Palaeoenvironmental application of magnetic measurements from inter-drumlin hollow lake sediments near Dungannon, Co. Tyrone, Northern Ireland

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Measurements of palaeomagnetic horizontal remanent intensity, saturation isothermal remanence, coercivity of remanence, high field remanence and magnetic susceptibility, have been made on lateglacial and postglacial sediments from two small, inter-drumlin hollow lakes from central Northern Ireland. These magnetic measurements have been compared with pollen and chemical analyses from the same profiles and with complementary mineral magnetic data from local soils. Representative sediment samples have also been divided into a range of particle size fractions and each fraction has been subjected to magnetic investigation. Five distinctive stratigraphic horizons have been identified on the basis of the magnetic mineralogy. Two horizons relate to phases of pronounced erosion. One of these is connected with solifluction processes in the lateglacial and the other to an intensive period of farming activity which started in Medieval times. Two horizons are associated with periods of very high iron and manganese deposition and are possibly related to the precipitation of magnetic minerals within the lake. Hydrological changes during periods of local anthropogenic activity appear to produce magnetic mineral assemblages indicative of stream bed/bank substrate sources. The particle size data also support the suggestion that downcore changes in the mineral magnetic record are mainly caused by changes in the sediment source rather than particle size or sedimentological effects.

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Mineral magnetic studies have been applied to a variety of palaeoenvironmental investigations which have included the study of lake-sediment/drainage basin linkages (Oldfield 1977; Thompson *et al.* 1980). Downcore variations in lake sediment susceptibility have been used for core-core correlation in attempts to elucidate sediment budgets (Bloemendal *et al.* 1979; Dearing *et al.* 1981); as a tracer for erosional inputs of material (Thompson *et al.* 1975; Dearing & Flower 1982) and as an indicator of catchment fires (Rummery *et al.* 1979). The use of a combination of magnetic measurements, e.g. susceptibility (χ), saturation isothermal remanence (SIRM), coercivity of remanence ($(B_o)_{CR}$), and isothermal remanence ratios have been used to 'fingerprint' sediment types. Downcore variations in magnetic properties have been combined with chemical and palynological studies in order to infer changing sources of materials. They have been used as a surrogate index of the mobility of topsoil, as opposed to the erosion of streambed/bank substrates, in response to vegetational, climatic and anthropogenic pressures (Oldfield *et al.* 1979; Thompson *et al.* 1980; Björck *et al.* 1982; Oldfield *et al.* 1983).

Discussion of lake sediment magnetic mineralogy has concentrated on susceptibility variations. At Lough Neagh, Thompson *et al.* (1975) showed that the sedimentary susceptibility variations correlate well with pollen and chemical evidence for land-use changes and soil erosion within the lake catchment. Although these inferences were largely based on circumstantial evidence, corroboration from many sites supported this conclusion (Oldfield *et al.* 1978; Thompson & Morton 1979; Edwards & Rowntree 1980). Susceptibility was taken to be largely a measure of detrital magnetite, the concentration of which was increased by inwash of agricultural soils with enhanced susceptibilities. A similar enhancement of agricultural soils and movement of increased magnetic concentrations at times of erosion has been discussed for the Jackmoor Brook instrumented watershed (Oldfield *et al.* 1979; Walling *et al.* 1979). Differentiation of magnetic mineralogies was observed in streamborne material at times of low flow and flood. The authors suggested that differences in magnetic mineralogy between top soil and substrate could account for the changes. Alteration of primary haematite during soil development processes into a secondary ferrimagnetic form of magnetite or maghemite (Longworth *et al.* 1979; Oldfield *et al.* 1979), would provide the observed Jackmoor Brook magnetic contrasts.

Magnetic susceptibility changes may also be associated with changes in particle size distribution as suggested by data from sediments at Loch Lomond (Thompson & Morton 1979) and Lough Catherine (Thompson & Edwards 1982). In both these studies particle size data from marginal, deltaic lake sediments showed that the coarser sand size fractions had the lower susceptibilities. These results are at variance with the data of Dearing *et al.* (1981) and Björck *et al.* (1982), where it was found that susceptibilities peaked in the silt or fine sand size range on account of the high concentration of natural magnetite crystals in these 5–200 μm fractions. These findings led Dearing & Flower (1982) to re-interpret the explanations of Thompson *et al.* (1975). They suggested that the origin of the Lough Neagh correlations between land-use changes and susceptibility are to be found in particle size changes caused by the hydrological affects of catchment events. They consider that land-use changes, rather than causing erosion of magnetically enhanced topsoil, produce increased peak flow and discharge which leads to an increased removal of streambed and bank materials of coarser particle size, and hence to greater susceptibility values.

Interpretation of lake sediment susceptibility profiles is further complicated by the possibility of authigenic formation of ferrimagnetic minerals at or near the sediment/water interface or by the precipitation of paramagnetic iron, particularly where the substrates lack primary ferrimagnetic mineral content (Oldfield 1977; Rummery *et al.* 1979). Although these processes have been suspected at a small number of sites (e.g. Loch Davan, Edwards 1978, also see Oldfield *et al.* 1983), the relevant pH and Eh conditions necessary for such precipitations are unknown (Oldfield 1977) so they cannot be predicted with any confidence. In summary, susceptibility is generally considered to represent predominantly detrital allochthonous materials from either eroded substrates (Dearing & Flower 1982), or from soils (Thompson *et al.* 1975; Oldfield *et al.* 1978), possibly enhanced by secondary magnetic minerals formed by burning or fermentation (Mullins 1977; Oldfield 1977).

Study area and sampling methods

The study sites lie in adjacent inter-drumlin hollows near the town of Dungannon in E. Co. Tyrone (54°32′N, 6°46′W) at an altitude of approximately 100 m Irish OD (Fig. 1). The larger lake, Killymaddy Lough (Irish Grid Ref. H783620), has a present open water area of approximately 2.5 ha within a catchment of 54.5 ha. The catchment was reduced from an original area of 122.5 ha by the construction of a canal in the last century. Weir's Lough (Irish Grid Ref. H784216) has a present-day area of only 0.4 ha but it receives water from Killymaddy Lough and has a total catchment area of 212 ha including that of Killymaddy. A plan of the study sites showing the catchment boundaries is shown in Fig. 1.

The drumlins of the study area form part of the mid-Irish drumlin belt which stretches in a broad band between Sligo Bay and Strangford Lough. The drumlins in the study area are composed of local Carboniferous sandstone and limestone-de-

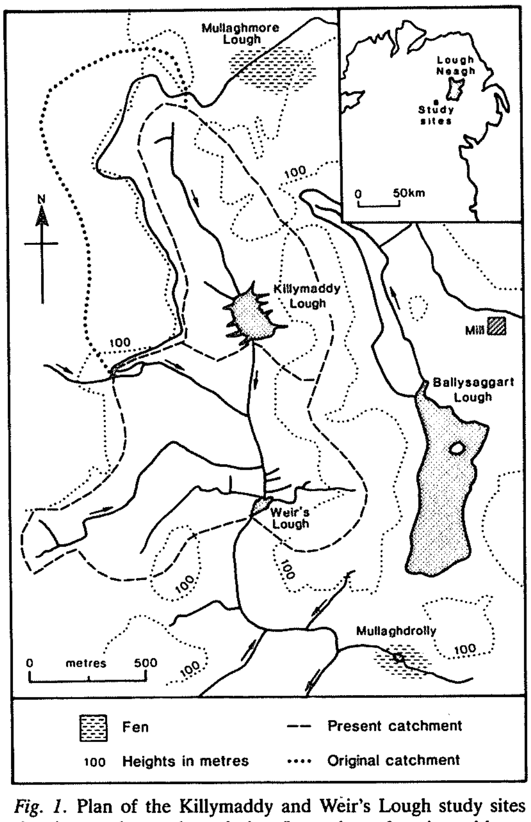

Fig. 1. Plan of the Killymaddy and Weir's Lough study sites showing catchment boundaries. Inset shows location with respect to L. Neagh in N. Ireland.

rived tills, sands and gravels. They also contain variable amounts of Tyrone Granite erratics derived from the Tyrone uplands to the north west and of Cretaceous chalk and Tertiary basalt erratics derived from the east (Dardis 1980). Local tills may be up to 40 m in thickness (Fowler & Robbie 1963) but at the study sites limestone may outcrop below as little as 2 m of till (Bennett pers. comm.). Drumlins in this region have been grouped into larger structures apparently by the scouring action of meltwater. Both Killymaddy and Weir's Loughs lie in one of these scour channels.

The local drumlin soils are silty to sandy loams, fairly light in colour. The soils are extremely variable on account of local topographic variation. Where slopes are low, drainage is generally poor and gleying is widespread. In inter-drumlin hollows basin-peat is fairly extensive. Peaty gleys are developed on the footslopes of the hollow. On higher slopes the soils tend towards the acid-brown earth type with some gleying at depth. These soils are loamy in texture, sticky in places and generally of low base status.

Killymaddy Lough was cored at its deepest point in approximately 10.5 m of water using a 6 m Mackereth corer (Mackereth 1958); a core 5.03 m long (core K) was recovered. As Weir's Lough has a maximum depth of water of only 2.3 m, it could not be cored by this method and was sampled at the deepest point by means of a Russian-type corer (Jowsey 1966) 50 cm in length and 10 cm diameter semi-circular in cross section, from a securely anchored boat. 9.44 m of sediment were recovered at Weir's Lough.

Methods and instrumentation

Palynological investigations

Samples for pollen analysis were processed using a modification of the Faegri & Iversen (1975) preparation method. The samples were deflocculated with 10% NaOH, passed through a 180 μm sieve, treated with hydrofluoric acid, acetolysed and mounted in silicone oil via tertiary-butyl alcohol.

All pollen types were examined for preservation characteristics (e.g. Cushing 1964; Havinga 1964; Hirons 1984 and in prep.) but here only the proportion of determinable pollen grains considered to be well preserved is presented as a single measure of changes in the overall preservation characteristics of the pollen assemblages.

The close correspondence of clearance evidence in the pollen record and of diminished proportions of well-preserved pollen suggests a similar causal mechanism. Possibly the most likely mechanism involves a change in the relative importance of air- and waterborne recruitment pathways for the sedimentary pollen. In periods of intense local clearance activity changes in catchment hydrology would greatly increase the amount of pollen recruited via overland flow from higher peak discharges (Peck 1973) and from streamborne inputs. These changes would be coupled with reduced aerial pollen input resulting from tree removal. The expression of these changes in the pollen record would be to increase the representation of (1) preferentially waterborne pollen types, (2) pollen types concentrated by differential destruction in the soil, (3) pollen grains damaged by periods of exposure to non-preserving environments before recruitment, and (4) pollen grains damaged by transportation mechanisms (Pennington 1979; Tolonen 1980; Hirons 1983).

Chemical investigations

Determination of oxidizable organic carbon was by the wet oxidation method of Walkley & Black (1934). Samples for the determination of total metal content were processed according to a modification of the total elemental digestion method of Mackereth (1966).

Initial oxidation of organic matter was by nitric acid, further oxidation and digestion was by perchloric, hydrofluoric and hydrochloric acids (McAlister & Hirons 1984). Determination of total Fe and Mn and K was by atomic absorption spectroscopy. Total phosphorus determinations were carried out on the same sample digests using an ascorbic acid reduction method (Murphy & Riley 1962). Determination of total carbonates as calcium carbonate equivalent was by manometric determination of evolved carbon dioxide using a calcimeter method (Bascomb 1961).

Magnetic investigations

Whole core magnetic analyses were carried out on the sediment column as recovered by the Mackereth corer and could therefore only be carried out on the Killymaddy Lough sediments. The measurements of palaeomagnetic declination and horizontal intensity of natural remanent magnetization were carried out simultaneously using a whole core, computerized, slow-speed spinning fluxgate magnetometer (Molyneux *et al.* 1972). Whole core remanence measurements were made at 5 cm intervals. Measurements of initial, apparent, low field susceptibility were also obtained at 2.7 cm intervals on the unopened Mackereth core using the whole core scanning method of Molyneux & Thompson (1973).

Subsample measurements of susceptibility and isothermal remanence

Both the Killymaddy and Weir's Lough cores were cut into 5 cm slices and air dried at 35°C for approximately three days (Thompson 1979). Alternate samples were crushed to pass a 2 mm sieve and packed into pre-weighed 10 ml (2 cm deep × 2 cm diameter cylindrical) plastic boxes with magnetically clean foam which helped to minimize sample movement during measurement.

Initial apparent susceptibility was measured using an air cored bridge system in a low magnetic field at a frequency of 10 kHz (Molyneux & Thompson 1973). Isothermal remanent magnetization of the samples produced by a 1 Tesla d.c. magnetic field (SIRM) was measured using a fluxgate magnetometer (Molyneux 1971). The measurements of cores K and W were standardized for varying sample weights and expressed as specific susceptibility (χ) in units of $\mu m^3 kg^{-1}$ and specific SIRM in units of mAm^2kg^{-1}.

Stability

Information about the magnetic mineralogy of the samples was sought using coercivity tests which determined the stability of SIRM. Following magnetization in a forward 1 Tesla field selected subsamples were subjected to progressively greater d.c. magnetic fields in the reverse direction. The sample IRM was remeasured after each back field magnetization step and standardized as IRM/SIRM. The reverse d.c. field required to reduce the IRM to zero is known as the coercivity of remanence; $(B_o)_{CR}$ was determined by plotting the reverse field against the IRM/SIRM ratio and interpolating between measurements. Eight samples from Killymaddy Lough and fourteen from Weir's Lough were tested for their magnetic stability.

All of the lake sediment samples were subjected to a reverse field of 0.1 T after determination of their SIRM. The ratio S (–IRM–0.1 T/IRM 1 T) was calculated (Stober & Thompson 1977; Oldfield *et al.* 1981). S, which varies between −1 and +1, is an indicator of the ratio of low to high coercivity minerals and was calculated in order to show changes in the 'magnetite to haematite' ratios within the sediment profiles.

High field remanence

High field remanence (HIRM) has also been calculated for all samples used in this study. HIRM is defined as that specific IRM grown in fields above 0.1 T (Bradshaw & Thompson 1985). At these field strengths all the ferrimagnetic minerals (magnetite, maghaemite) are assumed to be almost completely saturated and the HIRM is considered to be carried almost entirely by haematite and/or geothite.

Results

Dating and biostratigraphy

Outline pollen assemblage and sediment composition data for Killymaddy and Weir's Loughs are presented, respectively, in Figs. 2 and 3. The data are plotted against depth and a suggested timescale based on cubic spline interpolations (cf. Edwards & Thompson 1984) of 10 ^{14}C dates from Killymaddy Lough and 14 ^{14}C dates from Weir's Lough (Hirons 1983, 1984) are included with each profile. All dates are quoted in uncalibrated radiocarbon years B.P., A.D./B.C.

Lateglacial sediments were not penetrated at Killymaddy Lough although a lateglacial sequence of clays and carbonates was collected from Weir's Lough. Detailed pollen analysis was only undertaken on the postglacial and uppermost lateglacial sediments.

The pollen data have been zoned according to the criteria of the American Commission on Stratigraphic Nomenclature (1961). Nine site pollen assemblage biozones have been defined from Weir's Lough and eight from Killymaddy. The zones are illustrated in Figs. 2 and 3 prefixed K and W for Killymaddy and Weir's respectively.

Sediment accumulation was possible at the study sites at least from the base of Jessen (1949) pollen zone II of around 12,000 B.P. ^{14}C dates for the initiation of organic accumulation are complicated by carbonate deposition (Figs. 2 and 3) and possible hardwater errors. However, extrapolation from apparently more reliable dates in the overlying organic-rich sediments yields an age of around 10,000 B.P. for the opening of the postglacial.

The initial period of open lateglacial vegetation conditions and the more recent reduction in tree cover caused by man's clearance and farming activities are illustrated by the expanding herb-pollen curve in Figs. 2 and 3. Periods of relatively greater anthropogenic impact as deduced from the proportional composition of the subfossil pollen are outlined by the shading of relevant subzones in the assemblage zone column of Figs. 2 and 3. The changes in pollen preservation characteristics match assemblage zones well, with pollen quality deteriorating in periods of intensive local activity, illustrating a link between man's impact and changing modes of pollen transport. Sediment deposition rates are initially low increasing around 6,600 B.P. and again at the time of the elm-decline dated to *c.* 5,225 B.P.

Disruption of the sequence of ^{14}C dates occurs at both sites near the sediment surface. The disruption suggests that after *c.* 1320 A.D. (Weir's Lough) and *c.* 1510 A.D. (Killymaddy) the intensity of erosion of old organic residues from the

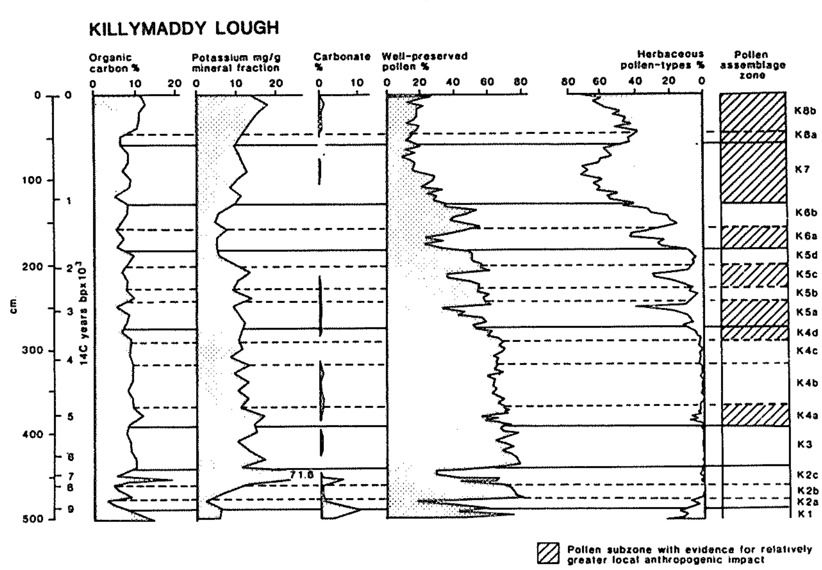

Fig. 2. Summary biostratigraphic and sediment composition data for postglacial sediments from Killymaddy Lough. Oxidizable organic carbon and carbonate determinations (% dry wt.) and potassium content of the sediments expressed as mg/g mineral matter compared with outline pollen data and pollen assemblage zones and a curve for well-preserved pollen. Pollen zones showing evidence of relatively high anthropogenic impact are shaded. Data plotted against depth with approximate dating scale indicated.

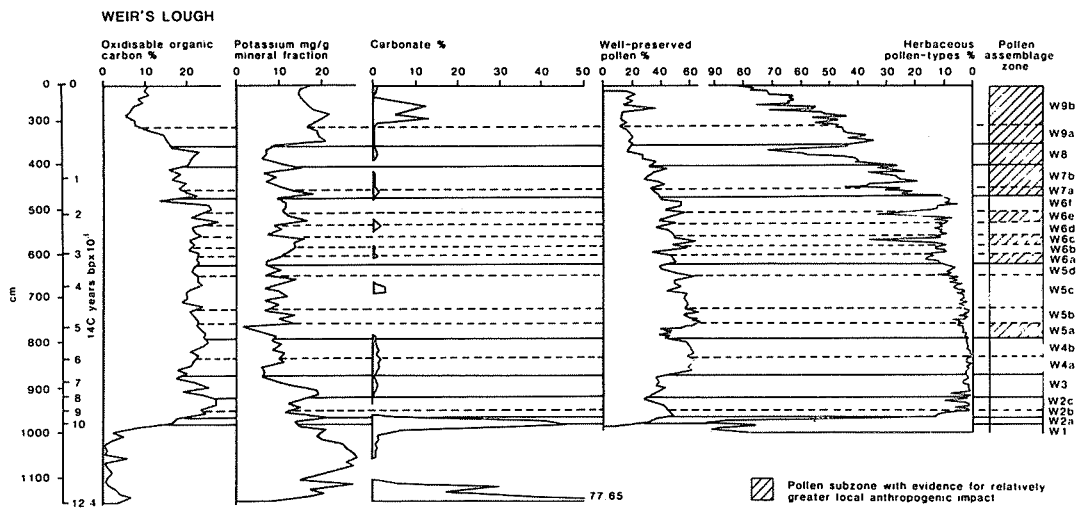

Fig. 3. Summary biostratigraphic and sediment composition data for late- and postglacial sediments from Weir's Lough as Fig. 2. Pollen data for postglacial sediments only.

Table 1. Summary of the chronology, sediment characteristics and environmental history of the study lakes.

^{14}C years B.P.	Expansion of tree species	Sediments	Local environment
0		Carbon values low at Weir's Lough	Plantation/modern farming Expansion of early Medieval farming
1		Increased mineral content with carbonate	Major, local, continuous clearance
2			Intermittent local anthropogenic activity
3			
4	*Fraxinus*	Increased mineral content and deposition rates	Man's impact minor/non-local
5	*Ulmus* Decline	Organic carbon values high	Some local anthropogenic activity
6			
7	*Alnus*		Spread of alder
8	*Quercus*	Clay and carbonate layers	Periods of possible lake level fluctuation
9	*Ulmus*		Start of local establishment of major forest trees
	Corylus	Rapid rise in organic content	
10	*Betula/Juniperus*	Carbonate	High lake productivity and rapid stabilisation of soils
11		Deposition of inorganic clays and silts	Unstable soliflucted soils
12		Carbonate	Interstadial period of high lake productivity

catchments was severe enough to cause apparent increase in age with decrease in depth of deposit (cf. Tutin 1969; O'Sullivan *et al.* 1973).

Palaeoecology

Table 1 summarizes the chronology of events and environmental history of the study sites. Sequences of lateglacial deposits of up to 3 m in thickness in the inter-drumlin hollows show an interstadial carbonate deposit of up to 60% CO_3 with organic content usually less than 10% (cf. basal samples from Weir's Lough, Fig. 3). The basal carbonates have pollen assemblages similar to the early interstadial *Juniperus–Empetrum* phase of Watts (1977) dated to around 12,000–12,400 B.P.

Organic and carbonate-poor grey-blue to pinkish clays succeed the interstadial deposits at Weir's Lough and are interpreted as representing the onset of solifluction during the Nahanagan stadial. The oldest pollen zone presented here (W1, Fig. 3) corresponds to Watts (1977) *Artemisia* assemblage considered to end around 10,200 B.P. A transition occurs at the end of this period. Organic carbon values increase, clay deposition becomes less important and a further period of carbonate deposition occurs. The two periods of carbonate deposition are interpreted as representing solute instability of soils under conditions of moderate physical stability. The carbonate may have been precipitated from charged waters under productive lake conditions as a result of CO_2 depletion.

Maximum carbon values and the end of carbonate deposition suggest stabilization is achieved after initial vegetation succession has proceeded via *Juniperus* and *Betula* to domination by hazel *c.* 9,500 B.P.

Between *c.* 9,000 and 7,200 B.P. organic and carbonate rich clay layers are deposited which, along with increased proportions of deteriorated pollen, are interpreted as a result of lake-level changes and remobilization of peripheral sediments including poorly preserved pollen and scouring of channel substrates. This phase continues after the local arrival of oak *c.* 8,000 B.P. but ceases before *Alnus* becomes established locally *c.* 6,575 B.P.

A further period of relative stability follows only to be broken again several centuries before the elm-decline – here dated to around 5,250 B.P. Evidence for some local anthropogenic activity including possible cereal cultivation is found just before the elm decline from *c.* 5,620 B.P. (Edwards & Hirons 1984). From this time onwards there is an increase in deposition rates, particularly notable at Killymaddy Lough (Hirons 1983, Fig. 2) and organic carbon values gradually decline. In combination these observations suggest a gradual shift in sediment regime towards increased allochthonous inputs.

Evidence for re-working of soil pollen comes from increased proportions of deteriorated pollen (Figs. 2 and 3) and these correspond with recurrent phases of anthropogenic activity, three in the Bronze Age (Zones W6 and K5) one in the Iron-Age to Early Christian period (Zones W7 and K6) and a final major shift *c.* 1170 A.D. preceding medieval and plantation farming (Zones W8–9 and K7–8). Each of these phases is highlighted by shading in Figs. 2 and 3. In each phase varying intensities of tree-clearance and agricultural activity is suggested by reduced tree and hazel pollen and increased proportions of herbs especially Gramineae, *Plantago lanceolata, Rumex* spp., *Urtica* and, in many cases cereals (Hirons 1984).

Sediment chemistry

The maximum organic carbon content at Weir's Lough exceeds 25% but at Killymaddy Lough the sediments rarely exceed 10% (Figs. 2 and 3). The pattern of carbon variations is different at the two sites. The difference is thought to be partly due to the smaller size of Weir's Lough which has resulted in greater inputs there from aquatic macrophytes and to be partly due to a greater drainage density in the Weir's Lough catchment providing more sensitive pathways for eroding materials. The organic carbon curve for Weir's Lough

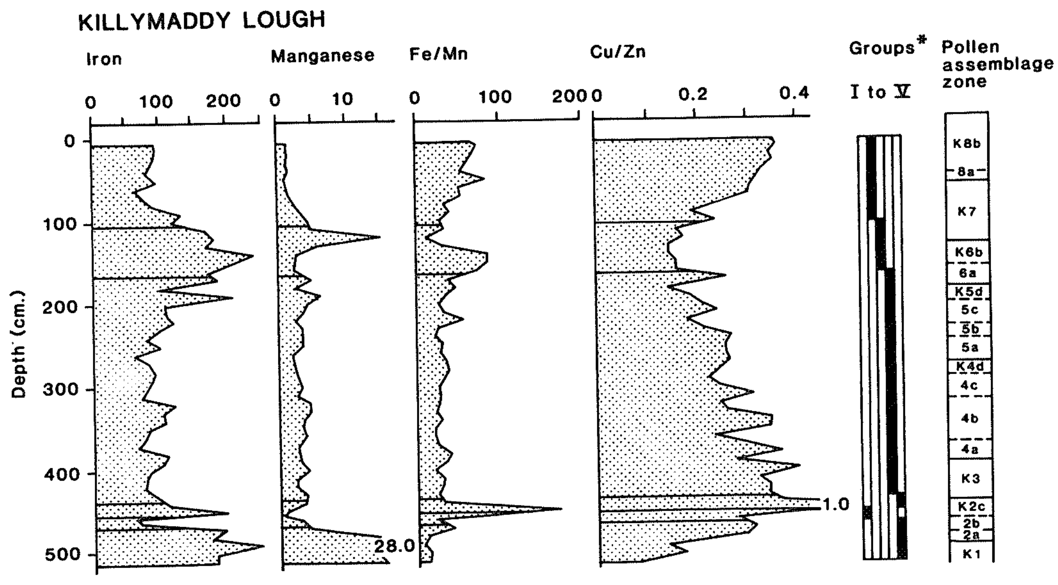

Fig. 4. Concentration profiles for iron and manganese (mg/g) and Fe/Mn, Cu/Zn plotted against depth in sediment for Killymaddy Lough. A column showing pollen assemblage zones is given, division of the profile on the basis of magnetic mineral groupings I to V are indicated.

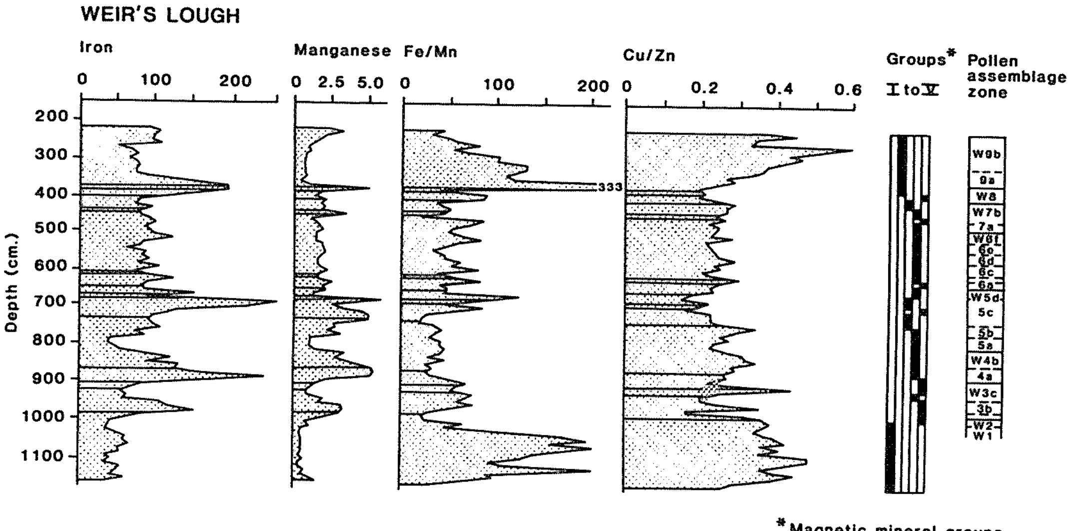

Fig. 5. Concentration profiles for iron and manganese (mg/g) and Fe/Mn, Cu/Zn plotted against depth in sediment for Weir's Lough. A column showing assemblage pollen zones is given, and division of the profile on the basis of magnetic mineral groupings I to V are indicated.

shows a clear distinction betweeen the lateglacial inorganic clays and postglacial sediments formed during periods of relatively stable catchment soils. The results of total analyses of Fe and Mn are presented as mg/g dry weight for Killymaddy Lough (Fig. 4) and Weir's Lough (Fig. 5) along with Fe:Mn and Cu:Zn ratios. Previous work on variations in the relative concentrations of these pairs of metals in lake sediments suggests they may relate to the redox conditions of the lake or catchment soils (Kjensmo 1964; Mackereth 1966; Hallberg 1974).

The concentration of highly mobile elements relative to the mineral fraction may be assumed to reflect the degree of weathering of substrates prior to recruitment (Mackereth 1966). One such element, potassium, is expressed on this basis in Figs. 2 and 3 illustrating the relatively unweathered nature of the lateglacial clays at Weir's Lough and also the clay layer at 455 cm in Killymaddy Lough. An increase in K in the mineral fraction towards the surface in both cores suggests the recruitment of greater proportions of relatively less weathered materials by progressive downcutting into mineral soils (Pennington & Lishman 1984).

Magnetism

Magnetic results have been obtained from the sediments of both lakes (Figs. 6 to 14 and Table 2) and from local soils (Figs. 11 to 14 and Table 2).

Killymaddy Lough

Whole core measurements of relative declination, horizontal intensity and initial susceptibility for Killymaddy Lough are plotted in Fig. 5, along with the pollen zones. The range of declination variations is similar to the variations found in other European lake sediments. Horizontal intensity can be seen to fall steadily from a maximum value of 14 mAm^{-1} after an initial rise from 1 mAm^{-1} at the base of the core. The fall is fairly steady other than a major minimum at 310 cm and two significant but less marked minima at 255 cm and 220 cm.

Mineral magnetic measurements on dried subsamples from Killymaddy Lough are presented in Fig. 7 on a mass specific basis. The mass specific susceptibility data compare well with the whole core measurements of Fig. 6. The small differences are explained by the standardization of susceptibility against the effects of variations in water content and density through expression on a specific dry weight basis. There are no major changes in density or water content in the Killymaddy core to effect the overall trends of susceptibility decreasing with depth. Susceptibility reaches a minimum at approximately 45–50 cm depth in pollen zone K8a before finally increas-

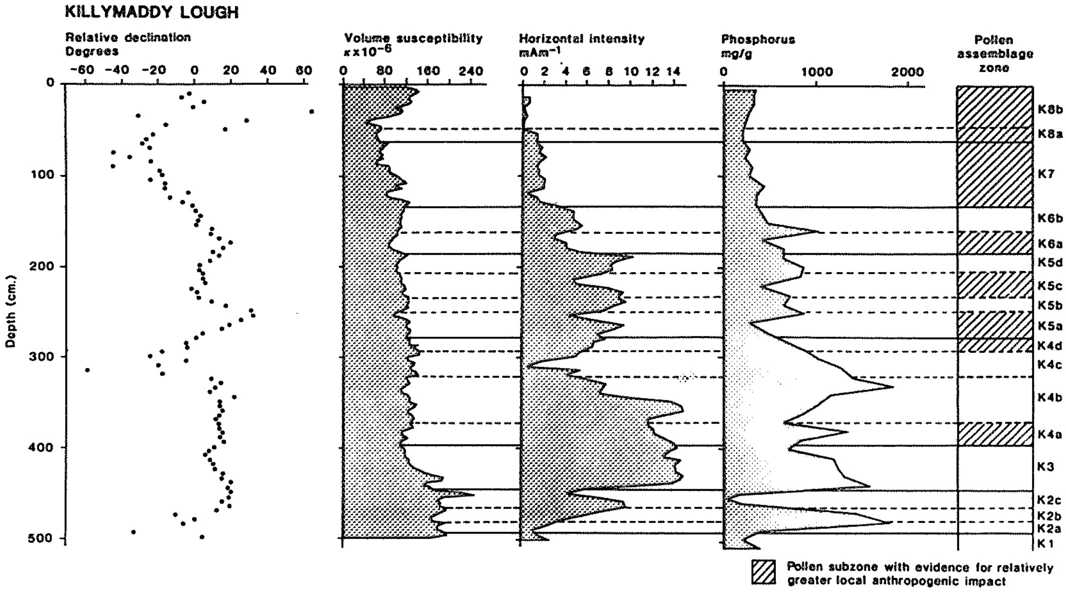

Fig. 6. Whole-core measurements of relative declination, volume susceptibility and horizontal intensity compared with total phosphorus for Killymaddy Lough. Pollen assemblage zones are indicated.

ing towards the surface. Another notable feature of the Killymaddy susceptibility profile is the peak at approximately 455 cm which appears to relate to a layer of inwashed clay. The susceptibility pattern of a slow decline from lateglacial values leading to a recent rapid increase is somewhat similar to susceptibility-depth changes found in more northerly European lake sediments (Thompson *et al.* 1980). Specific saturation isothermal remanence (Fig. 7) shows very similar variations to susceptibility.

The ratio of SIRM to χ (Fig. 7) peaks in zone K3 at 40 k Am^{-1} and falls to a minimum of 12 k Am^{-1} in zone K7. The S ratio (Fig. 7) reveals

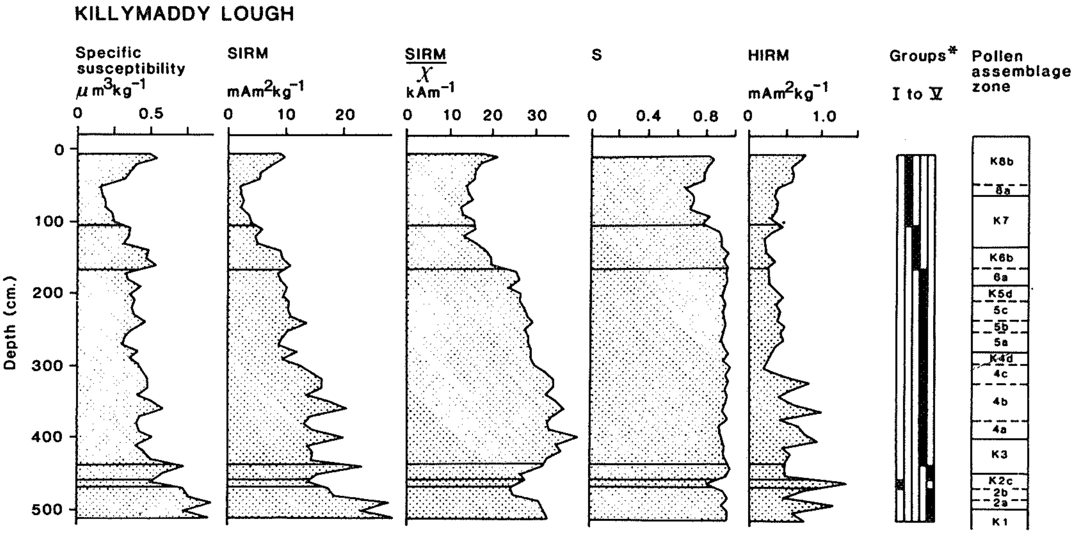

Fig. 7. Specific susceptibility (χ), saturation isothermal remanence (SIRM), SIRM/χ, S-ratio and high-field remanence (HIRM) plotted against depth in the Killymaddy Lough core. Magnetic mineral groupings and pollen assemblage zones are also indicated.

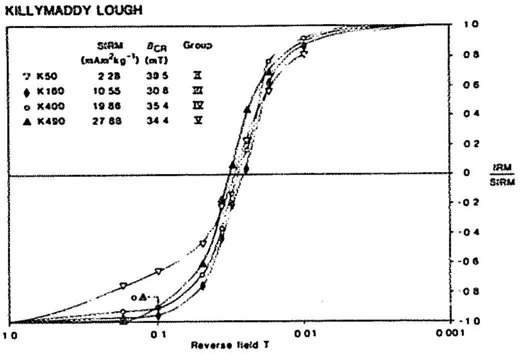

Fig. 8. Coercivity of remanence spectra for selected samples from Killymaddy Lough.

little variation with stratigraphic level save for lower values, indicating higher 'haematite to magnetite' ratios in the uppermost sediments of pollen zones K7 and K8 and in one horizon at 455 cm. The remanence acquired in fields above 0.1 T (HIRM) is also plotted in Fig. 7. Strong variations between 0.2 and 1.3 mAm^2kg^{-1} are found in the lower half of the core. Much of the upper half is dominated by low HIRM values which gradually rise to 0.8 mAm^2kg^{-1} at the sediment surface.

Four examples of back IRM measurements of Killymaddy lake sediments in Fig. 8 illustrate the range of variation of coercivity spectra in the profile.

Weir's Lough

Susceptibility, SIRM, SIRM/χ, S and HIRM are all plotted against depth for Weir's Lough in Fig. 9. Specific susceptibility shows a similar range of values to those at Killymaddy, varying between 0.25 and 1.0 μmkg^{-1}. The Weir's Lough data contain several notably sharp peaks in susceptibility (e.g. at 890 and 980 cm). Although again the general trend is for reduction of susceptibility up the core. The highly inorganic lateglacial clays at the bottom of the core appear as layers of slightly higher susceptibility. At the base of the core the susceptibility values of the interstadial carbonate deposits reach only 0.2 μmkg^{-1}.

SIRM follows a rather different pattern of variation with depth to that of susceptibility. The differences can be most easily seen by inspection of the SIRM/χ results in Fig. 9. Low SIRM/χ ratios, e.g. near 870 and 680 cm, mark particularly pronounced peaks in susceptibility. Such sharp variations in SIRM/χ are not found in Killymaddy Lough. Low SIRM/χ ratios are also found in the lateglacial clays and in the uppermost sediments.

The S ratio at Weir's Lough splits the profile into three regions – a lower region corresponding to the lateglacial clays with S ratio values of between 0.7 and 0.8; a middle region with S ratio values of close to 1.0; and an upper region, corresponding to pollen zone W9 and the top half of zone K8, which again has lower S values of around 0.7. The curve of S ratio values in Fig. 9

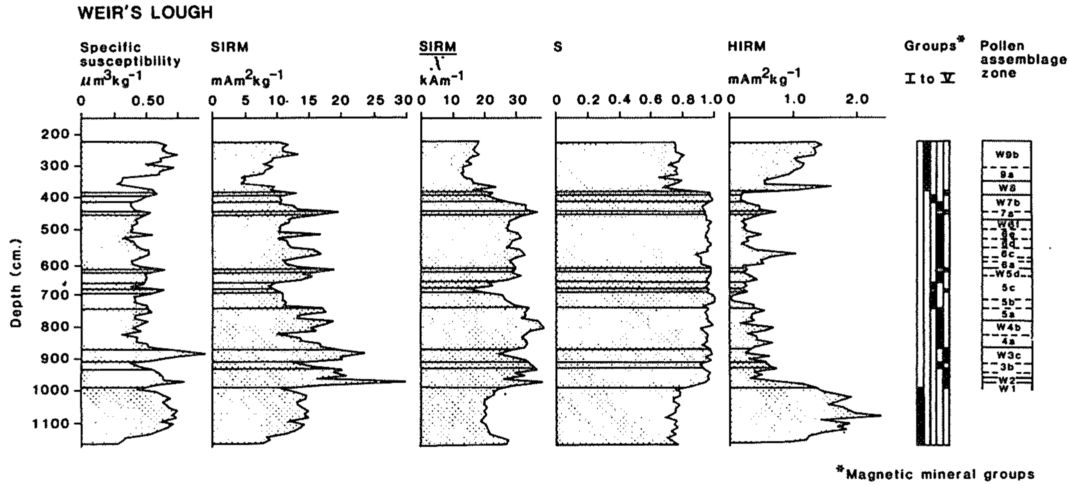

Fig. 9. Specific susceptibility, saturation isothermal remanence, SIRM/χ, S-ratio and high-field remanence (HIRM) plotted against depth in the Weir's Lough core. Magnetic mineral groupings and assemblage pollen zones are also indicated.

follows the SIRM/χ curve at certain periods. However, the major minima of SIRM/χ near 680, 870 and 980 cm are not reflected in the S ratio, showing that S is revealing different changes in magnetic mineralogy to those dominating either χ or SIRM.

Variations in HIRM are the inverse of the S ratio with low values of around 0.2 mAm^2kg^{-1} occurring in the middle section of the Weir's profile and higher values of over 1 mAm^2kg^{-1} dominating the lateglacial clays and the uppermost pollen zones (Fig. 9). A conspicuous minimum in HIRM is present in pollen zone W5c at 720 cm depth.

Four examples of the variation of isothermal remanence with back field are plotted in Fig. 10 for Weir's Lough sediment. The samples have been chosen to illustrate the range of variations that have been found. The coercivity of remanence $(B_o)_{CR}$ values for Weir's and Killymaddy Lough sediments range from 30.5 to 42.0 mT. These remanence coercivities are all fairly typical of comparable published sediment and soil data and are almost identical to remanence coercivities presented from the surrounding Lough Neagh catchment (Dearing & Flower 1982).

Soils data

Soil samples collected from surface (suffix; .1) and subsoil (suffix; .2) horizons near Killymaddy Lough have also been subjected to magnetic and chemical investigations. Susceptibility, SIRM, S ratio, HIRM and chemical results are presented in Tables 2 and 3 for fourteen soil samples.

These variable local soils display a wide range of magnetic properties which almost span the entire variation of properties found throughout the complete Killymaddy and Weir's sequences. Susceptibility tends on average to be higher in the soils than in the sediments, while average SIRM, S ratio and HIRM values are all very similar.

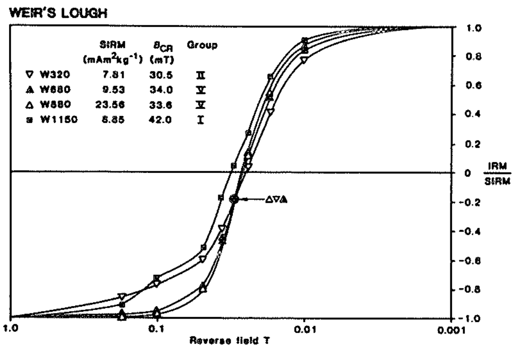

Fig. 10. Coercivity of remanence spectra for selected samples from Weir's Lough.

The soil samples KLM 15, 18 and 21 collected from a drumlin slope show some evidence of higher susceptibility, SIRM, S ratio and HIRM in their subsoils. Samples KLM 2, 37 and 40 collected at the base of the drumlin slope show indications of surface enhancement of susceptibility. At these sites at the base of drumlins the down-profile magnetic mineralogies seem to follow reverse trends to those of the soils from the less disturbed sites on the drumlin sides. Soil KLM 43 was collected near to the lake and is formed of hill-wash material which has accumulated on top of old lake muds.

There is no clear evidence for surface enhancement of susceptibility in the Killymaddy soils; a conclusion similar to that reached by Dearing & Flower (1982) for soils from other areas of the Lough Neagh catchment.

Particle size data

Information concerning possible variations in magnetic properties with particle size was investigated using three bulk samples from Killymaddy Lough (10–25 cm, 60–75 cm and 190–205 cm). The samples were split into seven particle size fractions using settling tanks, dried at low temperature and measured for χ, SIRM and S as described above. SIRM/χ and HIRM were also calculated.

The particle size fraction data (Table 4) reveal little within-sample variation, the between sample variations being much greater. These observations suggest that environmental processes leading to changes in source material would influence the downcore magnetic parameters at Killymaddy and Weir's Loughs much more than changes in particle size caused by hydrological or sedimentological fluctuations.

Interpretation of magnetic measurements

Scattergram diagrams have been drawn of various combinations of mineral magnetic parameters in order to aid in the determination of the range of mixtures of magnetic minerals which are to be found in the Killymaddy and Weir's lake sediments (Figs. 11, 12, 13 and 14). Fig. 11

Table 2. Specific susceptibility, SIRM, SIRM/χ ratio, HIRM, and S data for the soil samples. The samples have a code number followed by a suffix indicating; .1 surface sample or .2 subsoil sample.

Soil sample	χ $\mu m^3 Kg^{-1}$	SIRM mAm^2Kg^{-1}	SIRM/χ kAm^{-1}	HIRM mAm^2Kg^{-1}	S
2.1	1.02	15.3	15	1.50	.80
2.2	0.76	7.4	10	0.95	.74
15.1	0.74	10.7	15	1.58	.71
15.2	1.57	13.7	9	1.59	.77
18.1	0.71	7.4	10	1.03	.72
18.2	1.53	11.7	8	1.25	.78
21.1	0.47	4.9	10	1.04	.58
21.2	1.13	9.6	9	1.28	.73
37.1	1.15	14.9	13	1.24	.83
37.2	0.36	3.9	11	0.76	.61
40.1	2.72	28.6	11	1.77	.88
40.2	2.02	17.3	9	1.35	.84
43.1	1.62	19.6	12	1.60	.83
43.2	1.84	17.3	9	1.16	.86
Mean of soils					
.1	1.02	14.8	12	1.50	.80
.2	1.53	11.7	9	1.28	.77
Mean of sediments					
Weir's	0.52	13.2	26	0.73	.87
Killymaddy	0.44	11.9	26	0.50	.89

Table 3. Total iron, manganese and phosphorus analyses (mg/g), oxidizable organic carbon results (% dry wt.) and the ratios of Fe/Mn and Cu/Zn for soil samples. Sample codes as Table 2.

Soil sample	Mn mgg^{-1}	Fe mgg^{-1}	Fe/Mn	P mgg^{-1}	Cu/Zn	C %
2.1	.75	45.8	61	241.1	0.18	6.3
2.2	.49	27.7	57	105.1	0.25	1.7
15.1	.74	20.4	28	204.5	0.26	6.1
15.2	.77	28.8	37	72.8	0.37	2.0
18.1	.75	31.6	42	127.4	0.33	6.5
18.2	.71	29.2	41	64.2	0.39	1.6
21.1	.50	29.3	59	83.5	0.35	4.3
21.2	.87	29.0	36	59.8	0.47	2.0
37.1	.64	35.9	56	165.9	0.86	5.4
37.2	.35	49.0	140	47.2	0.20	0.5
40.1	.78	41.2	53	128.9	0.98	6.4
40.2	.49	44.2	90	97.0	1.00	2.3
43.1	.71	38.5	54	158.4	0.79	7.0
43.2	.47	32.7	70	52.5	0.34	6.4
Mean of soils						
.1	.69	75.3	50	158.5	0.54	6.0
.2	.58	34.37	67	71.2	0.43	2.4
Mean of sediments						
Weir's	1.79	91.3	73	670.5	0.27	16.4
Killymaddy	3.43	120.0	37	620.9	0.24	8.5

plots χ against SIRM for Killymaddy sediments. The same two parameters are used in Fig. 12 for Weir's sediments. The ratio of SIRM to χ is plotted against S ratio in the scattergrams of Figs. 13 and 14 for Killymaddy and Weir's samples respectively.

High SIRM/χ ratios are found for magnetic mineralogies of high stability such as those dominated by the magnetic properties of haematite, goethite or single domain magnetite (Nagata 1953). Low SIRM/χ ratios reflect low stability mineralogies with important paramagnetic, su-

Table 4. Results of magnetic investigations on particle-size fractions from three bulked samples from Killymaddy Lough. Samples K10–25 and K60–75 are from Group II mineralogies and K190–205 from Group IV.

Sample	Size fraction	χ $\mu m^3 Kg^{-1}$	SIRM mAm^2Kg^{-1}	SIRM/χ kAm^{-1}	HIRM mAm^2Kg^{-1}	S
K10–25	4φ+	0.29	4.8	16	0.92	0.81
	4–5φ	0.34	5.3	16	1.00	0.81
	5–6φ	0.32	5.3	17	1.05	0.80
	6–7φ	0.35	5.1	15	1.04	0.80
	7–8φ	0.34	5.0	15	1.01	0.80
	8–9φ	0.35	4.6	13	0.96	0.79
	<9φ	0.40	4.2	10	0.74	0.82
K60–75	4φ+	0.09	1.6	18	0.53	0.68
	4–5φ	0.12	1.7	14	0.56	0.67
	5–6φ	0.08	1.3	16	0.40	0.70
	6–7φ	0.14	2.0	14	0.62	0.68
	7–8φ	0.16	1.9	12	0.56	0.71
	8–9φ	0.20	2.1	11	0.61	0.71
	<9φ	0.15	1.8	12	0.41	0.77
K190–205	4φ+	0.29	7.8	27	0.49	0.94
	4–5φ	0.26	7.4	28	0.61	0.92
	5–6φ	0.27	6.6	25	0.56	0.92
	6–7φ	0.22	5.9	27	0.38	0.94
	7–8φ	0.26	5.6	22	0.51	0.91
	8–9φ	0.17	5.7	34	0.50	0.91
	<9φ	0.22	8.8	41	0.59	0.93

perparamagnetic or multidomain components (Nagata 1953). Samples containing high concentrations of ferrimagnetic minerals can also be recognized on the scattergrams as they plot towards the right hand side of the χ *v*. SIRM scattergram on account of their high SIRM values. Samples with unusually high imperfect antiferromagnetic to ferrimagnetic ratios (e.g. haematite to magnetite ratios) can also be easily distinguished on the scattergrams as they fall towards the left on the SIRM/χ *v*. S ratio diagrams on account of their low S ratios.

Mineral magnetic groupings

Using the scattergrams five major groupings of magnetic mixtures can be distinguished in the Killymaddy and Weir's sediments. These groupings have been highlighted by plotting samples from particular stratigraphic contexts with distinct symbols.

Samples from the oldest Weir's pollen zone W1 are plotted in Figs. 12 and 14 as squares and form the bulk of one mineral magnetic grouping (Group I). One Killymaddy sample from a distinct minerogenic rich layer at 455 cm depth has similar magnetic properties and is also plotted as a square (Figs. 11 and 13).

Samples from the most recent pollen zone of Weir's Lough (W9) and from the top half of the preceding zone (W8) also have separate magnetic properties. They are plotted as open triangles in Figs. 12 and 14 and form a second grouping (Group II). The most recent Killymaddy sediments have the same Group II mineral magnetic properties of low SIRM/χ ratios, low S ratios, high HIRM values and generally low SIRM and χ values. These samples from the upper Killymaddy pollen zone (K8) and the top half of the preceding zone (K7) are also plotted as open triangles in Figs. 11 and 13.

A third set of samples are plotted as diamonds in Figs. 11 to 14 and form a third distinct group (Group III). These samples come from stratigraphically immediately below the Group II samples in the lower half of pollen zones K7 and W8 and also from pollen zone W5c in the Weir's core.

The remaining samples are plotted as circles in Figs. 11 to 14 (Group IV). Filled triangles are used to distinguish samples with particularly high SIRM and χ values and form a fifth group (Group V). A column is included in Figs. 4, 5, 7 and 9 illustrating the stratigraphic context of samples falling into the groups of magnetic mixtures outlined above. This column facilitates compari-

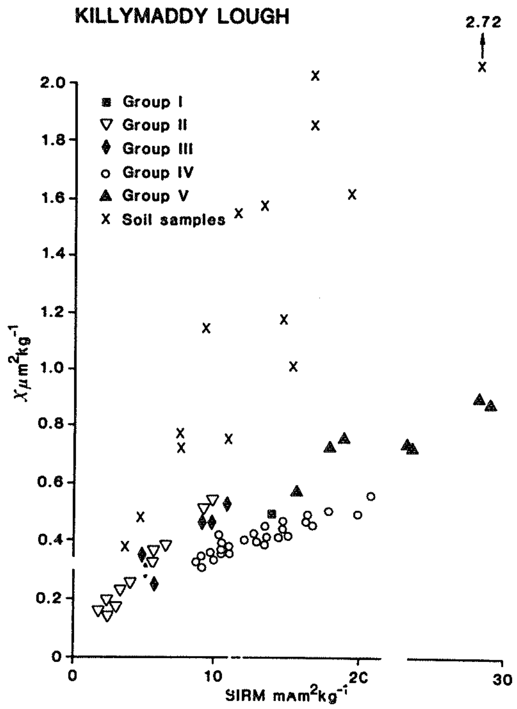

Fig. 11. Plot of specific susceptibility (χ) against specific SIRM for samples from the Killymaddy Lough core. Samples from suggested magnetic mineral groupings and soil samples indicated by symbols as in key.

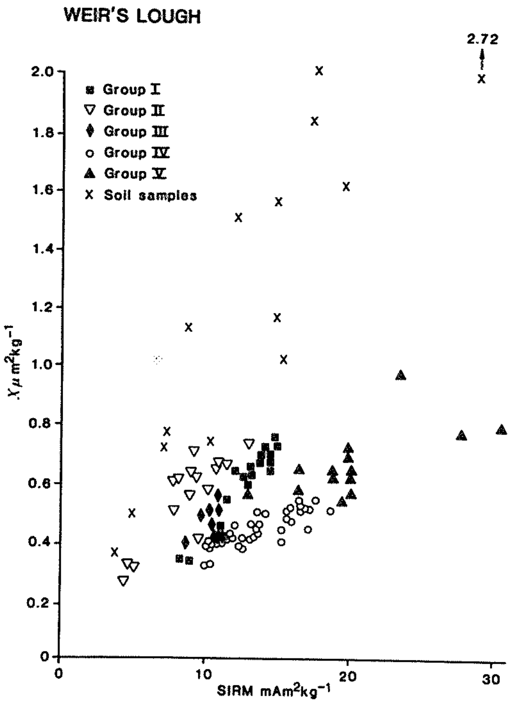

Fig. 12. Plot of specific susceptibility (χ) against specific SIRM for samples from the Weir's Lough core. Samples from suggested magnetic mineral groupings and soil samples indicated by symbols as in key.

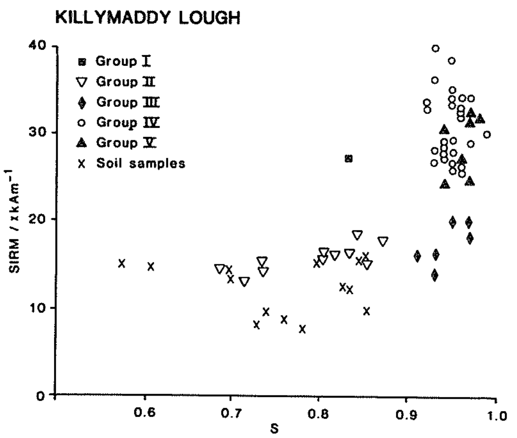

Fig. 13. Plot of the ratio SIRM/χ against S for Killymaddy Lough sediments and soil samples. Magnetic groupings indicated in key.

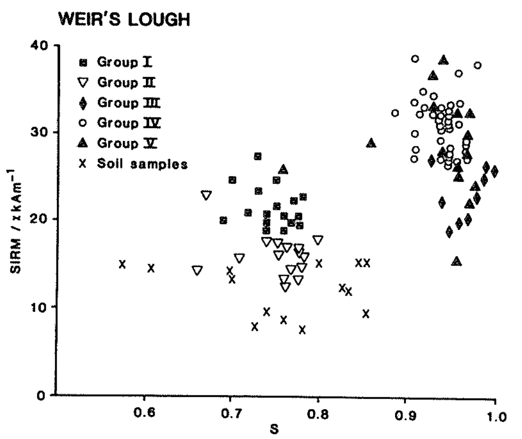

Fig. 14. Plot of the ratio of SIRM/χ against S for Killymaddy Lough sediments and soil samples. Magnetic groupings indicated in key.

sons with the magnetic and chemical data and the pollen assemblages zones. In Killymaddy these Group V samples are from the two oldest pollen zones (K1 and K2). The Weir's samples in Group V have quite a different stratigraphic context.

They are made up of samples with unusually high manganese concentrations and can be seen in Fig. 5 to be from the two oldest pollen zones (K1 and K2). The Weir's samples in Group V have quite a different stratigraphic context. They are made up of samples with unusually high manganese concentrations and can be seen in Fig. 5 to be from five horizons around 380, 450, 680, 880 and 980 cm depth. The remaining samples from both the Killymaddy and Weir's Loughs are all plotted as upright triangles and make up Group IV with high SIRM/χ ratios, high S ratios, fairly high SIRM/χ values and moderate susceptibilities.

In summary for the Killymaddy and Weir's lake materials five broad groupings of magnetic mineralogies can be picked out. High stability magnetic minerals (presumably haematite or geothite) are an important part of the magnetic mineralogy of Group I and Group II samples. Group II samples also tend to have low magnetic concentrations. Group III samples are characterized by a lack of high stability minerals and by fairly low concentrations of ferrimagnetic minerals. Group IV samples have low concentrations of high stability minerals and moderate ferrimagnetic concentrations while Group V samples are characterized by the highest ferrimagnetic concentrations.

Discussion

Erosion indicators

The linkages between magnetic mineralogy and catchment land-use changes that have been observed in two other Northern Irish sites at Lough Neagh and Lough Catherine are again found at Killymaddy and Weir's Loughs, although the details of the mineral magnetic/land-use linkages differ. The most pronounced effect in both the Killymaddy and Weir's catchments is the increase in proportion of high stability minerals during times of accelerated erosion.

The high stability mineral of Group I and Group II samples deposited during periods of increased erosion is thought most likely to be haematite. The change to Group II mineralogy around 1500 A.D. (mid zones W8 and K7) is clearly connected with the most recent farming period. Haematite content of the lake sediments, as judged by their HIRM values, increases along with pollen evidence for anthropogenic activity. At Weir's Lough from pollen zone W5d to the present day HIRM is the reverse of total tree pollen. Reduction in tree cover and associated environment instability presumably lead to a greater proportion of haematite in the inwashed material. The Group I samples which also have high haematite concentrations are taken to reflect inwashed immature lateglacial soils and drift with their low organic carbon content and higher proportions of K in the mineral fraction. At Weir's Lough, Group V samples with their relatively high proportions of ferrimagnetic ('magnetite' type) minerals were deposited during lateglacial times before catchment stability was established.

At Killymaddy Lough (Fig. 7), there is an inverse relationship between susceptibility and pollen evidence for increased anthropogenic activity. In pollen subzones with evidence suggesting reduced anthropogenic interference, for example in K4b, K5b, K5d and K6b, susceptibility is found to increase. In zone K7, a period of apparently very intensive anthropogenic activity, susceptibility falls to its lowest level. At Weir's Lough (Fig. 8) susceptibility tends to follow the total tree pollen curve and to show an inverse relationship with anthropogenic pressure. However, in the most recent period of intensive farming (pollen zones K8 and W7–9), the susceptibility is again high.

The land-use changes – magnetic linkages in the Killymaddy and Weir's catchments – are not easily explained in terms of topsoil erosion but are more likely to result from the hydrological affects of catchment clearance events and in the changing balance of material contributed from soils and from stream bed/bank sources as suggested for the Lough Neagh catchment by Dearing & Flower (1982). The greater drainage density at Weir's Lough appears to have resulted in a more sensitive catchment and in a more variable sedimentary record than at Killymaddy.

Particle size data (Table 4) suggest that any model relating changes in downcore susceptibility to enhanced topsoils containing high concentrations of ultra-fine superparamagnetic material (Thompson *et al.* 1975), may be discounted here. Similarly, there is no evidence for a concentration of magnetic minerals in the coarse particle fractions and models based on changes in depositional environments may also be ruled out (Thompson & Morton 1979; Thompson & Edwards 1982). The most likely available explanation for the downcore changes in magnetic properties is therefore one based on changes in the source of the magnetic minerals. Presumably the more active erosional regimes of the lateglacial and intensive agricultural periods have both been able to erode substrates relatively rich in magnetite and haematite throughout the 4 to 10 μm range.

Authigenic minerals

Variations in sedimentary iron and manganese concentration are probably related to changes in elemental solubility of the Killymaddy and Weir's catchment soils and lake basins caused by redox variations. Peak concentrations have probably been caused by precipitation and growth of authigenic minerals.

The Fe to Mn ratios of lateglacial clays at Weir's Lough are up to 200, far greater than mean Fe/Mn ratios for local soils of up to 50 for topsoils and 60 for subsoils (Table 3). Similar enhanced Fe/Mn ratios in lateglacial clays from the Lake District and Scotland (Mackereth 1966; Pennington *et al.* 1972) have been attributed to the mechanical enrichment or iron by a particle-size effect.

Preferential accumulation of manganese with respect to iron is witnessed by a decreasing Fe to Mn ratio at the base of the Killymaddy Lough profile (Fig. 4) and at the late- to postglacial transition in Weir's Lough (W1–2, Fig. 5). Iron and manganese concentrations in excess of mean soil values suggest solutional transport of these elements from a reducing soil and concentration in the sediments. The preferential movement of Mn is the result of its greater solubility at low redox potentials.

Patterns of iron and manganese deposition are radically different in the two cores but at both sites a reduced concentration of Fe and Mn occurs early in the postglacial. A similar pattern of events was found at Mackereth's (1966) Lake District sites where it was suggested that the development of a periodically reducing hypolimnion could facilitate a lowered concentration of Fe and Mn by release from the sediment. Recent work by Davison, however (Davison 1981; Davison *et al.* 1982; Pennington & Lishman 1984), has outlined the importance of decomposing organic matter for loss of Mn from the sediment and suggests that solutional losses of Mn and therefore the Fe to Mn ratio may relate to the productivity of the lake as a primary control on the availability of organic matter. Davidson could find no evidence for appreciable loss of iron from sediments.

Further striking peaks of iron and manganese, generally corresponding to low Fe/Mn, occur at W3–4, W5c and W8 at Weir's Lough. The second peak, dated at 8,000 to 6,000 B.P. at Weir's Lough is apparently a continuation of the initial phase at Killymaddy Lough. The period coincides with the deposition of a clay layer at Killymaddy Lough, and increased carbonate deposition and evidence for remobilized and therefore deteriorated pollen at both sides. The above suggestion of temporary low water levels at this time might have caused the breakdown of a reducing hypolimnion and prevented the loss of sedimentary iron and manganese (following Mackereth's scenario). Similar suggestions of the retention of manganese during early postglacial periods of low water level have been made by Pennington & Lishman (1984).

The third Weir's peak in iron and manganese of 4,000 years ago in pollen zone W5c perhaps suggests a similar period of oxidizing lake conditions, whilst the uppermost iron/manganese peak in W8, *c.* 1100–1500 A.D. comes immediately before a major erosion phase and so might relate to inputs of highly iron-charged water from the drainage of waterlogged soils. Evidence from the pollen record for clearance of local alder stands for agriculture (Hirons 1984) at a time of major settlement in the area supports this supposition. The Fe profile at Killymaddy Lough is less eventful showing only one major peak at 100–200 cm culminating with a Mn peak in K7 dating to around 1450 A.D. and possibly corresponding to the latter peak at Weir's Lough.

Hallberg (1974) has shown the value of the ratio of copper to zinc as a palaeoredox indicator in the Eastern Gotland basin. Digerfeldt *et al.* (1975) and Vuorinen (1978) have successfully applied this measure to the study of freshwater lake sediments. The copper to zinc ratio is plotted against depth in Fig. 4 and Fig. 5 for the Killymaddy and Weir's sediments. Hallberg showed that in reducing conditions copper is increased in relation to zinc and that the opposite holds in more oxidizing lake conditions. Copper to zinc ratios in the Weir's Lough lateglacial clays are relatively high (*c.* 0.4) but decline very rapidly in the postglacial. Fluctuations in the copper to zinc ratios at 980, 870, 680 and 380 cm depth all support the shift in lake redox conditions suggested by the iron and manganese data. At Killymaddy Lough the basal sediments have relatively low copper to zinc ratios (*c.* 0.1). The ratios increase to a peak of 1.0 in the clay layer at 455 cm. Above this they gradually decline to pollen zone K6a. After the minimum in zones K6 and K7, the ratio shows a gradual increase towards the surface, suggesting a return to oxidizing conditions.

The Group III magnetic samples from Killymaddy and Weir's Loughs come from the twelfth to sixteenth century levels of increased iron and manganese concentration and some at Weir's Lough from W5c approx. 4,000 B.P. The Group V magnetic properties from Weir's Lough of high susceptibility and high SIRM correspond to the other peak iron and manganese levels. Both the iron-manganese and copper-zinc chemical data then strongly point to changing redox conditions having led to the formation or precipitation of magnetic iron and/or manganese minerals from charged water inputs. Both ferrimagnetic and paramagnetic authigenic magnetic minerals must have been formed by the changing redox conditions.

Various other studies have compared total or extractable iron with susceptibility data in lake sediments. Thompson *et al.* (1975) showed that there is some relationship between total iron content and susceptibility in Lough Neagh sediments and suggested that magnetite is a major contributor to sedimentary iron there. Dearing *et al.* (1982) suggested that a lack of correspondence between iron analyses and magnetic records from English reservoir sediments indicated the allochthonous nature of sedimentary magnetic minerals rather than formation of iron oxide or sulphide minerals authigenically. Oldfield *et al.* (1983) report cases where high concentrations of paramagnetic iron contribute to susceptibility after deposition of iron from enriched groundwaters. Presumably this last mechanism operates to some extent in all iron-rich sediments but is only significant where primary and secondary ferrimagnetic concentrations are very low, as at Killymaddy and Weir's Loughs.

Authigenic paramagnetic minerals have been suggested to be responsible for peak susceptibility values which correspond to peak iron and manganese concentrations at L. Goddionduon in N. Wales (Bloemendal 1982), while precipitated iron minerals are also probably the cause of early Flandrian susceptibility maxima at Loch Davan in NE Scotland (Edwards 1978). At both these sites the susceptibility maxima coincide with minima in the SIRM/χ ratio. At Weir's, however, peaks occur in SIRM and even in SIRM/χ ratio at the χ maxima at 980 and 450 cm depth. This relationship suggests that at Weir's Lough ferrimagnetic minerals have been precipitated in addition to the precipitation of paramagnetic iron materials.

Intensity of natural remanence

The horizontal remanence intensity record (Fig. 6) does not follow the British archaeomagnetic intensity record (Aitken 1974) of past fluctuations in geomagnetic intensity. There does appear to be some relationship between intensity, total sedimentary phosphorus concentration and pollen evidence for local anthropogenic activity (Fig. 6) but the relationship is not a clear one. Natural remanence intensity in lake sediments seems to be controlled by many factors which can include catchment events, lake redox conditions, magnetic mineral concentration, sediment packing and deposition rates. These complex varied factors at Killymaddy, as at most other lakes, appear to have largely obscured past geomagnetic intensity changes in the palaeomagnetic record.

Conclusions

Late- and postglacial sediments from Weir's and Killymaddy Loughs have been divided into five distinct groupings on the basis of magnetic mineralogy. These groupings appear to have a stratigraphic basis and to relate to changes in the organic/inorganic content of the sediments and to changes in the concentration of elements such as Fe and Mn.

Two groups with both high 'magnetite' and high 'haematite' content are found in lateglacial (before *c.* 10,000 B.P.) and recent (post 1170 A.D.) sediments. These two magnetic groups are suggested to be related to erosion by solifluction and by intense soil disturbance caused by farming activity.

Two of the other magnetic groups are found in periods of high iron content. One being specific to periods of peak Mn in the sediments. Variations in the redox potential of the catchment soils and lake waters possibly caused by changes in lake-level, changes in stratification and perhaps drainage in the later postglacial are considered to have resulted in the formation of paramagnetic and ferrimagnetic authigenic minerals.

Smaller scale variations in susceptibility suggest deposition of sediments relatively low in ferrimagnetic minerals at times of moderate anthropogenic activity. Such material may be scoured from streambed and bank sources as a result of local hydrological changes. Particle size data revealed that between-sample magnetic variations were much greater than those between different size fractions, indicating that downcore magnetic variations had been caused by changing sources of magnetic minerals.

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