

THE HOLOCENE GEOMAGNETIC FIELD IN EUROPE

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DECLARATION

I hereby declare that the work presented in this thesis is my own, unless otherwise stated in the text, and that the thesis has been composed by myself.

## ABSTRACT

During the summers of 1975 and 1976, 29 six metre cores of lacustrine sediment were collected from France and Switzerland, and 59 from Poland. All of these cores were collected using a Mackereth type pneumatic corer. The natural remanent magnetization (N.R.M.) of these cores was studied in an attempt to investigate the pattern of long period secular variations of the geomagnetic field. The cores were then dated using palynological and radio-carbon techniques. A correlation between the patterns recorded from the different lakes, and between the lakes and the archaeomagnetic record for Europe was then attempted. The results obtained from the French and Swiss lakes were in general better than those from the Polish lakes. Further studies indicated that the percentage of magnetic material in the Polish lakes was much lower than in the French and Swiss ones and hence may be the reason for the poorer results.

An investigation into the carrier of the N.R.M. was then made, and in almost all of the cases studied was found to be fine grained magnetite.

Attempts were then made to simulate long period secular variations using an oscillating eccentric radial dipole model. The model allows eight radial dipoles as positioned by Alldredge and Hurwitz (1964) to oscillate as a sine function. The period and phase of the oscillations can be varied for each dipole, as can the strength and radial distance. The field at the surface is then calculated by summing the effects of the dipoles. A modification to the model, allowing the dipoles to drift as well as oscillate was also made.

The effect of varying the different parameters was then studied. An attempt to simulate a geomagnetic excursion was also made.

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Abbreviations Used in the Text

Declination	D
Inclination	I
Total Intensity	J
Magnetic Field Intensity	H
Susceptibility	k
Long Period Secular Variations	L P S V
Natural Remanent Magnetization	N.R.M.
Anhyseretic Remanent Magnetization	A.R.M.
Depositional Remanent Magnetization	D.R.M.
Chemical Remanent Magnetization	C.R.M.
Isothermal Remanent Magnetization	I.R.M.
Saturation Isothermal Remanent Magnetization	S.I.R.M.
Alternating Field	A.F.
Demagnetization	D.M.
Median Destructive Field	M.D.F.
Intensity of Remanent Saturation	$J_{rs}$
Saturation Field	$H_{sat}$
Coercivity of Remanence	$H_{cr}$
Maximum Entropy Method	MEM
Fast Fourier Transform	FFT
Number of Points in Error Prediction Filter	NPEF

## CHAPTER 1

### INTRODUCTION

#### 1.1 Secular field changes

In 1635, Henry Gellibrand stated that the easterly declination at London was steadily decreasing. This statement was based on observations spanning a period of 54 years. Approximately 50 yr later in 1683, Edmund Halley also concluded that changes in the declination of the field occurred after studying observations scattered over much of the earth's surface. Since that date the secular variations of the geomagnetic field components have been extensively studied and recorded. This has enabled the charting of secular variation for many different observation points over the globe. The difficulty is however, to try and determine the secular variations before observations started in the early seventeenth century.

This can be done by measuring the remanent magnetization of orientated samples of fired potteries or kilns (Kawai 1965; Thellier 1966; Aitken 1964, 1967; Kovacheva 1977). This method however, can only give discrete data points from archaeological dated finds and a method was needed that would render a continuous record of the long period variations. This was made possible by the study of long cores of continuously deposited lacustrine sediments. Work has already been carried out in such areas as North-West Europe, Great Lakes, Black Sea, and the Aegean. (Mackereth 1971; Creer 1974, 1976; Creer et al 1972; Opdyke 1972; Thompson 1975). The lakes studied for this thesis were in Central Europe and Northern Poland.

All of the cores taken were obtained using a pneumatically



operated, fixed piston Mackereth corer (Mackereth 1958) which is capable of taking cores of six metres in length. This method of investigating the secular variation pattern depends on the ability of the deposited sediment to record the direction of the geomagnetic field at the time of, or shortly after, deposition. By then measuring the changing direction of magnetization down the core (as described in Chapter 2), we can obtain a continuous record of the secular changes. The sediment is then dated at different levels using radio-carbon dating, or pollen analyses to provide us with a time scale. Great care must be taken to show that the pattern of variations so obtained are true geomagnetic variations and not ones produced by mechanical or other extraneous means.

## 1.2 Remanent Magnetization in Lake Sediments

As already stated, the above procedure depends on the ability of the sediments to record and preserve the geomagnetic signal at the time of deposition. The sediment can acquire a magnetic remanence in the direction of the ambient field by two different mechanisms. Firstly, it can acquire a chemical remanence (C.R.M.). This happens when the magnetic grains in the sediment grow through a critical size known as the blocking volume. At this time the remanent magnetization is parallel to the ambient field and remains fixed in this direction even if the field direction changes, or the grains increase further in size.

The second type of remanence is detrital remanence (D.R.M.). In D.R.M., the magnetic grains within the sediment which already have a remanent magnetization rotate to align themselves parallel to the ambient field direction. Originally it was thought that this mechanism occurred as the sediment fell through the water, but it has now been shown that this alignment occurs *after deposition*.

It is also possible for the fine grained

particles to rotate and align themselves with the ambient field direction in the water filled interstices of unconsolidated sediments. This specific type of remanence is called post depositional remanence (P.D.R.M.). The magnetization acquired by these above means is known as the primary magnetization and any magnetization acquired after consolidation, or due to new chemical changes is referred to as a secondary component. The secondary component of magnetization is removed by using alternating field (A.F.) demagnetization on the samples.

When we are satisfied that the secular variation records obtained are of true geomagnetic origin, we can then try to correlate the records from different lakes in the same area. The object of this correlation being to hopefully build up a Master curve of secular variations for different areas.

### 1.3 The Geomagnetic Field and Models

As can be seen from studying master curves already drawn up for certain areas, the geomagnetic field seems to display a regional character. Numerous models have been proposed for the field, both in terms of spherical harmonic analyses and in terms of dipoles (see introduction to chapter 6).

Studies have also been carried out on the apparent westward drift of the geomagnetic field and of the time span of this drift. (Bullard et al 1960; Hope 1957; Yukutake 1962, 1967, 1968; Skiles 1970). None of these models however, or the westward drift of the field, seems to account for the long period secular variations as observed in palaeomagnetic data.

As a result, the second part of the investigations carried out for this thesis is the proposal and testing of different geomagnetic models in an attempt to simulate the records obtained from the limno-

magnetic studies. Although by no means a definitive model for the geomagnetic field, it is hoped that the model suggested may go some way towards an explanation of the long period secular variations and of the apparent regional qualities of the field.

## CHAPTER 2

### COLLECTION, SAMPLING AND MEASUREMENTS

#### 2.1 Choice of Coring Site

The choice of lake, and the actual coring site within the lake are of great importance. The lake itself should have a relatively large drainage basin so as to provide enough detrital sediment for coring. It should also have a flat central plain from which the cores should be taken. This plain should be free of any strong currents which may disturb the sediment and should also be large enough so that the sediment will not be affected by any slumping at the edges.

Bathymetric maps, an echo sounder, and a depth line were used to decide on the coring position and also to establish the position within the lake. A marker buoy was usually left at the site after coring to enable us to return to the same location to take subsequent cores.

Data from past surveys on sediment thickness, currents, rates of sedimentation etc., are also very useful in the choice of the site.

#### 2.2 Collection of Cores

As already stated, all the cores for this research project were collected using a Mackereth Corer. This pneumatically driven corer, working on the fixed piston principle, enables one to collect 6 metre vertical cores of sediment from the lake floor.

After collection the core is sealed at both ends and if the core is not a full 6 metres in length, the tube is packed so as to prevent movement of the sediment.

At least two cores, or preferably more, are taken from each site within the lake, and usually at least two sites within a lake are

sampled.

After measurements were done on some of the cores, and by checking the working of the corer on dry land, it was discovered that the corer was occasionally twisting during the coring operation. To check which cores were being twisted and to try and establish the amount of twist, a slight modification was carried out on the corer.

A sharpened metal scriber was attached to the end of the guide block on the corer. This scriber was spring loaded and scratched a mark on the plastic core tube as it was pushed out of the guide block and into the sediment. This confirmed that some of the cores, but not all of them, were twisting on entering the sediment. The amount of twist varied in all cases, and although this could be measured, it was not possible to give an indication of the amount of twist of the sediment. This is because there is no evidence to suggest that the sediment was twisted by the same amount as the core. If it was twisting, we cannot tell if it did so in a continuous, or discontinuous fashion.

This problem has turned out to be a very serious one in the interpretation of the data obtained from some of the cores, and is in the process of being eliminated by the testing of different modifications to the corer.

### 2.3 Transportation and Handling of Cores

The transportation of the cores back to the laboratory is also a matter for careful consideration. It is also possible that heat may cause chemical changes within the core and may also lead to the drying out of the sediment if the core is not properly sealed, hence allowing the sediment to rotate within the core tube.

Excessive driving over rough or cobbled roads may also disturb the sediment and could in fact be part of the cause of the scattered

results found in many of the cores taken in Poland.

For the above reasons the full cores were strapped securely to the transporting vehicle and covered on very hot days.

#### 2.4 Long Core Spinner Measurements

The first measurements carried out on the cores are long core measurements. These are very rapid ones which can be done in the laboratory or in "the field" if the necessary equipment is taken. The measurements are carried out using a digico long core spinner apparatus (Molyneux 1972) (fig. 2.1) and have the advantage of being non-destructive, as they are carried out without opening or cutting the core.

The core is spun horizontally on rollers and a flux gate head, connected to the computer, is passed along the length of the core. This enables one to measure the declination and the horizontal intensity along the core at any chosen spacing. This is usually done at five centimetre spacing which leads to a slight smoothing of the obtained record. As the instrument is only measuring in the horizontal plane, the angle of inclination cannot be found.

These records have a twofold use. Firstly, they can help decide whether the core is worth sub-sampling for further measurements. The two factors in deciding this are the intensity of the magnetization and the scatter of the data in the declination record. Any core with a very low intensity and scattered declination record will probably not yield any better results on sub-sampling.

Secondly, the long core records can be used for correlations with the sub-sampled records. This enables one to decide whether the core has been disturbed during cutting and whether a feature on the sub-sampled plots is real or just due to the sub-sampling procedure.

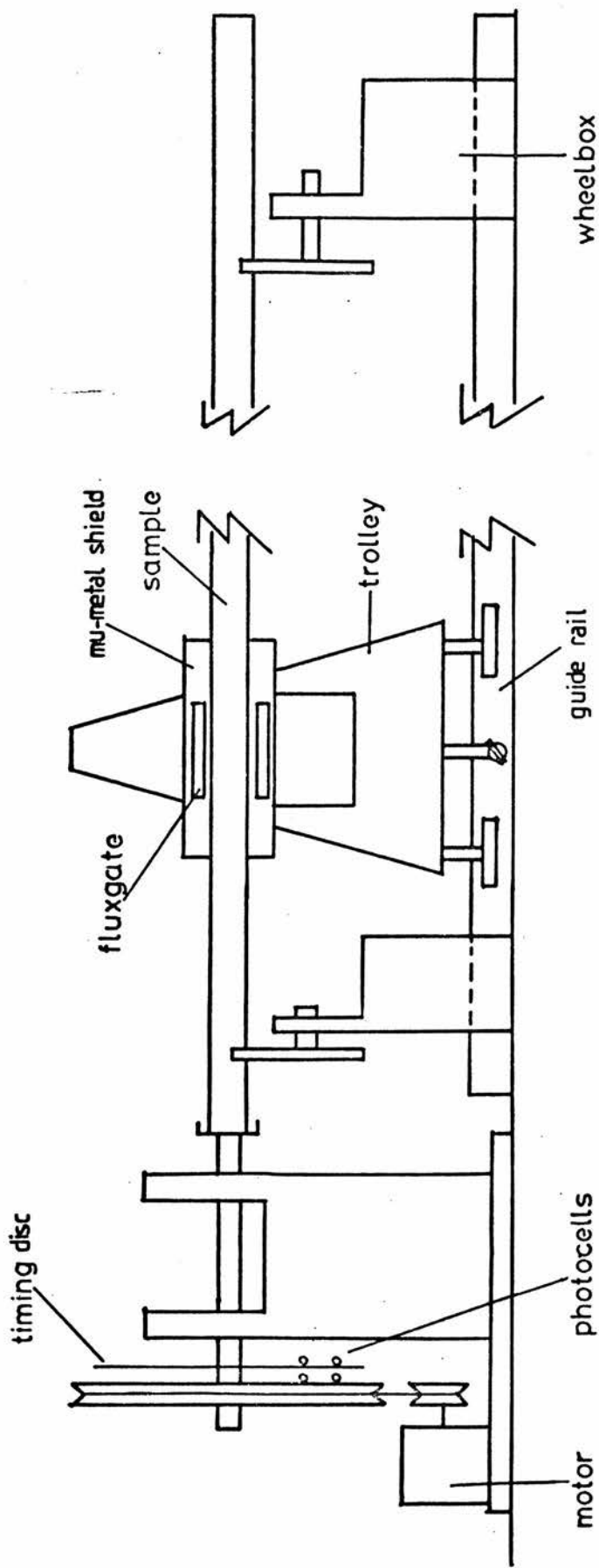


FIG 2.1 Horizontal Fluxgate Spinner Magnetometer

## 2.5 Long Core Susceptibility

Susceptibility of the whole core can be measured very rapidly and easily using a digico long core susceptibility bridge (Molyneux 1973). This gives a fast and easy way to show if cores within a lake can be correlated. Again, if used in conjunction with the other long core measurements they can help one decide whether a set of cores should be sub-sampled.

## 2.6 Sub-Sampling of the Cores

After the long core measurements have been carried out, the selected cores have to be sub-sampled to allow measurements of declination (D), inclination (I), total intensity (J), and susceptibility (k) to be made. As the cores were not orientated when collected, the first procedure is to mark an arbitrary orientation line down the length of the core. Care must be taken that this line is straight and that the core tube is not twisted while the line is being marked.

The core has then to be cut into more manageable lengths. Firstly, however, the core should be unsealed at both ends to release the pressure in the tube due to the build up of gases. If this is not done a significant amount of sediment can be lost from the tube when the initial cut is made.

The six metre core is then cut into four equal lengths, each section being labelled and arrows marked on to indicate the direction to the top of the core. These sections are then clamped in a cutting jig, and sliced in half using a circular saw set to cut only the core tube, and therefore not disturbing the sediment. The sediment itself is sliced in half using a piece of very fine wire.

The next stage is to take a description of the core, noting colour changes, varving and changes in grain size for possible correla-



tion at a later date with intensity or susceptibility. This should be done quickly before oxidation and hence colour changes can take place. The sections are then sub-sampled by pushing 2.5 cm cubic or cylindrical plastic boxes into the sediment down the length of the core. These boxes have a small hole drilled in the top face to let the enclosed air escape while pushing them into the sediment. Great care must be taken that the boxes are pushed in perpendicular to the exposed surface and that all the boxes are parallel to one another.

The boxes are then numbered, orientated and the depth to the centre of each box is noted. They are then removed from the sediment using a non-magnetic spatula, care being taken to leave as much of the unsampled sediment behind as possible, so that it can be used for radio-carbon dating and pollen analyses. The holes in the boxes are sealed to prevent drying out of the sediment. The core sections are then rewrapped and sealed in polythene tubing. After sub-sampling the boxed specimens are placed in zero field for a few days before measuring to remove any soft component of magnetization. This is done by storing the samples inside a large set of Helmholtz coils or inside a set of mu-metal shields.

## 2.7 Measurements of Sub-Samples

Measurements of D, I and J are made by using a balanced flux-gate spinner magnetometer, interfaced with a digico M16 V mini-computer. This enables one to obtain a direct printout of the values on a teletype console.

The sample is spun in six different orientations, at the centre of the flux-gate head, which is itself placed inside a set of mu-metal shields. The six orientations allow measurements parallel and anti-parallel to three mutually perpendicular axes, which are in turn

fixed relative to the fiducial mark on the single sample.

The sample holder, or platform as it is called, is attached via a rod to a slotted disc which spins within a photo cell. A single measurement is taken each time a slot passes the eye of the photo cell and these measurements are averaged over every complete revolution. The number of revolutions required for each sample depends upon its intensity. The lower the intensity, the lower the signal to noise ratio becomes, and hence more spins are required to obtain the same degree of accuracy in the measurements.

The number of spins is calculated so that the recordings are repeatable to within  $\pm 1^\circ$  regardless of the intensity.

The instrument is calibrated using a standard sample of known intensity and is usually recalibrated after every ten samples measured.

The platform of the spinner is made of non-magnetic impregnated wood and ideally should have a zero magnetization. This however is not the case, and with small pieces of dirt and sediment collecting on the platform and with the addition of some static, the intensity can become quite appreciable. Although the computer should average out any random noise in the six spins, this is not always the case, and care must be taken to keep the platform clean and demagnetize it if the intensity becomes too high.

The susceptibility is measured on a single sample susceptibility bridge and again a print out of the susceptibility is obtained directly on the teletype console.

## 2.8 Demagnetization

The next stage in the measuring procedure is to demagnetize the samples to get rid of any secondary component of magnetization. This

procedure can also be used to test the stability of the samples.

Firstly single pilot samples are chosen at roughly equal spacing down the core. These samples are then stepwise A.F. demagnetized up to a field of 900 oe, the direction and intensity of the magnetization being measured after each step.

Plots of  $J$  versus the demagnetizing field ( $H$ ) and a stereographic projection of the directions are then obtained. Using this information, the demagnetizing field for the whole core is then decided upon. The field chosen is ideally one that removes any secondary component but does not destroy the primary component completely (examples of this are given in chapters 3 & 4).

The mean destructive field (M.D.F.) of the samples can also be calculated. This is the field at which the intensity has fallen to a half of its original value and gives an indication of the stability of the samples. If the M.D.F. is high and the pilot samples very stable it may not be necessary to demagnetize the whole core, as in fact was the case in many of the cores studied.

In this project most of the samples were demagnetized about 3 perpendicular axes as opposed to tumbling, though a few of the specimens were demagnetized using a two axis tumbler. The demagnetization about the perpendicular axes was done on four of the six faces of the cube. The fourth face being demagnetized at half the D.M. field. It was not performed on all six faces to prevent the growth of any A.R.M.'s (Snape 1974). The coil itself was placed at the centre of a set of mu-metal shields which reduced the ambient field to approximately 20 $\mu$ G. Although this may be considered quite high for demagnetizing, any A.R.M.'s grown in this field will be very small compared with those due to the irregular and fluctuating A.C. mains

power supply.

## 2.9 Plots Obtained

After all these procedures have been carried out, all the data from one core ~~is~~<sup>are</sup> plotted on a graph. The declination is plotted about an arbitrary zero, hence we are studying only the relative changes in declination. Work is in progress at present to orientate the cores and hence give an absolute value for the declination. Inclination, intensity, susceptibility and Q-ratio are also plotted together with the declination. The Q-ratio (or modified Konigsburger Ratio) is the ratio of the N.R.M. intensity to the initial susceptibility. Although this may be used as an indication of the palaeointensity for igneous rocks, this cannot be said for lacustrine deposits. It was also thought that it might be useful to distinguish between chemical and detrital remanent magnetization although this is no longer considered to be the case. It does however help in the correlation of the cores within a lake and is occasionally better than using the intensity or susceptibility separately. After correlating the plots of cores within a given lake we can then hopefully try to correlate them with cores from other lakes in the same region.

(Examples of this are again given in chapter 3 & 4)

## 2.10 Errors in Sampling and Measuring

There are many sources of error which occur during the sampling and measuring procedures. As already stated it should be possible to check if some large errors have been made by checking the final plots against the long core plots.

However there are numerous smaller errors which would not show using the above method..

The first error occurs in the cutting of the sections of core

along the orientated line. There is liable to be an error of  $\pm 2^\circ$  or  $3^\circ$  taking into account the twisting of the pliable core tube, the thickness of the cutting blade and the accuracy of the positioning of the core within the cutting jig.

The next error arises in the insertion of the boxes into the sediment. A positioning error of  $\pm 2^\circ$  is quite possible about any of the 3 perpendicular directions. The largest error however undoubtedly comes from the physical disturbance of the sediment with the actual pressing of the boxes into the sediment. The wetter the sediment is the greater the disturbance. The largest error from this will therefore be at the top of the core and decrease down the length of the core.

Another error in the angles can arise from the calibration of the fluxgate spinner. However if this is checked at regular intervals the errors should be negligible. As already stated, the error in the repeatability of any one sample, providing the number of spins is correct, is one degree. Hence a scatter of  $\pm 3^\circ$  or  $4^\circ$  between adjacent samples must be expected.

Errors in the intensity measurements can arise from the calibration assumption that a standard volume is being measured, which is not always the case.

The noise level of the platform will also lead to an error in the final intensity. It was also found by testing, that the plastic sample box itself could have a remanence of  $2\mu\text{G}$ . This was found to be caused by drilling of the holes in the boxes with a metal drill piece. If care is taken to clean the drill beforehand, the remanence of the box could be kept negligible.

On testing the susceptibility bridge it was found to be accurate

to only  $\pm 0.5 \mu\text{G}/\text{oe}$ . This error was found to be an absolute error and therefore occurred regardless of the value of the susceptibility. Hence samples with a low susceptibility had a much higher error associated with them and any samples of susceptibility values under  $1 \mu\text{G}/\text{oe}$  were made almost meaningless. This in turn led to the Q-ratios becoming very unreliable and some "impossible" values could then occur, as was true in several cases measured.

## CHAPTER 3

### Palaeomagnetic Studies of Holocene Lake Sediments from France and Switzerland.

#### 3.1 Introduction

As already stated in Chapter 1, palaeomagnetic studies have been carried out on post-glacial lake sediments collected in Europe (Mackereth 1971, Creer et al 1972, Thompson 1973) and in North America (Creer et al 1976). These studies were carried out in the hope of investigating the nature of the geomagnetic field during the last 10,000 yr and of building up a record of time variations at local and regional levels. Palaeomagnetic studies have also been carried out on rapidly deposited marine sediments, e.g. Aegean (Opdyke et al, 1972) and the Black Sea (Creer 1974). Another source of palaeomagnetic data, used for studying the long period secular variation (L P S V) record, is cave sediments (Creer and Kopper 1976). All of these studies show a secular variation pattern for the palaeofield. The period of the oscillations found is in the order of 2,000 - 3,000 yr and hence these studies can reveal variations on a much longer time scale than is possible from observatory records.

Another use of these palaeomagnetic records is in the dating, and correlation of Holocene sediments. The main problem with this use of secular variation records is to try to verify over how large an area the records remain valid.

It was as a result of trying to solve the above problem, and also to augment the data that had already been obtained on L P S V that a palaeomagnetic investigation was carried out on cores collected from France and Switzerland.

#### 3.2 Field Work and Geology

A collection of 32 cores varying in length from 3.50m to 6.0m was made in the summer of 1975, using a 6m Mackereth fixed piston corer. Twenty-six of these cores were transported back to Edinburgh for palaeomagnetic investigations, and six were left at Geneva University for pollen and chemical analyses.

The cores were collected from lakes Annecy, Le Bourget, Geneva, Morat and Lac De Joux. All these lakes lie in the area best described as the French Sub-Alps (Fig. 3.1). They all lie in the Sub-Alpine Massifs, but the drainage basins of lakes Annecy and Geneva have as their underlying basement rocks the crystalline Alpine Massifs. All the lakes sampled had been well glaciated and were, on the whole, very deep. As a result the coring operations were carried out in water depths of between 40m and 70m.

Unfortunately the cores were taken before the addition of the metal scriber to the corer so there was no physical evidence of any twisting in the cores collected. Although initially apprehensive that the long core spinner device might disturb the wet sediment, almost all of the cores returned to Edinburgh were long core spun, as described in Chapter 2. From the long core records, it was then decided which cores should be sub-sampled for further investigations. The main factors governing this choice being i) the scatter of the records ii) the horizontal intensity of remanence iii) the physical length of the sediment column.

### 3.3 Results from Lake Annecy

With the help of Liverpool University Geography Department, who carried out pollen analysis and also allowed access to mini-cores they had collected, Lake Annecy was the lake studied in greatest detail.

Lake Annecy is situated in the Northern Prealpine zone of France,



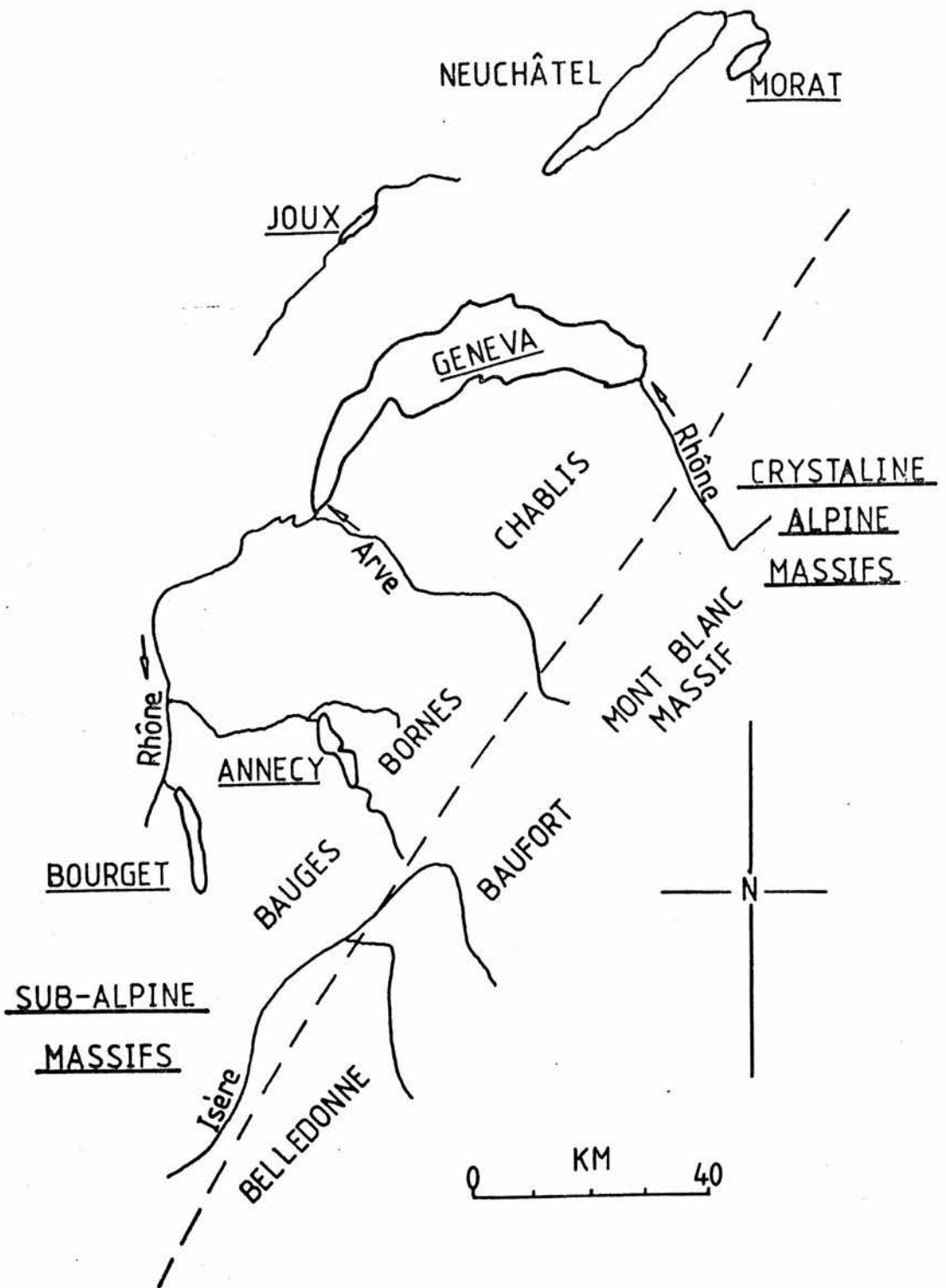


FIG 3-1 Position of Lakes within the Sub-Alpine Massifs

between latitudes  $45^{\circ} 54'$  N and  $45^{\circ} 47'$  N and longitudes  $6^{\circ} 7'$  E and  $6^{\circ} 15'$  E. The position of the lake within this zone can be seen in Fig. (3.1). The surface of the lake covers  $26.5 \text{ km}^2$  and the drainage basin covers a total area of  $278 \text{ km}^2$ . The lake itself comprises of two basins which are partially separated by the Roc de Chère (considered to be a fallen block from the Tournette massif). The two basins are the Grand Lac to the north and the Petit Lac to the south.

There are seven major rivers draining into Lake Annecy. Fig.(3.2) illustrates the drainage network of the basin. Of the seven rivers, only three drain into the Grand Lac. Note should be made of the relative size of the drainage areas of the two basins, as this is very important in explaining the different sedimentation rates of the two basins, and the seemingly different palaeomagnetic records. The only outflows from Annecy are via the Thiou Canal and the Canal Vassé, which combine to form the River Thiou, which flows from the northern end of the Grand Lac. There is a dominance of calcareous parent materials in the drainage basin which obviously leads to a high calcium carbonate content in the deposited sediment.

Although impossible to determine the ratio of autochthonous (formed within the lake) to allochthonous (carried into the lake by external processes) sediments, it is probably true to say that due to the large drainage area, and the erodable nature of the bedrock, that a very large proportion of the sediments originated from an external source.

Six cores were taken from Lake Annecy: three from the Grand Lac and three from the Petit Lac. The average length of the six cores was 5.25m. Fig. (3.3) shows a bathymetric map of Lake Annecy, with the coring positions marked. Fig. (3.4) is an East-West profile

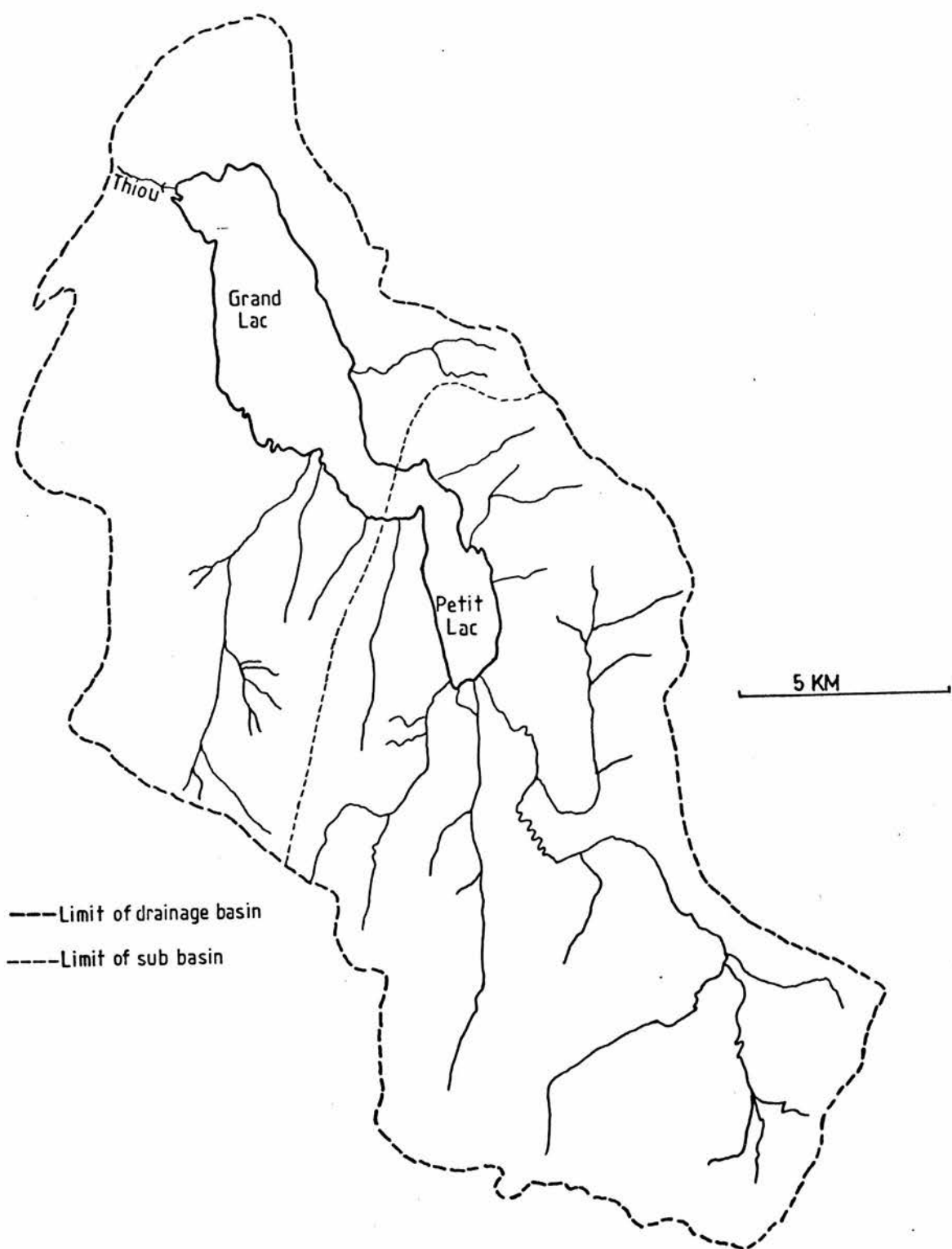


FIG 3-2 Map Showing the Drainage Basin of Lake Annecy

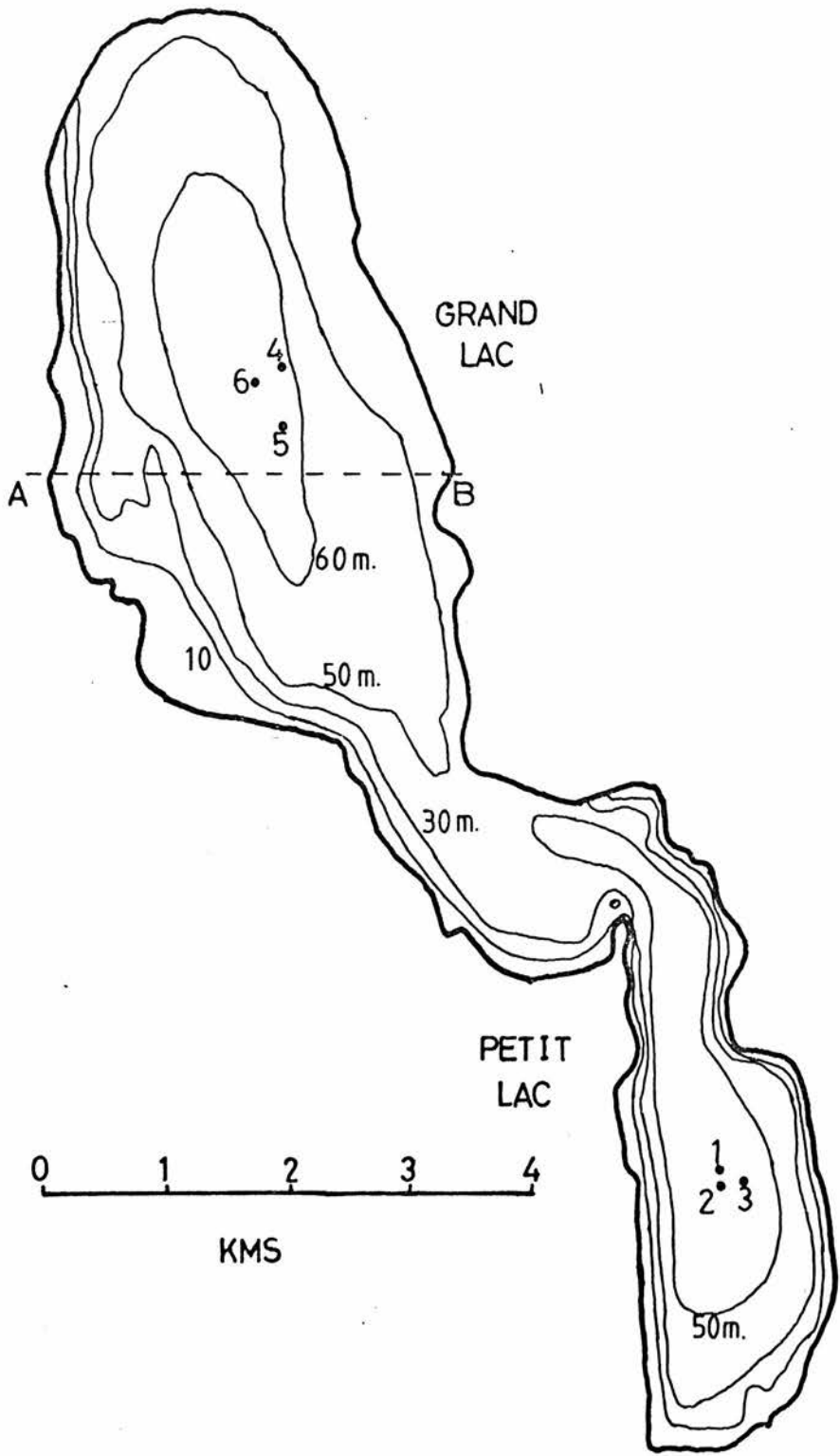


FIG 3-3 Bathymetric Map of Anney Showing Coring Sites

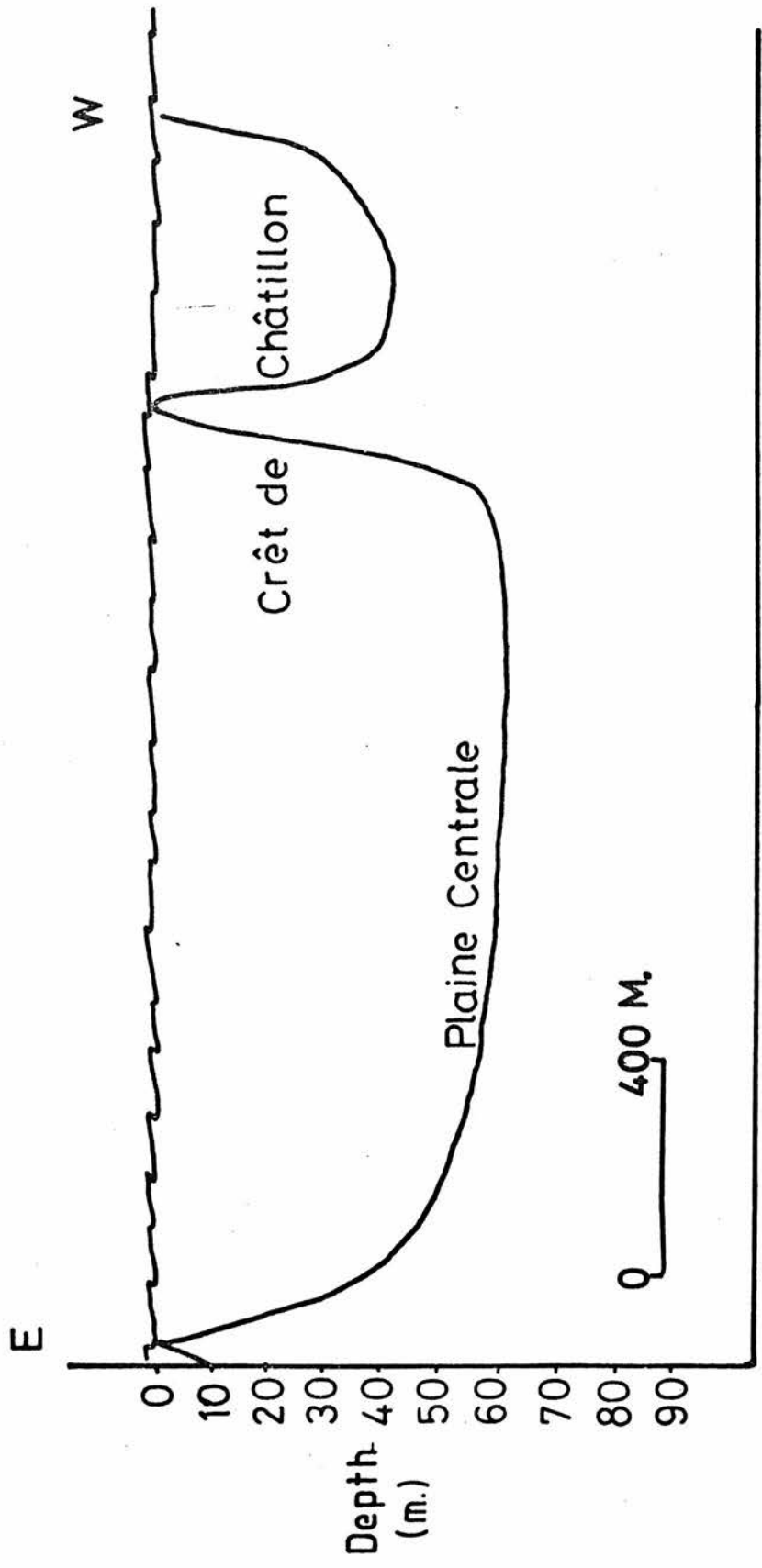


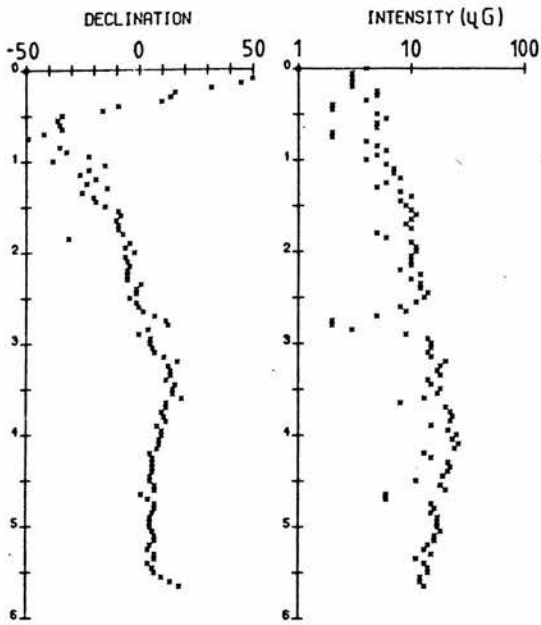
FIG 3.4 Profile of Grand Lac across Line A-B (see fig 3.3)

across the Grand Lac, which shows the Plaine Centrale where the cores were taken. By coring in the middle of the Plaine Centrale we hopefully avoided any slumping of the sediment which may have occurred at slopes on the lake-side or near the "Cret de Chatillon" ridge.

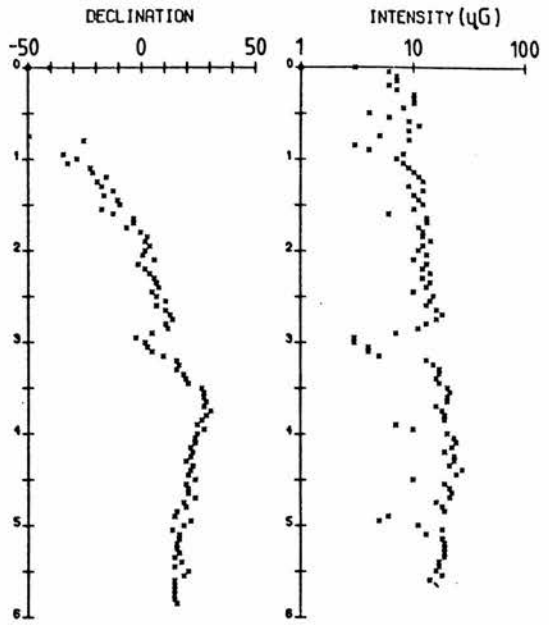
Of the six cores collected, one was left in Geneva and five transported back to Edinburgh. Of these five, core No. 2 was too short to be of interest and hence cores 1, 3, 4, 5, were measured, using the digico long core spinner apparatus as described in Chapter 2. (Molyneux et al 1972). Fig. (3.5) shows the results obtained from the spinner; cores 1 and 3 being from the Petit Lac, and cores 4 and 5 from the Grand Lac. As can be seen, cores 1 and 3 correlate ~~v~~<sup>g</sup>ery well both in D and horizontal intensity. The D and horizontal intensity records from cores 4 and 5 however, do not seem to show any correlation whatsoever. Referring back to the notes taken during field work, it was found that there was great doubt about the authenticity of core 4. The impression obtained at the time being that the corer had somehow managed to go through the coring operation twice without surfacing. Later, pollen analysis of the top and bottom of cores 4 and 5 seemed to agree with this conclusion, as the pollen at the bottom of core 4 was very similar to that at the top. For this reason it was decided to open and subsample cores 1, 3, and 5 only.

As already described, the next stage of the procedure is to split open the core and sub-sample it. At the same time a description is taken of the core, noting the stratigraphic and grain size changes. Fig. (3.6) shows in diagrammatic form, the stratigraphy of the cores.

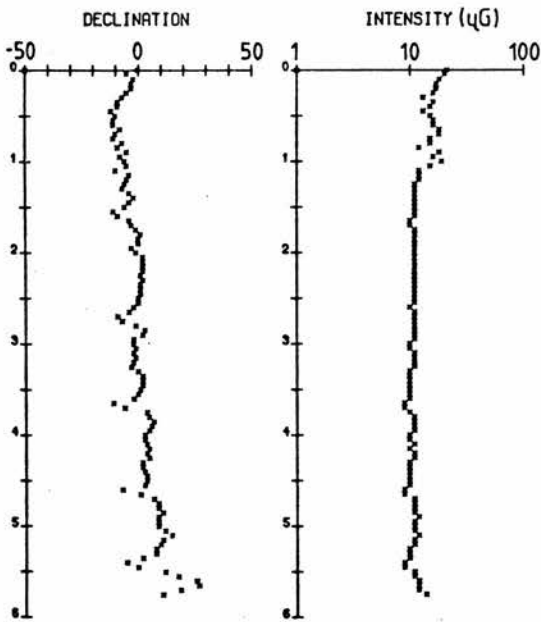
After sub-sampling, the D, I and J of the specimens are measured



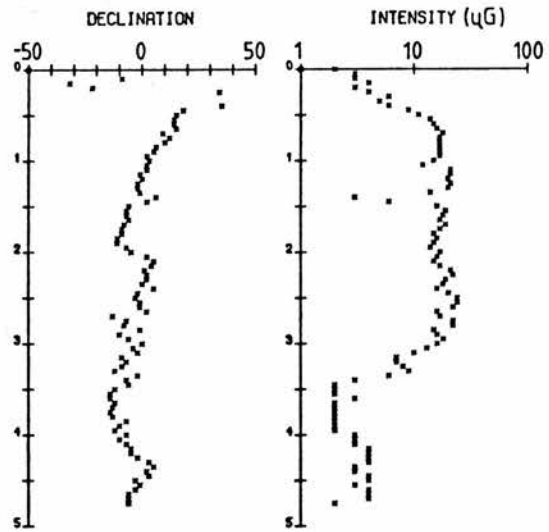
ANNECY 1



ANNECY 3



ANNECY 4



ANNECY 5

FIG 3-5 Long Core Measurements of AnneCy 1,3,4&5

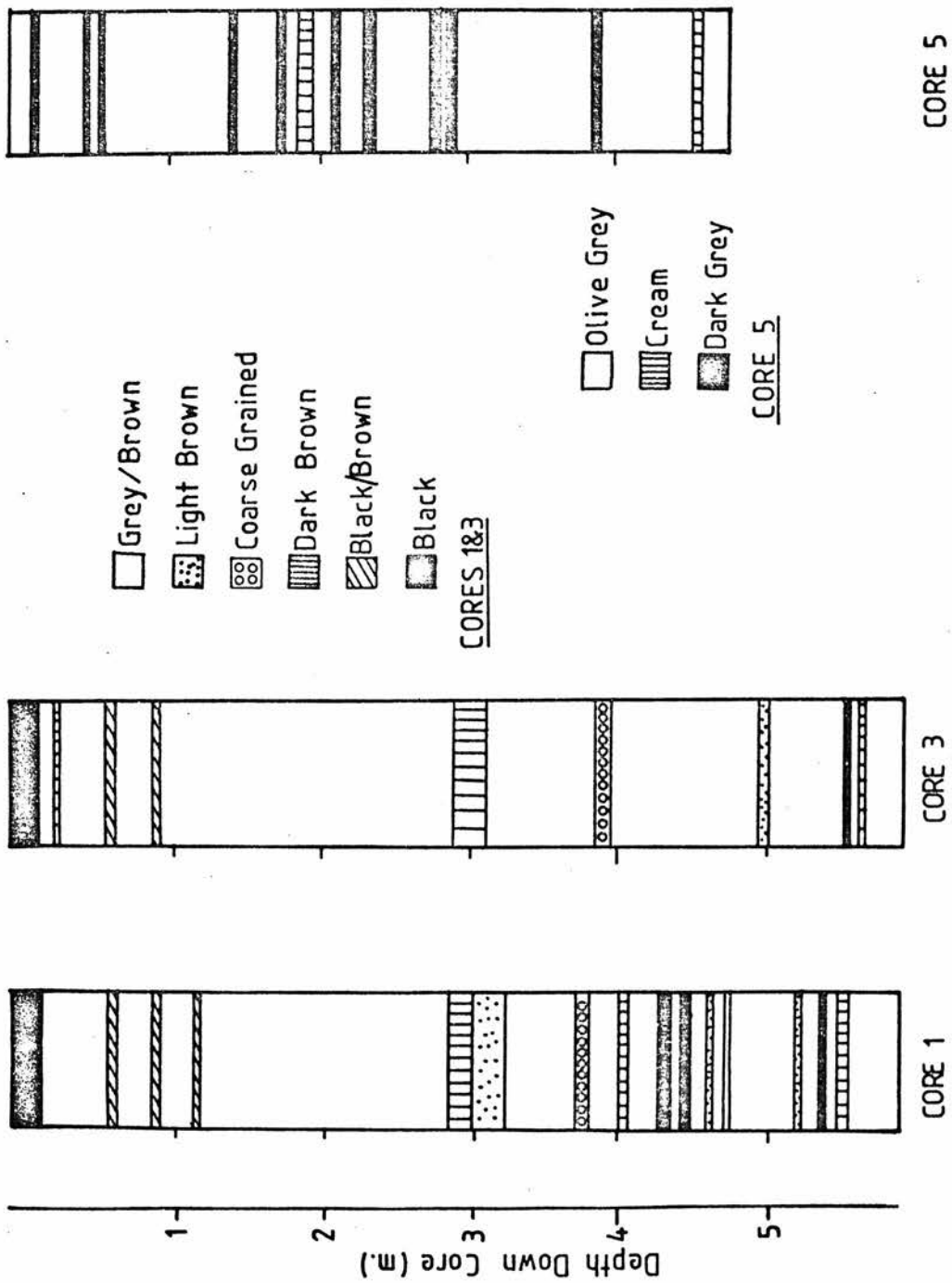


FIG 3-6 Stratigraphy of Ancey Cores 1,3&5



using a Digigo fluxgate spinner magnetometer (Molyneux 1971) and the susceptibilities ( $k$ ) are measured in a low field susceptibility bridge. Fig. (3.7) shows the long core results plotted against the single sample results for the cores measured. As can be seen the correlation between them is very good and suggests that no errors of major importance have been made while sub-sampling. This figure also demonstrates the advantage of having carried out preliminary long core measurements. As the cores are cut into four sections at 1.50m, 3.0m, 4.50m, it would have been impossible to say whether the variation in the declination record of core 3 at 3.0m depth was a real variation or one due to the slicing of the core at this point. One may have been tempted to suggest that this variation was not real, but the evidence of the long core results shows us that it is.

Using the D and J record for cores 1 and 3, it is a very easy task to correlate the depths of the different cores. Fig. (3.8) shows the plots of the single sample measurements for cores 1 and 3, side by side. The correlation between these cores is obvious in all the four quantities plotted. The susceptibility plots especially show a very fine structure which can be easily correlated. Fig. (3.9) shows the plot for core 5, which does not seem to show any correlation with the other two cores.

If we study the D and I plots of cores 1 and 3, we can see that the top 1.0m in each core is very disturbed. In some cases the specimens actually plot outside the scale shown. This is due to a very high water content in the top metre of these cores, the unconsolidated sediment then being free to rotate inside the core tube. There is also evidence to suggest that the top of the cores may be twisted. In core 3, for instance, between 0.5m and 2.0m, the declination swings

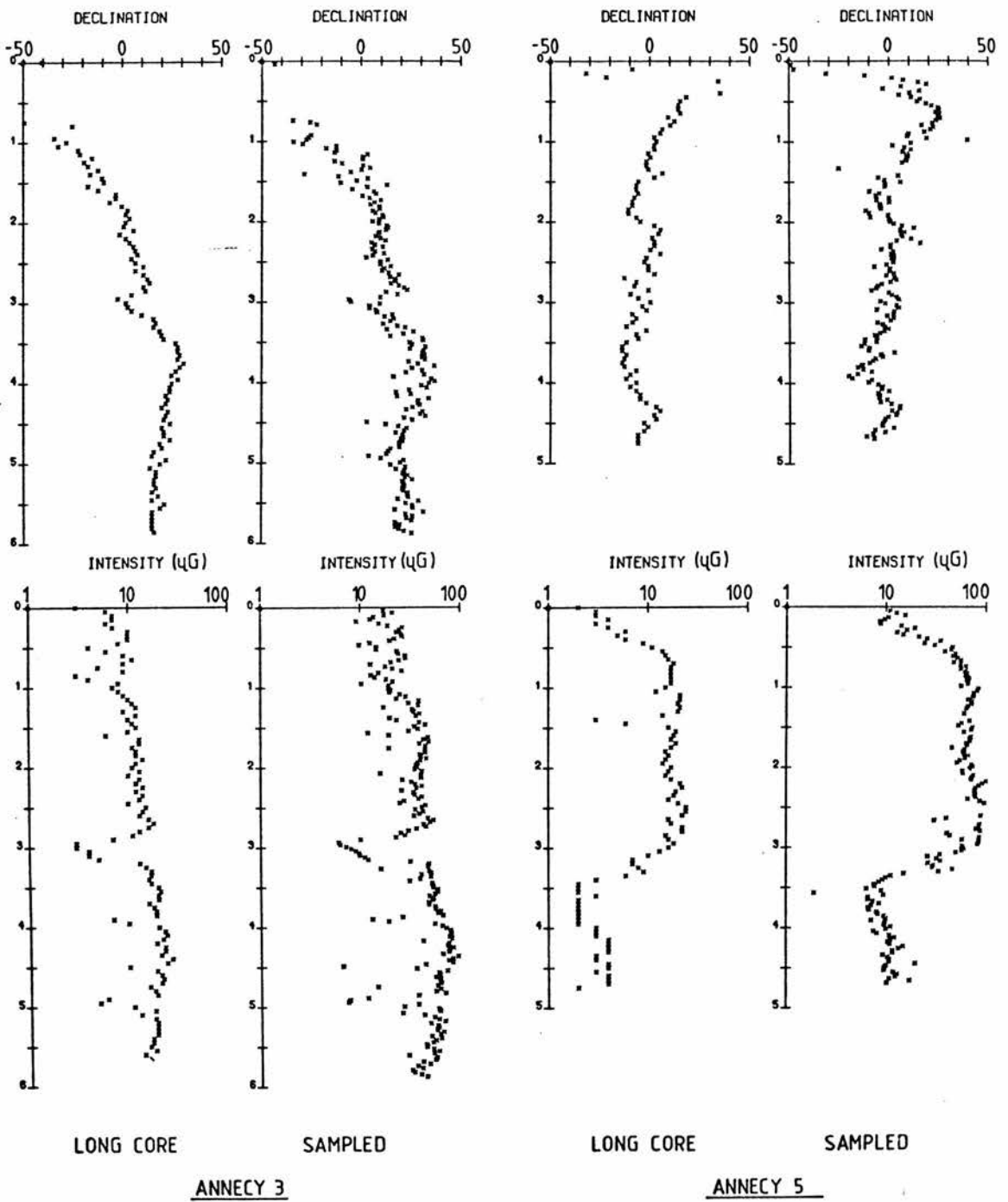


FIG 37 Plots showing the Correlation between Long Core and Single Sample Measurements

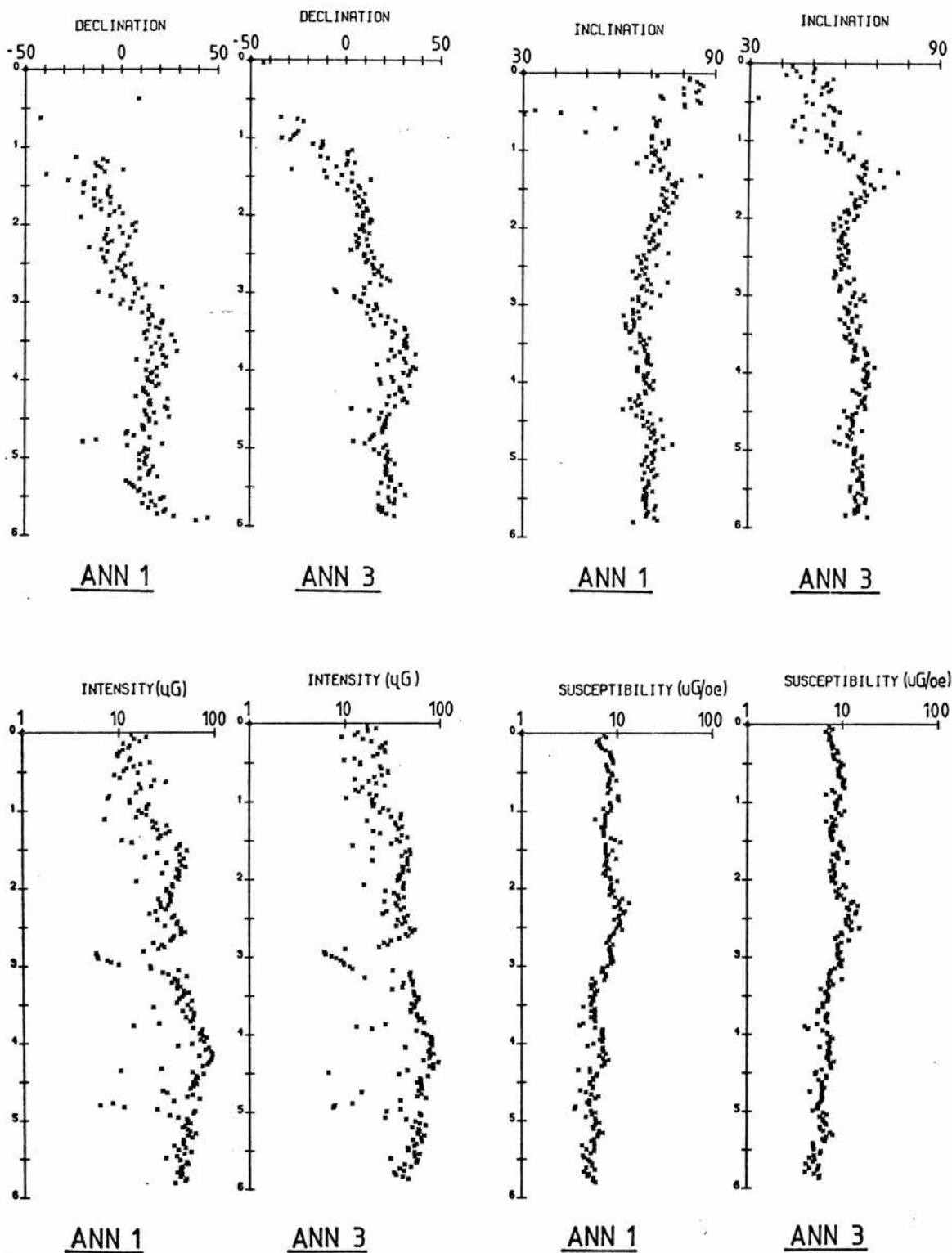
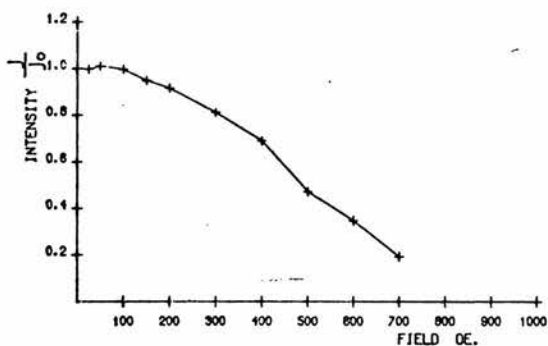


FIG 3-8 Plots showing Correlation between Annecy Cores 1&3

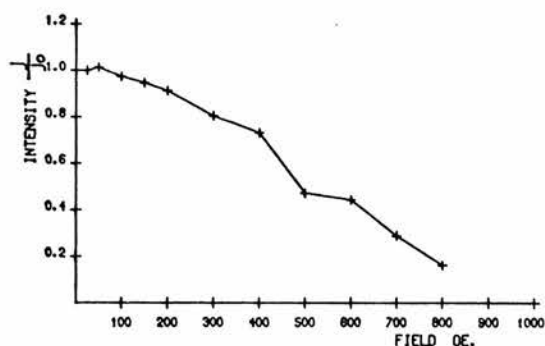
from  $-40^\circ$  to  $+15^\circ$ . This is a fairly large shift in declination over such a small depth, and may suggest that the core has been twisted. Unfortunately, there is no means by which we can decide whether or not this is true. Other arguments which may help solve the problem will be given later.

The next step is to test the stability of the samples. This is done by step wise A. F. demagnetizing 8 pilot samples chosen from approximately equally spaced levels down the core, and also by testing the viscosity of the samples. Fig. (3.10) shows the results of stepwise A. F. demagnetization of 4 of the chosen samples from core 3. The results show that the samples are in fact quite stable, with an average M. D. F. of 475 oe. The directions of the demagnetized samples stay stable up to at least 700 oe, and at 800 oe the intensity of magnetization, in most cases, is still 0.2 of the original intensity. The small increase in intensity at 50 or 100 oe is due to the removal of a soft secondary component of magnetization which is in the opposite sense to the primary component. If this secondary component is removed, then the total magnetic intensity vector will in fact increase.

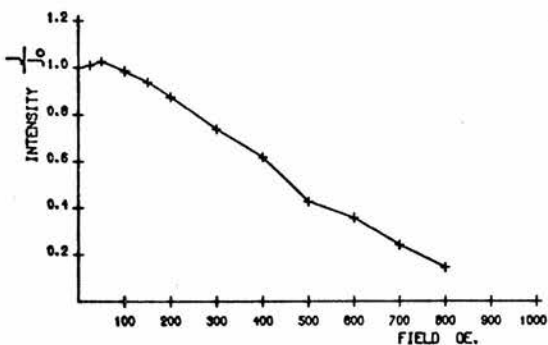
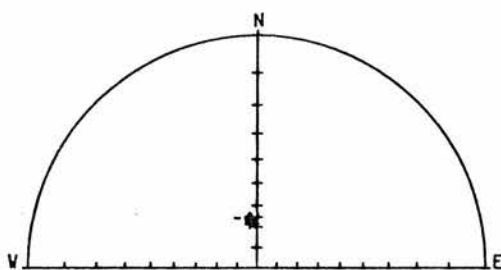
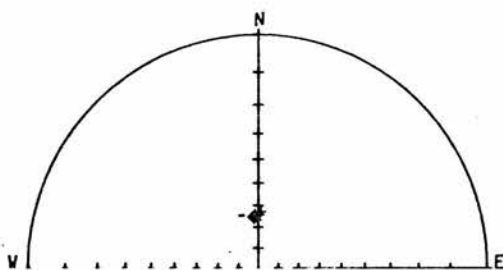
To test the viscosity of the specimens accurately, one needs to remeasure the samples at regular intervals to find the dependence between direction and intensity and the time. This however was not carried out on the samples, but instead certain samples were remeasured after being stored in the earth's field for over one year. Table 3.1 shows the directions and intensities of a few of the samples before and after storage in the earth's field. As can be seen, the declinations and inclinations have systematically decreased, but only a matter of a few degrees. There does not seem to be any evidence of a



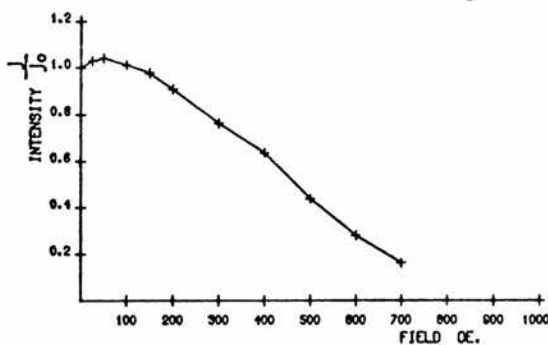
3ANN 13



3ANN 55



3ANN 77



3ANN 107

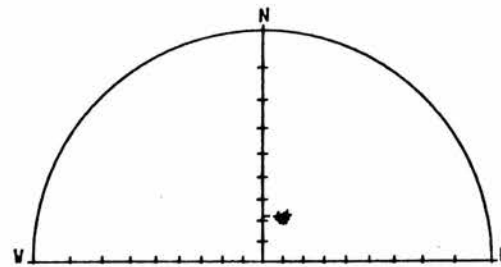
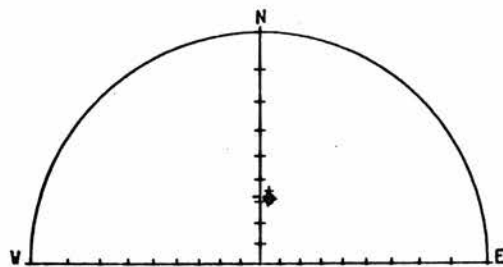


FIG 3-10 Demagnetization Plots of Pilot Samples  
from Ancey Core No.3

significant viscous component of magnetization.

SPECIMEN NUMBER	BEFORE STORAGE			AFTER STORAGE		
	D	I	J( $\mu$ G)	D	I	J( $\mu$ G)
95	46.2	69.0	86	44.3	66.4	58
97	38.9	64.2	80	36.8	59.9	50
100	33.6	61.4	44	35.0	58.1	28
105	38.1	65.9	58	34.4	62.3	39
109	36.4	71.1	34	31.1	68.4	22
113	44.8	70.9	26	41.7	67.8	17

TABLE 3.1 Measured Samples Before and After Storage

The intensities are however significantly decreased. This is due to the drying out of the samples during storage.

When we are satisfied that the samples are stable and that the variations are of true geomagnetic origin, the fact that we can get two cores to correlate being the biggest deciding factor, we can then try to establish a time scale for the variations. In the case of Lake Annecy this was achieved by having pollen analysis carried out on cores 3 and 5. Pollen analysis was preferred as the sediment was too rich in calcareous material to make it suitable for  $C^{14}$  radiometric dating.

It was hoped that the pollen analysis might give some clues as to why cores 3 and 5 did not appear to correlate. The ages obtained from the pollen are however very approximate as each age has an error of a few hundred years. Moreover, the pollen was sampled at 0.50m intervals,

so the age versus depth correlation is only accurate to 0.50 m. It does however, give us an idea of the time scale involved.

The two main pointers in the pollen analysis are the decline in fir pollen frequency at approximately 2,500 yr B. P., and the increase in Walnut pollen (*Juglans*) at approximately 660 yr B.P. This increase in Walnut pollen is due to the planting of great numbers of Walnut trees in Central Europe by the monks in the early fourteenth century. This peak also coincided with a maximum in the Cereal pollen, which has slowly declined to the present day with the change to arable farming. This peak was found at approximately 3.50 metres in core 3 and at 1.50 metres in core 5. The fir decline was not found in core 3 and is thought to be at a depth of 4 metres in core 5. The estimated ages at the bottom of the two cores are, for core 3 - c 2,000 yr B. P. and for core 5 - c 3,800 yr B.P. With this evidence it is clear that the two basins have differing sedimentation rates, which may seem at first to be somewhat surprising, as the basins are interconnected. However, if one looks at Fig. (3.2) showing the drainage basins, one can find an easy explanation for this apparent anomaly. The drainage basin for the Petit Lac is relatively much larger than that for the Grand Lac, leading to a much faster rate of sedimentation in the former.

Fig. (3.11) shows the correlation between cores 3 and 5, using the pollen evidence; and Fig. (3.12) shows the possible sedimentation rates in the two basins. The significant feature in Fig. (3.12) is the fact that up to 660 yr B. P., the sedimentation rate in the two basins was approximately equal (0.15 cm/yr), but then the rate in the Petit Lac increased to twice that of the Grand Lac (0.39 cm/yr and 0.20 cm/yr. This could have occurred as a result of human activ-

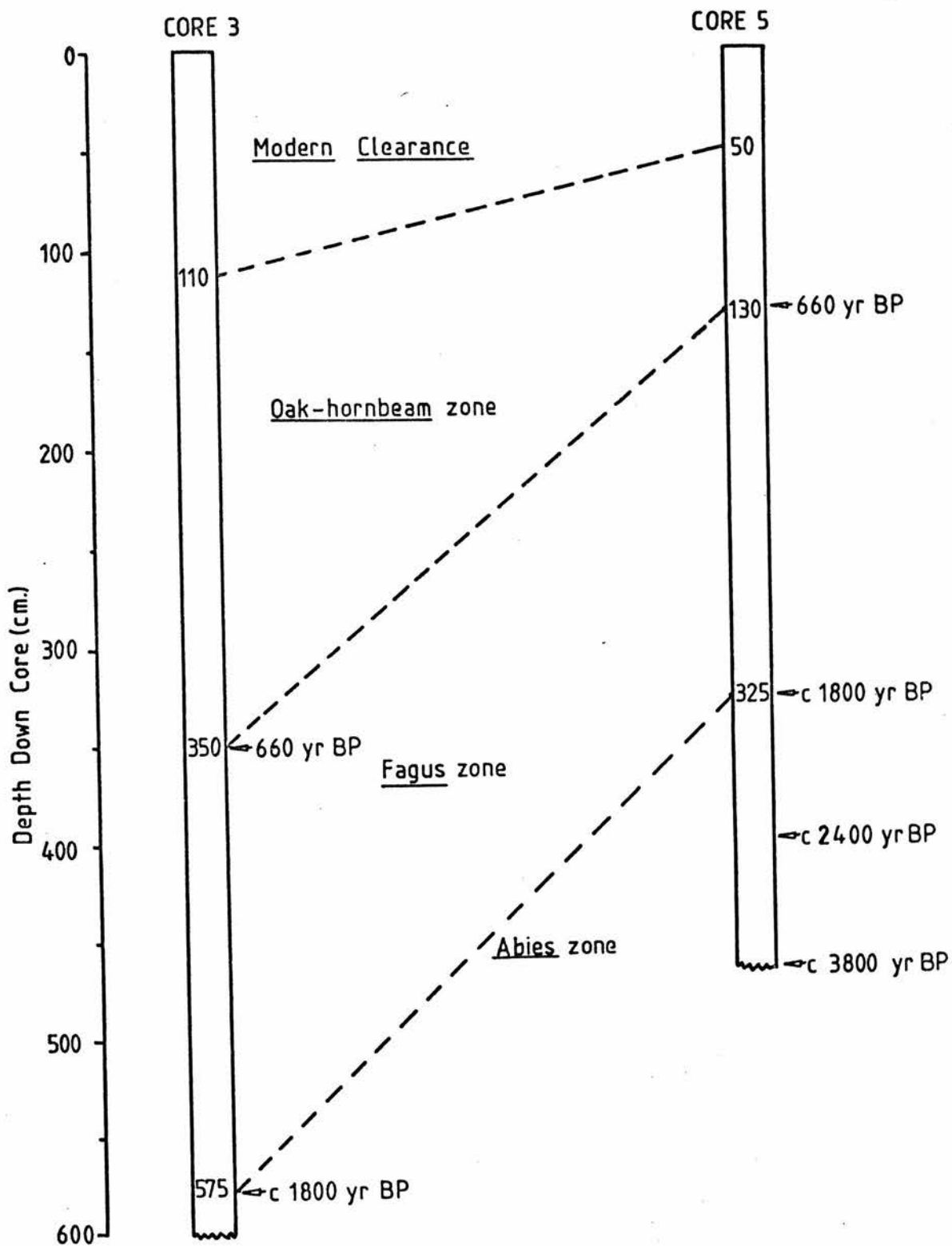


FIG 3-11 Correlation of Annecy Cores 3&5



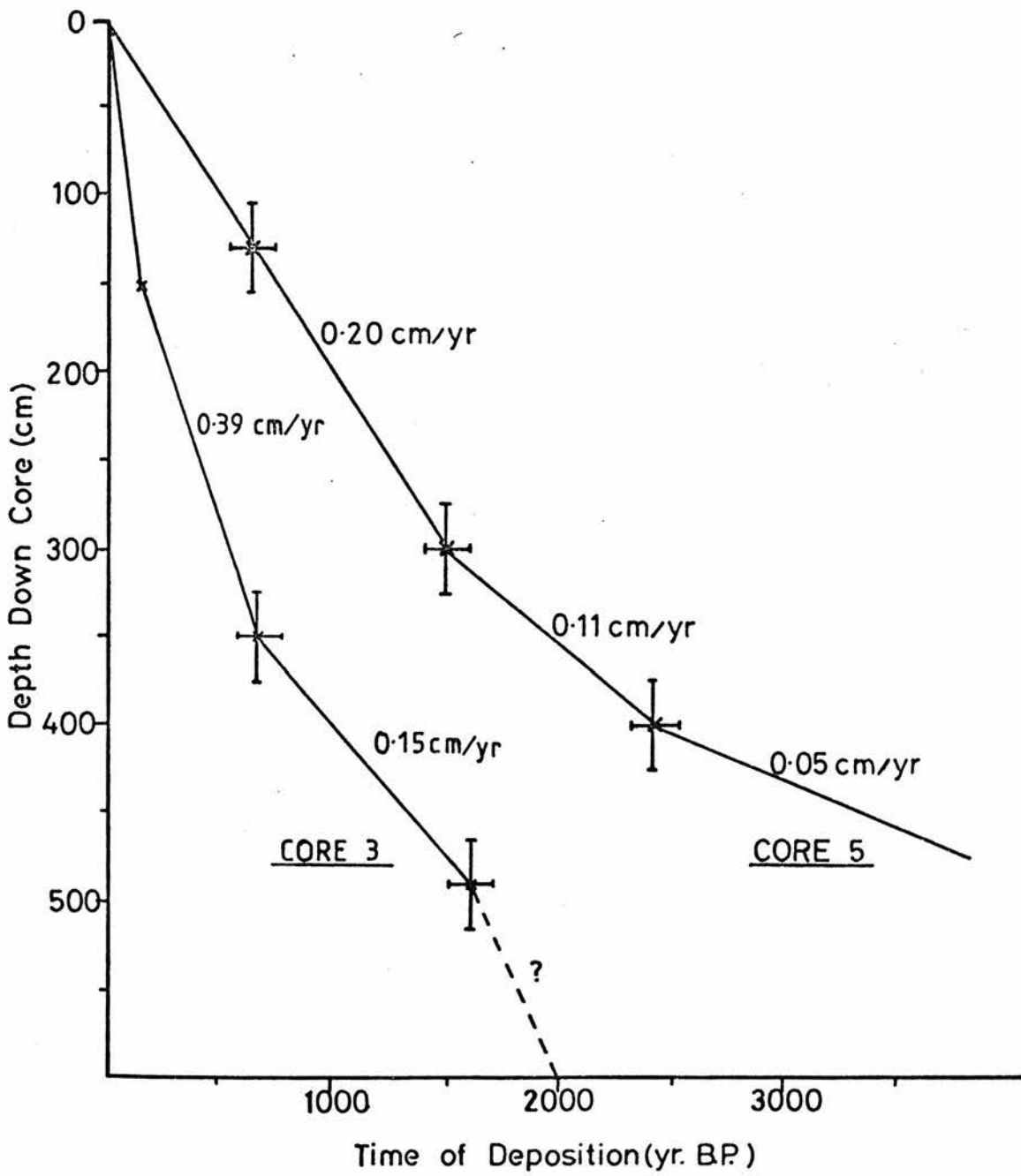
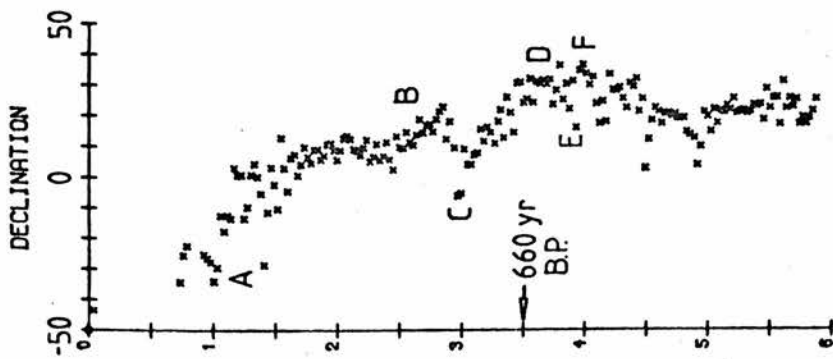


FIG 3-12 Possible Sedimentation Rates in Annecy

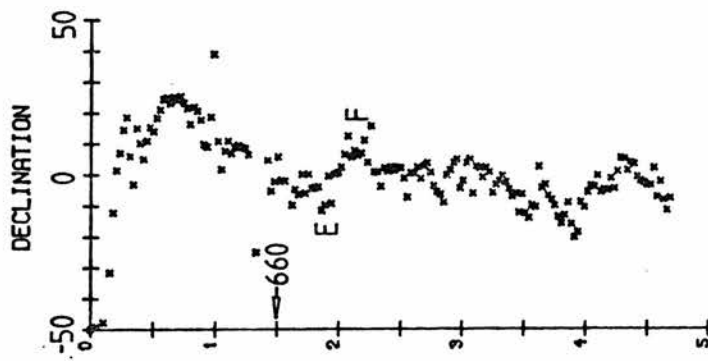
ity leading to an accelerated erosion rate. Another factor perhaps governing this difference in sedimentation rate is the fact that the volume of material reaching the centre of the lake is dependent upon the distance it has to be transported, thus explaining the slower sedimentation in the Grand Lac.

If one now studies the palaeomagnetic data, a tentative correlation can now be made on the evidence of the pollen data. Fig. (3.13) shows the D and I plots of cores 3 and 5 and the possible correlation between them. It would seem that the base of core 3 corresponded to a depth of 3.25m in core 5, as the minimum value in the inclination record at 3.50m in core 5 is not seen in the record from core 3. The lettering on fig. (3.13) has also been transferred onto fig. (3.14) to show the possible correlation between the cores and the historic archaeomagnetic curves for north-west Europe. There are a few points which arise from this possible correlation with the archaeomagnetic curve which will now be discussed.

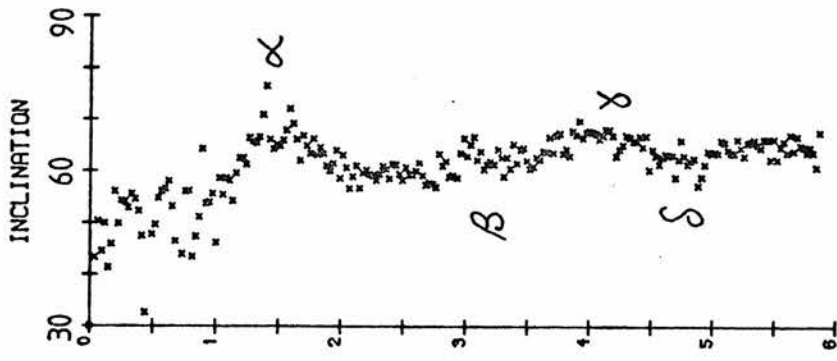
Firstly there is the question, as already mentioned, of the possible twisting of the corer and hence of the sediment as well. In Annecy 3, the section between 2.75m and 1.0m could be explained in two different ways. It may be that this section A-B corresponds to the east-west swing A-B in the archaeomagnetic curve or, on the other hand, it may be due to the twisting of the core. However, the archaeomagnetic curve has an amplitude of  $35^{\circ}$  for this section, whereas the core displays an amplitude of at least  $60^{\circ}$ . This amplitude is too large to be realistic for such a short time scale, but could be explained by a combination of twisting of the core, and the natural east-west declination swing occurring at this point. Without a scribe mark on the core, however it is impossible to tell which is the correct interpreta-



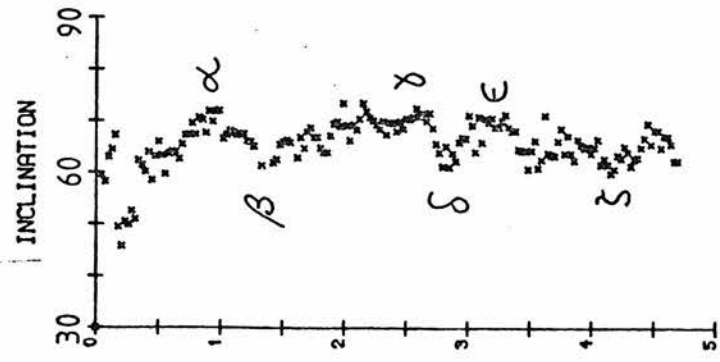
ANNEXY 3



ANNEXY 5



ANNEXY 3



ANNEXY 5

FIG 3-13 Possible Correlation in the Declination & Inclination Records of Annex Cores 3 & 5

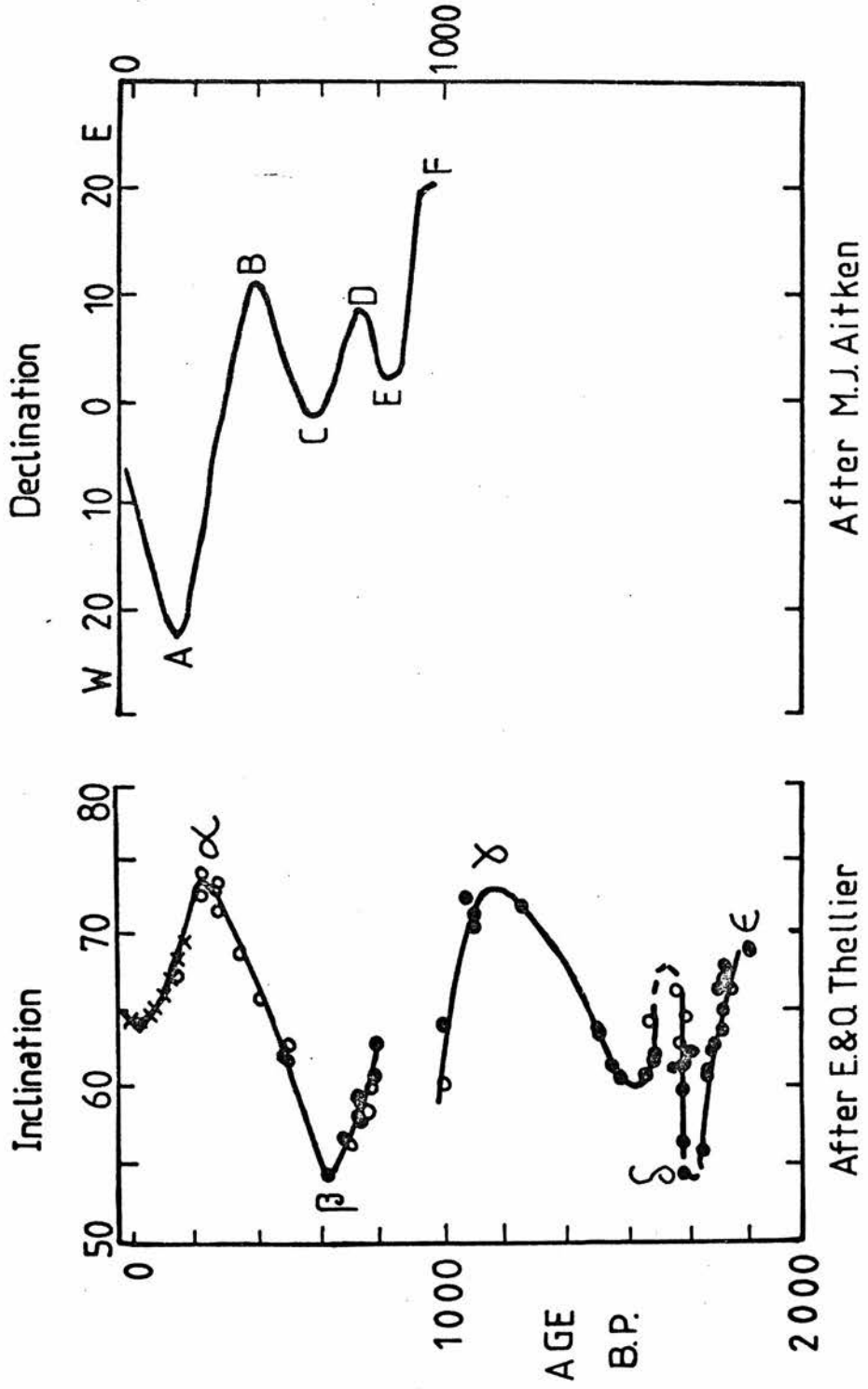


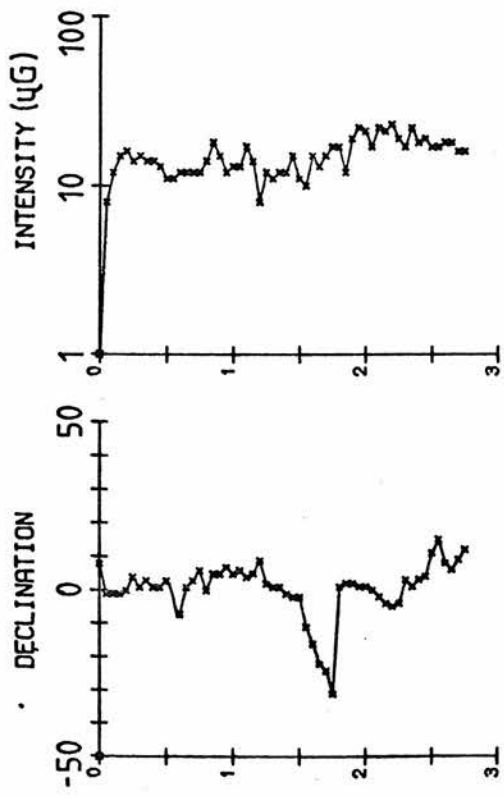
FIG 3-14 Historic Archaeomagnetic Curves for N-W Europe

tion.

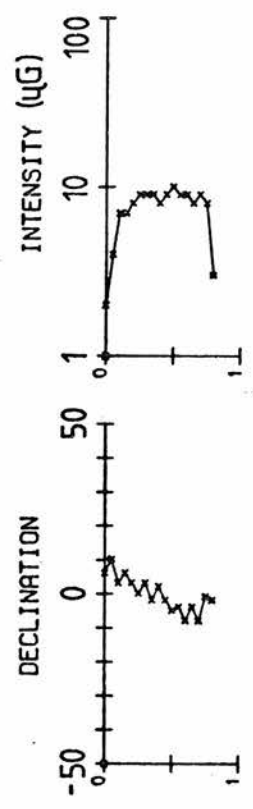
The second point to be made is that the lettering on swing D - E - F has been put on rather tentatively. On the archaeomagnetic curve the amplitude of this swing is only  $15^{\circ}$ , which is the approximate magnitude of the scatter in the corresponding section of the declination curve for core 3. Because of the magnitude of this scatter, points D, E and F would not normally be labelled as a swing in the declination record. They are therefore only marked on as "possible" positions, taking into account the archaeomagnetic curve and the sedimentation rate deduced from the pollen evidence.

The declination record in the top 1.0m of Ancey 5 is also very difficult to explain as it appears to show an east-west swing for the first few hundred years instead of the west-east swing shown on the archaeomagnetic curves. This is probably disturbed sediment due to the high water content in the top of the core, and as it is seen in a lot of cases, the top 1m of a 6m Mackereth core gives rather unreliable results. The top 1m (approx) of sediment can also be disturbed by the actual coring procedure which entails the 'anchoring' of the corer into the sediment.

To try to recover the top metre of sediment with the minimum of disturbance, a 1.0m mini-core can be taken (Mackereth 1969). This corer disturbs the top sediment to a much lesser extent than the 6m version. The long core plots of three, 1 metre mini-cores, and one, 3 metre core, collected by Liverpool University Geography Department are shown in fig. (3.15). These plots seem to help explain some of the earlier troubles in interpretation. The two plots from the Petit Lac, especially the 3m plot, seem to suggest that the large amplitude swing in core 3 may not be real, and is in fact caused by



ANNECY PETIT LAC



ANNECY GRAND LAC

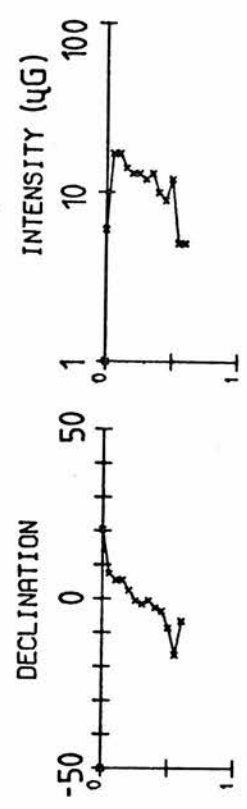


FIG 3-15 Long Core Plots of Mini-Cores from Lake Annecy

twisting. The 150 yr B. P. minimum in declination as shown on the archaeomagnetic curve, appears to be at approximately 1.50m depth. This would seem to tie in with the plot of core 3, and with the sedimentation rate already calculated for the Petit Lac. The two plots of the Grand Lac also seem to reveal the error as discussed in the top metre of core 5. Both of these plots show a west-east swing in the declination in the top metre which again would correlate with the observed behaviour and suggests that the top metre of core 5 was in fact disturbed.

The correlation of the Lake Annecy results with the others from France and Switzerland will be shown at the end of this chapter.

#### 3.4 Results from Lake Geneva

Lake Geneva (or Lac Lemman as it is properly called) is the largest fresh water lake in Europe, and lies between latitudes  $46^{\circ} 12' N$  and  $46^{\circ} 33' N$ , and longitudes  $6^{\circ} 10' E$  and  $7^{\circ} 0' E$ . The position of the lake within the Northern Prealpine zone is shown in fig. (3.1). The lake, similar to Annecy, comprises of two basins. One is a very small basin at the south-west end of the lake, next to Geneva itself, with the other much larger basin stretching to the north and east. The river Rhone flows into the lake at the east end and out again at the south-west end, next to Geneva. Numerous smaller rivers also flow into the lake along its length, but with the Rhone being the only outflow. Like Annecy, the catchment area of the lake is rapidly eroding and rich in calcareous material.

Twelve cores in all were taken from the lake, six in the centre of the small basin, and six in the north of it; the average depth of water being 50m. Cores were not taken from the large basin, simply because the water depth was too great to operate the corer. Of the

six cores taken in the north of the basin, the average length was only 3.40m. In this area, as well as the six collected, we had several unsuccessful attempts at collecting any sediment. This is possibly due to the fact that the area cored in, was at the 'neck' of the two basins, and any sediment would be carried by the fast currents and deposited in the smaller basin to the south. Certainly no difficulty was encountered in obtaining six cores of average length 5.75m in the central plain of the smaller basin. Fig. (3.16) shows the coring sites within the lake.

Unfortunately, as these were the first cores to be measured on arrival back in Edinburgh, they were subsampled prior to deciding on long core spinner measurements for all the cores. As the only long core of sediment obtained from the northern site yielded an intensity that was too weak to measure with any accuracy, only the cores collected in the central basin were considered for further investigation. Of these cores, number 7, 8 and 10 were subsampled and measured. Fig. (3.17) shows the D and I plots of the three cores and their possible correlation, and similarly fig. (3.18) for the J and k plots. Fig. (3.19) shows the demagnetization plots for pilot samples chosen from core 7 and fig. (3.20) shows the comparison between the N.R.M. of core 7 and results obtained after A. F. demagnetization in 300 oe. As the plots demonstrate, the samples were exceptionally stable and, except for the top few samples, the average M. D. F. was approximately 500 oe, and the specimens kept their directions even at 800 oe. Apart from a small decrease in intensity, the plots showing the results before and after D. M. are almost identical. As with Annecy, a number of samples were remeasured after one year's storage in the earth's field and were found to be unaltered except for a decrease in



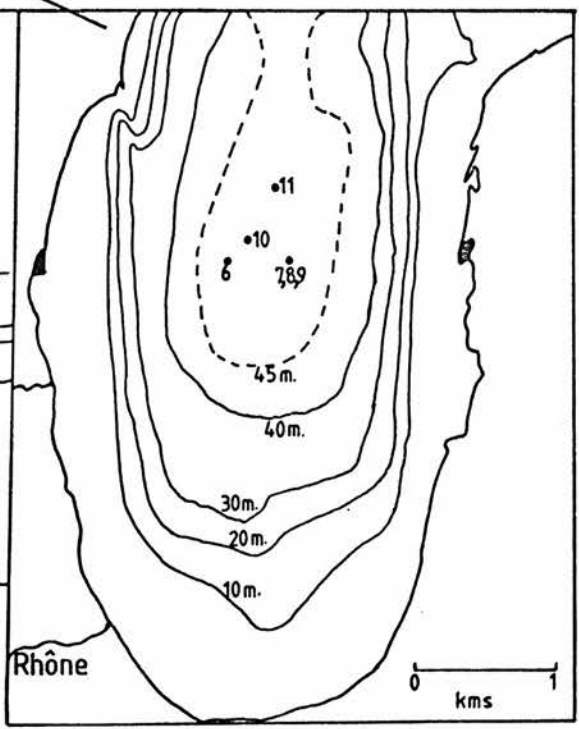
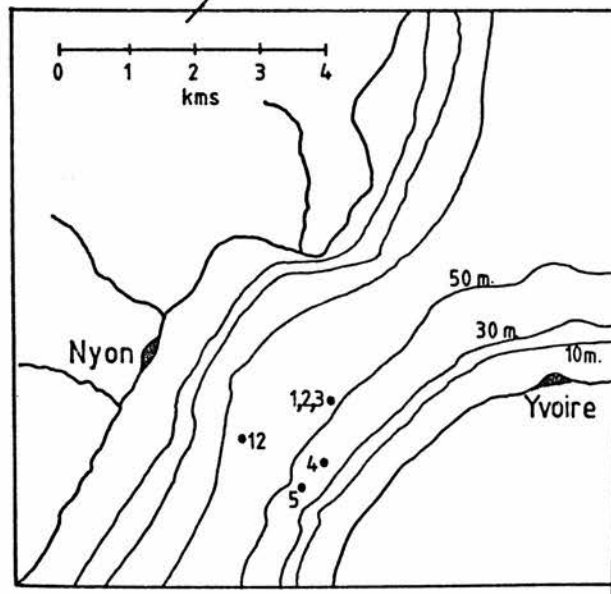
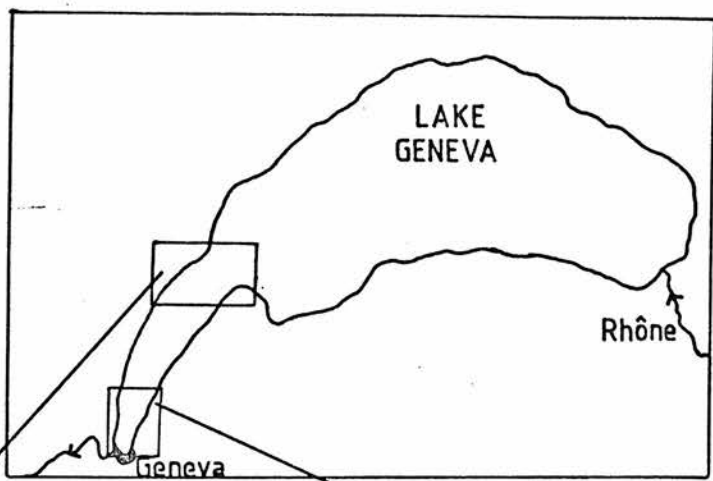
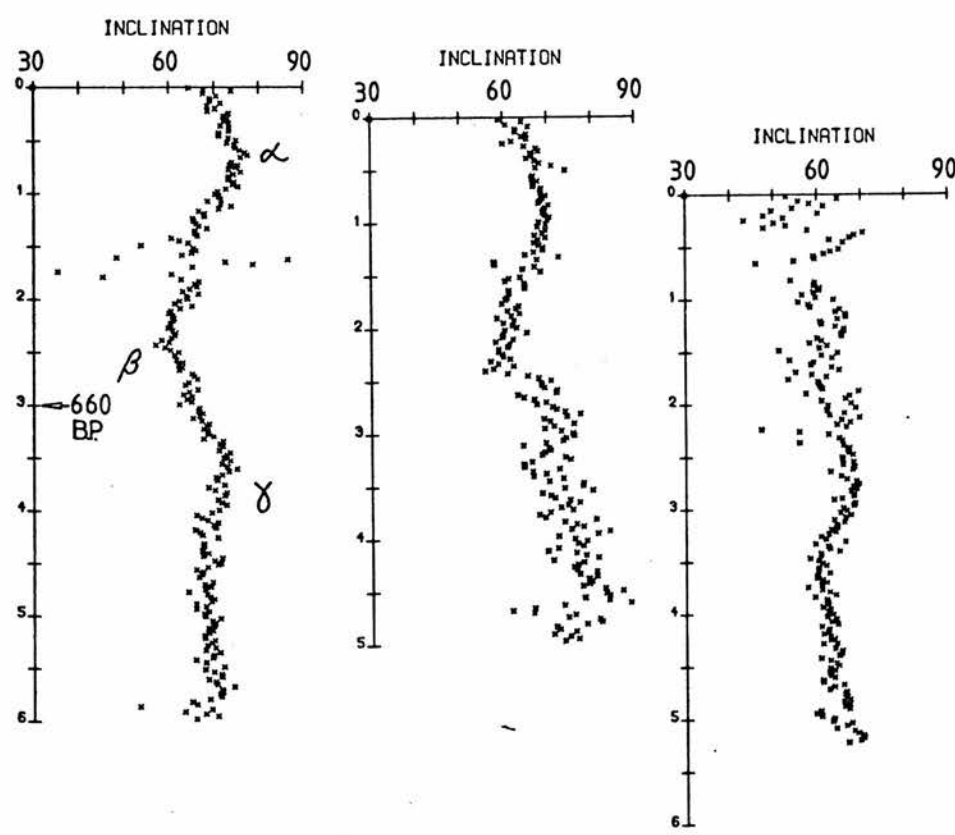
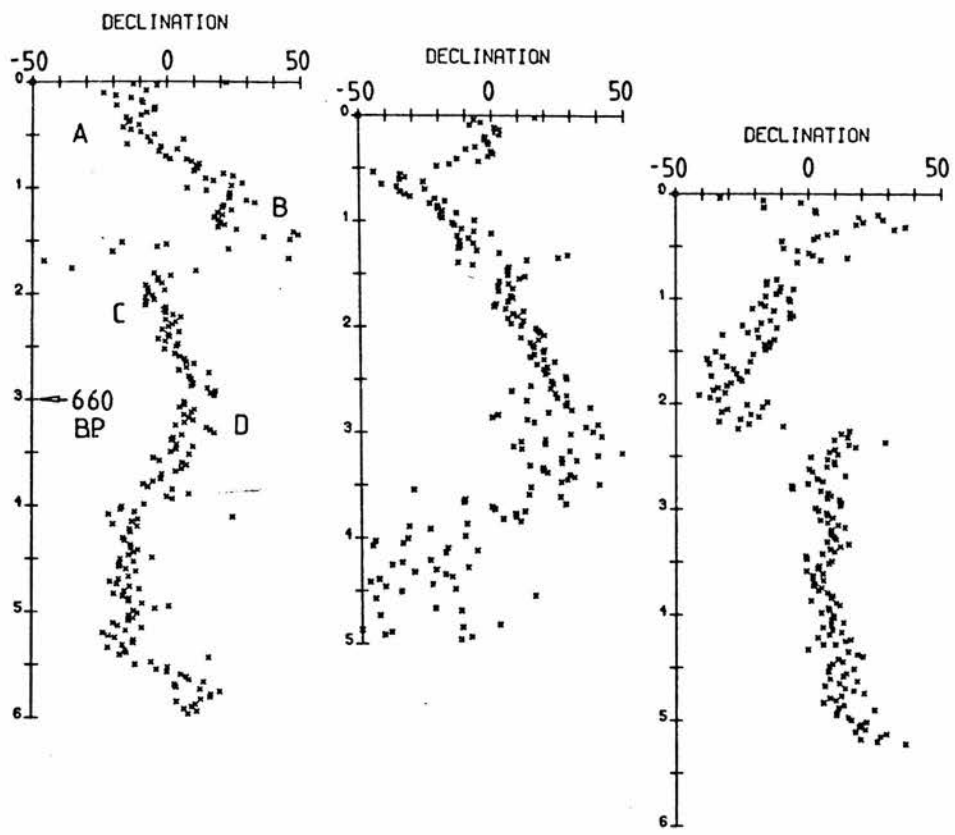


FIG 3-16 Maps showing the Coring Locations in Lake Geneva

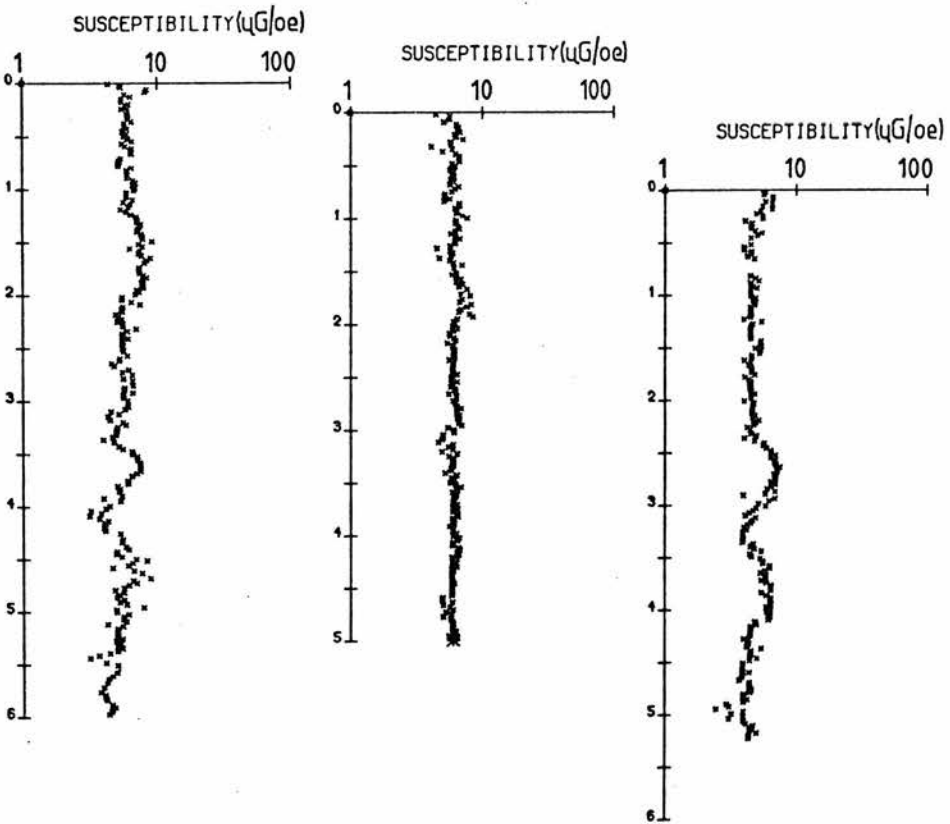
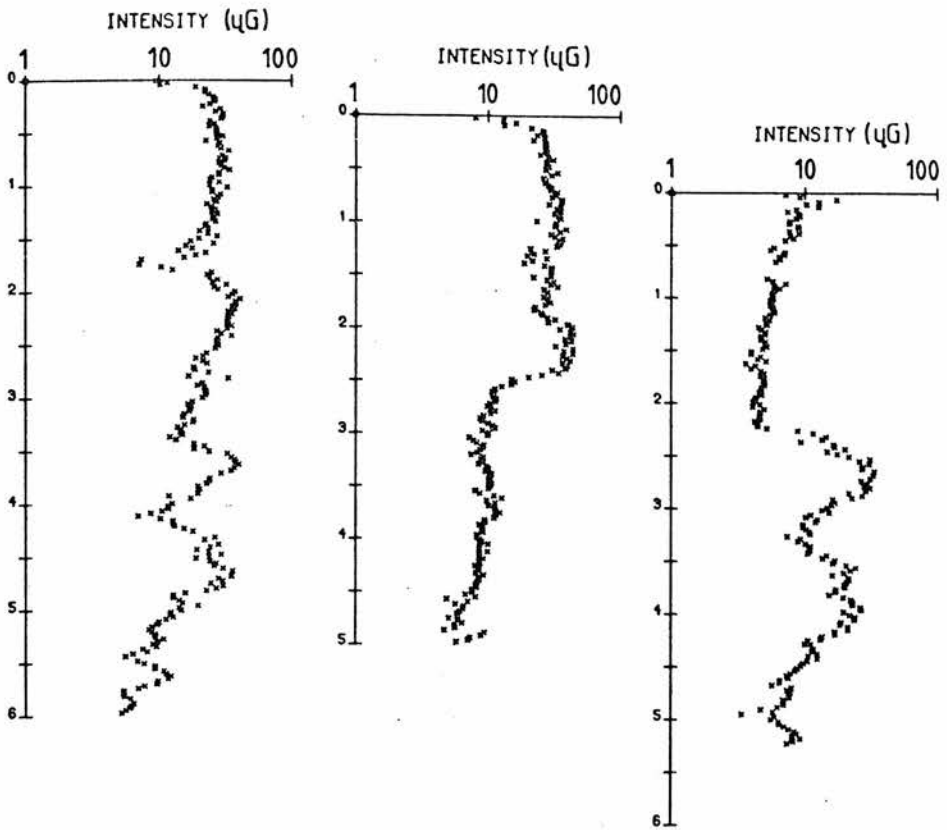


GENEVA 7

GENEVA 8

GENEVA 10

FIG 3-17 Plots showing the Correlation between the Declinations, and Inclinations in Geneva Cores 7, 8 & 10

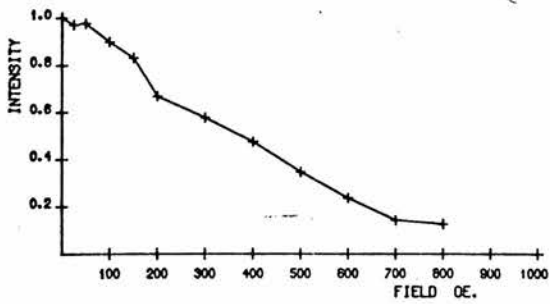


GENEVA 7

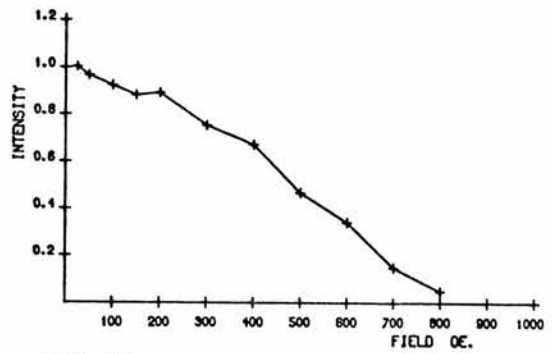
GENEVA 8

GENEVA 10

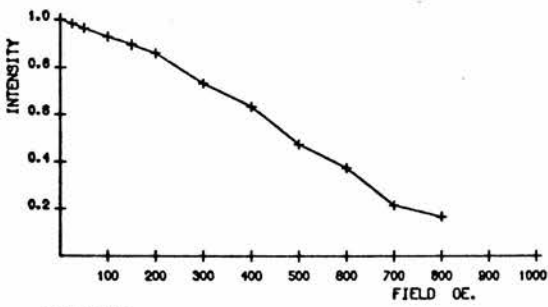
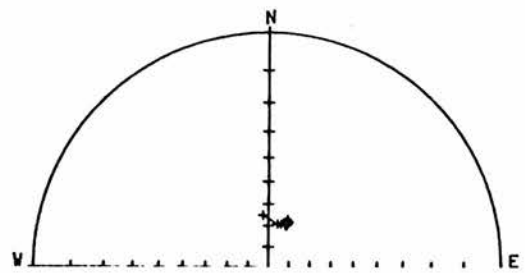
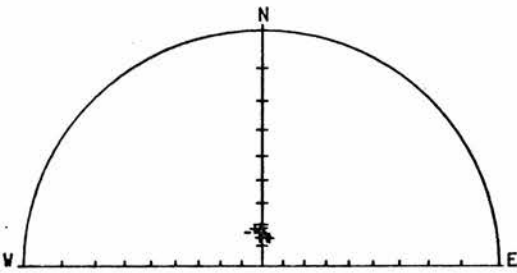
FIG 3-18 Plots showing the Correlation between Intensities, and Susceptibilities in Geneva Cores 7, 8, & 10



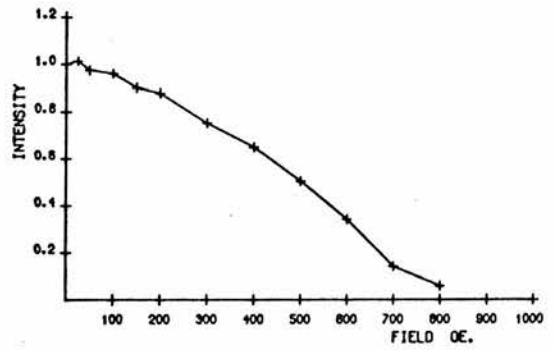
7GEN 15



7GEN 92



7GEN 146



7GEN 214

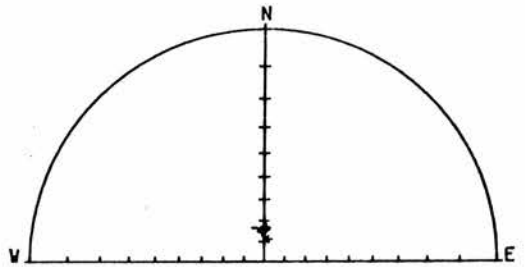
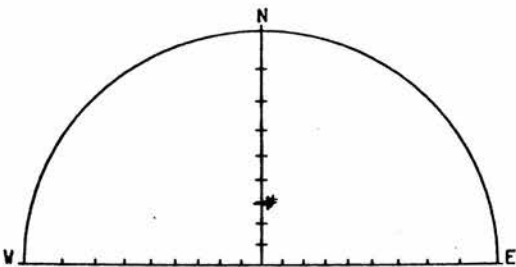


FIG 3-19 Demagnetization Plots of Pilot Samples from Lake Geneva

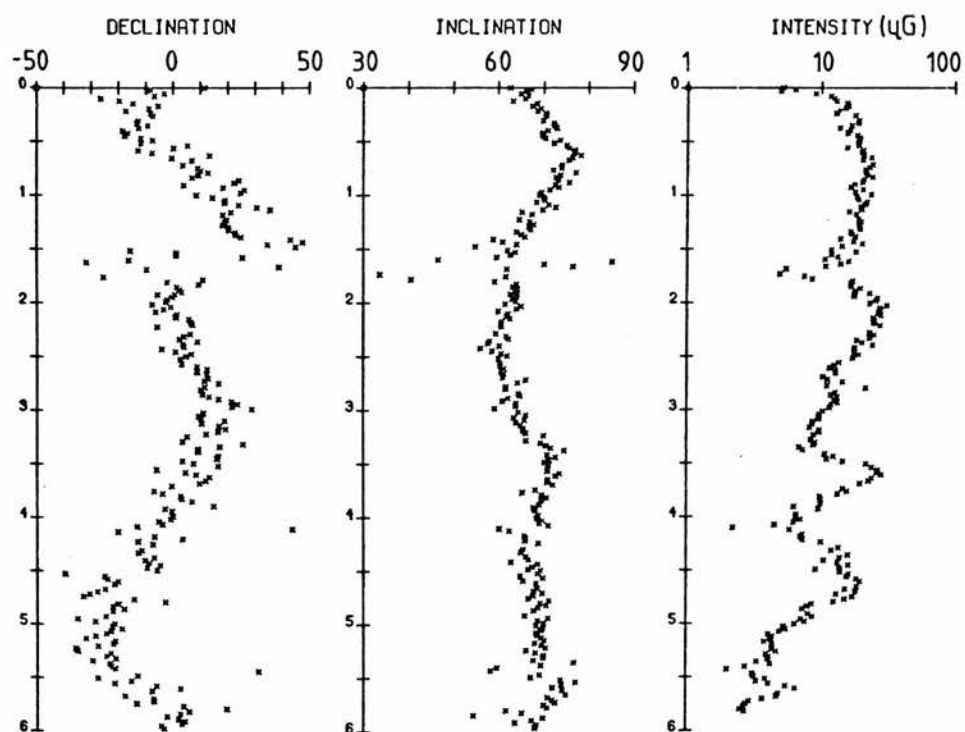
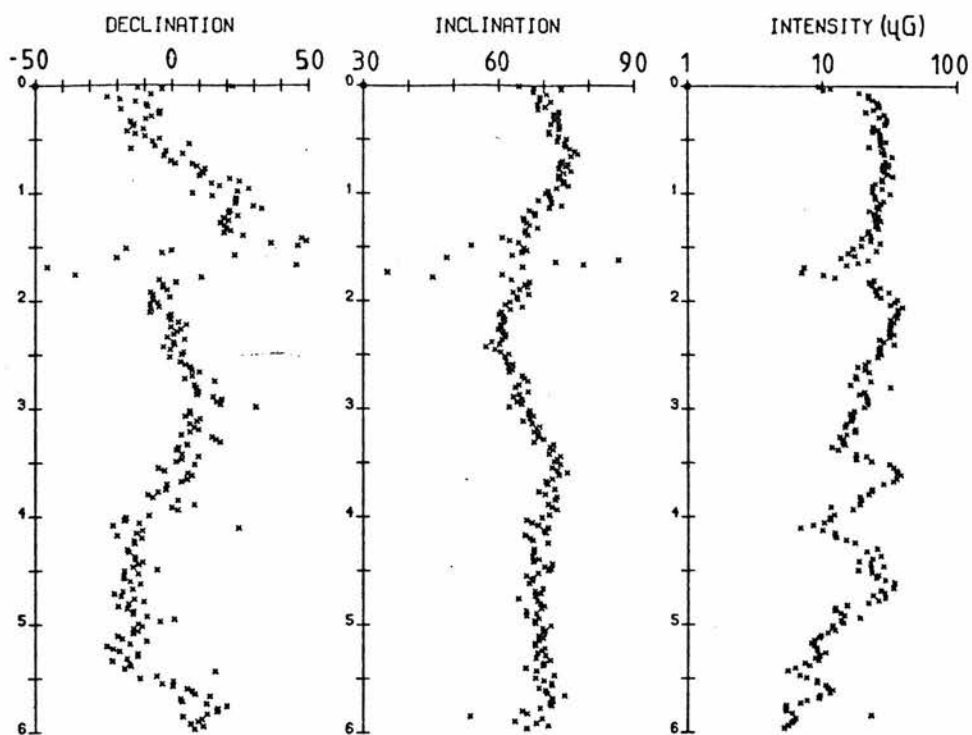


FIG 3-20 Comparison of Results before and after A.F. Demagnetization in 300 oersteds

the intensity.

If one studies figs. (3.17) and (3.18) of the postulated correlations between cores 7, 8 and 10, the following features become apparent. Firstly, the sedimentation rates in the cores are the same, as would be expected over such a small area of collection, but varying amounts of sediment are absent from the top of the cores. As previously explained, this could be due to the disturbance caused by the corer and the 'anchoring' procedure.

The best evidence for correlating between cores is given by the intensity and susceptibility records. It would appear that there is approximately 0.25m of sediment missing from the top of core 8, and 1.0m missing from the top of core 10 (assuming zero loss in core 7). There also seems to be a disturbance in the sediment at levels 1.60m and 1.40m in cores 7 and 8 respectively. This disturbance shows up in the D, I and J records and could be due to slumping of the sediment. The lettering on the figure corresponds to the lettering used on the Lake Annecy cores (fig. 3.13) and the historic archaeomagnetic curves (fig. 3.14). Again it would seem that cores 8 and 10 have been twisted during collection. In the top 3.0m of both records the declination swings through  $80^{\circ}$  -  $100^{\circ}$  and features in core 7 cannot be seen in cores 8 and 10. The fact that the scatter between points is relatively small compared to the amplitude of the variation would suggest a twisting of the core rather than just disturbed sediment. The inclination records however seem to correlate with each other reasonably well and also with the historic archaeomagnetic record. The correlations shown are based on pollen evidence, as with Annecy. The pollen gives the following correlation between Geneva and Annecy Petit Lac (core 3) (Oldfield, pers. comm.)

Geneva	=	Annecy
350 - 400 cms.	=	350 - 400 cms.
250 cms.	=	200 - 250 cms.
70 cms.	=	150 cms.

Before the pollen analysis was carried out however, two radio-carbon dates were obtained for Geneva core 7. The carbon ages obtained were, (Harkness, 1977):

47 to 82 cm - 2455  $\pm$  75 yr B.P.

and

465 to 505 cm - 4758  $\pm$  55 yr B.P.

It is obvious on the evidence of the pollen analysis date that these carbon ages are much too old. As we have only two radio-carbon dates, and the pollen data is only to a depth of 4.0m, it is impossible to say whether the carbon dates are systematically too old or whether they bear no relationship at all to the pollen. As there ~~is~~<sup>are</sup> only the two carbon dates it is impossible to estimate the change in sedimentation rate that obviously occurs at about 3m. As with Annecy this is most probably due to increased erosion due to human activity at this time. The error in the radio-carbon dates can be explained by the double error resulting from a hard water effect, plus the inwash of stable organic residues from old soil. These effects could easily occur due to the very high carbonate content in the catchment area. This shows that any radio-carbon dates obtained from lake sediments must be viewed cautiously, and cannot necessarily be accepted even within the range of errors quoted with them. Numerous radio-carbon dates would have to be obtained from a core that has some other method of dating control, before it could be decided if C14 dating was useful for limnomagnetic work.

If the inclination records are studied, it can be seen that the mean inclinations of the three cores are not the same. For core 7 it is  $69.1^{\circ}$ , for core 8  $71.3^{\circ}$ , and for core 10  $63.8^{\circ}$ . By calculation it can be found that the inclination of a time - averaged axial dipole field at Geneva would be  $64.5^{\circ}$ . King (1955), by carrying out redeposition experiments on glacial clays showed that there was an inclination error in depositional remanent magnetization. This error led to an inclination that was in all cases shallower than that of the applied field. Geddes (1966) found an inclination error that led to a steeper inclination, but this could be attributed to the apparatus used, which did not simulate the deposition process in a realistic way. Redeposition experiments were carried out on sediment from Geneva core 7 (Papamarinopoulos, 1978) and a small mean inclination error of  $3^{\circ}$  was found. The redeposited sediment giving an inclination less than that of the applied field, but being attributed to disturbances in sampling, as opposed to an inherent inclination error. This does not therefore explain the high mean inclinations in cores 7 and 8. The likely explanation for this is that the cores did not enter the sediment in an exactly vertical position, or that on entering the sediment the core tube was bent while coring. If the core does not enter vertically, it can lead to either an increase or a decrease in the measured inclination. As the degree of the tilt is the same as the error in the measured inclination, a core taken  $5^{\circ}$  -  $7^{\circ}$  off the vertical would explain the high mean inclination in cores 7 and 8. This would lead to a non-horizontal layering of the stratigraphic boundaries relative to the core tube, but as the sediment in the Geneva cores was homogeneous, this would not be noticed.

A further discussion of the correlation between the Geneva cores



cores and cores from the other lakes in the area is found at the end of the chapter.

### 3.5 Results from Le Bourget

Le Bourget lake is situated just to the south-west of Lake Annecy, between latitudes  $45^{\circ} 47'$  N and  $45^{\circ} 37'$  N, and longitudes  $5^{\circ} 51'$  E and  $5^{\circ} 57'$  E. The position of the lake relative to Geneva and Annecy can be seen in fig. (3.1). The main river flows into the lake in the south-west corner and out at the north end where it flows into the Rhone.

Only four cores were taken from Le Bourget, two each from two different sites at the south/end of the lake. Fig. (3.21) is a bathymetric map of the south end of the lake showing the coring positions. The average length of core obtained from the first site was 5.50m, and the average length from the second was 4.30m. Of the four cores collected, three were brought back to Edinburgh, and the results of long core spinning are shown in fig. (3.22). As can be seen cores 1 and 2 correlate very well apart from the disturbed top metre in core 2. This was caused by accidentally "over-packing" the top end of the core and so disturbing the wet sediment. Core 3 is rather short but seems to correlate if we assume a much faster sedimentation rate. This is not surprising as it is much closer to the major inflow into the lake. It would appear that the bottom of core 3 (2.60m) corresponds to a depth of approximately 1.80m in core 2. If studied carefully, the correlation can be noticed in both the D and J records.

The correlations between the long core results and the subsampled results for cores 1 and 2 are shown in Fig. (3.23). Again an excellent correlation is obtained. As with Annecy and Geneva, pilot samples from one of the cores were stepwise A. F. demagnetized and

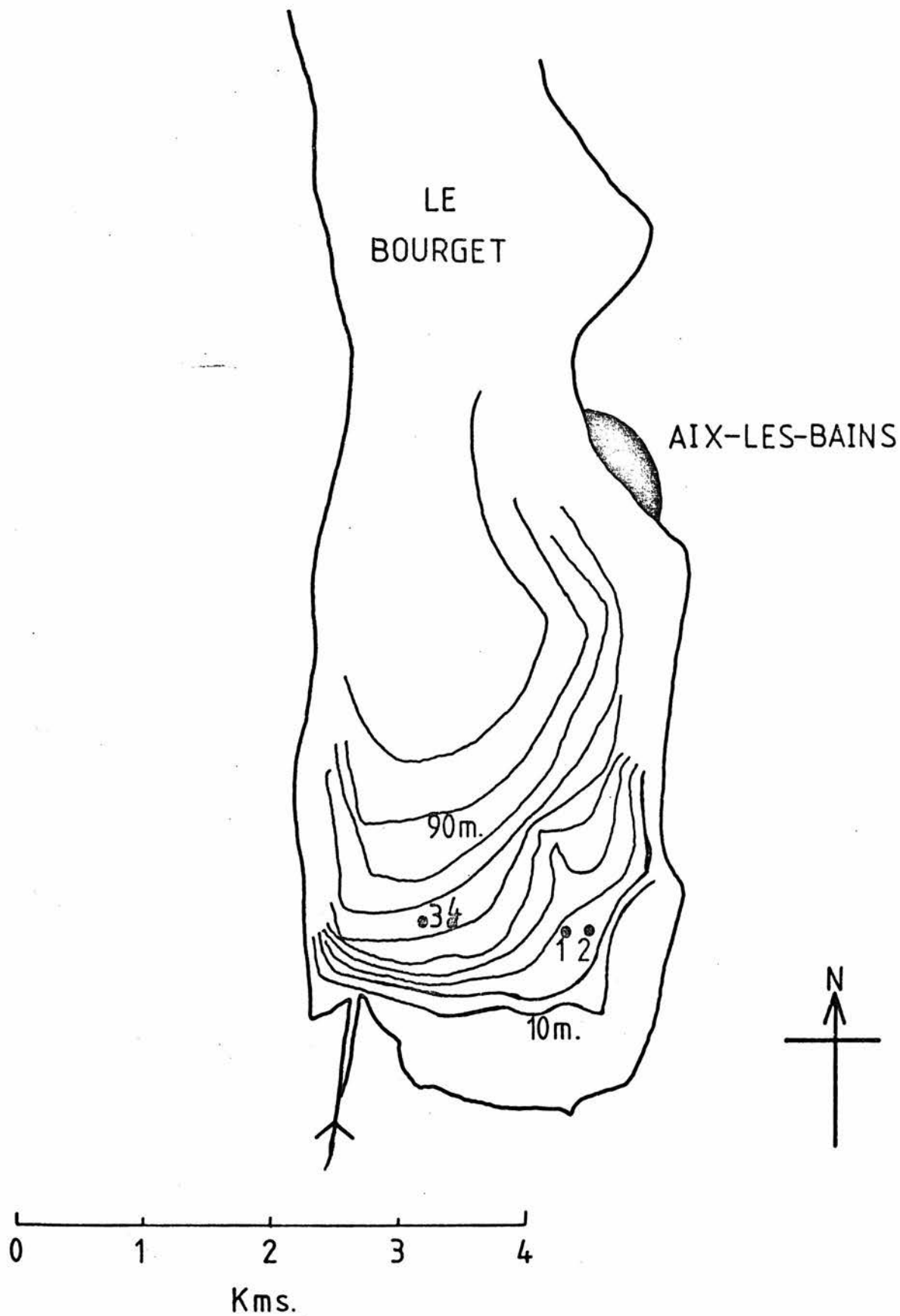
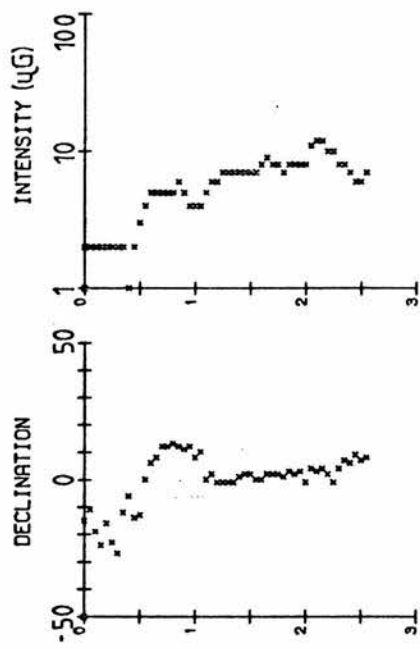
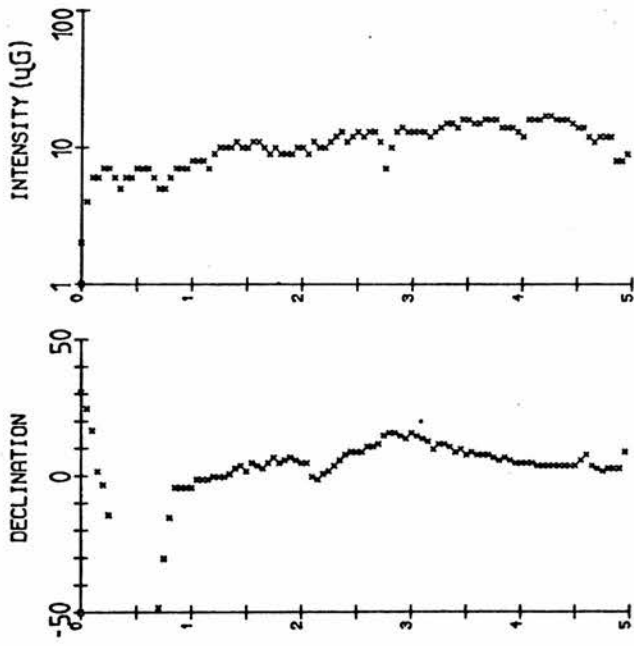


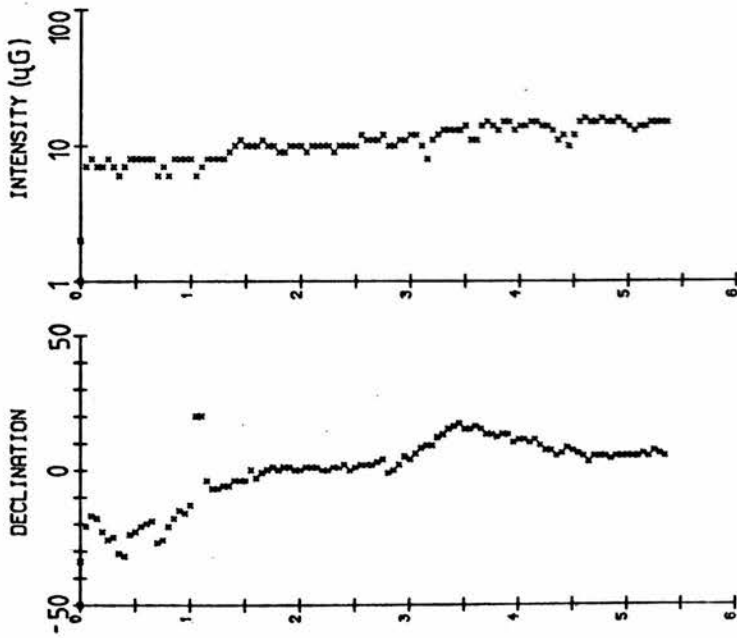
FIG 3-21 Map of Coring Sites in Le Bourget



LE BOURGET 3



LE BOURGET 2



LE BOURGET 1

FIG 3-22 Long core Measurements of Le Bourget 1,2&3

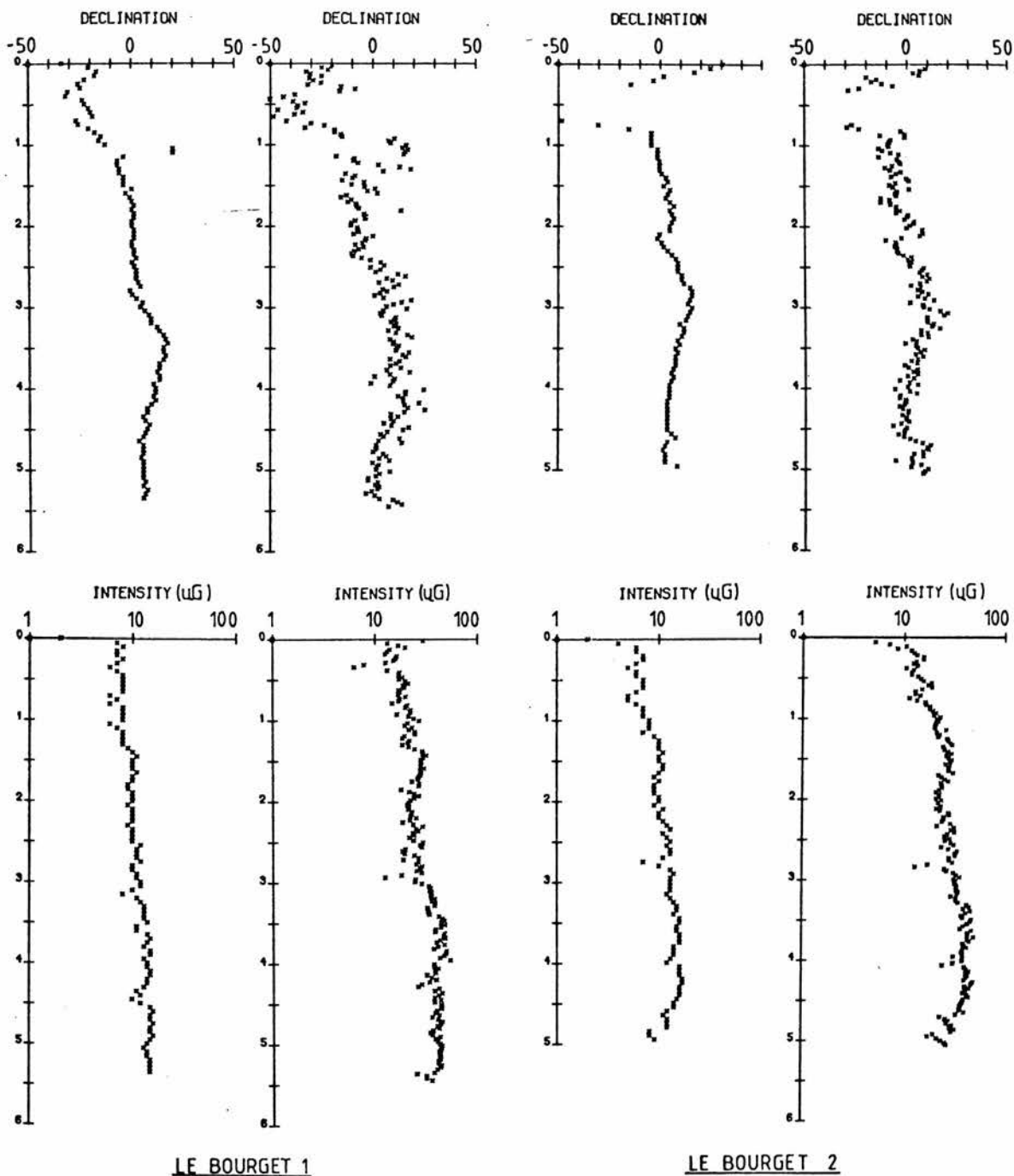


FIG 3-23 Correlation between Long Core and Sampled Results

four of the resultant plots are displayed in fig. (3.24). Although the samples are not as stable as those from Geneva and Annecy, they have an average M. D. F. of just over 300 oe and the majority of the samples keep their direction up to a field of 700 oe. They were considered sufficiently stable to assume that the N. R. M. would not be significantly altered by low field A. F. demagnetization.

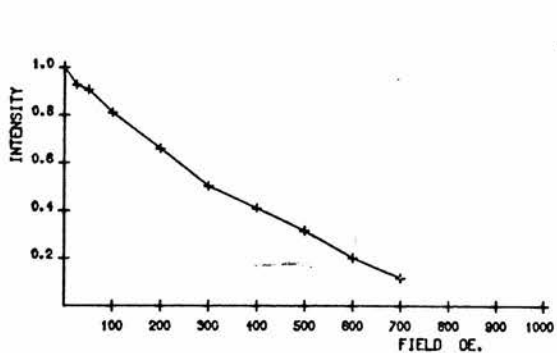
The correlations in D, I, J and k for cores 1 and 2 are shown in fig. (3.25). The J and k-records especially show the depth correlation between the cores. As expected, the sedimentation rates for the two cores are the same, with approximately 10 cm of sediment missing from the top of core 2, probably due to the packing in this end. This also explains the scatter in the top metre of the D and I records. As before, the lettering on the D and I plots corresponds to that on the previous plots from the other lakes. This lettering was based on pollen analysis data obtained from both cores 1 and 2. The following is the correlation obtained from the pollen, for Lakes Geneva, Le Bourget and Annecy Petit Lac. (Oldfield, pers. comm.)

Geneva		Le Bourget 1 and 2		Annecy
350 - 400 cm	=	350 - 400 cm	=	350 - 400 cm
250 cm		250 cm	=	200 - 250 cm
70 cm		50 cm	=	150 cm

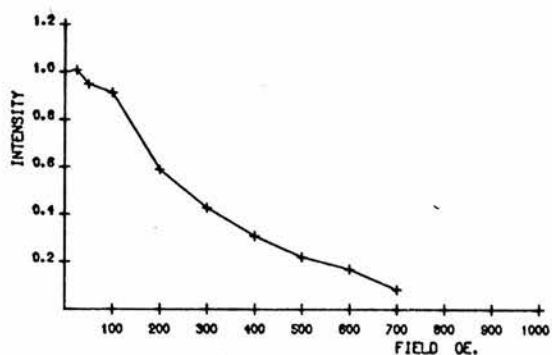
As with Geneva we only have approximate pollen dates down to 3.5 - 4.0m. Beneath this level we have no control over the age and only postulated dates can be given.

### 3.6 Results from Lake Morat

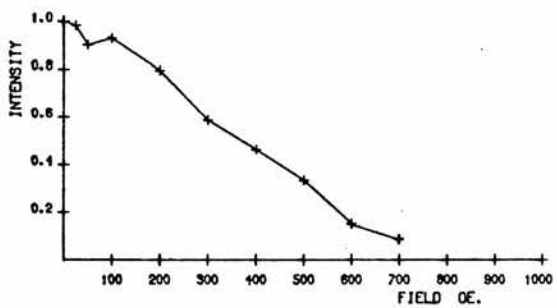
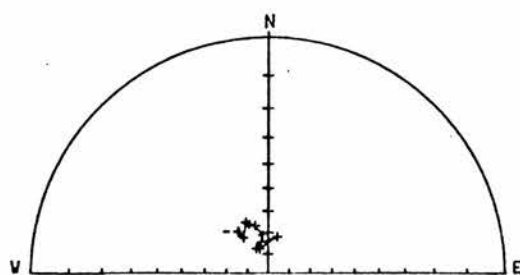
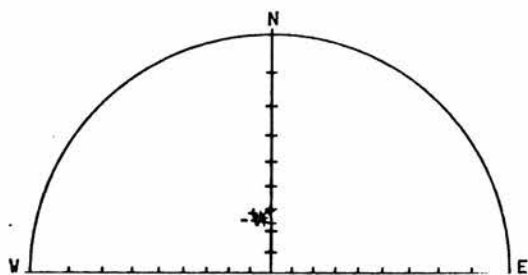
Lake Morat is situated north-east of Lake Annecy (fig. 3.1), between latitudes  $46^{\circ} 57'$  N and  $46^{\circ} 53'$  N, and longitudes  $7^{\circ} 2'$  E and



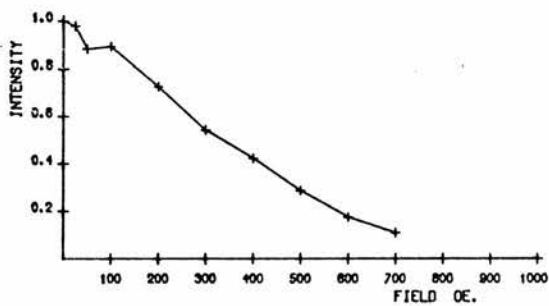
180U 40



180U 65



180U 100



180U 175

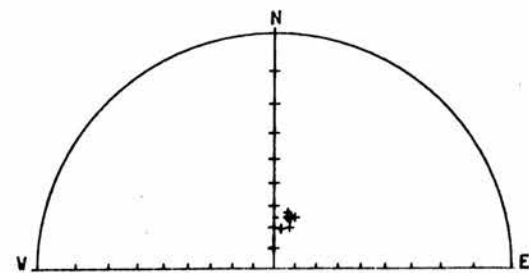
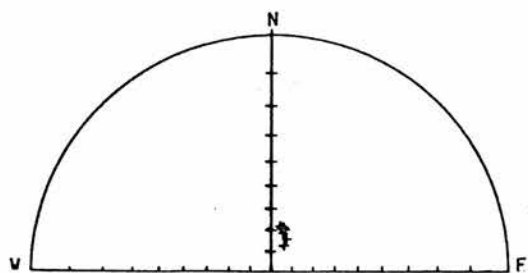


FIG 3-24 Demagnetization Plots of Pilot Samples from Le Bourget

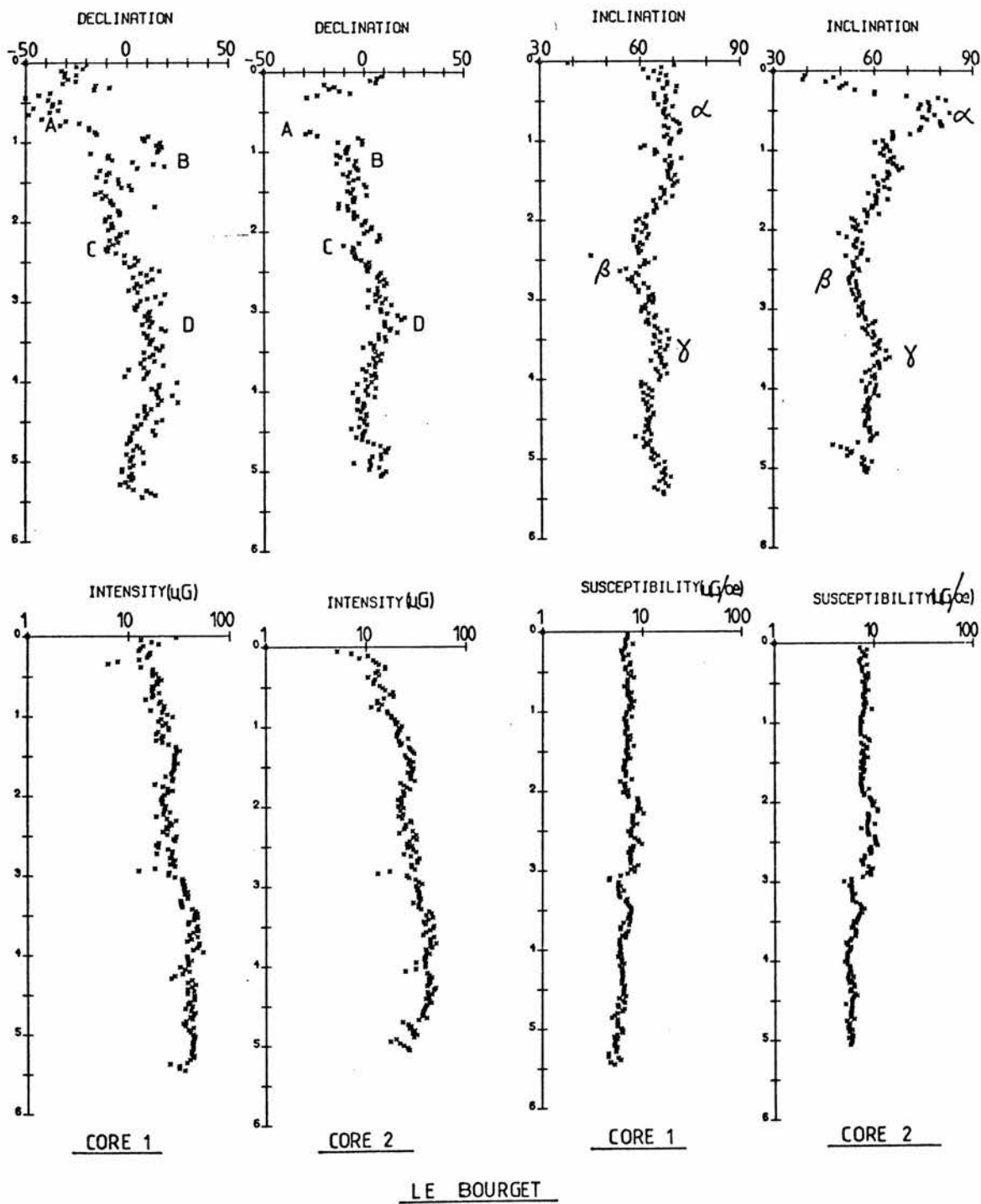


FIG 3-25 Plots showing the Correlation between Le Bourget Cores 1&2

7° 6' E. The main inflow is in the south-west corner and the outflow from the lake is in the north, which drains into the much larger lake, Neuchatel. The river flowing in at the south-west creates a 'spur-like' effect as can be seen in fig. (3.26), which is a bathymetric map of Morat showing the coring sites within the lake.

Five cores in all, of average length 5.75 m, were collected, and four were brought back for palaeomagnetic investigations. Two of these cores were sub-sampled immediately and the other two had long core measurements carried out on them at a later date. Fig. (3.27) shows the palaeomagnetic results from sampled cores 2 and 5 and fig. (3.28) shows the long core plots of cores 3 and 4. Core 4, although correlating in intensity with cores 2 and 5, was not sub-sampled as it looked as though it had been twisted. Core 3 was not sub-sampled as the correlation between it and the other cores was not obvious, and also because it was rather shorter. The lettering on fig. (3.27) is as before.

The plots of D and I show quite clearly a very large scatter in the top half of both cores 2 and 5. This is most probably due to the very high gas content in the core. After disconnecting the two cores from the piston of the corer, there was an immediate expansion of the sediment, resulting in the loss of a few tens of centimetres from the top of the cores. Even after sealing at both ends, the pressure inside was great enough to force out the rubber stopper, which had been securely fixed in the end of the core tube. On slicing the core tubes in half, it could be seen that the sediment in the top 3m of each core had expanded and was not compact, and that numerous large cracks had occurred in the sediment. As a result, sub-sampling was made very difficult, if not impossible in the top of each core.



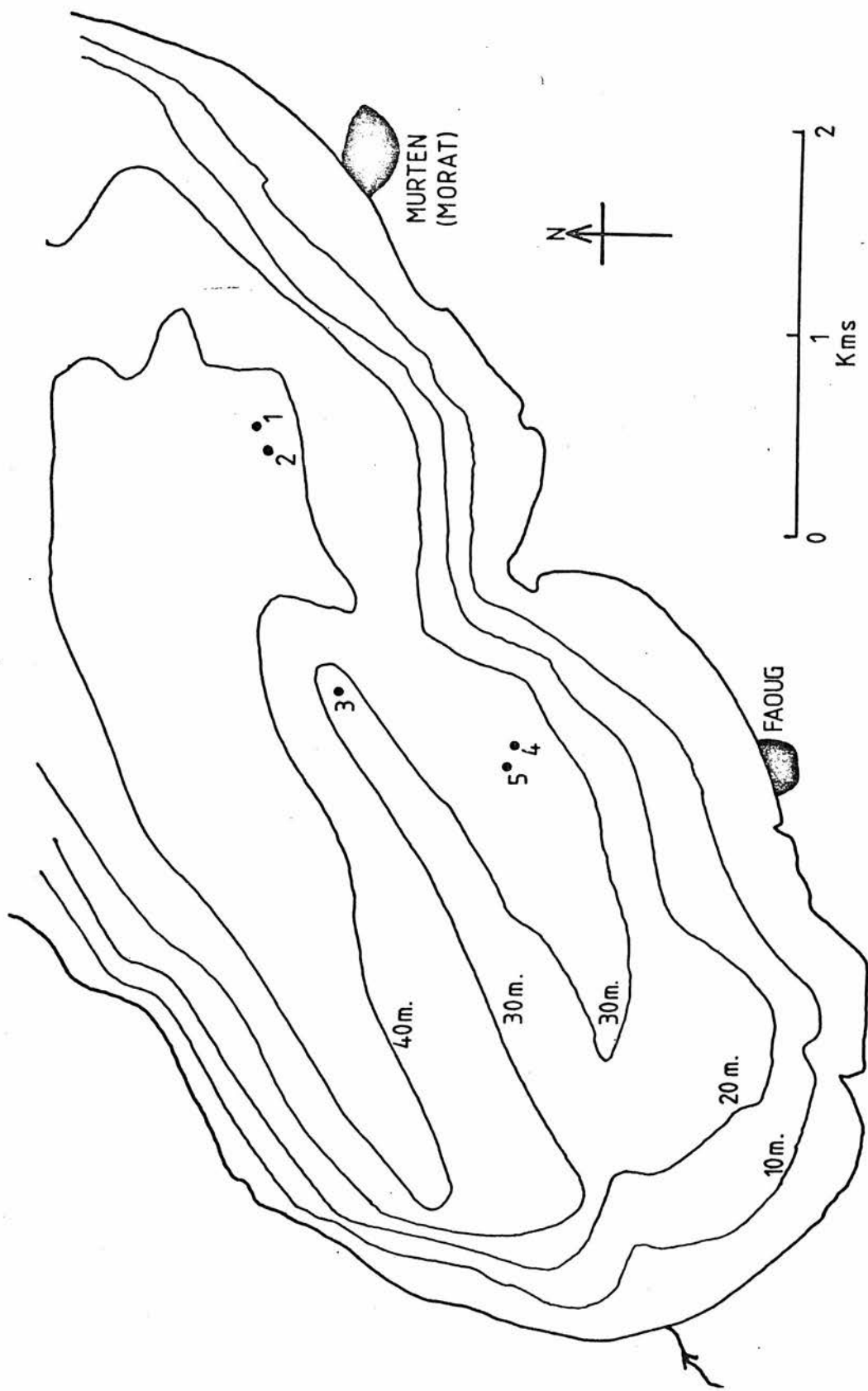


FIG 326 Bathymetric Map showing Coring Sites in Lake Morat

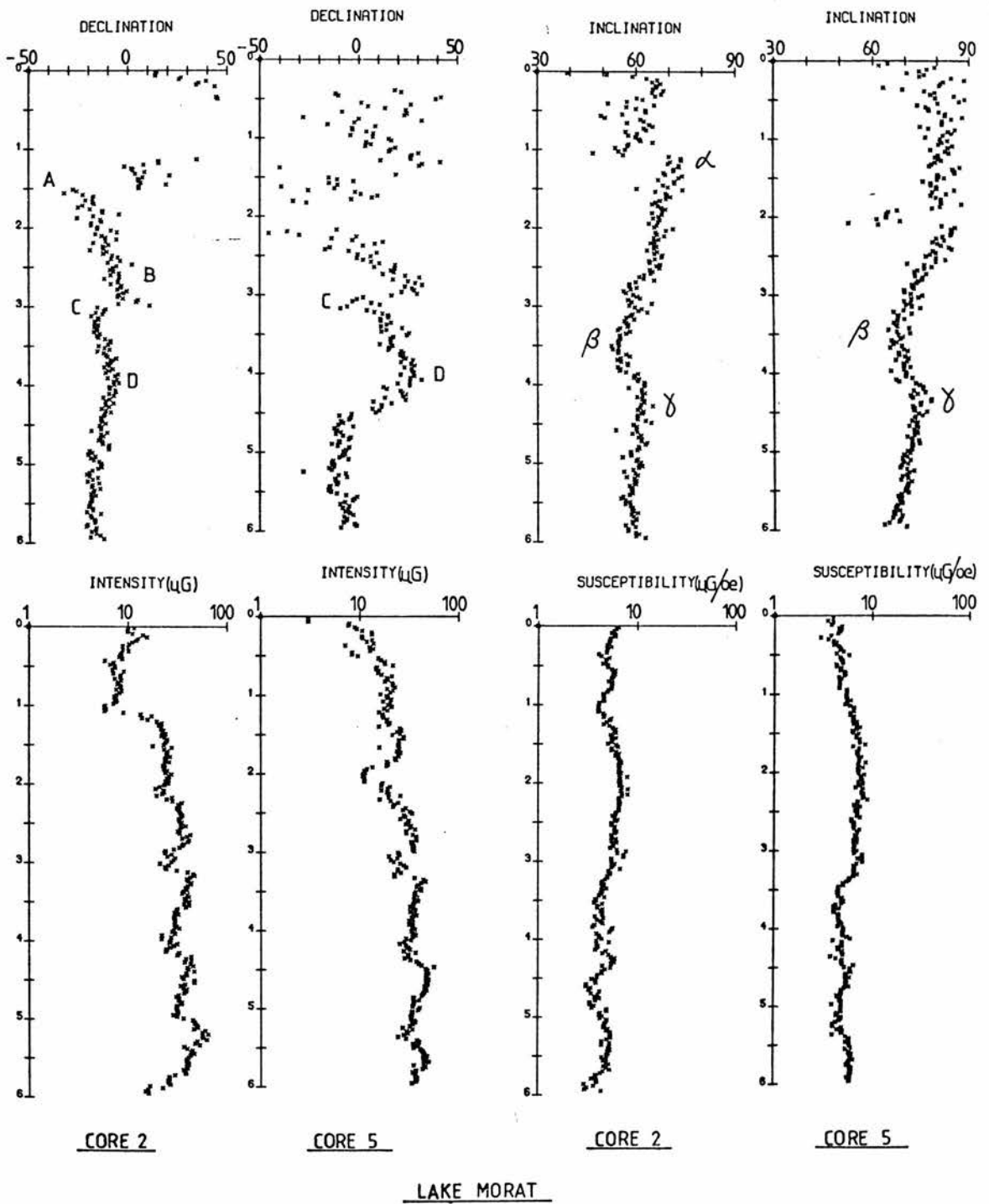
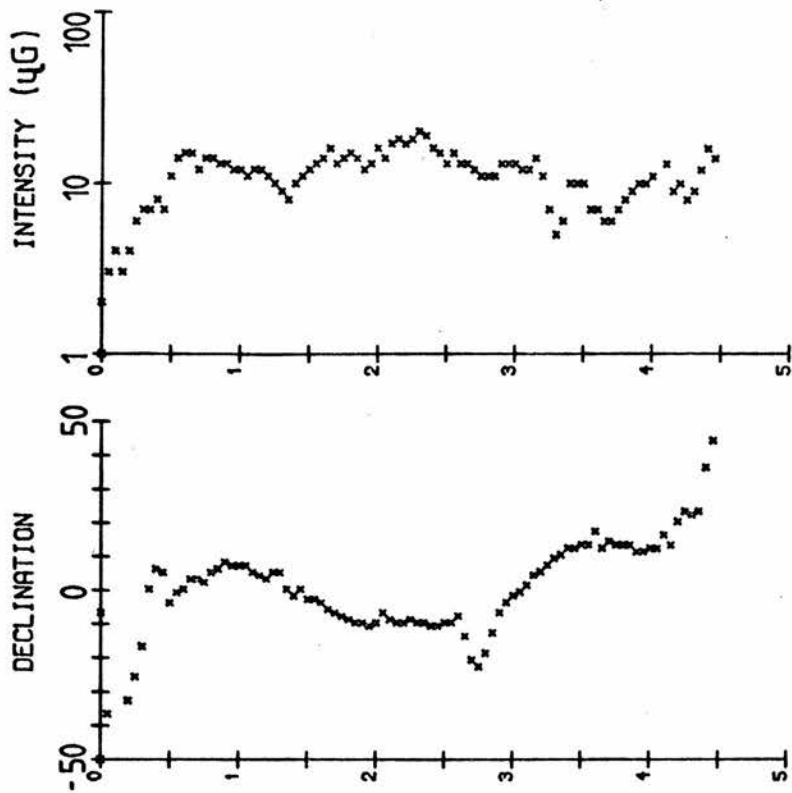
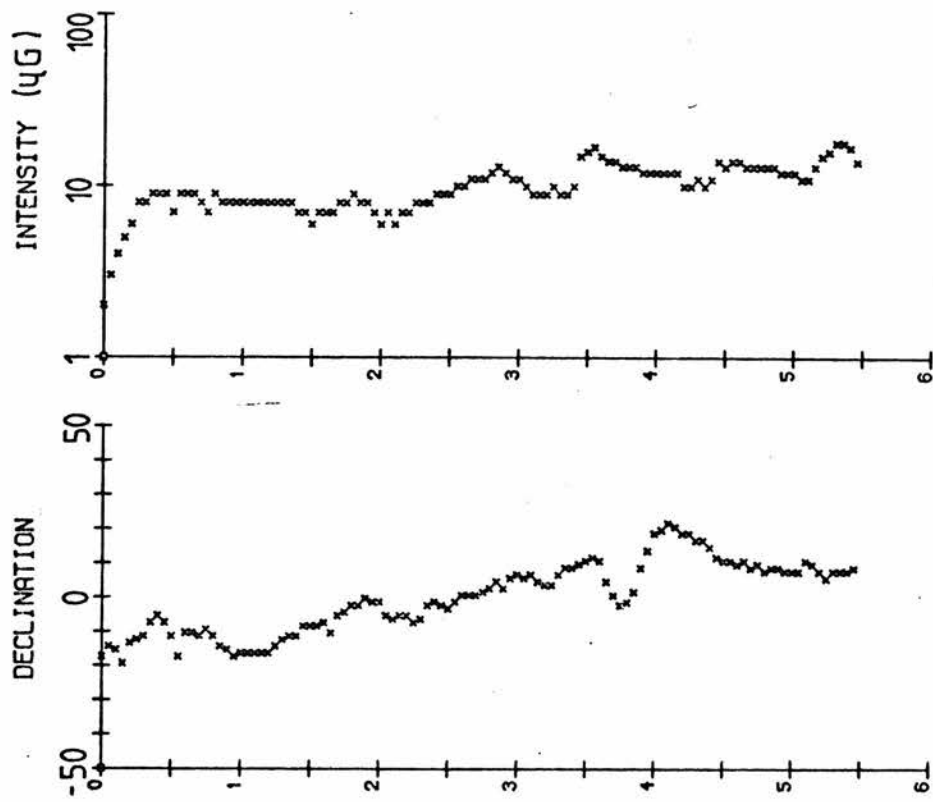


FIG 327 Plots showing the Correlation between Morat Cores 2&5



MORAT 3



MORAT 4

FIG 3-28 Long Core Measurements of Morat 3&4

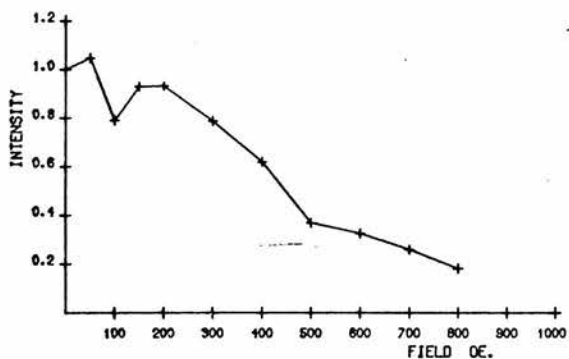
Fig. (3.29) shows the results of A. F. demagnetization of four of the pilot samples for core 5. The average M. D. F. is approximately 450 oe. and the directions remain stable up to 800 oe. There appears to be a weak secondary component which is removed in 100 oe, although this does not seem to alter the directions.

Unfortunately we have no dating control in either core 2 or 5 as pollen analysis and radio-carbon dating were not carried out on these cores. The two cores however appear to correlate well, especially in the inclination record, with others from Geneva, Annecy and Le Bourget. The lettering, therefore, has been placed on the plots as a result of magnetic correlations with other cores and the archaeomagnetic curve, rather than by pollen correlation. It does not seem unreasonable though, to expect Lake Morat to have approximately the same rate of sedimentation as other lakes in the same area.

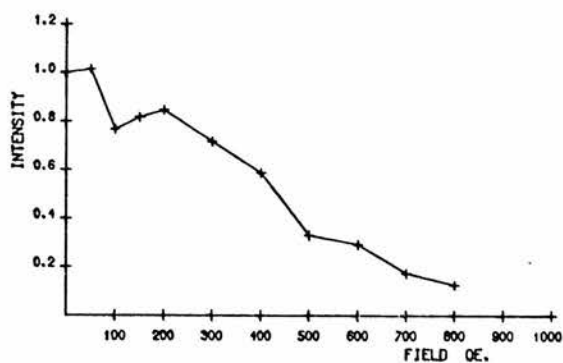
As with Geneva, it can be seen that the two cores have different mean inclinations; Morat 2 has a mean inclination of  $64^{\circ}$ , whereas Morat 5 has one of  $77^{\circ}$ . The scatter at the top of core 5 may be partly responsible for this, but the mean inclination beneath 2m is still around  $70^{\circ}$ . This again would suggest a non-vertical entry of the core tube into the sediment. Modifications have since been added to the corer in the form of a watertight camera, focussed on a compass and two spirit levels to enable the determination of orientation and angle of entry of the core tube.

### 3.7 Results from Lac de Joux

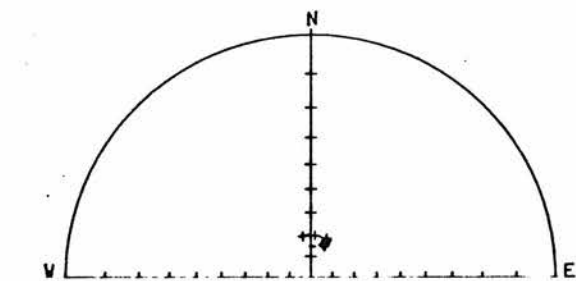
Lac de Joux is situated just to the north of Lake Geneva, at an altitude of well over 1,000m and lies between latitudes of  $46^{\circ} 41' N$  and  $46^{\circ} 38' N$ , and longitudes  $6^{\circ} 17' E.$  and  $6^{\circ} 20' E.$  The lake itself is smaller than any of the others visited and only has two very small



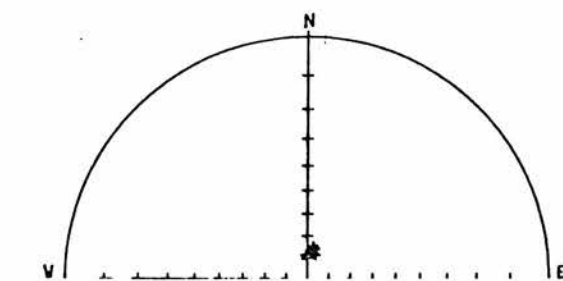
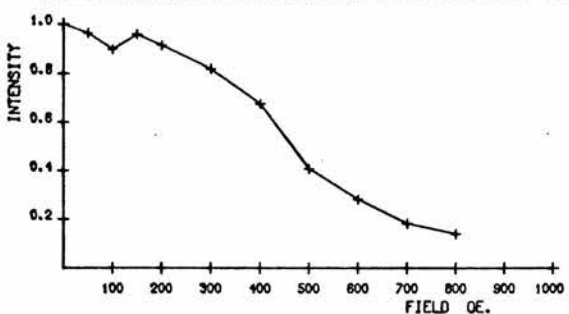
SMOR 16



SMOR 46



SMOR 146



SMOR 176

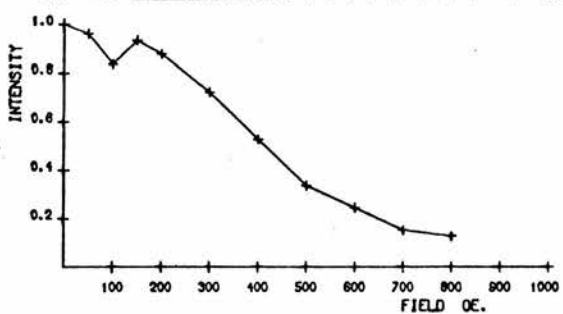


FIG 3-29 Demagnetization Plots of Pilot Samples from Lake Morat

rivers running into it, and one outflow at the north end.

Fig. (3.30) shows the coring positions within the lake. Although normally trying to obtain two cores from each site in a particular lake, it was found impossible to obtain any more than the one core from the first site, and even this core was only 3.0m long. The trouble was that the sediment was too hard, and the corer was lifting off the lake floor instead of coring into it. The average length of the other cores collected was only 4.0m and only one core greater than 5.0m in length was obtained. This long core was left in Geneva for chemical and pollen analysis and the others returned to Edinburgh. Long core measurements done on the cores showed very scattered results and no correlation was obvious.

The fourth core, however, was sub-sampled in Geneva and measured in Edinburgh. The results from this core are shown in fig. (3.31).

No correlation with the cores from the other lakes seemed possible at first, until the results of the pollen analysis were obtained. The surprising fact to come out of the pollen analysis was that the base of the core had an approximate age of 13,000 yr B. P. and that the core had penetrated the Late Glacial Post Glacial boundary that occurred at about 10,000 yr B. P. Approximate ages obtained from the pollen analysis are also on fig. (3.31), along with a colour description of the stratigraphy of the core. This also explains the unsuccessful attempts to collect any long cores of sediment from the lake, the corer in all cases except this one being unable to penetrate the very hard glacial clays at approximately 3.30m depth.

Fig. (3.32) shows the demagnetization plots of the pilot samples from this core. The samples are again stable and have an average M. D. F. of about 400 oe. A weak secondary component is removed in

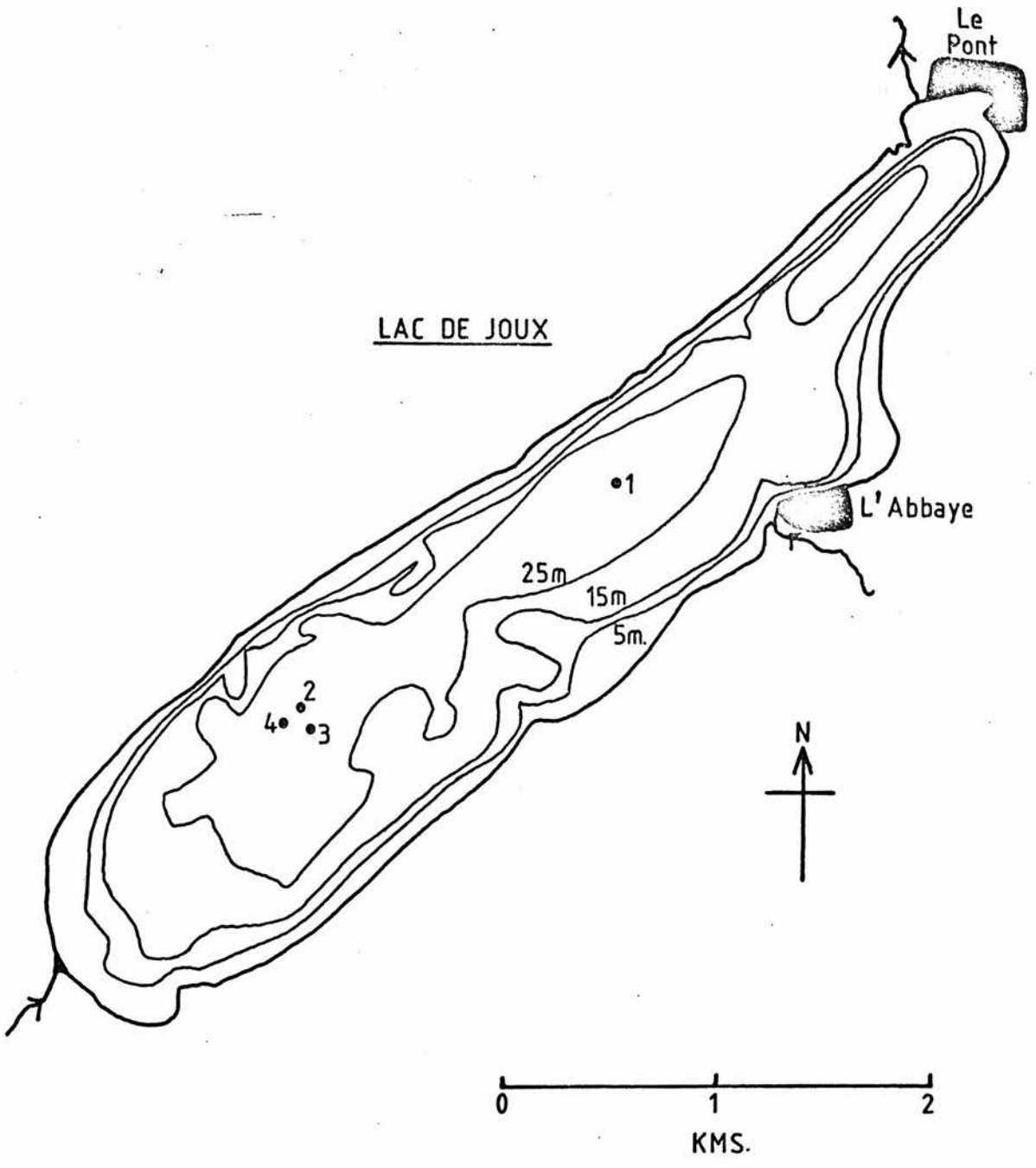


FIG 3:30 Bathymetric Map showing Coring Sites in Lac de Joux

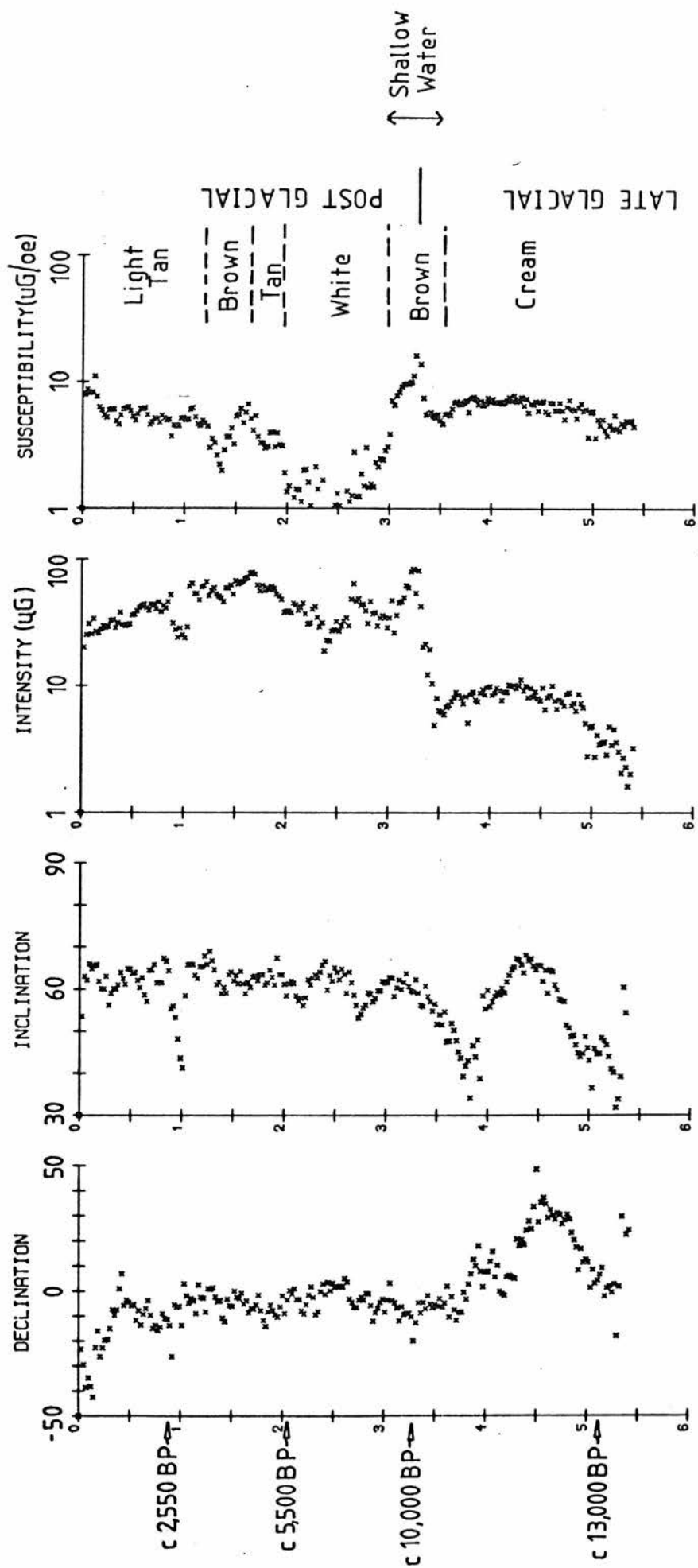
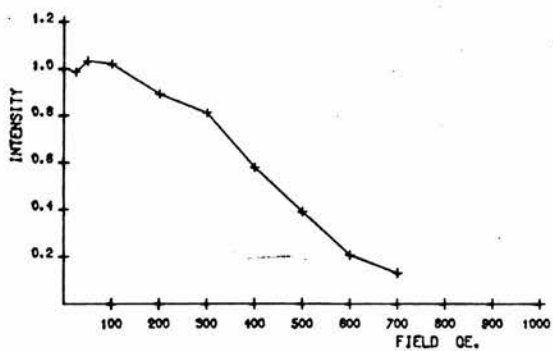
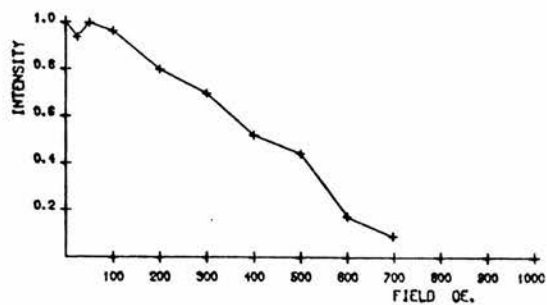


FIG 3-31 Results from Lac de Joux Core 3, with Pollen Dates and Colour Description

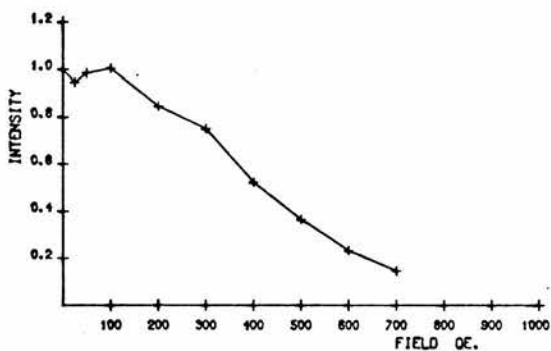
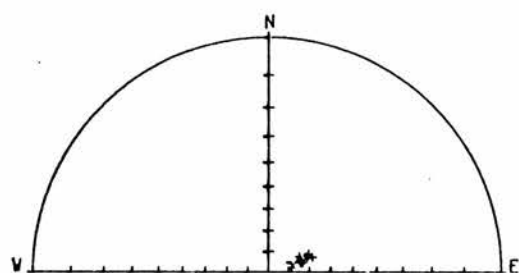
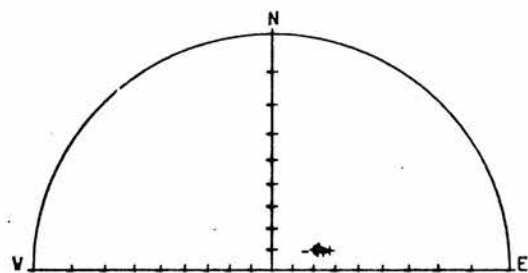




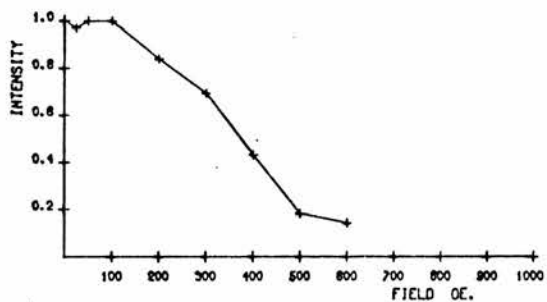
3JOU 85



3JOU 155



3JOU 205



3JOU 235

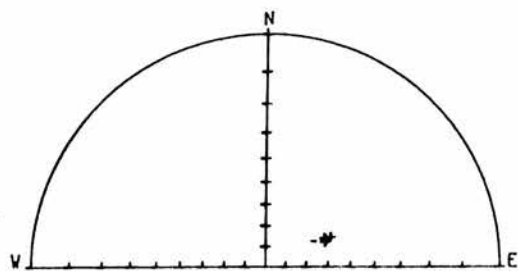
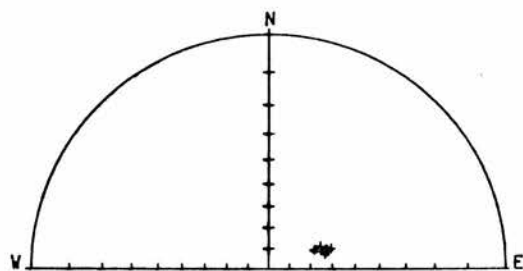


FIG 332 Demagnetization Plots of Pilot Samples from Lac de Joux

50 oe, but does not seem to significantly alter the direction of the remanence.

A few interesting features arise from the results shown in Fig. (3.3f). The most obvious is the very marked change between late and post glacial at a depth of 3.30 m. Both the intensity and susceptibility change quite markedly at this point; the intensity of the late glacial clays being much lower than those of the post-glacial. The colour of the sediment also seems to correlate well with the susceptibility, which was not the case in any of the other cores studied. This would suggest changes of the source material being carried into the lake. This may be a feasible explanation in this case, considering the time scale involved.

In the top 1.00m of the core we have the rather strange situation of the intensity increasing (up to 70 µG) and the susceptibility decreasing (down to 3 µG/oe). *This suggests that the remanence may be of a composite nature, possibly detrital plus chemical.* As the lake has an 85 - 90% CaCO<sub>3</sub> content, a possible cause of the <sup>chemical</sup> remanence could be the presence of greigite (Thompson, pers. comm.). Greigite has been found to grow in lakes with a high alkalinity, as this lake certainly has.

Another interesting feature is the very low inclinations at 3.75m and 5.25m. The inclinations at these points become as low as 35° and occur between 10,000 and 13,000 yr B. P. Low normal field inclinations have been found during this period in other parts of Europe. Both the Windermere record (Mackereth 1971) and two cores collected in southern Sweden (Thompson and Berglund, 1976), show inclination of between 45° - 50° for approximately 11,000 and 12,700 yr B.P. Morner (1971) reported an excursion found in cores from Gothenburg and dated

it at 12,350 yr B.P. Noel (1975) also reported an event at about 10,200 yr B.P., occurring in varied clays from Blekinge in southern Sweden. However, in Lac de Joux there is no supporting evidence from the declination record that this could be an excursion (or attempted excursion). There is also no supporting evidence from any other core, as this was the only one to penetrate to this depth. Thompson (1976) explained Noel's data as scatter related to the variable sedimentary sequence. Thompson and Berglund (1976) explained the late Weichselian geomagnetic 'reversal' found by Morner as a slumping of the sediment in the stratigraphic level corresponding to the Fjards interstadial. As the low inclinations at 3.75m occur at the late glacial - post glacial boundary, where there is a very distinct change in sediment, and also at a time of varying water level within the lake (Reynaud, pers. comm.), it would be reasonable to suggest that the reason for the low inclinations could as easily be physical as geomagnetic. The same would apply to the low inclinations at the base of the core. Only the last few samples taken from the core are in fact lower than  $45^{\circ}$ , and it is obvious from the scatter that they have been physically disturbed..

As a result of the very slow sedimentation rate in the lake, no correlation has been possible with the other cores, or with the archaeomagnetic curves. Apart from the bottom 1m, the peak to peak amplitude of the declination swings is only  $20^{\circ}$ . As this is not much greater than the scatter of the individual points, any attempts to correlate this core with other records must be considered carefully and any resulting correlation must be viewed with a certain amount of caution. Clark and Thompson (1978) have devised a method of cross-validation to test objectively, and with the help of only the internal data, whether

swings in palaeomagnetic data are 'real' or just noise. In this case however, with the help of the pollen dates, a subjective correlation with the lake Windermere master curve (Mackereth, 1971) is given in Fig. (3.33). The bottom 1m of the Lac de Joux core is not taken into account, and as a result a new mean declination for the rest of the core is drawn. This mean, therefore, does not coincide with the zero degree line as is normally the case.

The correlation as shown seems reasonable and agrees well with the pollen dates, but as stated above, the small amplitude of the variations make it difficult to justify them as maxima to minima. There does not seem to be much correlation between the inclination records, but both plots show a low inclination value just after 10,000 yr B. P. Both these low inclination values seem to correspond to the 'h' maximum value in declination. However, the Windermere record shows what seems to be a discontinuity at this point and the low values may be due to the same reasons, as quoted above, for the low Lac de Joux values.

### 3.8 Correlation of the plots from Annecy, Geneva, Bourget and Morat

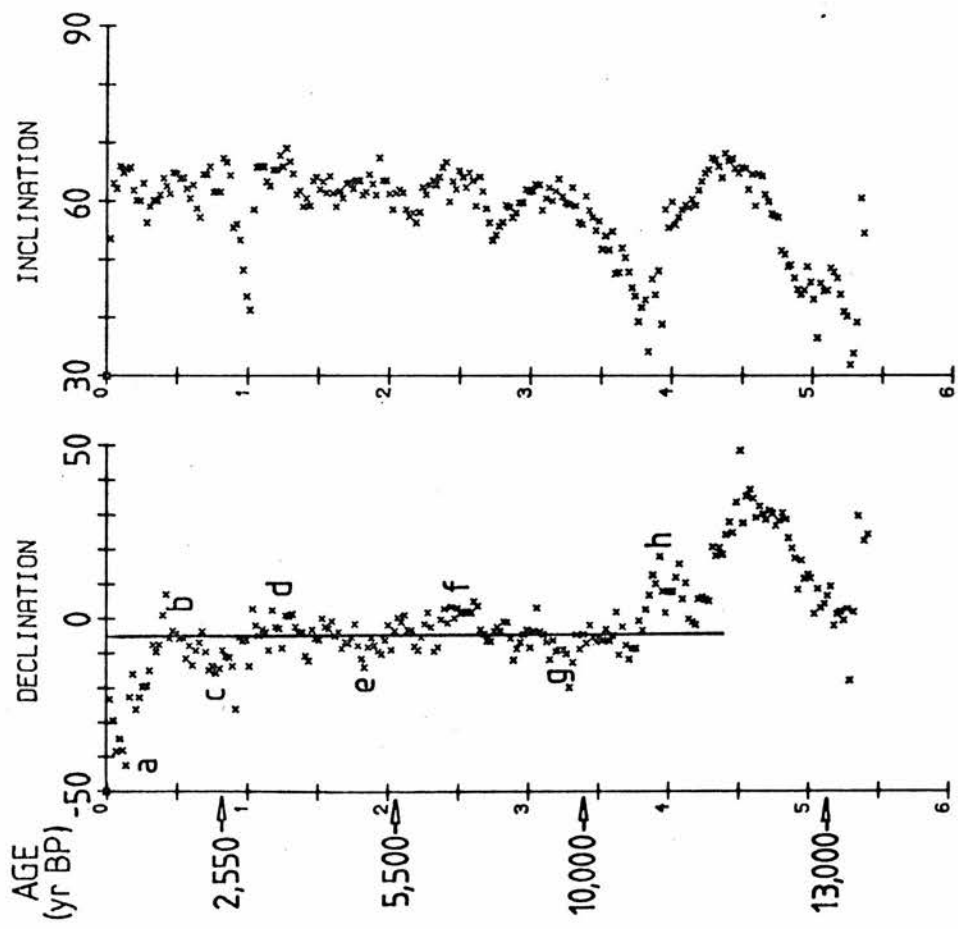
In the earlier sections of this chapter the within site, and within lake correlations for the different lakes have been shown. As the lakes are only a few hundred kilometres apart, similar patterns of the secular variation should be seen in them if they are of true geomagnetic origin. This is assuming the geomagnetic field is uniform over small distances, and also taking into account the slightly different sedimentation rates within the lakes.

The best correlation is in the inclination records and is shown in Fig. (3.34). The records are aligned so that the most prominent feature, that of the maximum inclination value at 1,200 yr B.P.,

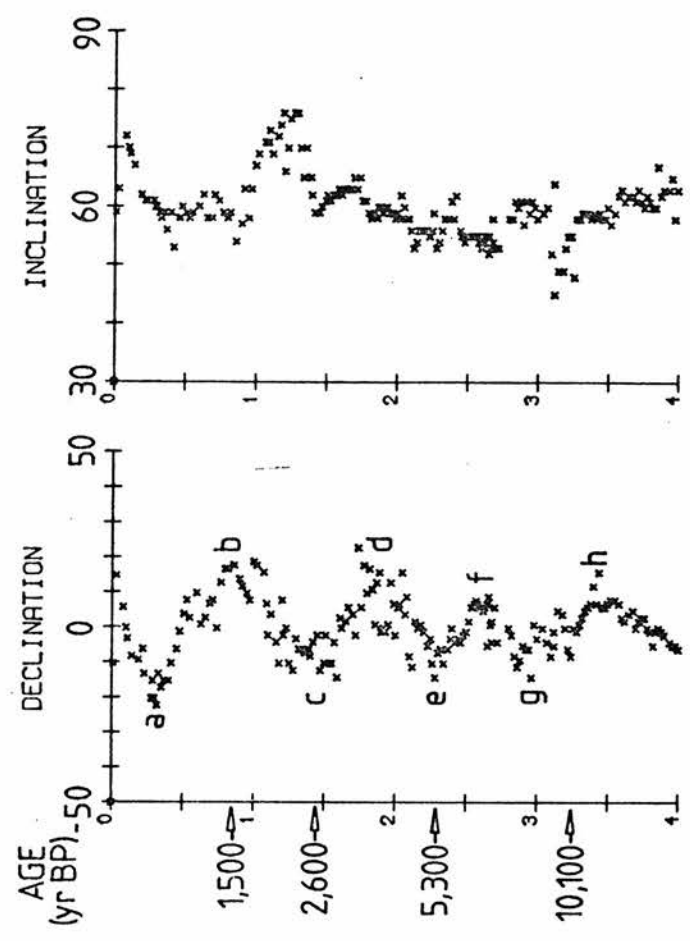
appears at the same level in each. The declination plots (3.35) are also aligned using this same common level. The lettering on both plots is at the same depth as previously (see Fig. (3.14) for archaeomagnetic curves). The inclination plots show a very convincing correlation and also agree very well with the pollen data.

This correlation was the one proposed before any pollen analyses had been carried out on the cores. The only age control until the pollen dates was the two C14 dates from Lake Geneva. As can be now seen, the magnetic correlation was correct, but the time scale was incorrect. Originally the declination swings marked A, B, C, and D were correlated to the Lake Windermere swings a, b, c, and d shown in Fig. (3.33). This shows the necessity for a very firm age control before any assumptions about correlation, or possible periods of oscillation of the variations can be made.

The declination records do not correlate as well as the inclination records and the lettering has <sup>been</sup> put on the plots more as a result of the pollen evidence than of obvious geomagnetic correlations. Features 'C' and 'D' do however seem to show clearly on all the plots. Any attempt at a correlation between these records and the Lac de Joux or Windermere ones is made nearly impossible by the vastly differing sedimentation rates; the only possible correlation being the minimum declination at the bottom of Geneva, Le Bourget and Morat corresponding to the minimum value marked as feature 'C' in Fig. (3.33). This could be quite possible as the pollen evidence shows a distinct slowing of the sedimentation rate in the bottom half of all the cores. The bottom of Lake Annecy still shows a westerly declination and could still be part of the westerly maximum marked as 'b' in Fig. (3.33). A pollen date of 1,800 yr at the bottom of this core would be in accordance with this theory.

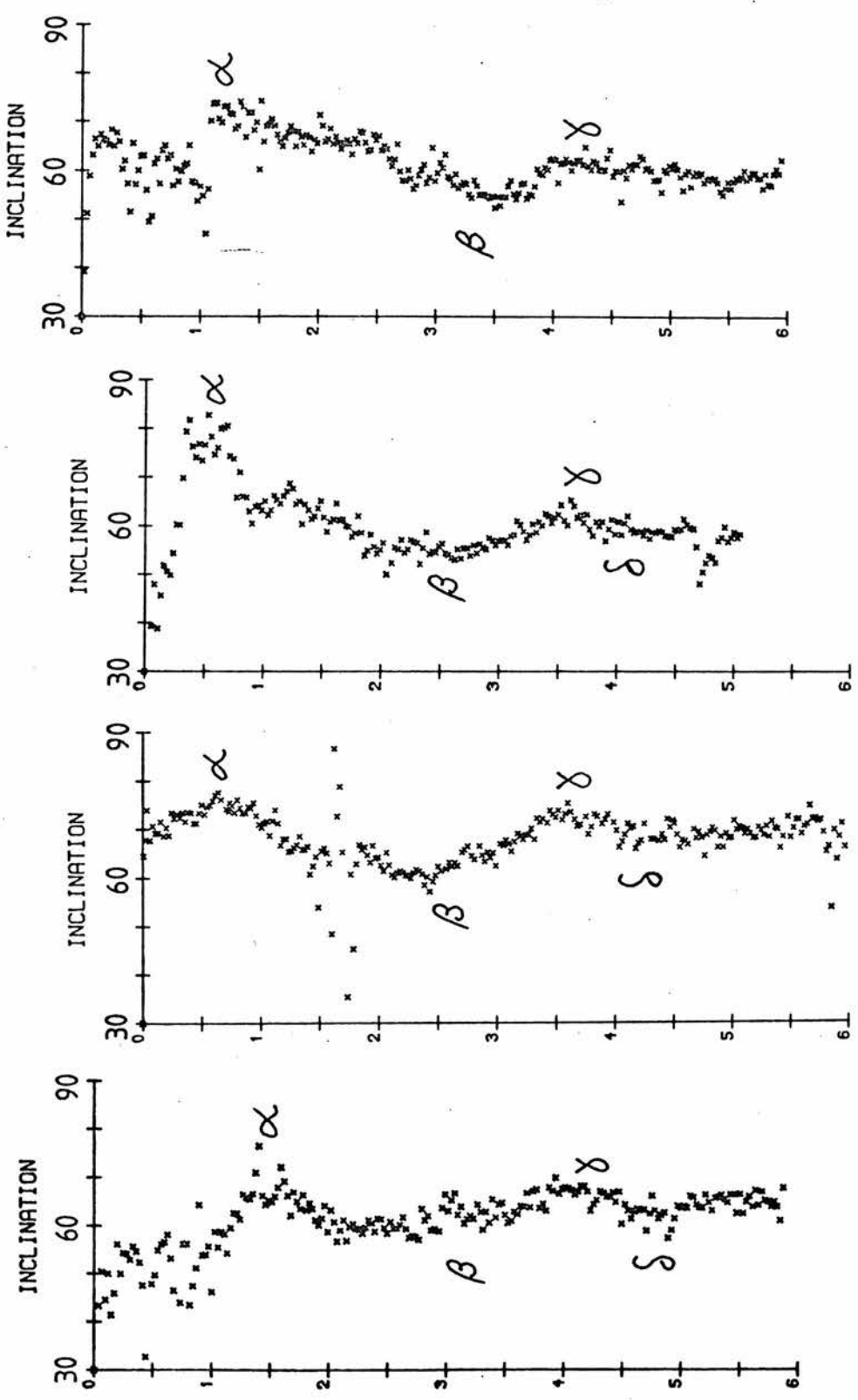


LAC DE JOUX



WINDERMERE

FIG 333 Possible Correlation between Lac de Joux and Windermere Declination Records



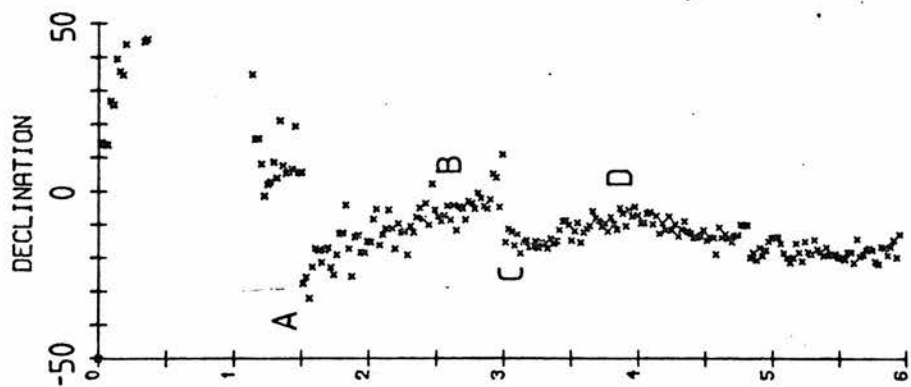
MORAT 2

LE BOURGET 2

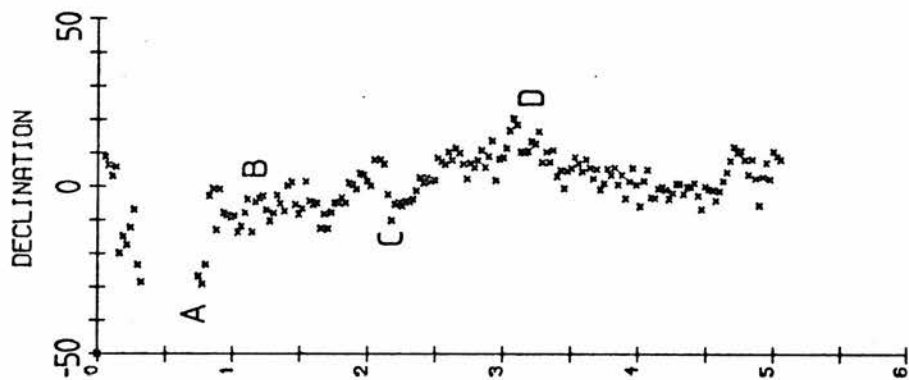
GENEVA 7

ANNECY 3

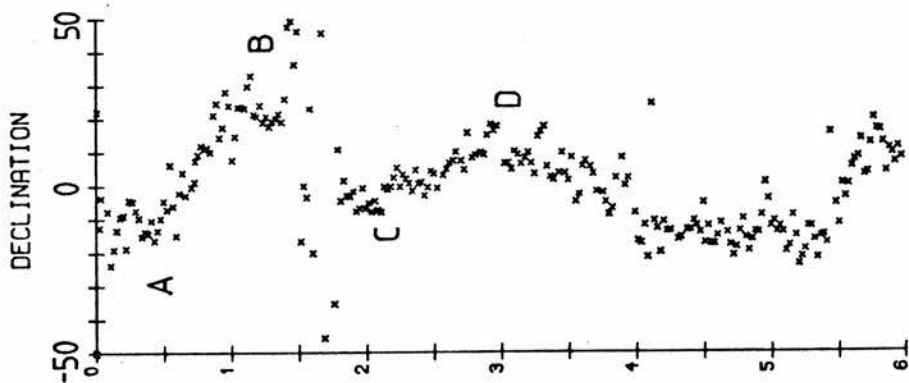
FIG 334 Correlation in the Inclination Records from Anncy, Geneva, Le Bourget, & Morat



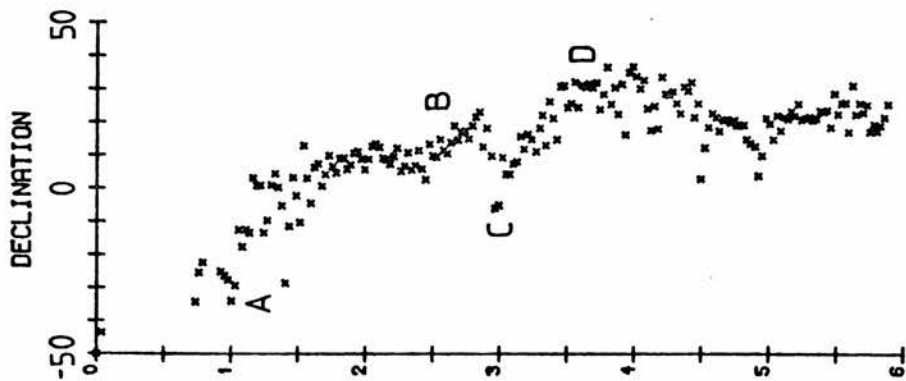
MORAT 2



LE BOURGET 2



GENEVA 7



ANNECY 3

FIG 3:35 Correlation of the Declination Records from Anncy, Geneva, Le Bourget, & Morat



## CHAPTER 4

### Palaeomagnetic Studies of Holocene Lake Sediments from Poland

#### 4.1 Introduction

The following palaeomagnetic study was carried out in conjunction with the Institute of Geophysics, Polish Academy of Sciences, Warsaw. The object of the study was to further contribute to the palaeomagnetic data that had been obtained from numerous other European lakes. As previously discussed, this palaeomagnetic data would hopefully assist in the study of the L P S V of the geomagnetic field. It was also hoped that this data would help solve the problem of verifying over how large an area the geomagnetic field shows a regional character and also if there is any evidence of westward (or eastward) drift over Europe in the last 10,000 years. This would be done by comparing the Polish records with those of Britain and Central Europe, and then trying to establish whether or not there was a phase lag between the records. As will be shown in this chapter however, not only was the precision of the dating insufficient to resolve the problem of westward drift, but the standard of the palaeomagnetic records on the whole was rather poor. As a result, only a few of the lakes that were sampled gave records good enough for further study. Palaeomagnetic records from all of the lakes sampled will be shown however, and possible explanations for the poor quality of the records will be given.

#### 4.2 Fieldwork and Geology

During the summer of 1976, 59 6m cores were collected from ten different lakes in Northern Poland. Of these cores, 40 were returned to Edinburgh and 19 were left in Warsaw for palynological

studies. The ten lakes visited covered all of Northern Poland from the western boundary with East Germany to the eastern boundary with Russia. Fig.(4.1) shows the positions of all of these lakes. The lakes themselves were Charzykowskie, Powidskie, Moszczonze, Mikolajski, Sniardwy, Radunskie-Gorne, Radunskie-Dolne, Zarnowieckie, Drawsko and Miedwie. They are all located in the region of the moraine plateau of the North Polish (Vistulian) glaciation. The first three mentioned are located in the area of the older Poznan phase of the main stadial and therefore are liable to contain older sediments (Mojski, 1969), if they can be penetrated. The others are located in the region of the youngest (Pomerania) phase of the main stadial. The Vistulian glaciation of Northern Poland included two distinct units, the later being from 75,000 yr B.P. to about 10,000 yr B.P. (Starkel 1977). The Poznan phase however ended 18,000 - 19,000 yr B.P. and the Pomerania phase ended approximately 16,000 years ago. All ten of the lakes lie in subglacial channels.

An interesting feature is that most of these lakes have peat layers which underlie the lacustrine sediment (Wieckowski 1966,1969). These peat layers occur at depths of up to 60m below the present water level and underneath gyttja beds which may have a thickness of up to 10m. These peats all have the same age of about  $10,800 \pm 460$  yr B.P. irrespective of water depth or overlying gyttja thickness. The explanation for this (Gross 1937) was that the peat developed on top of the deposits covering the ice masses, so that when the ice melted in the Allerød, the peat then dropped to the bottom of the lake. As a result this peat layer was used as a marker level in some of the lakes where the 6m core managed to penetrate the gyttja into the peat. As a result of the ice melting

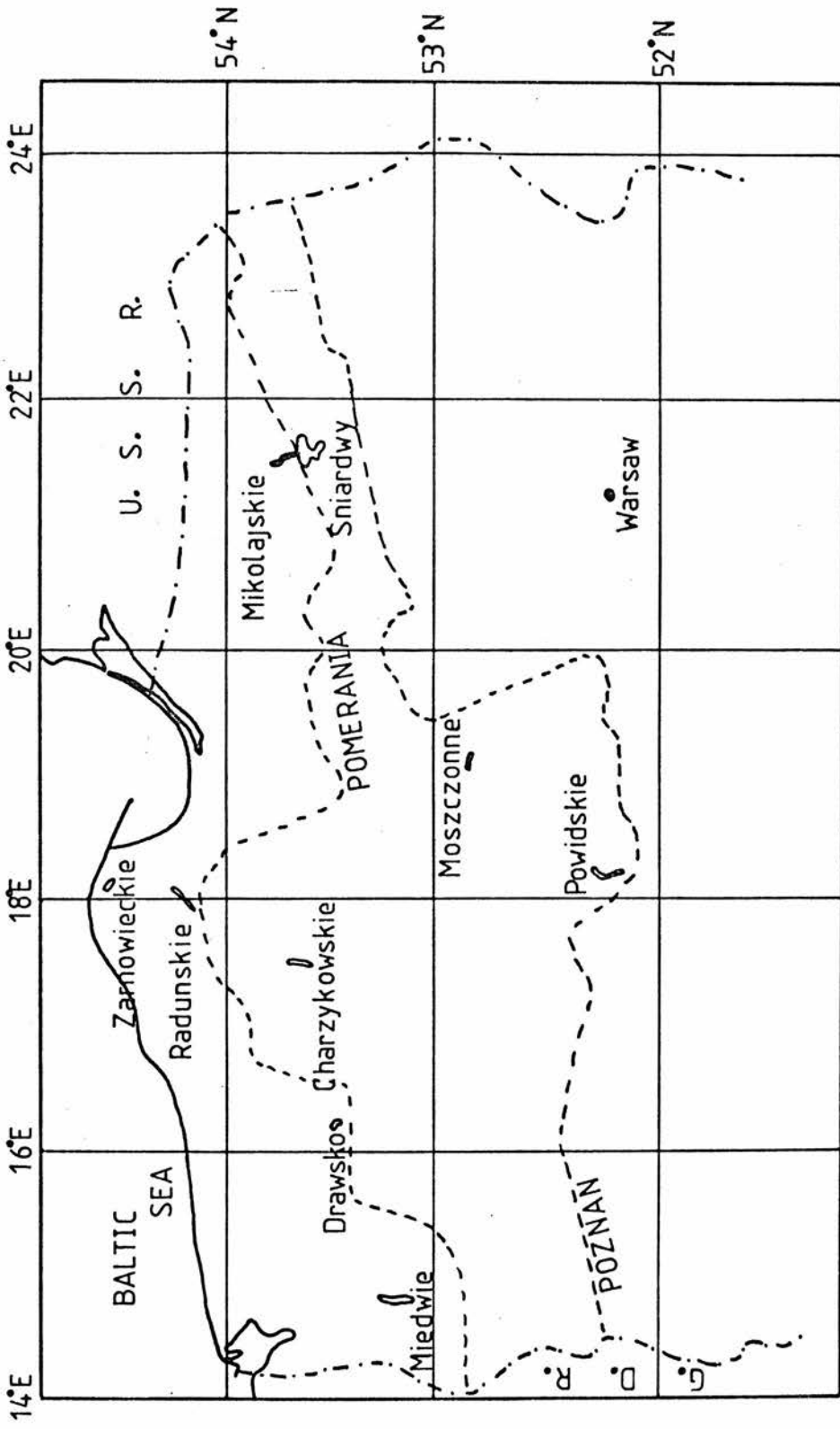


FIG 4-1 Map of Northern Poland showing the Lakes and the Southern Limits of the Poznan and Pomerania Phases of the North-Polish Glaciation

in the Allerød, the sediments collected mainly belong to the Younger Dryas and Holocene.

Fig. (4.2) shows the coring positions within six of the larger lakes visited.

#### 4.3 Preliminary Studies on the Collected Cores

Of the 59 cores collected, the lengths recovered varied from 3m to 6m and had an average length of 5m. Of the 40 returned to Edinburgh, 28 had long core measurements carried out on them. The same criteria as for the French and Swiss lakes was used to decide upon cores for subsampling i.e. cores should have a reasonable intensity of magnetization, and long cores would be preferred to short cores. This time however we had the added help of a scribe mark down the plastic core tube to indicate the amount of twist encountered during coring. As stated earlier though, this does not necessarily give the amount of twist in the sediment. Table 4.1 gives a list of the cores that had long core measurements carried out on them, along with the depth of water in which they were collected, the length of the core and to what degree they had been twisted. From the table it can be seen that of the 28 cores measured, 24 had visible scribe marks of which 8 were straight, 10 had small twists in all or parts of the core, and 6 had large twists of  $90^\circ$  or greater. Therefore only 1 in 3 cores from this collection did not have some amount of twist. Reliable declination records therefore can only be expected from a small proportion of the cores collected. More reliable information is obtained from the inclination records, as the inclination should not be affected by the twisting of the corer. As a result, any correlation between cores is made on the basis of the inclination variations rather than the

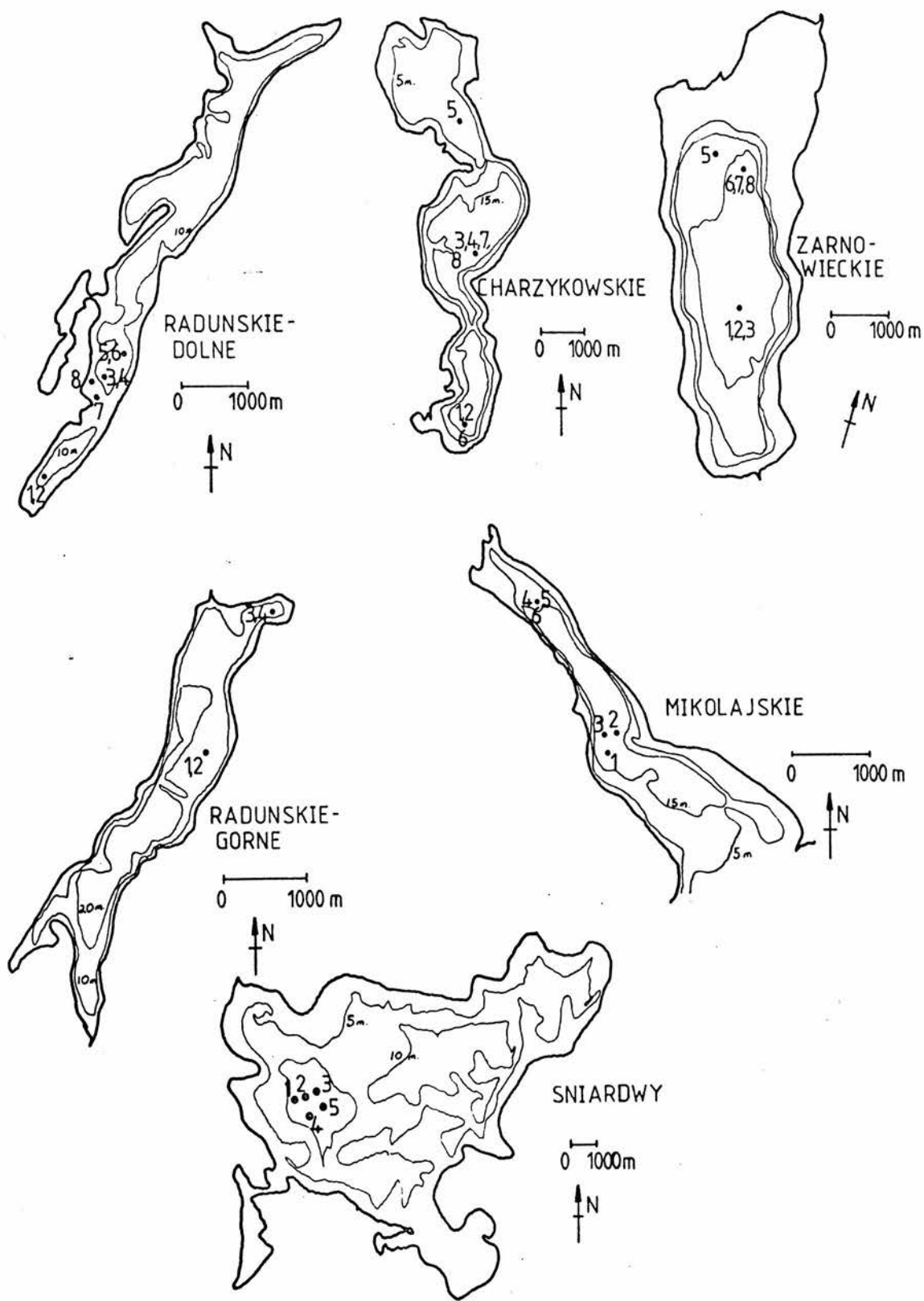


FIG 4-2 Coring Positions within the 6 Major Polish Lakes

LAKE	No.	Depth(m)	Length(m)	Scribe Mark
MIKOLAJSKI	2	25.5	6.0	Small Twist
	3	26.3	6.0	Straight
	5	15.7	5.7	20° Twist
	6	15.7	4.4	No Scribe
SNIARDWY	3	12.9	5.0	Small Twist
	4	12.9	5.3	Twisted
ZARNOWIECKIE	2	17.7	5.8	Small Twist
	3	17.7	5.8	Straight
CHARZYKOWSKIE	1	21.9	4.5	Twist 130°
	3	20.0	6.0	Twist 130°
	6	21.9	5.9	Straight
POWIDSKIE	3	44.3	5.8	Straight
	4	41.0	6.0	Twist in Top
MOSZCZONNE	3	16.4	4.2	Straight
	4	15.7	4.3	Small Twist
DRAWSKO	2	30.1	4.3	No Scribe
	3	37.8	6.0	Twist in Top
	4	22.9	5.8	Twist 90°
	7	54.5	5.0	No Scribe
RADUNSKIE-GORNE	1	14.7	5.0	Twist 90° in Bottom 1.5m
	2	14.7	5.5	Straight
	4	8.5	4.2	Twist Top 1m
RADUNSKIE-DOLNE	3	13.8	5.8	Twist 90°
	5	13.8	4.3	Straight
	6	13.8	5.4	Small Twist
	8	13.8	5.8	Large Twist
MIEDWIE	1	38.7	5.8	No Scribe
	3	28.4	5.5	Straight

TABLE 4.1 List of Long Cores Measured

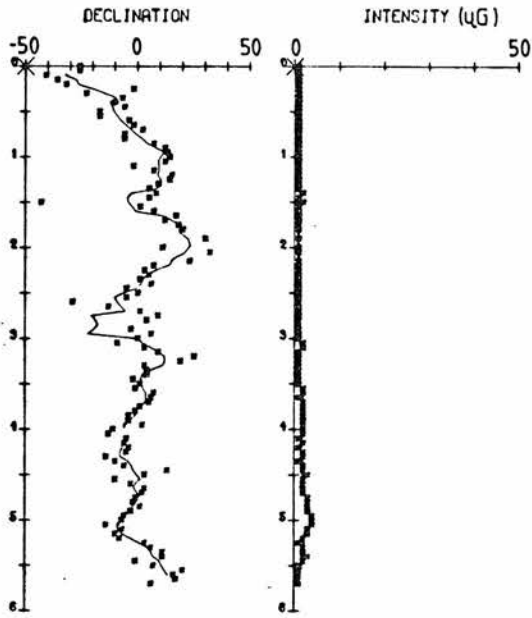
declination. The number of twisted cores emphasises the need for modification to the Mackereth corer to prevent twisting.

#### 4.4 Results from Long Core Measurements

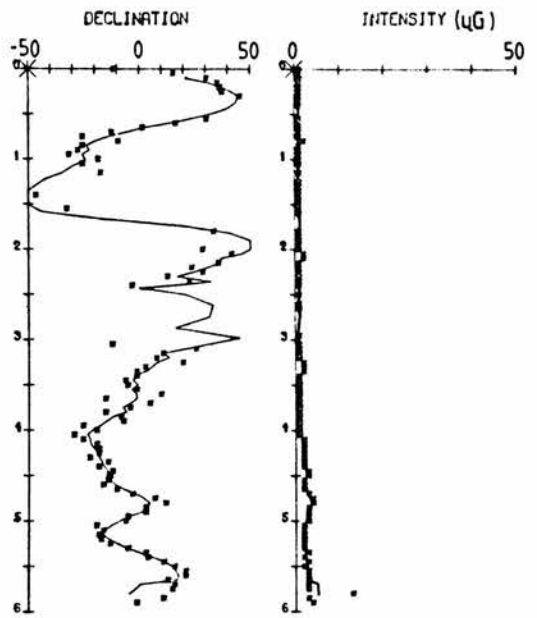
Typical results obtained from the whole core measurements are shown in Figs. (4.3, 4.4., and 4.5). The continuous lines on the diagrams are running means calculated over 5 points.

Fig. (4.3) shows the results obtained from cores that had a very low intensity. It is obvious that the declination shows almost a random scatter of points, many of which do not even lie within the limits of the graph. These cores and numerous similar ones were therefore discarded as not suitable for further palaeomagnetic investigations.

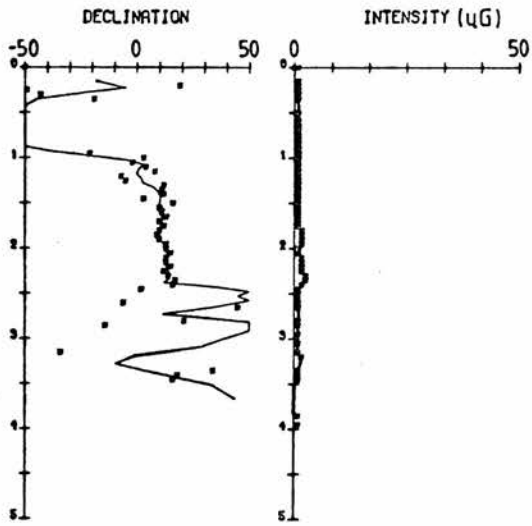
Fig. (4.4) shows 4 plots from cores that had large twists as shown by the scribe marks on the core tubes (see Table 4.1). It can be seen from these plots that the sediment inside the core tube has also been twisted. If it was possible to say that the twisting of the sediment had been smooth and continuous, then a mean line could be drawn through the points and the plot rotated so that the mean was vertical, hence correcting for the twist. As it is not possible to state whether the twisting has been continuous or discontinuous, these cores were also disregarded as far as further investigations were concerned. Fig. (4.5) shows the results for some cores which it was decided to open and subsample for further measurement. In the case of the 4 plots shown, the scribe marks on the core tubes were found to be straight, the declination plots were not excessively scattered as was the case in Fig. (4.3), and they were all nearly 6m in length. The above were the criteria used in deciding to subsample these and other similar cores. The number



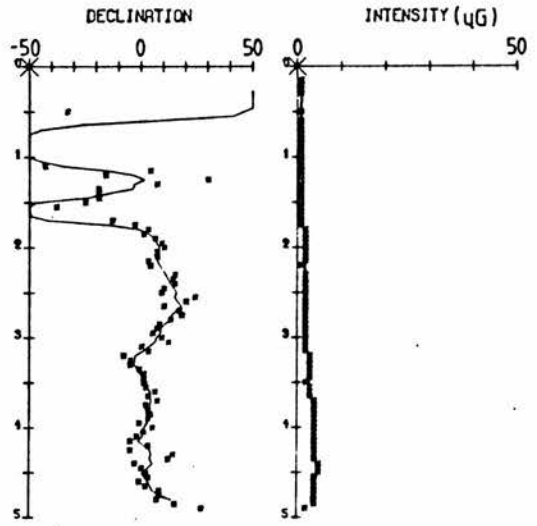
DRAWSKO 3



POWIDSKIE 4



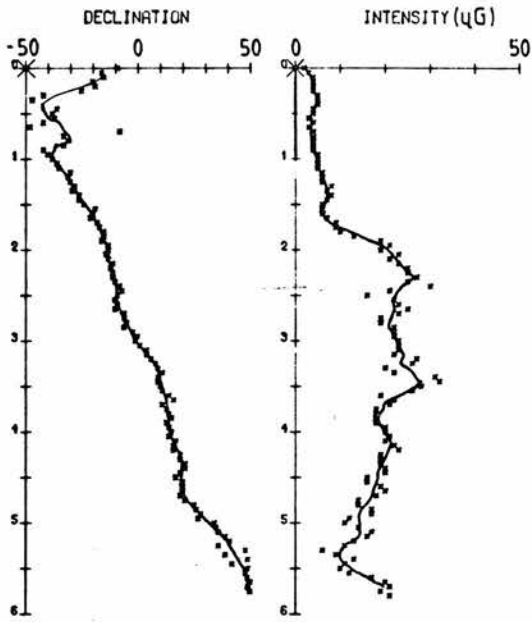
MIEDWIE 3



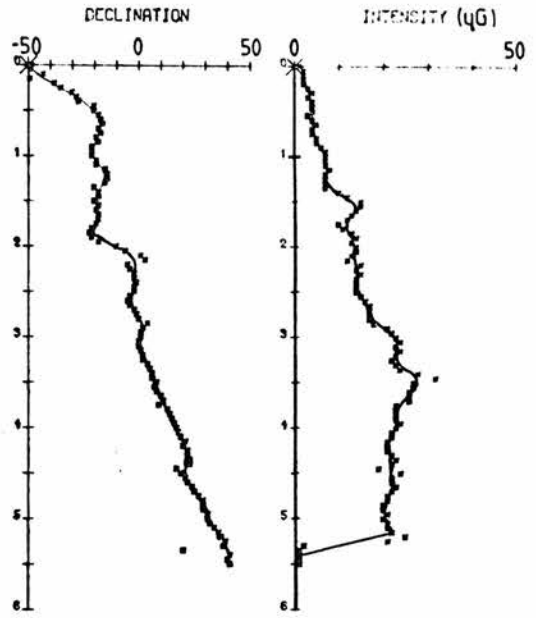
SNIARDWY 3

FIG 4-3 Scattered Results obtained from Long Core Measurements

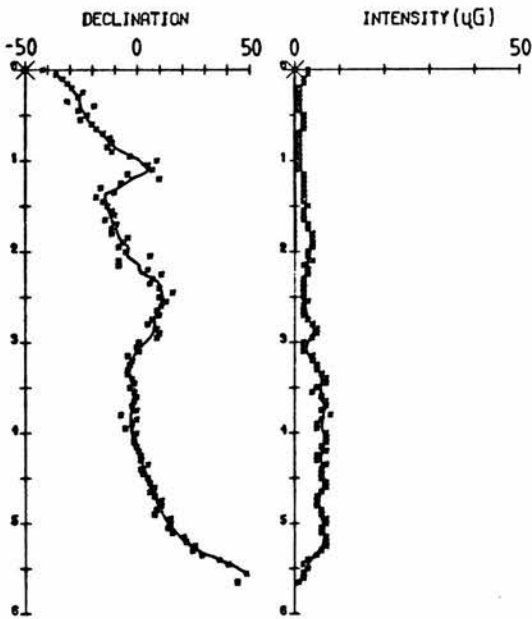




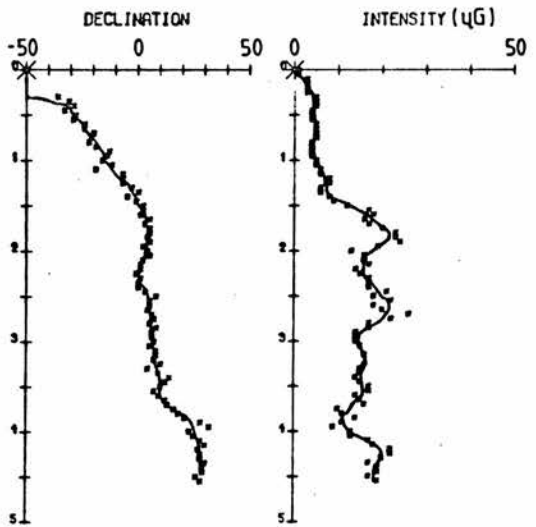
CHARZYKOWSKIE 3



RADUNSKIE-DOLNE 8

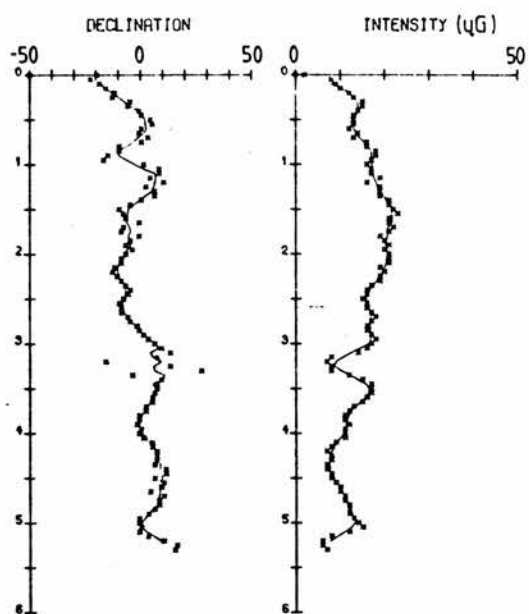


DRAWSKO 4

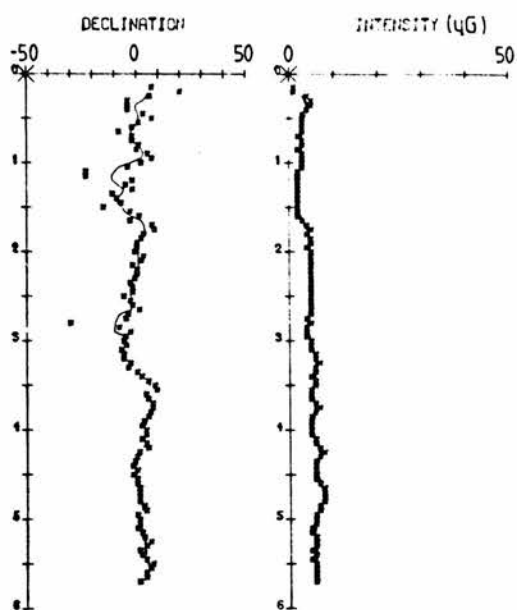


CHARZYKOWSKIE 1

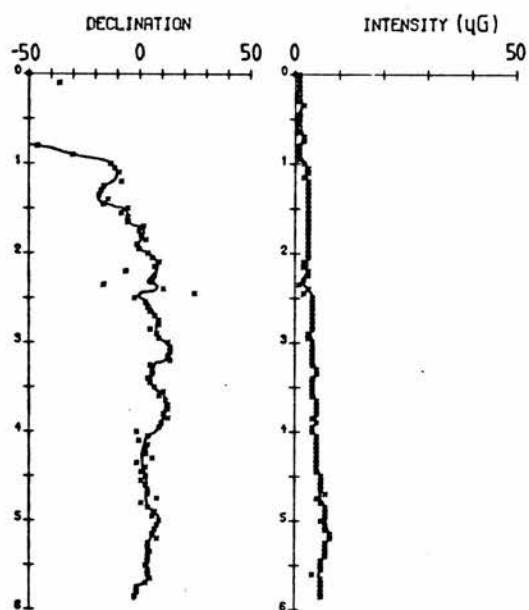
FIG 4.4 Long Core Measurements showing Evidence of Twisting



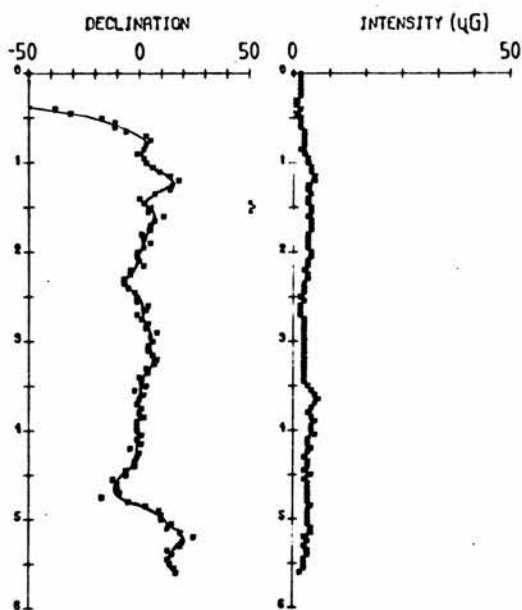
RADUNSKIE-GORNE 2



POWIDSKIE 3



MIKOLAJSKI 3



CHARZYKOWSKIE 6

FIG 4-5 Long Core Results from Cores which were Subsequently Subsampled

of cores with very low intensity, or with excessive twisting, limited the number of cores that were available for subsampling. Of the cores left in Poland, there was no way of measuring their intensity and as a result selected cores were subsampled and sent to Edinburgh on the basis of the information available about their length and any visible scribe mark. Of the original 59 cores collected only 23 were finally selected for opening and subsampling.

#### 4.5. Lithology, Palynology and Radio-Carbon Dating

Lithological descriptions of five selected cores are given in Appendix I. The colours were noted when the cores were opened and hence were still wet, though inevitably some oxidation would have occurred in the laboratory immediately upon opening. All the cores studied had large proportions of gyttja along with a high calcium carbonate content. This indicates stable chemical conditions at the time of deposition.

Pollen studies were carried out at the Institute of Geology, Warsaw by Borowko-Dluzakowa (1977) on core 6 from Lake Charzykowskie (CH6) and on core 2 from Radunskie-Gorne (RG2). Zarnowieckie cores 1 and 3 (ZR1 and ZR3) were analysed at the Institute of Biology, University of Gdansk by Latala (1977). Interpretation of the palynological analyses was carried out using data by Starkel (1977), who has dated the age limits of the floristic subdivision of the Holocene from the area in which the cores were collected. The ages of these subdivisions are given below.

Sub-Atlantic	0 - 2,000 yr B P
Sub Boreal	2,000 - 5,100 yr B P
Atlantic	5,100 - 8,400 yr B P
Boreal	8,400 → yr B P

For Charzykowskie, pollen counts from 5.65m and 4.30m indicate an assemblage typical of the Atlantic period. A sample from 3.85m is identified with the Sub-Boreal.

For RG2, samples from 1.50m and 1.55m yielded a spectrum<sup>um</sup> typical of the Sub-Boreal period. Samples between 3.40m and 4.50m indicated the Atlantic period. Hence the Sub-Boreal/Atlantic boundary at 5,100 yr B P lies between 1.55m and 3.50m.

For ZR1 and ZR3 samples between 2.80m and 5.00m are Sub-Boreal and two samples from 1.25m and 2.00m are assigned to the Sub-Atlantic.

Radio-carbon dates were measured on cores from Charzykowskie, Radunskie-Gorne, Mikolajski and Miedwie. Unfortunately they were carried out before all the palaeomagnetic measurements had been done and hence the dates on Lake Miedwie have not been of use because of the poor palaeomagnetic records from this lake. The dating was carried out at the radio-carbon laboratory at Gliwice by Pazdur and Pazdur (1977). Two sets of measurements were made: (i) on organic material, and (ii) on extracted carbonate samples.

As was the case for the dates on Lake Geneva, they were all found to be older than the palynological ages. Again this is caused by the fact that modern sediments have a finite age caused by 'old' carbon being washed into the lake.

A discussion of the radio-carbon ages and on the palynological data is given at the end of the chapter. Table 4.2 summarizes the 'raw' radio-carbon dates obtained.

#### 4.6 Palaeomagnetic Results

From both the long core and sub-sampled information, the best palaeomagnetic results are obtained from Lakes Charzykowskie, Radunskie, Mikolajski and perhaps Zarnowieckie. A possible explana-

Radiocarbon dates measured at Polytechnical School, GliwiceCharzykowskie, CH6

depth	ref. no.	date	
		organic	carbonate
150	Gd 451	2850 ± 170	
150	Gd 475		3270 ± 160
350	Gd 452b	4870 ± 150	
350	Gd 476		6220 ± 120
500	Gd 460		7770 ± 220
560	Gd 458		8670 ± 220

Mikolajskie, MK2

225	Gd 461	1640 ± 140	
225	Gd 471		1850 ± 120
440	Gd 472	3150 ± 130	
440	Gd 464		2740 ± 150
440	Gd 470		2700 ± 130

Radunskie Gorne, RG2

150	Gd 442a	6620 ± 180	
150	Gd 442b	6600 ± 250	
150	Gd 454		7430 ± 190
340	Gd 446	9360 ± 300	
	Gd 439		9470 ± 270
	Gd 438		9740 ± 300
450	Gd 449a	10020 ± 320	
450	Gd 449b	9880 ± 280	
450	Gd 445		9610 ± 210

Miedwie, MD3

170	Gd 459		2370 ± 150
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TABLE 4.2 Radio Carbon Dates on Polish Cores

tion for this is given in Chapter 5. As a result, all the lithology, palynology and radio-carbon dating work was carried out on cores from these four lakes.

Although most of the work was concentrated on these four lakes, it is interesting to look at some of the results obtained from the other lakes. Of these, Lake Miedwie did not give any cores which seemed to record a palaeomagnetic record. In the other lakes (Drawsko, Moszczonne, Sniardwy, Powidskie) it was very difficult to find more than one core that did not have a very scattered record or a large twist in it. Even if it was possible, no obvious correlation was found between them or with those from other lakes, with the possible exception of the inclination record. Fig. (4.6) shows a possible correlation between the inclination records from one core in each of these four lakes. As ~~it is~~ there is no palynological or radio-carbon data for these cores, it is impossible to say whether this is a correct correlation. The lettering on the diagram corresponds to the lettering used in chapter 3 and on the historic archaeomagnetic curve (Fig. 3.14). Two correlation tie lines are also drawn on as well as the lettering.

It is interesting to note that there seems to be a trend in the inclination record of Drawsko 6, leading to a shallowing of the inclination towards the bottom of the core. This trend could be similar in a way to the twist in the declination, and could be caused by the bending of the pliable PVC core tube as it is coring through the sediment. If the core did start to bend, then it would continue to do so until the end of the coring operation. A bend in the core tube while coring could lead to either a steepening or shallowing of the inclination record.

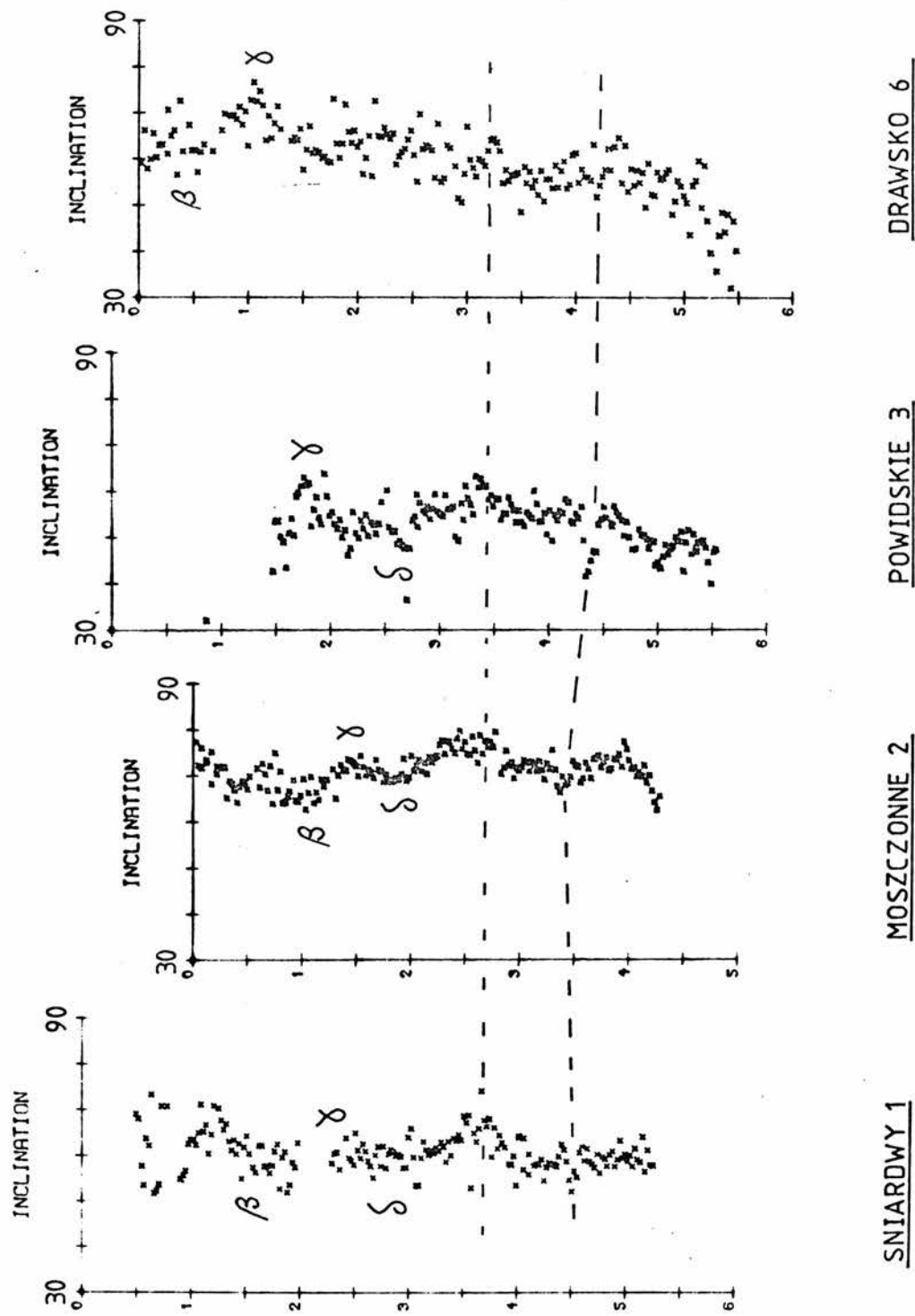


FIG 4-6 Selected Inclination Results from Sniardwy, Moszczonne, Powidkie & Drawsko

Fig. (4.7) shows the corresponding declination plots for these cores and as can be seen, there is no obvious correlation between them. There is however evidence to suggest that twisting may have occurred in all the cores except Powidskie.

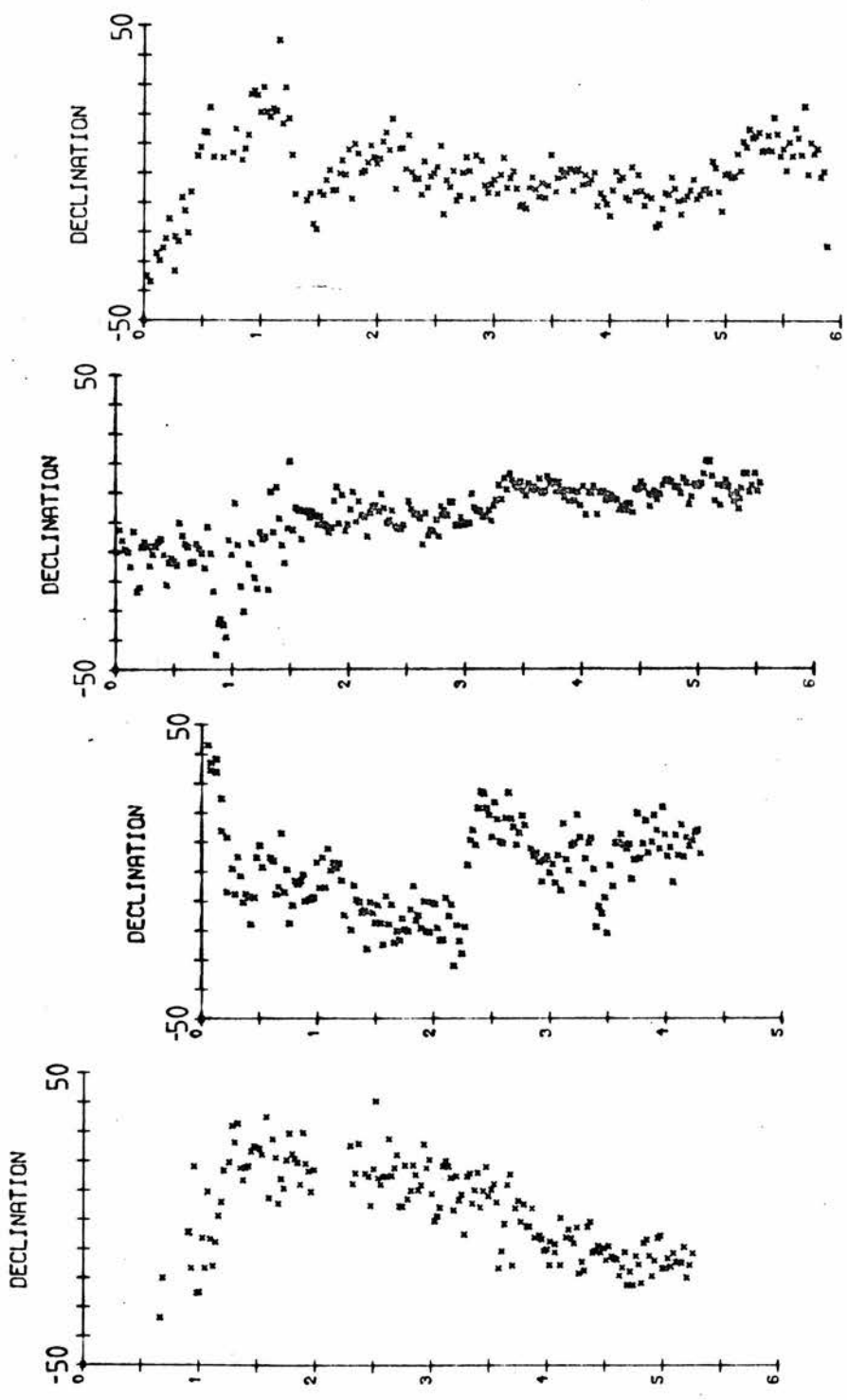
In the other four lakes, although some of the records tended to be scattered, both within lake and between lake correlations were possible.

Pilot samples from each lake were stepwise A.F. demagnetized similar to the procedure used for the samples discussed in chapter 3. Fig. (4.8, 4.9 and 4.10) show the results obtained for lakes Radunskie, Charzykowskie and Mikolajski. Typical M.D.F.'s lie between 200 and 250 oe. These values are substantially lower than those obtained from the French and Swiss lakes. A.F. demagnetization carried out on the other Polish lakes yielded M.D.F.'s of approximately 100-150 oe. This shows that the Polish samples are on the whole less stable than the French and Swiss ones.

Demagnetization carried out on whole cores did not enhance the sharpness of the declination and inclination logs. Most of the cores were however demagnetized in a peak field of 50 oe before measuring, to remove any soft component of magnetization.

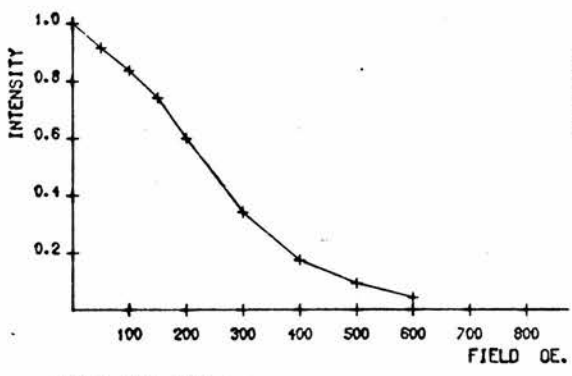
In the following sections, the palaeomagnetic results obtained from Lakes Radunskie, Charzykowskie, Mikolajski and Zarnowieckie are discussed. As before, the lettering not only shows the correlations between the lakes, but also corresponds to the lettering used on the other Polish lakes, the French and Swiss lakes, as well as the historic archaeomagnetic curves. Most of the correlations between cores from an individual lake have been based on the intensity and susceptibility data. Although no lettering is attached to these plots,



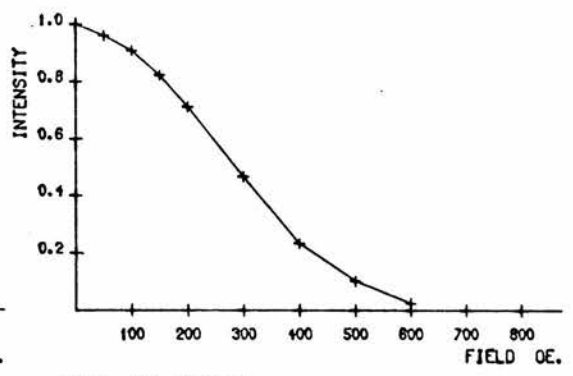


SNIARDWY 1                      MOSZCZONNE 2                      POWIDSKIE 3                      DRAWSKO 6

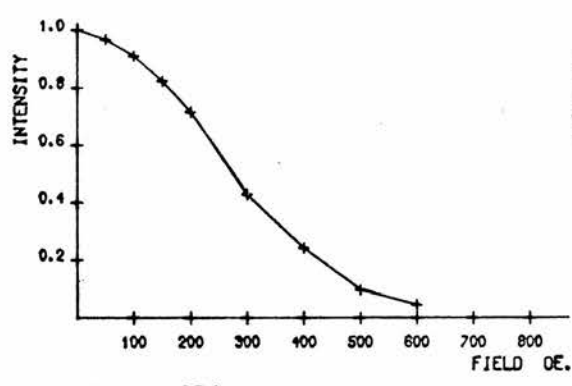
FIG 4-7 Declination Results Corresponding to Inclinations shown in fig 4-6



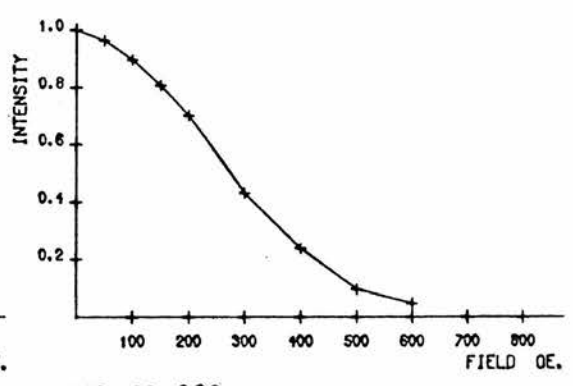
1RAG 20 47 cm



1RAG 80 189 cm



1RAG 100 234 cm



1RAG 120 282 cm

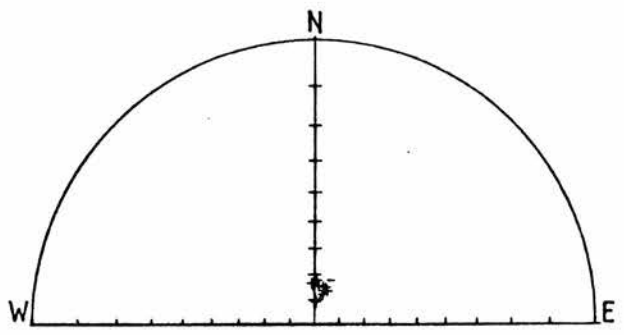
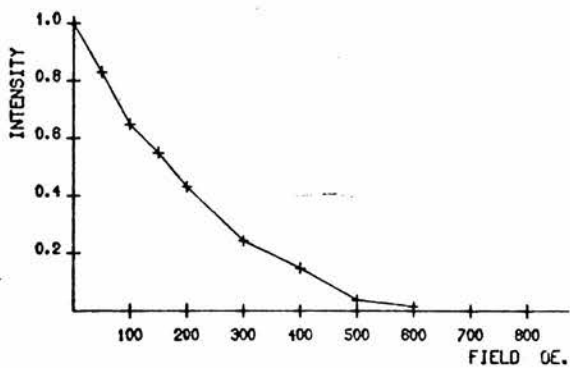
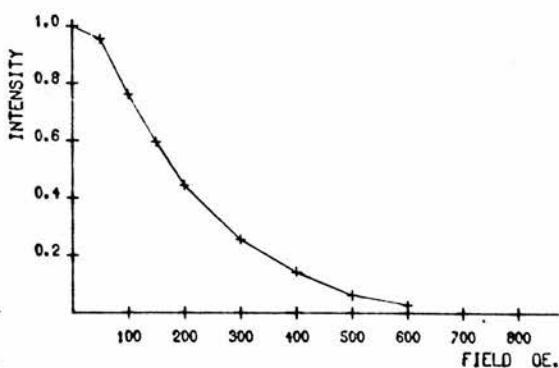


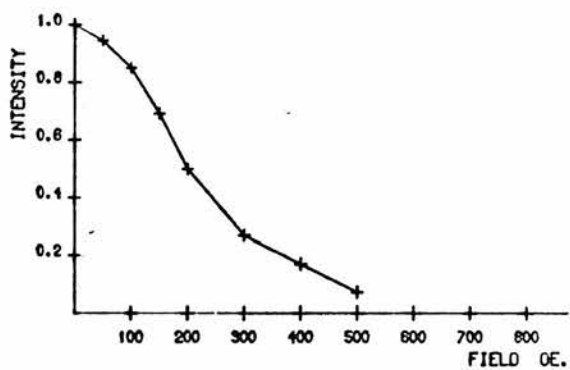
FIG 4-8 Demagnetization Results from Lake Radunskie-Gorne



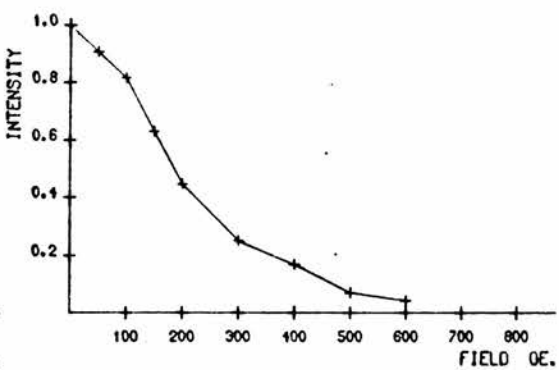
6CHA 30 87 cm



6CHA 90 229 cm



6CHA 120 299 cm



6CHA 180 439 cm

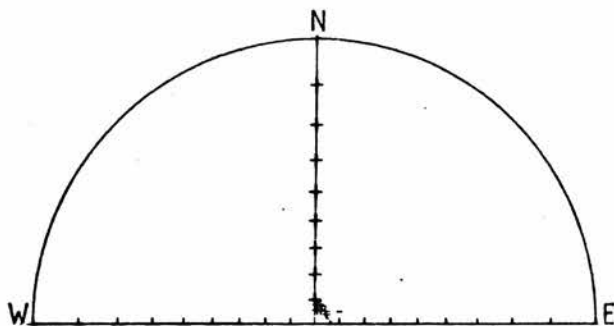
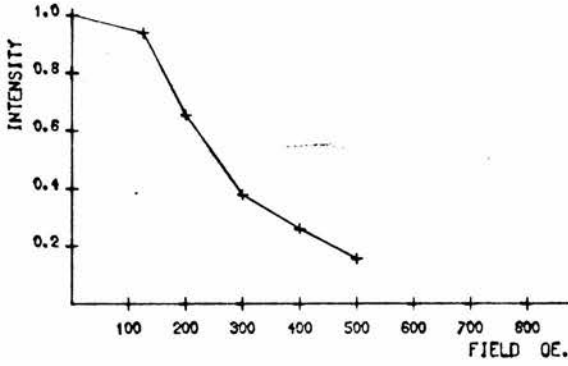
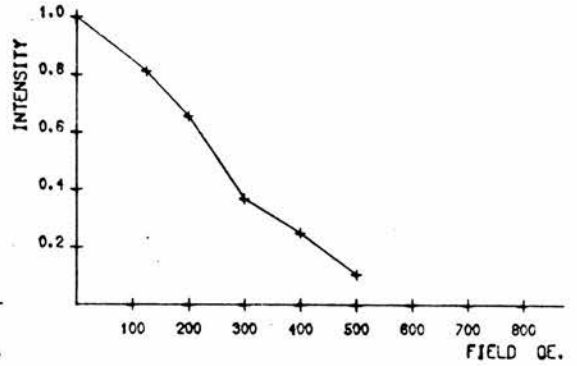


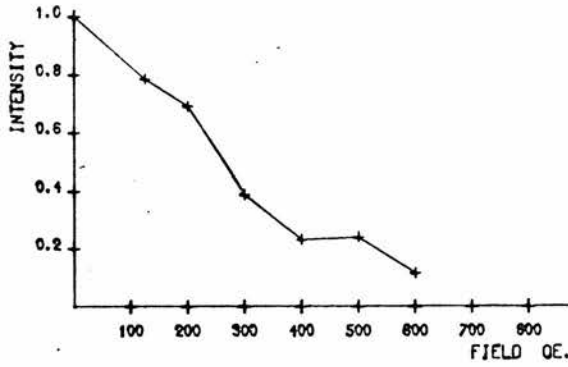
FIG 4-9 Demagnetization Results from Lake Charzykowskie



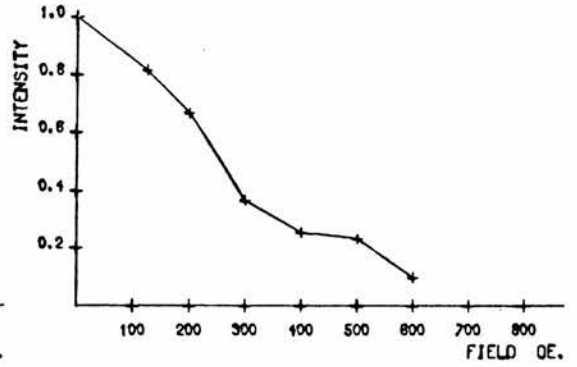
2MIK 120 279 cm



2MIK 150 352 cm



2MIK 180 423 cm



2MIK 210 502 cm

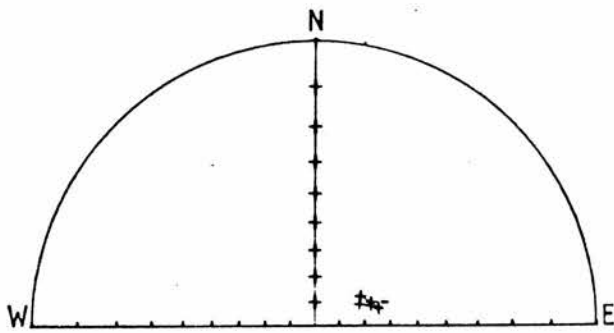


FIG 4-10 Demagnetization Results from Lake Mikolajski

correlation tie-lines have been drawn on to connect corresponding depths in the cores. Using these tie-lines a good correlation in the inclination records is generally found. However, many of the declination plots are rather scattered and the correlation between cores is not so obvious. In some cases for the declination, the labelling of the maxima and minima is put on at the correct depth, but not necessarily because a correlation between the cores is obvious.

#### 4.7 Palaeomagnetic Results from Lake Zarnowieckie

Fig. (4.11) shows the results obtained from cores 3 and 6 from Lake Zarnowieckie (Z3 and Z6). Any correlation in the susceptibility records is made impossible by the fact that most of core 3 has  $k$  values of less than  $1\mu\text{G}/\text{oe}$ . Even if these values were shown on the plot they would appear very scattered as recordings of less than  $1\mu\text{G}/\text{oe}$  obtained from the susceptibility bridge cannot be taken as accurate. From the intensity plots it can be seen that the two cores have approximately the same rate of sedimentation. An obvious disturbance in the sediment can be seen on the D, I and J plots at a depth of 5.00m in Z3 and at a depth of 4.60m in Z6.

The correlation and labelling of the declination and inclination plots is done by taking into account the palynological data for core Z3. The Sub-Boreal/Sub-Atlantic boundary (2,000 yr B P) is found to be between 2.00m and 2.80m in Z3. The inclination maxima labelled is dated at 2,000 yr B.P. from the archaeomagnetic curve and hence must lie in the above range. Below this depth of 2.80m, correlation of the D and I records becomes rather difficult and hence no labelling has been attempted.

#### 4.8 Palaeomagnetic Results from Lake Mikolajski

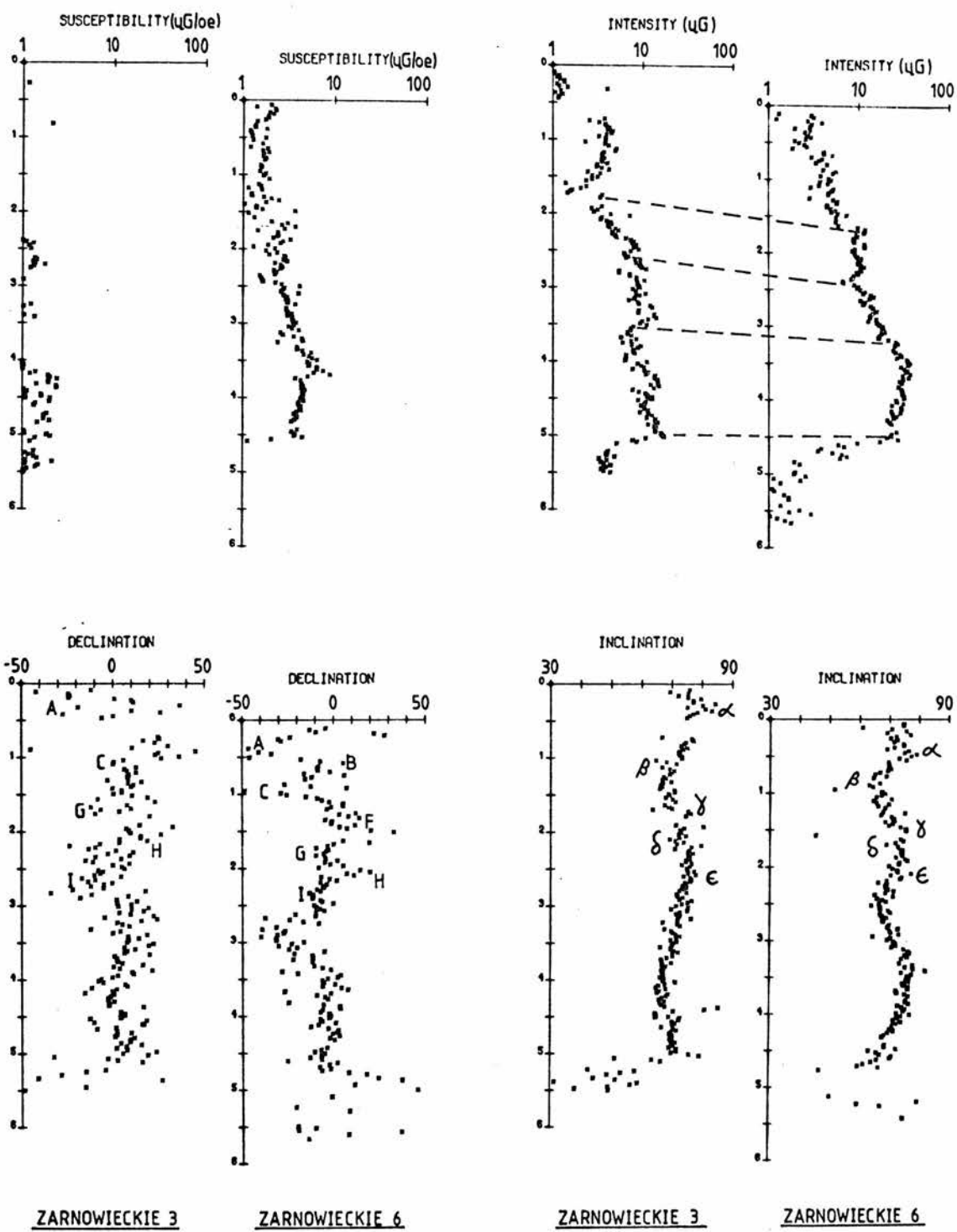


FIG 4-11 Palaeomagnetic Results from Zarnowieckie Cores 3 & 6

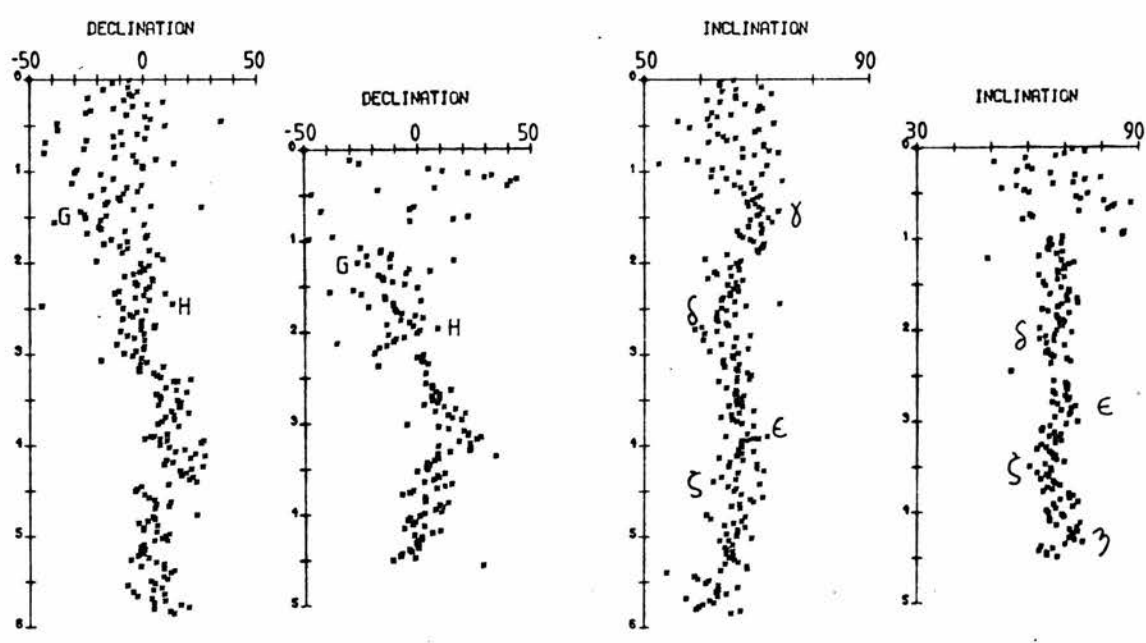
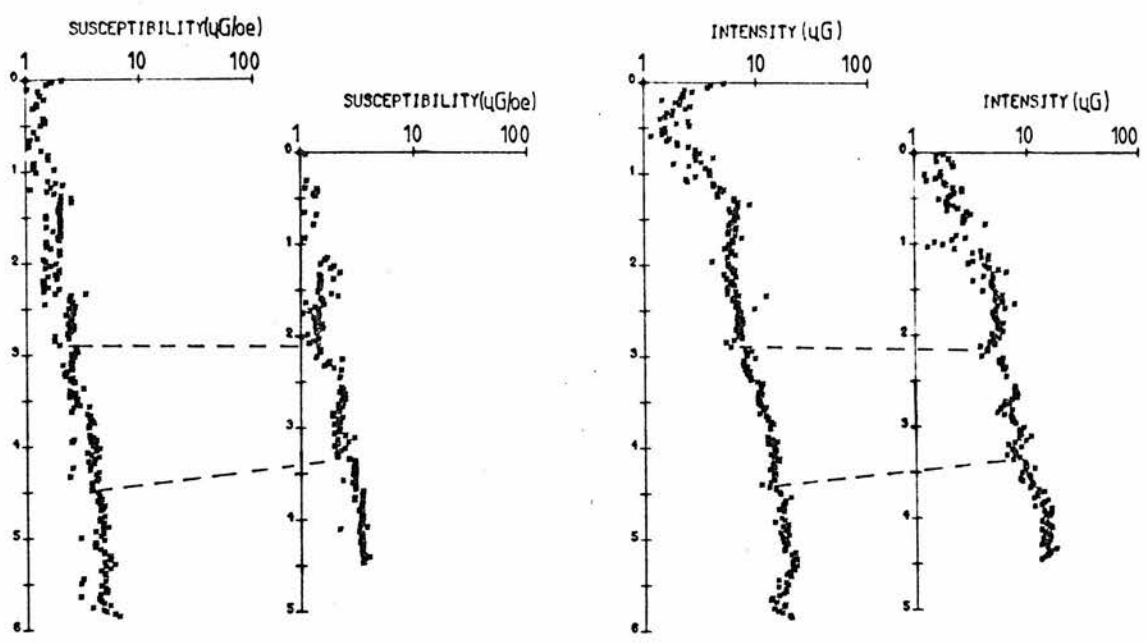
Fig. (4.12) shows the plots obtained for Mikolajski cores 2 and 3 (MK2 and MK3). A correlation this time between the susceptibility and the intensity records is possible. It would appear that Mikolajski has one of the fastest sedimentation rates of the lakes studied and this is in fact confirmed by the radio-carbon dating.

The very scattered D and I records at the top of the cores can probably be attributed to expansion of the sediment on opening, caused by the very high gas content in the core. A substantial release of gas occurred when both of these cores were opened. Wieckowski (1969) also found that a characteristic feature of the deposits in Mikolajski was their high content of  $\text{CH}_4$ ,  $\text{CO}_2$ , and H gases under pressure, and that after a core sample had been extracted, the expansion of these gases was apt to increase the core length by approximately 10%.

A correlation of the declination records is very difficult as a result of this scatter. The sudden shift in declination record in MK2 at about 3m is not real, and was probably caused by an orientation error in cutting the core tube at this point. This is confirmed by the long core plot (not shown), which does not show a shift in declination at this point. The discontinuity in the D plot for MK3 at 2.25m is due to a disturbance in the sediment as shown in the long core plot in Fig. (4.5).

#### 4.9 Palaeomagnetic Results from Lake Charzykowskie

The plots of susceptibility and intensity for this lake are shown on Fig. (4.13) and for declination and inclination on Fig. (4.14). Coring sites for CH2 and CH6 are situated in the same basin whereas CH8 is situated in a separate basin some 3.7 km to the north.(Fig. (4.2)). Therefore we would expect to find a closer



MIKOLAJSKI 2

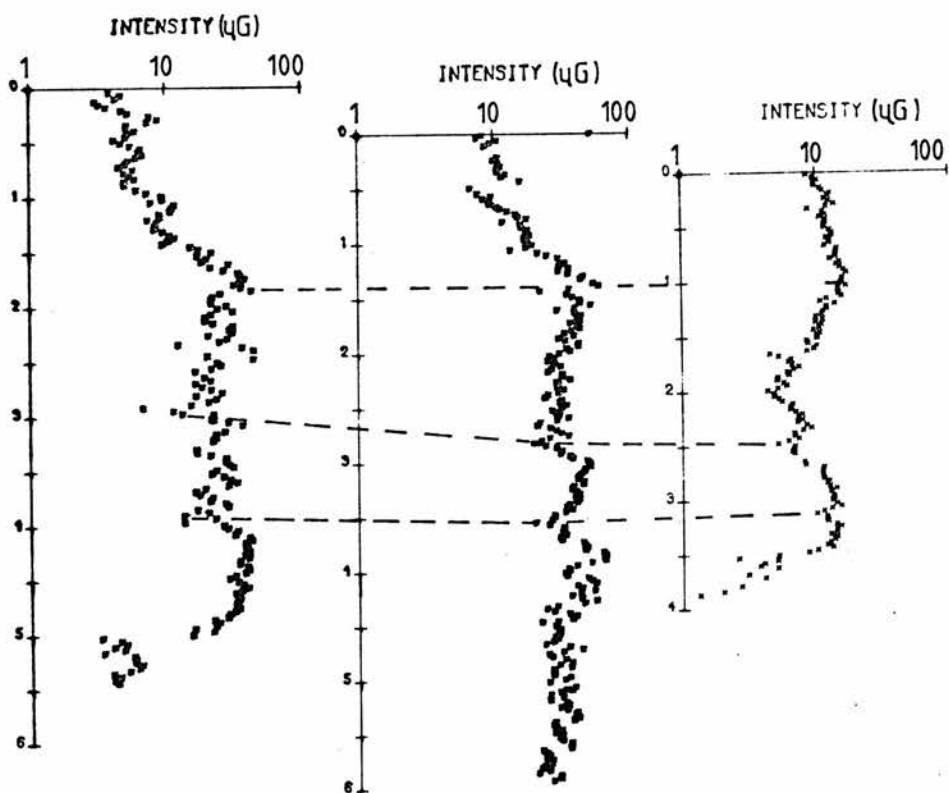
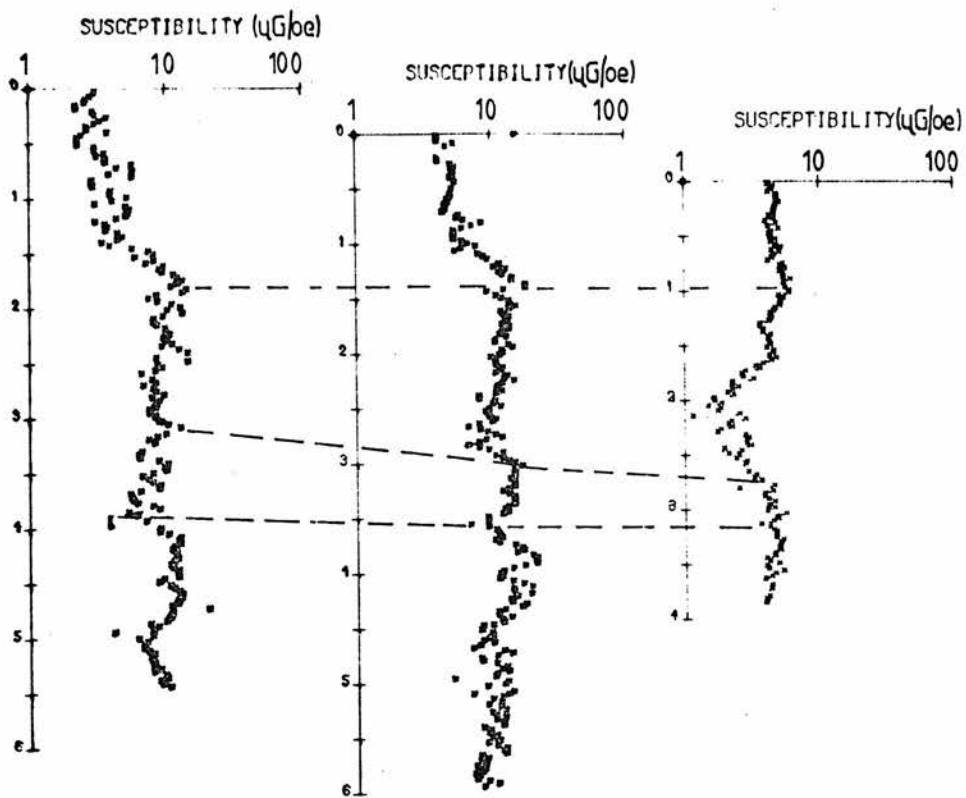
MIKOLAJSKI 3

MIKOLAJSKI 2

MIKOLAJSKI 3

FIG 4-12 Palaeomagnetic Results from Mikolajski Cores 2 & 3





CHARZYKOWSKIE 2

CHARZYKOWSKIE 6

CHARZYKOWSKIE 8

FIG 4-13 Plots of Susceptibility and Intensity from Charzykowskie Cores 2,6&8

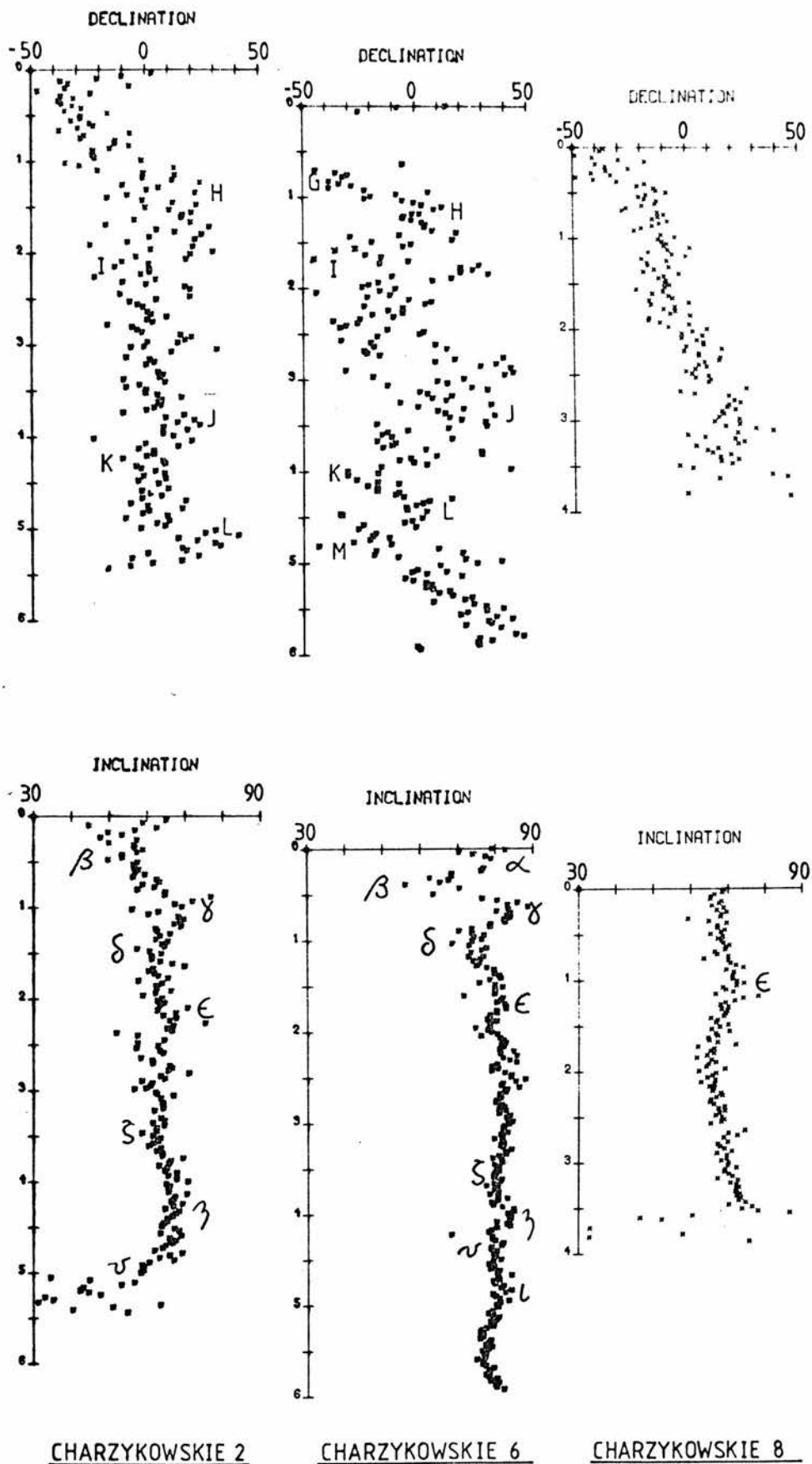


FIG 4-14 Plots of Declination and Inclination from  
Charzykowskie Cores 2, 6 & 8

correlation between CH2 and CH6 than of either of these with CH8. As can be seen from Figs. (4.13 and 4.14), this is in fact the case. CH2 and CH6 show a clear correlation in both the k and the J logs, but the correlation with CH8 is not as obvious. As before, the declination logs, although being greatly scattered, do show certain maximum and minimum features. Unfortunately the swing K-L-M cannot be distinguished in core 6 because of the scatter. No correlation in declination is possible with CH8 and it is obvious from the declination plot that this core has been badly twisted. No correlation can be found either with the inclination record. This may be due to the lower sedimentation rate which is apparent in core 8, a depth of 1.00m in CH8 representing approximate depths of 2.00m and 1.50m in cores CH2 and CH6 respectively.

#### 4.10 Palaeomagnetic Results from Lake Radunskie -Dolne

Fig. (4.15) shows the results obtained from Lake Radunskie-Dolne cores 3 and 4 (RD3 and RD4). Here again an obvious correlation is seen both in the k and J logs. From this it would seem that the two cores have an approximately equal sedimentation rate, which should be the case as they were collected from the same site. The inclination logs from these two cores are probably the best ones obtained from any of the lakes studied. The inclination record from RD3 would seem to correlate extremely well with that of Annecy 5 (see Fig. 3.13). This would give RD3 a date of approximately 3,800 yr B.P. at a depth of about 3.40m. By correlation with Radunskie-Gorne a palynological age of 5,000 yr B P is possible down to a depth of 4.30m for RD3 which is in agreement with the age obtained from the inclination records.

In the declination records, there seems to be a correlation

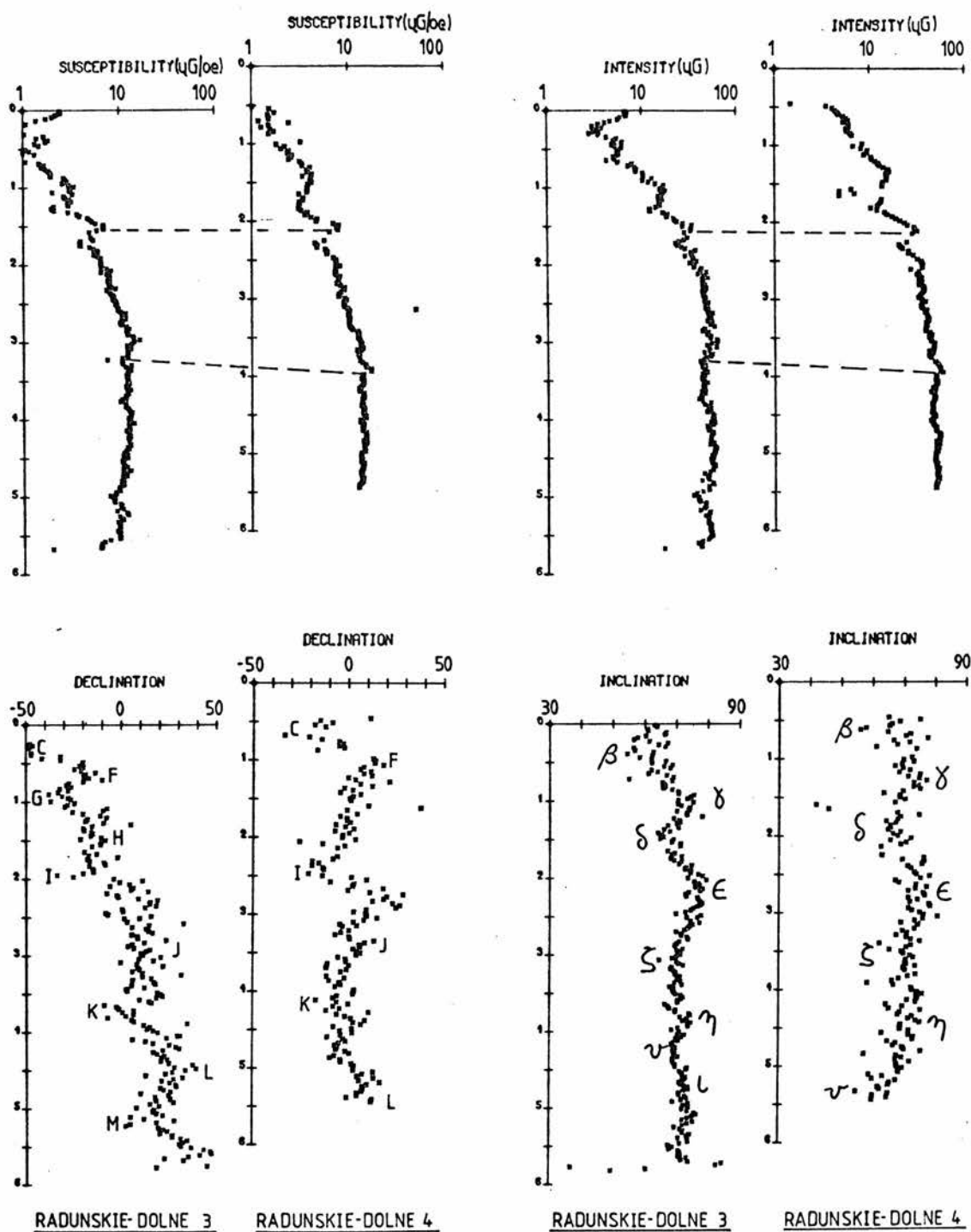


FIG 4-15 Palaeomagnetic Results from Radunskie-Dolne Cores 3 & 4

if we take into account the fact that core RD3 is twisted (as seen by the scribe mark on the core tube; see Table 4.1). Although RD4 was subsampled in Warsaw and hence was not long core measured, it would seem that the top 2.50m of this core may also be twisted. As a result of this, the declination swing G-H-I seems to be lost.

#### 4.11 Palaeomagnetic Results from Lake Radunskie - Gorne

Fig. (4.16) shows the k and J logs obtained from cores 1, 2, 3 and 4 (RG1, RG2, RG3 and RG4). Fig. (4.17) shows the corresponding D and I plots for these cores. RG1 and RG2 were taken from the same site and RG3 and RG4 from another site approximately 2km distant. These plots reveal a similar sedimentation rate in all of the cores.

As with all the other lakes, a positive correlation can be found in the inclination records, whereas one in the declination records is perhaps rather dubious. Core RG3 shows definite signs of twisting and from the scribe mark information in Table 4.1 it can be seen that the bottom 1.00m of RG1 and the top 1.00m of RG4 are also twisted. Although the declination plots have been labelled, this has been done using the information from the inclination plots and not by correlation of the declination records themselves.

In core RG2 between 3.20m and 3.50m a disturbance can be seen in the D, I and J plots. This would appear to have been caused by a slumping of sediment in this region of the core. The disturbance can be seen at the very bottom of RG1, especially in the intensity record. The disturbance in core RG2 seems to have obscured the swing J-K-L in the declination record.

#### 4.12 Comparison of Magnetic, Radio-carbon and Palynological Results

As was discussed earlier in the chapter, the radio-carbon ages

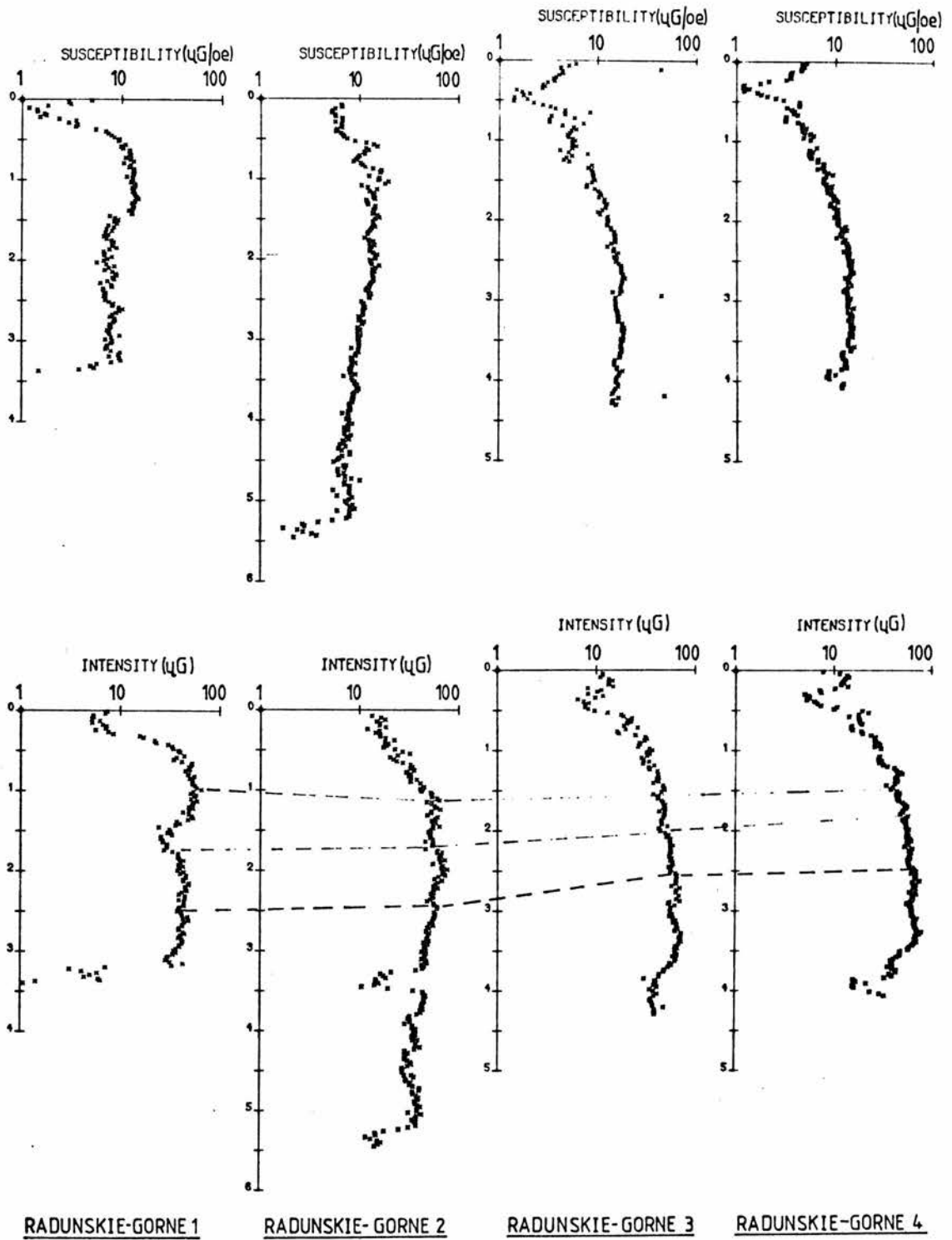


FIG 4-16 Plots of Susceptibility and Intensity from Radunskie-Gorne Cores 1,2,3 & 4

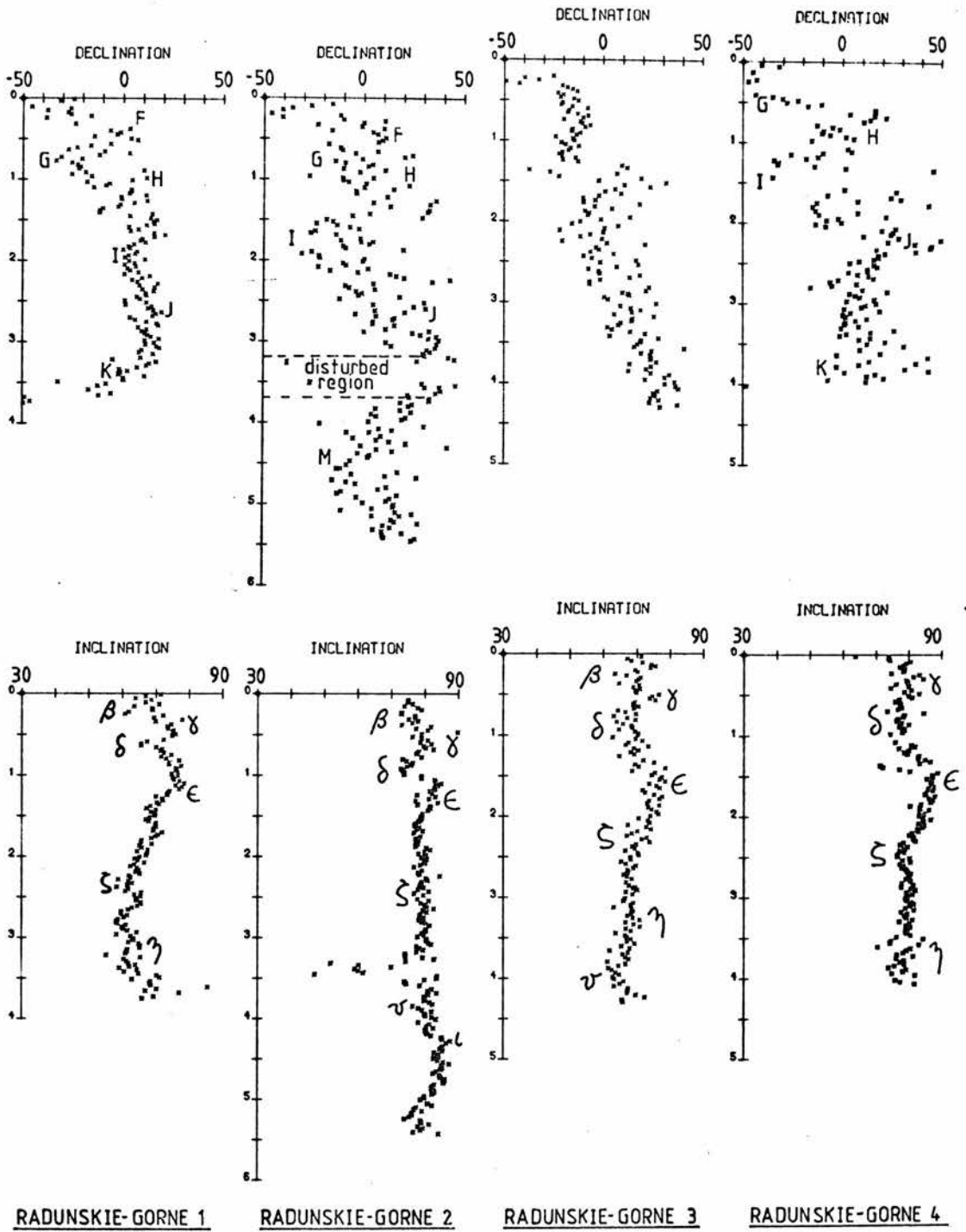


FIG 4-17 Plots of Declination and Inclination from Radunskie-Gorne  
Cores 1,2,3 & 4

obtained for the Polish lakes were found to be always older than the palynological ages. As will be shown here, they were also found to be older than the 'magnetic' ages ascribed to the plots. Figs. (4.18 and 4.19) show the result of plotting the radio-carbon and palynological ages against depth for core RG2 and CH6. Apart from the very large uncertainty in RG2 (Fig. 4.18) for the palynological age, it is obvious that radio-carbon ages on both the carbonate and organic extracts are older than the palynological one. The large error in the pollen date arises from the fact that the core was not sampled at close enough intervals to obtain an accurate date. It can also be seen that the age centred on 3.30m is approximately the same as that for 4.60m. This can be attributed to the disturbance in the core between 3.20m and 3.50m as was seen in Figs. (4.16 and 4.17), or just due to the inaccuracy of the dating. Even if this date is taken to be correct, the inaccuracy of the dating of lacustrine sediments is displayed in this figure. On Fig. (4.18), the two extreme fitting lines (a and b) have been drawn through the *organic* radio-carbon dates. The equations for these two lines are

$$t = 14.43d + 3950 \quad - (a)$$

$$t = 8.80d + 5750 \quad - (b)$$

These two equations lead to an average sedimentation rate of 0.69mm/yr for (a) and to 1.14mm/yr for (b), assuming the constant term to be corrected to zero. These equations are of course assuming a constant sedimentation rate and, as can be seen, lead to two significantly different answers. The constant term in the two equations is the 'apparent age' of the sediment (i.e. the age at zero depth). If we assume the 3.50m date to be in error and disregard it, or if a non-uniform sedimentation rate is assumed, even larger discrepancies will



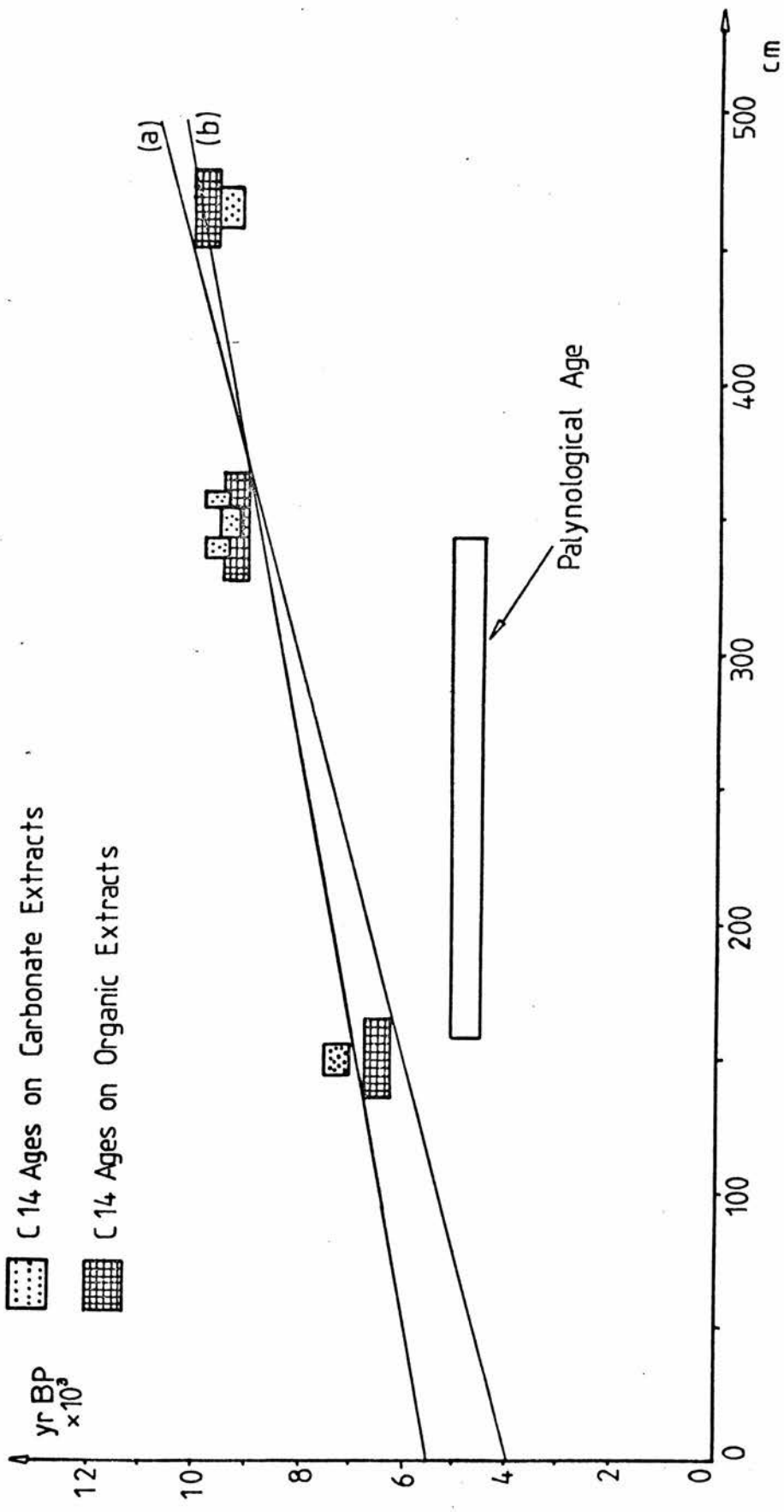


FIG 4-18 Plot of Radio-Carbon and Palynological Ages versus Depth for Core RG 2

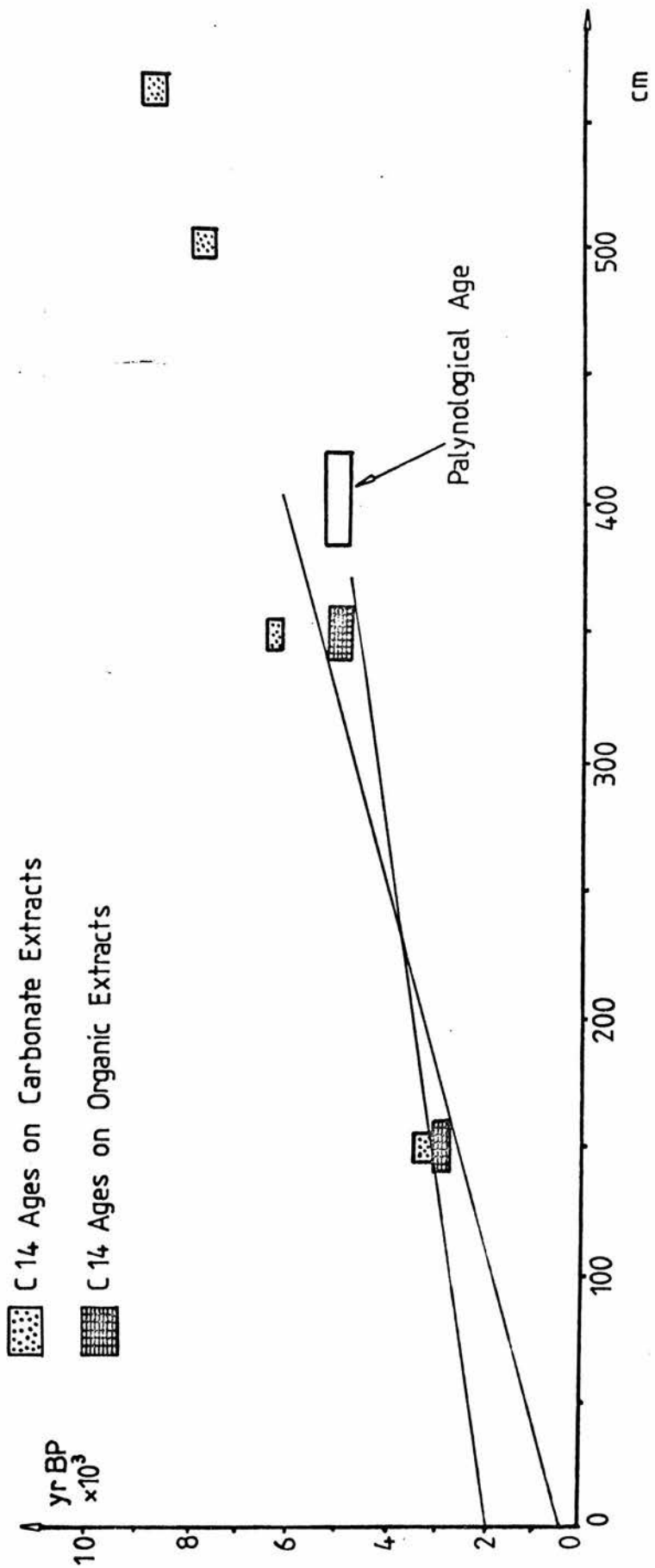


FIG 4-19 Plot of Radio-Carbon and Palytological Ages versus Depth for Core CH 6

occur in the average sedimentation rate.

Table (4.3) summarizes all of the palaeomagnetic data obtained from the Polish lakes and also shows the ages acquired from magnetic, palynological and radio-carbon dating. The first two columns of the table show the relative positioning of the inclination and declination swings as labelled in previous diagrams. Column 3 gives the archaeomagnetic age of the swings as shown in Fig. (3.14). Column 4 shows the palynological dates obtained from cores ZR3 and RG2. Column 5 shows the dates obtained if we subtract the average "apparent age" of the radio-carbon dates from the dates measured. The date measured was taken as the average date for the organic extract. For RG2 the average apparent age is 4850 yr, and for CH6 it is approximately 1,000 yr. The organic dates for Mikolajski appear to have zero "apparent age". The final column shows the positioning and the ages of the Windermere swings shown in Fig. (3.33), if a correlation between the Polish lakes and Windermere is attempted.

It would seem that certain of the Polish declination maxima and minima can be correlated with these seen at Windermere, but because of the faster sedimentation rates, other swings may also be distinguished. This was also the case for the French and Swiss lakes.

Inclination Swings	Declination Swings	Archaeo-magnetic Age (yr B.P.)	Palynological Age (yr B.P.)	'Corrected' C14	Windermere Swing & Age
$\alpha$	A	150			a (150)
$\beta$	B				
	C	600			
	F				
$\gamma$	G	1200			
$\delta$	H	1600		1640 (MK2)	b (1500)
				1850 (CH6)	
$\epsilon$		2000	2000 (ZR3)	1760 (RG2)	
	I $\updownarrow$				c (2600)
$\zeta$	J $\updownarrow$			3150 (MK2)	
	K			3870 (CH6)	d (3900)
$\eta$				4510 (RG2)	
$\nu$	L		5000(RG2)		
$\iota$	M			5150 (RG2)	e (5300)

TABLE 4.3 Relative Positioning of Inclination and Declination Swings with Increasing Depth down Core with Related Ages Obtained from Archaeomagnetic, Palynological, and Radio Carbon Data

## CHAPTER 5

### Investigations into the Carriers of the N.R.M.

#### 5.1 Introduction

The object of the following experiments was to try to identify both the sizes and the types of particles carrying the remanent magnetization in both the French and the Polish samples. It was also hoped that these experiments might help explain why the Polish sediments did not seem to be as good recorders of the geomagnetic field secular variations as the sediments collected from Central Europe.

The experiments carried out included the measurement of A.R.M.'s and I.R.M.'s of chosen pilot samples, as well as magnetic separation, X-ray analysis, optical microscopy and thermomagnetic measurements.

#### 5.2 Hysteresis of Isothermal Remanence

One helpful experiment in determining the properties of the magnetic minerals is to obtain a hysteresis loop for the different samples studied. Because of the obvious experimental difficulties in obtaining complete hysteresis curves, it is more convenient to study the hysteresis of I.R.M. If a sample is placed in a magnetic field and the field is then reduced to zero, all at room temperature, the sample acquires a remanent magnetization.

If this

procedure is continued in increasing applied field strengths, a maximum value of the remanence is obtained and is called the saturation isothermal remanence (S.I.R.M.) and is denoted by  $J_{RS}$ . The field at which this saturation occurs is called the remanent saturating field  $H_{sat}$ . If successively increasing fields are applied to the sample in the reverse direction the remanence will be reduced to zero. The 'back' field required to reduce  $J_{RS}$  to zero is called the coer-

civity of saturation remanence and is denoted by  $H_{cr}$ . This procedure was carried out on chosen samples from the different lakes using an electromagnet to supply the increasing field.

Roquet (1947, 1954) studied the response of both magnetite and haematite powders to this experimental procedure. She found that magnetite saturated in a field of approximately a few thousand oersted and that the coercive<sup>ity of</sup> remanence was in the order of 300 oe. On the other hand, haematite did not saturate in fields of 30,000 oe and had a coercive<sup>ity of</sup> remanence of several thousand oersteds. So, as a result of this very high saturating field for haematite, this experiment carried out up to a field of 10K oe should show the presence of haematite in our samples if it exists. It should be noted that for convenience and speed of measuring, the samples were only placed in the applied field and removed again into the earth's field while the magnet remained switched on. As a result of this and also the non-uniformity of the field at the edges of the pole pieces, the intensity of the remanence can be found to decrease by as much as 10% at higher fields. This will be due to the disalignment of the magnetic grains as the sample is passed through this non-uniform field. Some of the samples showing this decrease at higher fields were remeasured after leaving them in position while the field was reduced to zero. They all showed a constant saturation value up to 10 K oe. Because of this, the graphs displaying the experimental results have been adjusted to show this constant value rather than the actual decrease that was measured. Figs. (5.1, 5.2 and 5.3) show the results obtained from the French and Swiss lakes and Figs. (5.4 and 5.5) show the results from the Polish lakes. Only one plot is shown for each lake except Lac de Joux because of the similarity of the results obtained

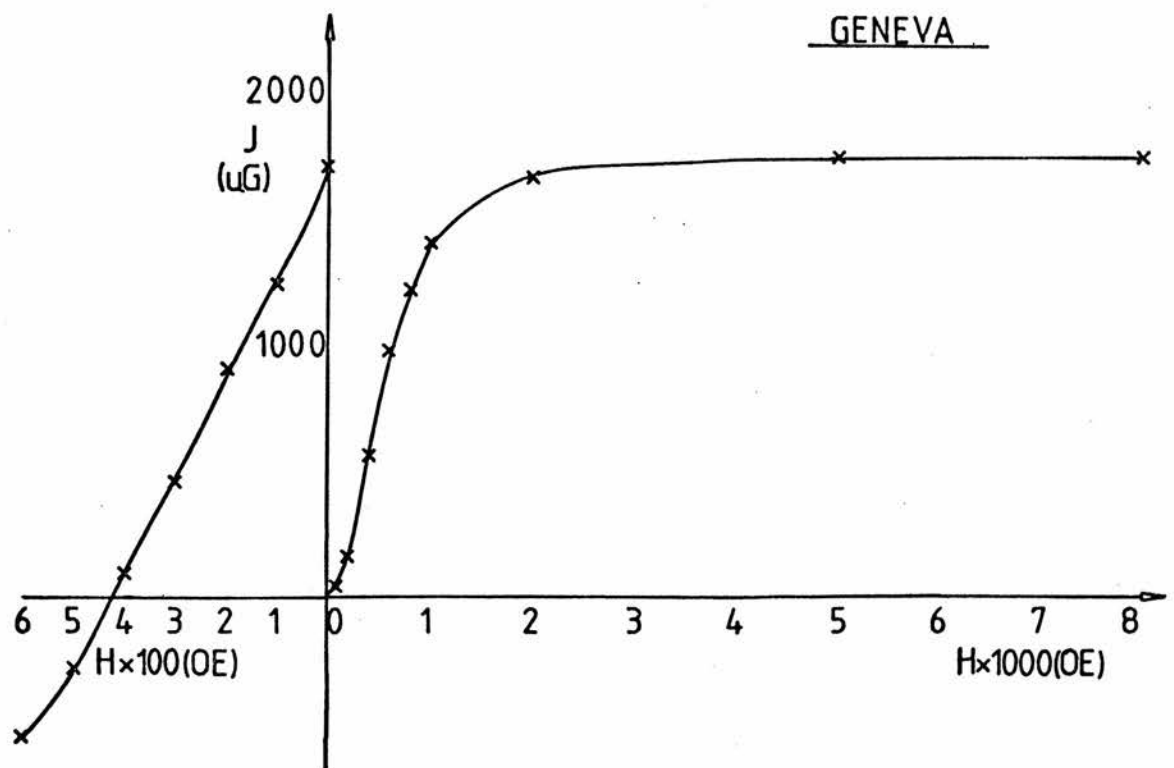
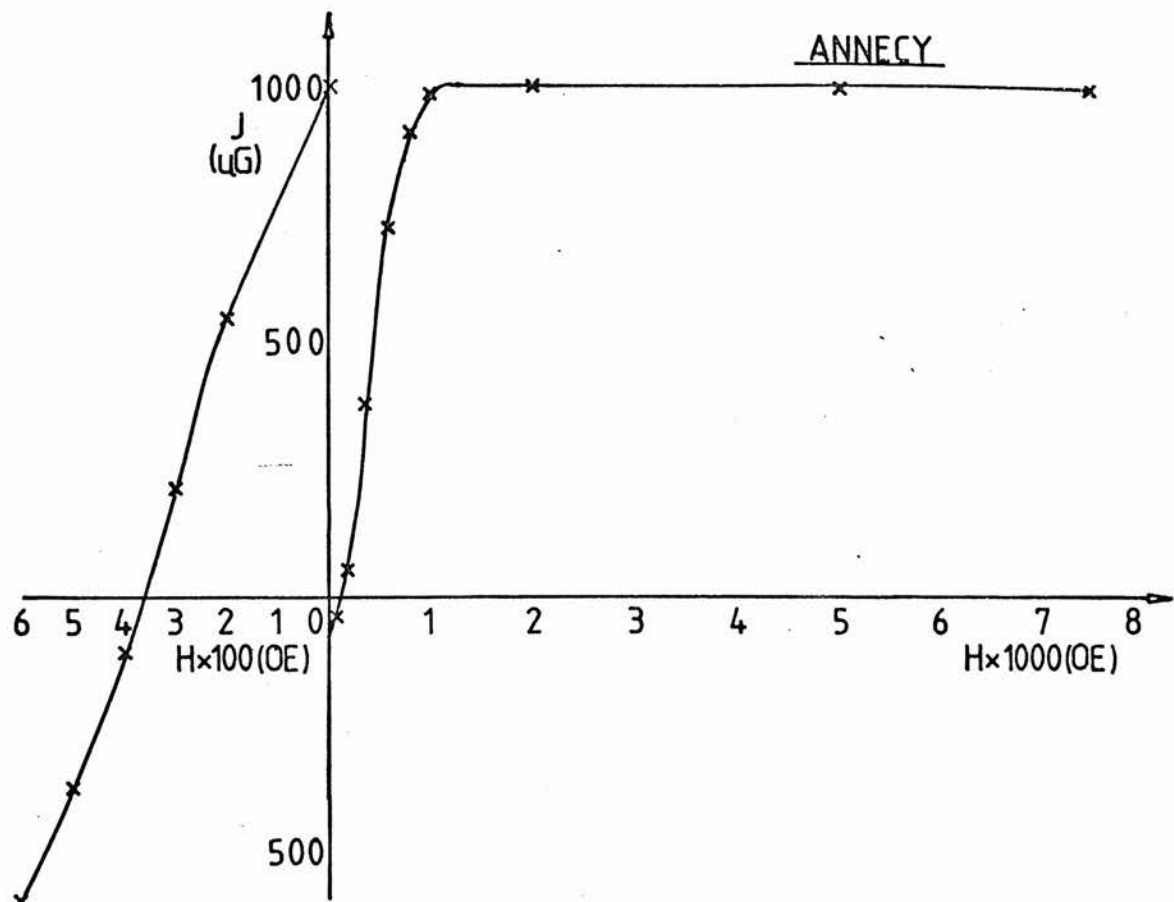


FIG 51 Hysteresis of IRM in Lakes Annecy & Geneva

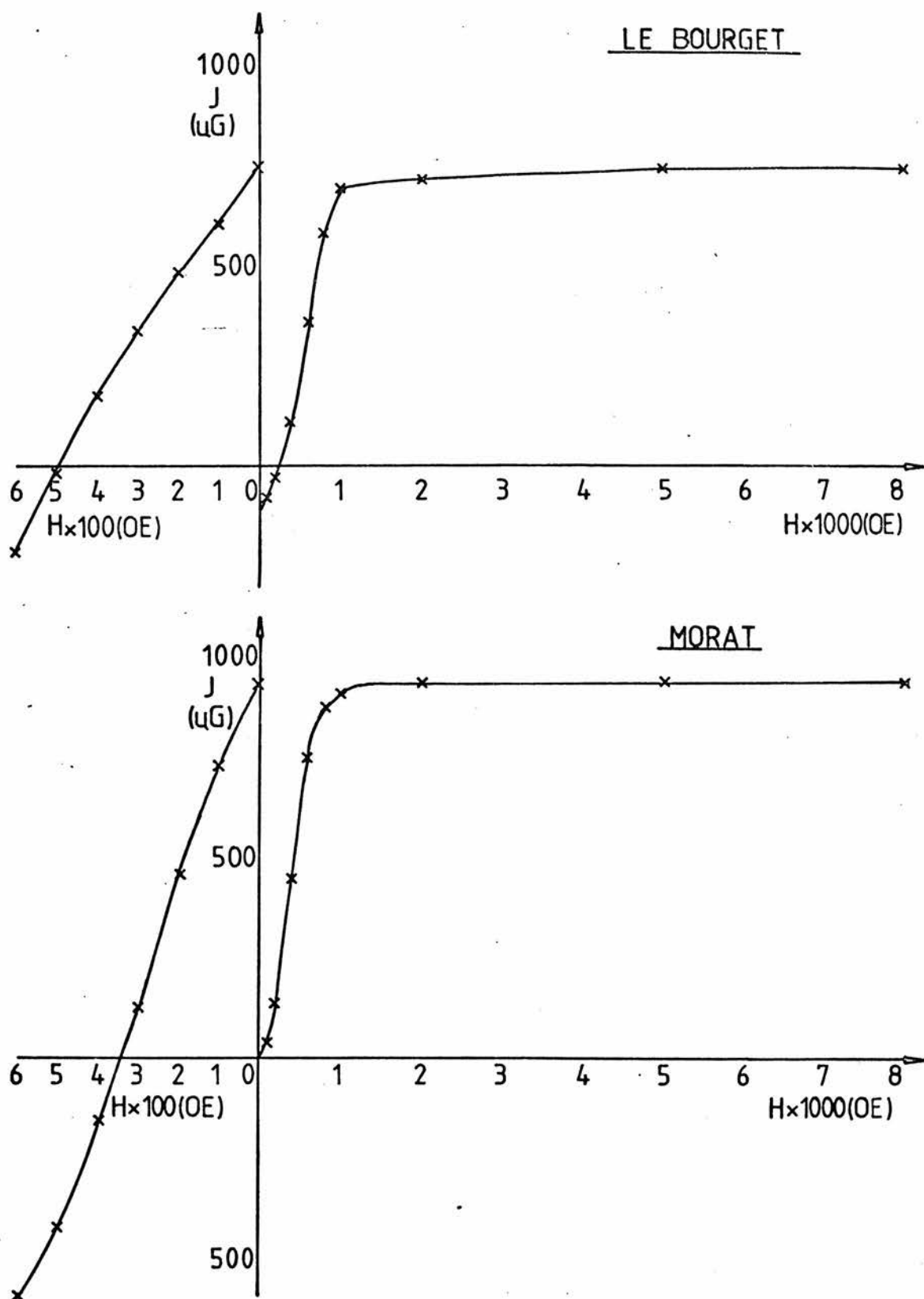


FIG 5-2 Hysteresis of IRM in Lakes Le Bourget & Morat



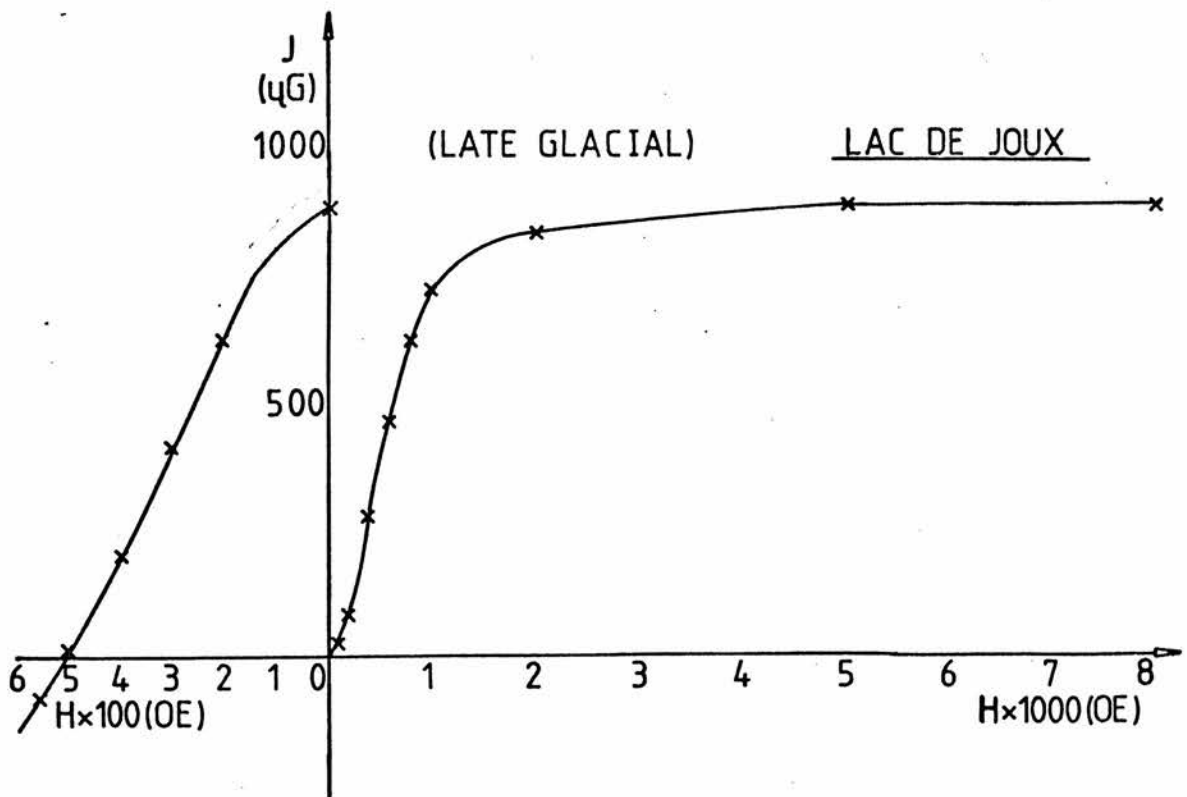
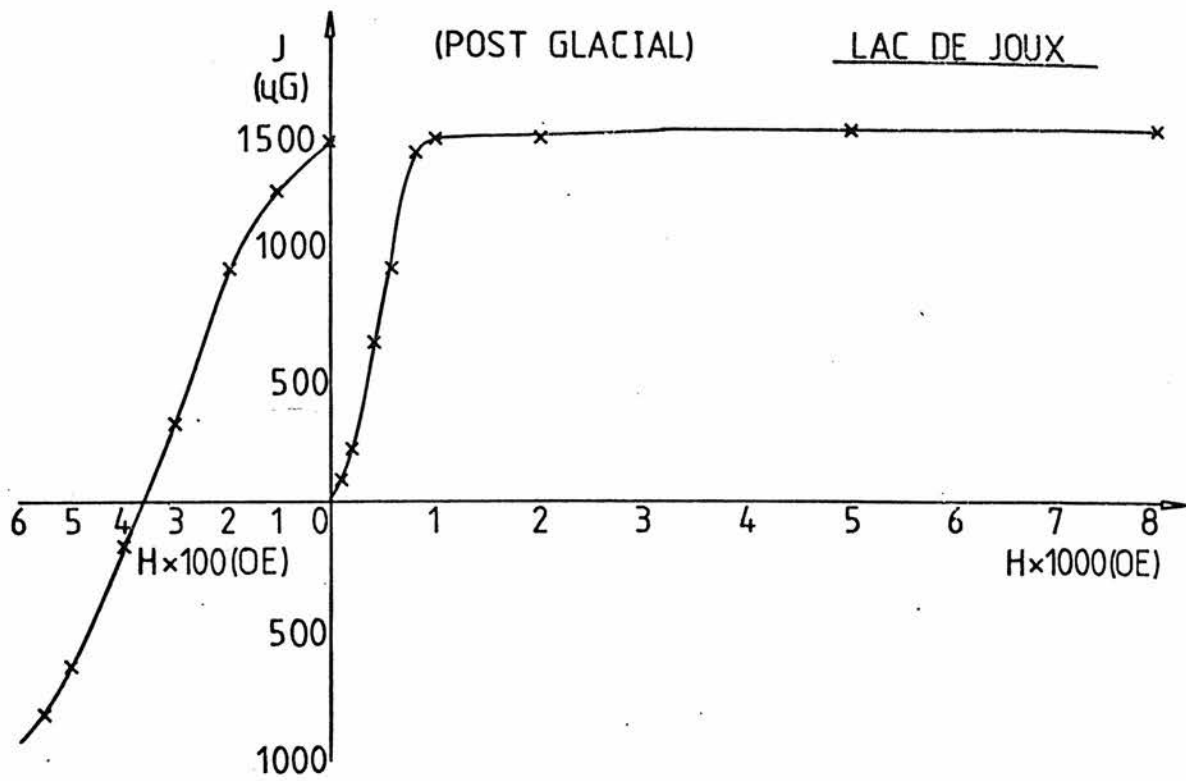


FIG 5-3 Hysteresis of IRM in Lac de Joux

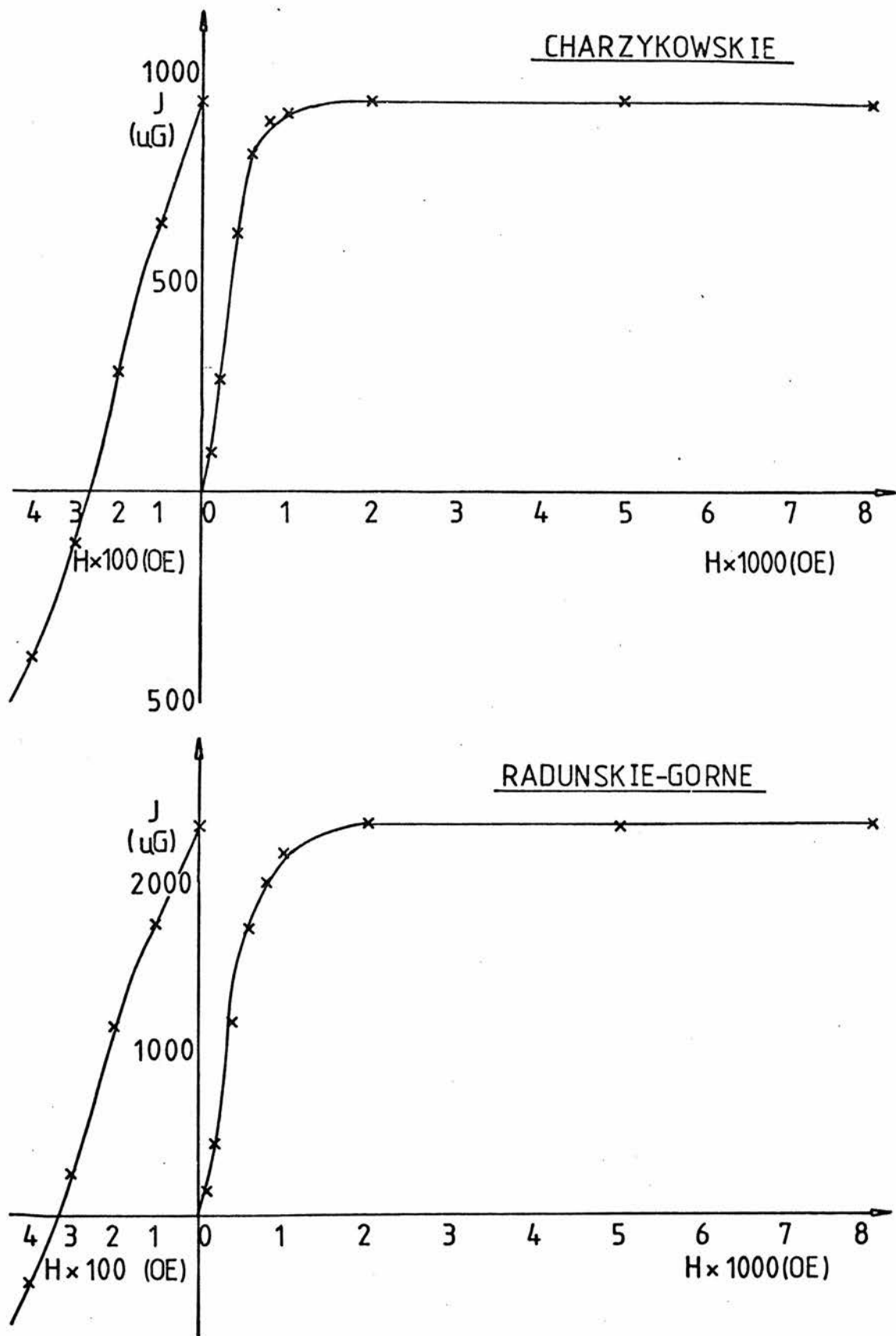


FIG 5.4 Hysteresis of IRM in Lakes Charzykowskie & Radunskie-Gorne

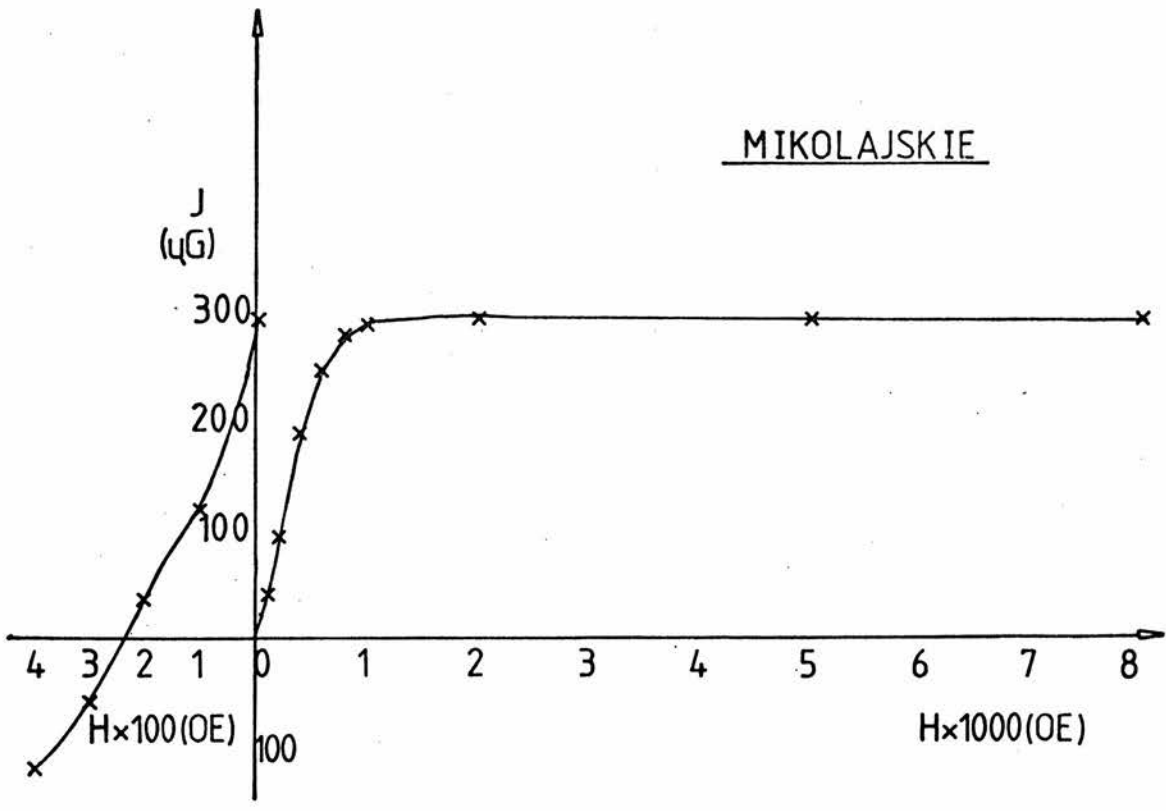
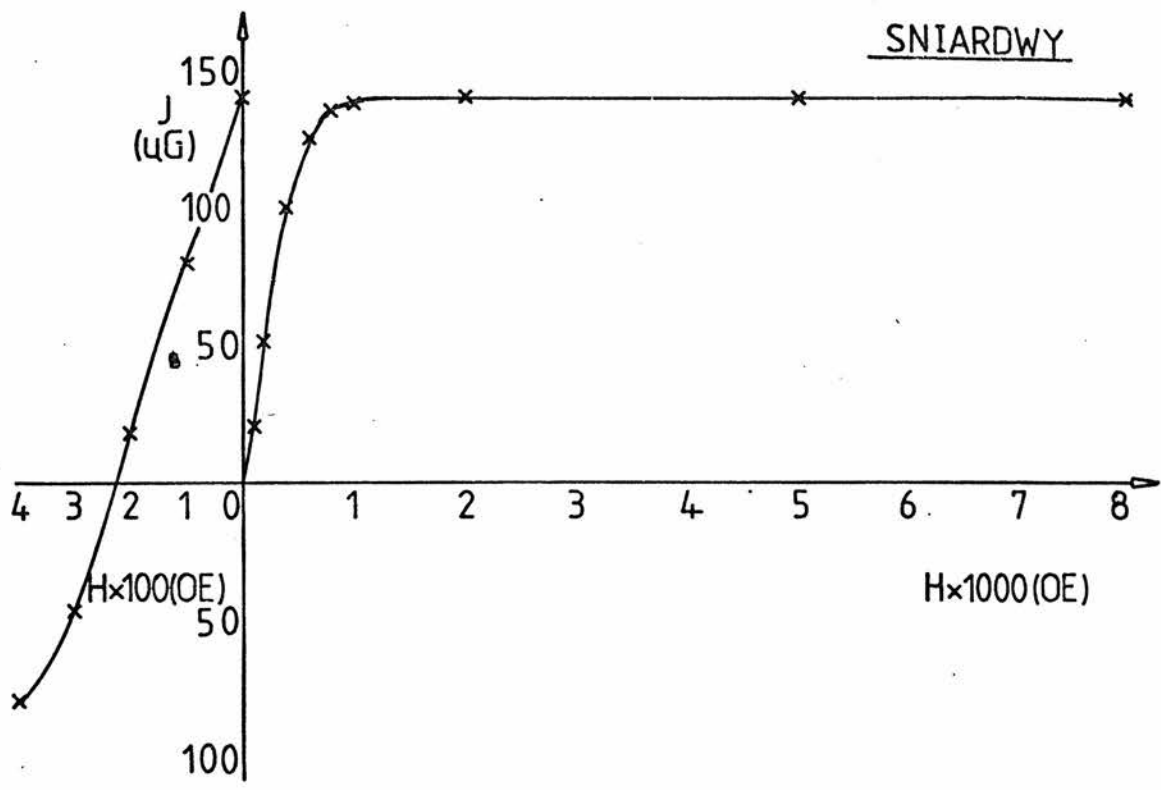


FIG 5-5 Hysteresis of IRM in Lakes Sniardwy & Mikolajskie

within each lake. Lac de Joux however showed a distinct difference between the post glacial and late glacial.

For the French and Swiss lakes, the Morat, Annecy, and post glacial Lac de Joux sediments below 1.00m depth, all have  $H_{\text{sat}} \approx 1,500$  oe, and  $H_{\text{Cr}} \approx 350$  oe. This would suggest the presence of magnetite rather than haematite, although the  $H_{\text{Cr}}$  value is fractionally high for magnetite and may suggest a very small quantity of haematite. Both Geneva and Le Bourget have  $H_{\text{sat}} \approx 5,000$  oe and  $H_{\text{Cr}}$  between 425 and 500 oe. Both of these values are too high to be solely due to magnetite, and would suggest a mixture of magnetite and haematite, but still dominated by the magnetite. The Lac de Joux late glacial clays do not saturate even in 10 K oe and have an average  $H_{\text{Cr}}$  value of approximately 500 oe. This  $H_{\text{Cr}}$  value is however rather low for haematite alone, and again would suggest a mixture of magnetite and haematite, with the proportion of haematite being greater than in Le Bourget and Geneva.

All of the Polish lakes, with the possible exception of Radunskie-Gorne, showed a definite magnetite behaviour. They all saturated between 1 and 2 K oe and had  $H_{\text{Cr}}$  values of between 200 and 300 oe. There is perhaps some evidence to suggest very small quantities of haematite in Radunskie -Gorne. As a result of the similarity in the  $H_{\text{sat}}$  and  $H_{\text{Cr}}$  values for all the lakes, two plots are shown from each extreme regarding the  $J_{\text{rs}}$  values. As can be seen, Radunskie-Gorne has a  $J_{\text{rs}}$  value of  $2,300 \mu\text{G}$  and Sniardwy  $140 \mu\text{G}$ . These very low  $J_{\text{rs}}$  values would suggest almost no magnetic content at all in the sediment.

To try to estimate the percentage of magnetite within each sample, approximate calculations were carried out for all of the

lakes. The saturation remanence of magnetite varies with the shape of the crystal and also with stress. As the calculations were only approximate, the saturation remanence was given a value of  $80 \text{ G cm}^3 \text{ g}^{-1}$ . As the saturation remanence value of haematite is only  $0.4 \text{ G cm}^3 \text{ g}^{-1}$ , this would not significantly alter the approximate calculation of the percentage of magnetite within the sample. To carry out the calculation, the volume and dry weight of the samples were measured. The  $J_{rs}$  value of the samples was then converted into units of  $\text{G cm}^3 \text{ g}^{-1}$  and the ratio of this value to the saturation remanence value of  $80 \text{ G cm}^3 \text{ g}^{-1}$  gave the proportion of magnetite in each sample. Table 5.1 shows the results obtained from the above calculations. Magnetite content is given in parts per million (p.p.m.).

	Bourget	Morat	Ann.	Geneva		Charzy.	Radun.	Zarn.	Sniard.
Magnetite (p.p.m.)	12	10	20	20		15	30	3	2

TABLE 5.1 Magnetite Content in the Lakes in Parts per Million

Calculations were not carried out on the Lac de Joux samples as there is evidence of chemical remanence and that an appreciable amount of haematite may exist in the late glacial clays. The proportion of magnetite obviously varied down the length of the cores, and the results quoted are an average value obtained for each lake.

In parts of the cores from Sniardwy and Zarnowieckie where the intensity and susceptibility are at a minimum, values for the proportion of magnetite of less than 1 p.p.m. were found. Very low values for Lakes Powidzkie, Miedwie and Mosczone were also

found. This is quite possibly the answer for the poor palaeomagnetic records from these lakes; the reason being that there is not enough magnetic material to give a good record of the geomagnetic field signal. There is evidence as shown in chapter 4 however, that some information may be obtained from the inclination records.

### 5.3 Modified Lowrie-Fuller Test

Having carried out experiments on the hysteresis of isothermal remanence to try to differentiate between haematite and magnetite, and having found magnetite dominance in almost all of the cases, the next stage was to try to determine whether this magnetite was fine or coarse grained.

In 1971, Lowrie and Fuller suggested an experimental procedure that would determine whether the thermoremanent magnetization (T.R.M.) of a magnetic mineral was carried by single or multidomain grains. Their theory was based solely on observational results and had no theoretical explanation. The test they proposed relied upon the observational evidence that the stability of T.R.M. against A.F. demagnetization was dependent upon grain size. Single domain grains gave a stability that decreased with increasing strength of the biasing field, whereas multidomain grains gave a stability that increased with increasing strength. The test itself was to compare the characteristics of the A.F. demagnetization curves of weak field T.R.M. with strong field I.R.M. If the normalized stability curve of the I.R.M. was less than that of the T.R.M. then single domain grains were believed to be present, and vice-versa for multidomain grains. They suggested weak field A.R.M. might be used in place of T.R.M. which had an irreversible effect on some of the samples. Dunlop et al. (1973) tested this hypothesis and found it true for

single domain particles, but did not obtain satisfactory results for multidomain grains. Johnson et al (1975) carried out further experiments on the stability trends of A.R.M. in both single and multidomain synthetic samples. They showed experimentally that A.R.M. could be used instead of T.R.M. in the Lowrie-Fuller test (1971). They also showed that pseudo-single domain grains behaved in a similar fashion to single domain grains and that their results were consistent with those of Parry (1965), at placing the pseudo-single domain limit at  $17\mu\text{m}$ . There was difficulty however, in distinguishing between pseudo-single domain grains of size nearer the upper limit and multi-domain grains. This difficulty showed in the crossing of the stability curves, which was also the case found if a mixture of grain sizes was used.

Figs. (5.6 and 5.7) show the results of carrying out this "modified Lowrie-Fuller test" on samples from France and Switzerland, and from Poland. For the French and Swiss lakes, Fig. (5.6), Morat and Geneva both showed single or pseudo-single domain behaviour. Lakes Annecy and Le Bourget however showed a crossing of the curves at higher D.M. fields. As just explained above, this could be caused by pseudo-single domain grains near the upper size limit or by an inclusion of some coarse grained magnetic particles within the fine grained. Coarser grained magnetite may in fact be the answer, as was shown by optical microscopy experiments that were carried out on magnetic extracts from the samples. Results of this work will be discussed later in the chapter. Fig. (5.7) shows the results obtained from four of the Polish lakes. They all show single or pseudo-single domain behaviour, as was the case in all the Polish lakes. Only results from four of the lakes are shown because of

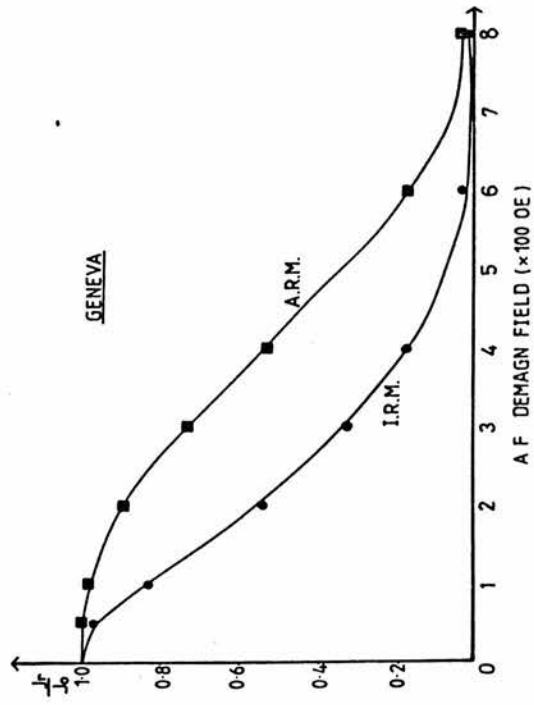
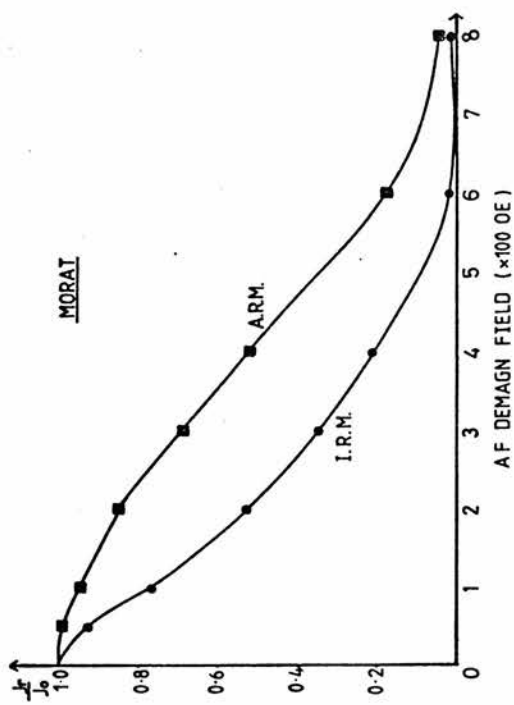
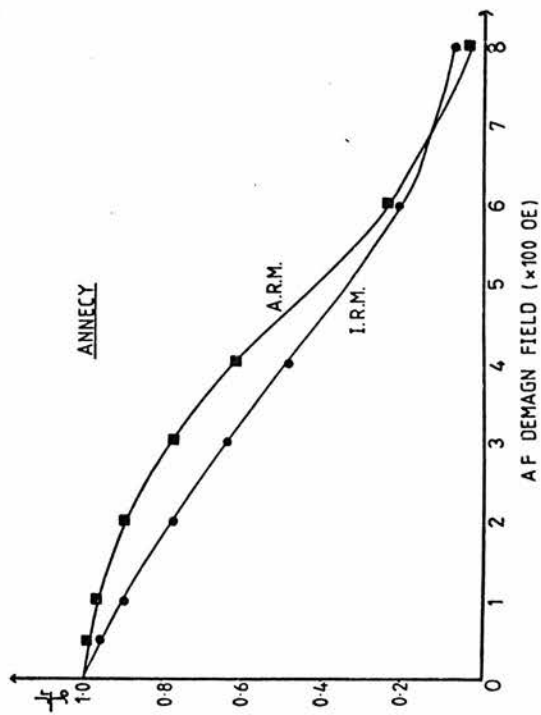
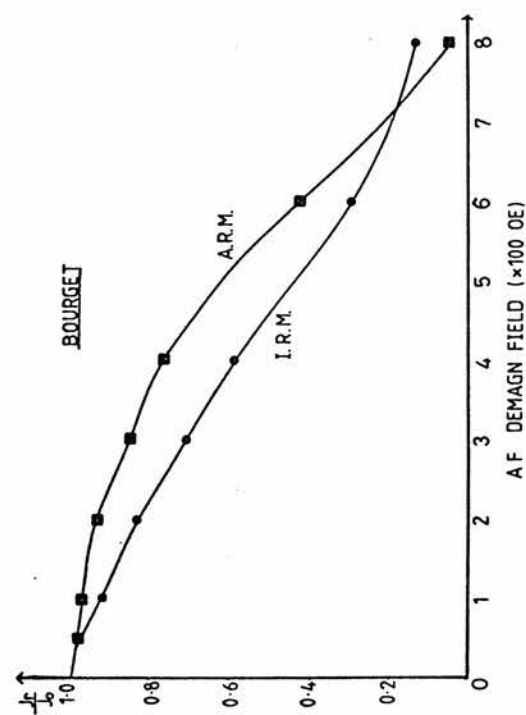


FIG 5-6 Examples of AF Demagnetization of IRM & ARM for the French & Swiss Lakes



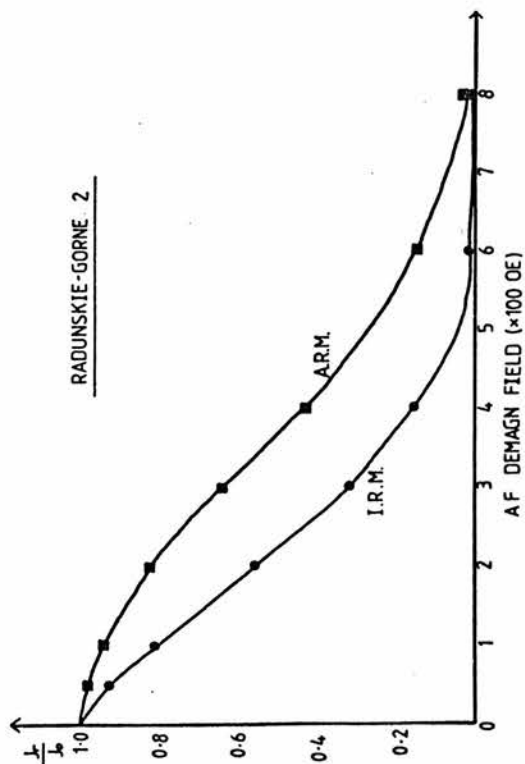
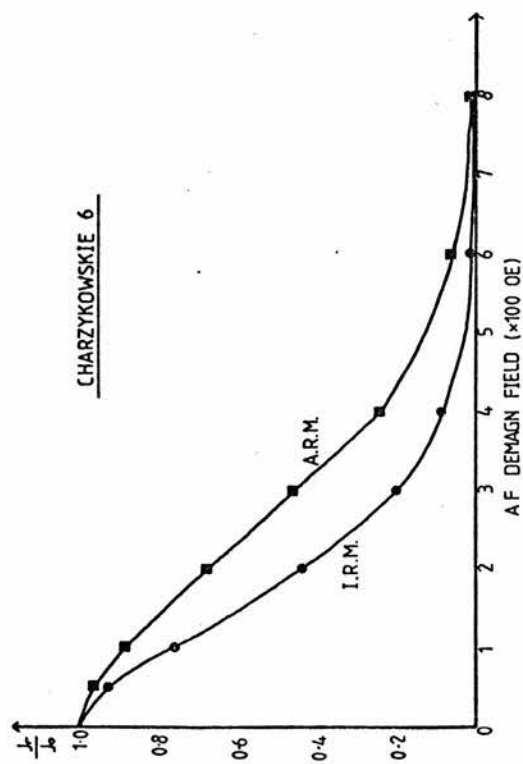
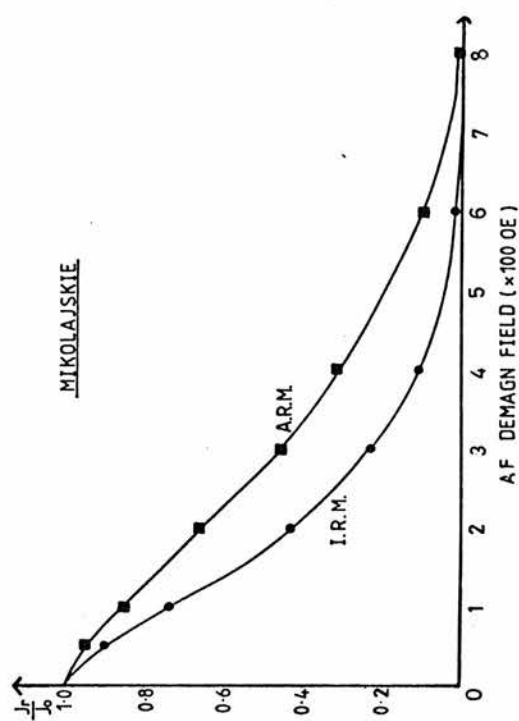
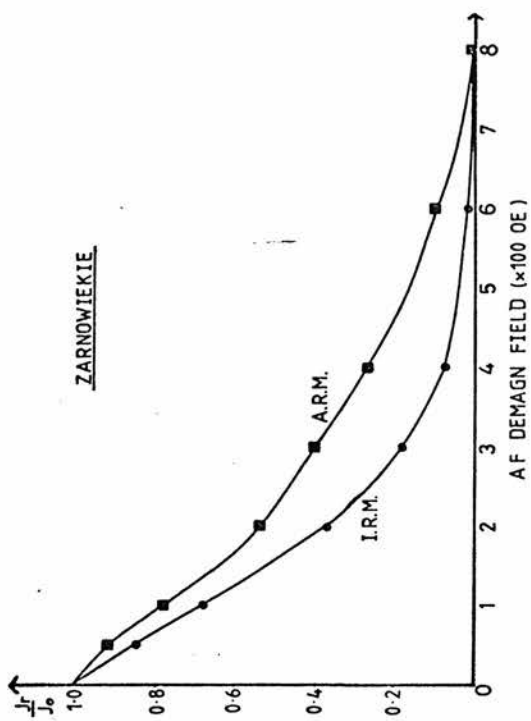


FIG 57 Examples of AF Demagnetization of IRM & ARM for the Polish Lakes

the similarity in all the lakes studied.

#### 5.4 Magnetic Separation

Magnetic separation was carried out on sediment from Lakes Geneva, Bourget and Annecy in France, and Lakes Radunskie-Gorne and Charzykowskie in Poland. The purpose of this separation was to obtain a small quantity of magnetic extract for X-ray and optical microscopy purposes.

The extract was obtained by continuously passing a dilute suspension of the sediment along a glass tube which passed between the poles of a permanent magnet. The magnetic particles then collected along the sides of the glass tube. The sediment was kept in suspension by continuously stirring the reservoir of water - sediment mixture with an electric stirrer and was passed along the tube by using a peristaltic pump. The magnet used had a strength of 2 K oe and had shaped pole pieces to help focus the magnetic field along the side of the glass tube. The usual suspension used was 50g of sediment in 2 l. of water. The extract was removed from the tube every day until enough had been collected for the relevant experiment. The extract removed from the tube had a lot of clay and other impurities clinging to it and, as a result, it in turn was diluted and separated again several times. This time however the extraction was done by hand using a 740 oe magnet. If this was repeated several times a purity of between 20% and 30% could be obtained. The efficiency of the separation is obviously time dependent and can be quoted approximately by measuring the susceptibility and S.I.R.M. values for a sample before and after separation. It was found to be approximately 10% efficient at extracting the magnetic grains over a period of two days and up to 80% efficient over a period of

about three weeks.

### 5.5 X-Ray Analysis

For X-ray analysis, between 0.5g and 1.0g of extract was obtained and then dried in a temperature of 50°C. It was then ground with a mortar and pestle so that the powder would have a uniform grain size. A powder mount was then made with the dried sediment for the X-ray analysis. The film was left exposed for one day. The results of the X-ray analysis on samples from different lakes are shown in Table 5.2 (Readman, pers. comm.)

	Magnetite	Haematite	Quartz
Geneva	xxx	trace	trace
Bourget	xxx	x	x
Annecy	xxx	x	x
Radunskie	x	x	trace

TABLE 5.2 Results from X-Ray Analysis

It can be seen from Table 5.2 that magnetite is present in substantial quantities in Lakes Geneva, Bourget and Annecy, whereas only a small amount was found in Radunskie. A trace of haematite was evident in Geneva and was present in small quantities in the other lakes. Quartz lines were also apparent on the film for Lakes Bourget and Annecy. This would agree with the hysteresis of I.R.M. curves that showed the French and Swiss lakes with a  $H_{CR}$  value too high to be due to magnetite alone. Considering the proportion of magnetite to haematite and also their saturation value ratio of  $80 \text{ G cm}^3 \text{ g}^{-1}$  to  $0.4 \text{ G cm}^3 \text{ g}^{-1}$  or 200:1, it is obvious that magnetite will be the dominant magnetic mineral and will be carrying almost all of the remanence.

Although the extract is only 20% pure in magnetic materials,

the X-ray film showed only 2 faint lines of non-magnetic crystals, with the magnetite line being by far the most dominant one. This suggests a high percentage of non-crystalline material within the extract.

### 5.6 Optical Microscopy

Optical microscopy was also carried out in the Geology Department on polished sections of the magnetic extract. Most of the magnetic crystals were found to be fragments of fresh unaltered magnetite (Gill, pers. comm.). A small portion of them however had been partially oxidised into haematite. The grain size on the whole for these magnetite crystals was  $1\mu\text{m} - d\ 5\mu\text{m}$ . This would put them at the lower end of the pseudo-single domain size limits. Some of the samples showed a few crystals of size between  $20\mu\text{m}$  and  $30\mu\text{m}$ . This would put them above the pseudo-single domain size boundary and into the multidomain category. This, as stated earlier, may explain the crossing of the A.R.M. and I.R.M. curves of the modified Lowrie-Fuller test, shown in Fig. (5.6).

### 5.7 Low Temperature and Thermomagnetic Curves

Low temperature and thermomagnetic experiments were carried out on the Polish samples only, the X-ray analysis and optical microscopy experiments along with the others having confirmed magnetite as the carrier of the remanence in the French and Swiss lakes.

The object of doing low temperature studies on samples is to look for transitions occurring that may point to the presence of either haematite or magnetite. For haematite a transition called the Morin transition occurs at a temperature of  $-15^{\circ}\text{C}$ . For temperatures below this, the weak ferromagnetism occurring in haematite disappears. A transition also occurs in magnetite at about  $-150^{\circ}\text{C}$ .

The low temperature experiments should be carried out on dried sediments rather than wet sediments. This is because of the 'faked Morin Transition' that can occur due to the misalignment of grains caused by the freezing of included water (Stober and Thompson, 1977). The reduction in intensity caused by this method is observed at the same temperature at which the Morin transition can be expected. To increase the signal/noise ratio and so obtain a sharper transition, the experiments were carried out on an I.R.M. given to the sample rather than the N.R.M. A typical result obtained is shown in Fig. (5.8). In the case of (a), the I.R.M. was given at room temperature and the sample cooled down to liquid nitrogen temperature ( $-196^{\circ}\text{C}$ ). Fig. (b) shows the I.R.M. given at liquid nitrogen temperature and then warmed to room temperature. Fig. (a) shows the decrease in I.R.M. over a wide temperature range. This is probably due to the non-homogeneous cooling of the sample. A transition is also noted between  $-4^{\circ}\text{C}$  and  $-17^{\circ}\text{C}$ . As it is very difficult to dry the sample completely, this is probably due to the 'faked Morin transition', as it is not observed in Fig. (b). Fig. (b) on the other hand, shows a sharper magnetite transition at  $-150^{\circ}\text{C}$ . These results show that magnetite is the carrier of the I.R.M. as opposed to haematite.

Thermomagnetic experiments were carried out on both dried samples and on magnetic extracts. The measurements were carried out by P.W. Readman at Newcastle University. The samples were heated in air to  $600 - 700^{\circ}\text{C}$  in a vertical magnetic torsion balance. The samples that had already been dried in  $50^{\circ}\text{C}$  underwent a further weight loss of between 10 and 60% during the heating. The curves obtained for the dried samples were rather complex and the discontinuities were not well defined. They also showed numerous chemical

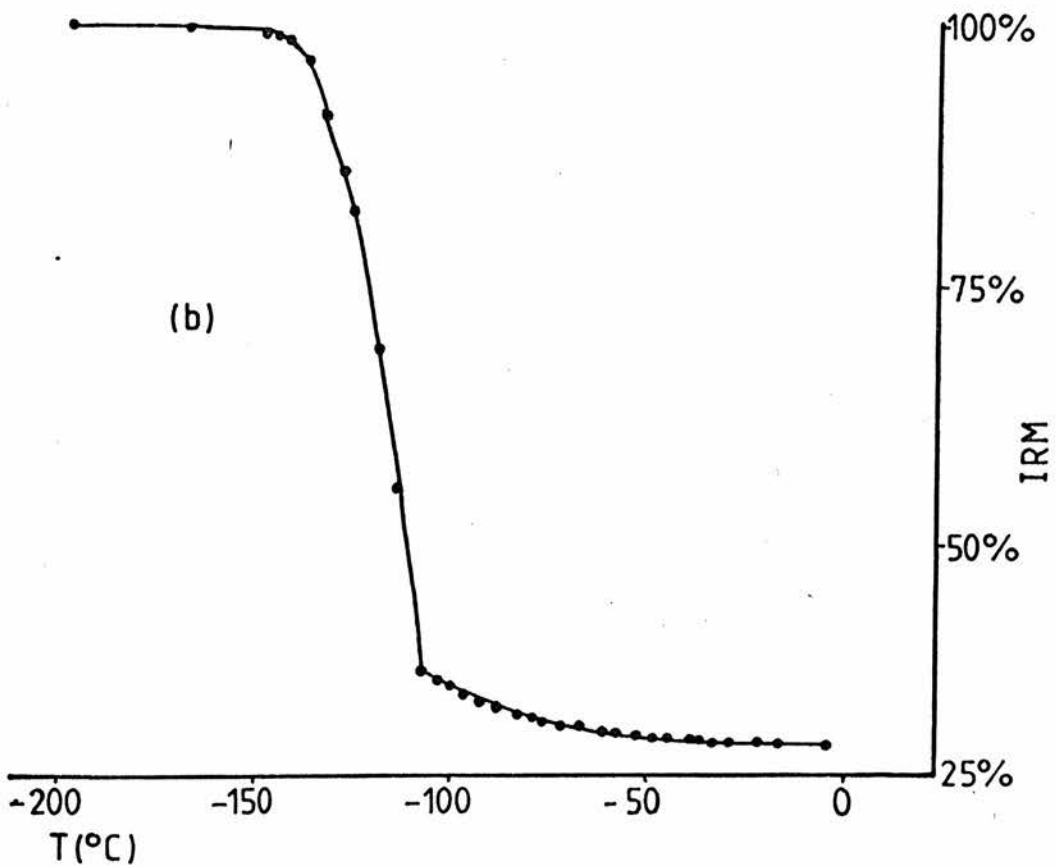
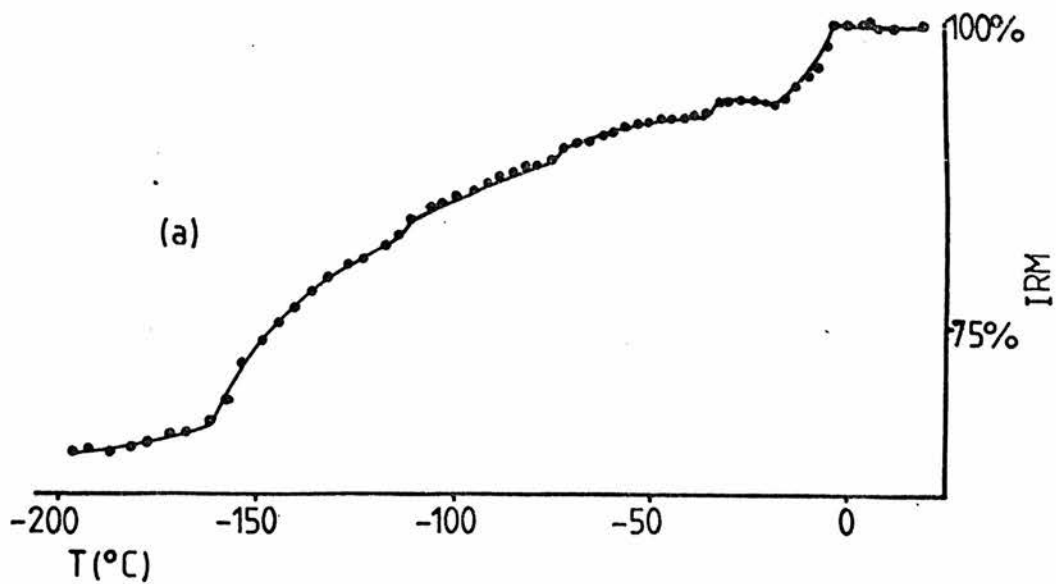


FIG 5-8 Typical Low Temperature Curves for Polish Holocene Sediments

changes taking place. The curves obtained from the magnetic extract were clearer and easier to interpret. Curves obtained for extracts from Lakes Charzykowskie and Radunskie-Gorne are shown in Fig. (5.9). Both curves are very similar up to point C at approximately  $450^{\circ}\text{C}$ . Both curves show a decrease in intensity from A - B due to a chemical change, as is shown by the irreversible curve on cooling. This part of the curve probably represents the oxidation of magnetite to maghaemite. From B - C the curve is reversible, as is shown by cooling and reheating. In the case of Charzykowskie there is an increase in magnetization from C-D, which is confirmed by cooling from D and then reheating. The curve then falls to E and shows a Curie temperature of about  $580^{\circ}\text{C}$ . The curve then shows a much reduced magnetization in cooling from E - F. A possible explanation of the above would be the production of magnetite from C - D, which is subsequently oxidised to haematite at higher temperatures. This would also explain the reduced magnetization from E - F. In the case of Radunskie-Gorne there is no increase in magnetization and it shows a Curie temperature of about  $550^{\circ}\text{C}$ . This again is probably due to the forming of haematite at higher temperatures. Both of these curves suggest the presence of magnetite in the original sample.

### 5.8 Chemical Analysis

Chemical analysis was carried out on cores number 2 from Radunskie-Gorne <sup>and</sup> ~~to~~ core 6 from Charzykowskie. The results of this analysis are shown in Fig. (5.10). The quantities measured were, the total iron content (represented by  $\text{Fe}_2\text{O}_3$ ), the carbonate content which was assumed to be in the form of  $\text{CaCO}_3$ , the sand fraction (greater than 0.1mm), the organic carbon content and the percentage water.

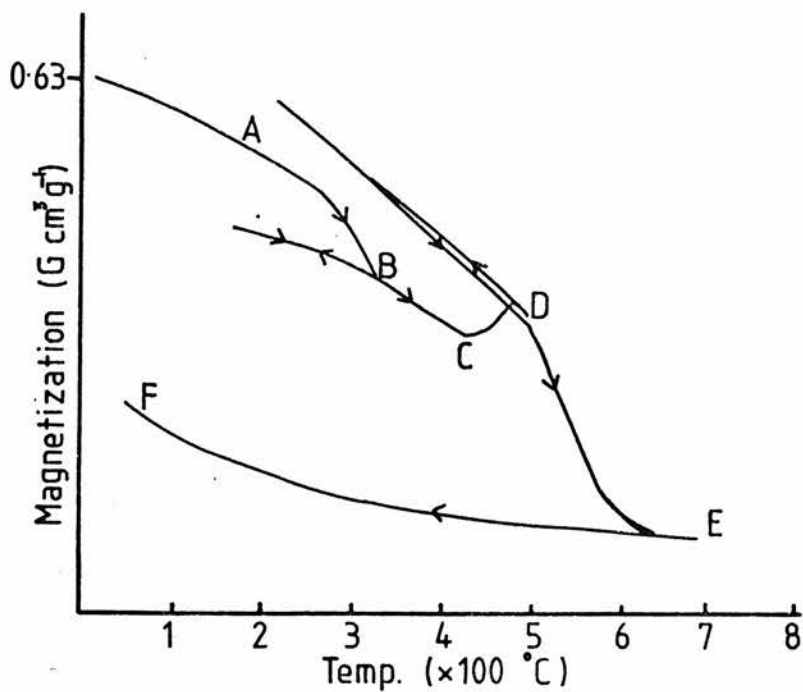
The sand fraction content in CH6 is less than 0.5% and in RG2 is between 4 and 8.5%. The content of organic carbon in CH6 is between 3 and 10% and between 3 and 7% in RG2. The carbonate content in CH6 varies between 40% at the top of the core to 90% towards the bottom. The carbonate content in RG2 however never falls beneath 80%. The average iron content in CH6 is approximately 2.5% whereas in RG2 it is only 1.5%. However, the average NRM to  $J_{rs}$  values for Radunskie are considerably higher than those for Charzykowskie ( $50 \mu\text{G}$  &  $3000 \mu\text{G}$  cf.  $30 \mu\text{G}$  &  $1000 \mu\text{G}$ ). This is explained by the fact that there is a larger percentage of magnetite in the Radunskie sediments (see Table 5.1). As magnetite will account for approximately 0.1% of the total iron content then its presence will not affect the overall iron content, but will affect the NRM and IRM intensities.

There seems to be a positive correlation between the iron content and the NRM intensity in Radunskie, but not however in Charzykowskie. In Charzykowskie there seems to be a positive correlation between carbonate content and NRM intensity. The reverse of this is usually found in lake sediments (as is the case for RG2). The only possible explanation is that the magnetite is being washed into the lake along with the limestone. This would suggest that the carbonate content is acting as a detrital input indicator.

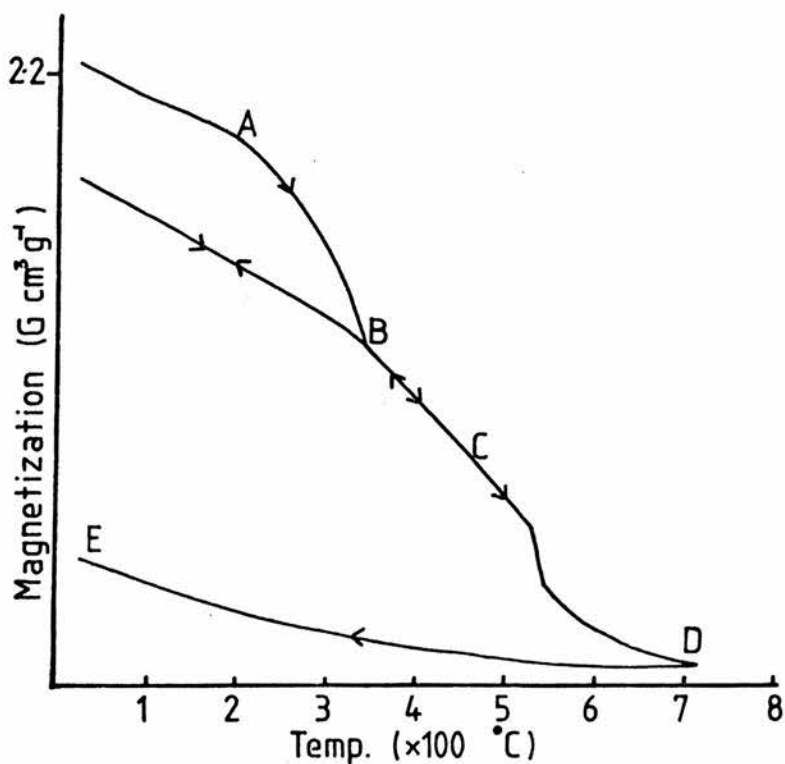
### 5.9 Summary of Results

A summary of the results discussed in this chapter along with average N.R.M., M.D.F. and k values for both the French and Polish lakes is given in Table 5.3. From this table the large differences between the individual Polish lakes can be seen more easily. The Polish lakes fall into three different categories. These categories





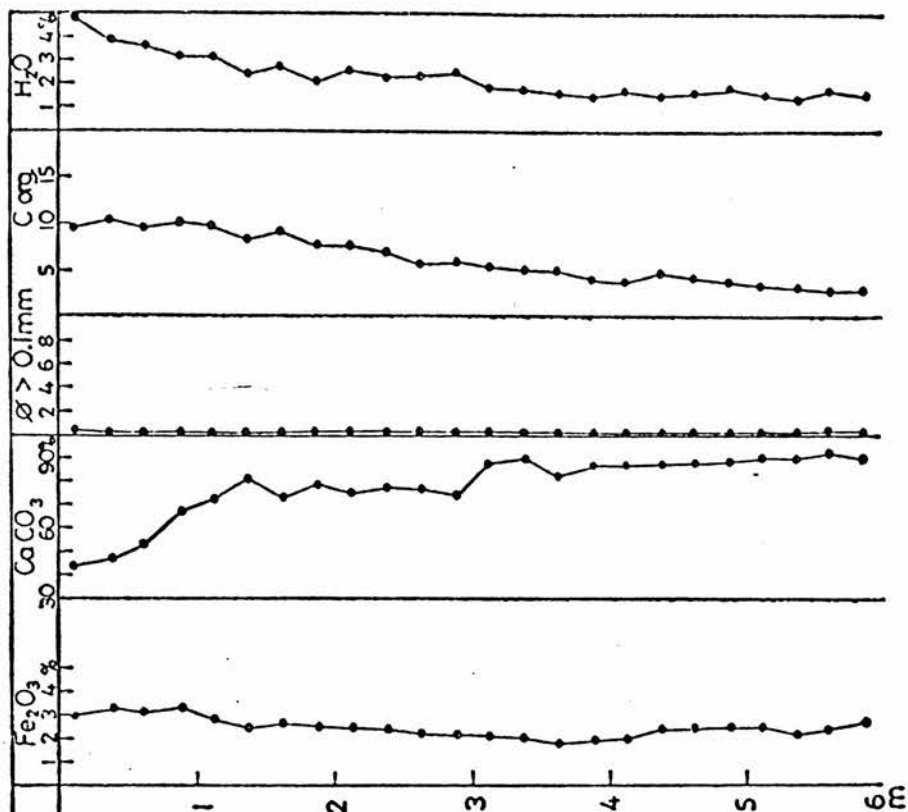
CHARZYKOWSKIE



RADUNSKIE-GORNE

FIG 5.9 Examples of Thermomagnetic Curves for Two Polish Lakes

Charzykowskie  
core no.6



Raduńskie Górne  
core no.2

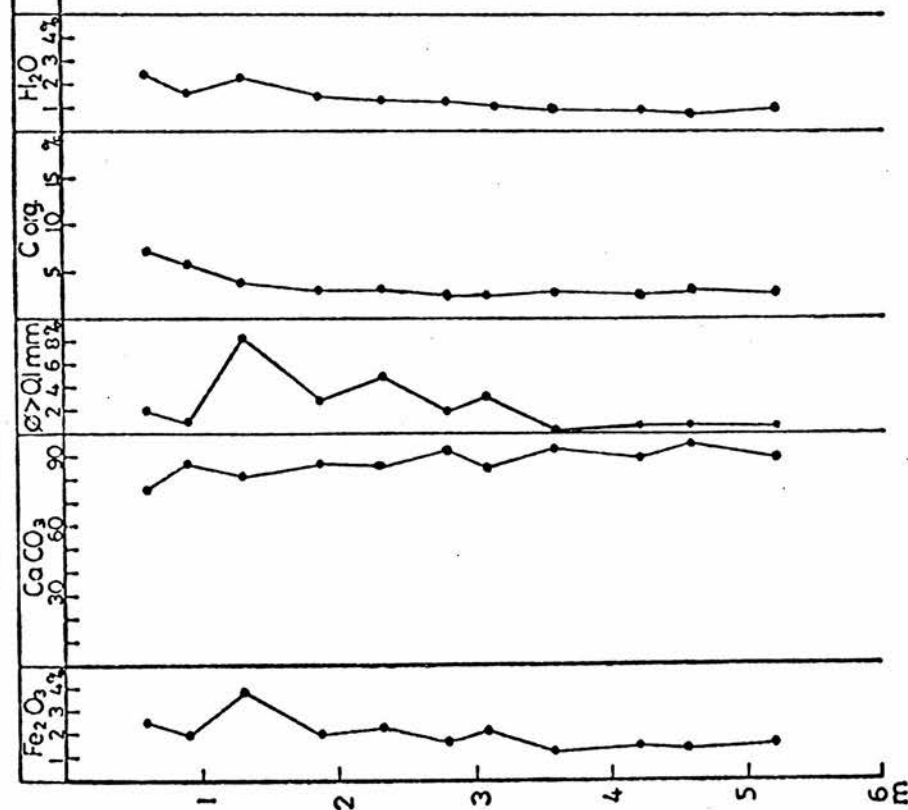


FIG 5-10 Results of Chemical Analysis carried out on 2 Polish Cores

are most easily distinguished by the values of the N.R.M., M.D.F, k and  $J_{rs}$ . It would seem that the factor governing these three groups is the amount of magnetic material present in the sediments from the lakes: the first three lakes listed having a fair proportion of magnetic material, down to the last four which have very little indeed. The values for the first three Polish lakes are approximately the same as those for the French and Swiss lakes, the only difference being the higher M.D.F. values of the latter. It is also interesting to note that all the French and Swiss lakes yielded good palaeomagnetic results, and the best Polish results were obtained from Charzykowskie and Radunskie-Gorne and Dolne (the first three listed in the table). It would now seem that the over-riding factor responsible for the poor palaeomagnetic records and the large scatter of results obtained in most of the Polish lakes is the lack of magnetic minerals within the lakes. As a result the sediment is not capable of recording a strong and stable geomagnetic signal.

Although the above seem to be generally true, and ~~that~~ for the lakes with a low magnetic content a correlation between the D, J and k records tends to be very difficult if not impossible, a possible correlation between a few of the inclination records can be found (as shown in chapter 4).

LAKE	Av. N.R.M. Intensity ( $\mu\text{G}$ )	Av. M.D.F. of N.R.M. (oe)	Av. k ( $\mu\text{G}/\text{oe}$ )	Av. $J_{rs}$ ( $\mu\text{G}$ )	Av. $H_{cr}$ (oe)	Approx. $\text{Fe}_3\text{O}_4$ Content (p.p.m.)
Radun-G	50	250	10	3,000	350	40
Radun-D	45	-	10	2,500	270	30
Charzy.	30	175	10	1,000	290	15
Moszcz.	15	-	8	800	270	13
Mikol.	10	250	3	300	230	5
Drawsko	10	225	3	300	270	8
Powid.	5	125	2	300	210	7
Miedwie	5	125	2	-	-	-
Zarnow.	5	150	3	175	260	2
Sniardwy	4	120	1	140	230	2
Anancy-G	50	475	10	2,000	420	25
Anancy-P	30	475	8	1,000	375	20
Geneva	30	500	8	1,500	425	20
Bourget	30	325	8	750	500	12
Morat	30	425	7	1,000	350	10

TABLE 5.3 Summary of Results

## CHAPTER 6

### Geomagnetic Field Modelling

#### 6.1 Introduction

If one studies the palaeomagnetic records obtained from Lake Windermere (Creer et al 1972) and from Lake Michigan (Creer 1976), it becomes obvious that the geomagnetic field seems to display a regional character. This assumption is based on the fact that the Windermere records shows an approximate 2,700 yr cyclic period in declination using corrected C14 ages (Mackereth 1971). This reduces to 2450 yr when uncorrected C14 ages are used (Spiker et al 1977). The period of the Michigan declination swings are significantly different, displaying an approximate 2,000 yr period (using uncorrected C14 ages). This leads to the problem of proposing a geomagnetic model which would not only explain the secular variations, but would also explain the apparent regional character of the field.

The geomagnetic field is usually and most accurately described in terms of its spherical harmonic coefficients (S.H.C.). The 1975 international reference field, for instance, is specified by eighty S.H.C. of degree  $1 < n \leq 8$  (I.A.G.A. 1975). The number of S.H.C. calculated, and hence the accuracy of the fit, depends on the density of data available. In Quaternary times the coverage is only sufficient to calculate seven terms ( $n = 3$ ) (Georgi 1974, Creer et al 1973).

Another method of representing the earth's field is by the use of dipoles. In 1936, Bartels approximated the field by the use of a single eccentric dipole which is equivalent to the dipole ( $n = 1$ ) and quadrupole ( $n = 2$ ) terms in a spherical harmonic expansion. Since then, other attempts have been made to approximate the earth's field

to various number and types of dipoles.

In 1951 Lowes and Runcorn explained the 1922 epoch field by 12 vertical dipoles placed at a depth of  $0.6 R$  ( $R = \text{earth's radius}$ ). Allredge and Hurwitz (1964) obtained a best fit for the 1945 U.S. charts using one central dipole and 8 radial dipoles, all located at the same depth. Bochev (1975) approximated the 1942-6 field using a 6 dipole model, positions and orientations free. Other models using 20 and 34 radial dipoles have been proposed by Stearns and Allredge (1973). All of these however are best fitting models to a specific epoch. The complexity of the models has progressed with the development of computers.

Spherical harmonic analysis of the field expresses the scalar potential of the field as a series of solid harmonics, each being the potential of a dipole or multipole at the geocentre. It has been suggested (Elasser 1939, 1946) that the secular variations are due to motions in the fluid core of the earth, but spherical harmonic methods do not help in the location of the physical sources. These motions are probably eddies whose axes may be remote from the geocentre.

Although we may not know what causes these eddies, we can assume that the external magnetic field arising from the electric current circuits caused by the eddies would most easily be described by dipoles placed near the centre of the eddies. The simplest way to describe the secular variation in a certain region would then be by one of these dipoles whose magnitude or direction was changing with time.

As a starting point for the current investigation a requirement was a relatively simple model which described the field in terms of a number of dipoles. The model chosen for the studies was the

Allredge-Hurwitz (1964) radial dipole model (AH 64), which described the geomagnetic field in terms of a central dipole and 8 radial dipoles. The basic idea was to use this model as a starting point and try to explain the secular variation records obtained from our limnomagnetic work by allowing the magnitude of these dipoles to vary.

## 6.2 The Allredge Hurwitz Model

The reason the AH 64 model was chosen in preference to newer models (Stearns 1973) was simply because a model with 20 or 34 dipoles would be too complex and have too many variable parameters to cope with.

The A.H. model took as its starting point the 1945 U.S. world charts. They then placed radial dipoles under each of the Z foci of the nondipole field. Two dipoles were placed under elongated foci, and one dipole under near circular ones, the sign of each dipole accounting for the nondipole Z field immediately above the dipole itself. A least-squares method was then used to adjust the amplitude, latitude, and longitude of each dipole, to obtain the best fit to the observed field. (Fig. 6.1). This was carried out for different depths of the dipoles (all the dipoles having the same depth) until again the best fit was found. Skin depth arguments led them to start with their R.D. near the core-mantle interface ( $r/R=0.54$ ). Iteration led to a deepening of the dipoles, the best fit being at  $r/R = 0.28$ .

They explained this great depth of the dipoles by a shielding caused by a conducting medium surrounding the dipole. A primary radial dipole in the outer core, would, due to the relative motion between the core and mantle, induce a secondary dipole in the lower mantle. The shape of the field produced by these two dipoles would seemingly be very similar to a single dipole placed at a greater depth in

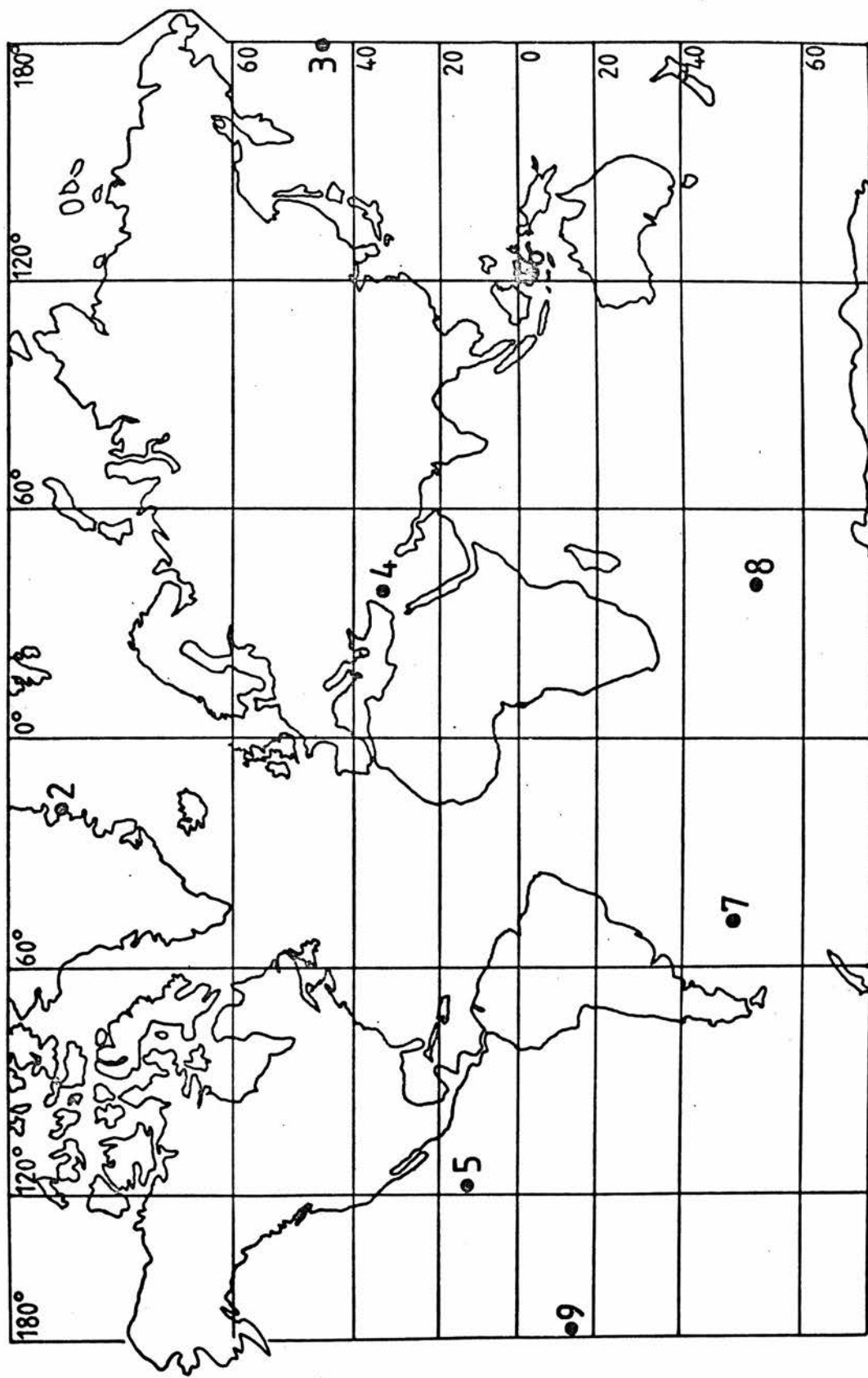


FIG 6-1 Location of Alldredge-Hurwitz (1964) Radial Dipoles



addition of a period and phase term.

The program for the calculations allows the position, depth, moment, period and phase of the dipoles to be varied. As is obvious, this would lead to a great number of variable parameters. To keep the model relatively simple the positions and depths of the dipoles are kept as they are in the AH 64 model. It is assumed that the amplitudes of all the radial dipoles are the same, but that their present values differ because they are out of phase with one another. It is also assumed that dipole number 8, which is the largest, is at present at its maximum value. Hence as a starting point for the modified model, all the dipoles are given the amplitude of dipole 8, and the present day values used to calculate the phase of the other radial dipoles. The term introduced to create the oscillatory effect is:-

$$\begin{aligned} & \sin (2\pi\omega T + \phi) \\ = & \sin \left( 2\pi \frac{T}{TP} + \phi \right), \end{aligned}$$

where  $T$  = time and  $TP$  = period

Hence if we take the 1945 field as  $t = 0$ , it is an easy calculation to determine the relative phases of all the dipoles.

The choice of the period of oscillation for each dipole is more difficult. First of all we calculate the effect of each individual radial dipole at different sites. From this we can see which dipole, or dipoles, are dominant in specific areas. If there ~~is~~ *are* palaeomagnetic data from that area which seems to show a cyclic period, we assign  <sup>$t$</sup>  to the dominant dipole.

In Lake Windermere and in lakes from central Europe, as has been shown in earlier chapters, the period of oscillation in the declination record seems to be approximately 2,700 yr (for corrected

ages) or 2,450 yr (for uncorrected). In Lake Michigan in the Great Lakes area of the United States, the period in declination seems to be 2,000 yr (based on uncorrected C 14 ages) (Creer 1976). Some earlier calculations on the dominant dipoles and their influence in different areas have been carried out by Creer (1977). By calculation it is found that dipole 4 has the greatest influence on the declination record of Lake Windermere and hence is given a period of 2,700 yr. Similarly, dipole 5 is given a period of 2000 yrs. Unfortunately a lack of good palaeomagnetic records from world wide sites makes the decision on the periods for the other dipoles a rather arbitrary matter. It is assumed (perhaps wrongly) that the other dipoles will have periods of oscillation of the same order as those of dipoles 4 and 5.

With these changes made to the original model, it was hoped that it would be possible to simulate the secular variation records obtained from the lake sediment studies. Following this, attempts were made to simulate geomagnetic excursions.

Changes were also made to the model to accommodate drifting dipoles, both oscillating and non-oscillating. Results from these attempts and from the different models will be shown and discussed in this chapter.

#### 6.4 The Program for Calculation of the Model

A full listing of the basic program used for the calculations based on the model is given in appendix II to this text. Fig.(6.2) shows the angles referred to in the program. A brief outline of the calculations is given in Fig. (6.3). Other modifications carried out to the program will be discussed later.

The following are the abbreviations used in the flow chart and in the main program.

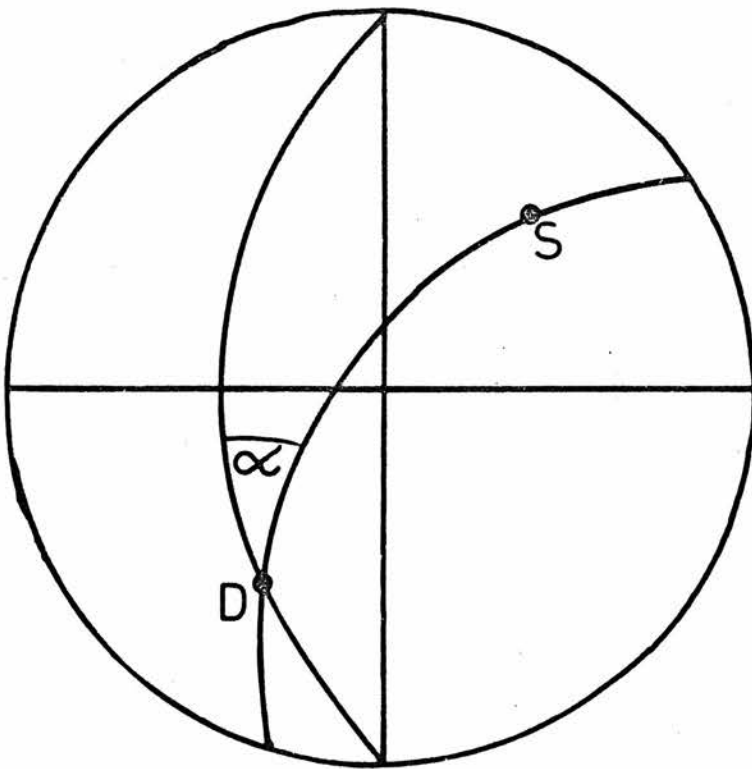
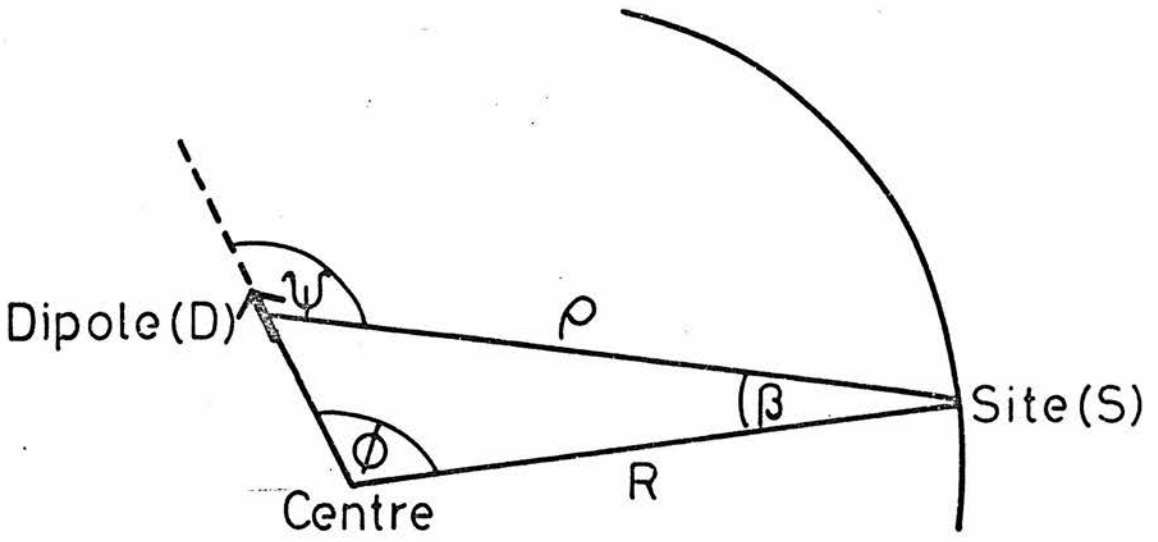


FIG 6.2 Diagram showing Angles referred to in the Calculations

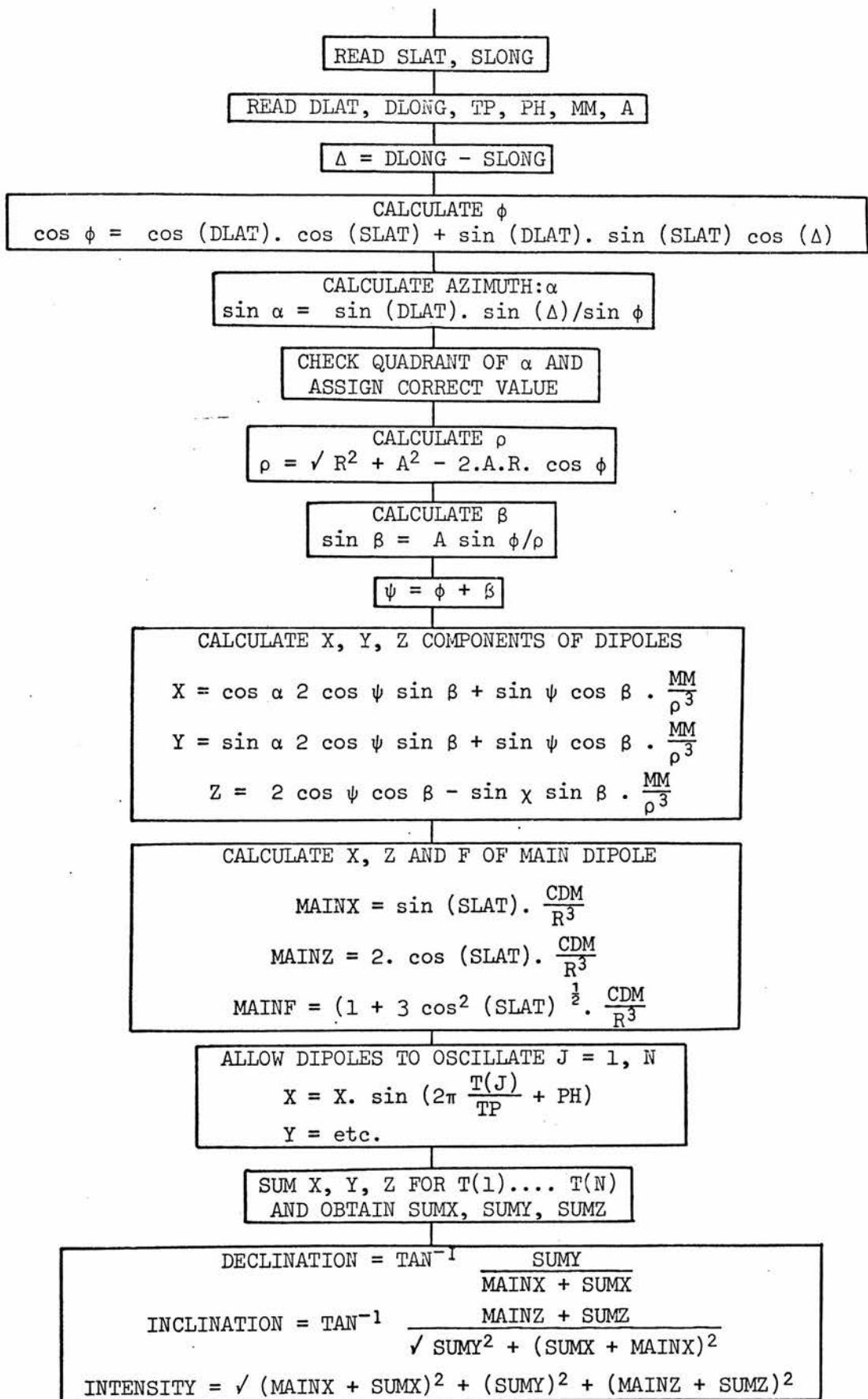


FIG. 6.3: Flow Chart of Calculation of DEC, INC, INT.

Angular distance from dipole to site	=	$\phi$
Azimuth from dipole to site	=	$\alpha$
Distance from dipole to site	=	$\rho$
Radius of earth	=	R
Site colatitude and longitude	=	SLAT, SLONG
Dipole colatitude and longitude	=	DLAT, DLONG
Period and phase of dipole	=	TP, PH
Moment and radial distance of dipole	=	MM, A
Moment of central dipole	=	CDM
Time	=	T

### 6.5 Results from the Oscillating Dipole Model

As previously discussed, it is assumed that dipole 4 has a period of oscillation of 2,700 yr and dipole 5 a period of 2,000 yr with the other dipoles assumed to have periods of the same order of magnitude. In the first attempt to model the field, the other dipoles were all given a period of 2,000 yr, with all the dipoles having the same strength but with a phase delay. The results of this model for latitudes and longitudes corresponding to Lakes Windermere and Michigan are shown in Figs. (6.4 and 6.5) respectively. The figures show the individual contribution of each of the dipoles (numbered 2 to 9) in declination, inclination and intensity. The final column shows the summed effect of the eight radial dipoles plus the central axial dipole. The strength of the axial dipole was as quoted in Table 6.1. As can be seen, the declination variations at Windermere show a period of approximately 2,700 yr without showing a regular pattern. The declination record at Michigan shows a period of 2,000 yr but is very regular. The inclinations at both

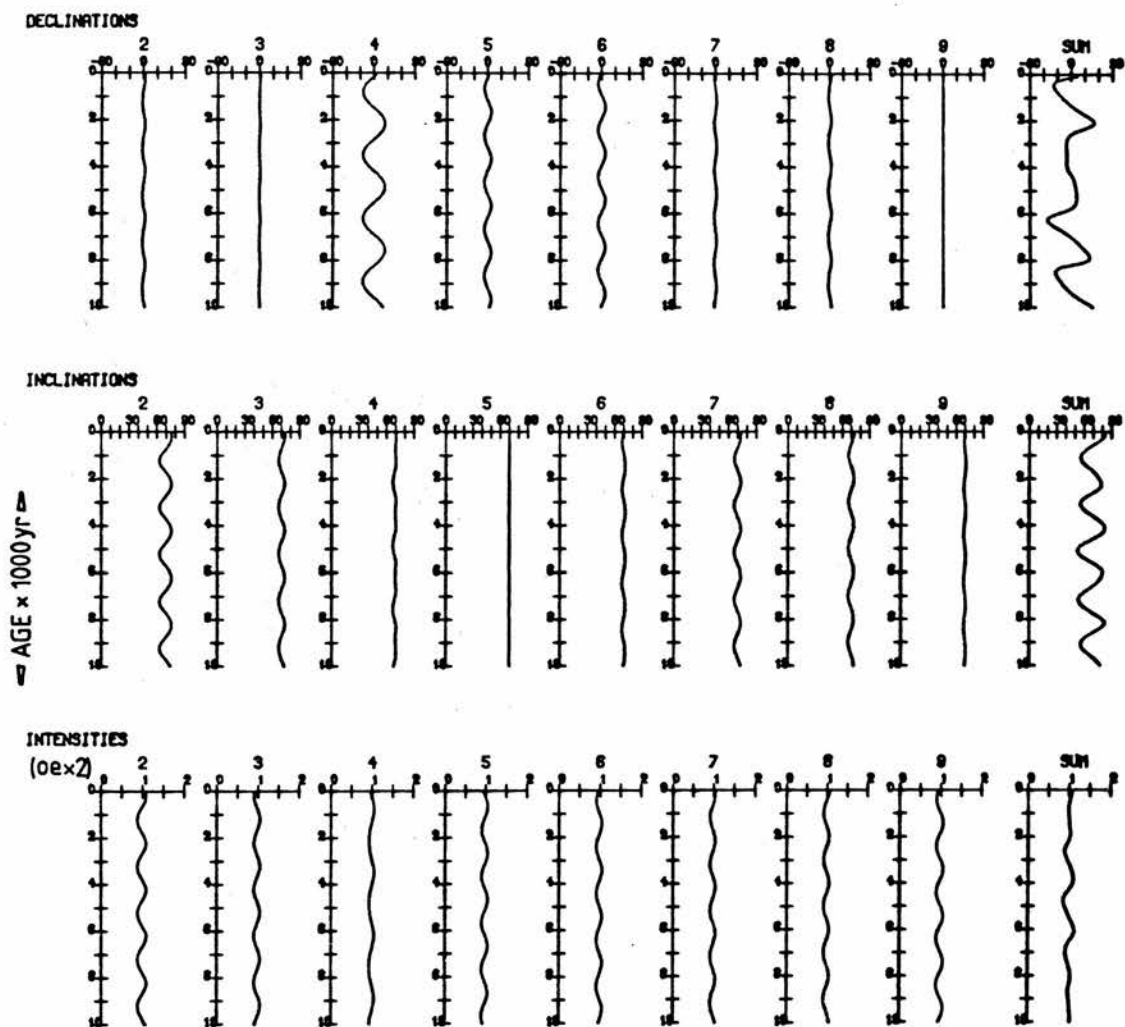


FIG 6-4 Synthetic Plot for Lake Windermere: All Dipoles have a Period of 2,000yr except Dipole 4 with a Period of 2,700yr.

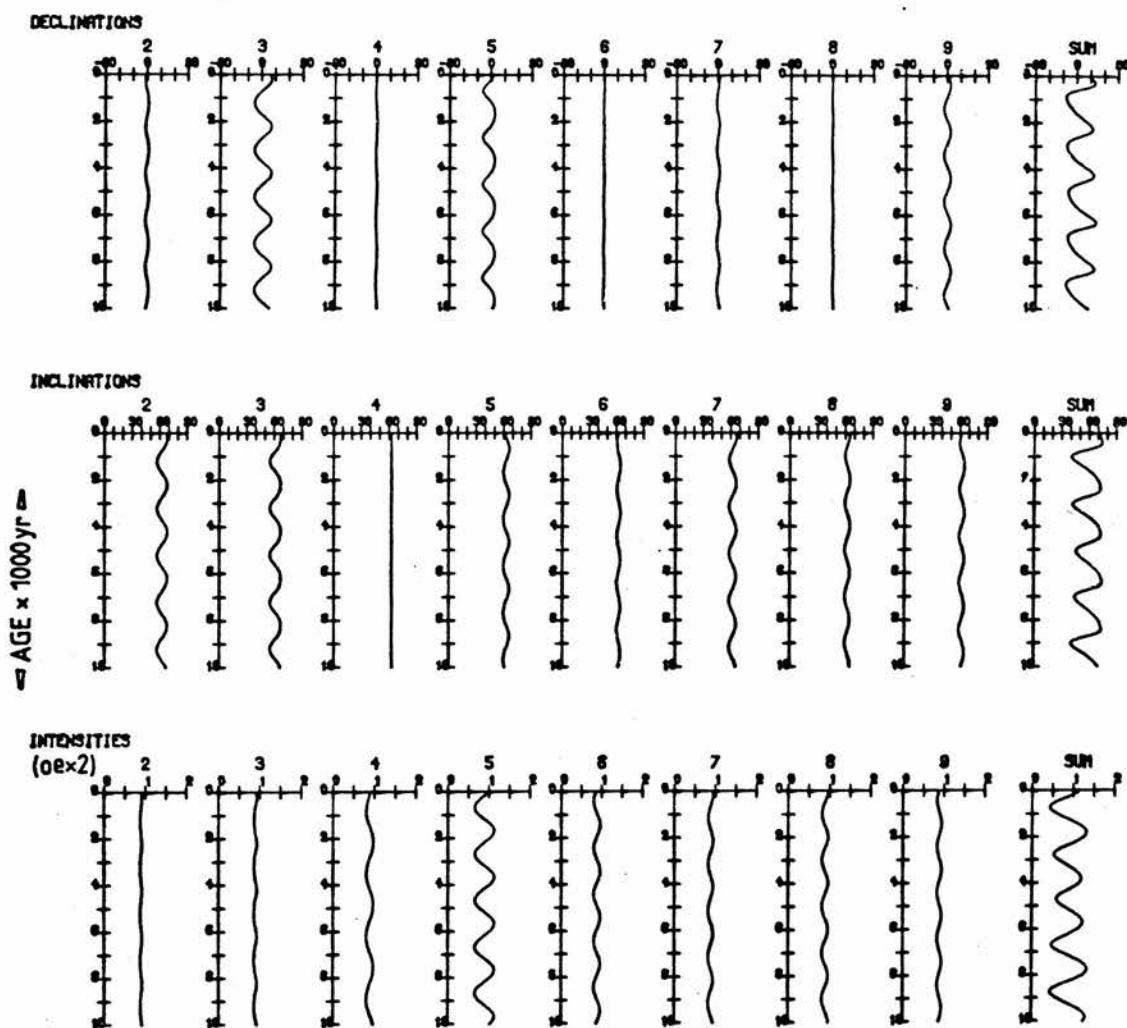


FIG 6-5 Synthetic Plot for Lake Michigan: Data as in fig. 6-4.

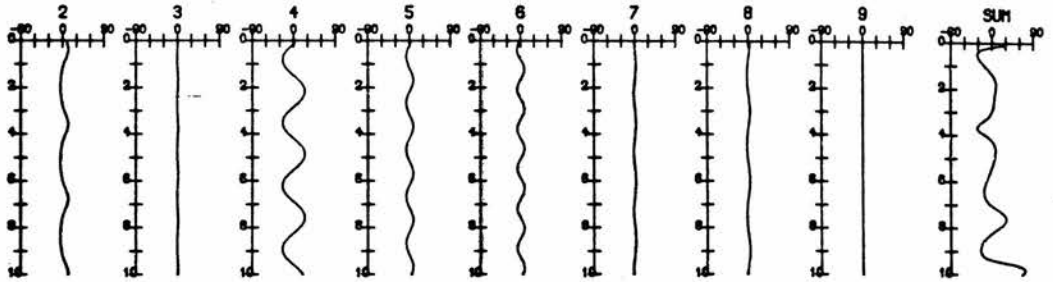
sites show a very regular and quite large oscillation of 2,000 yr period. Although the declination plots show a similarity to the real case, the inclination plots certainly do not. As was shown in Chapter 3, the inclination variations at Windermere and in fact the other lakes studied, have a much smaller amplitude of variation and do not seem to demonstrate a regular period. As can also be seen from the results of Chapters 3 and 4, the inclination records show slightly fewer oscillations in a given time than the declination records.

The regular 2,000 yr period seen in the inclinations of Figs. (6.4 and 6.5) is obviously due to the fact that 7 of the 8 dipoles were given this period. The next step was therefore to give the dipoles slightly differing periods but of the same order of magnitude. As dipole 2 is the one with the largest influence on the inclination records for these two sites, it was given a period greater than the period of dipoles 4 and 5. The effect of the above alterations are shown in Fig. (6.6). Although the regular 2,000 yr period has now gone from the inclination, the amplitude of the variations is still rather large. Note that the declination has still maintained its 2,700 yr period.

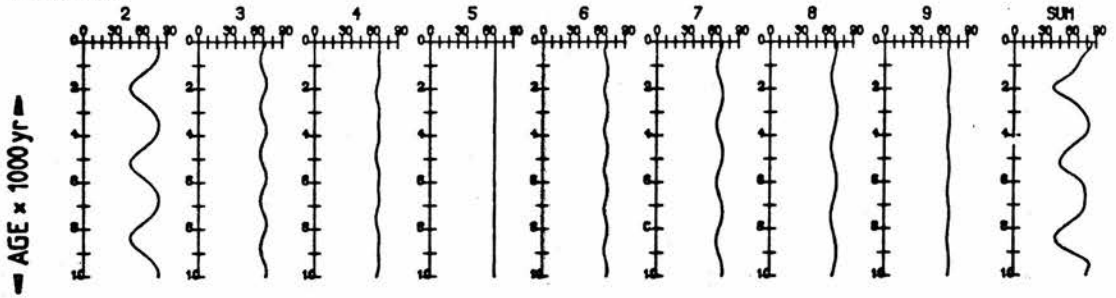
Although making the model simpler, there is no reason to believe that all the dipoles should oscillate between the same values. As a result, and also to try and decrease the amplitude of the inclination variation, the next step was to reduce the maximum strength of dipole 2. The effect of this change is shown in Figs. (6.7 and 6.8) for Lakes Windermere and Michigan. It can now be seen that although the declination records remain similar to the original ones, the large, regular oscillations in the inclination records have disappeared. The rather high inclination values for today's field are



DECLINATIONS



INCLINATIONS



INTENSITIES

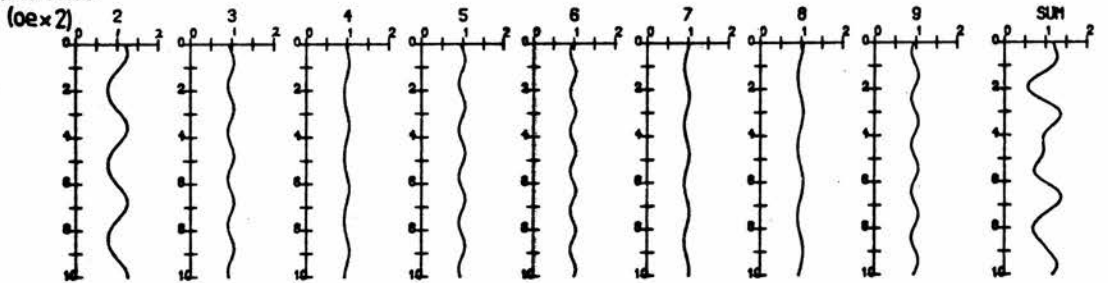


FIG 6-6 Synthetic Plot for Lake Windermere: Data as in Table 6-2, except Dipole 2 Moment equals 0.231 G.

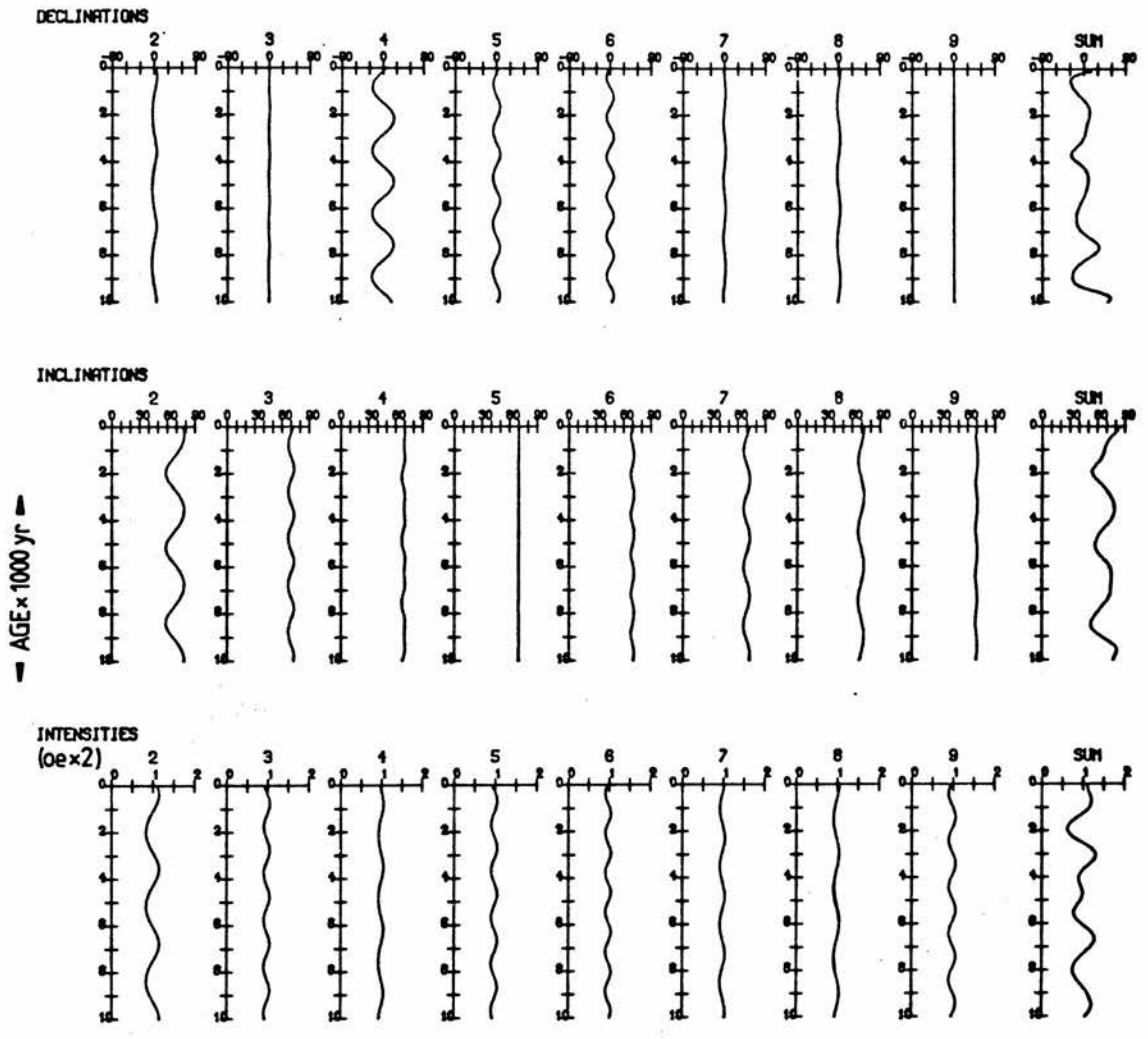


FIG 6-7 Synthetic Plot for Lake Windermere: Data as in Table 6-2.

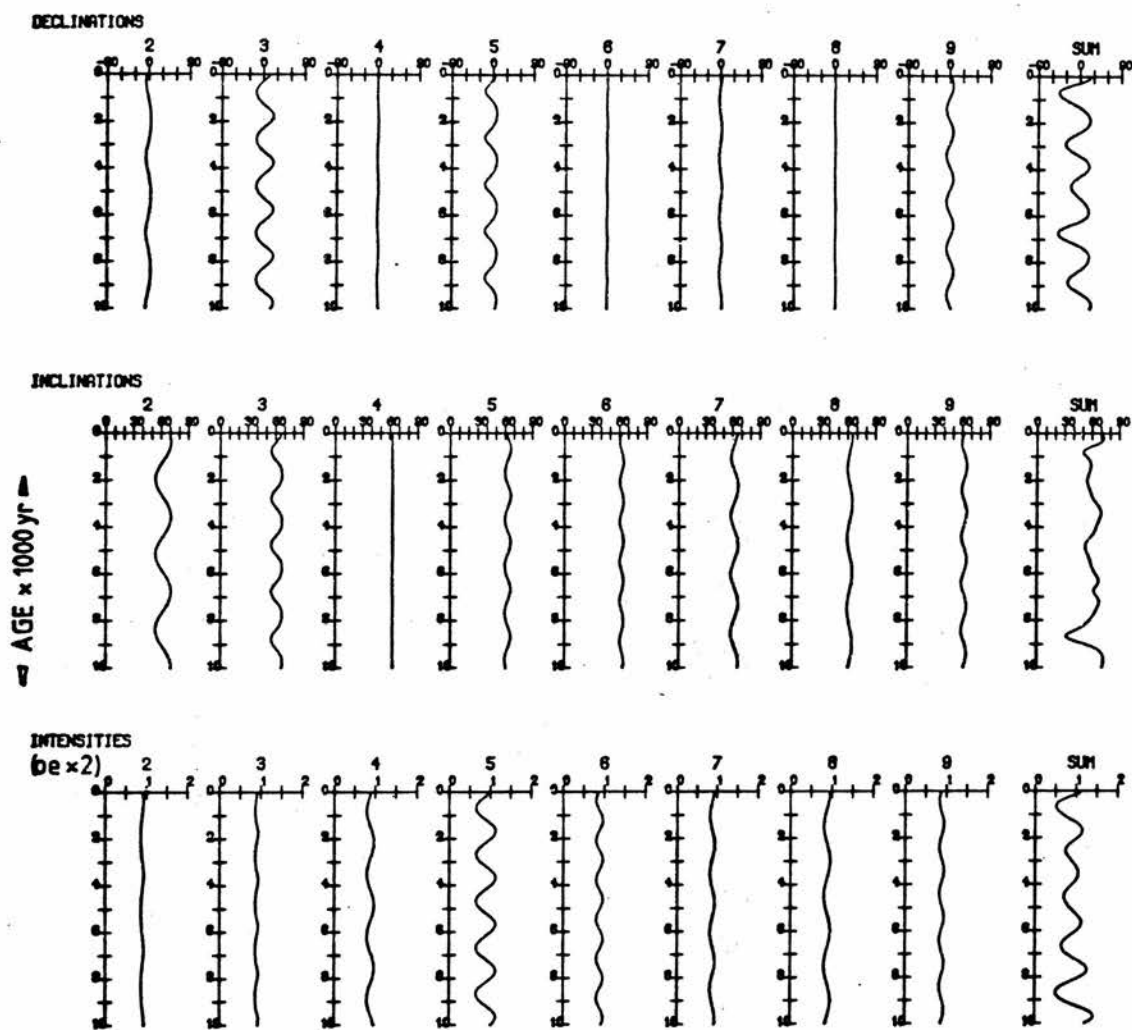


FIG 6-8 Synthetic Plot for Lake Michigan: Data as in Table 6-2.

caused by the fact that in this model, the central dipole is assumed to be axial, whereas in the A-H model it was tilted slightly off the axis.

A slight modification to the program enables it to calculate the summed declinations, inclinations and intensities, of several locations and plot them side by side. Fig. (6.9) shows the summed quantities for nine different locations over the globe, using the same input data as for Figs. (6.7 and 6.8). The parameters used for this figure are given in Table 6.2. The locations which are abbreviated in the diagram are Windermere, Salonika, Helsinki, Madrid, Reykjavik, Michigan, San Francisco, Biwa (Japan) and Tashkent (U.S.S.R.).

Dipole No.	Period (yr)	Strength (G km <sup>3</sup> )	Phase (°)	A(Km)
2	3200	0.150	227.8	1750
3	2000	0.231	309.2	1750
4	2700	0.231	161.3	1750
5	2000	0.231	326.9	1750
6	1700	0.231	189.9	1750
7	2500	0.231	120.5	1750
8	3000	0.231	90.0	1750
9	2000	0.231	193.5	1750

TABLE 6.2 Parameters Used in Fig. (6.9)

Fig. (6.9) shows that it is possible with this model to obtain L P S V patterns which vary over the globe, but are similar over smaller regions, e.g. Europe (plots 1 to 4 in Fig. 6.9).

It is obvious that with so many variable parameters the number of different plots that could be obtained is very great. As a result of this, it is the basic characteristics of the curves that are of interest rather than any fine detail.

The next stage in the study was to try and simulate an excursion of the geomagnetic field using the same model. To do this, the first

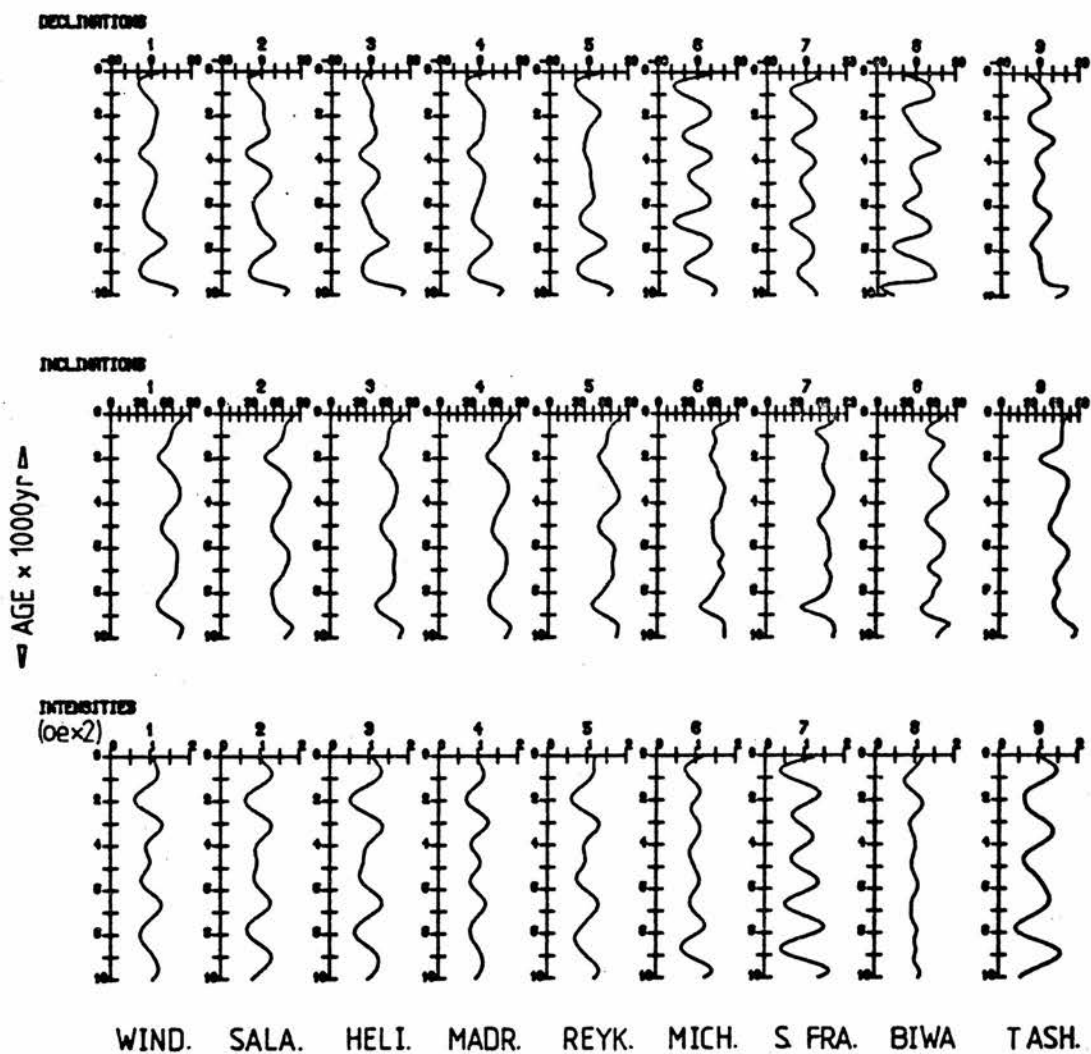
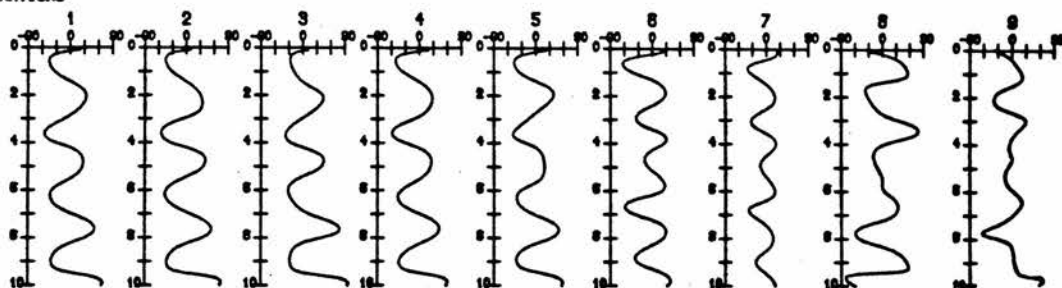


FIG 6-9 Synthetic Plots for 9 Global Locations: Data as in Table 6-2.

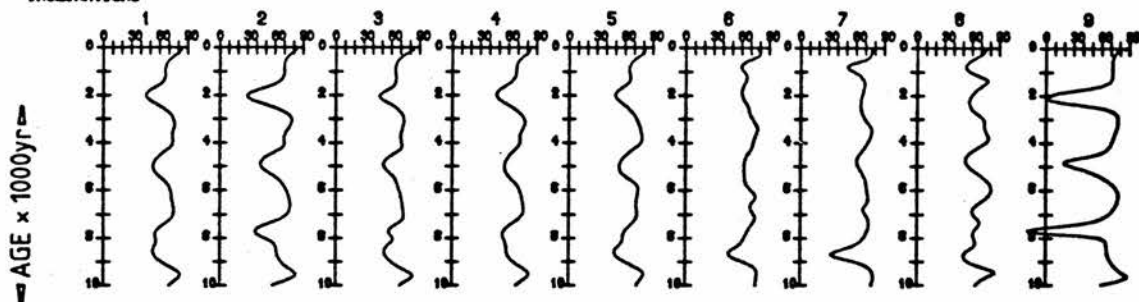
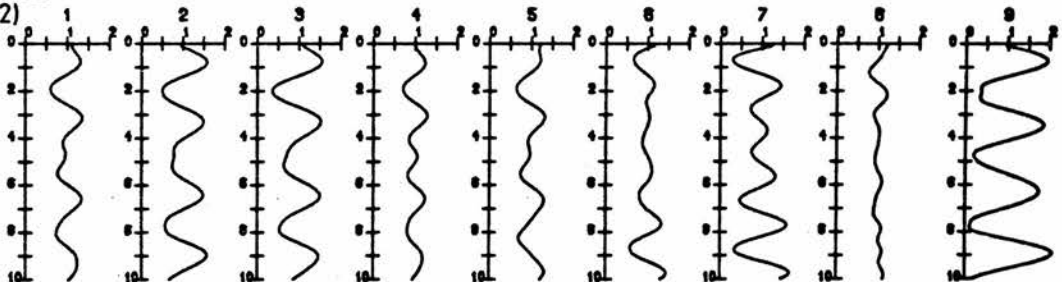
method adopted was to let one of the radial dipoles increase in strength to a value much greater than that of the other dipoles. Then by feeding these data into the program for different locations over the globe, it was hoped that an excursion would be simulated. The data used in this procedure were as defined in Table 6.2 except that dipole 4 was allowed to oscillate between  $\pm 0.400 \text{ G km}^3$ . Fig. (6.10) shows the results obtained for the same locations as used in Fig. (6.9). It can be seen that excursions and also a short period reversal in inclination are found at Tashkent but not at any other location. The other European locations show a low inclination at the time of the excursions, but for Michigan and San Francisco, the inclinations stay at approximately their mean value. Fig. (6.11) shows the individual contributions of each of the radial dipoles to the excursions seen at Tashkent. It can be easily seen that dipole 4 is the main contributor to these excursions and reversal. The intensity plot also shows low values for the field during the time of an excursion or reversal. A low field intensity has been found to be the case during a true reversal of the field. This also shows that with this model, it is possible to obtain a short lived reversal without having a reversal of the main dipole. It also demonstrates that a geomagnetic event would not necessarily be seen on a world-wide basis. It also shows that the summed effect of all the radial dipole sources can be to produce regional secular variations which are much more rapid and of larger amplitude than the variations of any single source.

Although managing to model an excursion, this does not seem to be a realistic model on account of the regularity of the excursions. A more realistic model would perhaps be one where a dipole was al-

## DECLINATIONS



## INCLINATIONS

INTENSITIES  
( $oe \times 2$ )

WIND. SALA. HELI. MADR. REYK. MICH. S. FRA. BIWA TASH.

FIG 6-10 Synthetic Plots for 9 Global Locations: Data as in Table 6-2, except Dipole 4

Moment equals 0.400.

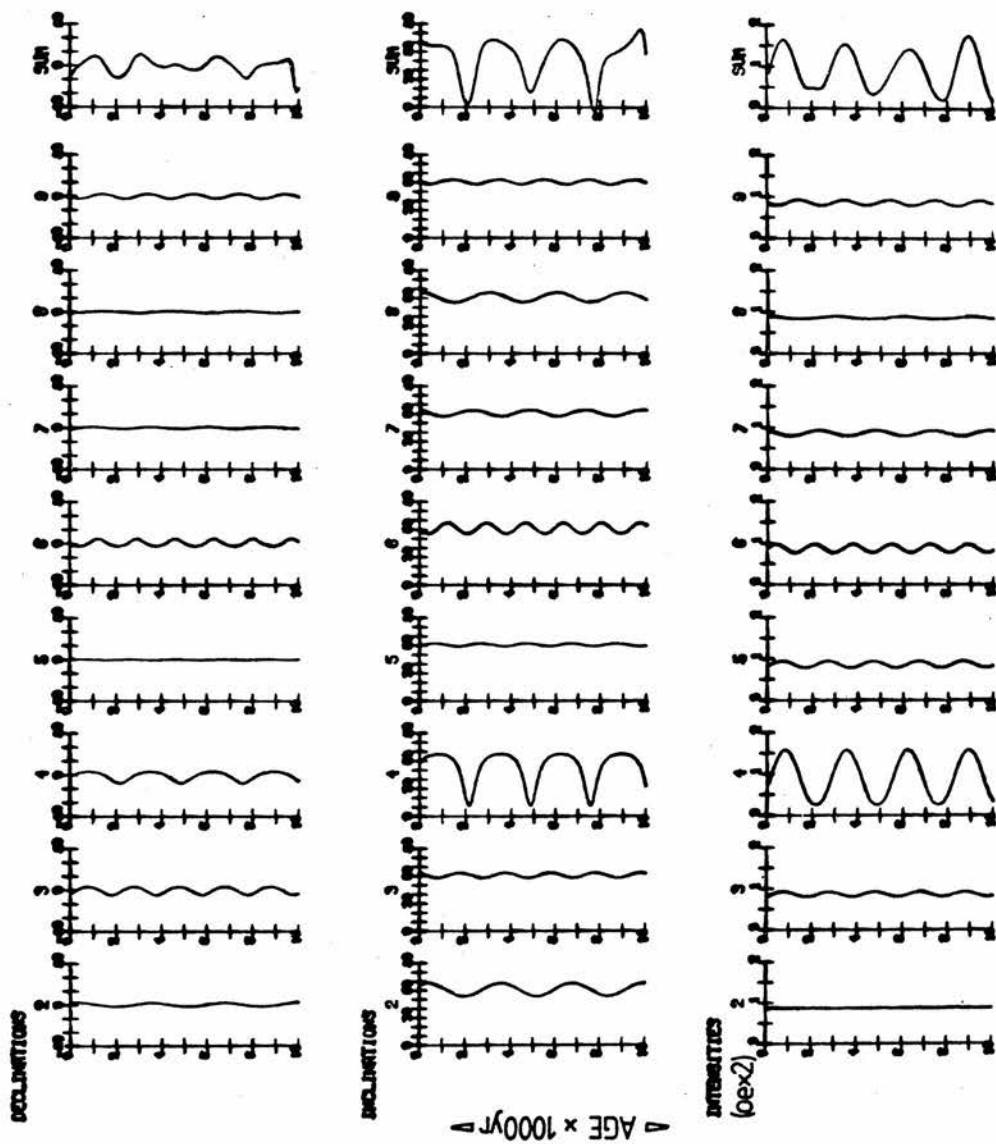


FIG 6-11 Synthetic Plot for Tashkent: Data as for fig 6-10.



lowed to increase to a greater value for one oscillation only and not regularly, and hence lead to a single excursion instead of a periodic one.

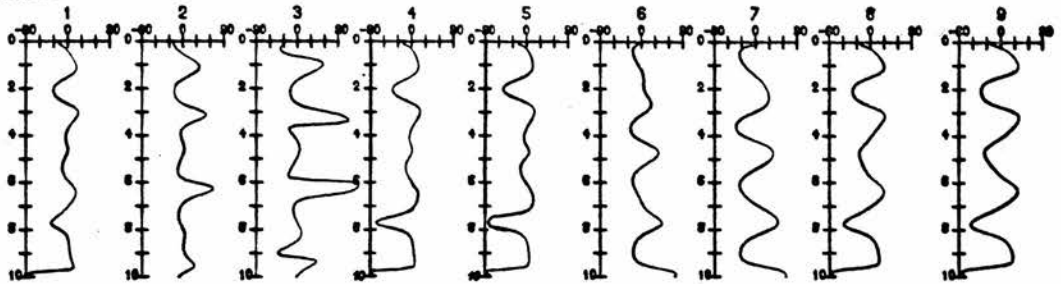
If this model is to be thought of in a physical sense, the radial dipoles representing disturbances on the core-mantle interface for instance, it is reasonable to imagine that if these disturbances were growing and decaying, that they would not necessarily grow to the same magnitude every time. The program was unfortunately not modified to deal with this situation.

Now that a short period reversal had been simulated, the question to be answered is over how large an area would this event be seen. To examine this, the data were fed in for points on a N-S line through Tashkent and also for points lying on an E-W line. The strength of dipole 4 was increased to  $0.500 \text{ G km}^3$  to enhance the reversal at Tashkent. The resulting plots are shown in Fig. (6.12). In this case the field would seem to show a reversal between approximate latitudes  $0^\circ$  to  $60^\circ\text{N}$  and longitudes  $30^\circ\text{E}$  to  $90^\circ\text{E}$ . If the strength of dipole 4 was increased even more, then the reversal would obviously be seen over a larger area.

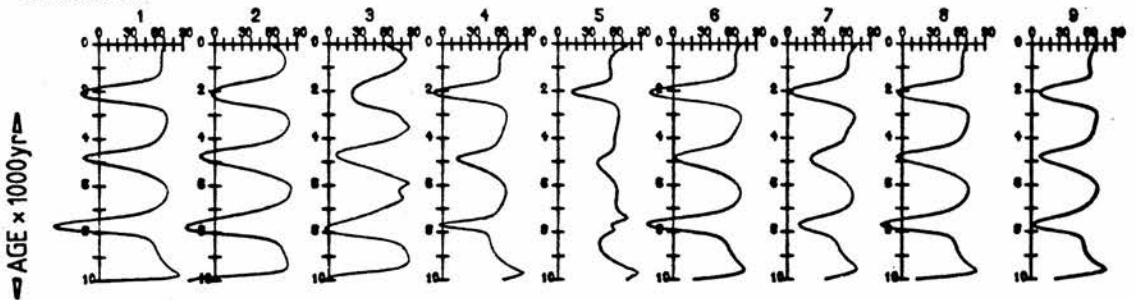
#### 6.6 The Charting of the Synthetic Geomagnetic Field

The plots shown to date that have arisen from the model, demonstrate the L P S V of the field. They do not however show very clearly the changes over a shorter time scale of say 50 - 100 yr, especially on a world-wide basis. As a result of this, the program was again changed slightly so as to calculate the field components over a world-wide  $10^\circ$  grid network for any specific time chosen. A contouring program was then very kindly loaned by the I.G.S. Geomagnetic Unit to help display the data. As well as helping to

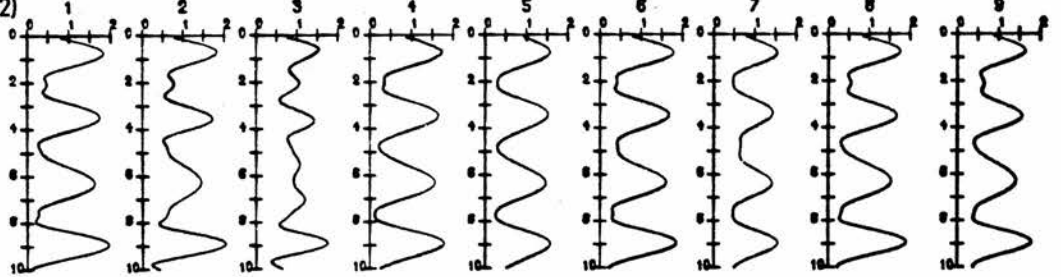
DECLINATIONS



INCLINATIONS



INTENSITIES  
( $oe \times 2$ )



42N 69E    22N 69E    02N 69E    52N 69E    62N 69E    42N 49E    42N 29E    42N 79E    42N 09E

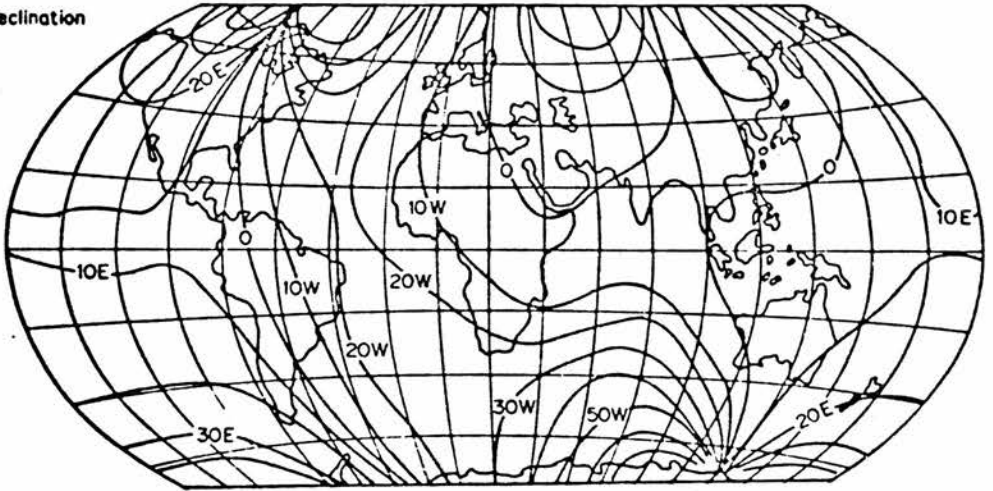
FIG 6-12 Synthetic Plot showing the Extent of the Reversal seen in fig 6-11.

demonstrate the effect of the model on a world-wide basis, this modification also made it possible to check that the model was calculating all the components correctly. To do this a time of 0 yr B.P. was fed into the program and the resulting charts compared to the 1955 World Charts. The 1955 Charts were used as they were the closest obtainable to the zero data point for the model, which was the 1945 U.S. World Charts.

Fig. (6.13) shows the 1955 World Charts and Figs. (6.14, 6.15) show the D and I synthetic plots for 0 yr B.P. (1945) and 50 yr B.P. The object of this exercise was not to produce an exact copy of the world charts for 50 yr B.P. but rather to see if the magnitude of the changes produced were of the correct order for this short period.

If the 0 yr B.P. charts are compared to the 1955 World Charts, except for a few minor details, they are found to be the same, thus proving that the program is calculating the components correctly. On Figs. (6.14 and 6.15), the positions of London and Cape Town are shown. Yukutake (1971) produced graphs of the declination and inclination changes at London and Cape Town for the past 350 yr. From these it can be seen that the declination at London varied ~~in~~ from  $10^{\circ}\text{W}$  to  $17^{\circ}\text{W}$  in the time 0 - 50 yr B.P., during which time the inclination remained almost constant. At Cape Town, the declination varied from  $23^{\circ}\text{W}$  to approximately  $29^{\circ}\text{W}$ , and the inclination from  $-65^{\circ}$  to  $-60^{\circ}$ . The charts produced by the model agree very well for the London data and for the declination data from Cape Town. The inclination at Cape Town is found to be only fractionally different over this period. There are obviously many places where the chart will not be in as good agreement with the real data,

(a) Declination



(b) Inclination

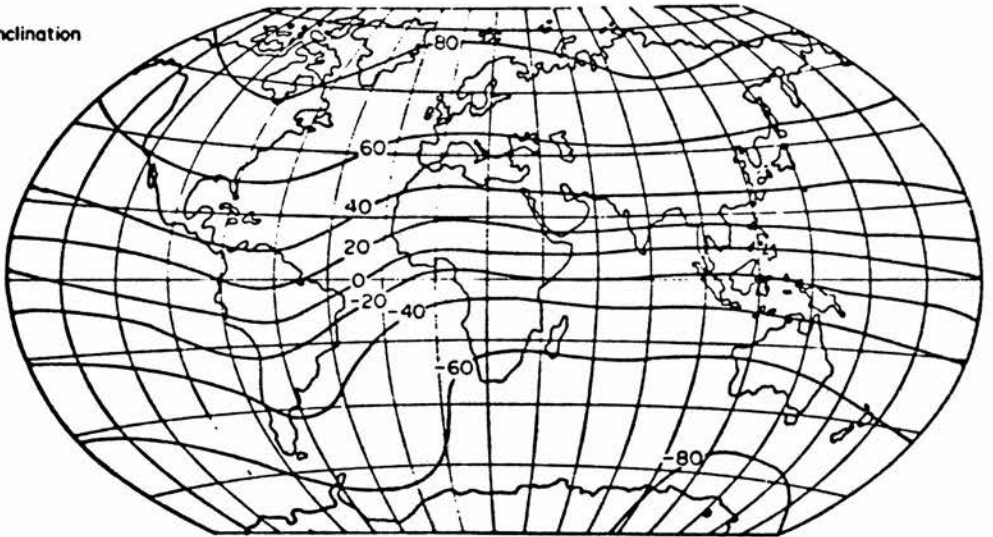
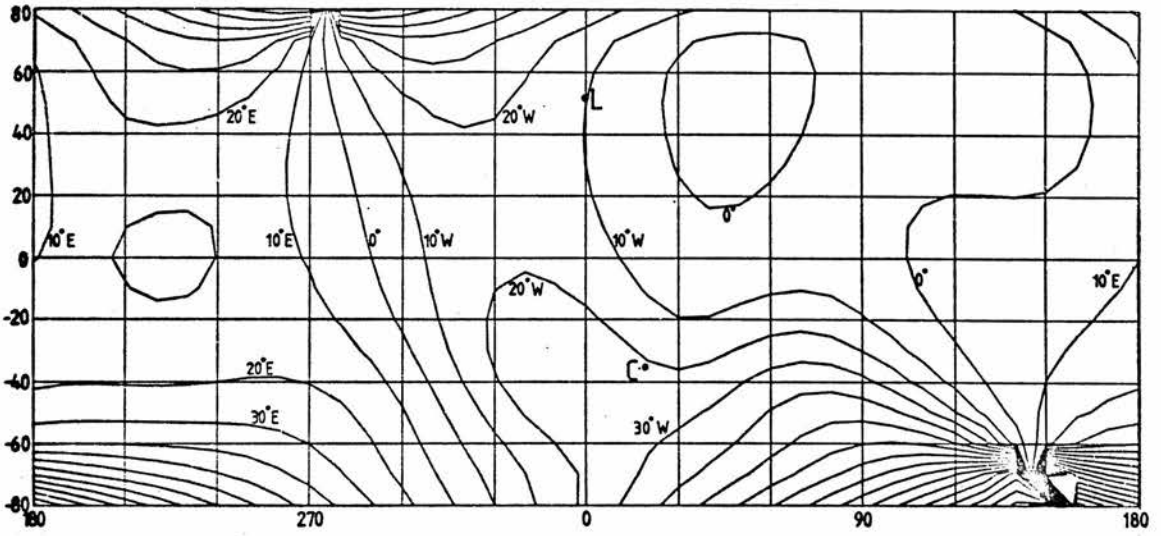
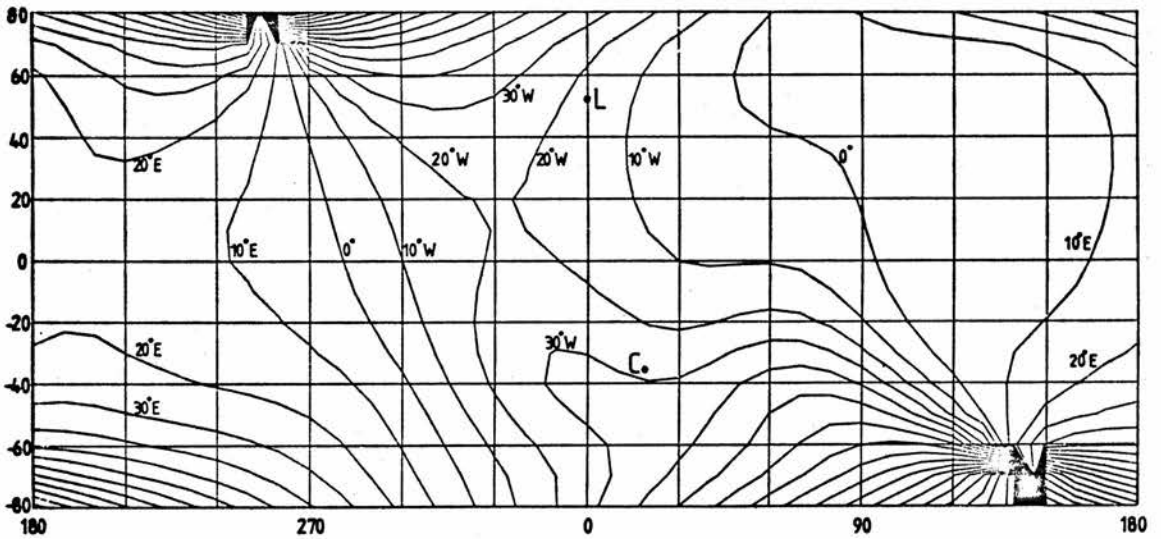


FIG 6-13 The 1955 World Charts for Declination and Inclination.



DECLINATION 0 B.P.



DECLINATION 50 YR BP

FIG 6-14 Synthetic World Charts for Declination, 0 and 50 yr BP

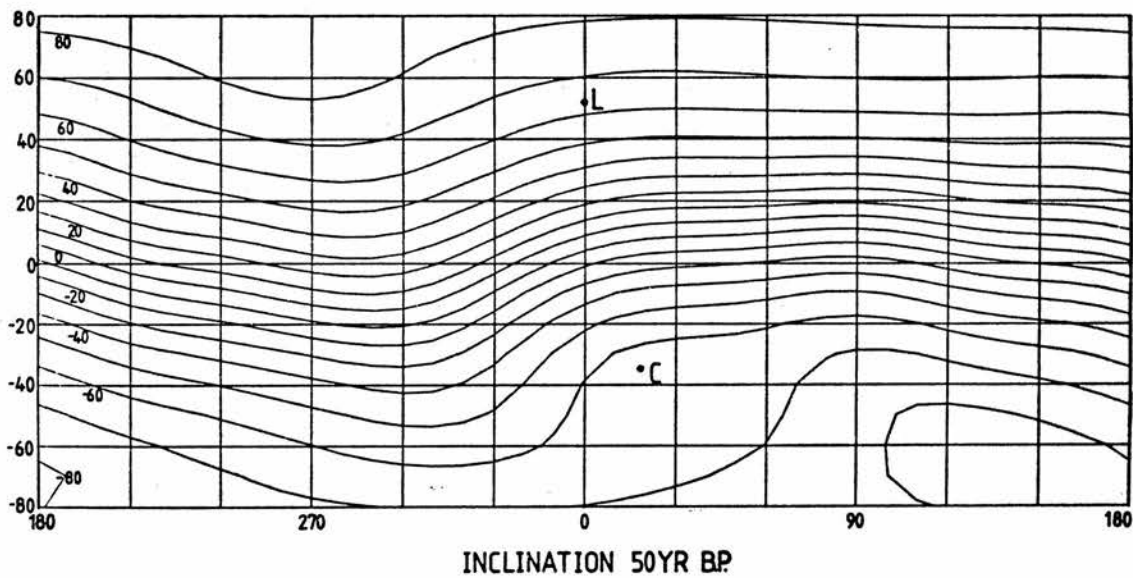
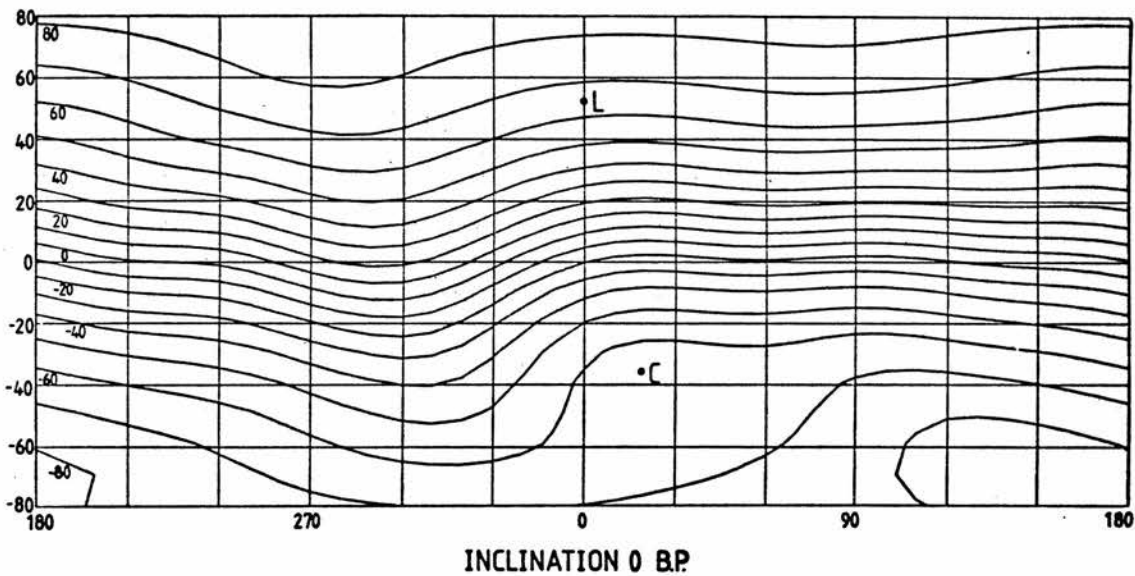


FIG 6-15 Synthetic World Charts for Inclination, 0 and 50yr BP.

but as stated before, it is not a definitive model that is being sought, but rather one that will produce the basic characteristics and order of magnitude variations of the field.

From the declination plots it can be seen that between 50 and 0 yr B.P. the north pole has drifted approximately  $20^{\circ}$  east and the south pole has remained virtually stationary. Although perhaps considered a rather large change in pole position over this time scale, charts of declination produced by Yukutake (1971), and Barraclough (1974) show that shifts of this magnitude and greater are possible over a 50 yr period.

#### 6.7 A Non-Oscillating Drifting Model

As a result of the apparent westward drift of the field in modern times, an attempt was made to model the field using a drifting dipole model. Modifications were again made to the program and as before, the A-H (1964) radial dipole model was taken as the starting position. The rate of drift of the dipoles was set by observing the change in the dipole positions as calculated by Alldredge and Hurwitz for the 1945 and 1955 geomagnetic field. A value of  $+ 0.27$  deg/yr, (west), was given to the positive dipoles and  $- 0.36$  deg/yr, (east), to the negative dipoles. The resulting plot for Lake Windermere is given in Fig. (6.16). As can be seen, a regular pattern of short period variations is found in the declination record and almost zero variation in the inclination record. The regular pattern is seen in this case as the dipoles return to their starting positions every 4,000 yr.

This model therefore does not seem to be satisfactory as the L P S V are lost and also there is no chance of simulating a geomagnetic excursion.

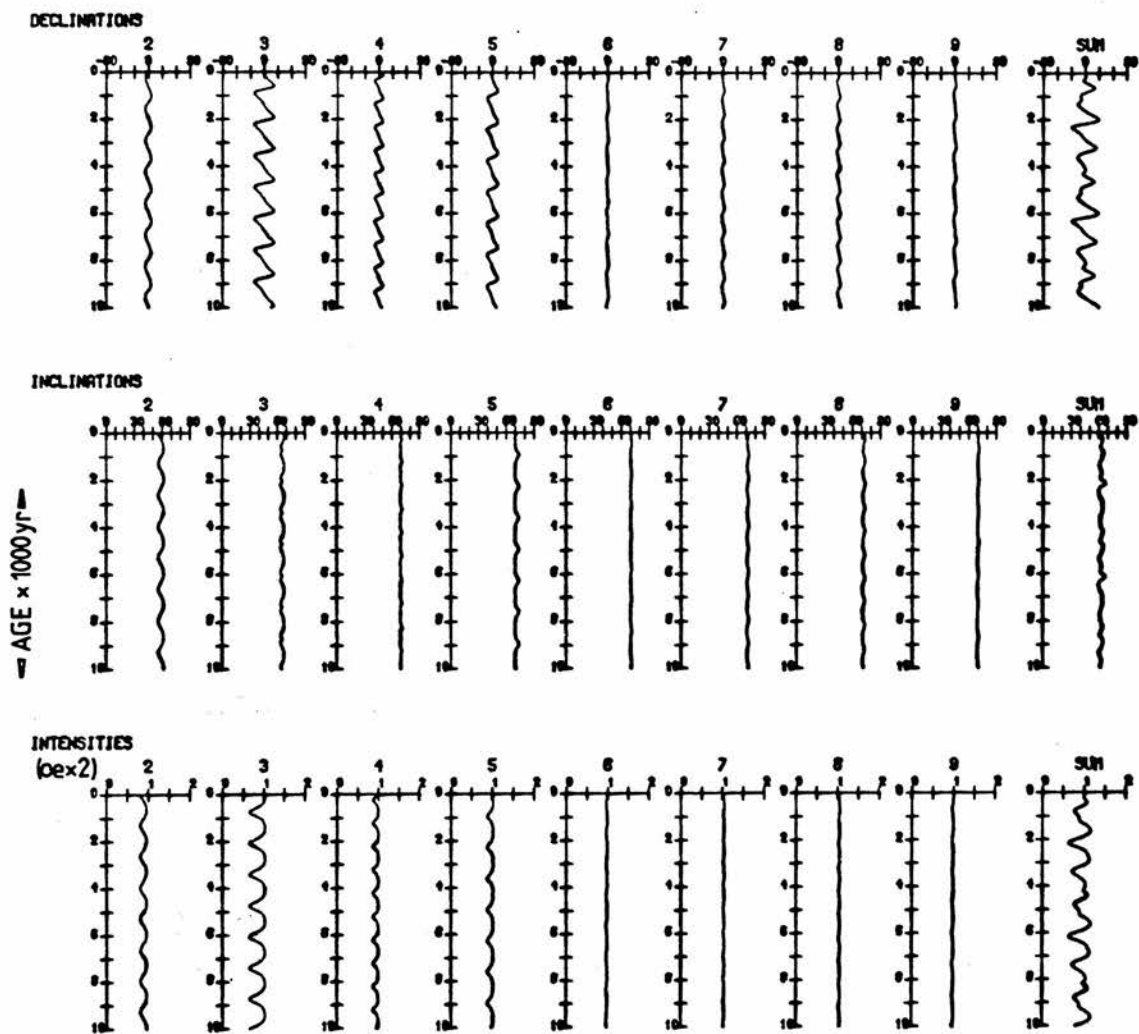


FIG 6-16 Synthetic Plot for Lake Windermere: Obtained from a Drifting Dipole Model,

+ve Dipoles have a Drift of  $0.27^\circ/\text{yr}$  and -ve Dipoles  $-0.36^\circ/\text{yr}$ .



## 6.8 An Oscillating and Drifting Model

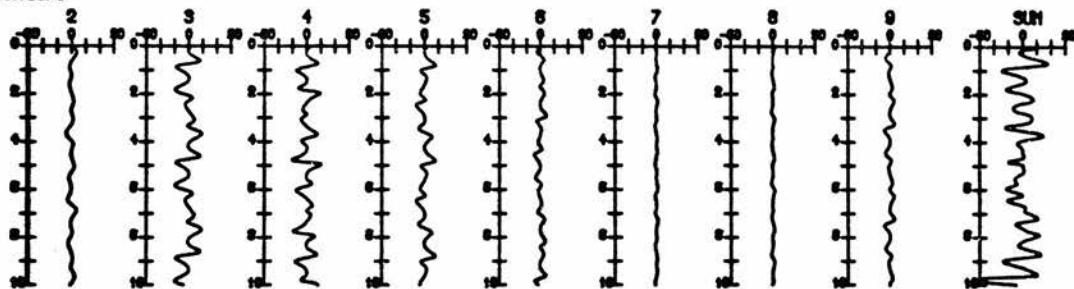
In an attempt to restore the L P S V to the declination record, while at the same time hopefully superimposing some smaller oscillations on them as seen in the archaeomagnetic and limnomagnetic data, an oscillating and drifting dipole model was proposed. A listing of the program used in the calculations is given in Appendix III to the text.

As stated above, this model was proposed as a result of the lake sediment data which seemed to show more oscillations than were seen in the more slowly deposited Lake Windermere sediments. The first attempt was a combination of the last two models, i.e. the same periods and strength as the first and the same drift rates as the second. The result of this combination is shown on Fig. (6.17). The effect on the declination is just to enhance the shorter period variations as seen in the previous model. The inclination record still shows the very small amplitude variations, but this time superimposed on a longer and larger amplitude variation. This longer period variation seems to be governed by dipole 2 as was the case in the first model. Results of a time series analysis on the declination and inclination records are given in Chapter 7.

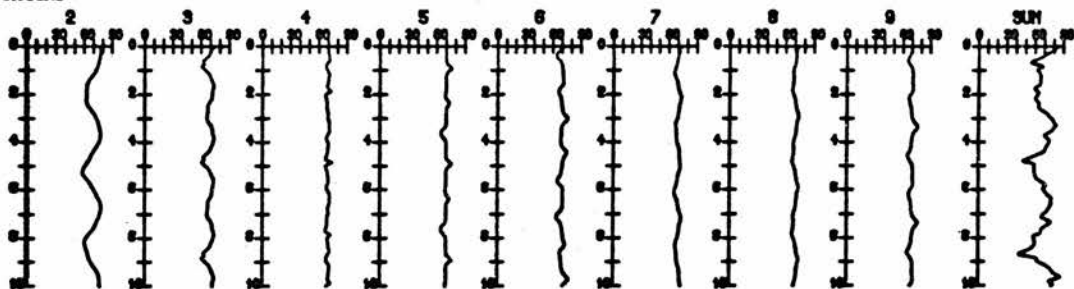
To try and reduce the number of short period oscillations slightly the next step was to reduce the rate of drift of the dipole. Fig. (6.18) shows the result of reducing the drift rates of the dipoles by one third. Although now having a more realistic number of oscillations in the declination record, the basic period of oscillation as shown in the original model is still missing.

It would appear that although not showing as many oscillations as the archaeomagnetic curves, the original model is the best and

## DECLINATIONS



## DECLINATIONS



## INTENSITIES

(oe x 2)

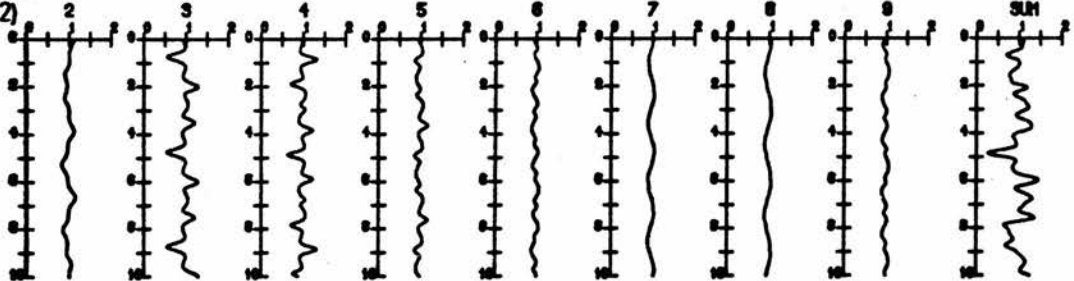
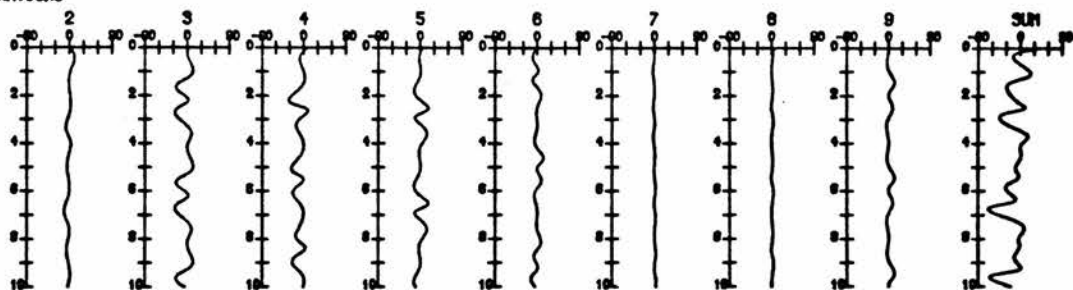
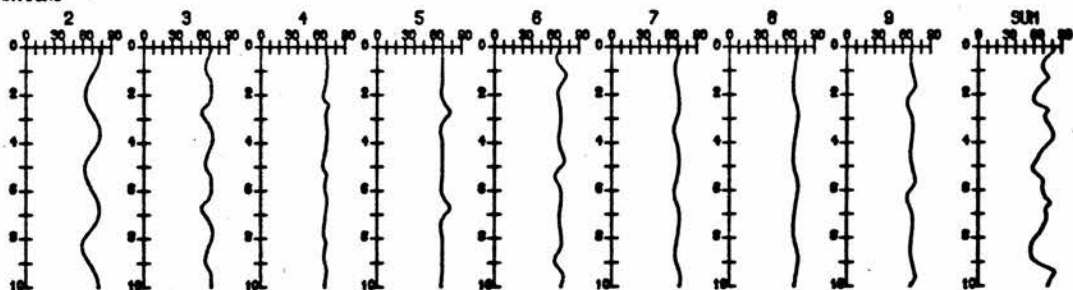


FIG 6-17 Synthetic Plot for Lake Windermere: Obtained from a Drifting and Oscillating Model. Periods as in Table 6-2, Drift Rates as in fig 6-16.

## DECLINATIONS



## INCLINATIONS



## INTENSITIES

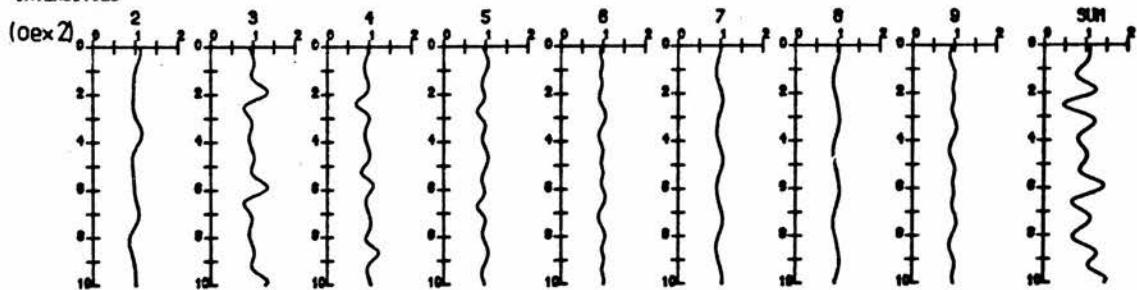


FIG 6-18 Synthetic Plot for Lake Windermere: Data as for fig 6-17, except Drift Rates are  $1/3$  of those used in fig 6-17.

most versatile one for modelling the L P S V of the geomagnetic field. To try and retain the basic character of the original curves but with a greater number of oscillations, perhaps the original model with a superimposed (non-oscillating) drifting field would be the answer. This model has not been tested and, as a result the variations obtained from it, can only be speculated. However it would seem to be a possible model for any further studies in this field.

CHAPTER 7Time Series Analysis of Real and Synthetic Data7.1 Introduction

As has been previously discussed, interesting periodicities have been noticed in the study of magnetization in recent lacustrine sediments (Mackereth 1971; Creer 1974; Creer et al 1976; Opdyke et al 1972). These periodicities are of great importance in trying to understand the mechanics of secular variations, especially in the case of the model proposed in Chapter 6. Most of the periods quoted to date however were established from visual inspection of the data. Fourier analysis techniques on palaeomagnetic data from lake sediments are made rather difficult by both the short length of data available and by the high noise levels.

It is generally accepted that to obtain well defined peaks from a Fourier transform one needs a data set which is approximately ten times the length of the period being investigated. In the case of secular variations, periods of between 1,700 yr and 2,800 yr have been reported. Therefore to define these as clear peaks in a Fourier transform, one would need data sets of about 20,000 to 30,000 yr in length. For the sediments collected from France and Poland at least, records of this length are not nearly approached. As a result it was decided to analyse the data by means of the maximum entropy method (MEM) of spectral analysis. The maximum entropy spectral estimator was proposed by Burg (1967, 1968) as a method of analysing data sets that were short in comparison to the observed period. Discussions of this technique can be found in Lacoss (1971) and Ulrych (1972). MEM has been carried out in the past on palaeomagnetic data by

Obeng and Evans (1976).

One of the significant points about the MEM is that the prediction - error - filter coefficients are determined by using only the available data and no null extension of the data is required. The program used in this thesis was developed in the department and calculates the prediction filter coefficients using N. Andersens recursive procedure. It then uses these coefficients to extend the data set by a factor of two in the forward and reverse direction. A normal fast Fourier transform (FFT) is then carried out on the extended data set.

Arguments have been put forward in the past about the validity of the MEM. Most of these arguments stated that false periods could be found using this method. It has even been suggested that periods could be "manufactured" to agree with ones theories. Greatly differing power spectra can in fact be found for any one individual data set, depending on the number of terms used in the prediction error filter. Experiments on the effect of changing the number of points in the error filter (NPEF) were carried out by Chen and Stegen (1974). Briefly they found that when the number of terms was small the spectral resolution is poor: the peak is broad and the side bands high. If the number of terms is too high the filter can amplify the noise and produce several spurious peaks with comparable power densities to that of the original signal. They found that using a 24 sample data set of a 1 - Hz sinusoid with 5% superimposed white noise as input data, the best resolution was obtained using 9 terms in the prediction error filter. Experiments using the synthetic data created by the model discussed in Chapter 6 showed that correct results were obtained if this ratio of the samples in the data set to the

NPEF was used. If this ratio was changed a different power spectrum could be obtained that did not agree with the input data.

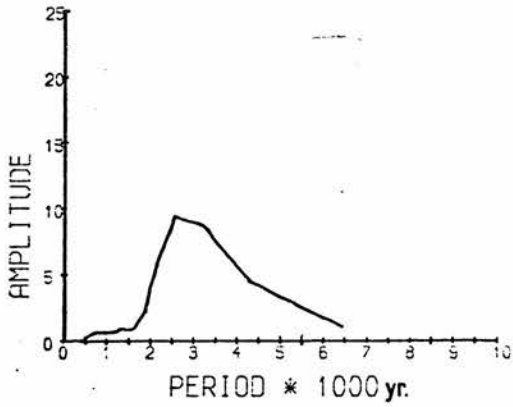
## 7.2 MEM and FFT Results obtained from the Oscillating Dipole Model

The input data used to test both the MEM and a normal FFT were synthetic declination data for Lake Windermere obtained by using the model described in Chapter 6. The dominant dipole was given a period of oscillation of 2,700 yr and periods of 2,000 yr and 1,700 yr were also introduced. The data points were equally spaced at 100 yr intervals, so that a data set of length 1,500 yr was generated by 15 points, etc. Fig. (7.1) shows plots of amplitude against period for four different lengths of data set obtained by using a maximum entropy approach. The ratio of data points to NPEF was kept at 24:9 as given by Chen and Stegen (1974). It can be seen that the dominant period of 2,700 yr is picked out in all four plots, even in the data set of length 1,500 yr which is only half of the observed period. The peak appearing on the plot of the 1,500 yr data set is however rather broad and although centred on 2,700 yr would be rather ambiguous if the answer was not already known. The periods of 2,000 yr and 1700 yr are not however picked out. There is a peak in the records at 1,000 yr which will be due to the double effect of being a harmonic of 2,000 yr as well as the difference between 2,700 yr and 1,700 yr.

Fig. (7.2) illustrates the effect of carrying out a normal FFT on different lengths of the same data set. For comparison, the first plot is the one obtained by using maximum entropy on 10,000 yr of data, the other three showing the results obtained by using Fourier analysis on 10, 15 and 20 thousand years of data. Even at 20,000 yr, the 2,700 yr peak is not as well defined as the one for 7,500 yr

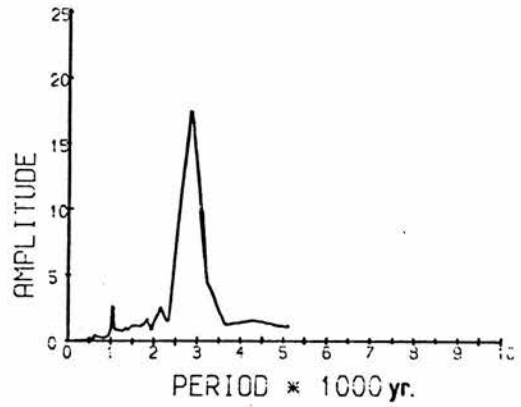
### WINDERMERE 1500

15 DATA POINTS



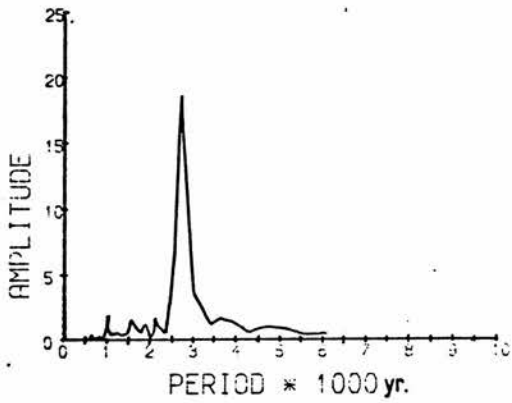
### WINDERMERE 5000

50 DATA POINTS



### WINDERMERE 7500

75 DATA POINTS



### WINDERMERE 10000

100 DATA POINTS

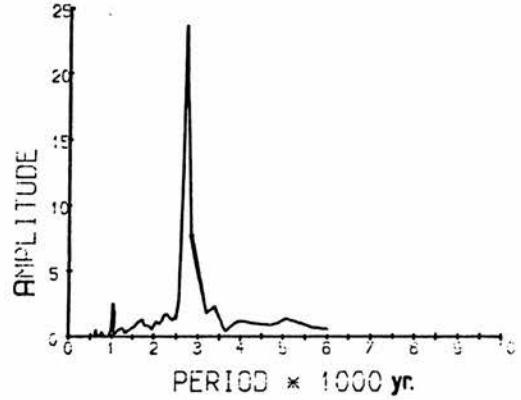
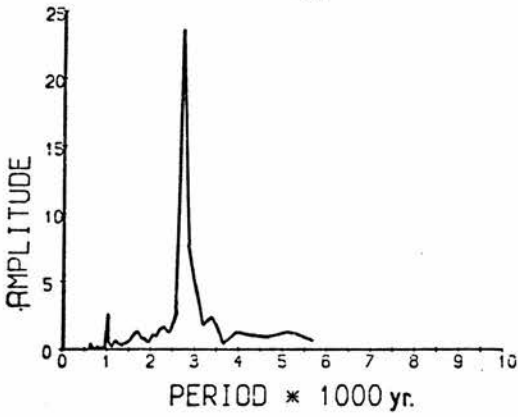


FIG 7-1 Results from MEM carried out on Synthetic Data from Lake Windermere



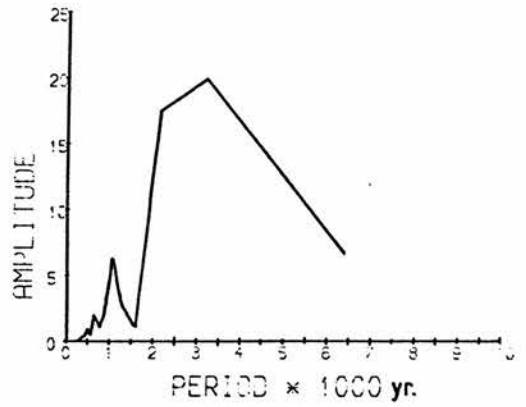
WINDERMERE 10000 (MEM)

100 DATA POINTS



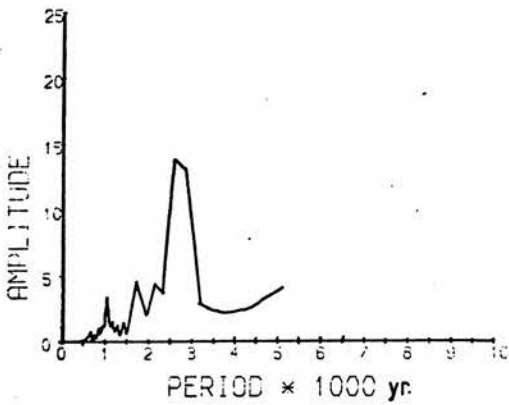
WINDERMERE 10000 (FFT)

100 DATA POINTS



WINDERMERE 15000 (FFT)

150 DATA POINTS



WINDERMERE 20000 (FFT)

200 DATA POINTS

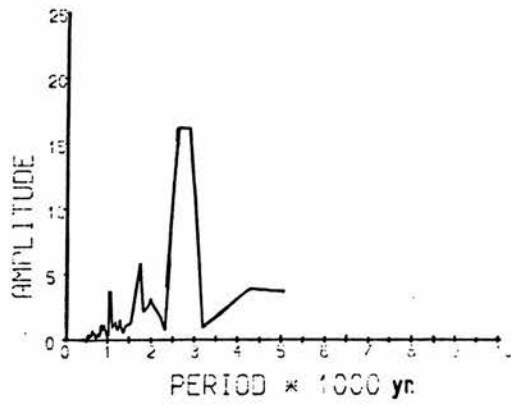


FIG 7-2 Comparison of Results using MEM & FFT on Synthetic Data from Lake Windermere

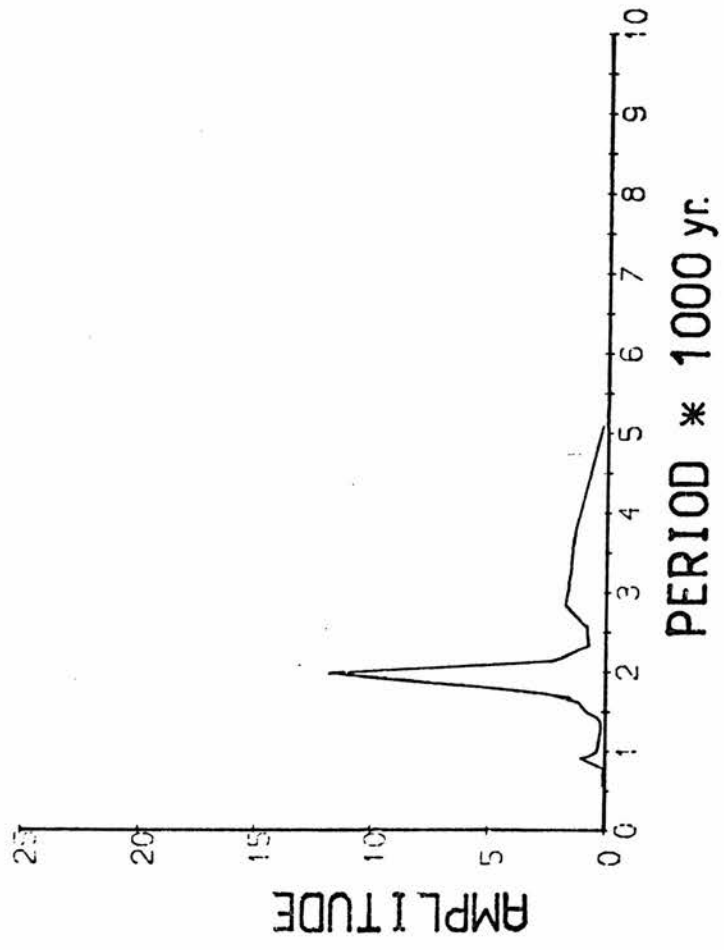
using MEM. Using the Fourier analysis on 20,000 yr of data does however pick out the 2,000 yr and 1,700 yr periods. The peak at 1,000 yr also occurs using the FFT method.

Fig. (7.3) shows the effect of changing the number of terms in the prediction error filter. The data set in both cases was 10,000 yr (i.e. 100 x 100 yr). For the original analysis 36 terms were used in the filter whereas in the two cases shown 20 and 50 terms were used. In the former case, the 2,000 yr period is seen as the dominant one, with a very small broad peak occurring at 2,700 yr. In the latter case, the 2,000 yr peak is seen with even greater resolution, whereas the 2,700 yr peak vanishes completely and a new peak is found at 3,200 yr. These two diagrams clearly show how spurious peaks can be obtained by altering the ratio of data points to the NPEF. If however the ratio that Chen and Stegen (1974) found to be the best is adhered to, it would appear that maximum entropy could be used on palaeomagnetic data to resolve any dominant period that existed. It would seem though, that the MEM is not so suitable for resolving any of the smaller amplitude periods that may exist.

### 7.3 FFT Results obtained from the Oscillating and Drifting Model

The declination and inclination data obtained from this model and shown in Fig. (6.17) were analysed using a FFT. The results of the FFT are shown in Fig. (7.4). The two drift rates used in the model were 0.27 deg/yr and 0.36 deg/yr. The FFT on the declination record shows two distinct peaks at 1,000 yr and approximately 1,300 yr. This obviously corresponds to the periods of rotation of the dipoles. The dipoles have a drift rate of 0.36 deg/yr taking 1,000 yr to rotate through  $360^\circ$  and the dipole with a rate of 0.27 deg/yr taking 1,333 yr. There is also a very broad peak centred on about

100 DATA POINTS NPEF=20



100 DATA POINTS NPEF=50

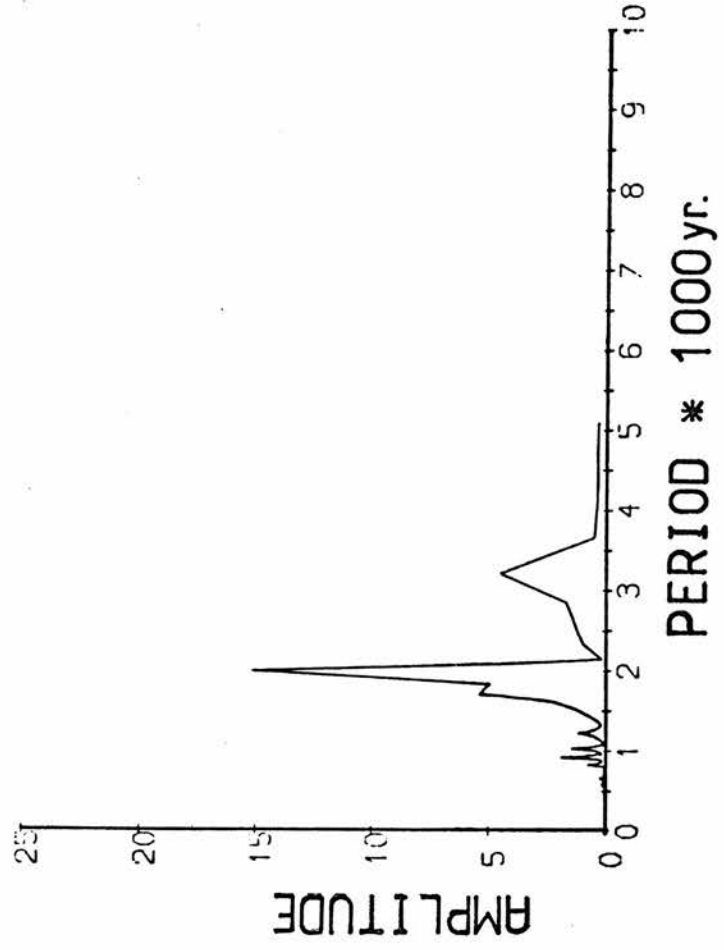


FIG 7-3 Results showing the Effect of Changing the NPEF for the Same Data Set

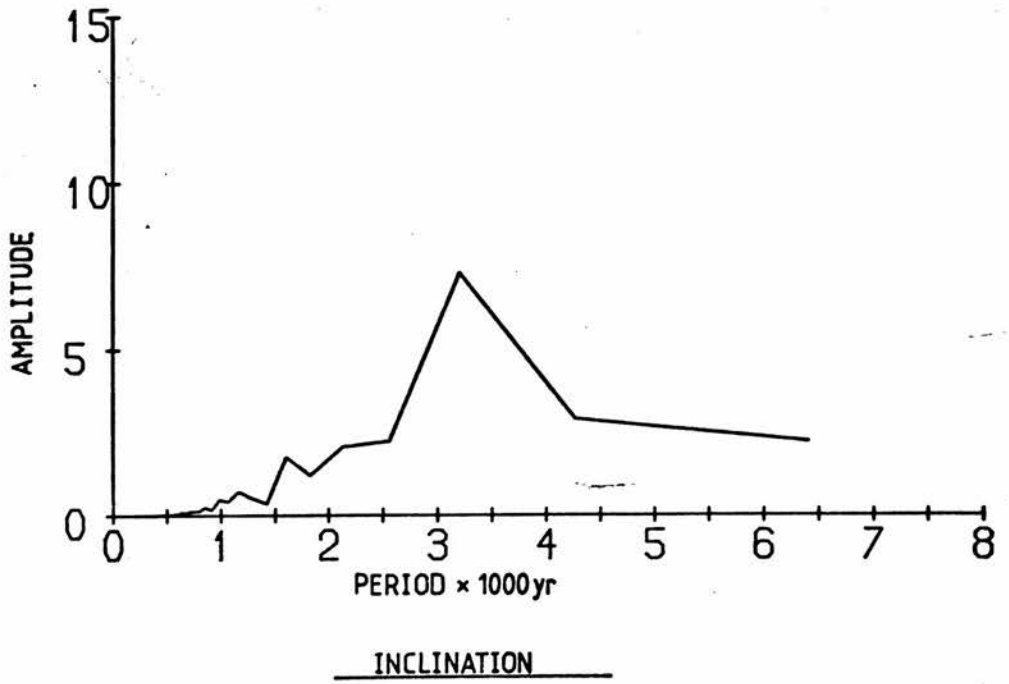
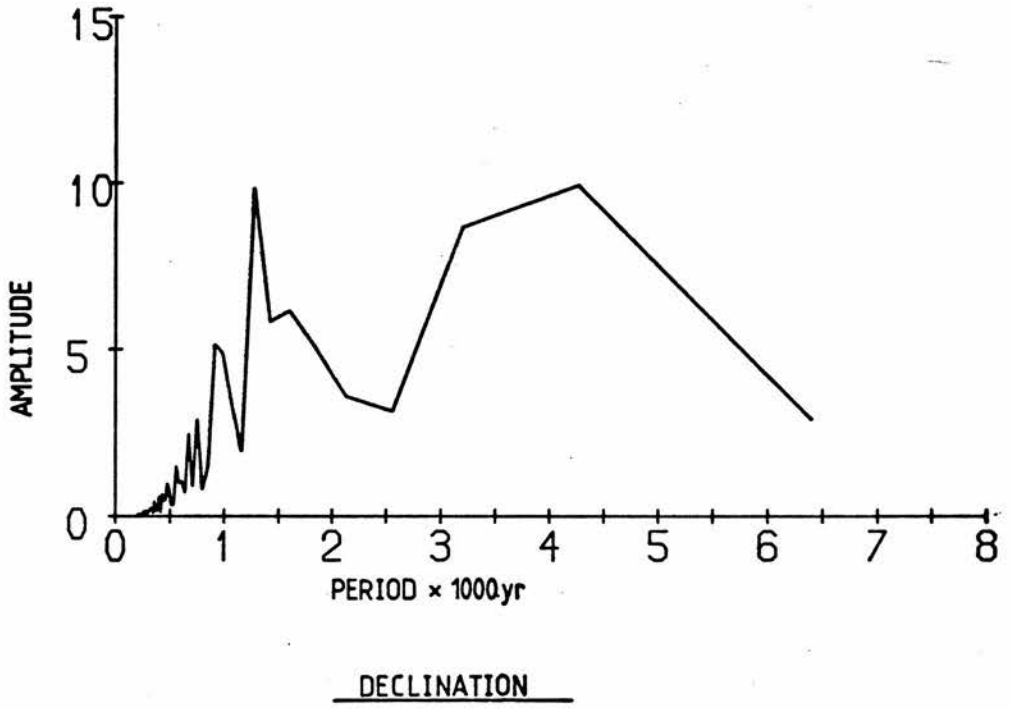


FIG 7-4 Results of FFT on Synthetic Data Obtained from a Drifting and Oscillating Dipole Model.

4,000 yr which is the time taken for all the dipoles to return to their original position. This proves the conclusions arrived at in Chapter 6 that the declination variations derived from this model depend on the rate of drift of the dipoles and not the period of oscillation. As a result of this, all places would then demonstrate the same period and no regional periodicities of the field would be noticed. As can be seen from the FFT on the inclination record, the 3,200 yr period picked out is that of dipole 2. This shows that the inclination record is more dependent upon the period of oscillation of the dominant dipole rather than the drift rates of the individual dipoles.

#### 7.4 MEM and FFT Results from Limnomagnetic Data

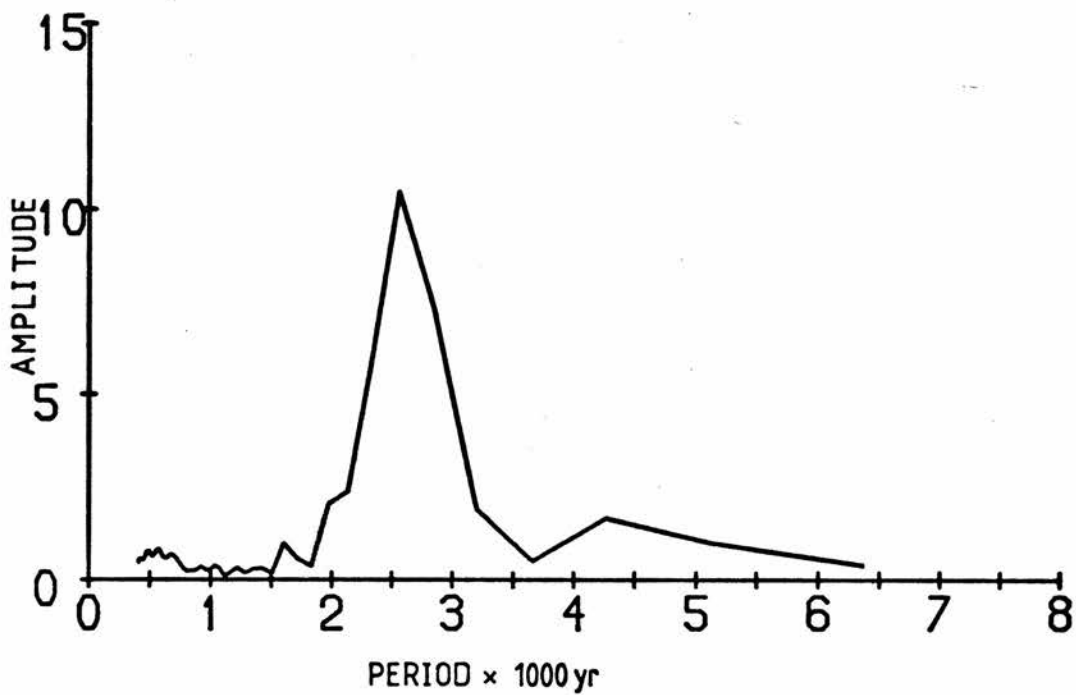
The first step in this procedure is to smooth the data as in its original form there is a very low signal/noise ratio. In the cases shown here, the smoothing was done by hand. A smooth curve through the points, using the lettering already placed on the diagrams as guidance, was drawn by hand. This smooth curve was then digitized at equally spaced time intervals (50 yr). This was done by assuming a constant deposition rate between the available dates, obtained by either pollen or magnetic dating. The data from the digitized curve were then fed into the MEM routine which extended the data set. The extended data set was then used as the basis for a standard FFT.

It was found that as a result of the very large scatter, the twisting of the cores, and the 'missing swings' in the Polish declination records, that there was no suitable record for a time series analysis. For the French and Swiss lakes, Geneva was chosen for analysis as it seemed to show the best declination record. Un-

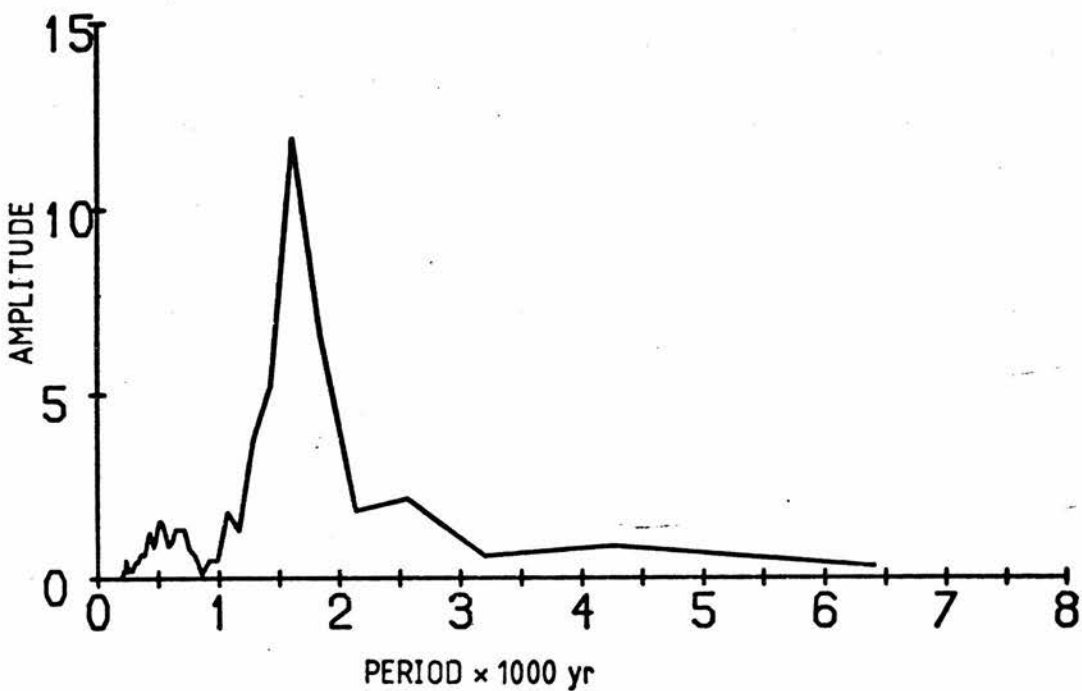
fortunately there is no dating control beneath about 4.0m, and consequently the record was digitized in 2 different ways. The first was to take the dates obtained from the pollen and archaeomagnetic curves from both the declination and inclination records (Fig. 3.17), and then assume the westerly minimum in declination beneath 4.0m to correspond to the 2,600 yr minimum as seen at Windermere. The second method was to use the pollen and magnetic data, and then assume the same rate of sedimentation between the last date and the bottom of the core as between the last two dates. The resulting plots are shown in Fig. (7.5). If the first method is used peaks are seen at approximately 2,700 yr, 4,250 yr and 1,600 yr. If the second method is used, peaks can be seen at 1,600 yr, 2,700 yr and 1,100 yr. The scale used in both plots is the same although in arbitrary units. It can be seen that 2 different answers are obtained although both show peaks at 1,600 yr and 2,700 yr. It must be remembered however that the MEM does not seem to be too reliable at picking out the correct smaller amplitude periods, as shown earlier in the chapter.

If the first plot is to be believed, then a similar period to that of Windermere is found, **I**f the second one is true, then there would not seem to be a correlation. The main point proved by these plots however is probably the fact that a much stricter age control is needed on the data before a time series analysis can be carried out. The two plots shown were obtained from the same curve with only one date being different between them.

The same procedure was carried out on inclination records from Geneva, Radunskie-Gorne and Charzykowskie, the resulting plots being shown in Fig. (7.6). It should be noted that the scale is exaggerated from the one used for the declinations so as to enhance the

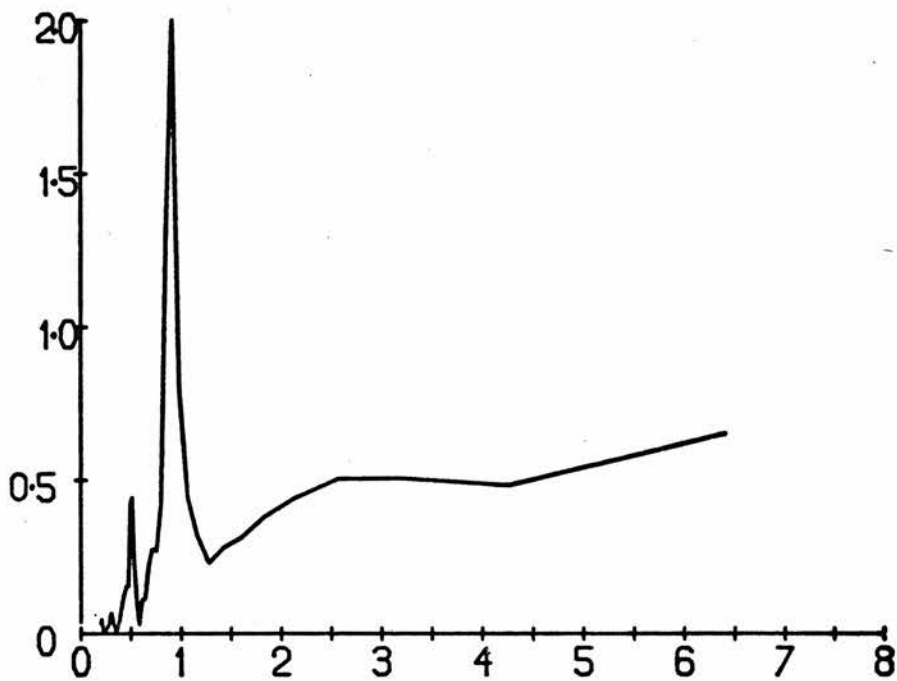


GENEVA-DECLINATION CF. WINDERMERE CURVE

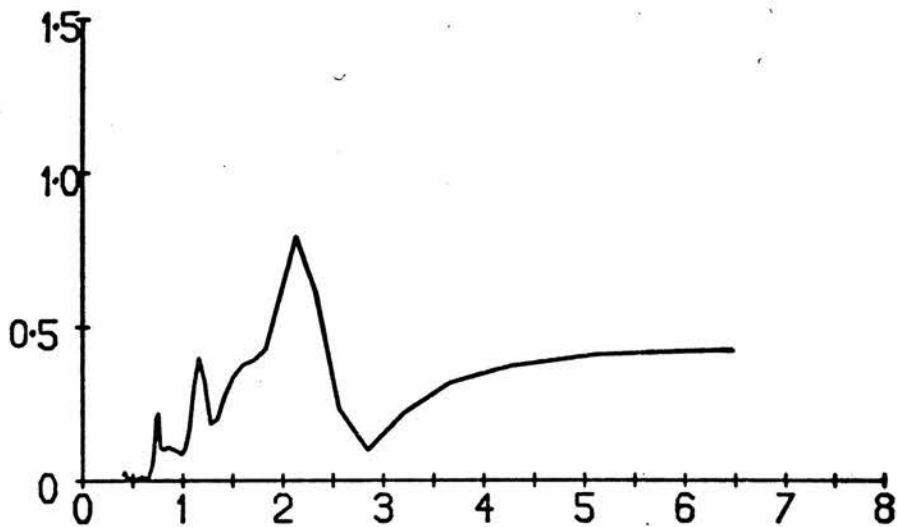


GENEVA - DECLINATION CF. ARCHAEOMAGNETIC CURVE

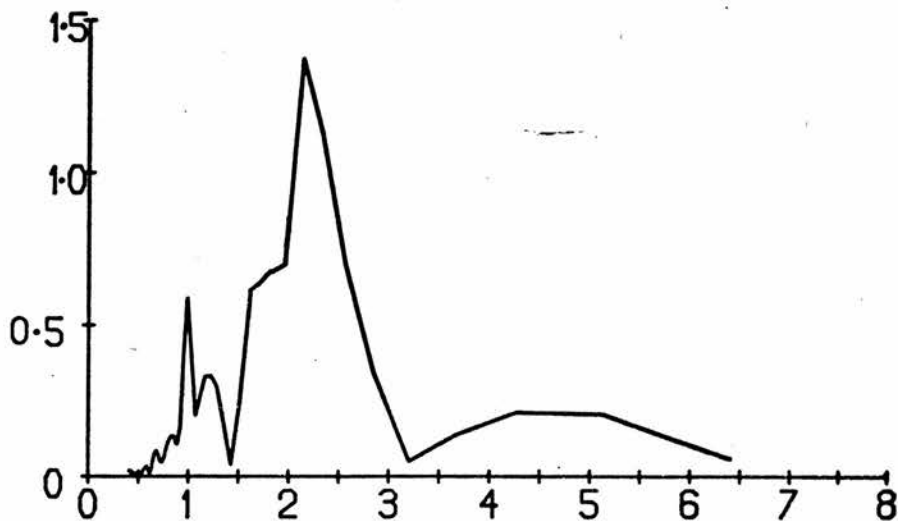
FIG 7-5 MEM on Geneva 7 Declination Record



GENEVA 7



RADUNSKIE-GORNE 3



CHARZYKOWSKIE 2

FIG 7-6 MEM on Chosen Inclination Records



output. The first thing to be noticed is the much lower power in the periods found. The Polish lakes seem to show a peak at 2,300 yr and other peaks at about 1,000 - 1,300 yr. Lake Geneva, (dated as in method 2), shows a distinct peak at 1,000 yr. However due to the small power associated with them and also the ratio of the power to the surrounding 'noise level' it is debatable whether they are significant. As with the declination, before any statement on the existence of a periodicity could be made, better records with a stricter age control would have to be studied.

As well as better dating controls, a more objective method of smoothing the records would probably be helpful. Running means were not used in this case as they tend to induce higher frequencies than are actually in the data.

CHAPTER 8CONCLUSION8.1 Palaeomagnetism of Lake Sediments

One of the first things that becomes apparent on studying palaeomagnetic records from lake sediment cores is that not all lakes have sediment that is capable of producing a good geomagnetic record. Even within one lake it is not always possible to obtain a good record from each core taken in that lake. Numerous factors could be responsible for the poor records, some of which are listed below:

- (1) size and shape of the lake
- (2) currents and physical movement of the sediment within the lake.
- (3) the environment of the catchment area, which in turn affects
  - (a) sedimentation rate and
  - (b) type of sediment input and proportion of magnetic materials.
- (4) disturbances due to the coring operation.

At the present moment, with the knowledge of the results from the French and Polish lakes, as well as results obtained from other departmental field trips, it would appear that the chance of any single core revealing a good palaeomagnetic record is probably not better than 1 in 5. It would seem however that these odds could be reduced for further studies by the following methods. Firstly better records could be obtained if the corer was prevented from twisting. This in fact has been accomplished and will be ready for future use. Secondly it may be possible to carry out a preliminary survey on several lakes before deciding in which ones to core. This survey could

be carried out quickly and would involve the sampling of the sediment from the lake itself and from the input sources. From both long core and subsampled measurements, it would appear that one would stand a better chance of obtaining a good paleomagnetic record if the sediment sampled had a relatively high intensity and susceptibility. If the sediment in a particular lake had almost zero intensity and susceptibility, then this lake could be neglected. The results from this thesis would perhaps suggest that a lower limit for these quantities could be set at about  $10\mu\text{G}$  for the intensity and  $7\mu\text{G/oe}$  for the susceptibility.

As a result of the difficulty in obtaining a good record even within a particular lake, it is obvious that as many cores as practically viable should be taken from each site. Then as stated in earlier chapters, only cores that can be correlated within a lake can be seriously considered to be true recorders of the ancient geomagnetic field.

As regards limnomagnetic work as either a means of dating or of solving the problem of westward or eastward drift, then it would appear that the results obtained at present are not sufficiently accurate ~~enough~~ to justify them being used for either purpose. To be used as a dating tool alone, one would have to be sure that all the 'swings' in the record were real and that all the variations of the palaeofield had been recorded. Unfortunately this is not possible as there are many occasions when it is impossible to decide whether a certain feature is representative of a variation in the geomagnetic field. This uncertainty was shown in Geneva core 7 when two different interpretations were given to the record according to either the radio-carbon or the pollen dates. Used in conjunction with a

reliable dating control however, the records are very useful in revealing information about the ancient field and the secular variations. As shown in earlier chapters, the precision of the dating control techniques are not sufficient to resolve the problem of westward drift over the relatively short distances studied. If however cores could be dated and studied from different global sites, the results would be very useful as they would show the pattern of variation of the geomagnetic field over roughly the same time scale. This in turn is very helpful in trying to understand the geomagnetic field on a global rather than regional scale. Additional information could also be obtained if the cores collected were orientated. This has also been made possible for future studies in the department by the addition of an orientation device to the Mackereth Corer. This device was developed by Barton and Burden at the National University, Canberra, Australia.

In general, the cores collected on field work in the summer of 1975 from France and Switzerland gave good palaeomagnetic records which correlated well with the archaeomagnetic curves for N.W. Europe. The cores collected in the summer of 1976 from Poland did not give as good results on the whole and tended to be more scattered than the French and Swiss ones. As previously stated, this was most probably due to the amount of magnetic material contained within the sediments from the different lakes.

## 8.2 Carriers of the Remanence

Almost without exception, the experiments showed that the NRM was detrital in nature and caused by the presence of fine-grained magnetite. Only in a few cases was there any evidence of haematite and even then in very small quantities. Again in a very few cases

there was evidence of a mixture of fine and coarse grained magnetite within the sediment.

### 8.3 Geomagnetic Field Modelling

As a result of the very complex nature of the global geomagnetic field and of its L P S V, it is obvious that no simple model is going to explain its exact behaviour. As stated earlier, the object of the field modelling was to try and propose a model which while remaining relatively simple, was able to simulate the basic characteristics of the observed field. The model although being a 'non-definitive' one, would hopefully be able to model the L P S V and the short lived excursions and reversals of the field. Of the three models tested, the original oscillating dipole model would seem to be the most appropriate. With this model it was possible to obtain varying declination records for different areas while using the same input data. It was also possible to model excursions and inclination reversals without reversing the main dipole. It was however found to be rather difficult to obtain the shorter period variations as seen on the archaeomagnetic curves. As mentioned in Chapter 6, a possible model for future investigations would be an oscillating dipole model to produce the longer period variations, coupled with a drifting model used to superimpose the shorter periods variations.

### 8.4 Time Series Analysis

From the studies carried out on the synthetic data obtained from the oscillating dipole model, it was shown that the MEM appeared to be a suitable one, to a limited extent, for use on palaeomagnetic data. This was only true however if the fixed ratio of data points to the NPEF was kept constant. It also appeared to be valid for the dominant period only. Where it was applied to the real data however,

the results were not as satisfactory as was hoped. This was not a fault of the method though, but rather of the data and the age control on the data. To carry out successful time series analysis on lake sediment results, an appropriate smoothing technique would have to be used on the data and more importantly, a strict age control at numerous points down the core would be needed. If this was done, then it would seem possible to further investigate the apparent periodicities of the field, and to show over how large an area they remained valid.

APPENDIX ILithological Descriptions of Selected CoresA1. Charzykowskie Lake - core no. 6 (CH6)

Sections: I: 0-1.5m, II: 1.5-3.0 m, III: 3.0-4.5 m, IV: 4.5-6.0 m.

0-8 cm:

Unlayered, dark grey gyttja.

8-282 cm:

gyttja, grey at the top, becoming lighter below steadily; indistinctly streaky in some places. Plant remains occur between 53 and 56 cm with some layered streaks of light, yellow substance; the sediment is somewhat darker between 150 and 130 cm and very weakly speckled between 282 and 270 cm.

282-600 cm:

Gyttja, as in the upper part of the core, but lighter and indistinctly streaky. The streaks are very distinct between 359 and 363 cm. The mean thickness of streaks is 1 mm. A fine layered insert of gyttja containing about a dozen small light and dark 'varves' of thickness 0.5 to 1.0 mm possibly reflecting seasonal changes occurs between 359 and 363 cm.

The whole profile contains calcium carbonate.

A2. Radunskie Dolne Lake - core no. 3 (RD3)

Sections: I: 0-1.15 m, II: 1.15-2.65 m, III: 2.65-4.15 m, IV: 4.15-5.65 m.

0-550 cm:

Greyish-yellow gyttja very weakly but thickly layered in some

places, with very small shell fragments at 500-520 cm. Very large pelecypod shells at 545-550 cm.

550-565 cm:

Bright-grey limnic chalk, with high content of calcium carbonate, with single material grains and big shells.

The whole profile contains calcium carbonate.

A3. Radunskie Gorne Lake - core no. 2 (RG2)

Sections: I: 0-0.95 m, II: 0.95-2.45 m, III: 2.45-3.95 m, IV: 3.95-5.45 m.

0-5 cm:

Brown gyttja, with valves of *Dreissensia polymorpha*.

5-240 cm:

Greyish-yellow gyttja with very small shells, sometimes crumbled, unlayered.

240-545 cm:

Gyttja as above, in some places very indistinct, but thick layers with very thin valves of snails at 542 cm.

The whole profile contains calcium carbonate. The sediment is more homogeneous and uniform along the whole profile than for any other core studied.

The mollusc fauna which appears in the sediments of this core has been studied in detail by S. Skompski to evaluate changes of ecological conditions. Ten samples, each from 0.5 m of the core with volume about 230 cm<sup>3</sup>, were studied from which 400 specimens of snails and pelecypods, belonging to 12 species, were identified. The state of preservation of the shells was bad. All species identified are living at present in Poland, ten of them in running or stagnant



waters and two in stagnant waters.

The occurrence of shells is concentrated above level 3.0 m. The frequency below this depth is very low. The upper limit of sediments is precisely dated by presence of *Dreissena polymorpha* which appears in the water of this lake, for the first time, not earlier than 1820 A.D.

A4. Mikolajskie Lake - core no. 2 (MK2)

Sections: I: 0-1.5 m, II: 1.5-3.0 m, III: 3.0-4.5 m, IV: 4.5-6.0 m.

0-40 cm:

Light greyish-yellow gyttja, but the top of core brown.

40-98 cm:

Gyttja as above, with lighter streaks, with thickness 1 to 2 mm and length up to 2.0 cm.

98-140 cm:

Gyttja as above with dark grey streaks and with higher content of plants.

140-180 cm:

Gyttja, as above, but with progressive change of colour to dark brownish grey. The streaks change steadily into layers, of typical thickness 0.5 to 1.0 cm. Light ones are not so numerous as dark ones. A rusty tinge (from Fe-oxides) is visible in some places.

180-250 cm:

Light greyish-yellow gyttja with dark grey streaks.

250-310 cm:

Grey gyttja with delicate streaks.

310-580 cm:

Greyish-yellow gyttja, with thin, brighter streaks varying in frequency from 2 to 5 per cm to only about 1 per 2 or 3 cm.

580-600 cm:

Gyttja as above but darker.

The whole profile contains calcium carbonate.

A5. Zarnowieckie Lake - core no. 3 (ZR3)

Sections: I: 0-1.25 m, II: 1.25-2.75 m, III: 2.75-4.25 m,

IV: 4.25-5.75 m.

0-250 cm:

Dark-brown, clayish gyttja in the upper part, with a small amount of calcium carbonate. There are no streaks or layers.

250-275 cm:

The same gyttja as above, but a little brighter.

275-367 cm:

Gyttja as above, brighter in the lower part, almost brownish-grey.

367-575 cm:

Brown or dark-grey gyttja. Plant detritus occurs in some places. The whole profile contains calcium carbonate.

## APPENDIX II

```

C PROGRAM TO CALCULATE FIELD ELEMENTS DUE TO AN
C OSCILLATING A-H RADIAL DIPOLE MODEL OVER 100*100 YR
C
REAL MM,MAINX,MAINZ,MAINF,MAINI,MAINY,R,CDM,IMR
INTEGER DIPOLE,D,NAME(8)
DIMENSION DATA(100,6),TABLE(100,11),XX(8,100),
1YY(8,100),ZZ(8,100),SX(100),SY(100),SZ(100),
2T(100),F(100)
REAL*8 YR(100),DECL(100),RINCL(100),RINT(100),
1DEC(8,100),RINC(8,100),FF(8,100),SDEC(100),
2SINC(100),SINT(100),YRI(100),YRJ(100),SC1,SC2
C - - - - -
PI=3.141593
PI2=PI*2.
CONVR=PI/180.
C - - - - -
C READ IN NAME AND LOCATION OF OBSERVATION POINT
C READ(4,9999) NAME
9999 FORMAT(8A4)
WRITE(6,9998) NAME
9998 FORMAT(5X,8A4)
C SLAT=CO-LATITUDE OF SITE
C READ(4,1001) SLAT,SLONG
1001 FORMAT(2F6.0)
WRITE(6,1002) SLAT,SLONG
1002 FORMAT(/5X,'COLAT=' ,F6.1,5X,'LONG=' ,F6.1//)
SLAT=SLAT*CONVR
SLONG=SLONG*CONVR
C - - - - -
C READ IN SCALING FACTORS
C SC1 FOR X AXIS
C SC2 FOR Y AXIS
C READ(4,1007)SC1,SC2
1007 FORMAT(2F5.3)
IF(SC1.EQ.0) SC1=1.000
IF(SC2.EQ.0) SC2=1.000
WRITE(6,1008) SC1,SC2
1008 FORMAT(/5X,'X AXIS SCALING FACTOR ='1X,F5.3,5X,
1'Y AXIS SCALING FACTOR =' ,1X,F5.3//)
C - - - - -
C READ IN NUMBER OF RADIAL DIPOLES (ND) AND STRENGTH OF
C CENTRAL DIPOLE (CDM)
C READ(5,1000) ND,CDM
1000 FORMAT(I1,E9.3)
WRITE(6,1003) ND,CDM
1003 FORMAT(/12X,'NUMBER OF RD =' ,I1, //12X,'CENTRAL DIPOLE
1 MOMENT = ' ,E9.3//)
C - - - - -
C READ IN DATA FOR RADIAL DIPOLES
C COLAT=CO-LATITUDE OF DIPOLE=DATA(I,1)
C LONG=LONGITUDE OF DIPOLE=DATA(I,2)
C PERIOD=PERIOD OF OSCILLATION OF DIPOLE=DATA(I,3)
C PHASE=PHASE DELAY OF DIPOLE IN DEGREES=DATA(I,4)
C MOMENT=STRENGTH OF DIPOLE=DATA(I,5)
C A(KM)=DISTANCE OF DIPOLE FROM GEOCENTRE=DATA(I,6)

```

```

      READ (5,999) ((DATA(I,J),J=1,6),I=1,ND)
999  FORMAT (2F6.1,F7.0,F6.1,E10.3,F7.1)
      WRITE (6,991)
991  FORMAT (/13X,'COLAT',4X,'LONG',3X,'PERIOD',3X,'PHASE',
25X,'MOMENT',6X,'A(KM)'/)
      WRITE (6,990) ((DATA(I,J),J=1,6),I=1,ND)
990  FORMAT (12X,F6.1,2X,F6.1,2X,F7.0,2X,F6.1,2X,E10.3,
12X,F7.1)
C    CONVERT COLAT AND LONG INTO RADIANS
      DO 3 I=1,ND
      DO 3 J=1,2
3    DATA(I,J)=DATA(I,J)*CONVR
C  - - - - -
C    START LOOP THROUGH ALL RADIAL DIPOLES
C    PHI=ANGULAR DISTANCE FROM DIPOLE TO SITE
C    ALPHA=AZIMUTH FROM DIPOLE TO SITE
C
      DO 2 I=1,ND
      DLAT=DATA(I,1)
      DLONG=DATA(I,2)
      DELTAL=DLONG-SLONG
      IF (DELTAL.LT.0.) DELTAL=-DELTAL
      IF (DELTAL.GE.PI) DELTAL=PI2-DELTAL
      PHI=ARCOS(COS(DLAT)*COS(SLAT)+SIN(DLAT)*SIN(SLAT)
1*  COS (DELTAL))
      ALPHA=ARSIN(SIN(DLAT)*SIN(DELTAL)/SIN(PHI))
      TABLE(I,1)=I+1
      TABLE(I,2)=PHI
2    TABLE(I,3)=ALPHA
C  - - - - -
C    CALCULATE RD,PHI,ALPHA,AZIM,PSI,BETA,RHO,X,Y,Z,F FOR
C    EACH RD AND PRINT A TABLE
C    RHO=DIST FROM DIPOLE TO SITE IN KMS
C    X,Y,Z ARE FIELD COMPONENTS AT SITEDUE TO RADIAL DIPOLE
C    F=TOTAL VECTOR COMPONENT
C    RD=NO. OF THE DIPOLE
C    AZIM=ALPHA=AZIMUTH
C
      DO 4 I=1,ND
      IDPL=IFIX(TABLE(I,1))-1
      PHI=TABLE(I,2)
      ALPHA=TABLE(I,3)
      AZIM=ALPHA
C
C    CHECK QUADRANT OF AZIM AND ASSIGN CORRECT VALUE
      TEST=COS(DATA(IDPL,1))-COS(SLAT)*COS(PHI)
      IF (TEST.GT.0.) AZIM=PI-AZIM
      DELT2=SLONG-DATA(IDPL,2)
      IF (DELT2.GT.PI) DELT2=DELT2-PI2
      IF (DELT2.LE.-PI) DELT2=DELT2+PI2
      IF (DELT2.LE.0.) AZIM=PI2-AZIM
      TABLE(I,4)=AZIM/CONVR
C
C    MM=MOMENT OF RADIAL DIPOLE
C    A=DIST OF DIPOLE FROM GEOCENTRE
C    R=RADIUS OF EARTH
C
      R=6.37*10**3
      MM=DATA(I,5)

```

```

A=DATA(I,6)
RHO=SQRT(R*R+A*A-2.*A*R*COS(PHI))
TABLE(I,7)=RHO
BETA=ARSIN(A*SIN(PHI)/RHO)
PSI=PHI+BETA
TABLE(I,5)=PSI/CONVR
TABLE(I,6)=BETA/CONVR
TABLE(I,2)=TABLE(I,2)/CONVR
TABLE(I,3)=TABLE(I,3)/CONVR
RH03=RHO**3
TANG=(2.*COS(PSI)*SIN(BETA)+SIN(PSI)*COS(BETA))
1*MM/RH03
TABLE(I,8)=TANG*COS(AZIM)
TABLE(I,9)=TANG*SIN(AZIM)
TABLE(I,10)=(2.*COS(PSI)*COS(BETA)-SIN(PSI)*SIN(BETA))
1)*MM/RH03
TABLE(I,11)=SQRT(TABLE(I,8)**2+TABLE(I,9)**2+TABLE
1(I,10)**2)
4 CONTINUE

```

```

C
WRITE(6,2003)
2003 FORMAT (///25X,'PARAMETERS FOR RADIAL DIPOLES'//)
WRITE(6,2004)
2004 FORMAT(1X,'RD',5X,'PHI',3X,'ALPHA',4X,'AZIM',5X,'PSI',
24X,'BETA',6X,'RHO',9X,'X',10X,'Y',10X,'Z',10X,'F'//)
WRITE(6,2000) ((TABLE(I,J),J=1,11),I=1,ND)
2000 FORMAT (//1X,F2.0,3X,F5.1,3X,F5.1,3X,F5.1,3X,F5.1,3X,
2F5.1,3X,F7.0,3X,F8.5,3X,F8.5,3X,F8.5)

```

```

C - - - - -
C CALCULATE FIELD COMPONENTS DUE TO AXIAL CENTRAL DIPOLE
MAINX=CDM/R**3*SIN(SLAT)
MAINZ=2.*CDM/R**3*COS(SLAT)
MAINF=CDM/R**3*(1+3*COS(SLAT)**2)**0.5
MAINI=ATAN2(MAINZ,MAINX)/CONVR
WRITE(6,2001)
2001 FORMAT(///15X,'MAIN FIELD PARAMETERS'//)
WRITE(6,2005)MAINX,MAINZ,MAINF,MAINI
2005 FORMAT (/5X,'X= ',F7.3,3X,'Z= ',F7.3,3X,'F= ',
1F7.3,3X,'INCL= ',F6.1//)

```

```

C - - - - -
C ALLOW RADIAL DIPOLES TO OSCILLATE
C TP=PERIOD OF OSCILLATION OF DIPOLE
C PH=PHASE OF DIPOLE
C T(J)=YEARS*100 B.P.
C T(1)=100 YRS B.P. ETC.
C XX(I,J)=X CMPT. OF DIPOLE(I) AT TIME(J)
C YY(I,J)=ETC.
C DEC(I,J)=DECL. AT SITE DUE TO DIPOLE(I) AT TIME
C RINC(I,J)=INCL. AT SITE DUE TO DIPOLE(I) AT TIME (T(J))
DO 22 I=1,ND
TP=DATA(I,3)
C CONVERT PH TO RADIANS
PH=DATA(I,4)*CONVR
DO 21 J=1,100
T(J)=J*100
XX(I,J)=TABLE(I,8)*SIN(PI2*T(J)/TP+PH)
YY(I,J)=TABLE(I,9)*SIN(PI2*T(J)/TP+PH)
ZZ(I,J)=TABLE(I,10)*SIN(PI2*T(J)/TP+PH)
FF(I,J)=SQRT((MAINX+XX(I,J))**2+YY(I,J)**2)

```

```

2+(MAINZ+ZZ(I,J))**2)
DEC(I,J)=(ATAN2(YY(I,J),MAINX+XX(I,J)))/CONVR
RINC(I,J)=(ATAN2(MAINZ+ZZ(I,J),SGRT((YY(I,J))**2+
1(XX(I,J)+MAINX)**2)))/CONVR
C SCALE T(J) TO SIZE FOR GRAPH PLOTTING SUBROUTINE
C AND CALL ANSWER YR(J)
YR(J)=- (T(J)*0.0015)

```

```

21 CONTINUE
22 CONTINUE

```

C

```

C -----
C WRITE TITLE FOR TABLE OF D,I,F VALUES FOR EACH RD
C DO 31 I=1,ND
C MD=IFIX(TABLE(I,1))
C WRITE(6,3001) MD
3001 FORMAT(/72X,'FIELD VARIATIONS OVER 100*100 YRS FOR
1DIPOLE NO',I4,78X,'XX',10X,'YY',10X,'ZZ',8X,'DEC',7X,
2'INC',6X,'INT'//)
C WRITE(6,3002) ((XX(I,J),YY(I,J),ZZ(I,J),DEC(I,J),
1RINC(I,J),FF(I,J)),J=1,100)
3002 FORMAT(5X,F8.5,3X,F8.5,3X,F8.5,3X,F7.1,4X,F7.1,3X,F7.4)
31 CONTINUE

```

C

```

C -----
C SUM EFFECTS OF ALL RADIAL DIPOLES
C SINT(J)=TOTAL INTENSITY AT SITE DUE TO SUMMED EFFECT
C OF ALL RD AT TIME T(J)
C SDEC=DECLINATION AT SITE AT TIME T(J)
C SINC=INCLINATION AT SITE AT TIME T(J)
C DO 32 J=1,100
C SX(J)=0.
C SY(J)=0.
C SZ(J)=0.
C SDEC(J)=0.
C SINC(J)=0.

```

```

32 CONTINUE

```

```

WRITE(6,3011)
3011 FORMAT(/79X,'SX',8X,'SY',9X,'SZ',7X,'SDEC',6X,
1'SINC',6X,'SINT'//)

```

```

36 DO 33 J=1,100
DO 34 I=1,ND
SX(J)=SX(J)+XX(I,J)
SY(J)=SY(J)+YY(I,J)
SZ(J)=SZ(J)+ZZ(I,J)

```

```

34 CONTINUE
SINT(J)=SQRT((MAINX+SX(J))**2+SY(J)**2+(MAINZ+SZ(J)
1)**2)
SDEC(J)=(ATAN2(SY(J),MAINX+SX(J)))/CONVR
SINC(J)=(ATAN2(MAINZ+SZ(J),SQRT((SY(J))**2+(SX(J)+
1MAINX)**2)))/CONVR

```

```

33 CONTINUE
WRITE(6,3012) ((SX(J),SY(J),SZ(J),SDEC(J),SINC(J),
1SINT(J)),J=1,100)

```

```

3012 FORMAT(5X,F8.5,2X,F8.5,3X,F8.5,2X,F7.1,3X,F7.1,
13X,F7.4)
CALL GP2(ND,DEC,RINC,FF,SDEC,SINC,SINT,YR,NAME,
1SC1,SC2)
STOP
END

```

```

C -----
C   GPAPH PLOTTING SUBROUTINE
C   PLOTS NINE GRAPHS, THE FIRST EIGHT ARE OF RD 2 TO 9,
C   THE NINTH IS OF THE SUM OF THE EIGHT RD
C   SUBROUTINE GP2(ND,DEC,RINC,FF,SDEC,SINC,SINT,
1YR,NAME,SC1,SC2)
   REAL*8 R,S,P,Q,G,H,U,V,YR(100),SDEC(100),SINC(100),
1SINT(100),DEC(8,100),RINC(8,100),FF(8,100),
2DECL(100),RINCL(100),RINT(100),XORG,YORG,
3YRI(100),YRJ(100)
   INTEGER NAME(8)
   CALL OPENGR(80)
   CALL DRSTRG('HGGG,JCMB',10)
   CALL GRAREA(0.00,0.00,72.00,72.00,'CMS')
   NP=ND+1
   RDN=1.000
   DO 17 J=1,100
   YR(J)=YR(J)-5.000
   YRI(J)=YR(J)-23.000
   YRJ(J)=YR(J)-46.000
17 CONTINUE
   DO 11 I=1,NP
   DO 15 J=1,100
   DECL(J)=0.
   RINCL(J)=0.
   RINT(J)=0.
15 CONTINUE
C   SET UP ORIGIN FOR SUCCESSIVE PLOTS
   IF(I.EQ.1) XORG=0.00
   IF(I.EQ.2) XORG=7.500
   IF(I.EQ.3) XORG=15.000
   IF(I.EQ.4) XORG=22.500
   IF(I.EQ.5) XORG=30.000
   IF(I.EQ.6) XORG=37.500
   IF(I.EQ.7) XORG=45.000
   IF(I.EQ.8) XORG=52.500
   IF(I.EQ.9) XORG=61.000
C   SHIFT WHOLE SET OF PLOTS
   XORG=XORG+5.000
   YORG=70.0
C   SCALE ORIGIN POINTS
   XORG=XORG*SC1
   YORG=YORG*SC2
   RDN=RDN+1.000
   CALL SCALGR(XORG,YORG,SC1,SC2,0.00)
C   WRITE NAME
   IF(I.NE.1) GO TO 21
   CALL ANNOGR(30.000,0.600,0.900,0.00)
   CALL DRSTRG(NAME,32)
C   WRITE RD NUMBER AT HEAD OF EACH COLUMN
C   OR *SUM* AT HEAD OF FINAL COLUMN
21 IF(I.EQ.9) GO TO 31
   CALL ANNOGR(1.900,-3.500,0.400,0.00)
   CALL DRNUMG(RDN,1,0)
   GO TO 32
31 CALL ANNOGR(2.200,-3.500,0.400,0.00)
   CALL DRSTRG('*SUM*',3)
32 CONTINUE
C   LABEL DEC -90 TO +90

```

```

R=-0.6D0
S=-90.D0
DO 1 N=1,3
CALL ANNOGR(R,-4.5D0,0.30D0,0.D0)
CALL DRNUMG(S,1,0)
R=R+2.7D0
1 S=S+90.
C LABEL DEPTHS
G=-5.1D0
H=0.D0
DO 2 N=1,6
CALL ANNOGR(-1.2D0,G,0.30D0,0.D0)
CALL DRNUMG(H,1,0)
G=G-3.0D0
2 H=H+2.0
41 IF(I.NE.1) GO TO 22
CALL ANNOGR(-4.8D0,-2.0D0,0.4D0,0.D0)
CALL DRSTRG('DECLINATIONS',12)
22 CALL AXISGR(0.D0,-5.0D0,'X',0.90D0,6)
CALL AXISGR(0.D0,-5.0D0,'-Y',1.5D0,10)
IF(I.EQ.9) GO TO 33
CALL ANNOGR(1.9D0,-26.5D0,0.4D0,0.D0)
CALL DRNUMG(RDN,1,0)
GO TO 34
33 CALL ANNOGR(2.2D0,-26.5D0,0.4D0,0.D0)
CALL DRSTRG('SUM',3)
34 CONTINUE
C LABEL INC 0 TO 90
P=-0.6D0
Q=0.D0
DO 3 N=1,4
CALL ANNOGR(P,-27.5D0,0.30D0,0.D0)
CALL DRNUMG(Q,1,0)
P=P+1.8
3 Q=Q+30D0
C LABEL DEPTHS
U=-28.1D0
V=0.D0
DO 4 N=1,6
CALL ANNOGR(-1.2D0,U,0.30D0,0.D0)
CALL DRNUMG(V,1,0)
U=U-3.0
4 V=V+2.0
42 IF(I.NE.1) GO TO 23
CALL ANNOGR(-4.8D0,-25.0D0,0.4D0,0.D0)
CALL DRSTRG('INCLINATIONS',12)
23 CALL AXISGR(0.D0,-28.0D0,'X',0.60D0,9)
CALL AXISGR(0.D0,-28.0D0,'-Y',1.5D0,10)
IF(I.EQ.9) GO TO 35
CALL ANNOGR(1.9D0,-49.5D0,0.4D0,0.D0)
CALL DRNUMG(RDN,1,0)
GO TO 36
35 CALL ANNOGR(2.2D0,-49.5D0,0.4D0,0.D0)
CALL DRSTRG('SUM',3)
36 CONTINUE
C LABEL INT 0 TO 2
C=-0.4D0
D=0.D0
DO 5 N=1,3

```



```

CALL ANNOGR(C,-50.500,0.3000,0.00)
CALL DRNUMG(D,1,0)
C=C+2.700
5 D=D+1.0
C LABEL DEPTHS
E=-51.100
F=0.00
DO 6 N=1,6
CALL ANNOGR(-1.200,E,0.3000,0.00)
CALL DRNUMG(F,1,0)
E=E-3.0
6 F=F+2.0
43 IF(I.NE.1) GO TO 24
CALL ANNOGR(-4.800,-48.000,0.400,0.00)
CALL DRSTRG('INTENSITIES',12)
24 CALL AXISGR(0.00,-51.000,'X',1.3500,4)
CALL AXISGR(0.00,-51.000,'-Y',1.500,10)
C PLOT POINTS
IF(I.GT.ND) GO TO 13
C PLOT RD 2 TO 9
DO 12 J=1,100
DECL(J)=DEC(I,J)*0.03+2.700
RINCL(J)=RINC(I,J)*0.06
RINT(J)=FF(I,J)*2.70
12 CONTINUE
13 IF(I.LE.ND) GO TO 14
C PLOT SUM OF RD
DO 16 J=1,100
DECL(J)=SDEC(J)*0.03+2.700
RINCL(J)=SINC(J)*0.06
RINT(J)=SINT(J)*2.70
16 CONTINUE
14 IF(SC1.EQ.1.000) GO TO 18
CALL LINESG(DECL,YR,1,100,1.00,0.00,0,0.000)
CALL LINESG(RINCL,YRI,1,100,1.00,0.00,0,0.000)
CALL LINESG(RINT,YRJ,1,100,1.00,0.00,0,0.000)
GO TO 11
18 CALL LINESG(DECL,YR,1,100,0.00,0.00,1,0.100)
CALL LINESG(RINCL,YRI,1,100,0.00,0.00,1,0.100)
CALL LINESG(RINT,YRJ,1,100,0.00,0.00,1,0.100)
11 CONTINUE
CALL CLOSGR
RETURN
END

```

## APPENDIX III

```

C   PROGRAM TO CALCULATE FIELD ELEMENTS DUE TO AN
C   DRIFTING AND OSCILLATING A-H RADIAL DIPOLE MODEL
C   OVER 200*50 YEARS
      REAL MM,MAINX,MAINZ,MAINF,MAINI,MAINY,R,CDM,IMR
      INTEGER DIPOLE,D,NAME(8)
      DIMENSION DATA(200,7),TABLE(200,11),XX(8,200),
1YY(8,200),ZZ(8,200),SX(200),SY(200),SZ(200),T(200),
2F(200),DLONG(8,200)
      REAL*8 YR(200),DECL(200),RINCL(200),RINT(200),
1RINC(8,200),FF(8,200),SDEC(200),SINC(200),SINT(200),
2YRI(200),YRJ(200),SC1,SC2,DEC(8,200)
C   -----
      PI=3.141593
      PI2=PI*2.
      CONVR=PI/180.
C   -----
C   READ IN NAME AND LOCATION OF OBSERVATION POINT
      READ(4,9999) NAME
9999  FORMAT(8A4)
      WRITE(6,9998) NAME
9998  FORMAT(5X,8A4)
C   SLAT=CO-LATITUDE OF SITE
      READ(4,1001) SLAT,SLONG
1001  FORMAT(2F6.0)
      WRITE(6,1002) SLAT,SLONG
1002  FORMAT(/5X,'COLAT=',F6.1,5X,'LONG=',F6.1//)
      SLAT=SLAT*CONVR
      SLONG=SLONG*CONVR
C   -----
C   READ IN SCALING FACTORS
C   SC1 FOR X AXIS
C   SC2 FOR Y AXIS
      READ(4,1007) SC1,SC2
1007  FORMAT(2F5.3)
      IF(SC1.EQ.0.) SC1=1.000
      IF(SC2.EQ.0.) SC2=1.000
      WRITE(6,1008) SC1,SC2
1008  FORMAT(/5X,'X AXIS SCALING FACTOR =',1X,F5.3,5X,
1'Y AXIS SCALING FACTOR =',1X,F5.3/)
C   -----
C   READ IN NUMBER OF RADIAL DIPOLES (ND) AND STRENGTH OF
C   CENTRAL DIPOLE (CDM)
C   COLAT=COLATITUDE OF DIPOLE=DATA(I,1)
C   LONG=LONGITUDE OF DIPOLE=DATA(I,2)
C   DRIFT=DRIFT OF DIPOLE IN DEGREES PER YR:WEST +VE,
C   EAST -VE=DATA(I,3)
C   PERIOD=PERIOD OF OSCILLATION IN YRS=DATA(I,4)
C   PHASE=PHASE DELAY IN DEGREES=DATA(I,5)
C   MOMENT=STRENGTH OF DIPOLE=DATA(I,6)
C   A(KMS)=DISTANCE OF DIPOLE FROM GEOCENTRE=DATA(I,7)
      READ(5,1000) ND,CDM
1000  FORMAT(I1,E9.3)
      WRITE(6,1003) ND,CDM

```

```

1003 FORMAT(/12X,'NUMBER OF RD =',I1,/,12X,'CENTRAL DIPOLE
1 MOMENT = ',E9.3//)
C - - - - -
C READ IN DATA FOR RADIAL DIPOLES
READ(5,999) ((DATA(I,J),J=1,7),I=1,ND)
999 FORMAT(2F6.1,F6.2,2F6.1,E10.3,F7.1)
WRITE(6,991)
991 FORMAT(13X,'COLAT',4X,'LONG',3X,'DRIFT',3X,'PERIOD',
13X,'PHASE',5X,'MOMENT',6X,'A(KM)')//
WRITE(6,990) ((DATA(I,J),J=1,7),I=1,ND)
990 FORMAT(12X,F6.1,2X,F6.1,2X,F6.2,2X,F6.1,2X,F6.1,2X,
1E10.3,2X,F7.1)
C CONVERT ANGLES TO RADIANS
DO 3 I=1,ND
DO 3 J=1,3
3 DATA(I,J)=DATA(I,J)*CONVR
C
C CALCULATE COMPONENTS DUE TO AXIAL CENTRAL DIPOLE
C R=EARTH RADIUS=6370 KM
R=6.37*10**3
MAINX=CDM/R**3*SIN(SLAT)
MAINZ=2.*CDM/R**3*COS(SLAT)
MAINF=CDM/R**3*(1+3*COS(SLAT)**2)**0.5
MAINI=ATAN2(MAINZ,MAINX)/CONVR
WRITE(6,2001)
2001 FORMAT(///15X,'MAIN FIELD PARAMETERS'//)
WRITE(6,2005)MAINX,MAINZ,MAINF,MAINI
2005 FORMAT(/5X,'X= ',F7.3,3X,'Z= ',F7.3,3X,'F= ',
1F7.3,3X,'INCL= ',F6.1//)
C - - - - -
DO 1234 J=1,200
C START LOOP THROUGH ALL RADIAL DIPOLES
C PHI=ANGULAR DIST FROM DIPOLE TO SITE
C ALPHA=AZIMUTH
C
C CALCULATE POSITION OF DIPOLES DUE TO DRIFT
DO 2 I=1,ND
DLAT=DATA(I,1)
IF(J.GT.1) GO TO 20
DLONG(I,J)=DATA(I,2)
GO TO 30
20 K=J-1
DLONG(I,J)=DLONG(I,K)-(DATA(I,3)+50)
30 CONTINUE
DPLONG=DLONG(I,J)
IF(DPLONG.LT.0) DPLONG=DPLONG+PI2
IF(DPLONG.GT.PI2) DPLONG=DPLONG-PI2
DLONG(I,J)=DPLONG
DELTAL=DLONG(I,J)-SLONG
IF(DELTAL.LT.0.) DELTAL=-DELTAL
IF(DELTAL.GE.PI) DELTAL=PI2-DELTAL
PHI=ARCOS(COS(DLAT)*COS(SLAT)+SIN(DLAT)*SIN(SLAT)
1*COS(DELTAL))
ALPHA=ARSIN(SIN(DLAT)*SIN(DELTAL)/SIN(PHI))
TABLE(I,1)=I+1
TABLE(I,2)=PHI
2 TABLE(I,3)=ALPHA
C - - - - -
C CALC. RD,PHI,ALPHA,AZIM,PSI,BETA,RHO,X,Y,Z,F FOR EACH RD

```

```

C   RHO=DIST FROM DIPOLE TO SITE IN KMS
C   X,Y,Z ARE COMPONENTS AT SITE DUE TO DIPOLES
C   F=TOTAL VECTOR COMPONENT
C   RD=NO. OF THE DIPOLE
      DO 4 I=1,ND
        IDPL=IFIX(TABLE(I,1))-1
        PHI=TABLE(I,2)
        ALPHA=TABLE(I,3)
        AZIM=ALPHA
        TEST=COS(DATA(IDPL,1))-COS(SLAT)*COS(PHI)
        IF(TEST.GT.0.) AZIM=PI-AZIM
        DELT2=SLONG-DLONG(I,J)
        IF(DELT2.GT.PI) DELT2=DELT2-PI2
        IF(DELT2.LE.-PI) DELT2=DELT2+PI2
        IF(DELT2.LE.0.) AZIM=PI2-AZIM
        TABLE(I,4)=AZIM/CONVR
C   MM=MOMENT OF RADIAL DIPOLE
C   DIST OF DIPOLE FROM GEOCENTRE
      MM=DATA(I,6)
      A=DATA(I,7)
      RHO=SQRT(R*R+A*A-2.*A*R*COS(PHI))
      TABLE(I,7)=RHO
      BETA=ARSIN(A*SIN(PHI)/RHO)
      PSI=PHI+BETA
      TABLE(I,5)=PSI/CONVR
      TABLE(I,6)=BETA/CONVR
      TABLE(I,2)=TABLE(I,2)/CONVR
      TABLE(I,3)=TABLE(I,3)/CONVR
      RHO3=RHO**3
      TANG=(2.*COS(PSI)*SIN(BETA)+SIN(PSI)*COS(BETA))
1    *MM/RHO3
      TABLE(I,8)=TANG*COS(AZIM)
      TABLE(I,9)=TANG*SIN(AZIM)
      TABLE(I,10)=(2.*COS(PSI)*COS(BETA)-SIN(PSI)*SIN(BETA)
1    *MM/RHO3
      TABLE(I,11)=SQRT(TABLE(I,8)**2+TABLE(I,9)**2+TABLE(I,
110)**2)
4    CONTINUE

C   -----
C   ALLOW RADIAL DIPOLES TO OSCILLATE
C   DO 22 I=1,ND
      TP=DATA(I,4)
      PH=DATA(I,5)*CONVR
      T(J)=J*50.
      XX(I,J)=TABLE(I,8)*SIN(PI2*T(J)/TP+PH)
      YY(I,J)=TABLE(I,9)*SIN(PI2*T(J)/TP+PH)
      ZZ(I,J)=TABLE(I,10)*SIN(PI2*T(J)/TP+PH)
      FF(I,J)=SQRT((MAINX+XX(I,J))**2+YY(I,J)**2
2    +(MAINZ+ZZ(I,J))**2)
      DEC(I,J)=(ATAN2(YY(I,J),MAINX+XX(I,J)))/CONVR
      RINC(I,J)=(ATAN2(MAINZ+ZZ(I,J),SQRT((YY(I,J))**2+(XX
1(I,J)+MAINX)**2)))/CONVR
22    CONTINUE

C   -----
C   SUM EFFECTS OF ALL RADIAL DIPOLES
C   SINT(J)=TOTAL INTENSITY AT SITE DUE TO SUMMED
C   EFFECT OF ALL RD AT TIME T(J)

```

```

C   SDEC(J)=DECLINATION AT SITE AT TIME T(J)
C   SINC(J)=INCLINATION AT SITE AT TIME T(J)
      SX(J)=0.
      SY(J)=0.
      SZ(J)=0.
      SDEC(J)=0.
      SINC(J)=0.
      DO 34 I=1,ND
      SX(J)=SX(J)+XX(I,J)
      SY(J)=SY(J)+YY(I,J)
      SZ(J)=SZ(J)+ZZ(I,J)
34  CONTINUE
      SINT(J)=SQRT((MAINX+SX(J))**2+SY(J)**2+(MAINZ+SZ(J)
1) **2)
      SDEC(J)=(ATAN2(SY(J),MAINX+SX(J)))/CONVR
      SINC(J)=(ATAN2(MAINZ+SZ(J),SQRT((SY(J))**2+(SX(J)+
1MAINX)**2)))/CONVR
1234 CONTINUE
      WRITE(6,3012) ((SX(J),SY(J),SZ(J),SDEC(J),SINC(J),
1SINT(J)),J=1,200)
3012 FORMAT(5X,F8.5,2X,F8.5,3X,F8.5,2X,F7.1,3X,F7.1,
13X,F7.4)
C
      CALL GP2 (ND,DEC,RINC,FF,SDEC,SINC,SINT,YR,NAME,
1SC1,SC2)
      STOP
      END

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