LIMNOMAGNETIC STUDIES ON GREEK SEDIMENTS

by

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submitted
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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.

Stavros Papamarinopoulos.


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SYNOPSIS.

Investigations in the whole sediment (reversed isothermal remanence, cryomagnetic experiments, modified Lowrie-Fuller test), showed the presence of fine grained magnetite in dominance of single domain or pseudo-single domain in character, whereas magnetic extracts studies (Debye-Scherer X-ray diffractometry, thermomagnetic experiments, Mössbauer spectroscopy and optical microscopy) showed the presence of angular fresh magnetite or partially oxidized towards haematite, with size ranging from less than 1µm up to few microns. The natural remanence is of stable character producing smoothly falling demagnetization curves, well grouped directions and mediadestructive fields ranging between 200 and 500 Oe after cleaning with alternating magnetic fields. Anhysteretic and isothermal remanence studies showed that the saturating field is 1,000 Oe peak field and 1,500-2,000 Oe direct field respectively. Redeposition with slurries produced remanence of post-depositional origin, which recorded almost precisely the applied magnetic field without inclination error and of stable character with smoothly falling demagnetization curves, well grouped directions and mediadestructive fields of about 200 Oe. Its strength is directly proportional to the strength of the applied magnetic field and its growth remains constant with time. Long column redepositions under controlled conditions produced stable remanence when the water content was about 60% with the same characteristics of stability as the slurries, but with an inclination error of about 20°, attributed in compactive effects, produced by unnaturally fast rate of deposition and consolidation. Comparison of the post-depositional remanent magnetizations produced at 5°C and at room temperature showed no difference in their intensities. Susceptibility, anhysteretic, isothermal and post-depositional remanences were used as normalizing parameters to
compensate the variations of the magnetic content along the studied limnic cores, but comparisons with the established European archaeomagnetic intensity curve showed no success. The declination, inclination, geomagnetic variations of the last 2,000 yr. B.P. recorded in the sediments of Lake Volvi correlate with the corresponding European archaeomagnetic records. The same variations recorded in the sediments of Lake Trikhonis of the last 6-7,000 yr. B.P. are correlative with those recorded at Lake Begoritis (Greece), and Lake Windermere (England) and several other records in central Europe. The declination appears to be periodic having a 2,700 years periodicity while the inclination is oscillatory but aperiodic.
DEDICATION

This work is dedicated with clarity, to all the people who established the ideal of HELLENISM, a way of Olympic life towards perfection with Doric simplicity, a multiple path to the enigmatic unknown, through philosophy and science, through irrational drama and comedy, through geometrized arts or mystisism, a continuous sparkling pass to unity with the HOLON, without fear or hope.
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Artemis, who was there and here, always inspiring, introducing fresh ideas, emotions and energy.
ABBREVIATIONS

jn : NRM intensity (natural remanent magnetization)
jo : Initial NRM intensity
jd : Normalized NRM intensity
jdo : Normalized NRM intensity after storage in zero magnetic field
jcr : CRM (chemical remanent magnetization)
jdr : DRM (depositional remanent magnetization)
jp : PDRM intensity (post-depositional remanent magnetization)
jpo : PDRM intensity after storage in zero magnetic field
jpa : Normalized PDRM with wet mass
jpb : Normalized PDRM with dried mass
jpc : Normalized PDRM with water content
jar : ARM intensity (anhyysteretic remanent magnetization)
jrs : IRM intensity (Saturation isothermal remanent magnetization)
jv : VRM (viscous remanent magnetization)
k : Initial magnetic susceptibility of naturally deposited sediments
kd : Normalized magnetic susceptibility per wet mass of naturally deposited sediments
kp : Initial magnetic susceptibility of redeposited sediments
kpa : Normalized magnetic susceptibility per wet mass of redeposited sediments
kpb : Normalized magnetic susceptibility per dried mass of redeposited sediments
kpc : Normalized magnetic susceptibility per water content of redeposited sediments
Q : (jn/k)
Qd : (jd/kd)
Qp : (jp/kp)
ix.

D : NRM declination
Dd : NRM declination after storage in zero magnetic field
Dp : PDRM declination
Dpo : PDRM declination after storage in zero magnetic field
I : NRM inclination
Id : NRM inclination after storage in zero magnetic field
Ip : PDRM inclination
Ipo : PDRM inclination after storage in zero magnetic field
Ie : Geomagnetic inclination at the spot of the experiment
Ia : Inclination of applied magnetic field
\( \hat{s} \) : Inclination error
A95 : Alpha 95
K : Precision parameter
R : Length of the vector sum of the direction cosines
N : Number of specimen
Wa : Wet mass
Wb : Dried mass
We : Water content
AF : Alternating field
AFC : Alternating field cleaning
MDF : Medium destructive field
H : Applied direct magnetic field
Hsat : Saturating field
Hcr : Coercivity of the maximum remanence
\( t \) : Time in days
\( \log(t) \) : The logarithm of time
MD : Multidomains
SP : Single domains
PSP : Pseudo single domains
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INTRODUCTION

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1.1 On the discovery of the Geomagnetic field.

Carlson (1975) established that the Olmec people in San Lorenzo Veracruz, Mexico 1,000 yr. B.C., were capable of sophisticated work of magnetic minerals, knew the properties of lodestone and in fact the directive properties of it. He showed that a discovered impure haematite artifact was indeed a magnetic compass. The properties of the magnetized rocks were first established by the Greeks approximately 600 yr. B.C., who actually gave the names magnet, magnetism, etc. after the discovery of the lodestone in Magnesia in Asia Minor. The first observations were attributed to Thales. The magnetic compass was also known to the Chinese approximately 200 yr. B.C. (Needham, 1962) who constructed a lodestone spoon rotating on a smooth board. The foundations of geomagnetic studies were probably established in China, where, at least by 1,093 A.D. the directive property of a freely suspended magnet was known at large, (Mitchell, 1932). The Chinese were theorizing about the declination, as well as the polarity of the magnet from 800 to 900 A.D., before Europe knew even the polarity (Smith and Needham, 1967). By the year 1187 the magnetic compass was in use in northwestern Europe for the purpose of navigation in the primitive form of a suspended lodestone. It was brought by an English monk called Alexander Necham, who gives the first reference of its arrival in Europe. Roger Bacon, in 1210 A.D. and Petrus Peregrinus, a few years later questioned the universality of the north-south directivity of the compass needle, (Smith, 1970). Georg Hartmann in 1544 and Robert Norman in 1576 independently discovered the inclination. In 1600 William Gilbert established that the earth itself is a great magnet. In 1635 H. Gelibrand, by
comparing observations of magnetic declination made in the preceding 54 years in London, discovered that the declination altered in a regular way with time (Chapman and Bartels, 1940). The secular variation of magnetic direction contradicted Gilbert's hypothesis which asserted that the Earth was a permanent magnet. However Gelibrand's conclusions have now been verified by numerous observatory records which demonstrate that the geomagnetic field is indeed variable in both time and space. This result has been active in determining the course of modern theories to explain the source of geomagnetic phenomena.

Two hundred years later, Gauss first mathematically described the earth's magnetic field using potential theory, but another century passed before palaeomagnetism was widely employed to trace field behaviour through geologic time.

To a first approximation, the geomagnetic field can be represented by a simple inclined geocentric dipole at the Earth's centre. The increase in the number of magnetic observations and surveys in the last 60 years and more recently, satellite studies, has enabled a better description of the field over the surface of the globe and has improved the estimates of the residual, non-dipole, components. Contour charts of the non-dipole field reveal extensive regions of enhanced or diminished intensity which are also changing and these regions which are entered as "isoporic foci", bear no obvious relations to the positions of the continental masses.

This feature, together with the discovery that the foci drift slowly westwards, suggests a deep internal source for the field. A conclusion which is confirmed by spherical harmonic analysis, which shows that more than 99% of the total field is of internal origin and proved by finding field gradient with depth down the deep mines.
Below a depth of about 25 km rocks are at a temperature exceeding the Curie points of all magnetic minerals, so that the mantle and lower crust can make no permanent contribution to the geomagnetic field. Following work by Lowes and Runcorn (1951), Alldredge and Hurwitz (1964) found that they obtained the best fit to the observed field by postulating a central dipole surrounded by eight radial dipoles midway between the Earth's centre and the core-mantle boundary. The model proposed a connection between geomagnetic sources and some mechanism within the core. Seismological indications show strongly an outer liquid core, while geochemical and density considerations in high temperature and pressure are compatible with a core consisting largely of iron and nickel.

All these facts have led to various proposals of a geomagnetic dynamo in which the fields are produced by electric currents which are sustained by fluid motions. Stacey (1969) proposed that the field would decay rapidly with a time constant of roughly 1,000 years. However, if the liquid core continually undergoes shear flow then toroidal field lines become trapped in the conducting iron and move with it to create poloidal fields, thus resulting in a magnification of any pre-existing poloidal fields, (Elsasser, 1950).

The increase of the magnetic energy reduces the rate of shear flow which must therefore be sustained if the dynamo is to be continuous. It is accepted that the energy requirements are very small - about $10^{12}$ watts, something which could be supplied from a lot of available sources, like heat generated by radioactivity in the interior convection effects caused by the planet's cooling at the surface and mechanical torques due to precession of the Earth's axis. The phenomenon of the geomagnetic reversal, is well established from palaeomagnetic
studies (Cox et al, 1967; Bullard, 1968; Cox, 1975; Cox et al, 1975). After the analysis of a large number of data, it was found that the field direction is divided about equally between normal and reversed states, although the durations appear to be randomly controlled.

Cox (1975) developed a statistical model in which he formulates a distribution function for polarity intervals. In this model, the geomagnetic dynamo is assumed to be steady dipole oscillator which undergoes a polarity reversal only when triggered by random fluctuations in the non-dipole field. Kono (1972) analysed Cox's model and found it inconsistent with the palaeointensity data. An example of simple mathematical models which do not contradict the palaeomagnetic information was given by him. The model is composed of tens of dipoles in the core with equal movements and directions either parallel or antiparallel to the rotational axis. The state of the geomagnetic field changes as direction inversion takes place in each dipole in a stochastic manner. Advances in the dynamo theory mean that features of the secular variation can now be explained in terms of slow changes in the pattern of convective motions in the core or by the growth and decay of fluid eddies.

1.2 Limnomagnetism

Limnomagnetism is a branch of palaeomagnetism the scope of which is the recovery of the magnetic signature of the geomagnetic field as it was recorded by limnic fresh-water sediments. The development of the coring procedures and especially of the Mackereth corer, (Mackereth, 1958) has given the possibility of recording the finest fluctuations of the geomagnetic field in a serial manner. Consequently the geomagnetic secular variations can be studied
in detail and periods can be identified. The obtained data have regional and global importance. The regional significance is the establishment of the master limnomagnetic curve in a given area, which can be used as dating platform in association with possible archaeomagnetic data. The global significance is the possibility of testing proposed models for the nature of the geomagnetic field, in terms of correlating the regional limnomagnetic curves in a global scale. For example, Alldredge and Hurwitz (1964) suggested eight radial dipoles placed at 0.3 Earth radii in the outer liquid core and a central dipole to give the best fit for the 1945-U.S. chart. Bochev (1975) proposed a model with six radial dipoles in order to explain the 1942-46 geomagnetic field. These dipoles are unconstrained in position and orientation starting with them being arranged equidistant from each other and orientated vertically in the equatorial plane going into an iteration process. Computerized rapid spinner-magnetometers allowed complete recovery of the fossilized remanence at closely spaced time stratigraphic intervals. Currently cryogenic magnetometers have improved the sensitivity by a factor of about 100. The used specimen can be as small as 2mm³ allowing detailed study of supposed short period geomagnetic episodes, like the Laschamp event reported to have occurred in France, Canada, North Atlantic, New Zealand, Czechoslovakia, the Northern Pacific, the Gulf of Mexico, Japan and Sweden. Thompson and Berglund (1976) discredited the event reported in Sweden by Mörner Lanser and Hospers (1971), Mörner and Lanser (1974), Noé (1975), Noé (1975) as a result of climatic changes which produced sediments of very variable mechanical properties, particularly at times of periglacial activity, which were poor recorders of the ambient magnetic field.
Detailed limnological studies can produce magnetic parameters like k or jrs from which one could obtain the following parameters of limnological interest:

a) Spatial and temporal variations in rates of accumulation and influx.

b) Quantifying accumulation and influx on a whole lake/whole drainage basin basis.

c) Developing and extending tephro chronologies.

d) Gaining rapid insight into major climatic variations as expressed in changing erosion rates.

e) Details of sample correlation and combination for further analysis where bulk is needed (e.g. for 14C or for 137Cs in tropics and southern hemisphere.)

f) Identifying and characterising major influx events (e.g. post-burn erosions).

g) Evaluating the within and between lake consistency of dating techniques.

h) Estimating ancient sedimentation rates.

i) Estimating palaeolake level fluctuations.

j) Identifying water quality changes and primary productivity in the lake (Thompson, 1973; Thompson et al, 1975; Thompson, 1977; Winter and Wright, 1977; Wallis, 1977; Oldfield, personal communication).
EXPERIMENTS WITH MAGNETIC CRYSTALS

2.1 Magnetic mineralogy.
2.2 Extraction procedure.
2.3 Debye-Scherrer X-ray diffractometry.
2.4 Cryomagnetic and thermomagnetic experiments.
2.5 Mössbauer spectroscopy.
2.6 Optical microscopy.
2.7 Discussion and conclusions.
2.1 Magnetic mineralogy.

The mineralogy of magnetic grains extracted from limnic, cave sediments and soils has been studied, emphasis being given to the extracts from the Greek limnic sediments, which recorded the geomagnetic fluctuations (Chapter 6), and which were used for redeposition experiments (Chapter 4).

Identification of the magnetic minerals is based on optical microscopy, Debye-Scherrer X-ray diffractometry, cryomagnetic and thermomagnetic experiments and Mössbauer spectroscopy. The study of the identity of the size and shape was performed with optical microscopy.

2.2 Extraction procedure.

Fig. 2.1 illustrates the magnetic separator, which is based on the principle of the attraction of magnetic grains from a water sediment mixture, passing through the high gradient of a magnetic field. It consists of a commercially available hand magnet with 2kOe initial nominal field which was increased up to 3.5kOe by placing two soft iron prismatic pieces between its poles, and a peristaltic pump with 25 ml/min rate of flow. The mixture is kept in suspension with a stirrer. The inclined glass tube with a 8mm internal diameter is connected with a plastic tubing creating a self-circulating system. The system is completed with a vibrator, which disperses further the fluid. The separator works in two stages: a) it extracts magnetic grains continuously for few hours every day; and b) when enough accumulation of magnetic grains is observed, the plastic tubing is placed within clean water, which eventually cleans the extract from the heaviest non-magnetic minerals or organic compounds. The efficiency of the system is
MAGNETIC SEPARATOR

Figure 2.1 Automated magnetic separator
calculated as \( \Delta \text{jrs} (\%) = \frac{(\text{Jrs}_1 - \text{Jrs}_2)}{\text{Jrs}_1} \times 100 \). Jrs has been found reduced by 50 and 80% in some cases, whereas the ks has been reduced by 31 and 46% respectively. It is known that k reflects the paramagnetic and diagenetic constituents together with the ferrimagnetic content, whereas the jrs reflects only the ferrimagnetic content. Thus jrs serves as a better guide to efficiency than susceptibility.

Each sample consisted of up to 20g of dry sediment and the material extracted by this procedure constituted just tenth of one per cent up to 4% in some cases by dry weight, however, this does not mean that all of the extracted material is necessarily ferrimagnetic content. The purity of the samples is 20-30%, due to contaminants of crystalline nature like quartz, illite, plagioclase and montmorillonite, but probably of amorphous material as well. Assuming that all the magnetic content of the bulk sediment of the Greek lakes contains magnetite, then its content is ranged between 0.0003 and 0.01% computed from the jrs values (Chapter 3).

2.3 Debye-Scherrer X-ray diffractometry.

Plate 2.1 and 2.2 illustrate the found front and back patterns of the X-ray diffraction of powder magnetic extract from homogenized limnic sediments of Lake Volvi. It was found necessary to dry the extract in 50°C and ground it in an agate mortar in order that each powder specimen might achieve a uniform grain size for a non-orientated powder mount. The analysis was performed by means of the Debye-Scherrer method. The film was left, in each case, for one day's exposure. As Plates 2.1 and 2.2 show the principal and stronger lines correspond in magnetite and haematite, which is a typical example of the X-ray diffraction results for the rest of the extracts, shown in Table I.
Debye–Scherrer X-ray diffractometry

Front reflections

<table>
<thead>
<tr>
<th>d(Å)</th>
<th>hkl</th>
<th>Mineral</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.4829</td>
<td>440</td>
<td>Magnetite</td>
<td>s</td>
</tr>
<tr>
<td>1.6927</td>
<td>333.511</td>
<td>Magnetite</td>
<td>s ?</td>
</tr>
<tr>
<td>1.7090</td>
<td>116</td>
<td>Haematite</td>
<td>v.f</td>
</tr>
<tr>
<td>1.8395</td>
<td>422</td>
<td>Magnetite</td>
<td>v.f ?</td>
</tr>
<tr>
<td>2.0963</td>
<td>204</td>
<td>Haematite</td>
<td>v.f</td>
</tr>
<tr>
<td>2.5284</td>
<td>400</td>
<td>Magnetite</td>
<td>f</td>
</tr>
<tr>
<td>2.7011</td>
<td>311</td>
<td>Magnetite</td>
<td>v.s</td>
</tr>
<tr>
<td>2.9627</td>
<td>104</td>
<td>Haematite</td>
<td>v.f</td>
</tr>
<tr>
<td>3.2173</td>
<td>220</td>
<td>Magnetite</td>
<td>s</td>
</tr>
<tr>
<td>3.3146</td>
<td>040</td>
<td>Plagioclase</td>
<td>v.f ?</td>
</tr>
<tr>
<td>5.4822</td>
<td>006</td>
<td>Illite</td>
<td>v.f</td>
</tr>
</tbody>
</table>

Plate 2.1 X-ray diffraction powder patterns of magnetic crystals extracted from the sediments of Lake Volvi.
Debye–Scherrer X-ray diffractometry

Back reflections

<table>
<thead>
<tr>
<th>d(Å)</th>
<th>hkl</th>
<th>Mineral</th>
<th>Intensity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.2977</td>
<td>203</td>
<td>Quartz</td>
<td>f</td>
</tr>
<tr>
<td>1.2636</td>
<td>533</td>
<td>Magnetite</td>
<td>v.f</td>
</tr>
<tr>
<td>1.2428</td>
<td>0.0.016</td>
<td>Illite</td>
<td>v.f</td>
</tr>
<tr>
<td>1.1206</td>
<td>64.2</td>
<td>Magnetite</td>
<td>v.f</td>
</tr>
<tr>
<td>1.0914</td>
<td>553.731</td>
<td>Magnetite</td>
<td>s</td>
</tr>
<tr>
<td>1.0478</td>
<td>800</td>
<td>Magnetite</td>
<td>f</td>
</tr>
<tr>
<td>0.98951</td>
<td>660.822</td>
<td>Magnetite</td>
<td>v.f</td>
</tr>
</tbody>
</table>

f = faint
v.f = very faint
s = strong
v.s = very strong

Plate 2.2 X-ray diffraction powder patterns of magnetic crystals extracted from the sediments of Lake Volvi.
<table>
<thead>
<tr>
<th>Lake</th>
<th>Country</th>
<th>Magnetite</th>
<th>Haematite</th>
<th>Quartz</th>
<th>Others</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trikhonis</td>
<td>Greece</td>
<td>xxx</td>
<td></td>
<td>x</td>
<td>P, M, ?</td>
</tr>
<tr>
<td>Begoritis</td>
<td>Greece</td>
<td>xxx</td>
<td></td>
<td>x</td>
<td>M, ?</td>
</tr>
<tr>
<td>Volvi</td>
<td>Greece</td>
<td>xxx</td>
<td>x</td>
<td>x</td>
<td>I, P, ?</td>
</tr>
<tr>
<td>Geneva</td>
<td>Switzerland</td>
<td>xxx</td>
<td>trace</td>
<td>trace</td>
<td>M, ?</td>
</tr>
<tr>
<td>Le Bourget</td>
<td>France</td>
<td>xxx</td>
<td>trace</td>
<td>x</td>
<td>M, trace Ch, ?</td>
</tr>
<tr>
<td>Annecy</td>
<td>France</td>
<td>xxx</td>
<td>x</td>
<td>x</td>
<td>M, ?</td>
</tr>
<tr>
<td>Radunskie Cave</td>
<td>Poland</td>
<td>x</td>
<td>x</td>
<td>trace</td>
<td></td>
</tr>
<tr>
<td>Canet</td>
<td>Spain</td>
<td>xxx</td>
<td></td>
<td>x</td>
<td>I, ?</td>
</tr>
<tr>
<td>Petralona</td>
<td>Greece</td>
<td>xxx</td>
<td></td>
<td>x</td>
<td>I, ?</td>
</tr>
<tr>
<td>Ball's Cavern (Alpha)</td>
<td>U.S.A.</td>
<td>xxx</td>
<td>xx</td>
<td>x</td>
<td>I, ?</td>
</tr>
<tr>
<td>Ball's Cavern (Omega)</td>
<td>U.S.A.</td>
<td>xxx</td>
<td>x</td>
<td>x</td>
<td>I, ?</td>
</tr>
</tbody>
</table>

P = plagioclase; M = montmorillonite; Ch = chamosite; I = Illite.
2.4 Cryomagnetic and thermomagnetic experiments.

Magnetite undergoes a crystallographic transformation from cubic to orthorhombic at 120 °K. It also exhibits a minimum magnetocrystalline anisotropy at about 180 °K. When pure magnetite is cooled through this temperature in zero magnetic field, it loses some of its remanence. Similarly it loses some of any remanence acquired at low temperatures, on warming up through the transition temperatures. Experiments such as this have been used to identify magnetite as a carrier of remanence. The transition is suppressed by impurities and very fine grained magnetite.

Fig. 2.2 illustrates two representative examples characteristic of several cryomagnetic experiments performed with wet and dried sediments both for the jn and jrs. All the wet sediments sampled from several horizons in the three representative cores V8, B9, T2, showed a decrease in the horizontal intensity corresponding closely to Morin transition for coarse haematite, both for jn and jrs, which made the result highly suspicious because it was hardly probable to find haematite in all cases. The horizontal intensity was measured with the spinner magnetometer and the temperature was monitored with a thermocouple attached to the sample, which was rotating in a vertical fashion within a dewar tank full of liquid nitrogen. To verify or discredit the supposed Morin transition, several cryomagnetic experiments were performed. In all cases no Morin transition was found (Papamarinopoulos and Readman, 1978a). Fig. 2.2 illustrates the pseudo Morin transition produced by ice crystals, which randomized the directions of the magnetic crystals locked in the sediment. The jn cryomagnetic curves were found to be noisy, because of the low sensitivity of the low temperature magnetometer and most of them did not show the magnetic transition,
CRYOMAGNETIC EXPERIMENTS

LAKE VOLVI

Change in IRM (12 kOe given at 293 K) on cooling

(A) Dried sample V8-9A
(B) Wet sample V6-40

Figure 2.2 Cryomagnetic curves of whole sediment from Lake Volvi
Figure 2.3  Thermomagnetic curves of extracts, from sediments of the Greek lakes.
whereas the JRS curves usually showed it for several horizons in all three Greek limnic sediments. Fig. 2.3 illustrates three thermomagnetic experiments performed with extracts from the sediments of the three Greek lakes. The first (Volvi) and the second (Begoritis) were performed in 10kOe with 20°C/min rate of heating and cooling, whereas the third (Trikhonis) was performed in 4.5kOe with 10°C/min rate of cooling and heating. The extracts were placed in a tiny quartz bucket placed in the most sensitive place of a vertical torsion balance. Each experiment was repeated twice to confirm the initial experimental results.

2.5 Mössbauer spectroscopy.

Fig. 2.3 illustrates the Mössbauer spectra produced by Maniatis and Simopoulos, (personal communication), with magnetic extracts from the sediments of the three Greek lakes. The spectra were obtained at room temperature and showed three patterns: (I) dominant magnetite in all three cases; (II) haematite with small contribution, which was recognizable in the case of the extracts from Lake Volvi and Begoritis; (III) which probably corresponds to the type of minerals like mica, Morillonite, with very small contribution. The spectra of the Begoritis extract is fairly complex and further work is required at liquid helium temperature to interpret it fully. Mössbauer spectra obtained from the sediments of Canet Cave (Spain) and Petralona Cave (Greece) produced an entirely different picture. Magnetite is absent in both cases with dominance of haematite and some contribution of hydrous iron oxides like goethite or lepidocrocite and some iron minerals as well (Maniatis and Simopoulos, personal communication).
Figure 2.4  Mössbauer spectra of extracts, from sediments of the Greek lakes.
2.6 Optical microscopy.

Magnetic extracts from limnic and cave sediments in which palaeomagnetic studies were performed together with extracts from archaeological soils in which magnetometer and magnetic susceptibility surveys were carried out, were studied in detail with optical microscopy, with the purpose of identifying the carriers of the acquisition of the remanence locked in the limnic and cave sediments and the source of the magnetic anomalies observed at the sites of archaeological interest. In all presented illustrations the horizontal field of view is 190μm, except for Plate 2.4 which is 50μm. Plates 2.3, 2.4 illustrate a representative example of magnetic extracts from the sediments of Lake Volvi. The field of view is dominated by angular fresh and fine grained fragments of pink magnetite (b, c, d) with sizes ranging between less than 1μm and a few microns. In the E-S quarter of the field of view a 12.4μm angular bright haematite grain with red marginal reflections is located. Plate 2.4 illustrates a 10μm angular oxidized magnetite crystal with heavy oxidation towards haematite (a). Plates 2.5, 2.6 illustrate representative magnetic extracts from the sediments of Lake Begoritis. Plate 2.5 exhibits a 33μm large angular, bright haematite grain with blood red marginal reflections (a), a 33μm pink, skeletal magnetite grain and several other angular fresh magnetite grains (c, d, e), with sizes ranging between less than 1μm up to a few microns. Plate 2.6 exhibits a 31μm large composite pyrite rhomboid (an aggregate of minute sulphite spheres). On the left and above this a 9.6μm haematite grain (b) is located. On the left and below this a cluster of angular fragments of fresh pink magnetite occur with sizes ranging between less than 1μm and a few microns. Plate 2.7 illustrates magnetic extracts from the sediments of Lake Trikhonis. In the centre of the field of
Optical microscopy of magnetic extracts

Plate 2.3
(a) Oxidized angular magnetite towards haematite surrounded by fresh magnetite fragments. Lake Volvi (Greece).
Initial field of view 50 μm, magnified 21 times

Length of horizontal field of view 190 μm

Plate 2.4
(a) Whole haematite grains with red marginal reflections;
(b, c, d) Clusters of fresh angular fragments of magnetite dominating the field of view. Lake Volvi (Greece).
Optical microscopy of magnetic extracts
Length of horizontal field of view 190 μm

Plate 2.5  (a) Angular large grain of bright haematite with blood red marginal reflections; (b) Skeletal large magnetite grain; (c) Diamond shaped magnetite fragments. Lake Begoritis (Greece).

Plate 2.6  (a) Composite pyrite rhomboid (aggregate of minute sulphite spheres); (b) Oxidized magnetite fragments towards haematite; (c) Cluster of angular magnetite
Optical microscopy of magnetic extracts
Length of horizontal field of view 190 μm

Plate 2.7 (a) Large diamond shaped magnetite crystal; (b) Composite pyrite rhomboid; (c, d) haematite grains with tiny magnetite fragments stuck on them; (e, f) Clusters of fresh angular magnetite. Lake Trikhonis (Greece).

Plate 2.8 (a) Diamond shaped broken magnetite crystal; (b, c) Clusters of fine grains of bright, haematite which dominate the field of view; (d, e) Hydrous iron oxides probably goethite or lepidocrocite with grey-red internal
view a 32μm large fractured diamond shaped magnetite crystal (a) occurs. On the left a 19μm composite pyrite rhomboid (b) is located. On the left two 0.6, 0.8μm angular haematite grains (c) occur. On the right and above this a 1.2μm angular haematite grain (d) is located. The haematite grains appear with deep brown-red internal reflections having tiny fragments of angular pink magnetite stuck on them. In the S-W quarter of the field of view clusters of angular fresh pink magnetite grains (e, f) occur with sizes between less than 1μm and several microns. Plate 2.8 exhibits magnetic extract from a terra rossa sediment from Canet Cave (Spain). A 21μm diamond shaped broken pink magnetite crystal (a) is located. The field of view is dominated by angular bright haematite fragments (b, c) with sizes ranging between less than 1μm and several microns. The lower reflectivity phases with grey-red internal reflections are most probably hydrous iron oxides (goethite or lepidocrocite) with sizes approximately 15μm (d, e), (Gill, personal communication). Plates 2.9, 2.10 illustrate magnetic extracts from archaeological soil in Balfargh (Scotland). Plate 2.9 exhibits a large 44μm angular titanomagnetite grain crossed by a distinct pink, unaltered ilmenite lamella visible along its major axis (a) is located. On the left and above this a 29μm angular titanomagnetite with colour variations (b) occurs. In the W-S quarter of the field of view several angular titanomagnetites (c) occur with sizes ranging between few and several microns. Plate 2.10 exhibits a 36μm angular titanomagnetite heterogeneously and partially oxidized. A pink lamella of unaltered ilmenite crosses the grain along its major axis, whereas the N-E quarter of the grain has been replaced by maghemite, which appears with white colourations and poor crystalline appearance (a). On the left and below this a cluster of angular titanomagnetites with colour
Plate 2.9  
(a) Large titanomagnetite crystal crossed by a distinct unaltered ilmenite lamella along its major axis;  
(b, c) Titanomagnetites with colour variations.  
Glacial soil, Balfargh (Scotland).

Plate 2.10  
(a) Large titanomagnetite crossed by a distinct unaltered ilmenite lamella along its major axis, partially and heterogeneously oxidised towards a poorly crystalline shaped maghemite, which is recognised by the replacement of the N-E quarter of the host mineral;  
(b) Broken angular coarse fragments of titanomagnetite.  Glacial soil.
variations (b) occur, with sizes ranging between few microns and several microns.

2.7 Discussion and conclusions.

The reversed Jrst studies of the bulk sediment revealed the presence of fine grained magnetite (Chapter 3). The application of the Lowrie-Fuller test with pilot samples, revealed that the magnetite is SD or PSD in character. Debye-Scherrer X-ray diffractometry illustrated that the principal and stronger lines correspond to magnetite and haematite with some contaminants like quartz, plagioclase, illite, montmorillonite. Cryomagnetic experiments in dry samples illustrated magnetite transition when Jrst was given to the samples. Thermomagnetic experiments performed in air with extracts showed that the dominant magnetite was oxidized in 350-450°C probably into a cation deficient spinel which was inverted into haematite, remaining unaltered in cooling. Mössbauer spectroscopy showed clearly the presence of magnetite, haematite and the dominance of the first upon the second. The spectrum produced from the extract from the sediments of Lake Trikhonis showed no evidence of haematite probably because its content was below the detection limit of the technique, whereas the detailed study of the optical microscopy revealed dominant fine grained magnetite, which was either fresh or oxidized towards haematite. Coarse grains of magnetite and haematite of crystal or skeletal shape were observed very rarely. The range of the size which was less than 1μm up to few microns supported the results of the Lowrie-Fuller test about the SD or PSD character of it. The study of the magnetic extracts from the sediments of Caves Canet and Petralona (Papamarinopoulos and Readman, 1978b) revealed the presence of fine and coarse haematite in abundance, whereas magnetite
together with hydrous iron oxides like goethite or lepidocrocite were found very rarely. This does not rule out the possibility that magnetite could be responsible for the measured high valued magnetic parameters of naturally and artificially deposited sediments in the laboratory. Further detailed work should be done to answer the question of the nature of the magnetic carriers responsible for the remanence in cave deposits. The study of the extracts from the glacial soils, which had produced unusual negative anomalies (-200 $\gamma$) showed that the dominant minerals were fine and coarse titanomagnetite, either unaltered or heterogeneously and partially oxidized towards ilmenite and maghemite.
THE MAGNETIC PROPERTIES OF THE FRESH WATER LIMNIC DEPOSITS

3.1 The Greek lakes.
   3.1.1 Lake Volvi.
   3.1.2 Lake Begoritis.
   3.1.3 Lake Trikhonis.

3.2 Long core description and measurements.

3.3 Single sample measurements \( j_n, k \) and \( Q \)-ratio.

3.4 Remanent hysteresis.

3.5 Significance of jar in limnic deposits.

3.6 Low temperature treatment.

3.7 Conclusions.
3.1 The Greek Lakes.

All three Greek lakes shown in Fig. 3.1 are of break-tectonic origin.

3.1.1 Lake Volvi.

The Promygdonian basin is located about 10 km NE of Thessaloniki in Chalkidiki peninsula. It is the ancestor of the Mygdonian valley (Psilovikos, 1977) which is the deepest part of the present elongated basin, situated between Kamela mountain and Regina village. A system of ridges, low hills and terraces divide the Mygdonian valley into two smaller valleys named Lagatha and Volvi. Exposures in the Promygdonian basin reveal torrential, fluvial and limnic sediments including conglomerates, sandstones and silty sands of Miocene age, (Demopoulos, 1972). Red beds were deposited during the lower Pleistocene (Melentis and Koupos, 1977), after the discharge of the lake into the sea due to a general stadial regression of the area (Psilovikos, 1977). The whole Promygdonian system was deposited into the Promygdonian basin between the Miocene and lower Pleistocene (Psilovikos, 1977) when the basin joined Strymonikos gulf by means of two rivers flowing through the old valleys of Redina and Kakia Skala. The formation of Mygdonia valley took place, shown in Fig. 3.2 due to the activation of the existing systems of faults in the area (Oswald, 1938; Georgalas-Galanopoulos, 1953; Kochel et al, 1971; Psilovikos, 1977), which occurred several times during the lower Pleistocene. The joining part between the new valley of Mygdonia and Strymonikos underwent a transient interruption during which water was concentrated in the valley and thus the Mygdonian lake came into existence (Psilovikos, 1977). This process was closely related to typical climatic conditions of the lower Pleistocene in particular of the first interglacial period (Günz-Mindel) about
Figure 3.1  Map of Greece with the positions of the main lakes.
Figure 3.2  The geomorphology of the area around lake Volvi.
Lake Volvi

The bathymetry: Depths (m) After (A. Psilovikos)

Lake Volvi Coring Stations

\[ V_{1,2}: 15.3 \text{ m}, \quad V_{3}: 15.6 \text{ m}, \quad V_{4,5}: 20.2 \text{ m}, \quad V_{6,7}: 19.5 \text{ m} \]
\[ V_{8}: 20.2 \text{ m}. \]

Figure 3.3 Isobaths and coring stations in Lake Volvi.
500,000 years ago. The 500km$^2$ Mygdonian basin followed five distinct phases of development due to activation of faults and the consequent drainage of water, which eventually created the lakes Lagatha and Volvi. Lake Volvi, shown in Fig. 3.3, occupies the eastern part of the old Mygdonian lake. The sediments consist of detritus eroded by rain, which originates from the mountains around the lake. The lake has two outlets which have been artificially enlarged. At its western part it communicates with lake Lagatha through a narrow furrow and at the eastern part Rehios river transfers the water into Strymonikos Gulf through the Redina valley. The rate of deposition as an average is 2-3mm/yr, (Psilovikos, 1977). The geological exposures around the lake reveal basic eruptives and intrusives (Fels, 1950) and metamorphic rocks like gneiss with marble horizons, graphite from Kerdyllia mountains (Demetriadi, 1974), amphibolites which gave 4.4% in magnetic content (Psilovikos, personal communication).

3.1.2 Lake Begoritis.

The lake shown in Fig. 3.4 has a typical diluvial karst-origin and it is the deepest remaining part of the large depression of Ptolemais (Fels, 1954), which is verified by the numerous large karst-springs occurring in various parts a few kilometres away from the lake, shown in Fig. 3.5. The sediments reach the lake after rain falls from both torrents and karst-tunnels. The natural outlet of the lake is the subterranean river Vodas. Basic eruptives, palaeosoiis and limestones are the geological exposures which contribute in the detritus of the sediments.
Figure 3.4
The geomorphology of Lake Begoritis.

NORTHWESTERN GREECE
Figure 3.5  Isobaths and coring stations in Lake Begoritis.
3.1.3 Lake Trikhonis.

Lake Trikhonis is shown in Fig. 3.6. It is located within a large depression, which looks like a gigantic moat. It contains the sub-basins of Agrinio, Lesino and the one into which the river Acheloos flows. It also contains numerous terraces, consisting of deposits which are remains of a large ancient lake that covered the entire depression during the Pliocene (Fels, 1952; Leontaris, 1967). The ancient lake was supplied by Acheloos river and rainfalls. Its water level started falling down and the lake was restricted in area, due to stadial overflows and accidental discharge, due to the activation of numerous faults existing in the area (Galanopoulos, 1963, 1965; Leontaris, 1967). At first lake Amvrakia became independent of the big lake, because it was on a higher level than the other two lakes, which were split in two stages (Leontaris, 1967). In the course of the first stage Lysimachia and Trikhonis were separated by deposition of alluvia. During the second stage lakes Lysimachia and Ozeros were split by means of the same mechanism (Leontaris, 1967). The sediments reach the lake mainly from the North eroding palaeolimnic deposits, pebbles, sandstones and geological exposures with a large petrological spectrum. The outlet of the lake, shown in Fig. 3.7, is a natural furrow westwards of it flowing into lake Lysimachia.

3.2 Long core descriptions and measurements.

Fig. 3.8, 3.9 and 3.10 illustrate the stratigraphy of three cores representative of the 25 cores taken from the Greek lakes.

Core V8 from lake Volvi is divided into five major units with different distinct colouration. The first from the top is dark olive grey, the second light olive grey, the third dark greenish grey, the
Figure 3.6 The geomorphology of Lake Trikhonis.
Figure 3.7 Isobaths and coring station in Lake Trikhonis.
The core is divided into five major units with different distinct colouration.

Type of sediments

Mainly muds

<table>
<thead>
<tr>
<th>Colour</th>
<th>Thickness (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deep brownish</td>
<td>(3.2)</td>
</tr>
<tr>
<td>Deep brownish</td>
<td>(3.2)</td>
</tr>
<tr>
<td>Deep brownish</td>
<td>(3.5)</td>
</tr>
<tr>
<td>Deep brownish</td>
<td>(3.3)</td>
</tr>
<tr>
<td>Deep brownish</td>
<td>(3.1)</td>
</tr>
<tr>
<td>Deep greenish</td>
<td>(3.2)</td>
</tr>
<tr>
<td>Deep greenish</td>
<td>(3.3)</td>
</tr>
</tbody>
</table>

Figure 3.8 The stratigraphy of Lake Volvi, core VS.
Figure 5.9 NRM, PDRM, NRM/PDRM and the ks of the naturally and artificially deposited samples are plotted side by side against the depths of cores B9 and T1, of Lakes Begoritis and Trikhonis, respectively.
<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Age $^{14}C$</th>
<th>Pollen yrs. B.P.</th>
<th>Lithology</th>
<th>General colour of the core</th>
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</thead>
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<tr>
<td>1</td>
<td>$^{14}C$ 2344±60</td>
<td></td>
<td></td>
<td>(Light olive gray)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Type of sediments</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Mainly muddy</td>
</tr>
<tr>
<td>2</td>
<td>$^{14}C$ 3648±60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L1 Deep olive greenish</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>(6.0)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L2 Deep olive greenish</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>(6.8)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L3 Deep olive greenish</td>
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<td></td>
<td></td>
<td></td>
<td>(4.8)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L4, L5 2mm deep greenish</td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>3</td>
<td>$^{14}C$ 5410±70</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pollen 6000-7000</td>
<td></td>
<td>L9 Deep olive greenish</td>
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<td></td>
<td>(4.0)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L10 Deep olive greenish</td>
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<td>(2.6)</td>
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<td>L13 Deep olive greenish</td>
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<td></td>
<td>(4.0)</td>
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<td></td>
<td>L14 Deep olive greenish</td>
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<td></td>
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<td></td>
<td>(4.0)</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>L16 Deep olive greenish</td>
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<td>(4.0)</td>
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<td>finely laminated zone</td>
</tr>
<tr>
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<td></td>
<td>L31 Brownish gray</td>
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<td></td>
<td>(4.0)</td>
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<td>5</td>
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<td></td>
<td></td>
<td>L32 Deep olive greenish</td>
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<td></td>
<td></td>
<td>Pollen 6000-7000</td>
<td></td>
<td>(5.2)</td>
</tr>
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<td></td>
<td></td>
<td></td>
<td>L33 Shells</td>
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<td>L34 Deep dark greenish</td>
</tr>
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<td>(24.0)</td>
</tr>
</tbody>
</table>

Figure 3.9 The lithostratigraphy of Lake Begoritis, core B9.
Lake Trikhonis - Core T2 - Greece

**DESCRIPTION**

- General colour of core: (Light olive gray)
- Type of sediments: Mainly muds
- Colour

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Age $^{14}$C, yrs B.P.</th>
<th>Lithology</th>
<th>$^{14}$C Age, yrs B.P.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$^{14}$C: 5089±75</td>
<td>Deep olive greenish (8.0)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>$^{14}$C: 2284±85</td>
<td>Tephra horizon (18.0)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>$^{14}$C: 5769±90</td>
<td>Brownish gray (4.8)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>$^{14}$C: Pollen 6500</td>
<td>Brownish gray (3.6)</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td>Brownish gray (3.2)</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>Brownish gray (2.4)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Brownish gray (6.0)</td>
<td></td>
</tr>
</tbody>
</table>

Figure 3.10 The lithostratigraphy of Lake Trikhonis, core T2.
fourth light olive grey and the fifth at the bottom gellowish dark grey. The sediments are fine-grained. X-ray diffraction on the samples from depths 96 and 422 cm in core V6 showed calcite, siderite, quartz, plagioclase, illite, chamosite, smectite (Readman et al, 1976). Seven deep brownish layers about 3.1 to 3.5 cm thick occur at 290, 310, 340, 355, 358, 365, 470 cm and one deep greenish layer with 3.3 cm thickness occurs at 472 cm. Six of them are located in the third unit and the other two near the boundary between the fourth and the fifth unit.

Core B8 from lake Begoritis is mainly light olive grey interrupted by 34 layers of different thickness and colour. The sediments are fine-grained except in the bottom part of the core between layers 31 and 34 at 310 and 370 cm respectively. Within this zone a 8 cm thick layer contains shells. Two zones have distinct characteristics from the rest of the core. The first zone, which is defined between layers 14 and 19 at 10 and 100 cm respectively, contains five laminations 2 mm thick. Similarly the second zone defined between layers 17 and 30 at 250 and 285 cm correspondingly contains thirteen laminations 2 mm thick probably corresponding to cyclic seasonal episodes in the water supply of the lake. The sediments are mainly dolomite, calcite, siderite, quartz, illite, talc, chlorite (Müller, personal communication).

Core T2 from lake Trikhonis consists of light olive grey fine-grained sediments. X-ray diffraction on a sample from depth 145 cm in core T3 showed calcite, quartz, plagioclase, illite, interstratified clays (Readman et al, 1976). The homogeneous clays are interrupted by five deep olive greenish layers with thickness 4.8, 3.6, 3.2, 2.4, 6.0 cm at 510, 520, 540, 542.4 and 580 cm respectively. J, k and Q-ratio as Fig. 3.16 illustrates at 280 cm exhibit a peak corresponding to a layer, which was visually observed only when the core was left to dry.
This layer is associated with a tephra layer, (Headman et al., 1976) however, Müller has examined thoroughly samples taken from this layer in core T2 and found no direct evidence of glass material coming either from the volcano of Santorini in the Aegean sea or from Italian volcanoes. He does not entirely exclude the possibility of the tephra, because it is possible that an unstable glass component might have been diagenetically altered to crystalline material like silicates (Müller, personal communication).

In Fig. 3.11, 3.12 and 3.13 horizontal intensity is plotted against the depth for all the cores taken from lakes Volvi, Begoritis and Trikhonis. These figures illustrate the remarkable correlation existing from one part of a given lake to the other. Similar correlations have been obtained with long core susceptibility measurements. To verify and get a more detailed picture of the limnomagnetic parameters, the cores were cut into sections 150 cm long and then sliced into two halves. One half was preserved for radiocarbon, pollen dating and sedimentological analyses and the other half for palaeomagnetic sampling. 2.3 cm cube-shaped plastic sample holders were pushed centrally into the soft but very firm sediment. Plate 3.1 illustrates the sampling method. The top of the sample holders had been drilled to allow easy escape of the trapped air as the sample holders were pressed into the sediment. The holes were later covered with lasso-tape to avoid partial drying or oxidation. When the sample holders were filled up, they were cleaned and measured with the Digico magnetometers. The declination and inclination patterns are presented in detail in Chapter 6.
Sub-sampling of specimens from a sliced core of Lake Trikthonis. Plastic 2.3 cm cube-shaped sample holders are pressed serially into the soft sediment.
Figure 3.11  Long core measurements of NRM horizontal intensity from Lake Volvi and their correlation.
LAKE BEGORITIS - GREECE

NRM horizontal intensity (μG)

Figure 3.12 Long core measurements of NRM horizontal intensity from Lake Begoritis and their correlations.
Figure 3.13  Long core measurements of NRM horizontal intensity from Lake Trikhonis and their correlations.
3.3 **Single sample measurements jn, k and Q-ratio.**

jn is the initial measured remanence of a rock or sediment without reference to its mode of origin. Jn is determined by the concentration, composition and physical state of the contained magnetic minerals as well as by the geomagnetic field. If this is true, k, which is almost solely a function of the magnetic mineralogy, should vary directly with jn. Figs. 3.14, 3.15 and 3.16 illustrate the logs of k and Q-ratio plotted in parallel for cores V8, B9 and T2. As it is shown, the variation in jn is matched by a similar variation, however, there are also differences indicating that their relation cannot be exactly linear. The ratio of jn to induced magnetization in low field is called the modified Koenigsberger ratio (Q = jn/k). This ratio varies from 1 to 5 in these cores as Figs. 3.14, 3.15 and 3.16 illustrate. It has been suggested that the Q-ratio reflected the changes of the intensity of the geomagnetic field (Harrison and Somayajulu, 1966).

3.4 **The stability of jn.**

Of more importance from a palaeomagnetic point of view, is not the absolute intensity of magnetization, but rather the ability of jn to resist change. Fields and laboratory tests are commonly employed to obtain some indication of the stability of a rock's jn. Field tests (Graham, 1949; Irving, 1964) are never applicable to deep lakes, primarily because of the inherently limited lateral sampling of a sediment horizon at a site and the general restriction of a single rock type. Johnson et al (1948) applied the test of the coercivity of jn by measuring the reversed field required to produce a jrs equal and opposite to jn. The values that were obtained (2-40 Oe) indicated that
Figure 3.14  Single sample measurements of NRM intensity, susceptibility and Q-ratio of core V8, of Lake Volvi.
Figure 3.15  Single sample measurements of NRM intensity, susceptibility and Q-ratio of core B7, of Lake Begoritis.
Figure 3.16  Single sample measurements of NRM intensity, susceptibility and Q-ratio of core T2, of Lake Trikthonis.
jn of these sediments could not be readily altered by magnetic fields or the magnitude of the geomagnetic field (<10 Oe). However, the coercivity of jn gives a general guide to stability, since low values do not necessarily reflect that stable components are absent. This is because jn is being compared to magnetic components of low coercivity that probably do not contribute to it. Better understanding of the stability of jn can be obtained through either AF or thermal demagnetization in stepwise increasing AF or temperature. The main advantage of these techniques is that low coercivity magnetizations can be easily removed. The jn of the limnic deposits can be classified as a) stable; b) unstable; and c) multi component. Normalized AF demagnetization curves of selected samples along cores VB, B9 and T2 are presented in Fig. 3.17. The samples from lake Volvi show MDFs in the range between 200 and 350 Oe, whereas lake Begoritis' MDFs fall in the range between 200 and 400 Oe and those from lake Trikhonis, between 300 and 500 Oe. The results of individual samples are presented in Fig. 3.18, for lake Volvi, Fig. 3.19 (a, b) for lake Begoritis, and in Fig. 3.20 for lake Trikhonis. Samples B9 - 1, 5 taken from the top of core B9 of lake Begoritis with initial jn 14.25 and 14.16µG show not smooth demagnetization curves and their directions are not well grouped. This is explained by the removal of very soft jv components during AFC. Most of the samples from all three lakes show smooth demagnetization curves and the directions of remanence appear to be well grouped at least up to 300 Oe and often up to 500 Oe. AF greater than about 500 Oe could not be used for magnetic cleaning of these specimens due to increasing problems with anhysteretic remanence induced to the specimens. The stability of jn does not appear to be simply related to the gross lithology of the sediment nor to the initial jo, nor to the depth.
Figure 3.17  Normalized NRM demagnetization curves of pilot samples from Lake Volvi, Begoritis and Trikhonis.
Normalized NRM demagnetization curves together with stereographic projection of their directions of individual pilot samples taken from Lake Volvi core VB.
Figure 3.19a Normalized NRM demagnetization curves together with stereographic projections of their directions of individual pilot samples taken from Lake Begoritis, core B9.
Figure 3.19b Normalized NRM demagnetization curves together with stereographic projections of their directions of individual pilot samples taken from Lake Begoritis, core B9.
Figure 3.20 Normalized NRM demagnetization curves together with geomagnetic projections of their directions of
This is not surprising, since there was no simple correlation between gross lithology and magnetic mineralogy. Thermal demagnetization was not performed in order to avoid mineralogical changes during heating.

3.5 Remanent hysteresis.

Magnetic hysteresis parameters give important information about the bulk magnetic properties of a magnetic material. The experimental procedure was to take a well-demagnetized specimen and briefly expose it to a direct magnetic field by placing the specimen between the pole pieces of an electromagnet, which could generate fields up to 12kOe. Fig. 3.21 illustrates the produced curves for pilot samples taken along cores V8, B9 and T2. The Hsat is 1.5-2kOe in all the cases of the examined specimens. Jrs for core V8 is ranging from 0.8-1.9 x 10^-3 μG, for core B9 is from 2.6-8.3 x 10^-3 μG and for core T2, from 0.3-1.8 x 10^-3 μG. Fig. 3.22 illustrates the Hcr required to reduce the reversed jrs to zero. This falls within the range of 300-340 Oe for core V8, except for the case of sample V8 - 145 which shows Hcr - 560 Oe, indicating difference in size and shape of the magnetic content in the horizon at 418.2cm, for core B9 falls within the range of 280-300 Oe and for core T2 between 380-440 Oe. The values of Hcr imply that fine grained magnetite is the dominant magnetic mineral along the core, which masks the possible presence of haematite (Chapter 2). The variation of the jrs along the cores most likely reflects a variation of the magnetic mineral concentration in each core. This is indicative that perhaps jrs could be a suitable normalizing factor for relative intensity studies in these cores, however, it is necessary that certain criteria should be satisfied before any general conclusion comes out. In Chapter 5 the effect of jrs along two cores is discussed.
Figure 3.21 IRM curves of pilot samples taken along cores V6, B9, and T2 of Lakes Votvli, Begoertis, and Trikhonis, respectively.
Figure 3.22  Reversed IRM curves of pilot samples taken along cores
3.6 **Significance of jar in limnic deposits**

Another type of remanence, which can be induced to sediments without causing any chemical change is jar, the anhysteretic remanence magnetization. Suites of pilot samples taken from cores V8, B9 and T2 were placed in an AF demagnetization coil whose axis was parallel to the geomagnetic field. When the axis of the coil is aligned perpendicular to the geomagnetic field the jar is about a half of that in the parallel configuration. Fig. 3.23 illustrates the shape of the growth of the jar, which was induced into samples, which were previously well demagnetized. The $H_{sat}$ ranges between 800-1000 Oe implying that it is a common parameter for the limnic sediments. The jar ranges for core V8 from 8-150uG, for core B9 from 62-165uG and for core T2 from 9-118uG. The illustrated variations of the jar along the cores reflect differences of concentration of magnetite, however, they demonstrate a different degree of sensitivity in comparison with the jrs for the same samples. Fig. 3.24 illustrates the effect of the AF in a suite of samples carrying jar given from 200 up to 1000 Oe. They also show that the normalized jn are closer to the normalized demagnetization curves of the jar between 800-1000 Oe, which implies that jar of such a value could be used as normalizing parameters of jn.

3.7 **Low temperature treatment**

Figs. 3.26, 3.27 and 3.28 illustrate normalized demagnetization curves of pilot samples taken along the core B9 of Lake Begoritis and normalized demagnetization curves of adjacent samples after low temperature treatment. Fig. 3.26 illustrates the demagnetization curves of jn. The appear to be similar in shape and with practically the same MDFs except for samples B9 - 70, 72, in which the MDFs are 250 and 270 Oe
Figure 3.23: ARM curves of pilot samples taken along cores V8, B9
Figure 3.24  Spectrum of normalized ARM demagnetization curves given to pilot samples (V8-16, V8-41, V8-65, V8-93), together
Figure 3.25: Evolution of normalized AER and AER degradation curves given to plot samples (A9-109, A9-110, A9-111, A9-112).
Figure 3.26 NRM normalized demagnetization curves before and after cooling, at liquid nitrogen temperature and warming up in zero magnetic field.
Figure 3.27 ARM normalized demagnetization curves before and after cooling, at liquid nitrogen temperature and warming up in zero magnetic field.
Figure 3.28 IRM normalized demagnetization curves before and after cooling at liquid nitrogen temperature and warming up in zero magnetic field.
respectively and for samples B9 - 90, 92 the MDFs are 310 and 210 Oe correspondingly. It is interesting that the remanence remaining in samples B9 - 70, 72, was harder than the original jn. It is possible that this harder fraction not removed by the low-temperature treatment was due to SD magnetic grains attached to parent MD grains. Fig. 3.27 shows the demagnetization curves of the jar (F = 0.40 Oe, I = 70°, D = 0°, AF = 1000 Oe). In all cases the demagnetization curves look similar in shape and have similar MDFs except for sample B9 - 90, 92, which has 300 and 250 Oe, which means that a significant portion of jar was removed after low-temperature treatment. Fig. 3.28 shows the demagnetization curves of jrs (H = 10000 Oe). The demagnetization curves before and after low-temperature treatment look similar except in the case of sample B9 - 90, 92, which shows MDFs 170 and 120 Oe, which reflects that a significant part of jn, jar, and jrs is removed. It is interesting that the low-temperature treatment has the same effect on jr, jar and jrs of sample B9 - 90, 92, whereas only in jn for sample B9 - 70, 72.

3.8 Conclusions.

Jn in all limnic sediments has a stable component with MDFs between 300 and 500 Oe. Jn, k and Q-ratio can be correlated between cores in a given lake. Low-temperature treatment in general had the same effect in samples magnetized with jn, jar or jrs, as AFC showed.
CHAPTER 4

4.1 Magnetization processes in sediments.
4.1.1 Depositional remanent magnetization.
4.1.2 Post-depositional remanent magnetization.
4.2 Experimental methods.
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4.1 Magnetization processes in sediments.

Depositional remanent magnetization (DRM) is the remanence of the sediments caused by the statistical alignment of magnetic grains as they fall through the water of deep lakes and oceans. The acquired DRM is preserved to some extent when the magnetic particles make contact with the sediment surface. Post-depositional remanent magnetization (PDRM) may then result from further alignment of the magnetic particles, after deposition but prior to consolidation of the sediment, due to rotation within the sediment interstices. In addition to the above processes, chemical remanent magnetization (CRM) is of importance in sediments. These three kinds of remanence magnetization occur either separately or in combination.

4.1.1 Depositional remanent magnetization.

McNish and Johnson (1938) noted a discordance in declinations as recorded by the summer and winter layers of a single varve. The coarser summer layers were found to be magnetized more nearly towards the present geomagnetic field direction and they attributed this to a realignment of magnetic grains within the pore interstices. Ising (1942) investigated magnetic polarization of recent sediments considered the magnetization to arise from a preferential alignment of magnetic minerals developed while settling through water. Nagata et al (1943) investigated the mechanism of acquisition of DRM in sedimentary rocks and inclined towards the depositional origin of the remanence. Johnson et al (1948) deposited samples of varved clays from a suspension and found that although the declination was consistent with the applied field, the inclination was $20^\circ$ too shallow. Nagata et al (1950) examined the mechanism of remanent magnetization in Pleistocene deposits and concluded
in the depositional origin of the acquisition.

Lloyd performed a redeposition experiment with powdered Triassic red sandstone (quoted in the paper by Clegg et al, 1954), produced an $8^\circ$ deviation from the inclination of the ambient magnetic field. This effect was estimated as high as $30^\circ$ and named inclination error by King (1955). In addition to this he defined another error, which he named bedding error, which can be $25^\circ$ steeper than the inclination of the geomagnetic field. The inclination and bedding errors are expressed by the equations $\delta = I_r - I_0$ (1) and $\theta = I_e - I_0$ (2), where $\delta$ is the inclination error, $I_r$ is the inclination of the geomagnetic field, $I_0$ the remanent inclination, $\theta$ is the bedding error, $I_e$ is the remanent inclination of deposited material onto a surface sloping at an angle $a$ to the horizontal. He also found that magnetic grains with diameters between 10 and 150um are affected significantly by turbulence as they fall. He observed that current velocities as low as 1cm.s$^{-1}$ could cause significant rotations and that velocities about 5 to 10 cm.s$^{-1}$ could cause declination errors up to $10^\circ$, while greater velocities could even produce a complete reversal of declination. The equation which describes the angular motion of a magnetic grain of moment of inertia $I$, magnetic moment $\sigma$, as it falls through calm and still water at a constant temperature in the presence of a magnetic field $H$ and aligned at an angle $\theta$ with $H$ is

$$I \cdot \ddot{\theta} + \lambda \cdot \dot{\theta} + \sigma \cdot H \cdot \sin \theta = 0 \quad (3.1)$$

where $I \cdot \ddot{\theta}$ is the inertia term, $\lambda \cdot \dot{\theta}$ the viscous damping torque and $\sigma \cdot H \cdot \sin \theta$ the magnetic torque.

Griffiths et al (1960) showed that natural inclination errors were only half as large as those occurring in laboratory redeposition experiments. Nagata (1962) showed that the time constant describing the
alignment of an assemblage of initially random particles of magnetic moment in suspension to which a magnetic field \( H \) is applied at \( t = 0 \) is \( \lambda / \sigma \cdot H \). He also showed that equilibria will be established over an angle of values \( \Theta \) due to the fact that natural magnetic grains will differ their mechanical, thermal, electric, hydrodynamic and magnetic properties, so as to limit the efficiency of the alignment process of a sediment suspension.

Rees (1961) found that for near-spherical particles below about 10\,\mu m other factors affect the anisotropy of susceptibility. As the particles settle through still water the induced magnetization of the grain orientates the axis of maximum susceptibility parallel to the ambient magnetic field. When these particles reach the sediment/water interface, they roll into the nearest depression. This produces an inclination error in the remanent magnetization. In the presence of flowing water, shear in the sub-laminar flow layer, rotates the grain with its maximum susceptibility axis towards the direction of the current. This phenomenon is naturally analogous to the current rotation effect on the remanence. Collinson (1963) found that the term \( I \cdot \ddot{\Theta} \) can be neglected due to the fact that the motion is highly damped, in which case the solution of (3.1) is

\[
\tan \frac{\Theta}{2} = \tan \frac{\Theta_0}{2} \cdot e^{-\frac{(\sigma \cdot H \cdot t)}{\lambda}} \tag{3.2}
\]

He found that the alignment is largely complete in \( t \leq 15 \) seconds for most natural grains so that in still calm and thermally stable water the grains will have optimum alignments long before settling. In nature the alignment of the magnetic moments will never be complete, because of the water currents, Brownian motion and gravitational torques.
Keen (1963) describes experiments on graded turbidities taken from deep-sea sediments, which showed that only sediments with a grain diameter between 0.1 and 50μm could produce reliable palaeomagnetic directions. Hamilton and King (1964) demonstrated that the bedding error is approximately equal to the slope of bedding plane.

Collinson (1965) found that magnetic grains with diameters between 0.1 and 5μm should only be affected by randomization of the Brownian motion. King and Rees (1966) showed that the lower limiting grain size which can produce a stable remanence is 0.1μm. They showed that the orientation of inhomogeneous or non-spherical magnetic grains will be additionally perturbed by a gravitational torque arising from the separation of their centres of mass and drag. This gravitational torque will be proportional to the product of the mass and diameter of the grain for a given degree of inhomogeneity and increases with grain size. The inhomogeneity effect appears to be primarily significant for grains having a diameter between 1 and 10μm.

Harrison (1966) extended Keen's work by showing that samples from 38 cores with a latitude range of almost 90° had inclinations which were consistent with a geocentric axial dipole. He also recognised that bioturbation could destroy any jdr. Nozharov (1966a, b, 1967, 1968a, b) analysed theoretically the mechanism of the acquisition of jdr in various conditions and showed the complexity of the phenomenon. Opdyke and Henry (1969) reported a comprehensive study of 52 cores from all oceans of the world. Approximately 100 samples representing the entire Brunhes normal epoch, were demagnetized and measured from each core. Their mean core inclinations were then compared to those predicted by a geocentric axial dipole. The excellent agreement led Opdyke and Henry to conclude that averaged over periods of a million
years, the earth's field was indeed that of a geocentric axial dipole. Since this conclusion assumes that sediments were accurately recording the earth's magnetic field, Opdyke and Henry were implicitly concluding that there was no inclination error. Dymond (1969) provided strong evidence for the importance of water content when he demonstrated that the Brunhes-Matuyama palaeomagnetic boundary was displaced 150 cm downward in a deep sea core with respect to the corresponding radiometric boundary. This distance was well below the limit of bioturbation and the additional depth was attributed to slow dewatering of the disturbed sediment. Nozharov et al (1970) presented a theoretical model with which he attempted to explain the origin of jdr. Denham and Cox (1971) who studied limnic deposits found no evidence of inclination error. Stacey (1972) showed that the strength of the ambient magnetic field affects this range of the grain sizes. He calculated that the magnetization $M$ of a sediment with a uniform distribution of magnetic moments up to a maximum $M_{\text{max}}$ is given by equation

$$M = \frac{M_0}{x} \ln \left( \frac{\sinh x}{x} \right)$$

(4.1)

where $M_0$ is the saturation magnetization and $x = M_{\text{max}} \frac{H}{\sigma KT}$.

For $x \gg 1$ the magnetization approaches saturation $M_0$ and for $x \leq 1$ reduces to

$$M = \frac{M_0 \cdot x}{\sigma} = \frac{M_0 \cdot M_{\text{max}} \cdot H}{\sigma KT}$$

(4.2)

Although Stacey was dealing specifically with jdr, his theory is applicable to jpr as well. Several other research workers, who attempted to see if there is inclination error like Creer et al (1972), Vitorello et al (1974), Levi and Banerjee (1975) did not find any evidence of it.
4.1.2. Post-depositional remanent magnetization.

Irving (1957) suggested that after deposition the sediments might contain water filled interstices within which magnetic grains would be free to rotate. This hypothesis would imply that when the water content drops below a critical value, characteristic of a particular sediment, the magnetic grains can no longer rotate and the magnetization becomes locked. Granar (1958) who worked with varves from Nyland Fjord in N-Sweden, suggested that in nature the bedding error rarely exceeds $5 \times 10^5$. This result could be explained if the magnetic grains were able to rotate towards the field direction after deposition. Rouse (1961) showed that the water zone close to the bottom of the lake which is a laminar sub-layer is not turbulent and its thickness depends on the slope of the bottom and the velocity, depth and viscosity of the overlying moving water. Irving and Major (1964), carried out experiments on synthetic sediments and showed that a $\text{jp}$ mechanism produced directions parallel to the induced magnetic field after less than 24 hours. King and Rees (1966) considered the reduction in inclination error to be due to a $\text{jp}$ caused by the upward flow of water through pore interstices during gradual compaction. Geddes (1966) found that in general $\text{jp}$ was inclined more steeply than the field as the result of a downward drainage through the sediments, because the used apparatus allowed the draining of the water from the bottom of it. Meade (1966) in the review of the factors influencing the compaction of certain clays and sands points out that particle size is the main determinant of water content although clay mineral composition and shape are also important. In the case of $\text{jp}$ arising from the bodily rotation of magnetic grains in water filled interstices, the microscopic properties of sediments, which are likely to be important are sediment particle size, shape and
mineralogy, as well as magnetic particle size and composition. In particular, the ratio of sediment size to magnetic carrier size will determine the free volume available to the grains and the ease with which the carriers can rotate. Khramov (1968) deposited red clays from suspension. For some samples he increased the intensity of the applied field after sedimentation had been completed. For sediment with a water content of 70% this procedure increased the magnetization while for water content of 30% there was no effect. He also found that there was a linear dependence between intensity and applied field up to 5 Oe and that the growth of JP has an exponential shape reaching saturation in less than two days. Wimbush and Munk (1970) showed that the laminar sub-layer close to the bottom of the lake is created by the damping effect of the lake floor. Kent (1973) who redeposited marine sediments and found that the produced JP is directly proportional to the magnetic field in the region between (0.20 and 1.20)Oe. Nezhinsky (1973) suggested that the JP mechanism can be attributed to burrowing benthic organisms, which cause a mixing and subsequent remagnetized of the sediment and to grain rotation in the interstitial pore spaces during post-depositional agitation of the sedimentary deposits. Davis (1974) working on limnic deposits found that some freshwater organisms are clearly capable of large-scale bioturbation of the sediments. Løvlie (1974) deposited marine clays from a suspension. Midway through the experiment the magnetic field was reversed and a calcium carbonate marker horizon was deposited. When the deposited sediment was sampled, the palaeomagnetic boundary was found to be displaced downward substantially with respect to the marker bed. The experiment represents the first reported observation of JP in a sediment suspension. Yaskawa (1974) has attempted to estimate the lock-in
depth of $jp$ based on a simple viscous fluid model in which the viscosity is affected by gravitational compaction. Niitsuma (1974) describes a slump bed in which a portion of the remanence appears to be $jdr$ while the remainder is $jp$. Although nothing is yet known about the microscopic properties of this material, it is possible that the range of carrier sizes is great enough, so that some were able to reorient within the sediment while others were locked in with their initial orientation after rolling. Thompson and Kelts (1974) reported that the basal portions of turbidite layers in Lake Zug, Switzerland, have lower magnetic intensities and lower inclinations for this is that the coarser basal portions preserve a $jdr$ while the finer material of the upper portions reflects a $jp$. This implication means rapid deposition of coarse material leads to a water content lower than the critical packing structure value. From all these studies the limnic sediment which locks the falling magnetic crystals is highly important to be studied, because its great heterogeneity which results from variations in climate, water depth and nutrient supply (Wetzel, 1975). Noël (1975) has offered an alternate explanation for the Swedish results based on a large-scale fluctuation in the geomagnetic field. He also showed by numerical approach that inclination could be reduced from $10^\circ$ to $5^\circ$ by an increase of the compaction of only $10\%$. Blow and Hamilton (1978) performed series of sophisticated experiments with grain-by-grain deposition from a dilute suspension which provided a depositional inclination error and with a slurry deposition, which provided no depositional inclination error. They estimated that the compactive inclination shallowing exhibited by these laboratory sediments may be associated with the rapidity of either sediment deposition or compaction or — perhaps both of them. In natural conditions this resulted sediment package might not
be produced, consequently the inclination error of such sediments will be significantly modified by compactive effects. Kodama and Cox (1977) gave a jar (D.C = 1 Oe, AF = 1,000 Oe) to mixture of artificial kaolinitic sediment containing 0.03% needle-shaped magnetic grains with mean grain size 0.5μm. The axis of maximum compression was shortened by 33%, which produced no significant change in the direction of magnetization with a decrease in intensity of 28%. The proposed discontinuous model explained the results and showed only the magnetic grains in the shear zones rotate and from symmetry considerations no net change in the direction of magnetization is predicted. The reason of the phenomenon is that the magnetic grains rotate in opposite directions in complementary sets of the model predicts consequently a decrease in intensity comparable to that which was observed. Hamano (1978) working with artificial sediments proposed that the decrease of the void ratio corresponds to the decrease of the blocking temperature is a sum of the remanence acquired during each step of the temperature decrease. Niitsuina (1978) proposed two models of acquisition of magnetization working with deep-sea sediments and attempting to explain the depth log fixation of j.p. The first, the plane magnetization model, 100% fixation of remanent magnetization occurs in a plane. In the second zone-magnetization model, magnetization is locked gradually to describe the experimental procedures and results, which were performed in order to have better understanding of the mechanism of acquisition of j.p.

4.2 Experimental methods.

In order to understand the mechanism of the acquisition of the magnetic remanence in limnic deposits, several pieces of apparatus were designed and constructed. Initially apparatus I shown in Fig. 4.1
Figure 4.1 Apparatus performing long column redeposition experiments under controlled conditions of temperature, rate of deposition and consolidation.
Plate 4.1  The long column under controlled redeposition apparatus within the Helmho$\phi_{1/2}$ coils system.
and on Plate 4.1 were used to determine the nature of \( j_d.r \) and \( j_p \) as well. The experiment allowed the acquisition of \( j_d.r \) and \( j_p \) under a constant temperature of 5\(^\circ\)C, which is at the bottom of lakes. It consists of a 1m long perspex cylinder with 6cm internal diameter and placed within and co-axially in another perspex cylinder 0.80m long with 15cm internal diameter. The shorter tube was glued to a perspex base 3cm thick. The longer tube was grooved on a circular groove fitting the diameter of it and it was held apart from the shorter tube by a circular locating ring near the top. The internal tube was filled up with tap water. The external tube formed a pair of a cooling circuit driven and maintained at constant temperature by a Grant type circulator. The sediment slurry was inserted into the top of the inner tube at a controlled rate by a peristaltic pump using a 2mm plastic tubing leading to a dispersion device consisting of a stainless steel tube with numerous tiny holes, producing a cloud of tiny droplets of falling slurry at the top of the deposition tube. The reservoir of sediment slurry was kept in suspension by an electric stirrer. The peristaltic pump was controlled by an electronic timer so as to pump in a precise amount of slurry for a short time of a few minutes every hour or so. The stirrer was automatically switched on to disperse the slurry in the reservoir about 10 min (time adjustable) before such a dose of slurry was injected. Helmholtz coils produced an 80cm\(^3\) volume of field up to ±20\(\gamma\). The current through each pair was supplied from a constant current power source. Fig. 4.2, 4.3 show redeposition apparatus II, which was used strictly for the study of the acquisition of \( j_p \). It consists of a plastic beaker of 1000ml volume with a tap located on its side, 1cm above its bottom. Inside a plastic perforated platform, covered with filter paper having
REDEPOSITION APPARATUS II

Lifting head

Screw

Filter paper
Plastic perforated plate

Sample holder

TOP VIEW

Figure 4.2  Apparatus performing slurry redepositions.
REDEPOSITION APPARATUS II

Figure 4.3  Apparatus performing slurry redepositions with synchronous six specimen sampling.
a diameter equal to the internal diameter of the beaker, sits on three plastic legs at a height of 5cm from the base. A 15cm brass rod of 2mm diameter is screwed into the middle of the platform to facilitate lifting the firm slurry containing the marked square-shaped sample holders of side 2.3cm. Orientation lines were marked along the bottom apart down the cylindrical sides of the beaker, which were aligned along marked on the table top. The Förster fluxgate magnetometer was used to measure the components of the geomagnetic field at the position of the beaker. Some experiments were carried out in the earth's magnetic field, others in a field applied either by a simple pair of Helmoltz coils, 30cm in diameter or by a set of three pairs of orthogonal aluminium Helmoltz coils producing a field uniform to within and over a volume approximately 20cm$^3$. Three identical single pairs of Helmoltz coils were built up and each was aligned along the direction of the total intensity of the earth's magnetic field with a JP apparatus at its centre. The three sets of coils were calibrated against one another. When the water was drained off, the settled wet sediment sample holders were pushed vertically along the marked settling tank into the sediment, which was then lifted gently as a whole. The filled plastic boxes were then removed, cleaned and immediately measured in the spinner magnetometer.

Fig. 4.3 shows the same apparatus with modified sampler consisting of a 6.5 x 7.5cm perspex frame with six windows in which six sample boxes were placed. A hollow plastic tube 10cm long is attached to the middle of the frame. This fits round the vertical brass rod attached to the platform on which the sediment was deposited and facilitates the smooth removal of the frame with its six boxes of sediment. Care was taken not to twist the sampling frame during withdrawal.
REDEPOSITION APPARATUS III

Figure 4.4  Single sample slurry redeposition apparatus.
Fig. 4.4 shows redeposition apparatus III, which essentially is a small scale version of apparatus II, consisting of a 100ml plastic beaker, which was designed for carrying out experiments in very small volumes of sediment taken from successive along the core. Only one standard sized plastic box of artificially deposited sediment could be withdrawn.

4.3 Jp and its relationship with external applied magnetic fields.

Sediments from various lakes studied by colleagues were deposited in a range of ambient field strengths under controlled conditions in order to find out whether they could record the applied magnetic field precisely. Wet sediments from lengths of core of the following limnic deposits were thoroughly dispersed: (1) Geneva; (2) Vuokon; (3) Morat; (4) Hjortson; (5) Bourget; (6) Kitteen; (7) Begoritis. 1000ml samples of the mixtures were redispersed for 30 minutes and poured into plastic beakers, which were oriented along the direction of the total intensity of the ambient magnetic field placed at the centre of the set of three orthogonal aluminium Helmoltz coils. The magnetic field, which was produced by the coils was \( F = 0.38 \text{ Oe}, I = 45^\circ, D = 0^\circ \). The slurries were left to settle in this field for two days after which 2cm of water was observed on the top. This was siphoned off with a pipette. Then the tap was opened and the water drained off.

When firm sampling was performed as described above, sediments from lakes 5 to 7 were then redeposited under identical conditions. The results are shown in Table I. The Jp intensity, declination, inclination and susceptibility were measured in the usual manner. The weight and the water content were not calculated in the first experiments performed. In Table I all the Jp magnetic parameters are presented together with its statistics. Divergence of the mean direction of Jp
<table>
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<tr>
<th>Lake</th>
<th>Total Time (days)</th>
<th>Jp (µg)</th>
<th>Jp/µg</th>
<th>Qp (µg/µe)</th>
<th>Jp/µg</th>
<th>Tp (°)</th>
<th>T (°)</th>
<th>AS5 (°)</th>
<th>X</th>
<th>R</th>
<th>N</th>
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<tbody>
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<td><strong>Geneva</strong></td>
<td>9</td>
<td>4.44 ± 0.08</td>
<td>9.17 ± 0.30</td>
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<td><strong>Vuokon</strong></td>
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**PDDM after storage**

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<th>Jp/µg</th>
<th>Qp0 (µg/µe)</th>
<th>Jp/µg</th>
<th>Tp0 (°)</th>
<th>T (°)</th>
<th>AS5 (°)</th>
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</tr>
<tr>
<td><strong>Kitteen</strong></td>
<td>17</td>
<td>2.93 ± 0.12</td>
<td>7.84 ± 0.35</td>
<td>0.38 ± 0.02</td>
<td>356.1</td>
<td>40.7</td>
<td>4.3</td>
<td>3.3</td>
<td>267</td>
<td>7.97378</td>
</tr>
<tr>
<td><strong>Begoritia (top)</strong></td>
<td>17</td>
<td>6.66 ± 0.25</td>
<td>15.57 ± 0.30</td>
<td>0.42 ± 0.02</td>
<td>6.8</td>
<td>38.8</td>
<td>5.2</td>
<td>4.2</td>
<td>174</td>
<td>7.95971</td>
</tr>
</tbody>
</table>
from the declination and inclination of the applied magnetic field can be attributed to experimental error as the A95 shows. In Table II the results of the measurements of \( j_p \) are shown after storage in zero-magnetic field from 14 to 19 days. Specimen were kept moist, wrapped in wet paper towels and enclosed in polythene bags.

4.3.1 Presentation and interpretation of the results.

Comparing the initial \( j_p \) intensities and direction with those after storage in zero-magnetic field, it is obvious that a randomization process is reflected. For example, the group of samples with sediments from Lake Geneva in which the \( j_p \) had been allowed to grow for nine days, had initial intensity 4.44μG. Reductions in the intensity after storage in zero-magnetic field by 6.8% shows that \( j_p \) contains an appreciable viscous component. This could be explained by the rotation of some of the smaller grains into more comfortable orientation in the interstices of the mud on removal of the magnetic aligning couples. The \( j_p \) intensity for samples of Lake Vuokon (Finland) with initial intensities of 10.20 and 14.50μG after being left in zero field 10 and 14 days respectively, decayed by 11.8% and 13.9%. No appreciable further decay was observed on storing period for 19 days. The experiment was repeated on two groups of samples taken from the redeposited slurry of Lake Morat. After 10 and 14 day periods of drying in zero-magnetic field, the two groups showed decays of 34.7 and 35.1% respectively, indicating a more marked randomization process than observed for the lake Vuokon sediments. Samples taken from redeposited slurries of Lakes Hjortson, Bourget, Kitteen and Begoritis sediments with the same drying and storing times decayed by 53.7%, 22.6%, 10.6%, 32.5%, 47.5% respectively. In most cases the A95 increased
### TABLE IX

**PDYX intensities**

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Jn (µo)</th>
<th>Jp (µo)</th>
<th>Qp (µo)</th>
<th>Qp (µoe)</th>
<th>Qp (Oe)</th>
<th>W (g)</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>(82-96)</td>
<td>19.54 ± 1.18</td>
<td>3.10 ± 0.14</td>
<td>2.91 ± 0.04</td>
<td>5.84 ± 0.38</td>
<td>6.83 ± 0.14</td>
<td>5.37 ± 0.14</td>
<td>0.54 ± 0.01</td>
</tr>
<tr>
<td>(218-232)</td>
<td>19.80 ± 1.16</td>
<td>1.69 ± 0.06</td>
<td>0.96 ± 0.07</td>
<td>4.94 ± 0.43</td>
<td>4.03 ± 0.05</td>
<td>4.01 ± 0.12</td>
<td>0.42 ± 0.02</td>
</tr>
<tr>
<td>(360-382)</td>
<td>27.09 ± 0.48</td>
<td>1.12 ± 0.05</td>
<td>0.82 ± 0.16</td>
<td>7.65 ± 0.21</td>
<td>5.67 ± 0.04</td>
<td>5.54 ± 0.01</td>
<td>0.21 ± 0.06</td>
</tr>
<tr>
<td>(518-530)</td>
<td>22.60 ± 0.37</td>
<td>6.99 ± 0.11</td>
<td>6.30 ± 0.11</td>
<td>7.74 ± 0.59</td>
<td>7.84 ± 0.10</td>
<td>2.91 ± 0.05</td>
<td>0.88 ± 0.02</td>
</tr>
</tbody>
</table>

### TABLE II

**PDYX directions**

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Dn (°)</th>
<th>Tp (°)</th>
<th>A95 (°)</th>
<th>K</th>
<th>R</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>(82-96)</td>
<td>6.1</td>
<td>67.2</td>
<td>3.8</td>
<td>5.4</td>
<td>152.8</td>
<td>5.95728</td>
</tr>
<tr>
<td>(218-232)</td>
<td>358.6</td>
<td>64.2</td>
<td>6.8</td>
<td>7.7</td>
<td>61.4</td>
<td>6.90238</td>
</tr>
<tr>
<td>(360-382)</td>
<td>358.8</td>
<td>68.3</td>
<td>2.7</td>
<td>11.2</td>
<td>29.7</td>
<td>6.79855</td>
</tr>
<tr>
<td>(518-530)</td>
<td>357.8</td>
<td>66.1</td>
<td>4.9</td>
<td>3.3</td>
<td>329.4</td>
<td>6.98167</td>
</tr>
</tbody>
</table>

\[ I_e = 71^\circ.0 \]

**PDYX directions after storage**

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Dp (°)</th>
<th>Tp (°)</th>
<th>A95 (°)</th>
<th>K</th>
<th>R</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>(82-96)</td>
<td>4.6</td>
<td>65.0</td>
<td>6.0</td>
<td>6.2</td>
<td>115.1</td>
<td>5.95659</td>
</tr>
<tr>
<td>(218-232)</td>
<td>358.1</td>
<td>63.1</td>
<td>7.9</td>
<td>10.4</td>
<td>34.0</td>
<td>6.82577</td>
</tr>
<tr>
<td>(360-382)</td>
<td>355.7</td>
<td>66.5</td>
<td>4.5</td>
<td>13.2</td>
<td>21.5</td>
<td>6.72201</td>
</tr>
<tr>
<td>(518-530)</td>
<td>358.4</td>
<td>69.4</td>
<td>1.6</td>
<td>3.7</td>
<td>259.2</td>
<td>6.97085</td>
</tr>
</tbody>
</table>

\[ I_e = 71^\circ.0 \]
Variations in Q-ratio are attributed to differences in concentration of magnetic mineral content and differences in the magnetic grains shapes and sizes and physical state. In Tables II and III the $j_p$ results from Lake Kitteen and Geneva are shown. The sediments of Lake Kitteen were chosen because they were highly organic (Stober, personal communication) in opposition with the sediments of Lake Geneva, which were highly inorganic (Hogg, personal communication), so as to have two different media for redeposition. 250g portions of sediment were collected from specific depths from core 5 of Lake Kitteen and core 3 of Lake Geneva and mixed thoroughly dispersed with 800ml of deionized water and then poured into 1000ml plastic marked beakers and left to settle in the Earth's magnetic field (constant to $\pm 2-3\%$) on a wooden table.

After two days, 2cm of water had been squeezed out to the surface of the slurry and was siphoned off with a pipette. The rest of the water was left to drain off through the tap of the apparatus at the bottom of the beaker. The slurries were allowed to dry for seven days before being sampled. The mean $j_n$ was calculated in each case from the measured values of the specimen corresponding to the consumed lengths of core taken for redeposition. The estimated water content for the top sediments was 70% and for the rest of the core 60%. It was found that $j_p$ were considerably lower than $j_n$ by 81.1%, 91.5%, 95.9% respectively and 68.8% for the sediments of Lake Kitteen, and 69.0%, 80.3%, 60.9%, 69.3% respectively for the sediments of Lake Geneva.

These results may be explained by, a) poor dispersion due to high organic content, especially for the sediments of Lake Kitteen, having caused the formation of clusters of grains resulting in high $A95$s, and
### TABLE III

**PDBM intensities**

Lake Geneva core 5

<table>
<thead>
<tr>
<th>Depth cm</th>
<th>( \frac{A}{100} )</th>
<th>( \frac{3}{100} )</th>
<th>( \frac{7}{100} )</th>
<th>( k )</th>
<th>( kp )</th>
<th>( Q )</th>
<th>( Qp )</th>
<th>( W )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(82-92)</td>
<td>26.07 ± 1.04 6.06 ± 0.11 8.02 ± 0.34 6.40 ± 0.22 5.85 ± 0.11 4.80 ± 0.70 1.33 ± 0.05 7.62 ± 0.06</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(220-270)</td>
<td>32.30 ± 0.21 6.36 ± 0.30 6.04 ± 0.30 5.51 ± 0.12 5.04 ± 0.17 5.62 ± 0.13 1.27 ± 0.06 7.58 ± 0.09</td>
<td>7</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(370-380)</td>
<td>24.60 ± 1.40 9.50 ± 0.18 9.48 ± 0.27 5.98 ± 0.30 5.20 ± 0.18 4.12 ± 0.14 1.75 ± 0.12 7.59 ± 0.06</td>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(505-515)</td>
<td>10.40 ± 0.66 3.19 ± 0.22 3.18 ± 0.25 5.15 ± 0.27 4.44 ± 0.17 2.02 ± 0.13 0.71 ± 0.09 7.37 ± 0.09</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**PDBM directions**

<table>
<thead>
<tr>
<th>Depth cm</th>
<th>( \overline{U} ) (°)</th>
<th>( \overline{V} ) (°)</th>
<th>( \overline{R} ) (°)</th>
<th>A95 (°)</th>
<th>K</th>
<th>R</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>(82-92)</td>
<td>5.2</td>
<td>63.9</td>
<td>7.1</td>
<td>7.8</td>
<td>60.0</td>
<td>6.90004</td>
<td>7</td>
</tr>
<tr>
<td>(220-270)</td>
<td>354.6</td>
<td>70.2</td>
<td>0.8</td>
<td>4.7</td>
<td>160.8</td>
<td>6.96257</td>
<td>7</td>
</tr>
<tr>
<td>(370-380)</td>
<td>356.3</td>
<td>65.2</td>
<td>5.8</td>
<td>10.3</td>
<td>167.6</td>
<td>3.98210</td>
<td>4</td>
</tr>
<tr>
<td>(505-515)</td>
<td>1.8</td>
<td>68.6</td>
<td>2.4</td>
<td>5.6</td>
<td>55.9</td>
<td>4.92656</td>
<td>5</td>
</tr>
</tbody>
</table>

**PDBM directions after storage**

<table>
<thead>
<tr>
<th>Depth cm</th>
<th>( \overline{U} ) (°)</th>
<th>( \overline{V} ) (°)</th>
<th>( \overline{R} ) (°)</th>
<th>A95 (°)</th>
<th>K</th>
<th>R</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>(82-92)</td>
<td>0.1</td>
<td>72.3</td>
<td>-1.3</td>
<td>11.9</td>
<td>26.5</td>
<td>6.77641</td>
<td>7</td>
</tr>
<tr>
<td>(220-270)</td>
<td>355.1</td>
<td>73.4</td>
<td>-2.4</td>
<td>5.4</td>
<td>124.7</td>
<td>6.95188</td>
<td>7</td>
</tr>
<tr>
<td>(370-380)</td>
<td>349.2</td>
<td>65.1</td>
<td>5.9</td>
<td>7.3</td>
<td>159.0</td>
<td>3.93114</td>
<td>4</td>
</tr>
<tr>
<td>(505-515)</td>
<td>4.4</td>
<td>65.3</td>
<td>5.7</td>
<td>12.0</td>
<td>41.2</td>
<td>4.90305</td>
<td>5</td>
</tr>
</tbody>
</table>

\( \theta = 71°.0 \)
low precision parameter $K$ (see Table II, III); b) the nine days allowed for the alignment of the magnetic grains of the sediments of the two lakes being sufficient for complete alignment; and c) the water content of the redeposited samples is 40-50% for the sediments of Lake Kitteen and 20-40% for the sediments of Lake Geneva of the total mass, whereas the water content of the naturally deposited samples were found to be 70% for the top of the core and 60% for the rest of the core of Lake Kitteen (Stober, personal communication) and 60% for all the core of Lake Geneva (Hogg, personal communication).

In Tables II, III the results after storage in zero magnetic field are shown. This further decay accompanied by more scattered directions (higher $A_{95}$, lower $K$) due to an increase in magnetic viscosity after redeposition. The $k_s$ of the artificially deposited samples appear with higher values than the $k_s$ of the natural samples due to higher water content, except for the case of sediments taken between 82-95cm of Kitteen in which the $k$ of artificially deposited samples is lower, due to experimental error in sampling. Tables IV, V list the results of two experiments, which were performed with sediments from Lake Begoritis, core B8 as it was described in 4.2. The scope of these experiments was to show the relationship of the obtained $J_p$ in the laboratory and the applied low (0 - 0.80 Oe) and high (0 - 4 Oe) magnetic field. For both experiments 1Kg portions of sediment was mixed with 8000ml of water in a big vessel, which was kept covered with a polythene sheet to keep constant the initial ratio of sediment upon water. At every step of the experiment the entire mixture was thoroughly dispersed for thirty minutes and 800ml of mixture was taken and poured into the settling tanks. The duration of each experiment was chosen to be seven days. Fig. 4.5 illustrates the relationship between the intensity of $J_p$ and the
Lake Begoritis
Homogenized redeposition experiments
Core B₈

Mean PDRM
Least-square test
Slope = 2.29 ± 0.09 μG.cm⁻³/0e
Intercept = 0.15 ± 0.04 μG.cm⁻³
r = 1.000
Prob/ty = 0.023%

Least-square test
Slope = 2.72 ± 0.07 μG.cm⁻³/0e
Intercept = 0.71 ± 0.08 μG.cm⁻³
r = 0.998
Prob/ty = 0.011%

Figure 4.5 Intensity of PDRM before and after AFC to remove VRMs is plotted against the intensity of the applied magnetic field.
<table>
<thead>
<tr>
<th>H (Oe)</th>
<th>( \theta_p )</th>
<th>( \theta_{pa} )</th>
<th>( \theta_{pb} )</th>
<th>( \theta_{pa} )</th>
<th>( \theta_{pb} )</th>
<th>( \theta_{po} )</th>
<th>W_a</th>
<th>W_b</th>
<th>W_c</th>
<th>Q_p</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20</td>
<td>4.77 ± 0.22 0.61 ± 0.03</td>
<td>3.90 ± 0.06 15.42 ± 0.15 1.93 ± 0.06 5.01 ± 0.14 3.84 ± 0.08 7.89 ± 0.08 3.84 ± 0.08 4.01 ± 0.08 0.31 ± 0.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.40</td>
<td>8.20 ± 0.24 1.07 ± 0.03 2.50 ± 0.01 2.18 ± 0.06 13.80 ± 0.02 1.80 ± 0.01 3.82 ± 0.02 3.56 ± 0.07 7.68 ± 0.03 3.61 ± 0.02 4.11 ± 0.03 0.65 ± 0.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.60</td>
<td>12.00 ± 0.36 1.52 ± 0.05 3.01 ± 0.50 2.78 ± 0.09 14.93 ± 0.27 1.86 ± 0.05 3.96 ± 0.07 3.66 ± 0.07 7.89 ± 0.05 3.77 ± 0.08 3.08 ± 0.03 0.76 ± 0.03</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.80</td>
<td>15.61 ± 0.41 1.99 ± 0.05 3.89 ± 0.11 3.87 ± 0.11 15.66 ± 0.14 1.99 ± 0.02 3.89 ± 0.04 3.89 ± 0.05 8.04 ± 0.05 4.02 ± 0.03 4.04 ± 0.04 1.00 ± 0.03</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Table IV**

FDRM intensity and the field
Lake Begoritis core BS

FDRM directions

<table>
<thead>
<tr>
<th>H (Oe)</th>
<th>( \theta_p ) (°)</th>
<th>( \theta_{pa} ) (°)</th>
<th>( \theta_{pb} ) (°)</th>
<th>K (°)</th>
<th>R (°)</th>
<th>N (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.20</td>
<td>355.3</td>
<td>75.1</td>
<td>71.1</td>
<td>4.0</td>
<td>5.4</td>
<td>80.4</td>
</tr>
<tr>
<td>0.40</td>
<td>356.9</td>
<td>73.2</td>
<td>70.4</td>
<td>2.8</td>
<td>3.2</td>
<td>188.9</td>
</tr>
<tr>
<td>0.60</td>
<td>358.2</td>
<td>74.7</td>
<td>69.8</td>
<td>4.9</td>
<td>3.5</td>
<td>160.9</td>
</tr>
<tr>
<td>0.80</td>
<td>359.1</td>
<td>74.6</td>
<td>72.0</td>
<td>2.6</td>
<td>3.1</td>
<td>205.4</td>
</tr>
</tbody>
</table>
TABLE V  
PDRM intensity and the field  

<table>
<thead>
<tr>
<th>H (Oe)</th>
<th>( j_p ) (( \mu G ))</th>
<th>( j_{pa} ) (( \mu G \cdot cm^3 \cdot g^{-1} \cdot 10^3 ))</th>
<th>kp (( \mu G/\text{Oe} ))</th>
<th>kpa (( \mu G \cdot cm^3 \cdot g^{-1} \cdot Oe^{-1} \cdot 10^3 ))</th>
<th>Wa (( g ))</th>
<th>Qp (Oe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.40</td>
<td>14.0 ± 0.56</td>
<td>1.92 ± 0.08</td>
<td>14.95 ± 0.10</td>
<td>2.05 ± 0.04</td>
<td>7.29 ± 0.12</td>
<td>0.94 ± 0.04</td>
</tr>
<tr>
<td>0.85</td>
<td>22.8 ± 0.72</td>
<td>2.89 ± 0.10</td>
<td>15.30 ± 0.12</td>
<td>1.94 ± 0.04</td>
<td>7.90 ± 0.14</td>
<td>1.49 ± 0.05</td>
</tr>
<tr>
<td>1.40</td>
<td>34.9 ± 0.84</td>
<td>4.41 ± 0.17</td>
<td>15.13 ± 0.14</td>
<td>1.91 ± 0.05</td>
<td>7.92 ± 0.22</td>
<td>2.31 ± 0.06</td>
</tr>
<tr>
<td>2.70</td>
<td>64.0 ± 1.32</td>
<td>8.14 ± 0.22</td>
<td>15.08 ± 0.11</td>
<td>1.82 ± 0.03</td>
<td>7.86 ± 0.14</td>
<td>4.24 ± 0.09</td>
</tr>
<tr>
<td>4.00</td>
<td>93.4 ± 2.06</td>
<td>11.93 ± 0.32</td>
<td>15.22 ± 0.16</td>
<td>1.94 ± 0.03</td>
<td>7.83 ± 0.11</td>
<td>6.14 ± 0.15</td>
</tr>
</tbody>
</table>

**PDRM directions**

<table>
<thead>
<tr>
<th>H (Oe)</th>
<th>( \bar{D}_p ) (°)</th>
<th>( \bar{I}_p ) (°)</th>
<th>( \bar{\delta} ) (°)</th>
<th>( A_{95} ) (°)</th>
<th>K</th>
<th>R</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.40</td>
<td>355.6</td>
<td>67.1</td>
<td>5.9</td>
<td>4.5</td>
<td>214.4</td>
<td>5.97668</td>
<td>6</td>
</tr>
<tr>
<td>0.89</td>
<td>359.9</td>
<td>66.8</td>
<td>6.2</td>
<td>4.6</td>
<td>206.6</td>
<td>5.97579</td>
<td>6</td>
</tr>
<tr>
<td>1.50</td>
<td>350.3</td>
<td>69.1</td>
<td>3.9</td>
<td>3.2</td>
<td>235.2</td>
<td>5.99352</td>
<td>6</td>
</tr>
<tr>
<td>2.70</td>
<td>359.9</td>
<td>64.2</td>
<td>8.8</td>
<td>3.8</td>
<td>222.5</td>
<td>5.98541</td>
<td>6</td>
</tr>
<tr>
<td>4.00</td>
<td>356.8</td>
<td>66.4</td>
<td>6.6</td>
<td>4.9</td>
<td>180.9</td>
<td>5.96609</td>
<td>6</td>
</tr>
</tbody>
</table>

\( I_a = 73^\circ.0 \)
intensity of the applied magnetic field. AFC in 100 Oe removed the jv, which was superimposed upon jp. A weighted least-square test was applied to both cases and showed statistically significant linearity between the two parameters. It seems that jv occurs mainly during the period of the sampling which lasts approximately 20-30 minutes due to carefulness and cleaning procedures before the samples are measured.

4.3.2 Inclination error in the Greek lakes.

Table VI lists the mean values of inclination of the single samples measurements of three groups of cores from lakes Volvi, Begoritis and Trikhonis.

<table>
<thead>
<tr>
<th>Core No.</th>
<th>T (°)</th>
<th>A95 (°)</th>
<th>K</th>
<th>R</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>V2</td>
<td>60.12</td>
<td>0.91</td>
<td>112.37</td>
<td>213.10</td>
<td>215</td>
</tr>
<tr>
<td>V5</td>
<td>56.87</td>
<td>0.78</td>
<td>148.10</td>
<td>222.49</td>
<td>224</td>
</tr>
<tr>
<td>V6</td>
<td>64.00</td>
<td>1.19</td>
<td>66.43</td>
<td>208.82</td>
<td>212</td>
</tr>
<tr>
<td>V7</td>
<td>61.74</td>
<td>1.32</td>
<td>50.75</td>
<td>223.53</td>
<td>228</td>
</tr>
<tr>
<td>V8</td>
<td>60.47</td>
<td>2.05</td>
<td>21.03</td>
<td>223.87</td>
<td>235</td>
</tr>
<tr>
<td>B7</td>
<td>49.95</td>
<td>0.94</td>
<td>114.81</td>
<td>196.27</td>
<td>198</td>
</tr>
<tr>
<td>B8</td>
<td>56.07</td>
<td>2.15</td>
<td>20.89</td>
<td>205.71</td>
<td>216</td>
</tr>
<tr>
<td>B9</td>
<td>41.83</td>
<td>0.87</td>
<td>112.77</td>
<td>233.92</td>
<td>236</td>
</tr>
<tr>
<td>T1</td>
<td>63.33</td>
<td>0.84</td>
<td>118.36</td>
<td>236.00</td>
<td>238</td>
</tr>
<tr>
<td>T2</td>
<td>68.16</td>
<td>0.69</td>
<td>175.69</td>
<td>236.65</td>
<td>238</td>
</tr>
<tr>
<td>T3</td>
<td>49.86</td>
<td>0.80</td>
<td>131.17</td>
<td>234.21</td>
<td>236</td>
</tr>
<tr>
<td>T5</td>
<td>45.62</td>
<td>0.82</td>
<td>134.30</td>
<td>218.37</td>
<td>220</td>
</tr>
</tbody>
</table>

The present day geomagnetic inclination and declination at the sites of the lakes Volvi, Begoritis and Trikhonis are 57°17', 1°30'; 56°90', 1°09'; 54°36', 0°57' respectively (Stavrou, personal communication). The deviations of the mean inclinations from the present value
of the inclination of the geomagnetic field, shown in Table VI do not reflect any inclination error but the effect of the tilting of the cover which sometimes is accompanied by bending of the PVC core tube distorting anomalously the inclination record. For example the mean inclination record of core B9 is shallower in general than the present value of the geomagnetic inclination at the site of the lake; in addition it exhibits anomalous low values between 230 and 300cm in which inclined horizons were observed in the stratigraphy of the core reflecting bending of the core tube (Chapter 6).

4.4 The stability of \( j_p \).

To test the stability of the obtained \( j_p \) under laboratory conditions pilot samples were progressively demagnetized in alternating fields. In Fig. 4.6 are shown the normalized demagnetization curves falling smoothly against the increasing AF, with MDFs about 200 Oe. The \( j_p \) directions changed minimally on demagnetization, as Figs. 4.7 and 4.8 illustrate.

4.5 The growth of \( j_p \).

Mixtures from core B7 of lake Begoritis approximately 1Kg were mixed with 8000ml of dionized water in a big vessel. The mixtures were dispersed thoroughly with a stirrer for about two hours. Then 600ml of the liquid dispersed mixture was poured into 1,000ml plastic beakers, marked and placed along the magnetic meridian, on a 2 x 1.5\( \text{m}^2 \) wooden table on which the total magnetic field was different from one edge to the other less than 5%. The beakers were sealed up with thin polythene covers as the slurries were left to settle for logarithmically
Figure 4.6 Normalized demagnetization curves, of redeposited specimen, sampled from slurries.
Figure 4.7 Normalized demagnetization curves of redeposited representative specimen for each redeposition experiment performed between 0.20 and 0.80 Oe, with their direction stereographically projected during APC.
Figure 4.8 Normalized demagnetization curves of redeposited representative specimens for each redeposition experiment performed between 0.40 and 4.00 Oe with remanent directions from each horizon oriented during AF demagnetization.
The growth of PDRM
Lake Begoritis

Least-square test
Slope = 0.002 ± 0.103 \mu G.cm^{-3}.g^{-1}/Days
Intercept = 1.511 ± 0.104 \mu G.cm^{3}.g^{-1}

Slope = -0.001 ± 0.103 \mu G.cm^{3}.g^{-1}/Days
Intercept = 1.248 ± 0.104 \mu G.cm^{3}.g^{-1}

AFC 100 Oe

Figure 4.9 The growth of PDRM, before and after AFC to remove superimposed VRMs is plotted against the time.
time intervals between two and 24 days. After two days 2cm of water had been squeezed out to the surface of the slurry. When the beakers were unsealed at logarithmic time intervals the water was siphoned from the top with a pipette and all the slurries were left for four days to dry. Table VII lists the \( j_p \) intensity results which are illustrated in Fig. 4.9. When AFC in 100 Oe was applied, the superimposed \( j_v \) on \( j_p \) found in other experiments was removed. Experimental points for time <2 days could not be achieved due to rotation of the magnetic grains when very moist samples were placed to be measured in the spinner. Khramov (1968) has shown that saturation \( j_p \) can be obtained in less than two days probably the same exponential like curve could be the case for the \( j_p \) growth of the limnic deposits. AFC showed smoothly falling demagnetization curves and MDFs about 200 Oe.

4.6 \( j_p \) under controlled conditions.

The effect of temperature and rate of deposition on \( j_p \) was investigated. Apparatus I (see section 4.1.1) was placed in a uniform magnetic field (\( F = 0.73 \) Oe, \( I = -73^\circ \), \( D = 0^\circ \)). The experiment was divided into three stages, the depositional stage which consisted of 10 days at 2cm/day, 10 days at 1cm/day and 10 days at 0.5cm/day. The self compaction stage which lasted 30 days and the compaction stage in which excess water was siphoned off. The top of the sediment was then covered with 5 x 10ml of CaCO\(_3\), followed by the addition of 100ml of dried sand at five day intervals, up to a total of 500ml over 25 days. The CaCO\(_3\) horizons were used as markers indicating the time of the addition at each case. At the end of the deposition a 32.8cm of slurry had been deposited. The volume was reduced by 40% after self compaction and a further 15% compaction occurred under the load of sand. Subsampling was performed by pushing the core with a piston and getting
### Table VII

#### The growth of PDRM
Lake Bocorita Core B8

<table>
<thead>
<tr>
<th>Total time (t) (days)</th>
<th>log(t) (s)</th>
<th>( \frac{dP}{d(t)} ) (( \mu g ))</th>
<th>( \frac{dP}{d(t)} ) (( \mu g \cdot cm^{-2} \cdot s^{-1} \cdot 10 ))</th>
<th>( k_{p} ) (( \mu g/\text{day} ))</th>
<th>( k_{p} ) (( \mu g \cdot cm^{-2} \cdot s^{-1} \cdot 0.01 \cdot 10 ))</th>
<th>Wa (g)</th>
<th>Qp (( \text{cm}^{2} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.3</td>
<td>13.21 ± 1.00</td>
<td>1.51 ± 0.11</td>
<td>15.41 ± 0.41</td>
<td>1.76 ± 0.05</td>
<td>6.71 ± 0.11</td>
<td>0.66 ± 0.07</td>
</tr>
<tr>
<td>4</td>
<td>0.6</td>
<td>13.30 ± 0.81</td>
<td>1.55 ± 0.10</td>
<td>15.38 ± 0.38</td>
<td>1.77 ± 0.05</td>
<td>6.68 ± 0.16</td>
<td>0.66 ± 0.06</td>
</tr>
<tr>
<td>6</td>
<td>0.8</td>
<td>13.17 ± 0.44</td>
<td>1.54 ± 0.06</td>
<td>16.00 ± 0.13</td>
<td>1.67 ± 0.05</td>
<td>8.56 ± 0.22</td>
<td>0.82 ± 0.03</td>
</tr>
<tr>
<td>10</td>
<td>1.0</td>
<td>13.24 ± 0.51</td>
<td>1.50 ± 0.06</td>
<td>15.28 ± 0.04</td>
<td>1.74 ± 0.03</td>
<td>6.60 ± 0.17</td>
<td>0.87 ± 0.03</td>
</tr>
<tr>
<td>14</td>
<td>1.2</td>
<td>13.36 ± 0.41</td>
<td>1.54 ± 0.05</td>
<td>15.41 ± 0.23</td>
<td>1.78 ± 0.03</td>
<td>8.66 ± 0.09</td>
<td>0.87 ± 0.03</td>
</tr>
<tr>
<td>20</td>
<td>1.3</td>
<td>13.25 ± 0.68</td>
<td>1.54 ± 0.09</td>
<td>15.68 ± 0.18</td>
<td>1.62 ± 0.05</td>
<td>8.59 ± 0.23</td>
<td>0.84 ± 0.04</td>
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</table>

#### FDRM directions

<table>
<thead>
<tr>
<th>Total time (t) (days)</th>
<th>log(t) (s)</th>
<th>( \bar{P}_{p} ) (( \text{cm}^{2} ))</th>
<th>( \bar{I}_{p} ) (( \text{cm}^{2} ))</th>
<th>( \bar{P}_{p} ) (( \text{cm}^{2} ))</th>
<th>( \bar{I}_{p} ) (( \text{cm}^{2} ))</th>
<th>( A_{95} ) (( \text{cm}^{2} ))</th>
<th>K</th>
<th>R</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.3</td>
<td>2.9</td>
<td>71.2</td>
<td>73.6</td>
<td>-2.4</td>
<td>7.6</td>
<td>72.4</td>
<td>5.93624</td>
<td>6</td>
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<tr>
<td>4</td>
<td>0.6</td>
<td>359.3</td>
<td>73.1</td>
<td>73.1</td>
<td>0.0</td>
<td>4.9</td>
<td>235.8</td>
<td>4.98304</td>
<td>5</td>
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<tr>
<td>6</td>
<td>0.8</td>
<td>0.9</td>
<td>71.5</td>
<td>60.3</td>
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<td>4.7</td>
<td>200.1</td>
<td>5.97501</td>
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<td>1.0</td>
<td>0.7</td>
<td>71.3</td>
<td>60.1</td>
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<td>5.9</td>
<td>126.9</td>
<td>5.96059</td>
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<tr>
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<td>1.2</td>
<td>2.7</td>
<td>73.8</td>
<td>67.5</td>
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<td>3.9</td>
<td>224.9</td>
<td>5.98245</td>
<td>6</td>
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<tr>
<td>20</td>
<td>1.3</td>
<td>0.5</td>
<td>75.0</td>
<td>69.8</td>
<td>5.2</td>
<td>7.0</td>
<td>91.7</td>
<td>5.94552</td>
<td>6</td>
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</table>
TABLE VIII

PDRM under controlled conditions.

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>(j_p) ((\mu)G)</th>
<th>(j_{pa}) ((\mu)G.cm(^3).g(^{-1}))</th>
<th>(W) (g)</th>
<th>(D) ((^\circ))</th>
<th>(I) ((^\circ))</th>
<th>(\delta) ((^\circ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.3</td>
<td>22.82</td>
<td>30.90</td>
<td>7.39</td>
<td>6.5</td>
<td>-44.8</td>
<td>28.2</td>
</tr>
<tr>
<td>4.6</td>
<td>18.74</td>
<td>24.70</td>
<td>7.58</td>
<td>2.6</td>
<td>-49.8</td>
<td>23.2</td>
</tr>
<tr>
<td>6.9</td>
<td>19.59</td>
<td>23.90</td>
<td>8.24</td>
<td>3.2</td>
<td>-65.6</td>
<td>7.4</td>
</tr>
<tr>
<td>11.5</td>
<td>28.43</td>
<td>33.80</td>
<td>8.43</td>
<td>0.1</td>
<td>-69.6</td>
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</tr>
<tr>
<td>13.8</td>
<td>34.23</td>
<td>42.10</td>
<td>8.12</td>
<td>0.9</td>
<td>-70.9</td>
<td>2.1</td>
</tr>
<tr>
<td>16.1</td>
<td>28.55</td>
<td>33.90</td>
<td>8.51</td>
<td>9.0</td>
<td>-50.8</td>
<td>22.2</td>
</tr>
</tbody>
</table>

\(\bar{D}\) (\(^\circ\)) \(\bar{I}\) (\(^\circ\)) \(\bar{\delta}\) (\(^\circ\)) \(A_{95}\) (K) R N

| 4.4        | -58.6          | 12.4            | 9.6  | 49.4   | 5.89897 | 5      |

Observed differences in \(j_{pa}\) are due to inhomogeneities in the sediment column, produced by the CaCO\(_3\) marker which partly passed through it.
Figure 4.10 Normalized demagnetization curves of specimen sampled along the redeposited column.
Figure 4.11 Normalized demagnetization curves of individual specimens sampled along the redeposited column and their directions of PDRM during AFC is shown in stereographic projections.
samples from the bottom by pushing the plastic boxes within the sedi-
ment.

Fig. 4.10 illustrates the normalized demagnetization having MDFs
about 200 Oe, and Fig. 4.11 shows the groupings of the obtained direc-
tions. Table VIII lists the obtained results along the core.

4.7 Discussion and conclusions.

All redeposition experiments performed in the laboratory under the
described conditions in this chapter showed that limnic sediments can
record the direction of external applied magnetic fields almost pre-
cisely. When the sediments contain organic material in high quantities
an unstable jp was produced, due to the fact that magnetic grains were
mixed with organic material in aggregates which did not allow them free-
dom to align themselves in the water medium along the direction of the
magnetic field. Storage in zero-magnetic fields and AFC removed super-
imposed jvs upon the jp created in the laboratory which is explained by
rotation of the finest grains within the water interstices and the coar-
ser grains and showed that the remanence obtained was of stable charac-
ter with smoothly falling demagnetization curves, well grouped directions
and MDFs about 200 Oe. The intensity of jp is directly proportional to
the intensity of the external applied magnetic field and its growth
remains constant with time.

It was found not possible to measure redeposited samples with jp
produced in less than 48 hrs with the spinner magnetometer because the
sediments were not sufficiently solidified and the magnetic grains could
rotate easily in random directions within the water interstices. The
growth of the remanence is most probably of exponential character and it
can be studied successfully either by an astatic magnetometer (Collinson,
personal communication), or by a cryogenic magnetometer (Barton, 1973).

The latter case is an excellent opportunity for studying in detail and accurately, the growth of the remanence in small time periods from minutes and hours up to days, with different conditions of density of sediment, percentages of magnetic content and degree of compaction, possibly under controlled temperature. In the experiments presented in this chapter no difference was found between jps produced in 5°C or 23°C, however this can be established only if one could measure the growth of the remanence during the actual experimental procedure.

The highly time consuming experiments under controlled conditions illustrated unstable remanence when the water content was too high, 80-90% and stable remanence when the water content was 50-60% with smoothly falling demagnetization curves, well grouped directions and MDFs about 200 Oe, as AFC showed.

The observed inclination error was δ = 15-20° in some experiments and it is attributed to unnaturally fast deposition and consolidation which produced high rapid compaction effects. Although the redepositions with slurries did not produce significant inclination error, by no means reflect that the mechanism of acquisition of the remanence is strictly of post-depositional character, because they allow the water draining off the bottom of the beaker, while in nature goes most probably upwards due to gravitational compaction. The long column experiment is a better simulation to what happens in nature, but still one must avoid fast deposition and take into account possible action of jcr, if oxidation of magnetic content occurs after deposition (Chapter 2).
CHAPTER 5

LIMNOMAGNETIC PALAEOINTENSITIES

5.1 Introduction.
5.2 The k, jär and jrs normalization methods for relative palaeointensities.
5.3 PDRM as normalization parameter.
5.4 Discussion and conclusions.
5.1 Introduction.

Attempting to determine the palaeointensity of the Earth's magnetic field from the remanent magnetization is one of the most difficult tasks in palaeomagnetism, because of chemical changes which have taken place within the rock either since it was formed or during laboratory experiments carried out to determine the palaeointensity. The most reliable method described by Thellier and Thellier (1942) is for rocks with thermoremanent magnetization.

Although no successful method has been developed to determine the absolute palaeointensity from the remanent magnetization of unbaked sedimentary rocks, many attempts have been made to determine relative changes in palaeointensity with time from magnetic measurements on sedimentary sequences. Some limnic deposits may be well suited for this purpose, if they were deposited continuously under relatively stable conditions over long periods of time, in the range of several millennia, because it could be possible for the record to be compared with the established archaeomagnetic intensity data. It is necessary (but not sufficient) to compensate for variations in the content of magnetic minerals in the sediments. Susceptibility, awhysteretic remanence and saturation isothermal remanence have been used by different workers to normalize the intensity of the natural remanence, for instance in deep-sea sediments Johnson et al (1948) first used jrs, Keen (1963), and Harrison and Somayajulu (1966) used k; Opdyke et al (1973) compared the variation of k, jar and jrs with the variation of jn in a long deep sea core. However, the advantages, if any, of using one of these parameters instead of another for the purpose of jn normalization are still not clear. K and jrs receive disproportionate contributions from different regions of the magnetic grain size distribution. K is most
influenced by very fine, superparamagnetic grains and coarse multi-domain grains (Nagata, 1961, p.28). It also includes a paramagnetic or diamagnetic contribution from the matrix. On the other hand, jrs receives the greatest contribution from stable SD or PSD grains. For example, the jrs may be as much as half the saturation magnetization for non-interacting SD grains (with uniaxial anisotropy), but perhaps several orders of magnitude lower for coarse, MD magnetic grains, and zero for superparamagnetic grains (Dunlop, 1973). The jn of the Greek limnic deposits appears to be carried mainly by SD or PSD fine magnetite particles and partly by coarse magnetite grains, which contribute in smaller proportion (Chapter 2), consequently k, jar and jrs all have been used as normalization parameters. It is more difficult to choose between jar and jrs as the more affective normalizing parameters, because both the remanences will be most affected by SD or PSD magnetic grains, the same magnetic grain size range as is believed to be carrying jn in many other cases.

Nakajima and Kawai (1974) used jn/jrs as a normalizing parameter and they obtained a palaeointensity record from a core from Lake Biwa in Japan and correlated it with the palaeoclimatic record deduced from pollen analysis studies. H. P. Johnson (1975) preferred to use jar rather than jrs or k as a normalizing parameter, arguing that the latter two parameters probably over-emphasize the role of multi-domain particles. Hence he normalized partially demagnetized jn by undemagnetized jar in order to obtain intensity trends in his cores. Levi and Banerjee (1976) used demagnetized jar as a normalization parameter in order to obtain palaeointensities from 6m sedimentary cores from Lake St. Croix, Minnesota and were able to correlate these with the archaeomagnetic record which exhibited periods of 300-400 years. Liddicoat
(1976) used jar to normalize $jn$ obtained from direct limnic exposures from Lake Mowo, U.S.A.

5.2 The $k$, $jar$, and $jrs$ normalization methods for relative palaeo-intensities.

To interpret fluctuations of the normalized remanence intensity (usually partially demagnetized $jn$) as fluctuations of geomagnetic intensity, it is assumed that the measured remanence of sedimentary deposits is linearly related to the external field fixing the remanence and to the magnetic content of the sediment. It is assumed that fluctuations of variables, such as density of sediment, pressure, temperature of water, together with its content during the acquisition of the remanence are either very small or else they have a negligible effect on the remanence intensity. To establish possible fluctuations of the density of the sediment or of the water content along core V8, samples were weighed wet and dry and the water content was calculated. All these three parameters were plotted against the depth, together with $jn$ normalized per gram of wet and dried mass, all shown in Fig. 5.1. $jn$ per gram of dried mass magnifies the fluctuation of the remanence along the core. Below the horizon at 4m an interesting depression is recognized, which corresponds to an increase in both the dried and wet mass. The water content does not alter along the 6m core except for some small variation in the last two meters.

In Chapter 3 it was shown that the pilot samples from core B9 show stable directions with smooth demagnetization curves up to 400 Oe. Fig. 5.2 illustrates the normalized demagnetization curves of $jn$, $jar$ and $jrs$ for pilot samples taken along core B9, showing that the magnetic carriers are probably of single domain or pseudo single domain
Figure 5.1 NRM intensity normalized per wet and dried mass of core V8 of Lake Volvi is plotted side by side with the dried, wet mass and the water content along the core.
Figure 5.2 Normalized NRM, ARM, IRM and PDRM curves of pilot specimen taken along core B9 of Lake Begoritis.
because the ARM demagnetization curve lies above the IRM one (Lowrie and Fuller, 1971) which is in agreement with the observed mean size of the magnetic crystals (Chapter 2). One could choose any field between 100 and 400 Oe, which would have yielded substantially the same directions.

It seems reasonable that a similar AF demagnetization level should be used to evaluate the relative palaeointensities. In Fig. 5.3 the normalized \( j_n \) are plotted against the normalized \( j_{ar} \) for the same AF. It is illustrated clearly that linearity almost exists between the \( j_n \) and \( j_{ar} \) except in the low and high AF. To be consistent with the palaeomagnetic direction data, the relative palaeointensities at \( AF = 200 \) Oe should be plotted, however substantially the same results would be obtained by choosing AF anywhere in the range between 100 and 400 Oe. The existing non-linearity in low AF can be explained as the effect of a soft \( j_n \). The non-linearity in high AF is due to the fact of the \( j_{ar} \) imparted with a peak alternating field of only 1,000 Oe. In both cases this can be seen from the intersection of the normalized \( j_n \) and \( j_{ar} \).

Another way to examine if there is any linearity between \( j_n \) and either \( j_{ar} \) or \( j_{rs} \) is to plot their ratios against the AF and see if there is a flat portion of the plotted curve. Fig. 5.4 illustrates the \( j_n/j_{rs} \) ratio plotted against the AF. It is shown that no flatness occurs indicating that the rapid increase of the ratio reflects the high sensitivity of the \( j_{rs} \) to be used as a normalizing parameter. Similar results have been obtained from core VB and core T1. To illustrate all these attempts \( k, j_{ar}, j_{rs} \) and their ratios with \( j_n \) are plotted against depth side by side and presented in Fig. 5.5, 5.6 for cores B9 and VB respectively. In Fig. 5.5 \( k \) exhibits three peaks at 180, 250 and 345 cm from which it decreases progressively down the core.
Figure 5.3 Normalized NRM intensity plotted against normalized ARM of pilot samples sampled along core B9.
Figure 5.4 The NRM/IRM ratio is plotted against the AF of pilot specimen sampled against Bg.
The normalizing parameters $k$, ARM, IRM and their ratios upon NRM are plotted side by side against the depth of core VS of Lake Volvi.

Figure 5.6
Figure 5.5 The normalizing parameters k, ARM, IRM and their ratios upon NRM are plotted side by side against the depth of core B9 of Lake Begoritis.
Jar exhibits similarly three peaks at 290, 345 and 430cm, from which it decreases progressively down the core. Jrs exhibits two peaks at 180, 345 and below 440cm starts to decrease with depth. The three ratios \( jn/k \), \( jn/jar \) and \( jn/jrs \) exhibit a slow progressive increase up to 510cm, \( jn/k \) shows similarities with \( jn \). In Fig. 5.6 \( k \) exhibits a slow decrease up to 150cm remaining practically unchanged and a peak at 500cm. The other two ratios show the same pattern with some clear dissimilarities with the \( jn/k \) ratio.

5.3 \textbf{PDRM as a normalization parameter.}

In Chapter 4 it was shown that PDRM obtained in the laboratory is stable and directly proportional to the applied magnetic fields. Detailed single sample redeposition experiments were performed along core B9, V8 and T1 (Chapter 4). The object of these experiments was to establish whether the ratio \( jn/jp \) could produce palaeointensity geomagnetic variations. 60g of wet sediment was sampled every 20cm along the core and was mixed with 80ml of dionized water. From each redeposition 100ml pot a single sample was recovered and measured in the magnetometer. The value corresponded to the mean value of two 2.3cm cube-shaped specimens, which were sampled from the sedimentary horizon from which the sediment had been collected for redeposition. Pilot samples from all the cores were subjected to stepwise AF treatment. The normalized demagnetization curves produced are smooth, indicating that \( jp \) are softer than \( jn \), with well grouped directions.

Fig. 5.7 illustrates that \( jn \) and \( jp \) are linearly proportional to one another through a series of AF demagnetization steps, so that can be used as a normalizing parameter. Fig. 5.8 and 5.9 illustrate \( jn \), \( jp \), \( jn/jp \) and \( ks \) of the naturally and artificially deposited
Figure 5.7 Normalized NRM is plotted against normalized PDRM of redeposited pilot samples taken along core B9 of Lake Begoritis.
Figure 5.8  NRM, PDRM, NRM/PDRM and the k's of the naturally and redeposited samples are plotted side by side against the depth of core V8.
Figure 5.10  NRM, NRM/k, NRM/SARM, NRM/SIRM and NRM/PDRM are plotted side by side against the depth of core B9 of Lake Begoritis.
Figure 5.11  NRM, NRM/k, NRM/SARM, NRM/SIRM and NRM/PDRM are plotted side by side against the depth of core V8 of Lake Volvi.
sediments plotted side by side for cores V8, B9 and T1. The ks show certain similarities and some dissimilarities which are explained by differences in the water content between the natural and artificial samples, ranging up to 10% but also in experimental error which might allow either loss or gain of sediment by sampling not exactly from the depth horizon corresponding in the naturally deposited sample.

All the produced jn/jp ratios are dissimilar to their corresponding jn curves. They are also dissimilar between representative cores from different lakes, for instance cores B9 and T1 of Lakes Begoritis and Trikhois respectively. Fig. 5.10 and 5.11 illustrate all the possible ratios which could be obtained as normalizing parameters. They are plotted against depth side by side with jn of cores V8 and B9 respectively covering 3,000 to 7,000 yr B.P. Fig. 5.12 illustrates the European archaeomagnetic intensity curve plotted in parallel with jn/k, jn/jar, jn/jrs and jn/jp ratios produced from core B9.

5.4 Discussion and conclusions.

The detailed experimental work which was performed with the limnic fresh water deposits from Greece showed that while k, jar, jrs are useful parameters for correlating magnetostratigraphically a number of cores within a site of a given lake or from site to site in a whole lake, which is a very rapid inexpensive way for limnological and hydrogeological research, none of them is to correct for the different quantities of magnetic content contributing in the natural remanence, which is essential requirement for palaeointensity determination. The reason for which the normalization parameters are different along the core is because they reflect and emphasize variation in magnetic content, its physical state, its shape and size and the degree of oxidation, with three different ways, along the length of the sedimentary cores.
Figure 5.12 Normalized archaeomagnetic intensity curve plotted side by side with normalized \( \text{J}\text{n}/\text{Jp} \), \( \text{J}\text{n}/\text{Jrs} \), \( \text{J}\text{n}/\text{J}_{\text{ar}} \times 10^{-1} \), and \( \text{J}\text{n}/K(\text{Oe}) \). (\( F\text{o} \) is the present day field intensity, whereas \( F\text{t} \) is of the past).
The attempt with the new parameter $jp$ appears not to have been successful because the palaeointensity curves produced were not compatible with the European archaeomagnetic intensity record. The reason for the disagreement between normalized $jn$ by $jp$ and the archaeomagnetic intensity curve, is either the possible inadequacy of the single sample redeposition slurries technique or that a chemical component acts in parallel or in combination with $jp$ in the form of $jcr$, in natural conditions which cannot be simulated in the laboratory.

For future research it is very important that the origin and the nature of haematite to be established, because the outcome of this investigation would give light to many problems like the true nature of the magnetic remanence and the acquisition mechanism of it, and probably would help in refining the $jp$ normalization technique described in this chapter. Detailed magnetic extractions along sedimentologically homogeneous cores could help to establish the magnetic content itself as a new normalization parameter.

Another way to approach the problem of normalization is to establish the relationship between the magnetic content and $jp$. This can be done with redeposition experiments under controlled conditions, by using initially a non-magnetic matrix clay, consisting of known size and shape natural magnetic grains in which different quantities of known extracted magnetic content can be mixed. The experiments should be performed in the same applied magnetic field and the strength of the obtained $jp$ should be plotted against the used quantities of the magnetic content. If the relationship is linear, then the slope of the curve could be used as another normalization parameter which hopefully could normalize $jn$. 
CHAPTER 6

LIMNOMAGNETIC PALAEODIRECTIONS

6.1 Dating controls.
6.2 Archaeomagnetic and limnomagnetic correlations.
6.3 Correlation of the Greek and British limnomagnetic master curves.
6.4 Discussion and conclusions.
6.1 Dating controls.

Table I lists a suite of radio carbon dates, supplied by Harkness (Scottish Nuclear Research and Reactor Centre, personal communication) and provisional pollen estimations by Bottema, University of Gröningen (personal communication). The radio carbon dates are in general too old to give the real time controls of the fluctuations of the geomagnetic field recorded in the sediments. This is supported by the pollen analysis of the bottom sediments of the three representative cores V8, B7 and T2, which presuppose a rate of deposition 2-3, 1-1.17 and 1-1.11 mm/yr respectively. The correction of radio carbon dates into tree ring calendar years was based on Mc Kerrell's conversion tables (Mc Kerrell, 1975).

Radio carbon dates assigned in cores V2, V8, B9, T1, T2, T5, in Chapter 3 (Fig 3.8, 3.9, 3.10, 3.14, 3.16), Chapter 5 (5.1, 5.5, 5.6, 5.8, 5.9, 5.10, 5.11), Chapter 6 (Fig 6.1, 6.2, 6.6, 6.7, 6.8, 6.9, 6.10), by stratigraphic and palaeomagnetic correlations with cores V9, B7, and T3, in which radio carbon dates were obtained directly, see (Table I).

6.2 Archaeomagnetic and limnomagnetic correlations.

The NRM horizontal and single sample measurements illustrate a remarkable correlation in the three Greek lakes (Chapter 3), however, it is important to find out if the palaeodirections show correlation.

Fig. 6.1 shows the NRM inclination, declination, intensity and Q-ratio before and after cleaning in 200 Oe AF. Certain changes in the pattern of direction of the variations of the geomagnetic field occur; for instance, the mean NRM inclination was about 70°, whereas after cleaning it is about 60° for the top 250cm, which is closer to the present day value of the axial geomagnetic dipole at the site, the profound step at 290cm in the NRM, disappears in the cleaned inclination record. Similarly, the NRM intensity and Q-ratio are reduced by about 50%. These changes are explained by the removal of jv soft components during AFC. Similar results have been obtained after AFC in 200 Oe, with measured samples from the other two lakes. In additi
### TABLE I

**Radio Carbon Dates**

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Lake</th>
<th>Core No.</th>
<th>Depth (cm)</th>
<th>Uncorrected (age)</th>
<th>δ¹³C</th>
<th>Corrected (age)</th>
<th>⁸⁷⁷⁷oo</th>
<th>yr. B.P.</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRR-885</td>
<td>Volvi</td>
<td>5</td>
<td>44-80</td>
<td>844±50</td>
<td>-25.6</td>
<td>830</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRR-886</td>
<td>Volvi</td>
<td>5</td>
<td>304-337</td>
<td>1,743±55</td>
<td>-29.4</td>
<td>1,730</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRR-887</td>
<td>Begoritis</td>
<td>7</td>
<td>35-71</td>
<td>2,344±60</td>
<td>-25.4</td>
<td>2,400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRR-888</td>
<td>Begoritis</td>
<td>7</td>
<td>161-187</td>
<td>3,648±60</td>
<td>-22.2</td>
<td>4,050</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRR-889</td>
<td>Begoritis</td>
<td>7</td>
<td>291-319</td>
<td>5,410±70</td>
<td>-34.2</td>
<td>6,200</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRR-884</td>
<td>Trikhonis</td>
<td>3</td>
<td>67-101</td>
<td>2,284±85</td>
<td>-26.8</td>
<td>2,400</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRR-884</td>
<td>Trikhonis</td>
<td>3</td>
<td>249-282</td>
<td>5,089±75</td>
<td>-30.0</td>
<td>5,830</td>
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<td></td>
</tr>
<tr>
<td>SRR-699</td>
<td>Trikhonis</td>
<td>3</td>
<td>526-559</td>
<td>5,769±90</td>
<td>-26.8</td>
<td>6,600</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Provisional Pollen Estimations**

<table>
<thead>
<tr>
<th>Lake</th>
<th>Core No.</th>
<th>Depth (cm)</th>
<th>Estimated (age)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volvi</td>
<td>5</td>
<td>bottom</td>
<td>2-3,000</td>
</tr>
<tr>
<td>Begoritis</td>
<td>7</td>
<td>bottom</td>
<td>6-7,000</td>
</tr>
<tr>
<td>Trikhonis</td>
<td>3</td>
<td>bottom</td>
<td>5-6,600</td>
</tr>
</tbody>
</table>

### TABLE II

**Lake Volvi - Core V2**

<table>
<thead>
<tr>
<th>Depth (cm)</th>
<th>Magnetic ages (yr. B.P.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>150</td>
</tr>
<tr>
<td>200</td>
<td>250</td>
</tr>
<tr>
<td>260</td>
<td>400</td>
</tr>
<tr>
<td>310</td>
<td>800</td>
</tr>
<tr>
<td>370</td>
<td>1,200</td>
</tr>
<tr>
<td>390</td>
<td>1,300</td>
</tr>
</tbody>
</table>
Figure 6.1 NRM declination, inclination, intensity and Q-ratio are plotted side by side with their cleaned record after AFC, against the depth of core V8 of Lake Volvi.
to the reduction of NRM intensity by about 50% after AFC, reduction has been observed during storage in zero-magnetic field up 20-30% due to partial drying of the samples.

Since the azimuthal orientation of the cores is not known the mean declination for the whole core set to zero and the variations plotted relative to this arbitrary zero.

Fig. 6.1 illustrates the fluctuations of the Earth's field down core V8, which is a representative example of the rest of the cores, which correlate very well, both palaeomagnetically and stratigraphically, by inspecting the same bands and the same changes in the colour down the core. The inclination at the top of core V8 of the cleaned record is in the range between 56-60° in close agreement with both the axial dipole field value (~59°6') and the present day value of the geomagnetic inclination in Greece (Chapter 4).

The upper part of Lake Volvi is compared with the archaeomagnetic record, because below 400cm the mean jn makes this part of the record less reliable for correlation with other records. The correlation is clear in all cores from Volvi.

Fig. 6.2 illustrates the limnomagnetic cleaned declination and inclination record of Lake Volvi (core V2), showing some similarities with the archaeomagnetic record. The declination exhibits a broad and pronounced westerly swing (labelled A) with 20° amplitude, followed by the easterly swing (labelled B) with 15° amplitude. Below B two small swings follow (labelled C, D) with amplitude less than 10°. Below D there follows another broad easterly swing (labelled E) in which archaeomagnetic ages 150, 400, 600, 900 and 1,300 yr B.P. are assigned.

The inclination record illustrates four distinct peaks (labelled
Figure 6.2 Limnematical declination and inclination curves of core Y2 after AFC in 200 Oe plotted against the depth of the core and the European (N.W.) archaeomagnetic declination and inclination records.
a, b, c and d) which may be compared with features of the archaeomagnetic record. Hence ages 250, 700, 800 and 1,200 yr. B.P. are assigned from the archaeomagnetic curve, to the record of core V2. Table II lists all the deduced 'magnetic ages' and the depth to which they correspond. The limnomagnetic pattern of the direction of the geomagnetic field appears to be less sharp in comparison with the archaeomagnetic one. This is explained by the fact that every 2.3 cm cube-shaped specimen probably needs \( 3 \) to \( 10 \) years to be deposited, whereas the archaeomagnetic record is formed from a series of spot values each of which was obtained during the short time taken for a pot to cool having been taken out from the kiln.

6.3 Correlation of the Greek and British limnomagnetic master curves.

In Chapter 3 it was shown that the obtained pattern of the NRM horizontal intensity of long core measurements of cores collected in all three Greek lakes, in several sites of them are correlative. Similar correlations were observed in the measured magnetic susceptibilities of the same cores. However the long core declination data, obtained from the measurements of the cores collected from Lake Begoritis clearly reveal rotation of the Mackereth core tube during penetration in the bed of the lake. Fig. 6.3 and 6.4 illustrate the declination and inclination patterns of cores B7, B8 and B9 produced from the measurements of the single samples respectively, in which lines illustrate the correlation points especially between cores B7 and B8 at any fine detail. Similarly, the corresponding \( j_n \), \( k \) and \( Q \)-ratio demonstrate satisfactory correlations (Chapter 3), (Papamarinopoulos, 1977c).

The pattern produced from core B9 appears with shallower inclination in general, both from the axial geomagnetic dipole field (59°6')
Lake Begoritis - Greece
NRM Declinations

Figure 6.3  NRM declination patterns of single sample measurements plotted against the depth of cores B7, B8 and B9. Correlation lines were constructed on the base of the inclination record.
Figure 6.4: NRM inclination patterns of single sample measurements plotted against the depth of cores B7, B8, and B9.
Figure 6.5 NRM, inclination, declination, intensity and Q-ratio are plotted side by side with their cleaned record after AFC against the depth of core B9 of Lake Begoritis.
and the present day value of geomagnetic inclination at the site of the lake (Chapter 4), however it preserves the same characteristics as the two other cores. In Fig. 6.5 the NRM and RM after AFC in 200 Oe, declination and inclination are shown. The records after cleaning appear slightly scattered especially the top 200cm. The NRM intensity and hence the Q-ratio are reduced by about 50%, indicating the removal of soft magnetic components. The inclination is characterized with variations over 10° which is to be expected as normal, exhibiting two broad maxima at 250 and 360cm respectively. Fig. 6.6 and 6.7 illustrate a representative example of correlative single sample measurements of specimens taken along the collected group of cores from Lake Trikhonis. They exhibit NRM inclination and declination, together with the measurements of them after storage in zero-magnetic field for six months and the RM results after AFC in 200 Oe of single specimen sampled along core T2, are plotted against the depth side by side. The mean inclination appears to be steeper than the axial geomagnetic dipole (57°7') and the present day value of the geomagnetic inclination (Chapter 4) due to tilting of the Mackereth cover. The directions appear slightly scattered, in general, both after storing and AFC. I shows a tendency to become shallower after cleaning.

Fig. 6.8 illustrates the correlation made between the inclination records of Lake Begoritis (core B9) and Lake Trikhonis (core T3). Swings b, c and d correspond to those identified with the archaeomagnetic record, but swing a is not observed in the records from cores B9 and T3, possibly due to loss of the topmost sediment during coring. Corrected radio carbon dates and pollen estimations are assigned along the records. Both the records appear with shallower inclinations (see Chapter 4).
Lake Trikphonis - Greece
Core T2
Declinations

Figure 6.6  NRM declination variation plotted together with its record after six months storage in zero magnetic field and after AFC side by side against the depth of core T2.
Lake Trikonis - Greece
Core T2
Inclinations

Figure 6.7  NRM inclination variation plotted together with its record after six months storage in zero magnetic field and after AFC side by side against the depth of core T2.
The observed lower inclinations at f, g and h are lower in B9 than in T3, most probably due to the bending of the core tube at 230cm.

Fig. 6.8 illustrates how the rate of deposition may either exaggerate or reduce the particularly fine details of the fossilized signature of the geomagnetic field variations. The mean inclinations appear to be shallower than both the axial geomagnetic dipole field at the sites (59°06', 57°07') at Begoritis and Trikhonis respectively and the present day value of the geomagnetic field at the sites of the lakes (Chapter 4).

In Fig. 6.10 the established pattern of the swings with a period of up to 2,800 years from Lake Windermere (England) in parallel with the declination pattern from Lake Trikhonis (Greece) core T5 can be seen. Swings (labelled A to E) are clear in both records. Swing A is bigger in Windermere, C is bigger in Trikhonis, whereas B, D and E are about the same. The peaks of the swings appear relatively in the same chronological order. At the left-hand side of Fig. 6.9, corrected radiocarbon ages are assigned according to published data for Windermere (Mackereth, 1971; Creer et al, 1972; Thompson, 1973). The magnetic age of 150 yr. B.P. has been assigned for swing A from the correlation of the declination pattern with the British archaeomagnetic record. In Fig. 6.9 the inclination pattern of the same cores is shown. At the left-hand side of the Figure, the magnetic and radiocarbon ages are assigned, as in the declination record. The inclinations of both the records correlate reasonably well between the depths of swings c and e, they do not correlate between b and c, whereas above b the Windermere record does not show any detail. In both cases similar swings are indicated by correlation lines.
Inclination

Figure 6.8  Inclination correlations between core B9 and core T3 of Lakes Begoritis and Trikhonis respectively.
Figure 6.9 Inclination correlation between Lake Trikhonis (Greece) and Lake Windermere (England).
Figure 6.10  Declination correlation between Lake Trikhonis (Greece) and Lake Windermere (England).
6.4 Discussion and conclusions.

The limnic fresh water deposits in Greece have preserved the fossilized record of the geomagnetic declination and inclination variations during the last 2-3,000 years (14C and pollen) in Lake Volvi, and the last 6-7,000 years (14C and pollen) in Lakes Begoritis and Trikhonis. The geomagnetic declination and inclination recorded in the limnic deposits in Volvi exhibit features which correlate with both the archaeomagnetic pattern of the NW European record (Readman and Papamarinopoulos, 1976; Papamarinopoulos, 1978a) and with individual limnomagnetic curves from central Europe (Creer et al., 1978) with approximately the same amplitude. The inclination pattern appears to be oscillatory but aperiodic, whereas the declination pattern exhibits cyclic shifts of 20°-30° amplitude. The limnomagnetic declination recorded in Begoritis are not correlative with the corresponding one of Lake Trikhonis due to distortion of the picture of the first due to rotation of the core tube, whereas the inclinations recorded in the sediments of both the lakes are correlative. In addition to this the limnomagnetic declination pattern obtained from Lake Trikhonis illustrates cyclic shifts with period approximately 2,700 years and it is correlative with the declination recorded in Windermere (England), whereas the inclination record appears to be oscillatory and aperiodic but reasonably correlative with Windermere's corresponding inclination record and the various central European records.

The pollen estimations are consistent with these correlations, whereas the 14C dates are generally about \( \frac{7,000}{2,700} \) years too old. The source which left its magnetic signature at Trikhonis could be either the main geomagnetic dipole or the non-dipole. The first explanation would require sinusoidal inclination variations in the Greek and British.
record, which is clearly not the case.

The second explanation is more plausible as the compelling mechanism, for the recorded geomagnetic secular variation at Trikhonis in the form of two A-H dipoles (Alldredge and Hurwitz (1964), Creer (1977), Hogg (1978)) which are closer to the European terrain. Fresh data from Windermere illustrate better and clearer correlation both with the Trikhonis inclination record and other inclination records from British lakes (Turner, personal communication; Turner and Thompson, 1978), and with the British and European archaeomagnetic record.
CHAPTER 7

SPELEOMAGNETISM

7.1 Introduction.
7.2 Petralona Cave.
7.3 Palaeomagnetic sampling.
7.4 Palaeomagnetic results.
7.5 The nature of remanence.
7.6 Discussion and conclusions.
7.7 Arago Cave.
7.8 Palaeomagnetic results.
7.9 Discussion and conclusions.
7.10 Ball's cavern.
7.11 AF demagnetization.
7.12 Presentation of palaeomagnetic data.
7.13 Discussion and conclusions.
7.1 Introduction.

This seventh part of the thesis describes the investigation of the author in series of cave sediments, with the hope to get the record of the fossilized geomagnetic field, the origin of the mechanism of the acquisition of the observed remanence, its characteristics and the nature of the magnetic carriers.

Cave sediments contain, in general cases, archaeological artifacts and palaeontological remains, which can give chronostratigraphical controls together with results from established dating techniques either in the geological material or in the bone pieces. Reversely, when the magneto stratigraphy is established, it can be used for dating the speleothems or other animal remains. The recovery of the record of the palaeointensity and palaeodirection of the geomagnetic field has relied over the last decades on historical records, ancient kilns, hearths and pottery, for example (Thellier and Thellier, 1959; Burlatskaya, Nechaeva and Petrova, 1965; Aitken and Weaver, 1965; Bucha, 1967; Kitazawa and Kobayashi, 1968; Bucha et al, 1970; Aitken, 1970; Hirooka, 1971; Aitken, 1974; Kobacheva and Veliovich, 1977).

It is clear that a serial record cannot be obtained from such a data, because civilizations had always interruptions intervals and were not suitably distributed around the globe at any one epoch. An answer to the problem was the limnic and cave deposits. The advance of the researchers using limnic sediments as recorders of the geomagnetic field have been described already in Chapter 3.

Pioneer research work started by Kopper and Creer (1973), Creer and Kopper (1974), Creer and Kopper (1976), who used a variety of Mediterranean cave deposits for palaeomagnetic work. Cave deposits are characterized by Kukla and Lozek (1957) in two categories:
a) entrance, and b) interior facies. Entrance facies deposits often contain dateable artifacts or palaeoanthropological and palaeontological remains and they record climatic cycles (Sweeting, 1973). They record cave-wide cycles of erosion, clastic deposition, stalagmitic formation, calcite-resolution and erosion, together with the magnetic signature of the field (Creer and Kopper, 1976). They provide sedimentation rates, including hiatus and removal episodes with values from 0.25 to 1.0 mm/yr over the past 50,000 years in the Mediterranean region (Kopper, 1972). Interior facies sediments, on the other hand, are beyond the reach of surface weathering and accumulate or disperse only under hydrological controls (Reams, 1972). They are characterized by low sedimentation rates, uniform temperatures, high humidities (85-100%) and a sparse and unique biota (Kopper, 1975). The biomass in one deep cave zone having been estimated at 20-30g.ha⁻¹ (Kopper, 1975). Clays predominate and sometimes occur in bands with silts and sands suggesting that sedimentation was controlled by annual or possibly longer period precipitation cycles (Kopper, 1975). Creer and Kopper (1976) have shown that Mediterranean cave sediments have recorded geomagnetic cyclic shifts. For example the palaeomagnetic record for a 2.4m section of interior facies sediments from the Upper Dry Cave, Jeita, Lebanon, reveals inclination oscillations, which can be correlated with those recorded 1,000Km away in core 1474 from the Black Sea. The 'magnetic' ages so obtained for the Jeita section are consistent with the age (0-16,000 yr B.P.) deduced from anthropological and palaeoclimatic evidence. At Tito Bastillo, Ribadesella, Asturias, Spain, a 0.54m section was dated palaeomagnetically by Creer and Kopper (1974). The magnetic ages of 11,200-11,660 yr B.P. were obtained by correlation with the limnomagnetic record of Lake Windermere, England. In
this way the polychrome famous paintings of this Upper palaeolithic cave were dated independently of stylistic comparison or the radiometric 14C method. At Arbreda Cave, Spain, a 3.4m section from entrance facies sediments with 35,000-50,000 yr B.P. deduced from anthropological and palaeoclimatic controls, gave an abnormally low inclination, which may correlate with a geomagnetic excursion reported in an Indian Ocean core at about 40,000 yr B.P.

At Hermit's Cave, Catalonia, Spain, a 1.1m section belonging to the middle palaeolithic, the palaeomagnetic record exhibits large amplitude swings. In this part of the thesis the palaeomagnetic record of Petralona Cave, Greece, Arago Cave, France and Ball's Cave, U.S.A. is presented and discussed in connection with the nature of the remanence and the nature of the magnetic carriers locked in the sediments of these caves.

7.2 Petralona Cave.

Fig. 7.1 illustrates the caves with archaeological interest which were the object of investigation and exploration by Kopper and the author. Extensive work has been done in Frachthi Cave in Pelogenese, but the results are not satisfactory due to the disturbed sediments found in the cave, however another extensive work performed in Petralona cave, located near Petralona village (40°01'N, 25°03'E) in Chalkidiki peninsula in Northern Greece. The reason of the palaeomagnetic investigation was to date, if possible, the 450cm exposed section within the cave by Poulianos (Poulianos, 1971) containing interesting remains of palaeoanthropological and palaeontological origin. In addition to this, by establishing the magnetostratigraphy, hopefully the recovery of the Brunhes/Matuyama geomagnetic reversal, occurred 700,000 yr
Figure 7.1 Map of Greece with the main caves with palaeoanthropological and archaeological interest.
B.P. could be obtained. According to Poulianos (personal communication; 1978), the bottom layer of the section correlates stratigraphically to the layer in which the cranium was found. If this hypothesis was correct the palaeomagnetic age would help dating this layer, but not necessarily the cranium, shown in Plate 7.1, which was discovered by a local farmer C. Sarianidis in 1960 (Poulianos, 1971) a year after the discovery of the cave in 1959 by another farmer. Poulianos (1971) reported the existence of other anthropological remains relative to the cranium. Fig. 7.2 illustrates the 2Km V-shaped cave situated underneath the Katsika mountain (642m).

The valley in which Katsika mountain lies is 290m above sea-level, and coincides with the first floor of the cave. The V-shaped cave consists of two elongated corridors which communicate into small or large chambers of 8-10m height, occasionally with 50m deep precipices. The floor of the cave is composed of flat, rough travertine layers. The walls of the cave are covered with layers of red and white stalagmite. The natural entrance is 170m N-NE of the artificial entrance, as Fig. 7.2 shows. Petrohelos (1960) first explored the cave speleologically and constructed the first profile in 1964, Kokkoros and Kanellis (1960) identified that the human skull was Homo Neanderthalensis, Kanellis and Savvas (1964) agreed, by measuring craniometric indexes. Sickenberg (1964) studied the palaeontological remains and identified them as belonging to the Pleistocene era. Marinos et al (1964) completed Sickenberg's investigation by finding more palaeontological remains. They also found human remains like teeth, together with primitive tools. Poulianos estimated that the section exposed in 1968 belonged in the mid-Upper Pleistocene (Courten and Poulianos, 1978). His detailed study of the craniometric indexes led him to interpret the cranium as
Plate 7.1 The fossilized cranium found in Petralona Cave.
Figure 7.2  The profile of Petralona cave.

Source: Greek Speleological Society
(After I. Petrohelos)
Completion: University of Thessaloniki
(After G. Marinos et al)
Excavated: Greek Anthropological Society (After A. Poulianos)
a Homo Erectus which Kokkoros and Kanellis (1960) concluded to be Neanderthal, consequently any direct or indirect time controls were necessary to approach and hopefully solve the existing controversy.

7.3 **Palaeomagnetic sampling.**

In Fig. 7.3 a schematic representation of the excavated site is shown. The natural former sinkhole entrance, which was a death trap for the animals, was gradually filled up with water transported sediments. The excavated section shown in Fig. 7.4 illustrates the stratigraphy of sediments reflecting the climate and human and animal activities. Breccia in the top layers from triangular small and big stones and occasional very thin travertine layers, did not allow us to get oriented 2.3cm cylindrical samples, which were collected from the moist soft red and brown layers using the orientational device shown in Fig. 7.5, which measures the azimuth and the dip of the cylindrical axis. Samples were pushed out into the plastic containers with a piston. The sample depths recorded in Fig. 7.4 were measured by means of a tape placed at the top of the stalagmitic column. Duplicate samples were collected at same horizons.

7.4 **Palaeomagnetic results.**

The 120 samples were measured with the spinner magnetometer, they were then stored in zero-magnetic field for 6 months. In the meantime samples 371, 322, 272, 561, 81 and 731 were subjected to AF. In Fig. 7.6 the normalized jn demagnetization curves are plotted and their directions are shown stereographically. The normalized demagnetization curves fall smoothly as the AF increased. The directions show good groupings up to 300 Oe. A peak field of 100 Oe was chosen for the AF of the
Figure 7.3  Schematic cross-section of the excavated section and the site of the fossil.
The excavated section and the logs of NRM intensity, magnetic susceptibility and Q-ratio plotted side by side.
Speleomagnetic orientational sampler

Figure 7.5 Orientational sampler for collecting samples along moist core sediments.
Figure 7.6 Normalized NRM demagnetization curves and stereographic projections of their directions of individual pilot samples, taken along the Petralona section.
bulk of the samples. The deposits of Petralona cave possess a stable remanence. Poulianos' thesis was based on the observation of many palaeontological finds belonging to the Pleistocene epoch and in recent dating of the top stalagmite column, which gave two dates of 260,000 and 300,000 yr B.P. (Ikeya, 1977; Schwarcz, 1977), respectively. The latter are not considered reliable in the first case, because the method of the electron paramagnetic resonance used requires the rate of growth of stalagmite to be known and that it remains constant during its formation. It also presupposes known background radiation. In the second case, the uranium content was found very low (Liritzis, personal communication). The new U/Th dates which were obtained, the first from the top stalagmite, gave an age of 65,000 yr B.P. and the second, from a travertine layer located at 185 cm, gave 90,000 yr B.P. (Schwarcz et al., 1978) shown in Fig. 7.4. In Fig. 7.7 the NRM inclination together with those after storage in zero-magnetic field and after AFC are plotted against the depth of the section. In Fig. 7.8 similarly the declination log is shown. Both logs appear to be scattered and they do not show any significant improvement after AFC. The presented palaeomagnetic data show that no evidence of the Brunhes-Matuyama geomagnetic reversal is present. Taking into account the estimated rate of deposition to be 50,000 yr/m, (Kopper, personal communication) together with the U/Th dates, it is conceivable that the deposits span an age approximately 200,000 years. Another major point of Poulianos' thesis is the existence of ashes within the studied section (Poulianos, 1971, 1977). One would expect that jn and k would be clear indicators of the ash remains mixed with sediments. As Fig. 7.4 shows the first peak at approximately 80 cm coincides with the layer containing ashes (Poulianos, 1971) whereas the second peak at 330 cm is
Figure 7.7  NRM inclination logs plotted together with their values after storage in zero-magnetic field and after AFC in 100 Oe.
PETRALONA CAVE - GREECE

Declinations

NRM  Stored in O-MagField  Cleaned in A.F.C (100 Oe)

-60°  60°-60°  60°-60°  60°-60°  60°

0  1  1  1  1

1  2  2  2  2

3  3  3  3  3

4  4  4  4  4

Depth (m)

U/Th

-90000 yrsBP

Figure 7.8. NRM declinations plotted side by side with their values after storage in zero-magnetic field and after AFC in 100 Oe.
is 10-15 cm higher than the layer with the ashes. Liritzis (personal communication) attempted to characterize burnt and unburnt soil from these layers by using thermoluminescence but the glow curves produced by the soil overmasked the glow curves of the feldspar and quartz at 350 and 365°C.

7.5 The nature of the remanence.

To test if $j_p$ could be accounted for the mechanism of acquisition a redeposition experiment was performed and six samples were sampled in the way described in Chapter 4. The geomagnetic field measured on the spot of the experiment was ($F = 0.38$ Oe, $I = 75^\circ$, $D = 0^\circ$). It lasted seven days. At the end of the second day, 2 cm of water was siphoned from the top, then the tap of the settling tank was opened to allow a slow drainage of the water during the next five days. On the last day of the experiment the volume of the slurry had been reduced by 50%. Table I illustrates the obtained results of the mean values of the measured parameters.

<table>
<thead>
<tr>
<th>$\bar{j}_p$</th>
<th>$\bar{j}_{pa}$</th>
<th>$\bar{k}$</th>
<th>$\bar{k}_{pa}$</th>
<th>$\bar{Q}$</th>
<th>$\bar{W}_a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(μG)</td>
<td>(μG.cm$^{-3}$.g$^{-1}$x10)</td>
<td>(μG/0e)</td>
<td>(μG.cm$^{-3}$.g$^{-1}$E$^{-1}$x10)</td>
<td>(Oe)</td>
<td>(g)</td>
</tr>
<tr>
<td>9.80±0.30</td>
<td>1.06±0.03</td>
<td>3.60±0.30</td>
<td>3.91±0.07</td>
<td>0.27±0.01</td>
<td>9.21±0.09</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$\bar{D}$</th>
<th>$\bar{I}$</th>
<th>$\bar{\delta}$</th>
<th>A95</th>
<th>K</th>
<th>R</th>
<th>N</th>
</tr>
</thead>
<tbody>
<tr>
<td>(°)</td>
<td>(°)</td>
<td>(°)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td>73.2</td>
<td>1.8</td>
<td>6.9</td>
<td>93.4</td>
<td>5.94648</td>
<td>6</td>
</tr>
</tbody>
</table>

Fig. 7.9 illustrates AFC of a representative redeposited sample, which shows smooth demagnetization curve with MDF = 120 Oe and satisfactory grouped directions.
Figure 7.9  Normalized PDRM demagnetization curve and the direction of it during AFC in stereographic projection.
7.6 Discussion and conclusions.

The deposits of Petralona cave possess a stable remanence as the AFC showed and they are probably of PDRM origin as the redeposition experiment demonstrated. They contain fine grained haematite and magnetite with $H_{cr} \approx 450$ Oe, as the reversed jrs studies showed. The scattered inclinations due to possibly disturbed sediments showed no negative values after AFC which means that the earth's magnetic field had normal polarity up to 410cm depth. Taking into account the U/Th offered dates and the estimated rate of deposition 50,000 yr/m, the total time span of the 450cm section is estimated to be $\sim 200,000$ years. The existence of a large variety of palaeontological remains within the layers of the section clearly of the Pleistocene period does not necessarily rule out the possibility that the age of these remains cannot be less than 100,000-200,000 years because it is generally assumed that the animals of the Pleistocene had a progressive extinction up to 50,000 years. The dating techniques on bones like the epimerization of amino acids, 14C of the new advanced type and thermoluminescence, could help to characterize all these remains. The lithotechnic speleothems clearly demonstrate activity of the occupants of the cave, however, they are vague indicators of the age in which they were used. The susceptibility peaks are indicative towards the ashes hypothesis, however only optical and electron scanning microscopy for fused material sampled exactly from the horizons with the supposed ashes mixed with soil could be the direct proof (Mckerrell, personal communication).
7.7 Arago cave.

Arago cave is located (42°82'N, 2°85'E) near the town of Tautavel in France, 19Km north-west of Perpignan, Pyrenees Orientales, France. It is one of the most important Palaeolithic, archaeological and anthropological sites in Europe, containing the partial remains of at least three early Homo Sapiens (Preneanderthal) who lived in the cave 300,000 yr B.P. Evidence of lengthy human occupation in the form of stone tools (Archaic Tayacien) and the bones of hunted animals occur as layers in the entrance facies deposit of the cave. These layers are well dated by lower Palaeolithic standards providing cultural-stratigraphic and bio-stratigraphic controls for the sediment samples through the upper 240cm of the excavation. In Fig. 7.10 the cave plan and the stratigraphy of the excavated section are shown. It contains, in addition to the other controls, chronostratigraphic controls, provided by uranium disequilibrium series dating of the upper travertine at 95,000 yr B.P. 10,000 yr (Turekian and Nelson, 1976) and epimerization of amino-acids dating technique of bone in the Sol F layer at 220,000 yr B.P. and Sol G at 320,000 yr B.P. (Bada and Masters Helfman, 1976).

The cave lies more than 100m above the Verdouble River in the flank of a bare, heavily Karsted ridge. The cave cannot be dated morphologically, but the fill of travertines, wind deposited sand and silty sand have been assigned to the Riss I and Riss III glacial stades of the penultimate glacial period of the Alpine sequence (Miskovsky, 1976). Several palaeosols have been identified and other alterations of the soft sediments have occurred due to prolonged exposure to weathering in the layer open cave mouth. One of these weathering effects under dry hot conditions was the formation of several zones containing high concentrations of Fe.
CAUNE DE L'ARAGO
TAUTAVEL, PROVENCE

CAVE PLAN

STRATIGRAPHY

- Breccia 95,000 Th/U
- Zone of alteration, high Fe,Mn
- Paleosol F 220,000 B.P. A.A.
- Paleosol G

Figure 7.10 Stratigraphy of the sampled section and the plan of Arago Cave in which palaeoanthropological fossils were found.
L'ARAGO CAVE - FRANCE

NRM

Declination  Inclination  Intensity  Susceptibility  Q-Ratio
μG           μG/Oe         Oe

Figure 7.11 NRM declination, inclination, intensity, susceptibility
and Q-ratio logs plotted side by side against the depth
of the sampled section.
Figure 7.12a NRM normalized demagnetization curves and stereographic projections of their direction of individual pilot samples collected along the excavated section.
Figure 7.12b NRM normalized demagnetization curves and stereographic projections of their direction of individual pilot samples collected along the excavated section.
7.8 Palaeomagnetic results.

Approximately 86 square-shaped 2.3 cm samples were collected by Kopper, by pushing 0.50 cm rectangular containers, in which empty sample-holders had been placed tightly covering the space of the steel container. The logs of inclination and declination are presented in Fig. 7.11. No geomagnetic reversals are present. The susceptibilities are low and the remanence appears to be unstable with MDFs between 70-100 Oe, as it is shown in Fig. 7.12 (a, b), which represents the group of the demagnetization curves. A viscous component is present causing the directions to change as Fig. 7.12 (a, b) clearly show.

7.9 Discussion and conclusion.

The sediments collected from Arago cave possess a weak and unstable remanent magnetization. The viscous probably grew during transportation from the site to the laboratory. These sediments are classified as bad geomagnetic recorders.

7.10 Ball's Cavern.

Ball's (or Gage's) Cavern is located (42°67'N, 74°28'W) on Barton Hill about 7 km northeast of Schoharie, New York, U.S.A. It contains no archaeological materials and its only cultural significance is that it supplies, indirectly, part of the town of Schoharie's water supply. The cave is situated about 13 m below a heavily Karsted sinkhole plane and trends in a NE-SW direction. Its known length of approximately 650 m is entirely developed in a Devonian limestone. Like most caves in the region it consists mainly of a single level linear solution tube of small cross section with occasional sinkholes connecting it with the
surface. Ball's Cavern is unique in the immediate area in having several large rooms in its system and one of these, the "Rotunda Room" contains about 8m of soft sediments deposited in it. These sediments were chosen by Kopper for palaeomagnetic study. They were sampled with the same technique that has already been described in the case of Arago cave.

Ball's Cavern has striking similarities with Jeita Cave in Lebanon (Creer and Kopper, 1976) in that it contains very thick sediments which are presently accumulating due to its location below the water table, though deposition has not been continuous in the past, having been controlled by it. The strata consist of finely laminated tan silty clays, sandy layers, gravel aboulis and finely laminated reddish-brown silts. Two sections, Omega and Alpha, banked at opposite sides of the main chamber were sampled. It is quite certain that the cave did not accumulate deposits during the Wisconsin Stadials, because it is located in a formerly glaciated area. The cave plan and the stratigraphy of the sampled area are shown in Fig. 7.13. No estimations of the rate of deposition or chronostratigraphic evidence are available. The cave carries a free surface stream that disappears into a fissure in another lower room that also contains sediment. It would first appear that this stream carried the accumulated sediments into the cave as suspended load but this is decidedly not the case. In fact the sediments were brought in through small diameter vertical openings communicating with the surface by a separate, low energy hydraulic system. Both fine material from the surface, silts and clays, as well as coarser detritus from freeze-thaw (mechanical) weathering of the cave ceiling are present in the deposit as distinct layers of one or another of the grades. These layers measure
from 1mm to several mm and more in thickness and consist predominantly of one grade of sediment, sand, silt or clay.

At the top of the Rotunda Room deposit a thick layer of large angular cryoturbated blocks are lying near the surface, undoubtedly the result of glacial action. The sinkhole plane under which the cave lies is known to have been covered by the Wisconsin and Illinoian ice sheets and probably by earlier Pleistocene glaciers.

7.11 AFC demagnetizations.

In Fig. 7.14 the demagnetization curves for Alpha and Omega section are presented. The MDFs of the Alpha samples are extremely high, in the range of 450-800 Oe while those of the Omega samples are in the range of 120-200 Oe. In Fig. 7.15 (a, b) the same samples are plotted individually in two parallel columns. In the first column the normalized in demagnetization curves are shown, while in the second their directions during AFC are shown stereographically. The direction of magnetization show remarkable groupings between 0 and 600 Oe for Alpha samples while for Omega samples the groupings are formed up to 300 Oe. It is clear that in the case of Alpha section, we deal with magnetic carriers of high coercivity. The magnetic carriers of Omega appeared with lower coercivity.

7.12 Interpretation of the palaeomagnetic data.

Fig. 7.16 illustrates the NRM declination and inclination, together with those after AFC in 100 Oe, plotted against the depth, side by side with Omega section in the top and Alpha in the bottom. Both the records appear scattered, with the inclination having a
The stratigraphy of the sampled section and the plan of Ball's Cavern.
Figure 7.14  NRM normalized demagnetization curves of pilot samples from Alpha and Omega sections.
Figure 7.15a  NRM normalized demagnetization curves with stereographic projections of their directions of individual pilot samples during AFC, from Alpha section.
Figure 7.15b NRM normalized demagnetization curves with stereographic projections of their directions of individual pilot samples during AFC, from Omega section.
Figure 7.16  NRM intensities and their cleaned record plotted together side by side with Q-ratio and the magnetic susceptibility, with Omega section in the top and Alpha in the bottom.
Figure 7.17  NRM inclination and declination logs plotted in parallel together with their record after AFC with Omega section in the top and Alpha section in the bottom.
tendency towards shallower values after AFC. The declination record exhibits profound swings with 10-20° amplitude, whereas the inclination record exhibits two broad maxima at 130 and 255cm respectively.

Fig. 7.17 illustrates the NRM intensities, together with their cleaned values after AFC plotted against the depth side by side with the Q-ratio and the ks. The intensities and hence the Q-ratios of the Omega section are reduced by about 60-70% whereas those of the Alpha are reduced by 10-15%. The differences in jn, k and Q-ratio between the two deposits are explained by differences in the concentration of the magnetic content. The jns of Omega and Alpha are in the range of 1,000 and 1,700 µG respectively, reflecting higher concentration of magnetic content in the Alpha deposit.

7.13 Discussion and conclusions.

The deposits of Ball's Cavern show highly stable remanence which probably is of PDRM origin, as the conditions of sedimentation in the cave, and the redeposition experiment showed. The sediments are deposited in a gigantic settling tank and the acquisition of the remanence is fixed when the water goes upwards as it occurs in the lakes due to gravitational compaction of the newly coming sediments. The settling tank is the entire "Rotunda" chamber. The Q-ratios follow the usual pattern of the low values, which can be explained as contribution of other magnetic minerals different from magnetite. The existence of magnetite is assumed from the Hcr≈450 Oe obtained value and from the X-ray diffraction data, however detailed Mossbauer spectroscopy, at room temperature and at liquid helium should be performed to specify in detail the nature of the magnetic carriers locked in these cave sediments, together with the thermomagnetic,
cryomagnetic experiments and optical microscopy. The observed swings cannot be dated or associated with other existing serial geomagnetic records in U.S.A., due to lack of both archaeological controls and direct ratiometric ages on travertine layers.
APPENDIX

THE MACKERETH CORER

8.1 General description.
8.2 Operation of the corer.
8.3 Discussion and conclusion.
8.1 General description.

The corer invented by Mackereth (Mackereth, 1958) consists of two PVC plastic tubes approximately 6m long, one tube within the other, and a 1.20m long drum with 0.40m diameter. The entire system weighs only 30kg. The external tube has a 7.2cm diameter and an 0.105cm wall thickness. The internal hollow core-tube has a 5.3cm diameter and 0.45cm wall thickness. The outer tube (A) engulfs the inner tube (B). The inner tube is attached to a piston (C) and can slide past an inner piston (D) which is attached to the top of the outer tube by means of a narrow innermost tube (E). The drum (F) is fixed to the lower part of the outer tube. In operation an air pressure hose (G) is attached to the top of the outer tube and a hose (H) which is connected to a pump, is attached to the top of the drum. A short pipe (I) leads from the lower part of the outer tube to the top of the anchor chamber and a release valve (J) is also fitted to the top of the drum.

Figure 8.1 Diagrammatic representation of the main features of Mackereth corer.
8.2 Operation of the corer.

The corer is lowered to the lake bed by means of a nylon rope. The hoses (1) and (2) are payed out at the same time. Small floats can be added to facilitate the operation. When the corer has reached the lake floor a slight tension is retained on the rope; this tension and the attached floats maintain the corer in a vertical position, as is shown in Fig. 8.2a. Once the corer is settled, a buoy is attached to the taut tether. The line and tether are then let out and the boat is anchored, some 40m away, as is shown in Fig. 8.2b.

![Figure 8.2a](image1)

**Figure 8.2a**
The boat with the corer in a vertical position.

![Figure 8.2b](image2)

**Figure 8.2b**
The boat has moved 40m away and the float holds the nylon rope, which is connected with the boat.

The water in the drum is now pumped out through the point (4), as is shown in Fig. 8.3(a, b) of the hose (2) extending to the top of the corer. This occurs by passing compressed air to the drum from the hose (1). The compressed air is supplied by air bottles laid on the boat.

Consequently the hydrostatic forces act on the drum and push it
into the sediment. This procedure lasts approximately ten minutes at low pressure. It is highly important that the drum is completely pumped out. After the completion of the slow-penetration of the sediments from the drum, air is passed down from hose (2) causing the main piston with the hollow core tube to be pushed out of the corer into the soft sediments. The rate of coring can be monitored by observing the amount of water which comes out of the retract tube (attached to point (3)). This water is displaced from inside the core tube (B) and passed back up to the retract tube.

Once the core is fully extended, that is when the main piston passes outlet (4), the coming air is by-passed through (4) into the drum and the retrieval process is enacted. The bypass of air through (4) causes the drum to fill with air. This causes the drum to lift from the sediment and when sufficient buoyancy is reached the whole corer is propelled to the lake surface for retrieval. The assemblage is kept afloat by the continuing passage of air keeping the drum positively buoyant. The sequence of events is illustrated in Fig.8.4(a, b).

A. The drum rests in contact with the sediment on the lake floor. The corer is supported by a nylon rope and the hoses from the drum and the top of the corer are connected to a pump and to a supply of compressed air in the boat.

B. The water is pumped out and the drum penetrates vertically the soft top sediments.

C. The water trapped in the drum has been pumped out and the hydrostatic pressure has pushed the chamber into the sediment. The hose used to pump out the water is sealed out the core is about to be taken.

D. Compressed air has been admitted into the space between the piston at the top of the core tube and the outer tube and the core tube is being pushed into the sediment.
Figure 8.3a. Details of the functional procedures during coring.

Figure 8.3b. A realistic picture of the corer and its major components.
Figure 8.5a  Phase (D) : The coring procedure is completed.
Phase (E) : The corer starts to rise up.
Phase (F) : The corer is going to the surface of the lake.
Figure 8.4a  Phase (A) : The vertical position of the corer on the lake bed.  
Phase (B) : The slow penetration into the soft sediment.  
Phase (C) : The penetration is completed.
E. The core has been taken and compressed air has entered the drum from the outer tube by means of the short pipe shown in Fig. 8.3a. The air pressure being greater than the hydrostatic pressure is raising the drum from the lake bed.

F. The corer is now rising to the surface being lifted by the buoyancy of the air trapped in the drum. Some of the air is escaping from the drum through the air release valve.

Figures 8.1, 8.2 and 8.4 are modifications of drawings based on Smith's schematic representation of the corer (Smith, 1959).

8.3 Discussion and conclusion.

The main profound advantage of the pneumatically operated corer are the portability of it on the roof of a Land Rover, its independence from big depths (~300m limit), the easy operational procedures requiring only two people and an outboard motor, the very low construction and running costs together with new improvements which do not allow rotation during coring and the possibility of taking oriented cores by placing a submarine camera on the top of the drum which would give precise photographs of a compass and the degree of tilting of the corer by measuring the degree of deviation of the bubble from the centre of the spirit levels, are intriguing prospects for new advances in palaeomagnetic research, Jackson (personal communication), Barton (1978).
BIBLIOGRAPHY


Phys. Earth Planet. Interiors, 5, 140-150.

Kopper, J.S., (1972). Geophysical surveying of cave sites, Pyrenae, 8, 7-16.

Caves and Karsts, 15, 13-20.


Poulianos, A.N., (1977). Traces of fire at the Petralona cave the oldest known up to date. (Preliminary report) Anthropos. 4, 144-146.


