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Magnetic remanence acquisition in Finnish lake sediments

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Summary. Magnetic studies have been carried out on organic sediments from five Finnish lakes to determine the carrier(s) of the stable NRM and to find how the remanence is acquired. Single or pseudo-single domain 'magnetite' is thought to carry the NRM. It was found that drying and cooling sediment samples resulted in a loss of NRM which was attributed to the misalignment of small magnetic particles. Low-field experiments were carried out on sediment samples in different physical states and from the results of these investigations it was concluded that post-depositional processes are important in the acquisition of an NRM. Stabilization of magnetic grains is thought to be due to the growth of gels in the organic sediment rather than to dewatering.

1 Introduction

Lake sediments are used in secular variation studies as their relatively rapid deposition rates (~ 0.1 cm/yr) allow changes in the geomagnetic field of the order of 10^2–10^3 yr to be recorded. An understanding of the methods by which lake sediments acquire a stable natural remanent magnetization (NRM) is necessary for a more critical approach to the interpretation of data obtained from the sediments. It might also help to explain why some lake sediments are poor recorders of the geomagnetic signal.

Sediments were collected from five lakes in southern and eastern Finland using a 6-m pneumatic Mackereth (1958) corer so that secular variation records might be obtained. The locations of the five lakes studied are shown in Fig. 1. The oldest sediments were dated by pollen analysis (Huttunen, private communication) at ~ 9500 yr BP and all the sediments were found to carry a stable NRM. The sediments were mainly organic muds with, in some cases, clays of late Glacial or early Flandrian age at the base of the cores.

A study was undertaken to identify the mineral(s) responsible for the NRM and to determine the methods by which the NRM was acquired and stabilized. The various techniques used, experiments carried out and the results are described in this paper.

2 Bulk magnetic mineralogy

Although the NRM carriers are only part of the total magnetic fraction of the sediments, it is possible to derive information about likely NRM carriers from a study of the total

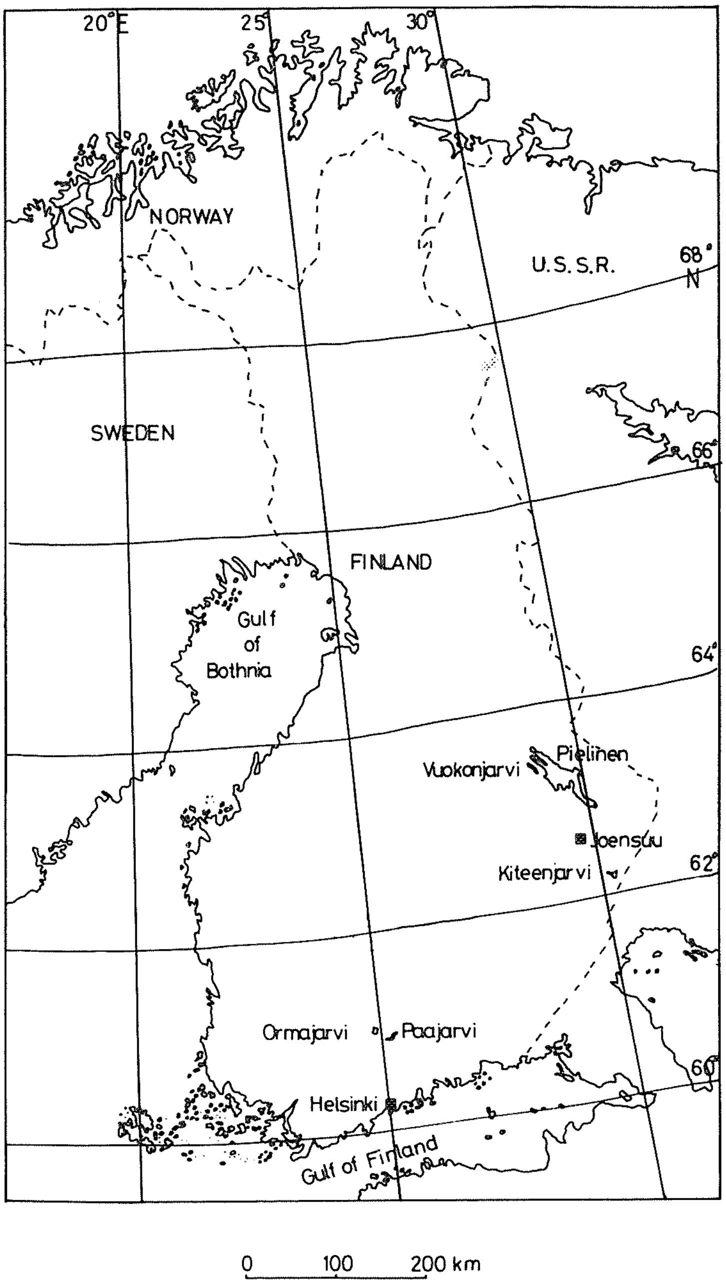

Figure 1. Locations of the five Finnish lakes studied.

magnetic mineralogy. By applying magnetic fields of up to 10 kOe to sediment samples in small plastic boxes and measuring the isothermal remanent magnetization (IRM) after each stage, it was possible to obtain the saturation remanent magnetization, J_{rs}, and the saturating field, H_s. The coercivity of remanence, H_{cr}, was then found by applying magnetic fields in the opposite direction to H_s until the remanence was reduced to zero. A Digico fluxgate, slow-speed spinner magnetometer was used for the IRM measurements. The ferrimagnetic minerals, here referred to for convenience as 'magnetite', saturate in fields of 1 or 2 kOe

Table 1. Ranges of values of magnetic parameters for sediment cores from the five lakes.

Core		NRM (μG)	mdf NRM (Oe)	χ (μG/Oe)	J_{rs} (μG)	H_{cr} (Oe)	H_s (kOe)	mdf IRM (Oe)	mdf ARM (Oe)
Vuokonjarvi	min	4	320	2	200	340	5	170	300
	max	550	520	75	30 000	550	>10	220	400
Kiteenjarvi	min	5	320	4	360	270	2	180	270
	max	50	430	16	1500	360	2	240	360
Paajarvi	min	30	470	4	1200	440	2	270	270
	max	90	560	17	1900	580	2	320	360
Ormajarvi	min	3	350	4	530	430	1	300	400
	max	70	500	8	1800	480	2	350	430
Pielinen	min	6	310	60	11 500	340	2	80	280
	max	450	390	120	27 000	350	2	90	360

but fine-grained haematite, which owes its magnetic properties to a combination of canted antiferromagnetism with a superimposed parasitic ferrimagnetism, requires much greater fields for saturation. From H_s and H_{cr} the presence of these minerals can thus be detected.

Sets of eight samples from the sediment cores from each lake were used for the IRM measurements and the ranges of the data are presented in Table 1 along with the NRM and susceptibility ranges. Values of H_{cr} were generally in the range of 350–500 Oe with H_s being 1 or 2 kOe, results which indicated that 'magnetite' was the major magnetic mineral present. The Vuokonjarvi sample measurements showed evidence of haematite in that H_s was 5 kOe or greater and H_{cr} values were slightly higher than for sediment samples from other lakes. A sample from near the top of the Vuokonjarvi core was not saturated in 10 kOe, indicating that a fairly large proportion of fine-grained haematite was present in the sample. Values of J_{rs} increased down the Vuokonjarvi core but H_{cr} did not change very much. The increase in J_{rs} was thus probably due to an increase in the concentration of 'magnetite' rather than to a decrease in the grain size, which would have produced higher H_{cr} values as well as high J_{rs} values. Changes in J_{rs} and H_{cr} with depth in the other cores did not have well-defined trends.

The IRM measurements showed 'magnetite' to be the dominant magnetic mineral in the lake sediments studied.

3 Domain state

An important consideration affecting the stability of any NRM carried by the sediments was the domain state of the magnetic minerals. The modified Lowrie–Fuller test (Johnson, Lowrie & Kent 1974) was used to determine the domain state of the 'magnetite' present. In this test the stabilities of an anhysteretic remanent magnetization (ARM) and an IRM are compared. Samples were given an ARM in a peak AF of 990 Oe with a DC field of 0.4 Oe superimposed, the DC field being applied parallel to the axis of the coil generating the AF. After measurement the ARM was then progressively demagnetized before an IRM was induced in a field of 1 kOe and itself demagnetized in stages. The two demagnetization spectra were then compared. In all cases the median destructive fields for the IRMs were found to be lower than for the ARMs as shown in Table 1, where maximum and minimum values are presented, which indicated that the 'magnetite' was single, or pseudo-single, domain. Some crossing of the two demagnetization curves occurred for the Paajarvi samples.

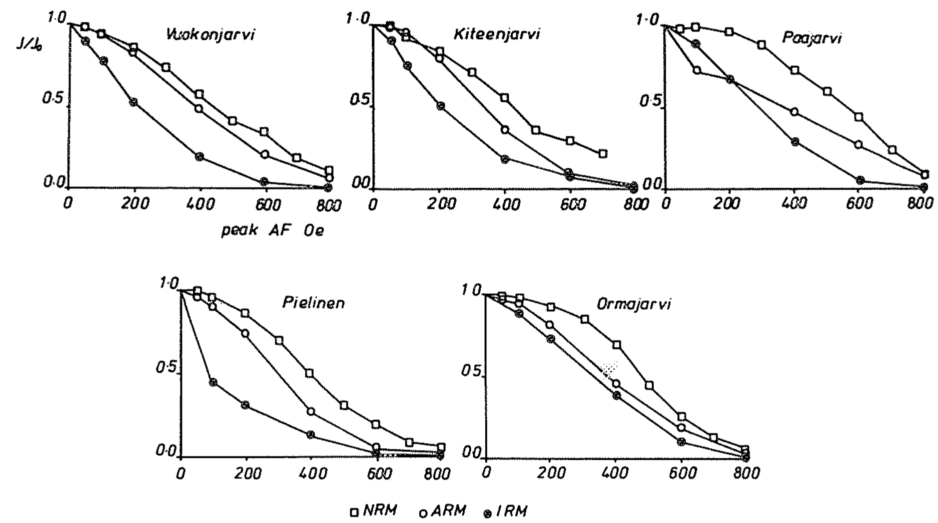

Figure 2. Comparisons of demagnetization spectra for NRM, ARM and IRM carried by sediment samples from the five lakes.

This type of result was interpreted by Johnson *et al.* (1974) as being due to a mixture of multidomain and single domain 'magnetite' grains or to grains in the transitional size range. Examples of the spectra are shown in Fig. 2 where they are compared with the NRM demagnetization curves. For some of the samples (e.g. those from Paajarvi) the NRM and ARM intensities were similar. Both remanence types were low-field magnetizations but the ARM was always a softer remanence then the NRM, so that different grains were responsible for the natural and laboratory remanences.

4 Thermal demagnetization

Heating rock samples provides a method of identifying remanence carriers from the blocking temperatures. Difficulties arise when the technique is applied to unconsolidated organic sediments which may be liable to chemical alteration on heating. A number of the more clay-rich samples from the sediments of Pielinen, Paajarvi and Vuokonjarvi were used as these were found to withstand heating without disintegrating, unlike the more organic sediments. After slowly drying in air the samples were thermally demagnetized in stages of 50 or 100°C and the remanence measured after each heating stage when the samples had cooled to room temperature in field-free space to prevent remagnetization. Typical examples of the demagnetization curves obtained are shown in Fig. 3.

The NRM became negligible after heating to 650°C indicating that 'magnetite', but not haematite, was responsible for the remanence. From the curves a number of samples appeared to have two components of the NRM, showing that more than one grain size or composition was responsible for the NRM. No change in the susceptibility measured at room temperature occurred during the thermal demagnetization experiments. If pure maghaemite had been responsible for any of the NRM, a decrease in susceptibility and NRM would have occurred between 300 and 400°C when the maghaemite inverted to haematite. In most cases 50 per cent of the NRM was lost between 0 and 350°C. The thermal demagnetization showed that pure magnetite and titanomagnetite grains were the most probable carriers of the NRM.

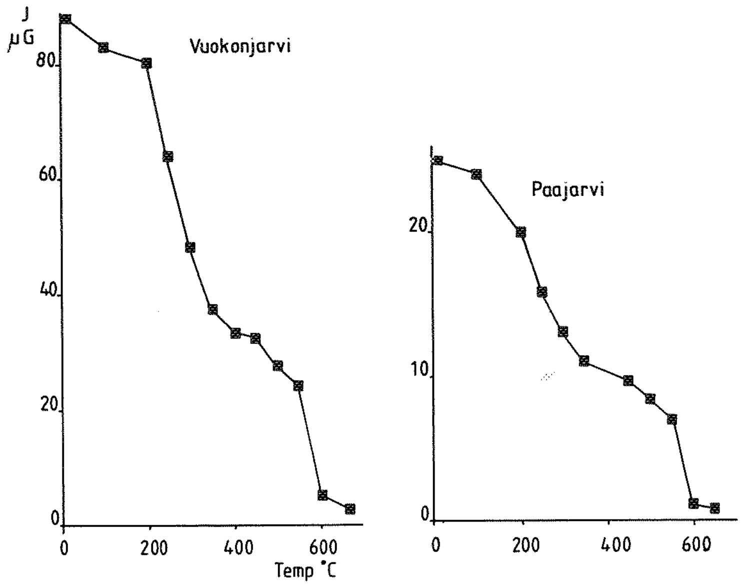

Figure 3. Behaviour of NRM carried by sediment samples from Vuokonjarvi and Paajarvi during thermal demagnetization.

5 Dehydration

Sediment samples were found to lose up to 60 per cent of their initial NRM on drying from the natural state at room temperature. The intensity decrease was accompanied by very little change in remanence direction. Any directional changes which did occur were found to be greater in the more organic samples which did not keep their shape so well on drying as the more clay-rich samples.

Further investigation showed that the remanence decrease was linearly related to the weight loss as shown in Fig. 4 (Stober & Thompson 1977). When samples were allowed to dry in a carbon dioxide environment in a furnace at 40°C, the same loss was observed, ruling out the possibility that oxidation was the cause of the decrease. Similarly, samples left in damp conditions which allowed oxidation, but not evaporation, to occur showed no remanence loss. Water thus seemed to play an important part in the remanence stability.

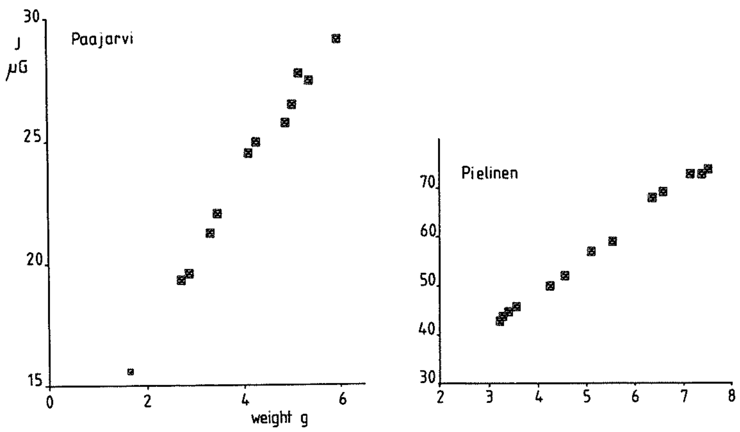

Figure 4. Examples of remanence and weight loss during drying of sediment samples from Paajarvi and Pielinen. Initial intensity is remanence after drying.

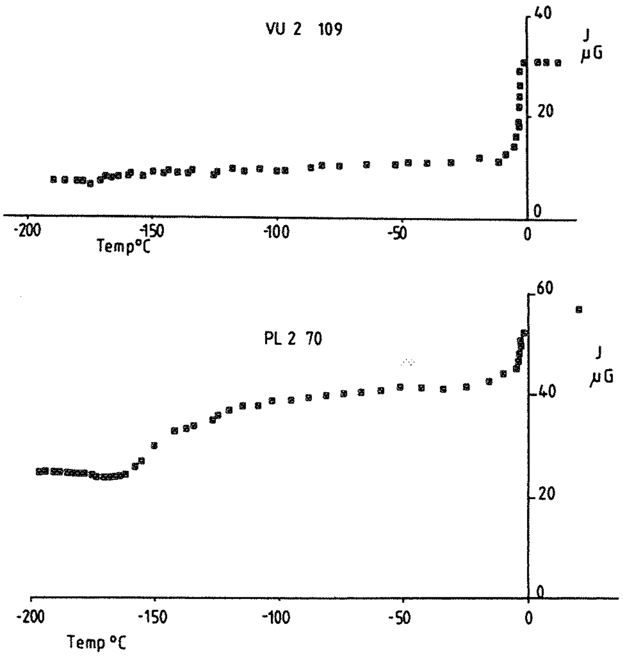

Figure 5. Loss of NRM on cooling sediment samples from Vuokonjarvi and Pielinen. Intensity decrease at lower temperature due to magnetite transition and decrease at higher temperature due to reorientation of fine magnetic particles.

6 Low-temperature demagnetization

Another method of identifying remanence carriers is to observe any decreases in remanence as samples are cooled. Both haematite and magnetite undergo changes in their structures, at −15°C for haematite and −143°C for pure magnetite, which cause the loss of any remanence carried by the grains. In both cases impurities cause suppression of the transitions and the Morin transition in haematite does not occur if the grains are very small.

Measurements were made using a Digico low-temperature spinner magnetometer. The sample spins in a glass tube within a dewar containing liquid nitrogen. A copper–constantan thermocouple was inserted into the sample and both the temperature and one plane of the magnetization of the sample were continuously measured as it cooled. Sharp decreases in NRM intensity were found to occur at around −10°C as shown in Fig. 5. When dry samples were treated in this way, however, this sharp decrease was absent, and the only decrease observed was that attributed to the magnetite transition. Another peculiarity of the decrease at −10°C was that the rate of cooling through it was very slow with a number of intensity measurements being made at the same temperature. The decrease in magnetization was evidently not the Morin transition since dry samples should have exhibited the same remanence decrease and the Morin transition would not have affected the rate of cooling.

7 Impregnation and the physical effect of water

From the foregoing dehydration and low-temperature results it appeared that water was important to the NRM stability. The water in samples can be replaced with little disturbance to the microstructure by impregnating with polyethylene glycol (Greene-Kelly & Chapman 1970). A number of samples were impregnated using this wax and the NRM before and after impregnation were compared. The differences were found to be very small. From this result it appeared that both cooling and drying the sediment samples caused decreases in the remanence by disorientating small grains which carried the NRM. In the case of cooling, ice crystals developed which were able to move the small grains out of their original alignment and into random positions (Stober & Thompson 1977). The reason for the decrease not occurring at 0°C was presumably because the interstitial water was not pure and also because the ice crystals probably did not form instantaneously. The equilibration of temperature and release of latent heat on ice formation resulted in the characteristic reduction in the rate of cooling seen in Fig. 5. When samples were dried the physical equilibrium of the remanence-carrying grains was upset resulting in a decrease in the NRM. Small ferrimagnetic grains would be drawn to larger grains by surface tension effects. Drying had a more pronounced effect on the small grains than cooling because when samples were dried after cooling a further loss of NRM occurred. Cooling wax-impregnated samples in which grains had been fixed in their original positions would be the best method of obtaining the true proportion of remanence carried by pure magnetite as none of the grains would become disorientated at – 10°C.

8 Low-field experiments

Three experiments were carried out using low magnetic fields to find how firmly grains were bound into the sediment and to observe the effects of viscous magnetization on the samples. The lake sediments did not appear to have a viscous component in their measured remanence since cleaning in AFs of a few hundred Oe did not change the direction of the NRM. Zero-field storage had little effect on the NRM unless the sediments dried out. As water was important in the remanence stability, low-field experiments were carried out using samples in different physical states.

The first of these investigations involved using three samples from the same part of Vuokonjarvi core. Two were dried out, the third being kept damp. All three were demagnetized and then water was added to one of the dry samples so that it was soaked up by the sediment. All the samples were then placed in a field of 10 Oe and the remanence measured at frequent intervals over a 4-hr period, after which the field direction was reversed and the remanence measured over a further few hours. The sample to which water had been added acquired the largest remanence and the dry sample the least as shown in Fig. 6. Reversing the field reversed the remanence direction.

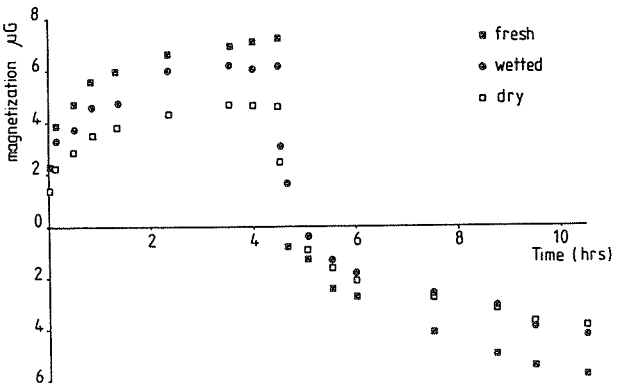

Figure 6. Remanence acquisition before and after reversal of a 10 Oe magnetic field for sediment samples from Vuokonjarvi in different physical states.

In the second experiment, pairs of samples were taken from both the Paajarvi and Vuokonjarvi sediments and one of each pair was impregnated with wax. All were placed in a solenoid producing a field of 10 Oe in a direction perpendicular to the main NRM component. The magnetization was measured at known intervals. When the remanences grown were compared it was found that the natural Paajarvi and Vuokonjarvi samples had gained 70 and 40 per cent more remanence respectively than the impregnated equivalents over the 72-hr period of the experiment. The NRM of the samples on which the new remanence was superimposed did not change. Grains other than those responsible for the NRM were evidently carrying the additional remanence. The differences in magnitude between the remanences grown in the impregnated and fresh samples were evidently caused by the fact that only a viscous remanence (VRM) could be grown in the impregnated samples, but magnetic grains were free to rotate in the natural samples producing a further remanence. The remanence grown through grain rotation could be termed physical rotation remanent magnetization (PRRM). For both the dry samples and the impregnated samples used in the above two experiments, grain rotation was impossible. The fact that magnetic grains other than those carrying the NRM were able to rotate implies that some fine grains were not firmly fixed into the sediment but were able to rotate in a fairly low magnetic field. The PRRM and VRM grown in this way had a low coercivity of under 50 Oe.

The third experiment was designed to compare the VRM and PRRM contributions to the remanence grown in fields of 5, 2 and 1 Oe. Samples were selected from the Kiteenjarvi and Vuokonjarvi sediments at intervals down the cores. These two lakes were chosen because of their different sediment types, the Kiteenjarvi sediments being richer in organic matter than those of Vuokonjarvi. Six pairs of samples were taken from each core, making 24 samples in all. One sample of each pair was dried out while the other sample was kept fresh. All the samples were then demagnetized in a peak AF of 950 Oe before being placed in a pair of Helmholtz coils producing a field of 5 Oe. The remanence of each of the samples was measured at intervals over a period of about 100 hr. Each measurement took about 2 min and the samples were then replaced in the same orientation in the coils. The experiment was repeated in fields of 2 and 1 Oe and the samples were demagnetized before each stage. It was found that all the remanences grown were linearly related to the logarithm of the acquisition time. Viscous remanence is known to be related to time by the equation

$$J = S \log t_a + \text{constant}$$

where t_a is the acquisition time and S the viscosity coefficient (e.g. Néel 1949; Dunlop 1973).

Inspection of the residual sum of squares in fitting Chebychev-series polynomials of increasing order to the data, showed that a linear relationship was adequate. The gradients of the straight lines were then used in the interpretation, S_N being the coefficient for natural samples and S_D the coefficient for dry samples. These values are shown in Table 2 along with the S_N/S_D ratios and the sample depths. Examples of the types of result obtained are shown in Fig. 7. It was found that the remanence grown in the dry samples over 100 hr was proportional to the field strength as expected for a VRM.

The remanences grown in the 5 Oe field were very similar for the pairs of wet and dry samples so that the remanence grown was mainly a true VRM. For the Kiteenjarvi samples the ratio S_N/S_D increased with decreasing field strength. This was also the case for the second pair of Vuokonjarvi samples. Values for the other Vuokonjarvi samples showed no well-defined trend with remanences grown in the same field being similar for any one pair. An exception to this was the uppermost sample pair in which the S_N/S_D ratios for 2 and 1 Oe were large.

Table 2. Values of S for Vuokonjarvi and Kiteenjarvi dry and natural samples with ratios S_N/S_D for pairs of samples.

Sample	Depth (cm)	NRM (μG)	5 Oe	2 Oe	1 Oe
Dry Kiteenjarvi samples			S_D	S_D	S_D
DK1	30	20	1.93	0.84	0.19
2	160	16	1.15	0.43	0.12
3	260	25	1.95	0.77	0.17
4	360	27	3.25	1.35	0.35
5	470	37	2.00	0.54	0.21
6	566	40	6.30	1.23	0.74
Natural Kiteenjarvi samples			S_N	S_N	S_N
FK1	30	20	2.04	0.97	0.61
2	160	16	1.20	0.52	0.31
3	260	25	2.33	1.18	0.64
4	360	27	2.68	1.51	0.86
5	470	37	2.00	1.10	0.76
6	569	40	3.08	1.58	1.19
Dry Vuokonjarvi samples			S_D	S_D	S_D
DV1	49	8	0.89	0.19	0.17
2	186	36	1.66	0.53	0.28
3	263	120	2.84	1.14	0.69
4	360	136	4.05	1.52	1.12
5	422	340	16.90	7.25	4.35
6	565	440	12.50	5.60	3.06
Natural Vuokonjarvi samples			S_N	S_N	S_N
FV1	49	8	0.94	0.58	0.42
2	189	36	1.46	0.59	0.35
3	266	120	3.01	1.10	0.74
4	360	136	4.07	1.45	0.76
5	424	340	19.10	9.20	5.25
6	568	440	13.90	7.20	3.68

		S_N/S_D				S_N/S_D	
Vuokonjarvi	5 Oe	2 Oe	1 Oe	Kiteenjarvi	5 Oe	2 Oe	1 Oe
1	1.05	3.15	2.42	1	1.06	1.15	3.11
2	0.88	1.11	1.23	2	1.04	1.20	2.50
3	1.06	0.97	1.06	3	1.19	1.52	3.71
4	1.01	0.95	0.68	4	1.22	1.11	2.49
5	1.13	1.27	1.21	5	1.00	2.05	3.51
6	1.11	1.29	1.20	6	1.06	1.29	1.62

It was thought that the reason for the increasing S_N/S_D ratio with decreasing field strength in the Kiteenjarvi samples might have been due to a preferential alignment in the natural samples being retained from the application of the 5 Oe field. The experiment was therefore repeated using new samples each time, taken from close to the originals in the core. The new results, however, still showed an increase in S_N/S_D as the applied field was decreased. A probable reason for this increase is that at lower fields it was harder for potential energy barriers within grains to be overcome to produce a VRM, but still relatively easy for loosely bound magnetic grains to rotate in the wet sediment. These results imply

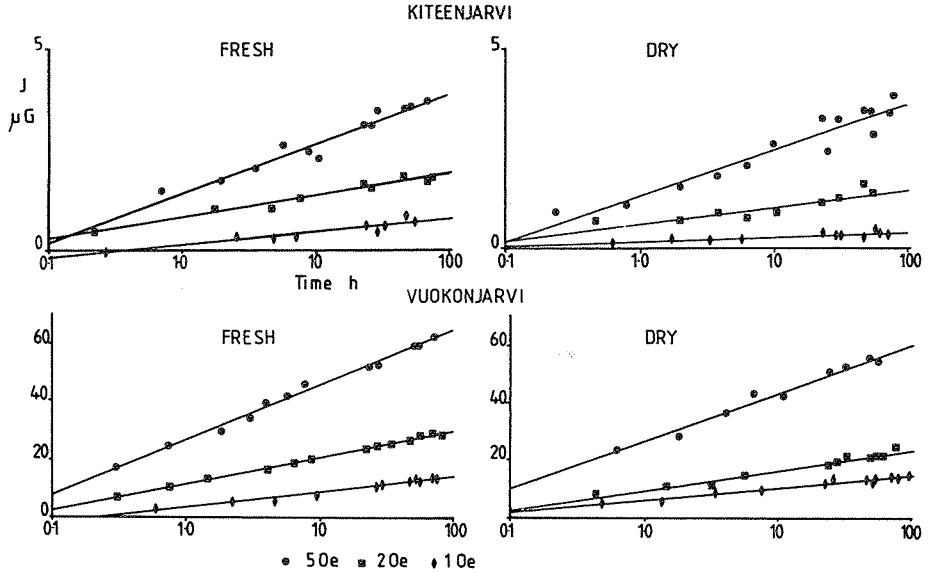

Figure 7. Examples of remanences grown in dry and fresh sediment samples from Vuokonjarvi and Kiteenjarvi when subjected to fields of 5, 2 and 1 Oe.

that magnetic grains are less well bound into the Kiteenjarvi sediments than the Vuokonjarvi sediments. The actual values of the remanences grown always decreased with decreasing applied field strength as expected.

The values of S_N were compared with the original NRM intensities of the samples. It was found that for the uppermost four Vuokonjarvi sediment samples there was an approximately linear relationship between S_N and NRM but the two samples from nearer the base of the core deviated from this trend. This was probably a consequence of the different sediment composition near the base of the core with more fine grains capable of rotation present as the PRRM of these samples was greater than expected from the S_N to NRM relation of the upper sediments. No relation between S_N and NRM was observed in the Kiteenjarvi samples.

9 Stabilization of the NRM

The fact that the median destructive field of the NRM carried by the sediments was 300–500 Oe implies that the process by which the small magnetic grains acquire an NRM and are then fixed in place is efficient. Even though the grains are in wet sediment their behaviour is comparable to that of remanence carriers in a rock. Rotation of grains in wet sediment shortly after deposition seems to be the method by which the NRM is initially acquired. The investigations described in this section throw some light on the way in which the NRM carrying grains are fixed in place in the sediment. One sample was taken from the uppermost sediments of each of the five lakes and dried out. The sediment in each sample holder was then mixed with water after which the reconstituted samples were left in damp conditions in a field of 2 Oe for a few days. A field of 2 Oe was chosen as it was fairly close to that of the Earth, but allowed more easily measurable results to be obtained. The samples were then allowed to dry in the field and demagnetized. Median destructive fields (mdf) of between 50 and 200 Oe were obtained, lower than the mdf of the NRM which was usually around 400 Oe. These lower coercivities presumably resulted from the method by which the magnetic grains were fixed in place.

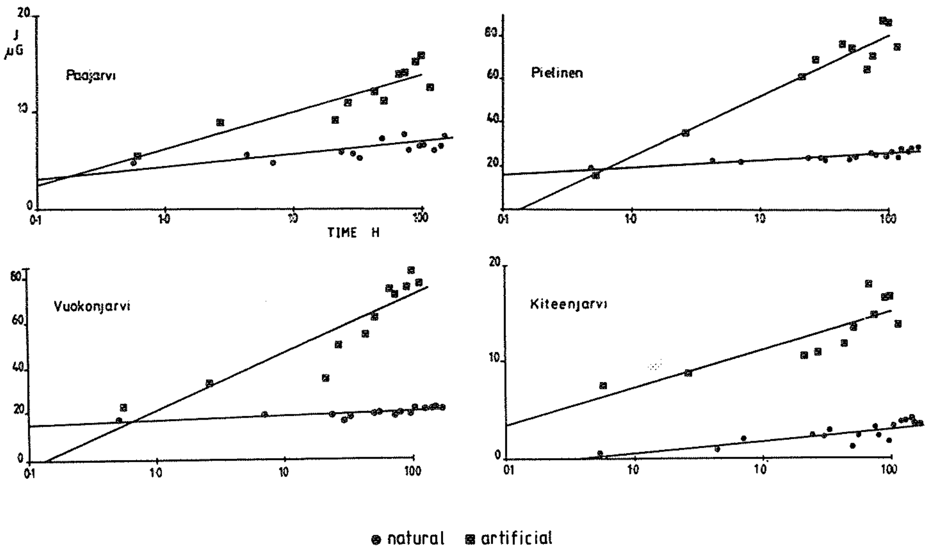

Figure 8. Comparisons of remanence acquisition in a 2 Oe field for natural and remixed samples from Paajarvi, Pielinen, Kiteenjarvi and Vuokonjarvi.

When mixing water into dry sediment it was never possible to attain water contents as high as those found in the natural lake sediment samples without the water obviously being in excess. The maximum water content achieved by mixing in the laboratory was about 30 per cent whereas cohesive natural samples can have a water content of 90 per cent. Within the natural samples water was probably held in the form of gels as well as interstitially. The gels, developing close to the sediment–water interface, could contribute to the fixing in place of magnetic grains after they had become aligned in the ambient field.

In the artificially mixed samples described above the grains became fixed in place by dewatering of the sediment which presumably caused much disturbance to the microstructure so that small high coercivity grains became misaligned leaving only the larger lower coercivity grains in place which gave rise to the low mdf values measured.

In order to investigate the presence of gels, paired samples were taken from the uppermost sediments of Paajarvi, Pielinen, Kiteenjarvi and Vuokonjarvi. One sample of each pair was dried in air and then remixed with water. All the samples were placed in a field of 2 Oe and the remanence growth measured over 100 hr. The natural samples were placed in the field in such a way that the remanence grown would be in a direction perpendicular to the main (vertical) NRM component.

The remanence grown was plotted against log t_a and examples are shown in Fig. 8. The remanence grown in the artificially mixed samples was much greater than that acquired by their counterparts in the natural state. This result confirmed that grains carrying the NRM in the natural samples had been effectively locked in place and grains were unable to rotate as easily as those in the artificial sediments, even though the water content of the natural samples was the greater. The ratio of S for the artificial Pielinen and Vuokonjarvi samples to S for the natural ones was larger than the same ratio calculated for the Kittenjarvi and Paajarvi sample pairs. From this it appeared that magnetic grains were more firmly fixed in the Pielinen and Vuokonjarvi sediments.

It is interesting to note that the basal clays of the Vuokonjarvi core had lower mdfs for the NRM than the upper organic sediments implying that coarser grains carried the NRM in the basal sediments. Evidence from the PRRM experiments, however, suggested that more fine grains capable of rotation were present at the base of the core and the J_{rs}/susceptibility ratio was high which also indicated the presence of fine grains. The explanation of this apparent conflict may lie in the fact that gels are connected with organic sediments and were not formed in the clays. As the clay was compacted the finer grains lost their orientation so that the remanence carriers were the coarser lower coercivity grains which would give rise to the lower mdf.

10 Conclusions

The investigations described in this paper showed that fine-grained magnetite was responsible for the stable NRM carried by the Finnish lake sediments. Both drying samples and cooling them through – 10°C resulted in remanence losses which were attributed to misalignment of small grains carrying the NRM when their physical equilibrium was upset. In low-field experiments it was found that samples in the natural state were able to acquire greater remanences than their dry or wax-impregnated equivalents. The largest low-field remanences, however, were grown in samples which had been dried and subsequently mixed with water, even though the water content of the natural samples was greater than that of the remixed samples.

The ease with which grains were able to rotate in low fields in wet sediment suggested that grain rotation in the wet uppermost sediment of lakes is the most likely remanence acquisition mechanism. This process was first suggested by Irving (1957) and has been found to occur in deep sea sediments (Kent 1974; Løvlie 1974). The experimental evidence described above also points to the existence of gels stabilizing the small NRM-carrying grains in the natural sediments, rather than to the grains being fixed in place by dewatering of the sediment to a critical level as suggested by Verosub (1977). Indeed, natural dewatering of the uppermost sediments might have the effect of misaligning particles, as was found in laboratory drying, rather than stabilizing the magnetic remanence carriers.

Although samples carried a stable NRM it was possible to grow additional remanences in low laboratory fields. Large grains acquired a VRM and small grains which had not been fixed in place were able to rotate and give rise to a PRRM. The grains carrying the NRM, being firmly fixed in position in the sediment, were not affected by low laboratory fields. Both VRM and PRRM were found to be proportional to log t_a.

It seems unlikely that any alignment of grains in the ambient magnetic field achieved as they settle through the water would be retained when grains meet the wet organic sediment of the lake floor. Post-depositional alignment processes appear to be more important.

References

Dunlop, D. J., 1973. Theory of the magnetic viscosity of lunar and terrestrial rocks, *Rev. Geophys. Space Phys.*, **11**, 855–901.

Greene-Kelly & Chapman, S., 1970. The preparation of thin sections using polyethylene glycol, in *Micromorphological Techniques and Applications*, pp. 15–24, Tech. Monogr. Soil Surv., No. 2, Rothamsted Experimental Station.

Irving, E., 1957. Origin of the palaeomagnetism of the Torridonian sandstones of northwest Scotland, *Phil. Trans. R. Soc. Lond. A*. **250**, 100–110.

Johnson, H. P., Lowrie, W. & Kent, D. V., 1974. Stability of anhysteretic remanent magnetization in fine and coarse magnetite and maghaemite particles, *Geophys. J. R. astr. Soc.*, **41**, 1–10.

Kent, D. V., 1974. *PhD thesis*, University of Columbia.

Løvlie, R., 1974. Post depositional remanent magnetization in a redeposited deep sea sediment, *Earth planet. Sci. Lett.*, **21**, 315–320.

Mackereth, F. J. H., 1958. A portable core-sampler for lake deposits, *Limnol. Oceanogr.*, **3**, 181–191.

Néel, L., 1949. Théorie du traînage magnetique des ferromagnétiques en grains fins avec application aux terres cuites, *Ann. Geophys.*, **5**, 99–136.

Stober, J. C. & Thompson, R., 1977. Palaeomagnetic secular variation studies of Finnish lake sediment and the carriers of remanence, *Earth planet. Sci. Lett.*, **37**, 139–149.

Verosub, K. L., 1977. Depositional and postdepositional processes in the magnetization of sediments, *Rev. Geophys. Space Phys.*, **15**, 129–143.