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# Icelandic Holocene palaeolimnomagnetism

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Sediments spanning the last 9000 y from two sites in lake Vatnsdalsvatn (Lat. 66°N; Long. 23°E) in northwest Iceland hold repeatable palaeomagnetic direction records. The Vatnsdalsvatn sediments have mean palaeomagnetic inclinations of 76° close to that expected for a geocentric axial dipole field, and direction fluctuations of around 20° from the mean. The palaeomagnetic directions are stable under alternating field partial demagnetization experiments. A time scale for the Vatnsdalsvatn sediments has been estimated from $^{14}C$ dating. The pattern of palaeomagnetic secular change shows few similarities with British records 2000 km distant and a central North American record 5000 km distant.

## 1. Introduction

Lake sediments have been found to carry a natural record of many environmental and geological processes which have occurred on time scales of hundreds and thousands of years. Mackereth (1971) was the first to recognize that on account of their stable natural remanent magnetization organic-rich lake sediments present the geophysicist with the opportunity of studying ancient geomagnetic field changes. Mackereth was able to measure remanent declination fluctuations of around 10°–40° amplitude in the sediments of Lake Windermere on account of the excellent coring properties of his pneumatic coring equipment (Mackereth, 1958, 1969). His equipment produced less sediment distortion than many other systems and also allowed continuous 6 m long cores to be obtained from water between six and several hundred meters depth.

Similar Holocene palaeosecular variation fluctuations to those observed by Mackereth were found in the organic-rich sediments of Lough Neugh (Thompson, 1973). However, many other lakes have been found to yield scattered or clearly biased palaeomagnetic remanence directions in their sediments, and it now appears that fewer than one lake in ten, in temperate regions, holds a palaeomagnetic signal of the quality of the Windermere or Neagh records. Many of the best palaeolimnomagnetic records have been found for lakes with magnetite rich rocks or tills in their catchments, and organic-rich rather than inorganic sediments.

Barton (1978) demonstrated within- and between-site reproducibility of palaeolimnological direction fluctuations in a volcanic region on the Victoria–South Australian border. Further within- and between-site palaeolimnomagnetic reproducibility in Britain was found by Turner and Thompson (1981). Possibly the best North American results are those of S.P. Lund from the Minnesota area (Banerjee et al., 1979). Geomagnetic secular variation is geographically complex (Bauer, 1896) and since 1600 A.D. has been very different in these three regions from which reproducible Holocene palaeolimnomagnetic records have been obtained (Thompson and Barraclough, 1982; Thompson, 1984).

The study of Icelandic lake sediments was ini-

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tiated to address the question of the geographic extent of Holocene secular variation patterns and in particular to explore the gap between North American and European sites.

## 2. Collection sites

Six lakes were sampled. The locations of these six lakes are shown in Fig. 1.

### *2.1. Choice of sites*

The criteria for choosing the lakes to be studied were firstly, ease of access from a road; secondly, freedom from present day glacial effects such as high sediment input during the spring thaw; thirdly, reasonable separation from active volcanic centres, as thick ash bands might have limited core recovery; fourthly, at least one lake to be from a locality which was deglaciated early; and fifthly, at least one lake to be in the fallout area of the postglacial Hekla acid tephra layers. The five criteria limited the choice of lakes from an initial list of 150 to about a dozen. The final choice was determined by local conditions at the time of the field work such as the prevailing wind direction and access possibilities. Whenever possible, two sites or basins were cored in each lake and a pair of long cores were taken from a fixed buoy at each site.

### *2.2. Vatnsdalsvatn*

This paper deals mainly with palaeomagnetic results from Vatnsdalsvatn (translates to Lochglenlochy). Vatnsdalsvatn which lies on the northwest peninsula of Iceland is a glacially eroded valley lake on basalt bedrock with a maximum water depth of about 40 m. Two sites were sampled in Vatnsdalsvatn. A trial 3 m core tube, followed by two 6 m core tubes were used at the southern site of Vatnsdalsvatn in 31 m of water, and two 6 m core tubes were used at the northern site in 25 m of water, closer to the main inflow. The longest core recovered was 5.85 m in length.

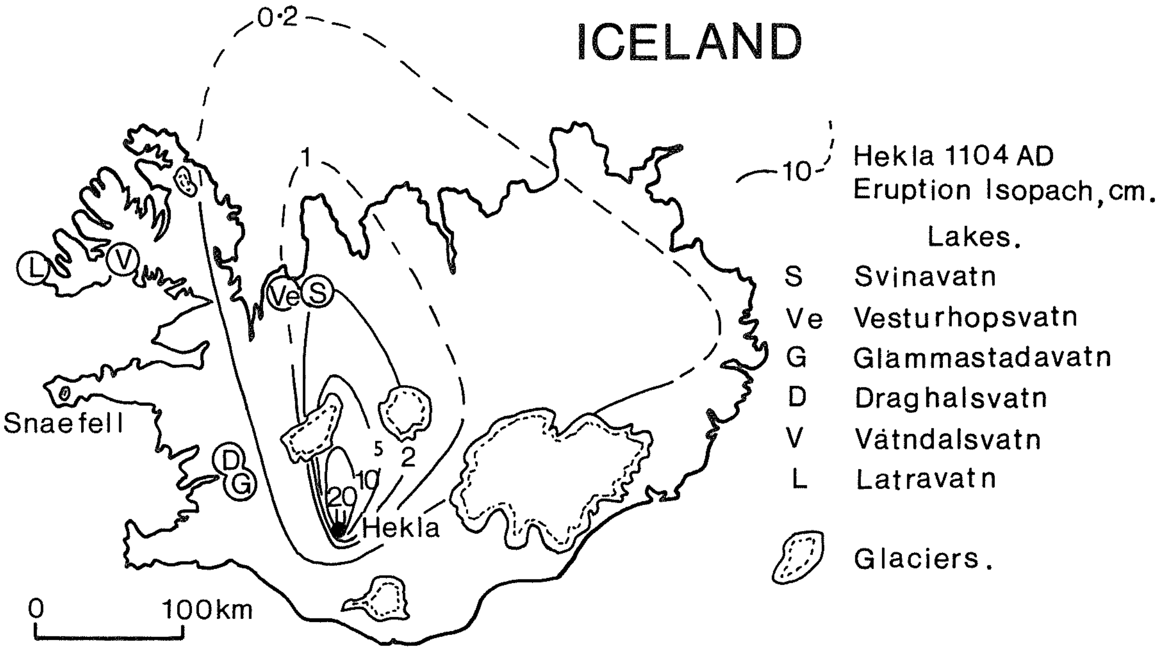

Fig. 1. Coring sites S, Svinavatn; V, Vatnsdalsvatn; L, Latravatn; Ve, Vesturhopsvatn; G, Glammastadavatn; and D, Draghalsvatn drawn on the tephra distribution map for the A.D. 1104. Hekla eruption (after Thorarinsson, 1967).

## 3. Sampling and measurement methods

### 3.1. Core collection

During a three week visit to Iceland in the summer of 1979 sediment cores were collected from six lakes. A total of sixteen cores were successfully recovered using 6 m long Mackereth (1958) corers from five of the six lakes. Seventeen surface cores were also collected using a 1.3 m Mackereth (1969) mini corer. The cores were taken from areas of the lake shown by our bathymetric surveys to be deep, flat and away from steep slopes. The 6 m cores were slotted as part of a keyway system designed to reduce core tube twist. All the cores were sealed in their liners on site, and transported back to Edinburgh by road and sea for analysis.

The Mackereth piston coring system does not always recover a full core, nor does the mud/water interface always lie at the top of the core tube. For the three main cores studied, VDVS2, VDVS3 and VDVN5, the lengths of sediment obtained were 570 cm, 585 cm and 530 cm, respectively and the mud/water interfaces were estimated to fall at 30 cm, 27 cm and 50 cm, respectively. All depths have been corrected to refer to distance below the mud/water interface.

### 3.2. Palaeomagnetic instrumentation

All magnetic remanences were measured using a fluxgate magnetometer. The whole core instrument of Molyneux et al. (1972) was used to measure relative declination and horizontal intensity at 5 cm intervals. The full remanence vector of sediments subsamples was measured using the ring fluxgate system of Molyneux (1971). Alternating field partial demagnetization was performed using a 2 axis tumbler and a conventional tuned, mains frequency coil with current reduction provided by a triple variac. Zero field for the demagnetizer was produced by a triple mu-metal shield. Magnetic susceptibility was measured using the air cored coil system of Molyneux and Thompson (1973). Whole core susceptibility measurements were made every 2.5 cm.

## 4. Dating

### 4.1. Tephra chronology

Icelandic vulcanologists have established an excellent post-glacial tephra chronology through detailed analyses of ash layers in peat, soil and ice core profiles (Steinporsson, 1966; Thorarinsson, 1970; Larsen and Thorarinsson, 1977). The acid tephra provide distinctive, often widespread marker horizons. One acid tephra was clearly visible in our cores. Glass particles were separated from the tephra for major and trace element chemistry using the NERC/Edinburgh University electron microprobe operated by the Geology Department. Energy dispersive techniques were used for detection of the major elements and crystal spectrometry for the minor elements. The gun potential was set at 20 kV and the probe current at 6 nA for the major element work. Analyses were made on the polished surfaces of the longest grains. Except for occasional counts of Sr and Zr trace elements were well below the instrument's detection limit. The major element results are summarized in Table I. The low total percentages partly result from exclusion of $H_2O$ (typically about 2%) from the totals and partly from beam scattering due to the vesicular nature of the particles. The chemical analyses, and the location of Vatnsdalsvatn (< 100 km to the northeast of the volcano Snaefell) suggest that the tephra might be one of the two found by Steinporsson (1966) in peat profiles on the Snaefell peninsula with $^{14}C$ ages of 1750 and 3960 y BP, respectively.

TABLE I

Average chemical analyses of six glass particles

| | |
|---|---|
| $SiO_2$ | 68.0% |
| $TiO_2$ | 0.27 |
| $Al_2O_3$ | 14.3 |
| $\Sigma FeO$ | 3.0 |
| CaO | 1.0 |
| MnO | 0.17 |
| $Na_2O$ | 4.0 |
| $K_2O$ | 4.4 |
| $ClO_3$ | 0.22 |
| Total | 95.4 |

### 4.2. *C-14 dating*

Sixteen radiocarbon age determinations (SRR-1770 to 1775 and SRR-2491 to 2500, Table II) have been obtained for the Vatnsdalsvatn sediments. Six analyses were made on material from core VDVS3 and ten from core VDVS2. The Vatnsdalsvatn $^{14}$C age determinations, with one exception, lie in sequence (Table II). Despite this internal measure of agreement and the reasonably low laboratory counting precision errors with standard deviations of around 1 to 2% the $^{14}$C ages are problematical. The main problem is that the VDVS3 $^{14}$C ages do not tie in with the Snaefell tephra chronology nor with the VDVS2 $^{14}$C ages.

The VDVS2 sequence of dates all lie in sequence and thus appear to be the more reliable. The ten VDVS2 $^{14}$C age depth pairs plus the VDVS2 mud/water surface have thus been used for dating the palaeomagnetic direction variations. Ages have been interpolated between these eleven time-depth pairs and extrapolated to the base of the cores using a smoothing spline curve. The $^{14}$C ages have been calibrated to calendar years before present (BP) using Clark's (1975) tree ring calibration curve.

TABLE II

Dating information

| Sample | Conventional age C-14 years ±2sd | Depth below mud/water interface (cm) | Core |
|---|---|---|---|
| SRR | | | |
| 1770 | 3010±840 | 103 | VDVS3 |
| 1771 | 2630±220 | 173 | VDVS3 |
| 1772 | 3620±240 | 213 | VDVS3 |
| 1773 | 4250±300 | 323 | VDVS3 |
| 1774 | 4930±240 | 423 | VDVS3 |
| 1775 | 5410±500 | 498 | VDVS3 |
| 2491 | 2740±140 | 130 | VDVS2 |
| 2492 | 3470±160 | 180 | VDVS2 |
| 2493 | 4270±160 | 240 | VDVS2 |
| 2494 | 4560±140 | 279 | VDVS2 |
| 2495 | 5040±140 | 350 | VDVS2 |
| 2496 | 5300±320 | 432 | VDVS2 |
| 2497 | 6540±140 | 452 | VDVS2 |
| 2498 | 7540±120 | 519 | VDVS2 |
| 2499 | 7750±160 | 539 | VDVS2 |
| 2500 | 8400±140 | 559 | VDVS2 |
| Tephra thickness | | | |
| 0.5 cm | 1750 or 3960 | 153 | VDVS2 |
| 2.3 cm | 1750 or 3960 | 161 | VDVS3 |
| 1.5 cm | 1750 or 3960 | 231 | VDVN5 |

## 5. Palaeomagnetic data

### 5.1. *Measurements*

Whole core relative declination (Fig. 2) and horizontal intensity measurements suggested that the Vatnsdalsvatn sediments were worth investigating in detail. All the Vatnsdalsvatn sediments revealed clear correlatable whole core declination records (Fig. 2). Two cores VDVS2, VDVS3 from the southern site and core VDVN5 from the northern site were chosen for subsampling and detailed magnetic analyses. The procedure followed was to: (1) split cores into two "D" shaped sections; (2) push contiguous 6 ml volume cuboid plastic boxes into one half noting the depths of the centres of the boxes; (3) extract the boxes using a plastic knife, cap, seal and store in a humid environment in zero magnetic field for 48 h; (4) measure the

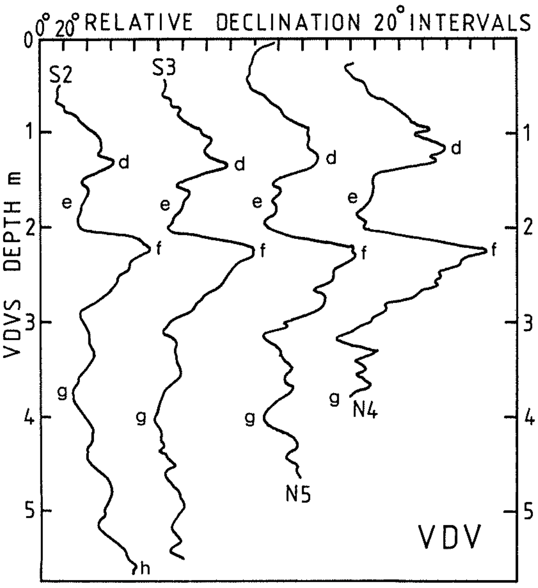

Fig. 2. Whole core relative declination records from the southern (S) and northern (N) sites of Vatnsdalsvatn. Small letters mark the main declination turning points. The depth scales have been offset to align turning point f.

natural remanent magnetization using a fluxgate magnetometer; and (5) partially demagnetize and remeasure selected pilot samples using alternating magnetic fields of up to 60 mT.

### *5.2. Data processing*

The processing of palaeolimnomagnetic data falls into two categories. Firstly remanence directions can be adjusted by rotation on the sphere, and secondly depth scales can be converted into time scales.

The need for direction adjustments arises because palaeolimnomagnetic remanence measurements are often unorientated. With our sediments we only know that the long axis of the coring tube was aligned roughly vertically. On account of this lack of orientation raw palaeolimnomagnetic direction measurements need careful assessment. For example the larger relative declination amplitudes of core VDVN4 to be seen in Fig. 2 are most likely to have been caused by off-vertical corer penetration. This type of orientation difficulty can be reduced by rotating all palaeolimnomagnetic directions to a common reference frame. Useful rotations are to set all the mean declinations and mean inclinations to zero ($\bar{D} = 0$, $\bar{I} = 0$) or else to set the mean declinations to zero and the mean inclinations to that of a geocentric axial dipole ($\bar{D} = 0$, $\bar{I} = a \tan(2 \tan \lambda)$, where $\lambda$ is the site latitude). It can also be helpful to convert the direction pairs into virtual pole positions or to project them onto a tangential plane to the unit sphere.

The second category of mathematical manipulation procedures involves converting the sediment depths of the palaeomagnetic observations into times. The approach we have used is to take the time-depth pairs of Table II and to use an interpolation method (a smoothing cubic spline) to transform the sediment depth of each palaeomagnetic subsample into tree ring calibrated $^{14}$C years before present (O BP = A.D. 1950).

An estimate of the statistical reliability and serial correlation of palaeolimnomagnetic data can prove helpful in assessing the quality of the data. The statistical approach used in this work has been to assess the scatter about best fitting curves based on robust weighted least squares functions and hence to calculate 95% coincidence limits for the best fitting curves. The cross validation approach employed in selection of best fitting curves has been described in Clark and Thompson (1978) and Thompson and Clark (1981).

The serial correlation, as estimated from the average (median) angle between the remanence directions of adjacent samples, increases with partial demagnetization from 2.7° to 3.1°. The overall scatter of the remanence directions, however, is slightly reduced by cleaning. The circular standard deviation, for example, decreases from 7° for the stored natural remanence directions to 6° for the partially demagnetized remanence at both sites.

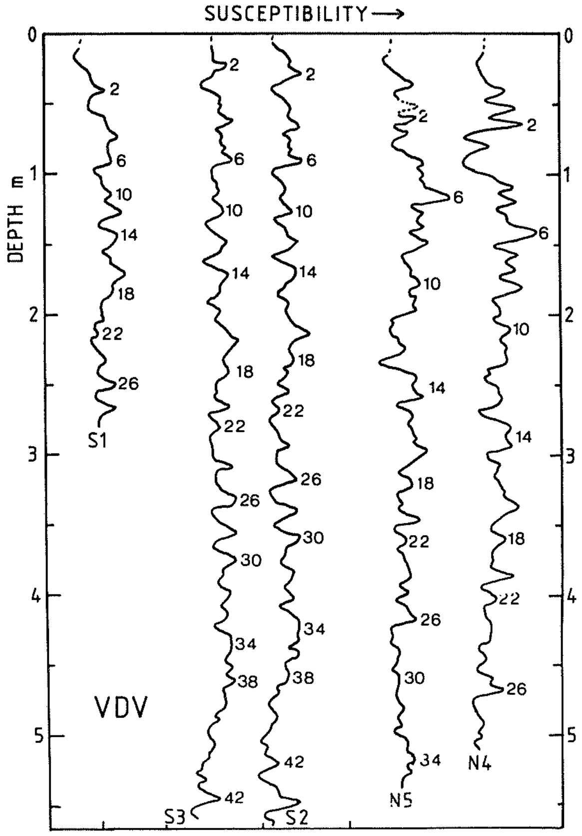

Fig. 3. Whole core initial susceptibility records for the southern (S) and northern (N) sites of Vatnsdalsvatn. Even numbers mark susceptibility maxima which can be seen to correlate between cores.

### *5.3. Palaeolimnomagnetic results*

The palaeomagnetic remanence of the Vatnsdalsvatn sediments has a higher intensity than has been found in many other lake sediments. This high intensity with a mean value of about 150 mAm$^{-1}$ makes measurement of the remanence straightforward. The high intensity results from relatively high magnetite concentrations in the basalt bed rock and source materials.

Whole core declination measurements from the four long Vatnsdalsvatn cores are presented in Fig. 2. The major features have been labelled and can be seen to match well between cores. The declination oscillation f-e-d is particularly clear in all four cores.

Whole core susceptibility measurements were also carried out. These results are presented in Fig. 3 for the four long Vatnsdalsvatn cores and the short trial core VDVS1. Alternate susceptibility

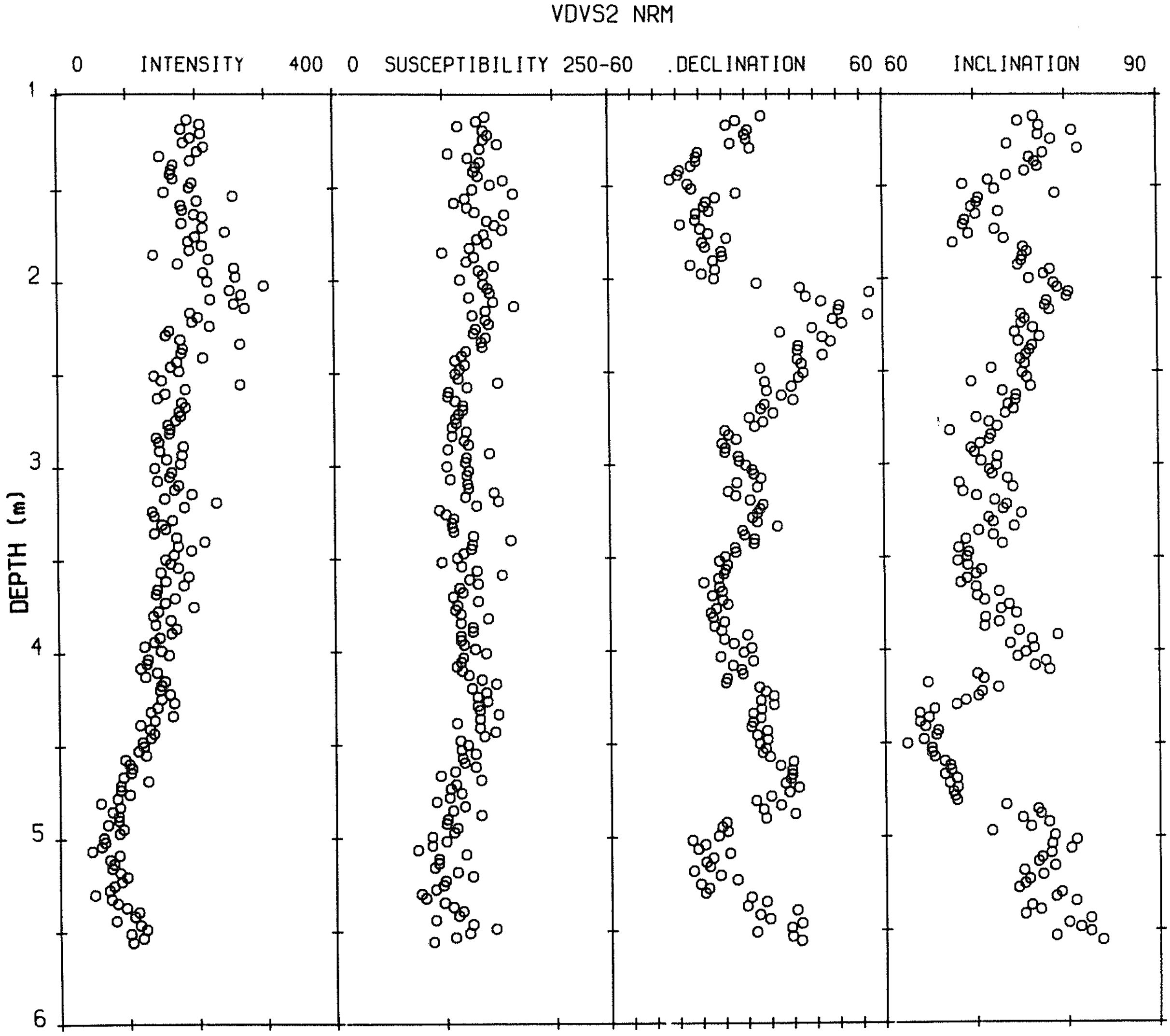

Fig. 4. Subsample intensity, susceptibility, declination and inclination measurements plotted against depth for Vatnsdalsvatn core S2. The intensity scale is from zero to 400 mAm$^{-1}$. The susceptibility scale is from zero to 250×10$^{-6}$ SI units. Declination and inclination in degrees.

maxima have been labelled as even numbers. Forty-three susceptibility maxima and minima are to be found in the VDVS2 log. The same features can be identified in the VDVS3 core. Many of the features can also be recognized in the two cores from the more northerly site. Core VDVS2 appears on the basis of the susceptibility variations to hold the longest sedimentary record. The comparatively large number of susceptibility features is caused by a sequence of numerous thin basaltic tephra layers. On average Iceland has a volcanic eruption every 5 y, and this continued volcanic activity has led to complicated sequences of minor ash falls in the Icelandic lake sediments.

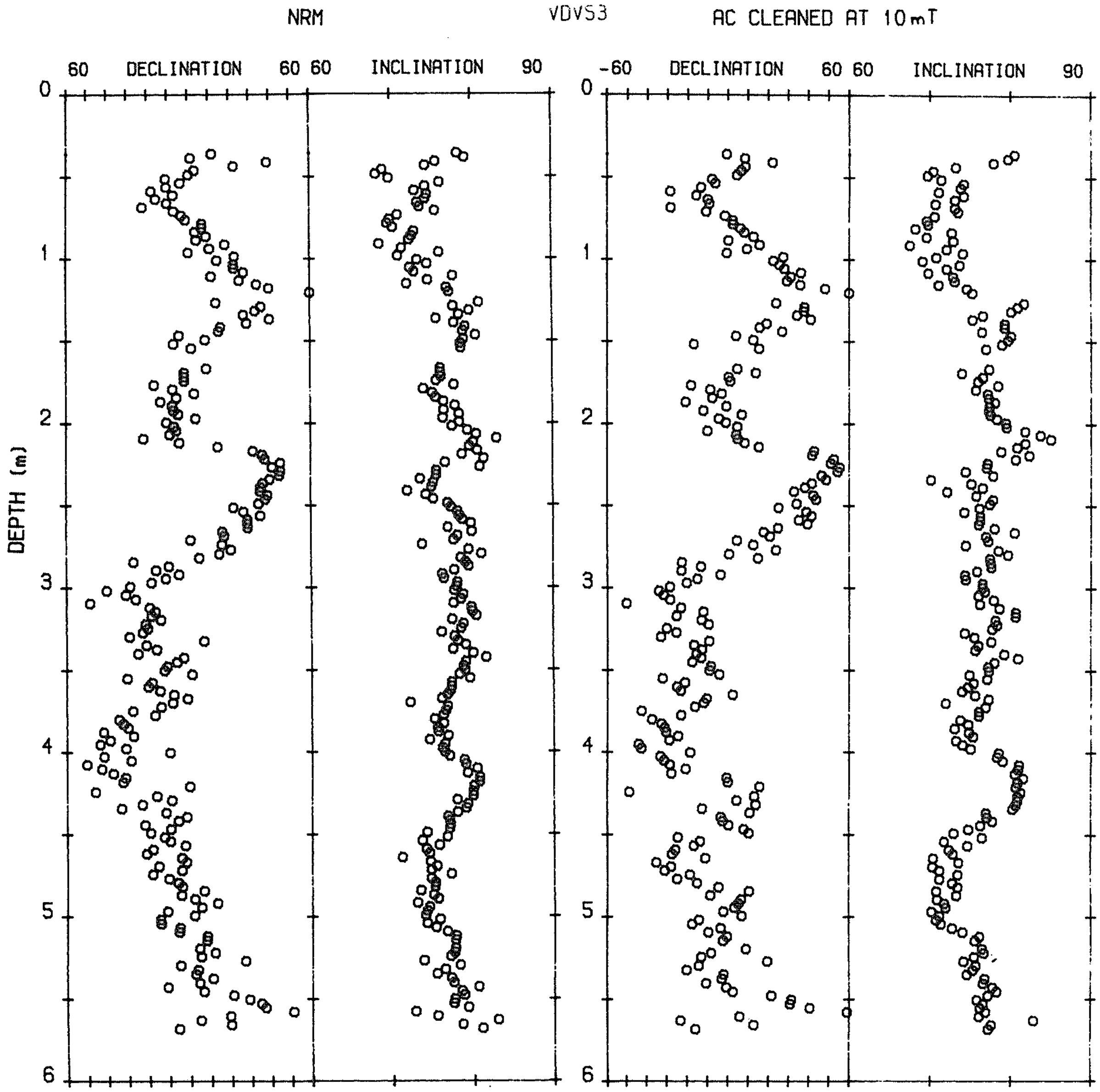

Fig. 5. Vatnsdalsvatn core S3 single sample measurements of stored and partially demagnetized remanence versus depth.

The whole core susceptibility scans are easier to correlate than the subsample susceptibility logs. In subsampling thin tephra layers can be missed or only partially sampled so the subsample logs are influenced by the details of the sampling. One example of a subsample susceptibility log is presented in Fig. 4 for the sediments of core VDVS2. Subsample intensity data are also shown in Fig. 4 for core VDVS2.

Subsample declination and inclination data are plotted against depth for cores VDVS2, S3 and N5 in Figs. 4, 5 and 6. The declination features found in the whole core measurements can again be clearly seen as can inclination fluctuations. The

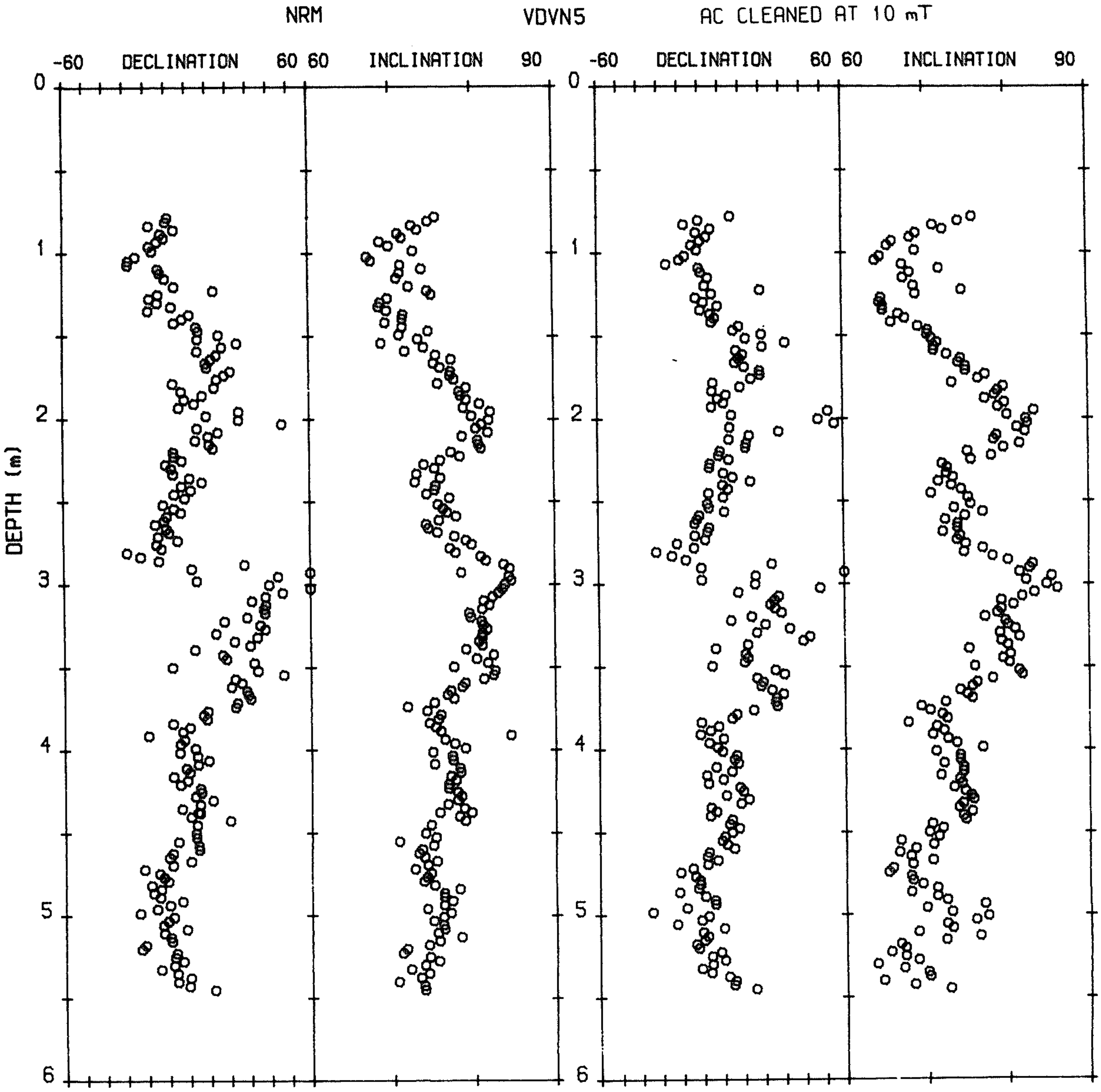

Fig. 6. Vatnsdalsvatn core N5 single sample measurements of stored and partially demagnetized versus depth.

solid angle amplitudes of the direction changes are similar to those found in British lake sediments of around 20°. All natural remanence measurements on subsamples were made on material that had been stored in zero magnetic field for at least 48 h.

Two examples of alternating field demagnetization of the Icelandic lake sediment remanences are shown in the orthogonal projections of Fig. 7. The remanence directions change little with cleaning in alternating fields of up to 60 mT and the removal of more than 90% of the stored natural remanence. The stability of the stored remanence is further confirmed by bulk partial demagnetization in fields of 10 mT. Examples of partial demagnetization experiments on cores VDVS3 and N5 are shown in Figs. 5 and 6 along with the stored remanence directions. The cleaning fields were chosen to remove roughly half the stored remanence. Again little change is to be seen in the directions before and after partial demagnetization. The mean inclinations of cores VDVS2, VDVS3 and VDVN5 are 74°, 77° and 76°, respectively. The inclination at the collection site of a geocentric dipole field would be 77°.

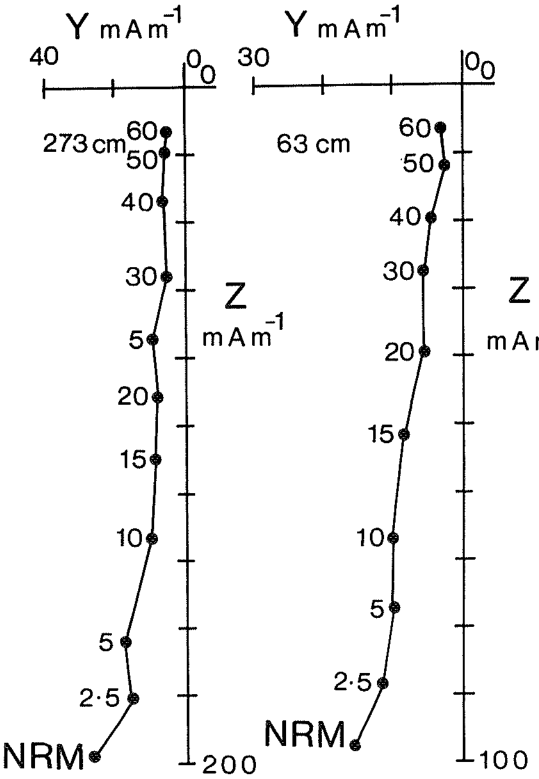

Fig. 7. Orthogonal plots of the locus of the magnetic vector of two pilot samples from 63 and 273 cm depth in Vatnsdalsvatn south site core 3 during alternating field demagnetization. The Z (down) direction refers to the axis of the core tube. Demagnetization fields are noted in mT up to a maximum of 60 mT.

### *5.4. Type record*

Best fitting curves have been constructed using least squares spline functions following the cross validation procedure of Thompson and Clark (1981). An example of a best fitting curve along with its 95% confidence limits is shown in Fig. 8. This curve for the paleomagnetic direction of core VDVS3 is based on 206 data points from 36 to 568.2 cm depth. Figure 9 shows the variation of the cross validation mean square error for the core VDVS3 palaeomagnetic data for different spline fits. A broad minima is found in the mean square error for spline fits with between 18 and 38 spline pieces. The lowest value for the mean square error was found for 24 spline pieces. This number of cubic spline pieces was used in constructing the best fitting curve of Fig. 8. The broad minimum indicates that the fitting is not critically dependent on the number of spline pieces used.

The confidence limits plotted in Fig. 9 can act as a guide when trying to assess features of likely geomagnetic significance. For example directional features which have smaller amplitudes than the width of the confidence bands in Fig. 8 are likely to have only random or statistical origins (Wilson, 1972).

The best fitting cubic spline curves to the VDVS2 data have been chosen as the type records for Iceland.

## 6. Discussion

In Fig. 10 we plot our type Iceland palaeomagnetic record, in terms of common site virtual poles (Wilson, 1972), along with a British (Turner and Thompson, 1981) and a central North American (Banerjee et al., 1979) record. Inspection of Fig. 10 reveals few similarities between the British and Icelandic secular variation records but

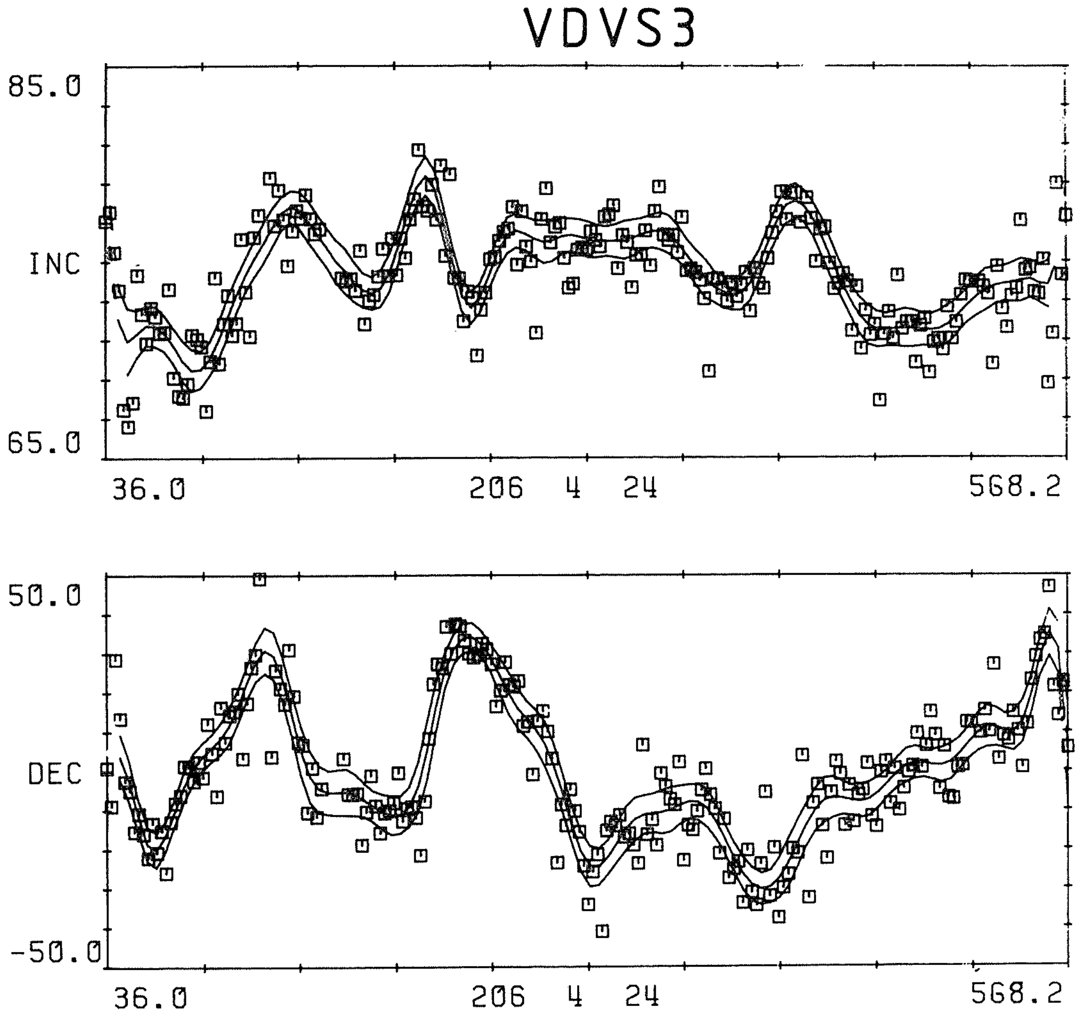

Fig. 8. Least squares cubic spline fit with 24 equal length pieces and 95% confidence limits to the 206 Vatnsdalsvatn core S3 palaeomagnetic data points.

many differences. Some of the differences could be accounted for by poor dating. Nevertheless we suggest that the 2000 km distance between these two localities is about that at which palaeolimnomagnetic records are beginning to reflect significant differences as caused by the changing configuration of the Earth's non-dipole field. Over shorter distances (a few hundred kilometres) between lake sites, secular variation records can be expected to be similar at all epochs. Over longer distances, such as between central north America and Britain, we would again emphasize the differences between the secular variation records. We attribute the few palaeomagnetic similarities that occur between these widely separated localities to chance, e.g., the righthandedness of the virtual poles around 2400 y ago.

## 7. Conclusions

(1) The Holocene Icelandic palaeomagnetic variations can be adequately explained using a uniformitarianism approach namely that present geomagnetic field behaviour has been reasonably typical of the field behaviour over the last $10^4$ y.

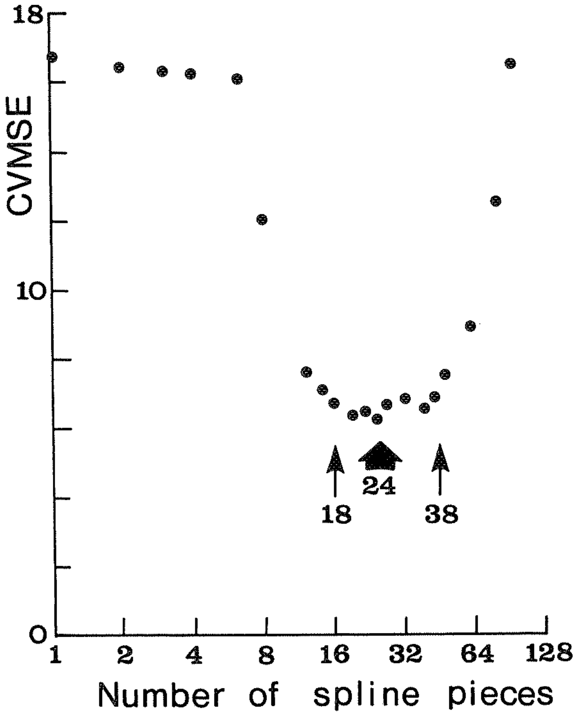

Fig. 9. Cross validation mean square error versus number of cubic spline pieces. For various least square fits to the palaeomagnetic directional data of Vatnsdalsvatn core S3. A broad minimum in the mean square error is found between 18 and 38 spline pieces.

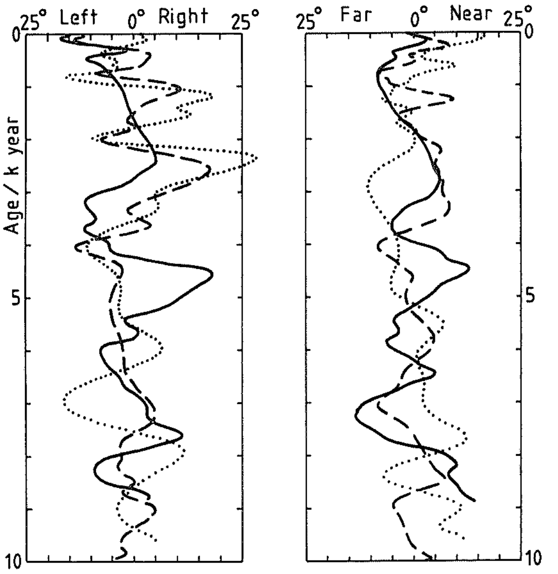

Fig. 10. Summary diagram of common site longitude palaeomagnetic virtual pole positions for Iceland (solid line), Britain (dashed line) and North America (dotted line). Tree ring calibrated ages before present.

(2) There is no evidence in the Holocene Icelandic palaeomagnetic data for field reversals, excursions, unusually large secular changes, regular pulsating sources or other unexpected geomagnetic phenomena.

(3) The characteristic one to two thousand year long features of palaeolimnomagnetic records may well have been caused by the chance succession of comparably short lived (~ 400 y) non-dipole foci coupled with a smoothing of the geomagnetic signal by palaeomagnetic recording processes.

(4) For Holocene palaeomagnetic records from sites separated by several thousands of kilometres, e.g., from different continents, we find more differences than similarities. The few similarities that are to be found over such distances are quite likely to have been caused by chance occurrences.

(5) The palaeomagnetic direction variations in Lake Vatnsdalsvatn have mainly been caused by changes in the Earth's non-dipole field.

## Acknowledgements

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