A PALAEOECOLOGICAL STUDY OF RECENT ENVIRONMENTAL CHANGE IN THE DRAINAGE BASIN OF THE LAC D'ANNECY (FRANCE)

Thesis submitted in accordance with the
requirements of the University of Liverpool
for the degree of Doctor in Philosophy by
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August, 1985

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ABSTRACT

A palaeoecological study of sediments from the Lac d'Annecy has been undertaken in order to assess the impact of man on soil-vegetation systems in the lake basin.

The geology of the drainage basin is dominated by weakly magnetic calcareous Jurassic and Cretaceous deposits, but natural soil forming processes and artificial burning have produced assemblages of strongly magnetic minerals within topsoils of the catchment area. These can be characterized by mineral magnetic parameters which are preserved as the eroded soil fractions become incorporated within the lake sediments.

Man's impact on the landscape appears to have been most dramatically felt from c. 1100 AD; fossil pollen assemblages give evidence for widespread forest clearance, associated with arable and pastoral farming activities, which are thought to reflect the earliest intensive agricultural development of the higher slopes within the catchment area. At the same time there is a marked change in the nature of the sedimentary matrix. An increase in the concentration of major cations and magnetic minerals indicates a regime of more intensive soil erosion and a change in the magnetic mineral assemblage itself indicates a shift in the relative importance of different catchment sources to the total allochthonous material flux.

Reconstruction of environmental change during more recent centuries has been aided by reference to primary and secondary documentary sources of evidence relating to past patterns of land-use. The mixed farming system of the eighteenth century, characterized by a regime of relatively intensive arable cultivation, was not particularly well-suited to the natural environment. A decrease in the concentration of major cations and magnetic minerals, together

with a decline in the total sediment accumulation rate from the mid-nineteenth century onwards, is thought to reflect a fall in the rate of loss of material from catchment surfaces. It has been suggested this was related to a shift in focus of the rural economy from the semi-arable, semi-pastoral subsistence agricultural system to one which concentrated increasingly on the breeding of livestock for the local dairying industry.

CONTENTS

		PAGE NO.
List of Tables		i
List of Figures		iv
Acknowledgements		viii
Chapter 1	Introduction	1
Chapter 2	The Physical Environment	9
Chapter 3	Man in the Lake Basin	64
Chapter 4	Materials and Methods	91
Chapter 5	The Establishment of a Chronological Framework for describing Environmental Change	138
Chapter 6	Description of Results	183
Chapter 7	Discussion of Results	218
Chapter 8	Conclusions	286
Appendix 1	Eighteenth and Twentieth Century Records of Land-use in Communes of the Petit Lac Catchment Area	293
Appendix 2	Colour Stratigraphy of APL6	309
Appendix 3	Pollen Diagrams	314
Bibliography		321

LIST OF TABLES

		PAGE NO.
2.1.	Principal morphometric characteristics of the Lac d'Annecy drainage basin	13
2.2	Principal morphometric characteristics of the Grand Lac and Petit Lac sub-basins	14
2.3	Lithology of the principal river basins in the Lac d'Annecy drainage basin	19
2.4	Morphometric and hydrological characteristics of the principal river basins in the Lac d'Annecy drainage basin	31
2.5	Significant floods of the Lac d'Annecy, 1570-1931	36
2.6	Relative importance of the principal diatom species in the Lac d'Annecy, 1965-1966	47
2.7	Relative importance of the principal phytoplankton groups in the Lac d'Annecy, 1961-1967	48
2.8	Comparison of factors relating to the intensity of eutrophication in Lac Léman, Lac du Bourget and Lac d'Annecy	50
2.9	Changes in the physico-chemical characteristics and phytoplankton composition of the Lac d'Annecy, 1967-1971	51
2.10	Composition of communal forests in the Annecy cluse in the 20th. century	62
3.1	Metric equivalents of the original square measures recorded in the "Cadastre Savoyarde"	74
3.2	Metric equivalents of the original capacity and weight measures recorded in the "1754 tabelle"	74
3.3	Agricultural production in the Petit Lac catchment area, 1754	77
3.4	Cultivation of walnut, chestnut, vine and hemp in the Petit Lac catchment area, 1730	78
3.5	Pastoral farming in the Petit Lac catchment area, 1754	78
3.6	Allocation of cereal grain from the 1754 harvest in Montmin	79
3.7	Decline of vine cultivation in four communes of the Petit Lac catchment area, 1730-1976	84
3.8	Agricultural change in the Petit Lac catchment area, 1929-1970	85

		PAGE NO.
3.9	Change in the pastoral farming system in the Petit Lac catchment area, 1929-1970	86
3.10	Change in the cover of forest and woodland in six communes of the Petit Lac catchment area during the 20th. century	87
3.11	Agricultural land in the catchment areas of the Grand Lac and Petit Lac, 1970	88
3.12	Pastoral farming in the catchment areas of the Grand Lac and Petit Lac, 1970	89
4.1	Basic principles of pollen analysis	96
4.2	Iron oxides and hydroxides in soils	115
4.3	Grain size thresholds for magnetite, maghemite and haematite	117
4.4	χ measurements of rock and drift samples in the Lac d'Annecy drainage basin	121
4.5	χ and SIRM measurements of brown earth soils from the Eau Morte river basin	123
4.6	Summary of χ measurements for soils, stream bedload and lake sediments in the Lac d'Annecy drainage basin	125
4.7	Units of measurement (c.g.s.) and conversion factors for S.I. units	136
5.1	Proposed correlation of magnetic features between AGL5, APL1 and APL6	147
7.1	Mineral magnetic measurements of particle-sized fractions of sediments from the Grand Lac	226
7.2	Spearman rank correlation coefficients between pollen and spore concentration data and geochemical and mineral magnetic measurements, APL6	231
7.3	Spearman rank correlation coefficients between frequency of unidentified deteriorated pollen and geochemical and mineral magnetic measurements for APL6, APL1 and AGL5	235
7.4	Spearman rank correlation coefficients between frequency of Compositae Liguliflorae pollen, Filicales undiff. spores and *Pteridium aquilinum* spores, and geochemical and mineral magnetic measurements for APL6, APL1 and AGL5	237
7.5	Percentage of tree and shrub pollen, herb pollen, pteridophyte spores and unidentified deteriorated pollen and spores in each preservation class	240

PAGE NO.

7.6 Spearman rank correlation coefficients between percentage of total pollen and spores in each preservation class (identified and unidentified) and geochemical and mineral magnetic measurements, APL6 242

7.7 Spearman rank correlation coefficients between percentage of total tree and shrub pollen in each preservation class and frequency of broken conifer pollen, and geochemical and mineral magnetic measurements, APL6 243

7.8 Spearman rank correlation coefficients between percentage of total herb pollen in each preservation class and geochemical and mineral magnetic measurements, APL6 245

7.9 Spearman rank correlation coefficients between percentage of total pteridophyte spores in each preservation class and geochemical and mineral magnetic measurements, APL6 248

LIST OF FIGURES PAGE NO.

1.1	Proposed model of linkages between environmental change, erosional processes and sediment χ traces in the Lac d'Annecy watershed ecosystem	4
2.1	Situation of the Lac d'Annecy drainage basin in the Northern French Alps	10
2.2	Relief of the Lac d'Annecy drainage basin	12
2.3	Lithology of the Lac d'Annecy drainage basin	17
2.4	Mean annual temperature and precipitation in the Lac d'Annecy drainage basin (1966-1967, 1968-1969 and 1969-1970)	22
2.5	Mean monthly temperatures at Annecy, Glières and Montmin (1966-1967, 1968-1969 and 1969-1970)	23
2.6	Mean monthly precipitation at Annecy, Veyrier, Glières, Montmin, Faverges, Seythenex, Chevaline and St. Jorioz (1966-1967, 1968-1969 and 1969-1970)	24
2.7	Mean decennial temperatures, frequency of precipitation and length of winter at Annecy, 1773-1913	26
2.8	Mean decennial seasonal temperatures at Annecy, 1773-1913	27
2.9	Dates of wine-harvests in the Lac d'Annecy drainage basin in the late 18th. and 19th. centuries	28
2.10	Drainage network of the Lac d'Annecy drainage basin	29
2.11	Hydrographs for the Biolon, Nant d'Oy, Eau Morte, Ire, Bornette, Ruisseau d'Entrevernes and Laudon, (1966-1967)	33
2.12	Hydrographs for the Nant d'Oy, Eau Morte, Ire, Ruisseau d'Entrevernes and Laudon (1968-1969) and for the Eau Morte and Laudon (1969-1970)	34
2.13	Underwater morphology of the Lac d'Annecy	37
2.14	Seasonal cycle of temperature conditions in the Lac d'Annecy	39
2.15	Temperature and oxygen profiles in the centre of the Grand Lac, Lac d'Annecy	40
2.16	Comparison of the dissolved oxygen content of waters in the centre of the Grand Lac between 5 October 1937 and 11-12 October 1966	44
2.17	Extension of deoxygenated waters in the lower strata of the Grand Lac between 5 October 1937 and 11-12 October 1966	45

PAGE NO.

2.18 Vegetation series in the Lac d'Annecy drainage basin 54

3.1 Population change in communes of the Petit Lac catchment area, 1411-1975 68

3.2 Population change in communes of the Petit Lac catchment area, 1861-1975 70

3.3 Settlement in the Lac d'Annecy drainage basin, 1975 76

4.1 Simple bathymetric map of the Lac d'Annecy 92

4.2 $CaCO_3$ content of the <40μ fraction of surface sediments in the Lac d'Annecy 108

4.3 The hysteresis loop 127

5.1 Proposed correlation of specific χ features in AGL5, APL1 and APL6 142

5.2 Proposed correlation of specific SIRM features in AGL5, APL1 and APL6 143

5.3 Proposed correlation of specific χ_{fd} features in AGL5 and APL1 144

5.4 Proposed correlation of IRM_{-400}/SIRM features in AGL5 and APL1 145

5.5 Mineral magnetic correlation best-fit curves, APL1 vs. AGL5, APL6 vs. AGL5, APL6 vs. APL1 146

5.6 Proposed correlation of pollen features in AGL5 and APL1 149

5.7 Comparison of five pollen types in APL6 and AGL5 150

5.8 Simplified model of ^{210}Pb flux into lake sediments 153

5.9 Total ^{210}Pb concentration vs. depth for AGL5 and APL1 157

5.10 Unsupported ^{210}Pb concentration vs. depth for AGL5 and APL1 158

5.11 ^{210}Pb and palaeomagnetic chronologies for AGL5 and APL1 159

5.12 Schematic representation of the acquisition of a depositional remanent magnetization and post-depositional remanent magnetization in lake sediments 162

5.13 Declination, Inclination and NRM intensity logs for APL6 165

		PAGE NO.
5.14	Vegetation change in the Northern French Alps during the Late-Glacial and Holocene	170
5.15	Location of the principal sites in the Northern French Alps for which pollen diagrams have been published	172
5.16	Pollen diagrams from the Grand Lac sub-basin of the Lac d'Annecy	175
5.17	Age/depth-profiles and sedimentation rates for AGL5 and APL1	177
5.18	Age/depth-profile and mean volumetric sedimentation rates for APL6	178
6.1	Zonation of pollen diagram from APL6	193
6.2	Zonation of pollen diagram from APL1	194
6.3	Zonation of pollen diagram from AGL5	195
6.4	Geochemical measurements from APL6	199
6.5	Geochemical measurements from APL1	200
6.6	Geochemical measurements from AGL5	201
6.7	Single sample χ, SIRM and SIRM/χ profiles from APL6	214
6.8	Mineral magnetic measurements from APL6	215
6.9	Mineral magnetic measurements from APL1	216
6.10	Mineral magnetic measurements from AGL5	217
7.1	Comparison of the gross sediment composition with mineral magnetic measurements, AGL5	219
7.2	Comparison of the gross sediment composition with mineral magnetic measurements, APL1	222
7.3	Comparison of the non-carbonate ignition residue content with mineral magnetic measurements, APL6	224
7.4	Comparison of the frequency and concentration of the main pollen and spore categories with geochemical and mineral magnetic indices of material flux from catchment surfaces, APL6	232
7.5	Sources of pollen in limnic sediments	233
7.6	Proposed model of the links between deforestation in the catchment area of the Petit Lac and the fossil pollen spectra preserved in the lake sediments	248

PAGE NO.

7.7 Summary of the evidence from APL6 for recent environmental change in the Petit Lac catchment area 252

7.8 Comparison of the mineral magnetic properties of "Pre-Monastic" and "Post-Monastic" sediments in APL6 264

7.9 Summary of the evidence from AGL5 for recent environmental change in the Grand Lac catchment area 275

7.10 Summary of the evidence from APL1 for recent environmental change in the Petit Lac catchment area 279

ACKNOWLEDGEMENTS

I should like to express my gratitude to Professor Frank Oldfield for his critical supervision and continuous encouragement during the preparation of this thesis, and to Professor K.M. Creer of the Department of Geophysics, University of Edinburgh, who provided two long sediment cores from the Lac d'Annecy for use in this project.

I am also indebted to Dr. Jan Bloemendal, Mr. Nigel Richardson and Mr. Simon Robinson for much constructive discussion and expert advice at all stages of the work, to Dr. Peter Appleby for help with dating the sediments, and to Dr. Elizabeth Steel, Dr. Anne Jones and Dr. David Siddle for their time spent in discussing the documented history of the Annecy area, and for kindly allowing the inclusion of many of their unpublished data.

I much appreciate the co-operation of the staff at the "Archives départementales de la Haute-Savoie" in Annecy, who granted access to the records and gave permission for the retrieval of information for use in this study.

Dr. Richard Bradshaw, Mr. Peter James, Dr. Barbara Maher and Dr. Christian Reynaud also allowed me to include some of their unpublished data.

The work greatly benefited from visits to the pollen laboratories at the University of Marseilles and the University of Geneva at the invitation of Dr. J-L. de Beaulieu and Dr. C. Reynaud respectively; my sincere thanks to them, and to their colleagues and families for their kind hospitality.

Thanks are also due to Dr. Elizabeth Steel, Mr. Peter James and Mr. Mark Higgitt for their help during periods of fieldwork in France, to the technical and cartographic staff in the Department of Geography for help with laboratory analyses and diagram construction, and to my mother, who so meticulously typed this manuscript.

Finally, I would like to acknowledge the endless support and practical help so generously given by both my parents since I returned to Liverpool to complete this work.

Research for this thesis was completed in the Department of Geography at the University of Liverpool, while the author held an N.E.R.C. research studentship (1978 - 1981) and during a short additional period of laboratory work in 1983.

CHAPTER 1

INTRODUCTION

1.1. Statement of the problem

Soil and vegetation systems are amongst the most valuable natural resources available to man, yet their exploitation has often been more immediately governed by the demand for food and firewood, and rather less urgently by any notion of the system's natural resilience to disturbance. Consequently, many ecosystems throughout the world have become degraded, often as a result of soil erosion.

The stability of a soil system is very closely related to the effectiveness of the ground cover, which is usually in the form of vegetation. A plant cover protects the soil from erosion by intercepting rainfall and reducing both the velocity of surface runoff and wind-speed near the ground. The removal of vegetation by deforestation, crop harvesting or overgrazing renders topsoils susceptible to erosion.

On a national scale, the loss of soil material may be catastrophic. In Nepal, which has the world's most acute erosion problem, population growth has led to the progressive deforestation of steep Himalayan slopes (Eckholm, 1975). Landslides involving loss of life, homes and crops, have become more and more frequent, and topsoil washing down into India and Bangladesh is now the nation's most precious export. The problem is exacerbated by the increasing scarcity of firewood which in turn forces farmers to burn more manure as fuel and apply less to their fields. The result is a decline in agricultural productivity which necessitates the clearance of more forest, often in the most marginal areas, thus intensifying the hazards of erosion and landslides. So the crisis spirals.

At the field scale, the progressive loss of inorganic plant nutrients, organic matter and fine soil particles may simply be seen in depressed crop yields and lower animal stocking rates. Even in Great Britain and Europe, where the removal of plant nutrients is countered by the application of manure and artificial fertilizers, erosion losses which are acceptable in current conservation practice have been questioned in terms of the long-term maintenance of soil fertility (Kirkby & Morgan, 1980).

There are many other consequences of sediment removal. For example, the formation of rills and gullies in agricultural land reduces the effectiveness of mechanical tillage, the siltation of natural and artificial waterways and water reservoirs may require costly dredging operations, and the transport of chemical fertilizers, pesticides, herbicides and fungicides in association with eroded soils, may impair the water quality of reservoirs, lakes and streams, reducing their value for recreation and other purposes (Holý, 1980).

In many parts of the world, man's exploitation of natural soil and vegetation systems is likely to continue, or to escalate in the future. Thus it is of crucial importance to evaluate the effects man has upon these ecosystems, particularly with regard to identifying limiting variables and critical thresholds. The ultimate objective of such research must be to plan for the future and to adopt suitable conservation measures.

Monitoring the processes of ecological deterioration can generate the empirical data upon which models of ecosystem dynamics are built; these may then be used to predict future trends and to help formulate policies for rational land-use management programmes. Yet this approach is limited by the time-scales available for observation or experimentation.

An extra dimension to the perception of ecological degradation, its causes and consequences, can be gained if the directions and magnitude of past environmental change are also considered.

It is widely appreciated that lake-watershed ecosystems provide very favourable contexts within which to reconstruct environmental change (Oldfield, 1977; O'Sullivan, 1979). The development of short-lived radioisotope measurements (^{210}Pb and ^{137}Cs), which make it possible to resolve chronologies within the past 100 - 200 years, has provided an opportunity for linking contemporary observations with historical reconstruction over the period in which man has often had his most dramatic impact (Oldfield, 1983).

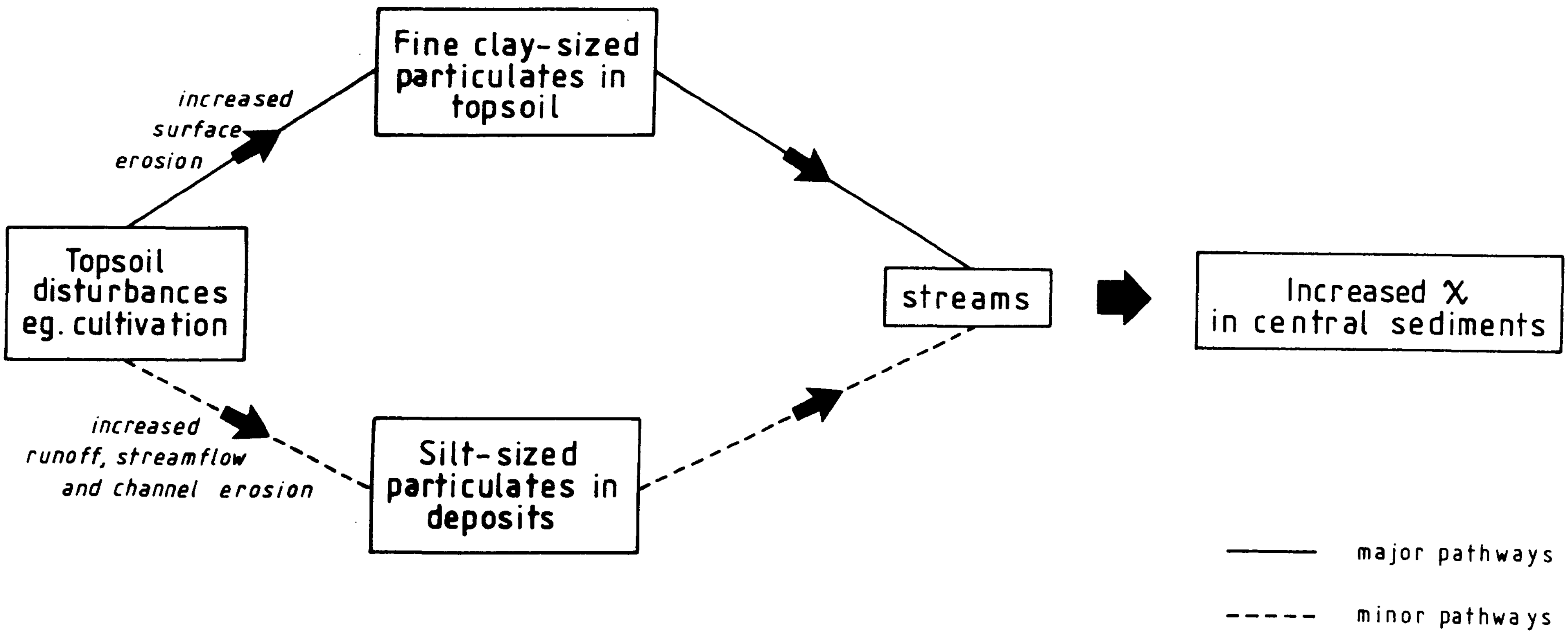
The reconstruction of environmental change over longer time-scales is also a valuable exercise. By studying the interaction of traditional agricultural societies with their immediate environments, and by exploring the subtle interplay between ecosystem exploitation and the dynamics of social, economic and demographic change, much can be learned of the natural resilience of different soil-vegetation systems to land-use pressure and man-induced ecological perturbation.

1.2. Choice of study site

In an earlier study, Dearing (1979) proposed a simple model of linkages between environmental change, erosional processes and the nature of the lake sediments in the drainage basin of the Lac d'Annecy (figure 1.1.).

Although the geology of the lake basin is dominated by rock types which are intrinsically poor in primary ferrimagnetic minerals, Dearing (1979) noted that topsoils in the catchment area showed widespread magnetic enhancement. This disparity was attributed to the transformation, within the soil profile, of weakly magnetic iron-

Figure 1.1. Proposed model of linkages between environmental change, erosional processes and sediment χ traces in the Lac d'Annecy watershed ecosystem (from Dearing, 1979)


Topsoil disturbances eg. cultivation
increased surface erosion
Fine clay-sized particulates in topsoil
increased runoff, streamflow and channel erosion
Silt-sized particulates in deposits
streams
Increased χ in central sediments
major pathways
minor pathways

oxides to strongly magnetic secondary ferrimagnetic minerals as a result of natural oxidation-reduction cycles or burning. Dearing envisaged that these secondary ferrimagnetic minerals are eroded from catchment surfaces, particularly in association with finer soil fractions, and transported via the drainage network to the lake sediments, where a sequential "magnetic" record of variations in the flux of soil material may be preserved. He was also able to demonstrate that changes in the flux of soil material, deduced from profiles of magnetic susceptibility in the deep-water sediments he studied, compared well with other palaeoecological and documentary evidence for environmental change. The present investigation was initiated as a sequel to Dearing's work.

In addition, this area of S.E. France possesses extremely detailed historical records of land-use and social structure which extend back over 400 years, providing one of the most comprehensive data bases in Europe for reconstructing the long-term evolution of rural systems (Jones & Siddle, 1982). Using these documents, D.J. Siddle and colleagues in the Department of Geography at the University of Liverpool have begun to investigate the complex man-land relationships operating in the marginal upland environments of the pre-alpine region, and to identify changes in the structure of these relationships over a long period of time. Fortuitously, their studies have centred on communities within the Annecy lake basin.

Thus, the distinctive "magnetic fingerprinting" of topsoils in the catchment area, together with the availability of detailed documentary evidence for past patterns of land-use and pressure on natural resources, suggests that the drainage basin of the Lac d'Annecy is an ideal site at which to undertake a detailed study of man's impact on the environment.

1.3. Aims of the present study

The immediate aims of this investigation are threefold:

1. To derive a history of vegetation change and land-use for the drainage basin of the Lac d'Annecy using the pollen record preserved within the lake sediments, together with documentary sources of evidence.
2. To derive a history of material flux from catchment surfaces using geochemical and mineral magnetic measurements of the lake sediments, and where possible to quantify rates of sediment accumulation.
3. To interpret changes in the flux of catchment-derived material within the context of changes in land-use regimes and landscape patterns.

A further aim is to contribute to a multi-disciplinary study of cultural and environmental change in the lake basin. At present the interest of historical geographers working in this area is very finely focussed on man-land interactions at the micro-scale:

> "..... we maintain that the key to understanding the peasant system lies in exposing the subtle relationships between the individual household, the land parcels of that household and the patterns of use and inheritance which characterize the family economy as it changes through time." (Jones & Siddle, 1982).

Similarly, individual communes (parishes) have often been considered as the basic unit of research for demographic studies; these systems have tended to remain rather conservative over time-scales of many centuries (Jones, 1983a and 1983b).

Yet the sediments of the lake contain a composite record of events, processes and trends on a total catchment scale. These two apparently disparate lines of research are potentially complementary. It is hoped that in the future they can be integrated, and the complex interfacing between the physico-ecological and socio-economic systems operating in the lake basin described in detail.

1.4. Outline of thesis

A geographical and historical background to the drainage basin of the Lac d'Annecy is presented at the beginning of this thesis.

The lake basin is extensive in area and altitude and so the physical environment of the site is described in some detail in Chapter 2. Palaeoecological reconstruction alone demands some appreciation of spatial variations in parent material-soil-vegetation systems. Furthermore, interpretation of the lake sediment records requires an understanding of the characteristics of the drainage network through which the greater part of the material flux is assumed to be transported, and also of the water body itself which may significantly influence sedimentation characteristics. The Lac d'Annecy has been the object of scientific research for the past 200 years[1]; of these studies the limnological observations undertaken by the "Centre de Recherches Géodynamiques de Thonon" have been of immense value in compiling this description.

In Chapter 3 a history of man in the lake basin has been outlined. An attempt has been made to collate empirical evidence for the description of demographic trends and land-use changes over the past few centuries. The opportunity to "observe" past agricultural systems is considered to be most useful as there are no contemporary analogues for the peasant community with its traditional subsistence farming economy.

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[1] A useful bibliography of the most significant pieces of work published up to 1971 has been compiled by Balvay (1971a).

The palaeoecological techniques used in this investigation are described and rationalized in Chapter 4. Included here is also a description of the materials analyzed.

Reconstruction of palaeoenvironments and palaeoprocesses requires the establishment of a secure chronology. The lake sediments need to be dated so that the evidence for environmental change may be described within their archaeological or historical context; only then can the relationship between the sediment record and the history of human activity in the catchment area be established. Secondly, it is desirable to express the results of the sediment analyses as flux densities, not only to overcome the interdependence of relative percentage and concentration data, but also to quantify the evidence for environmental change in terms of rates. The establishment of a chronological framework for the description of environmental change in the Annecy lake-catchment system is described in Chapter 5.

During the course of this investigation it has become clear that the results of the pollen, geochemical and mineral magnetic analyses are most meaningfully considered in relation to one another. For this reason these results are presented separately in Chapter 6. They are drawn together in Chapter 7, where their potential and limitations for deriving a history of vegetation, land-use and soil erosion are assessed, before being used to reconstruct environmental change in the lake basin.

CHAPTER 2

THE PHYSICAL ENVIRONMENT

2.1. Situation and site

The Lac d'Annecy (lat. 45°48'N - 45°54'N, long. 6°8'E - 6°14'E) and its drainage basin are situated in the PréAlpes of the Northern French Alps, a zone of relatively young calcareous strata, in which the massif summits are generally less than 3000m and there are no glaciers or permanent snows.

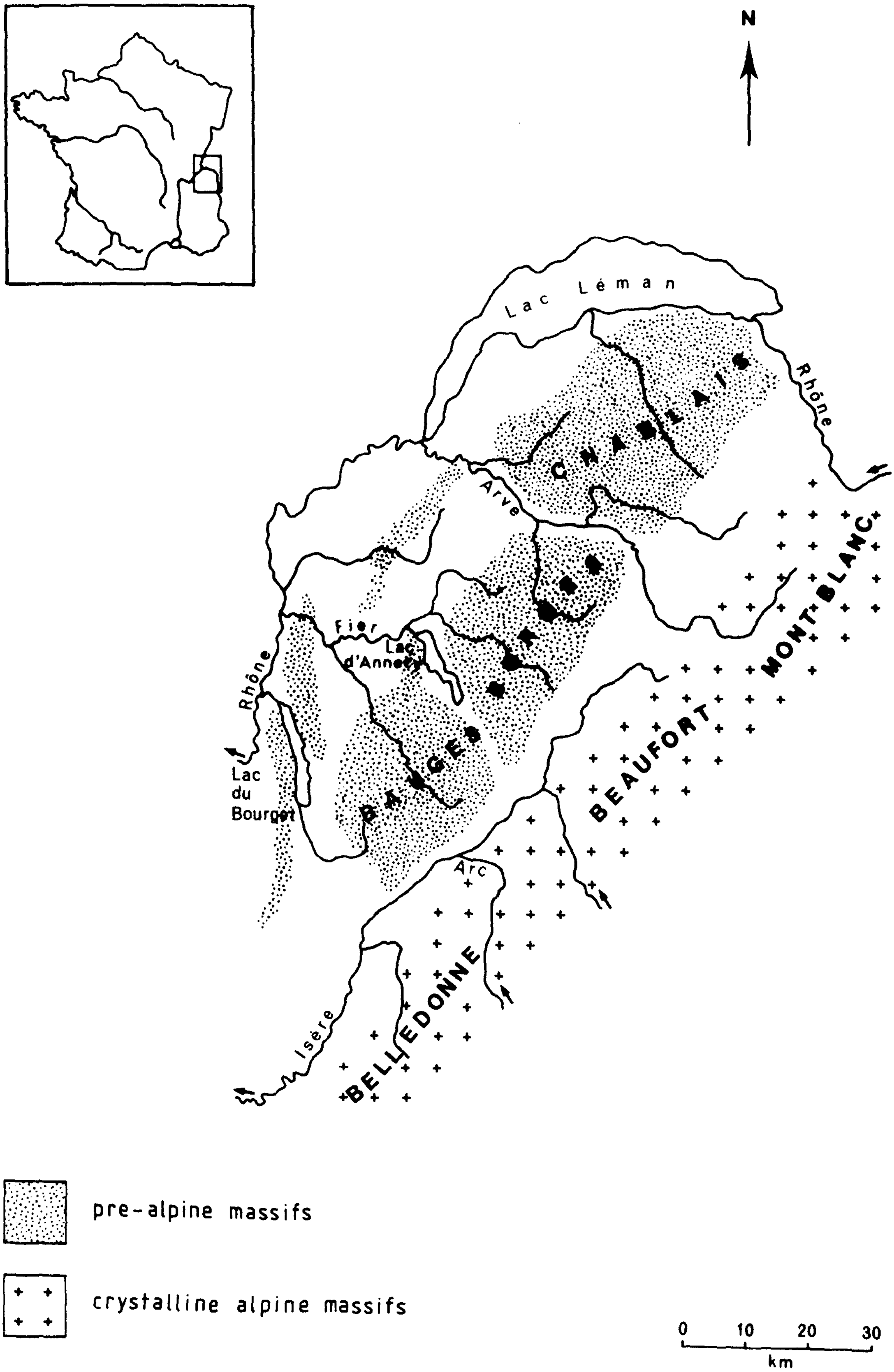
The lake occupies the northern end of the Annecy cluse[1] (30km between Annecy and Ugine) which separates the pre-alpine massifs of the Bornes to the north-east and the Bauges to the south-west (figure 2.1.). The cluse itself links two very contrasting physical regions on either side of the PréAlpes: the "massifs crystallins externes" of the Grandes Alpes to the south-east where granite, gneiss and schist form summits over 4000m, and the "avant-pays" lowlands to the north-west where molassic, glacial and fluvio-glacial deposits form rolling hills and plateaux (Balvay, 1978; Benedetti-Crouzet, 1972; Veyret, 1969).

The drainage basin of the Lac d'Annecy includes the section of the cluse between Annecy and Faverges (c. 20km), and is bordered by the crests of Mont Veyrier and La Tournette to the east, Dent de Cons and Pointe de l'Arcalod to the south, and Le Charbon and Montagne du Semnoz to the west. The cluse floor generally lies

---

[1] The term cluse refers to the four transverse valleys (Grenoble, Chambéry, Annecy and Arve) which cut across the main axis of the pre-alpine massifs.

Figure 2.1. Situation of the Lac d'Annecy drainage basin in the Northern French Alps (from Benedetti-Crouzet, 1972)


N
Lac Léman
CHABLAIS
Rhône
Arve
Fier
Lac d'Annecy
Rhône
Lac du Bourget
BAUGES
MONT BLANC
BEAUFORT
Arc
Isère
BELLEDONNE
pre-alpine massifs
crystalline alpine massifs
0 10 20 30
km

below 500m, the surrounding slopes rising steeply to over 1000m in the northern part of the basin and to over 2000m in the interior of the pre-alpine massifs (figure 2.2.).

The principal morphometric characteristics of the lake basin are listed in table 2.1.

The lake itself consists of two sub-basins, the Grand Lac to the north and the Petit Lac to the south, which are separated by a submerged bar between the Roc de Chère and the mouth of the Laudon (§ 2.5.1.) (figure 2.13.).

The two sub-basins are very different in terms of the relative size of their catchment areas[1]; the catchment area of the Grand Lac basin is approximately four times larger than the Grand Lac itself, whereas that of the Petit Lac basin is over twenty seven times the size of the Petit Lac (table 2.2.) (Benedetti-Crouzet, 1972).

2.2. Geology, lithology and soils

2.2.1. Geological history

The geology of the drainage basin is dominated by alternating series of limestones and marls of Jurassic and Cretaceous age, viz.

- marls and limestones (Tithonique facies) of the Upper Jurassic
- calcareous sandstones and marls of the Lower Cretaceous
- a reef limestone (Urgonien facies) of the Lower Cretaceous
- glauconite sandstones, lumachelle limestones and calcareous schists of the Upper Cretaceous

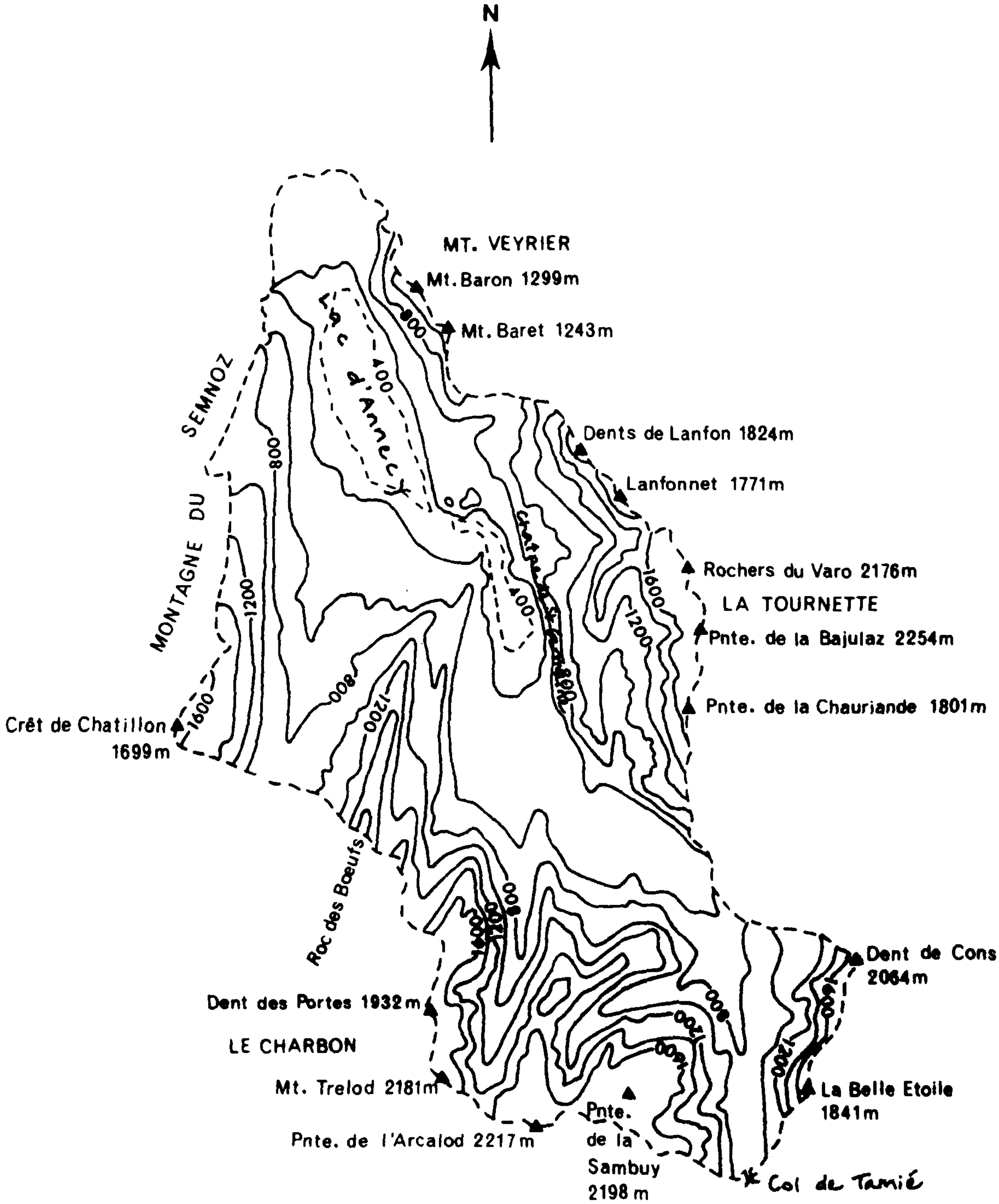
Tertiary sediments include:

- conglomerates, sandstones, marls and shales of the Oligocene

---

[1] The term catchment area refers to the area of land in the drainage basin (or sub-basin).

Figure 2.2. Relief of the Lac d'Annecy drainage basin (from Benedetti-Crouzet, 1972)


N
MT. VEYRIER
Mt. Baron 1299m
Mt. Baret 1243m
Lac d'Annecy
SEMNOZ
MONTAGNE DU
Dents de Lanfon 1824m
Lanfonnet 1771m
Rochers du Varo 2176m
LA TOURNETTE
Pnte. de la Bajulaz 2254m
Pnte. de la Chauriande 1801m
Crêt de Chatillon
1699m
Roc des Boeufs
Dent de Cons
2064m
Dent des Portes 1932m
LE CHARBON
Mt. Trelod 2181m
La Belle Etoile
1841m
Pnte. de l'Arcalod 2217m
Pnte.
de la
Sambuy
2198 m
Col de Tamié
0
5
km

Area of drainage basin	277·5 km^2
Catchment area	251 km^2
Surface area of lake	265 km^2
Volume of lake	1·123 km^3
Maximum altitude (Pointe de la Bajula, La Tournette)	2254 m
Altitude of lake	446·5 m
Average altitude of catchment area	900 m
Average slope in catchment area	6% (3·5°)

Table 2.1. Principal morphometric characteristics of the Lac d'Annecy drainage basin. (from Benedetti-Crouzet & Meybeck, 1971).

	Grand Lac	Petit Lac
Area of sub-basin (km^2)	100·85	176·65
Catchment area (km^2)	80.6	170·4
Surface area of lake (km^2)	20.25	6.25
Volume of lake (km^3)	0·878	0·243
Length (km)	≃ 10	≃ 4
Maximum width (km)	3·1	1·5
Maximum depth (m)	65[1] 82[2]	55

[1]Central plain } § 2.5.1.
[2]Boubioz

Table 2.2. Principal morphometric characteristics of the Grand Lac and Petit Lac sub-basins. (after Benedetti-Crouzet & Meybeck, 1971 and Balvay, 1978).

- molasse of the Miocene

(Benedetti-Crouzet, 1972; Finlow, 1978; Carte Géologique de la France 1/80.000: Sheet 160B (Annecy), 2nd. edition and Sheet 169B (Albertville), 2nd. edition).

During the Alpine orogeny a series of fold structures (with a predominantly NE-SW axis) was formed in the region, seen, for example, in the Semnoz anticline, the Leschaux syncline and the perched synclines of Entrevernes and Le Charbon (Benedetti-Crouzet, 1972; Veyret, 1969).

The original geological structure controlling the formation of the present lake basin is disputed, but thought to relate either to the system of anticlines and synclines described above, or to the fracture zone of an early Tertiary fault extending north-west from Faverges (see Benedetti-Crouzet, 1972). Nevertheless, a NW-SE oriented depression forming the axis of the Annecy valley had probably been formed by the end of the Tertiary, its future morphology largely determined by subsequent Pleistocene glaciations.

During the Würm (the final glacial stage in the Alps) a glacier originating in the crystalline Beaufort massif (figure 2.1.) moved through the Annecy valley. The present distribution of metamorphic erratics suggests that this glacier reached an altitude of at least 700 - 740m, and possibly up to 800m (Deleau, 1974). The main Beaufort glacier was joined by local glaciers emanating from valleys in the Bornes and Bauges massifs, with only the summits of La Tournette and Montagne du Semnoz emerging from the ice. Local Würmian glacial drift is found up to 900 - 1000m (Benedetti-Crouzet & Meybeck, 1971; Benedetti-Crouzet, 1972).

Gneiss and granite boulders near the Col de Tamié (907m) and metamorphic rock particles in soils at c. 1000m in Giez are thought to be remnants of an earlier glacial advance (Deleau, 1974; James, 1972a).

As the Würmian ice retreated, a glacial lake formed which, at its maximum, extended 30km from Faverges (figure 3.3.) to La Mandallaz. Lacustrine deposits are described by Becker (1952) below 2·25m depth at the 'Toubière de Macully', Poisy (513m altitude) indicating that the lake reached a maximum level of 510m (Benedetti-Crouzet, 1972).

During the Early Dryas stadial, a local readvance of ice affected the lake basin; small glaciers from the Bauges massif (Montagne d'Entrevernes, Le Charbon and Montagne de Seythenex) coalesced in the Annecy valley and continued to erode the present lake depression.

During the Alleröd interstadial a lake once more formed between Faverges and La Mandallaz; 30m+ terraces (at Chaparon, Doussard and Faverges, for example) indicate that the lake reached a maximum level of 480m. By the end of the Alleröd the northern and southern extremities of the lake had filled in (Benedetti-Crouzet, 1972; Deleau, 1974).

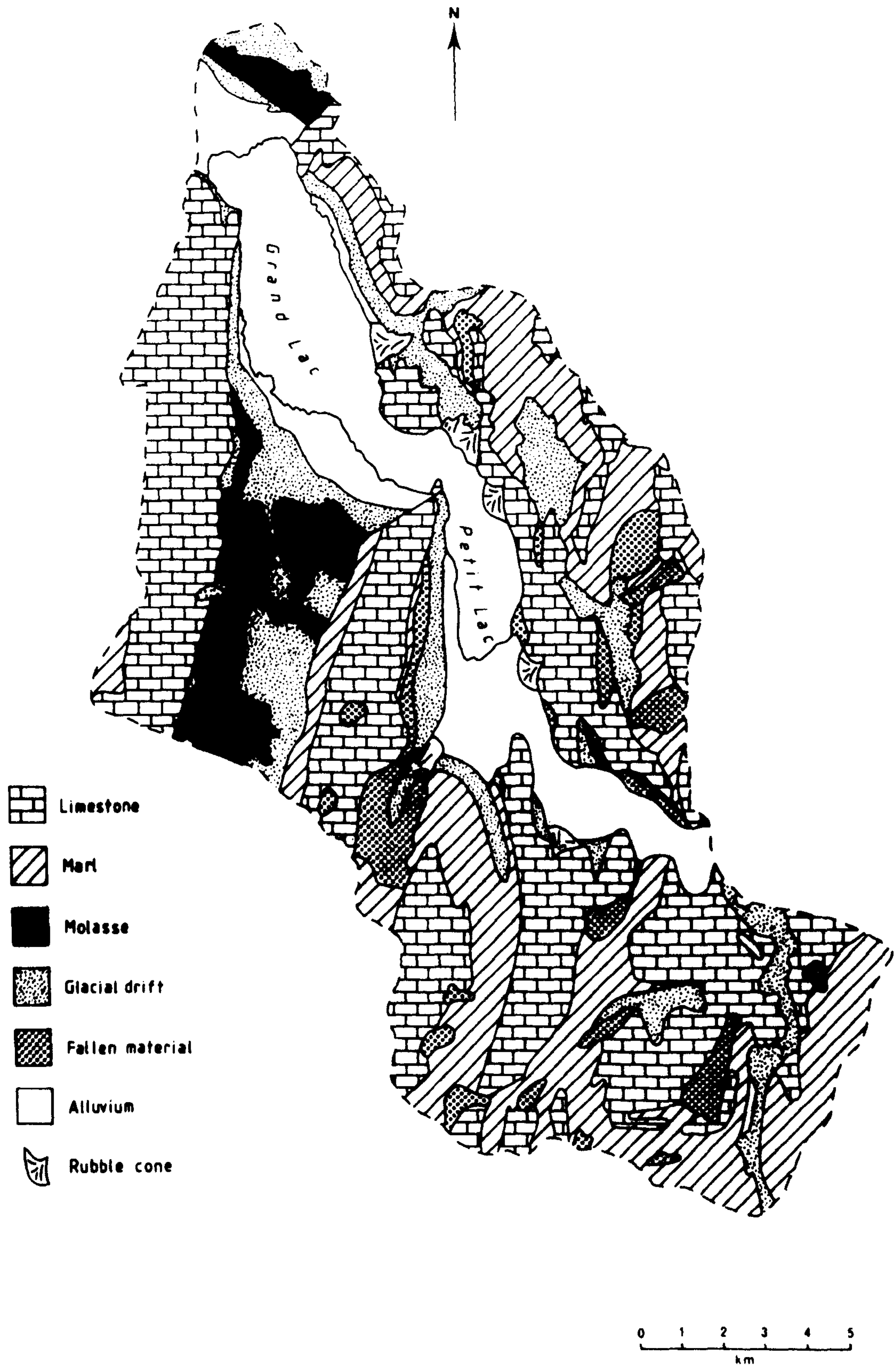
Throughout the Holocene the lake level has continued to vary in response to changes in climatic regime (see Benedetti-Crouzet, 1972), notably during the Sub-Boreal (§ 3.1.).

Post-glacial geomorphological processes have produced rubble cones and accumulations of scree on the steeper slopes and alluvial deposits along the cluse floor (Benedetti-Crouzet, 1972).

2.2.2. Lithology of the catchment area

The calcareous lithofacies are the most widely distributed sediments in the drainage basin (figure 2.3.); limestones account for c. 33% and marls 30% of the surface of the catchment area. The

Figure 2.3. Lithology of the Lac d'Annecy drainage basin (from Finlow, 1978)


N
Grand Lac
Petit Lac
Limestone
Marl
Molasse
Glacial drift
Fallen material
Alluvium
Rubble cone
0 1 2 3 4 5
km

massive limestones generally form the steeper slopes and massif summits (cf. figure 2.2.); the Tithonique facies outcrop at the Chaîne de St. Germaine, and the Urgonien facies at the cliffs of the Dents de Lanfon and La Tournette, and at the Roc des Boeufs, Le Charbon and Montagne du Semnoz. Marls generally form the gentler slopes and valleys, but also outcrop at the perched synclines of Le Charbon and Entrevernes. Although molasse covers c. 6% of the total catchment area, its distribution is limited to the Leschaux syncline (the Laudon valley) and the Plaine des Fins in the Grand Lac sub-basin. Quaternary deposits (glacial drifts, screes and recent alluvium) cover c. 31% of the catchment area (Benedetti-Crouzet, 1972).

The distribution of the main lithofacies in the basins of the Laudon, Eau Morte, Ire and Bornette streams are listed in table 2.3. (§ 2.4.1.).

2.2.3. Major soil groups in the catchment area

The purer, massive limestones render little insoluble weathering residue and so much of the soil material in the lake basin has originated from the impure limestones, marls, sandstones, shales, schists and non-local deposits.

Shallow rendzina soils are found on the steep forested slopes over a parent material of limestone or colluvium. On marly material, or on colluvium containing little humus, brown rendzina soils have developed with A horizons relatively rich in clay. On the harder limestones (Tithonique and Urgonien facies) clay is relatively deficient, giving rise to humic carbonate soils with humus-rich A horizons.

Soils of the Brown Earth group have formed on the gentler slopes of the valley margins and benches of the Bornes and Bauges valleys

	% of area of river basin			
River basin	Limestone	Marl	Molasse	Quaternary
Laudon	35	8	28	28
Eau Morte	31	41	0	27
Ire	32	56	0	12
Bornette	17	17	0	65

Table 2.3. Lithology of the principal river basins in the Lac d'Annecy drainage basin. (after Benedetti-Crouzet, 1972).

where material has been able to accumulate and a B horizon develop. Brown calcareous soils occur where $CaCO_3$ remains in the profile, but with increasing altitude leaching becomes more intense, and decalcified acid brown soils and leached brown soils have evolved. Acid brown soils have also developed on patches of acidic parent material, for example, on the molasse deposits of the Laudon valley.

Alluvial and gley soils are largely restricted to the flat valley floor (James, 1972a and 1972b).

2.3. Climate

2.3.1. Present climate

2.3.1.1. Factors affecting the climate of the lake basin

The orientation of the Annecy cluse means the lake basin is open to continental air masses from the north, which tend to be dry, and maritime air masses from the west, which tend to bring rain. So at Annecy, winds most frequently have a northerly or westerly component.

Southerly winds are experienced less frequently but are generally humid and in summer are often accompanied by thunderstorms.

The climate of the lake basin is further influenced by local factors, viz.

- the orientation of the massif crests and valley causes variations in aspect and therefore differences in exposure to sun and wind, resulting in micro-climates which characterize the adret (south-facing) and ubac (north-facing) slopes (§ 2.6.2.)
- the effect of altitude on temperature and precipitation (see below)
- the moderating influence of the lake (see below)

(Benedetti-Crouzet, 1972).

2.3.1.2. Temperature

Temperature is very closely related to altitude (figure 2.4.a; cf. figure 2.2.); a gradient of 0·6°C decrease in temperature per 100m increase in altitude has been determined. Annecy (448m) has a mean annual temperature of 10·3°C while that at Montmin (1020m) is only 6°C. The summits of the basin are estimated to have a mean annual temperature of c. 0°C.

The mean annual temperature at Glières (9·5°C) is lower than that at Annecy despite being at the same altitude. The annual temperature range is also lower; 16·5°C at Glières compared with 19·6°C at Annecy (figure 2.5.). Both are due to the location of Glières at the southern end of the lake (Benedetti-Crouzet, 1972).

2.3.1.3. Precipitation

Precipitation is high throughout the lake basin, largely due to the incursion of the maritime air masses; Annecy has a mean annual precipitation of 1160mm.

Precipitation levels are also related to altitude (figure 2.4.b; cf. figure 2.2.); annual precipitation increases by 70mm for every 100m increase in altitude, and above 1200m this gradient is probably even steeper.

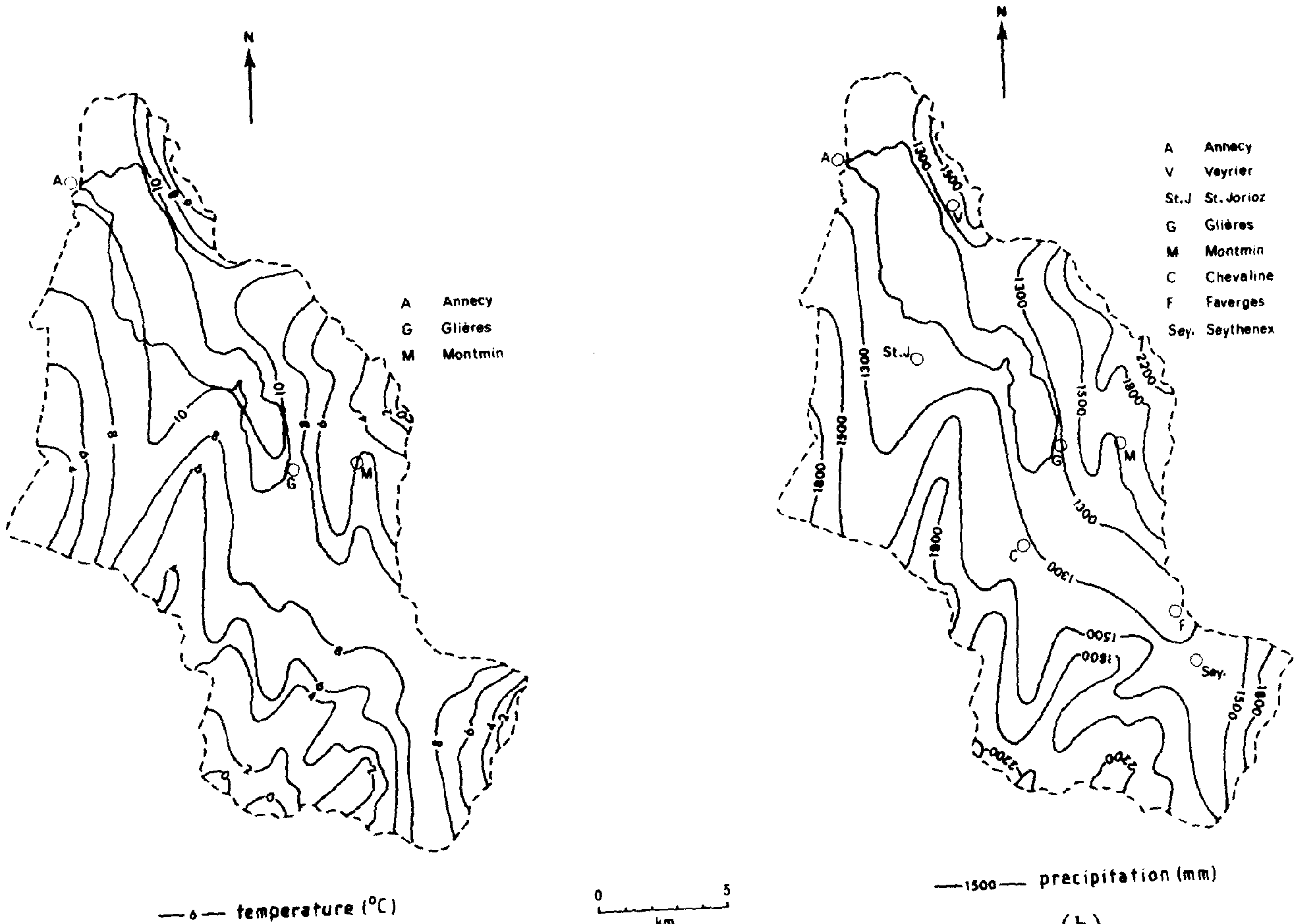
The wettest month of the year is generally February and October the driest (figure 2.6.) (Benedetti-Crouzet, 1972).

The lake basin experiences heavy falls of snow during the winter, especially at high altitudes; on average Montmin receives 2·7m of snow annually, between 6th. November and 24th. April (cf. an average of 0·53m at Annecy falling between 4th. December and 3rd. March) (Richard, 1973).

2.3.2. Secular warming of the nineteenth century

Annecy has one of the earliest meteorological series in France;

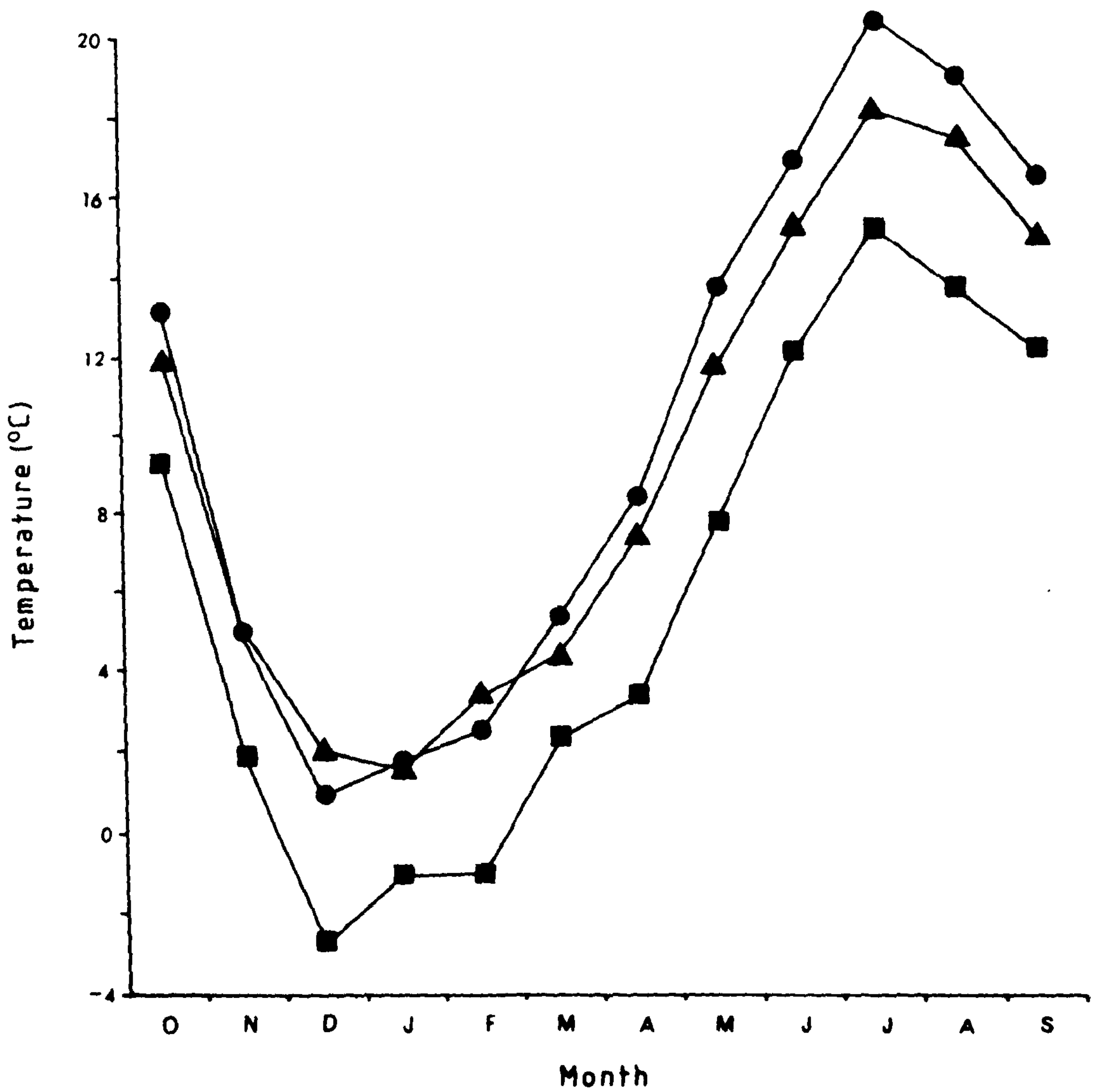
Figure 2.4. Mean annual temperature and precipitation in the Lac d'Annecy drainage basin for the years 1966 - 1967, 1968 - 1969 and 1969 - 1970 (from Benedetti-Crouzet, 1972)
(a) temperature; (b) precipitation.


N
A Annecy
G Glières
M Montmin
—6— temperature (°C)
0 5
km
N
A Annecy
V Veyrier
St.J St. Jorioz
G Glières
M Montmin
C Chevaline
F Faverges
Sey. Seythenex
—1500— precipitation (mm)

(a)

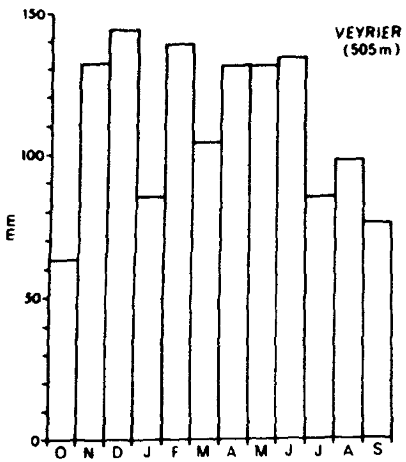
(b)

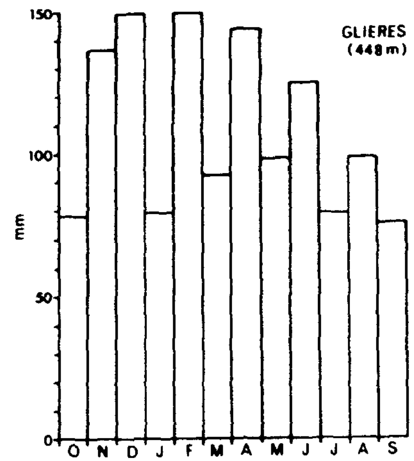
Figure 2.5. Mean monthly temperatures at Annecy (448m), Glières (448m) and Montmin (1020m) for the years 1966 - 1967, 1968 - 1969 and 1969 - 1970 (data from Benedetti-Crouzet, 1972) (Key: ● Annecy; ▲ Glières; ■ Montmin)

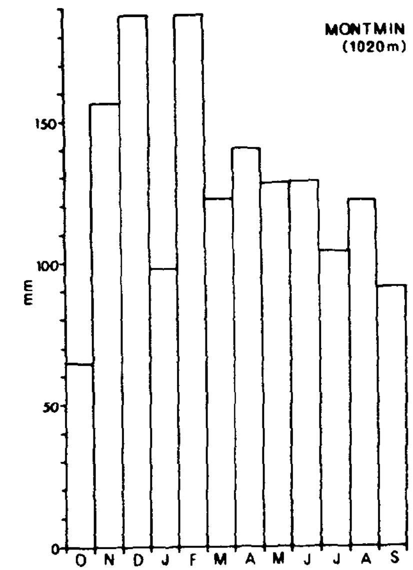


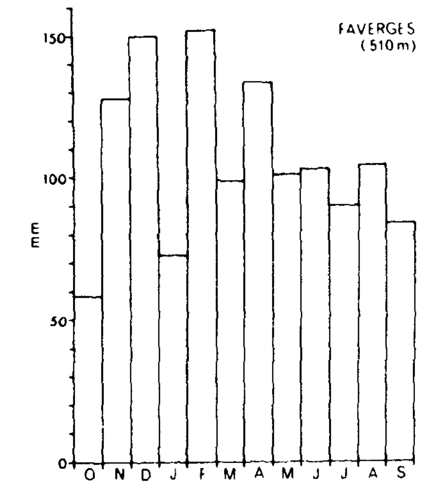
20
16
12
8
4
0
-4
Temperature (°C)
O
N
D
J
F
M
A
M
J
J
A
S
Month

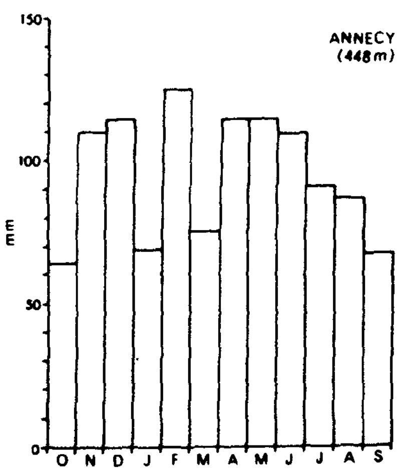
Figure 2.6. Mean monthly precipitation at Annecy, Veyrier, Glières, Montmin, Faverges, Seythenex, Chevaline and St. Jorioz for the years 1966 - 1967, 1968 - 1969 and 1969 - 1970 (data from Benedetti-Crouzet, 1972)

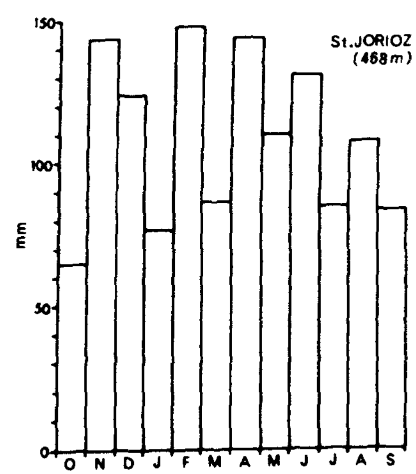

VEYRIER
(505m)
mm
0
50
100
150
O N D J F M A M J J A S

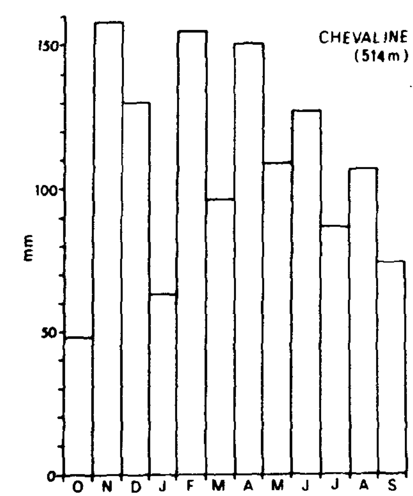

GLIERES
(448m)
mm
0
50
100
150
O N D J F M A M J J A S

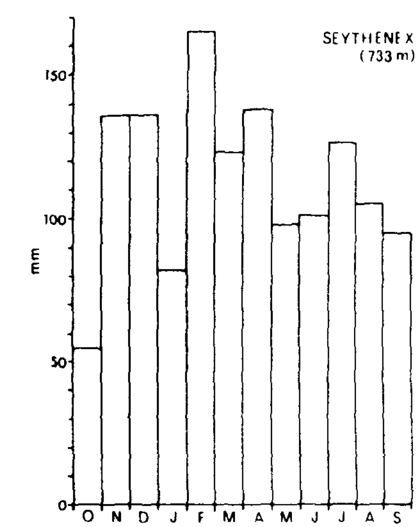

MONTMIN
(1020m)
mm
0
50
100
150
O N D J F M A M J J A S


FAVERGES
(510m)
mm
0
50
100
150
O N D J F M A M J J A S


ANNECY
(448m)
mm
0
50
100
150
O N D J F M A M J J A S


St.JORIOZ
(468m)
mm
0
50
100
150
O N D J F M A M J J A S


CHEVALINE
(514m)
mm
0
50
100
150
O N D J F M A M J J A S


SEYTHENEX
(733m)
mm
0
50
100
150
O N D J F M A M J J A S

meteorological and phenological observations have been noted since 1773. Early records included daily temperature and the occurrence, or otherwise, of precipitation, together with the arrival of the earliest and latest winter snows (Ladurie, 1972; Mougin, 1912 and 1925).

Data for the mean annual temperature, annual frequency of precipitation and the dates of the first and last snows of winter at Annecy have been calculated as decennial means for the period 1773 - 1913 (figure 2.7.). All parameters indicate that a milder climate prevailed during the second half of the nineteenth century compared with earlier decades.

The period 1773 - 1852 experienced precipitation more frequently, implying higher precipitation totals, and was generally cooler, 0·5 - 1°C, than later decades. These trends coincided with the growth of glaciers in the Mont Blanc massif (Ladurie, 1972; Mougin, 1912).

All seasons of the year grew milder after 1842 (except winters after 1882) (figure 2.8.), correlating with retreat of the Alpine glaciers (Ladurie, 1972).

The dates of wine-harvests in the lake basin reflect the amelioration of the climate described above (figure 2.9.); harvests were gathered about a week earlier in the second half of the nineteenth century (Mangé, 1883).

2.4. Hydrology

2.4.1. Drainage network

The principal streams flowing into the Lac d'Annecy are the Laudon and Biolon in the Grand Lac sub-basin, draining c. 44% of its catchment area, and the Eau Morte, Ire, Bornette, Nant d'Oy and Ruisseau d'Entrevernes in the Petit Lac sub-basin, draining 86% of its catchment area (figure 2.10.).

Figure 2.7. Mean decennial temperatures, frequency of precipitation and length of winter (period between first and last snow) at Annecy, 1773 - 1913 (data from Mougin, 1912)
The dotted line indicates the mean value for the fourteen decades recorded.

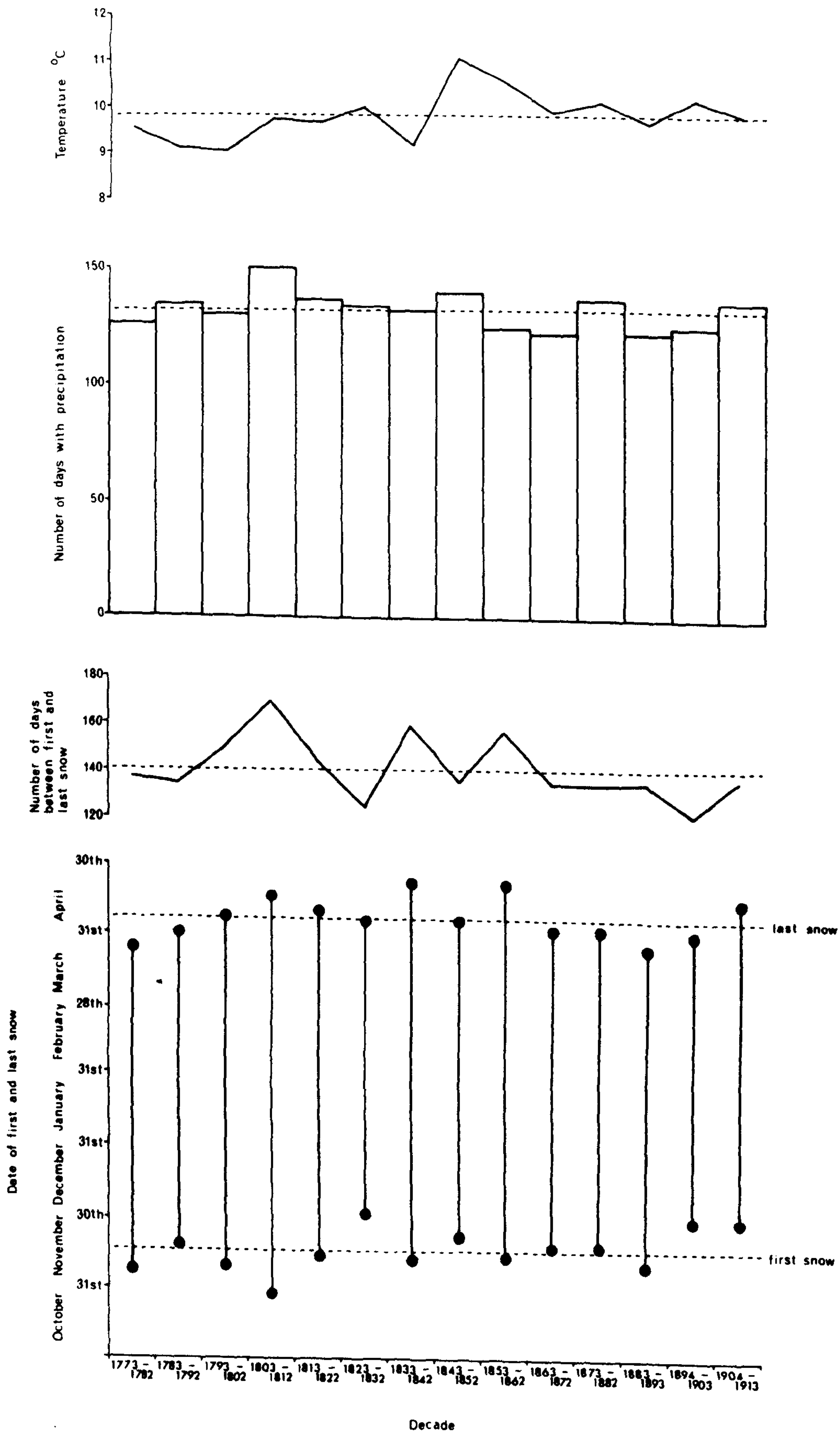

Temperature °C
12
11
10
9
8
Number of days with precipitation
150
100
50
0
Number of days between first and last snow
180
160
140
120
Date of first and last snow
30th
April
31st
March
28th
February
31st
January
31st
December
30th
November
31st
October
last snow
first snow
1773 – 1782
1783 – 1792
1793 – 1802
1803 – 1812
1813 – 1822
1823 – 1832
1833 – 1842
1843 – 1852
1853 – 1862
1863 – 1872
1873 – 1882
1883 – 1893
1894 – 1903
1904 – 1913
Decade

Figure 2.8. Mean decennial seasonal temperatures at Annecy, 1773 - 1913 (data from Mougin, 1912) The dotted line indicates the mean value for the fourteen decades recorded.

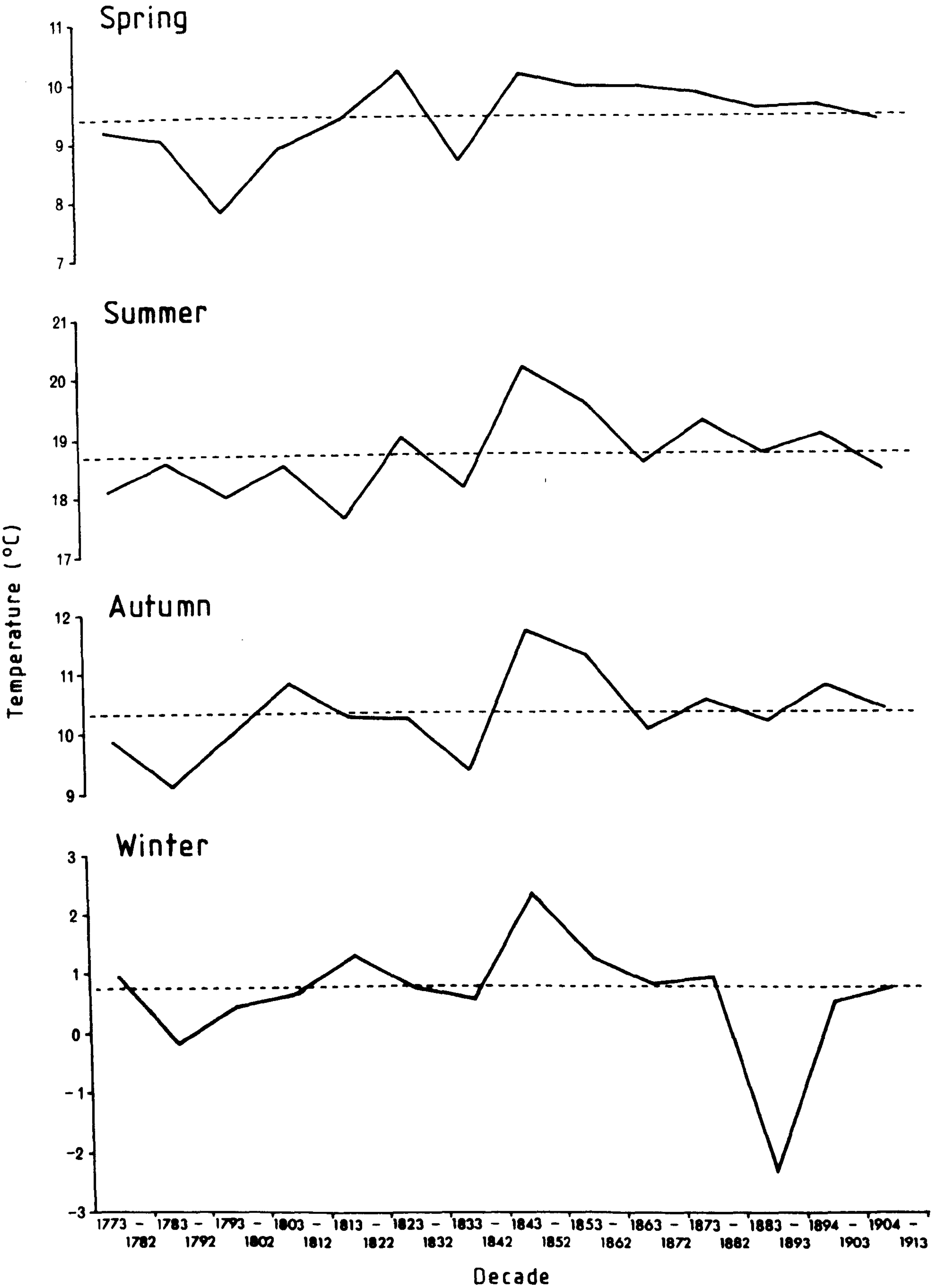

Spring
11
10
9
8
7
Summer
21
20
19
18
17
Autumn
12
11
10
9
Winter
3
2
1
0
-1
-2
-3
Temperature (°C)
1773 - 1782
1783 - 1792
1793 - 1802
1803 - 1812
1813 - 1822
1823 - 1832
1833 - 1842
1843 - 1852
1853 - 1862
1863 - 1872
1873 - 1882
1883 - 1893
1894 - 1903
1904 - 1913
Decade

Figure 2.9. Dates of wine-harvests in the Lac d'Annecy drainage basin in the late 18th. and 19th. centuries (data from Mangé, 1883)
The dotted line indicates the mean value for each set of data.

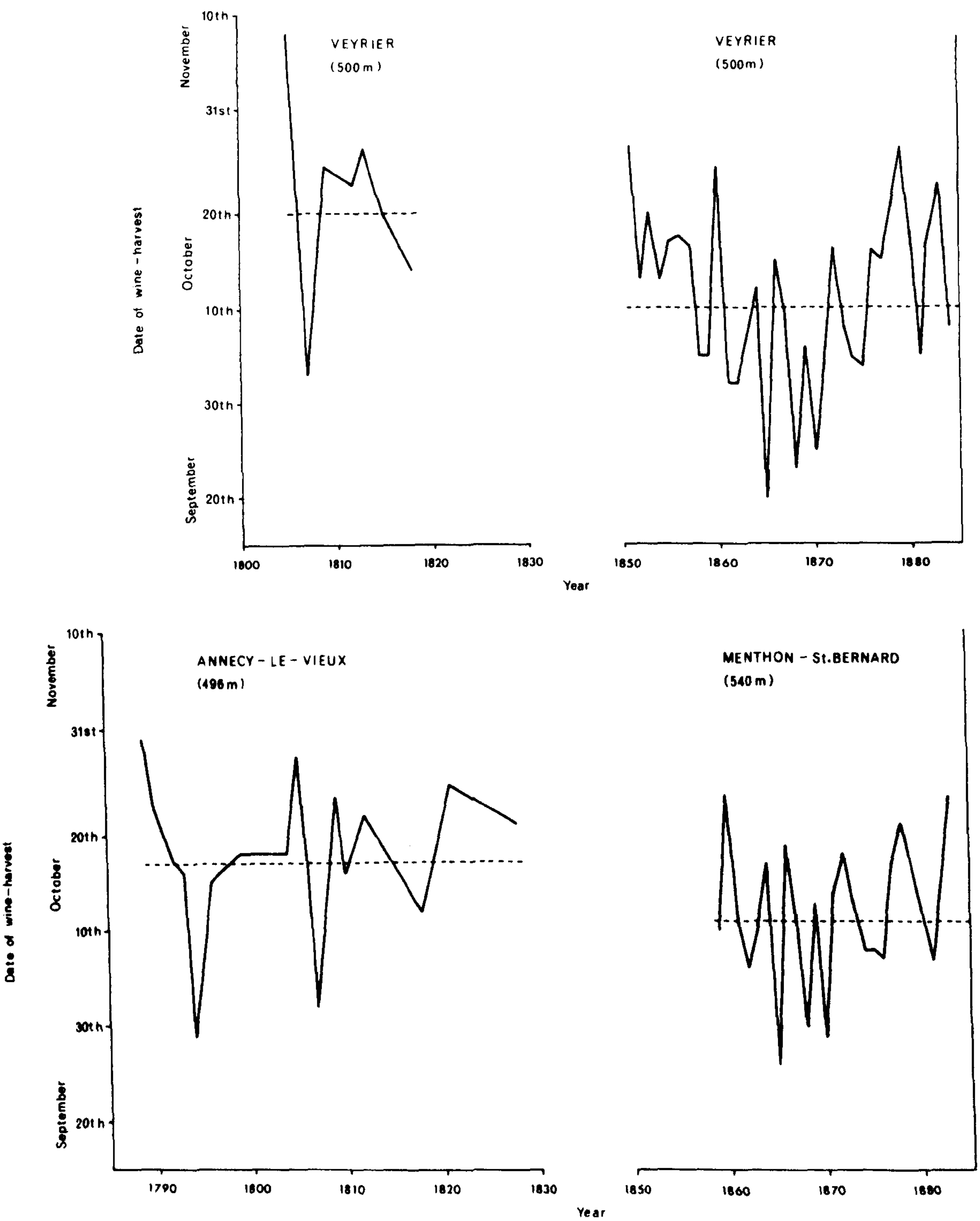
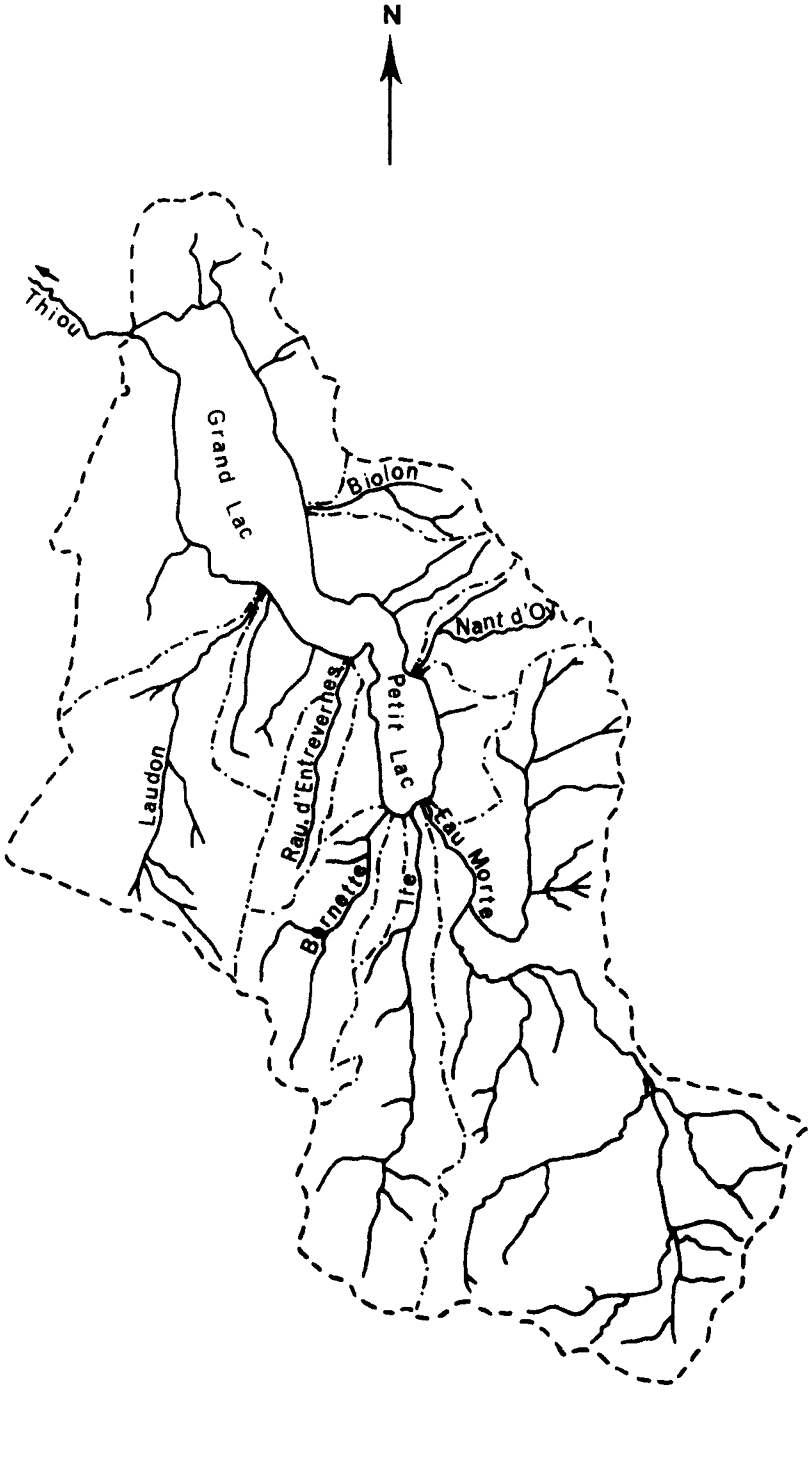

VEYRIER
(500 m)
VEYRIER
(500m)
ANNECY - LE - VIEUX
(496 m)
MENTHON - St.BERNARD
(540 m)
Date of wine - harvest
November
October
September
10th
31st
20th
10th
30th
20th
1790
1800
1810
1820
1830
1850
1860
1870
1880
Year

Figure 2.10. Drainage network of the Lac d'Annecy drainage basin (from Benedetti-Crouzet, 1972)


N
Thiou
Grand Lac
Biolon
Nant d'Oy
Petit Lac
Laudon
Rau. d'Entreverhes
Bornette
Ire
Eau Morte
0
5
km

The most important streams in terms of volume of water carried into the lake are the Eau Morte (42% of total inflow), the Ire (15%) and the Laudon (12%) (Benedetti-Crouzet, 1972).

The principal morphometric and hydrological characteristics of these tributaries are given in table 2.4.

Due to the relatively high rainfall experienced in the drainage basin, specific discharges are generally high, although there is some variation according to the altitude of the river basin and therefore the amount of precipitation received; the Ruisseau d'Entrevernes and Biolon, which drain land at relatively low altitudes, have the lowest specific discharges and the Ire, for most of its course a mountain torrent, the highest. This is reflected on a sub-basin scale; the Laudon and Biolon basins cover c. 14% of the total catchment area of the Lac d'Annecy and account for c. 13·5% of the total inflow, whereas the Eau Morte, Ire, Bornette, Nant d'Oy and Ruisseau d'Entrevernes basins together cover 58% of the total catchment area and yet their streams carry nearly 70% of the total inflow into the lake, reflecting the generally higher altitude of the Petit Lac sub-basin (figure 2.2.) and the higher precipitation (figure 2.4.b.).

The outlet of the lake consists of two canals, the Canal de Thiou and the Canal de Vassé, which join to form the Thiou, a tributary of the Fier and part of the Rhône system (figure 2.1.) (Benedetti-Crouzet, 1972).

2.4.2. River regimes

The streams have a nivo-pluvial regime; their maximum discharge is observed in spring following snow-melt, generally during the months of March - May. Minimum flows occur in the autumn, usually in September and October, the driest period of the year (q.v. figure 2.6.).

	Area (km²) [1]	Length of stream (km) [2]	Estimated proportion of total inflow (%) [2]	Average slope (%) [1]	Average altitude (m) [1]	Maximum altitude (m) [1]	Specific discharge 1/s/km² 1966-67 [1]	Specific discharge 1/s/km² 1968-69 [2]
<u>Grand Lac</u>								
Laudon	29·55	12·0	12	7·9	947	1699	19·3	30·8
Biolon	5·64	4·7	1·5	22·4	785	1824	18·5	
<u>Petit Lac</u>								
Eau Morte	90·99	20·0	42	6·2	1075	2254	33·6	37·0
Ire	27·64	12·5	15	9·2	1305	1932	35·5	40·0
Bornette	13·26	7·7	7	13·6	1055	1907	32·5	
Nant d'Oy	7·91	3·7	4	28·6	1075	2160	32·0	40·5
Ruisseau d'Entrevernes	6·74	5·7	1·5	10·9	870	1636	15·9	20·9

Table 2.4. Morphometric and hydrological characteristics of the principal river basins in the Lac d'Annecy drainage basin ([1] from Danloux, 1968; [2] from Benedetti-Crouzet, 1972).

Hydrographs for the principal streams of the drainage basin for the years 1966 - 1967, 1968 - 1969 and 1969 - 1970 are shown in figures 2.11. and 2.12.

Snow depth and temperature are the two most important controls over the timing of peak discharge in spring.

Maximum discharge is observed relatively early in the Ruisseau d'Entrevernes; its basin lies at relatively low altitudes and so experiences lighter falls of snow and earlier snow-melt. In contrast, the Nant d'Oy has its maximum discharge later in the spring as its basin is one of relatively high altitude, and therefore receives greater accumulations of snow and snow-melt is relatively late.

In 1968 - 1969 peak discharges for the main streams (Eau Morte, Ire and Laudon) occurred in April, whereas in 1969 - 1970 snow-melt was delayed due to the depth of snow that had accumulated during the snowy winter and so maximum flows were observed at the end of April - May.

A second maximum is observed in December due to the arrival of warm, humid maritime air masses which raise the temperature and cause the early snow to melt.

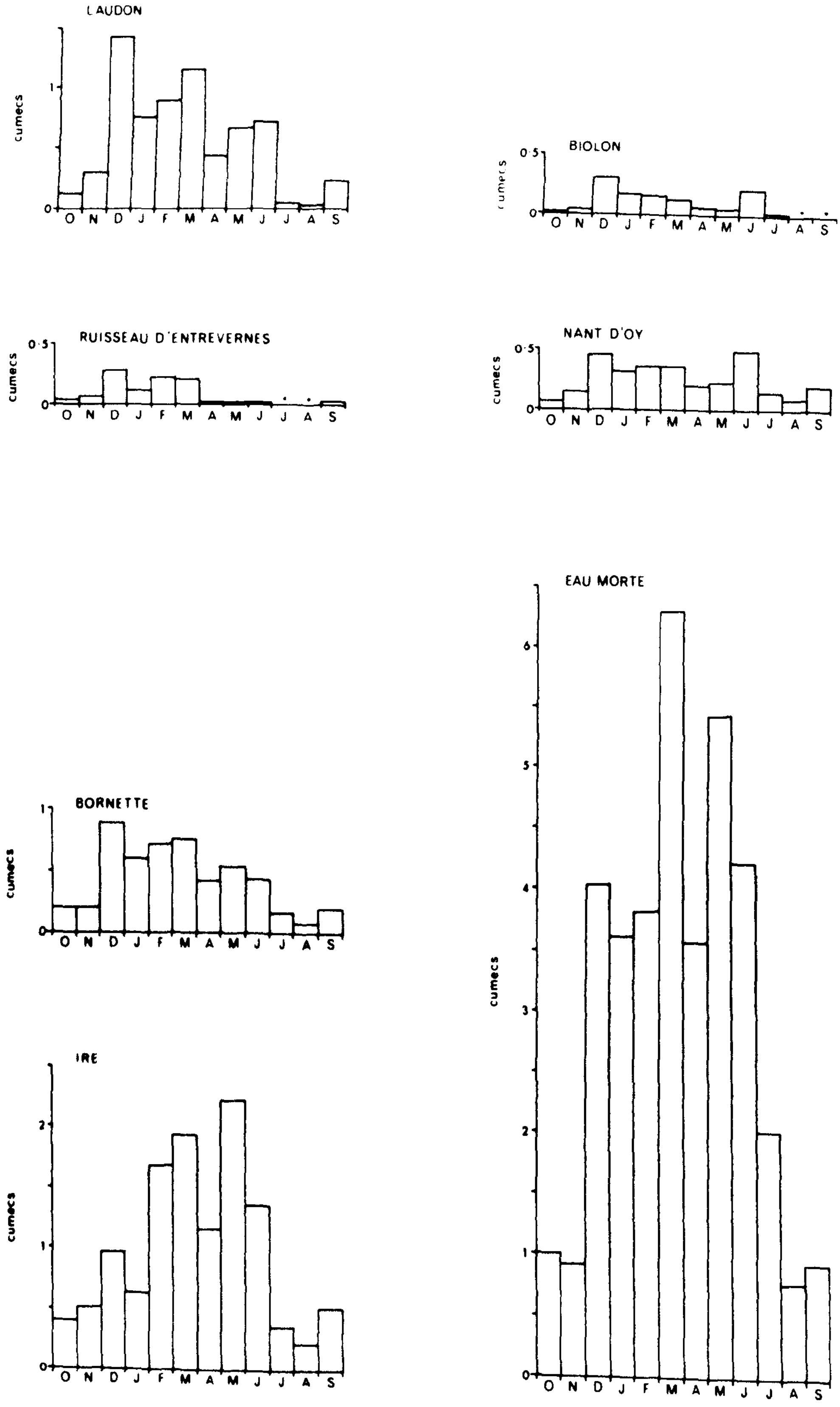
Peak discharges also result from prolonged periods of rainfall throughout the year, and also the heavy rainfall associated with summer storms (Benedetti-Crouzet, 1972).

2.4.3. Lake levels

The lake responds very quickly to increases in the discharge of the tributary streams due to the relative size of its catchment area; the lake occupies only 9·5% of the total drainage basin (§ 2.1.).

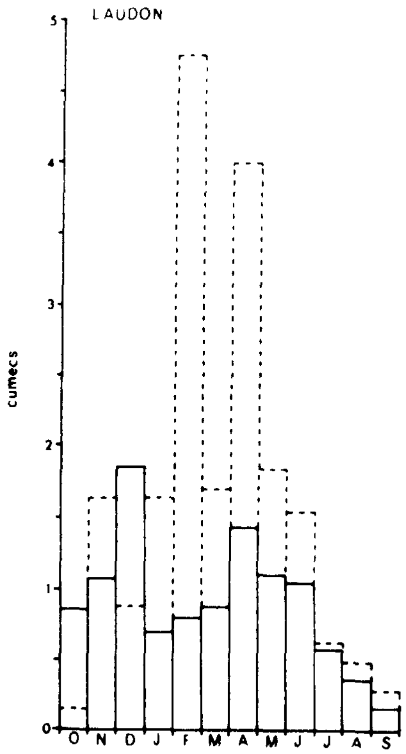
The installation of new sluices in the canals at the lake's outflow in 1965 - 1966 means that variations in lake level are now limited, rising by 0·5m at the most (Benedetti-Crouzet, 1972).

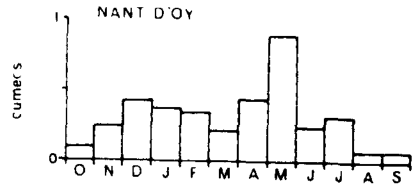
Figure 2.11. Hydrographs for the Biolon, Nant d'Oy, Eau Morte, Ire, Bornette, Ruisseau d'Entrevernes and Laudon for the year 1966 - 1967 (data from Benedetti-Crouzet, 1972)

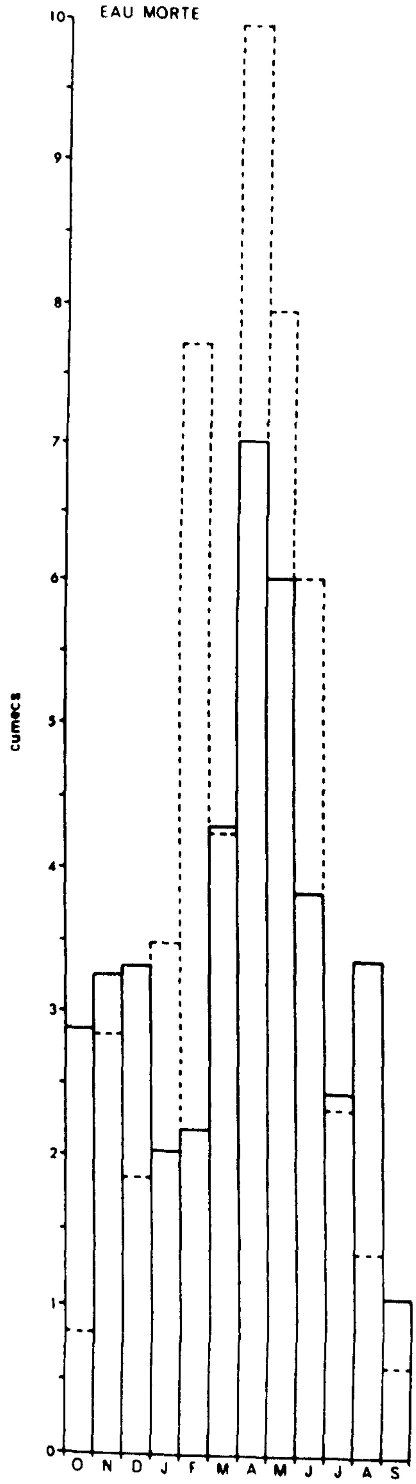

LAUDON
cumecs
0
1
O N D J F M A M J J A S
BIOLON
cumecs
0
0·5
O N D J F M A M J J A S
RUISSEAU D'ENTREVERNES
cumecs
0
0·5
O N D J F M A M J J A S
NANT D'OY
cumecs
0
0·5
O N D J F M A M J J A S
BORNETTE
cumecs
0
1
O N D J F M A M J J A S
IRE
cumecs
0
1
2
O N D J F M A M J J A S
EAU MORTE
cumecs
0
1
2
3
4
5
6
O N D J F M A M J J A S

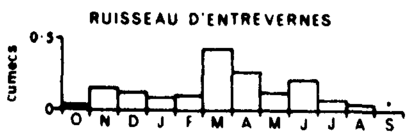
• <0·01 cumecs

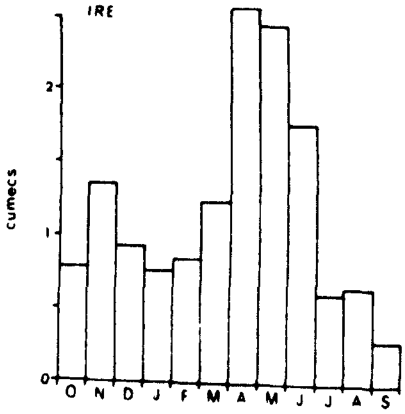
Figure 2.12. Hydrographs for the Nant d'Oy, Eau Morte, Ire, Ruisseau d'Entrevernes and Laudon for the year 1968 - 1969 (solid lines), and for the Eau Morte and Laudon for the year 1969 - 1970 (dotted lines) (data from Benedetti-Crouzet, 1972)


LAUDON
cumecs
0
1
2
3
4
5
O N D J F M A M J J A S


NANT D'OY
cumecs
0
1
O N D J F M A M J J A S


EAU MORTE
cumecs
0
1
2
3
4
5
6
7
8
9
10
O N D J F M A M J J A S


RUISSEAU D'ENTREVERNES
cumecs
0
0·5
O N D J F M A M J J A S


IRE
cumecs
0
1
2
O N D J F M A M J J A S

• < 0·01 cumecs

However, before this, the lake has been very susceptible to sudden showers and snow-melt and a series of floods have been recorded at Annecy when the canals have been unable to accommodate the increased discharge (table 2.5.). The lake has risen by as much as 0·4m in twenty four hours (Onde, 1944), which could be achieved by only 80 - 100mm of rainfall (c. 12mm/hour) falling in the drainage basin, assuming that 50% of the rainfall flowed directly into the stream channels (Benedetti-Crouzet, 1972).

2.5. Limnology

2.5.1. Morphology of the lake depression

The narrow neck of water separating the Grand Lac and Petit Lac is due to the presence of a sill of rock formed by the Roc de Chère, (possibly a fallen mass of rock from the Tournette massif), and the Montagne d'Entrevernes anticline. (The bathymetry of the Lac d'Annecy is shown in figure 4.1.).

Both sub-basins consist of a flat, central plain, at up to 65m depth in the Grand Lac and 55m depth in the Petit Lac, surrounded by a talus slope (4 - 40%) which is only absent at the Roc de Chère, where the central plain meets a 100m high near-vertical cliff, and at the Duingt peninsula where there is a smaller cliff (figure 2.13.).

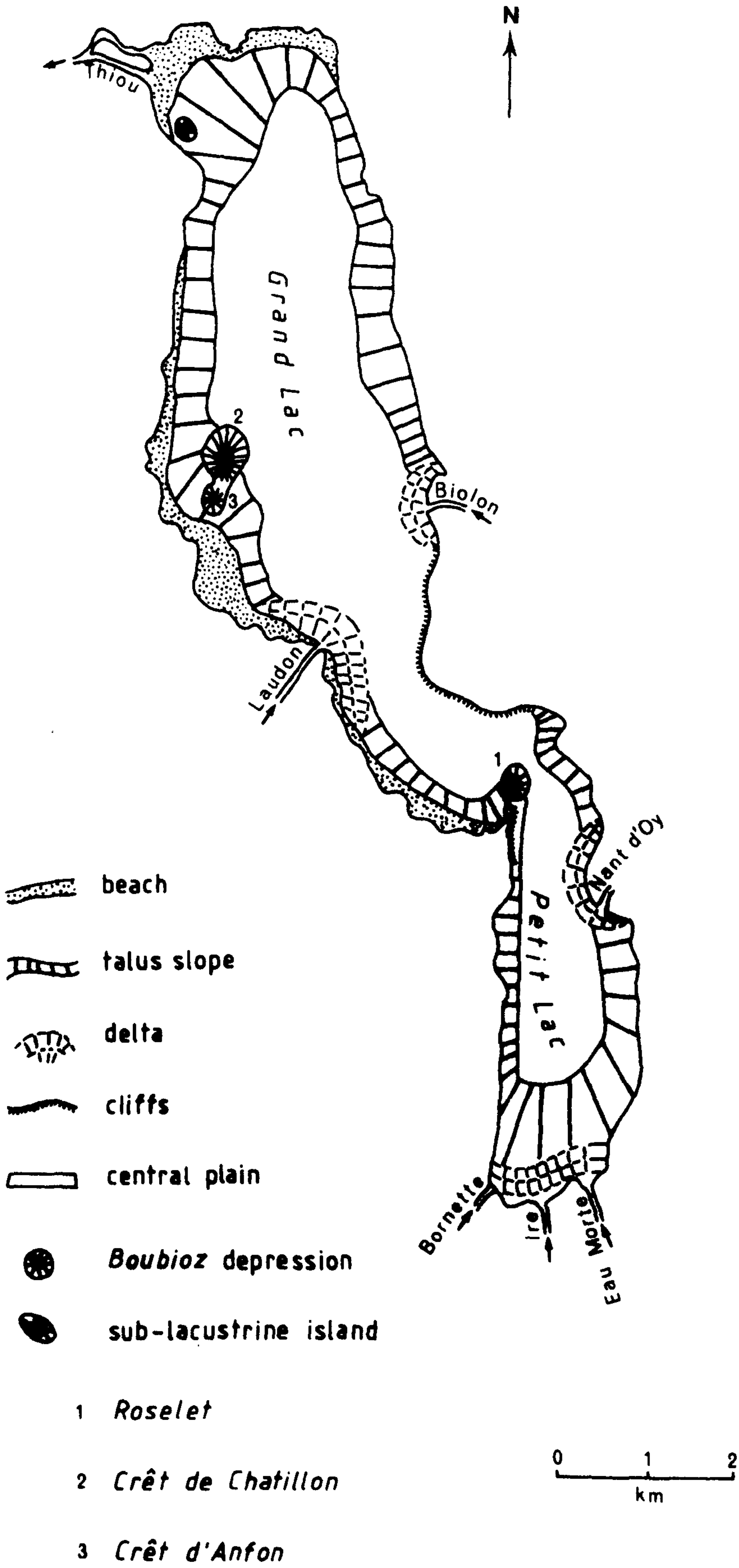
The talus slope is locally covered by rubble cones deposited by the tributary streams. The largest is that of the Laudon, its extent due to the lithological characteristics of its basin (q.v. table 2.3.). The delta of the Eau Morte has a gentler slope as the load transported by this river is much finer. The Ire and Bornette, however, have filled in the southern extremity of the Petit Lac with coarser sediments.

Date	Height of flood (m)†	Date	Height of flood (m)†
December 1570[4]		November 1840[3,4]	1·62
May 1575[4]		March 1876[4,5]	1·32
October 1583[4]		May 1877[4,5]	1·24
May 1640[4]		July 1879[4,5]	1·24
June 1649[4]		November 1882[4,5]	1·44
January 1651[2,4,5]	2·70	January 1883[4,5]	1·34
November 1651[3,4]		June 1889[4,5]	1·21
February 1658[4]		March 1895[4,5]	1·38
April 1665[4]		September 1896[4,5]	1·25
July 1673[4]		April 1897[4,5]	1·28
June 1689[4]		January 1899[4,5]	1·40
July 1703[4]		April 1901[4,5]	1·22
February 1711[1,3,4,5]	3·10	March 1902[4,5]	1·36
January 1728[4]		January 1910[4,5]	1·45
December 1740[4]		March 1914[4,5]	1·29
July 1758[3,4]	2·00	April 1914[5]	1·24
August 1774[4]		December 1916[5]	1·35
September 1778[3,4]		December 1918[5]	1·58
December 1801[3,4]	1·70	April 1922[5]	1·36
March 1806[3,4]		December 1925[5]	1·25
February 1807[3,4]	1·68	February 1928[5]	1·34
July 1816[3,4]		March 1931[5]	1·34
October 1820[4]			

† zero on the scale (Annecy) is 446·275m above sea level

Table 2.5. Significant floods of the Lac d'Annecy, 1570 - 1931. (from [1]Serand, 1870; [2]Ducis, 1875; [3]Tissot, 1875; [4]Crolard, 1909 and 1910; [5]Onde, 1944).

Figure 2.13. Underwater morphology of the Lac d'Annecy (from Benedetti-Crouzet, 1972)


N
Thiou
Grand Lac
2
3
Biolon
Laudon
1
Nant d'Oy
Petit Lac
Bornette
Ire
Eau Morte
beach
talus slope
delta
cliffs
central plain
Boubioz depression
sub-lacustrine island
1 *Roselet*
2 *Crêt de Chatillon*
3 *Crêt d'Anfon*
0 1 2
km

The Lac d'Annecy has three sub-lacustrine islands. The Ilot de Roselet, at 1m depth, is separated from the Duingt peninsula by a narrow, 17m deep channel of water. It is part of the Entrevernes anticline. The Crêt de Chatillon (3m depth) and Crêt d'Anfon (8m depth) are 800m and 450m respectively from the lake-side near Sevrier and separated from the mainland by a 40m deep channel of water (§ 3.1.). Both are thought to be erratic blocks.

Le Boubioz is an underwater spring, located 200m from the lake-side at Annecy. It consists of an elliptical opening measuring 200m × 250m, extending in a conical shape to a depth of 82m. The source of the spring water is the Urgonien facies of the Montagne du Semnoz.
(Benedetti-Crouzet, 1972).

2.5.2. Thermal characteristics of the lake

For most of the time the Lac d'Annecy can be classified as a monomictic lake; during the summer the water body is stratified, while in winter it is isothermal from surface to bottom.

The annual cycle of temperature conditions within the lake is summarized in figure 2.14., and can be seen to be closely related to climatic conditions. Temperature profiles for the end of the summer stagnation period and winter are shown in figure 2.15.

During the spring, the surface waters are gradually warmed, primarily by solar radiation. The heated surface layer is mixed downward by wind action, and by about May, the warmer and therefore lighter water of the epilimnion becomes distinct, lying above the cooler and denser water of the hypolimnion. The epilimnion attains its maximum temperature by about July to August, at which time the temperature gradient of the thermocline (at c. 10 - 15m depth) may be nearly 7°C per metre. Benedetti-Crouzet (1972) estimates that the

Figure 2.14. Seasonal cycle of temperature conditions in the Lac d'Annecy (from Balvay, 1978)

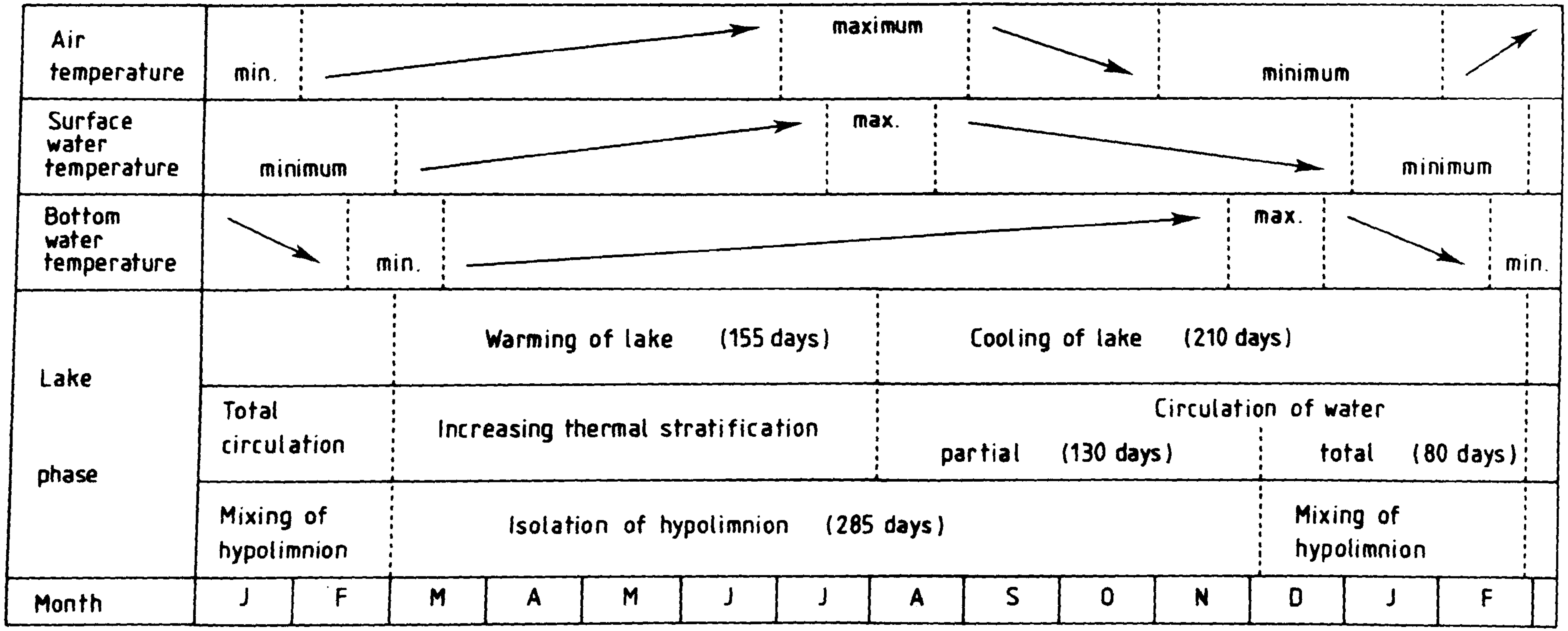
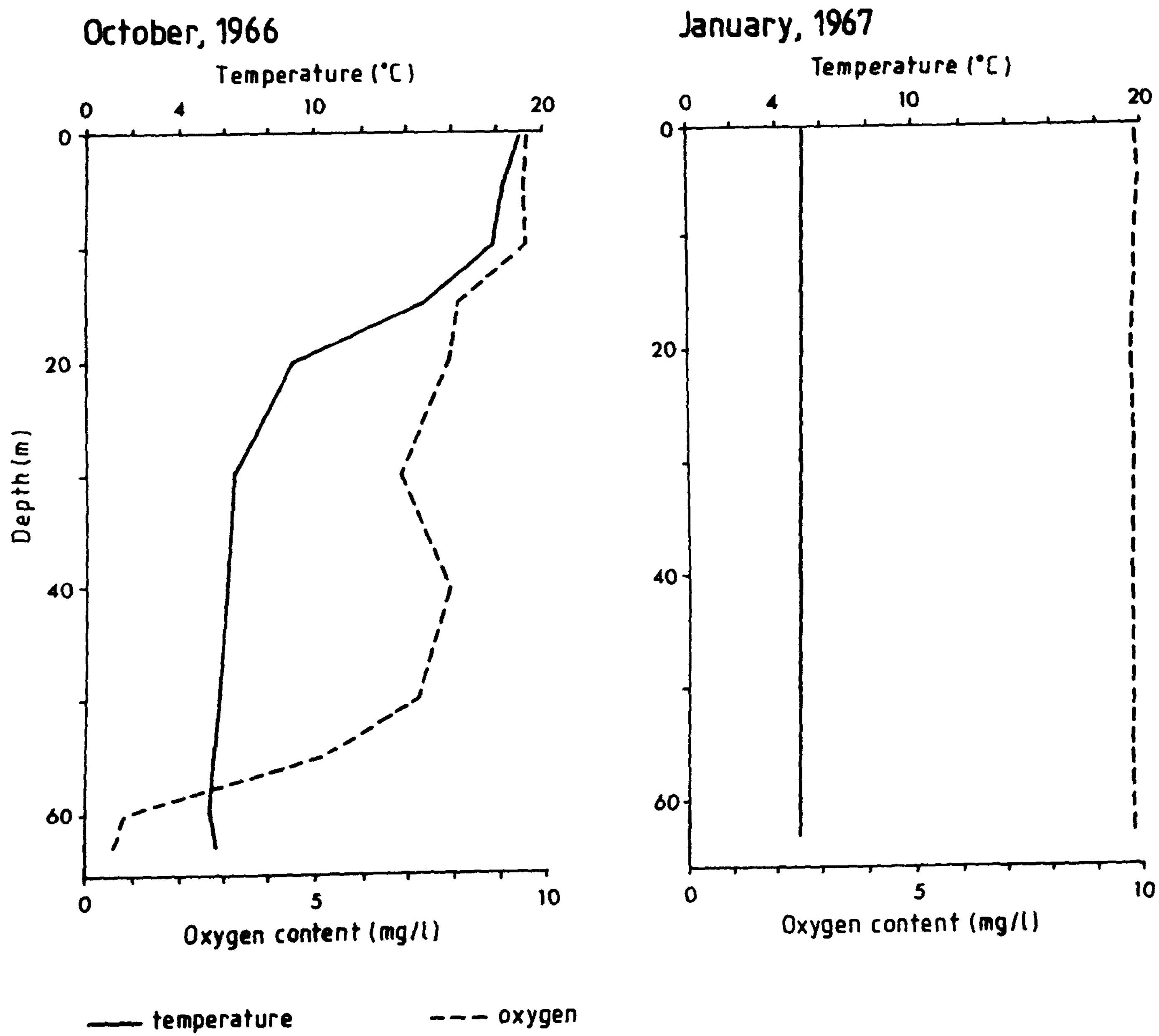

Air temperature
min.
maximum
minimum
Surface water temperature
minimum
max.
minimum
Bottom water temperature
min.
max.
min.
Lake phase
Warming of lake (155 days)
Cooling of lake (210 days)
Total circulation
Increasing thermal stratification
Circulation of water
partial (130 days)
total (80 days)
Mixing of hypolimnion
Isolation of hypolimnion (285 days)
Mixing of hypolimnion
Month
J
F
M
A
M
J
J
A
S
O
N
D
J
F

Figure 2.15. Temperature and oxygen profiles in the centre of the Grand Lac, Lac d'Annecy (from Balvay, 1967b)
(a) at the end of the summer stagnation period (10 October 1966); (b) following the autumn "overturn" (19 January 1967).


October, 1966
Temperature (°C)
0
4
10
20
0
20
40
60
Depth (m)
0
5
10
Oxygen content (mg/l)
January, 1967
Temperature (°C)
0
4
10
20
0
20
40
60
0
5
10
Oxygen content (mg/l)
temperature
oxygen

epilimnion will have a volume of ca. 373 × $10^6 m^3$ and the hypolimnion a volume of ca. 750 × $10^6 m^3$, or 75% of the total volume of the lake.

From August onwards, cooling of the air above the lake causes loss of heat from surface waters. This cooler, denser water descends conductively and cooling occurs throughout the epilimnion. Strong winds during the autumn help to mix the water. This partial circulation (the autumn "overturn") causes the epilimnion to increase in depth while its average temperature gradually decreases. Accordingly, the thermocline descends and decreases in intensity until, eventually, by about December, it disappears and the lake is no longer stratified; the surface and bottom waters are then able to mix freely and the total water body cools down, leading to minimum isothermal temperatures at the end of the winter.

Total circulation in winter may be broken by temporary periods of inverse stratification when a cold layer of water, with a temperature below 4°C, forms at the surface. Such conditions are rare, although a stable inverse stratification must have developed on the few occasions that the lake has completely frozen over (1573, 1830, 1880 and 1891) (Mangé, 1880 and 1890).

Water above the underwater spring in the Grand Lac is relatively warm; the average temperature of the water column between 30 and 80m depth is 6·2 - 6·3°C whereas elsewhere the equivalent temperature is only 5·8°C (Balvay, 1978; Balvay & Rougier-Michaud, 1967; Ragotzkie, 1978; Rougier-Michaud, 1969).

2.5.3. Oxygen content of the lake waters

The concentration of dissolved oxygen in the lake waters is essentially the balance between its production, by photosynthesis and gain from the atmosphere, and its consumption, by animal and plant respiration and organic decomposition; its distribution varies according to the season of the year.

At the end of the summer stagnation period the vertical distribution of dissolved oxygen is strongly clinograde (figure 2.15.); levels of oxygen are highest in the upper waters of the trophogenic zone, the region of maximum photosynthesis, while oxygen concentrations of the tropholytic zone decrease considerably as oxygen consumption becomes the dominant process. During the stagnation period the hypolimnion is isolated from the upper layers and becomes progressively poorer in oxygen, mainly due to the oxidation of organic material falling from the trophogenic zone above. By the end of the summer oxygen concentrations in the Grand Lac fall from 10 to 7 mg/l between 0 and 50m depth (a mean decrease of 0•06 mg/l/m), while beyond 50m they fall sharply from 7 to 0 mg/l (a decrease of 0•5 mg/l/m). However, the existence of this deoxygenated layer is not permanent; during the autumn "overturn", circulation of the whole water mass of the lake allows reoxygenation of the lower strata, and the oxygen concentration curve becomes orthograde (figure 2.15.), i.e. oxygen concentrations are more or less constant with increasing depth (c. 9•8 mg/l).

The oxygen content of the surface waters of the lake (0 - 20m depth) are actually highest during the spring (12 - 13 mg/l); at this time of the year the water temperature is still fairly low and therefore oxygen solubility is relatively high; winds are more frequent, encouraging the passage of the gas into solution across the air-water interface, and the season experiences the highest numbers of phytoplankton of the year and therefore high levels of photosynthesis. In summer, the surface waters are warmer, causing a decrease in oxygen solubility, and hence a fall in the oxygen concentration (8 - 9•5 mg/l), although the water remains supersaturated with respect to oxygen (up to 120 - 130%). Oxygen

concentrations rise again in the autumn and winter with a fall in the air temperature and therefore the surface water temperature together with a renewed increase in the frequency of winds.
(Balvay, 1967a, 1967b, 1967c and 1972; Reid, 1961; Rougier-Michaud, 1969).

The waters of the Petit Lac have been less well studied, although in February 1971 an oxygen concentration of 4·7 mg/l, at a depth of 55m, was lower than the 9·55 mg/l observed at 65m depth in the Grand Lac (Benedetti-Crouzet & Meybeck, 1971; Benedetti-Crouzet, 1972).

2.5.4. Eutrophication of the lake waters

In 1937 the Lac d'Annecy was described as "passant eutrophe"; at the end of the summer stagnation the profundal waters were observed to be more or less devoid of oxygen (0·56mg O_2/l at 63·5m depth in the Grand Lac and 2·9mg O_2/l at 54·5m depth in the Petit Lac) while the blue-green alga *Oscillatoria* (which thrives in highly trophic conditions) was identified in the surface waters, and the dipteran insect *Chaoborus* (which tolerates near anoxic conditions) was present in the benthos (Hubault, 1947).

The situation seemed to have worsened by 1952 when the bottom waters of the Grand Lac appeared to be yet more deoxygenated with a concentration of only 0·3mg O_2/l at 62m depth (Suchet, 1954).

From 1965 the composition of the plankton, and from 1966 the physico-chemical characteristics of the lake, began to be monitored regularly to assess water quality and the efficacy of a new sewage collecting system. It seems that eutrophication continued to intensify up to 1967; figure 2.16. shows the decrease in oxygen concentrations at all depths in the Grand Lac between 1937 and 1966, particularly from c. 15m depth, and figure 2.17. shows how the

Figure 2.16. Comparison of the dissolved oxygen content of waters in the centre of the Grand Lac between 5 October 1937 and 11-12 October 1966 (from Balvay, 1972)

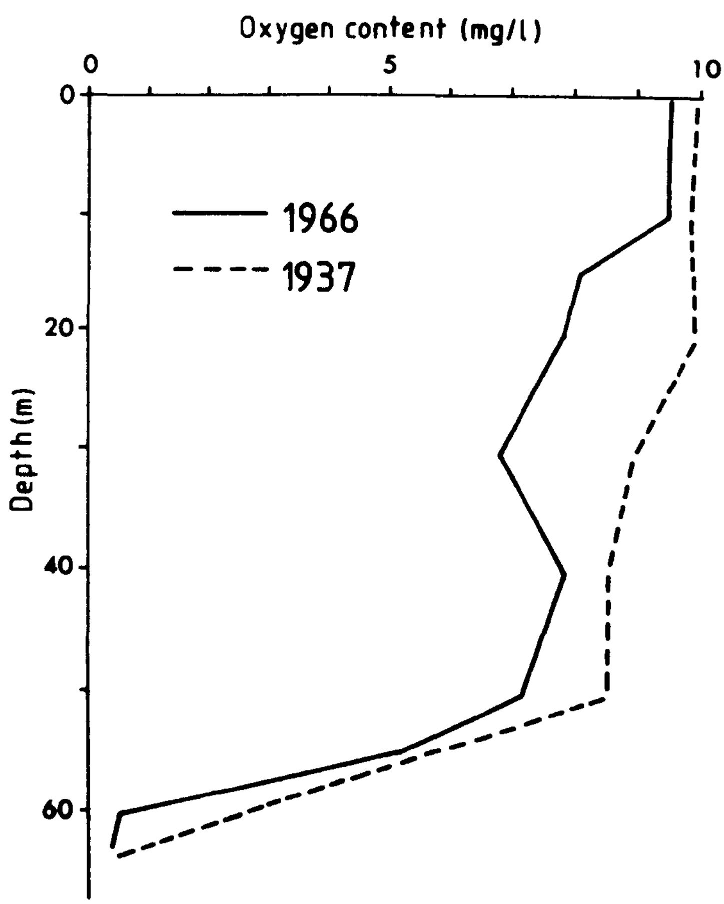
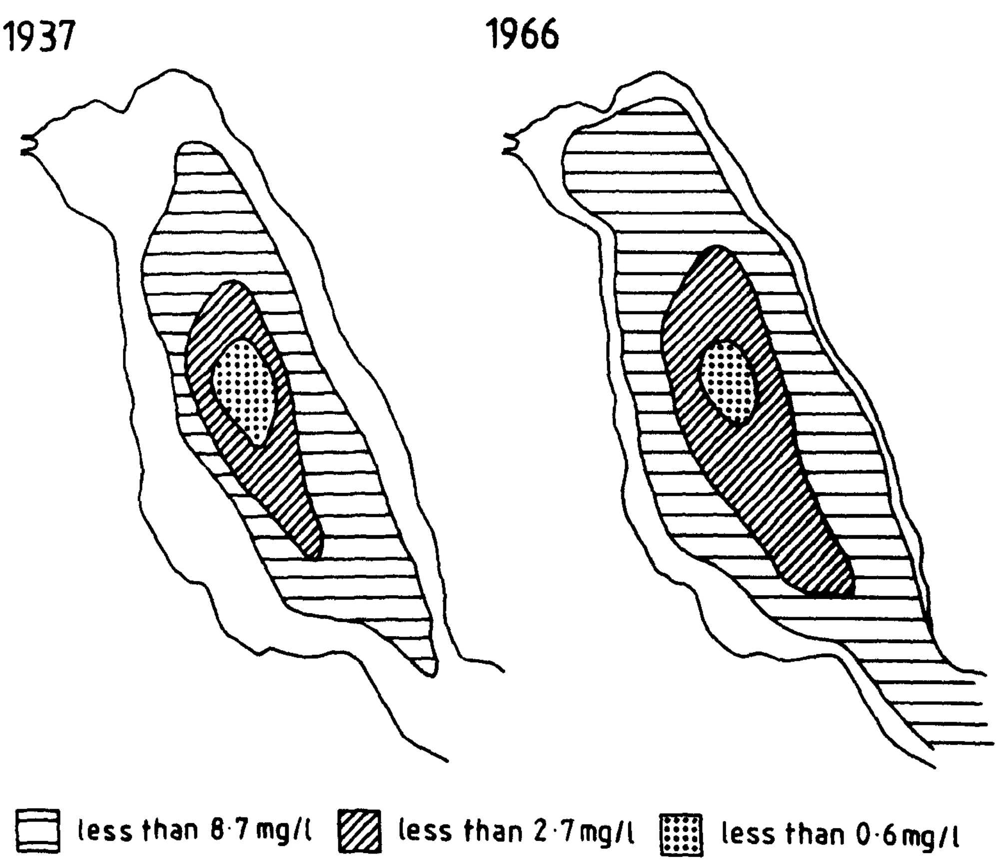

Oxygen content (mg/l)
0
5
10
0
20
40
60
Depth (m)
1966
1937

Figure 2.17. Extension of deoxygenated waters in the lower strata of the Grand Lac between 5 October 1937 and 11-12 October 1966 (from Balvay, 1972)



1937
1966
less than 8·7 mg/l
less than 2·7 mg/l
less than 0·6 mg/l

volume of relatively deoxygenated layers of water has extended in the Grand Lac sub-basin between 1937 and 1966. The plankton composition has also become modified; within the diatom group there has been a progression to dominance by the most phosphorus-demanding types. In 1907 *Asterionella formosa* was a dominant species accompanied by *Fragilaria crotonensis*, a species which was more exacting in its phosphorus requirements. In 1965 *Fragilaria crotonensis* was the dominant species (table 2.6.) and in 1966 *Tabellaria fenestrata*, the most phosphorus-demanding of the three, was the dominant species. In 1967 the cyanophyte group (the blue-green algae), requiring more phosphorus than the diatoms, were the dominant plankton group (table 2.7.). The group had earlier bloomed in 1961.
(Balvay, 1971 and 1972; Le Roux, 1907; Rougier-Michaud, 1969).

Observations from a variety of sources reflected the deteriorating quality of the lake waters; there was a significant reduction in the volume of fish netted (90 tonnes in 1954, 22 tonnes in 1968) and valuable species such as the char disappeared, the "Bureau d'Hygiène", responsible for monitoring water quality, became alarmed at the level of their bacterial counts, divers reported diminishing visibility in the lake due to the abundance of suspended materials, mainly attributable to the growing algal numbers, but also to the large quantity of exogenous animal and vegetable matter (Balvay, 1971; Servettaz, 1971).

The eutrophic state of the lake resulted from the inability of its biota to decompose completely the evergrowing volume of organic matter, both endogenous and exogenous in origin; the lake received untreated effluent and domestic sewage from lakeside communities and their dairy industries (fruitières) aswell as nutrient-rich and hydrocarbon-rich water draining from agricultural land and road surfaces. This progressive deterioration paralleled a significant

	% of total number of diatoms	
	1965	1966
Asterionella formosa	12·2	4·4
Fragilaria crotonensis	81·4	32·2
Tabellaria fenestrata	1·5	48·6

Table 2.6. Relative importance of the principal diatom species in the Lac d'Annecy, 1965 - 1966 (after Balvay, 1972)

	% of total number of phytoplankton		
	1961	1966	1967
Diatoms	3·7	91·7	19·67
Cyanophytes	95·8	0·6	79·17
Chrysophytes	0·4	6·2	0·99

Table 2.7. Relative importance of the principal phytoplankton groups in the Lac d'Annecy, 1961 - 1967 (after Balvay, 1971)

increase in the population of the catchment area (§ 3.1.) which grew from 11,000 in 1936 to 21,000 in 1968 (excluding Annecy), aswell as the increasing number of tourists in the summer, estimated to be between 30,000 and 60,000 annually (Benedetti-Crouzet, 1972; Laurent, 1972).

A critical situation was soon reached in the Lac d'Annecy because of its relatively small catchment area, and hence relatively dense population, together with its shallow depth, which restricted the lake's capacity for self-purification (cf. Lac Léman and Lac du Bourget, Table 2.8.) (Balvay, 1967b).

In 1955 the "Conseil supérieur d'Hygiène de France" proposed the construction of a sewage collecting network to remove untreated effluent and domestic sewage to a purification plant at Cran, downstream from the lake. Measures were considered to be essential due to the importance of the site as a tourist centre and fishing reserve, and not least because the communes of Annecy, Saint-Jorioz, Talloires, Menthon and Veyrier pump drinking water from the Grand Lac (Balvay, 1972; Servettaz, 1971). In 1962, under the auspices of the "Syndicat d'Assainissement des Communes riveraines" (which in 1966 became the "Syndicat intercommunal des Communes riveraines du Lac d'Annecy" - S.I.C.R.L.A.), construction of the peripheral sewage collecting system began, consisting of two main sewers following the left and right banks of the lake, the first sections of which were in operation by the end of 1964. By the end of 1970 the system had extended as far as Duingt and Talloires, with over half the lakeside population connected (Chaucoy, 1967; Lagrange, 1970a and 1970b; Servettaz, 1972).

Since 1967 there appears to have been an improvement in water quality, at least in the upper water layers, correlated with the gradual extension of the lakeshore sewers (table 2.9.); phytoplankton

	Mean oxygen concentration (mg/l)				Volume of water per m^2 of catchment area	Volume of water per inhabitant of catchment area
	October		January			
	0m to bottom	50m to bottom	0m to bottom	50m to bottom	(m^3)	(m^3)
Lac Léman	9·33	8·78	9·83	8·78	11·9	177·840
Lac du Bourget	7·72	6·89	9·00	7·65	6·8	33·519
Lac d'Annecy	6·70	3·51	9·83	9·80	4·5	17·825

Table 2.8. Comparison of factors relating to the intensity of eutrophication in Lac Léman (Lake Geneva), Lac du Bourget and Lac d'Annecy (after Balvay, 1967b)

	1967	1968	1969	1970	1971
Proportion of lakeside population connected to peripheral sewage collecting system (%)	32·6	44·2	51·3	56·6	63·6
Abundance of phytoplankton (ml/m³)	3·08	1·40	1·52	2·51	1·70
Frequency of diatoms (% total phytoplankton)	19·67	98·14	95·20	80·78	99·0
Frequency of cyanophytes (% total phytoplankton)	79·17	0·08	0·01	0·01	0·10
Frequency of chrysophytes (% total phytoplankton)	0·99	1·33	4·47	18·73	1·00
Concentration of dissolved oxygen, 0-10m depth (% saturation)	106·1	106·0	102·6	90·9	89·1
Transparency of water (m)	5·86	5·79	6·50	6·48	7·35

Table 2.9. Changes in the physico-chemical characteristics and phytoplankton composition of the Lac d'Annecy, 1967 - 1971. (after Balvay, 1972; Benedetti-Crouzet, 1972)

have become less abundant, and consequently the transparency of the lake water has steadily increased and the oxygen concentration decreased. The composition of the plankton biocoenosis has also been modified; the cyanophytes were only observed rarely from 1968, while the chrysophytes have steadily increased in number (except in 1971) and the diatoms are once more the dominant algae. Within the diatoms, *Tabellaria fenestrata* has decreased in frequency since 1968 and was practically absent from 1969. *Fragilaria crotonensis* has also become less abundant, while *Asterionella formosa* has become more frequent, indicating lower levels of phosphorus in the lake waters (Balvay, 1971b and 1972).

Benedetti-Crouzet (1972) considers that these early results merely reflect a stabilization and not yet a significant amelioration in water quality, and stresses that the new sewage collecting system still does not divert land drainage waters away from the lake.

2.6. Vegetation

2.6.1. Major vegetation zones in the catchment area

Vegetation patterns in the Alps are predominantly a function of altitude through its influence on a host of climatic characteristics such as the diurnal and annual temperature range, the length of the growing season, exposure to wind, the amount of rainfall and period of snow cover (Huxley, 1977).

Four altitudinal vegetation zones can be recognized in the Annecy region of the Northern French Alps (Richard, 1981):

- "étage collinéen" (hill zone), up to 700m
- "étage montagnard" (montane zone), 700 - 1500m
- "étage subalpin" (subalpine zone), 1500 - 2100m
- "étage alpin" (alpine zone), over 2100m

Within the Lac d'Annecy basin the natural vegetation of the "étage collinéen" is deciduous woodland, mainly alder, oak and hornbeam, while extensive forests of beech and fir dominate the "étage montagnard". Spruce forest and pine characterize the "étage subalpin", although semi-natural heath and meadow are now widespread. The open swards of the "étage alpin" are restricted to the summit of the Tournette massif.

2.6.2. Vegetation series in the catchment area

Variations in altitude, aspect and underlying parent materials (§ 2.2. and 2.3.) have led Richard (1973) to identify several vegetation series[1] in the Annecy valley and its surrounding massifs (figure 2.18.). The following account of the vegetation of the lake basin is taken from the document which accompanies Richard's ecological map.

"Etage collinéen" (Hill zone)

"Serie de l'Aune glutineux" (Common alder series)

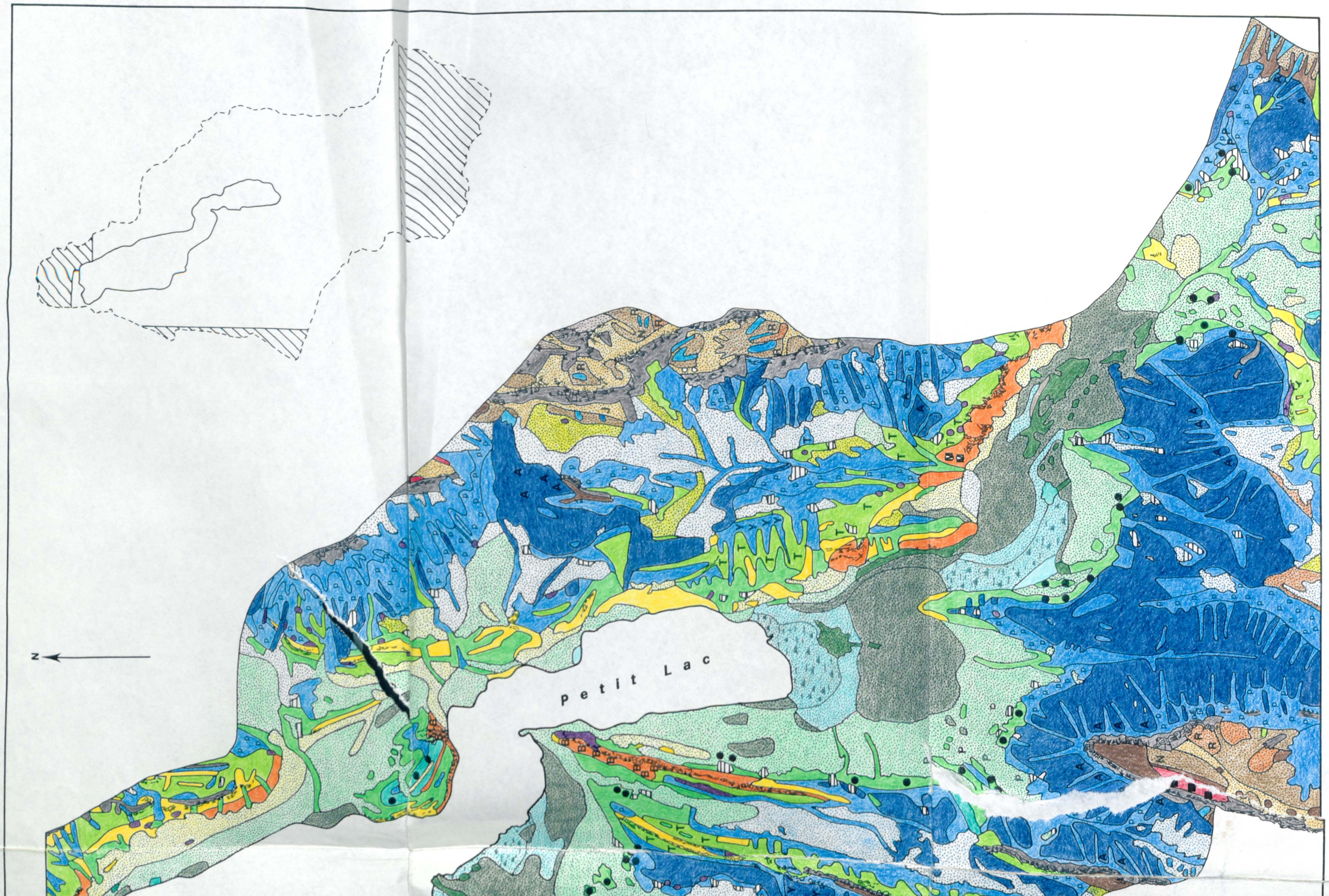
The Common alder series is found in marshy areas on the cluse floor where the water table is high and stagnant. A climax community dominated by *Alnus glutinosa*[2] and *Fraxinus excelsior* is now absent from the Lac d'Annecy basin according to Richard's map and the series is entirely represented by marshy meadows of reeds, sedges and *Molinia*.

---

[1] The vegetation series is a concept derived from French phytosociological theory. Each series corresponds to an area with fairly uniform environmental characteristics and therefore delimits "une zone d'égales potentialités biologiques". A vegetation series encompasses the climax community (which exists in equilibrium with its climatic and edaphic environment), those communities evolving towards the climax and may also include communities which have developed after disturbance or degradation of the climax (Patou, 1978; Richard, 1981).

[2] Botanical nomenclature follows that of Tutin *et al.* (1964, 1968, 1972, 1976 and 1980) in the "Flora Europaea" Volumes 1 to 5.

Figure 2.18. Vegetation series in the Lac d'Annecy drainage basin (after Richard, 1973)


N
Petit Lac
Grand Lac
0
1
2
3
km

HILL ZONE

COMMON ALDER SERIES

Reed beds

Sedge communities

GREY ALDER SERIES

Woodland

PEDUNCULATE OAK SERIES

Woodland

Meadows and cultivated land

DOWNY OAK SERIES

Xerophytic and mesophytic facies

Mesoxerophytic facies

Pinus sylvestris facies

Xerophytic grassland

SESSILE OAK-HORNBEAM SERIES ON NEUTRAL SOILS

Woodland and copses

Meadows and cultivated land (in common with the following series)

SESSILE OAK-HORNBEAM SERIES ON ACID SOILS

Woodland and copses

Facies rich in *Castanea sativa*

MONTANE ZONE

BEECH SERIES

Forest

Facies rich in *Picea abies*

Mesophytic meadows (in common with the following series)

FIR SERIES

Forest

Vegetation communities of rocky slopes

Xerophytic beech woodland

Pinus sylvestris facies

Xerophytic grassland

Cliff vegetation

Vegetation communities of damp valleys

Facies rich in *Acer pseudoplatanus*

SUBALPINE ZONE

SPRUCE SERIES

Forest

Heathland

Mesophytic grassland and meadows, little grazed

Mesophytic grassland and meadows, acidic, heavily grazed

Xerophytic grassland (in common with the following series)

MOUNTAIN PINE SERIES

Heathland with scattered thickets of *Pinus uncinata*

Vegetation communities of damp areas

Alnus viridis

Vegetation communities of rocky slopes

Vegetation on limestone cliffs, fixed screes, calcareous scree, avalanche tracks and schisty scree (in common with the following series)

ALPINE ZONE

Xerophytic calcareous grassland

M *Acer monspessulanum*

B *Buxus sempervirens*

T *Tilia cordata*

■ *Pinus uncinata*

R *Rhododendron ferrugineum*

J *Juniperus communis*

Y *Taxus baccata*

P *Populus tremula*

≡ *Picea excelsa*

Reed-beds of *Phragmites australis* have become established on recent alluvium near the lakeside, notably on the west banks of the Grand Lac and at the southern end of the Petit Lac around the mouths of the Bornette, Ire and Eau Morte, aswell as along the lower course of the Eau Morte.

Sedge communities of *Carex elata*, with *Salix cinerea*, are found on badly drained soils around the reed-beds, while *Molinia* has become established where upper soil horizons are relatively dry. *Frangula alnus* and *Salix cinerea* are frequently found on hillocks.

The series is agriculturally unproductive except for a few marginal areas where the silty soils are well drained at the surface and are suitable for growing maize.

"Série de l'Aune blanc" (Grey alder series)

A small area of riverine woodland, dominated by *Alnus incana*, exists along the Eau Morte near Faverges, although this has now been planted with *Picea abies*. Otherwise the series is absent from the lake basin.

"Série de Chêne pédonculé" (Pedunculate oak series)

The Pedunculate oak series covers a large part of the cluse floor and is found on alluvial soils which are well drained at the surface. The natural fertility of these soils, together with the flat topography, means that these areas provide the best agricultural land of the region, and, now, a climax community dominated by *Quercus robur* is restricted to a few patches of woodland where soils are less fertile, due to their poor texture or inadequate drainage. Artificial drainage has lowered the water table and consequently the series has recently expanded.

"Série du Chêne pubescent" (Downy oak series)

The Downy oak series is mainly found on the adrêt slopes above the main valley floor. Woodlands dominated by *Quercus pubescens* have become established on these steep rocky slopes, with species such as *Viburnum lantana*, *Cotoneaster nebrodensis* and *Rhamnus alpinus* in the shrub layer. *Buxus sempervirens* grows locally on the Roc de Chère and on the Montagne d'Entrevernes. On the warmest slopes thermophilous species, such as *Acer monspessulanum* appear. Where deeper soils have developed, a more mesic community is found, with species such as *Tilia cordata*, *Corylus avellana* and *Carpinus betulus* appearing in the shrub layer. Woodland of this type is found along the Montagne du Semnoz at an altitude of about 700m, on a parent material of scree and alluvium.

Pinus sylvestris grows where soils have become gulleyed. Although it appears to regenerate readily, it is not clear whether the species was originally introduced by man.

At the foot of the steep slopes, xerophytic grasslands have become established on the fixed screes. In the past these areas have been used for cultivating vines but now most plots are abandoned and have been invaded by *Juniperus communis* and *Cornus sanguinea* scrub.

"Série de Chênaies-Charmaies neutrophiles" (Sessile oak-Hornbeam series on neutral soils

On the gentle slopes of the valley margins this series actually forms a transition between vegetation communities of the valley floor and those of the mountain slopes. Soils are cool and well aerated, having developed on colluvial material. A climax community dominated by *Quercus petraea* and *Carpinus betulus* is now reduced to a few patches of woodland and copses in which the following species are characteristically found: *Viburnum lantana*, *Acer campestre*, *Ilex aquifolium*, *Daphne laureola*, *Lonicera xylosteum*, *Corylus avellana*, *Fraxinus excelsior*, *Tilia cordata*, *Sorbus aria*, *Crataegus* spp., *Cornus sanguinea*, *Fagus sylvatica*, *Picea abies*, *Viburnum opulus*, *Abies alba* and *Euonymus europaeus*.

Most of the series is now represented by grassland and meadows which are used for growing forage crops. Apple orchards have been planted around Faverges.

"Série de Chênaies-Charmaies acidiphiles" (Sessile oak-Hornbeam series on acid soils

Where acid brown soils have developed over morainic material *Quercus petraea* and *Carpinus betulus* are still the dominant woodland species, but are associated with a different vegetation community from that described above. Sites with a north-westerly or north-easterly aspect have a cooler micro-climate and species characteristic of the montane zone are commonly found. *Picea abies* has become established in this series, together with *Castanea sativa*. Richard has recorded the following species in addition to those mentioned above: *Fagus sylvatica*, *Ilex aquifolium*, *Sorbus aria*, *Betula pendula*, *Corylus avellana*, *Populus tremula*, *Quercus robur*, *Sorbus aucuparia*, *Frangula alnus*, *Juniperus communis*, *Fraxinus excelsior* and *Rosa pendulina*, together with *Vaccinium myrtillus*, *Lonicera periclymenum*, *Hedera helix*, *Calluna vulgaris* and *Vaccinium vitis-idaea*.

Agricultural use of land within this series is limited to the production of hay on gentler slopes where mechanization is possible.

"Etage montagnard" (Montane zone)

"Série du Hêtre" (Beech series)

Forests dominated by *Fagus sylvatica* have become established on the steep calcareous slopes of the Bornes and Bauges massifs. They are best developed on well drained, stony soils on slopes which are not north-facing; on the cooler ubac slopes a mixed forest of *Fagus sylvatica* and *Abies alba* is more common. Associated species include: *Rubus idaeus*, *Sorbus aria*, *Lonicera nigra*, *Salix appendiculata*, *Sambucus racemosa* and *Crataegus spp.*

On acid soils, which have developed over siliceous material, a mixed *Fagus sylvatica - Picea abies* forest has evolved with *Castanea sativa* often found at lower altitudes.

Many areas within this series have been cleared in the past for the production of hay but have since been abandoned; *Populus tremula* has quickly colonized such sites, and elsewhere conifer plantations have frequently been planted to reforest the land.

In zones managed by the "Office des Forêts" *Picea abies* has largely replaced the beech woodland (§ 2.6.3.).

"Série du Sapin" (Fir series)

Extensive forests of *Abies alba* have become established on ubac slopes where soils are cool, deep and quite fertile. They are mainly found on the northern flank of the Bauges massif and the north-facing slopes of the Tournette massif from altitudes as low as 700m to over 1300m. On drier slopes a mixed beech-fir forest is more common.

On decalcified soils *Betula* is invariably present, with *Alnus viridis* and *Vaccinium myrtillus* also very abundant.

Forests growing on siliceous materials above 1400m tend to be transitional with the subalpine heath communities above and are rich in ericaceous plants such as *Vaccinium myrtillus* and *Rhododendron ferrugineum*, and ferns such as *Lycopodium annotinum*, *Blechnum spicant* and *Thelypteris limbosperma*.

Large areas within the Beech and Fir series are used for summer grazing. Even where pastures have been very intensively grazed and have become acidified, they continue to be used, due to the importance of local cheese production (§ 3.2.2.).

At the same altitude Richard has identified two further vegetation formations which have evolved where edaphic conditions are not suitable for the development of a fir or beech/fir forest:

"Formations spécialisées des affleurements rocailleux" (Vegetation communities of rocky slopes)

On steep, rocky slopes soils tend to be thin and dry and consequently more xerophytic vegetation communities are found. Where soils have begun to develop within rock interstices the following species are characteristic: *Lonicera alpigena*, *Viburnum lantana*, *Sorbus aria*, *Juniperus communis*, *Acer opalus* and *Amelanchier ovalis*. Where soils are deeper, beech woodland has been able to establish, although the trees are typically stunted.

On marl-covered adrêt slopes between 700m and 900m *Tilia cordata* is abundant. *Pinus sylvestris* has colonized gulleyed slopes, as in the Downy oak series.

On south-facing scree slopes, where conditions are drier still, xerophytic grasslands have become established.

"Formations spécialisées des zones humides" (Vegetation communities of damp valleys)

Valleys of the ubac slopes tend to have cold and shaded micro-climates, with damp soils which are very suitable for the establishment of luxurious fern communities, including species such as *Athyrium filix-femina*, *Dryopteris carthusiana* and *Dryopteris filix-mas*, beneath which it is difficult for the coniferous species to regenerate. However, *Acer pseudoplatanus* is able to establish very easily in such areas and is now widespread, particularly on the northern slopes of the Bauges.

Where soils are less calcareous *Alnus viridis* is also abundant.

"Etage subalpin" (Subalpine zone)

"Série de l'Epicéa" (Spruce series)

Naturally occurring forests of *Picea abies* have a very limited distribution in the lake basin and are only found where soils are relatively deep, as on fissured limestones and fixed screes, aswell as on material poor in calcium. *Alnus viridis* is widespread along the sides of ravines.

At an altitude of about 1700m the woodland begins to open out and grades into subalpine heath, with species such as *Rhododendron ferrugineum*, *Alnus viridis* and *Juniperus communis* subsp. *nana* becoming frequent.

Most of the area considered to belong to the Spruce series is actually heathland, grassland or meadow. According to Richard, some heaths can be considered to be true climax communities, while others seem to have evolved from abandoned pasture, although the two are not distinguished on his ecological map. South-facing sites have *Juniperus communis* as the dominant species, while north-facing sites are dominated by *Alnus viridis* and intermediate sites by *Rhododendron ferrugineum*. Other shrubby species include: *Vaccinium myrtillus*, *Vaccinium vitis-idaea*, *Sorbus chamaemespilus*, *Sorbus aria*, *Salix appendiculata* and *Loiseleuria procumbens*.

The subalpine grasslands and meadows probably have an anthropogenic origin too. The gentler slopes of the valley sides tend to be more heavily grazed by cattle and are characterized by the appearance of *Nardus*. Where soils are shallow they quickly become colonized by ericaceous heath species.

However, more xerophytic grassland communities are found on steep calcareous slopes; they are seldom used for pasture and appear to be fairly stable plant associations, suggesting that they could occur naturally.

<u>"Série du Pin à crochets" (Mountain pine series)</u>

The Mountain pine series is restricted to the upper subalpine zone; the climax community is typically heathland with scattered thickets of *Pinus uncinata*.

Elsewhere edaphic factors make sites unsuitable for the species to grow and Richard has identified two specialized vegetation formations:

"Formations spécialisées des zones humides" (Vegetation communities of damp areas)

Alnus viridis replaces the pine in areas which are damp, cold and covered in snow for a relatively long time, although on marl the distribution of this species is limited (as in the Tournette massif).

"Formations spécialisées des zones rocailleuses" (Vegetation communities of rocky slopes)

Pine becomes rare or even absent in rocky areas such as cliff faces, on scree deposits and along avalanche tracks, and distinct plant associations better adapted to these site conditions have evolved; they are described in detail by Richard.

2.6.3. Reforestation

Over the past few decades the species composition of many forest areas in the lake basin has been changing under the management of the "Office des Forêts" (table 2.10.). Their objectives have been two-fold: to introduce conifers into woodland and to reforest abandoned pasture-land. There has been an overall increase in the proportion of coniferous trees, the principal species planted being *Picea abies* (Richard, 1973).

120 hectares of the Mont Veyrier massif have been successfully reforested with *Picea abies*, *Pinus nigra* subsp. *laricio*, *Cedrus atlantica*, *Larix decidua*, *Abies grandis* and *Abies nordmanniana* (Richard, 1973).

The northern end of the Montagne du Semnoz was completely

	Year	Deciduous	Coniferous	*Abies*	*Picea*	*Pinus*
		% of total forest				
Forêt de Chevaline (ubac)	1902	21	79	52	27	0
	1951	6	94	66	28	0
Veyrier du Lac (ubac)	1907	59	41	32	9	0
	1961	40	60	45	15	0
Forêt de Talloires (adret)	1904	48	52	5	44	3
	1951	46	54	9	41	4
Bouchet Mt.-Charvin (ubac)	1903	42	58	0	58	0
	1966	1	99	2	97	0

Table 2.10. Composition of communal forests in the Annecy cluse in the twentieth century (after Richard, 1973)

reforested[1] between 1861 and 1877 by the "Conseil Municipal de la Ville d'Annecy" to create the "Forêt du Crêt du Maure".

The following species were planted: *Pinus sylvatica*, *Pinus nigra* subsp. *laricio*, *Picea abies*, *Larix decidua*, *Fagus sylvatica* and *Acer pseudoplatanus*. *Abies alba* regenerated naturally. The present forest composition is 68% conifers (*Pinus* 30%; *Picea* 30%; *Larix* 6%; *Abies* 2%) and 32% deciduous species (*Fagus* 22%; *Quercus* 4%; *Castanea*, *Fraxinus*, *Acer* and *Betula* 3%; *Ulmus*, *Tilia* and *Salix* 2%). There are also several exotic species, such as *Pseudotsuga menziesii*, *Metasequoia glyptostroboides*, *Cedrus atlantica* and *Juglans nigra* (Serand, date unknown).

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[1] During the first half of the nineteenth century communal forest of the Crêt du Maure was cleared and a small hamlet, "La Colonie", established. However, the shallow, infertile soils were quickly exhausted and the plots abandoned.

CHAPTER 3

MAN IN THE LAKE BASIN

3.1. History of settlement and population change

3.1.1. Pre-monastic settlement

The first settlers in the Lac d'Annecy basin were the lake dwellers of the Neolithic and Bronze Ages. Four lake villages are known to have existed: Le Port (Neolithic, 2500 BC[1]), Veyrier (early Bronze Age, 1800 - 1500 BC[1]), Roselet (middle Bronze Age, 1500 - 1200 BC[1]) and Chatillon (late Bronze Age, 1200 - 800 BC[1]) (figure 3.3.) (Le Roux, 1912; Le Roux & Guinier, 1908; Revon, 1875; Serand, 1884). Although the remains of these settlements are now underwater and away from the present lake shores, they are thought to have been constructed on dry land during the Sub-Boreal when a warm dry climate caused the lake level to be much lower than at present[2] (Bocquet, 1979). The most recent settlement, Chatillon, was abandoned c. 800 BC, possibly due to a rise in lake level associated with the onset of a cooler and moister climatic regime at the beginning of the Sub-Atlantic[3] (Benedetti-Crouzet, 1972).

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[1] Dates are taken from Benedetti-Crouzet, 1972.

[2] The remains of Chatillon are found on the present-day sub-lacustrine island of Crêt de Chatillon (§ 2.5.1.). This suggests that the lake level fell by at least 40m during the Sub-Boreal, if it is assumed that the settlement was originally constructed on a hill surrounded by dry land (Benedetti-Crouzet, 1972).

[3] The long cool spell which introduced the Sub-Atlantic period lasted from c. 900 - 300 BC (Ladurie, 1972). A 5m terrace at the southern end of the Petit Lac indicates that the lake rose to a maximum level of 450m during the early Sub-Atlantic (Benedetti-Crouzet, 1972).

There is little evidence for Iron Age settlement in the region although the distribution of place-names of Celtic origin suggests the pre-alpine mountains became the most densely populated areas; most notable is the term "alpe" for the high mountain pastures from which the Alpine range takes its name (Cholley, 1925). In the Annecy lake basin itself there are a few indications of Iron Age settlement: the names "Vésonne" (a hamlet in Faverges), the "Ire" (an affluent of the Petit Lac) and "Isernon" (a gate in the ramparts of medieval Annecy) all have a Celtic root, and the remains of an Allobroge village have been found to the north-west of the lake and dated between 45 and 27 BC (Blanchard, 1977; Gardet, 1977).

Towards the end of the first century BC the Romans constructed a network of roads from Italy into Gaul via the Alps. Three strategic routes met at the northern end of the Annecy cluse and a nodal settlement, Boutae, developed which by the end of the third century AD had a population of about two thousand (Blanchard, 1977; Duparc, 1973; Gardet, 1977). A smaller town, Casuaria, grew up at a second nodal point at the eastern end of the lake basin near to present-day Faverges (Cholley, 1925). Rural settlement was centred around the Roman country estates; fifteen villas are known to have existed in the Annecy valley (Cholley, 1925). Boutae itself was destroyed by the Alaman invasions between 259 and 267 AD and despite being rebuilt during a short period of security following decentralization of Roman administration it never regained its former economic prosperity, and by the end of the fifth century no longer existed (Blanchard, 1977).

At the beginning of the fifth century AD Germanic tribes once more invaded this part of Europe and caused widespread destruction of rural property. However, with the migration of the Burgundian peoples into the region from the mid-fifth century, it appears that life became more secure (Baud, 1973a), and in the lake basin a rural population grew up between the sixth and twelfth centuries in an area which roughly approximates to the present-day commune of Annecy-le-Vieux (Blanchard, 1977; Duparc, 1973; Gardet, 1977).

3.1.2. Monastic and post-monastic settlement and demographic trends

Colonization of the uplands of the pre-alpine region began in the eleventh and twelfth centuries with the establishment of several religious houses (Cholley, 1925). A Cistercian monastery was founded at Tamié in 1132 along an international routeway which passed through the Annecy valley. The Cistercians grew crops and kept animals for subsistence and to provide hospitality for travellers; at first land was cleared and farmed in and around the Tamié valley, but within 25 years the monastery had acquired over a hundred subsidiary establishments ("granges") throughout Savoy. Place-name evidence suggests that clearance was predominantly in the "moyenne montagne" country, between 1000 and 1800m altitude. The "alpages", the natural and semi-natural meadows of the sub-alpine zone (§ 2.6.2.), were also exploited for summer pasture (Chavoutier, 1977).

In 1107 the Benedictine monastery at Talloires acquired the rights over the church at Montmin and its dependencies (Philippe, 1861), and in 1310 the first documentation of population there indicates four surname groups leasing ecclesiastical land (A.M. Jones, pers. comm.).

Agricultural development of the uplands coincided with a significant increase in population levels which occurred throughout Europe between the eleventh and thirteenth centuries. By the fourteenth century, however, this rapid growth in population had slowed considerably, apparently limited by agricultural production. Subsistence crises in Savoy were compounded by a series of civil wars during the period 1268 - 1355 (Baud, 1973b; Binz, 1963).

In 1348 and 1349 bubonic plague spread through Europe from the Mediterranean ports, and rural areas throughout the continent "virtually collapsed" (Langer, 1964). The population of Savoy is estimated to have been reduced by half, reaching minimum levels by the middle of the fifteenth century. The disease remained endemic for more than three centuries (Baud, 1973b; Binz, 1963; Duparc, 1965).

From the beginning of the fifteenth century the population of communes within the Annecy lake basin can be estimated for the first time. Records of the number of households in parishes belonging to the diocese of Geneva were made during episcopal visits from 1411 onwards. This documentary source, referred to as the "visites pastorales", is described further in Jones & Siddle (1982), and the data have been published in Binz (1963). From the mid-sixteenth century, population figures have been reconstructed for two communes within the Petit Lac catchment area, Montmin and Chevaline, by Siddle & Jones (1983). Population estimates for the period 1411 to 1518 derived from the "visites pastorales"[1] have been added to these reconstructions (figure 3.1.). It seems that in both communes the population increased at least threefold between the beginning of the fifteenth century and the middle of the sixteenth century; the sixteenth century maximum is thought to represent the largest number of people ever settled in Montmin (D.J. Siddle, pers. comm.). This demographic trend is common to other communes of the Annecy lake basin and is also characteristic of Southern Europe (Jones, 1983a).

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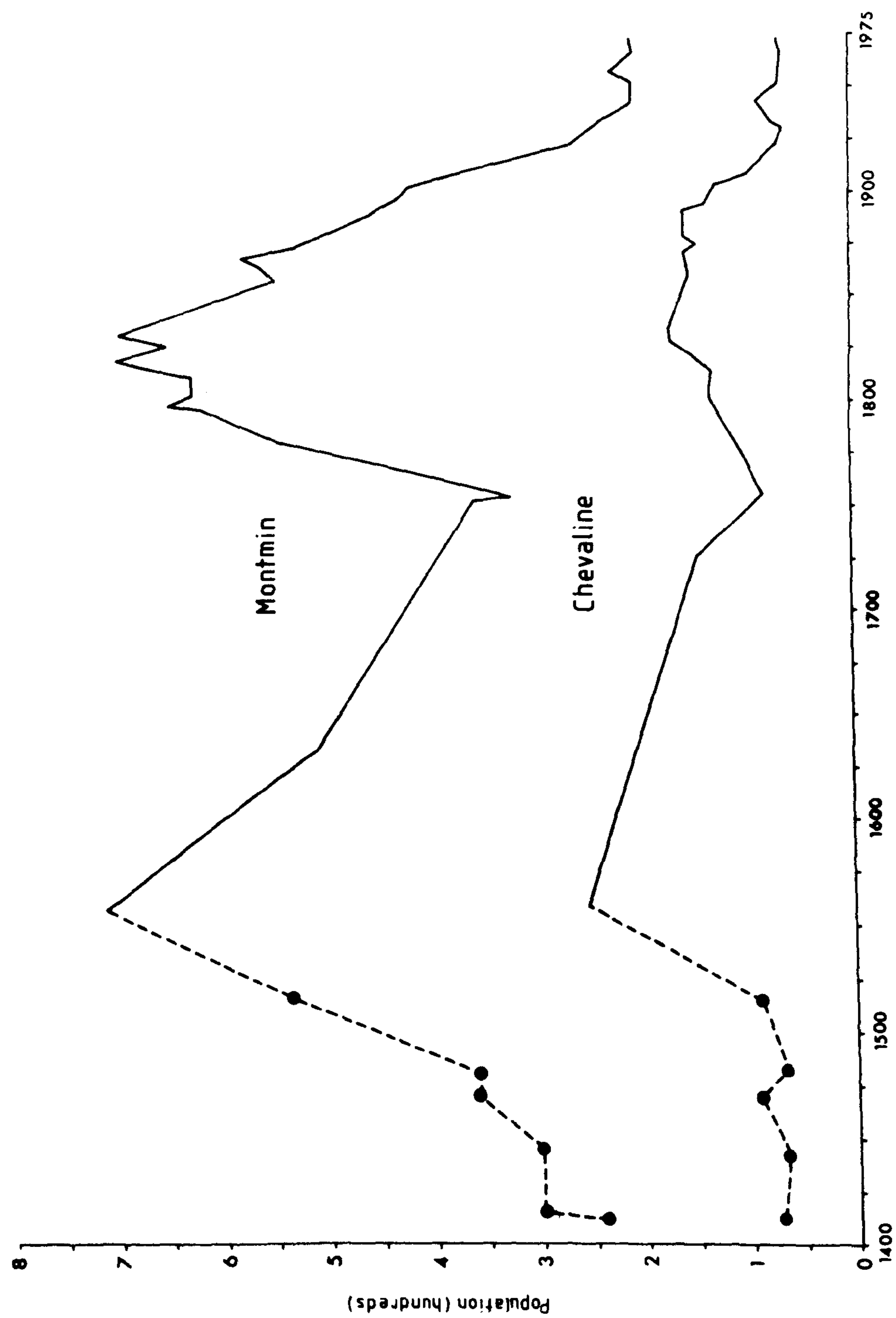
[1] The derivation of estimated population figures from household numbers in the "visites pastorales" is discussed in Devos *et al.* (1980); here the number of households have been multiplied by a factor of 5, the estimated number of household members, and by a factor of 1·19 to account for those exempt from the census ("les pauvres et misèrables").

Figure 3.1. Population change in communes of the Petit Lac catchment area , 1411 - 1975 (data from: dashed line - population estimates from the "visites pastorales" published in Binz (1963); solid line - population reconstructions from Siddle & Jones (1983))


Montmin
Chevaline
Population (hundreds)
Year
0
1
2
3
4
5
6
7
8
1400
1500
1600
1700
1800
1900
1975

Once more, population growth appears to have been checked by the availability of agricultural resources (Baud, 1973c) and up to the middle of the eighteenth century the population of communes in the lake basin declined through the combined effects of war, plague, poor harvests and a long tradition of outmigration (Jones, 1983a). However, the population rose to another maximum in the 1860s; this increase coincided with widespread cultivation of the potato, a crop which was frost-resistant and therefore well-suited to the poor soils of the uplands (Nicolas, 1973 and 1978). Whether the reliability of the potato crop meant a larger population could be supported, or whether increasing numbers stimulated the adoption of this new cultivar, is not clear, and is the subject of much debate (D.J. Siddle, pers. comm.).

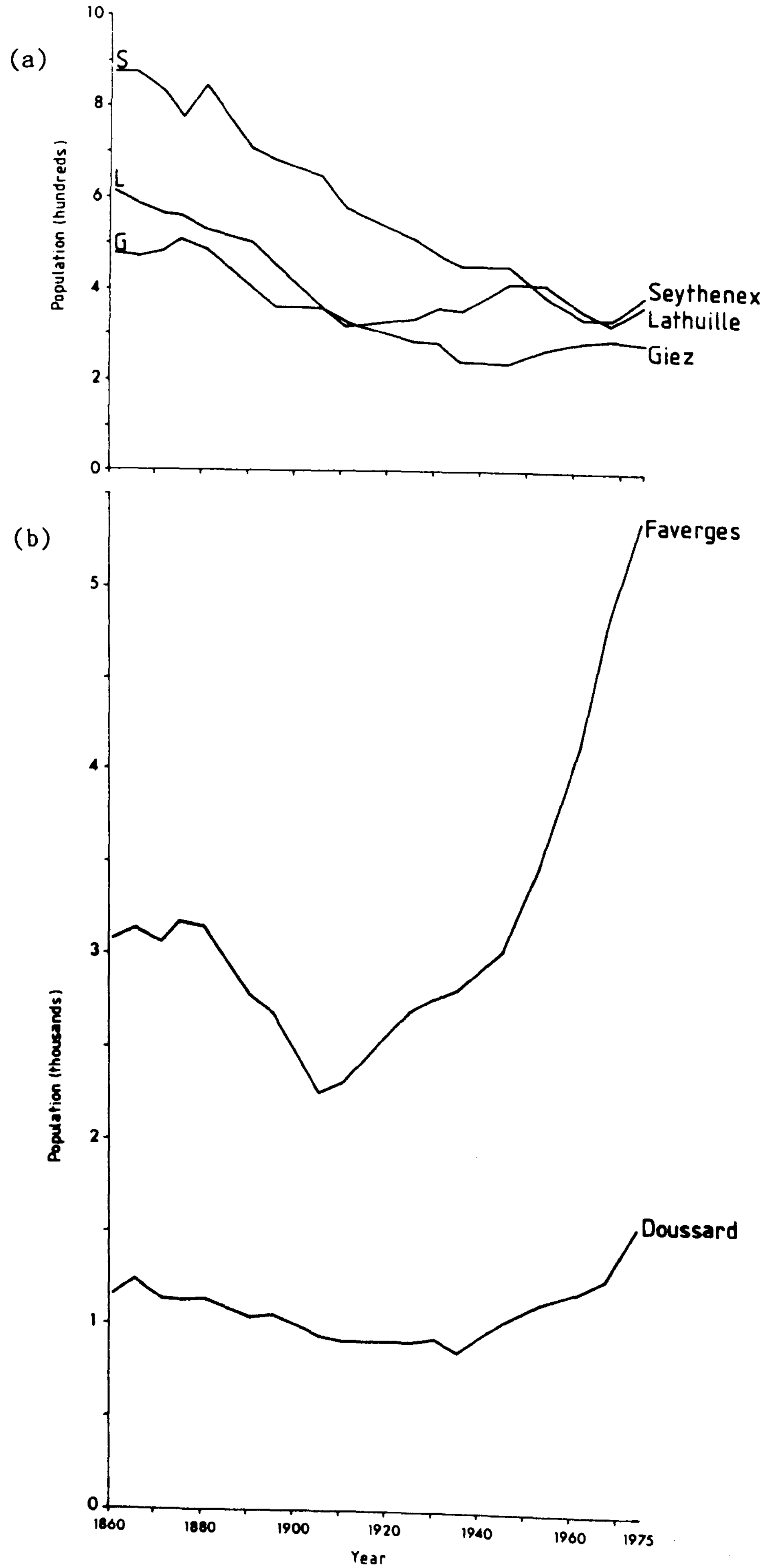
The decline in population observed for both Montmin and Chevaline since 1861 can be seen for other communes of the Petit Lac catchment area (figure 3.2.); this was partly due to a fall in the birth-rate and partly due to emigration, both associated with a breakdown in the traditional peasant subsistence economy and the shift to a pastoral economy centred around the "fruitière" system (§ 3.2.2.). There has been some sort of stabilization in numbers since the 1930s in the rural communes (figure 3.2.a.). However, both Faverges, now a major centre of light industry with suburbs of apartment blocks, and Doussard, recently a second local focus of industry and residential expansion, have experienced population growth during the twentieth century (figure 3.2.b.) (Steel, 1981).

3.2. History of land-use

3.2.1. Agriculture in the eighteenth century

A subsistence-type farming economy was perpetuated up to a

Figure 3.2. Population change in communes of the Petit Lac catchment area, 1861 - 1975 (data from census figures, ADHS†)
† collected by E.A. Steel
(a) rural communes (b) semi-urban communes


(a)
10
8
6
4
2
0
Population (hundreds)
S
L
G
Seythenex
Lathuille
Giez
(b)
5
4
3
2
1
0
Population (thousands)
Faverges
Doussard
1860
1880
1900
1920
1940
1960
1975
Year

relatively late date in the Annecy region. The duchy of Savoy was affiliated to the Piedmont state until its final annexation by France in 1860 and protectionist policies introduced in 1713, prohibiting importation of foodstuffs, effectively isolated the territory from neighbouring agricultural regions. The physical barrier presented by the alpine chain reinforced this political isolation by separating Savoy, and in particular the pre-alpine region, from the fertile piedmont plain to the east of the Alps. This resulted in the maintenance of a semi-arable, semi-pastoral farming system which was not particularly well-suited to the physical environment (Cholley, 1925).

Moreover, the peasant farmer was obliged to cultivate cereals in quantities vastly exceeding those for subsistence only; part of the harvest was used to pay tithes and other dues, and part was sold at market to raise money to pay royal taxes. Wheat in particular was demanded by the nobility and bourgeoisie of the large towns and cities, and so wherever possible this cereal was cultivated in preference to other types (Nicolas, 1978).

As a consequence of these political and socio-economic factors, the altitudinal limit of arable cultivation was pushed far higher during the eighteenth century than has been experienced at any time since (Cholley, 1925). In the lake basin itself, crops were grown at Montagelier (c. 750m), Le Sapey (c. 950m) and Replain-dessous (c. 1000m) above Giez (Cholley, 1925) in areas that are now only used for summer pasture. In Montmin, cultivated plots existed at 1300m compared with only 1100m today (Dearing, 1979). The intensity of cultivation was such that at Saint-Eustache, Saint-Jorioz and Leschaux some plots of land were cultivated continuously for ten to twelve years without being left fallow (Cholley, 1925).

Details of various elements of the farming system of the eighteenth century in the Annecy lake basin have been extracted from two original documentary sources now housed in the "Archives départementales de la Haute-Savoie" (ADHS) in Annecy.

The earlier "Cadastre Savoyarde" was a register of land-ownership and land-use compiled for taxation purposes between 1728 and 1738. An arbitrary date of 1730 has been assigned to these data in the relevant tables of this chapter and Appendix 1. Details of plot size, type of cultivation or land-use, land quality and relief were recorded for every single land parcel in Savoy (see Jones & Siddle, 1982). The pattern of land-use throughout the lake basin could be reconstructed using this data-base together with the accompanying commune maps; however the time available for collection of this information limited the exercise to the calculation of land areas used for the cultivation of walnut, chestnut, vine[1] and hemp in nine communes within the Petit Lac catchment area (Chevaline, Doussard, Duingt, Faverges, Giez, Lathuille, Montmin, Seythenex and Talloires). These four crops were specifically identified in the land register and their pollen can be distinguished as individual types in the fossil pollen record.[2] Details of 4793 individual land parcels were recorded for these four land-use categories and accounted for just over 10% of the total

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[1] Only the data for the cadastral land class "vigne" were collated here. The land class "hutins" (or "hautins"), referring to the cultivation of vine plants using trees or bushes as supports, was not considered.

[2] The pollen of *Cannabis sativa* (hemp) and *Humulus lupulus* (hop) are very similar; both species belong to the hemp family (Cannabiaceae). No attempt was made to distinguish the two pollen types in this study, but the high frequencies of *Cannabis* type pollen recorded during routine counting are assumed to represent cultivated hemp, the reasons for which are discussed later (§ 7.3.).

number of plots within these communes.[1] The original Savoyard measures of land area were converted to metric areas using the conversion factors listed in table 3.1. Data from the "Cadastre Savoyarde" were collected by the author.

An agricultural inquiry was completed in 1755 for which details of all crops grown and all animals kept in each commune of the Savoyard province of Genevois in 1754 were recorded. Agricultural production levels were also compared with estimates of the demand for produce by individual communes and so, in addition, some idea can be gleaned of the capacity of this agricultural system to provide subsistence and to generate surplus produce (see Jones & Siddle, 1982). This data source is hereafter referred to as the "1754 tabelle". Population statistics for the years 1755 and 1756 were recorded in the 1756 recapitulation. Records for selected subjects of this inquiry have been considered here for nine communes within the Petit Lac catchment area (Chevaline, Doussard, Duingt, Entrevernes, Faverges, Giez, Lathuille, Montmin and Seythenex); these included production levels of the main cereal crops (wheat, rye, barley and oats), hay, straw, hemp, wine and walnut oil, together with the numbers of cattle, sheep and goats. The original Annécien measures of production have been converted to metric units using the conversion factors listed in table 3.2.[2] The original data from the "1754 tabelle" were copied onto micro-film by D.J. Siddle and were

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[1] In retrospect it is thought that a more useful starting point for comparing these data with later cadastral records (the "Cadastre Français"), and with the fossil pollen spectra in the lake sediments, would have been to assess the ratio of forested to non-forested land. Woodland and forest "plots" tended to be relatively large in area, thus making their compilation an equally feasible exercise.

[2] At the time of writing no conversion factor was available for the volume of chestnuts produced and so data for this crop cannot be compared with the cadastral information for 1730.

"Mesure de Savoie"	Metric equivalent
1 journal (400 toises carrées)	2948·37m^2
1 toise carrée (8 pieds carrés)	7·37m^2
1 pied carré	0·92m^2

Table 3.1. Metric equivalents of the original square measures recorded in the "Cadastre Savoyarde" (from Nicolas, 1978)

"Mesure d'Annecy"	Metric equivalent
1 coupe (wheat, rye)	88·86 l
1 coupe (barley)	66·63 l
1 coupe (oats)	133·29 l
1 pot (walnut oil)	1·64 l
1 pot (wine)	1·43 l
1 quintal (hay, straw, hemp)	62·79 kg

Table 3.2. Metric equivalents of the original capacity and weight measures recorded in the "1754 tabelle" (from Nicolas, 1978)

compiled for this thesis by the author.

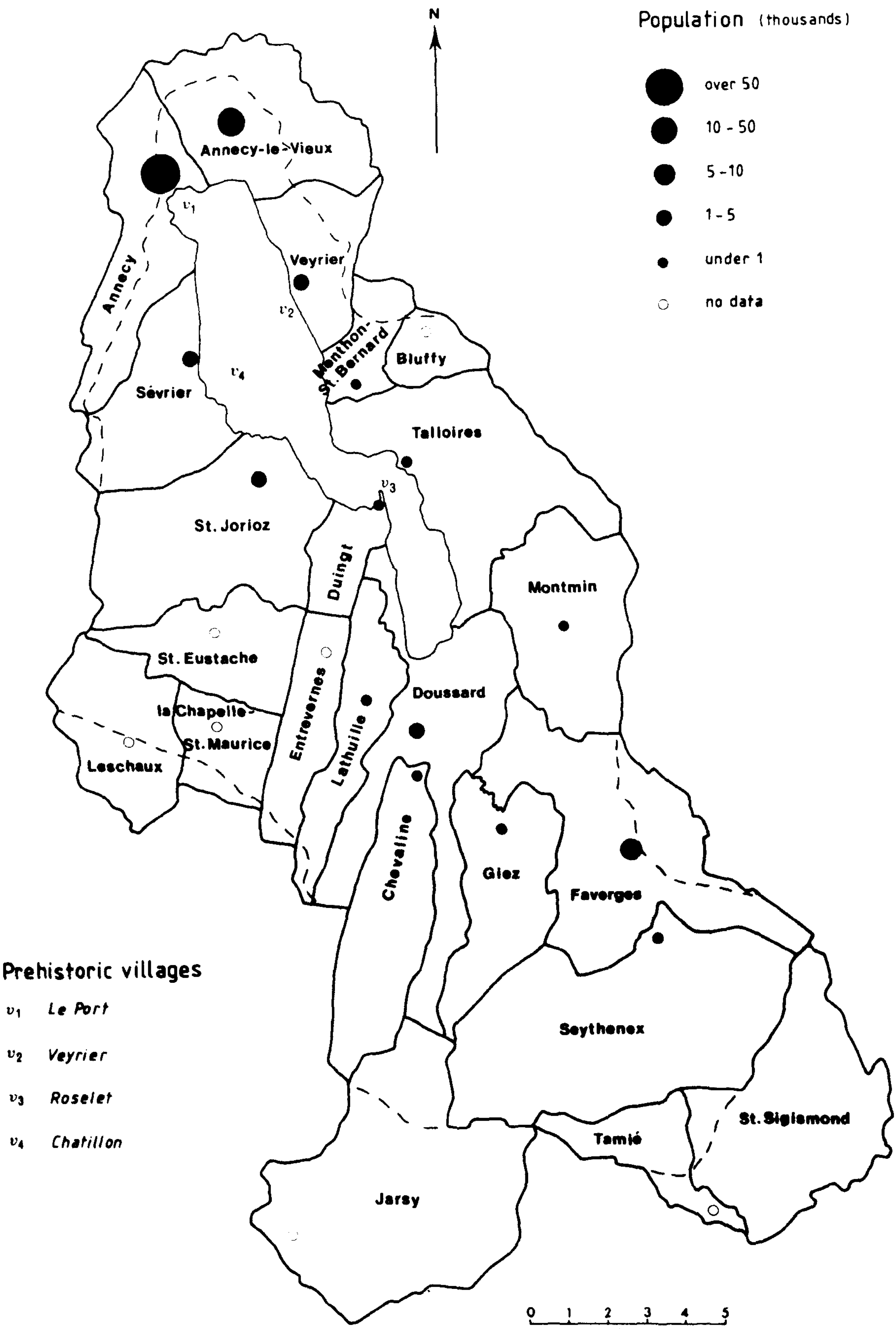
The nine communes for which data have been collected from the "Cadastre Savoyarde" approximately correspond to the Petit Lac catchment area (q.v. figure 3.3.). The commune of Entrevernes was not created until 1742; however, its territory was accounted for in the cadastral records as this land was previously divided between the communes of Duingt and Lathuille. Data for the communes of Talloires have not yet been copied from the "1754 tabelle" and so agricultural production and animal numbers presented here actually underestimate those for the whole Petit Lac catchment area and are not directly comparable with the cadastral records.

Data from these two documentary sources are summarized in tables 3.3. to 3.5. Detailed records for individual communes from which these catchment-scale totals have been compiled are placed in Appendix 1.

Although urban demand ensured that the most valuable crop was wheat, the cereal produced in most abundance in the Annecy lake basin was oats, as it was better suited to the thinner soils and harsher climate of the pre-alpine region. However, the value of wheat is still demonstrated by the fact that nearly half of the grain from the 1754 wheat harvest in Montmin was estimated to be surplus and therefore available for sale, compared to less than a fifth of the harvests of other cereal grains (table 3.6.), although to what extent these figures are representative of the rest of the catchment area is not yet known.

Both the walnut and chestnut were important elements of the subsistence economy and were often the subject of special clauses in the peasant farmer's contract. The walnut, "l'Olivier des Alpes", provided oil. The chestnut was a staple ingredient in the peasant diet before the potato was introduced. Walnut trees were planted

Figure 3.3. Settlement in the Lac d'Annecy drainage basin, 1975 (data from census figures, ADHS†)
The position of symbols for population size indicate the location of the "chef-lieu" of the commune. The dashed line indicates the drainage basin boundary where this does not correspond to a commune boundary
† collected in part by E.A. Steel


N
Population (thousands)
over 50
10 - 50
5 - 10
1 - 5
under 1
no data
Annecy-le-Vieux
Annecy
v_1
Veyrier
v_2
Menthon-St. Bernard
Bluffy
Sévrier
v_4
Talloires
v_3
St. Jorioz
Duingt
Montmin
St. Eustache
Entrevernes
Doussard
la Chapelle-St. Maurice
Lathuille
Leschaux
Chevaline
Giez
Faverges
Seythenex
St. Sigismond
Tamié
Jarsy
0 1 2 3 4 5
km
Prehistoric villages
v_1 Le Port
v_2 Veyrier
v_3 Roselet
v_4 Chatillon

	Total production
Wheat	1811•5 hl
Rye	1766•4 hl
Barley	1443•3 hl
Oats	7705•5 hl
Total cereals	12726•7 hl
Hay	1034•6 t
Straw	1524•3 t
Walnut oil	3293•2 l
Wine	2559•6 hl
Hemp	7660•6 kg

Table 3.3. Agricultural production in the Petit Lac catchment area, 1754 (data from the "1754 tabelle", ADHS)

	Area cultivated (ha)	Area cultivated (% of catchment area)
Walnut	3·3	0·02
Chestnut	167·1	0·98
Vine	256·5	1·51
Hemp	10·4	0·06

Table 3.4. Cultivation of walnut, chestnut, vine and hemp in the Petit Lac catchment area, 1730 (data from the "Cadastre Savoyarde", ADHS)

	No. of animals
Cattle	2132
Goats	861
Sheep	1473

Table 3.5. Pastoral farming in the Petit Lac catchment area, 1754 (data from the "1754 tabelle", ADHS)

(hl)

	Seed	"Dîme"	"Servis"	Subsistence	Surplus	Total production
Wheat	35·54	21·33	8·89	25·44	71·09	162·29
Rye	17·77	–	–	36·32	2·67	56·76
Barley	99·95	15·99	–	207·97	26·65	350·56
Oats	266·58	31·99	37·32	333·23	113·30	782·42

(%)

	Seed	"Dîme"	"Servis"	Subsistence	Surplus
Wheat	21·90	13·14	5·48	15·68	43·80
Rye	31·31	–	–	63·99	4·70
Barley	28·51	4·56	–	59·33	7·60
Oats	34·07	4·09	4·77	42·59	14·48

Table 3.6. Allocation of cereal grain from the 1754 harvest in Montmin (data from the "1754 tabelle", ADHS)
The "dîme" was the tithe paid annually to the church. The "servis" was an annual rent paid to the land-owner.

within village orchards, although nowhere above c. 900m, while the chestnut grew amongst natural woodland below c. 600m (Cholley, 1925).

Cultivation of the vine was of particular significance during the eighteenth century and was largely associated with the tending of vineyards belonging to the nobility, bourgeoisie and church. It is thought that vine cultivation reached its maximum extent during this period. The sunny adrêt slopes of the Bornes provided the best sites for vineyards in the lake basin, and at the beginning of the nineteenth century about a quarter of the commune of Veyrier (in the catchment area of the Grand Lac) was devoted to vine cultivation (Cholley, 1925).

Hemp was cultivated as a source of fibre for making cloth[1]. In 1730 the areal extent of hemp cultivation was fairly limited in the communes of the Petit Lac catchment area studied to date (table 3.4.) although in terms of weight its production seems to have been of some significance in 1754 (table 3.3.).

The overriding importance attached to cereal cultivation during this period limited the number of livestock kept; the extension of arable land restricted the amount of pasture available for summer grazing and also the amount of hay produced for winter feed, and any hay that was cut was primarily reserved for nourishing the draught animals. Each peasant household owned a small number of animals; their "herds" were characteristically mixed and included cattle, sheep and goats. With pasture in short supply, sheep and goats were valuable beasts to keep as they could browse along the woodland

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[1] Marshy land near the southern end of the Petit Lac is named "Les Chenevières" (Carte topographique 1:50,000: Sheet 3431 (Annecy-Ugine)) which may, according to Duparc (1973), indicate that in the past this site has been important for hemp cultivation. Perhaps the shallow waters near the shores of the Petit Lac were at the same time used for "water retting" hemp stems. Duparc (1973) refers to the use of the canals in Annecy for the same process from the beginning of the fourteenth century.

fringes, and in addition to milk and meat, they provided wool and tallow. Nevertheless, the pre-alpine massifs were rich in natural pasture, and so relatively large stocks of cattle could be supported in upland communes of the Annecy lake basin compared to other regions of Savoy (Cholley, 1925).

The "subsistence" agricultural system described above must have been fairly unique in terms of the combination of pressure on land resources generated by the prevailing demand for produce and the limits to production imposed by the natural environment itself. The political and socio-economic conditions peculiar to this period in history have already been outlined. These external controls on the nature and pattern of agricultural exploitation were superimposed upon the relatively poor climatic conditions prevalent at the time, ie. the low summer temperatures and associated weather conditions of the "Little Ice Age", the cold epoch which post-dated the middle of the sixteenth century (Bray, 1982; Ladurie, 1972; Lamb, 1965).

As a consequence, the early eighteenth century witnessed an agricultural depression of unprecedented proportions. The period was characterized by numerous subsistence crises and the population had declined to minimal levels by the middle of the century (§ 3.1.2.). The population of Doussard fell from 550 to 505 between 1755 and 1756, due to mortality and outmigration.

> "par rapport à la sterilité des recoltes passées et à la peste d'une partie de leurs bestiaux par les maladies epidemiques". ("1754 tabelle")

The vagaries of the climate were probably more keenly felt in the mountains where crop returns were anyway dependent on the vicissitudes of the seasons from year to year. So, at Montmin at c. 1000m, similar subsistence crises were experienced and resulted in high mortality rates. The coincidence of climatic deterioration, harvest failure and death for this commune have been examined in detail by Jones (1983b).

Returns from the land continued to be mediocre while manure was in short supply, while crop rotations were ignored and while farm implements remained archaic (Nicolas, 1978). Such conditions led Costa de Beauregard (1773) to say of agriculture in Savoy: "Elle est ..... dans un état misèrable". Improvements in farming methods were slow to infiltrate. Both the potato and maize were universally adopted towards the end of the eighteenth century, solving a subsistence crisis. However, the cultivation of forage crops and legumes was a rather more speculative investment for the peasant farmer, who required immediate returns from his land for direct consumption or sale, and there was no significant development in this direction until the beginning of the nineteenth century (Nicolas, 1978).

3.2.2. Agricultural change in the nineteenth and twentieth centuries

Social and economic change in the Annecy region has been described in detail by Steel (1981) for the post-eighteenth century era. The following brief account of agricultural change in the lake basin is almost exclusively drawn from this reference, and is illustrated with data collected by the same author.

During the nineteenth century the focus of agriculture in the pre-alpine region gradually changed, once more mediated by political events. For a brief period between 1792 and 1815 Savoy became part of France and when, in 1798, Geneva was also annexed, it had access to agricultural produce from the Swiss plains and the Lyon region. As a consequence, the acreage under cereal cultivation diminished and the natural pasture-lands and forest resources of the calcareous massifs were exploited more fully. In 1815 Savoy was once more ceded to the Piedmont state and agriculture reverted to its eighteenth century condition. However, in time, tariffs were reduced, allowing the region to import cereals and to export cattle and cheeses. Annexation by France in 1860 accelerated development of the pastoral economy and associated dairying industry, and in 1866 this was further encouraged by the completion of the railway line between Annecy and Aix-les-Bains which enabled cereals to be brought in from abroad. To make cheese production competitive, the Swiss "fruitière" system was often adopted; within individual communes farmers grouped themselves into co-operatives and cheeses were manufactured in the central "fruitière".

Alongside the decline in arable cultivation there appears to have been a reduction in the area of land devoted to viticulture, if it can be assumed that the data shown in table 3.7. are indicative of land-use change throughout the area. In the case of the major vine-growing communes, such as Faverges, the decline in vine cultivation appears to have been particularly marked sometime after 1929. The earlier decline observed for the other communes probably reflects the fact that these areas were more marginal in terms of the availability of sunny adrêt slopes; for example, the abandonment of vineyards in Chevaline (q.v. figure 3.3.) was most significant at some point before 1913.

A decline in all types of agricultural land in the Petit Lac catchment area during the present century can be seen in table 3.8., while in table 3.9. a shift in emphasis within the pastoral system is evident, viz. a reduction in numbers of sheep kept in contrast to the recent importance of pig-rearing.

As a consequence of the reduction in cultivated land during the present century, the area of forest and woodland has generally increased in the Petit Lac catchment area (table 3.10.). In addition, Steel (1981) has recorded a rise in the area of scrub and heath for

	Area cultivated (ha)				
	1730[1]	1913[2]	1929[4]	1970[5]	1976[3]
Chevaline	1·8	0·1	0	0	0
Doussard	43·9	32·6	15·0	0	0·2
Faverges	92·6	87·5	87·5	4·0	25·0
Lathuille	14·2	11·3	5·5	0	0

Table 3.7. Decline of vine cultivation in four communes of the Petit Lac catchment area, 1730 - 1976 (data from: [1] the "Cadastre Savoyarde", ADHS; [2,3] the "Cadastre Français", ADHS†; [4] the "Enquête Agricole de 1929, Département de Haute-Savoie", ADHS†; [5] "Résultats du Recensement Général de l'Agriculture de 1970. Département de Haute-Savoie." Ministère de l'Agriculture, 1971)
† collected by E.A. Steel

	Area (ha)		% of total land area	
	1929[1]	1970[2]	1929	1970
Total cultivated land	6523	2571	49·7	19·6
Ploughed land	1608	465	12·3	3·5
Cereal cultivation	390	138	3·0	1·1
Permanent grassland	3879	2069	29·6	15·8

Table 3.8 Agricultural change in the Petit Lac catchment area, 1929 - 1970 (data from: [1]the "Enquête Agricole de 1929, Département de Haute-Savoie", ADHS†; [2]"Résultats du Recensement Général de l'Agriculture de 1970. Département de Haute-Savoie." Ministère de l'Agriculture, 1971)
† collected by E.A. Steel
Data are included for the following communes: Chevaline, Doussard, Faverges, Giez, Lathuille, Montmin and Seythenex; these account for over 70% of the Petit Lac catchment area.

	Number			
	1929[1]	1970[2]	1970 as % of 1929	(1754)
Cattle	2488	2296	92·3	(1843)
Sheep	253	81	32·0	(1325)
Pigs	868	1219	140·4	(34)

Table 3.9. Change in the pastoral farming system of the Petit Lac catchment area, 1929 - 1970 (see legend to table 3.8. for sources of data and lists of communes for which data have been included)
Figures from the "1754 tabelle" are included for comparison.

	Area (ha)		
	1913	"Renovation"	1976
Chevaline	758·3	809·3 (1933)	821·8
Doussard	924·7	965·3 (1934)	1460·8
Faverges	1062·8	1163·3 (1950)	1099·2
Lathuille	156·1	293·2 (1936)	307·8
Montmin	499·6	698·2 (1955)	678·8
Seythenex	1882·0	2017·4 (1935)	1882·3

Table 3.10. Change in the cover of forest and woodland in six communes of the Petit Lac catchment area during the twentieth century (data from the "Cadastre Français", ADHS, collected by E.A. Steel)
In 1913 c. 45% of the total area of these communes was forested, compared to c. 53% in 1976.

	Area (ha)		% of catchment area	
	Grand Lac	Petit Lac	Grand Lac	Petit Lac
Total cultivated area	1823	3277	22·6	19·2
Ploughed land	292	527	3·6	3·1
Cereals	97	155	1·2	0·9
Forage crops	177	342	2·2	2·0
Permanent grassland	1511	2707	18·8	15·9

Table 3.11. Agricultural land in the catchment areas of the Grand Lac and Petit Lac, 1970 (data from the "Résultats du Recensement Général de l'Agriculture de 1970. Département de Haute-Savoie." Ministère de l'Agriculture, 1971) Data are included for those communes with over half their land area within the drainage basin of the Lac d'Annecy (q.v. figure 3.3.); for the Grand Lac catchment area these are Sevrier, Saint-Jorioz, Saint-Eustache, La Chapelle-Saint-Maurice, Menthon-Saint-Bernard and Veyrier; for the Petit Lac catchment area these are Entrevernes, Duingt, Lathuille, Doussard, Chevaline, Giez, Faverges, Seythenex, Montmin, Talloires and Bluffy.

	No.		No./km²	
	Grand Lac	Petit Lac	Grand Lac	Petit Lac
Cattle	1852	2889	23·0	17·0
Sheep	119	118	1·5	0·7
Pigs	743	1528	9·2	9·0
Goats	49	158	0·6	0·9

Table 3.12. Pastoral farming in the catchment areas of the Grand Lac and Petit Lac, 1970 (see legend to figure 3.11. for sources of data and lists of communes for which data have been included)

the same period.

The continued importance of the dairying industry is reflected in tables 3.11. and 3.12. In both the Grand Lac and Petit Lac catchment areas, most of the cultivated land is devoted to permanent grazing or to the production of forage crops. Milk is still collected for the manufacture of the local Emmenthal cheese.

CHAPTER 4

MATERIALS AND METHODS

4.1. Materials

4.1.1. Collection of materials

One long core and two short cores from the Lac d'Annecy were analysed in this study; APL6 and APL1 from the Petit Lac sub-basin and AGL5 from the Grand Lac sub-basin (figure 4.1.).

All three cores were retrieved from the sediments of the central plain of the lake (q.v. figure 2.13.) where there would be expected to be the least possibility of disturbance by turbidity flows, sub-aqueous slumping and debris flows, thereby preserving a continuous and chronologically-ordered sequence of mud.

The long core, APL6[1] (576cm), was obtained in the summer of 1975 by the Department of Geophysics, University of Edinburgh, using a 6m fixed piston corer (Mackereth, 1958). It was cut into 1·5m length sections at the lake-side, wrapped in polythene tubing and transported back to Edinburgh for palaeomagnetic measurements. After whole-core measurements were completed the sections were split lengthways and one half of each section was used for single sample NRM and χ measurements (Hogg, 1978). The remaining halves were stored in polythene tubing in a cold store until transported to Liverpool in 1980.

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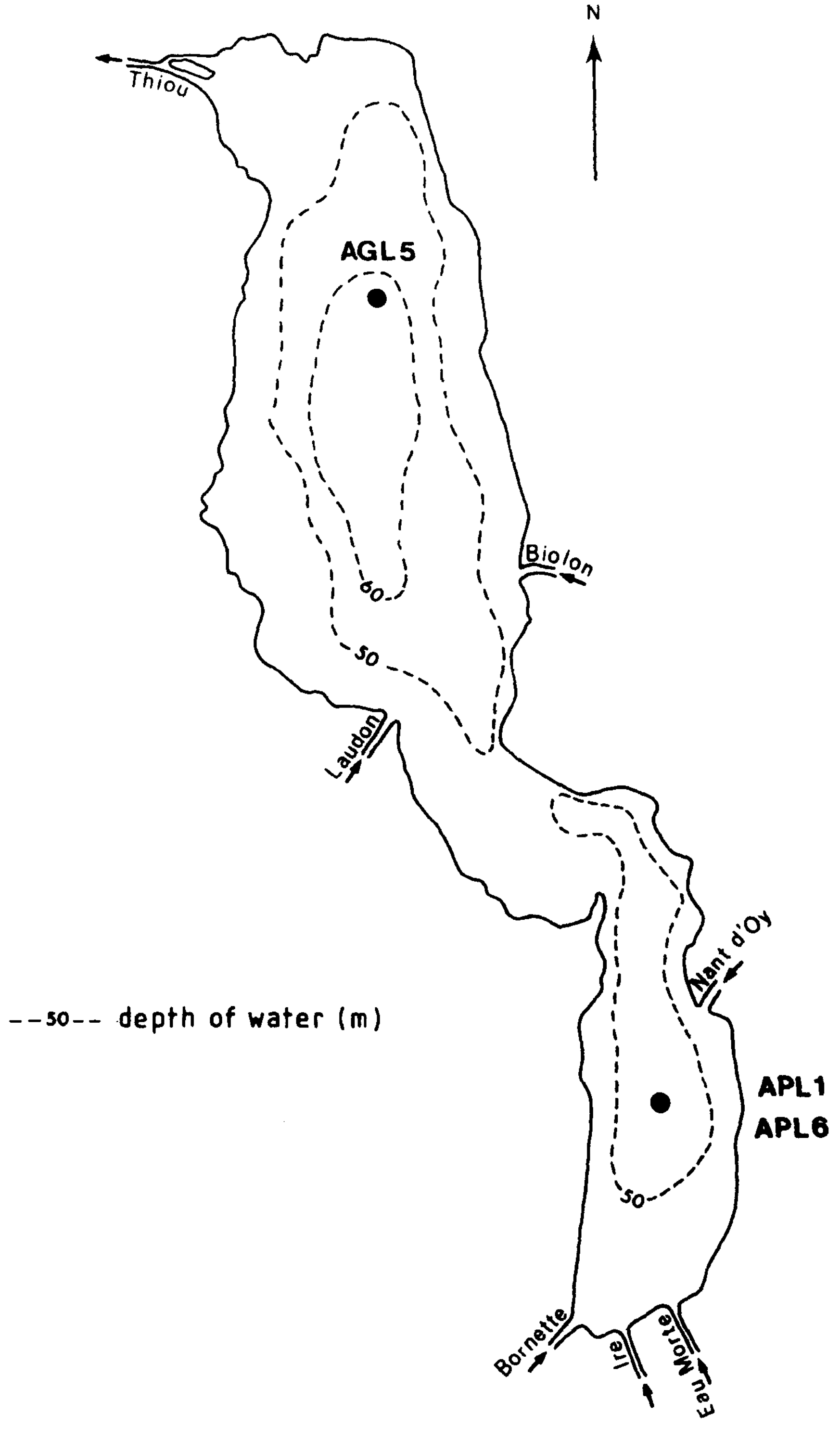
[1] This core was originally labelled ANN1 (Hogg, 1978), but here is referred to as APL6 to avoid confusion with the short core APL1. To the author's knowledge there is no other core existing from the Petit Lac labelled APL6.

Figure 4.1. Simple bathymetric map of the Lac d'Annecy showing the location of the three cores described in this study (after Balvay, 1978)


N
Thiou
AGL5
60
50
Biolon
Laudon
Nant d'Oy
--50-- depth of water (m)
APL1
APL6
50
Bornette
Ire
Eau Morte
0 1 2
km

The two short cores, APL1 (44cm) and AGL5 (81·5cm), were obtained in the summer of 1977 by the Department of Geography, University of Liverpool, using a 1m Mackereth mini-corer (Mackereth, 1969). The unextruded cores were transported back to Liverpool for mineral magnetic measurements (Dearing, 1979). After whole core χ measurements were completed the cores were extruded in 2cm slices and stored in sealed petri-dishes at room temperature.

4.1.2. Description of sediments

The sediments were fine-grained lake muds composed of varying proportions of Limus calcareus, Argilla steatodes and Argilla granosa (according to the simplified Troels-Smith system described by Aaby, 1979).

A colour stratigraphy of APL6 was recorded immediately after the polythene tubing was unsealed, using the standard Munsell soil colour charts (1975 edition); details are listed in Appendix 2.

Short sequences of mud were visibly laminated, composed of very narrow pale and dark bands. However, X-ray radiographs[1] indicated that laminations were present throughout most of the sedimentary sequence. These pale-dark couplets are thought to be calcareous laminations (P.E. O'Sullivan, pers. comm.) deposited in response to both annual cycles of primary production within the lake and seasonal trends in the flux of allochthonous material from catchment surfaces; the pale layers of calcite ($CaCO_3$) having been deposited during the late spring and summer (§ 4.3.1.) and the darker bands of organic and inorganic detritus having been formed in the autumn,

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[1] X-ray radiography of APL6 was carried out in the Nuclear Laboratory, Department of Mechanical Engineering, University of Liverpool.

winter and spring (O'Sullivan, 1983).

No stratigraphic details are available for the short cores.

4.1.3. Sampling procedure

Initially, 246 samples of mud were taken from the length of APL6; material was not sampled conventionally at regular depth intervals, but according to the colour stratigraphy referred to above.

The selection of individual samples for detailed pollen, geochemical and mineral magnetic analyses was considered carefully. The history of environmental change deduced from the results of palaeoecological analyses of non-contiguous samples of mud ultimately depends upon the initial sampling strategy. This would be expected to be most critical at sites where sediment accumulation is rapid and therefore temporal resolution very fine; an earlier study has indicated that 6m of mud from the Petit Lac represents only c. 2000 years of sediment accumulation (Higgitt, 1978).

A detailed profile of the mineral magnetic properties of the whole core was obtained from preliminary measurements of χ and SIRM (§ 4.4.4.) on all 246 single samples. In order to derive a general history of ecological change over the time period spanned by the core, 24 single samples, which were thought to reflect the main trends in these mineral magnetic properties (and therefore major trends in the nature of the material flux from catchment surfaces - see § 4.4.2.), were selected at approximately 25cm intervals; these are indicated on figure 6.7.

Six 2cm slices from APL1 and ten 2cm slices from AGL5 were sent to AERE Harwell for ^{210}Pb analyses shortly after the cores were collected; the remaining slices, sixteen from APL1 and thirty one from AGL5, were available for pollen, geochemical and mineral magnetic analyses. In addition, a small amount of material from three of the ^{210}Pb samples from APL1 had been retained and was used for pollen analysis.

Unfortunately, the sediments from all three cores were partially dried before sampling; consequently all results in this study are expressed on a dry weight basis only.

4.2. Pollen analysis

4.2.1. The role of pollen analysis and a framework for interpretation

The lake sediments were analysed for their fossil pollen and spore content in order to describe the sequence of vegetation change that has occurred in the catchment area of the Lac d'Annecy, and in particular to identify how man has modified the vegetative landscape.

Pollen analysis has long been the principal technique used to reconstruct Quaternary environments, and palynologists have continually sought to test the assumptions implicit in its rationale (table 4.1.) with a view to securing a more quantitative description of vegetation change and landscape reconstruction. A wealth of literature has been published during the last few decades recording investigations into the behaviour of pollen grains and spores in a wide variety of laboratory and environmental contexts (see Birks & Birks, 1980). Such studies suggest that there is an extremely complex relationship between the number of pollen grains in a deposit and the abundance of their parent plants in the pollen source area surrounding the site of deposition. The relationship is dependent on a myriad of interacting factors; the

1. Pollen or spores are produced in great abundance by plants.

2. A very small fraction of these fulfil their natural reproductive function, and the majority fall to the ground.

3. Pollen and spores rapidly decay, unless the processes of biological decomposition are inhibited by lack of oxygen. This occurs in places such as bogs, lakes, fens, and the ocean floor, where pollen is preserved.

4. Before reaching the ground, pollen is well mixed by atmospheric turbulence, which results in a more or less uniform pollen rain over an area.

5. The proportion of each pollen type depends on the number of parent plants, and hence the pollen rain is a function of the composition of the vegetation. Therefore a sample of the pollen rain will be an index of the vegetation at that point in space and time.

6. Pollen is identifiable to various taxonomic levels.

7. If a sample of the pollen rain is examined from a peat or mud of known age, the pollen spectrum is an index of the vegetation surrounding that place at a point of time in the past.

8. If pollen spectra are obtained from several levels through the sediment, they provide a picture of the vegetation and its development at that place through the length of time represented by the sediments.

9. If two or more series of pollen spectra are obtained from several sites, it is possible to compare changes in vegetation through time at different places.

Table 4.1. Basic principles of pollen analysis (from Birks & Birks, 1980)

genotypic and phenotypic properties of individual species affect the timing and volume of pollen production, while the physical and chemical properties of different types of pollen grain influence their dispersal, sedimentation and preservation, all of which are themselves influenced by a whole complex of environmental conditions such as temperature, wind strength, soil pH and so on.

In the case of the Lac d'Annecy drainage basin it should be appreciated that the pollen source area of the lake, assumed to correspond generally to the bounds of its catchment area (see paragraph below), is both extensive in area (§ 2.1.) and complex in pattern (§ 2.6.), consisting of several distinct vegetation formations which have been modified to a greater or lesser extent by man. These characteristics invoke questions of scale and complexity (sensu. Oldfield, 1970) in relating the fossil pollen assemblages observed in the lake sediments to the vegetation communities which gave rise to them; for any one point in time there will be an infinite combination of pollen source strengths and range of distances from the pollen collection point producing the pollen spectrum.

Moreover, studies of contemporary pollen budgets in open lake basins (ie. those receiving inflowing streams) suggest that a significantly high proportion of pollen is transported from catchment surfaces to the lake via the drainage network (Bonny, 1976; Peck, 1973). Consequently, it might be expected that the recruitment of pollen to the sediments of the Lac d'Annecy is to a large extent controlled by hydrological processes operating within the lake basin.

So, for the reasons outlined above, it is thought that interpretation of the pollen diagrams from the Annecy lake sediments, in terms of the reconstruction of vegetation communities and landscape patterns (on both a temporal and spatial scale), are best made within the following contexts: in comparison with Richard's ecological map (figure 2.18.); in the light of the documented land-use history (§ 3.2.); in respect of the lake basin morphometry and physical geography of the catchment area (Chapter 2.).

Firstly, assuming that Richard's proposed vegetation series are real entities, then they may be used as a reference for extrapolating former distributions of vegetation formations over the relatively recent time-scale spanned by the cores (c. 2000 years). During this period there are not thought to have been any major shifts in climatic regime causing large-scale vegetation changes (Ladurie, 1972) (cf. the evolution of vegetation in the Northern French Alps region throughout the Late-Glacial and Holocene, figure 5.14.).

Secondly, the availability of records, many of which are in numerical form, relating to man's agricultural exploitation of land in the lake basin, enables some assessment to be made of the pattern, scale and degree of vegetation modification within the pollen source area over the last 250 years.

4.2.2. Preparation of sediment samples

Sediment samples were prepared for pollen analysis following the method recommended by the Sub-department of Quaternary Research, University of Cambridge, and outlined in Berglund (1979), viz.

- removal of calcium carbonate with hot 10% HCl (APL1 and AGL5) or 30% HCl (APL6)[1]

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[1] 30% HCl was recommended for treating such highly calcareous samples (C. Reynaud, pers. comm.). Pollen counts for APL1 and AGL5 had been completed before this was suggested.

- removal of humic acids with hot 10% NaOH
- removal of coarse mineral and organic material by sieving through a 125μ mesh screen
- removal of siliceous material with hot 40% HF
- removal of cellulose with a mixture of 9 parts of acetic anhydride to 1 part of conc. H_2SO_4
- staining using aqueous safranin
- mounting in silicone oil (1000cs viscosity)

In order to determine the concentration of pollen in the sediment samples and therefore to overcome the interdependence of percentage counts (Davis, 1963; Faegri & Iversen, 1975), five tablets of *Lycopodium* spores (each containing 10850 ± 200 spores) were added to approximately 1g of sediment for samples from APL6 before the chemical treatments outlined above (Stockmarr, 1971). Sediments were dried at 40°C overnight before the addition of the exotic spore tablets in order to make the weight-based measurements directly comparable.

4.2.3. Pollen counting

Counts of pollen and spores were performed using a "Nikon" (L-Ke model) microscope. Routine counting was carried out at a magnification of × 400, while critical identifications were determined at a magnification of × 1000 using an oil immersion objective.

Counts were made in complete traverses, evenly spaced across each slide and were continued until both (i) a total of at least 300 determinable land pollen and spores had been identified; although total counts of less than 300 were accepted for eight samples from APL6 in which pollen concentrations were low and much pollen was too poorly preserved to identify (figure A3.1.), and (ii) all pollen and spores on a slide had been counted in order to avoid biasing due to a non-random distribution of grains beneath the cover-slip.

4.2.4. Pollen identification

Pollen and spores were identified using the pollen keys in Faegri & Iversen (1975) and Moore & Webb (1978), together with reference to the type-slide collections in the Palaeoecology Laboratory, Department of Geography, University of Liverpool; the Laboratoire de Botanique historique et Palynologie, Faculté des Sciences et Techniques Saint Jerôme, Marseille; and the Laboratoire de Géologie, Département de Géologie et de Paléontologie, Université de Genève.

Names assigned to pollen and spore types follow Faegri & Iversen (1975) and/or Moore & Webb (1978) except for the following two types:

Cereals type pollen

Cereals type pollen was distinguished from Gramineae undiff. pollen according to the criteria listed by Beug (1961) for acetolyzed material, viz.

- largest diameter of pollen grain, >37μ
- pore diameter, >2·7μ
- annulus width, >2·7μ
- annulus thickness, >2μ

Secale type pollen was distinguished from Cereals type undiff. pollen in samples from APL6, the additional criterion for identification being the position of the pore (Beug, 1961).

Oleaceae undiff. pollen

This pollen type was tricolpate, with distinct constrictions of the colpi in the equatorial region; sphaeroidal, with dimensions of c. 20μ; with a very coarse reticulum and thick exine of >2μ. It was tentatively identified as *Phillyrea* (J.L. de Beaulieu, pers. comm.) but due to the uncertainty of determination and because plants of this genus are not known to grow naturally in the lake basin today, it is here simply assigned to the family Oleaceae (see Renault-Miskovsky *et al*., 1976), with the qualification 'undiff.' as the pollen type *Fraxinus* is presented separately.

The degree of certainty in the determination of pollen and spores follows the convention proposed by Birks (1973) and is outlined below, using examples from this study:

Caryophyllaceae	family determination certain, no types or sub-groups determined
Artemisia	genus determination certain, no types or sub-groups determined
Plantago lanceolata	species determination certain
Plantago major/media	only two taxa are considered probable but further distinctions are not possible on the basis of pollen morphology alone
Onobrychis type	more than one taxa are possible but further distinctions are not possible on the basis of pollen morphology alone
Filicales undiff.	order determination certain, some morphological types distinguished and presented separately
Rosaceae undiff.	family determination certain, some morphological types distinguished and presented separately
Plantago undiff.	genus determination certain, some morphological types distinguished and presented separately

4.2.5. Recording the preservation states of pollen

During routine counting of the pollen and spore content of sediments from APL1 and AGL5, it was observed that high proportions of grains were too poorly preserved to be identified (between 13·4 and 36·7% in APL1 and between 11·7 and 39% in AGL5); these were recorded in the category unidentified deteriorated (figures A3.3. and A3.4.).

It was considered possible that some pollen types may have deteriorated more readily than others, resulting in their underestimation in the total pollen count, and conversely in an overestimation of the frequency of more resistant types. Moreover, some pollen grains have singularly distinctive features which enable them to be recognised by an experienced pollen analyst despite quite acute deterioration, while others may be rendered unidentifiable by only very limited damage.

Concern for the possible biasing effects of these phenomena within the fossil pollen spectra prompted a more thorough investigation into the preservation states of all pollen grains when samples from APL6 were counted. It was hoped that the results would also help to clarify the cause of deterioration, ie. whether poor preservation was a result of the number of chemical treatments and subsequent washings involved in the lengthy sample preparation, or whether it was simply a reflection of preservation conditions within the lake basin itself both prior to and following pollen deposition at the mud-water interface.

The preservation classes adopted to describe pollen preservation states follow those of Cushing (1967):

corroded - grains with exines which showed a distinctive etching or pitting degraded - grains in which the exines appeared to have undergone a structural rearrangement with sculptural and structural details only being resolved with difficulty

crumpled - grains that were badly folded, wrinkled or collapsed. (No distinction was made here between crumpled grains with a normal exine and those with a thinned exine).

broken - grains with a ruptured exine. (*Juniperus* type grains were not included in this category due to their natural tendency to split).

well-preserved - grains with no apparent signs of deterioration

The preservation classes described above are not necessarily mutually exclusive and so the convention for assigning grains to one particular class also follows Cushing (1967), ie. the five classes were arranged in a hierarchy from corroded through to well-preserved (in the order corroded, degraded, crumpled, broken, well-preserved) and grains were recorded as belonging to the highest class of which they were a member. Corroded, degraded, crumpled and broken grains are collectively referred to as deteriorated grains.

The frequency of broken conifer pollen was also recorded; each bladder was counted as a half-grain when free or singly attached to part of a pollen grain and the frequencies were calculated as a percentage of Σ *Abies* + *Picea* + *Pinus* (Oldfield, 1978).

4.2.6. Calculation of pollen data

Raw data from the pollen counts were managed using the Fortran program "POLLDATA Mk. 5", written by H.J.B. Birks and B. Huntley (Birks & Huntley, 1978), and adapted for use on the IBM 4341 computer at the University of Liverpool by J. Bloemendal and N. Richardson. The program was used to calculate pollen percentages for APL6, APL1 and AGL5, and pollen concentrations for APL6, and also to draw pollen diagrams by plotting these results against sample depth.

The calculation sum for deriving percentage data included all determinable land tree, shrub and herb pollen and excluded pteridophyte spores, the pollen of obligate aquatic plants, and unidentified grains (unknown, concealed and deteriorated).

Percentages for types excluded from the basic pollen sum were calculated as a percentage of the basic sum plus the sum of the group of types to which they belong. For example, percentages for *Pteridium aquilinum* were calculated as a percentage of the total pollen sum plus the sum of all pteridophyte spores.

Pollen concentrations were calculated following Stockmarr (1971) where the pollen concentration per gram dry weight of sediment is equivalent to:

$$\frac{\text{number of } \textit{Lycopodium} \text{ spores added} \times \text{number of fossil pollen grains counted}}{\text{number of } \textit{Lycopodium} \text{ spores counted} \times \text{dry weight of sediment prepared}}$$

4.2.7. Zonation of pollen diagrams

In order to overcome the subjectivity of placing pollen zone boundaries by eye (Gordon & Birks, 1972), the pollen diagrams from APL6, APL1 and AGL5 were zoned numerically, using the Fortran program

"ZONATION", written by A.D. Gordon, H.J.B. Birks and B. Huntley (Birks, 1979), and adapted for use on the IBM 4341 computer at the University of Liverpool by N. Richardson. The program carries out three numerical methods of zonation, constrained single-link analysis (CONSLINK), divisive information analysis (SPLITINF) and divisive sum-of-squares analysis (SPLITLSQ) (Gordon & Birks, 1972).

Of the pollen types included in the basic pollen sum, only those with at least one frequency of 5% or over were used for zoning (Birks, 1979): fourteen taxa were used for APL6 (*Picea*, *Pinus*, *Juniperus* type, *Alnus*, *Betula*, *Corylus*, *Fagus*, *Juglans*, *Quercus*, Gramineae undiff., Cereals type, *Cannabis* type, Compositae (Lig.) and Cyperaceae); eleven taxa for APL1 (*Picea*, *Pinus*, *Alnus*, *Corylus*, *Juglans*, *Quercus*, Gramineae undiff., Cereals type, *Cannabis* type, Compositae (Lig.) and Cyperaceae); and thirteen taxa for AGL5 (*Picea*, *Pinus*, *Juniperus* type, *Alnus*, *Castanea*, *Corylus*, *Fagus*, *Juglans*, *Quercus*, Gramineae undiff., Cereals type, *Cannabis* type and Cyperaceae).

4.3. Geochemical analysis

4.3.1. The role of geochemical analysis

Lake sediments are a complex mixture of materials. The inorganic mineral fraction is derived from various sources: the allochthonous component consists of clastic mineral particles resulting from the erosion of catchment soils and substrates which are transported to the lake via the drainage network, together with any dust particles deposited from the atmosphere (which are not necessarily catchment-bound); the autochthonous component comprises those materials produced by chemical processes within the water column, such as biochemically precipitated carbonate minerals, biogenic silica and so on; the authigenic component includes those minerals produced by diagenesis within the sediments, including both the structural change of allochthonous and autochthonous minerals and the formation of new minerals from solute species, these processes being governed by chemical gradients existing at the mud-water interface and in the zone of unconsolidated sediments below. The organic fraction is composed of humic compounds and plant and animal detritus, and may be of terrestrial origin or result from internal lake productivity. Organic matter can be significant in complexing or sorbing metallic ions from solution within the lake, while the allochthonous organic component may chelate cations from soil and stream solutions within the catchment area and transport these elements to the lake. Organic material may be subjected to further biological degradation once incorporated into the sediments (Engstrom & Wright, 1984; Håkanson & Jansson, 1983; Jones & Bowser, 1978).

Where lake sediments are derived predominantly from terrestrial surfaces, their chemical composition has been determined by palaeolimnologists in attempts to reconstruct ecosystem development and environmental change, as these profiles will largely reflect changes in soil erosion and leaching in the surrounding catchment area.

However, in lakes within areas dominated by calcareous bedrock, autochthonous precipitation of calcite ($CaCO_3$) may also be a significant source of sediment. Hard-water lakes have high concentrations of Ca^{++} and HCO_3^- or $CO_3^=$, and if dissolved CO_2 becomes exhausted, either biologically by the removal of CO_2 in algal photosynthesis (Wright *et al.*, 1980), or physically by an increase in temperature which reduces the solubility of CO_2 in water (Brunskill, 1969), then the carbonate system buffers this loss by the precipitation of calcite until a new equilibrium is reached. Calcite precipitation can be described by the reaction:

$$Ca^{++} + 2HCO_3^- \rightarrow CaCO_3(s) + H_2O + CO_2(g)$$

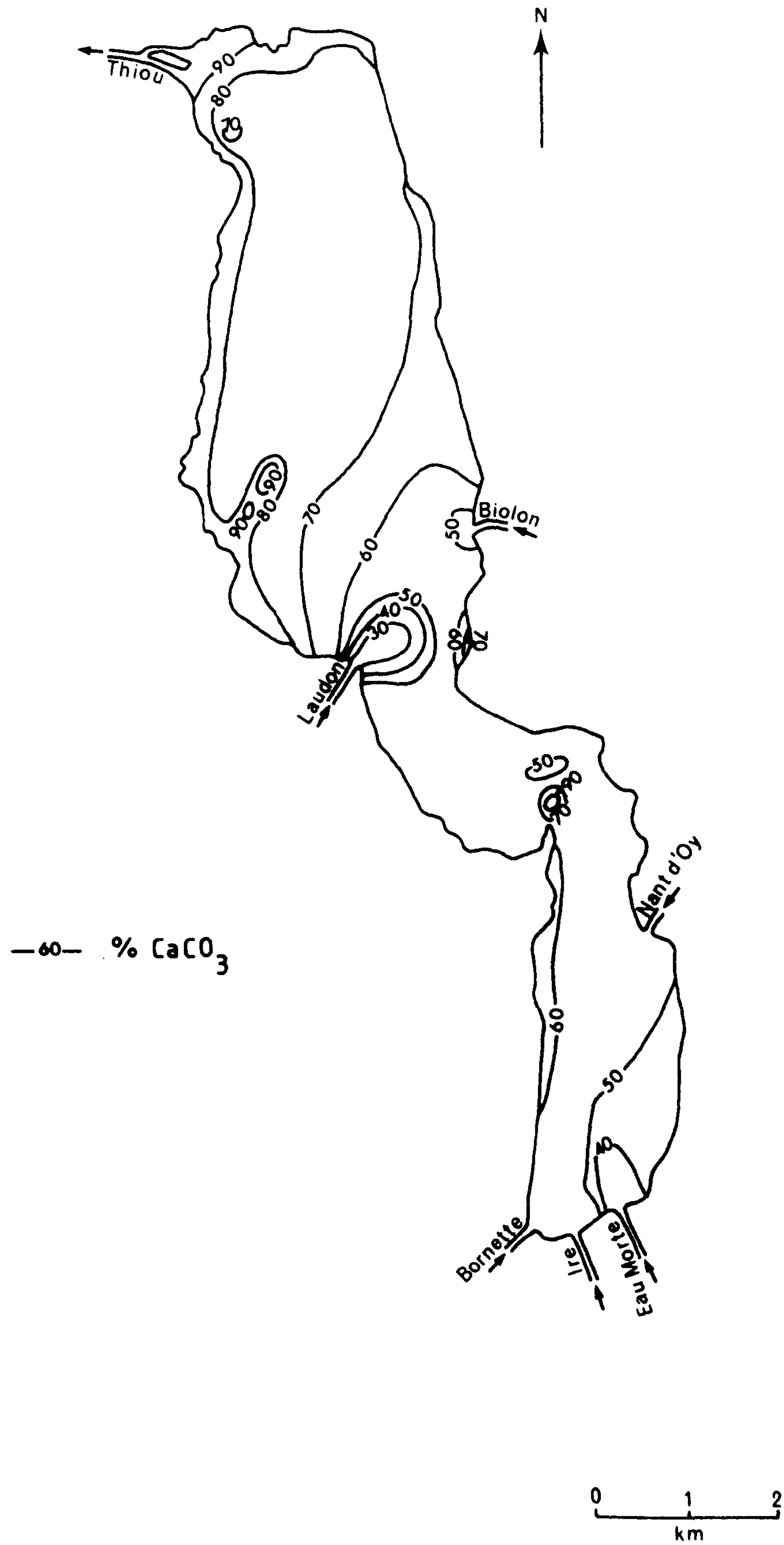
With increasing pH, calcite solubility decreases; so its precipitation is also favoured in productive lakes where intense photosynthesis may raise the pH by several units during the day (Håkanson & Jansson, 1983).

Calcite crystals settling through the water column may redissolve by coming into contact with the colder waters of the hypolimnion where CO_2 concentrations are higher, and in productive lakes calcite crystals reaching the lake bottom may dissolve in the presence of high CO_2 concentrations resulting from the breakdown of organic matter in sediments. Carbonates formed as a result of pH changes in the upper water strata may partially dissolve when reaching the hypolimnion or sediment surface where the pH is lower, due to the breakdown of organic material (Håkanson & Jansson, 1983). It is thought that surface coatings of amino acids, humic matter and other dissolved organic species may protect calcite crystals from dissolution and promote their incorporation into bottom sediments (Wetzel, 1970 and 1972).

In such lake-catchment systems, attempts to interpret changes in sediment chemistry in terms of catchment events and processes only may be fraught with more problems than usual, in that the concentration of allochthonous chemical elements and so on may be controlled in part or wholly by the deposition of autochthonous material. A similar problem can be envisaged when mass specific mineral magnetic measurements are considered.

The importance of autochthonous calcite precipitation in the Lac d'Annecy is reflected in the $CaCO_3$ content of the <40µ fraction within surface sediments (figure 4.2.). $CaCO_3$ values are generally highest in littoral zones and beneath the shallow waters which overlie the three sub-lacustrine islands (q.v. figure 2.13.), and are lowest in deep-water sediments, due to the partial dissolution of settling

Figure 4.2. $CaCO_3$ content of the <40μ fraction of surface sediments in the Lac d'Annecy (from Benedetti-Crouzet, 1972)


N
Thiou
Biolon
Laudon
Nant d'Oy
Bornette
Ire
Eau Morte
90
80
70
60
50
40
30
—60— % $CaCO_3$
0 1 2
km

calcite crystals. This pattern of autochthonous calcite sedimentation is superimposed upon the deposition of calcareous detritus delivered by the affluents; relatively low $CaCO_3$ values are particularly evident at the mouths of the Laudon and the Eau Morte (Benedetti-Crouzet, 1972).

Thus, it was thought to be important to gauge the $CaCO_3$ content of sediments analyzed in this investigation as an aid to interpreting profiles of all other concentration-based measurements.

The organic matter content was estimated so that in addition to assessing the relative proportion of allochthonous and autochthonous organic material preserved in the lake sediments, the magnitude of the non-carbonate mineral material fraction could be calculated for each sediment sample. This latter fraction includes mineral particles eroded from catchment surfaces, which are of interest in this study, although it is appreciated that this gross sedimentary division also includes internally produced biogenic silica, authigenically formed minerals and so on (see above).

In order to trace the flux of mineral material from catchment surfaces, sedimentary concentrations of sodium (Na), potassium (K), magnesium (Mg) and iron (Fe) were assayed. Na, K and Mg are major constituents of common silicate minerals. In solution, these elements tend to be conservative and are generally not sedimented in appreciable quantities through biological uptake or chemical precipitation. Therefore, their presence in most lake sediments is due to the inwash of mineral clastics from the catchment area (Engstrom & Wright, 1984). Fe is also supplied to the lake bound in the mineral lattices of allochthonous clastics, and in this form is highly stable. Particulate iron is also deposited as inorganic oxides or as oxide coatings on settling particles. Under reducing conditions Fe may also be released from catchment soils and transferred to the lake in solution as organic complexes or as colloidal particulates, and may reach the lake sediments in this form. Due to the high chemical mobility of Fe in lake sediments, this element may also occur in a number of authigenically formed oxides or sulphides, dependent upon the supply of Fe to the sediments in addition to changes in redox potential and pH at the mud-water interface and in the uppermost sediments (Engstrom & Wright, 1984; Håkanson & Jansson, 1983). Thus, Fe profiles may be complex to interpret.

4.2.2. Laboratory methods

Calcium carbonate content

This was determined by measuring the volume of CO_2 evolved when a sub-sample of known weight (0·5 - 1g) of oven-dried material was reacted with 3N HCl in a calcimeter. The $CaCO_3$ content was estimated from the mean of two replicate sub-samples, where the "% $CaCO_3$ equivalent" of each sub-sample

$$= \frac{\text{volume of } CO_2 \text{ (ml)} \times \text{barometric pressure (mm Hg)}}{\text{mass of sub-sample (g)} \times \text{temperature (°C + 273)}} \times 0{\cdot}1604$$

(Bascomb, 1974).

Organic matter content

Sub-samples of known weight (c. 2g) of oven-dried material (105°C overnight) were ignited at 450°C for four hours to provide an index of the organic matter content. The ignition procedure was standardized by putting the crucibles into a cool furnace and timing the ignition period from the moment the furnace was switched on; a temperature of 450°C was reached after c. one hour.

A low temperature ignition was used in order to minimize the loss of water from clay minerals, the greatest part of which occurs in the range 450 - 600°C (Ball, 1964; Hesse, 1971), and loss of CO_2 from the carbonate fraction, which occurs in the range 850 - 1000°C (Smith & Atkinson, 1975). The organic matter content was estimated from the mean % weight loss-on-ignition of two replicate sub-samples.

Element analysis

Sub-samples of known weight (c. 0·1g for APL1 and AGL5; 0·2g for APL6) of oven-dried material (105°C overnight) were prepared for element analysis by reaction with a series of acids, following the method recommended by the Department of Oceanography, University of Liverpool (J. Sharples, pers. comm.) for treating highly calcareous sediments, viz.

- hot conc. HNO_3 for digestion of organic matter
- hot 2N HCl for digestion of carbonate minerals
- hot 40% HF and conc. HNO_3 for digestion of siliceous minerals

Residues were brought into solution with 5ml of 2N HCl, were filtered and then diluted with distilled water to an appropriate volume for element determination.

Fe and Mg were determined by atomic absorption, while Na and K were determined by flame photometry.

4.4. Mineral magnetic analysis

4.4.1. The physical basis of the magnetic properties of minerals.

The magnetic properties of all natural materials arise principally from the creation of magnetic fields by the movement of electrons as they spin about their own axes and as they orbit their nucleus.

All substances possess the property of diamagnetism which derives from the presence of closed shells of electrons. When placed in a magnetic field the precession of electron orbits results in an induced magnetic movement being set up in opposition to the applied field. The magnetization acquired per unit field applied (the magnetic susceptibility) is small, less than 10^{-5} S.I., and is lost immediately upon removal from the applied field. Commonly occurring minerals which exhibit diamagnetism are quartz (SiO_2), calcite ($CaCO_3$) and dolomite ($CaCO_3 \cdot MgCO_3$).

If all the electrons of an atom exist in pairs, their spin and orbital angular momenta cancel each other out. However, in atoms containing unpaired electrons, there is a net magnetic moment. When placed in a magnetic field, these electron orbits precess, but the magnetic moment is aligned in the same direction as the applied field. This type of magnetic behaviour is termed paramagnetism. The paramagnetic effect is very much greater (c. 10^3 times) than the diamagnetic effect, having magnetic susceptibilities of the order of 10^{-3} to 10^{-5} S.I., and so substances with unpaired electrons are usually paramagnetic, although the net magnetic moment is reduced by the diamagnetism due to closed shells of electrons. The potential net magnetic moment is often still removed by chemical bonding and the sharing of electrons when compounds are formed. The paramagnetic effect is lost upon removal from the field due to the randomizing influence of thermal motions, and so paramagnetic substances do not exhibit any spontaneous magnetization. In natural materials, paramagnetism is generally due to the presence of ferrous (Fe^{2+}) and ferric (Fe^{3+}) ions, in which an external magnetic field arises almost entirely from the uncompensated spins of unpaired electrons in the 3d orbital shell. Important paramagnetic materials include ilmenite ($FeTiO_3$), biotite, siderite ($FeCO_3$), the clay minerals and the iron oxyhydroxides lepidocrocite ($\gamma FeOOH$) and ferrihydrite ($5Fe_2O_3 \cdot 9H_2O$).

Paramagnetic behaviour is modified in substances where the paramagnetic centres are not separated from one another by numbers of diamagnetic atoms. The spins of unpaired electrons in neighbouring or nearest-neighbour paramagnetic atoms are coupled by exchange interactions, either by direct exchange between adjacent atoms or by means of an indirect superexchange reaction via an intermediate anion, usually oxygen. Depending on the degree of overlap of electron orbits, the electron spins are coupled parallel or antiparallel to each other.

In materials in which the couplings of these electron spins are all parallel, a very strong spontaneous magnetization results even in the absence of an applied field; this type of magnetic behaviour is termed ferromagnetism. However, ferromagnetism is largely confined to iron and nickel-iron alloy systems, and is rarely observed in naturally-occurring materials at the Earth's surface.

When electron spin coupling is antiparallel, the magnetization can be thought of as consisting of two magnetic sub-lattices magnetized in opposite directions. If the magnetization of the two lattices is exactly balanced there is no resultant magnetic moment and thus no spontaneous magnetization is exhibited; this type of magnetic behaviour is termed antiferromagnetism. When the two magnetic lattices are antiparallel but not exactly equal, a net magnetic moment results from the difference between the two, and a spontaneous magnetization is exhibited; this type of magnetic behaviour is termed ferrimagnetism.

In haematite (αFe_2O_3) which has a rhombohedral crystal structure, the atomic Fe^{3+} moments on the A and B lattices are equal. However, the opposed magnetic moments of the two lattices are imperfectly aligned or "canted", which gives rise to a small net magnetic moment. Haematite exhibits a weak spontaneous magnetization, of c. 0·4 - 0·5 Am^2kg^{-1}. The initial mass susceptibility of natural material is in the range 60 - 600 × $10^{-8}m^3kg^{-1}$. The iron oxyhydroxide goethite ($\alpha FeOOH$) also behaves as a canted antiferromagnet.

Magnetite (Fe_3O_4) is a cubic mineral with an inverse spinel structure and behaves as a ferrimagnet. In each unit cell of this mineral there are eight Fe^{3+} atoms in the A sub-lattice, and eight Fe^{3+} and eight Fe^{2+} atoms in the B sub-lattice. The imbalance of Fe^{2+} in the B sub-lattice confers a net magnetic moment on the crystal. With the exception of iron, magnetite has the strongest magnetic properties; its spontaneous magnetization is 90 - 93 Am^2kg^{-1} and about 200 times that observed for haematite. The initial mass susceptibility of magnetite is typically ~ $5 \times 10^{-4} m^3kg^{-1}$ (1 - 2 orders of magnitude higher than for haematite). In naturally occurring materials, magnetite is not usually found in its pure state, and its magnetic behaviour is more variable due to the disordering effects of foreign cation subsistitution (commonly Ti^{4+}, Al^{3+}, Mg^{2+} and smaller quantities of Cr^{3+} and Mn^{2+}) and of lattice site vacancies. The term magnetite tends to be used rather loosely and refers to the members of the titanomagnetite solid solution series between magnetite (Fe_3O_4) and ulvöspinel (Fe_2TiO_4). Low temperature oxidation of magnetite during weathering often produces maghemite (γFe_2O_3). While maghemite has the same chemical composition as haematite, the retention of its cubic inverse spinel structure means that it exhibits ferrimagnetism, although its spontaneous magnetization of 70 - 85 Am^2kg^{-1} is slightly less than that of magnetite (Collinson, 1983; Nicholls, 1974; Tarling, 1983).

The most commonly occurring soil iron oxides are listed in table 4.2; their structure and magnetic properties are described in detail elsewhere (Collinson, 1983; Maher, 1984; Thompson & Oldfield, in press). Here, the term "magnetic mineral" is used generally to refer to the ferrimagnets magnetite and maghemite, and the canted antiferromagnets haematite and goethite. In addition to exhibiting a spontaneous magnetization these minerals may retain part of the

Mineral	Chemical formula	Magnetic state	Reported environmental associations
Magnetite	Fe_3O_4	ferrimagnetic	restricted occurrence, primarily derived or from soil firing
Maghemite	γFe_2O_3	ferrimagnetic	abundant in highly weathered tropical or sub-tropical soils
Haematite	αFe_2O_3	canted antiferromagnetic	relatively dry, highly oxidezed soils, usually in areas of elevated temperature
Goethite	$\alpha FeOOH$	canted antiferromagnetic	moister soils, abundant in well drained temperate areas
Lepidocrocite	$\gamma FeOOH$	paramagnetic	occurs in poorly drained soils
Ferrihydrite	$5Fe_2O_3 \cdot 9H_2O$	paramagnetic	poorly drained and podzolized soils

Table 4.2. Iron oxides and hydroxides in soils (after Maher, 1984)

magnetization induced in the presence of an externally applied magnetic field, ie. they may carry a remanent magnetization.

In crystals of these minerals there are directions along which it is easier for the substance to become magnetized; for example, haematite is 100 times more easily magnetized in the basal plane of its crystal than in any other direction, and in magnetite ellipsoids are more readily magnetized along their long axes. In the absence of an external field, the magnetic moment of each grain[1] spontaneously aligns along one or other "easy" axis (Tarling, 1983).

In relatively large crystals, alignment of the electron spin magnetic moment along an "easy" axis is modified; the magnetization within each grain spontaneously breaks down to form separate magnetic domains which are spontaneously magnetized in different directions. These crystals are known as multidomain grains. The effect of domain formation is to minimize the total magnetostatic energy of the crystal and in large multidomain grains orientation of the individual domain magnetic moments may be such that the crystal shows virtually no net spontaneous magnetization. Domains are separated by narrow zones - domain or Bloch walls - in which the direction of the magnetization of the electron spins cant over from that of one domain to the next. Domain walls are c. 0·1μ width, while domains are of the order 0·1 - 0·05μ in magnetite and possibly up to 1·5μ in haematite. Thus, in relatively small crystals there is only sufficient volume for a single domain; these are known as single domain grains. Estimates for the critical grain size threshold at which the single domain - multidomain transition occurs are given in table 4.3. for magnetite, maghemite and

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[1] The term grain size should not be confused with particle size. Grain, as used here, is interchangeable with the word crystal. Fine magnetic grains/crystals may occur as inclusions within coarse mineral particles or aggregrates; their magnetic properties are determined by the size of the individual crystals and not by the size of the particle.

Domain Status

Mineral	Superparamagnetic		Single domain		Multidomain
Magnetite		<0·025–0·03>		<0·05–0·06>	
Maghemite		<0·08>		<0·06>	
Haematite		<0·025–0·03>		<1·5>	

Table 4.3. Grain size thresholds (μ) for magnetite, maghemite and haematite (from Maher, 1984)

haematite. (These figures assume spherical grains).

When an external field is applied to a multidomain grain the domain walls unroll so that domains with magnetization parallel to the applied field increase in volume. The unrolling, or translation, of the domain walls may take them through energy barriers arising from the presence of defects and impurities in the crystal lattice. If these energy barriers are only small the domain walls can roll back to their original position upon removal from the field. In the presence of a strong applied field domain walls may roll past larger energy barriers, but when the field is removed not all walls will be able to relax spontaneously to their initial location and become trapped in new positions. These irreversible domain wall movements are known as Barkhausen jumps. The domains aligned with the applied field remain thus, and in this way the crystal acquires an <u>isothermal remanent magnetization</u>. As stronger magnetic fields are applied, domain walls can cross larger and larger energy barriers within the crystal and so the intensity of isothermal remanence increases. In sufficiently strong fields the magnetization of domains originally antiparallel to the applied field will "flip" into alignment with the field. A multidomain grain is finally saturated when all domain magnetizations are aligned in the field direction; this is referred to as <u>saturation magnetization</u>. Upon removal from the saturating field, weakly pinned domain walls may relax and the whole grain retains a <u>saturation isothermal remanent magnetization</u> (Tarling, 1983; Thompson & Oldfield, in press).

The magnetic properties of single domain grains are different from those of multidomain grains as their magnetization does not involve the movement of domain walls. When a direct field is applied perpendicular to the direction of spontaneous magnetization in a single domain grain, the grain magnetic moment will tend to rotate in the direction of the applied field, but upon removal of the field the magnetization will immediately relax back to the "easy" direction. When a direct magnetic field is applied opposite to the direction of spontaneous magnetization, the grain magnetic movement changes abruptly at a critical field strength, known as its intrinsic coercivity, and rotates through 180° to align in the direction of the field. When the field is reduced to zero the magnetization remains aligned in the direction of the applied field. Relatively high magnetic fields are required to overcome the energy barriers separating the "easy" axes in single domain grains, whereas in multidomain grains domain wall translations may occur in relatively low fields. Thus, the magnetic remanence of assemblages of single domain grains is higher and more stable than that of multidomain grain assemblages (Dankers, 1978; Thompson & Oldfield, in press).

Very small single domain grains are thermally unstable at room temperature and their spontaneous magnetization "flips" from one "easy" direction to another. In the presence of an external magnetic field the grain magnetic moment will spend longer periods of time in the direction of the applied field. However, as soon as the field is removed, thermal vibrations rapidly destroy this alignment and so these grains are unable to carry a remanent magnetization. The behaviour of these crystals is similar to that of paramagnetic substances (see above) but as their atomic moments are much larger than for normal paramagnets this behaviour is termed superparamagnetism. The grain size range over which the superparamagnetic - single domain transition occurs in magnetite, maghemite and haematite is given in table 4.3. (Again, these values assume spherical grains). Single domain crystals occurring at this transition exhibit a time-dependent magnetization, referred to as magnetic viscosity, which occurs within the time-range of experimental measurements (cf. the shorter response of superparamagnetic grains). These are known as viscous grains and are thus distinct from the stable single domain grains described above. Multidomain grains also exhibit magnetic viscosity; Dunlop (1983) has observed that magnetite crystals ~ 5-15μ are exceptionally viscous. However, the magnetic viscosity of multidomain grains is usually some two orders of magnitude less than that observed for single domain grains (Mullins & Tite, 1973a).

While the magnetic behaviour exhibited by natural materials is essentially determined by chemical composition and crystalline structure, the behaviour of "magnetic minerals" is very largely dependent on crystal size[1]. Natural soils and sediments may include a number of diamagnetic, paramagnetic, ferrimagnetic and antiferromagnetic materials in varying proportions, and within their magnetic mineral assemblage may contain a range of crystal sizes. The mineral magnetic properties of bulk sediment samples therefore reflect the composite behaviour of all substances within the sediment matrix.

4.4.2. The role of mineral magnetic analysis

On the basis of magnetic susceptibility (χ) measurements, Dearing was able to divide rock and drift samples from the Lac d'Annecy drainage basin into two general categories: (i) limestones and calcareous marls with relatively low or negative χ values and (ii) glacial drift and molasse deposits with relatively high χ values (table 4.4.). Higher χ values within the second group are assumed to

[1] The grain size dependence of domain status is further modified by grain shape, although this has not been considered in detail here. This factor is important in magnetite; the effect of increasing grain elongation is to raise the boundary of the critical grain size threshold at which the superparamagnetic - single domain and single domain - multidomain transitions occur.

Lithology	χ ($\times 10^{-6} Gcm^3Oe^{-1}g^{-1}$)
Limestone	all diamagnetic or extremely low values (< 2)
Calcareous marl	3
Glacial drift	9 - 12 (mean, 11)
Molasse	26 - 62 (mean, 48)

Table 4.4. χ measurements of rock and drift samples in the Lac d'Annecy drainage basin (from Dearing, 1979)

reflect the inclusion of primary ferrimagnetic minerals within erratic and molassic material. Drift deposits derived from outside the catchment area are largely restricted to below c. 800m altitude (§ 2.2.1.), while molassic deposits only outcrop in the Grand Lac catchment area, in particular in the Laudon river valley, (figure 2.3. and table 2.3.). Thus, it is clear that the lithology of the drainage basin is dominated by weakly magnetic or diamagnetic rock types.

Nonetheless, Dearing has demonstrated the widespread occurrence of magnetic enhancement in topsoils of the catchment area. Although enhancement was generally more pronounced in soils with higher χ values, the phenomenon was not solely restricted to lithologies rich in primary ferrimagnetic minerals. This he attributed to the *in situ* conversion of weakly magnetic iron oxides and hydroxides to highly magnetic ferrimagnetic forms by the mechanisms proposed by Le Borgne (1955 and 1960). Microcrystalline magnetite or maghemite may be formed as a result of the repeated oxidation-reduction cycles which occur under normal pedogenic conditions (known as the pedogenic or fermentation mechanism) or may result from the combustion of soil organic matter (the burning mechanism). The processes involved are described in detail elsewhere (Mullins, 1977; Thompson & Oldfield, in press). It is difficult to assess which mechanism is, or has been, dominant at any one site, although it is considered that burning is likely to have been an important method of land management in the past in this catchment area.

Magnetic enhancement is clearly seen in the upper horizons of three soil profiles developed over a parent material of local calcareous drift at an altitude well above the supposed extent of Würmian erratics (table 4.5.). It is interesting to note that fragments of charcoal have been observed in all three profiles

GC4 (Altitude, 1080m)

Depth (cm)	Horizon	χ	SIRM
2 - 4	A	3·32	135·09
8 - 10	A	3·01	130·81
18 - 20	B	1·82	75·39
28 - 30	B/C	0·87	36·68

GC60 (Altitude, 1050m)

Depth (cm)	Horizon	χ	SIRM
2 - 4	A	1·44	81·02
8 - 10	A	1·34	75·30
18 - 20	A	1·19	67·63
28 - 30	B	0·77	46·14
38 - 40	B	0·59	36·35
48 - 50	B	0·54	35·95
58 - 60	C	0·79	53·31

GC137 (Altitude, 1030m)

Depth (cm)	Horizon	χ	SIRM
2 - 4	A	8·06	298·83
8 - 10	A	8·92	331·19
18 - 20	A	7·77	246·90
	till matrix	0·88	34·96

Table 4.5. χ and SIRM measurements of brown earth soils from the Eau Morte river basin (P.A. James & B.A. Maher, unpublished data)

P.A. James, pers. comm.).

Measurements carried out by Mullins & Tite (1973b) have established that between 10 and 20% of the ferrimagnetic oxides in a typical soil developed on sedimentary deposits are well-dispersed single domain grains ~ 0·025μ in diameter, the majority being smaller and superparamagnetic. Mössbauer effect studies carried out on magnetic extracts from soils developed over calcareous bedrock in the Annecy lake basin have shown the presence of non-stoichiometric magnetite with an approximate formula $Fe_{2\cdot 9}O_4$, all of which was superparamagnetic (Longworth *et al.*, 1979).

Thus, in general, topsoils of the catchment area seem to be characterized by the presence of ultra-fine grained secondary ferrimagnetic minerals. The mineral magnetic measurements described below were carried out in order to quantify changing volumes of secondary ferrimagnetic oxides leaving catchment surfaces, and in addition to identify changes in the proportion of superparamagnetic and fine single domain ferrimagnetic grains within the mineral magnetic assemblage as an aid to identifying changing inputs of topsoil material.

A summary of the χ measurements made by Dearing in his study of the links between catchment sources of magnetic material and the mineral magnetic record preserved in the lake sediments is given in table 4.6. (q.v. figure 1.1.).

4.4.3. Preparation of sediment samples

Sediments were prepared by oven-drying at 40°C overnight and were then disaggregated by gently crushing in a polythene bag using a pestle, before being packed into clean perspex 10cc holders.

For mineral magnetic measurements made during 1978 - 1981 a wide range of sub-sample sizes was used, depending on the amount of

Source	χ ($\times 10^{-6} Gcm^3 Oe^{-1} g^{-1}$)
Grand Lac	
Soils	17 - 95 (mean, 50)
Stream bedload	7 - 48 (mean, 24)
Lake sediments	3 - 20 (mean, 11)
Petit Lac	
Soils	2 - 201 (mean, 40)
Stream bedload	1 - 45 (mean, 7)
Lake sediments	4 - 14 (mean, 9)

Table 4.6. Summary of χ measurements for soils, stream bedload and lake sediments in the Lac d'Annecy drainage basin (from Dearing, 1979)

material originally retrieved from the cores. However, when selected samples were re-prepared and measurements repeated in 1983, the weight of sub-samples was standardized for each core; c. 4g in the case of APL6 and c. 5g for APL1 and AGL5[1].

For remanent magnetic measurements which required inversion of the sample pots, the sediments were packed down with clean foam to prevent any movement of particles (which would begin to randomize the induced magnetization).

4.4.4. Mineral magnetic parameters

Most of the mineral magnetic parameters used in this study can be defined in relation to the hysteresis loop, a plot of the intensity of induced magnetization versus the strength of the applied magnetic field.

The response of individual grains of different domain status to the application and removal of direct magnetic fields has been described above (§ 4.4.1.). However, for the lake sediment samples analyzed here the measurements described below will probably reflect the response of assemblages of varied domain status. Figure 4.3. shows the hysteresis loop for an assemblage of randomly oriented ferrimagnetic grains of superparamagnetic, stable single domain and multidomain grain sizes. The application of increasing magnetic fields causes the magnetization of the whole assemblage to increase in a systematic manner, very similar to that already described for

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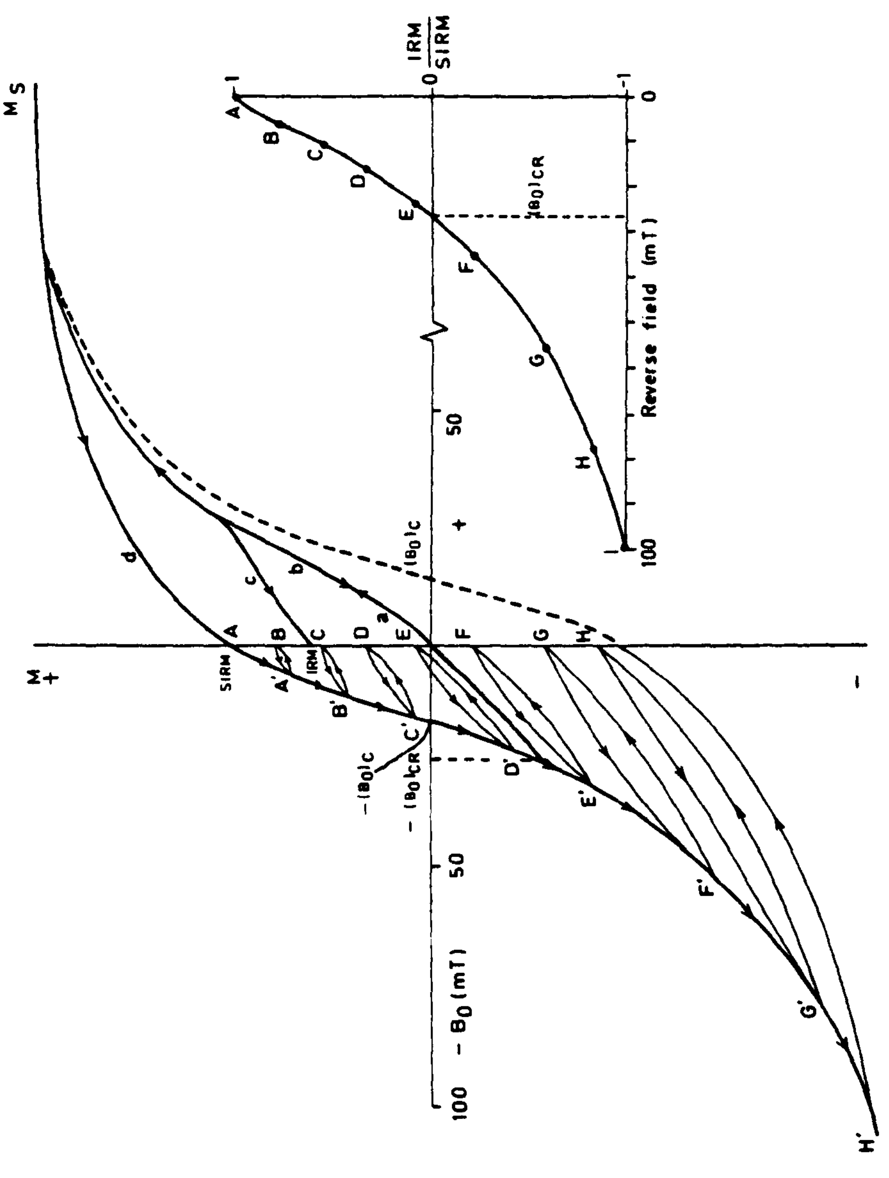
[1] The development of this project has spanned the time period during which the mineral magnetic laboratory in the Department of Geography (University of Liverpool) has become established. During the original three year research period (1978-1981) mineral magnetic analyses were limited to measurements of χ and SIRM only (see text). However, during the autumn of 1983 the author had access to a new range of equipment in the department, which provided an opportunity to complete a more comprehensive suite of mineral magnetic analyses for many of the lake sediment samples.

Figure 4.3. The hysteresis loop (after Bloemendal, 1982) The intensity of induced magnetization (M) vs. the strength of the applied magnetic field (B_0). (Abbreviations: M_s = saturation magnetization; IRM = isothermal remanent magnetization; SIRM = saturation isothermal remanent magnetization; $(B_0)_{cr}$ = coercivity of remanence).



M +
Ms
SIRM
IRM
a
b
c
d
$(B_0)_C$
$-(B_0)_C$
$-(B_0)_{CR}$
$(B_0)_{CR}$
$-B_0$ (mT)
50
100
+
-
IRM/SIRM
1
0
-1
Reverse field (mT)

individual multidomain grains (§ 4.4.1.), due to:

(i) the translation of domain walls in multidomain grains and eventually the rotation and alignment of domain moments originally antiparallel to the direction of the field.

(ii) the rotation of single domain grain moments perpendicular to the field and eventually the alignment of single domain grains originally antiparallel to the field as their intrinsic coercivities are exceeded.

(iii) the temporary alignment of superparamagnetic grains in the direction of the field.

In region "a" of the curve the magnetization induced (M) is directly proportional to the applied field (B_0) and the curve rises linearly from the origin. Once the field is removed the intensity of magnetization will return to zero.

In region "b" of the curve the applied field is strong enough to begin to cause irreversible domain wall movements in multidomain grains and irreversible 180° rotations of single domain grain moments, such that upon removal of the field the total magnetization will relax to a new state of minimum energy following the curve "c", and the assemblage retains an isothermal magnetic remanence (IRM).

As the applied field increases, the intensity of magnetization will continue to increase until there is maximum alignment of individual domains in multidomain grains and all single domain grains have aligned in the direction of the field in addition to the alignment of superparamagnetic grains. This is the saturation magnetization (M_s) of the assemblage. Once the "saturating" field is removed, this magnetization will relax following the curve "d", and the assemblage will retain a saturation isothermal remanent magnetization (SIRM).

While the growth of magnetization in the initial acquisition curve of the hysteresis loop takes the assemblage from an unmagnetized state to one of saturation magnetization, the application of reversed magnetic fields at this point will begin to reverse the direction of magnetization. Once the assemblage is removed from the field at each stage in the application of increasingly strong reversed fields, the magnetization will relax with a loss of part of the "downwards" magnetization (A' to B, B' to C, and so on). Eventually the assemblage will reach a state of saturation magnetization in the opposite direction. If the field were reversed once more, the hysteresis loop would follow the course shown by the dotted line.

The exact form of the hysteresis loop depends upon the mineralogy of the magnetic assemblage and upon its grain size characteristics (see below).

Magnetic susceptibility

Magnetic susceptibility (χ) is the only "in-field" measurement used in this study. It is the ratio of magnetization induced to the intensity of the magnetizing field in the reversible portion of the initial acquisition curve (labelled "a" in figure 4.3.). The total susceptibility is roughly proportional to the concentration of magnetic minerals present in a sediment sample, although the susceptibility of superparamagnetic grains is much greater than that of an equivalent amount of mineralogically similar stable single domain and small multidomain grains. The magnetic susceptibility of ferrimagnetic minerals is 100 - 1000 times higher than that of canted antiferromagnetic minerals (§ 4.4.1.), which means that the concentration of magnetite may be less than 1% of that of haematite for the two to contribute equally to the total susceptibility. Only if the concentration of ferrimagnetic minerals is extremely low will antiferromagnetic, paramagnetic and diamagnetic minerals significantly influence the total susceptibility value (Oldfield, 1982; Thompson & Oldfield, in press).

Susceptibility was measured in a very low field (~ 1 Oe) using a single sample susceptibility meter (1980 measurements) and a dual frequency susceptibility meter (1983 measurements; see frequency dependent susceptibility) (both Bartington Instruments Ltd.).

Mass specific susceptibility values (1983 measurements only) have been corrected for the diamagnetic effect of the carbonate fraction using a published value of $- 0{\cdot}48\ 10^{-8} m^3 kg^{-1}$ for the initial mass susceptibility of $CaCO_3$ (Collinson, 1983).

Saturation Isothermal Remanent Magnetization

As seen above, the SIRM is the maximum remanent magnetization that can be grown in a sample by the application of very high fields. Like χ, SIRM is also indicative of the volume concentration of magnetic minerals in a sample.

The saturation magnetization for magnetite is two orders of magnitude more than for haematite, which means that when placed in a strong magnetic field the SIRM for haematite is less than 1% of that of magnetite. Thus, unless present in very low volume concentrations, SIRM values will reflect the ferrimagnetic component of the mineral assemblage.

Above the superparamagnetic - stable single domain boundary SIRM values for ferrimagnetic minerals decrease significantly with increasing grain size, and below the transition SIRM values are negligible. Thus, in samples with a large proportion of superparamagnetic, viscous and coarse multidomain grains, the difference between M_s and SIRM may be large, and SIRM values will be relatively low. Maximum values of SIRM are observed in samples dominated by stable single domain ferrimagnetic crystals.

SIRM measurements were made on a parastatic magnetometer after placing samples in a strong field of ~ 0·85T (8500 Oe) produced by an electromagnet, in the Department of Geophysics, University of Liverpool. In 1983, IRM measurements were made using a "Minispin" fluxgate magnetometer (Molspin Ltd.), after placing samples in a field of 0·3T (3000 Oe) produced by a pulse magnetizer (Molspin Ltd.), in the Department of Geography, University of Liverpool. These measurements are referred to by the notation IRM_{3000}.

Ferrimagnetic materials saturate in fields of 0·01 - 0·1T (100 - 1000 Oe) while haematite does not saturate until fields of over 1 - 3T (10 - 30,000 Oe) (Tarling, 1983). So, while a ferrimagnetic component in the sediment is likely to be completely saturated in a field of only 0·3T, it is unlikely that a canted antiferromagnetic component will have been significantly magnetized.

SIRM/χ ratio

The difference in sensitivity of SIRM and χ means that the SIRM/χ ratio is a useful parameter for identifying grain size variations in assemblages dominated by a single mineral type, or shifts in the proportions of different mineral types in mixed mineral assemblages.

In the former case, maximum values for the SIRM/χ ratio occur in assemblages dominated by stable single domain grains, and low values are seen for assemblages with large proportions of superparamagnetic, viscous and coarse multidomain grains.

In the second case, high SIRM/χ values (>200 kAm^{-1}) occur in samples dominated by haematite, while the SIRM/χ ratio in samples dominated by magnetite varies from 1·5 to c. 50 kAm^{-1} as the grain size decreases. Samples with a high superparamagnetic content have SIRM/χ ratios below 0·01 kAm^{-1}. High concentrations of paramagnetic minerals may also result in very low ratios (Thompson *et al.*, 1980).

Due to the high saturating fields of haematite the IRM_{3000}/χ ratio must predominantly reflect grain size variations in a ferrimagnetic component, or changes in the contribution of paramagnetic minerals.

Demagnetization parameters

Demagnetization parameters measure the loss of remanent magnetization grown in a forward saturating field when a sample is placed in reversed fields.

Ferrimagnetic mineral assemblages containing high proportions of viscous and coarse multidomain grains exhibit "soft" demagnetization behaviour; their alignment within a forward saturating field is easily removed by applying relatively low fields in the opposite direction. In contrast, the grain moments of stable single domain crystals are relatively resistant to demagnetization in these low fields, but will "flip" into alignment in the direction of higher reversed fields as their intrinsic coercivities are exceeded. Thus, stable single domain grains exhibit relatively "hard" demagnetization behaviour.

The reverse field strength required to return a magnetized sample from its SIRM to zero is termed the coercivity of remanence $(B_0)_{CR}$ (figure 4.3.). At this point the forward and reversed remanent magnetizations cancel each other and the net assemblage remanence is zero.

Ferrimagnetic minerals have $(B_0)_{CR}$ values below 0·05T (500 Oe). In contrast, canted antiferromagnetic minerals are extremely resistant to demagnetization with $(B_0)_{CR}$ values above 0·2T (2000 Oe) (Thompson *et al.*, 1980).

Thus, demagnetization parameters are useful for distinguishing different magnetic mineral types, and may identify significant grain size variations within ferrimagnetic assemblages.

The following backfields were selected for measuring demagnetization from IRM_{3000}: 10mT, 20mT, 30mT, 40mT, 60mT, 80mT, 100mT, 200mT and 300mT (100 - 3000 Oe). They are expressed as a proportion of IRM_{3000} giving results between +1 and -1; these are referred to as S-values.

$(B_0)_{CR}$ values were estimated using the Fortran program "COPLOT", adapted for use on the IBM 4341 system at the University of Liverpool by J. Bloemendal. This program receives raw data for sets of SIRM (or IRM_{3000}) and backfield IRM values and $(B_0)_{CR}$ values are derived from the remanent hysteresis curve fitted to these data.

Three additional parameters were measured in order to indicate the presence of the ultra-fine ferrimagnetic crystals thought to be characteristic of soil-derived magnetic mineral assemblages in the lake basin: frequency dependent susceptibility, viscous loss of IRM_{3000} and anhysteretic remanent magnetization (in conjunction with IRM_{3000}).

Frequency dependent susceptibility (χ_{fd})

Frequency dependent susceptibility indicates the presence of viscous grains at the superparamagnetic - stable single domain boundary. It was measured using a dual frequency susceptibility meter (Bartington Instruments Ltd.) which uses two frequencies of 1 and 10 kHz. At low frequency (1 kHz) both the in-phase and out-of-phase components of the output signal are measured. The out-of-phase component is due to the delayed response of any viscous grains to the applied magnetic field and therefore χ_{LF} (susceptibility measured at low frequency) is a measure of the total susceptibility. At high frequency (10 kHz) only the in-phase component is measured and so χ_{HF} (susceptibility measured at high frequency) is only a measure of the non-viscous grains within the assemblage. The difference between χ_{LF} and χ_{HF} is taken to be a measure of χ_{fd} and reflects the proportion of viscous grains in the total magnetic mineral assemblage (Oldfield, 1982; Thompson & Oldfield, in press).

χ_{fd} is expressed in two ways in this study:

(i) as a percentage of total χ, where

$$\% \chi_{fd} = \frac{\chi_{LF} - \chi_{HF}}{\chi_{LF}} \times 100$$

(ii) as a mass specific value, where

$$\chi_{fd}\, g^{-1} = \frac{\chi_{LF} - \chi_{HF}}{\text{weight (g)}}$$

Values for χ_{LF} and χ_{HF} for each sample are the mean of ten replicate readings.

Using the same instrumentation, Thompson & Oldfield (in press) have encountered a range of values between 0 and 24% for naturally-occurring materials. The maximum χ_{fd} for coarse multidomain magnetite, which also exhibits magnetic viscosity (§ 4.4.1.), was found to be less than 0·3%.

Viscous loss of IRM_{3000}

Below 3m in APL6, where the total susceptibility is generally low, χ_{fd} was considered to be a poor measure of the quantity of viscous grains; very low concentrations of crystals within this size range could not be resolved and therefore any between-sample differences were not thought to be discriminated. In order to amplify the magnetic signal of these viscous grains, samples from APL6 were magnetized in a field of 3000 Oe and the viscous loss of IRM_{3000} was measured over a known period of time. A measuring period of 200 seconds was adopted as a compromise between observing a significant loss of IRM on the one hand and avoiding a significant calibration shift of the magnetometer on the other. Time 0 refers to the moment of discharge of the magnetic pulse in the magnetizer. The first measurements of IRM_{3000} at 10 seconds actually refers to the mid-point of the six second spin cycle (7 - 13 seconds) in the magnetometer; 7 seconds was considered to be the minimum time possible for the consistent transfer of samples from the magnetizer to the magnetometer.

The viscosity measured here is due to the time-dependent relaxation of fine (viscous) single domain grains and of relatively weakly pinned domain walls in multidomain grains (§ 4.4.1.). It is not a true viscous remanent magnetization, no viscous magnetization having been initially grown in the magnetic field.

The viscous loss of IRM_{3000} is expressed in two ways in this study:

(i) as a percentage of the total IRM_{3000}, where

$$\%\text{ viscous loss of } IRM_{3000} = \frac{IRM_{3000}\ (10s) - IRM_{3000}\ (200s)}{IRM_{3000}\ (10s)} \times 100$$

(ii) as a mass specific value, where

$$\text{viscous loss of } IRM_{3000}\ g^{-1} = \frac{IRM_{3000}\ (10s) - IRM_{3000}\ (200s)}{\text{weight (g)}}$$

<u>Anhysteretic remanent magnetization</u>

When a magnetic substance is subjected to a small direct field superimposed on an alternating magnetic field, it will acquire an anhysteretic remanent magnetization (ARM) as the alternating magnetic field is slowly reduced to zero and the direct field is subsequently removed (Dankers, 1978). The intensity of ARM is approximately proportional to the steady field and is indicative of the volume concentration of magnetic minerals. ARM seems to be particularly sensitive to fine single domain grain size material and thus, when combined with SIRM in the AIRM/ARM ratio, may indicate stable single domain versus multidomain contrasts in ferrimagnetic grain assemblages

(Bloemendal, 1982; Maher, 1984).

Here, the intensity of ARM was measured using a "Minispin" fluxgate magnetometer (Molspin Ltd.), after ARMs had been obtained by subjecting samples to a decreasing alternating field (0·1 → 0 T or 1000 → 0 Oe) with a steady field of 0·04mT (0·4 Oe) superimposed in an anhysteretic remanent magnetizer (Molspin Ltd.). These measurements have been combined with their corresponding IRM_{3000} values to give the IRM_{3000}/ARM ratio.

This parameter has also been combined with χ to give the ARM/χ ratio. Elsewhere, this parameter has been interpreted as indicating grain size variations within ferrimagnetic mineral assemblages such that low values for the ratio indicate the dominance of coarser grain sizes and high values indicate finer grain sizes, on the basis that ARM is sensitive to the finer grain size fraction, while χ is relatively more sensitive to the coarser grain size fraction (Banerjee *et al.*, 1981). However, variations in a significant superparamagnetic grain size or paramagnetic mineral component may modify such an interpretation, and the ARM/χ might then vary in a similar way to that described above for the SIRM/χ ratio.

<u>Units of measurement</u>

Although values for magnetic parameters are quoted extensively in S.I. units in this chapter, the results of the mineral magnetic analyses of the Annecy sediments are reported in c.g.s. units. Table 4.7. lists the corresponding c.g.s. and S.I. units for magnetic parameters used in this study and includes factors for conversion from one to the other.

Parameter	Symbol	c.g.s. unit	S.I. unit	Conversion to S.I.
Specific susceptibility	χ	$Gcm^3Oe^{-1}g^{-1}$	m^3kg^{-1}	÷ 79·6
Specific magnetization	σ	Gcm^3g^{-1}	Am^2kg^{-1}	÷ 1·0
Magnetic field strength	B_0	Oe	T	÷ 10,000

Table 4.7. Units of measurement (c.g.s.) and conversion factors for S.I. units

CHAPTER 5

THE ESTABLISHMENT OF A CHRONOLOGICAL FRAMEWORK FOR DESCRIBING ENVIRONMENTAL CHANGE

5.1. Strategy for deriving a common chronology

As the lithology of the Lac d'Annecy drainage basin is dominated by calcareous rock types (§ 2.2.), it was not possible to use the radiocarbon method of dating (see Deevey *et al.*, 1954). So, the sediments from AGL5, APL1 and APL6 have been dated using a combination of ^{210}Pb, palaeomagnetic and palynological age controls.

Individual ^{210}Pb chronologies have already been calculated for AGL5 and APL1 by P.G. Appleby, using the measurements carried out by J.D. Eakins at AERE, Harwell in 1977 (Dearing, 1979). However, these original chronologies have now been re-assessed and a more reliable chronology resolved; this was made possible by the comparison between cores of the results of mineral magnetic measurements and pollen analyses performed during the course of this study.

The Annecy chronology has been extended back beyond the nineteenth century using the palaeomagnetic record of secular variation preserved in the sediments of APL6 and measured by Hogg (1978).

The ^{210}Pb and palaeomagnetic chronologies have been joined together to give a composite chronology for all three cores which covers the past millenium; chronologies were transferred between the cores by identifying synchronous horizons using mineral magnetic measurements.

All the above chronologies have been calculated by P.G. Appleby of the Department of Applied Mathematics and Theoretical Physics, University of Liverpool.

The lower part of the long core APL6 has been dated by comparing the results of pollen analyses with published diagrams from the Northern French Alps.

5.2. Correlation of the sedimentary records

5.2.1. Assumptions made in correlating cores

Hogg (1978) has shown that both NRM (D, I and J) and mineral magnetic (χ) properties are repeatable between cores sampled from different locations in the central plain of the Petit Lac (including APL6). Therefore, as both APL6 and APL1 were collected from approximately the same site (figure 4.1.) it seems very probable that they will have accumulated a similar sedimentary record.

Dearing (1979) concluded that χ measurements alone could not be used to correlate sediments between the two sub-basins of the Lac d'Annecy; however, additional mineral magnetic measurements reported in this study (§ 6.3.) are thought to provide evidence for core correlations between AGL5 and APL1, and between AGL5 and APL6.

Recognition of between-basin correlations assumes that the features identified can in fact be attributed to catchment events and processes that happened synchronously in both sub-basins, involving an influx of material with comparable mineral magnetic properties. This seems a reasonable assumption.

Dearing (1979) has already established that the major source of magnetic material in the lake sediments is secondary ferrimagnetic minerals formed in soils of the catchment area (§ 1.2. and § 4.4.2.). Over the few centuries spanned by AGL5 and APL1 (indicated by the original chronology described by Dearing) the main controls over the influx of allochthonous material to the central sediments are likely to have been both land-use regimes, associated with prevailing socio-economic conditions, and meteorological events, most notably the amount, intensity and duration of rainfall.

It is known from documentary evidence that considerable areas of land at all altitudes in both sub-basins have been cleared for cultivation since the eighteenth century at least (§ 3.2.) and probably since the Middle Ages (§ 3.1.2.). So, both catchment areas would have had tracts of open land subjected to accelerated losses of soil material by slopewash and rainsplash.

Meteorological factors would almost certainly have operated synchronously in both catchment areas. Storm periods would have been particularly significant in yielding high energy conditions able to carry large quantities of particulate material from catchment surfaces to the lake.

However, it should be borne in mind that critical thresholds for the stability of soil material might well have been transgressed in some areas but not in others. Consequently, it is quite possible that features in the sedimentary record reflecting an influx of soil material may not be repeated in both sub-basins and here it is worth emphasizing the greater frequency of steep slopes within the Petit Lac catchment area (figure 2.2. and table 2.4.).

The relatively high concentrations of magnetic minerals seen in recent sediments are thought to be due to the influx of urban drainage waters containing magnetic material (§ 7.1.); this process is assumed to have begun simultaneously in both sub-basins.

Differences in the morphometry of the two sub-basins means that absolute values, such as total χ per gram dry weight of sediment, cannot be compared directly. The relatively large catchment area around the Petit Lac basin in relation to its lake volume (table 2.2.) might have two effects. Firstly, the resulting faster accumulation rate would be expected to "stretch out" magnetic features in terms of depth within the sedimentary profile compared to corresponding features in the Grand Lac sediments. Secondly, allochthonous-autochthonous material ratios would be expected to be higher in the Petit Lac sediments and, as a consequence, concentrations of magnetic minerals might also be expected to be higher when expressed as a concentration of total sediment weight. However, an influx of primary ferrimagnetic minerals with relatively high χ values from the molasse deposits of the Grand Lac catchment area (table 4.4.) may either mask or enhance features in AGL5, thus modifying the inference made above.

Overall, it is considered that features with similar mineral magnetic properties resulting from associated environmental events and processes are likely to be observed in the sedimentary record of both sub-basins, and therefore that they can be identified as synchronous horizons which can be used to correlate the cores studied here. Successive maxima and minima in the profiles of various mineral magnetic parameters have been matched and are discussed below.

5.2.2. Description of core correlations

Figures 5.1. to 5.4. show χ, SIRM, χ_{fd} and IRM_{-400}/SIRM plotted against depth for AGL5, APL1 and APL6. Proposed synchronous horizons are labelled 1 - 19, and the magnetic features used to correlate the cores are summarized in table 5.1.

Figure 5.5. shows the depth relationship between each pair of cores suggested by the mineral magnetic correlations; clusters of points for different magnetic parameters have been averaged and the resulting mean points joined by straight lines. Extrapolation of

Figure 5.1. Proposed correlation of specific χ† features in AGL5, APL1 and APL6 (units: $10^{-6} G cm^3 Oe^{-1} g^{-1}$)
For APL6, depths refer to the original uncorrected depths.
† 1980 measurements

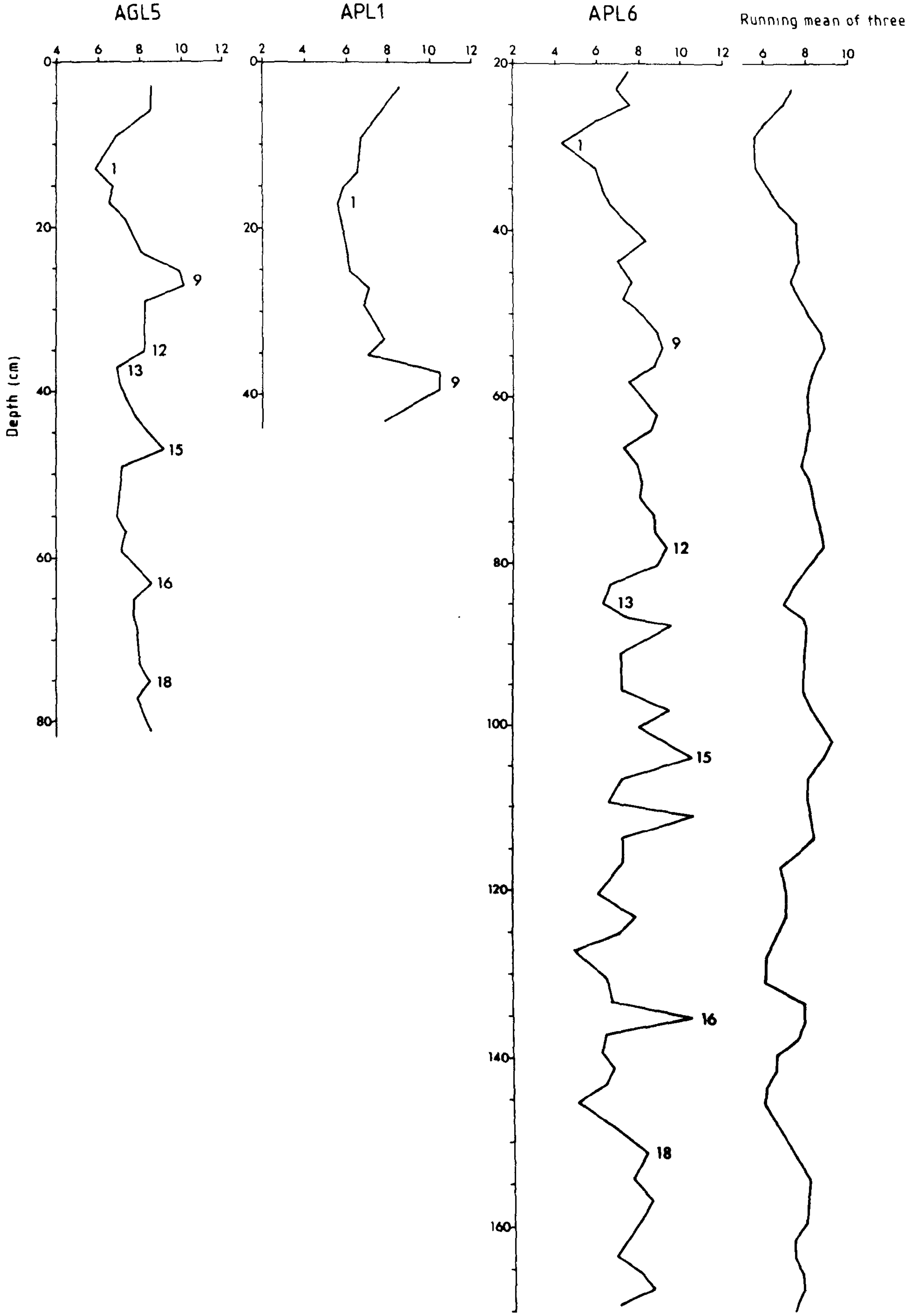
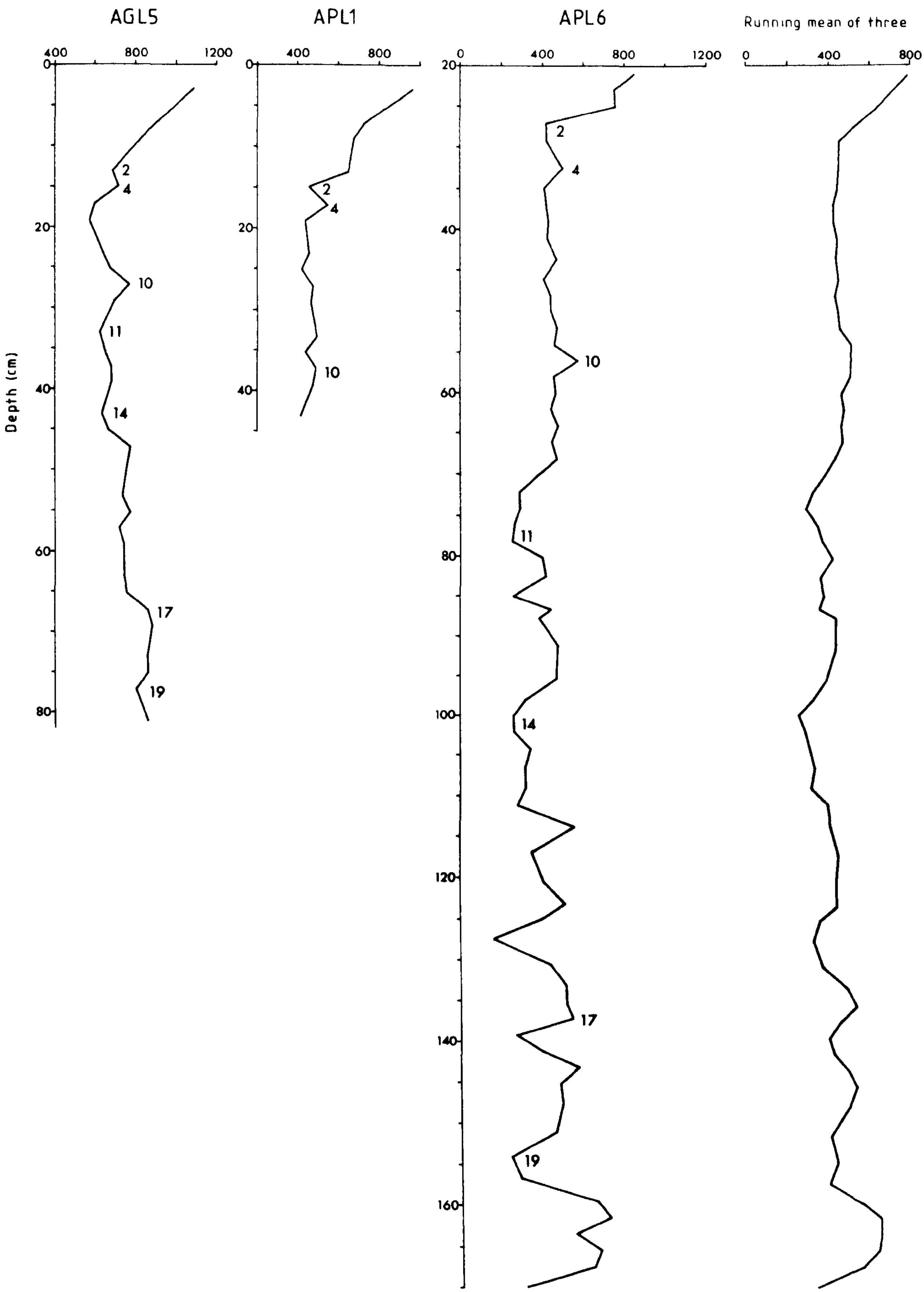

AGL5
APL1
APL6
Running mean of three
Depth (cm)
1
9
12
13
15
16
18

Figure 5.2. Proposed correlation of specific SIRM features in AGL5, APL1 and APL6 (units: $10^{-6}Gcm^3g^{-1}$) For APL6, depths refer to the original uncorrected depths.



AGL5
APL1
APL6
Running mean of three
Depth (cm)
400
800
1200
0
20
40
60
80
160
140
120
100
2
4
10
11
14
17
19

Figure 5.3. Proposed correlation of specific χ_{fd} features in AGL5 and APL1 (units: $10^{-8}Gcm^3Oe^{-1}g^{-1}$)

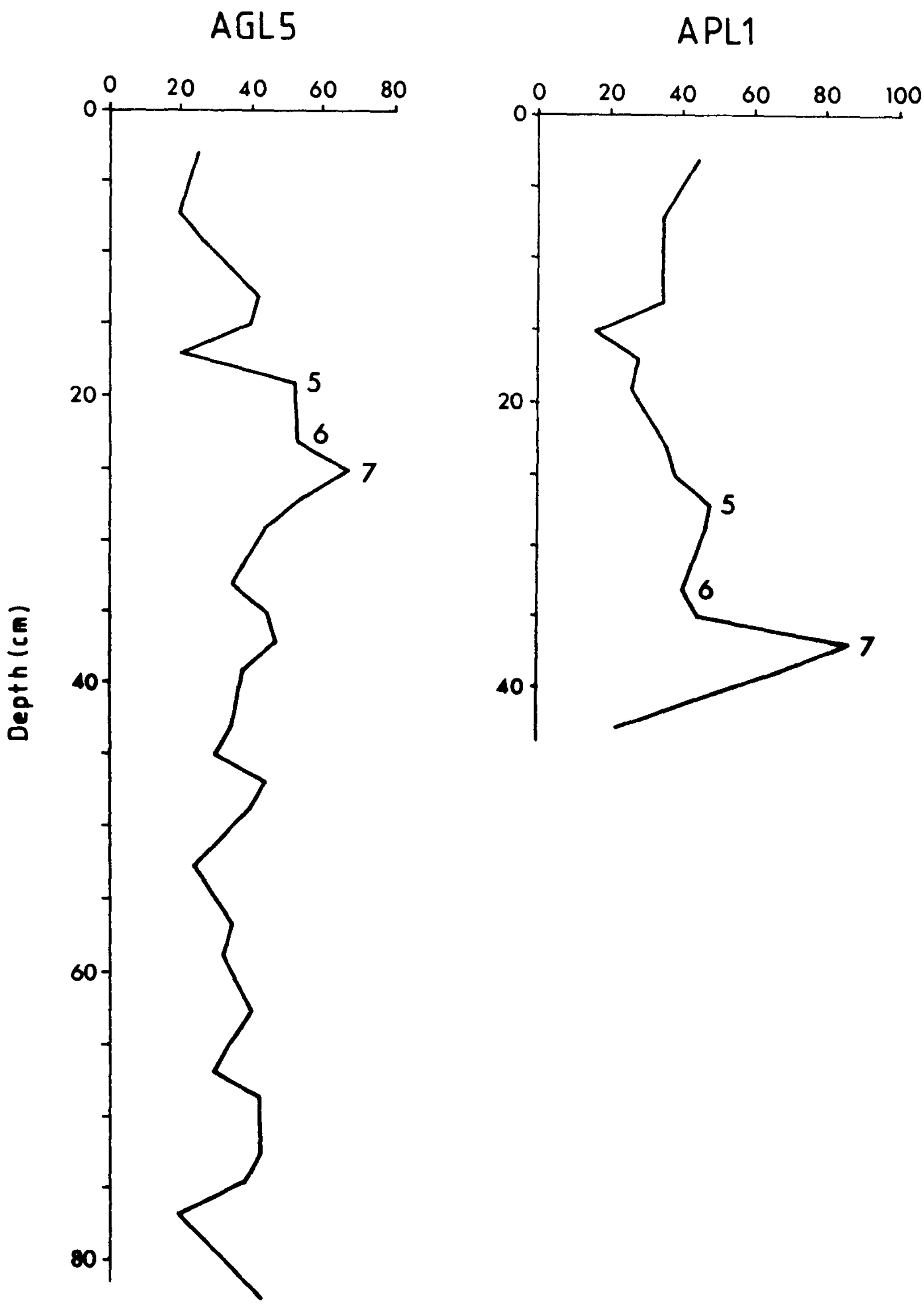

AGL5
APL1
Depth (cm)
0
20
40
60
80
100
5
6
7

Figure 5.4. Proposed correlation of IRM_{-400}/SIRM features in AGL5 and APL1

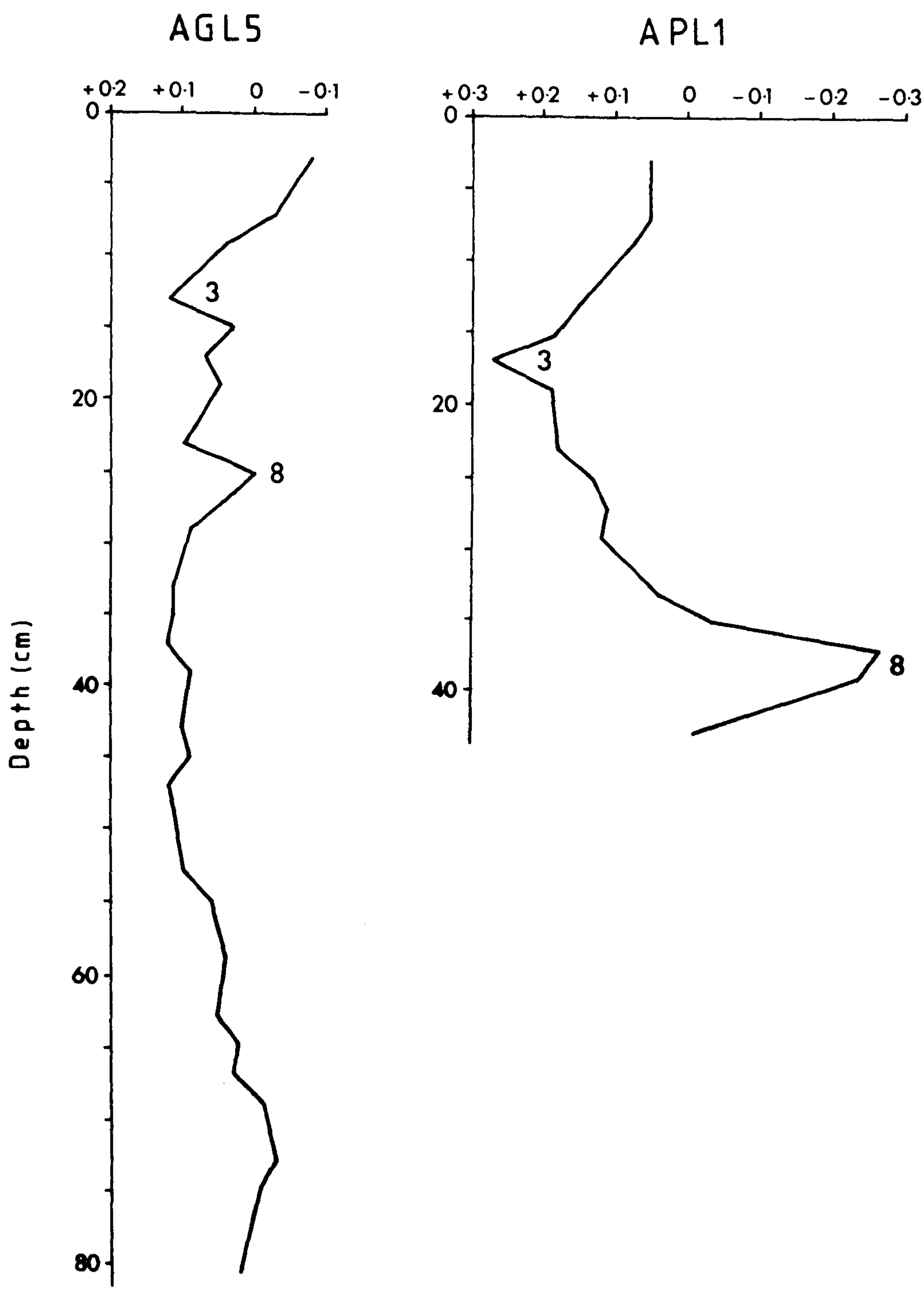
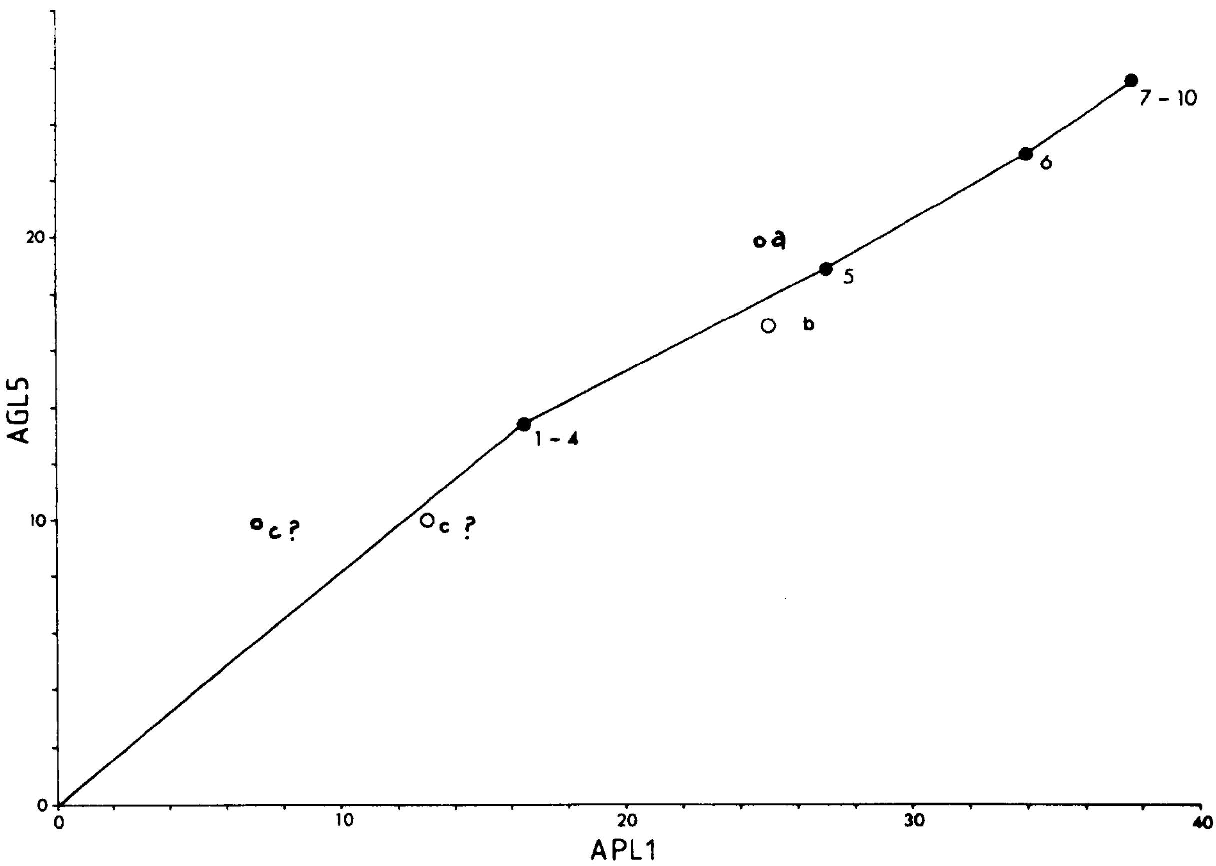
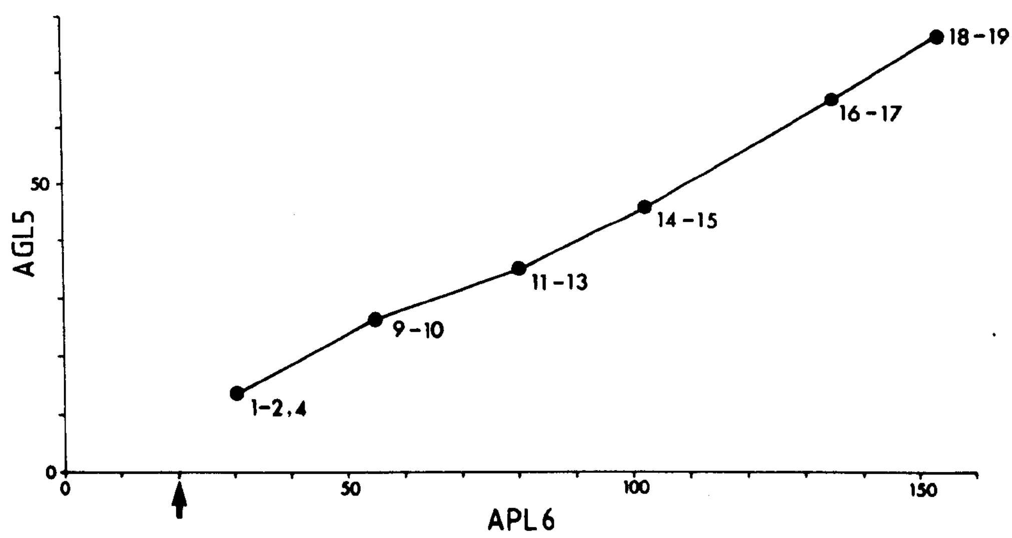
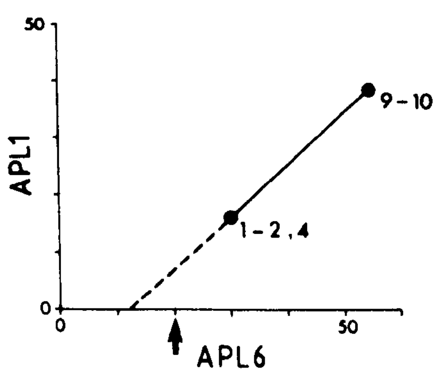

AGL5
+0·2
+0·1
0
-0·1
0
20
40
60
80
3
8
Depth (cm)
APL1
+0·3
+0·2
+0·1
0
-0·1
-0·2
-0·3
0
20
40
3
8

Figure 5.5. Mineral magnetic correlation best-fit curves (a) APL1 vs. AGL5 (b) APL6 vs. AGL5 (c) APL6 vs. APL1 (all depths in centimetres)
Numbers refer to the mineral magnetic features shown in figures 5.1. to 5.4. and listed in table 5.1.
Open circles indicate the pollen correlation features shown in figure 5.6. For APL6, depths refer to the original uncorrected depths; the top of the sediment column in the core-tube is arrowed.


AGL5
APL1
0
10
20
30
40
7 - 10
6
5
1 - 4
a
b
c ?
c ?


AGL5
APL6
0
50
100
150
18-19
16-17
14-15
11-13
9-10
1-2,4


APL1
APL6
0
50
9-10
1-2,4

	Depth of magnetic feature (cm)		
Feature	AGL5	APL1	APL6
Mud-water interface	0	0	not preserved
(1) χ min.	13	17	29·5
(2) SIRM min.	13	15	28·5
(3) IRM_{-400}/SIRM min.	13	17	
(4) SIRM max.	15	17	32·5
(5) χ_{fd} max.	19	27	
(6) χ_{fd} min.	23	34	
(7) χ_{fd} min.	25	37	
(8) IRM_{-400}/SIRM max.	25	38	
(9) max.	26	38	54
(10) SIRM max.	27	38	56
(11) SIRM min.	33		78
(12) χ max.	35		79
(13) χ min.	37		85
(14) SIRM min.	44		101
(15) χ max.	47		104
(16) χ max.	63		134
(17) SIRM max.	67		137
(18) χ max.	75		154
(19) SIRM min.	77		154

Table 5.1. Proposed correlation of magnetic features between AGL5, APL1 and APL6
For APL6, depths refer to the original uncorrected depths.

the best-fit line between corresponding features in APL1 and APL6 (shown by the dotted line in figure 5.5.c.) has enabled the depth of the mud-water interface to be estimated for the long core; approximately 8cm of sediment seems to have been lost from the top of APL6 during the coring operation. Depths below the top of the core-tube have been converted to depths below the mud-water interface for APL6; these corrected depths are used throughout this report unless otherwise indicated.

The mineral magnetic correlations compare well with the results of the pollen analyses (§ 6.1.). Curves for *Juglans* and *Cannabis* type pollen were compared in AGL5 and APL1 (figure 5.6.); both walnut and hemp are known to have been important elements of the subsistence farming economy of the lake basin (§ 3.2.1.) and so it is considered that any changes in the frequency of these two pollen types are likely to have been synchronous in the two sub-basins. Three significant features were identified in both cores: "a", the beginning of the final decline of the *Cannabis* curve; "b", the final maximum in the *Juglans* curve; "c", the final minimum in the *Juglans* curve. These three pollen features are also shown on figure 5.5.a. and are seen to lie very closely to the best-fit lines for the mineral magnetic correlations.

Contiguous pollen counts were not completed for APL6; therefore features in this pollen diagram can only be compared very generally with those from AGL5. Five pollen types were compared (figure 5.7.): *Pinus* percentages are thought likely to reflect regional pollen characteristics due to the size of the lake-catchment system under consideration and the capacity of this pollen type for long distance transport; *Fagus* and *Quercus* are two of the main forest trees in the lake basin (§ 2.6.) and therefore any major changes or trends in their pollen percentages might be expected to be synchronous in the

Figure 5.6. Proposed correlation of pollen features in AGL5 and APL1 (units: percentage of total pollen sum)

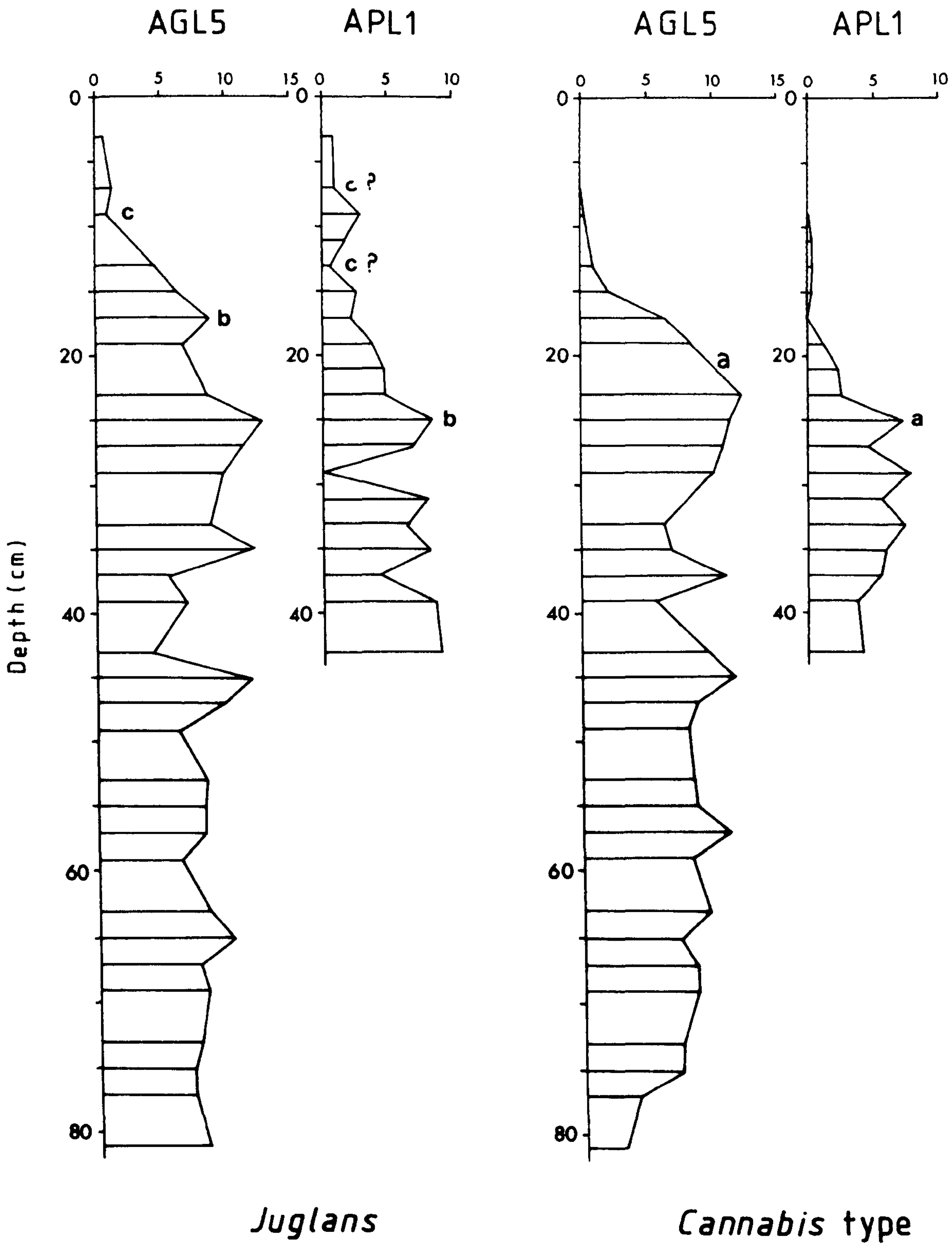
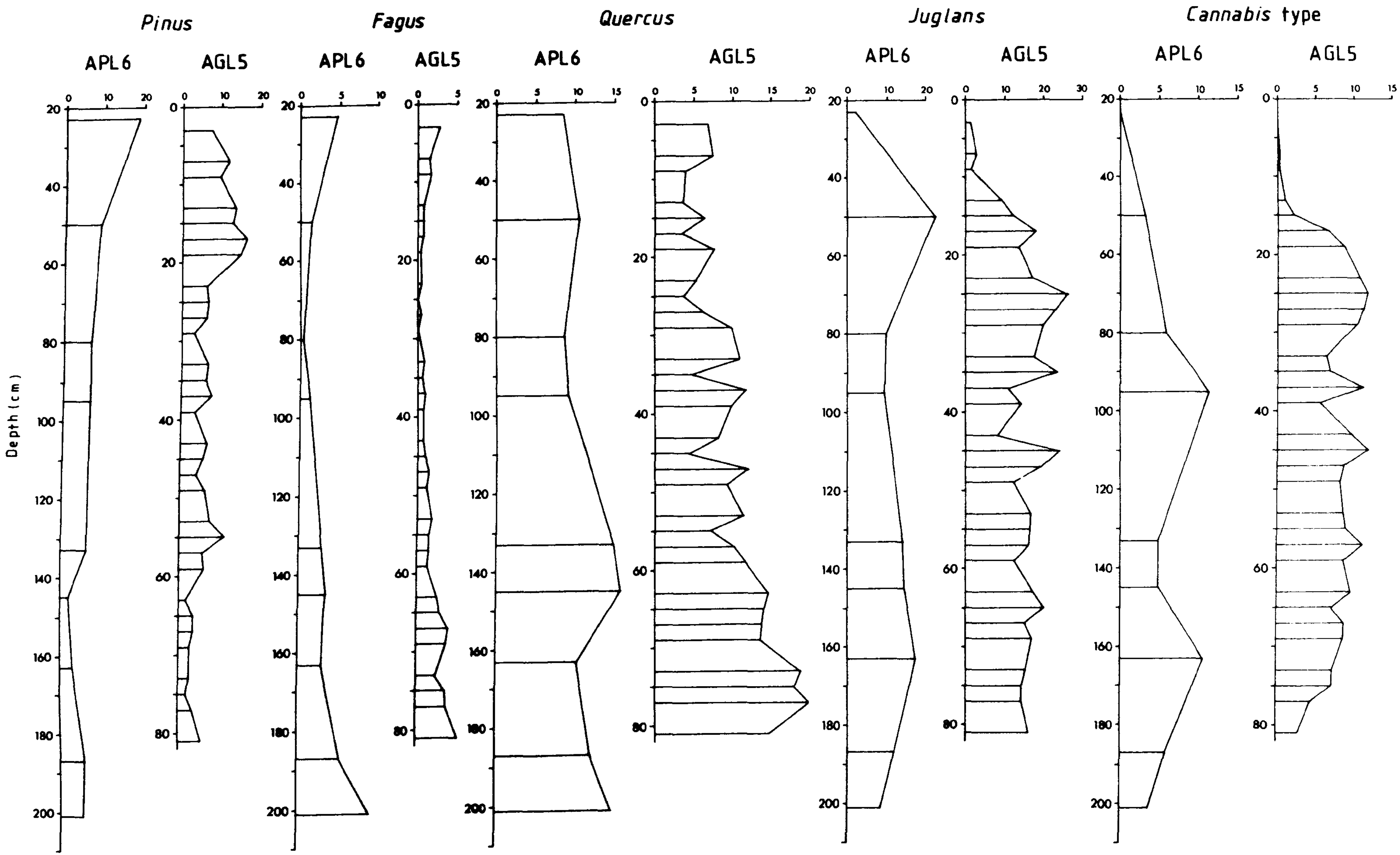

AGL5
APL1
AGL5
APL1
0
5
10
15
Depth (cm)
20
40
60
80
a
b
c
c ?
Juglans
Cannabis type

Figure 5.7. Comparison of five pollen types in APL6 and AGL5 (units: percentage of total pollen sum) For APL6, depths refer to the original uncorrected depths.



Pinus
Fagus
Quercus
Juglans
Cannabis type
APL6
AGL5
Depth (cm)

two sub-basins; *Juglans* and *Cannabis* type pollen were again compared for the reason outlined above.

Minimum frequencies for *Pinus* pollen can be seen between 150 and 140cm in APL6 and just above the base of AGL5, at c. 75cm, with frequencies gradually increasing towards the top of both cores.

The curves for *Fagus* pollen are very similar with percentages gradually decreasing up to minimum values anywhere between 90 and 50cm in APL6 and at c. 30cm in AGL5. From these low values frequencies then increase towards the top of both cores.

Percentages of *Quercus* pollen show similar trends; maximum frequencies can be seen at c. 145cm in APL6 and just above the base of AGL5, at c. 75cm, with percentages gradually decreasing above.

The relatively low values of *Juglans* pollen below 162cm in APL6 are not evident in the lower part of AGL5. The high frequencies seen at 50cm in APL6 may correspond to the region of maximum values around 25cm in AGL5. A marked decrease in the frequency of this pollen type above these possibly synchronous features can be seen at the top of both cores.

The curves for *Cannabis* type pollen are not very similar at all. The relatively low values at the base of AGL5 may correspond to the minimum at c. 200cm, or to that between 150 and 130cm in APL6. Only the second alternative could be accommodated by the correlations suggested by the other pollen types. The relatively high values around 23cm in AGL5 may correspond to the maximum seen at 95cm in APL6, although this seems unlikely in the light of the other pollen evidence.

Overall, the comparison of these pollen curves suggests that the whole sedimentary profile from AGL5 corresponds to the top c. 150cm of APL6. This compares well with the mineral magnetic correlations.

5.3. Establishment of a chronology

5.3.1. ^{210}Pb-dating

The principle of the ^{210}Pb-dating technique is that the radio-isotope ^{210}Pb decays according to the radio-active decay law and so its concentration in a lake sediment core will decrease exponentially from the surface with increasing age of the material. Knowing that the half-life of ^{210}Pb is 22·26 years, it follows that once the initial concentration of ^{210}Pb has been measured at the sediment surface, the age of a sample from anywhere in the profile can be calculated. The technique can be extended back to the point where unsupported ^{210}Pb values are unmeasurable against the supported ^{210}Pb activity arising from the presence of the parent isotope ^{226}Ra in the sediment.

The main pathways by which lake sediments accumulate unsupported and supported ^{210}Pb components are shown in figure 5.8. They are not yet fully understood, nor have their relative contributions been quantified in many contexts; research completed to date is reviewed elsewhere (Krishnaswami & Lal, 1978; Appleby & Oldfield, 1983; Oldfield & Appleby, 1984b).

^{226}Ra (half-life of 1622 years), a member of the naturally occurring ^{238}U series[1], is present in surface materials of the catchment. It decays to form the inert gas ^{222}Rn (half-life of 3·8 days), some of which diffuses via pore spaces into the atmosphere. ^{222}Rn soon decays through a series of short-lived isotopes to ^{210}Pb

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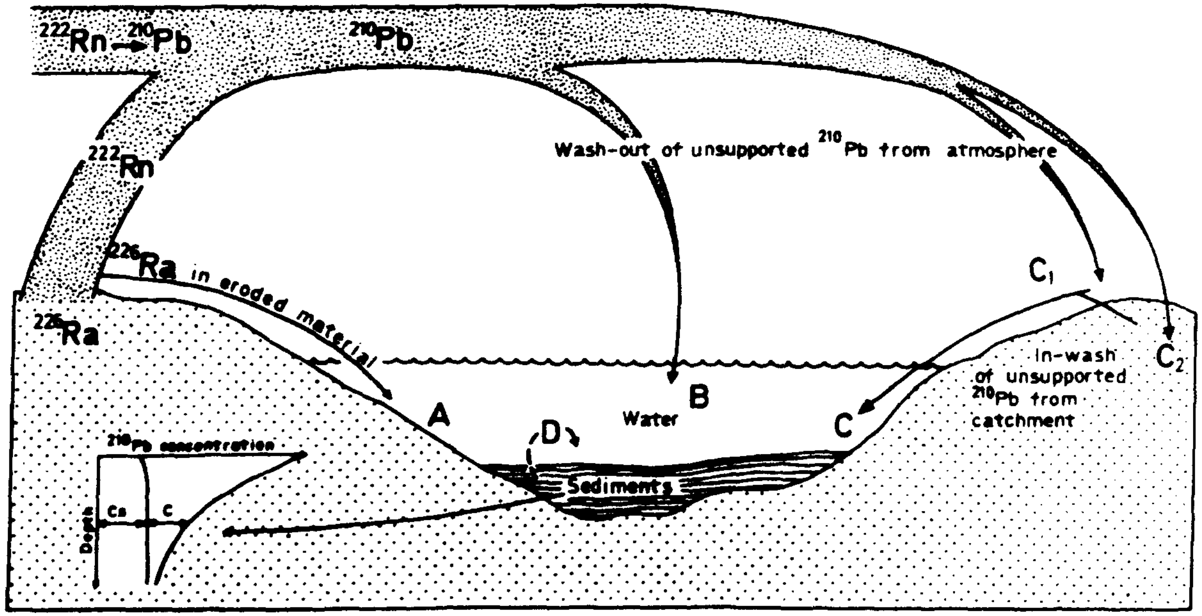
[1] ^{238}U was present during the formation of the earth and due to its very long half-life ($4{\cdot}51 \times 10^9$ years) is still present at the earth's surface (Krishnaswami & Lal, 1978).

Figure 5.8. Simplified model of ^{210}Pb flux into lake sediments (from Oldfield & Appleby, 1984b and 1984c)
Sources of ^{210}Pb are labelled A - D. A: particulate erosive input of ^{226}Ra. The ^{210}Pb formed by the *in situ* decay of this radium is termed the "supported ^{210}Pb". B: direct atmospheric fallout of ^{210}Pb. C: indirect atmospheric fallout of ^{210}Pb (the C_1 component is incorporated into the drainage network and flows quickly to the lake without being detained on solid terrestrial particles; the C_2 component may have a long residence time in the catchment area before being delivered to the lake in association with the erosive input of fine particles to which it is attached). D: radon decay in the water column. Components B, C and D give rise to ^{210}Pb activity in excess of the supported ^{210}Pb activity. This is termed the "excess" or "unsupported ^{210}Pb". The inset diagram shows the concentration of both supported ^{210}Pb (Cs) and unsupported ^{210}Pb (C) versus depth under conditions of constant sediment accumulation.


222Rn → 210Pb
210Pb
222Rn
226Ra in eroded material
226Ra
Wash-out of unsupported 210Pb from atmosphere
C1
C2
In-wash of unsupported 210Pb from catchment
A
B
Water
C
D
Sediments
Depth
C

which is lost from the atmosphere by dry deposition or wet fall-out. Atmospherically-derived ^{210}Pb falling onto a lake surface is adsorbed onto particulates falling through the water column and so becomes incorporated into the accumulating sediments. This source of ^{210}Pb is referred to as the unsupported or excess component, and it is this which forms the dating parameter. Unsupported ^{210}Pb will also fall onto catchment surfaces, and reach the lake directly via surface runoff and streamflow, or indirectly by association with soil material if initially trapped there. The contribution of soil-derived unsupported ^{210}Pb is very much an unknown quantity; Oldfield & Appleby (1984b) emphasize that further empirical investigations should explore this source.

Sediments from catchment surfaces washing into the lake contain ^{226}Ra, which will continually produce ^{210}Pb *in situ* throughout the sediment profile. ^{210}Pb originating from this source is referred to as the supported component. It is assumed to be in radioactive equilibrium with its parent ^{226}Ra; therefore roughly constant levels would be expected throughout the profile irrespective of the age of the sediments.

Unsupported ^{210}Pb at any one depth obviously cannot be measured directly, but it can be estimated by subtracting the supported ^{210}Pb concentration from the total ^{210}Pb concentration. The supported ^{210}Pb concentration itself is assessed by measuring the ^{226}Ra activity, assuming the two to be in equilibrium, or by using total ^{210}Pb concentrations where they have become more or less constant, ie. where the unsupported ^{210}Pb component has decayed to undetectable levels and the total ^{210}Pb concentration only reflects the supported component.

Where the atmospheric flux of unsupported ^{210}Pb and the sediment accumulation rate have both been constant, there will be a simple linear relationship between the unsupported ^{210}Pb concentration and depth, when plotted on a log-linear scale, and the age of the sediments can be derived from this graph. However, where sediment accumulation rates have varied, the chronology derived from the data depends upon which source of unsupported ^{210}Pb is assumed to be dominant at the site in question, either directly from the atmosphere or from the influx of soil from the catchment area. Two models have been presented in the literature which encompass these alternative theories; the constant rate of supply (c.r.s.) model and the constant initial concentration (c.i.c.) model. They are discussed in detail elsewhere (Appleby & Oldfield, 1983) but their main arguments are discussed below.

The c.r.s. model has as its crux the assumption that the flux of unsupported ^{210}Pb to the lake sediments will always be constant, despite any changes in the sediment accumulation rate, ie. if the sediment accumulation rate increases, the concentration of unsupported ^{210}Pb will be effectively diluted, and vice versa. Implicit is the assumption that unsupported ^{210}Pb is very largely derived from atmospheric input to the lake body.

The c.i.c. model assumes that the concentration of unsupported ^{210}Pb is directly related to the sediment accumulation rate either by its association with the influx of "^{210}Pb-enhanced" surface soil material, or by an increase in the amount of particulate material falling through the water column able to scavenge more unsupported ^{210}Pb from the lake waters per unit time.

Oldfield & Appleby stress the need for these ^{210}Pb-dating models to be empirically tested before a chronology is established (Oldfield & Appleby, 1984a, 1984b and 1984c; Appleby & Oldfield, 1983). The criteria they set out for assessing the most appropriate model largely rely on calculations of the total residual unsupported ^{210}Pb

and the pattern of its decline down sediment profiles.

Figure 5.9. shows the total ^{210}Pb concentrations, and ^{226}Ra assays, for AGL5 and APL1. It can be seen that the total ^{210}Pb concentrations in APL1 are consistently lower than in AGL5, bearing in mind that the profiles are plotted against depth and not age, and that if plotted against age the profile for APL1 would be condensed due to the faster accumulation rate in the Petit Lac sub-basin. This observation would be consistent with a constant rate of supply of unsupported ^{210}Pb to the sediment, the final concentration of which is a function of the rate of accumulation of the matrix material.

The profiles of unsupported ^{210}Pb in AGL5 and APL1 are shown in figure 5.10. It can be seen that away from the sediment surface, standard errors from the radio-isotope assays become larger. In APL1 the unsupported ^{210}Pb declines rapidly beyond 11cm depth, suggesting rapid dilution by a relatively high sediment accumulation rate. However, as the counting errors involved in the calculation of such low ^{210}Pb concentrations are so high below this depth, this part of the profile is only shown by a dotted line.

The ^{210}Pb chronology for the two cores was calculated assuming a constant rate of supply of unsupported ^{210}Pb to the sediment, according to the procedure detailed in Appleby & Oldfield (1978). The resulting ^{210}Pb age-depth curves are shown in figure 5.11. Calculations were only performed down to a depth of 21cm in AGL5 and 11cm in APL1 as beyond the concentrations of unsupported ^{210}Pb were too low and standard errors too large to make estimates reliable.

However, it is considered that the ^{210}Pb age-depth curve for a single core will inevitably contain inaccuracies due to errors in the data, assumptions and methods of calculation, some of which can be eliminated by inter-core correlation of data from cores from the same lake (Oldfield *et al.*, 1980). In the absence of replicate cores

Figure 5.9. Total ^{210}Pb concentrations vs. depth for AGL5 and APL1
Open circles indicate the ^{226}Ra content of the sediments (assumed to be in radioactive equilibrium with the supported component of the total ^{210}Pb concentration).

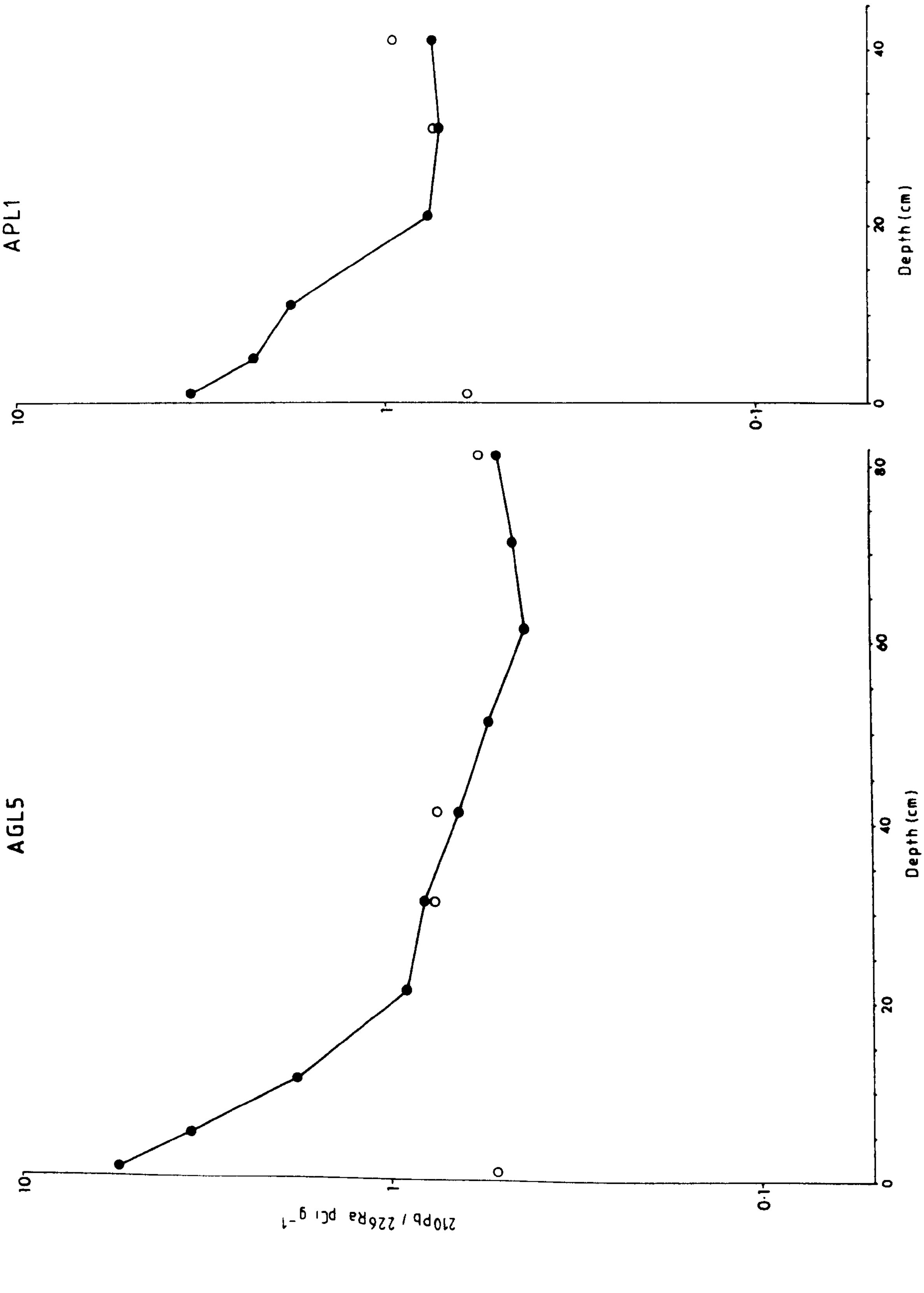
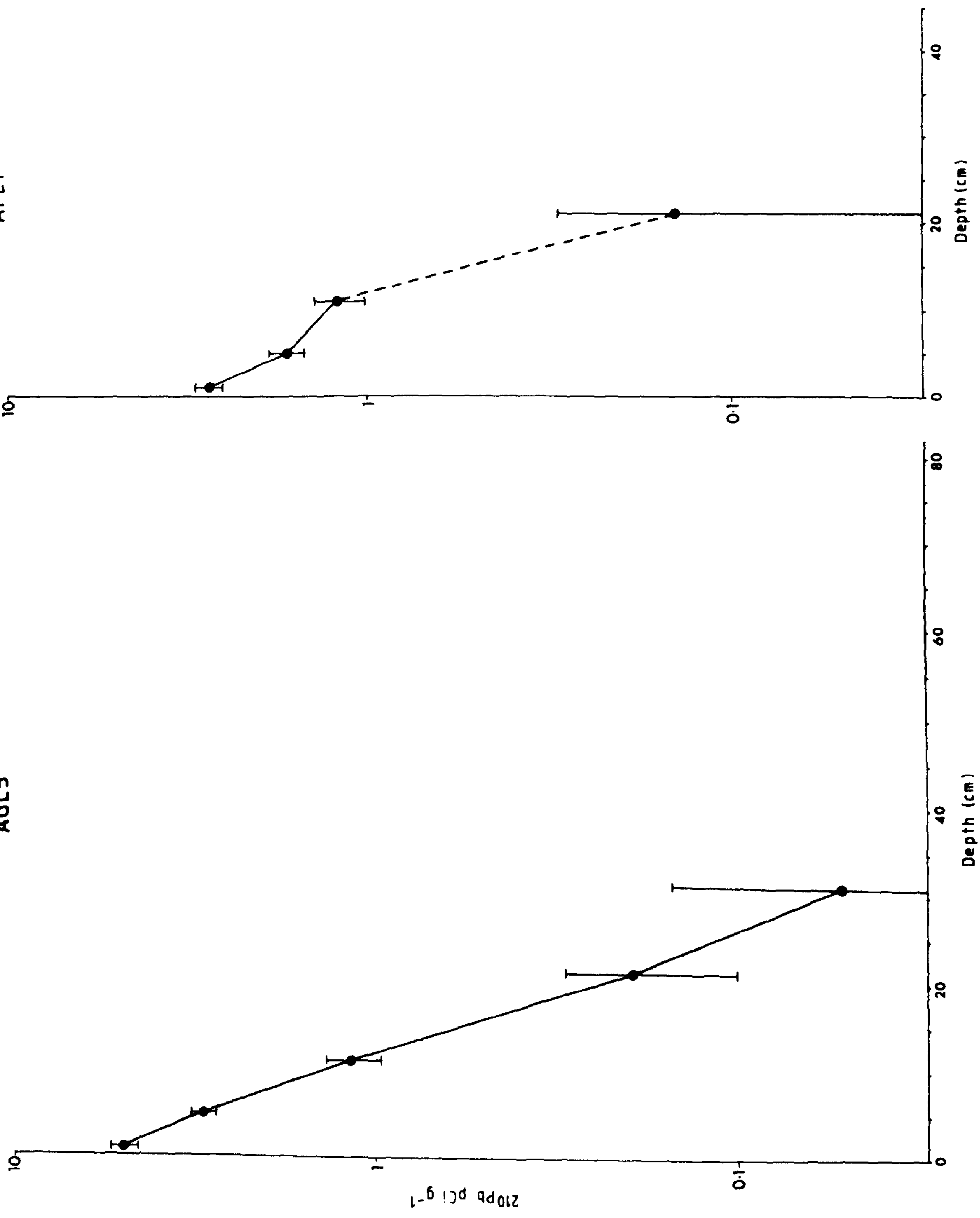
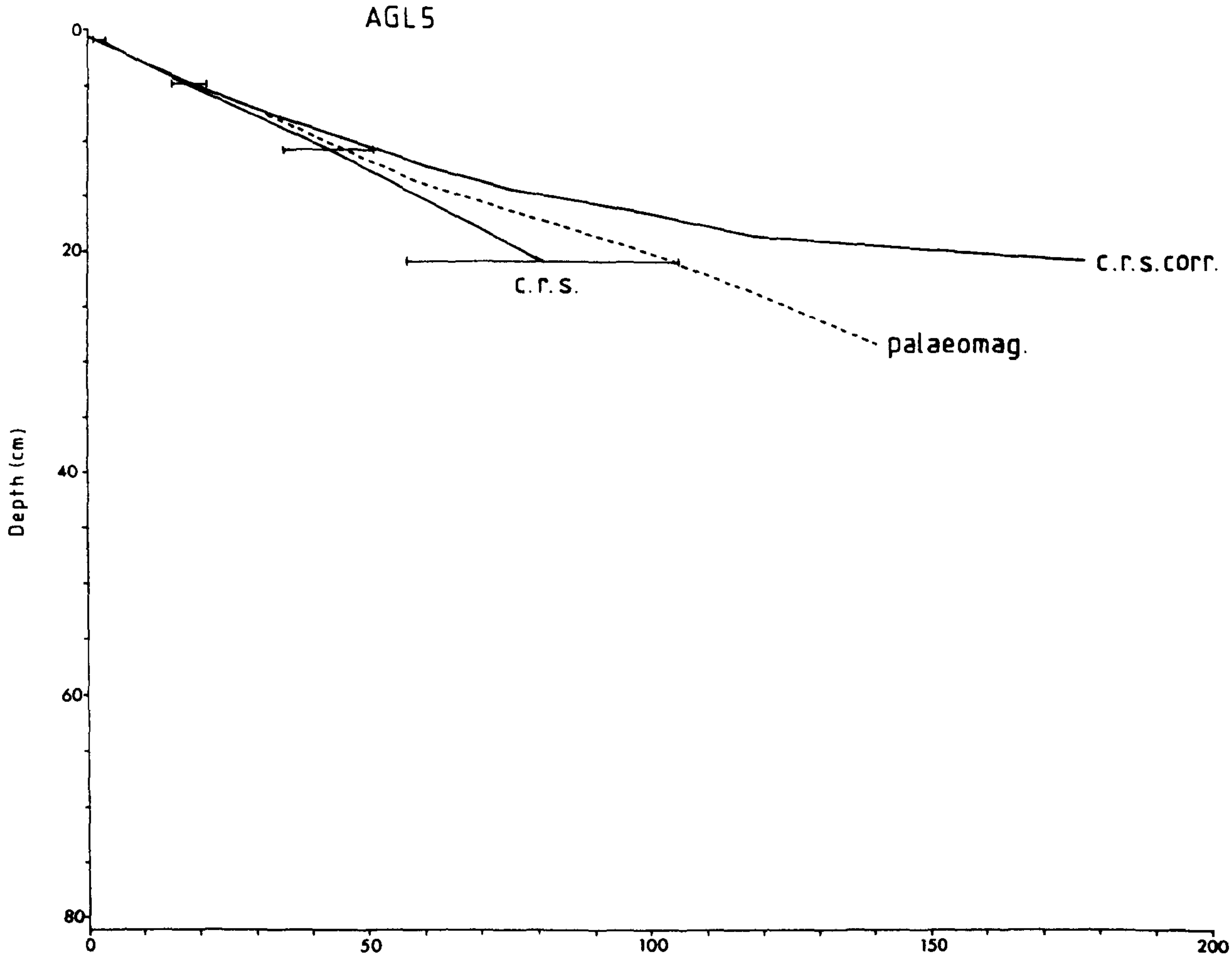

APL1
AGL5
Depth (cm)
210Pb / 226Ra pCi g-1
10
1
0·1
0
20
40
60
80

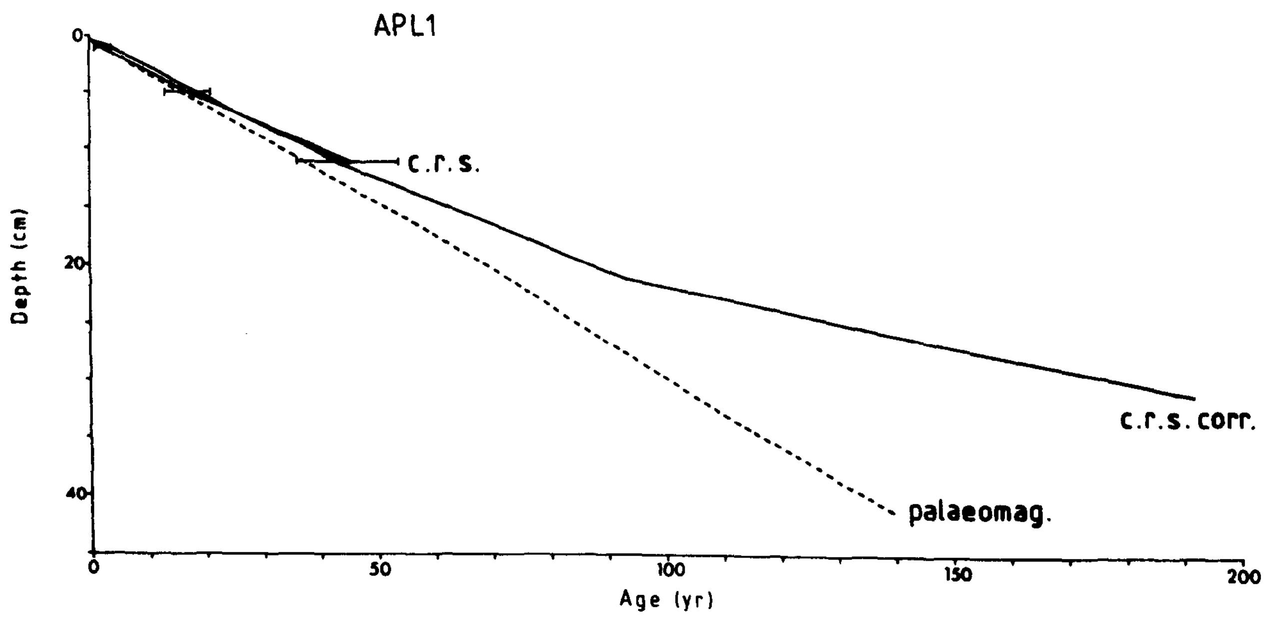
Figure 5.10. Unsupported ^{210}Pb concentration vs. depth for AGL5 and APL1 (standard errors are shown)



APL1
AGL5
Depth (cm)
Depth (cm)
210Pb pCi g-1
10
1
0·1
0
20
40
60
80

Figure 5.11. ^{210}Pb and palaeomagnetic chronologies for AGL5 and APL1
c.r.s: individual chronologies calculated using the results of the original ^{210}Pb and ^{226}Ra assays (standard errors are shown); c.r.s. corr: common chronology calculated by averaging the total unsupported ^{210}Pb between synchronous horizons; palaeomag: chronology derived from the palaeomagnetic dating of APL6.


AGL5
0
20
40
60
80
Depth (cm)
0
50
100
150
200
c.r.s.
c.r.s.corr.
palaeomag.


APL1
0
20
40
Depth (cm)
0
50
100
150
200
Age (yr)
c.r.s.
c.r.s. corr.
palaeomag.

from the individual sub-basins of the lake, it was considered to be more representative to amalgamate the ^{210}Pb data from the two cores in order to produce one profile of unsupported ^{210}Pb data from which to calculate a chronology (P.G. Appleby, pers. comm.). The resulting correlated chronology (c.r.s. corr.) is also shown on figure 5.11. This was calculated by averaging the total unsupported ^{210}Pb between synchronous horizons identified in the two cores using mineral magnetic measurements (§ 5.2.2.). The c.r.s. corr. chronology enabled a chronology to be extended down to 31cm for APL1.

5.3.2. Palaeomagnetic dating

Over time-scales shorter than the full polarity reversals that have occurred in geological history, the earth's geomagnetic field has been changing continuously in a more limited fashion; this is referred to as secular variation. It comprises changes in the position of the magnetic north pole, described by the directional components of magnetic declination (D)[1] and magnetic inclination (I)[2], aswell as changes in the intensity of the magnetic field.

As detrital particles composed of magnetic iron oxide crystals accumulate at the bottom of a lake they may preserve a record of the directional component of the earth's ambient magnetic field. Where sediments accumulate continuously and in sequence they may record the pattern of secular variation as a series of "turning points" of D and I when these parameters are plotted against depth. If these

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[1] Declination refers to the angle between the horizontal component of the earth's magnetic field and geographical (or true) north. A westerly variation is recorded as a positive declination, an easterly variation as negative.

[2] Inclination refers to the angle of dip of the earth's magnetic field below the horizontal plane. A downwards dip of the north seeking pole is recorded as a positive inclination and an upwards orientation as negative.

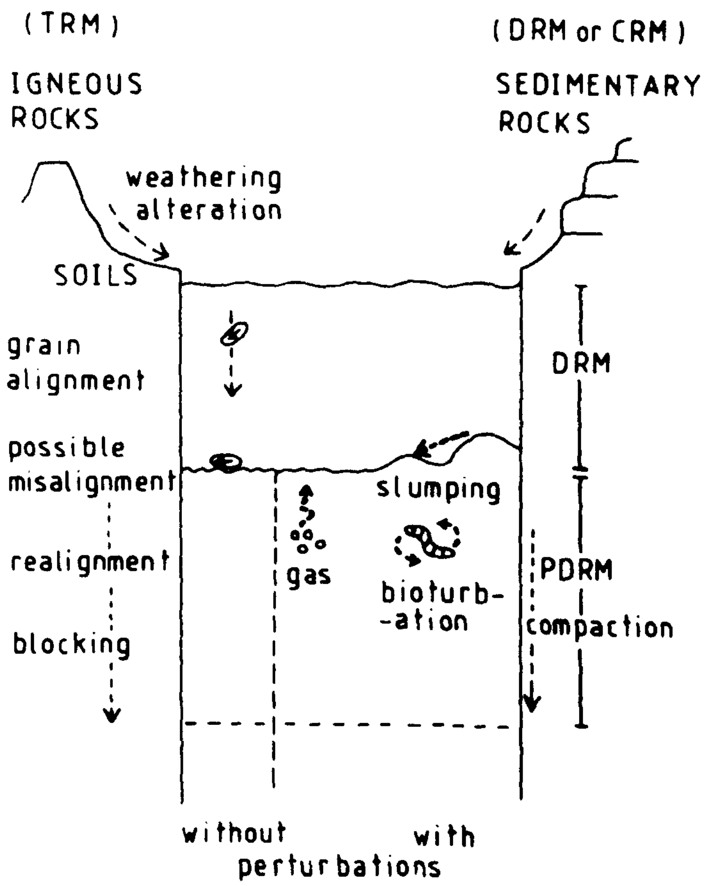
(Oldfield, 1982; Thompson & Oldfield, in press).

traces are then compared with a palaeomagnetic master curve in which the same features have been identified and independently dated, then the palaeomagnetic signal of secular variation can be used as a dating tool. Lake sediments are particularly favourable for using the technique as their relatively high accumulation rates permit such short-term and low-amplitude variations to be resolved in detail.

Thompson & Turner (1979) have produced a detailed master curve of ten D and thirteen I features spanning the last 10,000 years from palaeomagnetic measurements of sediments from Lake Windermere and Loch Lomond in Britain. The palaeomagnetic features were independently dated using a combination of radiocarbon dates and palynological age controls, together with a comparison of the geomagnetic features with archaeomagnetic results and magnetic observatory records. Calibration of master curves in this way is described more fully elsewhere (Oldfield, 1977; Turner, 1979; Thompson, 1982).

Magnetic properties which record the nature of the earth's magnetic field are types of natural remanent magnetization (NRM) and are quite distinct from the mineral magnetic properties outlined in § 4.4. An NRM acquired in the way outlined above is known as a depositional (or detrital) remanent magnetization (DRM). In most cases, however, it is thought that a stable NRM is only preserved some time after the particle has been deposited and further sediment accumulated above; the NRM is then referred to as a post-depositional remanent magnetization (PDRM). Figure 5.12. summarizes the way in which sediments acquire and preserve a PDRM. Before entering the lake itself, magnetic iron oxide crystals already possess a magnetic moment acquired as a primary magnetization or as a secondary magnetization (§ 4.4.2.). Their magnetic moments do not alter during deposition; instead whole particles rotate and become aligned

Figure 5.12. Schematic representation of the acquisition of a DRM (depositional remanent magnetization) and PDRM (post-depositional remanent magnetization) in lake sediments (from Tucker, 1983)
TRM: thermoremanent magnetization; CRM: chemical remanent magnetization.


(TRM)
IGNEOUS ROCKS
(DRM or CRM)
SEDIMENTARY ROCKS
weathering alteration
SOILS
grain alignment
DRM
possible misalignment
slumping
realignment
gas
bioturb-
-ation
PDRM
compaction
blocking
without
with
perturbations

with the earth's magnetic field as they fall through the water column, or once they are deposited at the mud-water interface. Here they continue to re-align with the changing field as long as there are no physical constraints to overcome the attracting force of the earth's magnetic field. Eventually, as more material accumulates and compacts the underlying sediments, individual particles can no longer physically move and the NRM becomes "blocked in". The time-lag before a stable NRM is acquired by the sediment, the "blocking time", depends on the relative sizes of the magnetic iron oxide and matrix particles and on the rate of sediment accumulation. Small magnetic particles will be able to continue to rotate in spaces between coarser matrix grains until compaction reduces the size of the voids; the matrix material may be so coarse that a stable remanence may not be preserved at all. The accumulation rate and particle size characteristics of the sediments together determine the rate of compaction.

The acquisition of a PDRM, as opposed to a DRM, means that the geomagnetic signal recorded by the sediment is most likely to post-date the time at which the magnetic particles were originally deposited at the mud-water interface; this will undoubtedly vary between sites and may even vary within a single sedimentary sequence depending on the local history of sediment accumulation.

A variety of physical peturbations may locally preclude the preservation of an NRM, such as gas bubbles disturbing the sediment, bioturbation, slumping and compaction, causing a "flattening" of the angle of rest of particles. Tucker (1983) discusses the theory of DRM and PDRM in detail.

The fine particles characteristic of the central sediments of the Lac d'Annecy would be expected to promote early compaction. In addition, a relatively fast accumulation rate has been established for these lake sediments (Dearing, 1979; Higgitt, 1978) which would also favour a short "blocking time" and would be expected to result in a finely resolved record of secular variation. Furthermore, the sedimentary sequence of APL6 is characterized by what are thought to be seasonal calcareous laminations (§ 4.1.2.) indicating that the sediments have for the most part been laid down in quiet bottom water conditions without disturbance by bioturbation and so on.

However, comparison of the D and I traces for APL6 (Hogg, 1978) with the palaeomagnetic master curve of Thompson & Turner (1979) is disappointing; there is no great similarity in the pattern of turning points and amplitude of swings and the only firm correlation point appears to be that of the easterly declination maximum feature "d" at 350cm[1] (R. Thompson, pers. comm.).

Mineral magnetic measurements (§ 6.3.) confirm that the sediments are not in fact very suitable for preserving a strong, stable geomagnetic signal despite the favourable accumulation conditions described above. The concentration of magnetic iron oxides is quite low throughout the sedimentary sequence, and especially below 3m. Furthermore, the magnetic minerals are largely composed of ultra-fine crystals which are unable to hold a stable remanence due to continual thermal randomization of their magnetic moments (§ 4.4.1.). Horizons which have not preserved a stable remanence are indicated by their scattered D and I traces and by their low NRM intensity (J)[2] values (figure 5.13.).

To invalidate the palaeomagnetic record further, the core tube

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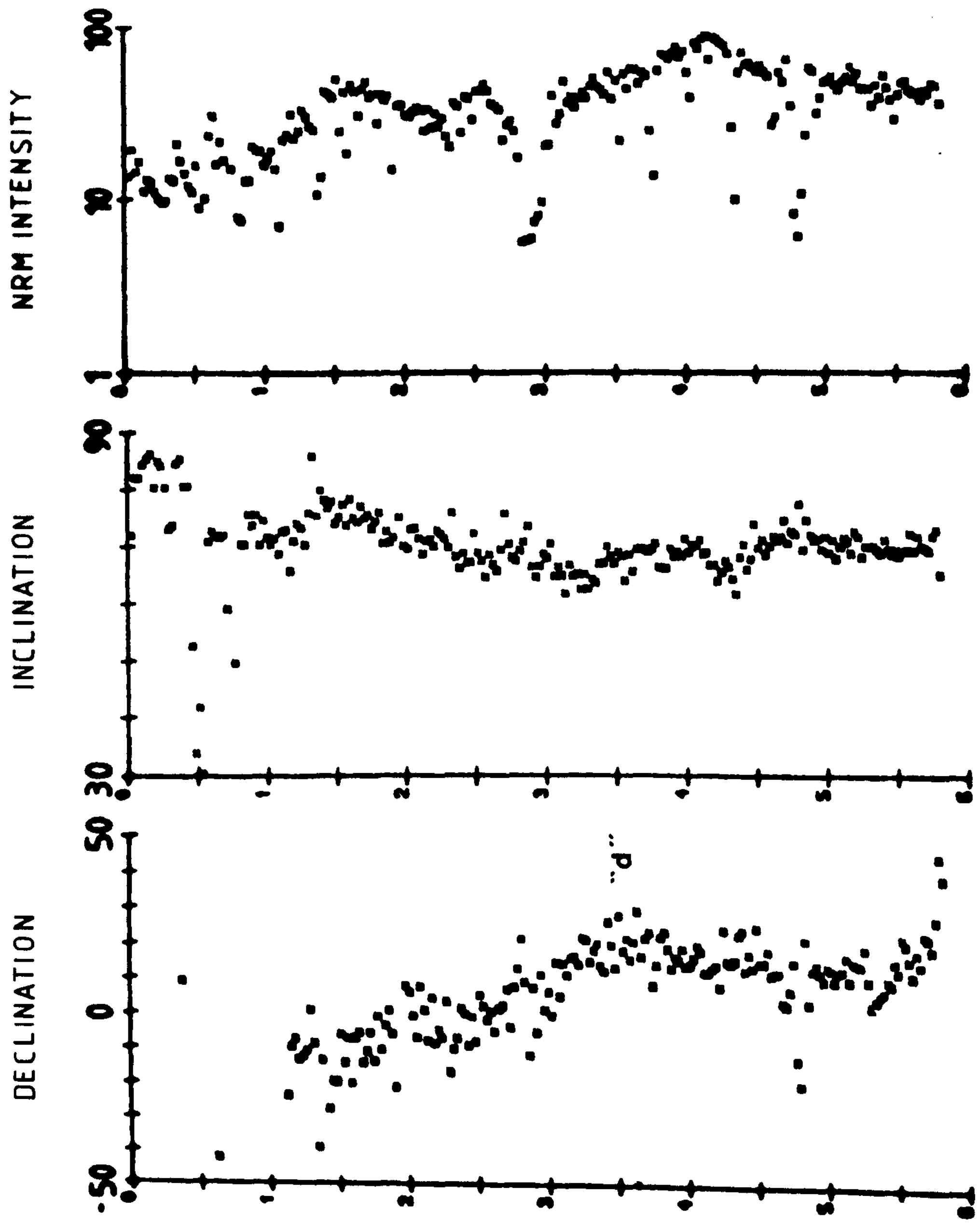
[1] The "corrected" depth for this feature is 338cm (§ 5.2.2.).

[2] The NRM intensity (J) is the magnitude of the natural remanent magnetization (Oldfield, 1982).

Figure 5.13. Declination (D), Inclination (I) and NRM intensity (J) logs for APL6† (from Hogg, 1978) Declination feature "d" (1000 years BP) is labelled.

† This core is labelled ANN1 in the original work.


NRM INTENSITY
100
10
INCLINATION
90
30
DECLINATION
50
0
-50

seems to have twisted somewhat (R. Thompson, pers. comm.). At the time of coring there was no scriber apparatus attached to the core tube to indicate whether or not twisting was occurring; Hogg (1978) considered this to be a serious problem when interpreting NRM profiles from cores in the Petit Lac, and suggests that twisting had modified the record of APL3, a neighbouring core.

Using radiocarbon dates of the same feature in sediments from five British lakes, Thompson & Turner (1979) suggest a date of 1000 years BP for easterly declination maximum feature "d" in their geomagnetic master curve. Transferring this date to the Annecy palaeomagnetic trace assumes that the easterly declination maximum was synchronous in Eastern France and Britain. It is generally considered that the main features of secular variation can be traced across Western Europe (Creer *et al.*, 1977; Creer & Tucholka, 1982; Turner, 1983), and palaeomagnetic traces which correlate well with the British curves have been reported for Swiss sites at around the same longitude as the Lac d'Annecy; at Lac de Joux (Creer *et al.*, 1980) and at Lake Zurich (Thompson & Kelts, 1974). It is not known whether there would have been absolute synchroneity in secular variation at such widely spaced locations. The internal mechanism which causes the drift, growth and decay of the earth's geomagnetic field is not fully understood. However, it is known that features of the non-dipole field[1] are presently drifting westwards at an

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[1] The earth's geomagnetic field is made up of the dipole and non-dipole parts. The non-dipole field is that part of the actual field not accounted for by a best-fitting dipole (tilted at 11·5° to the rotation axis for the present field). It consists of eight foci of maximum and minimum intensity distributed over the globe. Both the dipole and non-dipole fields contribute to secular variation, although the non-dipole variation is more marked; whereas features of the non-dipole field have changed markedly over the last 300 years, the dipole field has hardly changed orientation (Thompson & Oldfield, in press; Turner, 1979).

average rate of about 0·2° per year. This would result in a phase lag of about thirty years between the appearance of a feature at the longitude of the Lac d'Annecy and then in Britain. However, Creer *et al.* (1980) consider this discrepancy to be insignificant compared with the error involved in assigning a feature with a radiocarbon date from another site with its inherent lack of precision.

A palaeomagnetic chronology was calculated for APL6 by assuming a constant sediment accumulation rate between 1000 years BP at 338cm and 0 years BP at the mud-water interface. This chronology was transferred to AGL5 and APL1 using the mineral magnetic correlation best-fit curves described in § 5.2.2.

5.3.3. Composite ^{210}Pb/palaeomagnetic chronology

It can be seen that the ^{210}Pb c.r.s. corr. chronologies are similar to the palaeomagnetic chronologies down to a depth of c. 11cm in AGL5 and APL1 (figure 5.11.). Beyond this however they diverge, the palaeomagnetic chronologies suggesting a higher rate of sediment accumulation than the c.r.s. corr. chronologies. In fact, for APL1 this concurs with the earlier suggestion that the unsupported ^{210}Pb concentration below 11cm had been considerably diluted by a very rapid sedimentation rate (§ 5.3.1.).

In amalgamating the two chronologies to produce a composite ^{210}Pb/palaeomagnetic chronology for the Annecy sediments, the ^{210}Pb c.r.s. corr. chronology has been terminated at 50 years BP (at 10·5cm in AGL5 and at 12·8cm in APL1) beyond which the palaeomagnetic chronology has been adopted. The palaeomagnetic chronology itself has been re-calculated so as to effect a smooth join between the two individual chronologies; this was achieved by linear interpolation between the depth of the ^{210}Pb-dated 50 years BP in APL6 (estimated at 13·9cm by correlation of mineral magnetic features) and the depth of declination feature "d" (1000 years BP at 338cm), and the subsequent transference of this amended palaeomagnetic chronology back to AGL5 and APL1 by correlation of mineral magnetic features.

5.3.4. Palynological dating

Although absolute dates cannot be derived from palynological data, approximate dates may be inferred by correlating local pollen assemblage zones from the site in question with reference sites where regional vegetation changes have been established and independently dated. Where independently dated diagrams are not available, or where relevant sequences within other diagrams remain undated, pollen assemblages may be compared with sites where pollen data have been zoned with reference to a regionally adopted chronostratigraphic system. The latter method is obviously far less satisfactory.

Huntley & Birks (1983) have recently compiled an atlas of isopoll[1] maps for the main pollen and spore taxa during the European Late-Glacial (10,000 - 13,000 years BP) and Holocene (0 - 10,000 years BP); this summary of European palynological data provides a very useful reference work for comparing diagrams.

Bradshaw (1983) discusses the role of palynology as a relative dating tool and lists the following criteria for the use of pollen data in this way: (i) the sites to be compared must collect their pollen from similar vegetation, (ii) major vegetation changes must occur simultaneously around each site, and (iii) the sites must have

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[1] Isopolls are lines joining geographical localities with the same pollen frequency for a given taxon at the time for which the map is drawn.

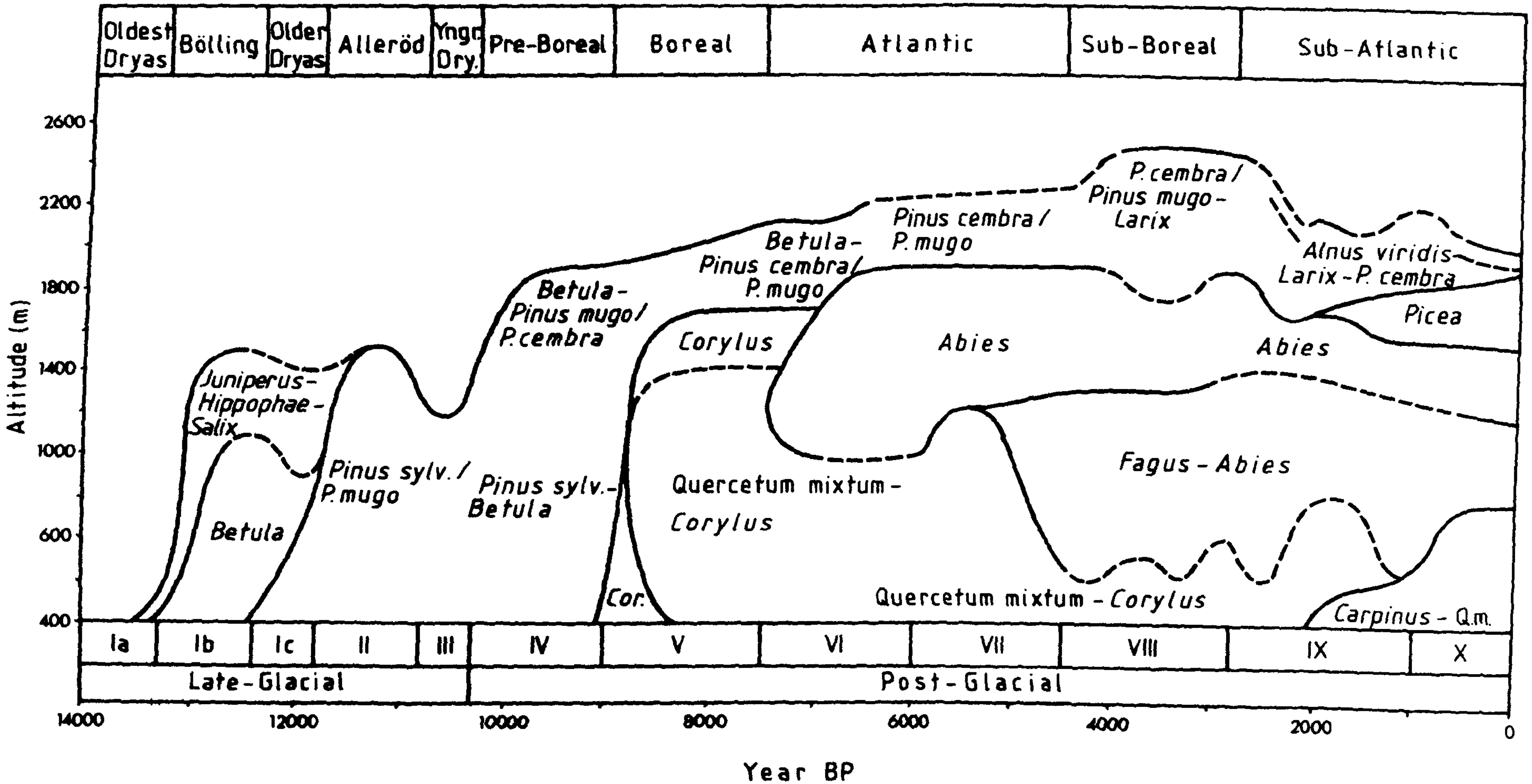
similar properties as pollen traps.

Since the early work of G. & C. Dubois (1940) much palynological research has been completed in the Northern French Alps (de Beaulieu, 1977; Becker, 1952; Couteaux, 1962, 1970 and in Malenfant *et al.*, 1970; Wegmüller, 1977) and a vegetation history has been established for the region for the Late-Glacial and Holocene periods (figure 5.14.) (see Borel, 1976a and 1976b; Jalut, 1969). Many of the pollen diagrams prepared by these authors have been radiocarbon-dated. In addition, de Beaulieu and Wegmüller have zoned their diagrams according to the zonation system of Firbas (1949); their interpretation of the chronological value of these zone boundaries is discussed by de Beaulieu (1982).

However, when pollen diagrams from the Lac d'Annecy are compared with these published studies, the criteria outlined by Bradshaw are not strictly satisfied.

Firstly, vegetation patterns are known to be extremely complex in this region of the Alps. Although the altitudinal decrease in temperature generally results in four characteristic vegetation zones (§ 2.6.1.), local differences in relief, geological structure, lithology and climate give rise to subtle variations in vegetation patterns and therefore to between-site variability in the nature of their pollen sources. Furthermore, as the composition of natural forest and woodland gradually changes away from the northern margins of the French Alps, pollen source areas must also evolve increasingly dissimilar characteristics; the climate tends to become more continental to the east and as a consequence beech (one of the more dominant species of the montane zone in the Annecy lake basin) becomes less frequent, while towards the south pine (a species of fairly limited distribution in the environs of the Lac d'Annecy) becomes more and more important as the climate becomes increasingly

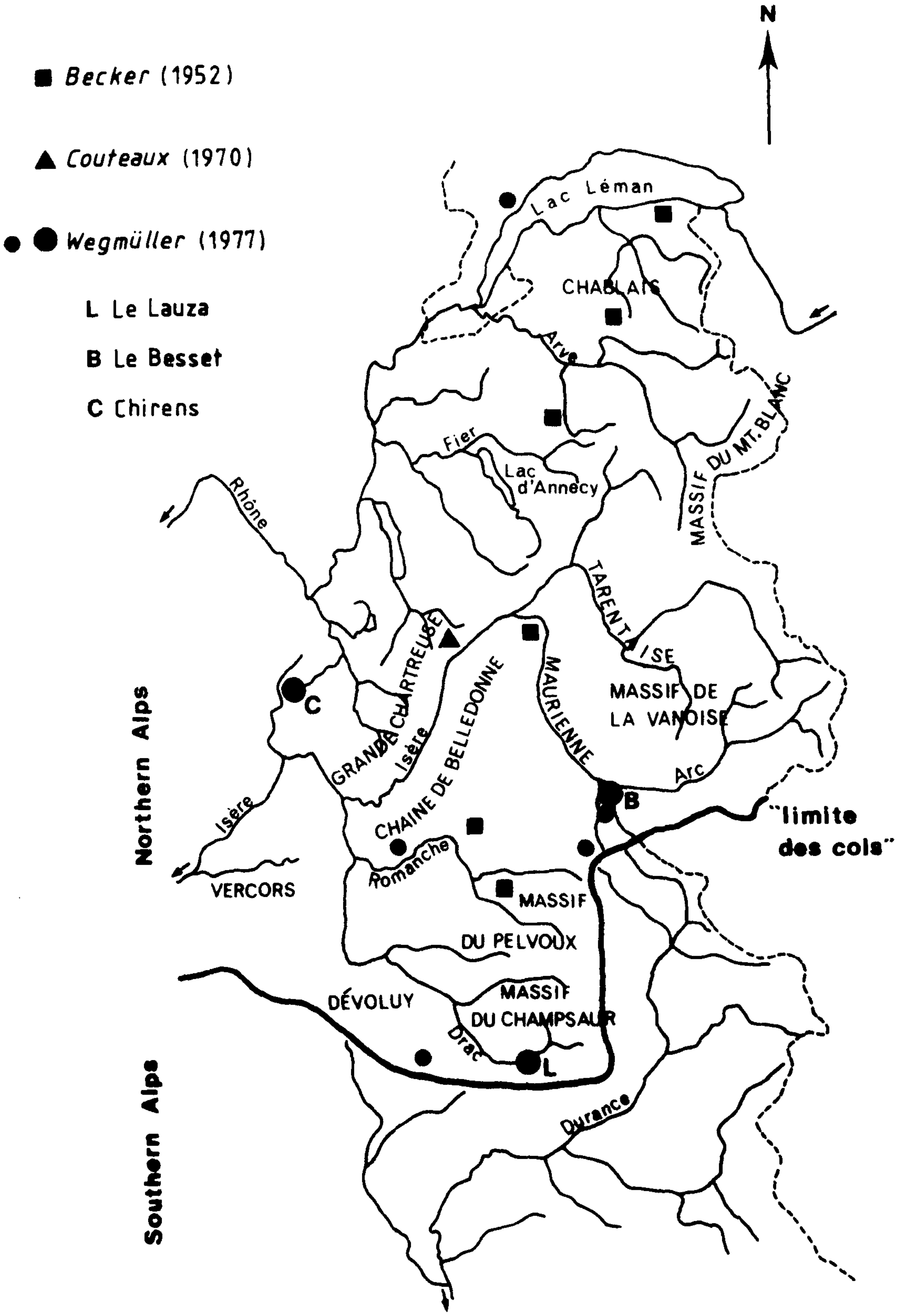
Figure 5.14. Vegetation change in the Northern French Alps during the Late-Glacial and Holocene


Oldest Dryas
Bölling
Older Dryas
Alleröd
Yngr Dry.
Pre-Boreal
Boreal
Atlantic
Sub-Boreal
Sub-Atlantic
2600
2200
1800
1400
1000
600
400
Altitude (m)
Juniperus-Hippophae-Salix
Betula
Pinus sylv./P. mugo
Betula-Pinus mugo/P. cembra
Pinus sylv.-Betula
Cor.
Corylus
Quercetum mixtum-Corylus
Betula-Pinus cembra/P. mugo
Pinus cembra/P. mugo
P. cembra/Pinus mugo-Larix
Alnus viridis-Larix-P. cembra
Picea
Abies
Abies
Fagus-Abies
Quercetum mixtum - Corylus
Carpinus - Q.m.
Ia
Ib
Ic
II
III
IV
V
VI
VII
VIII
IX
X
Late-Glacial
Post-Glacial
14000
12000
10000
8000
6000
4000
2000
0
Year BP

dry (Borel, 1976a). An ecological division between the Northern and Southern French Alps, in terms of their vegetation histories, has long been recognized (Becker, 1950). The two regions are separated by the "limite des cols", the boundary between the valleys of the Isère to the north and the Durance to the south. It is in reality a zone of transition in which species such as oak, hornbeam and spruce gradually disappear and pine becomes dominant (Borel, 1976a). Sites in the Northern French Alps for which diagrams have been prepared are shown in figure 5.15. It can be seen that Becker's sites, within the calcareous pre-alpine massifs, are nearest the Lac d'Annecy and therefore would be expected to have the most similar local pollen sources to those of the Annecy lake basin itself; however, these diagrams have not been independently dated. Unfortunately, most of the remaining sites are located towards the vegetation transition zone and so will have collected pollen from dissimilar vegetation formations.

Secondly, it is not possible to assume synchroneity in vegetation change over the past two to three millenia. During the Sub-Boreal *Abies* was the dominant forest tree; the "phase du Sapin" of Dubois & Dubois (1940) and Becker (1952), and zone VIII of Firbas, dated to between 4500 years BP and 2800 years BP by Wegmüller (1977) in the Northern French Alps. At the end of the Sub-Boreal and beginning of the Sub-Atlantic a climatic deterioration has been recognized involving a fall in temperature together with an increase in humidity which resulted in the expansion of *Fagus* into zones formerly dominated by *Abies* (figure 5.14.). However, the first significant settlement of the alpine massifs by late Bronze Age and early Iron Age populations also occurred during this period and so it is difficult to know whether a marked decline in *Abies* pollen in diagrams is a reflection of the climatic change at the Sub-Boreal/Sub-Atlantic transition or is

Figure 5.15. Location of the principal sites in the Northern French Alps for which pollen diagrams have been published (after Borel, 1976a and Wegmüller, 1977)



■ Becker (1952)
▲ Couteaux (1970)
● ● Wegmüller (1977)
L Le Lauza
B Le Besset
C Chirens
N
Lac Léman
CHABLAIS
Arve
MASSIF DU MT.BLANC
Fier
Lac d'Annecy
Rhône
TARENTAISE
GRANDE CHARTREUSE
CHAINE DE BELLEDONNE
MAURIENNE
MASSIF DE LA VANOISE
Isère
Arc
B
C
"limite des cols"
Northern Alps
Romanche
VERCORS
MASSIF DU PELVOUX
DÉVOLUY
MASSIF DU CHAMPSAUR
Drac
L
Durance
Southern Alps
0 10 20 30
km

the result of deforestation by man. As Borel (1976a) notes:

> "Jusqu'alors principalement determinée par l'évolution du climat, ..., la physionomie des forêts des Alpes du Nord se modifie et se différencie, parfois dès la séconde moitié du Sub-Boréal, essentiellement en fonction des besoins des population indigènes, protocelts et celts."

Comparison of the dates of the decline in *Abies* pollen at three of Wegmüller's sites attests to the asynchroneity of major vegetation change in this region for the recent Holocene. At Le Lauza the feature has been dated to 750 ± 110 years BC, and at Le Besset linear interpolation between two ^{14}C dates suggests a date of c. 720 years BC, although a later date may be envisaged if it is assumed that the matrix peat accumulated more rapidly during the Sub-Atlantic due to the moister climatic conditions. At Chirens, however, the decline in *Abies* has been dated to 430 ± 90 years BC. If the occurrence of this pollen feature at any one or more of these sites is the result of human action, then individual site characteristics probably account for the timing of the event; the relatively late date observed at Chirens is perhaps due to its location in the lowlands to the west of the Pré-Alpes.

Thirdly, all the pollen diagrams from the Northern French Alps referred to above have been prepared from peat-bog sites, while the Annecy sediments are lacustrine in origin. These two environments accumulate their pollen in very different ways (see Jacobson & Bradshaw, 1981) and so synchronous fossil pollen assemblages are not necessarily comparable. A further consequence of differences in the accumulation of these two types of matrix material is that few of the peat-based ^{14}C dates would be expected to be recent enough to compare with the diagram from APL6; lake sediments are generally deposited more rapidly than peat accumulates. This disparity is particularly exaggerated in the case of the Petit Lac sub-basin due to the size of its catchment area.

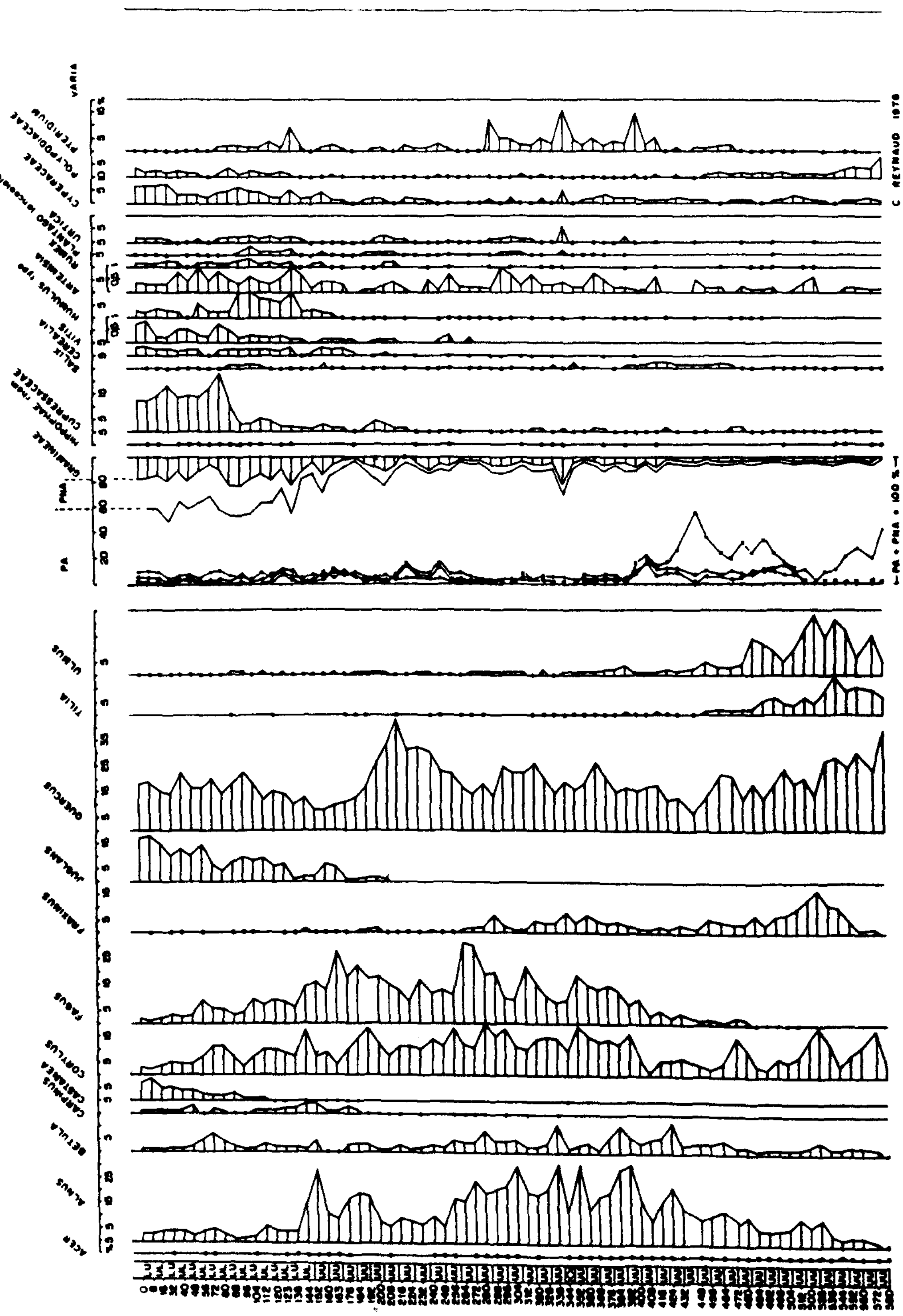
However, the composite ^{210}Pb/palaeomagnetic chronology calculated for APL6 only extends to a depth of 338cm and so, despite the problems involved in using palynological data for dating the Annecy sediments, it was considered vital to compare the pollen diagram from this core with dated work from the same region in order to make at least an estimate of the age of the lower half of the sedimentary sequence.

Reference to the relative pollen diagram from APL6 (figure A3.1.) shows that *Abies* pollen is nowhere present in significantly high frequencies indicating that the complete 6m profile post-dates the Sub-Boreal climatic period and lies entirely within the Sub-Atlantic, or zones IX and X of Firbas, dated to between 2800 years BP and the present-day by Wegmüller (1977).

Huntley & Birks (1983) summarize the history of the spread of *Juglans* pollen in Europe and note that in most cases the first appearance of this taxon occurs between 1500 and 2500 years BP, contemporaneous with Greek and Roman civilization. At Annecy, the introduction of *Juglans* can probably be attributed to the Romans (§ 3.1.1.) and so a closed curve for this pollen type would be expected to begin at a date of c. 2000 years BP at the earliest, or more probably at a later date assuming a time-lag before the introduction of the tree to the area and before pollen would have been produced in sufficient quantities to be represented in the lake sediment samples analyzed here. This feature can be seen at a depth of 475cm in APL6.

The base of APL6 has been dated by comparison with Wegmüller's diagrams from Le Lauza and Le Besset through the intermediary of a pollen diagram from the Grand Lac sub-basin of the Lac d'Annecy (Reynaud, unpublished data). Relatively high frequencies of *Abies* pollen can be seen between 400 and 500cm (figure 5.16) and have been assigned to Firbas' zone VIII. The decline in this pollen type at a

Figure 5.16. Pollen diagram from the Grand Lac sub-basin of the Lac d'Annecy (Reynaud, unpublished data) Abbreviations in summary diagram - PA: arboreal pollen; PNA: non-arboreal pollen; crosses: *Abies*; triangles: *Picea*; circles: *Pinus*. The following pollen and spore types are referred to by different names in this thesis: Cupressaceae (*Juniperus* type); *Humulus* type (*Cannabis* type); Cerealia (Cereals type); Polypodiaceae (Filicales undiff.)



LAC D'ANNECY 45°50'N - 6°10'E

depth of 400cm has been tentatively dated at c. 2700 years BP. This relatively early date (cf. the later date of the *Abies* decline at Chirens, described above) has been attributed to the pollen feature as there is archaeological evidence for man's presence in the Annecy lake basin for this period (§ 3.1.1.). In fact, trunks and branches of *Abies alba* have been retrieved from the remains of the prehistoric lake villages of Le Port (2000 BC) and Roselet (1500 - 1200 BC), indicating that the species was being selectively removed from nearby woodland for use as construction timber (Guinier, 1908a and 1908b), although whether forest clearance associated with these earlier settlements was ever of sufficient extent to influence pollen production significantly, and therefore to be registered in a pollen diagram, can only be speculated upon.

Linear interpolation between the *Abies* decline at 400cm (2700 years BP) and the beginning of a closed curve for *Juglans* at 200cm (2000 years BP) in Reynaud's diagram from the Grand Lac gives a date of c. 2140 years BP for a depth of 240cm which correlates biostratigraphically with the base of APL6.

5.4. Age/depth-profiles and sedimentation rates

Age/depth-profiles and sedimentation rates for AGL5, APL1 and APL6 are shown in figures 5.17. and 5.18. For AGL5 and APL1 both volumetric and dry-mass sedimentation rates have been calculated. For APL6, mean volumetric sedimentation rates have been calculated and are indicated on the age/depth-profile itself. It was not possible to assess mean dry-mass sedimentation rates for this core due to the partially-dried state of the material prior to sampling.

AGL5 seems to represent the past c. 450 years of sedimentation in the Grand Lac sub-basin and therefore spans the historical period

Figure 5.17. Age/depth-profiles and sedimentation rates for AGL5 and APL1 (year 0 is 1975)

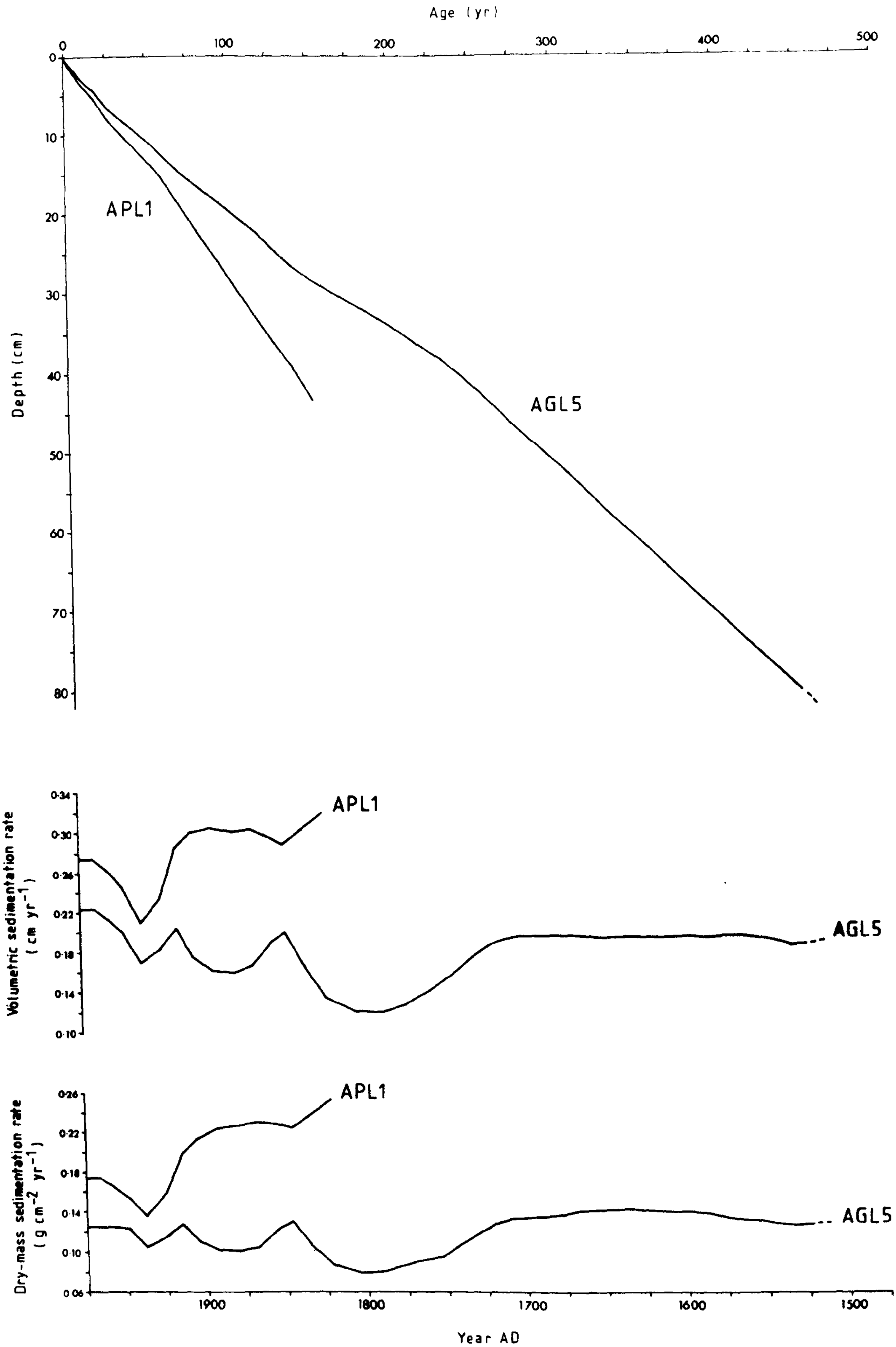
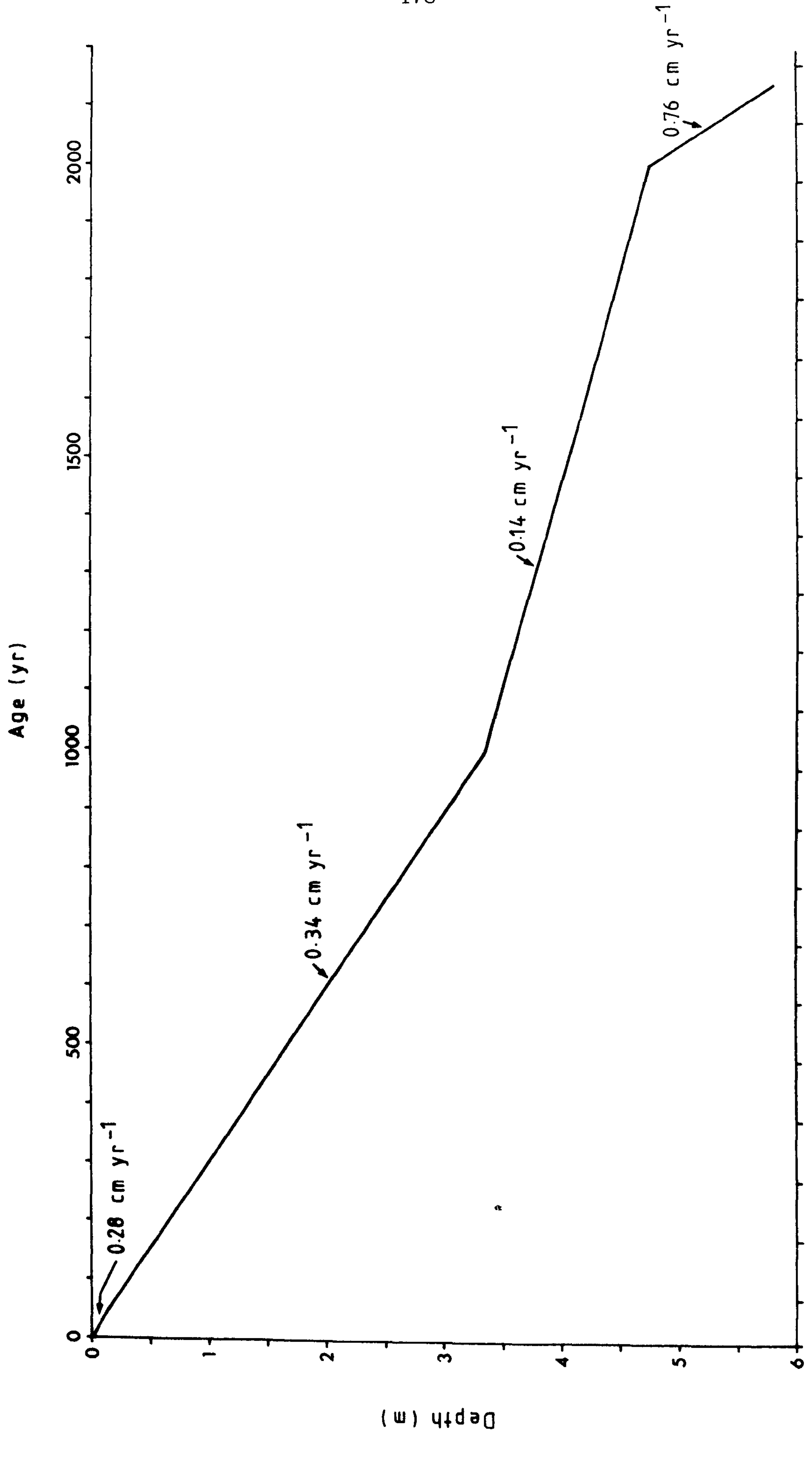

Age (yr)
0
100
200
300
400
500
Depth (cm)
10
20
30
40
50
60
70
80
APL1
AGL5
Volumetric sedimentation rate
(cm yr^{-1})
0·34
0·30
0·26
0·22
0·18
0·14
0·10
APL1
AGL5
Dry-mass sedimentation rate
(g cm^{-2} yr^{-1})
0·26
0·22
0·18
0·14
0·10
0·06
APL1
AGL5
1900
1800
1700
1600
1500
Year AD

Figure 5.18. Age/depth-profile and mean volumetric sedimentation rates for APL6 (year 0 is 1975)



Age (yr)
0
500
1000
1500
2000
Depth (m)
0
1
2
3
4
5
6
0·28 cm yr⁻¹
0·34 cm yr⁻¹
0·14 cm yr⁻¹
0·76 cm yr⁻¹

from the beginning of the sixteenth century up to the present day. APL1 appears only to represent the past 150 years of sedimentation and therefore spans the nineteenth and twentieth centuries.

The patterns of sediment accumulation suggested by the composite ^{210}Pb/palaeomagnetic chronology shared between these two cores (figure 5.17.) are very different from those suggested by the original ^{210}Pb c.r.s. chronologies (see Dearing, 1979). Here it is indicated that sediment accumulation rates in the Petit Lac (APL1) have been consistently higher than in the Grand Lac (AGL5). This seems a reasonable observation considering the relative size of the catchment areas in both sub-basins, and is in agreement with the difference in sedimentation rates already observed between APL6 from the Petit Lac and a 6m core from the Grand Lac over a much longer time-scale (q.v. figure 5.16.). The original individual ^{210}Pb chronologies suggested that the sedimentation rate in the Petit Lac was considerably slower than that in the Grand Lac. An explanation for this discrepancy has already been considered above, ie. that unsupported ^{210}Pb concentrations in the lower part of APL1 have been diluted by an accelerated influx of catchment-derived material generating apparently "old" radiometric dates.

The patterns of sediment accumulation shown by the volumetric and dry-mass sedimentation rates are not absolutely identical. Of the two, the dry-mass sedimentation rates are considered to be the more representative index of accumulation as variations in the water content of the sediments may have influenced the volumetric sedimentation rates. (It is assumed that the dry-weight/wet-volume ratios used in these calculations, for the most part derived from linear interpolation between assayed samples, are accurate estimates).

In APL1, the sedimentation rate apparently decelerated markedly throughout the nineteenth century and beginning of the twentieth century, from over 0·24g $cm^{-2}yr^{-1}$ to c. 0·14g $cm^{-2}yr^{-1}$. However, during the past fifty years the accumulation rate has accelerated, albeit only moderately, the increase being of the order of c. 10%.

Sedimentation rates appear to have been less varied in AGL5, fluctuating around 0·12g $cm^{-2}yr^{-1}$. Relatively low rates of sediment accumulation are indicated for the second half of the eighteenth century and beginning of the nineteenth century, and again during the second half of the nineteenth century. Relatively low sedimentation rates are also observed for the inter-war period in the twentieth century, with a slight acceleration during the past fifty years.

Thus, from the First World War period, the pattern of sediment accumulation in both sub-basins appears to have been similar. Prior to this the trends apparent in AGL5 may be in part, or even wholly, an artefact of the mineral magnetic correlations between this core and the palaeomagnetically-dated Petit Lac core.

APL6 is thought to represent c. 2140 years of sedimentation in the Petit Lac sub-basin and therefore spans the period from the late Iron Age to the present century. The age/depth profile suggests a period of very rapid sedimentation (0·76cm yr^{-1}) prior to 2000 years BP followed by a period of relatively slow sediment accumulation (0·14cm yr^{-1}) during the first millenium AD. This five- to six-fold difference in sedimentation rates may indeed be a true reflection of changes in the rate of material flux from catchment surfaces (and/or autochthonous material production) for this period, or may simply be the result of an error in the date assigned to the initial appearance of *Juglans* pollen in this sedimentary sequence. A date later than 2000 years BP has already been anticipated for this pollen feature, and if this was the case, then a slower sedimentation rate can be envisaged prior to the date of 475cm in APL6, and a faster accumulation rate afterwards. The appearance of *Juglans* pollen has also been identified and dated at 2000 years BP in Reynaud's Grand Lac core and so, if incorrect, the age of the base of APL6 will also have been incorrectly estimated and may be proportionally younger than supposed at present, other things being equal. There are, however, two additional sources of dating error. Firstly, it is possible that the date assigned to the *Abies* decline in Reynaud's core is incorrect. Depending on whether this pollen feature actually occurred before or after 2700 BP, then the age of the base of APL6 will have been under- or over-estimated. Secondly, the palaeomagnetic feature may possibly have an error of the order of a century or more due to counting errors associated with the radiocarbon dates used to date the same feature in British sediments. Sediment accumulation seems to have accelerated somewhat during the second millenium AD (0·34cm yr^{-1}), although once more if there is a significant error associated with the palaeomagnetic feature then this will be an inaccurate estimate of the rate of accumulation of sediments post-dating 338cm depth. For the past half-century (the ^{210}Pb-dated portion of the core) a similar rate of accumulation (0·28cm yr^{-1}) is indicated which corresponds closely with that observed in APL1 for the same period.

However, in view of the inferred sensitivity of sedimentation in the Petit Lac sub-basin to short-term changes in the flux density of allochthonous material (§ 7.1. and § 7.2.), it seems that reliable calculations of annual accumulation rates for the pollen, geochemical and mineral magnetic measurements would require calibration on a time-scale more finely resolved than that generated by the ^{210}Pb/ palaeomagnetic/palynological chronology described above. For this reason, and because of the lack of dry weight/wet volume ratios for this core, these results are simply presented as relative percentages or concentrations per gram dry weight of sediment in this thesis.

The prospect for quantifying rates of change in any future palaeoecological reconstruction seems to lie with the laminae present in the sediments, if indeed they prove to be annual features.

CHAPTER 6

DESCRIPTION OF RESULTS

6.1. Pollen analyses

The pollen diagrams are placed in Appendix 3. Results from the "ZONATION" program output are shown in figures 6.1., 6.2. and 6.3. for APL6, APL1 and AGL5 respectively. Local pollen assemblage zones derived from the agglomerative and divisive results are numbered or lettered from the base upwards; I, II etc. for the long core APL6, and a, b etc. for the mini-cores APL1 and AGL5. Zone labels are prefixed by the site designation APL for the profiles from the Petit Lac and AGL for the profile from the Grand Lac.

6.1.1. APL6

Five pollen assemblage zones have been identified: APL I (levels 24 - 19), APL II (levels 18 - 15), APL III (levels 14 - 10), APL IV (levels 9 - 2) and APL V (level 1). Boundaries between these zones have been arbitrarily placed mid-way between the depths of neighbouring levels. Dates assigned to these zone boundaries are derived from the chronology calculated in Chapter 5.

The pollen percentage and pollen concentration diagrams for this core are shown in figures A3.1. and A3.2.

APL I 584 to 438·5cm (2140 to 1670 years BP)

Pollen assemblage zone (p.a.z.) APL I is characterized by very high frequencies of arboreal pollen (mean, 90·38 ± 1·83%[1]) and

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[1] Throughout this chapter mean values are quoted ± 1 standard deviation.

relatively high total tree, shrub and herb pollen concentrations (mean, 104·91 ± 29·04 × 10^3 grains g^{-1}). The pollen of *Quercus* is prominent in APL I, reaching a maximum frequency of 41·41% in the middle of the zone (mean, 29·88 ± 7·15%). *Alnus*, *Corylus* and *Fagus* pollen frequencies are also relatively high (*Alnus* mean, 15·97 ± 3·98%; *Corylus* mean, 19·00 ± 2·30%; *Fagus* mean, 14·08 ± 3·87%). *Abies* pollen reaches the highest values of the whole profile of over 4% at the beginning of the zone. A continuous curve for *Juglans* pollen begins in the middle of the zone.

APL II 438·5 to 329·8cm (1670 to 965 years BP)

P.a.z. APL II is characterized by very high arboreal frequencies (mean, 92·33 ± 3·08%). Total pollen concentrations are also very high (mean, 169·01 ± 60·21 × 10^3 grains g^{-1}) with two individual peaks clearly distinguished, the first at the beginning of the zone at 428cm (235·14 × 10^3 grains g^{-1}) and the second in the upper half of the zone at 343cm (222·77 × 10^3 grains g^{-1}). *Fagus* pollen is very frequent (mean, 15·03 ± 6·17%), reaching maximum values of 23·29% in the middle of the zone. Relatively high frequencies of *Abies*, *Betula* and *Carpinus* pollen also occur (*Abies* mean, 2·11 ± 1·32%; *Betula* mean, 4·06 ± 2·77%; *Carpinus* mean, 2·85 ± 0·78%). Peaks in the concentration of *Pinus*, *Alnus*, *Betula*, *Carpinus*, *Corylus*, *Quercus* and unidentified deteriorated grains and similar features in the relative frequency of *Alnus*, *Betula*, *Corylus* and total arboreal pollen correspond with the double maxima already described for the total pollen concentration. *Castanea* pollen appears for the first time in APL II but does not constitute a closed curve.

The boundary between APL II and APL III is marked by a sudden decrease in the frequency of *Alnus* pollen, from 38·93% at the top of APL II to only 6·07% at the beginning of APL III.

APL III 329·8 to 204cm (965 to 600 years BP)

P.a.z. APL III is characterized by very high concentrations of herbaceous pollen (mean, 43·36 ± 10·92%), in particular reflecting the abundance of Gramineae undiff. pollen which increases to a maximum frequency of 15·20% in the middle of the zone (mean, 11·25 ± 4·09%). The mean total pollen concentration of only 22·34 ± 15·53 $\times 10^3$ grains g^{-1} is the lowest observed for the whole profile. Cereals type pollen are also frequent in APL III (mean, 3·99 ± 2·27%) and within this category *Secale* type pollen are significant with a maximum value of 6·19% in the bottom half of the zone. *Cannabis* type pollen and Compositae Liguliflorae pollen are also very frequent (*Cannabis* type mean, 9·00 ± 1·95%; Compositae Liguliflorae mean, 7·23 ± 4·55%) with peak values in the bottom and top of the zone at 287 and 219cm. The pollen of the following types all have higher frequencies than observed in APL I and APL II: Compositae Tubuliflorae undiff. (mean, 1·68 ± 0·95%), *Artemisia* (mean, 0·95 ± 0·38%), Cyperaceae (mean, 2·52 ± 1·27%) and *Plantago lanceolata* (mean, 3·64 ± 0·49%). A closed curve for *Castanea* pollen begins at the base of APL III, and the pollen of *Pinus*, *Juniperus* type and *Juglans* all exhibit enhanced frequencies (*Pinus* mean, 5·34 ± 2·26%; *Juniperus* type mean, 4·41 ± 1·78%; *Juglans* mean, 5·70 ± 1·92%). APL III is also characterized by very high frequencies of Pteridophyta spores (mean, 17·87 ± 7·65%), predominantly the Filicales undiff. and *Pteridium aquilinum*, together with very high frequencies of unidentified deteriorated grains (mean, 40·57 ± 10·16%), all of which show a double maxima which coincide with those described above for *Cannabis* type and Compositae Liguliflorae pollen.

The boundary between APL III and APL IV is marked by a significant increase in the total arboreal frequency from 44·44% at the top of APL III to 81·17% at the bottom of APL IV.

APL IV 204 to 24·5cm (600 to 79·5 years BP)

P.a.z. APL IV is characterized by high frequencies of *Juglans* pollen (mean, 13·77 ± 4·43%) which reach a maximum value of 22·89% at the top of the zone. *Castanea* pollen is also relatively abundant (mean, 3·15 ± 1·68%) as are the pollen of the Gramineae undiff. (mean, 7·63 ± 2·68%), Cereals type (mean, 2·87 ± 1·09%) and *Cannabis* type (mean, 6·35 ± 2·88%). Total arboreal pollen frequencies decline overall to a minimum of 54·80% at 83cm above which they increase to 67·96% at the top of the zone. The minimum arboreal frequency corresponds to peak values of Pteridophyta spores (15·79%), unidentified deteriorated grains (42·55%) and Compositae Liguliflorae pollen (9·37%). The mean total pollen concentration of 28·71 ± 13·29 $\times 10^3$ grains g^{-1} is still relatively low, although higher than that observed for APL III.

APL V 24·5 to 0cm (79·5 to 0 years BP)

P.a.z. APL V is characterized by relatively high frequencies of *Picea* and *Pinus* pollen (6·69% and 18·96% respectively), by the absence of *Cannabis* type pollen and by a fall in the frequency of *Juglans* (2·23%), *Castanea* (1·12%), Gramineae undiff. (4·83%) and Cereals type (2·23%) pollen. The frequency of total arboreal pollen of 74·35% is higher than those of APL IV, and the mean total pollen concentration of 50·61 $\times 10^3$ grains g^{-1} is also higher than those observed in zones APL III and APL IV, although still significantly lower than observed in APL I and APL II.

6.1.2. APL1

The main split in the pollen sequences from APL1 is defined by the divisive procedures, SPLITINF and SPLITLSQ, as being between levels 7 and 8 with a second split between levels 10 and 11 (figure

6.2.). The zonation scheme suggested by the agglomerative procedure, CONSLINK, differs, and identifies the most significant division to be between levels 1 - 12 and 14 - 19 with level 13 as a distinct pollen assemblage zone. The dissimilarity of level 13 is due to the zero count for *Juglans* pollen, and precludes level 12 (or the group in which level 12 is included) amalgamating with level 14 (or the group in which level 14 is included) until level 13 itself is joined to one or the other (see Gordon & Birks, 1972). A second division indicated by CONSLINK is that between levels 10 and 11, whereas a zone boundary between levels 7 and 8, clearly indicated by the other two procedures, is not as apparent. The divisive procedures consider data from the whole of a zone when zone boundaries are chosen, whereas the dissimilarity coefficient between groups calculated by CONSLINK is simply the dissimilarity coefficient between the most similar pair of objects, one in each group. Consequently, the divisive procedures are potentially more sensitive as detecting quantitatively small but stratigraphically consistent changes that occur over several levels, (Gordon & Birks, 1972). Each 2cm slice of sediment in APL1 only spans a few years of sediment accumulation (between 6·6 and 9·6 years) so the contiguous pollen counts would be expected to record progressive and possibly subtle changes in the properties of successive pollen assemblages. Thus, it would seem that the zonation scheme suggested by SPLITINF and SPLITLSQ should be preferred.

Two major pollen assemblage zones have been identified: APL a (levels 19 - 8) and APL b (levels 7 - 1). Zone APL a is further divided into two sub-zones: APL a(i) (levels 19 - 11) and APL a(ii) (levels 10 - 8).

The pollen percentage diagram for this core is shown in figure A3.5.

APL a(i) 44 to 24cm (151 to 87·5 years BP)

P.a.z. APL a(i) is characterized by relatively high frequencies of *Cannabis* type pollen (mean, 6·04 ± 1·52%) and *Juglans* pollen (mean, 14·77 ± 6·01%). Percentages for *Castanea*, Gramineae undiff. and Cereals type pollen are also relatively high (*Castanea* mean, 3·19 ± 0·92%; Gramineae undiff. mean, 14·00 ± 4·27%; Cereals type mean, 4·46 ± 1·27%), while the frequency of total arboreal pollen is relatively low (mean, 56·11 ± 11·11%). A continuous curve for *Abies* pollen ends in the middle of p.a.z. APL a(i), while a closed curve for *Fraxinus* pollen begins midway through the zone. Maximum values for the frequency of Compositae Liguliflorae pollen (6·83%) and Filicales undiff. spores (20·23%) occur at 37cm.

APL a(ii) 24 to 18cm (87·5 to 68 years BP)

P.a.z. APL a(ii) is essentially characterized by a decline in the frequency of *Cannabis* type pollen (to only 1·40%) and *Juglans* pollen (to only 8·68%). The percentage of Gramineae undiff. pollen is also relatively low (mean, 9·28 ± 1·84%) while total arboreal pollen frequencies are relatively high, (mean, 67·07 ± 2·4%).

APL b 18 to 0cm (68 to 0 years BP)

P.a.z. APL b is characterized by the disappearance of the *Cannabis* type pollen curve and by relatively low frequencies of *Juglans* pollen (mean, 3·77 ± 1·72%). Relatively low frequencies are also seen for the pollen of *Castanea* (mean, 1·73 ± 0·74%). The frequency of Cereals type pollen (mean, 2·26 ± 1·40%) declines through this zone, as do the percentages of Cyperaceae pollen. Total arboreal pollen frequencies are generally higher than in zone APL a, with values fluctuating between 57·53 and 75·62% (mean, 67·13 ± 6·80%). This reflects increases in the frequency of *Picea* (mean, 6·22 ± 2·31%), *Betula* (mean, 3·02 ± 1·48%), *Carpinus* (mean, 1·62 ± 0·46%), *Fraxinus* (mean, 2·78 ± 1·24%), *Quercus* (7·71 ± 1·00%) and

Salix (mean, 1·48 ± 0·91%) pollen. Both *Abies* and *Tilia* begin a more or less continuous curve in p.a.z. APL b. *Pinus* pollen increases in frequency through the zone boundary to reach a maximum of 17·98% at 15cm, above which its percentages are much lower (mean, 8·51 ± 1·39%).

6.1.3. AGL5

The divisive procedures both identify a major boundary between levels 4 and 5 (figure 6.3.) with a second split between levels 22 and 23 suggested by SPLITINF and between levels 23 and 24 by SPLITLSQ. A zone boundary between 4 and 5 is also picked out by CONSLINK, although this procedure does actually single out level 5 as a pollen assemblage zone or zonule; however, as there are no significantly high or low counts at this level it seems that CONSLINK has identified level 5 as a transition zone (see Gordon & Birks, 1972). CONSLINK also delimits a zone boundary between levels 23 and 24, agreeing with that suggested by SPLITLSQ. SPLITINF and SPLITLSQ both pick out a third boundary between levels 7 and 8 which is clear in the CONSLINK dendogram. As with APL1 individual pollen counts are derived from contiguous samples, with each 2cm slice spanning a relatively short period of time (between 8·9 and 17·0 years), although there are gaps where samples have been taken for ^{210}Pb analyses. So, for the reasons outlined above for APL1, the zonation schemes suggested by the divisive procedures would be expected to be more likely to detect small but significant quantitative changes.

Three pollen assemblage zones have been identified: AGL a (levels 31 - 24), AGL b (levels 23 - 5) and AGL c (levels 4 - 1). Zone AGL b is further divided into two sub-zones: AGL b(i) (levels 23 - 8) and AGL b(ii) (levels 7 - 5).

The pollen percentage diagram for this core is shown in figure A3.6.

AGL a 82 to 61cm (456 to 352 years BP)

P.a.z. AGL a is characterized by relatively high frequencies of total arboreal pollen (mean, 69•24 ± 3•48%) which decline throughout the zone from 75•66 to 63•59%. *Juglans* is one of the main contributors to the pollen sum (mean, 16•65 ± 1•93%), while the following pollen types all exhibit relatively high percentages which decline through the zone: *Quercus* (mean, 16•09 ± 2•38%), *Corylus* (mean, 7•61 ± 1•16%), *Alnus* (mean, 4•54 ± 1•45%), *Fagus* (mean, 3•63 ± 1•00%) and *Betula* (mean, 1•97 ± 1•11%). *Carpinus* has a more or less closed curve throughout AGL a, although frequencies are nowhere more than 1•21%. Values for the percentage of the Gramineae undiff. pollen are relatively low (8•96 ± 2•05%), as are those for *Pinus* pollen (3•34 ± 1•17%), *Picea* pollen (0•82 ± 0•29%) and Cereals type pollen (3•31 ± 0•74%), whereas frequencies for *Cannabis* type pollen increase, from 3•12 to 9•70%, and for *Castanea* pollen they increase from 0 to 2•23%. The percentage of *Juniperus* type pollen remains relatively high (mean, 8•45 ± 1•21%).

AGL b(i) 61 to 21cm (352 to 111 years BP)

P.a.z. AGL b(i) is characterized by relatively high frequencies of *Juglans* pollen (17•76 ± 5•00%) and *Cannabis* type pollen (9•69 ± 2•03%), although there is a marked minimum in the *Juglans* curve in the middle of the zone. The frequency of arboreal pollen is relatively low (mean, 59•78 ± 4•98%) with a general decline continuing from zone AGL a at the top of AGL b(i), which reflects a decline in several tree pollen types which reach a minimum near the top of the zone; *Alnus* (0•81%), *Betula* (0•27%), *Corylus* (1•35%), *Fagus* (0%) and *Quercus* (3•78%). The pollen of *Picea* and *Pinus* both have relatively high frequencies (means, 1•54 ± 0•08% and 6•22 ± 1•81% respectively). The percentages of *Juniperus* type pollen are generally high (mean, 8•31 ± 1•70% up to 32cm) but decline at the top of the zone. Both

Castanea and the Gramineae undiff. pollen also exhibit relatively high frequencies, but their values fluctuate widely, *Castanea* between 0·46 and 10·54% and Gramineae undiff. between 8·72 and 21·92%. The curve for the latter type very closely mirrors the curve for that of total arboreal pollen. Percentages of Cereals type pollen are similar to those in p.a.z. AGL a (mean, 4·11 ± 0·87%).

AGL b(ii) 21 to 14cm (111 to 67·5 years BP)

P.a.z. AGL b(ii) is a zone of transition between AGL b and AGL c; it is characterized by a decline in the frequency of both *Juglans* and *Cannabis* type pollen. The frequency of total arboreal pollen increases to 63·87% in this zone which in particular reflects the high values recorded for *Picea* and *Pinus* pollen; *Picea* increases to 6·93% and *Pinus* exhibits its highest values of the profile in AGL b(ii) (16·49%). The zone is also characterized by the beginning of closed curves, or more or less closed curves, for several tree pollen types such as *Abies*, *Buxus*, *Carpinus*, *Fraxinus* and *Ulmus*, together with increases in the frequency of *Alnus*, *Corylus* and *Fagus* following their low values towards the top of zone AGL b(i). *Platanus* appears for the first time in the zone and *Populus* begins a closed curve.

AGL c 14 to 0cm (67·5 to 0 years BP)

P.a.z. AGL c is characterized by the disappearance of the *Cannabis* type pollen curve and by a decline in the frequency of *Juglans* pollen (mean, 1·97 ± 0·72%) which reaches a minimum of 1·22% at the top of the zone. High frequencies of the Gramineae undiff. pollen also occur in AGL c, reaching a maximum of 31·00% in the middle of the zone. Both *Juniperus* type pollen and *Castanea* pollen have declining values throughout the zone to minimum values of 0·87% and 1·74% respectively at the top of the profile. Similarly, the Cereals type pollen also decline through the zone from a maximum value for the profile of 8·45% to 1·74% at the top of the zone. The total arboreal pollen curve mirrors that of the Gramineae undiff. pollen and reaches a minimum of 47·75% in the middle of the zone. The increase of arboreal pollen towards the top of the profile reflects an increase in the frequency of several tree pollen types, notably *Picea* which reaches a maximum frequency of 14·06% together with the following types which all increase to maxima at the top of the zone: *Alnus* (5·73%), *Betula* (2·78%), *Buxus* (0·52%), *Carpinus* (1·56%), *Fagus* (2·78%), *Fraxinus* (3·47%), *Platanus* (1·22%), *Populus* (1·22%) and *Salix* (3·82%). *Tilia* reappears in this zone.

6.1.4. Pollen preservation

The time available for pollen analysis limited the number of grains counted for each pollen and spore type. So, the records of preservation made during routine counting of samples from APL6 have been summarized into the main pollen and spore categories: trees and shrubs; herbs; pteridophytes; unidentified deteriorated grains.

For presentation in diagrammatic form these amalgamated data have been considered as individual pollen types, and calculated as relative percentages and concentrations in figures A3.5. and A3.6. respectively. For comparison with the full pollen percentage diagram in figure A3.1., the same basic pollen sum has been used for the calculation of the "pollen preservation" frequencies in figure A3.5.

The frequency and concentration of broken conifer pollen grains are also shown.

Figure 6.1. Zonation of pollen diagram from APL6
Dendograms for CONSLINK, SPLITINF and SPLITLSQ numerical zonations of the data and proposed pollen assemblage zones are shown to the right of the diagram. Only divisions that represent 10% or more of the residual variation are considered in the SPLITINF and SPLITLSQ dendogram. (Abbreviation: p.a. zone = pollen assemblage zone).

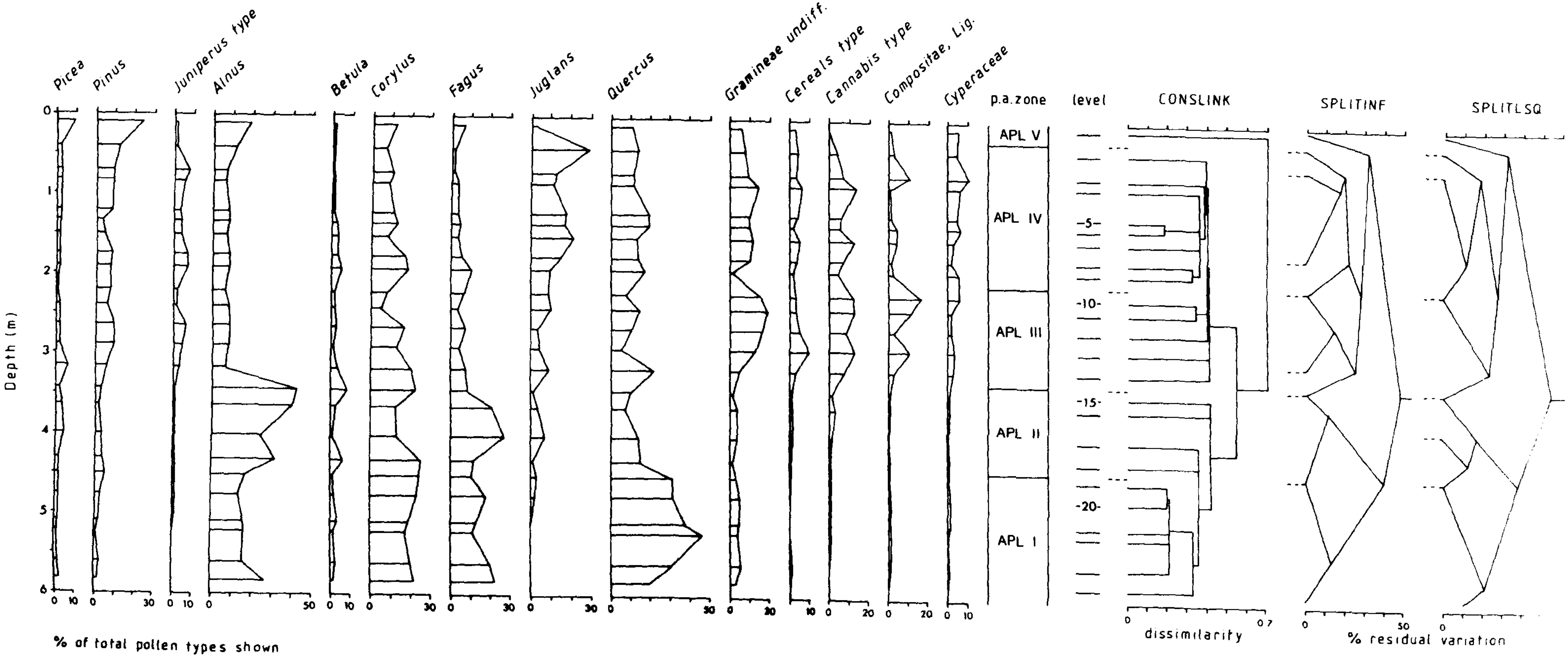

Picea
Pinus
Juniperus type
Alnus
Betula
Corylus
Fagus
Juglans
Quercus
Gramineae undiff.
Cereals type
Cannabis type
Compositae, Lig.
Cyperaceae
p.a.zone
level
CONSLINK
SPLITINF
SPLITLSQ
Depth (m)
APL V
APL IV
APL III
APL II
APL I
% of total pollen types shown
dissimilarity
% residual variation

Figure 6.2. Zonation of pollen diagram from APL1 Dendograms for CONSLINK, SPLITINF and SPLITLSQ numerical zonations of the data and proposed pollen assemblage zones are shown to the right of the diagram. Only divisions that represent 10% or more of the residual variation are considered in the SPLITINF and SPLITLSQ dendogram. (Abbreviation: p.a.zone = pollen assemblage zone).

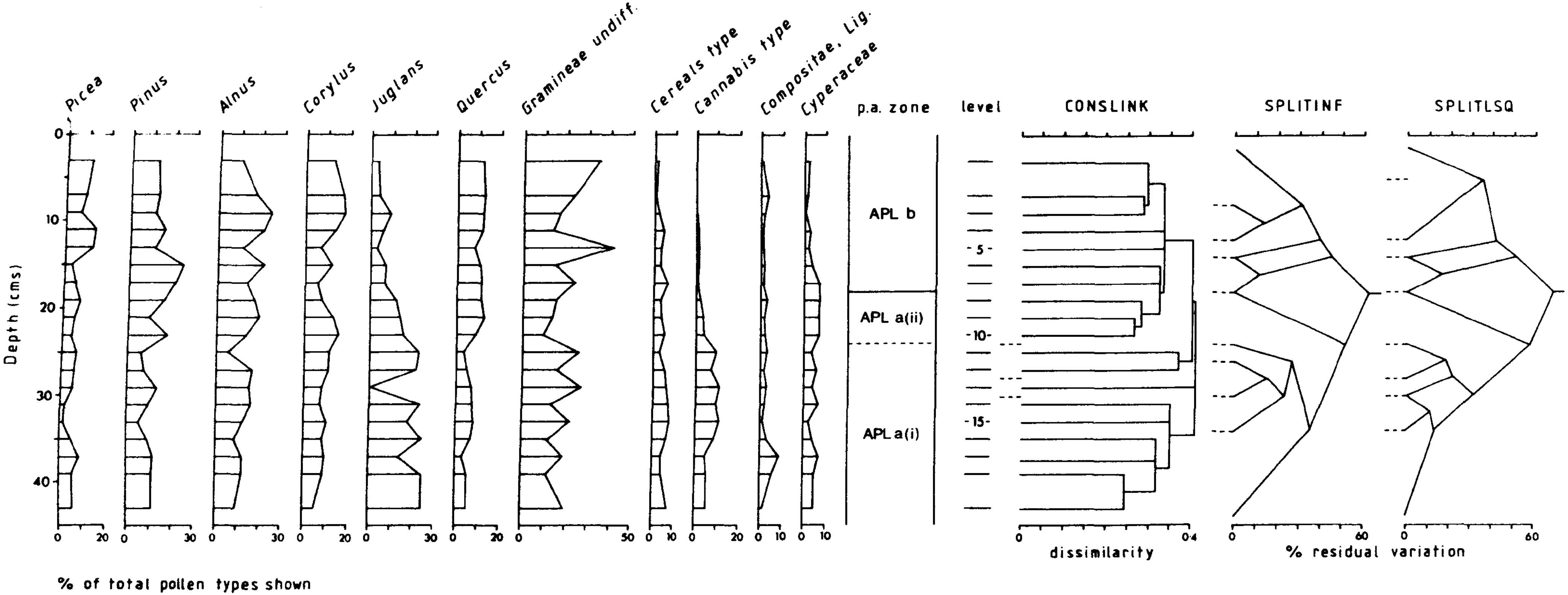
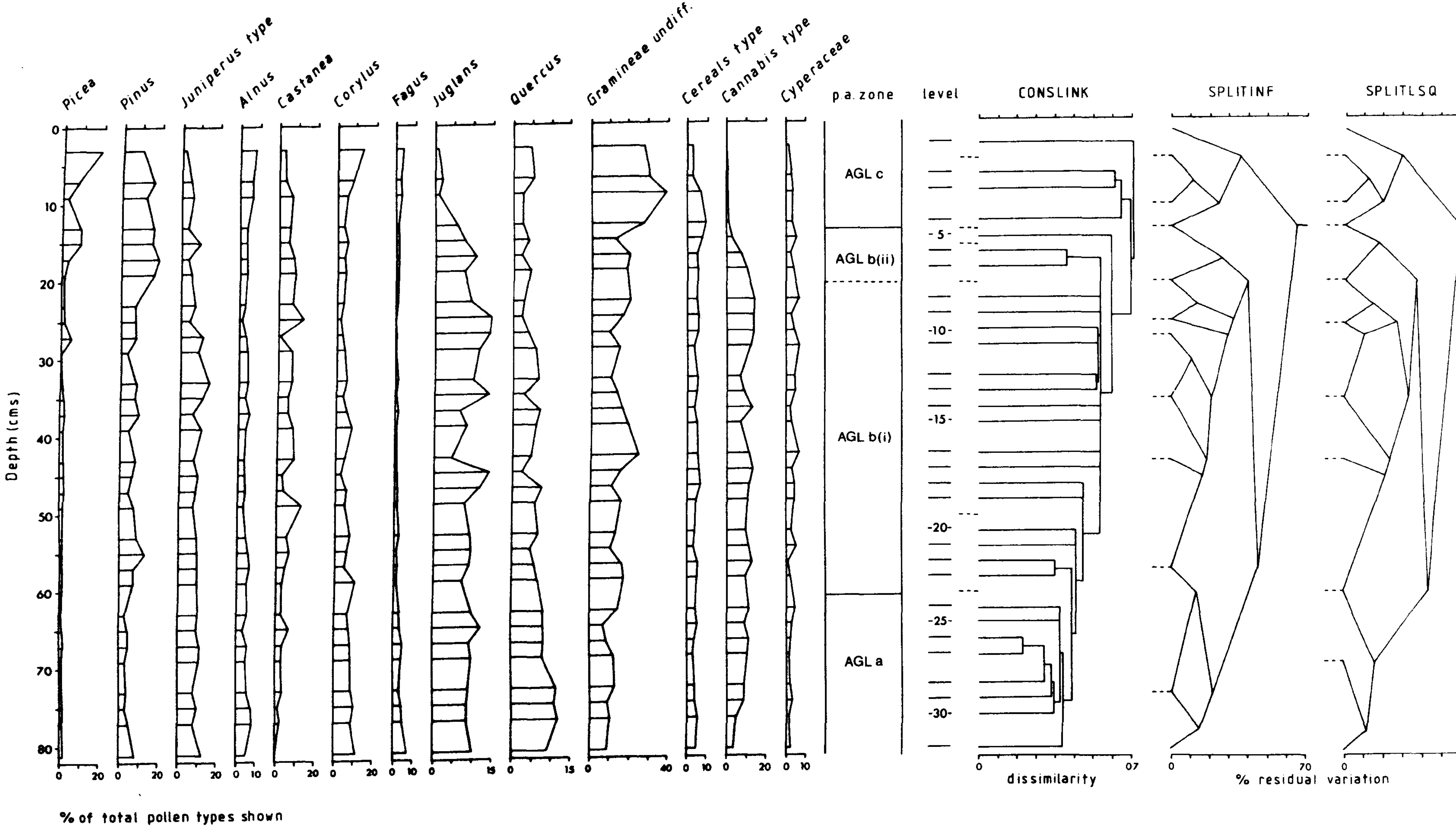

Picea
Pinus
Alnus
Corylus
Juglans
Quercus
Gramineae undiff.
Cereals type
Cannabis type
Compositae, Lig.
Cyperaceae
p.a. zone
level
CONSLINK
SPLITINF
SPLITLSQ
Depth (cms)
APL b
APL a(ii)
APL a(i)
dissimilarity
% residual variation
% of total pollen types shown

Figure 6.3. Zonation of pollen diagram from AGL5 Dendograms for CONSLINK, SPLITINF and SPLITLSQ numerical zonations of the data and proposed pollen assemblage zone are shown to the right of the diagram. Only divisions that represent 10% or more of the residual variation are considered in the SPLITINF and SPLITLSQ dendogram. (Abbreviation: p.a. zone = pollen assemblage zone).


Picea
Pinus
Juniperus type
Alnus
Castanea
Corylus
Fagus
Juglans
Quercus
Gramineae undiff.
Cereals type
Cannabis type
Cyperaceae
p.a. zone
level
CONSLINK
SPLITINF
SPLITLSQ
Depth (cms)
AGL c
AGL b(ii)
AGL b(i)
AGL a
dissimilarity
% residual variation
% of total pollen types shown

6.2. Geochemical analyses

The results of the geochemical analyses are shown in figures 6.4., 6.5. and 6.6. for APL6, APL1 and AGL5 respectively.

6.2.1. APL6

Relatively high values for the $CaCO_3$ content occur in p.a.z. APL I and II (mean, 47·38 ± 2.77%) and APL V (49·10%). Elsewhere $CaCO_3$ values are low. Two marked minima can be seen in p.a.z. APL III, at 287cm (31·11% $CaCO_3$) and at 219cm (30·99% $CaCO_3$), while $CaCO_3$ values are generally higher in p.a.z. APL IV (mean, 40.80 ± 2·57%).

The $CaCO_3$ profile is mirrored by the non-carbonate ignition residue curve. In p.a.z. APL I and II relatively low values for the non-carbonate ignition residue occur (mean, 48·57 ± 2·85%). A similar value (47·13%) is observed in p.a.z. APL V. In p.a.z. APL III two maxima occur, at 287 and 219cm (65·12 and 64·70% respectively). In p.a.z. APL IV non-carbonate ignition residue values are slightly lower than those observed in APL III (mean, 55·71 ± 2·47%).

Loss-on-ignition values fluctuate markedly between c. 3 and 5·5% and no general trends are very obvious, although from the upper part of p.a.z. APL III the sequence of maxima and minima for this curve follow those in the non-carbonate ignition residue profile.

The concentration of all elements is relatively low in p.a.z. APL I and II (K mean, 5·92 ± 0·36 mg g^{-1}; Na mean, 2·37 ± 0·25 mg g^{-1}; Fe mean, 10·27 ± 0·27 mg g^{-1}; Mg mean, 1·04 ± 0·20 mg g^{-1}). Through p.a.z. APL III all elemental concentrations increase; K to a maximum value of 10·58 mg g^{-1}, Na to 3·65 mg g^{-1} at the beginning of p.a.z. APL IV, Fe to 12·25 mg g^{-1} at the beginning of p.a.z. APL IV and Mg to 2·27 mg g^{-1}. In p.a.z. APL IV and APL V the concentration of all four elements is relatively high (K mean, 8·53 ± 0·61 mg g^{-1}; Na mean, 3·63 ± 0·15 mg g^{-1}; Fe mean, 11·52 ± 0·34 mg g^{-1}; Mg mean, 1·97 ± 0·12 mg g^{-1}), although concentrations of K, Fe and Mg tend to decline towards the top of the core.

6.2.2. APL1

$CaCO_3$ content values generally range between c. 40 and 50%, although between 36 and 40cm very low values have been measured (mean, 24·22%). From 36cm upwards, the $CaCO_3$ content increases up to a maximum value of 49·33%. Conversely, the non-carbonate ignition residue values vary for the most part between c. 45 and 60%, although between 36 and 40cm very high values occur (mean, 69·67%). Above 36cm this component decreases steadily to a minimum value of 46·51%.

Relatively high values for the loss-on-ignition occur between 36 and 40cm (mean, 6·12%). Above this feature, loss-on-ignition values are lower but generally increase from c. 3·5 to over 4·5%.

Relatively high concentrations of K occur between 36 and 40cm (mean, 9·05 mg g^{-1}), above which values are considerably lower and generally decrease from 6·98 to only 4·39 mg g^{-1} at the top of the core. Relatively low values of Na occur at the base of the core (mean, 2·42 ± 0·34 mg g^{-1} below 34cm) and at the top of the core (1·84 mg g^{-1}), in between which values fluctuate about a mean concentration of 4·23 ± 0·75 mg g^{-1}. Concentrations of Fe fluctuate markedly throughout the profile between 6·89 and 10·61 mg g^{-1}.

6.2.3. AGL5

Up to 25cm the $CaCO_3$ content fluctuates about a mean value of 54·35 ± 1·99%, above which a marked increase in this component can be seen extending through p.a.z. AGL b(ii) and AGL c and reaching a maximum value of 73·20% at the top of the profile. Conversely, up to

25cm the non-carbonate ignition residue varies about a mean of 42·28 ± 2·00%. From 25cm the non-carbonate ignition residue content decreases through p.a.z. AGL b(ii) and AGL c to a minimum value of 22·77%.

The loss-on-ignition content varies little in p.a.z. AGL a and AGL b(i) (mean, 3·37 ± 0·20%), but decreases through zone AGL b(ii) to 2·43% at the base of AGL c and increases to a maximum of 4·03% at the top of the core.

Concentrations of K and Na are both relatively high in p.a.z. AGL a (K mean, 6·23 ± 0·37 mg g^{-1}; Na mean, 2·24 ± 0·12 mg g^{-1}). The concentration of K declines through the rest of the profile, from c. 6 mg g^{-1} to only 2·86 mg g^{-1} at the top of the core. Likewise, the concentration of Na decreases from 2·34 to 1·38 mg g^{-1} in p.a.z. AGL b(i), but in p.a.z. AGL b(ii) and AGL c values are generally higher, reaching a maximum of 2·44 mg g^{-1} near the top of the core. Fe concentrations fluctuate around a mean of 8·26 ± 0·48 mg g^{-1} throughout p.a.z. AGL a, b(i) and b(ii), while in zone AGL c values are generally lower (mean, 7·79 ± 0·57 mg g^{-1}).

Figure 6.4. Geochemical measurements from APL6
The pollen assemblage zones described in § 6.1.1. are indicated on the diagram.

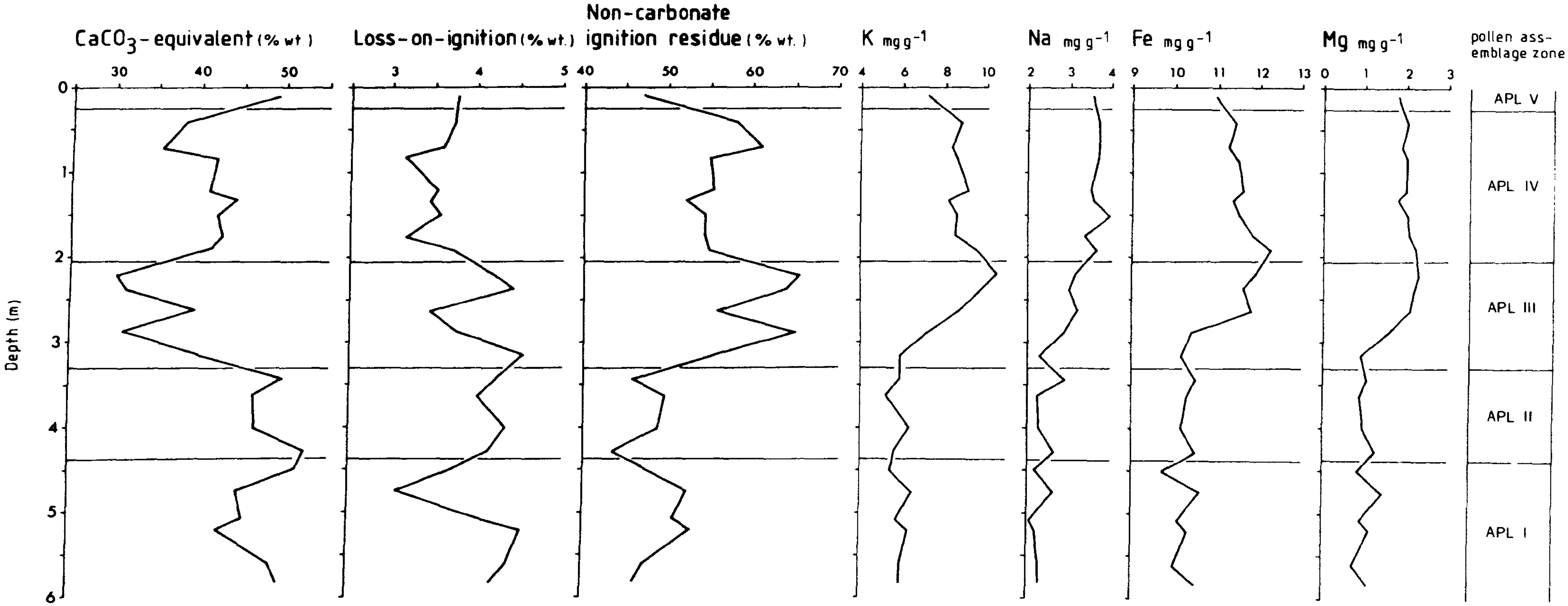

CaCO3-equivalent (% wt.)
Loss-on-ignition (% wt.)
Non-carbonate ignition residue (% wt.)
K mg g-1
Na mg g-1
Fe mg g-1
Mg mg g-1
pollen assemblage zone
Depth (m)
APL V
APL IV
APL III
APL II
APL I

Figure 6.5. Geochemical measurements from APL1
The pollen assemblage zones described in § 6.1.2. are indicated on the diagram.

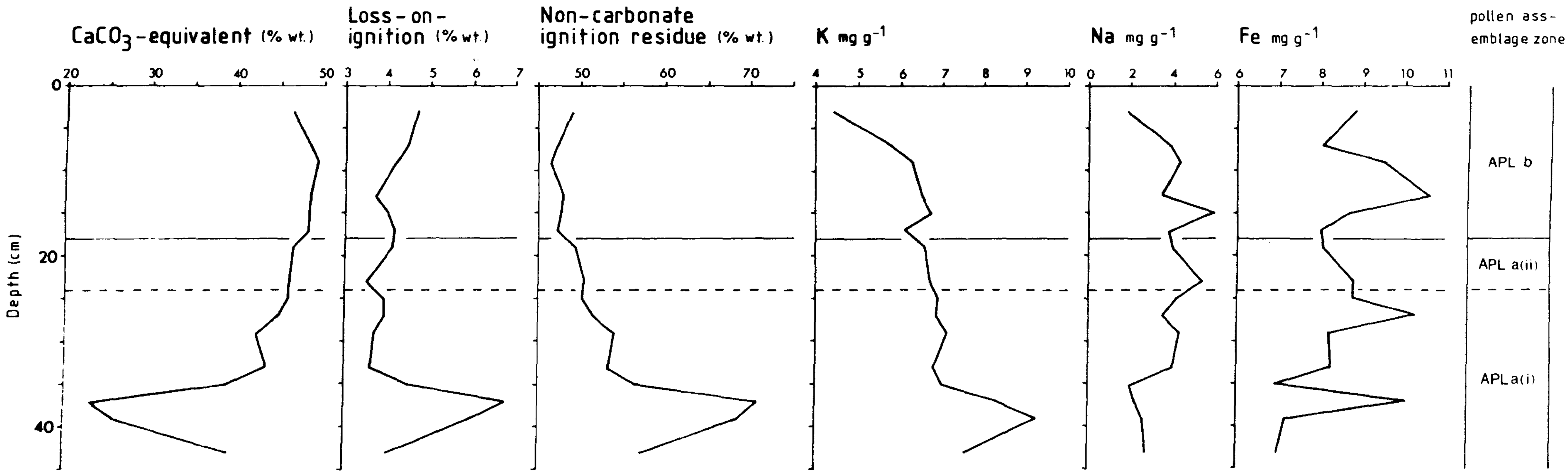
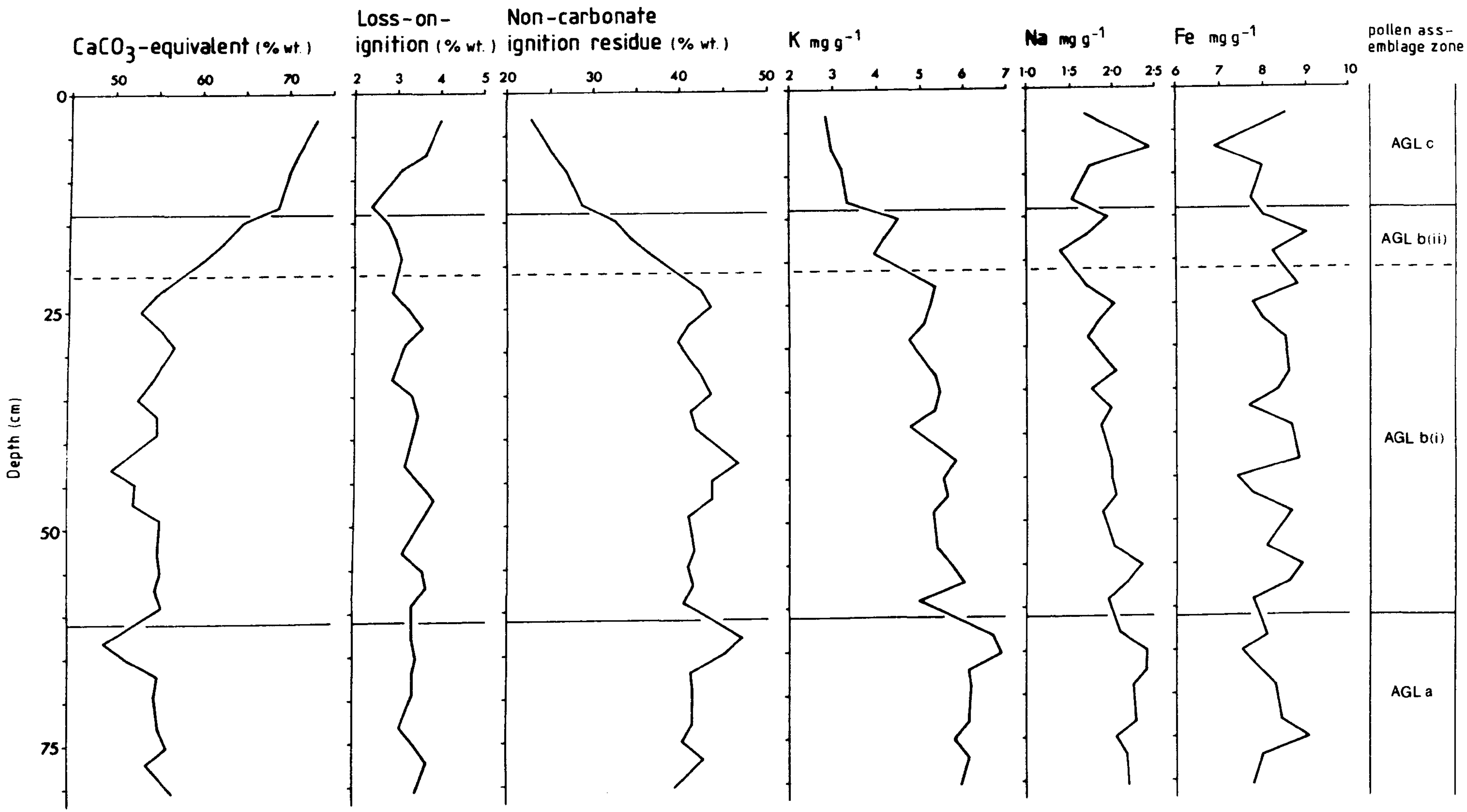

CaCO3-equivalent (% wt.)
Loss-on-ignition (% wt.)
Non-carbonate ignition residue (% wt.)
K mg g-1
Na mg g-1
Fe mg g-1
pollen assemblage zone
Depth (cm)
APL b
APL a(ii)
APL a(i)

Figure 6.6. Geochemical measurements from AGL5
The pollen assemblage zones described in § 6.1.3. are indicated on the diagram.



CaCO3-equivalent (% wt.)
50 60 70
Loss-on-ignition (% wt.)
2 3 4 5
Non-carbonate ignition residue (% wt.)
20 30 40 50
K mg g-1
2 3 4 5 6 7
Na mg g-1
1·0 1·5 2·0 2·5
Fe mg g-1
6 7 8 9 10
pollen assemblage zone
Depth (cm)
0
25
50
75
AGL c
AGL b(ii)
AGL b(i)
AGL a

6.3. Mineral magnetic analyses

6.3.1. APL6

Figure 6.7. shows the single sample χ, SIRM and SIRM/χ logs for APL6.

The main trends of the χ profile can be described as follows:

(i) base of core (584cm) to 435cm - relatively low χ values, with a mean of $3{\cdot}59 \pm 0{\cdot}62 \times 10^{-6}Gcm^3Oe^{-1}g^{-1}$.

(ii) 435 to 358cm - higher χ values, with a mean of $4{\cdot}73 \pm 0{\cdot}91 \times 10^{-6}Gcm^3Oe^{-1}g^{-1}$.

(iii) 358 to 218cm - χ values increase more than threefold, from $2{\cdot}91$ to $10{\cdot}49 \times 10^{-6}Gcm^3Oe^{-1}g^{-1}$.

(iv) 218 to top of core (8cm) - relatively high χ values fluctuating about a mean of $7{\cdot}61 \pm 1{\cdot}20 \times 10^{-6}Gcm^3Oe^{-1}g^{-1}$.

Three main zones can be identified in the SIRM profile:

(i) base of core (584cm) to 423cm - SIRM values generally increase, from around 320 to $1495{\cdot}82 \times 10^{-6}Gcm^3g^{-1}$.

(ii) 423 to 286cm - SIRM values generally decrease to a minimum value of $253{\cdot}44 \times 10^{-6}Gcm^3g^{-1}$.

(iii) 286 to top of core (8cm) - relatively low SIRM values fluctuating around a mean of $487{\cdot}18 \pm 140{\cdot}92 \times 10^{-6}Gcm^3g^{-1}$.

The SIRM/χ profile is very similar to the SIRM trace and likewise three main zones can be distinguished:

(i) base of core (584cm) to 417·2cm - values for the SIRM/χ ratio increase from c. 80 to 262.

(ii) 417·2 to 286cm - values for this ratio decrease, reaching a minimum of 42·17 at the top of the zone.

(iii) 286cm to top of core (8cm) - relatively low SIRM/χ values fluctuating about a mean of 67·79 ± 20·52.

It is apparent that general trends in the χ and SIRM profiles do not parallel one another, indicating that there are significant variations in the proportion of superparamagnetic and/or paramagnetic iron oxide crystals, and/or the relative proportions of ferrimagnetic and canted antiferromagnetic minerals within the total magnetic mineral assemblage. Although high SIRM/χ ratios may be indicative of a significant canted antiferromagnetic component, the maximum values observed in APL6 (262·32[1] at 440·6cm) are much lower than would be expected if this were indeed the case. It is possible that relatively high SIRM/χ values reflect the domination of remanent magnetic properties by stable single domain ferrimagnetic crystals while relatively low SIRM/χ values result from a significant proportion of superparamagnetic crystals and/or grains exhibiting significant viscosity, ie. those at the superparamagnetic - stable single domain boundary and/or coarse multidomain grains. If variations in the SIRM/χ ratio are simply the result of such grain size changes within a predominantly ferrimagnetic mineral assemblage then the χ profile will provide a record of the volume concentration of magnetic minerals throughout APL6.

Relatively low values of χ between the base of the core (584cm) and c. 350cm are associated with increasing values for the SIRM/χ ratio possibly indicating a low concentration of ferrimagnetic grains increasingly dominated by crystals in the stable single domain size range. Between c. 350cm and 218cm increasing χ values are associated with decreasing SIRM/χ values indicating that as the volume concentration of ferrimagnetic grains increases the proportion of crystals unable to hold a stable remanence increases. Above 218cm,

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[1] equivalent to 20·88 kAm^{-1} in S.I. units.

relatively high values of χ are associated with low SIRM/χ values, indicating that higher volume concentrations of ferrimagnetic material are associated with significantly high proportions of superparamagnetic and/or viscous crystals (either fine single domain or coarse multidomain grains). However, it is also possible that a low SIRM/χ ratio may be due to very high concentrations of paramagnetic minerals. Furthermore, it can be envisaged that both grain size shifts in the ferrimagnetic mineral assemblage and fluctuating contributions of paramagnetic material may be superimposed on one another.

Below 286cm, SIRM/χ values fluctuate quite markedly about the general trend of increasing and then decreasing values with relatively low values observed for the darker coloured sediments, particularly the very dark muds. Above 286cm, below average values for this parameter are often associated with the darker material. For the whole sedimentary profile mean values for the SIRM/χ ratio of the different coloured sediments are as follows: light sediments, 103·15 ± 51·92; dark sediments, 112·22 ± 55·49; very dark sediments, 70·89 ± 37·19; light and dark laminated sequences, 132·52 ± 13·07. So, very dark samples or sequences of mud are associated with relatively high proportions of ultra-fine superparamagnetic crystals and/or high concentrations of paramagnetic material while the lighter coloured sediments are associated with higher proportions of ferrimagnetic crystals above superparamagnetic size, or with insignificant concentrations of paramagnetic minerals.

Further measurements of 24 re-prepared single samples (indicated on figure 6.7.) have permitted these general trends in the mineral magnetic characteristics of APL6 to be described in more detail; these are shown in figure 6.8. Parameters involving measures of IRM and their associated demagnetization properties are particularly useful in that they only reflect those mineral types and crystal sizes able to retain a remanent magnetization, thus avoiding the ambiguity of interpreting parameters involving χ measures which in addition reflect superparamagnetic and paramagnetic behaviour.

The highest field initially available for imparting a forward remanent magnetization was only 3000 Oe, and so all IRM parameters presented in figure 6.8. involve an IRM initially grown at 3000 Oe (cf. the "saturating" field of 8500 Oe used for the SIRM measurements in figure 6.7.). However, it was later possible to magnetize the samples in a "saturating" field of c. 8500 Oe, using the same magnetometer apparatus to measure the IRM_{8500}. Measures of IRM_{3000} and IRM_{8500} were found to be more or less identical, indicating the absence of magnetic grains with an intrinsic coercivity between 3000 and 8500 Oe which might be expected if a significant canted antiferromagnetic component was present. This supports the contention made above, that changes in the SIRM/χ ratio do not involve a shift in the relative proportions of ferrimagnetic and canted antiferromagnetic components.

In p.a.z. APL I a slight decrease in the % loss IRM_{3000} (1·37 to 0·68%) and general increases in both the IRM_{3000}/χ ratio (119·55 to 213·37[1]) and ARM/χ ratio (10·57 to 16·86) indicate an increase in the relative proportion of stable single domain grains. A general increase in the IRM_{3000}/ARM ratio suggests this may be associated with the growth of a multidomain component. S-values show little variation throughout the zone and $(B_0)_{CR}$ values are consistently high (470 - 480 Oe) indicating there is little significant variation in the

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[1] equivalent to 9·51 to 16·98 kAm^{-1} in S.I. units.

proportion of viscous crystals. This suggests two things: (i) that changes in the IRM_{3000}/χ and ARM/χ ratios are mainly due to changing proportions of superparamagnetic crystals and/or paramagnetic material and (ii) that the growing multidomain component, if present, must either consist of relatively small multidomain crystals, as these are relatively stable, or it must be fairly insignificant in volume if composed of coarse multidomain grains, as these are highly viscous. All these trends could be accommodated by a general shift in the modal grain size range, from the finer end of the grain size spectrum at the beginning of APL I with relatively more superparamagnetic and finer single domain grains, to span relatively coarser grain sizes towards the top of the zone, with magnetic mineral assemblages increasingly dominated by stable single domain grains, alongside a subsidiary multidomain component. Due to the low χ values in this part of the core, measurements of χ_{fd} are not thought to be reliable and so it is not possible to discriminate any general trend in the proportion of those highly viscous grains at the superparamagnetic - stable single domain boundary.

Throughout p.a.z. APL II a general increase in values for the % loss IRM_{3000} (0·68 to 1·02%) is associated with decreasing IRM_{3000}/χ ratios (213·37 to 156·10) and ARM/χ ratios (16·86 to 13·34), suggesting a fall in the proportion of stable single domain grains with a relative increase in the concentration of grains exhibiting significant viscosity. As in p.a.z. APL I there is little significant variation in the S-values, and the $(B_0)_{CR}$ values remain high (470 - 480 Oe), indicating that decreases in the IRM_{3000}/χ and ARM/χ ratios are due to an increase in the proportion of superparamagnetic crystals or an increase in the contribution of paramagnetic material. The IRM_{3000}/ARM ratio generally decreases (13·91 to 11·70) possibly indicating a relative increase in the proportion of stable single domain grains within the grain size range above the superparamagnetic threshold. Thus, all parameters would seem to indicate a shift back to finer grain sizes throughout p.a.z. APL II. A sequence of relatively high values for χ_{fd} in the middle of APL II (mean, 3·49%) is paralleled by slightly higher values for the % loss IRM_{3000} (mean, 1·05%) suggesting that the viscous behaviour recorded in the latter parameter is at least in part a reflection of ultra-fine viscous crystals at the superparamagnetic - stable single domain boundary.

Throughout p.a.z. APL III, IV and V the S-values fluctuate markedly, as do the $(B_0)_{CR}$ values, indicating significant variations in the modal grain size of crystals above the superparamagnetic threshold. Similar patterns can be identified in both the concentration-dependent and concentration-independent parameters. Relatively high values for total χ coincide for the most part with relatively "soft" magnetic behaviour as indicated by low S-values, low $(B_0)_{CR}$ values and high values for % loss IRM_{3000} and % χ_{fd}. In addition, the IRM_{3000}/χ and ARM/χ ratios are low in these sediments. Conversely, low total χ values generally coincide with "harder" magnetic behaviour as indicated by high S-values, high $(B_0)_{CR}$ values and low values for % loss IRM_{3000} and ARM/χ ratios. Here, the IRM_{3000}/χ and ARM/χ ratios are relatively high. These data indicate that high volume concentrations of ferrimagnetic minerals are associated with high proportions of highly viscous material, possibly accompanied by an increase in the relative proportion of superparamagnetic crystals and/or paramagnetic material. Where volume concentrations of magnetic material are relatively low, the mineral magnetic assemblages contain relatively more stable single domain grains. These trends would be consistent with shifts to finer grain size ranges alongside larger concentrations of magnetic material, and shifts away from the finer grain sizes when the volume of magnetic minerals is lower.

For various reasons it seems probable that, at least in p.a.z. APL II - V, the relatively low IRM_{3000}/χ and ARM/χ ratios reflect increased proportions of superparamagnetic crystals of ferrimagnetic minerals rather than high concentrations of paramagnetic material: (i) the grain size range over which the superparamagnetic - stable single domain transition occurs is very narrow (table 4.3); therefore it seems very likely that high proportions of viscous crystals are associated with high proportions of superparamagnetic crystals; (ii) if very high concentrations of paramagnetic material were the cause of these low ratios, then disproportionately low χ_{fd} values might be expected, and these are not observed; (iii) variations in the remanent magnetization and demagnetization measurements correspond with variations in these ratios, which would not necessarily be observed if the ratio changes were solely due to varying concentrations of paramagnetic minerals. Thus in p.a.z. APL II - V it seems that total χ is indeed a useful index of the volume of ferrimagnetic minerals in the sediment samples.

Although the "soft" magnetic behaviour in p.a.z. APL III, IV and V can be explained in part at least by those viscous crystals at the superparamagnetic - stable single domain boundary, the IRM_{3000}/ARM ratio increases at the same time, suggesting the concurrent growth of a multidomain component. This observation is inconsistent with the grain size shifts proposed above, and suggests there might be a bimodal grain size assemblage associated with high concentrations of magnetic minerals. Further measurements are in progress to investigate these seemingly incompatible data.

6.3.2. APL1

The results of the mineral magnetic analyses are shown in figure 6.9.

In the lower part of p.a.z. APL a a distinctive magnetic feature extends between 36 and 40cm. χ values are very high (mean, 13·24 $\times 10^{-6}Gcm^3Oe^{-1}g^{-1}$) and are associated with low S-values and very low $(B_0)_{CR}$ values (mean, 300 Oe) which indicate relatively "soft" magnetic behaviour. Relatively high % χ_{fd} values (mean, 5·88%) indicate that this "soft" magnetic behaviour may be at least partially the result of an increase in the proportion of viscous crystals at the superparamagnetic - stable single domain boundary. Consequently, the specific χ_{fd} values also peak here (mean, 75·67 $\times 10^{-8}Gcm^3Oe^{-1}g^{-1}$). Maxima in the IRM_{3000} and ARM profiles are not so marked; therefore the IRM_{3000}/χ and ARM/χ ratios are relatively low (means, 64·70 and 4·18 respectively), although they are not significantly lower than the ratios observed above and below. Therefore it seems that this magnetic feature is characterized by high concentrations of magnetic minerals and relatively high proportions of viscous crystals.

From 36cm, χ values decrease throughout p.a.z. APL a(i) and (ii), reaching a maximum value of 7·01 $\times 10^{-6}Gcm^3Oe^{-1}g^{-1}$ at the beginning of APL b. This trend is accompanied by a general increase in S-values, an increase in the $(B_0)_{CR}$ values to 500 Oe and a general decrease in the % χ_{fd} to only 1·86%. Thus, throughout p.a.z. APL a the trend is one of a decreasing volume of magnetic material associated with increasing proportions of crystals able to hold a stable remanence ie. stable single domain and fine multidomain grains. Both the IRM_{3000}/χ and ARM/χ ratios generally increase to values of 123·13[1] and 11·31

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[1] equivalent to 9·80 kAm^{-1} in S.I. units.

respectively at the beginning of p.a.z. APL b. The magnitude of the IRM_{3000}/χ ratio suggests that the magnetic mineral assemblage is dominated by ferrimagnetic iron compounds, although the presence of a canted antiferromagnetic component cannot be dismissed as these samples have not been remeasured after magnetization in a "saturating" field of 8500 Oe. The correspondence of the trend observed in both ratios with the trends described above for the remanent magnetic properties and χ_{fd} measurements suggest that these also reflect an increase in the proportion of stable single domain and fine multidomain crystals rather than a diminishing paramagnetic contribution.

Throughout p.a.z. APL b the trend in most parameters reverses. The χ increases to a maximum value of $9{\cdot}74 \times 10^{-6}Gcm^3Oe^{-1}g^{-1}$ at the top of the profile. This is accompanied by decreasing S-values, a decrease in $(B_0)_{CR}$ values to 400 Oe and a general increase in the % χ_{fd} which reaches a maximum value of 4·55% at the top of the core. These data indicate an increase in the concentration of magnetic minerals associated with increasingly "soft" magnetic behaviour, part of which at least may be due to those fine viscous grains at the superparamagnetic - stable single domain boundary. However, both the IRM_{3000}/χ and ARM/χ ratios continue to increase throughout p.a.z. APL b, to maximum values of 159·42[1] and 15·14 respectively. The increase in these ratios reflects marked increases in the IRM_{3000} and ARM concentrations in zone APL b which reach maximum values of 1552·29 and $147{\cdot}46 \times 10^{-6}Gcm^3g^{-1}$ respectively at the top of the profile. These indicate a significant increase in the concentration of ferrimagnetic crystals above the superparamagnetic threshold.

As in the upper zones of APL6 it is difficult to reconcile the

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[1] equivalent to $12{\cdot}69\ kAm^{-1}$ in S.I. units.

trends in the IRM_{3000}/ARM ratio with the interpretation of the other magnetic parameters described above.

6.3.3. AGL5

The results of the mineral magnetic analyses are shown in figure 6.10.

In p.a.z. AGL a and b(i) there is a very general parallelism between the χ and $(B_0)_{CR}$ profiles; in AGL a relatively high values for χ (mean, $9{\cdot}19 \pm 0{\cdot}19 \times 10^{-6}Gcm^3Oe^{-1}g^{-1}$) coincide with relatively low $(B_0)_{CR}$ values (mean, $435{\cdot}00 \pm 8{\cdot}66$ Oe), while in AGL b(i) slightly lower values for χ (mean, $9{\cdot}74 \pm 0{\cdot}83 \times 10^{-6}Gcm^3Oe^{-1}g^{-1}$) are associated with slightly higher values for $(B_0)_{CR}$ (mean, $465{\cdot}63 \pm 14{\cdot}56$ Oe). This suggests that higher volume concentrations of magnetic minerals in AGL a are associated with "softer" magnetic behaviour, and vice versa in AGL b(i). The χ profile is characterized by two maxima in AGL b(i), the first at 47cm ($10{\cdot}35 \times 10^{-6}Gcm^3Oe^{-1}g^{-1}$) and the second at 25cm ($11{\cdot}68 \times 10^{-6}Gcm^3Oe^{-1}g^{-1}$); however, only the upper χ peak is clearly associated with lower $(B_0)_{CR}$ values (430 Oe). Mean values for % χ_{fd} show no close correspondence with these general trends except in the upper part of p.a.z. AGL b(i) where increasing values coincide with increasing χ values and decreasing $(B_0)_{CR}$ values suggesting that the "softer" magnetic behaviour is at least in part due to the presence of fine viscous crystals at the superparamagnetic - stable single domain boundary. Very generally, the IRM_{3000}/χ and ARM/χ values mirror the χ profile in terms of the sequence of maxima and minima. However, there is no close correspondence with the $(B_0)_{CR}$ profile except at the χ peak at 25cm where relatively low values for these ratios (IRM_{3000}/χ of 93·66; ARM/χ of 6·69) coincide with the "softer" magnetic behaviour described above for $(B_0)_{CR}$ and % χ_{fd}, suggesting that an associated superparamagnetic component might also be present. However, in general, higher values for these ratios are observed in zone AGL a (IRM_{3000}/χ mean, 131·55 ± 8·93; ARM/χ mean, 9·74 ± 1·16) and values generally decrease through zone AGL b(i) (IRM_{3000}/χ mean, 112·97 ± 12·17; ARM/χ mean, 8·24 ± 1·29). This indicates that relatively high values for these ratios coincide with "softer" remanent magnetic properties and vice versa. The opposite relationship would be expected if lower $(B_0)_{CR}$ values were predominantly due to the presence of fine viscous grains, which in turn might be expected to be associated with a larger superparamagnetic component. However, this is not the case, and the observed trends suggest that a paramagnetic component may well be significant here. Clearly the mineral magnetic assemblage is fairly complex in this part of AGL5.

From the top of p.a.z. AGL b(i) there are significant changes in the mineral magnetic assemblage. The χ generally declines through p.a.z. AGL b(ii) to a minimum value of $7{\cdot}82 \times 10^{-6}Gcm^3Oe^{-1}g^{-1}$ at the base of AGL c, and increases through p.a.z. AGL c to a maximum value of $9{\cdot}71 \times 10^{-6}Gcm^3Oe^{-1}g^{-1}$ at the top of the profile. The $(B_0)_{CR}$ decreases to 400 Oe and the S-ratio to -0·88, both indicating an increasingly "soft" mineral magnetic assemblage in AGL c. However, a general decline in the % χ_{fd}, to 2 - 2·5%, suggests that the "softer" behaviour is not due to the presence of fine viscous grains at the superparamagnetic - stable single domain boundary. The IRM_{3000} increases through p.a.z. AGL b(ii) and AGL c from 912·06 to a maximum of $1758{\cdot}14 \times 10^{-6}Gcm^3g^{-1}$ at the top of the core. The ARM remains more or less constant throughout p.a.z. AGL b(ii) but increases markedly through p.a.z. AGL c from c. 80 to a maximum value of 152·71 $\times 10^{-6}Gcm^3g^{-1}$. Consequently, the IRM_{3000}/χ and ARM/χ ratios both exhibit significant increases from the top of AGL b(ii) to the top of the core; the IRM_{3000}/χ ratio from c. 100 to 180·98[1] and the ARM/χ ratio from c. 75 to 15·72. The increase in these ratios is thought to indicate an increase, in the top 20cm of the core, in the proportion of ferrimagnetic grains able to hold a stable remanence, although again the influence of a high concentration of canted antiferromagnetic minerals cannot be discounted as the IRM_{3000} values have not been compared with IRM_{8500} values.

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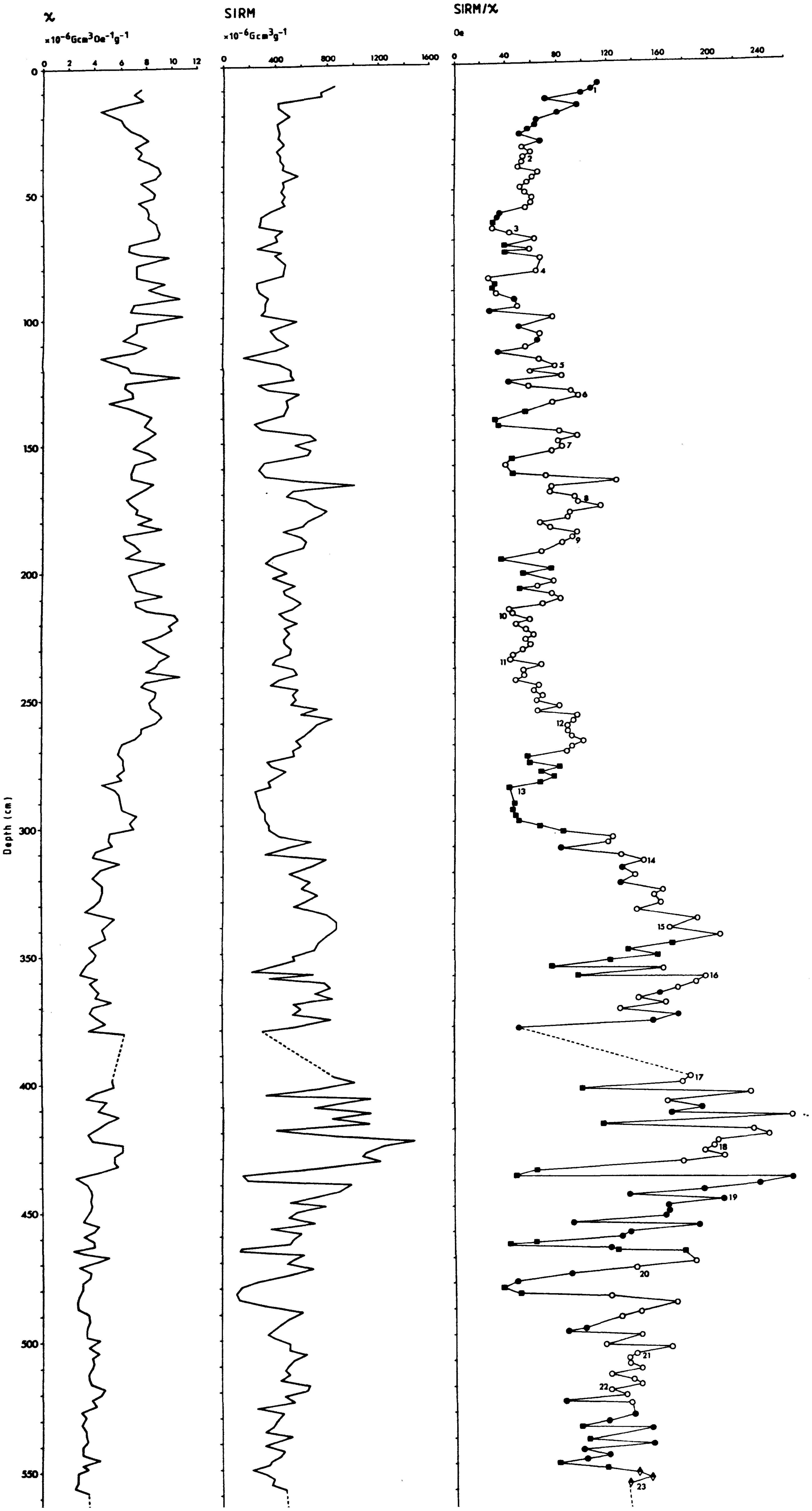
[1] equivalent to 14·41 kAm^{-1} in S.I. units.

Figure 6.7. Single sample χ†, SIRM and SIRM/χ† profiles from APL6
A simplified version of the colour stratigraphy described in Appendix 2 is indicated in the SIRM/χ log. (Key: ○ light coloured sediments, colour codes 2·5Y 8/2, 2·5Y 8/4, 10YR 5/3, 10YR 5/4, 2·5Y 5/4; ● dark coloured sediments, colour codes 10YR 4/3, 2·5Y 4/2, 10YR 4/2, 2·5Y 4/4, 10YR 4/4; ■ very dark coloured sediments, colour codes 10YR 3/3, 2·5Y 3/2, 10YR 3/2, 10YR 3/1; ◆ light and dark laminations, colour codes 2·5Y 8/2 and 2·5Y 4/2.)
Numbers refer to the single samples selected for detailed pollen, geochemical and mineral magnetic analyses.
† 1980 measurements



χ
×10⁻⁶Gcm³Oe⁻¹g⁻¹
SIRM
×10⁻⁶Gcm³g⁻¹
SIRM/χ
Oe
Depth (cm)

Figure 6.8. Mineral magnetic measurements from APL6
The pollen assemblage zones described in
§ 6.1.1. are indicated on the diagram.

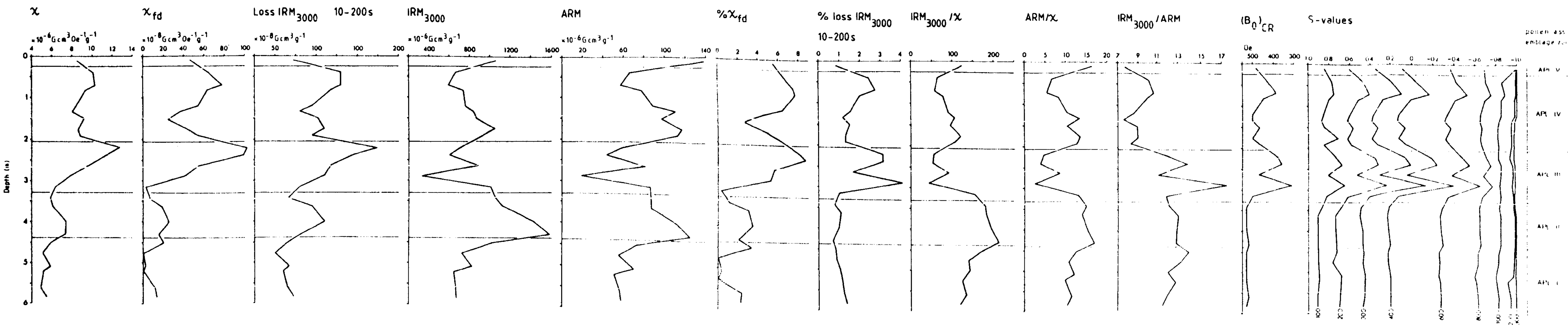
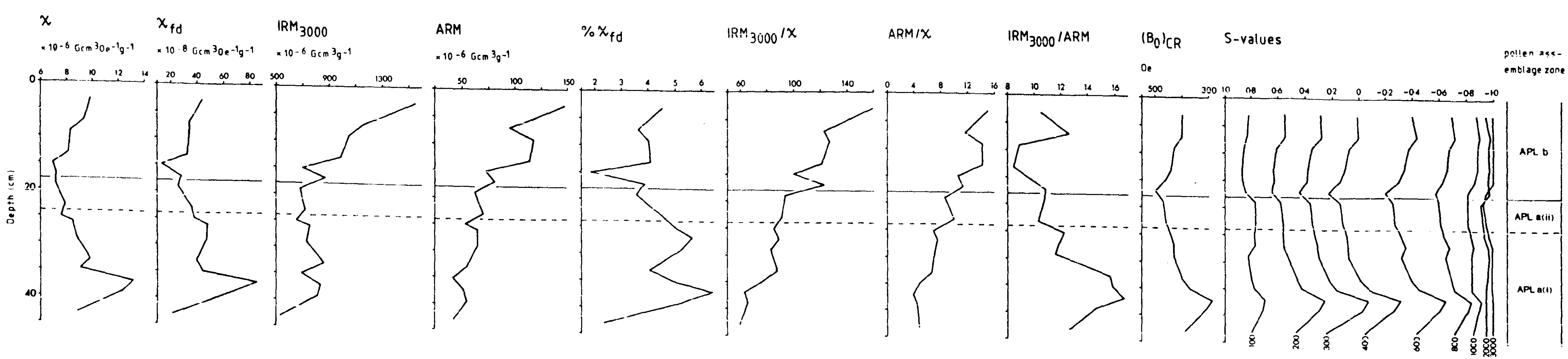
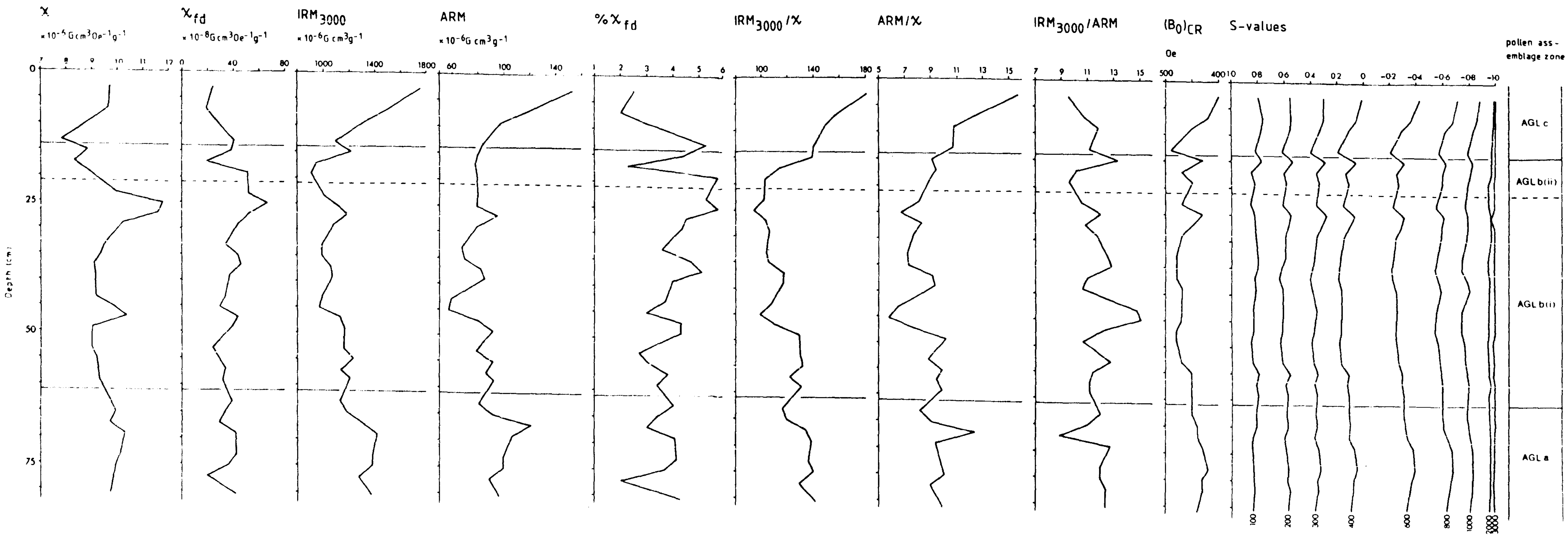

χ
$\times 10^{-6}$ G cm³ Oe⁻¹ g⁻¹
χfd
$\times 10^{-8}$ G cm³ Oe⁻¹ g⁻¹
Loss IRM3000 10-200s
$\times 10^{-8}$ G cm³ g⁻¹
IRM3000
$\times 10^{-6}$ G cm³ g⁻¹
ARM
$\times 10^{-6}$ G cm³ g⁻¹
%χfd
% loss IRM3000
10-200s
IRM3000/χ
ARM/χ
IRM3000/ARM
(B0)CR
Oe
S-values
pollen assemblage zone
Depth (m)
APL V
APL IV
APL III
APL II
APL I

Figure 6.9. Mineral magnetic measurements from APL1
The pollen assemblage zones described in
§ 6.1.2. are indicated on the diagram.



χ
× 10⁻⁶ Gcm³Oe⁻¹g⁻¹
χfd
× 10⁻⁸ Gcm³Oe⁻¹g⁻¹
IRM3000
× 10⁻⁶ Gcm³g⁻¹
ARM
× 10⁻⁶ Gcm³g⁻¹
%χfd
IRM3000/χ
ARM/χ
IRM3000/ARM
(B0)CR
Oe
S-values
pollen assemblage zone
Depth (cm)
APL b
APL a(ii)
APL a(i)
100
200
300
400
600
800
1000
2000
3000

Figure 6.10. Mineral magnetic measurements from AGL5
The pollen assemblage zones described in
§ 6.1.3. are indicated on the diagram.



χ
×10⁻⁶ G cm³ Oe⁻¹ g⁻¹
χfd
×10⁻⁸ G cm³ Oe⁻¹ g⁻¹
IRM3000
×10⁻⁶ G cm³ g⁻¹
ARM
×10⁻⁶ G cm³ g⁻¹
%χfd
IRM3000/χ
ARM/χ
IRM3000/ARM
(B0)CR
Oe
S-values
pollen assemblage zone
Depth (cm)
AGL c
AGL b(ii)
AGL b(i)
AGL a

CHAPTER 7

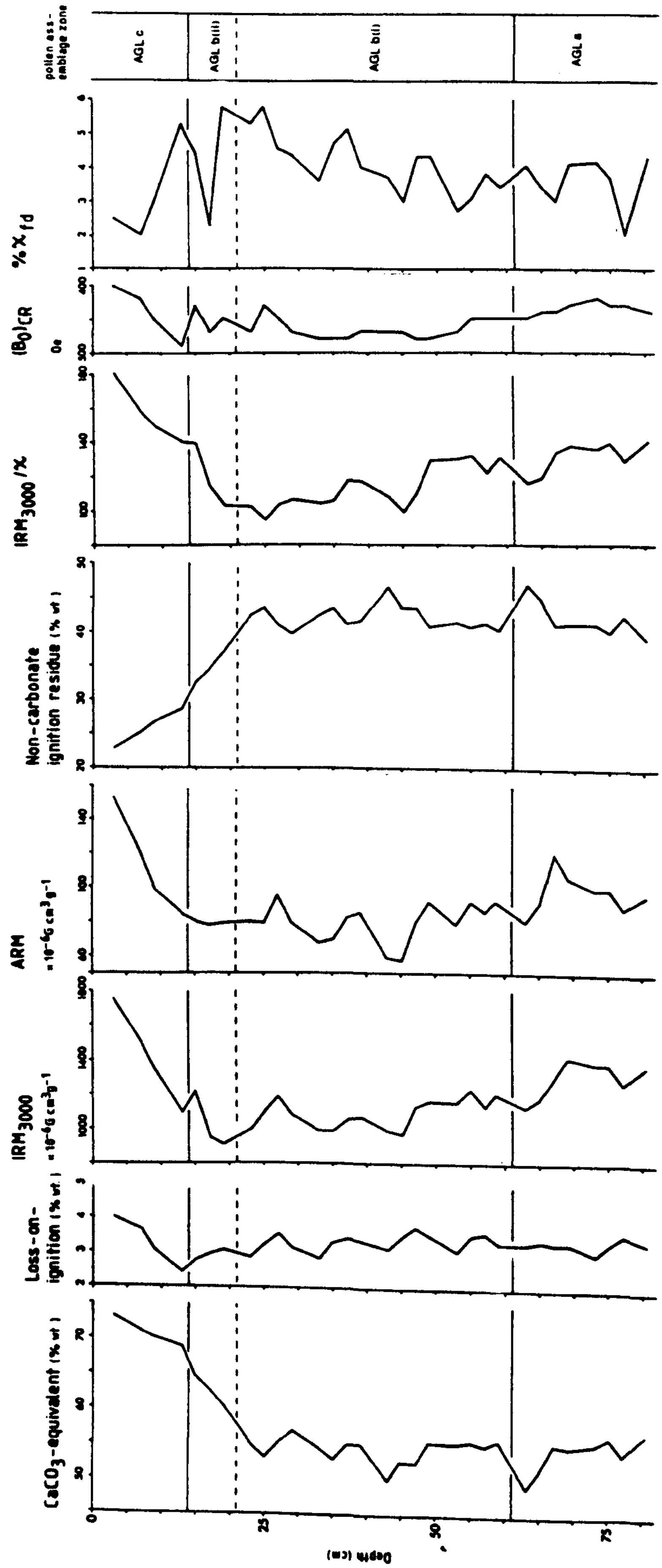
DISCUSSION OF RESULTS

7.1. The nature of the accumulating sediments: some implications for the derivation of a history of soil erosion

The lithology of the Lac d'Annecy drainage basin , together with the high productivity of the lake, provide a system in which concentrations of most elements and magnetic minerals in the lake sediments are likely to be strongly modulated by variations in the rate of $CaCO_3$ deposition. Therefore, before any attempt is made to interpret concentration-based measures of catchment-derived material in terms of changing rates and patterns of allochthonous material flux, it is necessary to consider the extent to which the carbonate fraction controls the relative proportions of other sediment components. It is appreciated that the gross sediment fractions assayed here ($CaCO_3$, loss-on-ignition and non-calcareous ignition residue) are not exclusively autochthonous or allochthonous in origin; however, the distribution of $CaCO_3$ in surface sediments of the central plain appears to be determined by the pattern of calcite ($CaCO_3$) precipitation and dissolution in the water column, rather than by the nature of the suspended sediments transported by affluent streams (§ 4.3.1.).

There is strong evidence that the rate of deposition of $CaCO_3$ has accelerated during the present century in the Grand Lac sub-basin. In AGL5 the $CaCO_3$ content has been seen to increase markedly between c. 25cm and the top of the core and from c. 13cm this is paralleled by a significant increase in loss-on-ignition and mass-specific IRM_{3000} and ARM values (figure 7.1.). This recent increase in the

Figure 7.1. Comparison of the gross sediment composition with mineral magnetic measurements, AGL5


pollen assemblage zone
AGL c
AGL b(ii)
AGL b(i)
AGL a
%χfd
(B0)CR
Oe
IRM3000/χ
Non-carbonate ignition residue (% wt)
ARM
IRM3000
Loss-on-ignition (% wt)
CaCO3-equivalent (% wt)
0
25
50
75
Depth (cm)

concentration of magnetic minerals is thought to be due to the discharge of anthropogenically-generated magnetic forms of iron from urban sources around the lakeside and appears to have its origins in the inter-war period (according to the ^{210}Pb chronology described earlier), a date which would be consistent with Hubault's observations that by 1937 the waters of the Grand Lac had already begun to deteriorate as a result of the receipt of untreated effluent and sewage (§ 2.5.4.). An increase in the amount of suspended organic material has been noticed in recent years and attributed to the influx of raw sewage and a massive growth in phytoplankton numbers; these might also account for the increase in loss-on-ignition values of recent sediments in AGL5.

It can be envisaged that algal photosynthetic activity has intensified in the upper strata of the lake waters as the water body itself has become increasingly eutrophic over recent decades, which in turn may have caused an increase in the rate of calcite precipitation (§ 4.3.1.) and consequently an increase in the rate of $CaCO_3$ deposition in bottom sediments. Vernet *et al.* (1982) have also noted a close correlation between increasing proportions of $CaCO_3$ in deep-water sediments from the Grand Lac sub-basin and enhanced concentrations of heavy metals (Hg, Cd and Pb) and organic matter during the past thirty years.

Thus, it seems that for the past half century or so, it is the rate of calcite precipitation which has controlled the relative proportion of the other sediment components in AGL5.

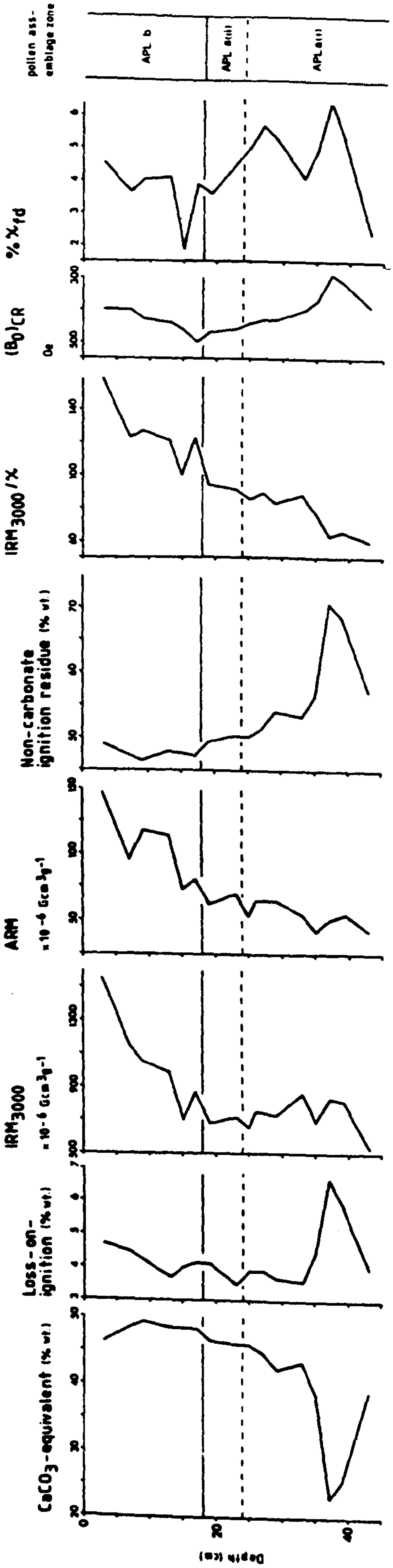
$CaCO_3$ values are generally higher above a depth of c. 18cm in APL1 than in the older, underlying sediments, but the significant increase observed in AGL5 is not repeated here. Furthermore, $CaCO_3$ values are consistently lower in the Petit Lac core. The $CaCO_3$ content of the most recent sediments in APL1 and AGL5 (c. 46% and

c. 73% respectively) compare well with Benedetti-Crouzet's estimates for surface sediments at these sites (figure 4.2.); thus the apparent difference in $CaCO_3$ content between the two cores seems to reflect a real difference in the quality of the sediments in the two sub-basins. Nevertheless, it can be seen that a significant increase in mass specific values for IRM_{3000} and ARM coincides with higher $CaCO_3$ values towards the top of the profile (figure 7.2.); it is assumed that these high magnetic mineral concentrations are also due to the influx of magnetic iron oxides in urban drainage waters. As the deep-water sediments of the Petit Lac sub-basin appear to have been affected by the discharge of waste from lakeside settlements, it seems likely that there will have been a concomitant increase in trophic status of the water body itself, resulting in accelerated rates of biogenic calcite precipitation and $CaCO_3$ accumulation in bottom sediments. The fact that an increase in $CaCO_3$ deposition is not so apparent in the Petit Lac may simply be a function of the supposedly higher allochthonous-autochthonous material ratios in this sub-basin (§ 2.5.1.). However, in addition there is evidence for an acceleration in the <u>total</u> sediment accumulation rate during the same period of time (figure 5.17.) which seems to be associated with an influx of material from catchment surfaces; the increasingly viscous magnetic mineral assemblage may reflect increased proportions of fine-grained secondary ferrimagnetic minerals derived from top-soils (see below).

Therefore, it seems that in APL1 the relative proportions of the major sediment fractions are mutually interdependent as a result of concurrent increases in the rate of calcite precipitation and the flux density of allochthonous material.

The problem of enhanced calcite precipitation in frustrating attempts to interpret changing concentrations of elements etc. as indicators of changing rates and patterns of deposition is resolved

Figure 7.2. Comparison of the gross sediment composition with mineral magnetic measurements, APL1

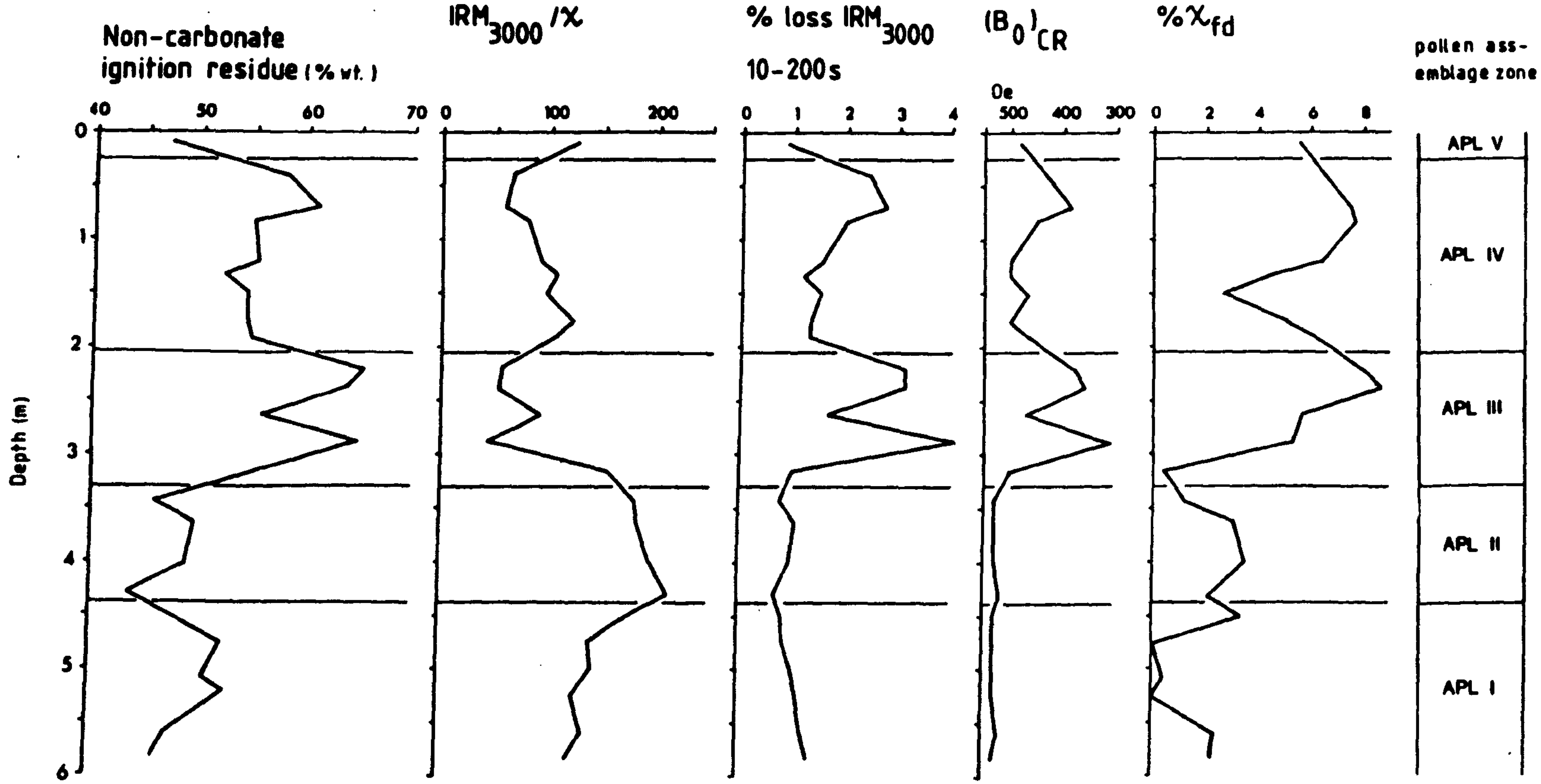

pollen assemblage zone
APL b
APL a(ii)
APL a(i)
% χfd
(B0)CR
Oe
IRM3000/χ
Non-carbonate ignition residue (% wt.)
ARM
x10-6 Gcm3g-1
IRM3000
x10-6 Gcm3g-1
Loss-on-ignition (% wt.)
CaCO3-equivalent (% wt.)
Depth (cm)

to some extent in both the Grand Lac and the Petit Lac by the availability of an accurate ^{210}Pb chronology; this means that measures of individual sediment components can be expressed independently in terms of annual accumulation rates.

There is no direct evidence to suggest that before the onset of cultural eutrophication, variations in the relative proportions of non-carbonate material in the lake sediments have been determined solely by fluctuations in the rate of biogenic calcite precipitation. Moreover, in the case of the Petit Lac sediments, it appears that the non-carbonate ignition residue content is at least partly a function of changing contributions of topsoil material. In figure 7.3. it can be seen that in APL6 the pattern of the non-carbonate ignition residue curve closely matches profiles of several concentration-independent mineral magnetic parameters (% loss IRM_{3000}, $(B_0)_{CR}$ and % χ_{fd}) considered to record changes in the modal grain size of the bulk magnetic mineral assemblage, such that relatively high values for the non-carbonate ignition residue content coincide with relatively "soft" magnetic behaviour, and vice versa. Here, it is assumed that "softer" magnetic mineral assemblages are a consequence of relatively high concentrations of viscous single domain crystals, thought to be characteristic of topsoils in the catchment area (§ 4.4.2.). A similar relationship can be seen in APL1 up to c. 18cm, the beginning of the "magnetic takeoff". In AGL5 there is no close correspondence between fluctuations or general trends in the non-carbonate ignition residue profile and measures of $(B_0)_{CR}$ and % χ_{fd} (figure 7.1.); however, it has already been seen that the mineral magnetic record is itself somewhat complex in this core (§ 6.3.3.).

The record of topsoil erosion preserved in the sediments of the Grand Lac is thought to be masked to some extent by the influx of primary ferrimagnetic minerals with material derived from molassic

Figure 7.3. Comparison of the non-carbonate ignition residue content with the mineral magnetic measurements, APL6


Non-carbonate ignition residue (% wt.)
IRM3000 /χ
% loss IRM3000 10-200s
(B0)CR
Oe
%χfd
pollen assemblage zone
Depth (m)
40
50
60
70
0
100
200
0
1
2
3
4
500
400
300
0
2
4
6
8
0
1
2
3
4
5
6
APL V
APL IV
APL III
APL II
APL I

deposits and erratics in this catchment area (§ 4.4.2.). Two distinct mineral magnetic components can be recognized in particle-size based measurements of sediments from this sub-basin (table 7.1.): values for χ and ARM are highest in the clay fraction and are thought to be due to the presence of soil-derived secondary ferrimagnetic minerals, while a maximum SIRM value in the coarse silt fraction is thought to reflect the presence of primary ferrimagnetic crystals included within igneous and metamorphic rock fragments. Relatively high SIRM/ARM ratios and low $(B_0)_{CR}$ values are observed in both silt fractions and may indicate a high proportion of multidomain grains in this primary magnetic mineral assemblage.

The IRM_{3000}/χ ratio is the only magnetic parameter to compare well with the non-carbonate ignition residue content in AGL5; the two curves mirror each other very closely (figure 7.1.). This can also be seen in sediments of the Petit Lac pre-dating the supposed period of eutrophication (figures 7.2. and 7.3.).

It has been suggested that in APL6 and APL1, variations in the IRM_{3000}/χ ratio are likely to be due to changing proportions of superparamagnetic grains (§ 6.3.1. and § 6.3.2.). These ultra-fine crystals would be expected to be secondary magnetic minerals associated with the influx of topsoil material; therefore the trends observed in this ratio would be consistent with the correlation proposed above between the magnitude of the non-carbonate ignition residue and the relative proportion of topsoil material within that fraction.

If, on the other hand, fluctuations in the IRM_{3000}/χ ratio are intrinsically determined by the concentration of paramagnetic minerals in the sediments, then the fact that the IRM_{3000}/χ ratio is inversely related to remanent magnetic indices of topsoil inwash tends to provide circumstantial evidence for a catchment source of paramagnetic

Particle size class	χ ($\times 10^{-6} Gcm^3 Oe^{-1} g^{-1}$)	SIRM ($\times 10^{-6} Gcm^3 g^{-1}$)	ARM ($\times 10^{-6} Gcm^3 g^{-1}$)	SIRM/χ	ARM/χ	SIRM/ARM	$(B_0)_{CR}$ (Oe)
32–63µ (coarse silt)	2•31	484	20•5	209•5	8•9	23•6	370
16–32µ (medium silt)	2•35	367	18•3	156•2	7•8	20•1	390
<0•5µ (clay)	3•63	395	79•6	108•8	21•9	5•0	450

Table 7.1. Mineral magnetic measurements of particle-sized fractions of sediments from the Grand Lac (R.H.W. Bradshaw, pers. comm.)

material in the Petit Lac sub-basin.

If low values for the IRM_{3000}/χ ratio in AGL5 also reflect high proportions of soil-derived superparamagnetic crystals and/or high concentrations of catchment-derived paramagnetic minerals, then again it appears that the non-carbonate fraction cannot be determined solely by fluctuations in calcite precipitation, and is to some extent governed by the contribution of allochthonous material.

At this juncture it seems reasonable to refer to the non-carbonate ignition residue curve as an index of variations in the contribution of allochthonous material to the deep-water sediments of both sub-basins, at least for the period of sedimentation prior to the onset of eutrophication in the first half of this century. However, without recourse to a finely-resolved time-scale, and without taking into account the contribution of biogenic silica to the non-carbonate ignition residue, it is not possible to establish the extent to which these variations are actually an index of changes in the <u>flux density</u> of material from catchment surfaces.

The 24 single samples selected from APL6 for detailed palaeoecological analysis are thought to represent <u>general</u> trends in mineral magnetic properties (§ 4.1.3.) and as such they are now assumed to represent only <u>general</u> trends in the relative contribution of allochthonous material to the deep-water sediments of the Petit Lac. Yet fluctuations in the χ and SIRM values observed for contiguous samples from the same core (§ 6.3.1. and figure 6.7.) indicate that variations in this component may be even more marked over shorter time-scales.

It has been seen that very dark coloured sediments are generally characterized by relatively low SIRM/χ values. Similar properties have been noted in another core (ANN2) from the Petit Lac sub-basin. In the light of the results of detailed magnetic measurements of the

24 single samples from APL6, it seems probable that these low ratios result from the influx of material from catchment surfaces[1] (see above).

It was thought that colour differences in the Petit Lac sediments may be a function of their organic matter content. However, preliminary measurements of samples from ANN2 have indicated that there is little significant difference in loss-on-ignition values between the different coloured muds. It seems more likely that it is the ratio between the $CaCO_3$ and organic matter content which is the major determinant of sediment colour rather than the concentration of organic material alone. If this is so, it implies that very dark sediments contain proportionally less $CaCO_3$ and proportionally more non-calcareous mineral material , which is partly allochthonous in origin. Thus, the combination of low SIRM/χ ratio values and the putative low carbonate-high clastic nature of these sediments may result from episodes in which the deep-water sediments are composed of very high proportions of catchment-derived material. Despite the sharp contacts between many of these dark bands and the underlying

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[1] A separate research programme was planned to characterize these different coloured sequences of mud in terms of their gross sediment composition, mineral magnetic properties and pollen content. It was thought that they may represent changes in the prevailing sedimentation regime and, as such, might be related to temporary shifts in meteorological conditions or land-use patterns, or some conjunction of the two. They were, therefore, considered to be of potential value in reconstructing a detailed history of soil erosion for this lake-catchment system. Although only 3m of sediment had been retrieved during the coring operation, core ANN2 was selected for these analyses as it had not been opened previously, and was therefore still in a moist condition, with laminations clearly visible to the naked eye (cf. the partially dried state of APL6). However, the exercise was terminated once it proved difficult to establish the time-scale spanned by the core. Furthermore, from preliminary mineral magnetic and elemental analyses, it appeared that the core may have repenetrated the sediments (F. Oldfield, pers. comm.). The remaining time for laboratory analysis was devoted to deriving a general vegetation and soil erosion history for the time period spanned by APL6, for which a palaeomagnetic trace was available.

lighter coloured sediments (see Appendix 2), most of these features are thought to represent several years of sedimentation rather than individual events as laminae are evident on the X-ray radiographs; although in ANN2 at least one micro-turbidite sequence has been identified.

Thus, it appears that the Petit Lac lake-catchment system is extremely sensitive to changes in the nature of sedimentation over relatively short time-intervals. In view of the relative size of the catchment area, and the reported sensitivity of this system to periods of very heavy rainfall, both in terms of the volume of water and volume of suspended sediments delivered to the lake (§ 2.4.3. and Benedetti-Crouzet, 1972), there seems to be a strong possibility that such marked increases in the proportion of allochthonous material in the deep-water sediments are at least partly due to accelerated losses of soil from catchment surfaces.

7.2. The influence of catchment-derived material on the fossil pollen spectra contained within the sediments of the Petit Lac: some implications for the derivation of a vegetation history

Pollen concentration values were originally determined in an attempt to overcome the interdependence of relative percentage data by expressing counts for individual pollen types in terms of annual influx rates. However, there is strong evidence that total pollen concentrations in the sediments of the Petit Lac are regulated by the flux of soil material from catchment surfaces.

The concentration of the total number of pollen grains included in the basic pollen sum (trees and shrubs plus herbs) is highly correlated with indices of changing proportions of topsoil material within the non-carbonate fraction of the matrix sediment (% χ_{fd},

% loss IRM_{3000}, $(B_0)_{CR}$ and IRM_{3000}/χ) aswell as with concentration-dependent measures reflecting changing volumes of topsoil material (non-carbonate ignition residue, mass specific χ and so on) (table 7.2.). Low pollen concentrations are generally associated with relatively high proportions and concentrations of soil, and vice versa. Total pollen concentrations are largely a reflection of the concentration of tree and shrub pollen; the concentration of herbaceous pollen alone is not highly correlated with these sediment properties (table 7.2. and figure 7.4.).

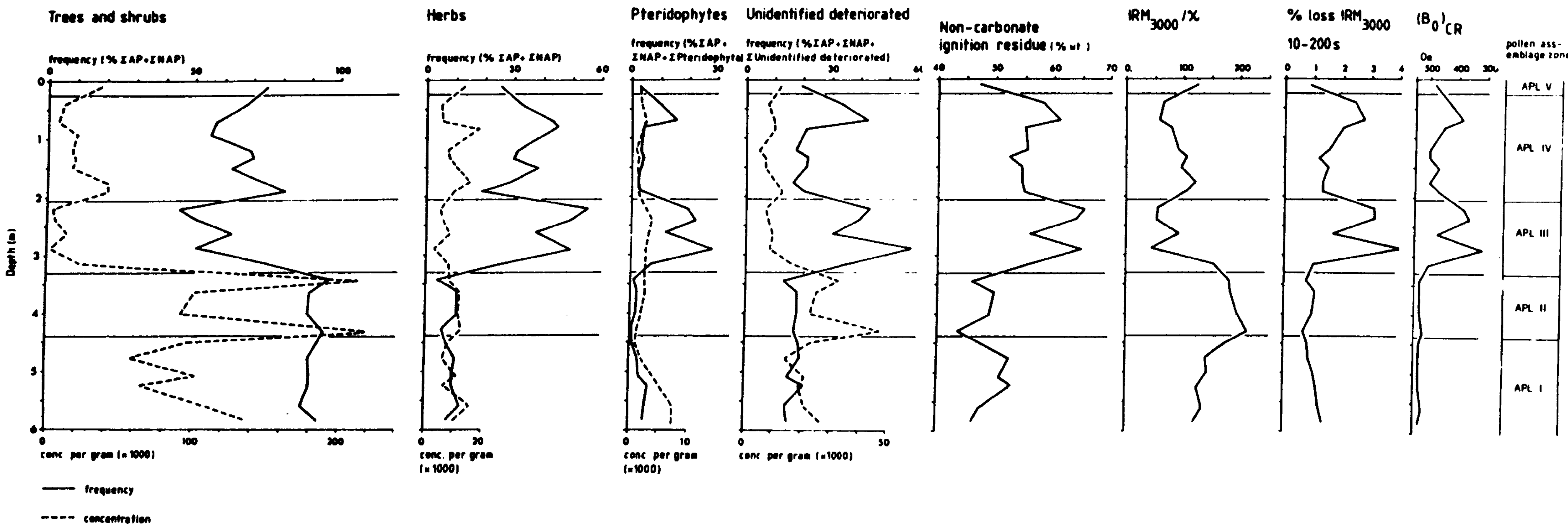
Although the fossil pollen preserved in sediments of open lake basins are derived from the pollen rain over the lake surface and indirectly from the pollen rain on the catchment (the pr and cpr components of West, 1973; figure 7.5.), it has been anticipated that a high percentage of pollen recruited to the sediments of the Lac d'Annecy is likely to be stream-borne (§ 4.2.1.), ie. the cpr component is dominant. Pennington (1979) has developed West's terminology by dividing cpr into cpr^1, pollen transferred from catchment surfaces soon after deposition, and cpr^2, pollen removed from catchment surfaces and transported to the lake sediments with eroded soil fractions (figure 7.5.). If there was no significant reservoir of pollen in soils of the Annecy lake basin, ie. if the cpr^2 component was negligible, this might explain the fact that low pollen concentrations are associated with high proportions of topsoil in the Petit Lac sediments.

Soils in the area are typically of high base-status due to the calcareous nature of bedrock and drift deposits (P.A. James, unpublished data; Richard, 1973). Pollen preservation tends to be poor in media with a high pH and high biological activity (Dimbleby, 1957; Dimbleby & Evans, 1974; Havinga, 1967 and 1971) and so, although the pollen content of soils at this site has not been studied

	Trees and shrubs plus herbs	Trees and shrubs	Herbs	Compositae Liguliflorae	Herbs minus Compositae Liguliflorae	Pteridophytes	Unidentified deteriorated
% non-carbonate ignition residue	−0·92***	−0·92***	−0·64***	0·12	−0·64***	0·11	−0·78***
% loss-on-ignition	0·25	0·28	−0·05	0·31	−0·05	0·54***	0·41*
% χ_{fd}	−0·72***	−0·73***	−0·27	−0·02	−0·25	−0·21	−0·66***
% loss IRM_{3000}	−0·79***	0·80***	−0·45*	0·07	−0·45*	0·23	−0·74***
$(B_0)_{CR}$	0·87***	0·87***	0·38	−0·20	0·40	0·07	0·77***
IRM_{3000}/χ	0·87***	0·88***	0·53**	−0·03	0·54**	−0·08	0·84***
$\chi\ g^{-1}$	−0·77***	−0·78***	−0·27	0·09	−0·27	−0·28	−0·72***
$\chi_{fd}\ g^{-1}$	−0·74***	−0·75***	−0·27	−0·01	−0·25	−0·24	−0·67***
loss $IRM_{3000}\ g^{-1}$	−0·69***	−0·71***	−0·22	0·09	−0·21	−0·06	−0·58**

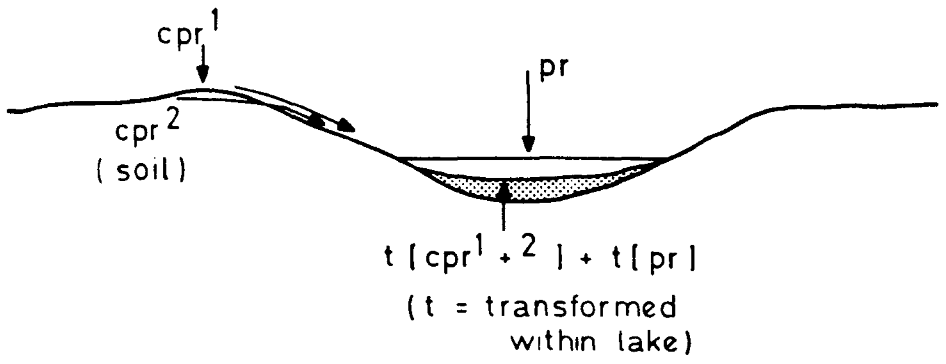
Table 7.2. Spearman rank correlation coefficients between pollen and spore concentration data and geochemical and mineral magnetic measurements, APL6 (* $p < 0·05$; ** $p < 0·01$; *** $p < 0·001$)

Figure 7.4. Comparison of the frequency and concentration of the main pollen and spore categories with geochemical and mineral magnetic indices of material flux from catchment surfaces, APL6



Trees and shrubs
frequency (% ΣAP+ΣNAP)
conc per gram (×1000)
Herbs
frequency (% ΣAP+ ΣNAP)
conc. per gram (×1000)
Pteridophytes
frequency (%ΣAP+ ΣNAP+ΣPteridophyta)
conc per gram (×1000)
Unidentified deteriorated
frequency (%ΣAP+ΣNAP+ ΣUnidentified deteriorated)
conc per gram (×1000)
Non-carbonate ignition residue (% wt)
IRM3000/X
% loss IRM3000 10-200 s
(B0)CR
Oe
pollen assemblage zone
APL V
APL IV
APL III
APL II
APL I
Depth (m)
frequency
concentration

Figure 7.5. Sources of pollen in limnic sediments (from Pennington, 1979)
(pr : pollen rain; t(pr) : pr transformed by various processes which take place between reception at the water surface and final deposition of the assemblage as sediment; cpr : pollen rain on soil of catchment area; t(cpr) : cpr transformed by dispersal and weathering processes (West, 1973); cpr^1 : cpr transferred rapidly from the surfaces of the catchment area; cpr^2 : cpr derived from erosion and bodily transport of soil containing well-preserved pollen (Pennington, 1979)).


cpr 1
pr
cpr 2
(soil)
t [cpr 1 + 2] + t [pr]
(t = transformed
within lake)

systematically by the author, it can be envisaged that conditions are not generally suitable for good pollen preservation. This contention is supported by the fact that in this core (APL6) high percentages of unidentified deteriorated grains are also associated with high proportions of soil in the non-carbonate mineral fraction of the lake sediments (table 7.3. and figure 7.4.). At the same time, the concentration of these grains is "diluted" (table 7.2. and figure 7.4.), suggesting that deterioration may have proceeded to the point where many grains are no longer even recognizable as pollen.

It is also conceivable that runoff may be most effective in removing pollen and soil particles from non-forested surfaces, especially from bare or partly vegetated land under tillage, where local pollen production is low and where the local pollen rain contains a relatively high proportion of herbaceous pollen. In these circumstances, it might be expected that the inwash of eroded soils is associated with relatively low numbers of pollen grains, regardless of any effects of pollen deterioration. Hence, the "selected" removal of material from areas of open land in the catchment area might also account for the fact that the fossil pollen spectra associated with high proportions of soil in the lake sediments are characterized by low total pollen concentrations, reflecting in particular the concentrations of tree and shrub pollen. In addition, this may explain why the correlation between total herbaceous pollen concentrations and indices of soil inwash is rather less significant than that observed between the total concentration of arboreal pollen and the same geochemical and mineral magnetic parameters (table 7.2.). Furthermore, this "selective" delivery of pollen and mineral particles from non-forested localities may in part determine the arboreal pollen (AP): non-arboreal pollen (NAP) ratio in the fossil pollen assemblages preserved in the lake sediments.

	APL6	APL1	AGL5
% non-carbonate ignition residue	0·81***	-0·19	0·07
% loss-on-ignition	-0·04	-0·04	-0·34*
% χ_{fd}	0·52**	-0·60**	0·23
% loss IRM_{3000}	0·60**		
$(B_0)_{CR}$	-0·76***	0·42*	0·53**
IRM_{3000}/χ	-0·67***	0·12	-0·50**
χ g^{-1}	0·63***	-0·38	-0·29
χ_{fd} g^{-1}	0·55**	-0·52*	0·14
loss IRM_{3000} g^{-1}	0·57**		

Table 7.3. Spearman rank correlation coefficients between frequency of unidentified deteriorated pollen and geochemical and mineral magnetic measurements for APL6, APL1 and AGL5 (* $p < 0·05$; ** $p < 0·01$; *** $p < 0·001$)

There is no correspondence at all between the concentration of Compositae Liguliflorae pollen and total pteridophyte spores, and the geochemical and mineral magnetic indices of soil inwash (table 7.2. and figure 7.4.), indicating that the fossil grains of these taxa are not "diluted" by the flux of soil material. This suggests that the removal of these grains and spores away from catchment surfaces may be in association with eroded soil fractions, or may be promoted by contemporaneous hydrological processes. It can be seen that high frequencies of Compositae Liguliflorae pollen and Filicales undiff. spores in this core (APL6) are associated with high proportions of soil in the non-carbonate fraction of the matrix sediment and with high total volumes of soil material (table 7.4.). The relative frequency of *Pteridium aquilinum* spores is similarly correlated with concentration-dependent mineral magnetic measures of soil inwash (table 7.4.).

The pollen of *Taraxacum* (a member of the Compositae Liguliflorae) is known to be fairly resistant to decay (Havinga, 1967 and 1971). Thus, it is possible that long-term preservation of this pollen type may have led to its persistence in soils of the catchment area (within a cpr^2 component) and to its over-representation in the fossil pollen spectra. Counts of the frequency of the Compositae Liguliflorae may be further biased as their exine[1] sculpturing is so distinctive that even extremely deteriorated grains may be recognized.

The majority of the spores in the Filicales undiff. category were actually Polypodiaceae spores. These are known to be highly resistant to deterioration in humus and soils, and it has been

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[1] The exine is the outer layer of the pollen grain wall. It is composed mainly of sporopollenin, a material which is very resistant to decay, and in fossilization is usually the only part of the pollen grain to be preserved.

	Compositae Liguliflorae			Filicales undiff.			*Pteridium aquilinum*		
	APL6	APL1	AGL5	APL6	APL1	AGL5	APL6	APL1	AGL5
% non-carbonate ignition residue	0·75***	0·43*	0·00	0·82***	0·59**	0·44**	0·60***	0·59*	0·02
% loss-on-ignition	-0·01	0·43*	-0·19	-0·12	0·46*	-0·16	0·31	0·04	-0·13
% χ_{fd}	0·49**	0·34	0·03	0·62***	0·25	0·09	0·23	0·25	0·10
% loss IRM_{3000}	0·69***			0·83***			0·65***		
$(B_0)_{CR}$	-0·76***	-0·41	0·05	-0·82***	-0·38	0·31*	-0·44*	-0·38	0·07
IRM_{3000}/χ	-0·75***	-0·57*	-0·14	-0·85***	-0·64**	-0·67***	-0·56***	-0·67**	-0·18
$\chi\ g^{-1}$	0·58***	-0·30	-0·08	0·62***	0·23	0·19	0·19	0·18	-0·08
$\chi_{fd}\ g^{-1}$	0·51**	0·32	0·02	0·62***	0·24	0·16	0·22	0·20	0·10
loss $IRM_{3000}\ g^{-1}$	0·49**			0·63***			0·34		

Table 7.4. Spearman rank correlation coefficients between frequency of Compositae Liguliflorae pollen, Filicales undiff. spores and *Pteridium aquilinum* spores, and geochemical and mineral magnetic measurements for APL6, APL1 and AGL5 (* $p < 0{\cdot}05$; ** $p < 0{\cdot}01$; *** $p < 0{\cdot}001$)

suggested that large numbers in a pollen count may indicate loss of other pollen types (Jacobson & Bradshaw, 1981). Their survival in soils of this catchment area may have led to their over-representation in the fossil pollen spectra, and once more, it is relevant to note that however badly these spores were corroded or broken, they were still easily identified as belonging to this category. In contrast, the spores of *Pteridium aquilinum* were often badly corroded and required careful examination before being positively identified; so, there is no reason to believe that this taxon is over-represented in the fossil pollen spectra due to counting bias.

High frequencies of Compositae Liguliflorae pollen and pteridophyte spores (Filicales undiff. and *Pteridium aquilinum*) may alternatively, or in addition, be due to their "selective" removal together with soil mineral particles from areas in which the parent plants of these taxa grew, as described above. It also seems likely that "local" sources of pteridophyte plants along streambanks and ravines may give rise to high spore frequencies in the fossil pollen spectra, if the high energy conditions associated with periods of intense or prolonged rainfall, capable of removing relatively large quantities of soil from catchment surfaces, also coincide with periods of spore production.

On the basis of the observations discussed above, it seems that the flux of topsoils from the Petit Lac catchment area involves the transport of material containing little identifiable pollen. The paucity of pollen in these sediments may be due to the calcareous nature of these catchment soils promoting rapid deterioration of grains, or may be a consequence of soils being eroded predominantly from areas of low pollen production, such as agricultural land. Both processes may be operative. If low pollen concentrations are at all a function of poor preservation in the catchment, this suggests that the stream-borne supply of pollen to the lake sediments must largely consist of grains removed from catchment surfaces fairly soon after deposition, ie. the cpr^1 component (figure 7.5.), and will therefore reflect the contemporaneous pollen rain. It is, however, appreciated that high frequencies of Compositae Liguliflorae pollen and Filicales undiff. spores may be due to the influx of "old" pollen and spores in association with eroded soils.

It is difficult to assess the degree to which the flux of pollen grains and allochthonous mineral particles are related in APL1 and AGL5; the difficulty of interpreting the mineral magnetic record of both cores in terms of changing contributions of soil material to these deep-water sediments has been discussed in § 7.1. Furthermore, pollen concentration values have not been determined. There is no clear relationship between the frequency of unidentified deteriorated grains in APL1 and AGL5, and measures of soil inwash (table 7.3.). However, in APL1, the short core from the Petit Lac, the frequency of Compositae Liguliflorae pollen, Filicales undiff. spores and *Pteridium aquilinum* spores are significantly correlated with the non-carbonate ignition residue content and the IRM_{3000}/χ ratio, two parameters which are thought to respond to changes in the proportion of soil material (§ 7.1.) (table 7.4.); high frequencies of these taxa are associated with high proportions of soil, and vice versa. These observations concur with those already noted for the Petit Lac lake-catchment system in APL6. In AGL5 only the frequency of Filicales undiff. spores is significantly correlated with the non-carbonate ignition residue content and the IRM_{3000}/χ ratio, parameters which are thought to reflect variations in the contribution of topsoil to the total sediment in AGL5 aswell (§ 7.1.) (table 7.4.).

The records of pollen preservation made during routine pollen counts of samples from APL6 (§ 4.2.5.) provide an opportunity for

Preservation class

	Corroded	Degraded	Crumpled	Broken	Well-preserved
Trees and shrubs	35•78 (± 10•22)	11•51 (± 4•70)	7•09 (± 3•44)	5•38 (± 1•71)	40•25 (± 9•64)
Herbs	30•77 (± 8•63)	11•16 (± 4•90)	18•94 (± 7•28)	4•87 (± 3•65)	34•26 (± 7•98)
Pteridophytes	39•52 (± 18•29)	3•15 (± 6•36)	5•85 (± 5•53)	18•80 (± 13•83)	32•68 (± 17•65)
Unidentified deteriorated	47•91 (± 13•26)	20•74 (± 13•17)	18•35 (± 6•97)	13•01 (± 4•77)	

Table 7.5. Percentage of tree and shrub pollen, herb pollen, pteridophyte spores and unidentified deteriorated pollen and spores in each preservation class
(Figures are means ± 1 standard deviation for the 24 samples in APL6).

looking in more detail at the links between sources of pollen in the catchment area and the preservation state of fossil pollen in the lake sediments.

In experimental studies of pollen preservation in biologically active soils, Havinga (1967, 1971 & 1984) has noted that the exines of deteriorated pollen grains were typically corroded. In addition, several workers have noted that fossil pollen spectra associated with the influx of material from catchment surfaces are characterized by a high frequency of corroded grains, thought to be due to their previous exposure to aerial oxidation and microbial attack (Birks, 1970; Cushing, 1964; Tolonen, 1980 and q.v. Lowe, 1982). On average, a large proportion of pollen grains within each pollen and spore category in this study showed some signs of corrosion (table 7.5.); nearly half of the unidentified deteriorated pollen grains were unidentifiable for this reason.

However, the only correlation between the general preservation state of individual pollen spectra in APL6 and corresponding geochemical and mineral magnetic indices of topsoil inwash involves the frequency of broken grains (table 7.6.). There is no correspondence at all between the general preservation state of the tree and shrub pollen assemblages at each level and the same measures of the influx of soil material (table 7.7.), although a double peak in the frequency of broken conifer grains in p.a.z. APL III (figure A3.5.) corresponds to a double maximum in the proportion of topsoil material (figure 7.3.) (see § 7.3.). On the other hand, relatively low proportions of well-preserved pollen, and therefore high proportions of deteriorated pollen, within the herbaceous pollen assemblage at each level are generally associated with relatively high proportions of soil in the non-carbonate fraction of the sediment matrix and high total concentrations of topsoil, and vice

	Preservation class				
	Corroded	Degraded	Crumpled	Broken	Well-preserved
% non-carbonate ignition residue	0·09	0·18	0·36	0·51*	−0·34
% loss-on-ignition	0·30	−0·26	−0·14	0·04	−0·30
% χ_{fd}	0·04	0·02	0·29	0·38	−0·14
% loss IRM_{3000}	0·24	0·09	0·19	0·36	−0·38
$(B_0)_{CR}$	−0·11	−0·22	−0·37	−0·42*	0·38
IRM_{3000}/χ	−0·29	−0·17	−0·10	−0·25	0·38
$\chi\ g^{-1}$	−0·13	0·15	0·48*	0·42*	−0·16
$\chi_{fd}\ g^{-1}$	−0·02	0·06	0·35	0·37	−0·15
loss $IRM_{3000}\ g^{-1}$	−0·10	0·03	0·55**	0·52**	−0·23

Table 7.6. Spearman rank correlation coefficients between percentage of total pollen and spores in each preservation class (identified and unidentified) and geochemical and mineral magnetic measurements, APL6 (* $p < 0{\cdot}05$; ** $p < 0{\cdot}01$)

	Preservation class					
	Corroded	Degraded	Crumpled	Broken	Well-preserved	Broken conifer grains
% non-carbonate ignition residue	−0·23	0·32	0·04	0·27	0·18	0·23
% loss-on-ignition	0·20	0·19	0·05	0·15	−0·35	0·35
% χ_{fd}	−0·19	0·07	−0·12	0·25	0·31	−0·10
% loss IRM_{3000}	−0·05	0·10	−0·05	0·16	0·13	0·07
$(B_0)_{CR}$	0·19	−0·34	−0·04	−0·21	−0·14	−0·15
IRM_{3000}/χ	0·02	−0·12	0·18	−0·07	−0·17	−0·03
$\chi\ g^{-1}$	−0·39	0·18	0·03	0·35	0·38	0·03
$\chi_{fd}\ g^{-1}$	−0·24	0·10	−0·06	0·27	0·32	−0·07
loss $IRM_{3000}\ g^{-1}$	−0·32	0·16	0·16	0·43*	0·25	0·11

Table 7.7. Spearman rank correlation coefficients between percentage of total tree and shrub pollen in each preservation class and frequency of broken conifer pollen, and geochemical and mineral magnetic measurements, APL6 (* $p < 0·05$)

versa (table 7.8.). This is largely a function of the frequency of broken pollen. It has been suggested that broken pollen may result from mechanical damage due to physical abrasion and compression (Birks, 1970) and Peck has observed that modern pollen entering lakes by stream transport are often broken (in Birks, 1970). So, it is conceivable that the relationship observed here is a consequence of high energy conditions within the hydrological system capable of eroding and transporting large quantities of soil from catchment surfaces, and at the same time promoting breakage of herb pollen either by water turbulence or by contact with clastics in the stream body. The overall preservation state of the pteridophyte spore assemblage at each level appears to be largely independent of sediment matrix properties (table 7.9.), although large proportions of crumpled spores are associated with high organic matter content.

Nevertheless, the essential point here is that there is no correspondence between the frequency of corroded pollen in the fossil pollen spectra and indices of topsoil inwash in the lake sediments which might have been expected, considering the physical and biological conditions associated with calcareous soils and the proposed effects of these on pollen survival in this catchment area.

It is possible that fluctuations in the frequency of corroded pollen have been masked to some extent by amalgamating these records of pollen preservation. Insufficient numbers of pollen grains were counted for the preservation states of individual pollen types to be considered. Yet it is known from experimental observations that the pollen and spores of different plants are differentially susceptible to deterioration (Sangster & Dale, 1961 and 1964; Havinga, 1964, 1967, 1971 and 1984). Thus, summarizing these data into the main pollen and spore categories is somewhat arbitrary and a gross oversimplification, and the profiles of the different preservation classes presented in

	Preservation class				
	Corroded	Degraded	Crumpled	Broken	Well-preserved
% non-carbonate ignition residue	0·05	0·13	0·26	0·39	-0·38
% loss-on-ignition	0·10	-0·11	-0·21	-0·21	0·19
% χ_{fd}	-0·09	0·06	0·37	0·45*	-0·38
% loss IRM_{3000}	0·16	0·14	0·25	0·26	-0·47*
$(B_0)_{CR}$	-0·13	-0·21	-0·23	-0·29	0·49*
IRM_{3000}/χ	-0·27	-0·21	-0·15	-0·16	0·47*
$\chi\ g^{-1}$	-0·04	0·15	0·34	0·47*	-0·47*
$\chi_{fd}\ g^{-1}$	-0·11	0·12	0·37	0·46*	-0·40
loss $IRM_{3000}\ g^{-1}$	-0·13	0·12	0·49*	0·47*	-0·49*

Table 7.8. Spearman rank correlation coefficients between percentage of total herb pollen in each preservation class and geochemical and mineral magnetic measurements, APL6 (* $p < 0{\cdot}05$)

	Preservation class				
	Corroded	Degraded	Crumpled	Broken	Well-preserved
% non-carbonate ignition residue	-0·06	0·35	0·29	0·02	-0·09
% loss-on-ignition	0·18	-0·27	0·47*	0·25	-0·50*
% χ_{fd}	-0·11	0·12	0·11	-0·06	0·08
% loss IRM_{3000}	0·12	0·12	0·21	-0·07	-0·12
$(B_0)_{CR}$	0·01	-0·22	-0·17	0·03	0·00
IRM_{3000}/χ	-0·15	-0·13	-0·15	0·21	0·02
$\chi\ g^{-1}$	-0·21	0·24	0·12	0·02	0·14
$\chi_{fd}\ g^{-1}$	-0·15	0·17	0·10	-0·03	0·11
loss $IRM_{3000}\ g^{-1}$	-0·23	0·21	0·25	0·15	0·04

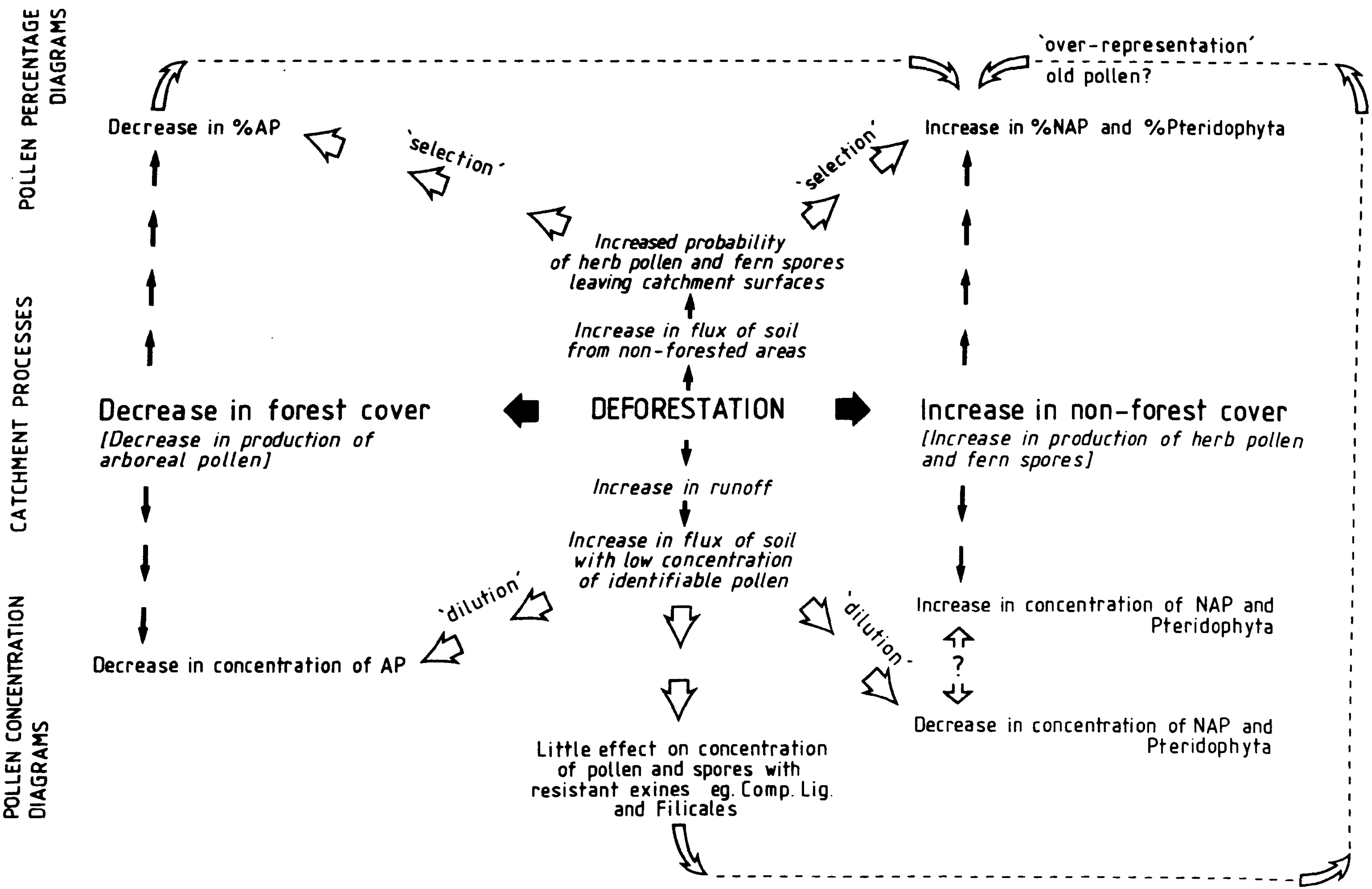
Table 7.9. Spearman rank correlation coefficients between percentage of total pteridophyte spores in each preservation class and geochemical and mineral magnetic measurements, APL6 (* $p < 0{\cdot}05$)

figures A3.5. and A3.6. may largely be a function of the preservation states of dominant pollen types.

However, if as suggested above, the majority of pollen are transported to the lake sediments soon after deposition, it can be envisaged that they are removed from catchment surfaces before significant numbers have been affected by oxidation and/or microbial attack. The preservation conditions of the identifiable pollen grains may then be more a function of those processes occurring during transport and deposition, and also possibly during preparation of the sediment samples in the laboratory. In this respect, these data are of rather limited value; only the corroded category can be considered to contain a true count of the frequency of grains showing this type of deterioration, whereas the frequency of pollen in the degraded, crumpled and broken classes are simply minimum estimates of the occurrence of these conditions, and, as such, must be modulated by the proportion of grains exhibiting types of deterioration higher in the preservation class hierarchy (§ 4.2.5.). Only the well-preserved category is mutually exclusive.

The deep-water sediments of the Petit Lac appear to be sensitive to variations in the relative contribution of soil material from catchment surfaces (§ 7.1.), which in turn appear to determine a number of features in the fossil pollen spectra. This has far-reaching implications if the pollen diagrams from this sub-basin are to be used in reconstructing a vegetation history in order to provide a context in which to interpret the geochemical and mineral magnetic records of soil erosion. A simple model describing the proposed effects of deforestation on properties of the fossil pollen assemblages preserved in the lake sediments has been developed from the observations discussed above (figure 7.6.). It seems that in a lake-catchment system of the extent, complexity and sensitivity of the Petit Lac, the

Figure 7.6. Proposed model of the links between deforestation in the catchment area of the Petit Lac and the fossil pollen spectra preserved in the lake sediments
(Abbreviations: AP = arboreal pollen; NAP = non-arboreal pollen).


POLLEN PERCENTAGE DIAGRAMS
CATCHMENT PROCESSES
POLLEN CONCENTRATION DIAGRAMS
'over-representation'
old pollen?
Decrease in %AP
'selection'
'selection'
Increase in %NAP and %Pteridophyta
Increased probability of herb pollen and fern spores leaving catchment surfaces
Increase in flux of soil from non-forested areas
Decrease in forest cover
[Decrease in production of arboreal pollen]
DEFORESTATION
Increase in non-forest cover
[Increase in production of herb pollen and fern spores]
Increase in runoff
Increase in flux of soil with low concentration of identifiable pollen
'dilution'
'dilution'
Increase in concentration of NAP and Pteridophyta
?
Decrease in concentration of AP
Decrease in concentration of NAP and Pteridophyta
Little effect on concentration of pollen and spores with resistant exines eg. Comp. Lig. and Filicales

expression of forest clearance in a fossil pollen diagram is likely to be out of all proportion to real changes in the catchment area itself. The two most salient features of the proposed model in figure 7.6. are as follows:

1. It seems unlikely that changes in the fossil AP : NAP ratio represent proportionally similar changes in the cover of forested : non-forested land in the catchment area. It can be envisaged that as deforestation progresses, real increases in the amount of NAP produced are likely to be reinforced by three additional mechanisms:
   (a) a decrease in the cover of forest or woodland, and therefore a decrease in the amount of AP produced in the catchment, must largely determine the magnitude of the reciprocal increase in NAP when expressed as a relative percentage of the total pollen sum (ΣAP + ΣNAP), as trees are the major pollen producers in terms of the numbers of pollen produced per land unit.
   (b) the "selective" removal of cpr[1] assemblages from non-forested surfaces which are assumed to comprise a <u>relatively</u> high proportion of NAP.
   (c) the influx of "old" cpr[2] grains of herbaceous pollen types resistant to decay and transported to the lake sediments in association with eroded soil fractions.

   It is possible that the relative frequencies of pteridophyte spores in the fossil pollen spectra are similarly exaggerated.

2. It appears that the influx of material from catchment surfaces effectively "dilutes" the total fossil pollen assemblage in the lake sediments. As Colinvaux (1978) has noted, pollen concentration diagrams are still a kind

of relative diagram in that they represent pollen relative to the concentration of clastic or detrital material. Thus, without a finely-resolved time-scale it is not yet possible to present meaningful pollen accumulation diagrams and overcome the sorts of problems outlined in (1) above.

At this point it should be stressed that the processes embodied in the model above have not been substantiated by a field investigation into patterns of pollen production, dispersal, storage and transport in this particular catchment area, nor was this theme originally planned as a separate line of research; the ideas presented above have simply been suggested as a consequence of comparing the observations made during routine pollen counting with measurements of the sediment matrix properties. The extent to which this model represents links between deforestation and the fossil pollen spectra in the Grand Lac lake-catchment system is not clear.

A final note to be made in the light of the proposed links between pollen and mineral particle flux in the Petit Lac system concerns the uncertainty of whether or not variations in the proportion of soil in the lake sediments are actually due to changes in the flux density of allochthonous material. Unless they are determined solely by changes in the flux of soil material from areas of low pollen production, the occurrence of low pollen concentrations may be due, at least in part, to variations in the flux of material with low pollen preservation. This in turn suggests that variations in the fossil pollen concentrations may be a function of changes in the rate of loss of soil from catchment surfaces, assuming a more or less constant rate of delivery of cpr[1] pollen.

7.3. Recent environmental change in the drainage basin of the Lac d'Annecy

The following account of environmental change in the Annecy lake basin focusses upon the historical periods defined by the pollen assemblage zones of the long core from the Petit Lac sub-basin, APL6. The transition between p.a.z. APL IV and APL V (§ 6.3.1.) has been more precisely identified by comparison with the pollen assemblage zones described for the short cores, APL1 and AGL5, which comprise more or less contiguous pollen spectra (§ 6.1.2. and § 6.1.3.).

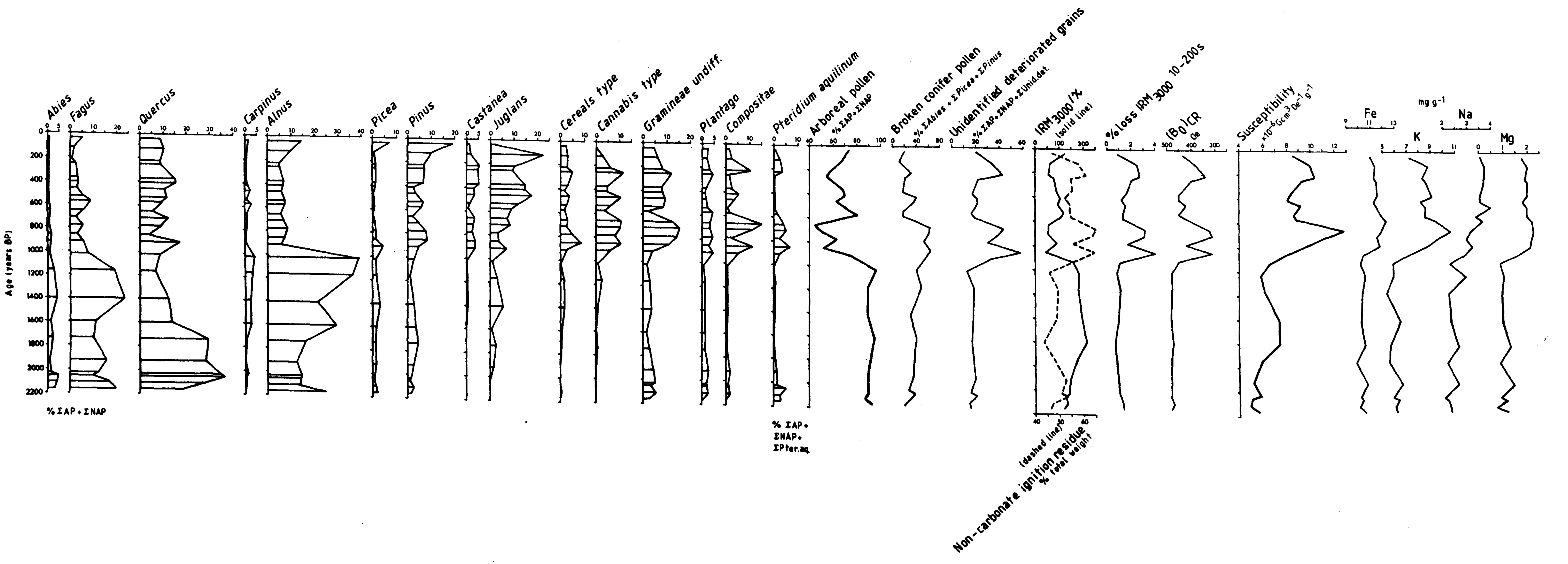
Palaeoecological evidence for environmental change is summarized in figure 7.7. for APL6 and in figures 7.9. and 7.10. for APL1 and AGL5.

Late Iron Age - Roman period 2140 to 1670 years BP (165 BC to 305 AD)

This period corresponds to p.a.z. APL I in APL6. The results of the palaeoecological analysis suggest there has not been any significant disturbance of the environment in the Petit Lac catchment area during this era, although there is archaeological evidence for the presence of man in the lake basin (§ 3.2.1.).

The pollen spectra show little variation in terms of forest composition and total arboreal pollen frequencies remain very high (§ 6.3.1. and figure A3.1.), suggesting that any modification of the forested landscape has been fairly insignificant. From c. 2000 years BP however, the frequency of *Quercus* (oak) pollen begins to decline, which may reflect partial clearance of oak woodland mapped as the Pedunculate oak and/or Downy oak and/or Sessile oak - Hornbeam series on the margins of the cluse floor and lower massif slopes (§ 2.6.2. and figure 2.18.), perhaps associated with the establishment of the estates around which Roman and Gallo-Roman agricultural exploitations

Figure 7.7. Summary of the evidence from APL6 for recent environmental change in the Petit Lac catchment area
Palynological, geochemical and mineral magnetic data are plotted against the proposed age of the sediments (yrs BP = years before 1975).



Abies
Fagus
Quercus
Carpinus
Alnus
Picea
Pinus
Castanea
Juglans
Cereals type
Cannabis type
Gramineae undiff.
Plantago
Compositae
Pteridium aquilinum
Arboreal pollen
% ΣAP+ΣNAP
Broken conifer pollen
% ΣAbies + ΣPicea + ΣPinus
Unidentified deteriorated grains
% ΣAP+ΣNAP+ΣUnid.det.
IRM3000/χ
(solid line)
% loss IRM3000 10-200s
(B0)CR
Oe
Susceptibility
×10⁻⁶Gcm³Oe⁻¹g⁻¹
mg g-1
Fe
Na
K
Mg
Age (years BP)
% ΣAP + ΣNAP
% ΣAP+
ΣNAP+
ΣPter.aq.
Non-carbonate ignition residue
% total weight
(dashed line)

were centred; this feature coincides with the introduction of *Juglans* (walnut) which has already been attributed to the Romans (§ 5.3.4.). A similar feature can be seen in Reynaud's diagram from the Grand Lac (figure 5.14.) where the relative frequency of *Quercus* pollen decreases from c. 216cm and again corresponds with the appearance of *Juglans* pollen.

However, there is no indication of any intensive agricultural activity during this period. Few cereal pollen grains were observed which might suggest this was not an important grain producing area. The grains of *Cannabis* type pollen, which occur in small numbers during this period, are thought to reflect the local cultivation of hemp or the local retting of hemp stems (§ 3.2.1.) rather than the local cultivation of hop (*Humulus lupulus*) which has morphologically similar pollen. Relatively high frequencies of this pollen type occur between the fourteenth and nineteenth centuries and coincide with relatively high frequencies of other cultivated plants and agricultural weeds, and are attributed to hemp (see below). In the eighteenth century records of land-use described in § 3.2.1. there is no specific mention of hop cultivation, whereas hemp cultivation and production is assessed in both the cadastral and tabelle documents. In addition, as Godwin (1967) notes, since it is the female hop inflorescence that is used in brewing, the male plants of hop are planted in small frequency only, and therefore significant numbers of *Humulus* pollen would not be expected. It is assumed that *Cannabis* type pollen observed here represents the same species as in later centuries. It is possible, however, that individual grains may be derived from wild hop plants.

Enhanced frequencies of Compositae (daisy family), *Plantago* (plantain) and Gramineae undiff. (wild grasses) pollen, together with *Pteridium aquilinum* (bracken) spores, are thought to indicate the existence of a predominantly pastoral farming economy. In view of the reported use of the highlands in the pre-alpine region by Celtic populations for grazing their animal herds (Cholley, 1925), together with the rather limited extent of potentially good quality pasture in the hill and lower montane zones of the catchment area, bearing in mind that the cluse floor was not effectively drained until the nineteenth century (Cholley, 1925), it seems likely that this feature reflects the use of grasslands and meadows in the subalpine zone, and possibly also in the high valleys of the Bornes and Bauges, for summer grazing. These pollen types tend to diminish in frequency, particularly after about 1800 years BP, a date which would correspond with the decline in Roman authority in the region and the onset of two to three centuries of insecurity associated with the barbarian invasions. The proposed decline in the use of the high pastures might therefore be a consequence of an associated agricultural recession.

There is no evidence in the results of the geochemical and mineral magnetic measurements to suggest there has been any significant loss of material from catchment surfaces during this period; total χ values and cation levels are consistently low. It has been suggested that within the magnetic mineral assemblage there has been a shift away from the ultra-fine crystal range (§ 6.3.1.) which in addition to the general decrease in the non-carbonate ignition residue content may reflect a decline in the input of soil material to the deepwater sediments of the Petit Lac (§ 7.1.). This may be a consequence of a reduction in the intensity and extent of grazing in the upper montane and subalpine meadows and reflect a decline in the flux density of material from these areas. However, this mineral magnetic feature is fairly insignificant and therefore can only be interpreted very tentatively in this way.

Here it is worth commenting that in a lake basin the size of the

Petit Lac catchment area it cannot be assumed that all eroded soil material is delivered to the stream system and to the lake sediments. It might be expected that much detached soil is stored temporarily or even long-term at various locations within the catchment area. A sediment delivery ratio as little as 0·1 might be expected for the Petit Lac lake-catchment system from the estimates of the U.S. Soil Conservation Service considering simply the size of the watershed (in Kirkby & Morgan, 1980). Furthermore, the gentle gradient of the Eau Morte river between Faverges and the Petit Lac may result in suspended sediments transported from the high valleys of the Bornes and Bauges being deposited on the alluvial floodplain of the cluse floor before delivery to the lake. In this respect, it is relevant to note that the waterlogged and reducing conditions of the gleyed and alluvial soils on the valley floor would not be expected to be suitable for the long-term persistence of ferrimagnetic minerals (Dearing, 1979; Maher, 1984). Thus, it can be envisaged that the scale of catchment disturbance, in terms of total sediment yield, may actually be underestimated in the lake sediment record for sediment fractions eroded from surfaces at relatively distant locations, and it is conceivable that the consequences of the proposed shift in land-use intensity may in reality have been more significant than is apparent from the palaeolimnological analyses.

Early Middle Ages 1670 to 965 years BP (305 to 1010 AD)

This period corresponds to p.a.z. APL II of APL6. Although total tree pollen frequencies remain very high the fossil pollen spectra indicate some changes in catchment vegetation patterns and land-use during the early Medieval period.

The most significant feature is the high frequency of *Alnus* (alder) pollen. During routine counting no distinction was made between the pollen of the lowland alder species, *Alnus glutinosa* (common alder) and *Alnus incana* (grey alder), and the pollen of *Alnus viridis* (green alder), a shrub which is found in the upper montane and subalpine zones. A similar double peak for *Alnus* pollen frequencies can be recognized at what are thought to be contemporaneous levels in Reynaud's Grand Lac diagram (figure 5.14.), viz. at c. 184 and 152cm, but again the different alder pollen types have not been distinguished. Hence, it is not clear if the enhanced frequencies of this pollen type here originate from former woodlands of the Common alder series and/or Grey alder series on the cluse floor[1] or whether they are derived from communities of green alder at higher altitudes.

In the Annecy lake basin *Alnus viridis* today characterizes the damp and cool north-facing subalpine heaths, the steep banks of ravines and gullies within the upper montane forests and is found elsewhere at similar altitudes wherever soils have become decalcified. However, the species has a very limited distribution (figure 2.18.) and is relatively scarce within the calcareous pre-alpine massifs in general as it demands very moist habitats and, in addition, will only thrive where soil profiles are devoid of free calcium and where competition from forest trees is virtually absent. In contrast, extensive stands of green alder are characteristically found in the subalpine zone of the high crystalline alpine massifs to the east of the PréAlpes (Richard, 1967, 1968 and 1969). Nevertheless, despite the limited number of sites suitable for colonization by *Alnus viridis* in the Annecy lake basin compared with the supposed former extent of the lowland alder woodlands (figure 2.18. and footnote below), it is still considered very

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[1] Recent drainage schemes have artificially limited the predicted cover of these woodland communities in Richard's ecological map (figure 2.18.). It is reasonable to suppose that in the past these alder woodland communities were more extensive on the valley floor of the Annecy lake basin.

likely that high frequencies of *Alnus* pollen here reflect an increase in the cover of green alder in the upper montane - subalpine zone; this explanation would be consistent with the decline in upland pasturage mooted above for previous centuries. Moreover, the marked drop in the frequency of this pollen type at the close of this period coincides with the upland forest clearances and management of the "alpage" pastures which signify the beginning of the Monastic period of the High Middle Ages described below. Thus, in the absence of definitive evidence to the contrary, it is hereafter assumed that during the early Medieval period, high *Alnus* pollen frequencies reflect the colonization of abandoned or less intensively grazed pastures in the high tributary valleys and sub-alpine zones by *Alnus viridis*, possibly the result of a continuing agricultural recession or a shift in land-use policy.[1] Unfortunately, very little is known of patterns of settlement and demographic change during this period.

The extremely high frequencies of *Alnus* pollen recorded in this zone may be in part due to the presence of individual plants of *Alnus viridis* along water courses, thus constituting "local" albeit relatively distant pollen sources. In addition, its pollination during early spring would probably have coincided with the main period of snow-melt and high stream discharge which might have been efficient in removing recently deposited pollen and catkins from the vicinity of stream and ravine banks. Furthermore, as the pollen of *Alnus* is produced in abundance and is very light, and as the green alder scrub of the subalpine zone would have grown in relatively open habitats above the altitude of the montane forests, it can be envisaged that a

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[1] In view of the likely response of this species to fluctuations in land-use regimes in the upper montane - subalpine zones during the past, it is vital that in any future work at this site, an attempt is made to distinguish separate curves for the upland and lowland alder pollen types.

significant proportion of this pollen type may have been transferred above the dense canopies of the lower slopes and reach the lake by an aerial transport route as a component of the regional pollen rain. It is interesting to note here that the *Alnus* pollen in this zone is typically well-preserved; within the total *Alnus* count at each level an average of 52·63% grains (± 6·21, 1 standard deviation) were classified as being well-preserved compared to a mean of only 26·64% (± 13·37) for the rest of the profile, which would tend to support a predominantly aerial transport route rather than a route which involved temporary residence at the catchment surface followed by stream transport (§ 7.2.).

A substantial airborne component may also explain why the same feature occurs in the Grand Lac sediments. In this catchment area *Alnus viridis* is today scarce, and has presumably been so in the past, due to the generally lower altitude of the massifs and predominance of south-facing slopes. *Alnus* pollen frequencies in the Grand Lac sediments are somewhat lower than those recorded in the Petit Lac sediments - 15 to 30% compared with 30 to 40%. This might be a distance decay effect in the quality of the regional pollen rain away from the Petit Lac catchment area and perhaps also away from the internal Alps where *Alnus viridis* communities are more abundant and probably have also been so in the past.

During the early Medieval period, the frequency of *Quercus* pollen continues to decline, while relatively high frequencies of *Carpinus* (hornbeam) pollen occur. *Carpinus* immigrated somewhat belatedly into the region, and according to Wegmüller (1977) was promoted by successive phases of forest clearance. Here, although the decline in *Quercus* frequencies may be exaggerated to an extent by the high alder pollen counts, it seems likely that progressive clearance of oak woodland in areas now mapped as belonging to the two Sessile oak -

Hornbeam series (figure 2.18.) may have reduced competition and favoured the establishment of hornbeam seedlings as woodland locally regenerated. Therefore, it is proposed that the *Quercus* decline here reflects in part the exploitation of *Quercus petraea* from the sessile oak woodlands of the valley margins and lower massif slopes.

The high values of *Fagus* (beech) pollen towards the middle of this period may reflect a short phase of regeneration and maturation of beech woodland in the montane zone (figure 2.18.). Similar features can be discerned in the curves for *Abies* (fir) and *Picea* (spruce) pollen, which may in the same way be due to the re-establishment of mature coniferous woodland on the steep massif slopes in the montane and subalpine zones (figure 2.18.). These features are bounded by peaks for the pollen of *Alnus* and the heliophytes *Betula* (birch) and *Corylus* (hazel) (figure A3.1.). The mirror image of the dominant forest trees *Fagus*, *Abies* and *Picea* on the one hand, and the pioneers *Betula* and *Corylus* together with what is thought to be predominantly *Alnus viridis* on the other hand, is possibly in some way the result of the mutual interdependence of these relative percentage counts, rather than being indicative of successive woodland regeneration and forest maturation phases. It is interesting to note that the concentration of *Alnus*, *Betula* and *Corylus* pollen appear to be reciprocally related to the flux of soil material (figure A3.2., q.v. figure 7.3.); they are therefore thought to be predominantly windborne (the pr component, figure 7.5.), or, if reaching the lake from catchment surfaces (the cpr component), are "diluted" by the influx of material from other sites. In contrast, the concentration of *Fagus*, *Abies* and *Picea* pollen appear to be largely independent of the proportion of allochthonous material in the lake sediments, which suggests that these pollen grains may be transported in association with the material leaving catchment surfaces. This observation would not be inconsistent with current understanding of taphonomic and pollen dispersal processes. *Fagus Abies* and *Picea* all pollinate when the forest is in leaf, the last two by virtue of being evergreen trees, in addition to which their pollen grains are relatively heavy. Thus, it might be expected that the majority of their pollen is deposited within these woodland areas. This seems a reasonable supposition in the light of the work of Andersen (1970) and Bradshaw (1981), who have demonstrated that within closed forest canopies, most pollen produced by individual trees are deposited within c. 30m of the parent plant.

In contrast, *Alnus*, *Betula* and *Corylus* all pollinate early in the year before the trees are in leaf which might be expected to favour relatively long distance dispersal, which would be further aided by the small size of the grains and the fact that the pollen is produced in relatively large quantities (Andersen, 1970). In addition, *Betula* and *Corylus* might be expected to colonize and pollinate most abundantly in relatively open sites, such as along woodland fringes and in woodland where the canopy has been opened, and therefore might be more likely to liberate their pollen to the turbulent air flow above the canopy, and thus contribute to the regional pollen rain. A similar line of reasoning has been discussed above for the relatively long distance aerial dispersal of *Alnus viridis* pollen.

Thus, it is conceivable that the peak in *Fagus*, *Abies* and *Picea* pollen during the mid-early Medieval period is simply a function of a shift in the relative importance of different sources of pollen in the catchment area controlled by variations in the flux of mineral material from catchment slopes, which are in turn probably largely controlled by land management practices. The peak in *Fagus*, *Abies* and *Picea* actually coincides with a slight increase in the non-carbonate ignition residue content and mass specific values for χ_{fd} and loss IRM_{3000} (figure A3.1., q.v. figures 6.4. and 6.8.) which are thought to indicate an increase in the relative contribution of topsoil material to the lake sediments (§ 7.1.). This might be the result of the removal of soil material from areas of beech, fir and spruce woodland which contains grains of these pollen types, and this pollen feature might therefore paradoxically be a consequence of the clearance of areas within these forests.

If this is the case, then the minimum in arboreal pollen frequencies in the mid point of this zone will simply be due to a decline in the relative contribution of the pollen of the high pollen producers *Alnus*, *Betula* and *Corylus*, with maximum arboreal pollen frequencies at the beginning and end of the period reflecting the relative importance of sources of these pollen types at these levels.

Similar features can be seen for the same period in Reynaud's diagram, and perhaps the same pollen source - sediment links may be invoked, although the extent to which the Grand Lac sub-basin is as sensitive as the Petit Lac sub-basin to these sorts of processes has not yet been established.

As in the preceding historical period there is little evidence for any intensive agricultural activity during the fourth to eleventh centuries. However, a decline in the frequency of *Plantago* and Compositae Liguliflorae pollen together with an increase in the counts of cereal pollen grains may indicate a shift towards a system with rather more emphasis on arable cultivation. This might be expected to have been concentrated in the better-drained sites on the valley margins, and if so would correlate well with the proposed clearance of sessile oak woodland in these areas. Higher values of *Cannabis* type pollen are thought to reflect more intensive cultivation of hemp. It is possible that the relative scale of agricultural exploitation might be underestimated during this historical period compared with later centuries, due to the high percentages of arboreal pollen which dominate the pollen spectra at these levels.

However, there is no evidence for serious ecosystem degradation in the geochemical and mineral magnetic record; cation levels remain low and there are no significant fluctuations in the mineral magnetic parameters. The full suite of mineral magnetic measurements described in § 6.3.1. for this zone suggest a shift back to finer grain sizes within the magnetic iron oxide assemblages and might therefore indicate an increase in the proportion of soil-derived crystals. If indeed a real feature, this might be associated with the clearance of oak woodland and arable cultivation suggested above.

High Middle Ages 965 to 600 years BP (1010 to 1375 AD)

This period corresponds to p.a.z. APL III of APL6. It is clearly one of major environmental change and ecosystem disturbance.

The total χ and concentrations of all cations (Fe, K, Na and Mg) increase quite markedly between these dates, suggesting an increase in allochthonous mineral input to the deepwater sediments in relation to other sedimentary fractions. This is supported by increases in the % loss IRM_{3000} and decreases in the IRM_{3000}/χ ratio and $(B_0)_{CR}$ which are all thought to indicate an increase in the proportion of soil-derived secondary ferrimagnetic crystals within the mineral magnetic assemblage. Mass specific values for χ_{fd} and loss IRM_{3000}, and the % χ_{fd} all increase in the same way (p.a.z. APL III in figure 6.8.). This relative increase in soil input is thought to give rise, at least in part, to the contemporaneous increase in the non-carbonate ignition residue content. There is a strong possibility that the changes observed in all geochemical and mineral magnetic parameters actually reflect an increase in the rate of loss of material from catchment surfaces. The change in magnetic mineral assemblages which occurs at the beginning of this period - viz. a shift to assemblages dominated by ultra-fine ferrimagnetic crystal sizes - seems to mark the onset of a new regime in terms of the nature of the material flux from catchment surfaces in the Petit Lac sub-basin, a regime which persists up to the present century. This is thought to be reflected in plots of IRM_{3000} and ARM versus χ (figure 7.8.). It can be seen that before this historical era (referred to as the "Pre-Monastic" period) these two remanent magnetic parameters are directly related to χ, indicating that in the first millenium spanned by the sediments in APL6, changes in the total concentration of magnetic minerals are largely due to fluctuations in crystals large enough to hold a stable remanence (stable single domain grains). In contrast, from around the mid-eleventh century (the "Post-Monastic" period) IRM_{3000} and ARM are inversely related to χ, indicating that changes in the concentration of magnetic minerals throughout the sediment sequence of the most recent millenium involves variations in the concentration of crystals unable to hold a remanence, here assumed to be superparamagnetic ferrimagnetic crystals indicative of topsoils.

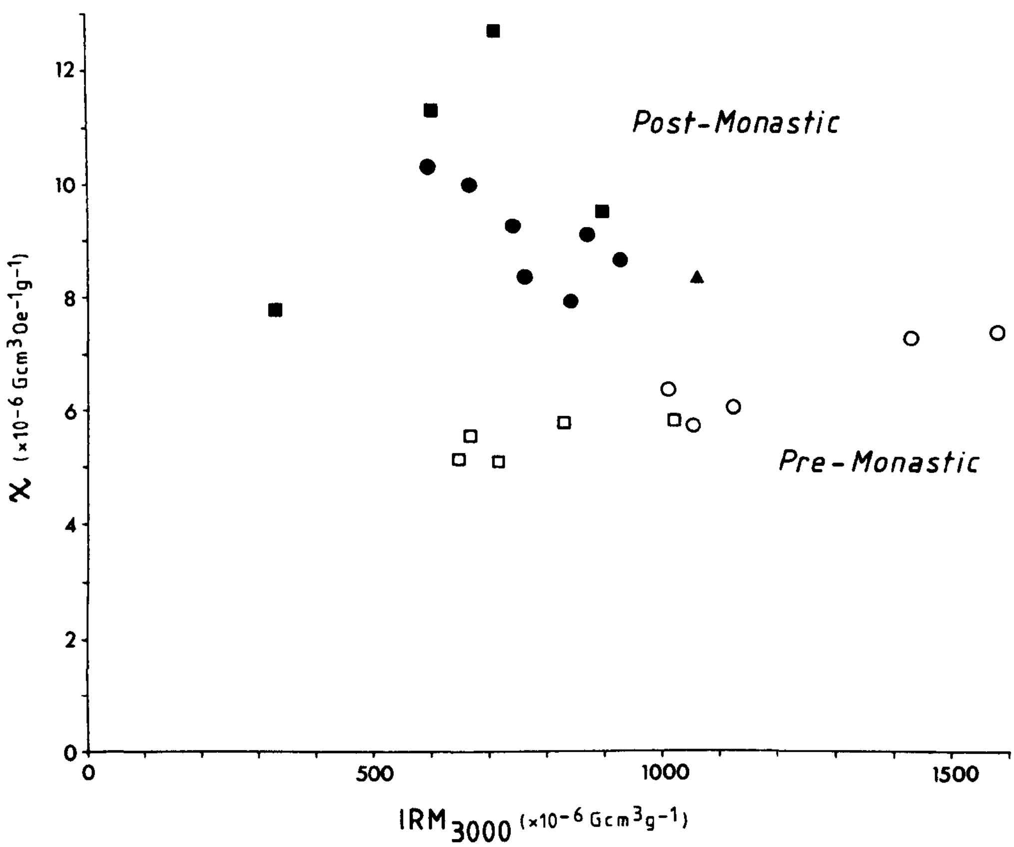
Reynaud has recorded a change in the nature of the sediments accumulating in the Grand Lac sub-basin from c. 150cm (figure 5.14.) which corresponds biostratigraphically with the beginning of this period in APL6. The sediments change from an almost pure marl to a lake mud composed of mineral detritus and marl, indicating that in the Grand Lac catchment system there has also been an increase in soil inwash from catchment surfaces.

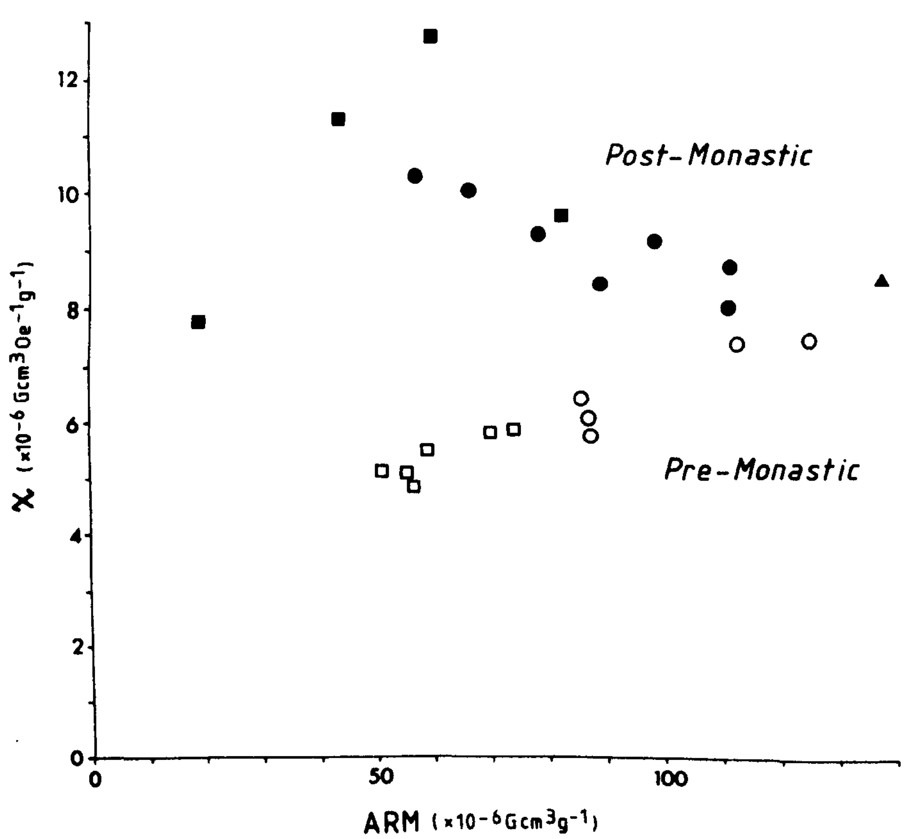
This marked change in the nature of the accumulating sediments is accompanied by significant changes in the fossil pollen spectra in the long pollen diagrams from both sub-basins. In the case of APL6

Figure 7.8. Comparison of the mineral magnetic properties of "Pre-Monastic" and "Post-Monastic" sediments in APL6

(a) IRM_{3000} vs. χ (b) ARM vs. χ

Key:
□ = p.a.z. APL I (2140 to 1670 yrs BP);
○ = p.a.z. APL II (1670 to 965 yrs BP);
■ = p.a.z. APL III (965 to 600 yrs BP);
● = p.a.z. APL IV (600 to 79·5 yrs BP);
▲ = p.a.z. APL V (79·5 to 0 yrs BP).


Post-Monastic
Pre-Monastic
χ (×10⁻⁶ Gcm³Oe⁻¹g⁻¹)
IRM3000 (×10⁻⁶ Gcm³g⁻¹)
0
2
4
6
8
10
12
0
500
1000
1500


Post-Monastic
Pre-Monastic
χ (×10⁻⁶ Gcm³Oe⁻¹g⁻¹)
ARM (×10⁻⁶ Gcm³g⁻¹)
0
2
4
6
8
10
12
0
50
100

from the Petit Lac, most notable is the decline in tree pollen frequencies and the reciprocal increase in herb pollen percentages, which are presumed to reflect significant deforestation in the catchment during this period. The pollen of many woodland dominants decline in frequency during this period, in particular those of *Picea* (spruce), *Abies* (fir) and *Fagus* (beech), suggesting that deforestation was in the main associated with forests of the montane and lower subalpine zones - the Beech, Fir and Spruce series recognized by Richard (§ 2.6.2. and figure 2.18.). This is supported by the influx of high percentages of broken conifer pollen. High frequencies of broken conifer pollen have been linked with ecosystem disturbance by other workers (Oldfield, 1978; Tolonen, 1980) and in this short sequence of sediments the association of a high frequency of broken conifer pollen together with high frequencies of unidentified deteriorated pollen and high proportions of soil material in the sediments may likewise indicate the erosion of forest soils from the massif slopes.

According to the literature reviewed in § 3.1.2. this period is characterized by the first major forest clearances in the uplands of the lake basin, associated with the foundation of the Cistercian and Benedictine monasteries, possibly also urged by population expansion, although to the author's knowledge the latter has not yet been specifically demonstrated for communities in this catchment srea.

The sudden decline in the frequency of *Alnus* pollen at the beginning of this period is thought to reflect the clearance of green alder (*Alnus viridis*) from the subalpine heaths to provide summer pasture. Chavoutier (1977) describes the extensive use of the "alpages" in Savoy by the Cistercians from this period.

It seems likely that fire was used as a method of clearing forest undergrowth and subalpine heath (see Chavoutier, 1977), which might explain the high percentages of broken conifer pollen and the highly viscous magnetic mineral assemblages within the inwashed soils.

Thus, there is much evidence to suggest that deforestation of the steep massif slopes and high tributary valleys in the Petit Lac catchment area has resulted in an accelerated flux of soil from these surfaces to the lake.

Wegmüller (1977) also notes that for sites he has studied in the Northern French Alps, deforestation at the upper montane - subalpine transition was most severe from the High Middle Ages (after 1000 AD).

The low frequencies of *Carpinus* (hornbeam) pollen may reflect clearance of woodland of the Sessile oak - Hornbeam series (§ 2.6.2. and figure 2.18.) on the lower massif slopes and valley margins. However, a similar decline is not seen for the pollen of *Quercus* (oak) which might have been expected considering the supposed coexistence of these two trees in these woodland communities. This might be due to the selective removal of hornbeam, or may result from local regeneration of oak providing competition for *Carpinus* seedlings (cf. the proposed situation in the Early Middle Ages). Another explanation might be that the regeneration of oak in different oak woodland communities (the Downy oak and/or Pedunculate oak woodlands) masks a decline in sessile oak (*Quercus petraea*). It is unclear how this might relate to patterns of ecosystem exploitation. However, the feature is repeated in Reynaud's diagram from the Grand Lac (figure 5.14.), suggesting that it represents some regional landscape pattern.

High frequencies of the pollen of many cultivated plants and associated agricultural weeds occur during this period, notably the Gramineae undiff. (wild grasses), *Plantago* (plantains), Compositeae (daisy family), Cereals type (cultivated cereals) and *Cannabis* type (hemp) together with *Pteridium aquilinum* (bracken) which are thought to indicate a mixed farming system involving arable cultivation and livestock grazing. The relative scale of agricultural exploitation may well be exaggerated in these relative frequency data due to the processes proposed in § 7.2. associated with deforestation and the decrease in arboreal pollen production. The high percentages of Compositeae Liguliflorae pollen may also represent "old" pollen.

Two other pollen types representing cultivated species are *Juglans* (walnut) and *Castanea* (sweet chestnut). Although both trees are thought to have been introduced by the Romans, high frequencies of these pollen are only observed from this period onwards. This may reflect a more intensive management of these trees for their nut crops during the High Middle Ages, although once more the marked increase in these may be in part a function of the significant decline in other tree pollen frequencies.

Increased frequencies of *Pinus* (pine) and *Juniperus* type (juniper) pollen are thought to reflect local secondary regeneration on the deforested massif slopes.

During the few centuries around 1000 - 1200 AD the climate is thought to have been appreciably warmer in Europe than that experienced today, of the order of c. 1°C (Lamb, 1964). In Central Europe vineyards were cultivated further north and up to 220m altitude higher than in recent decades. The upper limits of forests in the Alps are estimated to have lain 70 - 200m above the present (natural) limit until a rapid deterioration in climatic conditions occurred somewhere between 1300 and 1600 AD. In the French Alps the earliest cold periods associated with the onset of the "Little Ice Age" were experienced during the mid-sixteenth century (Bray, 1982). So, in addition to the religious houses exploiting the only extensive areas of undeveloped land available at this time, ie. in the uplands, it is conceivable that the high valleys of the pre-alpine massifs provided attractive sites for new settlement during the warm centuries of the "Little Optimum" climatic period. Such an increase in temperature must have meant that considerable areas of land at relatively high altitudes in the lake basin could have been used for arable cultivation (q.v. figure 2.4.a.), zones which must have proved to be marginal during the following, cooler, centuries. In this respect, it is interesting to note that *Secale* type pollen is more frequent than grains assigned to the Cereals undiff. type category (figure A3.1.). This pollen is assumed to represent the pollen of *Secale cereale* (rye), a cereal which is very hardy and can tolerate poor soil conditions and cooler temperatures, and therefore would have been well-suited to cultivation at higher altitudes. It is possible then that high frequencies of *Secale* type pollen here reflect the production of rye crops in the tributary valleys of the massifs, for example around the new village of Montmin (§ 3.1.2.).

The fact that *Secale* type pollen dominates the total cereal pollen counts at these levels does not necessarily mean that rye was the most important cereal grain cultivated; its relatively high frequencies may simply reflect the fact that the plant is wind-pollinated, its pollen being produced in large quantities and widely dispersed in comparison with other cereal pollen types. However, its relatively high values recorded in this zone compared to counts made for later periods may suggest that the production of rye grain during the High Middle Ages exceeded totals recorded in the mid-eighteenth century documents (table 3.3.).

<u>Late Middle Ages to the mid-nineteenth century 600 to 111 years BP (1375 to 1864 AD)</u>

Many pollen, geochemical and mineral magnetic properties change somewhat abruptly at the boundary between the sediments of the High Middle Ages, corresponding to p.a.z. APL III, and those of the Late Middle Ages, corresponding to p.a.z. APL IV. The close of the former historical period is marked in particular by a fall in total χ values. In addition, the non-carbonate ignition residue content declines appreciably at this point, as do the concentrations of K and Mg. At the same time, other mineral magnetic measurements indicate a decrease in the concentration of viscous ferrimagnetic crystals (mass specific χ_{fd} and loss IRM_{3000}; figure 6.8.) and also in the proportion of ultra-fine crystals within the ferrimagnetic mineral assemblage (IRM_{3000}/χ ratio, $(B_0)_{CR}$, % loss IRM_{3000} and % χ_{fd}; figure 6.8.). The change in all parameters indicates a decrease in the proportion of allochthonous material in these deep-water sediments and, for the reasons referred to in § 7.1., may actually suggest a deceleration in the flux of soils from catchment surfaces.

Corresponding with these features is a decrease in the frequency of the pollen of the Compositae (daisy family), Gramineae undiff. (grass family) and *Cannabis* type (hemp) and, reciprocally, an increase in the frequency of arboreal pollen percentages, most notably of the pioneers *Juniperus* type (juniper), *Pinus* (pine), *Betula* (birch) and *Corylus* (hazel), together with the forest dominants *Fagus* (beech), *Quercus* (oak) and *Carpinus* (hornbeam).

These features are thought to reflect the close of a period of several centuries of large-scale deforestation and soil disturbance. Two situations can be envisaged as having resulted in these palynological, geochemical and mineral magnetic features.

Firstly, a decrease in frequency of those pollen types associated with open land and cultivation, together with an increase in tree pollen percentages, may reflect a marked decline in agricultural activity alongside a significant degree of woodland regeneration. The proposed fall in the flux density of topsoil material from catchment slopes might then be explained in terms of the development of a protective vegetative cover, of pioneer scrub and maturing woodland, in abandoned plots or in less intensively grazed pastures, and therefore a reduction in the proportion of open land in the catchment area susceptible to accelerated losses of material.

However, it is also possible that even in the absence of any substantial reforestation, a significant deceleration in allochthonous material flux may still have occurred as slope-soil systems stabilized and adapted to a new regime of land management, one which did not involve any further large-scale forest clearance or perhaps one which did not involve large areas of land subjected to annual tillage, or some conjunction of the two, with the rate of loss of material from catchment surfaces fluctuating around a new lower mean erosion rate. In this case it can be appreciated that the agricultural decline and woodland regeneration apparent in the fossil pollen record might simply be artefacts of changes in the nature of the allochthonous material flux, ie. a decrease in the proportion of the allochthonous material fraction derived from <u>un</u>forested surfaces, as suggested in § 7.2.

Such changes in landscape patterns and processes may have been associated with a shift in land development policy on the part of the religious houses and other local land-owners, or might perhaps reflect the lack of suitable land for any further expansion. However, another possibility is that this marked change in the nature of the deepwater sediments, and associated palynological properties, might be the result of a pronounced shift in pressure on catchment resources, in turn controlled by population numbers. The date assigned to this zone boundary using the time-scale described in figure 5.18. roughly coincides with the arrival of the Black Death on the European mainland in the mid-fourteenth century. A severe rural depression may well have occurred if communities within this lake basin were affected by these epidemics, at least to the degree estimated for the Savoyard region in general (§ 3.1.2.). The opinion of historical demographers is that rural settlements within the alpine massifs may have been afforded some protection from successive waves of plague by virtue of their relative isolation, compared with villages and towns of the "avant-pays" lowlands to the west of the Pré-Alpes (Binz, 1963). However, the presence of an important international routeway passing through the Annecy and Tamié valleys, linking cities such as Lyon and Geneva with the alpine passes, suggests that the local population may have been exposed to infection and may have been significantly reduced. Therefore, it is tempting to explain a decline in the level of agricultural exploitation and associated reforestation in the Petit Lac catchment area, if indeed these did occur, together with the proposed decrease in the intensity of soil erosion, as being a consequence of a marked fall in population numbers.

During the following historical period, corresponding to p.a.z. APL IV, there is evidence for progressive deforestation within the catchment area of the Petit Lac. The relative frequency of the following tree pollen types all decline and suggest woodland clearance in the valley and on the steep massif slopes, ie. in both the hill and montane zones (figure 2.18.); *Quercus* (oak), *Carpinus* (hornbeam), *Betula* (birch), *Corylus* (hazel), *Ulmus* (elm), *Salix* (willow), *Fagus* (beech) and *Abies* (fir) (figure A3.1.). Minimum values for these pollen types generally occur between c. 1723 and c. 1767 according to the conjectural time-scale described in figure

5.18. (83·5 and 68cm depth in figure A3.1.). If this chronology can be assumed to be fairly accurate, then this would compare well with the historical account of land-use presented in § 3.2.1. for the same period; the eighteenth century was characterized by a regime of intensive arable cultivation, the socio-economic and political antecedents of which have already been outlined. The altitudinal limit of cultivation is not thought to have been exceeded during subsequent centuries. Furthermore, the palynological evidence reviewed here suggests that during the eighteenth century the areal extent of woodland clearance was the greatest experienced in this historical period.

At the same time, relatively high frequencies of many pollen types identified in the eighteenth century documents as being important components of the subsistence farming system occur, viz. *Castanea* (sweet chestnut), *Juglans* (walnut), Cereals type (cultivated cereals) and *Cannabis* type (hemp) (figure 7.7.).

The values for *Castanea* pollen are the highest observed in the whole profile (c. 5%) and correspond with eighteenth century cadastral estimates of 167·1 ha for the areal extent of woodland in which the sweet chestnut was frequent enough to be classified as an individual land-use category due to its economic importance.

The seemingly low area of planted walnuts in c. 1730 (3·3 ha) corresponds with relatively low fossil pollen frequencies of *Juglans* (c. 10%). In contrast, relatively high frequencies are recorded in the pollen diagram during the early sixteenth and mid-nineteenth centuries. Perhaps the growth and reproduction of this Mediterranean species was depressed during the cold periods of the "Little Ice Age"; in the mid-eighteenth century there was a succession of wet, cold winters in Savoy and walnut trees were wiped out in the Annecy region in 1738 (Nicolas, 1978).

Although very high frequencies of *Cannabis* type pollen generally occur during this period, a rapid decline in values occurs in sediments thought to post-date c. 1723. It has already been noted that a very small area of the Petit Lac catchment was used for the cultivation of these plants in c. 1730 (10·4 ha). So, preceding the fall in fossil *Cannabis* type pollen percentages, ie. prior to the late eighteenth century, it can be envisaged that hemp cultivation was far more important and involved greater areas of land.

Many other pollen types associated with pasturage and arable cultivation also occur in relatively high frequencies, such as the Gramineae undiff., Compositae Liguliflorae and Compositae Tubuliflorae, Cruciferae, *Plantago lanceolata*, *Oxyria/Rumex* *Ranunculus* type, Umbelliferae and so on, reflecting the mixed farming economy of local peasant communities. Relatively high frequencies of *Juniperus* type and *Pinus* pollen are thought to result from the colonization of deforested land with *Juniperus communis* scrub and *Pinus sylvestris*.

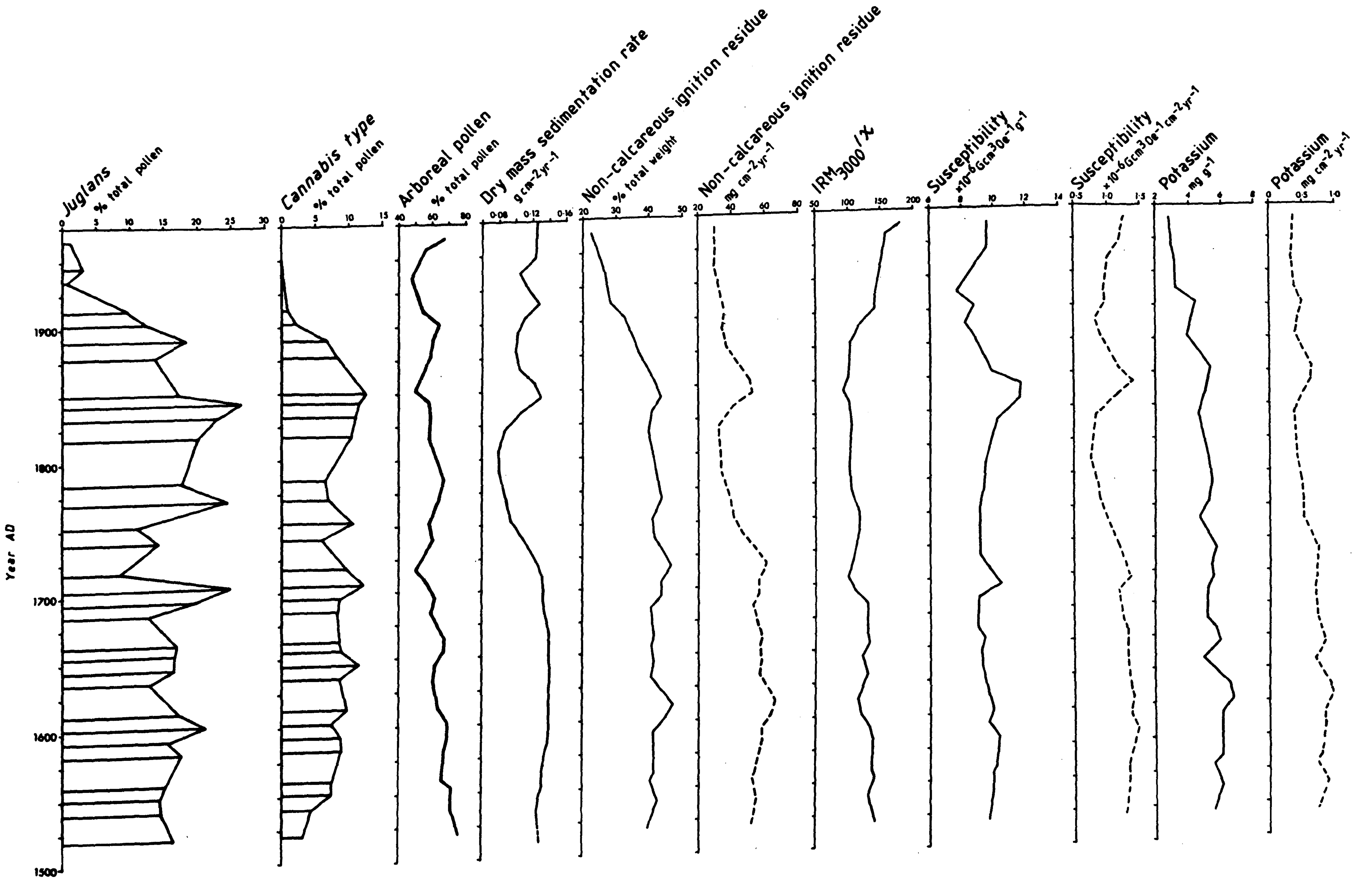
Within the geochemical and mineral magnetic records a well-defined feature occurs at c. 1767, characterized by high mass specific χ values, a high proportion of ultra-fine crystals within the ferrimagnetic mineral assemblage (indicated by high values for % loss IRM_{3000} and low values for IRM_{3000}/χ and $(B_0)_{CR}$) and a high non-carbonate ignition residue content (figure 7.7.). Together these properties indicate an increase in the proportion of soil-derived material within these sediments and, once more, may be the result of an increase in the flux density of allochthonous material. This feature coincides with the minimum arboreal pollen frequencies described above. Therefore, it seems reasonable to suppose that during the eighteenth century an accelerated flux of material from catchment surfaces occurred in the Petit Lac catchment area as a consequence of extensive woodland clearance. This may have been exacerbated by the relatively high proportion of arable land compared to permanent grassland that existed at this time.

P.a.z. AGL a and AGL b(i) of AGL5, the short core from the Grand Lac, also span the early-sixteenth to mid-nineteenth centuries (figure 7.9.). Throughout these two pollen assemblage zones a decline in the frequency of several tree pollen types is evident, including *Betula* (birch), *Corylus* (hazel), *Fagus* (beech), *Quercus* (oak) and *Carpinus* (hornbeam) (figure A3.4.). This suggests progressive deforestation within the Grand Lac catchment area too, around the lake shores and valley margins, and also on the lower massif slopes.

According to the present chronology described in figure 5.17. p.a.z. AGL a corresponds to the sixteenth century. It is characterized by relatively high albeit falling tree pollen percentages. P.a.z. AGL b(i) appears to span subsequent centuries and is characterized by relatively low tree pollen frequencies together with relatively high values of *Castanea* (sweet chestnut), *Juglans* (walnut), Gramineae undiff. (grass family) and *Cannabis* type (hemp) pollen, which suggest an era of further deforestation associated with an increase in the area of land used for providing subsistence for local rural communities. Minimum arboreal pollen frequencies appear to occur in the region of c. 1832 to 1843, ie. towards the mid-nineteenth century (27 - 25cm depth in figure A3.4.) and, at this stage, suggest that in the Grand Lac catchment maximum deforestation occurred at a later date than has been described above for the Petit Lac catchment. This apparent discrepancy may, however, simply be a function of the proposed mineral magnetic correlations.

It has already been considered that the mineral magnetic record of AGL5 is somewhat difficult to interpret solely in terms of the movement of topsoil material (§ 7.1.). However, if the IRM_{3000}/χ

Figure 7.9. Summary of the evidence from AGL5 for recent environmental change in the Grand Lac catchment area
Palynological, geochemical and mineral magnetic data are plotted against the proposed age of the sediments



Juglans % total pollen
Cannabis type % total pollen
Arboreal pollen % total pollen
Dry mass sedimentation rate g cm-2 yr-1
Non-calcareous ignition residue % total weight
Non-calcareous ignition residue mg cm-2 yr-1
IRM3000/χ
Susceptibility ×10-6 Gcm3 Oe-1 g-1
Susceptibility ×10-6 Gcm3 Oe-1 cm-2 yr-1
Potassium mg g-1
Potassium mg cm-2 yr-1
Year AD
1500
1600
1700
1800
1900

ratio can be considered to reflect fluctuations in the delivery of allochthonous material from catchment surfaces for these pre-twentieth century sediments, then it can be seen that declining values for the total arboreal pollen percentage between the fifteenth and mid-nineteenth centuries coincide with decreasing concentrations of allochthonous material, possibly suggesting that an increase in the rate of loss of material from catchment surfaces has occurred alongside the removal of forest and woodland. This is supported by the χ record. From the beginning of the seventeenth century, total χ values, reflecting the influx of both primary and secondary magnetic iron oxides from sources in the Grand Lac catchment, increase and reach a peak at c. 1843, thus correlating with the minimum arboreal pollen frequencies and low IRM_{3000}/χ ratio described above, aswell as with a relatively high non-carbonate ignition residue content. Thus, a high proportion of catchment-derived material in the deepwater sediments of the Grand Lac coincides with the fossil pollen evidence for relatively extensive woodland clearance.

The lowest pollen assemblage zone of APL1, APL a(i), spans the first half of the nineteenth century (and also into the post-annexation period, see below). It has already been proposed that maximum χ values at 38cm in APL1 (figure 6.9.) are contemporaneous with the mid-nineteenth century χ peak described above for AGL5 (figure 5.1.). However, in the sediments of the Petit Lac this feature is more exaggerated and is associated with very high values for the non-carbonate ignition residue content (§ 6.2.2.), a very "soft" ferrimagnetic mineral assemblage (§ 6.3.2.) and high percentages of Compositae Liguliflorae pollen and Filicales spores (§ 6.1.2.), which together indicate that the sediments here contain a very high proportion of soil material. This may have resulted from a relatively short-term increase in the flux density of allochthonous material. It can be envisaged that this palaeolimnological feature may even represent a single catchment "event" such as an intensive rainstorm which removed large quantities of topsoil. During the early nineteenth century a number of high floods were recorded at Annecy (table 2.5.), one of which may have been contemporaneous with the χ peak in APL1 and the putatively synchronous χ maximum in AGL5.

Post-annexation period 111 to 0 years BP (1864 to 1975 AD)

This basically corresponds to p.a.z. AGL b(ii) and AGL c of AGL5, and p.a.z. APL a(ii) and APL b of APL1. The approximate date assigned to the beginning of p.a.z. APL a(ii) of APL1 is actually only 87·5 years BP (§ 6.1.2.), ie. later than the beginning of the corresponding pollen assemblage zone in AGL5. However, as major trends in the nature of the accumulating sediments in APL1 coincide with what are thought to be contemporaneous sediments in AGL5 (in part determined by the mineral magnetic correlations), the earlier date of 111 years BP, which marks the beginning of p.a.z. AGL b(ii) of AGL5, is used here to define the beginning of this historical period. This is also thought to define more precisely the boundary between p.a.z. APL IV and APL V in the long core APL6, previously estimated by linear interpolation to 79·5 years BP (§ 6.1.1.).

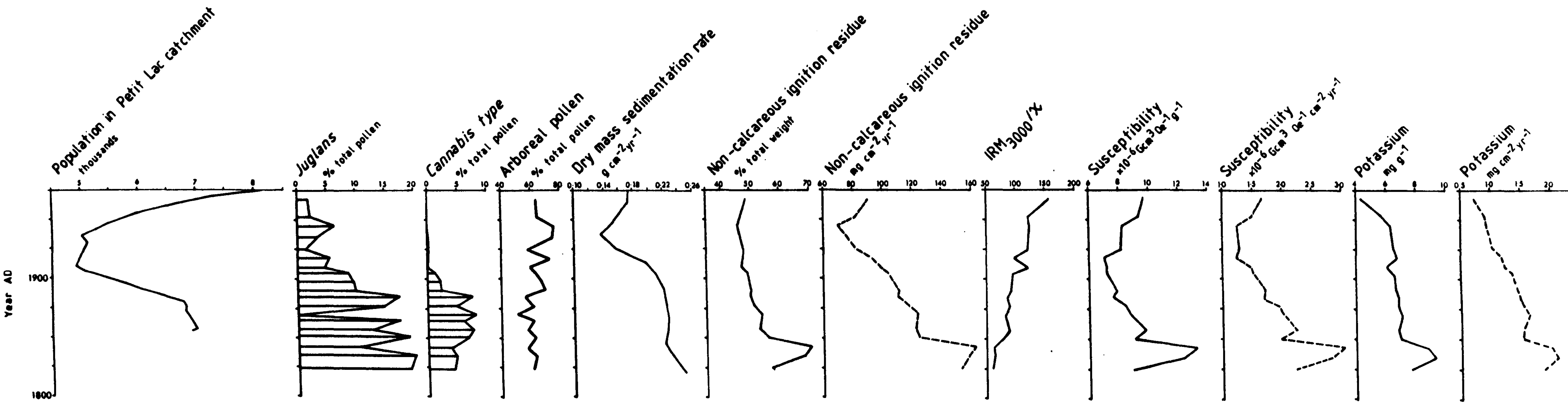
The beginning of this historical period roughly coincides with the date at which Savoy was annexed by France (1860). In terms of land-use history there was from around this time a shift away from the traditional semi-arable, semi-pastoral subsistence farming economy to one which increasingly concentrated on raising livestock, especially cattle (§ 3.2.2.). This was in turn associated with a decline in rural population levels which has been demonstrated for communes within the Petit Lac catchment area (figures 3.1. and 3.2.).

Numerical zonation of the pollen diagrams from AGL5 and APL1 has identified two phases in the expression of rural economic change within the fossil pollen records. The first phase approximately corresponds with the final decades of the nineteenth century (p.a.z. AGL b(ii) of AGL5 and APL a(ii) of APL1) and is characterized by a significant decline in the frequency of *Cannabis* type (hemp) and *Juglans* (walnut) pollen (figures 7.9. and 7.10.). The second phase approximates to the twentieth century (p.a.z. AGL c of AGL5 and APL b of APL1) and is characterized by the disappearance of *Cannabis* type pollen together with the occurrence of low values of *Juglans* pollen. The single pollen spectrum with p.a.z. APL V of APL6 corresponds with the latter phase according to the chronology described in figure 5.18., which is reflected in the zero count for *Cannabis* type pollen and low counts for *Juglans* pollen.

The former phase may in reality be one of transition, a time during which hemp and walnut trees were grown and managed less and less intensively, thus reflecting the decline in the traditional farming economy. However, it is also conceivable that the decline in hemp pollen may in part reflect the erosion of catchment soils containing "old" *Cannabis* type pollen, or the reworking of littoral sediments of the lake, especially if the retting of hemp stems has ever been important along the lake shores (see footnote p. 80). The appearance of *Juglans* pollen in twentieth century sediments probably largely reflects the continued pollination of mature walnut trees and of individual specimens which have regenerated naturally.

Of the other elements of the traditional peasant subsistence system described in § 3.2.1., the fossil pollen records of both short cores also reveal a decline in the frequency of the pollen of *Castanea* (sweet chestnut) and of the cultivated cereals, particularly during the twentieth century. The decrease in *Castanea* pollen percentages may reflect the fact that the sweet chestnut is no longer

Figure 7.10. Summary of the evidence from APL1 for recent environmental change in the Petit Lac catchment area
Palynological, geochemical and mineral magnetic data are plotted against the proposed age of the sediments


Population in Petit Lac catchment
thousands
Juglans
% total pollen
Cannabis type
% total pollen
Arboreal pollen
% total pollen
Dry mass sedimentation rate
g cm-2yr-1
Non-calcareous ignition residue
% total weight
Non-calcareous ignition residue
mg cm-2yr-1
IRM3000/χ
Susceptibility
x10-6Gcm3Oe-1g-1
Susceptibility
x10-6 Gcm3 Oe-1 cm-2 yr-1
Potassium
mg g-1
Potassium
mg cm-2 yr-1
Year AD
1900
1800

actively managed and that natural regeneration is now limited due to competition with co-dominant species within the sessile oak - hornbeam and beech woodlands (§ 2.6.2. and figure 2.18.). The decline in cereal cultivation, indicated by the relatively low percentages of this pollen type, is particularly marked for the post-Second World War period. This compares well with documentary evidence for a regression in arable cultivation during the same period; between 1929 and 1970 the area of land devoted to cereals in the Petit Lac catchment area was reduced by over 50% (table 3.8.).

Few grains of *Vitis* (vine) pollen have been recorded throughout either pollen sequence, so little information can be gleaned from these fossil pollen records about past fluctuations in the cultivation of vine. However, reference to land-use records spanning the period 1730 to 1976 has already enabled some general idea to be gained of the history of viticulture in the Petit Lac catchment area (table 3.7.). In terms of the total land area involved the most significant decline in local vineyards seems to have occurred sometime after 1929.

Alongside the decline in pollen types representing plants associated with the traditional peasant farming system there is evidence for an increase in woodland cover throughout the lake basin.

For AGL5 the pollen of several tree types increase in frequency in sediments spanning the past one and a half centuries, representing woodland within both the hill and montane zones, including *Quercus* (oak), *Carpinus* (hornbeam), *Ulmus* (elm), *Corylus* (hazel), *Fraxinus* (ash), *Salix* (willow), *Betula* (birch), *Fagus* (beech), *Abies* (fir) and *Picea* (spruce) (figure A3.4.). This is thought to indicate some degree of forest regeneration at all altitudes in the Grand Lac catchment area. The appearance of *Populus* (poplar) pollen is thought to reflect the recolonization of abandoned cultivated plots within the beech forests of the massif slopes by *Populus tremula* (figure 2.18. and figure A3.4.).

Major trends in the total arboreal pollen frequency curve for this core (figure 7.9.) suggest that there may have been two major periods of woodland regeneration - the first during the second half of the nineteenth century, perhaps in part reflecting the reforestation of the Montagne du Semnoz described in § 2.6.3., and the second post-dating the Second World War. During the first half of the present century an increase in the frequency of Gramineae undiff. pollen (grass family) and a reciprocal decrease in total arboreal pollen frequencies may be in part a function of the significant decline in *Juglans* pollen, up to this date a major contributor to the total pollen sum. However, these features may also be the result of an increase in agricultural production and/or timber extraction in this catchment, perhaps associated with the two World Wars. So, it is interesting to note here that relatively low counts for *Picea* (spruce) pollen have been recorded at these levels, perhaps reflecting the selected removal of spruce.

Tree pollen frequencies in APL1 are generally higher during this post-annexation period than in earlier decades of the nineteenth century (figure 7.10.). As in AGL5, increases in the frequency of several woodland pollen types are thought to reflect the regeneration of forest and woodland both in the valley and on the massif slopes, including *Quercus* (oak), *Carpinus* (hornbeam), *Corylus* (hazel), *Fraxinus* (ash), *Salix* (willow), *Betula* (birch), *Tilia* (lime) and *Picea* (spruce) (figure A3.3.). However, a notable exception to this list is the pollen of *Fagus* (beech). To some extent this may reflect the under-representation of this pollen type within the regional pollen rain. An alternative explanation lies with recent forestry policy. It has already been noted that forests within the lake basin have been extensively planted with coniferous species during the twentieth century, especially with *Picea excelsa* (Norway spruce), gradually altering the coniferous : deciduous woodland ratio (table 2.10.). This is reflected in all three pollen diagrams, where high frequencies of *Picea* pollen have been recorded within twentieth century sediments.

The pollen of *Pinus* (pine) also increases in frequency; apparently at the end of the nineteenth century in the case of the Grand Lac catchment area and at the beginning of the twentieth century in the Petit Lac catchment area. These features may in part reflect the deliberate planting of various native and exotic pine species in reafforestation programmes, in addition to the colonization of abandoned plots and gulleyed slopes by *Pinus sylvestris* (§ 2.6.2. and figure 2.18.).

It is not possible to discriminate any individual episodes of woodland regeneration in APL1 as appears to be the case in AGL5. The arboreal pollen frequency curve in the short core from the Petit Lac fluctuates markedly, largely as a mirror image of changes in the Gramineae undiff. curve (figure A3.3.). These "noisy" traces are probably a function of the fine resolution pollen counts. In fact, a general <u>decrease</u> in the total percentage of tree pollen is indicated in the fossil pollen record for the twentieth century, while an increase in woodland cover has been recorded for the majority of the communes within the Petit Lac catchment area (table 3.10.). This discrepancy may be due in part to the control of allochthonous sediment provenance over the properties of individual pollen spectra as suggested in § 7.2.

Recent sedimentation in both sub-basins has been described in detail in earlier sections, both from the point of view of changing rates of accumulation (§ 5.4.) and in considering the apparent influence of the influx of untreated sewage and effluent on the geochemical and mineral magnetic properties of the sediments (§ 7.1.).

It is clear that general changes in sedimentation rates and sediment quality correspond with changes in land-use and land-use intensity, as indicated by the palynological and documentary evidence (figures 7.9. and 7.10.). The late-nineteenth century decline in the traditional agricultural system, characterized in particular in the fossil pollen sequences by the fall in *Cannabis* type and *Juglans* pollen values (described above) together with an increase in the relative percentage of many arboreal pollen types, coincides with a fall in sedimentation rate in both sub-basins. In the case of the Petit Lac catchment these also correlate with the post mid-nineteenth century fall in population levels. (Rural population numbers for the Grand Lac catchment are not yet available for comparison). These features would seem to indicate an increase in the cover of protective vegetation at the ground surface, both due to the natural regeneration of woodland and commercial reafforestation, aswell as due to a relative increase in the ratio of permanent grassland to ploughed land as a result of the increasing importance attached to livestock. As a consequence, the rate of loss of material from catchment surfaces appears to have declined. This is reflected in the contemporaneous fall in mass specific χ values, and declining concentrations of K and non-carbonate ignition residue content, which all indicate a decrease in the proportion of allochthonous material in the lake sediments. At the same time there is evidence for a decline in the relative proportion of ultra-fine crystals within these ferrimagnetic mineral assemblages, indicated by relatively low or declining values for mass specific χ_{fd} and % χ_{fd} alongside increasing values for the IRM_{3000}/χ ratio, and in the case of APL1 increasing $(B_0)_{CR}$ and S-values (figures 6.9. and 6.10.). These features, in addition to the fall in total sediment accumulation rate in both sub-basins, would be consistent with a decline in the flux density of material from catchment surfaces in the two catchments.

During the later decades of the nineteenth century there was a decrease in the frequency of precipitation, associated with the retreat of the Alpine glaciers at the close of the "Little Ice Age" (figure 2.7.). This climatic amelioration may also have had a favourable influence on the stability of soil systems in addition to the suggested effect of the major change in land management practices. It is interesting to note that an increase in the mean sedimentation rate in the Grand Lac sub-basin at the beginning of the twentieth century (figure 5.18.) corresponds with a sequence of low arboreal pollen frequencies, which may indicate that a reduction in forest and woodland cover resulted in an accelerated loss of soil from catchment surfaces during this period. However, once more, an alternative explanation must also be considered, that an increase in soil erosion has resulted in an apparent decline in tree pollen percentages due to the sorts of sediment flux - pollen source links described for the Petit Lac lake-catchment system in § 7.2.

From the First World War period, an increase in the sediment accumulation rate is indicated in both sub-basins. Only in the Petit Lac drainage basin is this thought to have been a consequence of the influx of allochthonous material; the mineral magnetic assemblage here indicates an increase in the proportion of viscous ferrimagnetic grains, and an increase in the concentration and annual accumulation of non-carbonate ignition residue is thought to reflect, at least in part, the influx of soil material. The increase in the flux of allochthonous material from the Petit Lac catchment area occurs despite a documented decline in the area of ploughed land (table 3.8.), and an increase in the cover of woodland (table 3.10.). This may reflect road-cutting and construction in this catchment.

In contrast, in the Grand Lac catchment an increase in the rate of sediment accumulation appears to be solely due to the accelerated deposition of autochthonous $CaCO_3$ (§ 7.1.).

CHAPTER 8

CONCLUSIONS

This palaeoecological study of recent environmental change in the drainage basin of the Lac d'Annecy has involved a combination of palynological, geochemical and mineral magnetic analyses. While a multidisciplinary investigation of this nature is not an entirely unique approach to the reconstruction of past ecosystems and landscape change, a detailed comparison of individual pollen spectra with the geochemical and mineral magnetic properties of their matrix sediment has provided an opportunity to assess the extent to which the information content of these palynological data might be influenced by links between catchment sources of pollen and sediment flux processes in this "open" lake basin.

It seems likely that several characteristics of the pollen spectra at each level of the 6m pollen diagram from the Petit Lac may to some extent be determined by the flux of allochthonous material. High proportions of topsoil, thought to be due to accelerated fluxes of material from the catchment though this has not yet been unequivocally demonstrated, are associated in particular with high herbaceous pollen frequencies leading to the suggestion that AP : NAP ratios, for example, may be in part determined by the actual source of eroded soil fractions within the catchment. The concentration of many pollen types in the deepwater sediments of the Petit Lac appears to be regulated by the influx of soil material. This does not seem surprising in view of the calcareous and aerobic nature of many soils in the lake basin which would not be expected to promote the long-term preservation of pollen. In addition, it has been suggested that the selected removal of soil from non-forested surfaces, where local pollen production is low, may also give rise to relatively "dilute" fossil pollen concentrations. From such inferences, a tentative model of the links between pollen production, pollen transfer and the fossil pollen record in the Petit Lac lake-catchment system has been developed. These ideas have encouraged a rather cautious interpretation of the pollen diagrams from this site in terms of environmental change.

Such an approach to the interpretation of pollen diagrams from this sort of depositional environment is thought to complement the empirical studies of pollen flux in "open" lake basins referred to earlier (§ 4.2.1.). For any lake-catchment system in which topsoil material can be characterized in terms of its mineral magnetic properties, as in the Lac d'Annecy drainage basin, the inclusion of mineral magnetic measurements within a palaeoecological research programme might permit a more critical appraisal of the palynological evidence for the reconstruction of past vegetation patterns.

In view of the proposed links between the palynological properties of each sediment sample and the corresponding evidence for soil inwash in this particular study, it has not been possible to interpret the fossil pollen evidence independently, in order to derive a history of landscape change and in turn to provide a context within which to interpret the history of soil erosion as was originally envisaged (§ 1.3.); instead the three major data sets (palynological, geochemical and mineral magnetic) have been interpreted in relation to one another. Moreover, although the twenty four single samples used for these detailed analyses were originally selected in order to derive a general history of sediment flux from catchment surfaces, the fact that many basic palynological properties might actually be determined by the nature of the contemporaneous allochthonous material flux suggests that in order to obtain a meaningful account of vegetation and land-use change, at least over the kind of time-scale attempted here (of the order of centuries rather than millenia), the fossil pollen evidence should be obtained from a more finely resolved sample set.

While a general history of sediment flux from catchment surfaces has been derived from the geochemical and mineral magnetic measurements, at this stage it is not considered possible to quantify rates of sediment accumulation for the long core APL6. Although an approximate time-scale has been fitted to these sediments, a number of sources of error have been considered for the palynological and palaeomagnetic age controls. Moreover, there is much circumstantial evidence to suggest, in this lake-catchment system at least, that variations in the proportion of soil-derived material in the deep-water sediments are actually due to relatively short-term fluctuations in the rate of loss of material from catchment surfaces. In addition, the relatively large autochthonous mineral contribution has not yet been assessed in quantitative terms, ie. the biogenic silica within the non-carbonate ignition residue and the autochthonous precipitates of $CaCO_3$ within the total carbonate fraction, which would need to be considered if sediment accumulation rates are eventually to be calibrated in terms of the flux density of allochthonous sediment only.

The sorts of problems outlined above have been overcome to some extent by the analysis of contiguous sediment samples in the short cores APL1 and AGL5, together with the availability of a radiometrically-determined (^{210}Pb) chronology which has generated what are considered to be relatively accurate sediment accumulation rates. However, in the case of sediments from the Grand Lac sub-basin, it has been seen that the mineral magnetic record cannot be interpreted solely in terms of the influx of topsoil material. In future work it might be more useful to measure the mineral magnetic properties of these sediments on a particle-size basis as the soil-derived secondary ferrimagnetic minerals are thought to be associated with the finer fractions while the primary ferrimagnetic minerals would also be expected to be included in the coarser fractions (q.v. table 7.1.).

The availability of documentary evidence for past land-use patterns has been of immense value in this palaeoecological study for several reasons.

Firstly, reference to the eighteenth century cadastral and "tabelle" documents has enabled the main elements of the traditional subsistence farming system of previous centuries to be identified including, for example, those tree species which would have been conserved and actively managed. This has led to a more enlightened interpretation of the pollen diagrams, particularly in terms of assessing man's impact on the environment.

Secondly, the actual land areas associated with different types of cultivation have been quantified, enabling some perception of the intensity of land-use. These figures have been compared with the fossil pollen percentage data and some attempt has been made to extrapolate these relationships into earlier and later periods.

Thirdly, where comparable data are available from different periods, the direction and dimension of land-use change have been described and compared with the palynological evidence in the fossil pollen records. In this respect, the agricultural production data from the "tabelle" documents are of rather limited value; to the author's knowledge there are no other similar sets of data for comparison. However, the total livestock numbers derived from this source and already considered in relation to twentieth century figures, might prove to be particularly interesting once compared with similar statistics from the sixteenth century and later decades of the eighteenth century, enabling some assessment of the changing demand for pasture within the lake basin.

Bearing in mind the proposed relationship between the palynological and sediment matrix properties within the Petit Lac system, particularly marked in the "Post-Monastic" period, the existence of these documentary sources has allowed a fairly detailed description of land-use and vegetation change in this catchment area which, in the absence of a more finely resolved pollen record, would not have otherwise been possible.

To date documentary evidence for past patterns of ecosystem exploitation have only been researched in part; data have not yet been collated for communes around the Grand Lac, nor for the whole of the Petit Lac catchment area. This has been limited by the time available for the retrieval of information from archival sources in and around Annecy. Nevertheless, the information considered to date has proved to complement the palaeoecological analyses, at least for the time periods at which these records were originally made. Reconstruction of the eighteenth century cadastral information on a total lake basin scale for comparison with corresponding information from twentieth century records, and, where they still exist, with cadastral information from the nineteenth century, would provide a unique opportunity for describing landscape change in the Lac d'Annecy drainage basin and assessing man's impact on the environment, especially if the calcareous laminae observed in these lake sediments prove to be annual features and if the palynological, geochemical and mineral magnetic evidence for soil erosion can in future work be expressed in terms of annual accumulation rates.

Despite the fact that, at this stage, the original aims of the investigation have had to be modified somewhat, this palaeoecological study has revealed two particularly significant periods in the history of the lake basin with regard to the interaction between man and his natural environment.

Within the past two millenia, the most significant period in terms of the scale of catchment disturbance has been the High Middle Ages, spanning the eleventh to fourteenth centuries. The clearance of forest in the uplands of the lake basin, associated with the establishment of religious houses, appears to have resulted in accelerated losses of material from the steep massif slopes. In addition to the more conventional concentration-based geochemical analyses and measures of total magnetic χ which indicate a significant increase in the proportion of allochthonous material and magnetically enhanced soil material in the lake sediments at this point, the consideration of several concentration-independent mineral magnetic parameters has drawn attention to the contemporaneous shift in modal grain size within the ferrimagnetic mineral assemblage itself towards the ultra-fine crystal size range, thought to be characteristic of secondary, and therefore soil-derived, ferrimagnetic minerals.

The shift in focus of the rural economy which occurred in the later decades of the nineteenth century is clearly reflected in the fine-resolution palaeoecological analyses from APL1 and AGL5. The disappearance of the traditional mixed farming economy is characterized in particular in the fossil pollen diagram by a decline in the frequency of *Juglans* (walnut) and *Cannabis* type (hemp) pollen. This coincides with a decrease in the rate of sediment accumulation in both sub-basins which, on the basis of the geochemical and mineral magnetic analyses, appears to reflect a decline in the rate of loss of material from catchment surfaces, thought to be due to the development of permanent grazing lands for the dairying industry alongside a decline in the importance of arable land, the socio-economic consequence of which was a significant fall in rural population levels.

APPENDIX 1

Eighteenth and twentieth century records of land-use in communes of the Petit Lac catchment area

The documentary-based description of land-use and land-use change presented in the main text of this thesis has been limited to characteristics of the Petit Lac catchment area as a whole. However, a more detailed examination of records from individual communes enables some perception of land-use patterns on a much smaller scale for these particular periods in the history of the lake basin. Data from the eighteenth century documentary sources are presented in tables A1.1. to A1.7., and data from the twentieth century documentary sources are presented in tables A1.8. to A1.14.

In order that between-commune comparisons of agricultural productivity can be made, data from the "1754 tabelle" have been standardized using the population figures derived from the 1756 recapitulation. A population figure for Lathuille is not yet available and has been estimated from the number of people deemed to be "capables au travail" in the "1754 tabelle" itself. Faverges had become an important market town by the mid-eighteenth century. In the "1754 tabelle" only 300 people in this commune were classified as "capables au travail", yet in the 1756 recapitulation the population numbered 1346. It seems that in Faverges only a small proportion of the population was engaged in the full-time exploitation of agricultural land and this should be borne in mind when comparing standardized figures for this commune with those from elsewhere.

LIST OF TABLES

		PAGE NO.
A1.1	Cereal production in communes of the Petit Lac catchment area, 1754	295
A1.2	Production of hay and straw in communes of the Petit Lac catchment area, 1754	296
A1.3	Cultivation of walnut in communes of the Petit Lac catchment area in the 18th. century	297
A1.4	Cultivation of chestnut in communes of the Petit Lac catchment area in the 18th. century	298
A1.5	Cultivation of vine in communes of the Petit Lac catchment area in the 18th. century	299
A1.6	Cultivation of hemp in communes of the Petit Lac catchment area in the 18th. century	300
A1.7	Pastoral farming in communes of the Petit Lac catchment area, 1754	301
A1.8	Decline in the area of cultivated land in communes of the Petit Lac catchment area, 1929-1970	302
A1.9	Decline in the area of ploughed land in communes of the Petit Lac catchment area, 1929-1970	303
A1.10	Change in the area of cereal cultivation in communes of the Petit Lac catchment area, 1929-1970	304
A1.11	Change in the area of permanent grassland in communes of the Petit Lac catchment area, 1929-1970	305
A1.12	Change in the number of cattle in communes of the Petit Lac catchment area, 1929-1970	306
A1.13	Change in the number of sheep in communes of the Petit Lac catchment area, 1929-1970	307
A1.14	Change in the number of pigs in communes of the Petit Lac catchment area, 1929-1970	308

Annual production (hl)	Wheat	Rye	Barley	Oats	Total cereals
Chevaline	35·5	2·7	3·3	53·3	94·9
Doussard	295·9	177·7	89·3	666·5	1229·4
Duingt	91·5	108·4	111·3	285·2	596·5
Entrevernes	20·4	49·8	24·7	298·6	393·4
Faverges	710·9	807·7	14·0	3199·0	4731·6
Giez	222·2	177·7	466·4	333·2	1199·5
Lathuille	124·4	88·9	33·3	311·9	558·5
Montmin	162·3	56·8	350·6	782·4	1352·0
Seythenex	148·4	296·8	350·5	1775·4	2571·1

Annual production (hl/person)	Wheat	Rye	Barley	Oats	Total cereals
Chevaline	0·47	0·04	0·04	0·71	1·26
Doussard	0·59	0·35	0·18	1·32	2·43
Duingt	0·48	0·57	0·58	1·49	3·12
Entrevernes	0·11	0·26	0·13	1·56	2·06
Faverges	0·53	0·60	0·01	2·38	3·52
Giez	0·85	0·68	1·79	1·28	4·60
Lathuille	0·56	0·40	0·15	1·41	2·53
Montmin	0·51	0·18	1·10	2·45	4·23
Seythenex	0·34	0·69	0·81	4·10	5·94

Table A1.1. Cereal production in communes of the Petit Lac catchment area, 1754 (data from the "1754 tabelle" ADHS)

	Annual production			
	(t)		(t/person)	
	Hay	Straw	Hay	Straw
Chevaline	28•3	15•7	0•38	0•21
Doussard	188•4	200•9	0•37	0•40
Duingt	20•4	19•2	0•11	0•10
Entrevernes	10•1	22•0	0•05	0•12
Faverges	361•5	501•7	0•27	0•37
Giez	72•2	128•7	0•28	0•49
Lathuille	62•8	56•5	0•28	0•26
Montmin	126•8	251•2	0•39	0•78
Seythenex	164•2	328•4	0•38	0•76

Table A1.2. Production of hay and straw in communes of the Petit Lac catchment area, 1754 (data from the "1754 tabelle", ADHS)

	Area cultivated in 1730[1]	Production of oil in 1754[2]	
	(ha)	(l)	(l/person)
Chevaline	0	120·9	1·61
Doussard	0	483·4	0·96
Duingt	0	362·6	1·90
Entrevernes		0	0
Faverges	1·60	1087·7	0·81
Giez	0	423·0	1·62
Lathuille	0	362·6	1·64
Montmin	0	0	0
Seythenex	0·77	453·2	1·05
Talloires	0·93		

Table A1.3. Cultivation of walnut in communes of the Petit Lac catchment area in the eighteenth century (data from: [1] the "Cadastre Savoyarde", ADHS; [2] the "1754 tabelle", ADHS)

	Area cultivated in 1730 (ha)
Chevaline	21·37
Doussard	3·86
Duingt	25·53
Faverges	77·88
Giez	22·21
Lathuille	16·19
Montmin	0
Seythenex	0·05
Talloires	0

Table A1.4. Cultivation of chestnut in communes of the Petit Lac catchment area in the eighteenth century (data from the "Cadastre Savoyarde", ADHS)

	Area cultivated in 1730[1]	Production of wine in 1754[2]	
	(ha)	(hl)	(1/person)
Chevaline	1·78	14·5	19·34
Doussard	43·94	423·0	83·76
Duingt	5·46	62·8	32·90
Entrevernes		0	0
Faverges	92·58	1933·6	143·66
Giez	0·46	0	0
Lathuille	14·24	125·7	56·87
Montmin	0	0	0
Seythenex	0	0	0
Talloires	98·04		

Table A1.5. Cultivation of vine in communes of the Petit Lac catchment area in the eighteenth century (data from:
[1] the "Cadastre Savoyarde", ADHS:
[2] the "1754 tabelle", ADHS)

	Area cultivated in 1730[1]	Production of hemp in 1754[2]	
	(ha)	(kg)	(kg/person)
Chevaline	0•28	62•8	0•84
Doussard	1•95	1255•8	2•49
Duingt	0	188•4	0•99
Entrevernes		62•8	0•33
Faverges	3•67	3139•6	2•33
Giez	2•15	879•1	3•37
Lathuille	0•17	314•0	1•42
Montmin	1•81	502•3	1•56
Seythenex	0•11	1255•8	2•90
Talloires	0•21		

Table A1.6. Cultivation of hemp in communes of the Petit Lac catchment area in the eighteenth century (data from:
[1] the "Cadastre Savoyarde", ADHS;
[2] the "1754 tabelle", ADHS)

	No. of animals					
	No.			No./person		
	Cattle	Goats	Sheep	Cattle	Goats	Sheep
Chevaline	34	21	26	0·45	0·28	0·35
Doussard	144	0	110	0·29	0	0·22
Duingt	131	33	56	0·68	0·17	0·29
Entrevernes	158	78	92	0·83	0·41	0·48
Faverges	681	250	659	0·51	0·19	0·49
Giez	127	128	140	0·48	0·49	0·54
Lathuille	114	27	50	0·51	0·12	0·23
Montmin	315	100	165	0·98	0·31	0·51
Seythenex	428	224	175	0·99	0·52	0·40

Table A1.7. Pastoral farming in communes of the Petit Lac catchment area, 1754 (datd from the "1754 tabelle", ADHS)

	Area (ha)		% of commune area	
	1929[1]	1970[2]	1929	1970
Chevaline	1249	113	88·2	8·0
Doussard	815	423	40·5	21·0
Faverges	1278	778	49·4	30·1
Giez	464	228	36·7	18·0
Lathuille	445	304	50·8	34·7
Montmin*	891	364	54·7	22·3
Seythenex	1381	361	41·3	10·8

Table A1.8. Decline in the area of cultivated land in communes of the Petit Lac Catchment area, 1929 - 1970 (data from: [1] the "Enquête Agricole de 1929, Département de Haute-Savoie", ADHS†; [2] "Résultats du Recensement Général de l'Agriculture de 1970. Département de Haute-Savoie." Ministère de l'Agriculture, 1971)
† collected by E.A. Steel

	Area (ha)		% of commune area	
	1929[1]	1970[2]	1929	1970
Chevaline	41	23	2•9	1•6
Doussard	488	114	24•2	5•7
Faverges	400	163	15•5	6•3
Giez	130	55	10•3	4•4
Lathuille	222	51	25•3	5•8
Montmin	203	22	12•5	1•4
Seythenex	124	37	3•7	1•1

Table A1.9. Decline in the area of ploughed land in communes of the Petit Lac catchment area, 1929 - 1970 (see legend to table A1.8. for sources of data)

	Area (ha)		% of commune area	
	1929[1]	1970[2]	1929	1970
Chevaline	8	12	0•6	0•9
Doussard	109	28	5•4	1•4
Faverges	108	49	4•2	1•9
Giez	47	19	3•7	1•5
Lathuille	49	18	5•6	2•1
Montmin	25	5	1•5	0•3
Seythenex	44	7	1•3	0•2

Table A1.10. Change in the area of cereal cultivation in communes of the Petit Lac catchment area, 1929 - 1970 (see legend to table A1.8. for sources of data)

	Area (ha)		% of commune area	
	1929[1]	1970[2]	1929	1970
Chevaline	498	86	35•2	6•1
Doussard	302	307	15•0	15•2
Faverges	698	597	27•0	23•1
Giez	321	171	25•4	13•5
Lathuille	192	249	21•9	28•4
Montmin	681	340	41•8	20•9
Seythenex	1187	319	35•5	9•6

Table A1.11. Change in the area of permanent grassland in communes of the Petit Lac catchment area, 1929 - 1970 (see legend to table A1.8. for sources of data)

	No.		No./km²	
	1929[1]	1970[2]	1929	1970
Chevaline	53	97	3·7	6·9
Doussard	575	444	28·6	22·1
Faverges	742	608	28·7	23·5
Giez	230	187	18·2	14·8
Lathuille	248	320	28·3	36·5
Montmin	180	317	11·1	19·5
Seythenex	460	323	13·8	9·7

Table A1.12. Change in the number of cattle in communes of the Petit Lac catchment area, 1929 - 1970 (see legend to table A1.8. for sources of data)

	No.		No./km^2	
	1929[1]	1970[2]	1929	1970
Chevaline	2	0	0·1	0
Doussard	68	2	3·4	0·1
Faverges	99	64	3·8	2·5
Giez	0	0	0	0
Lathuille	14	15	1·6	1·7
Montmin	16	0	1·0	0
Seythenex	54	0	1·6	0

Table A1.13. Change in the number of sheep in communes of the Petit Lac catchment area, 1929 - 1970 (see legend to table A1.8. for sources of data)

	No.		No./km^2	
	1929[1]	1970[2]	1929	1970
Chevaline	0	0	0	0
Doussard	150	488	7•5	24•2
Faverges	300	329	11•6	12•7
Giez	80	140	6.3	11•1
Lathuille	131	70	15•0	8•0
Montmin	70	112	4•3	6•9
Seythenex	137	80	4•1	2•4

Table A1.14. Change in the number of pigs in communes of the Petit Lac catchment area, 1929 - 1970 (see legend to table A1.8. for sources of data)

APPENDIX 2

Colour stratigraphy of APL6

A colour stratigraphy was recorded by comparing the sediments with the standard Munsell soil colour charts (5th. edition). The soil colour names corresponding to the Munsell notation used in the colour descriptions are listed below:

Munsell notation	Soil colour name
10YR 3/1	very dark grey
10YR 3/2	very dark greyish brown
10YR 3/3	dark brown
10YR 4/2	dark greyish brown
10YR 4/3	dark brown/brown
10YR 4/4	dark yellowish brown
10YR 5/3	brown
10YR 5/4	yellowish brown
2·5Y 3/2	very dark greyish brown
2·5Y 4/2	dark greyish brown
2·5Y 4/4	olive brown
2·5Y 5/4	light olive brown
2·5Y 8/2	white
2·5Y 8/4	pale yellow

In the following table depths correspond to centimetres below the mud-water interface and not to the original depths below the top of the core-tube

The contacts are abbreviated as follows: m = merging, s = sharp.

Depth (cm)	Munsell notation	Contact	
8 - 19	2·5Y 4/2		
		m	
19 - 32·7	2·5Y 4/4		
		m	
32·7 - 33	2·5Y 4/2		
		m	
33 - 58·5	10YR 5/4		
		m	
58·5 - 63	2·5Y 4/2		
		m	
63 - 65	2·5Y 3/2		
		s	
65 - 72	10YR 5/4		
		m	
72 - 74	10YR 3/3		
		s	
74 - 75	10YR 5/4		
		m	
75 - 76	10YR 3/3		
		s	
76 - 87	10YR 5/4		
		m	
87 - 92·5	10YR 3/3		
		s	
92·5 - 92·9	10YR 5/3		
		m	
92·9 - 95·8	10YR 4/3		
		m	
95·8 - 98	10YR 5/3		
		m	
98 - 100	10YR 4/3		
		m	
100 - 103	10YR 5/3		
		m	
103 - 106·5	10YR 4/3		
		m	
106·5 - 110	10YR 5/3		
		m	
110 - 110·2	10YR 4/3		
		m	
110·2 - 114·2	10YR 5/3		
		m	
114·2 - 116·5	10YR 4/2		
		s	
116·5 - 126·2	10YR 5/4		
		m	
126·2 - 128	2·5Y 4/2		
		m	
128 - 138	10YR 5/4		
			join of core sections
138 - 145·5	10YR 3/3		
		s	
145·5 - c.156	10YR 5/4		
		m	

Depth (cm)	Munsell notation	Contact	
c.156 - 158•8	10YR 3/3		
		s	
158•8 - 162	10YR 5/4		
		m	
162 - 164•5	10YR 3/3		
		m	
164•5 - 193	10YR 5/4		
		m	
193 - 204•2	10YR 3/3		
		s	
204•2 - 209	10YR 5/4		
		m	
209 - 209•7	10YR 3/3		
		m	
209•7 - 274	10YR 5/4		
		m	
274 - 305•8	10YR 3/3		join of core sections at 288cm
		s	
305•8 - 310	10YR 5/4		
		m	
310 - 312•7	10YR 4/3		
		m	
312•7 - 317•5	10YR 5/4		
		m	
317•5 - 321	10YR 4/3		
		s	
321 - 324•5	10YR 5/4		
		s	
324•5 - 326	10YR 4/3		
		m	
326 - 348	10YR 5/4		
		m	
348 - 358	10YR 3/3		
		m	
358 - 359•7	10YR 5/4		
		m	
359•7 - 361	10YR 3/3		
		m	
361 - 367•5	10YR 5/4		
		m	
367•5 - 368	10YR 4/3		
		m	
368 - 376	10YR 5/4		
		m	
376 - 381	10YR 4/2		
			381cm - 398cm material missing
398 - 404•5	10YR 5/4		
		m	
404•5 - 406•2	10YR 3/3		
		m	
406•2 - 412	10YR 5/4		
		m	
412 - 416	10YR 4/3		
		m	

Depth (cm)	Munsell notation	Contact	
416 - 418•5	10YR 5/4		
		m	
418•5 - 420	10YR 3/3		
		s	
420 - 435	10YR 5/4		
		m	
435 - 439•2	10YR 4/2		join of core sections
		s	at 438cm
439•2 - 463•8	10YR 4/4		
		m	
463•8 - 465	10YR 3/3		
		m	
465 - 466•4	10YR 3/2		
		s	
466•4 - 467•6	10YR 4/4		
		m	
467•6 - 468•8	10YR 3/3		
		m	
468•8 - 470•7	10YR 4/4		
		m	
470•7 - 471•8	10YR 3/3		
		m	
471•8 - 478	10YR 5/3		
		m	
478 - 480•7	2•5Y 4/2		
		m	
480•7 - 485•8	10YR 3/3		
		s	
485•5 - 486•2	2•5Y 8/4		
		s	
486•2 - 487•2	10YR 4/2		
		s	
487•2 - 487•8	10YR 5/3		
		s	
487•8 - 488•3	10YR 4/2		
		s	
488•3 - 495	10YR 5/4		
		m	
495 - 500	10YR 4/2		
		s	
500 - 503•7	2•5Y 5/4		
		m	
503•7 - 511•2	10YR 5/4		
		s	
511•2 - 525•8	2•5Y 5/4		
		m	
525•8 - 526•8	2•5Y 4/2		
		s	
526•8 - 530	2•5Y 5/4		
		m	
530 - 535•3	2•5Y 4/2		
		m	
535•3 - 536	10YR 3/2		
		s	
536 - 539•2	2•5Y 4/2		
		m	

Depth (cm)	Munsell notation	Contact
539·2 - 542	10YR 3/1	
		s
542 - 549	2·5Y 4/2	
		m
549 - 553	2·5Y 3/2	
		m
553 - 560·2	laminations of 2·5Y 4/2 and 2·5Y 8/2	
		s
560·2 - 560·8	10YR 3/2	
		s
560·8 - 568·3	laminations of 2·5Y 4/2 and 2·5Y 8/2	
		s
568·3 - 568·9	10YR 3/2	
		s
568·9 - 572	laminations of 2·5Y 4/2 and 2·5Y 8/2	
		s
572 - 573·3	10YR 3/2	
		s
573·3 - 588	laminations of 2·5Y 4/2 and 2·5Y 8/2	

APPENDIX 3

Pollen diagrams

		FACING PAGE NO.
A3.1	Pollen percentage diagram, APL6	315
A3.2	Pollen concentration diagram, APL6	316
A3.3	Pollen percentage diagram, APL1	317
A3.4	Pollen percentage diagram, AGL5	318
A3.5	Percentage diagram of preservation classes by pollen and spore category, APL6	319
A3.6	Concentration diagram of preservation classes by pollen and spore category, APL6	320

Figure A3.1. Pollen percentage diagram, APL6
Pollen frequencies are expressed as a percentage of the basic pollen sum. The calculation of frequencies of pollen and spore types outside the basic pollen sum is described in § 4.2.6. (Abbreviations: undiff. = undifferentiated; Compositae (Lig.) = Compositae Liguliflorae; Compositae (Tub.) = Compositae Tubuliflorae; *Potamogeton* sect. *Eupot.* = *Potamogeton* section *Eupotamogeton*).

APL6

APL V
APL IV
APL III
APL II
APL I
CM
% TOTAL POLLEN
NUMBER OF TAXA
POLLEN SUM
SUM TREES AND SHRUBS
SUM HERBS

Figure A3.2. Pollen concentration diagram, APL6
Pollen concentrations are expressed per gram dry weight of sediment. (Abbreviations: undiff. = undifferentiated; Compositae (Lig.) = Compositae Liguliflorae; Compositae (Tub.) = Compositae Tubuliflorae; *Potamogeton* sect. *Eupot.* = *Potamogeton* section *Eupotamogeton*).

APL6


CM
APL V
APL IV
APL III
APL II
APL I
100
200
300
400
500
ABIES
PICEA
PINUS
JUNIPERUS TYPE
ACER
ALNUS
BETULA
BUXUS SEMPERVIRENS
CARPINUS
CASTANEA
CORYLUS
ERICACEAE
FAGUS
FRAXINUS
QUERCUS
SALIX
SAMBUCUS
TILIA
ULMUS
POLLEN SUM
NUMBER OF TAXA
EQUISETUM
POLLEN CONCENTRATION X1000

Figure A3.3. Pollen percentage diagram, APL1
Pollen frequencies are expressed as a percentage of the basic pollen sum. The calculation of frequencies of pollen and spore types outside the basic pollen sum is described in § 4.2.6. (Abbreviations: undiff. = undifferentiated; Compositae (Lig.) = Compositae Liguliflorae; Compositae (Tub.) = Compositae Tubuliflorae; *Saxifraga opp.* type = *Saxifraga oppositifolia* type; *Potamogeton* sect. *Eupot.* = *Potamogeton* section *Eupotamogeton*).

APL1


CM
APL b
APL a(ii)
APL a(i)
% TOTAL POLLEN
% TOTAL POLLEN
SUM TREES AND SHRUBS
SUM HERBS
POLLEN SUM
NUMBER OF TAXA

Figure A3.4. Pollen percentage diagram, AGL5
Pollen frequencies are expressed as a percentage of the basic pollen sum. The calculation of frequencies of pollen and spore types outside the basic pollen sum is described in § 4.2.6. (Abbreviations: undiff. = undifferentiated; Compositae (Lig.) = Compositae Liguliflorae; Compositae (Tub.) = Compositae Tubuliflorae; *Saxifraga opposit.* type = *Saxifraga oppositifolia* type; *Potamogeton* sect. *Eupot.* = *Potamogeton* section *Eupotamogeton*).

AGL5


CM
AGL c
AGL b(ii)
AGL b(i)
AGL a
LARIX
ABIES
PICEA
PINUS
JUNIPERUS TYPE
ACER
ALNUS
BETULA
BUXUS SEMPERVIRENS
CARPINUS
CASTANEA
CORYLUS
CRATAEGUS TYPE
EPHEDRA
ERICACEAE TYPE
FAGUS
FRAXINUS
HIPPOPHAE RHAMNOIDES
LIGUSTRUM
JUGLANS
OLEACEAE UNDIFF.
PLATANUS
POPULUS
QUERCUS
RUBUS
SALIX
SAMBUCUS
TILIA
ULMUS
VIBURNUM
GRAMINEAE UNDIFF.
CEREALS TYPE
FAGOPYRUM
CANNABIS TYPE
VITIS
CAMPANULA TYPE
LOBELIA TYPE
CARYOPHYLLACEAE
SPERGULA TYPE
CHENOPODIACEAE
COMPOSITAE (LIG.)
COMPOSITAE (TUB.) UNDIFF.
ARTEMISIA
CENTAUREA NIGRA TYPE
CRUCIFERAE
CYPERACEAE
LAMIUM TYPE
STACHYS TYPE
LEGUMINOSAE UNDIFF.
LOTUS TYPE
ONOBRYCHIS TYPE
ONONIS TYPE
TRIFOLIUM TYPE
MERCURIALIS
PLANTAGO UNDIFF.
PLANTAGO LANCEOLATA
PLANTAGO MEDIA/MAJOR
OXYRIA/RUMEX
POLYGONUM UNDIFF.
POLYGONUM AVICULARE
POLYGONUM BISTORTA TYPE
POLYGONUM CONVOLVULUS TYPE
RANUNCULUS TYPE
CALTHA TYPE
THALICTRUM TYPE
RHINANTHUS TYPE
SCROPHULARIACEAE
ROSACEAE UNDIFF.
DRYAS
FILIPENDULA
POTERIUM SANGUISORBA
POTENTILLA TYPE
RUBIACEAE
SAXIFRAGA UNDIFF.
SAXIFRAGA NIVALIS
SAXIFRAGA OPPOSIT. TYPE
SAXIFRAGA STELLARIS
SOLANUM NIGRUM
TOFIELDIA
UMBELLIFERAE
BUPLEURUM TYPE
URTICA TYPE
POLLEN SUM
NUMBER OF TAXA
FILICALES UNDIFF.
PTERIDIUM AQUILINUM
EQUISETUM
LYCOPODIUM
CALLITRICHE
POTAMOGETON SECT. EUPOT.
UNIDENTIFIED UNKNOWN
UNIDENTIFIED CONCEALED
UNIDENTIFIED DETERIORATED
SUM TREES AND SHRUBS
SUM HERBS
% TOTAL POLLEN

Figure A3.5. Percentage diagram of preservation classes by pollen and spore category, APL6
Pollen frequencies are expressed as a percentage of the basic pollen sum. The calculation of frequencies of pollen and spore types outside the basic pollen sum is described in § 4.2.6. The calculation of the frequency of broken conifer pollen is described in § 4.2.5. Preservation classes are described in § 4.2.5.

APL6

CM
APL V
APL IV
APL III
APL II
APL I
TREES AND SHRUBS - CORRODED
TREES AND SHRUBS - DEGRADED
TREES AND SHRUBS - CRUMPLED
TREES AND SHRUBS - BROKEN
TREES AND SHRUBS - WELL-PRESERVED
HERBS - CORRODED
HERBS - DEGRADED
HERBS - CRUMPLED
HERBS - BROKEN
HERBS - WELL-PRESERVED
POLLEN SUM
NUMBER OF TAXA
PTERIDOPHYTA - CORRODED
PTERIDOPHYTA - DEGRADED
PTERIDOPHYTA - CRUMPLED
PTERIDOPHYTA - BROKEN
PTERIDOPHYTA - WELL-PRESERVED
TOTAL PTERIDOPHYTA
UNIDENTIFIED - CORRODED
UNIDENTIFIED - DEGRADED
UNIDENTIFIED - CRUMPLED
UNIDENTIFIED - BROKEN
TOTAL UNIDENTIFIED DETERIORATED
BROKEN CONIFER GRAINS
SUM TREES AND SHRUBS
SUM HERBS
% TOTAL POLLEN
% TOTAL POLLEN

Figure A3.6. Concentration diagram of preservation classes by pollen and spore category, APL6 Concentrations are expressed per gram dry weight of sediment. Preservation classes are described in § 4.2.5.

APL6

CM
APL V
APL IV
APL III
APL II
APL I
TREES AND SHRUBS - CORRODED
TREES AND SHRUBS - DEGRADED
TREES AND SHRUBS - CRUMPLED
TREES AND SHRUBS - BROKEN
TREES AND SHRUBS - WELL-PRESERVED
HERBS - CORRODED
HERBS - DEGRADED
HERBS - CRUMPLED
HERBS - BROKEN
HERBS - WELL-PRESERVED
POLLEN SUM
NUMBER OF TAXA
PTERIDOPHYTA - CORRODED
PTERIDOPHYTA - DEGRADED
PTERIDOPHYTA - CRUMPLED
PTERIDOPHYTA - BROKEN
PTERIDOPHYTA - WELL-PRESERVED
TOTAL PTERIDOPHYTA
UNIDENTIFIED - CORRODED
UNIDENTIFIED - DEGRADED
UNIDENTIFIED - CRUMPLED
UNIDENTIFIED - BROKEN
TOTAL UNIDENTIFIED DETERIORATED
BROKEN CONIFER GRAINS
POLLEN CONCENTRATION X1000

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