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Palaeomagnetic and stratigraphic study of the Loch Shiel marine regression and overlying gyttja

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SUMMARY: Palaeomagnetic, chemical and pollen analyses have been carried out on cores 6 m long from the SW basin of Loch Shiel, Scotland. A marine regression in one core is dated at 4200 C^{14} years BP. Palaeomagnetic declination and inclination variations in the limnic gyttja are interpreted as reliable records of ancient geomagnetic field changes. Comparison with 4 other British limnic palaeomagnetic sites indicates that systematic errors in C^{14} age determinations have been caused in many of the sites by inwash of old soils and peats. The inwash effect is suggested to have been more pronounced and to have started significantly earlier in England than previously documented. Palaeomagnetic direction correlations and transference of C^{14} age determinations from the palaeomagnetic master curve described, can help overcome these dating difficulties.

The earliest palaeomagnetic investigations of British Holocene geomagnetic secular variations were carried out on Postglacial gyttja from the lakes of the English Lake District. C^{14} age determinations on the gyttjas allowed a chronology of fluctuations in direction of the geomagnetic field to be erected (Mackereth 1971). Piston cores, up to 6 m long, were extracted from the bed of Loch Shiel, NW Scotland, firstly to compare their magnetic remanence with the English records, and secondly as part of a project on the vegetational and raised shoreline history of part of NW Argyll. C^{14} dating of the palaeomagnetic direction variations in the Shiel limnic gyttja confirms their origin as records of ancient geomagnetic secular changes and permits refinement of the original Lake District chronology.

Coring sites

Loch Shiel separates the district of Moidart from Ardnamurchan and Ardgour in the NW Highlands of Scotland. The loch surface is 3.5 m above sea level, 27 km long, and up to 1.5 km wide. Its deepest point is 125 m below sea level, and its surface is 870 m below the highest surrounding hills. At Polloch the loch turns westwards into a large, broad basin. This southwesterly basin is floored and almost completely filled by fluvio-glacial sands and gravels upon which an extensive bog has developed, Claish Moss. The whole of the Shiel basin was occupied by the ice of the Loch Lomond readvance, with a limit at its western end (McCann 1966). Two coring sites were chosen in regions of low bottom surface gradient. Cores 1 and 2 were taken in a central, open area at a water depth of 25 m, 0.5 km SW of Dalelia Pier. Core 3 was taken at a more marginal site. The water depth at this second site, 1.5 km off Dalelia Pier, was 15 m. All cores were taken in 6 m long UPVC liners using a pneumatic piston corer (Mackereth 1958).

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Palaeomagnetic methods and instrumentation

Whole-core magnetic scanning was carried out on-line to a 4K micro computer using apparatus developed by Thompson and Molyneux (Molyneux *et al.* 1972; Molyneux & Thompson 1973). This magnetic scanning established the magnetic stratigraphy and palaeomagnetic chronology. The core with the longest limnic sequence (core 3) was then chosen for more detailed studies. It was sliced lengthwise, one half being subsampled for further palaeomagnetic studies and the other half used for palynological, chemical, and C^{14} analyses. The palaeomagnetic subsamples were taken perpendicular to the slice using plastic 'cubic' holders of sides 20×20×17 mm. A 'digico' low-noise, ring, fluxgate magnetometer was used to measure the remanence of the individual subsamples. Reversible, initial susceptibility was measured with an air cored coil susceptibility bridge. Partial alternating field demagnetization was performed using a transistorized optical ramping system (De Sa & Widdowson 1975) modified with an active filter.

Core correlations, magnetic intensity, and susceptibility variations

The whole-core horizontal intensity logs of cores 1 and 3 (Fig. 1) contain a pronounced double peak (numbered 1 and 2) followed by an intensity minimum and a rapid rise to peak 3. Peaks 1 and 2 lie at 220 and 160 cm, and the rise at 120 cm in core 1. In core 3 the depths of the features are 330, 270, and 230 cm (Fig. 1), showing a displacement of 110 cm. Similarly, whole-core susceptibility records show a correlative

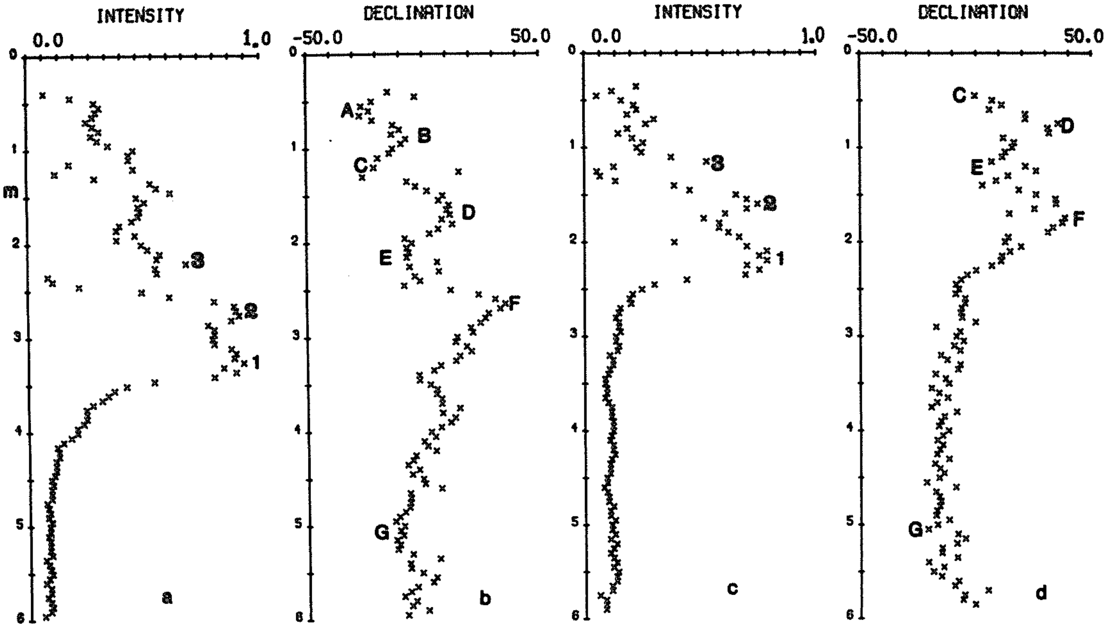

FIG. 1. Whole-core horizontal intensity (a, c) and relative declination (b, d) logs for cores 1 (c, d) and 3 (a, b). Turning points *A–G* discussed in text. Mean declination set to zero. Intensity range in 10^{-1} $\mathrm{Am^{-1}}$.

broad double peak followed by low values, then an abrupt rise (Fig. 3).

The mud/water interface lies at about 40 cm in both core tubes. (Note depths in text and diagrams refer to depth in core tube, rather than depth below mud/water interface). Core 1 contains a compressed upper record but a longer, older sequence. Core 3 with the longer and more detailed upper succession was thus chosen for palynological, chemical and further magnetic analyses.

Stratigraphy and the pollen record

Core 3 contains 540 cm of undisturbed sediment and has two major stratigraphic sections. From 600 to 400 cm the dark brown organic mud has an abundance of *in situ* shells of *T. flexonosa*, a species which presently inhabits sandy muds around the British Isles between depths of 11–180 m (Tebble 1966). This marine sediment is lithologically homogeneous, and with the exception of the shells is very similar to the overlying lacustrine sediment. There is a lithologically clear boundary at 400 cm which marks the marine regression. The overlying sediment is again homogeneous. Fine silt is disseminated in the sediment at depths of 350–360, 200, and 160–180 cm. From 180 to 60 cm the sediment is a dark brown, flocculated organic mud, with occasional fine-grained mica fragments. The top 20 cm of sediment is very disturbed, and the true mud/water interface is difficult to recognize, but is estimated to lie near 40 cm below the top of the core tube.

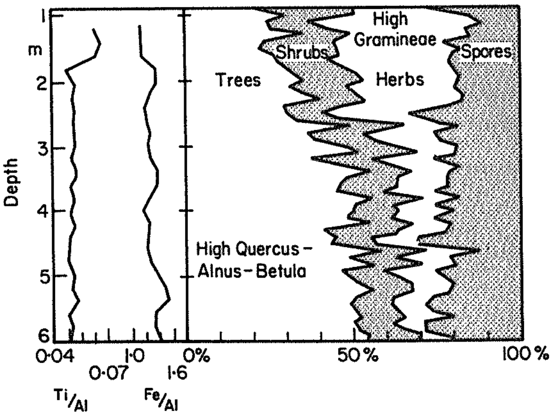

FIG. 2. Summary diagram of pollen and chemistry for core 3, Loch Shiel. Depths measured from top of core tube.

An absolute pollen diagram has been constructed from the analysis of samples taken at 52 levels and it shows two major pollen zones (Fig. 2).

Pollen zone 1 (600–260 cm)

This represents a complex period, but with a fairly constant input of the major pollen components. High

Betula and *Quercus* values reflect the mixed oak woodlands of the surrounding hills. Comparison with a complete Postglacial pollen diagram from the adjacent Claish Moss (Moore 1977) suggests that this zone represents a series of forest clearances, after the elm decline.

There is no indication in the fossil record of the change from a marine to freshwater environment. This may reflect the lack of suitable locations for saltmarsh development. Moore (1977) does not find any evidence of a marine transgression across Claish Moss, though shorelines along the margin of the loch suggest that part of the Moss should have been inundated by the Postglacial sea. Peat accumulation may have been sufficiently rapid for it to have kept pace with the rising sea level. This situation would have been analogous to that of Flanders Moss in the Forth Valley (Sissons & Smith 1965).

Pollen zone 2 (260–80 cm)

This zone is marked by a fall in tree pollen and a rise in non-arboreal pollen values, especially *Gramineae*, *Cyperaceae*, *Plantago* spp, and *Ericaceae*. Extensive forest clearance is indicated in this zone.

Chemical changes (Fig. 2) are minimal down the core, suggesting that true marine conditions were never attained in Loch Shiel.

Radiocarbon age determinations

Five C^{14} age determinations (SRR-1143–1146, Table 1) were made by D. D. Harkness at the Reactor Centre, East Kilbride. The 5 samples were all taken from the limnic sediments to avoid erroneously old ages which could result from marine input of aged carbon. Two of the determinations show increasing apparent C^{14} age up the core (Fig. 3). The likeliest explanation of these anomalously old near-surface age determinations is the recycling of older carbon from soils and peat in the drainage basin (e.g. O'Sullivan *et al.* 1973). The pollen record for the section of anomalously old ages, 260–100 cm, indicates possible increased erosion of soil profiles associated with forest clearance. The lower two age determinations are potentially useful chronologically. They are compared below with palaeomagnetic age estimates and used with these palaeomagnetic declination oscillations to date the marine regression at 4200 years BP.

TABLE 1: C^{14} age determinations

Sample	Depth, cm	Age determination, Yr	$\delta^{13}C$,%
Core 3			
SRR-1143	165–175	2741±45	−27.1
SRR-1144	205–215	2484±40	−28.0
SRR-1145	265–275	2366±55	−28.3
SRR-1146	342–352	3471±100	−27.3
Core 1			
SRR-1210	346–356	3883±65	−24.0

Age determinations expressed as conventional C^{14} years BP at the ±1 σ confidence level.

Sea-level change

At present, Loch Shiel drains into the sea via the River Shiel over a waterfall with a threshold height of approximately 2.5 m. At high spring tides this fall is submerged and seals are able to swim up into the loch. Two raised shorelines, cut into fluvio-glacial gravels around the margins of the loch in the southern basin, imply that Loch Shiel must have been a sea loch for a considerable part of the Postglacial. The highest shoreline is at 10 m, which correlates with the main Postglacial shoreline in the area (Wain-Hobson, unpublished data), while the lowest shoreline is at approximately 3 m. Assuming that the main Postglacial transgression would have flooded the loch by about 6500 years BP (Sissons 1977), then a date for the regression of about 4200 years BP would not be unreasonable.

Palaeomagnetic record

Stability of natural remanence

In order for sediment to hold a true record of past geomagnetic field changes, the natural remanent magnetization (NRM) must have a coercivity considerably higher than typical earth field values (50 μT). Magnetization of low coercivity will not remain in the ancient field direction but will continually follow changes of the ambient field. Low coercivity may result from the movement of domain walls within magnetic grains or more simply from the physical rotation of small magnetic grains in the sediment. Alternating field (AF) demagnetization was performed on 16 pilot samples to test the stability of remanence. The median destructive field (MDF) varied between 12 and 55 mT. The natural remanence changed direction by less than 3° during partial demagnetization up to the MDF. The natural remanence is thus magnetically stable.

Between measurement of the NRM and AF demagnetization, the subsamples were stored in zero field in order to remove any viscous components. Varying amounts of remanence, from less than 10% up to 80%, were lost during storage while the directions of remanence remained constant. These losses were originally attributed to viscous magnetic behaviour, but are now thought to result predominantly from physical rotation of the magnetic grains with drying during storage as discussed in detail by Stober & Thompson (1977).

Magnetic declination

Clear oscillations with peak amplitude of 40–50° are labelled *A*–*G* in Fig. 1. The same oscillations can be

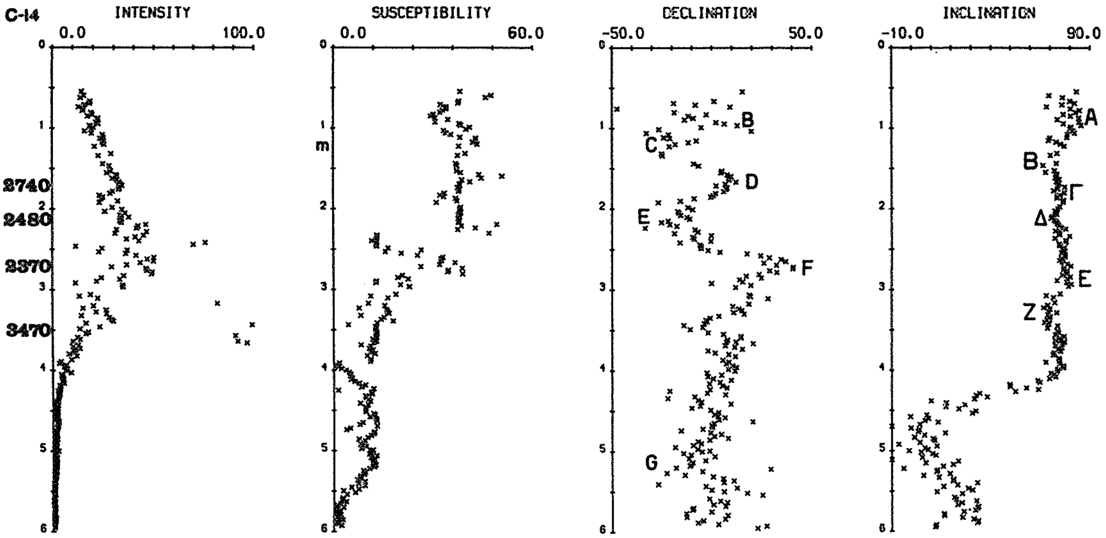

FIG. 3. Core 3. Single sample NRM intensity (10^{-3} Am^{-1}), initial susceptibility (SI units), relative declination, and inclination. Turning points *B–G* and *A–Z* discussed in text. Mean declination set to zero.

seen in each whole-core declination record. This repeatability gives confirmation that these oscillations are a reflection of past changes of the geomagnetic field. In the lower section of both cores, minimal changes in declination are found which suggests the marine sediments were deposited more rapidly than the limnic sequence above.

The declination record can be matched with other secular variation patterns from British lakes. Turning point *A* is interpreted as the AD 1815 westerly maximum known from historic records. *B* and *C* are the smaller fluctuations found at about 60 cm depth in Lake Windermere (*see* Thompson 1977, fig. 2). *D* is the Windermere turning point at 100 cm, *E* corresponds to a westerly maximum which is characteristically broad or double in a record of high deposition rate (as in Lough Neagh, Thompson 1973, fig. 3; Thompson 1975, fig. 4). Turning point *F* in contrast to *E* is sharp, often of large amplitude, and lies at 185 cm depth in Lake Windermere.

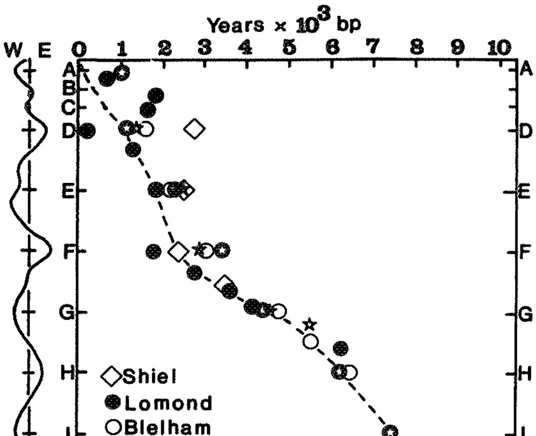

FIG. 4. Geomagnetic declination variations (*A–L*) *v.* conventional C^{14} age for 5 British lakes. Dashed line shows preferred ages of geomagnetic fluctuations as discussed in text.

Magnetic inclination

Inclination measurements were made on 219 subsamples from core 3. In the upper 414 cm of core 3 magnetic inclination varies by only 15° peak to peak and has a mean inclination of 75.4°. Fisher's α_{95} of these upper 138 measurements is 0.9°. The inclination expected on a time-averaged geocentric axial dipole model is 72.0°. The difference is probably due to non-vertical penetration of the corer. The oscillations *A* to *Z* (Fig. 3) although of low amplitude and only here shown from one core, show many similarities to the inclination record from 3 cores from Loch Lomond (Dickson *et al.* 1978; Turner & Thompson, in prep) and are likely to be a reflection of past field changes.

The lowest 1.5 m of the core shows markedly lower inclinations of around 10–20° (Fig. 3). Such palaeomagnetic records (Noel & Tarling 1975; Morner 1977; Abrahamsen & Knudsen 1977) have been interpreted as recording excursions of the geomagnetic field. Thompson & Berglund (1976) have argued that these Late Weichselian and Holocene low-inclination palaeomagnetic directions are more likely to be a result of sedimentary processes than a true reflection of the ancient magnetic field. It has been repeatedly demonstrated that the geomagnetic field was of normal polarity during the period 5000–3000 years BP (Mackereth 1971; Opdyke *et al.* 1972; Kovacheva & Veljovich 1977). The stable low-inclination remanence in Loch Shiel thus cannot be a true reflection of the ancient magnetic field. Remanence in recent fine-grained sediments is most probably a post-depositional remanent magnetization (PDRM) (Kent 1973; Lovlie 1974; Stober & Thompson 1977). The low inclinations correlate with marine deposition, suggesting that the structure of fabric of the sediment, related to the packing of clay minerals, can influence the stable PDRM. Interestingly, the declination is not markedly affected.

Promoters of recent excursions draw attention to the common occurrence of low-inclination, normal declination from European localities (Morner 1977) and interpret this direction as of geomagnetic significance. The Shiel record, however, demonstrates that this palaeomagnetic direction is not alone sufficient for determining a recent excursion and highlights the difficulties which can be encountered in shallow-water estuarine sediments.

Comparison with other British limnic palaeomagnetic sites

Figure 4 summarizes available palaeomagnetic declination data and conventional C^{14} age determinations from 5 British sites. Following Mackereth (1971) we plot the palaeomagnetic declinations as abscissa so that the major swings (*A, D, E, F, G, H, I, L*) lie at equal intervals. Mackereth suggested the oscillations in declination may be periodic. However, later work has revealed additional higher frequency changes in declination and no clear long-term periodic fluctuations in inclination. The interpretation of age determinations advanced here also leads to the declination cycles having markedly different lengths, particularly when a dendrochronology calibration is applied. The British geomagnetic field declination record is thus seen to be composed of a series of fluctuations of different frequencies but with a concentration of energy in the periods between 2500 and 3000 years.

The palaeomagnetic curves from Lochs Lomond and Shiel show more detail than do the original Windermere records. The greater resolution of these geomagnetic records probably results from the higher ratio of rate of deposition to rate of stabilization of remanence in Lomond and Shiel.

Recognition of the above fine geomagnetic detail permits a correlation, between the lake sediments investigated, which is based solely on the palaeomagnetic records. Thus a direct comparison of C^{14} age determinations can be made between lakes in geographically distinct regions. Such an exercise has not been possible previously for the post-Elm decline period, because of the lack of synchronous bio- or litho-stratigraphical horizons.

In most of the lakes studied apparently old C^{14} age determinations have been found near the top of the sediment profiles, i.e. increasingly older ages are found in stratigraphically younging sediments. In general, Quaternary research workers accept age determinations falling on a positive time–depth curve as reliable and only reject those on an inverted, negative time–depth curve.

C^{14} laboratory experimental errors (including errors due to the random disintegration of C^{14} atoms) are small (roughly equivalent to the size of the symbols in Fig. 4) compared to the between-lake discrepancies. Errors in matching the palaeomagnetic curves from lake to lake are also considered to be small, as extensive curves with high-frequency fine details are being correlated. The typical total random error involved can be best judged by the closeness of fit of the age/feature points in Fig. 4 to a smooth curve below turning point *F*. It follows that there must be additional large systematic errors influencing the C^{14} age determinations during the time range of fluctuations *F–D*.

We now consider which, if any, of the age determinations are useful in the range *F–D*. Discrepantly young ages could result from diffusion of young carbon down the core. A more plausible possibility would be contamination by young carbon due to smearing from wall friction during coring. This is unlikely to be a common problem, as Mackereth cores have an internal fixed piston, and laminated material shows only minor signs of smearing. Also, material for C^{14} dating is routinely taken only from the centre of the cores. However, particularly anomalously low ages, for example at turning point *F*, could have resulted in this manner. The major systematic errors are thus thought to result from contamination by old material, in particular from influx of old soils and peats. We suggest this effect has been more pronounced and started significantly earlier than previously believed. C^{14} age determinations may be significantly anomalously old during times of forest clearance and ploughing even though the time–depth curve has not inverted from a positive to a negative relationship.

Palaeomagnetic correlations offer a possibility of assessing this dating difficulty and transferring reliable age estimates between sites. Our preferred ages of geomagnetic fluctuations in Fig. 4 are given by a smooth curve passing through the youngest C^{14} age determinations at each level (excluding Lomond points *D* and *F*). We propose that transference of ages from this master curve to the lake sediments under investigation gives the best estimate of the true C^{14} age of the deposits.

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