A Holocene palaeomagnetic record and a geomagnetic master curve from Ireland

ROY THOMPSON AND KEVIN J. EDWARDS

BOREAS

Thompson, Roy & Edwards, Kevin J. 1982 12 01: A Holocene palaeomagnetic record and a geomagnetic master curve from Ireland. *Boreas*, Vol. 11, pp. 335–349. Oslo. ISSN 0300-9483.

Magnetic analyses have been carried out on sediments collected from Lough Catherine, Northern Ireland, as part of a wider environmental study. The sediments span the whole of the Holocene. Radiocarbon and pollen dating of the palaeomagnetic signature locked in the sediments form the basis of an Irish Holocene geomagnetic master curve. The mineral magnetic characteristics of the sediments correspond with environmental changes, such as eighteenth century landscaping and the elm decline as revealed by pollen analyses. Both marginal and central sediments have been analysed. The sediments can be correlated by using either magnetic, pollen, or ^{14}C measurements. These three independent core correlation methods all agree extremely well with each other. A mathematical method is described which can be used to calculate continuous accumulation rates and influxes.

Roy Thompson, Department of Geophysics, University of Edinburgh, Mayfield Road, Edinburgh EH9 3JZ, United Kingdom; Kevin J. Edwards, Department of Geography, University of Birmingham, P.O. Box 363, Birmingham B15 2TT, United Kingdom; 12th January, 1982.

Following Mackereth's (1971) work on the magnetic declination recorded in the sediments of Lake Windermere in Northern England, Thompson (1973) demonstrated that similar declination changes could be found in the sediments of Lough Neagh, Northern Ireland. The palaeomagnetic records of these organic lake sediments are interpreted as recording the changes in direction of former geomagnetic fields. Irish palaeomagnetic measurements on organic sediments of both declination and inclination have now been extended to cover the whole of the Holocene in Lough Catherine, Co. Tyrone. Detailed ^{14}C and pollen analyses of the Catherine lake sediments and nearby peat profiles provide a good chronology for the palaeomagnetic results. An Irish geomagnetic master curve has been constructed from the Catherine data and is compared with results from other Irish sites. In all over 50 ^{14}C age determinations from eight sites have been combined to date the palaeomagnetic measurements from three Irish lakes.

The weak remanent magnetization of a lake sediment does not necessarily accurately reflect the direction of the ancient geomagnetic field at the time of deposition of the sediment. As natural remanences can be produced in several ways this situation can lead to the mistaken interpretation of fluctuations in palaeomagnetic direction as ancient field changes. As Watkins (1971) has shown, such mistaken interpretations tend to be reinforced and to become very difficult to correct. It is necessary in such circumstances continually to check and review previous interpretations. The Lough Catherine study provides an important independent Irish data set which can be compared and contrasted with British mainland Holocene palaeomagnetic data.

Sediment collection

Lough Catherine (54.7°, 7°, 5°W and Irish Grid Ref. H365 840) is the largest and lowermost lake of a natural triple lake system. It is located on the Barons Court Estate, 4 km south-west of the town of Newtonstewart, County Tyrone, Northern Ireland. The lake lies at 60 m Irish O.D., only a few metres below the level of Lough Mary (Fig. 1). It is about 1,600 m long, 250 m wide and 8 m in depth, and drains via an outlet at its northern end into the River Derg, eventually reaching the sea by way of Lough Foyle north of the city of Londonderry. The catchment of Lough Catherine, which encompasses that of the two lakes above it, covers an area of about 22 km^2. The flanking hill slopes reach a height of 423 m to the south-east (Bessy Bell) and 167 m to the west (a spur of Mullaghcroy hill). The bedrock of the area is composed mainly of Dalradian

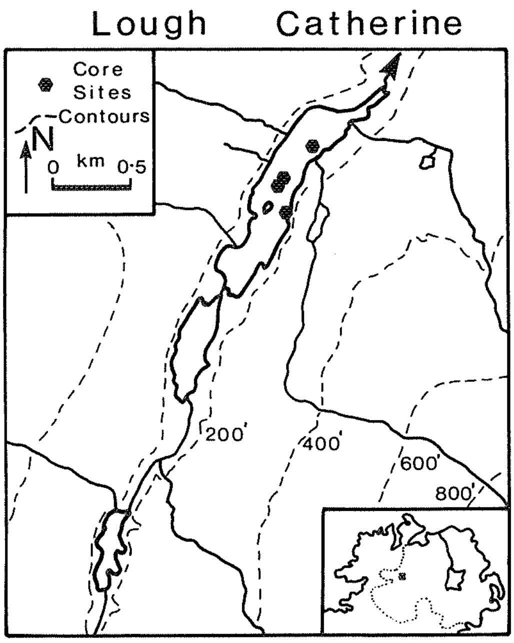

Fig. 1. Lough Catherine coring site map.

quartzites and schists with a glacial drift cover. The land use of slopes surrounding the lakes is plantation woodland and pasture which have been managed since the mid-eighteenth century A.D.

The Lough Catherine material was collected using Mackereth (1958, 1969) corers. Two 6 m long cores LCI and LCII and three 1 m long cores were collected by P. O'Sullivan in 1972 with the equipment of the School of Environmental Sciences at the New University of Ulster. The long cores were collected in 7 m of water near the centre of the lake. Four 6 m long cores and four 1.3 m long cores were also collected in 1978 using the Edinburgh University Geophysics Department equipment. One of these 6 m cores was taken close to the eastern margin of the lake in 6 m of water. Interestingly this marginal core contains the oldest and apparently most uniform sediment sequence of all the cores studied.

Pollen analysis

Samples of sediment (volume 0.5 ml) were extracted from the cuboid box containers used for the detailed magnetic measurements. Sediment digestion by standard hydrofluoric acid and Erdtman's acetolysis procedure (Faegri & Iversen 1975) was followed by pollen counting on a Wild M20 microscope. The pollen sum was based on 500 total land pollen and the sampling interval varied between 20 and 50 mm. Counts of pollen were made on both the central sediments of core LCI and the marginal sediments of core LCVI.

The changing pattern of the fossil flora is represented by the summary diagram for core LCI (Fig. 2). An early postglacial vegetational landscape featuring *Juniperus–Salix* scrub was superseded by a succession of woodland dominants as temperatures increased and soil profiles developed with *Betula–Corylus* giving way to *Pinus–Ulmus–Quercus* and with the distinctive appearance of *Alnus* at the traditional Boreal–Atlantic transition generally thought to denote wetter conditions (504.5 cm in core LCVI and represented at 534 in core LCI). The elm (*Ulmus*) decline (465 cm in core LCVI and 487 cm in core LCI) is a largely synchronous horizon in north-west European pollen diagrams (Smith & Pilcher 1973). The reduction in elm pollen values is generally accepted as reflecting the early stages of forest clearance by Neolithic agriculturalists (Edwards 1980). Major, progressive woodland clearance is not indicated until about the 400 cm level in both pollen-analysed cores. This clearance is matched by inferred arable/pastoral activity and the possible deterioration of soils suggested by increases in such wetland taxa as Cyperaceae and *Calluna vulgaris*. All cores show an expansion in such arboreal taxa as *Pinus, Fagus, Picea, Acer* and *Tilia* at the tops of their pollen profiles – this undoubtedly reflects the start of woodland plantation on the Barons Court Estate from around 1750 A.D. (McGuigan 1979).

A comparison of the pollen profiles of cores LCI and LCVI using the dynamic programming algorithm (Delcoigne & Hansen 1975) implemented in the SLOTSEQ program (Gordon 1973; Birks 1979) resulted in a ψ value of 0.95. This low value indicates an excellent slotting fit.

Data acquisition techniques and instrumentation

Magnetic measurements

Preliminary magnetic measurements of horizontal remanence (declination and intensity) and initial susceptibility were made on all the cores

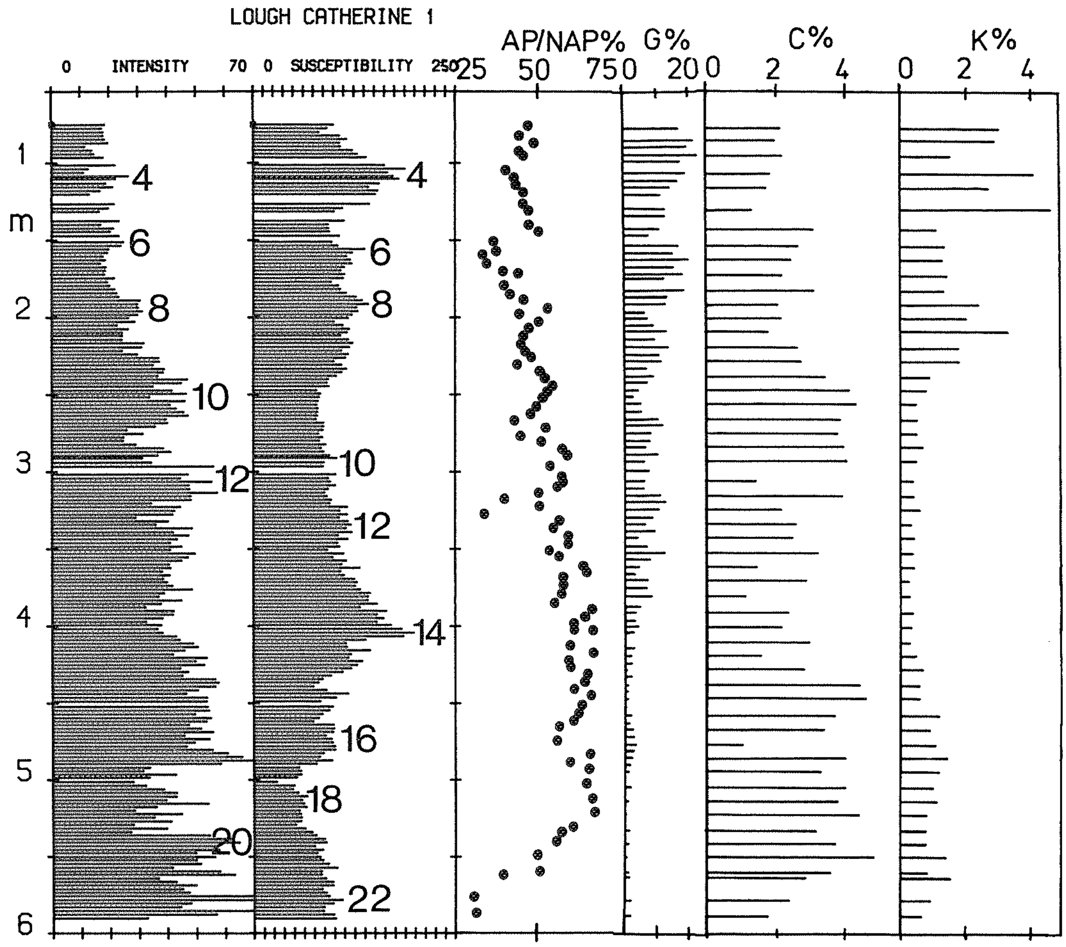

Fig. 2. Core LCI NRM, χ, AP/NAP ratio, Grass pollen, Carbon and Potassium vs. depth.

while they were still complete in their liner tubes. The whole core apparatus and measuring techniques are described in Molyneux *et al.* (1972) and Molyneux & Thompson (1973). Orientated samples in cuboid plastic boxes of volume 5 ml were taken at intervals of about 25 mm from the split half of the three cores selected for more detailed studies. A Digico fluxgate magnetometer (Molyneux 1971) was used to measure the remanent magnetic properties of the gyttja. Initial susceptibility was measured in an air cored bridge similar to that used for the whole core measurements. Partial alternating field demagnetization was carried out at 50 Hz frequency using a two axis tumbler in a zero magnetic field environment produced by a triple mu-metal shield. A conventional electromagnet with truncated conical pole tips was used to produce isothermal remanent magnetizations in uniform magnetic fields of up to 1 T (10 kOe).

Radiocarbon dating

Ten samples from core LCVI and thirteen samples from core LCI (all 15 cm thickness) were submitted for dating to the Palaeoecology Centre of the Queen's University of Belfast, under the supervision of Mr. Gordon Pearson. The samples were prepared by acid and alkali washes followed by combustion to obtain elemented carbon. This was converted to methane gas for counting purposes (Smith *et al.* 1970).

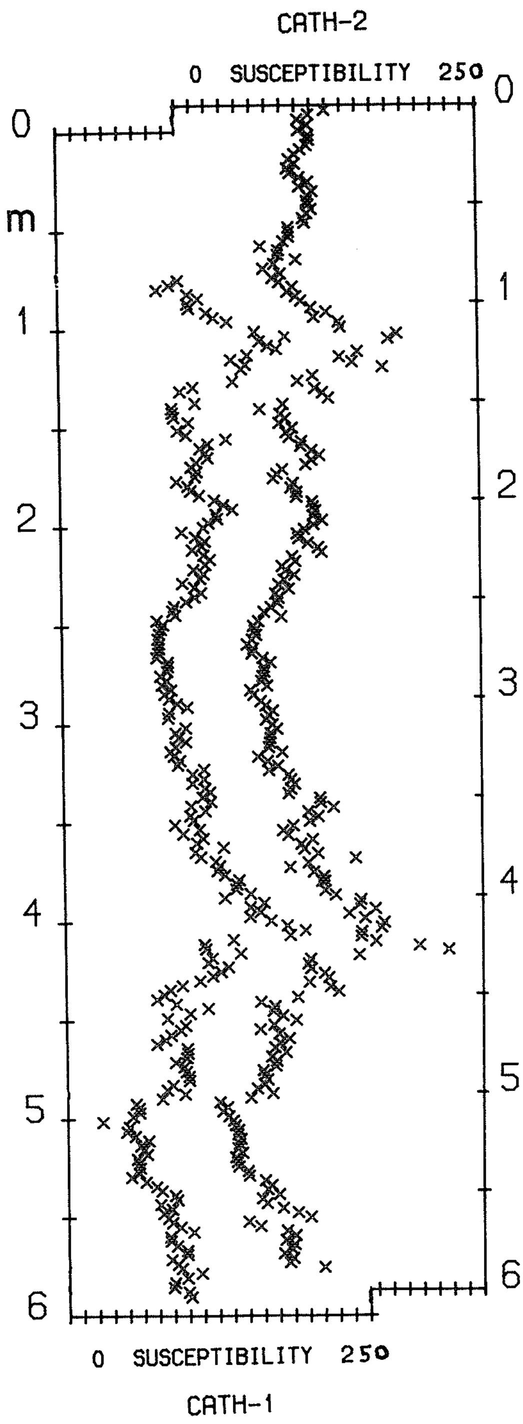

Fig. 3. Core correlation. Susceptibility vs. depth. Cores LCI & II.

Sediment chemistry

Samples of sediment from core LCI were oven dried and digested by a nitric acid–hydrogen peroxide procedure (Krishnamurty *et al.* 1976). Element determination (K, Mg, Ca, Cu, Al, Mn, Fe) was by atomic absorption spectrophotometry. Total organic carbon was determined by the wet oxidation method (Tinsley 1950).

Magnetic mineralogy

Magnetic susceptibility

The variation of magnetic susceptibility with depth in a lake sediment mainly depends on the concentration of ferrimagnetic iron oxides in the sediment (Thompson *et al.* 1975). Susceptibility has often been observed to form a useful parameter for correlating cores. Fig. 3 illustrates the similarity of the susceptibility characteristics of two of the Catherine long cores. Iron oxide concentrations in lake sediments have been found to reflect the pattern of erosion in the watershed, as recorded by selected pollen percentages or chemical variations (Thompson *et al.* 1975). In the Lough Catherine sediments such broad correlations can again be seen. Magnetic susceptibility shows a decline between 10,000 and 5,000 years B.P. and a series of rising cycles from 5,000 years ago to the present day (Fig. 4). The change in trend from declining to rising concentrations occurs precisely at the elm decline. Many of the later cycles do not correlate in detail with any obvious erosion indicators in the pollen or chemical records. A major susceptibility peak (maximum 4) is found, however, near the top of the sediments in all the long cores (Figs. 2, 4, 5) and also in the central short cores. This feature occurs close to a dramatic increase in *Pinus, Fagus, Picea, Acer* and *Tilia* pollen frequencies which clearly reflects landscaping of the Park in the mid-eighteenth century. The susceptibility peak could reflect erosion associated with plantation of the trees or with a raising of lake level or with agriculture somewhere in the catchment.

The susceptibility logs also demonstrate differences in sedimentation at the central and marginal coring sites of LCI/II and LCVI respectively. At the central sites the susceptibility rises quickly following the elm decline to a marked peak (maximum 14, Figs. 2 and 5). At the marginal site the susceptibility increase is slower. The marked susceptibility maximum in the central

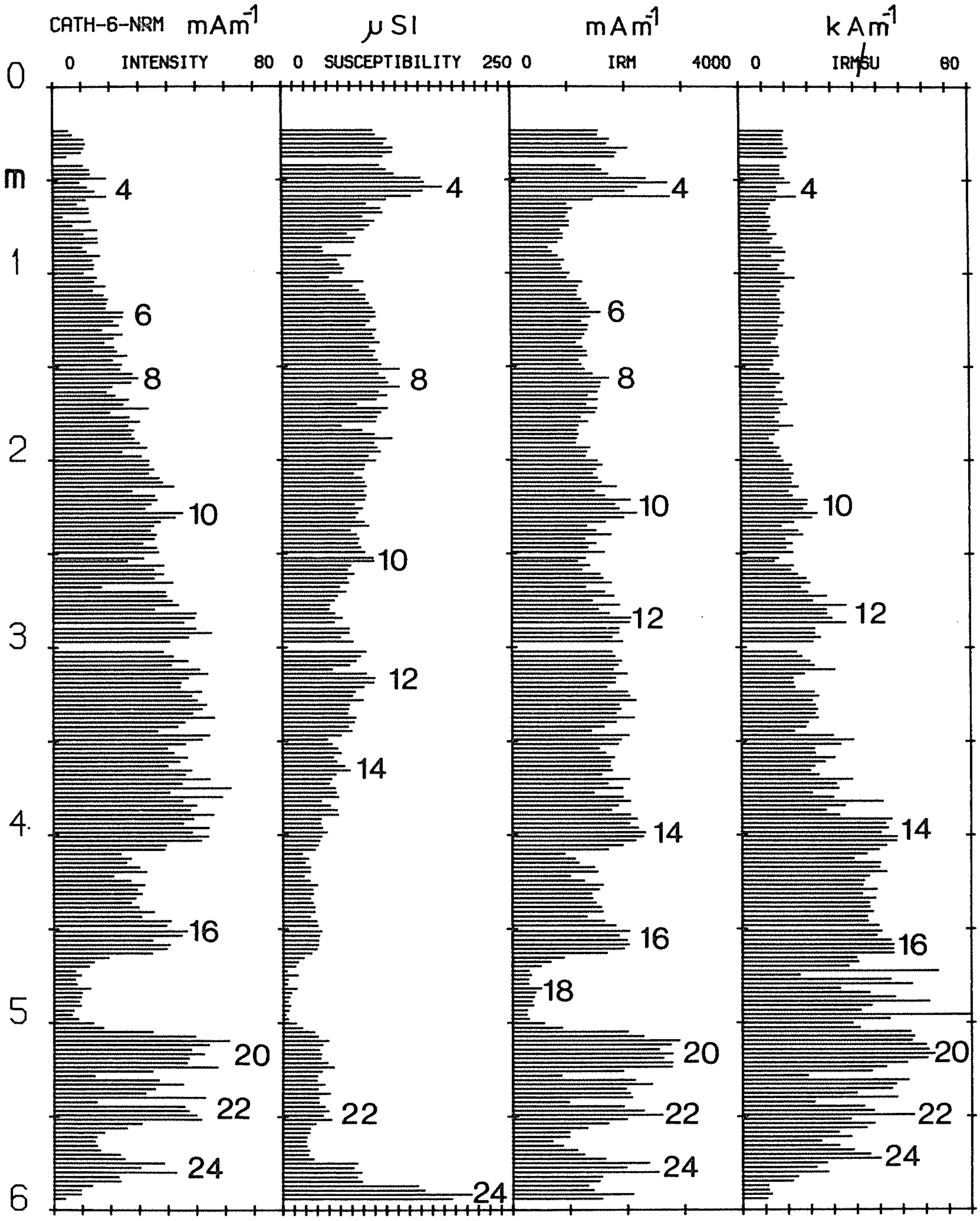

Fig. 4. Core LCVI NRM, χ, SIRM and SIRM/χ vs. depth.

cores is interpreted as a rapidly deposited layer which is some 33 cm thick in core LCII, 22 cm thick in core LCI and is effectively absent in the marginal core LCVI. McClintock (1973) found from analysing the pollen content of two 80 cm long cores, that the rate of deposition above the landscaping level varied by a factor of five between her two cores.

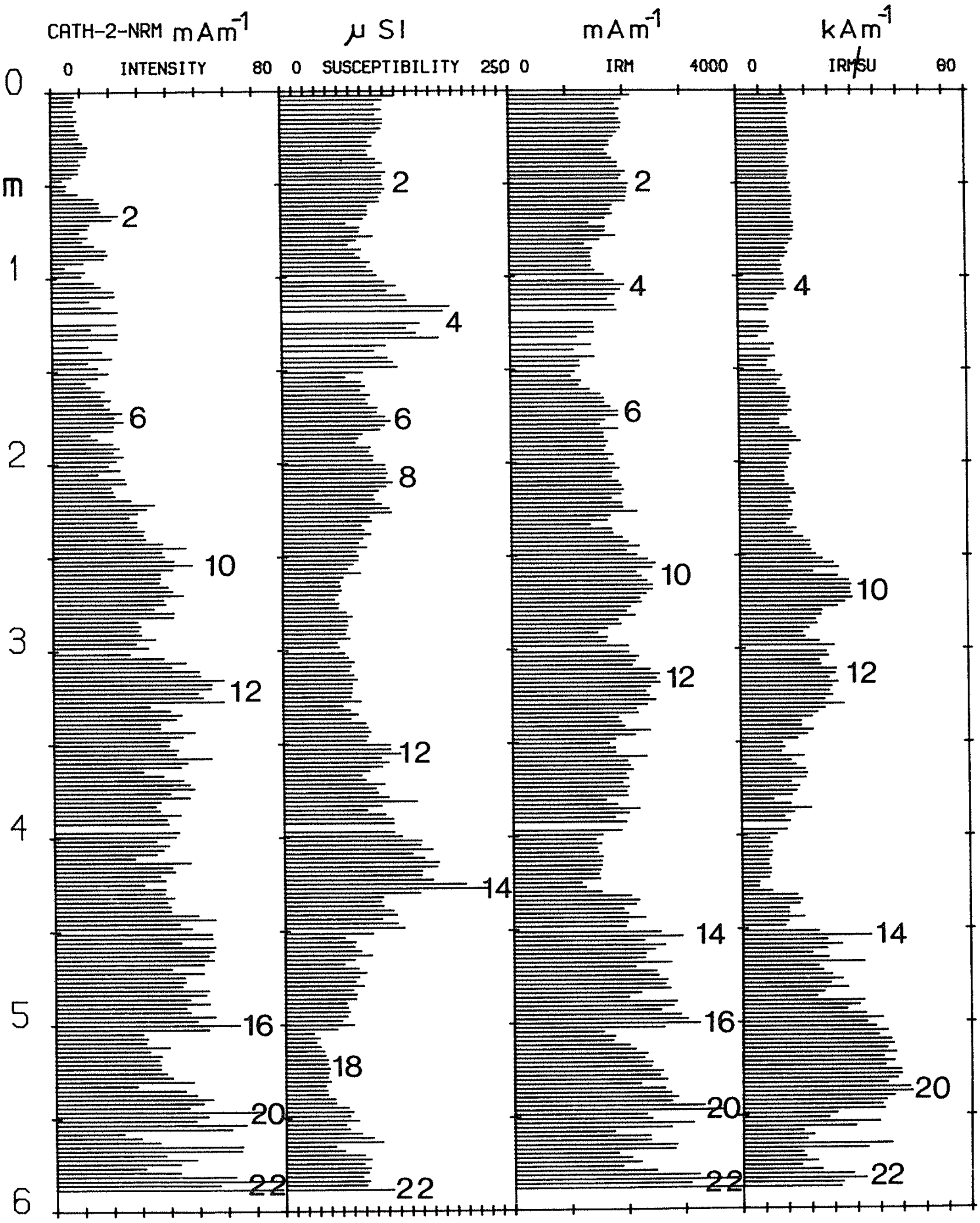

Fig. 5. Core LCII NRM, χ, SIRM and SIRM/χ vs. depth.

Ratio of saturation isothermal remanence and susceptibility

The ratio of saturation isothermal remanent magnetization to magnetic susceptibility (SIRM/χ) depends mainly on the magnetic grain size and mineralogy of the iron oxides in a specimen rather than on their absolute concentration (Thompson *et al.* 1980). In lake sediments and soils high proportions of superparamagnetic iron oxides (grains with diameters less than 0.03 μ) will decrease the SIRM/χ ratio. Many soils have high susceptibilities in their top soils (Le Borgne 1955; Mullins 1977; Vadyunina & Babanin 1972; accompanied by low SIRM/χ ratios (Thompson & Morton 1979) due to the formation of superparamagnetic iron oxides by burning or fermentation.

Inspection of the χ, SIRM and SIRM/χ logs of core LCVI (Fig. 4) reveals that the SIRM/χ tends to be low when χ is high. The broad trends in both χ and SIRM/χ ratio would appear to be compatible with gradually increasing topsoil erosion since the elm decline, though a deciduous woodland acid brown earth and a parkland brown earth near the banks of Lough Catherine did not show magnetic enhancement in the topsoil.

In summary, although mineral magnetic properties are very useful in the Lough Catherine sediments for core correlation, they do not show such distinctive erosional features as revealed elsewhere. This is possibly an indication that less disturbance of the Catherine catchment has occurred during the Holocene than at many other British localities.

Particle size fractions

The dependence of magnetic properties on sediment particle size (as opposed to magnetic grain size) was investigated in a 110 cm long surface core, LCM5, collected from the eastern margin of the lake at the infall of a small stream (Fig. 1). The variations of magnetic susceptibility, intensity of SIRM and SIRM/χ ratio are shown against depth in Fig. 6 for this core. The particle size distribution is also shown for six units of the core. There is a clear variation in magnetic properties with the change in particle size distribution. The coarser units have lower concentrations of magnetic minerals and lower SIRM/χ ratios. Magnetic properties of the individual particle-size fractions of the six units are listed in Table 1. It can be seen that the concentration of magnetic minerals is consistently high in the finest (fine silt) fractions. It is also occasionally high in the coarsest fraction. This pattern is similar to that observed in Loch Lomond (Thompson & Morton 1979). However, the changes of magnetic properties with depth in core LCM5 occur in all the particle size fractions. The magnetic petrology and granulometry of the Lough Catherine sediments thus appears to be rather complicated, depending on a number of factors, including particle size distribution and provenance, and so making it difficult to interpret the down core variations in terms of specific environmental effects.

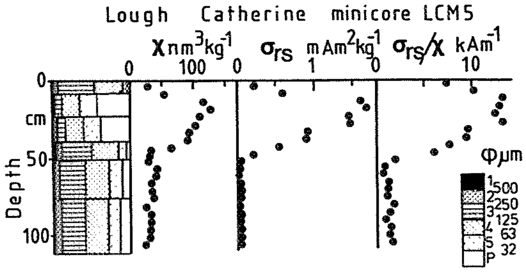

Fig. 6. Mini core 5 particle size, χ, SIRM and SIRM/χ, vs. depth.

Core correlation

Cores from the various coring sites were correlated in order to permit comparison of the palaeo-

Table 1. Lough Catherine Core LCM5: particle-size magnetic data.

Depth cm	Phi	χ SI units nm^3kg^{-1}	SIRM μAm^2kg^{-1}	SIRM/χ kAm^{-1}
0—10	2	100	490	5.0
"	3	30	140	4.8
"	4	90	610	6.6
"	5	200	1400	7.0
"	>5	350	3000	8.8
10–28	2	400	13400	33.0
"	3	190	5000	26.0
"	4	160	1900	12.0
"	5	180	1500	8.5
"	>5	210	1400	6.9
28–43	2	190	3600	19.0
"	3	150	2000	13.0
"	4	130	900	6.9
"	5	150	760	5.2
"	>5	200	1300	6.4
43–56	1	35	70	2.0
"	2	30	120	3.8
"	3	45	110	2.6
"	4	60	250	4.2
"	5	160	620	3.8
"	>5	170	850	5.2
56–76	3	40	40	1.1
"	4	70	90	1.3
"	5	95	170	1.7
"	>5	100	300	2.9
76–106	2	40	45	1.2
"	3	45	40	1.0
"	4	75	80	1.1
"	5	90	90	1.0
"	>5	90	140	1.4

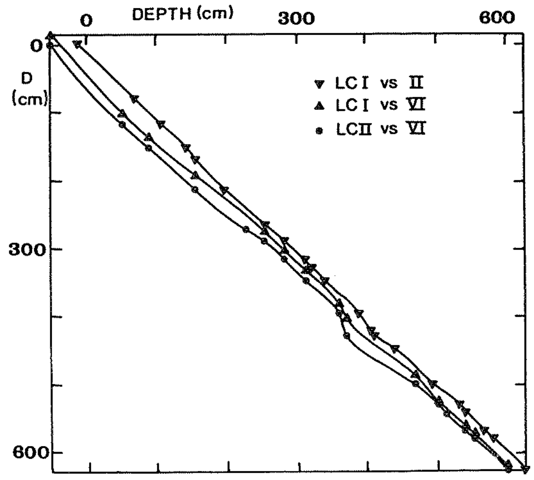

Fig. 7. Depth correlations with interpolating splines based on magnetic features listed in Table 2.

magnetic and pollen records preserved in the different sequences. The correlations are based on the mineral magnetic properties of the sediments such as the intensity of SIRM and NRM. As a first step in correlation the mathematical

Table 2. Lough Catherine depth correlation. Depths in brackets extrapolated from first differences.

χ	NRM and IRM	Core LCI Depth (cm)	Core LCII Depth (cm)	Core LCVI Depth (cm)
Top		(−14)	0	(−50)
1	1	–	32	–
2	2	–	50	–
3	3	68	82	–
4	4	104	118	52
5	5	141	153	90
6	–	157	174	–
–	8	196	215	156
9	–	255	270	–
–	10	–	274	228
–	11	279	291	254
–	12	307	318	282
11	–	319	330	–
12	–	337	350	313
14U	–	386	398	–
14M	–	404	426	–
14L	–	408	431	–
17	17	491	503	467
19	–	529	533	500
–	20	541	547	512
–	21	565	572	538
–	22	578	584	552
–	23	–	–	563
–	24	–	–	580
Base		(625)	(632)	600

procedure of Clark & Thompson (1979) was applied to the NRM intensities of cores LCI and LCII. It produced an estimate of the best linear relationship between the two cores as having an offset of 15 cm and a stretching factor of 1.01. However, the correlation did not pass the associated F test, and so a more complicated relationship was investigated.

Individual features in the variation of mineral magnetic property with depth were identified (Fig. 3). Altogether 31 mineral magnetic features lying at 25 different horizons, as listed in Table 2, were used to correlate the cores. An interpolating cubic spline (De Boor 1978:199) was fitted to the various depth pairs of Table 2. Relationships between cores LCI and II, cores LCI and VI and between cores LCII and VI were produced and these three correlation curves are plotted in Fig. 7. Core LCVI was chosen as a master core because of its longer history of sedimentation. The correlation functions were used to convert the age information and palaeomagnetic data of cores LCI and LCII to the depth scale of core LCVI for between core comparisons.

The pollen counts and radiocarbon age determinations (Table 3) can also be used to correlate the Catherine cores. In Fig. 8 the magnetic (lithostratigraphic), pollen (biostratigraphic), and ^{14}C (chronostratigraphic) correlations between cores LCI and VI are compared. An excellent agreement can be seen between the three methods.

Palaeomagnetic results and data manipulation

Pilot sample partial demagnetization

Alternating field cleaning of eight Lough Catherine pilot samples showed the NRM to be predominantly a stable single component. The change in remanence with step alternating field demagnetization for two LCI samples from 250 and 540 cm depth is shown in Fig. 9. Both samples have a median destructive field of about 33 mT (330 Oe). The samples were stored in zero magnetic field before measurement of NRM in order to remove any viscous remanent magnetization. In lake sediments viscous magnetizations appear to be dominated by physical rotation of the magnetic grains (Stober & Thompson 1979). Such rotations can lead to a reduction of the amplitude of the palaeomagnetic signature of

Table 3. Lough Catherine timescale. Core LCVI depths in brackets derived from depth correlations of Table 2 and Fig. 7.

Feature	Age (years)	Calibrated age (years)	Core 6 Depth (cm)	Core 2 Depth (cm)
Top of sediment	1978 A.D.	-28	-50	0
Plantation	1750 A.D.	200	52	118
UB-2309	1145 B.P.	1130	160	
UB-2310	1550 B.P.	1520	(208)	260
UB-2385	2105 B.P.	2115	243	
UB-2311	2425 B.P.	2495	(275)	310
UB-2386	2765 B.P.	2940	293	
UB-2312	3055 B.P.	3340	(313)	350
UB-2313	3555 B.P.	3930	(349)	380
UB-2387	3520 B.P.	3880	348	
UB-2314	3785 B.P.	4240	(371)	420
UB-2388	4150 B.P.	4800	403	
UB-2266	5280 B.P.	6085	(454)	494
UB-2389	5190 B.P.	5980	466	
UB-2390	6140 B.P.	7025	505	
UB-2315	6235 B.P.	7105	(507)	540
UB-2316	7360 B.P.	8010	(552)	584
UB-2391	9145 B.P.	9355	573	
Top of Late Glacial Clay	10,000 B.P.	10,000	600	

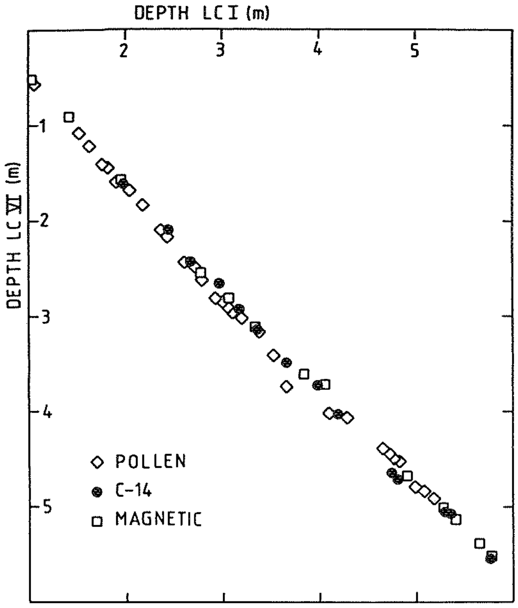

Fig. 8. Litho-, bio- and chrono-stratigraphic correlations of cores LCI and LCVI.

geomagnetic field changes (Stober 1978), which is very difficult to detect by partial demagnetization experiments. The question of the quality of the palaeomagnetic recording process is discussed further below. In terms of demagnetization studies the Lough Catherine sediments are of high palaeomagnetic quality.

The individual specimens of cores LCI and LCII were magnetically cleaned using a peak alternating field of 20 mT (200 Oe), while core LCVI was cleaned at 15 mT (150 Oe).

Rotation of axes to a standard frame of reference

Since the cores are not orientated absolutely, all the declination measurements are relative to an arbitrary zero and the inclination measurements are referred to the long axis of the core tube. As corers do not always penetrate vertically and our declination references vary it is necessary to rotate the palaeomagnetic vectors into a standard frame of reference in order to compare results between cores or to stack the records. One frame of reference that has been found useful (Turner & Thompson 1981) is entered by rotating the palaeomagnetic vectors so that the mean declination is zero and then rotating the vectors so that

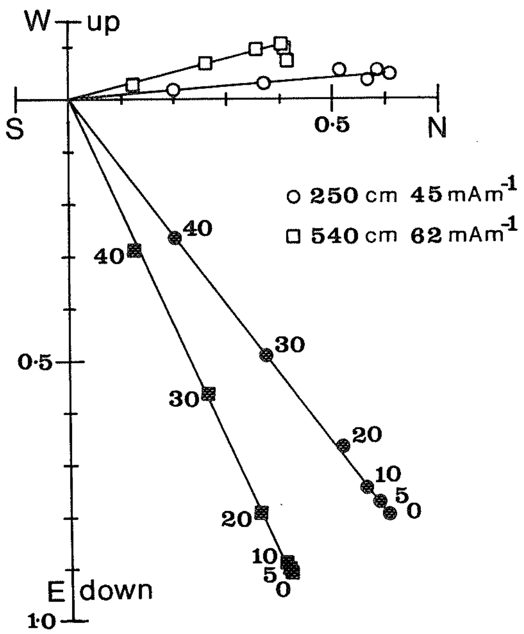

Fig. 9. Pilot sample demagnetization. Two samples from core LCI. Orthogonal plot of change in remanence with peak alternating field in mT.

Table 4. Mean directions. δD linear detrend (degrees per metre) of declination; δI linear detrend (degrees per metre) of inclination; D mean declination; Ī mean declination; N number of data points after removal of outliers; K Fisher's concentration parameter after detrending.

	δD	δI	D	I	N	K
CATH 2						
NRM	−19.8	0.2	−111.0	77.9	225	56.4
20 mT	−23.5	0.7	−116.0	78.5	225	88.1
CATH 1						
NRM	4.7	−2.2	79.7	61.8	210	123.2
20 mT	3.0	−2.1	86.1	61.3	210	116.2
CATH 6						
NRM	0.6	−2.0	−103.7	68.6	230	120.2
15 mT	0.7	−1.5	−106.8	67.3	230	111.3

the mean inclination is also zero. This frame of reference is very convenient for statistical analyses and is used below. Barton & McElhinny (1981) describe a reference frame, centred on a mean declination of zero and a mean inclination of 53.7° which they found to be useful when comparing results from different latitudes.

Virtual pole positions

The nature of the geomagnetic secular variation changes with latitude. For example, the amplitude of the angular changes of the geomagnetic field is greater at low latitudes. This latitudinal effect complicates the comparison of records between sites. It can be helpful to reduce the latitudinal effect by making an assumption about the form of the geomagnetic field. The simplest assumption is that the field largely has the form of a geocentric dipole field. Declination and inclination measurements can then be transformed, using a dipole field model, into virtual pole positions and expressed in terms of their latitude and longitude.

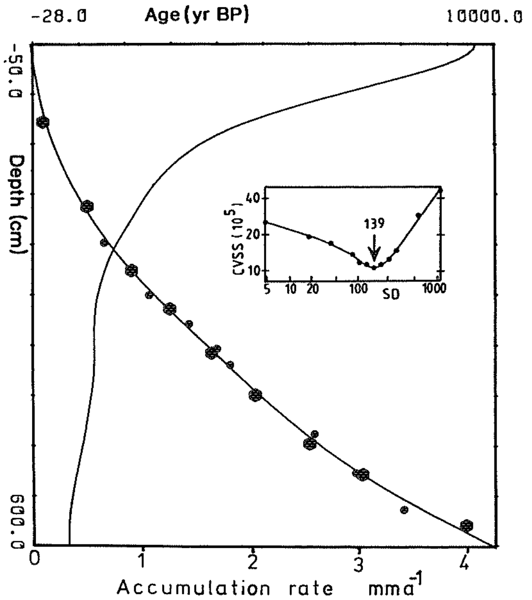

Fig. 10. Depths vs. calibrated age for core LCVI based on smoothing cubic spline. Inset shows cross validation analysis. Hexagons are age-depth points from core LCVI, circles are from core LCII. The gradient of the spline fit is plotted as an accumulation rate curve.

Detrending

One of the 1972 cores twisted severely on entering the sediment. This motion strongly affected the declination results. It would appear to be a fairly straightforward scalar problem to detrend the declination results using a low order least squares polynomial. However, such a scalar approach is not strictly correct and a vector approach is necessary. An associated coring problem is that of the core tube bending and affecting the inclination results. Again scalar detrending of the inclination is not satisfactory. We have tackled the problem by fitting weighted least square splines to the transformed palaeomagnetic declination and inclination data using the procedures described by Thompson & Clark (1981). It was found possible to detrend satisfactorily after rotating the data to our standard frame of reference by subtracting single piece linear splines (equivalent to straight lines). The magnitude of the detrending is listed in Table 4.

Transformation to a timescale

A timescale for the accumulation of sediment in Lough Catherine has been established from the Catherine ^{14}C age data. The detailed timescale has been constructed by using radiocarbon dates from both the marginal core LCVI and central core LCII (Fig. 10). Table 3 gives these ^{14}C data in terms of the depth scale of the master core LCVI. Six ^{14}C dates were rejected as being erroneously old (presumably due to old organic material having been eroded and deposited in the lake; O'Sullivan *et al.* 1973; Olsson 1979). The rejected dates were from the uppermost samples in both of the cores LCII and LCVI, and the sample at 458 cm depth in core LCII. The remaining sixteen age determinations were calibrated for variation in the atmospheric $^{14}C/^{12}C$

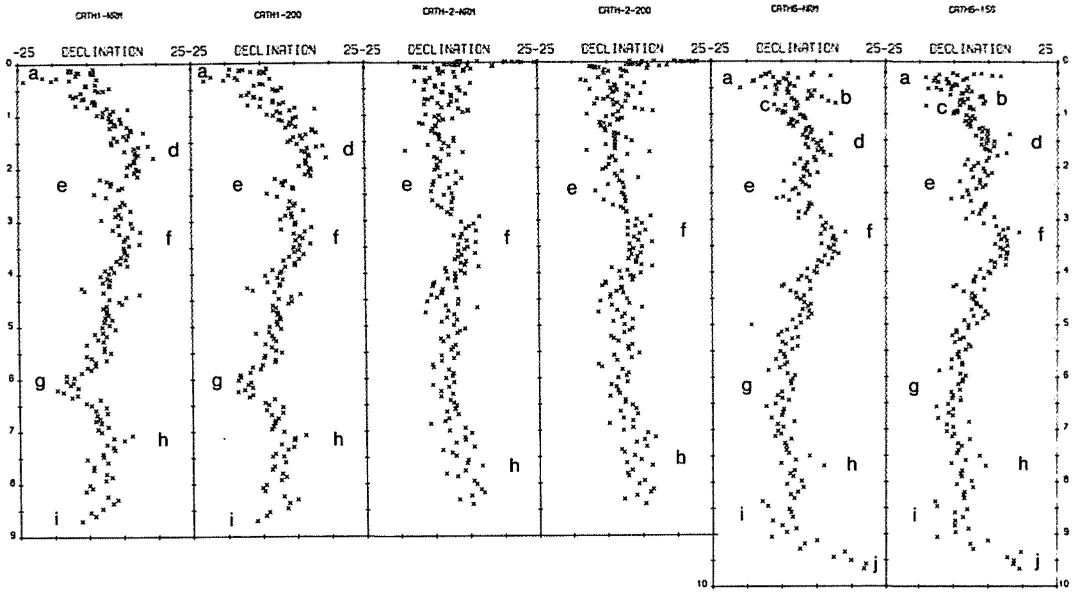

Fig. 11. Transformed declination of Cores LCI, II and VI. NRM and cleaned data vs. calibrated age. 0–10000 years B.P.

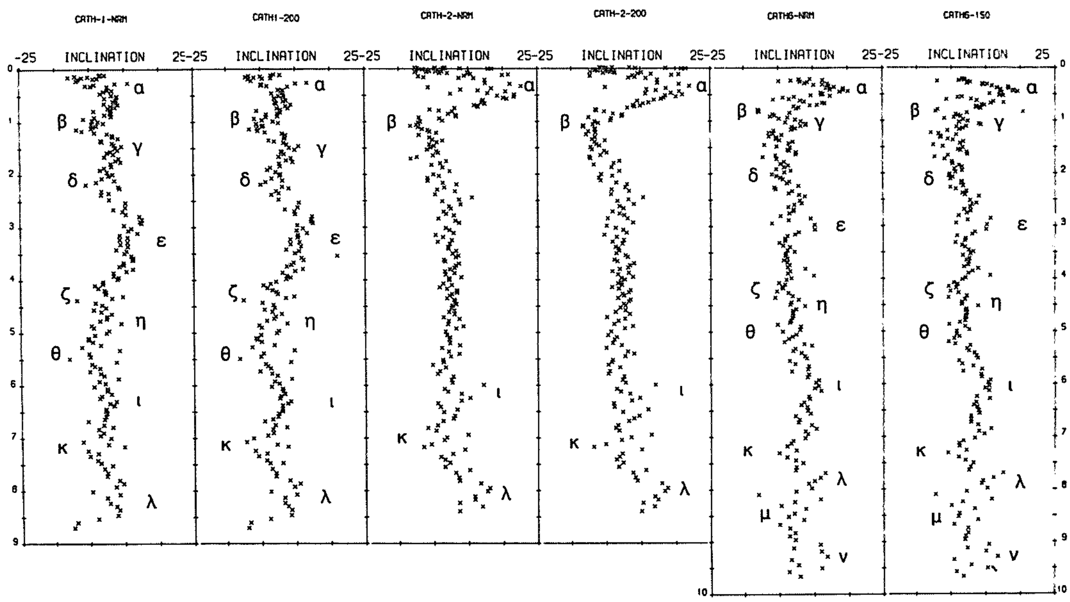

Fig. 12. Transformed inclination of Cores LCI, II and VI. NRM and cleaned data vs. calibrated age. 0–10000 years B.P.

ratio according to Clark's (1975) calibration curve. Beyond the limit of Clark's analysis a linear calibration taper was applied back to zero correction at 10,000 years B.P. Three additional ages were used in constructing the timescale. These are the sediment surface (1978 A.D.), the planting of 'introduced' trees on the Baronscourt estate (taken to be 1750 A.D. from land

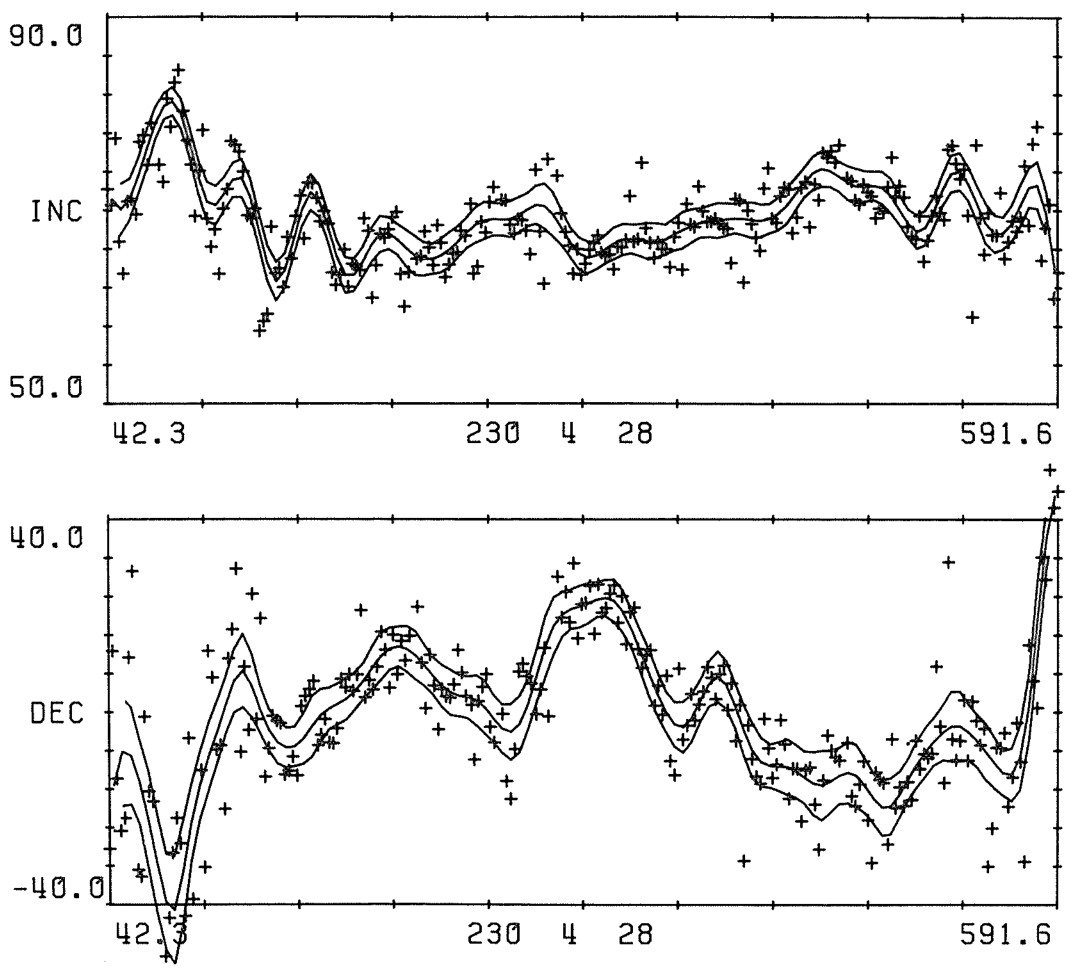

Fig. 13. Confidence limits core LCVI of relative declination and inclination. The central curve is the best fitting least squares cubic spline. The outer curves are the 95 % confidence bands about the best fitting curve. The depth range, number of data points, spline order and number of spline pieces are listed below each figure.

use records) and the base of the gyttja (taken to be 10,000 years B.P.). Cross validation (Stone 1974) was used to assess the random errors in the set of nineteen ages and to fit an appropriately smooth curve to the depth-age data. The function, a smoothing cubic spline (De Boor 1978:240) is shown in Fig. 8 along with the first derivative of the function (the rate of sediment accumulation). The advantages of this spline approach to fitting a timescale are that the rate of accumulation curve is continuous and that the timescale curve fits local features well without biasing the curve elsewhere. This type of curve is particularly useful for calculating influx or accumulation rate parameters.

The comparatively large number of age determinations for one sediment sequence produces a detailed timescale. The accuracy of the timescale also appears to be high since a comparison, using dated pollen assemblage zone boundaries from a nearby peat deposit at Fairy Water confirms the Lough Catherine ^{14}C age determinations.

The smoothing cubic spline of Fig. 7 was used to convert the depths in core LCVI to calendar ages.

The palaeomagnetic directions could thus be plotted against time (Figs. 11 and 12) rather than just against sediment depth.

Palaeomagnetic directions

Secular changes in the direction of palaeomagnetic remanence can be seen in the Lough Catherine records. Changes in inclination have a peak to peak amplitude of around 15 to 20°, while the declination changes tend to be greater with peak to peak amplitudes of some 30° to 40°. This difference in amplitude is largely a result of a trigonometric effect caused by the steep inclination of the geomagnetic field in high to middle latitudes. This amplitude effect is removed by viewing the secular changes in the standard frame of reference (Figs. 11 and 12), while the overall pattern of secular change, of course, remains the same in both frames of reference.

The peaks, or turning points, of the palaeomagnetic direction changes have been labelled in Figs. 11 and 12. The direction changes are clearest in core LCVI and are least distinct in core LCII. Indeed both the declination and inclination variations have been severely attenuated in the central section of core LCII. The labelling of turning points follows Thompson & Turner (1979). Ten declination features (*a* to *j*) and thirteen inclination features (α to ν) are identified. The turning points can be recognized in both the natural and partially demagnetized remanences (Figs. 11 and 12). Most of the features can be seen to recur between cores. The overall quality, however, is not as fine as the British mainland results from Lake Windermere and Loch Lomond (Mackereth 1971; Thompson & Turner 1979). The best Lough Catherine record probably consists of the NRM measurements of core LCVI. A cubic spline fit with its confidence bands to these data is shown in Fig. 13. The data here are shown plotted against the original depth scale, having been linearly detrended and rotated to a mean inclination of 70°. The 95 % confidence limits (Fig. 13) show that the changes in direction down the core are significant since the width of the limits is less than the amplitude of the direction changes of the best fitting curve. The spline function of Fig. 13 was chosen using a full cross validation procedure which indicated that a 28 piece spline was appropriate for the Catherine LCVI NRM data.

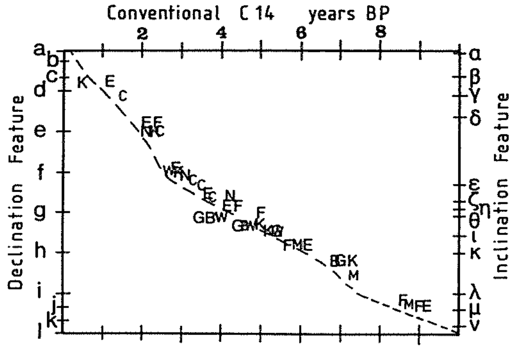

Fig. 14. Radiocarbon dating of Irish geomagnetic features. Conventional ^{14}C ages plotted against magnetic features. Dotted line shows the feature-age relationship of the British mainland master curve. – C Catherine central core LCI; E Catherine edge core LCVI; F Fairy Water peat; M Meenadoan peat; K Killymaddy Lough; B Ballynagilly peat; G Beaghmore peat; N Lough neagh.

Irish geomagnetic master curve

The Lough Catherine palaeomagnetic data are compared in Fig. 13 with palaeomagnetic results from two other Irish sites, namely Lough Neagh and Killymaddy Lough, and with British mainland palaeomagnetic records. The diagram has been constructed by plotting conventional ^{14}C age determinations as abscissa against palaeomagnetic features as ordinates. The palaeomagnetic declination features (*a, d* through *i, l*) have been spaced at equal intervals along the ordinate axis for convenience. The sixteen Lough Catherine radiocarbon age determinations of Table 3 are plotted in Fig. 14. Also shown are radiocarbon age determinations of Lough Catherine pollen assemblage zone boundaries as dated in the nearby Meenadoan (Pearson 1979) and Fairy Water peat profiles. Three ^{14}C age determinations from Lough Neagh core LN have been transferred to other Lough Neagh cores with palaeomagnetic records (Thompson 1973) using the pollen analyses of O'Sullivan (O'Sullivan *et al.* 1973) and these dates too are plotted in Fig. 14. Ten ^{14}C age determinations have been made on a core from Killymaddy Lough on which magnetic declination measurements have been made (Hirons *et al.* 1982). Six of these age determinations are also included in Fig. 14. The Killymaddy age determinations are supported by radiocarbon dates on pollen assemblage zones in the neighbouring Weir's Lough (Hirons 1982) and Beaghmore and Ballynagilly fen-peat deposits (Pilcher 1970).

All the Irish results can be seen to be highly consistent. Datings of the palaeomagnetic features in the three lakes agree well. Furthermore, the ^{14}C dates based on peat profiles (which are taken to be the most accurate as they should not suffer from possible contamination of 'old' carbon incorporated in the profile, is possible in a lake environment) provide strong support for the Irish lake chronology. The Lough Catherine core LCVI NRM data would thus appear to be a suitable record to form an Irish geomagnetic master curve.

The shapes of the major features of the Irish palaeomagnetic curves are very similar to those of the mainland curves and the ages of the features are in general agreement. However, as can be seen in Fig. 14, the Irish features tend to be older than those of the mainland master curve of Thompson & Turner (1979:Table 1) by a few hundred ^{14}C years.

Conclusions

The Lough Catherine sediments carry a palaeomagnetic record of past geomagnetic field changes. The magnetic records can be used to date new Irish sequences with an accuracy of around 500 years. The consistency of the Irish ^{14}C results, in particular the peat dates, suggests that the British mainland curve might in parts be a few hundred years too young. The Catherine central and marginal sediments can be correlated well by either litho-, bio- or chrono-stratigraphic methods. The major magnetic susceptibility changes in the sediments can be explained by environmental changes in the catchment. Sediment accumulation, as judged by magnetic mineralogy, has been most uniform at the marginal site. The ^{14}C age determinations of the marginal and central sediments agree well and can be pooled to provide sufficient ages for the use of the statistical technique of cross validation in the assessment of the random errors associated with the ^{14}C ages. Cubic spline regressions can be used to construct continuous time-depth curves and sediment accumulation rate curves. These functions can be further employed in order to calculate pollen, chemical or mineralogical accumulation rates at particular points in the lake and to form the basis of a whole lake influx study.

Acknowledgements. – We particularly thank F. Oldfield and P. E. O'Sullivan for drawing our attention to Lough Catherine and for the initial core collection. Permission to work at the site was given by His Grace the Duke of Abercorn. The field work was supported by N.E.R.C. All the radiocarbon analyses used in dating the Irish geomagnetic master curve were carried out at Queen's University, Belfast under the supervision of G. W. Pearson. Some of the data reported here are based on joint research with R. Larmour and K. Hirons.

References

Barton, C. E. & McElhinny, M. W. 1981: A 10,000 yr geomagnetic secular variation record from three Australian maars. *Geophys. J. R. Astr. Soc. 67,* 465–485.

Birks, H. J. B. 1979: Numerical methods for the zonation and correlation of biostratigraphical data. *In* Berglund, B. E. (ed.): *Palaeohydrological Changes in the Temperate Zone in the Last 15000 Years,* 99–123. Subproject B. Vol 1, LGCP. Lund.

Clark, R. M. 1975: A calibration curve for radiocarbon dates. *Antiquity 49,* 251–266.

Clark, R. M. & Thompson, R. 1978: An objective method for smoothing palaeomagnetic data. *Geophys. J. R. Astr. Soc. 52,* 205–213.

Clark, R. M. & Thompson, R. 1979: A new statistical approach to the alignment of time series. *Geophys. J. R. Astr. Soc. 58,* 593–607.

De Boor, C. 1978: *A Practical Guide to Splines.* Springer-Verlag, New York.

Delcoigne, A. & Hansen, P. 1975: Sequence comparison by dynamic programming. *Biometrika 62,* 661–664.

Edwards, K. J. 1980: Vegetational changes associated with man in Co. Tyrone. *Ir. Ass. Quat. Studies Field Guide 3,* 44–51.

Faegri, K. & Iversen, J. 1975: *Textbook of Pollen Analysis.* Oxford.

Gordon, A. D. 1973: A sequence-comparison statistic and algorithm. *Biometrika 60,* 197–200.

Hirons, K. R. 1982: Palaeoenvironmental studies in east Co. Tyrone, Northern Ireland. Unpublished thesis, Queen's University, Belfast.

Hirons, K. R., Edwards, K. J. & Thompson, R. 1982: Palaeomagnetism in the Quaternary history of Ireland. Academic Press, London. In press.

Krishnamurty, K. V., Shpirt, E. & Reddy, M. M. 1976: Trace metal extraction of soils and sediments by nitric acid – hydrogen peroxide. *Atomic Absorption Newsletter 15,* 68–70.

Le Borgne, E. 1955: Susceptibilité magnétique anomale du sol superficiel, *Annales de Geophysique.*

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

Mackereth, F. J. H. 1969: A short core sampler for subaqueous deposits. *Limnol. Oceanogr. 14,* 145–151.

Mackereth, F. J. H. 1971: On the variation in direction of the horizontal component of remanent magnetization in lake sediments. *Earth Planet. Sci. Lett. 12,* 332–338.

McClintock, M. 1973: Pollen analysis of lacustrine sediments from Lough Catherine linked with possible human activity over the last four centuries. Unpublished dissertation, New University of Ulster.

McGuigan, M. 1979: The manor of Derrigoon Baronscourt, a study of agrarian change on a County Tyrone handed estate 1756–1858. Unpublished MSc thesis, New Univ. of Ulster.

Molyneux, L. 1971: A complete result magnetometer for measuring the remanent magnetization of rocks. *Geophys. J. R. Astr. Soc. 24,* 429–434.

Molyneux, L. & Thompson, R. 1973: Rapid measurement of the magnetic susceptibility of long cores of sediment. *Geophys. J. R. Astr. Soc. 32,* 479–481.

Molyneux, L., Thompson, R., Oldfield, F. & McCallen, M. E.

1972: Rapid measurement of the remanent magnetization of long cores of sediment. *Nature 237,* 42–43.

Mullins, C. E. 1977: Magnetic susceptibility of the soil and its significance in soil science – a review. *J. Soil Sci. 28.*

Olsson, I. U. 1979: A warning against radiocarbon dating of samples containing little carbon. *Boreas 8,* 203–207.

O'Sullivan, P. E., Oldfield, F. & Battarbee, R. W. 1973: Preliminary studies of Lough Neagh sediments I. Stratigraphy, chronology and pollen analysis.

Pearson, G. W. 1979: Belfast radiocarbon dated IX. *Radiocarbon 21,* 274–290.

Pilcher, J. R. 1970: Palaeoecology and radiocarbon dating of sites in Co. Tyrone, Northern Ireland. Unpublished thesis, Queen's University, Belfast.

Smith, A. G., Pearson, G. W. & Pilcher, J. R. 1970: Belfast radiocarbon dates I. *Radiocarbon 12,* 285–290.

Smith, A. G. & Pilcher, J. R. 1973: Radiocarbon dates and vegetational history of the British Isles. *New Phytol. 72,* 903–914.

Stober, J. C. 1978: Palaeomagnetic secular variation studies on Holocene lake sediments. Unpublished thesis, University of Edinburgh.

Stober, J. C. & Thompson, R. 1979: Magnetic remanence acquisition in Finnish lake sediments. *Geophys. J. R. Astr. Soc. 57,* 727–739.

Stone, M. 1974: Cross validatory choice and assessment of statistical predictions. *J. R. Stat. Soc. B 36,* 111–147.

Thompson, R. 1973: Palaeolimnology and palaeomagnetism. *Nature 242,* 182–184.

Thompson, R., Bloemendal, J., Dearing, J. A., Oldfield, F., Rummery, T. A., Stober, J. C. & Turner, G. M. 1980: Environmental applications of magnetic measurements. *Science 207,* 481–486.

Thompson, R. & Clark, R. M. 1981: Fitting polar wander paths. *Phys Earth Planet. Int. 27,* 1–7.

Thompson, R. & Morton, D. J. 1979: Magnetic susceptibility and particle size distribution in recent sediments of the Loch Lomond drainage basin, Scotland. *J. Sedimentary Petrology 49,* 801–812.

Thompson, R., Oldfield, F., Battarbee, R. W. & O'Sullivan, P. E. 1975: Magnetic susceptibility of lake sediments. *Limnol. Oceanog. 20,* 687–698.

Thompson, R. & Turner, G. M. 1979: British geomagnetic master curves 10,000–0 yr B.P. for dating European sediments. *Geophys. Res. Lett. 6,* 249–252.

Tinsley, J. 1950: The determination of organic carbon in soils by dichromate mixtures *Trans. 4th Internat. Congr. Soil Sci. 1,* 161.

Turner, G. M. & Thompson, R. 1981: Lake sediment record of the geomagnetic secular variation in Britain during Holocene times. *Geophys. J. R. Astr. Soc. 65,* 703–725.

Vadyunina, A. F. & Babanin, V. F., 1972: Magnetic susceptibility of some soils in the USSR. *Soviet Soil Sci. 4,* 588–599.

Watkins, N. D. 1971: Geomagnetic polarity events and the problem of 'The Reinforcement Syndrome'. *Comments Earth Sci. Geophys. 2,* 36–43.