NRM, ARM and IRM carried by pure magnetite and titanomagnetite and the degree with which the carriers are bound into the structure of the sediment can be seen to vary with clear trends through core 2 (Table 1). For example, pure magnetite proportionally decreases in the higher sediments as a carrier of both NRM and IRM, titanomagnetite is seen to dominate the ARM while pure magnetite controls the IRM more than in the case of NRM or ARM. Also the grains which carry the ARM and IRM are less reorientated on cooling (and on drying) than those carrying the NRM. This contrast is also seen in warming a sample which had acquired an IRM at −40°C. The sample loses 10% of the IRM on warming which is the same proportion as is lost on cooling a sample with an IRM to −40°C, in contrast to 30% lost on cooling the NRM of an equivalent sample. This difference implies that large grains are contributing to the IRM but not to the NRM.

6.6. *Discussion of origin of natural remanent magnetization*

Magnetite and titanomagnetite grains appear to be the main carriers of remanence in the Vuokonjarvi sediments. There is no evidence for chemical remanent magnetization or for haematite being a major remanence carrier. The most likely mechanism for acquisition of NRM is that small grains are able to rotate in the wet upper sediment near the mud-water interface. As the water content decreases some grains will become fixed in position and become carriers of NRM. The grains carrying the NRM are thus probably only a small proportion of the total magnetic fraction with size being a critical factor. The water content decreases from over 75% at the top of the core and is typically 35% near the base. It seems that some grains in the core are still able to rotate if the field is of sufficient strength (e.g. 10 Oe) and have not been completely fixed in position. From an examination of these and other Finnish lake sediment cores it can be shown that the sediment takes of the order of 100 years to acquire a stable remanence. This result is obtained from the depth over which the uppermost NRM directions are very scattered and the NRM intensity unusually low, and from the estimated sedimentation rates.

The results of experiments in low magnetic fields are of relevance when deciding whether particular lake sediments are accurate recorders of the earth's magnetic field behaviour. An example of this occurred when some sediment from Lake Frisa, Mull, Scotland was investigated. A field of 10 Oe was found capable of moving some of the magnetic grains carrying the NRM implying that these sediments are not good geomagnetic field recorders. The 10 Oe isothermal remanence, like VRM, has a time dependence so that even in a low field such as that of the earth, movement of magnetic grains could occur at depths penetrated by coring. If the magnetic fraction contains a high proportion of very fine grains, these may not have become physically fixed in position and have changed direction with the geomagnetic field. This might explain why in some lake sediments no oscillations in declination or inclination are seen.

Growth of minerals and/or gels may contribute to the process of fixing the magnetic grains in the sediment and thus producing a stable remanence. In sediment in which there is a positive correlation between NRM intensity and organic carbon content (e.g. Lake Windermere), this process may be more important than simple physical compaction. In Vuokonjarvi there is an inverse correlation of NRM intensity with organic carbon content.

7. Conclusions

The post-depositional remanent record of the Finnish geomagnetic field shows several similarities to the British record. Both records are attributed to the same activity in the earth's core. As Holocene records are extended to other geographical localities, the regions of activity will be located more closely.

The importance of grain size of magnetic minerals in producing a stable remanence is illustrated by the sensitivity of magnetization to changes in micro-structure of the sediment.

The large decrease of natural remanence with dehydration first observed in the Vuokonjarvi sediments has been subsequently established in lakes from Mediterranean to Arctic conditions (our unpublished data). The probability of such decreases, and possible modification of remanence, in dry lake deposits must now be assessed as well as the relevance of such decreases to geomagnetic palaeointensity studies on partially dried deposits or partially dried laboratory redeposition samples.

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