FOR MY PARENTS

PALAEOENVIRONMENTAL INVESTIGATIONS AT LOGIE, FIFE.

by

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A multi-disciplinary study of the palaeoclimatic history of Fife during the Lateglacial period of the Late Devensian. A Thesis submitted for the degree of Master of Science at the University of St. Andrews.

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DECLARATION

I Michael Walsh hereby certify that this thesis has been composed by myself, that it is a record of my own work, and that it has not been accepted in partial or complete fulfilment of any other degree or professional qualification

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ABSTRACT

The aim of this study was to investigate environmental reconstruction derived from Coleoptera and pollen evidence in eastern Scotland where there has been no such study until now.

A Lateglacial section not previously studied for its pollen content and capable of being sampled in bulk was sought. Hence Lateglacial lake sediments were sampled from a site near Logie in the Ochil Hills of north-east Fife, Scotland. An experimental method of sampling permitted sufficient sediment for pollen, coleoptera and chemical analysis to be taken. The top of this core proved to be of Loch Lomond Stadial age; thus a Russian core, encompassing the Loch Lomond Stadial and the earliest Flandrian was taken for further pollen analysis. The Coleoptera indicated a thermal climate cooler than is presently the case in eastern Scotland. The values estimated for the average temperature of the warmest month during the Lateglacial Interstadial are 12-13 °C, falling to about 8 °C during the Loch Lomond Stadial. Pollen analysis clearly shows that the vegetation around the site changed from open grassland to Juniper/Empetrum heath during the Lateglacial Interstadial. The vegetation of the Loch Lomond Stadial is indicative of broken ground at first developing into open grassland later in the stadial phase. The beginning of the Flandrian Interglacial is marked by the development of birch forest. Comparison of the two approaches to palaeoclimatic reconstruction shows basic agreement, although the earliest phases of the Lateglacial Interstadial are not represented in the section studied. This was disappointing because it is in these early Interstadial sediments that discrepancies arrive between the Coleopteran climatic inferences and the traditional picture derived from pollen.

KEYWORDS: Lateglacial, lake sediments, pollen analysis, palaeoentomology, vegetation history, climatic change.

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PREFACE

The marked climatic changes which are characteristic of the Quaternary period have been studied for many years using a variety of different methods. This study has become more relevant with the growing awareness that human activity may be having an effect on the global climate. A change in climate as a result of natural processes is also a possibility. Thus it is important to understand the impact of such climatic changes on the world's flora and fauna. The only adequate means of modelling this is to look at past climatic changes and to assess the effect these changes had on the vegetation and the animals.

The reconstruction of Quaternary climates and environments has been achieved using a wide variety of methods derived from geomorphology, lithology, chemistry and biology. However the method which has produced the greatest amount of palaeoclimatological data is the use of biological evidence in the form of fossil plant and animal remains. The review of literature which follows is concerned with two of these: plant remains in the form of fossil pollen and animal remains in the form of fossil insects.

The use of biological evidence to reconstruct Quaternary climates has its basis in the principles of uniformitarianism. Using the theory of "the present as a key to the past", knowledge of modern ecology of plants and animals is applied to fossil assemblages. However this does involve making several assumptions about the relationship between the animal or plant and its environment and also the nature of the fossil evidence. These assumptions, as listed by Lowe and Walker, (1984) are:

1. that we fully understand and are able to isolate the environmental parameters governing present day distributions of plants and animals;

2. that present plant and animal distributions are in equilibrium with those controlling variables;

3. that former plant and animal distributions were in equilibrium with their environmental controls;

4. that former plant and animal distributions have analogues in the modern flora and fauna;

5. that the ecological affinities of plants and animals have not changed through time;

6. that a fossil assemblage is representative of the death assemblage and has not been biased by differential destruction of its original component parts or by contamination by older or younger material;

7. that the taphonomy of the fossil assemblage can be established;

8. and that the fossil remains can be identified to a sufficiently low taxonomic level to enable uniformitarian principles to be applied.

These assumptions apply to both pollen and entomological analysis, although the extent to which they are satisfied depends on the method being used. However it is rare for all the requirements to be met by one particular method.

SECTION 1

REVIEW OF LITERATURE
ON
QUATERNARY POLLEN ANALYSIS
AND PALAEOENTOMOLOGY

1.1 INTRODUCTION

The aim of this section is to review the scientific literature relevant to the pollen analytical and entomological methods of palaeoclimatic reconstruction. The techniques involved differ to such an extent that the two methods are described in different chapters. However as they both share a common theoretical background an introduction to the ideas behind palaeoclimatic reconstruction is given in the Preface.

As pollen analysis is the most widely used method in palaeoclimatological reconstruction it has now generated a large body of literature. Thus the scope of Chapter 1.3 has been limited to the papers relevant to either the theory behind pollen analysis or those concerning pollen analysis in central Scotland.

Quaternary entomological analysis has not produced as many papers as pollen analysis, and no work has yet been done on the fossil insects of central and northern Scotland. Thus the scope of Chapter 1.2 is wider than that for pollen analysis, although emphasis is placed on those papers which outline the theory and techniques used in this method.

Chapter 1.4 considers the results obtained using the two reviewed methods and their relative merits by examining previous multidisciplinary studies.

Discussions of the effect of lacustrine sedimentation on the results obtained from the use of palaeoclimatic indicator fossils, and also the problems associated with establishing a chronology for the Lateglacial period are presented in Chapters 1.5 and 1.6 respectively.

A full reference list is included (Section 3).

1.2. ENTOMOLOGICAL ANALYSIS

1.2.1 Introduction

The presence of fossil insects in Quaternary deposits has been known for many years, e.g. Wollaston (1863) and Ami (1894). Bell (1901) made what may well be the first palaeoclimatic reconstruction using beetles. He found a large number of fossil beetles, and was able to identify one genus. This genus is rare in Britain but commonly found in continental Europe. Thus he inferred that Britain's climate at this time (late Pleistocene) was much more continental than it is now. However the work attempted on these fossil beetles was mostly of a palaeontological nature until the mid-1950s when a clear picture of evolutionary stability began to emerge. The systematic use of insect fossils as palaeoclimatic indicators was pioneered by Professor C.H. Lindroth in Scandinavia and developed at the University of Birmingham by Dr. G.R. Coope and Prof. F.W. Shotton. At present the principle centres of research in Quaternary Entomology are in North America, Britain and Sweden, although many other countries have specialists in this field.

The study of Quaternary insect assemblages is undertaken for two principal reasons. The most common aim of such research is palaeoecology, for use in reconstructing Quaternary environments. This work also gives an important time dimension to our knowledge of present day ecology and biogeography of insect species. As such work is a combination of biology and geology the relevant literature is spread over a wide variety of journals. No single publication exists which adequately covers the wide variety of applications for Quaternary palaeoentomology (archaeology, palaeoclimatology, palaeoecology etc.).

For the purposes of this literature review, the scope of the papers studied has been limited to those which review the theory relevant to the use of insects as palaeoclimatic indicators, and those which outline the methods used in such studies. The palaeoclimatic data provided by insects in Scotland are very sparse, with only one major study having been undertaken, and that for the south of the country (Bishop and Coope, 1977). A multidisciplinary study of a Late Devensian site in Perthshire yielded a small but significant insect fauna (Merritt *et al.*, 1990). Smaller scale investigations have also been conducted at Airdrie (Coope, 1962) and Corstophine (Coope, 1968). The palaeoentomology of central Scotland has not been studied previously.

The data most commonly used are derived from studies of the Coleoptera (beetles) as this order, for reasons which will be outlined later, has proved to be the most suitable for this work.

1.2.2 Ecology of Beetles

Beetles occur in almost every terrestrial environment. There are over 100 families of beetle and about 750,000 species scientifically described and named, each with its own ecological requirements. There are aquatic beetles, beetles which live in the immediate proximity of water, either on the sandy or muddy banks of rivers, ponds and lakes and others on plants growing in water. Beetles can be carnivorous or herbivorous. Some species, including some scavengers, are omnivorous. There are beetle species that feed entirely on plants. Those that can eat a variety of different types of plant ("polyphagous" species) are of some use in palaeoclimatic reconstruction. However, those that depend exclusively on on one plant taxon ("monophagous" species) are of limited use as their distribution will be governed by the distribution of their host plant whose distributional controls may not necessarily be thermal climate. Such monophagous species may, for the same reasons, be valuable in palaeoecological studies.

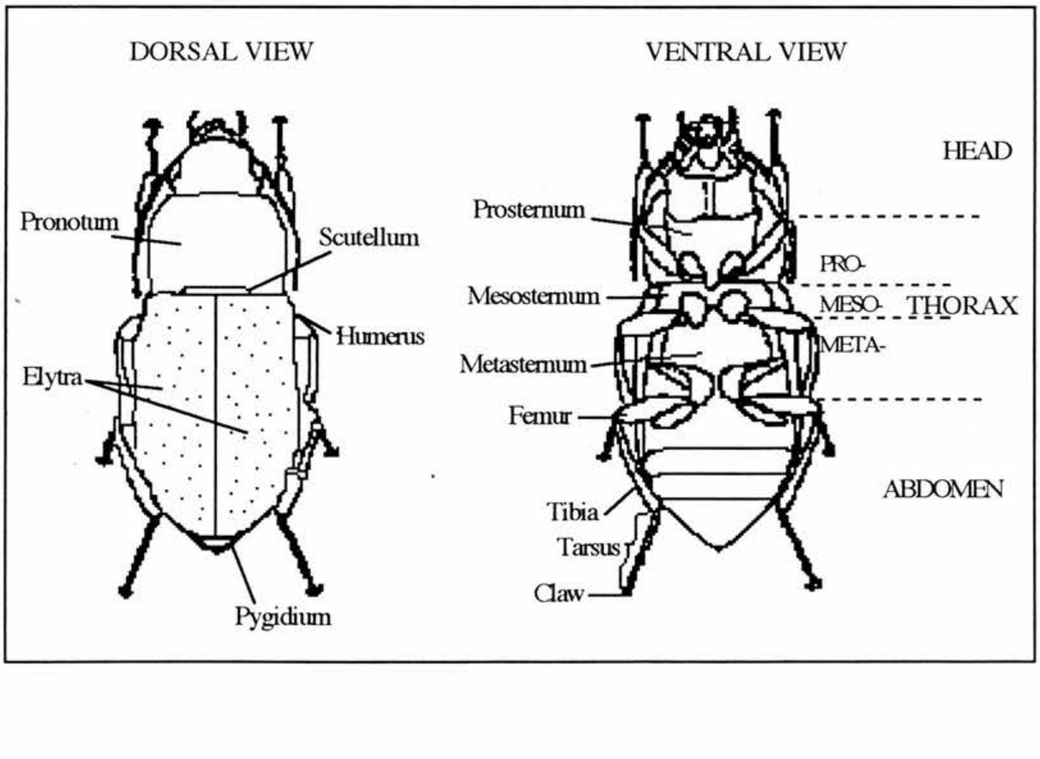
Beetle communities are most diverse in tropical regions; the further the distance from this zone generally the lesser is the diversity. However the study of beetles in the tropics has been haphazard, whereas Europe, North America and Japan have been studied thoroughly. Beetles have been found in virtually all parts of the world, but knowledge of them might be confined to the larger and more striking examples that are more easily collected. Beetles have been found in desert regions, although the fauna is somewhat limited as regards both number and variety of species. This does not apply to the oases which have an abundant insect fauna. Certain species are adapted to arctic environments. Certain species have their modern distribution confined to high arctic or mountain environments. These are very useful in palaeoclimatological studies as they are found as fossils in places such as Britain, thus indicating previously cold conditions in the past.

Thus the Coleoptera are a numerous and diverse order, occurring in a wide variety of environments. They appear to have changed their distribution, rather than their environmental tolerances with time and changes in the climate. Therefore their occurrence as fossils, can provide a wealth of information on their ecology and environment.

1.2.3 Methodology

Insects occur as fossils in most non-marine Quaternary sediments, generally wherever macroscopic plant remains are found (Schwert and Ashworth, 1985). On account of their robust nature the best preserved and most useful insects for palaeoclimatic reconstruction are the Coleoptera. Identifiable remains are found mostly as disarticulated parts of their chitinous exoskeleton, because the process which separates the insects from the sediment matrix generally precludes the possibility of finding complete animals. Coope (1959) found such an example where the enclosing medium was a felted peat and the insect was buried without much post mortem transport. The parts most commonly found are elytra, pronota and heads (figure 1.1.)

Figure 1.1 The anatomy of a beetle (after White,1983).



Although proteins, lipids and waxes are largely removed from the skeleton, detailed structures are well preserved. This includes the retention of structural colours, although pigments do not usually remain. The preservation of such fine details as legs and male genitalia within the abdomen (a useful guide to identification) is not unknown. Coleoptera fossils are found well preserved in acidic and alkaline conditions, although in very acidic peats they often show signs of corrosion. Insect fossils do not usually survive in oxidising conditions.

The recovery of fossiliferous material from the field is usually from exposed sites (e.g. quarries and stream banks). The techniques used in the recovery of such material vary from site to site, generally however the whole thickness of the deposit is sampled in 50 mm units, with a stratigraphic log made of the sequence. For this study the section was exposed by excavation, as no suitable outcropping site could be found. Sediment was then recovered using a large plastic tube to take a "core" of the sequence. Doubts about the accuracy of results obtained from sample thicknesses of 50 mm have been expressed (Whittington, 1990 - personal communication), thus the core recovered from Logie has been divided into samples 20 mm thick for the insect samples. Different methods require different amounts of material, for example palynological investigations need only a gram or two of sediment and analysis of chironomid larvae only needs a few grams of material. However when larger insects, such as the Coleoptera, are to be studied several kilograms of sediment are needed to ensure a sufficiently diverse assemblage on which to base results is obtained.

1.2.4 Preparation

Prior to the mid-1950s fossil insects were extracted from the sediment matrix by splitting the material parallel to the bedding planes and then searching the exposed areas for insect remains (Coope, 1959). This technique allowed complete insects to be found, but led to a bias toward the more obvious types i.e. the large, shiny and brightly coloured beetles. A procedure for the extraction of fossil insects using flotation and wet sieving has been developed. This method is outlined below. A more detailed account of this procedure can be found in Coope (1986).

Samples for examination are soaked in water in a polythene washing-up bowl with a "lip" melted into it. Gentle manual agitation is used to break up the sediment with water flowing into the bowl through a hose. Fine sand and silt will go into suspension and can then be drained off through a 300 μm sieve. This process is continued until most of the fines have been washed away. Sodium carbonate (or sodium hydroxide in extreme cases) can be added to break up the sediment, as it deflocculates clay minerals although the use of chemicals should be kept to an absolute minimum . The lighter materials can then be panned off into the sieve.

The remaining lighter fraction is soaked with paraffin in the washing-up bowl. Any excess paraffin is decanted through a gauze filter so that it can be used again. The bowl is then filled with cold water and the sediment is then left to settle. Insect remains and some plant material will float to the top and are then skimmed off into the sieve. Schwert (1989) recommends using heptane separately after one or two paraffin flotations to maximise floating efficiency for fossil separation, apparently with some success. Once in the sieve the material is washed with detergent to remove any paraffin left on the sample and then the water is expelled from the sample using ethanol. The sample is then ready for sorting by hand under a binocular microscope.

The insect specimens obtained are sorted from any plant matter that was also floated off. The fossil insects are then are stored in alcohol to prevent them drying out.

1.2.5 Theory

The field of Quaternary entomology covers a wide range of insect orders. These include Hemiptera (bugs), Diptera (two-winged flies) Trichoptera (caddis flies), Hymenoptera (e.g. bees), Odonata (dragon flies) and Coleoptera (beetles). Some of these orders have been used in palaeoenvironmental investigations (Buckland, 1976) but many of them are of little value. The Diptera, for example, may be well preserved but little palaeoecological work has been attempted using this order. Other groups such as the Odonata are limited by their infrequent occurrence as fossils, whereas others (e.g. the Chironomidae - midges) occur in great numbers but there are difficulties in identifying them beyond the generic level. The Coleoptera, to a large degree, are not affected by these limitations, rather they have several characteristic features which make them an invaluable tool for the interpretation of Quaternary environments.

Beetles have a robust chitinous exoskeleton which makes for good fossils but their vulnerability makes transport, and thus derivation, infrequent. The Coleopteran fossils are thus well enough preserved to display sufficient structural detail to permit identification, in most cases, to species level. They are found in virtually all terrestrial and freshwater environments, including the intertidal zone (Coope, 1977b). The use of beetles as palaeoenvironmental indicators relies on the fact that many of the species are stenotopic i.e. they show a marked preference for one particular environment.

The study of Quaternary insect fossils has shown that the Coleoptera have been evolutionarily stable throughout the Quaternary (Coope,1977a). There is no evidence of any speciation through the middle and late Pleistocene, nor is there any indication of global extinctions of insects through this period. The only evidence for any morphological change in the Coleoptera during the Quaternary was found in the lower Pleistocene of Alaska by Matthews (1974). The changes are slight, involving the reduction in the already vestigial wings of a Staphylinid (rove) beetle - *Tachinus apertus.* These differences are so small that they are comparable to racial differences within a species.

The concept of this evolutionary stability was established in the late 1950s largely through the work of Dr Coope and Prof Shotton at the University of Birmingham. Many papers before circa 1955 had listed the occurrence of "extinct" species and accordingly gave them new names. In some cases the specimens identified as extinct have been reviewed and have proved to be identical to living species e.g Shotton *et al.* (1962) revised the earlier identifications of Wollaston (1863).

It is also significant that the ecological affinities of most coleopteran species do not appear to have changed with time. This is harder to establish than morphological stability, but the evidence suggests that both fossil and modern species are found in similar associations. Other palaeobotanical and geological evidence supports the theory that fossil species occur in the same environments today as in the past. Thus it appears that the Coleoptera have been stable not only morphologically but physiologically also (Coope,1977a).

The major factor affecting the distribution of beetles on a regional scale is climate, principally thermal climate. It can be shown from modern distribution maps that the geographical range of many beetle species corresponds with definable climatic zones (figure 1.2.). The species which are limited to one climatic zone, and therefore the most useful in palaeoclimatic reconstruction, are called "stenotherms". Those with a broader climatic range are called "eurytherms".

There exists a large amount of neontological data concerning the geographical and climatic distributions of Coleopteran species which can be applied to palaeoenvironmental studies. Most entomological work has been done in western Europe. North America too has been the subject of much study, but outside these areas there is less detailed knowledge of Coleopteran ecology. At present there are about 3,800 species found in Britain (Coope,1977a) and about 350,000 worldwide (Harde, 1984). Estimates of the total number of beetle species still to be discovered range from about 300,000 to 2,000,000 (Harde, 1984). The tropical rainforests, with their beetle fauna still largely unknown, account for much of these figures.

1.2.6 Response to Climatic Change

If a group of animals or plants is to be used as a palaeoclimatic indicator then it is necessary to know how that group responds to the geologically sudden climatic changes of the Quaternary period. It is known that beetle species which are not found in Britain today did occur in the geologically recent past. Species whose modern distribution is limited to the Mediterranean area (Coope, 1990) or northern Scandinavia both lived in Britain during different stages of the Lateglacial period. An extreme example of such mobility of species distribution is given by Coope (1973). He cites a species of beetle (*Aphodius holdereri*) once common in Britain which is now only found in a restricted habitat in eastern Asia.

The fossil evidence from various sites in Britain shows that during prolonged periods when the climate was glacial, many arctic and high mountain species extended their ranges to lower latitudes and lower altitudes, living in the extensive tundra regions south of the continental ice sheets. This phenomenon has been recognised for some time. What has been less clear is that during the shorter interglacial periods southern species extended their ranges further north from where they occur today (Coope, 1990). The fossil record gives us a valuable time dimension to modern biogeographical distribution studies. This shows that present day distributional patterns are but the latest stage in a complex history of successive waves of invasions and local extinctions. Thus although species remain the same, their geographical settings are constantly changing in response to the glacial/interglacial fluctuations.

This change in distribution is shown by many different organisms including plants, vertebrates, molluscs and insects. The beetles clearly illustrate the large scale biogeographic response forced upon species by the drastic Pleistocene climatic changes.

Coope (1990) demonstrates these distributional changes with beetles from several different families, so that these changes are shown not to be confined to any ecologically restricted group of species. Several species which have been found as fossils in Britain are shown to have distributions which are now confined to the Mediterranean area, such as *Asaphidon cyanicorne* .

Different species of both animals and plants colonise newly available areas at different rates. Thus the incoming of a species in a stratigraphical sequence is influenced not only by the arrival of suitable physical conditions, but also by the rate of spread of the species and the distance it has had to traverse. The two latter variables are difficult to assess and so, though the presence of a species indicates the presence of suitable environmental conditions, these conditions may have prevailed for some time before the arrival of the species in the area. Thus the use of time of colonisation of a species is an unreliable index of the timing of climatic change. This problem is highlighted by Idso (1989) who calls this phenomenon "biological inertia". Coope (1981) suggests that the local extermination of species by unacceptable conditions is not subject to the problems of time and distance mentioned above. Extinctions are sudden and can be well correlated with the onset of intolerable physical conditions. However the use of negative evidence should be treated with some caution, the absence of a species from the fossil record does not necessarily mean that it is locally extinct. When there are numerous absentees however, which form a consistent ecological picture it is hard to dismiss it as a sedimentological feature. It is not permissible to use this local extinction of individual species as evidence of climatic change. Local extinction can be the result of many factors unrelated to climate, although when the extinction involves a large number of species with different ecological requirements, but broadly the same geographical range, then the conclusion is difficult to resist that a large change in the physical environment has occurred. The most probable cause of this is a change in climate.

The sensitivity of beetles to climatic change can be demonstrated by using modern entomological investigations. Hengeveld (1985) studied the distributions of ground beetles (Carabidae) in Holland between 1890 and 1975. He was able to correlate changes in beetle dynamics with climatic changes, and also found that human influences have little effect on faunal composition on this spatio-temporal scale. Thus if changes in beetle dynamics can be recognised over a relatively short timescale and in a geographically restricted area they must, by inference, be very sensitive to the larger scale climatic changes in the Pleistocene.

1.2.7 Problems

The dominant factor affecting the regional distribution of beetles is climate. However, insect assemblages have representatives of species from a wide variety of local habitats. The vegetation, soil, micro-climatic variations and hydrological conditions will all affect the local distribution of insects. Thus the palaeoecologist must be able to identify these habitats and species and, if possible, to quantify them. This problem is more acute for an archaeologist who deals with smaller environments (e.g. grain stores, tanneries, stables) than a palaeoclimatologist. Kenward (1976) has considered this problem and contends that the theoretical basis of insect death-assemblage investigations in archaeological contexts is weak. He suggests that a "background fauna" formed, for example, of flying insects and the contents of bird droppings is present in fossil assemblages. This "background fauna" may be biased in favour of one species and the presence of a high proportion of one species or association is usually indicative of a particular habitat. However these problems are less important for a palaeoclimatologist than Kenward suggests. Most palaeoclimatological work is concerned with reconstructing regional climates, thus the presence of a background fauna will only help to give a regional picture undistorted by micro-climatic variations.

Lowe and Gray (1980) urge caution in the study of fossil insect assemblages. Interpretations rest heavily on the assumption that present (and past) beetle distributions are limited by thermal thresholds. They maintain that not enough modern distributional studies have been undertaken to allow full acceptance of this premise. However, neither of these authors were in possession of adequate entomological data to support this statement (Coope, 1992 pers. comm.). Secondly, the size of bulk samples required for palaeoentomological work (commonly 5 cm thick) may have the result of masking small-scale climatic changes. This could, for example, prevent the resolution of an "Older Dryas". However palaeoenvironmental reconstructions based on Coleopteran evidence, unlike those based on pollen analysis, are not dependent on the relative abundance of the different taxa. Thus if a small scale climatic oscillation does occur within a 5 cm thick sample the "cold" and "warm" beetles can be separated and the climatic change can be recognised. Nevertheless for the purposes of this investigation samples 2 cm thick have been taken to make them more comparable with pollen sampling procedures.

The palaeoclimatic reconstructions obtained by using fossil insect data are heavily dependent on neontological literature. There is a great deal of information available on European beetles; however it does not provide much detail on all but a small number of species. This is further complicated by the often contradictory nature of this information. Kenward (1978) uses the Carabid beetle *Trechus quadristriatus*

(Schrank) as an example of this. In Joy (1932) the *Trechus* species are said to be found in 'damp places, on the banks of rivers etc.' In Scandinavia *T. quadristriatus* is xerophilous (Lindroth, 1945). Whereas in the guide to the British Carabidae (Lindroth, 1974) its habitat is given as 'open, rather dry country with short vegetation'. The species may well have a wider range of habitats than quoted in the literature, or there are variations in the principal habitat of the species in different parts of its range. It is also possible that the habitat records for the species may be inadequate. It is very difficult for the palaeoentomologist to overcome this problem as there has to be a great deal of dependance on entomological literature. The only way to minimise this is to use as wide a range of literature as possible, so that such variations can be recognised.

1.2.8 Interpretation

The identification of fossil insects is achieved by direct matching with modern comparative material. This involves a precise comparison of the same exoskeletal characters as those used by entomologists working on modern material. However the process of identification is complicated by the disarticulated nature of the fossils. Thus the identification procedures have much in common with vertebrate palaeontology, although the preservation of the exoskeleton's fine detail allows identification to species level in many cases. One of the most outstanding problems with Coleopteran analysis is the aquisition of adequate expertise in so diverse a group.

Quaternary insect fossils have been used to quantify climatic change in a variety of different ways. Originally the climatic reconstruction was made by identifying the modern geographical ranges of the fossil beetles, and the climate from the area where most species occurred was taken to infer the past climate (Coope, 1959). In an attempt to quantify any climatic change Coope and Sands (1966) compared British fossil assemblages of Carabid (ground) beetles with the present day occurrences of those species in the floral zones which mark different altitudes in the Scandinavian mountains. However, species were found as fossils whose modern range lies outside Europe and in some cases are confined to eastern Asia. Coope (1973) illustrates this with a dung beetle (*Aphodius holdereri*) which is found in many Devensian sites across the English midlands between 42,000 and 26,000 years ago. This species now has its distribution limited to high Tibetan plateaus. Coope and Joachim (1980) described a method of interpretation based on the geographical distribution of stenothermic species. Species with similar distributions are grouped together in order to simplify the large amount of data from the fossil insect record. Subsequently workers tried to identify optimum climatic regimes on biogeographic grounds. However the actual quantification of the climatic parameters has proved to be very difficult. Atkinson *et al.* (1986) attempted to quantify limits for many species to use in the Mutual Climatic Range database (Chapter 1.2.9). This was accomplished by superimposing species distribution maps on a master map of climate stations. The thermal limits for the various species thus obtained gives only a conservative estimate of the true limits as microclimatic variations were not taken into account.

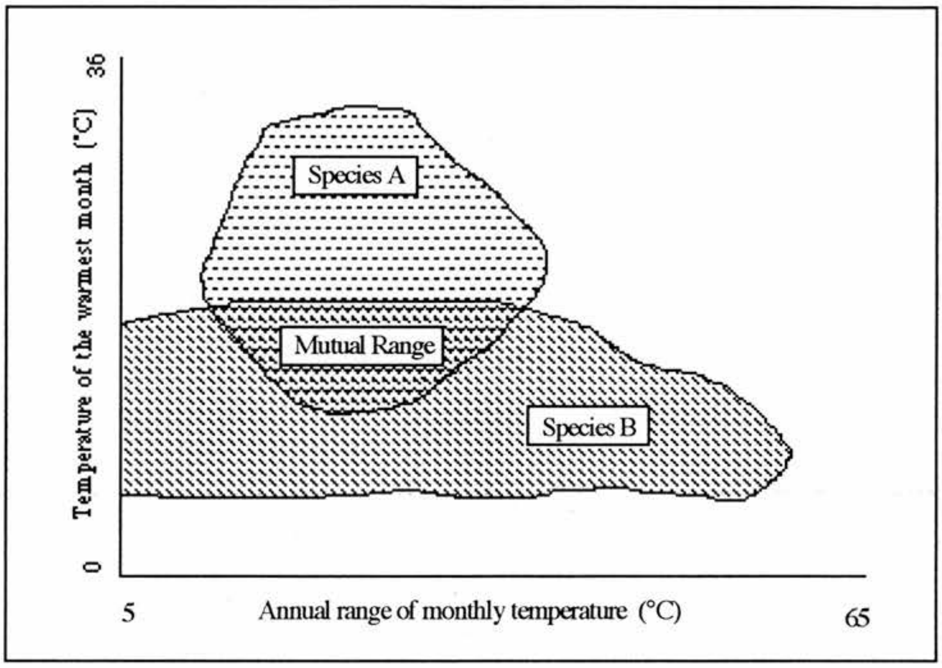
Morgan (1973) used the fact that present insect distributions are largely governed by the thermal requirements of modern species to establish climatic zones for fossil species. Thus the distribution of stenothermic species within a fossil assemblage indicates the conditions which the fossil fauna found acceptable. Kenward (1978) sets out a whole range of numerical methods such as rank order curves and indices of diversity. His principle aim was to recognise the "background fauna" that he suggests forms part of an insect death assemblage (Chapter 1.2.7). However the palaeoecolgical techniques he descibes can be of use where information on limited habitats is sought. Thus these methods are more useful to archaeologists than geologists. Different species of beetle have different importance in palaeoclimatic reconstruction, for example one stenotypic species is worth many eurytopes. Numerical analysis cannot cope with such concepts. Buckland (1979) doubts whether Kenward's "reconstructed environments would have been any different if they had been based....purely upon natural historical lines".

1.2.9 Computer Methods

One of the most important developments in the field of Quaternary palaeoentomology in recent years lies in the use of computers in the palaeoenvironmental analysis of fossil Coleoptera. The Mutual Climatic Range Reconstruction Programme (MCRRP) was developed from earlier work on pollen assemblages (Grichuk, 1969). The basis of the method is the assumption that if the present day climatic tolerances of a beetle species are known then fossil occurrences of that species imply a palaeoclimate within the same climatic tolerances. If several species occur together as fossils then the palaeoclimate of the time when they were living must lie within the mutual intersection of their tolerance ranges (figure 1.3.). In general the intersection (Mutual Climatic Range - MCR) will be smaller and the palaeoclimate deduced more accurately, the greater the number of co-existing species.

The database of Coleoptera consists of 436 species with well defined climatic tolerances. Only carnivorous species from the families Carabidae (ground beetles), Dytiscidae (predaceous diving beetles), Gyrinidae (whirligig beetles), Haliplidae (crawling water beetles), Hydrophilidae (water scavenger beetles) and Scarabaeidae (dung beetles) were included. Phytophagous beetles (those species whose distribution is governed by their host plants) were omitted from the list to ensure that thermal climate was the dominant control on distribution.

Figure 1.3. Mutual Climatic Range (after Atkinson *et al.*, 1986).



A map of the present distribution of each species was compiled from information in the entomological literature. Each map was then transformed into a diagram of the species distribution in terms of climatic tolerances. This was achieved by superimposing the geographical range onto a base map of 495 climate stations scattered across the palaeoarctic region from Greenland to Japan. Thus a Species Climatic Range (SCR) was defined for each species. It was found that 96% of the variance in thermal climate is described by two groups of variables which can be defined as follows:

1. The warmth of the summer (mean temperature of the warmest month t_{max} is a very good correlation.)

2. The temperature range between the warmest and the coldest months (t_{range}).

The precise value of the thermal climate cannot be determined, only that it lies within the Mutual Climatic Range.

A "most probable" value for the palaeoclimate cannot be derived. Systematic deviations can be corrected using data from regression equations of the present day temperatures at various localities. This is then compared with the median reconstructed temperatures based on the Coleoptera from the same localities. Two independent sets of data were combined and the following equations were derived (Atkinson, Briffa and Coope, 1987).

$$t_{max}(\text{corrected}) = 1.066\, t_{max}(\text{median}) + 0.0142\text{NSPEC} - 2.96$$

$$(r = 0.94,\ s = 0.83°\text{C})$$

$$t_{min}(\text{corrected}) = 1.416 t_{min}(\text{median}) + 1.904$$

$$(r = 0.94,\ s = 2.42°\text{C})$$

(All temperatures are in °C.

NSPEC is the number of species used in the reconstruction.)

The corrected values provide unbiased estimates of the most probable palaeoclimate within an MCR, with a precision of ±2°C for t_{max} and ±5°C for t_{min}.

A full description of the theory and methods employed by the MCRRP can be found in Atkinson *et al.* (1986). The MCRRP has a useful feature in that it can be tested. Living assemblages of Coleoptera can be used to test the accuracy of the reconstruction by checking the results with nearby climate stations. The method is thus capable of being verified, it provides quick and reasonably accurate quantified reconstructions of the thermal climate.

1.3. POLLEN ANALYSIS

1.3.1. Introduction

Pollen analysis includes the study of pollen and spores; they have a common origin in meiotic cell division, but are quite different in terms of their function. The pollen grain, being the housing for the male gametophyte generation of the angiosperm and gymnosperm, fulfils its function only if it arrives at the stigma of another plant of the same species. Cryptogram spores have only to arrive at a site where they can germinate as they are independent gametophytes.

Fossil pollen grains were discovered in the mid-nineteenth century. Scandinavia was the centre of the early development of the technique of pollen analysis with researchers like C.A. Weber extending their studies of macroscopic plant remains to small scale microfossils. It was realised that these pollen grains could be identified to a low taxonomic level. This feature, combined with the abundance of pollen grains, led to an early realisation of the potential of pollen analysis to reconstruct past vegetation distributions.

The fields which make use of pollen analysis are quite varied, and include: (after Moore and Webb, 1978)

1. tracing the history of plant groups and species,
2. tracing the history of plant communities and hence habitats,
3. dating deposits,
4. studying climatic history,
5. following the course of human influence upon the environment,
6. studying the pollen count of the atmosphere and its effects on human health,
7. pollen content of honey (melissopalynology),

8. criminology.

This literature review is concerned with the use of pollen analysis to reconstruct past vegetation cover. Since the plants which produced the pollen have responded to the series of climatic changes characteristic of the Quaternary period we can infer climatic history from the changes in this vegetation cover.

As pollen analysis is the most widely used means of palaeoclimatic reconstruction, a great deal of literature has been produced on the subject. Thus the scope of this review has been limited to those works which are relevant to the theory and problems associated with the method. Palaeoclimatic reconstructions are only included if they are relevant to eastern Scotland.

1.3.2 Methodology

Pollen is distributed by wind or insects and will accumulate on any undisturbed surface and is usually preserved differentially depending upon the matrix into which it is incorporated. It is commonly well preserved in lake sediments and peat; in soils, however, the preservation is usually poor with different taxa weathering to varying degrees (Havinga, 1984). The factors which influence the state of preservation of pollen grains are the grain size and composition of the sediment matrix and the degree of anaerobicity of the depositional environment. Samples can be taken from open exposures, pits or alternatively by using coring equipment. Pollen analysis has the advantage over palaeoentomology in that it requires considerably less sediment to in the region of one cubic centimetre per sampled horizon in order that a second preparation can be made if there is any problem with the first preparation.

Generally in pollen analytical studies the whole core is not used systematically for pollen extracts, unlike the procedure followed in palaeoentomological investigations. Subsamples are taken at selected intervals. The spacing of these intervals depends on the degree of precision required, the rate of deposition and the time available to the researcher. It is not unusual for samples to be taken at fairly wide intervals such as 16 or 8 cm at first, and then to sample between these in areas which exhibit vegetational change.

Samples are best taken from the core in the laboratory. The surface of the core is cleaned by cutting away superficial material with a clean scalpel. All cleaning cuts should be made horizontal to the axis of the core so that material is not smeared up or down the core. The cubic centimetre of sediment is then removed from the core. If the pollen content is only to be expressed in relative percentage terms then the precise size of the sample is not important.

All of these, and subsequent, procedures should be carried out in an atmosphere which is kept free from pollen contamination. It is possible to distinguish modern contaminant pollen grains if they were incorporated at a late stage of preparation. However, if contamination by modern grains occurred at an early stage in the process, or by fossil grains at any time then the contamination will not be noticed. Contamination can also occur *in situ*, bioturbation can disrupt the pollen stratigraphy by mixing modern sediments with older deposits, or vice versa.

1.3.3 Preparation

In order to separate pollen grains and spores from the sediment matrix, whether it is organic or inorganic, rigorous chemical treatment is required. Samples of sediment 0.5 cm^3 in volume are measured. The standard preparation technique involving sodium hydroxide, hydrofluoric and acetolysis traetments is used. (The complete laboratory procedure is set out in Faegri and Iversen (1989)). During this process tablets containing a known number of *Lycopodium clavatum* spores are added so that absolute pollen concentrations can be calculated (Stockmarr, 1971). Once most of the matrix has been removed the remaining material (including the pollen grains) is mounted, unstained, on a slide in silicone oil of 12,500 cSt. viscosity for microscopic analysis.

1.3.4 Pollen Diagrams

Analysis of pollen from different horizons within a stratified sequence of sediments will show any changes in the pollen content over time. These changes are normally shown graphically in the form of pollen diagrams, either percentage or absolute pollen diagrams. Percentage pollen diagrams usually take one of two forms. In some cases a set number of pollen grains is counted, 300 or 500 grains are typical amounts. The individual pollen types are then expressed as a percentage of this total number of land pollen grains. The other form of percentage diagram is based on a pollen sum of arboreal grains only. This latter form is generally only still used in archaeological investigations and in studies of Flandrian landscape change. However increasing interest in the cold stages of the Quaternary, where tree pollen is less abundant, has led to greater use being made of diagrams whose pollen sum is based on the concentration of land pollen or "absolute" pollen diagrams.

One problem with the use of percentage pollen diagrams is that the percentages for individual taxa are interdependent on the others, for example an influx of *Corylus* will lead to a suppression of the relative percentages of the other taxa represented in the diagram. Thus statistical fluctuations, which do not represent ecological change, will be reflected in the diagram. This problem can be overcome by the use of absolute pollen diagrams which are based on changes in the total number of pollen grains per unit volume of sediment. Pollen concentration can be established in a number of different ways. Peck (1974) investigated three different methods of determining absolute pollen concentration, as stated by Davis (1966), Jorgensen (1967) and Matthews (1969). She found that although Matthews's method is the most convenient to prepare, the method used would depend on the purpose of the study. A typical means of determining pollen concentration is to add a known quantity of 'exotic' spores (e.g. *Lycopodium clavatum*) to a measured amount of sediment during the laboratory preparation. The exotic spores are then counted until the required number of land pollen grains has been reached. The ratio of fossil spores to exotic pollen can then be used to calculate the number of pollen grains in a unit volume of sediment. Changes in the concentration can then be represented graphically.

The concept of a local pollen zone as a fossil assemblage was first suggested by Cushing (1967). He strongly advocated the use of the pollen assemblage zone as the basic unit of Quaternary pollen stratigraphy. The method was pioneered by Cushing and since that time the use of pollen assemblage zones is now ubiquitous. Thus pollen diagrams are divided into biostratigraphic units characterised by distinctive pollen group types; these are called pollen zones. The zones may have local or regional significance. The boundaries used on pollen diagrams were mostly subjective, but

Gordon and Birks (1972) attempted a classification of pollen zones and advanced the constrained agglomerative and divisive procedure as an objective method of zonation. Simplified pollen zones have been applied to temporal changes, climatic phases, geological and geomorphological events.

Cushing (1967) split his stratigraphy from Minnesota into local pollen assemblage zones. Comparisons can then be made between these local zones and, using similarities between them, regional pollen assemblage zones can be established. For example, Walker and Lowe (1979) defined regional pollen assemblage zones for the Grampian Highlands and used them for the correlation of ecological changes in the Rannoch Moor area.

To avoid any of the problems associated with subjective pollen zonation, a number of computer based methods have been developed, ranging from simple sequential correlation (Yarranton & Ritchie, 1972) to informational analysis without any stratigraphical constraint (Dale & Walker, 1970) to a stratigraphically constrained, agglomerative and divisive dissimilarity techniques (Gordon & Birks, 1972). All these methods are capable of defining both major and minor zone boundaries and permit objective comparisons to be made between sites.

1.3.5 Interpretation of Pollen Diagrams

The interpretation of pollen diagrams requires knowledge of pollen-production, -dispersal, -source, -deposition and -preservation. The relationship between fossil pollen assemblages and former vegetation cover must also be understood if any inferences are to be made about former climates.

Different plant species produce different amounts of pollen. Autogamous (self-pollinating) plants such as *Triticum* (wheat) liberate very little pollen into the atmosphere, whereas some species of *Hordeum* (barley) can produce vast amounts of pollen. Insect pollinated plants produce small quantities of pollen; whereas wind pollinated species produce larger amounts. Relatively little work has been done on the variability of pollen production. Anderson (1970) attempted to quantify the relative pollen productivity of various tree taxa to calculate correction factors for fossil spectra.

It is also necessary to know the relationship between the frequency of a plant species in an area and the total pollen rain from that species. This is to enable pollen data to be used to calculate the actual composition of the surrounding vegetation. For example a plant community consisting of 10% pine, 35% maple and 65% beech would be represented by equal amounts of pollen (Bradley, 1978).

In order to reach any conclusions about vegetational history from pollen assemblages it is important to understand how the pollen was deposited at the site being studied. There are three principal means of transport for pollen grains; insect, wind or water.

Insect transported pollen provides very little pollen for stratigraphical studies. Plants that are insect pollinated produce little pollen, as the mode of distribution to other plants is less haphazard than other means.

Wind transport is more problematic for palaeoenvironmental studies, as the various controls on its distribution are harder to quantify. Tauber (1965) states that the factors affecting atmospheric pollen transport are:

(1) turbulence of the atmosphere,

(2) wind speed and direction,

(3) weight and shape of the pollen,

(d) height and strength of the pollen source.

Studies on modern pollen show that maximum pollen deposition occurs about 600 metres from the source. The deposition rate falls off inversely proportional to the distance from the source up to about 2 km. After that a low, constant deposition is maintained (Raynor *et al.*, 1970).

Many investigators prefer sediments from large lake basins (greater than one square kilometre) as pollen produced from individual plants, or groups of plants, cannot be detected above the regional pollen rain more than a few hundred metres from the source plants. Thus the vegetation within the immediate vicinity of the site will not distort the regional pollen picture unduly. The majority of wind transported pollen is tree pollen. The transport of non-arboreal pollen (NAP) from herbs and shrubs has not been studied in detail. However it would appear that as wind speeds and turbulence are lower close to the ground, such pollen is carried much shorter distances than arboreal pollen. Herb and shrub pollen is thought to reflect local site conditions.

Some pollen grains can be transported very great distances in the atmosphere. Several studies have found pollen that must have been transported hundreds of kilometres. Tyldesley (1973) found tree pollen (*Betula* and *Pinus*) in low (20 and 30 grains m^{-3} respectively) but significant densities in the atmosphere of the treeless Shetland Isles. (The source areas for this pollen are thought to be Britain and Scandinavia.) Such "long-distance transport" of pollen is most likely to cause confusion where local pollen production was low. Walker (1975) gives several examples of sites in the Grampian Highlands which show a relatively low pollen content during the Loch Lomond Stadial. Thus a constant long-distance component in the fossil pollen record will constitute a greater percentage of the pollen assemblage.

Research has shown that pollen transported by streams and rivers is by far the largest source of pollen into lake basins. Peck (1973) studied a catchment in Yorkshire containing two lakes. She placed pollen traps on the surface of the lakes and at various depths, and took monthly samples over 14 months. Her conclusions were that aerial deposition only forms a small proportion of the total pollen input into the lake and that between 91 and 97% of the pollen influx was through water transport. The pollen transported by streams was also found to be of a consistent amount and taxonomic composition, whereas the aerially transported pollen was subject to seasonal variation.

The main sources of stream-borne pollen are (after Birks and Birks, 1980):

(1) direct fall of pollen from plants growing along the banks,

(2) bank erosion,

(3) surface runoff. This appears to be the major source, particularly during floods.

In her study of Blelham Tarn Bonny (1976) found similar proportions of water and aerial pollen input to those found by Peck (1973). She demonstrated that the different modes of transport produced different assemblages. Larger proportions of *Pinus*, *Betula* and *Urtica* pollen were found in the aerial component; and of *Corylus*, *Alnus* and *Calluna* in the water-borne component.

Sedimentary processes in a lacustrine environment also affect the final pollen assemblages. Differential settling velocities of pollen in lakes and ponds, combined with the disturbance of sediment by currents or burrowing fauna, can complicate the fossil pollen record. Resuspension and deposition can also affect the composition of pollen assemblages obtained from lake sediments. Davis (1968) demonstrated that between 2 and 4 times as much pollen was deposited in pollen traps in the water column than was deposited on the sediment surface of Frains Lake, Michigan. The greatest resuspension of sediment occurred at the autumnal overturn with a lesser amount in the spring.

Secondary pollen is also washed into lake basins by streams, solifluction or the collapse of sediments on the basin edge. These secondary grains will be older than those from the contemporaneous pollen rain. They can often be distinguished by deterioration of the exine (see below). However, they can cause confusion in palaeoclimatic reconstruction by masking or distorting the representation of the contemporary vegetation cover. Fewer problems of this nature are encountered where the site is terrestrial (such as a peat bog), rather than lacustrine, in nature.

Some pollen grains are more susceptible to deterioration than others. This can lead to over-representation of some taxa and under-representation of others. Therefore it may be important to determine which grains may be missing from the fossil record. Cushing (1967) attempted to develop this idea and defined six classes of exine deterioration:

1. corroded grains, exines scratched and pitted;
2. degraded grains, structural elements of the exine rearranged and apparently fused;
3. crumpled grains, folded with exine collapsed and thinned;
4. crumpled grains, with a normal exine;
5. broken grains with the exine ruptured;
6. well-preserved grains.

In studying late Quaternary lake sediments in Minnesota he found that there was significant variation in the preservation of different taxa in the same sample, and also the same taxon in different samples. He correlated the mode of preservation with the lithology of the sediment.

The question of how far fossil pollen assemblages can be related to former plant communities and how we can infer climate and environment from pollen and plant associations is a vexed one. Many plant communities, especially those dominated by the herbaceous taxa are thought to represent cold periods during the Quaternary, and are thought to have no exact modern analogue. Pennington (1980) suggests that vegetation and associations found in West Greenland can aid the interpretation of British Lateglacial pollen spectra. Latitudinal and altitudinal variations in association with seasonal and diurnal temperature fluctuations would probably combine to produce significantly different plant communities during past cold phases in western Europe from those existing in modern tundra regions (Lowe and Walker, 1984).

1.3.6 Reconstruction of Vegetation History and Climate

The reconstruction of the vegetational history of an area can be problematic because of the nature of dispersal of pollen from the parent plants. The size and nature of the area of deposition also has an affect on the pollen assemblages. (Pollen from a small lake or pond is more likely to be of local derivation than that found in a large body of water (Tauber, 1965)). The differences in vegetation between sites can be the result of many other factors beside climate. Turner and Hodgson (1979), using evidence from the

Pennines, demonstrated that such differences could be explained in terms of geology, soil type, drainage and altitude. Also individual plant communities can be rarely reconstructed because fossil pollen spectra are usually integrated from an area containing several different communities. Thus the reconstruction of past plant communities and hence the vegetational history of a site, from which palaeoclimate is inferred, is problematic. There are several approaches to this reconstruction: the preservation of a plant community in exceptional circumstances such as burial in a landslide; or by establishing numerical relationships in time between fossil taxa; or finding modern analogues for past assemblages by defining recurrent groups.

As pollen spectra cannot provide a direct reconstruction of past plant communities an indirect method must be used. These methods fall into three distinct groups (Birks and Birks, 1980).

1. The statistical approach, leading to the delimitation of "recurrent groups".

2. The retrospective application in time of known ecological preferences of taxa. Those with a well-defined narrow ecological tolerance can be used as "indicator species".

3. The comparison of fossil pollen spectra with modern spectra from known vegetation types.

The statistical approach supposes that an assemblage of fossils consistently occurring together represents a past life assemblage, or community. Groups of fossil taxa such as these are called "inter-specific associations" or "recurrent groups". However, the usefulness of this approach is limited in Quaternary sequences as there is a better method available, using analogies with modern plant associations. However for pre-Quaternary assemblages, where the ecology of the plants is unknown, it is usually the only method available to attempt reconstruction of plant communities. The method has its drawbacks in that the unit of study, the fossil pollen assemblage, is not closely related to the death assemblage and thus to the life assemblage. Pollen is derived from an undefinable source area, and the pollen which enters a lake or bog may be deposited many times before being preserved.

Plant communities can best be reconstructed by grouping taxa with modern ecological preferences, especially if there is some indication of their past abundance. Iversen (1964) evaluated the usefulness of different types of plant as indicators of palaeoclimate, soil and other factors. He found that trees are good climatic indicators, but many have the disadvantage of a slow migration rate after a period of climatic warming, e.g. at the start of an interglacial. The use of the indicator species approach is based upon the assumption that the ecological tolerances of the taxa involved have not changed with time. The veracity of this assumption is difficult to test especially as conditions of competition have changed with time, as communities have evolved. A species ecological tolerance in the past may be different from its tolerance today in the presence of competition. This reservation is particularly important when reconstructing communities from Lateglacial assemblages, where conditions were open and soils were unleached in contrast to today (Birks, 1973).

The third approach to the reconstruction of past plant communities involves comparing modern plant associations and the pollen assemblages they produce with fossil pollen assemblages. Interpretations can then be made about the plant communities which provided pollen for the fossil assemblage. If similar pollen assemblages can be recognised in a stratigraphical sequence of fossil pollen spectra then changes in the past vegetation over time can be interpreted in terms of modern spatial vegetational differences. If no modern analogue for a fossil pollen assemblage can be found it can be concluded that the past plant communities have no modern equivalent. The influence of human activity can cause problems when comparing modern pollen spectra with fossil assemblages. The use of this method is further complicated by the different properties of different pollen catchment areas, different surfaces of pollen accumulation, bias when using subjective methods to compare pollen diagrams and different migration rates of taxa in response to climatic change. Despite these problems, the comparative approach is probably the soundest method currently available for the reconstruction of plant communities from pollen diagrams (Birks and Birks, 1980). For example, Pennington (1980) suggested that the modern pollen spectra from West Greenland provided an analogue for British Lateglacial pollen assemblages. The approach is most suitable when fossil spectra can be matched with modern spectra which are:

1. distinctive from all other modern spectra,
2. refer to characteristic and homogeneous vegetation types,
3. derived from comparable sites of deposition in topographically similar areas.

In some cases indicator species can be used to give more precise information about particular plant communities, depending upon the site being investigated and the taxonomic precision of the identifications.

When the changes in past plant communities, as represented by fossil pollen assemblages from a stratigraphical sequence, have been reconstructed the next step is to infer the palaeoenvironment of the area around the site being investigated.

Palaeoenvironmental and palaeoclimatic reconstruction can be achieved by inferring that the climatic and environmental conditions that prevail in a modern analogue area are the same as in the period being studied. Another method of reconstructing a palaeoenvironment is to extend the known ecological preferences of certain individual taxa back in time. Thus the plant community can be reconstructed by grouping taxa with similar modern ecological preferences, especially if there is some indication of their abundance. This approach requires knowledge of the ecological factors which control the distribution of the organism at the present day. However, Quaternary palaeoclimatology is becoming increasingly a multidisciplinary area of research, with investigations involving only one form of proxy data becoming more rare. Birks and Birks (1980) point out that to achieve a reasonable palaeoclimatic reconstruction several data sources must be used, both organic (for example, pollen, insects, molluscs, tree rings) and inorganic (e.g. lithology, stable isotopes).

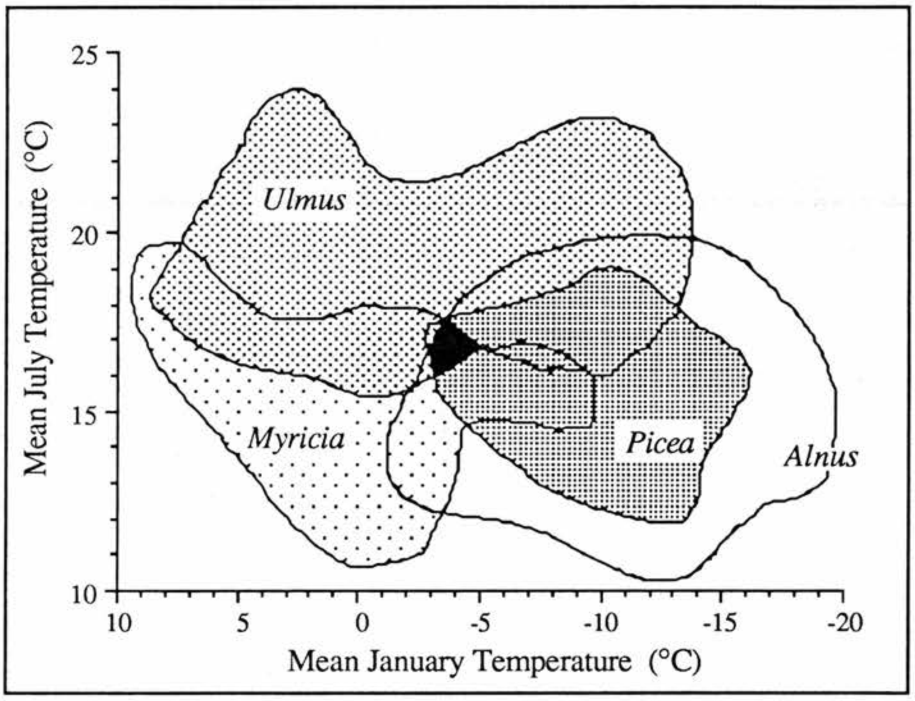
The fundamental assumption in this type of analysis, namely that modern analogues provide an adequate basis for climatic and environmental reconstruction does not apply in those Lateglacial situations when non-analogue floras and faunas occur. At such times, for example after abrupt and intense climatic changes, the whole biota may be thrown so out of equilibrium that no modern analogue exists. At such times the climatic and environmental picture must be built up by reference to the presence of particular species rather than community structures (Coope pers. comm., 1992). It also should be stressed that non-analogue communities do not necessarily mean non-analogue conditions.

1.3.7 Problems with Pollen Analysis

Pollen analysis can be taxonomically relatively imprecise. Some pollen grains and spores can be identified to species level, for example *Rumex* or *Lycopodium*. More commonly grains, such as *Salix, Betula* and *Artemisia,* can be identified to generic level. However, there are some taxa which can only be identified to the family level e.g. Cyperaceae. Thus pollen diagrams show data on a variety of taxonomic levels and this places a large constraint on the reconstruction of plant communities as some plant families and genera contain species with markedly different ecological affinities.

Palaeoclimatic reconstruction using pollen data depends to a large extent on key species within the pollen diagram - the indicator species approach. This usually involves fitting a plant's distribution to selected climatic parameters. One notable study which employs this method is that of Grichuk (1969) who attempts to extend the concept of climatic limits to entire assemblages of vegetation. Grichuk selects a fossil horizon and lists all the flora represented. The data are then plotted on climatograms (fig 1.4.) using modern mean January and July temperatures along the present distributional boundaries of the flora in question. Each species will have its own climatic constraints, but when these thermal limits are superimposed an area of overlap may be apparent. This overlap should define the climatic limits of the whole assemblage. Similar graphs can then be prepared for total annual precipitation and growing season length. Testing on modern assemblages has enabled Grichuk to estimate that the method is accurate to ±1 °C for January and July temperatures, ±50 mm for annual precipitation, and ±15 days for growing season length. However although this technique is widely used it is not without its problems. Moore (1980) highlights some of these. The method assumes knowledge of the various factors affecting plant distribution and it requires intuition in the interpretation of pollen diagrams because of the problems of taxonomic imprecision. This leaves climatic values unquantified and somewhat vague.

Figure 1.4. A climatogram showing the thermal limits of *Ulmus* (elm), *Picea* (spruce), *Alnus* (elder) and *Myricia* (myrtle) in northern Europe. Each line represents the range of temperatures within which the genus is known to survive today. The solid area where the lines overlap indicates the mean temperatures in July and January when a fossil sample containing the pollen of all four genera was deposited (after Grichuk, 1969).



1.4 CHEMICAL ANALYSIS

1.4.1.Introduction

The bulk of work on lake sediments concerning the interpretation of climatic history involves palaeoecological studies of plant or animal fossils such as pollen, diatoms, insects and molluscs. However, chemical analysis of samples of the sediment matrix can provide a method for further environmental reconstruction.

Studies of lake sediment chemistry were pioneered by Mackereth in the English Lake District. He suggested that the inorganic component of lake sediments and the proportions of sodium and potassium reflect the intensity of erosion in the catchment area (Mackereth, 1966). Thus the less stable a landscape is, the greater the influx of unweathered material may be. This will be reflected in the lake sediments by a greater content of sodium and potassium and a higher proportion of mineral to organic material.

Chemical studies of Lateglacial sediments have provided an estimation of the history of landscape stability as it responds to climatic change. During the Lateglacial period mineral sediments were dominant, although during the interstadial phase the content of organic matter increased somewhat. Calcium, sodium and potassium all have high values in Lateglacial sediments compared to those in Flandrian deposits. The lower values of magnesium and potassium during the interstadial are attributed to the loss of these elements during the weathering of feldspars to clay minerals in the catchment area (Pennington *et al.*, 1972).

Lacustrine sediments can be classified according to their origin. Those components derived from outside the lake basin are called *allocthonous,* and those from within the lake, *autocthonous*. Elements in the allocthonous fraction are generally derived from the decomposition of rock material through terrestrial weathering within the catchment area.

The results of geochemical analyses from stratigraphic data are commonly represented by units of concentration. The main difficulty in using this form of data representation is the interdependence of the chemical constituents of the sediment. For example, if elemental concentrations are expressed per gram of dry sediment, an increase in the sedimentation rate of organic matter or biogenic silica will dilute the sedimentary concentrations of elements associated with clastic minerals (Engstrom & Wright, 1984).

1.4.2. Sodium, potassium, magnesium and calcium

The alkali and alkaline earth elements are major constituents of common silicate minerals and occur in most lake sediments primarily in allocthonous clastic material eroded from catchment soils and rocks. There is very little evidence for the authigenesis of clay minerals in lake sediments (Jones & Bowser, 1978). Thus because these detrital minerals are altered little in the lacustrine environment, their distribution in lake sediments is particularly useful in assessing weathering, soil development, and erosion in the catchment.

Calcium has a strong affinity for organic ligands, and thus organic sediments may contain substantial amounts of calcium not associated with allocthonous materials. A general correspondence between calcium and organic content has been noted in the sediments from a variety of lakes (e.g. Mackereth, 1966).

Mackereth (1966) suggested that the processes of leaching of mineral matter *in situ* and the erosive transport of soil particles could be reconstructed from sedimentary profiles of the alkali and alkaline earth elements. The two processes should produce contrasting patterns in the sediments. During periods of active erosion, the mass transport of unleached soils should increase the level of sodium, potassium and magnesium both in the mineral fraction and in the sediments as a whole. During a period of relative soil stability the deep weathering of soil profiles should reduce the alkali content of mineral matter prior to its erosive removal and sedimentation. Mackereth concluded that sedimentary alkaline earth elements, as they are associated with detrital minerals, directly reflect the intensity of weathering and erosion within the catchment area of the lake. Palaeoclimatic information has been inferred from studies of Lateglacial sediments from the Lake District and Scotland. Pennington (1981) suggests that the decreased levels of sodium and potassium in interstadial deposits are the result of an amelioration of the climate leading to vegetated and stable soils. The glacial conditions and intense solifluction of the Loch Lomond stadial are reflected in an increase in sodium and potassium and a decrease in organic content. Pollen analysis of the same sites shows a good correlation between the inferred soil changes and the vegetational history of the areas. These conclusions rely heavily on the assumption that changes in the soil composition, as reflected in the mineral content of the lake sediments, are directly related to variations in the intensity of erosion. However as Mackereth realised, if the rate of deposition of other sedimentary components varies; the composition of the sediment may be altered independently of the rate of mineral erosion. Thus although it may seem obvious that a vegetated soil will erode more slowly than one that is not vegetated, the hypothesis cannot be tested solely by total sediment composition.

1.4.3 Iron and manganese

These two elements are probably the most significant in palaeolimnology as their abundance in the sediments is determined by conditions both in the catchment area and in the lake. However, as the transport and deposition of these elements is determined by a number of different environmental factors, iron and manganese profiles are difficult to interpret. Iron and manganese are also less stable than the alkaline earth elements. Thus any interpretation of iron and manganese stratigraphy must take into account the processes which control the rate of supply to the lake and the degree of preservation of the elements.

Iron and magnesium become soluble under reducing conditions (magnesium more than iron). Mackereth (1966) realised that changes in soil composition control the supply of these elements to the lake basin and thus allow the palaeoredox reactions in the catchment soils to be reconstructed. However, humic and fulvic acids produced by the microbial decay of terrestrial plant materials appear to play an even more important role in the transport of these elements (Gjessing, 1976). A close correlation between sedimentary organic material and iron and manganese content has been found (e.g. Kukkonen, 1973).

There are many factors which affect the sedimentation of iron and manganese, these include: ionic composition of the water, redox conditions, pH, temperature, light penetration and microbial activity. However, apart from redox reactions, little consideration has been given to these controls in palaeolimnological studies. There is also the possibility of post-depositional migration of iron and manganese, if the surface muds do not remain oxidised.

1.4.4 Aluminium

Aluminium typically is the second most abundant inorganic element in lacustrine sediments after Silica, originating largely from clastic silicate minerals. In most lakes aluminium is primarily allogenic, it is usually regarded as a resistant mineral useful for studies of erosional intensity and soil leaching Aluminium has also been used as a conservative element against which variations in the accumulation of biological elements and anthropogenic input are compared.

The solubility of aluminium in lakes and soils is thought to be strongly dependent on pH, and rises markedly below a pH of 5 (Engstrom & Wright 1984).

1.5. PREVIOUS WORK

1.5.1 Introduction

The aim of this section is to present some of the palaeoenvironmental work that has previously been published. This work is related to Scotland in general and Fife in particular. There has not been a major investigation involving palynological and palaeoentomological palaeoclimatic reconstructions undertaken in Scotland prior to 1991. Therefore the two methods are dealt with in separate chapters. A chapter which compares the results obtained from multidisciplinary studies in other areas is also included.

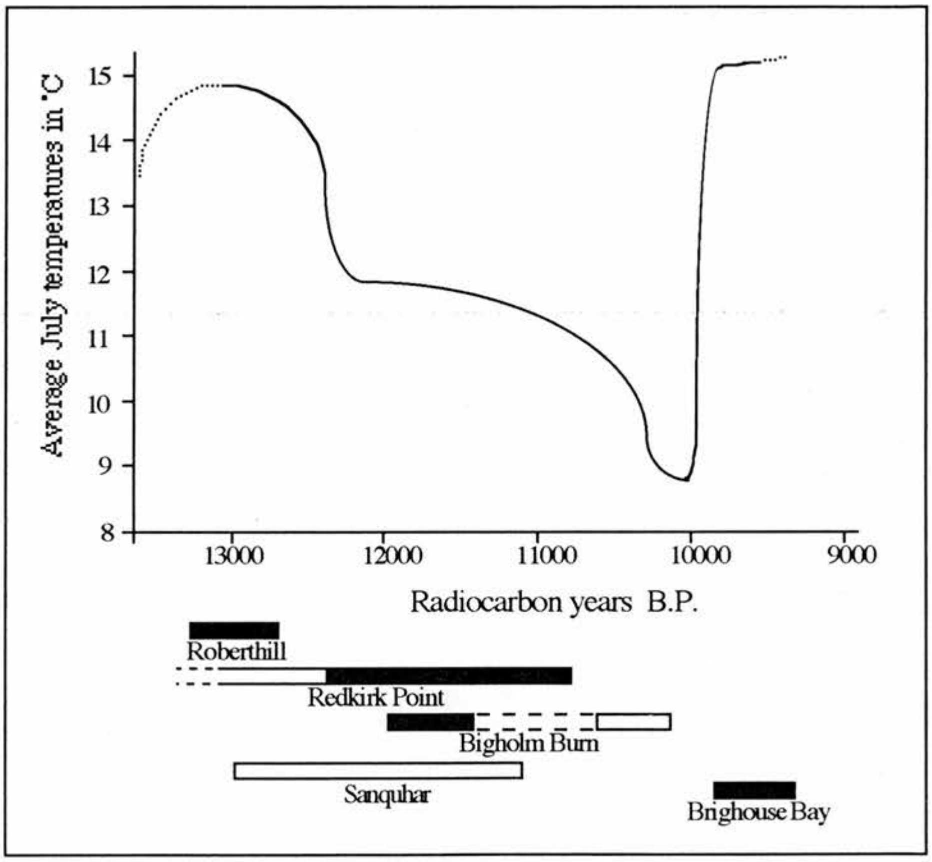
1.5.2 Entomological Analysis

Fossil Coleoptera have been analysed for palaeoenvironmental reconstruction for over 30 years. As this work was pioneered at the University of Birmingham, most of the work has been confined to England, particularly the English midlands. Only one major palaeoentomological study has been undertaken in Scotland (Bishop & Coope, 1977). A number of sites in south-western Scotland were sampled giving a faunal list of over 200 taxa. The sites were originally sampled in 1964, but the environmental interpretation of these insects was so much at variance with the accepted picture of the intensity and timing of the climatic change that supporting evidence from other sites was needed before the results could be published. It was established that over the course of 4,000 years the insect fauna of south-west Scotland changed from one dominated by temperate species through an arctic assemblage and back again to a temperate fauna. The amplitude of the climatic changes that would have been the cause of these fluctuations in the insect fauna may be estimated to some degree of accuracy. This is possible because species at present only found in areas well to the north, or to the south, successively inhabited this part of Scotland. Thus in the relatively short span of the Lateglacial/early Postglacial period the climate must have varied between conditions at least as warm as those of the present day, to conditions of arctic severity.

A combination of the results from five different sites allowed Coope to construct a palaeotemperature curve for southern Scotland. This graph is shown in figure 1.5.

It was found that organic-rich sediments contained a cold temperature beetle assemblage. The period between 12,000 and 11,000 years B.P. was, on palynological evidence, broadly equated with the Alleröd interstadial. The Coleoptera from deposits of this age suggest a colder climate than that of the immediately preceding period, akin to that near the treeline in the Scandinavian mountains where tree birches dominate the forests. The interpretation of a climate so close to the critical conditions for tree growth may provide the grounds for recognising these conflicting viewpoints. Any small-scale fluctuation in temperature may well cross and recross the threshold limiting tree growth and thus cause apparently large scale changes in pollen assemblages without any comparable large scale changes in insect assemblages.

Figure 1.5. Changes in the average July temperature inferred from Coleoptera assemblages plotted against radiocarbon years B.P. (for south-west Scotland). The age of the fossil-bearing sites are shown in black where radiocarbon dates are available and inferred ages are shown by open boxes where only stratigraphical and faunal evidence exists. (After Bishop and Coope, 1977).

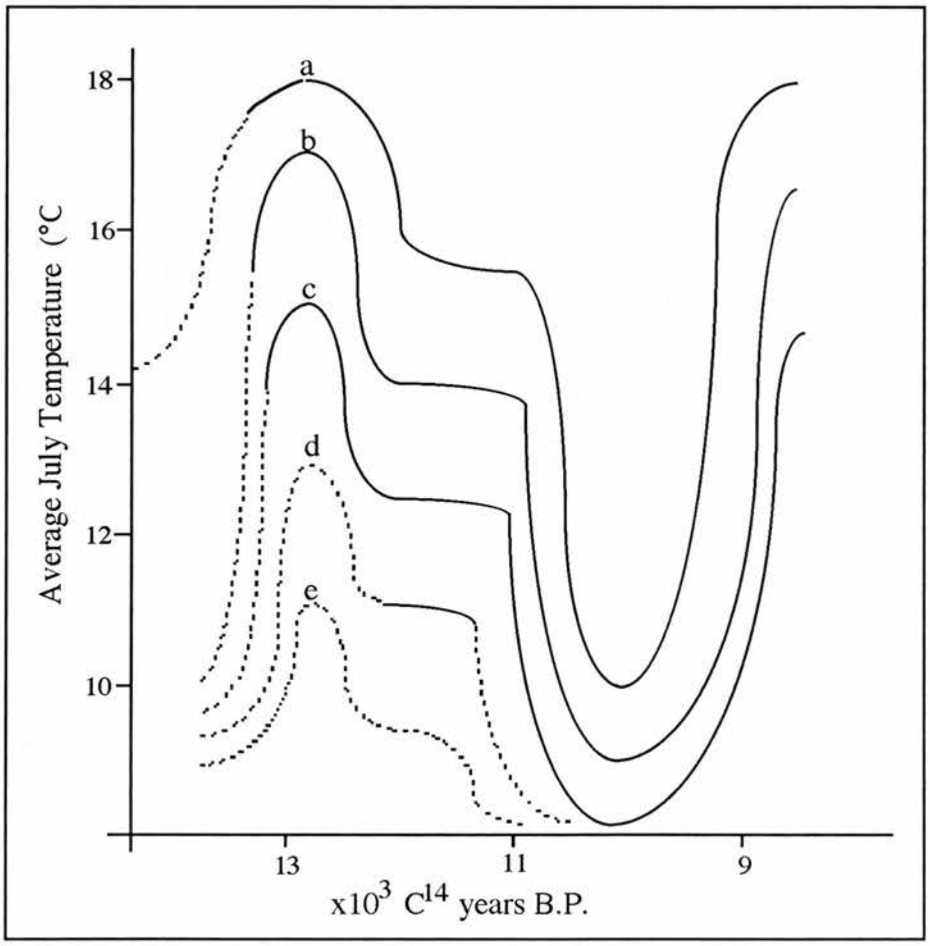


A study of organic deposits beneath till in Perthshire indicated a long Loch Lomond Stadial stratigraphic record. An analysis was made of the palaeoentomolgy of a borehole taken for this investigation. The sediment yielded a small, but interesting, beetle fauna including boreomontane species such as *Olophrum boreale*, *Euchnecosum brachypterum* and *Otiorhynchus arcticus*. The results, both from beetle and pollen analysis, seem to show a considerable lag time between the onset of the Loch Lomond Stadial and the arrival at the site of the valley glacier (Merritt *et al.*, 1990)

Palaeoentomologists are now working in most western European countries, the Soviet Union, Canada and the United States. Thus a coherent picture of climatic changes during the Quaternary is beginning to emerge. This is especially true for the British Isles where slight climatic differences in the different regions have been found. Coope (1977a) illustrates this with a palaeotemperature graph (figure 1.6.).

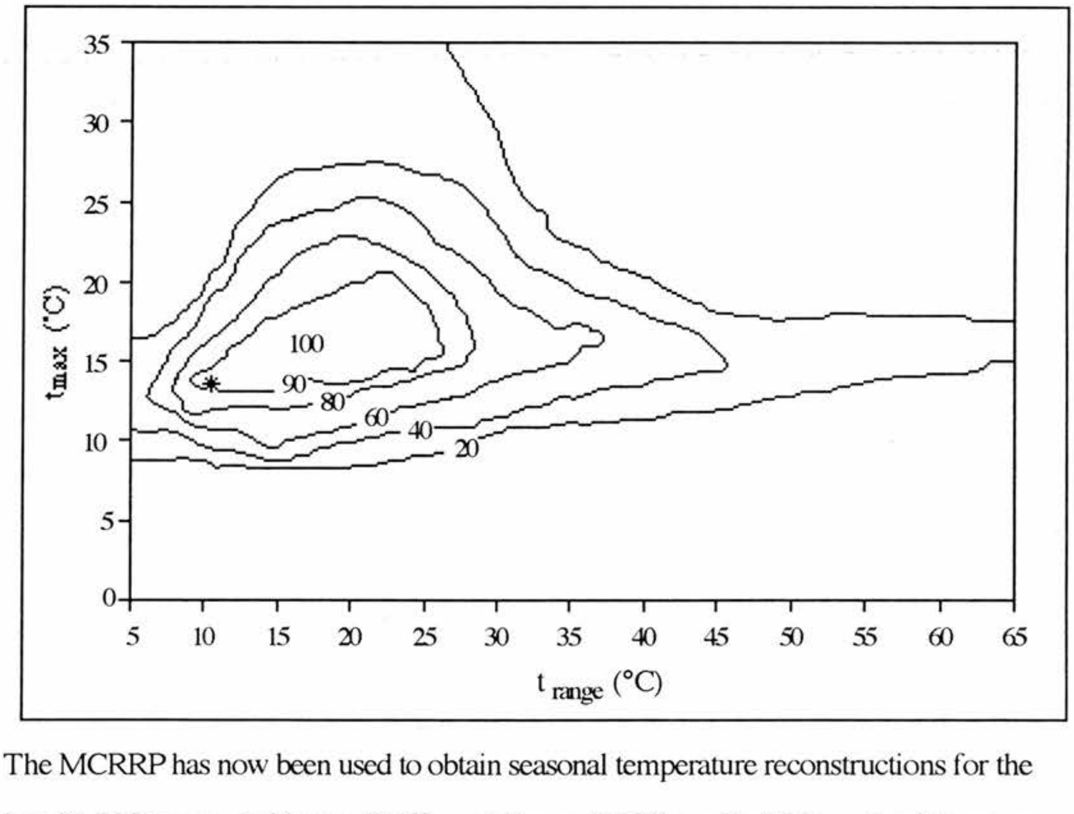
The presentation of results from palaeoentomological work can be in a variety of different forms. One way is to give a faunal list, usually in the form of a diagram showing the occurrence of species at different levels within the section. This is similar to a pollen diagram, only the abundance of the various taxa is relatively unimportant. Alternatively a table showing the minimum number of individuals at the various levels can be drawn.

Figure 1.6. Variations in the average July temperature near sea level during the closing phases of the last Devensian cold stage (a) for southern England, (b) for central England and north Wales, (c) for northern England and south-western Scotland, (d) for central Scotland and (e) a hypothetical extrapolation for the north of Scotland. Dashed lines are used where conjectural. (After Coope, 1977a). It is based on assemblages of Coleoptera from over 25 widely scattered localities covering most of Britain except the north of Scotland.



Recently with the advent of computer processing of palaeoentomological data using the Mutual Climatic Range Reconstruction Programme (MCRRP) (Atkinson *et al.,* 1986), another method of presenting data is now available. For a particular assemblage the thermal limits of the taxa are plotted as a mean July temperature (t_{max}) against the range of temperatures (t_{range}) (figure 1.7.). The resulting overlaps are shown on the printout. The area of 100% overlap between the thermal limits is the range of temperatures at which the various species, which make up the assemblage, co-exist.

Figure 1.7. Contour plot showing the MCRRP estimated thermal climate for the modern fauna recorded from Close House (research station of the University of Newcastle). The actual climate is indicated by *. (after Atkinson et al., 1986)

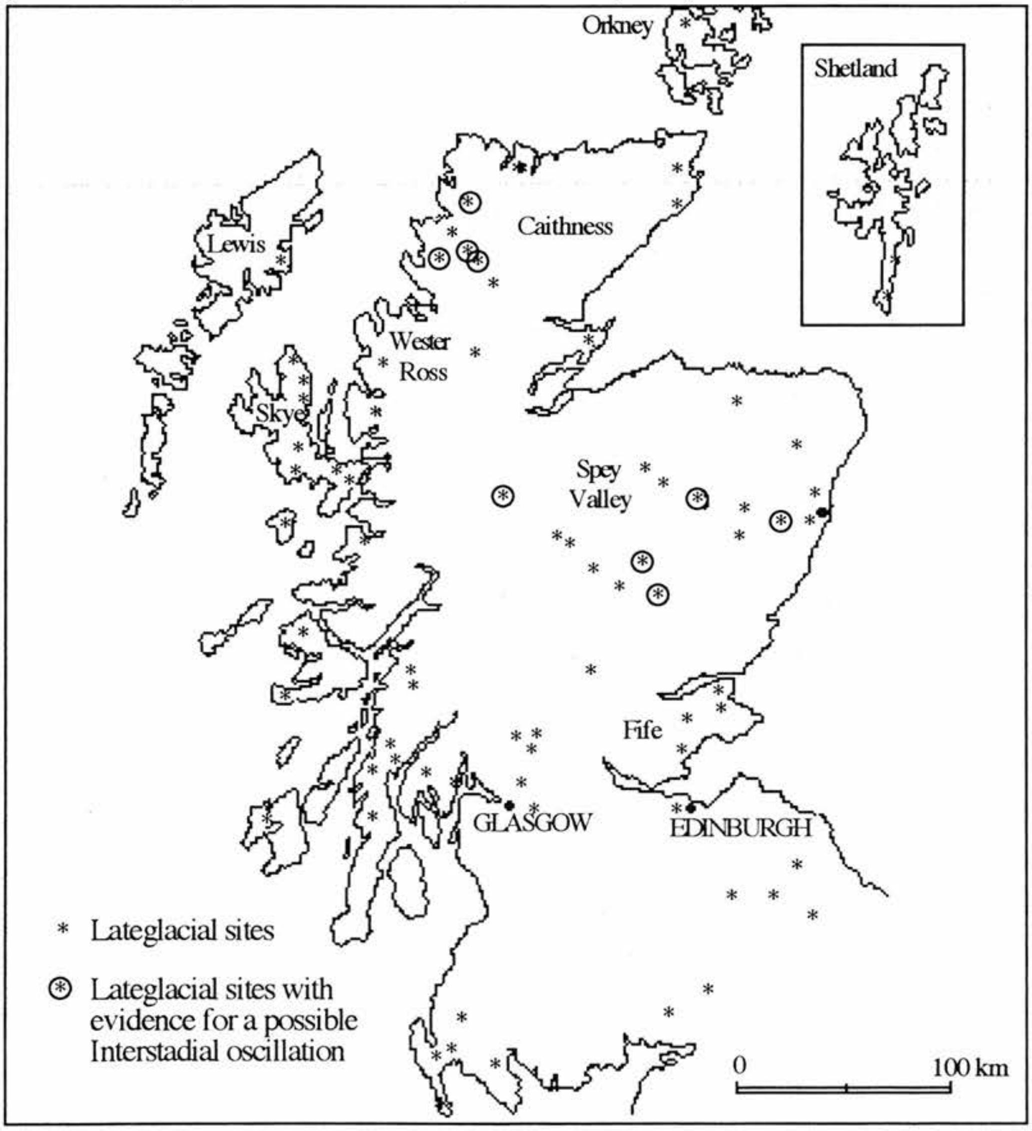


The MCRRP has now been used to obtain seasonal temperature reconstructions for the last 22,000 years. Atkinson, Briffa and Coope (1987) applied this method to many sites that had been studied previously for their Coleoptera fossils.

1.5.3 Pollen Analysis

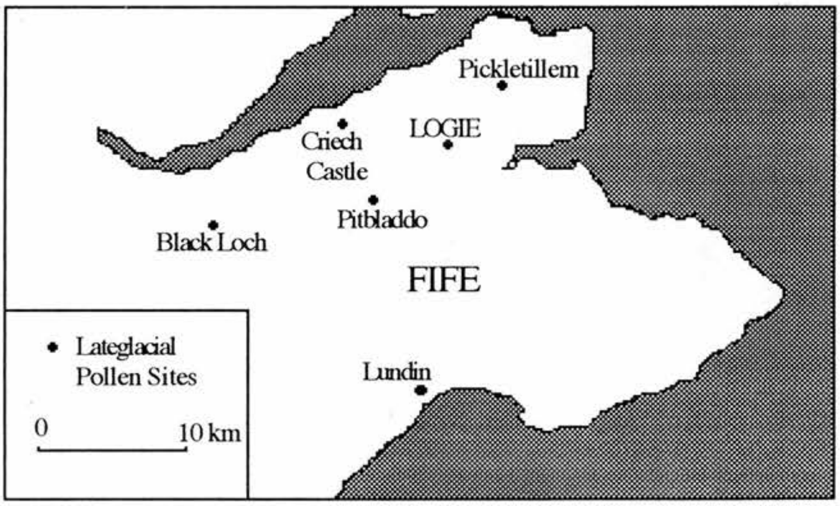
It is over 60 years since the first paper on Scottish pollen was published (Erdtman, 1924), since which the method has been a topic of intense research. Erdtman's work demonstrated the potential of pollen analysis for research into vegetational history and climatic change. The first Lateglacial site in Scotland was discovered by Mitchell, (1948). It was not until the 1960s that pollen analysis became more widely used, and now the results from over 200 sites in Scotland have been published (figure 1.8.).

Figure 1.8. Lateglacial sites in Scotland (after Walker, 1984).



Published pollen research from Fife is limited (fig. 1.9.), despite the existence of many suitable sites. The list is limited to: a pollen diagram of the Lateglacial and Postglacial periods from Pitbladdo, near Cupar (Donald, 1981); a coastal site which covers part of the Postglacial (Morrison *et al.*, 1981); a problematic Lateglacial and early Postglacial site at Criech Castle in the Ochil Hills (Cundill and Whittington, 1983); a modern land-use study from Morton Lochs (Cundill, 1985a); surface pollen samples from Bankhead Moss, south-west of St. Andrews (Caseldine and Gordon, 1978 and Caseldine, 1981) and Morton Lochs Nature Reserve (Cundill, 1985b); a detailed study of Black Loch in the Ochil Hills (Whittington *et al.*, 1990), and also a Lateglacial and early Postglacial site from Pickletillem in north eastern Fife (Whittington *et al*, 1991).

Figure 1.9. Map of the Lateglacial pollen sites in Fife.



Limitations of time, expertise and the availability of appropriate deposits have acted as constraints on the undertaking of multidisciplinary studies of single sites. Thus such investigations are extremely infrequent in Scotland as a whole, and totally absent from Fife. However Whittington *et al.* (1990) used chemical analysis, particle size characteristics and radiocarbon chronology to supplement data from Black Loch.

Black Loch (Whittington *et al.*, 1990) has provided data from the Lateglacial (circa 12,670 years B.P.) through into the Flandrian. It has been found that the late Devensian vegetation was dominated by the herbaceous taxa (Gramineae, *Salix* and *Rumex*) typical of the Windermere Interstadial phase in central Scotland. This passes up into a phase represented by more frequent ruderal taxa (Compositae, *Artemisia*, Caryophyllaceae and Cruciferae). This seems to suggest a more disturbed environment. The sharp change from stadial to interstadial conditions can be determined from the rise of *Betula* and peaks in the values of *Juniperus* and *Filipendula* while Gramineae, *Artemisia*, Cruciferae and *Rumex* decline,indicating a change from open tundra through a juniper and tall herb stage to birch woodland. The Flandrian began with high *Betula* values and a marked rise in *Corylus* pollen (both in relative and absolute terms) until about 7,600 years B.P.

Cundill and Whittington (1983) investigated another Lateglacial/early Postglacial site at Criech Castle, Fife. The late Devensian pollen assemblage included anomalous arboreal taxa and three possible sources of this pollen are suggested: contamination, long distance transport and reworking of interstadial material. No definitive explanation can be given to account for the occurrence of such thermophilous tree pollen in the late Devensian. However the authors suggest that previous similar anomalies, which have been dismissed as contamination from use of the Hiller borer, may well be worth considering further. Another feature of this site was the unusual pollen record from the first 1,500 years of the Flandrian. This has been attributed to local environmental conditions. As pollen studies in Scotland are spatially and altitudinally restricted, it is likely that there will be variations between local pollen assemblages.

Another Lateglacial site at Pitbladdo has been the subject of a palynological investigation. Donald (1981) studied a section similar to that being studied in this investigation at Logie. He found a local development of the *Betula-Juniperus* scrub in the Windermere Interstadial. This was followed by a period of open habitat during the Loch Lomond Stadial, and an early Postglacial forest dominated by *Corylus* and *Betula*.

Whittington *et al.* (1991) have studied a site at Pickletillem in north-east Fife. The results of this study show that the Lateglacial vegetation cover in this part of Eastern Scotland was formed largely of dwarf-shrub heath, with *Juniperus* present. Evidence of an "Older Dryas" revertance was found at this site. Whittington *et al*. conclude that the thermal maximum of the Lateglacial interstadial preceded this revertance. This in turn was followed by a gradual temperature decline prior to the severe conditions of the Loch Lomond Stadial. Several C^{14} dates were obtained from material recovered from Pickletillem. However, as a date of 9,750±280 B.P. was recorded for the onset of the Loch Lomond Stadial it is thought that the dates from this site are all approximately 1,000 years too young.

The other published palynological investigations undertaken in Fife are concerned with Postglacial marine transgressions (Morrison *et al.*, 1981) and modern pollen spectra (Caseldine and Gordon, 1978; Cundill, 1985b).

A major change of the climate around 11,000 years B.P. brought about significant changes in the environment, and the Loch Lomond readvance of glaciers. Pollen assemblages from this period are dominated by *Rumex* with small amounts of *Juniperus* and *Betula*. The sudden termination of this cold period is reflected in a change from minerogenic to organic sediments. The pollen records show an initial colonisation by grassland species followed by *Salix-Empetrum* heath, *Juniperus* heath and then *Betula* woodland within 1,000 years of the end of the harsh stadial conditions.

A more general palaeoenvironmental reconstruction for eastern Scotland is given by Lowe and Walker (1977). They studied six sites in the southern and eastern Grampian Highlands and found a relatively open habitat with predominantly herbaceous vegetation despite an apparently mild climate. Only in the more southerly sites were there any significant amounts of shrub pollen. During the Lateglacial interstadial there was an increase in the *Betula* curve, although this is more obvious in the south. There was sparse tree cover as the presence of such shade-intolerant plants as *Juniperus* and *Empetrum* emphasises. Little direct evidence of the temperature levels is available for the study area. An attempt was made using the present temperature difference between Scotland and the English midlands (1-2°C) and a temperature for the Lateglacial of 17 °C declining to about 12-13 °C (Coope *et al.*, 1971) to estimate a probable temperature for central Scotland.

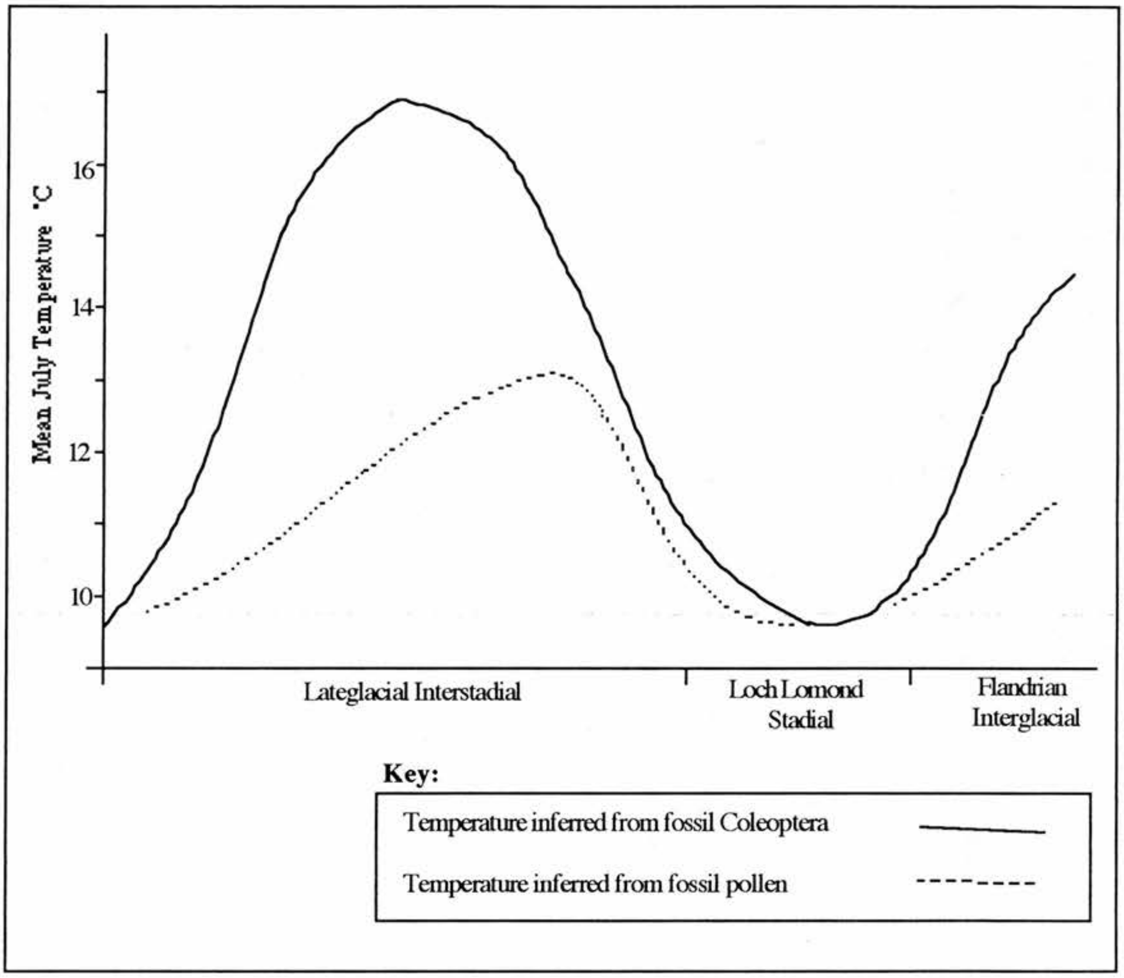
1.5.4. Multidisciplinary Investigations

Over recent years there has been an increasing trend towards multidisciplinary investigations in order that a complete palaeoenvironmental investigation can be attempted. There have been several studies combining palaeoclimatic data inferred from fossil beetle and pollen evidence. These have shown a great deal of concurrence between the two methods for periods early in the Quaternary. However, the period with which this investigation is concerned (the Lateglacial period of the Devensian) has been the subject of much heated debate over the years. The crux of the debate is the intensity and rate of the climatic changes which occurred during the closing stages of the last glacial period. Pollen evidence is somewhat contradictory, with the presence of a short stadial event separating two interstadials between the end of the last glacial period and the onset of the Loch Lomond Stadial. This "Older Dryas" revertance is shown at some sites, but others relatively close by may not show it. Beetle evidence gives a relatively consistent picture of rapid climatic warming at the end of the glacial period followed by a gradual cooling until the stadial conditions of the Loch Lomond Stadial are reached. The beginning of the Flandrian interglacial is marked by another phase of rapid climatic warming. This disagreement between the entomologists and the pollen analysists is summarised in figure 1.10.

The conflict between the two methods is a matter of interpretation of the data derived from the different proxy data. A comparison between the two sets of results would superficially appear to be a simple matter. However, the two methods are essentially measuring different things. It is not changes in climate that are recorded by documenting changes in floral and faunal fossil assemblages but the responses of those plants or animals to the climatic changes. Thus if the two communities respond in a different way to the same climatic change or, if the there are other factors controlling the distribution and occurrence of an animal or plant apart from thermal climate then different climatic reconstructions will be obtained for the same period of time.

The differences between the two methods were highlighted by Coope and Pennington (1977) who attempted to construct a chronology for a Lateglacial type section at Low Wray Bay, Windermere. They found it impossible to construct a unified stratigraphic division because of the different results obtained from pollen analysis.

Figure 1.10. Variations in mean July temperature in lowland Britain during the Lateglacial period (after Coope 1970).



It is thought that the difference between palaeoclimatic results derived from fossil pollen and fossil beetles could be the result of differing response rates of beetles and certain important plant taxa such as *Betula* (Pennington, 1986). This is probably because of the slow development of suitable soils preventing the rapid colonisation of the areas made available by amelioration of the climate. This causes a "lag" in the response of pollen evidence to major climatic events. It should be noted that this lag only affects those periods where major climatic changes occur over a short period of time; after a period of climatic stability the two forms of proxy data produce similar results.

1.5.5. Chemical Analysis.

There have been several multidisciplinary palaeoenvironmental investigations in Scotland that have utilised the technique of chemical analysis. The method of chemical stratigraphy has "...not yet reached the point where it can be used independently of microfossil and other biotic evidence to reconstruct lake history" (Engstrom & Wright, 1984). Although pioneered by Mackereth, much of the early chemical stratigraphic work in Scotland was done by Professor W. Pennington. She studied a number of lochs from northern Scotland and found 3 with conformable Lateglacial and Flandrian sedimentary sequences (Pennington *et al.*, 1972). Pollen, diatom and chemical evidence were used to reconstruct the environmental and limnological history of the lochs. The chemical analysis showed continuous soil maturation from pre-Interstadial to Interstadial times. The Stadial period, represented by the *Artemisia* zone has a low organic content.

Lowe and Walker (1986) in their study of the Lateglacial environmental history of Mull used chemical analysis in conjunction with pollen data. They found a strong correlation between the concentration trends of various elements and the pollen stratigraphy. Thus the chemical data were interpreted in terms of rates of erosional activity around the basin catchments. Their conclusion about the use of chemical analysis to augment pollen data in environmetal reconstruction is that the chemical curves ".....can be used as indices of landscape changes around the sites....." (Lowe & Walker, 1986).

Whittington *et al.* (1990) used chemical analysis in their multi-core study of Black Loch in Fife to suggest a sediment history for the loch during the Lateglacial period.

1.6. LACUSTRINE SEDIMENTS

Lacustrine sediments have been studied in great detail, despite forming only a small fraction of the stratigraphical record. Lake sedimentation is regarded as being a microcosm of sedimentology, providing small scale facies models which geologists can use in the interpretation of larger scale features. However the great range of sedimentary environments found in lakes means that any stratigraphical sequence of lake deposits must be studied in fine detail.

Two features of lakes stand out. The first is the variation of sedimentary facies in vertical sequences as a result of biochemical fluctuations in lake waters and shifting of the shorelines. The second is their sensitivity to climatic change; ancient lake deposits are some of the best indicators of palaeoclimate (Allen & Collinson, 1986).

The features of lake deposits discussed here affect both fossil insects and pollen, although sometimes in different ways. However it should be noted that pollen is more resistant to weathering and abrasion than insect exoskeletons.

Lake sediments, such as those at Logie, contain a high proportion of material derived from outside the lake basin. The sediment normally consists of inorganic and organic allocthonous detritus, organic material from organisms growing within the lake and an input of pollen direct from the atmosphere. Sediment is also derived from surrounding regions through drainage water and secondarily transported pollen from polliniferous deposits which have been eroded by the drainage waters.

Lake sediments develop a stratified sequence, therefore the depth of the deposit is related to age. However this relationship need not be a linear one. Unlike peat deposits, there is no leaching of sediment through lake deposits, thus there is no problem with the downward movement of pollen. However, both pollen and beetles may be affected by detritus-feeding animals within the upper layers of sediment, which can result in bioturbation. Another problem is water turbulence which has been studied in detail. Davis (1968) found that the deposition of sediment was not constant throughout the year, and that resuspension and redeposition of sediment occurred during the year. However it would take a great deal of turbulence to affect palaeoclimatic data as the resolution of such data cannot be refined to annual levels.

Another complication to sedimentation is the fact that erosion of surface sediments tends to be greatest in the shallow water at the lake margin, but redeposition occurs unevenly over the whole lake basin. The nature of sediment deposition within a lake basin is extremely complex, even in a relatively small and simple lake basin. Multiple core studies of the same basin at Black Loch in Fife (Whittington *et al.*, 1990) have shown through variations in elemental composition and rates of deposition that sediment focussing has taken place over long periods (Edwards & Whittington, in press). There are two implications of this phenomenon for palaeoclimatic work. Firstly the lateral movement of pollen and insects will lead to some variation between sampling sites. Thus a single core, or set of samples will provide an adequate representation of the climatic history of the basin. Secondly, each year's pollen or insect input will be mixed with that of previous years. Thus a sample taken at a given point will be, not representative of a single year's input but, an average of several years' input. This has the effect of reducing variation in fossil assemblages taken from adjacent samples and "smoothing" the final palaeoclimatic reconstruction.

Sediment redistribution can have an adverse effect on palaeoclimatic reconstructions. For example, streams entering and exiting a lake basin may deposit extraneous material or erode lake sediment causing a disconformity. Both of these processes will reduce the accuracy of a palaeoclimatic reconstruction, particularly if any statement on the rate of climatic change is to be made. Problems such as these are best avoided by sampling only those sediments which show no sign of disturbance. These are most likely to occur in the deepest parts of the basin or away from any input or output channel. However as a large number of insects, particularly the beetles, are washed into a lake basin by streams and rivers, sampling sites for these benefit from being reasonably close to such a source of material.

There have been attempts to separate redeposited pollen from that laid down "in situ" on the basis of the different degrees of deterioration of the pollen grains. Cushing (1967) attempted to develop this technique and defined six classes of exine deterioration (Chapter 1.3.5). He found that the different types of deterioration were associated with different sediments in Minnesotan lakes. Birks (1973) in his work on Skye, separated the rebedded pollen into "secondary" pollen from the older eroded deposits and "inwashed" pollen from contemporary vegetation. The former contained a high proportion of broken and degraded grains, while the latter tended to be corroded by aerial oxidation and microbial decay before deposition.

It is also possible to distinguish the pollen that has been washed into the lake - the regional component, from the pollen of plants that grew in the lake - the local component. This is not possible for sediments such as peat as both components might be represented by the same taxa. However the aquatic plants are of a different pollen type from regional components e.g. the occurrence of aquatic pollen such as *Potamogeton* and *Myriophyllum* .

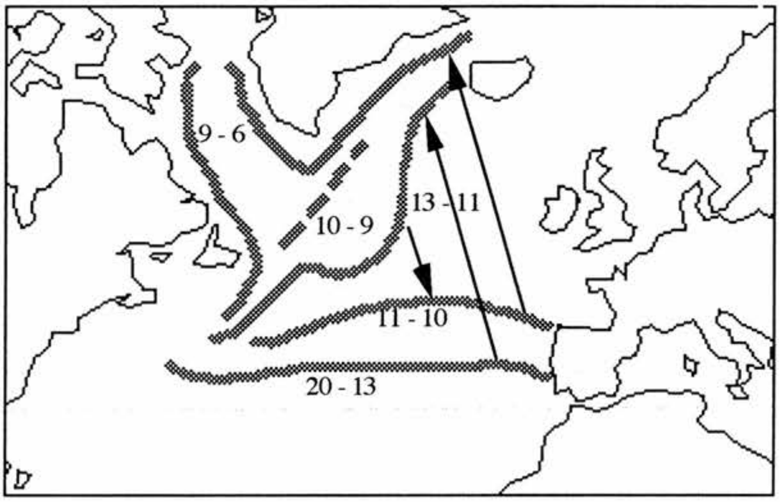
1.7. CHRONOLOGY

1.7.1 Introduction

The temporal division of the Quaternary of north-western Europe is based on climatic phases. This division has been the subject of much debate and suffers from a surfeit of terminology, with the same phases being referred to by different names in different places. An example of this is the stadial period between approximately 11,000 and 10,000 years B.P. This climatic phase is known by several different names in different places viz. Younger Dryas (continental north-west Europe), Loch Lomond Stadial (Britain) and the Nahanagan Stadial (Ireland). There is considerable agreement on the Lateglacial climatic history of north-west Europe (Mangerud & Berglund, 1978), and the area seems to be a natural geographical region for a common stratigraphical nomenclature for the Quaternary. Birks (1982) attempted to rationalise the stratigraphy of the Flandrian (or Littletonian) stratigraphy in Britain and Ireland. Birks used the pollen zones from a Flandrian type section to propose a unified chronology. However, he states that such a task is made difficult because there are no major climatic events during the Flandrian on which to base a stratigraphic division. He concludes that pollen assemblage zones combined with radiocarbon dating are useful in palaeoclimatic and palaeoecological reconstruction but "they cannot form the basis of a chronostratigraphy except in very local situations".

The climatic events experienced by north-west Europe were not the same as those in North America. It is generally agreed that major climatic changes are related to the movement of the oceanic polar front. The western end of this front remained fairly static during the Lateglacial, whereas, on the eastern side of the Atlantic the front was oscillating over great distances (fig.1.11.). Thus the differences between North American and European stratigraphic terms are justified during the Lateglacial.

Figure 1.11. Movements of the oceanic polar front during the Lateglacial (after Coope, 1986). (All figures refer to dates in years B.P. x10^3.)



Certain aspects of the Lateglacial environment are more contentious. The existence of a short period of climatic deterioration (the Older Dryas) between about 12,000 and 11,800 years B.P. is the subject of much debate. Also, entomological evidence has suggested the presence of more severe and abrupt climatic events than those shown by vegetational data. The insect evidence does not conform with the traditional palynological concepts of Bölling, Older Dryas and Alleröd climatic episodes during the Lateglacial interstadial. The conflict with the insect evidence can be explained by the fact that insect populations are far more mobile than plant communities, thus vegetational developments will lag behind major climatic changes (Coope, 1975 & 1977a; Pennington, 1986).

Climatic reconstruction as a basis for chronological division is problematic because of different interpretations of biostratigraphic parameters. In addition, climate is the result of a combination of different components, the most important of which are temperature and precipitation. Also climate is only one of a number of different ecological factors which determine the distribution of palaeoclimatic indicators such as plants and insects. Thus palaeoclimate can be a poor guide to geological chronology.

1.7.2 Stratigraphic Subdivision

The International Subcommission of Stratigraphic Classification (ISSC) stated that the most widely used methods in stratigraphy are:

1. Lithostratigraphy
2. Biostratigraphy
3. Chronostratigraphy

Mangerud *et al.* (1974) added two further methods to this list that are used in Quaternary stratigraphy:

4. Morphostratigraphy
5. Climatostratigraphy

They also proposed a stratigraphy for the Lateglacial defining 4 chronozones (figure 1.12).

An attempt has been made to define a type section for the British Lateglacial. A site at Low Wray Bay, Windermere, has been subdivided using lithostratigraphic, palaeoentomological and palynological methods (Coope & Pennington, 1977).

However, as was the case at Windermere, these methods do not always produce the same climatostratigraphical boundaries. If the definition of an interstadial is based on climatic parameters, different interpretations are made using different methods of palaeoclimatic reconstruction. As only biological and lithological proxy data of climate have been used there has been much debate over the validity of using climate as a basis for Quaternary stratigraphic division. Also the boundaries are likely to be diachronous, causing problems in the relatively short timespan of the Lateglacial period.

Figure 1.12. Chronostratigraphic subdivision of the Lateglacial in Scandinavia (after Mangerud *et al.*, 1974).

C^{14} years B.P.	**Chronozones**
10,000	
	YOUNGER DRYAS
11,000	
	ALLERÖD
11,800	
	OLDER DRYAS
12,000	
	BÖLLING
13,000	

Gray and Lowe (1977) constructed a climatostratigraphic subdivision of the Scottish Lateglacial. They recognised two distinct climatic phases, viz. a Lateglacial Interstadial followed by a stadial period (the Loch Lomond).

The Quaternary is one of the most complex geological periods to divide stratigraphically. There are many features of the Quaternary which limit the use of conventional stratigraphic methods. Bowen (1978) lists some of these features: the short time span of the Quaternary; the inadequacy of the fossil record for biostratigraphy (for the same reasons it is good for palaeoclimatic reconstruction); the fragmentary nature of its depositional record; unusual stratigraphic relations caused by the influence of the geomorphic situation; and the way it has been subdivided using climate as a standard.

The ISSC stress that there are stratigraphic situations where hard and fast rules cannot be applied. The Lateglacial, with its rapid time transgressive units based on reconstructions of climate, must be one of these.

Lowe and Gray (1980) suggest a general climatostratigraphy for north-west Europe. Their proposal of two climatostratigraphic units in the Lateglacial has been supported by several workers. Berglund (1979) states that the traditional subdivision of the Lateglacial in southern Sweden into two interstadials (Bölling and Alleröd) separated by a short stadial (Older Dryas) is "questionable". Thus Lowe and Gray (1980) produced a revised stratigraphy for the Lateglacial of north-west Europe (fig. 1.13.).

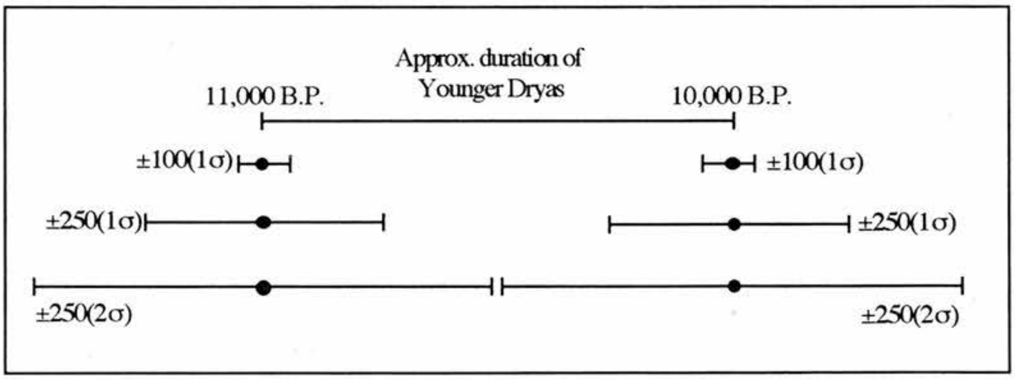
Figure 1.13. Suggested general climatostratigraphic subdivision and terminology for the Lateglacial of north-west Europe (after Lowe and Gray, 1980).

C^{14}years B.P.	**Climatostratigraphic Unit**
	FLANDRIAN INTERGLACIAL
10,000	
	transition
10,500	
	YOUNGER DRYAS STADIAL
11,000	
	transition
12,000	
	LATEGLACIAL INTERSTADIAL
13,000	
	transition
14,000	
	LATE DEVENSIAN GLACIAL

1.7.3 Radiocarbon Dates

Carbon^{14} dating is the most practical method of establishing a time framework for the late Pleistocene climatic changes. Despite advances in varve chronology and dendrochronology they are still of very limited use for this period. The many errors that can be associated with radiocarbon dating are well known. In addititon to these errors the method has its limitations e.g. the resolution of C^{14} dating. Most dates from the early Flandrian and Lateglacial have standard deviations of ±100 to ±250 years. It must also be borne in mind that there is only a 68% probability of the true age falling within that single standard deviation. For a 95% probability then two standard deviations must be quoted. Radiocarbon "dates" are in fact just measures of C^{14} activity and thus should be treated with some caution. An example of the resolution of C^{14} dates from the Lateglacial is given in figure 1.14.

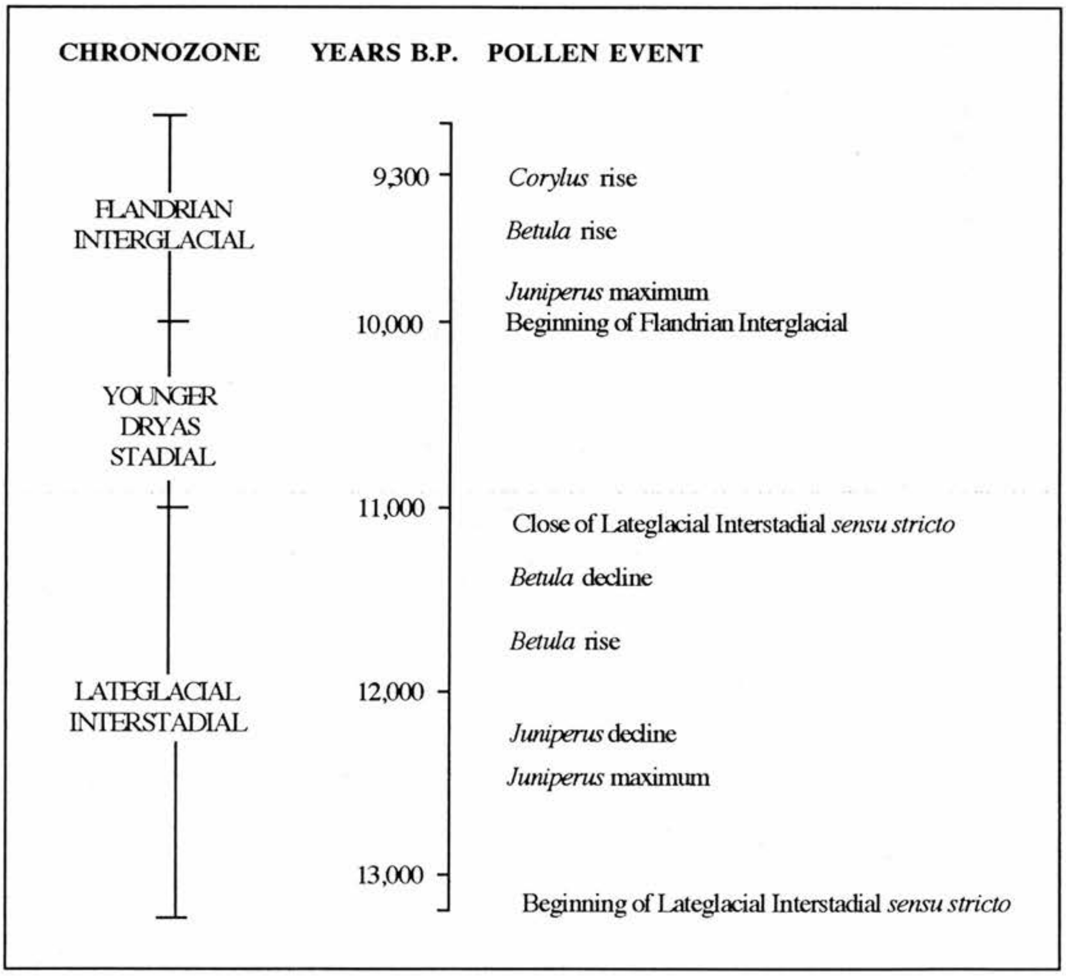
Figure 1.14. An illustration of the resolution problems in dating the Younger Dryas boundaries (after Lowe and Gray, 1980).



The most recent review of C^{14} dating of the Lateglacial period (Walker and Harkness, 1990) suggests absolute dates for the timing of certain vegetational events. The site used for this was Llanilid, South Wales, where a kettle hole had been exposed by opencast coal workings. As the site was exposed and not sampled with a small-diameter corer it was possible to remove enough material from the sequence to obtain good quality dates. When a site is cored there is a problem with obtaining enough material for a date. Either multiple cores have to be taken (with the loss of stratigraphic control that would entail), or thick core segments (up to 20 cm long) have to be taken from the core. The samples from Llanilid could be split into humic and humin components for independent C^{14} dating. This process will show the presence of non-contemporaneous carbon in the samples. The potential problems with C^{14} dating of whole sediment are clearly illustrated by the fact that of the 12 dated horizons at Llanilid only 4 showed age agreement between the humic and humin fractions.

The problems involved with establishing a chronology for the Lateglacial based on C^{14} dating are not just the result of using small diameter corers. Hard water error, the presence of reworked mineral carbon and/or contamination by younger carbon residues and the occurrence of aquatic plants (e.g.*Drepanocladus*) that fix their own carbon from the water, can affect the accuracy of C^{14} dates. The errors can be reduced by having large enough quantities of sediment available so that only identifiable material is dated.

Figure 1.15. Chronology of the British Lateglacial (based on Walker & Harkness, 1990).



1.7.4 Conclusion

One of the main problems in using climate in stratigraphic classification is that it is only the effects of climatic change that are being observed. Thus the units are interpretative or inferred, and as can clearly be seen in Coope and Pennington (1977) they are open to different interpretations depending on the method of palaeoclimatic reconstruction being used.

If evidence for time-transgressive climatic change were to be found across north-west Europe during the Lateglacial then narrower transition zones may well be identified for different regions. These zones could then be related to a general climatostratigraphy.

Bowen (1978), in discussing Quaternary correlation, points out that the evidence is so problematic that "........the use of a "floating chronology"......is desirable, wherein units are flexibly disposed temporally, and are readily amenable to changing emphasis due to new discoveries or interpretations".

SECTION 2

METHODOLOGY, RESULTS AND INTERPRETATION

2.1. THE SITE

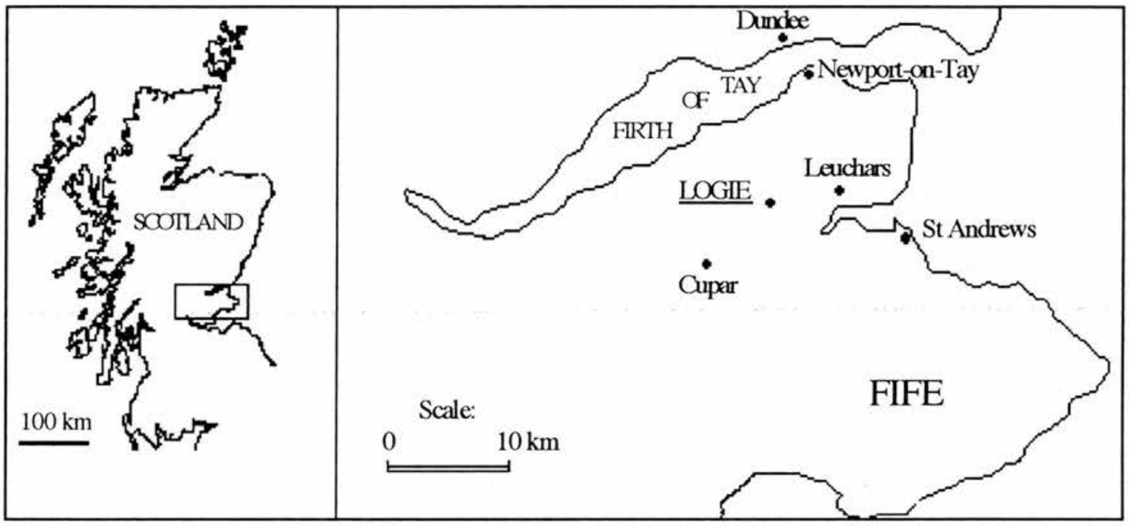
2.1.1. Introduction

For the purposes of this research project a site fulfilling several requirements was sought. A section spanning the Lateglacial period was required as this would give the opportunity to distinguish major climatic changes over a relatively short time-span. It was also decided to find a site in eastern Scotland as no palaeoentomological investigations have been carried out in this area. However, a site that had not been studied previously for its pollen content was desired. Attempts were made to find an exposed section as this is the most convenient for palaeoentomological studies allowing easy removal of bulk samples of sediment. Unfortunately no outcropping Lateglacial section could be found in eastern Scotland. A potential site at Logie, in north-east Fife, was known from an undergraduate dissertation (Anderson, 1985) which presented a study of a Flandrian pollen profile from Logie; although this study was concerned with the Flandrian period the presence of Lateglacial sediments was recorded.

2.1.2. Description of the site

The area of study is a large basin just to the south-west of the village of Logie, approximately 8 miles to the north-west of St. Andrews (Grid Ref. NO 402201) (figure 2.1.).

Figure 2.1. The situation of Logie, Fife.



The site chosen for this investigation is a basin containing a poorly-drained bog (figure 2.2.), situated at an elevation of about 120 m above sea level in the Ochil Hills of northern Fife. In common with many other similar basins in the Ochil Hills it was probably formed by ice-scouring. During the Lateglacial period the site was a lake with a large main basin and a smaller subsidiary one along the southern margin (figure 2.3). The local geology is predominantly Lower Devonian volcanics and the variable composition of these rocks may have resulted in locally more concentrated scouring (Cundill and Whittington, 1983). The evolution of the basin from its formation is difficult to interpret because of the presence of a glacial channel of a so far unexplained nature (figure 2.3.).

Figure 2.2. Map of the basin studied; Logie, Fife.

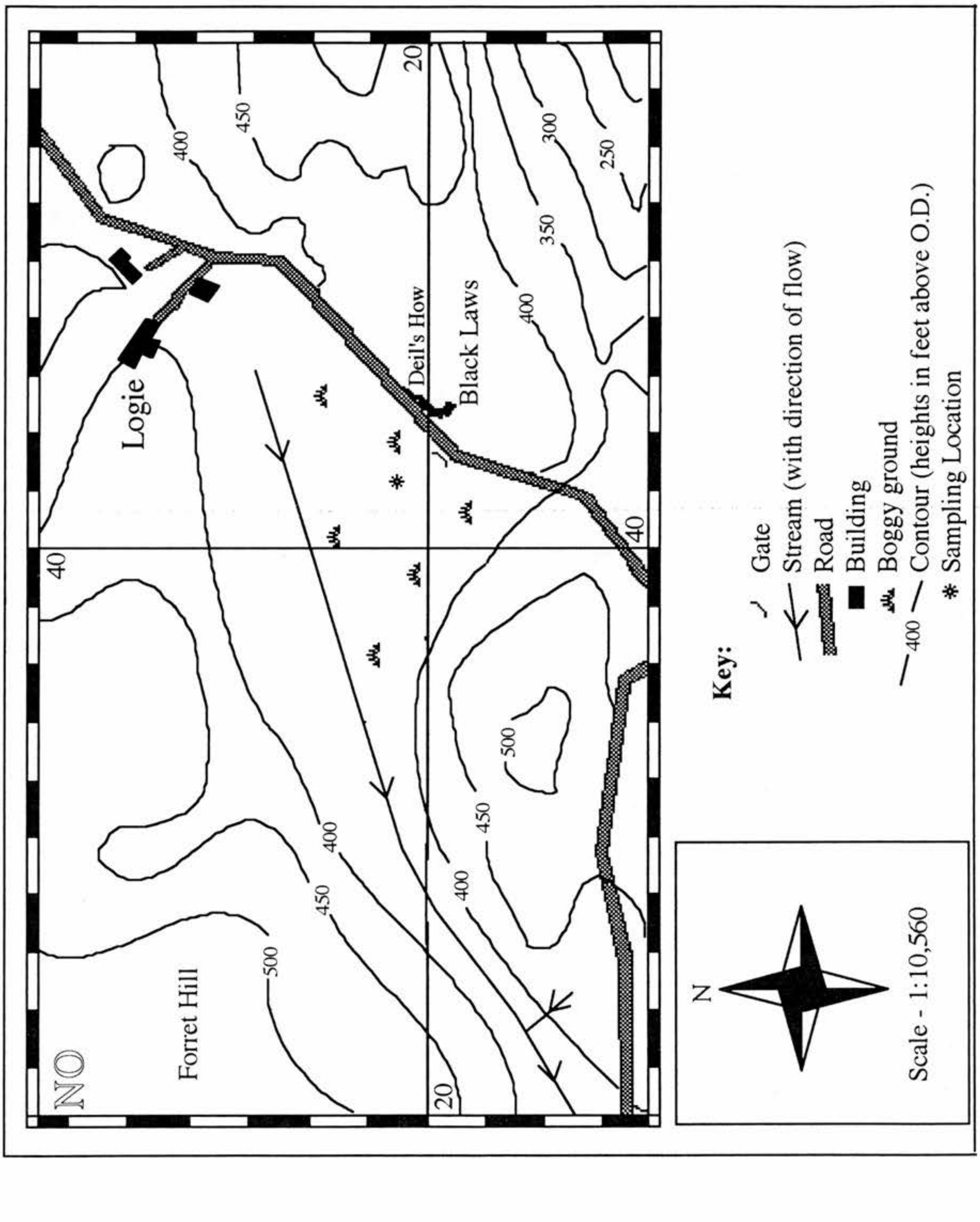


Plate 2.1. Photograph of the site at Logie (looking north-west from Deil's How).

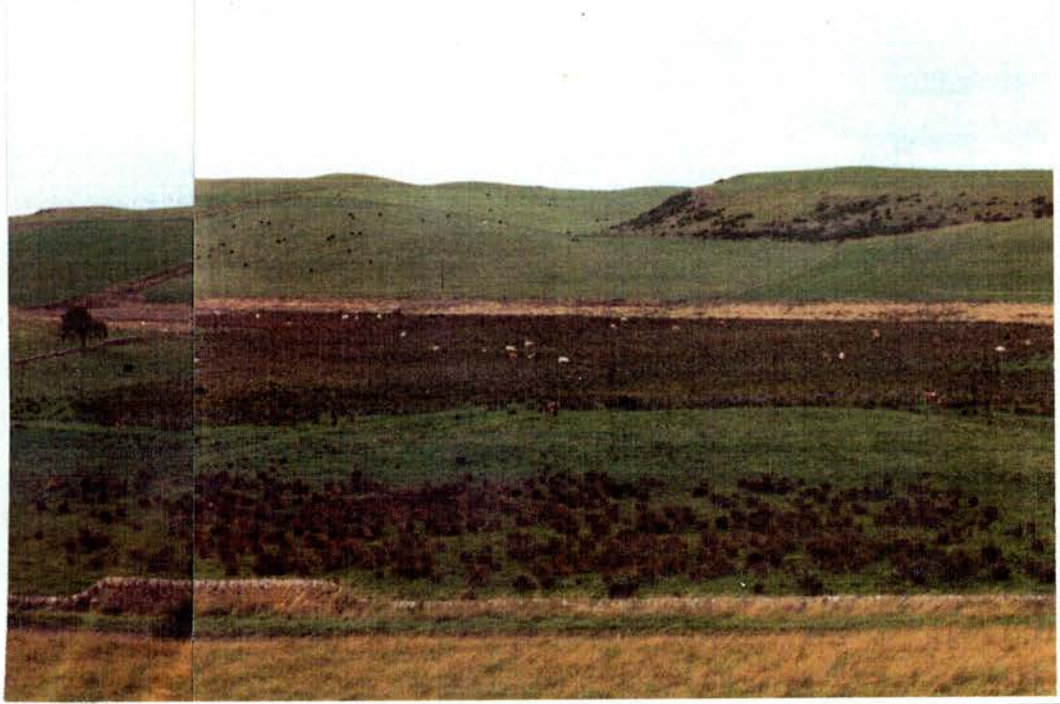
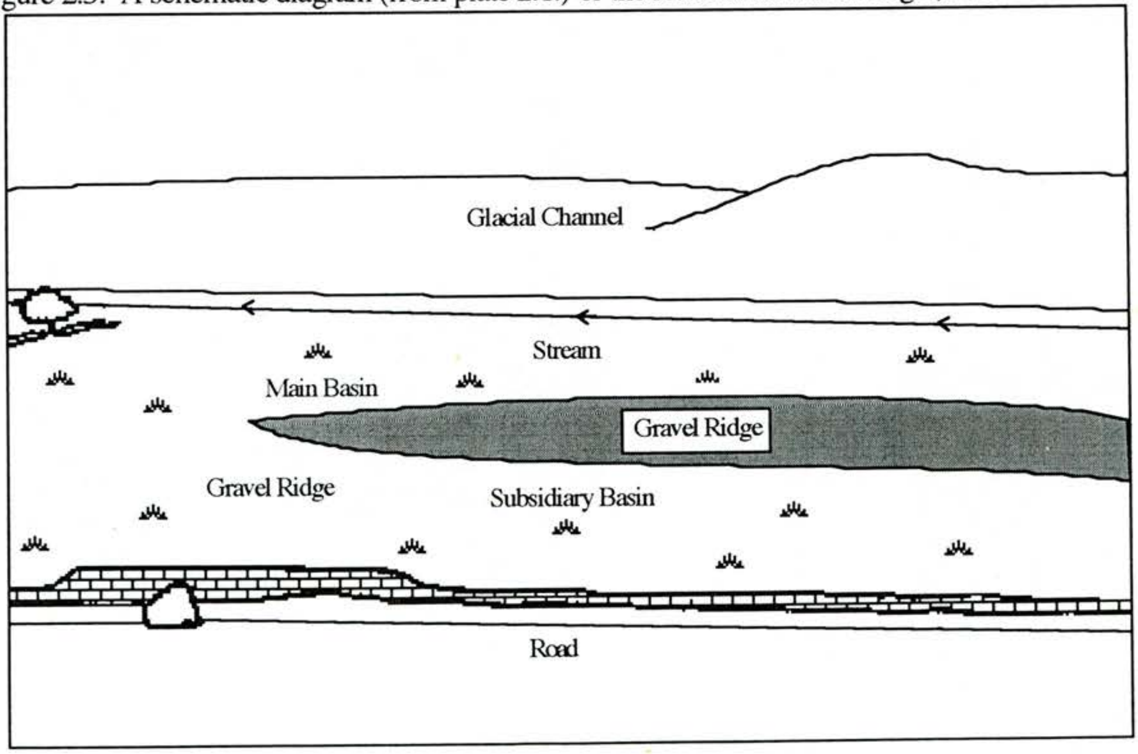


Figure 2.3. A schematic diagram (from plate 2.1.) of the features shown at Logie, Fife.



2.1.3. Geomorphology of north-east Fife

The geomorphology of Fife is poorly served by the literature. Few papers exist, and these are mostly concerned with the Lateglacial and Postglacial raised shore lines of the area (Sissons et al., 1966; Cullingford and Smith, 1966; Browne et al., 1981).

Deglaciation in north-east Fife at the end of the last glacial period took the form of recession of the main ice-front into the Firth of Tay. This left an area of stagnant ice in the Leuchars-Wormit area, partly overlain by late Devensian marine deposits (Chisholm, 1966). Deglaciation was influenced by the thinning of the ice over the hills of northern Fife, which caused the separation of the ice in the Howe of Fife from the glacier in the Firth of Tay. The deglaciation of north-east Fife may thus have been quite rapid as intervening stagnant ice melted, thus allowing early access to the area by the Lateglacial sea (Browne.*et al.*, 1981). This rapid deglaciation of the Howe of Fife may have allowed sedimentation to have started relatively early in the Lateglacial in some areas.

The area to the northwest of Logie, between Leuchars and Wormit, displays an assemblage of both fluvioglacial and marine features. The former were produced by glacial meltwater from the Firth of Tay glacier traversing stagnant ice mass in the Wormit/Leuchars/Tentsmuir area (Rice, 1961), and the latter by contemporaneous changes in sea level. During this period kettleholes at Leuchars Lodge developed when ice buried under raised beach deposits finally melted (Chisholm, 1966).

The higher ground of the Ochil Hills of north-east Fife has no such fluvioglacial or marine deposits. With the exception of some lake deposits in hollows, such as those found at Logie, the area is mostly covered by till at or close to the surface. Such till is generally thin and patchy or even absent on the higher ground (Armstrong *et al.*, 1985).

There appears to be no evidence of the ice movement direction in the area immediately around Logie, but Highland erratics, to the south of Wormit, indicate an east-north-easterly origin for the ice that crossed northern Fife.

The Lateglacial period in Fife was one of rapid isostatic uplift after circa 13,000 B.P. During deglaciation the sea penetrated as far inland as Balmullo and Dairsie (Armstrong *et al.*, 1985), approximately 3 km from the site at Logie. The uplift continued until circa. 11,000 B.P. with sea level at that time being lower than present. During the Loch Lomond Stadial Fife experienced periglacial conditions and possibly permafrost with sea level lower than present (Ballantyne, C.K.; pers. comm.).

2.2 METHODOLOGY

2.2.1. Introduction

The nature of fossil insect distribution in a sediment is such that a much greater bulk of sample must be taken than would be the case if the sampling was solely for pollen analysis. In order to find sufficient numbers of beetles to provide an assemblage diverse enough for palaeoecological work, several kilograms of material must be recovered for each stratigraphic division. Other palaeoentomological studies have relied, for the most part, on exposed sections (in stream banks, coastal sites, quarries etc.). However no such exposure could be found in north-eastern Scotland. As no palaeoentomological work has been attempted, it was important to have the site in this part of Scotland; thus it was decided to excavate a site.

The location of the site selected for study is detailed in chapter 2.1.2. Cores were taken using a Russian corer during a pilot pollen analysis by Dr. G. Whittington which showed that the section was worthy of further investigation.

The larger, main basin was cored with a Russian corer and was found to be very deep with thicknesses of gyttja in excess of 12 m in its centre. At first two holes were dug by a JCB at the margins of the larger basin. However even at the edge of the basin the gyttja was too thick (in excess of 4 m) and too unconsolidated to dig a stable hole without extensive shoring. The Lateglacial sequence was also too thin and too fine grained for Coleopteran studies. The smaller basin, separated from the main basin by what appears to be a gravel ridge, was then cored with a Russian corer and a suitable section was located at a maximum depth of 2.5 m. It was therefore decided to take the sample material from the smaller basin.

During the analysis of both the pollen and the beetles originally recovered from Logie it was found that the youngest sediment removed was Loch Lomond Stadial in age. As the aim of the project was to make a palaeoenvironmental reconstruction of the Lateglacial period it was felt that it was important to include the earliest part of the Flandrian Interglacial. However, financial constraints meant that the option of hiring an excavator again was not open. Therefore different methods of sampling the site had to be used to recover a second set of samples ("Logie 2"). The procedures used in this operation are set out in section 2.2.3.

2.2.2. Sampling Procedure ("Logie 1")

A hole was dug by a JCB exposing the sequence in the smaller basin down to the gravel base. As this section appeared to be suitable, a "step" was dug next to the hole, removing much of the Flandrian peat overlying the Lateglacial sequence. This step was then levelled off and the exposure cleaned up. A series of measurements were taken so that the various samples could be correlated. The samples were then taken by embedding large plastic tubes into the step, ensuring that they were vertical, and then pushing them into the sediment with the excavator's bucket. The tubes, now full of sediment, were then dug out and removed from the hole by the excavator. The tubes were then brought back to the laboratory and stored at 4 °C until sub-sampling could take place.

2.2.3. Division of the Core ("Logie 1")

The largest core taken from Logie was in a plastic tube 1 m long and 40 cm in diameter. This core was selected to provide the material for pollen and Coleoptera analysis and is referred to as "Logie 1". Subsequently small samples were also taken from this material for loss-on-ignition and particle size analysis. Calcareous sediment was also removed for further analysis in the future.

The core was divided using the following procedure. The core was stood upright, and the top circa. 25 cm of sediment was exposed by removing part of the plastic tube with a hacksaw. The sediment was then divided, one layer at a time, into 2 cm thick slabs with a knife. Pollen samples of a few grams of sediment were taken, two from each slab at this stage. Samples for chemical analysis were taken; one sample of about 15 cm^3 of wet sediment was taken from each 2 cm slab. A metal strip, sprung with an elastic band, around the core helped to maintain a constant cut. The samples for Coleoptera analysis were bagged and labelled; samples for pollen and chemical analysis were placed in plastic storage jars and labelled. All the samples were stored in a cold room (kept at about 4/5°C) until they were taken for preparation. A sedimentary log was made throughout this procedure (figure 2.5.) noting the lithology, plant macrofossil content and the colour (using Munsell's colour charts).

2.2.4. Sampling Procedure ("Logie 2")

In order to collect material younger in age than that from the top of "Logie 1" a second sampling trip was made to Logie. A Russian corer with a 50 cm long chamber was used to collect a core from approximately 2 m west of the original sampling point. A core containing sediment thought to be deposits of Loch Lomond Stadial age and also encompassing the earliest part of the Flandrian Interglacial was recovered. The stratigraphy of the core recovered is shown in figure 2.6.. Samples for pollen analysis were removed from this core and stored in the same way as that for "Logie 1". However due to limited time being available for counting these, pollen samples were only taken every 4 cm from the base of the Loch Lomond Stadial deposits. This boundary, though at a different depth from that at found in "Logie 1" provides a clear marker horizon which can be used to correlate the two cores.

2.2.5. Preparation (Coleoptera).

The procedure used to prepare the samples from Logie for Coleoptera analysis follows that outlined in Chapter 1.2.4. and stated in some detail by Coope (1986). However, a misunderstanding of the procedure as explained by Coope (1986) led to chemicals being added to deflocculate the clay minerals. Sodium hydroxide was added, often in some quantity to the samples as they were being disaggregated. Many of the samples from Logie processed early on in the research, had sodium hydroxide added to aid the deflocculation of the clay as a routine measure. Such chemical treatment should only be used when a sample will not break down at all using the conventional method (water and manual agitation only). However, the addition of these chemicals proved counter-productive as it resulted in an inordinate amount of plant material floating with the insect fossils thus creating many more hours of sorting under the microscope.

2.2.6. Identification of the fossil Coleoptera

The beetle fossils recovered from Logie were identified by Dr. G.R. Coope at the University of Birmingham. This was accomplished by direct comparison between the fossil material and modern reference collections held at Birmingham University. In several cases identification keys were used to confirm the identification. The nomenclature of the beetles and the taxonomic order in which they are listed follows, for the most part, Lucht (1987); for those species which do not occur in central Europe the nomenclature follows (Lindroth, 1960). The entomological literature was used in determining the present distribution and habitat of the taxa found at Logie in particular were the works of Holdhaus and Lindroth (1935), Lindroth (1985 & 1986), Holmen (1987), Balfour-Browne (1950) etc.

Although several orders of insect were found at Logie including Trichoptera, Hymenoptera, Chironomidae and Diptera, only the Coleoptera have been identified and used in this investigation.

2.2.7. Preparation (pollen)

Samples for pollen analysis were prepared by Mrs L. Wood at the University of St. Andrews. The preparation procedure was carried out in a "clean" laboratory with a filtered air supply to minimise the risk of pollen contamination. The process used to prepare the samples follows that detailed by Faegri and Iversen (1989).

2.2.8. Identification of the fossil pollen.

The pollen from Logie were identified at a x600 magnification using a Nikon research microscope. The pollen grains were identified by comparison with modern pollen from the type collection held in the Palynology Laboratory of St. Andrews University. Use was also made of reference works, such as Moore and Webb (1978), as aids in the identification of pollen grains and spores. Dr. G. Whittington and Mrs. L. Wood provided assistance with the identification of some of the more obscure grains, for which I am extremely grateful.

2.2.9. Chemical and fabric analyses

The sediment for loss-on-ignition, particle size analysis and chemical analysis were all dried overnight in an oven at 105 °C to remove any moisture. The dried sediments were broken up gently using a pestle in a mortar and then passed through a 2 mm and then a 63 μm sieve to catch any sand size fraction. (The sediments analysed from Logie contained no grains larger than 63 μm).

2.2.10. Loss-on-ignition

For the loss-on-ignition (L.O.I.) measurements crucibles were weighed and numbered, and a measured weight of dry sediment was placed in the crucible. The crucibles were then placed in a furnace for four hours at 550 °C. Once the crucibles had cooled they were weighed with the sediment ,and the percentage of mass lost (i.e. the organic fraction) could be calculated.

2.2.11. Particle size analysis

Dry disaggregated sediment, the same as that used for LOI analysis, was used for this procedure. The Sedigraph can only analyse particles within the range 0.1 - 300 μm. Thus the sample should be dry, weigh between 2 and 3 grams and have passed through a 300 μm sieve. The dry sediment is added to 40 ml of 1% Calgon mix. The samples are then broken down into their constituent particles by placing them for 5 minutes in an ultrasonic bath. The samples are stirred thoroughly by a magnetic stirrer before they are put into the Sedigraph. The fine fractions of material, within the silt- and clay-size ranges are then measured electronically with a Sedigraph 5100.

2.2.12. Trace metal chemical analyses

Elemental analyses for trace metals were conducted by atomic absorption. The preparation procedure largely follows that laid out by Krishnamurty *et al.* (1976). A measured weight of dry disaggregated sediment (approximately 0.5 grams) is added to 0.5 ml of deionised water to minimise sample splash and to facilitate a rapid reaction with the acid added later. 10 ml of HCO_3 is added to the mixture which is then left to digest for 2 hours on a sand bath set at 100 °C. After 2 hours have elapsed, the mixture is allowed to cool for 15 minutes before adding 3 ml of 30% H_2O_2. Heating is then continued for 1 hour with intermittent stirring of the mixture, after which it is left to cool.

After cooling, the mixture is then filtered through Whatman 44 filter paper into a volumetric flask and diluted to the 50 ml mark with deionised water. This solution can be used directly, although some of the more abundant elements may require a further dilution. Measurements are then made on a Pye Unicam PU9000 atomic absorption spectrophotometer. The chemical elements are expressed as a concentration as $mg.g^{-1}$ dry sediment (Mackereth, 1966).

2.3. STRATIGRAPHY

2.3.1. Introduction.

The stratigraphy of the sediments show a typical Lateglacial sequence of silts and clays overlain by a highly organic gyttja of early Flandrian age (Plate 2.V.). The youngest sediments represented at Logie are peats, presumably deposited after the lake dried up, some time during the Flandrian Interglacial. The sediments are all silts and clays, sieving prior to particle size analysis revealed that there was no sand-sized fraction in the deposits recovered from Logie.

Anderson (1985) took a series of Russian cores across the two basins at Logie and constructed a rough cross-section (figure 2.4.) showing the difference between the stratigraphy of the two basins.

Sedimentary Logs were made of the core "Logie 1" as it was being divided. (Changes in colour were recorded using Munsell's colour charts.) The Russian core, "Logie 2", was logged as it was sampled for pollen analysis. The stratigraphy of "Logie 1" is shown in figure 2.5. and that of "Logie 2" in figure 2.6. Particle size and loss-on-ignition analysis was conducted on sediments from both cores and the results are included with the sedimentary logs.

The sediments are described in their age divisions, as defined by the pollen stratigraphy and the major differences in lithology which in this case are coincident.

Plate 2.2. The Lateglacial sequence "*in situ* " at Logie.

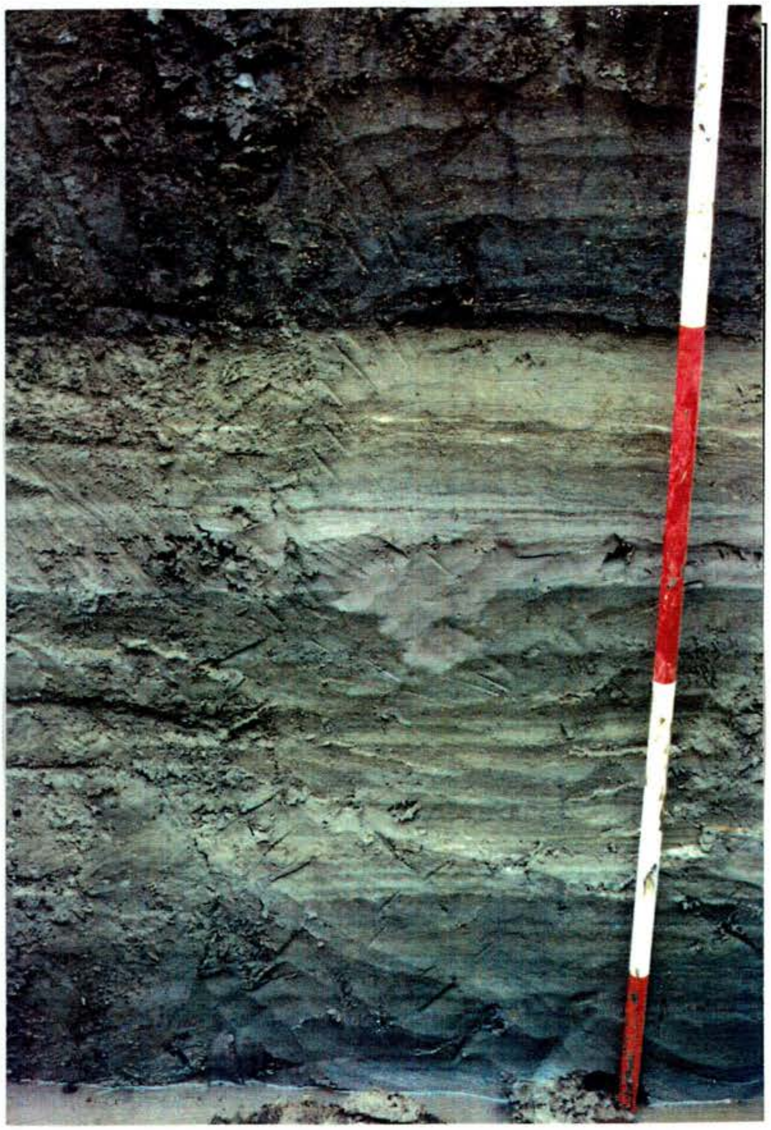


Figure 2.4. A generalised cross-section through the Quaternary sediments at Logie. (Adapted from Anderson, 1985.)

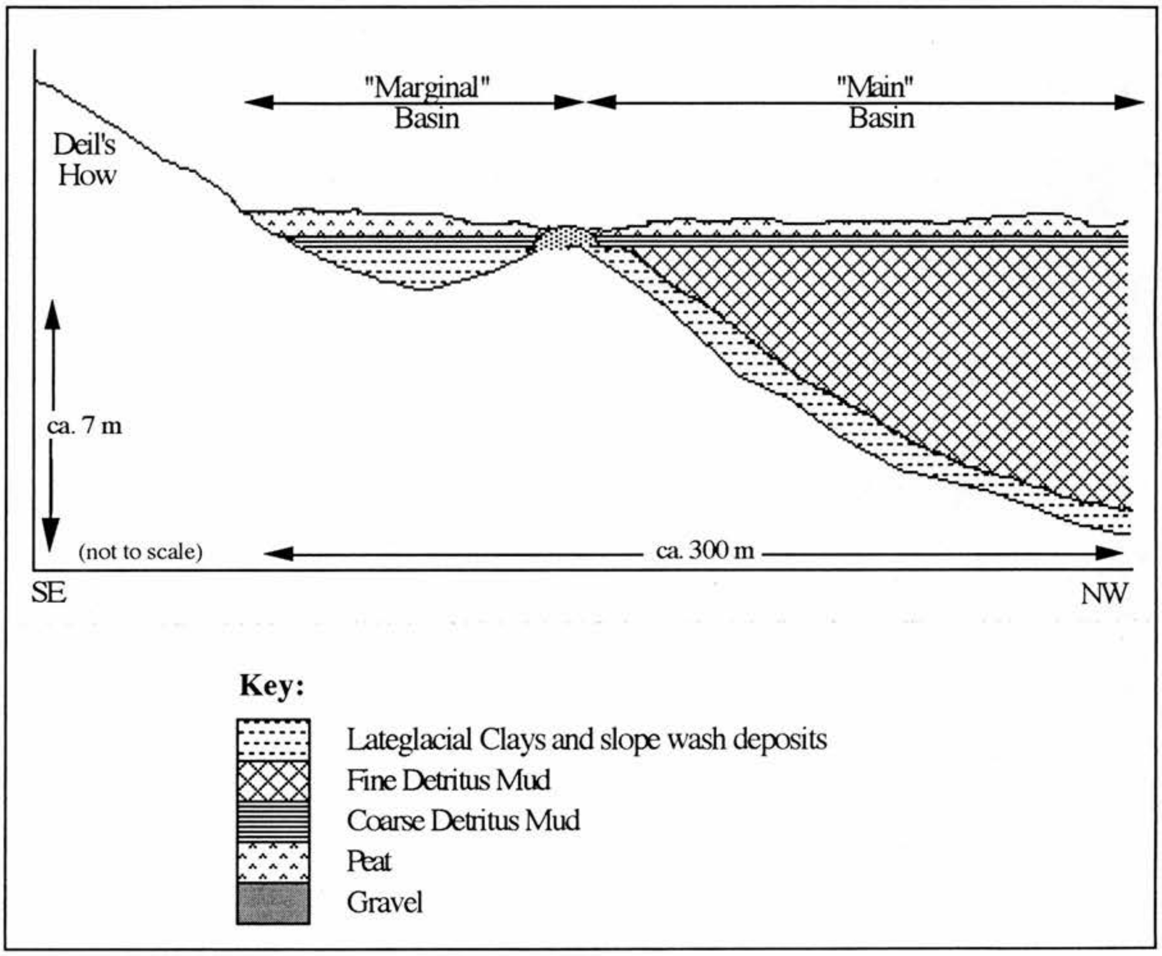


Figure 2.5. The stratigraphy of the core "Logie 1".

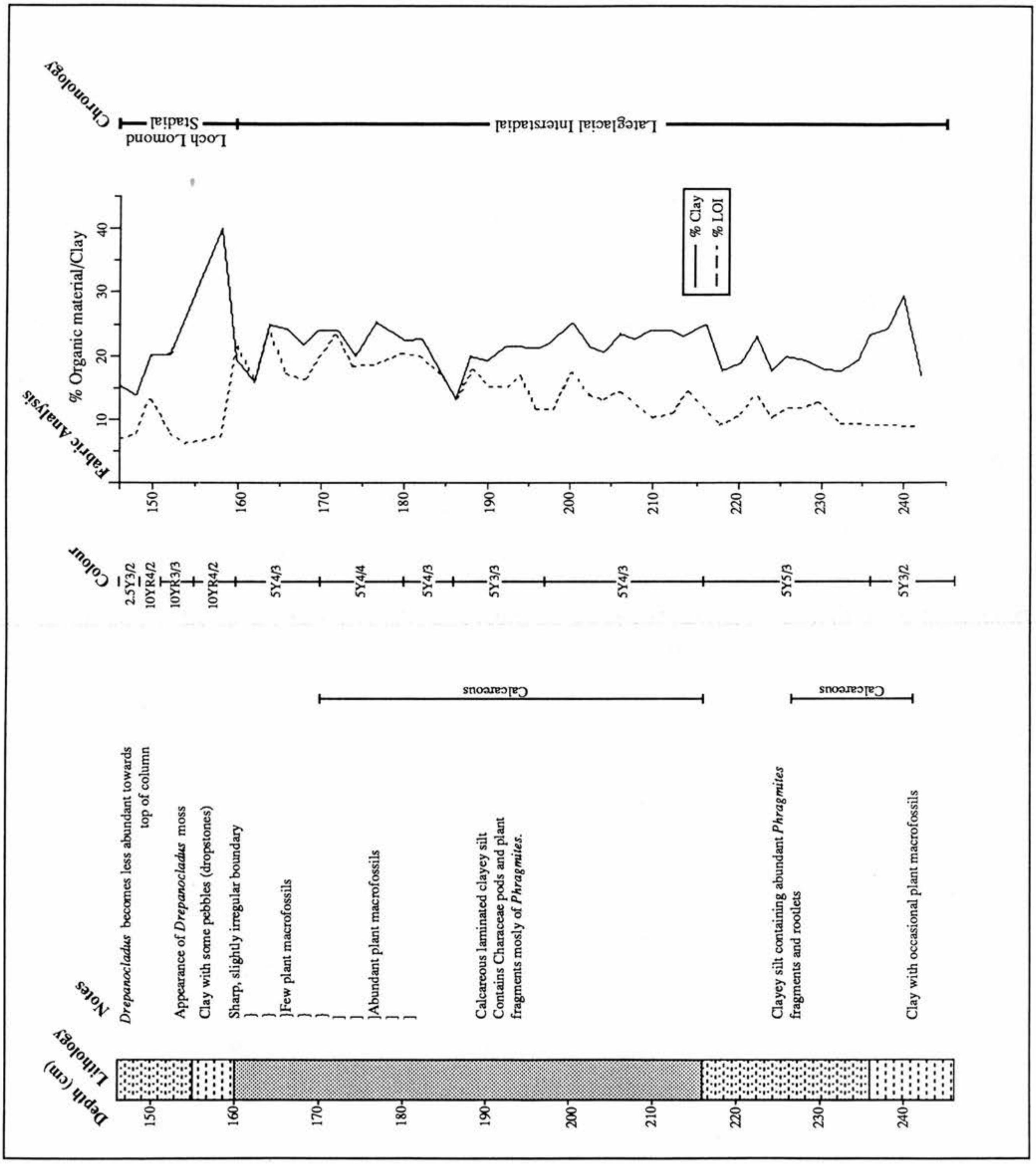
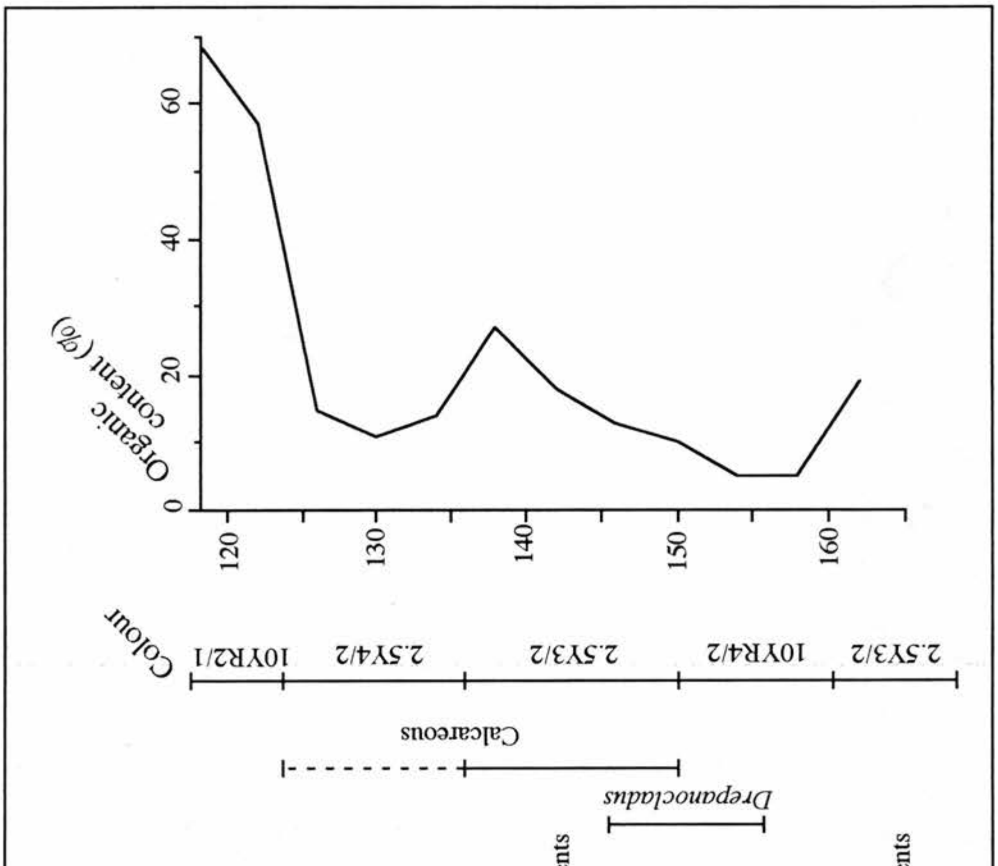


Figure 2.6. The stratigraphy of the core "Logie 2".



2.3.2. Lateglacial Interstadial

The sediments of this age comprise about one metre of section in the sampling area at Logie. A sequence of the top 85 cm of the interstadial sediments was recovered in the core "Logie 1". The basal part of this sequence is a clay containing some plant macrofossils. This grades up into a clayey silt, green in colour containing abundant plant macrofossils, notably *Phragmites* and rootlets.

The thickest lithology of the Lateglacial Interstadial is a mostly calcareous clayey silt. The calcareous part of the sequence is laminated, with the laminae highlighted by some layers richer in carbonate that others. The presence of Characeae in samples prepared for Coleoptera analysis suggests that the carbonate in the sediments at Logie is a product of algal activity. It is unlikely that the carbonate is reprecipitated from the local country rocks as these are Devonian intermediate volcanics. Characeae provide a relatively hostile lacustrine environment, and thus the number of insects living in such a habitat is likely to be reduced. There are exceptions to this, for example the Dytiscid species *Haliplus obliquus* whose larvae feed on Characeae (Holmen, 1987).

The amount of plant macrofossil material appears to be reduced towards the top of the Interstadial sequence, however this is not borne out by the loss-on-ignition results.

2.3.3. Loch Lomond Stadial

The sediments of this age are seen in both "Logie 1" and "Logie 2". The latter core shows a full stadial sequence.

The boundary between the Interstadial and the overlying Stadial sediments is sharp and slightly irregular. It is hard to determine whether or not this boundary is disconformable. When the boundary was exposed by excavation the nature of the contact could not be determined, it is possible that there is a disconformable relationship between the Stadial and Interstadial sediments.

The basal clay is pink in colour and typical of Scottish deposits of that age. It is clay-rich with virtually no organic content. There are some pebbles (up to 3 cm in diameter) within the clay that are thought to be dropstones. Drepanocladus moss occurs in abundance at the top of "Logie 1" and for a short part of the sequence in "Logie 2".

The clay passes up into a clayey silt similar to that deposited during the Lateglacial Interstadial. When the core "Logie 1" was taken it was thought that this lithology represented the earliest part of the Flandrian Interglacial. However, subsequent pollen and Coleoptera analysis shows that stadial conditions prevailed at the time of deposition of these sediments.

2.3.4. Flandrian Interglacial

A sharp contact marks the start of the Flandrian Interglacial. Only a few centimetres thickness of sediment from this period was recovered at the top of "Logie 2". The deposit is a black organic-rich gyttja.

2.3.5. Conclusions

The site at Logie contains an apparently continuous stratigraphic record from the Lateglacial Interstadial through into the Flandrian Interglacial. The sediments form a typical lacustrine Lateglacial sequence of silts and clays.

The sources of the sediment were of hillslope processes, biological activity within the lake and input from streams. There are too many variable factors involved to make a quantified estimate of the relative contributions of the various sources of sediment. The organic content of the sediment, as represented in the loss-on-ignition results, can give an indication of the organic productivity of the lake. However, organic precipitates, such as the calcium carbonate produced by the Characeae algae, will not be included in the L.O.I. results. The beetle fauna shows that there was stream input into the lake through the presence of species which inhabit running water. The relatively fine grained nature of the sediments suggest that such an input was distal from the sampling location. The amount of sediment derived from hillslope processes depends on many interrelated factors such as vegetation cover, slope stability and precipitation. Thus sediment provenance is extremely difficult to establish.

2.4. ENTOMOLOGICAL ANALYSIS

2.4.1. Introduction

In the Coleoptera and ecological diagrams (figures 2.7. and 2.15.) the frequencies of the various taxa are quoted as the minimum number of individuals. These values are calculated from the most abundant skeletal component. The nomenclature of the beetles and the taxonomic order in which they are listed follows, for the most part, Lucht (1987). The entomological literature was used in determining the present distribution and habitat of the taxa found at Logie.

2.4.2. Interpretation of the fossil Coleoptera.

The aim of the beetle studies at Logie was principally to attempt a quantified palaeoclimatic reconstruction of the Lateglacial period in Fife. This has been achieved by using the Mutual Climatic Range Reconstruction Program (Atkinson *et al*.., 1986) to provide an estimate of the thermal climate. A more detailed palaeoenvironmental reconstruction has also been attempted using information gleaned from the entomological literature on species' habitat and distribution and a summary palaeoecological diagram (after Ponel and Coope, 1991) drawn.

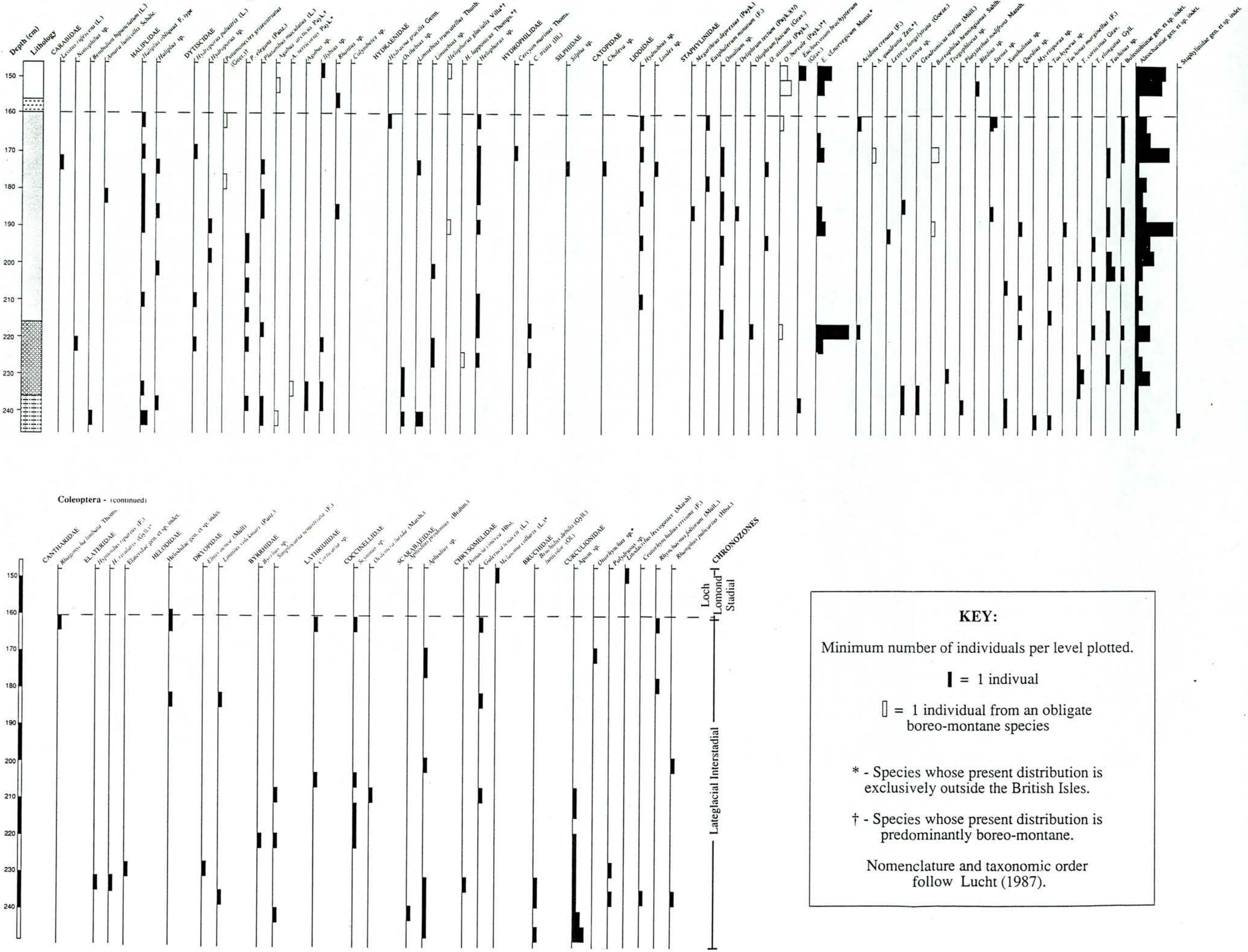
Changes in the aquatic fauna of the lake are traced. This is accomplished by calculating the ratio between aquatic and terrestrial beetles for each sample (the individual number of aquatic Coleoptera divided by the total individual number of Coleoptera) (Lemdahl, 1988). The abundance of other aquatic insect orders such as the Trichoptera or the Chironomidae could also be used for the same purpose.

As the diversity of species is highest in the tropics and lowest in arctic regions the number of taxa in the fossil record could give some information about the environment. The number of recorded taxa in each sample might be thought to give a crude estimation of changes in the diversity of species at a particular site through time. However the frequencies of individuals of selected species are difficult to interpret in terms of population dynamics (Coope, 1986). Thus although the number of individuals in each sample is given, no climatic or environmental inference can be drawn from it.

2.4.3. Coleopteran fossil assemblage

The sediments recovered from Logie yielded a fauna of 85 taxa from 20 families and of these 49 taxa were identified to species level. A complete list of the taxa identified is included in Appendix I and their occurrence is illustrated in figure 2.7. The information shown graphically in the diagram below is also presented in table form in Appendix II. 10 species whose present-day distributions are exclusively outside the British Isles were identified from Logie. These species are listed in figure 2.8.

Figure 2.7. Beetle Occurrence Diagram



KEY:

Minimum number of individuals per level plotted.

▌ = 1 indivual

▯ = 1 individual from an obligate boreo-montane species

* - Species whose present distribution is exclusively outside the British Isles.

† - Species whose present distribution is predominantly boreo-montane.

Nomenclature and taxonomic order follow Lucht (1987).

Despite the apparent abundance of the beetles found at Logie the fossil assemblage was quite fragmented, with a very low frequency of occurrence for the individual taxa. This is due largely to the relatively small size of the samples and the nature of the deposit. Ideally larger samples should be taken, preferably of coarser material nearer to a site of input into the basin. However, although the assemblage is not large, it is sufficient to give a clear climatic reconstruction.

The fauna found at Logie is dominantly a boreomontane assemblage. The stenotopic species identified from Logie virtually all have a preference for cool, northern climates. The only exception to this is the individual identified as *Bruchidus debilis* (Gyll.) or*unicolor* (Ol.). This species has a central or southern European distribution. However, both these species are phytophagous and the ecological information in the neontological literature is confused (chapter 2.5.4.). Of all the species found at Logie that no longer occur within the British Isles (figure 2.8.), such as *Helophorus glacialis* Villa., *H. lapponicus* Thomps., *O. boreale* (Payk.) and *Boreaphilus henningianus* Sahlb., all have a largely Scandinavian distribution.

Figure 2.8. Beetle species found at Logie whose present distribution is out with the British Isles.

Species	**Family**
Agabus serricornis Payk.	Dytiscidae
Helophorus glacialis Villa.	Hydraenidae
Helophorus lapponicus Thomps.	Hydraenidae
Olophrum boreale (Payk.)	Staphylinidae
Euchnecosum cf. *norvegicum* (Munst.)	Staphylinidae
Acidota quadrata Zett.	Staphylinidae
Boreaphilus henningianus Sahlb.	Staphylinidae
Hypnoidus rivularis (Gyll.)	Elateridae
Melasoma collaris (L.)	Chrysomelidae
Otiorhynchus sp.	Curculioidae

2.4.4 Notes on selected species

Haliplus obliquus F.

A eurytopic species found all over Europe as far north as Southern Fennoscandia. It prefers base-rich, stagnant waters commonly in lakes of depths greater than 1 m. It usually occurs among characeans, on which the larvae feed (Holmen, 1986).

Potamonectes griseostriatus (Geer.)

A northern species whose modern distribution extends as far south as the northern parts of the British Isles. It inhabitats cold, boggy pools.

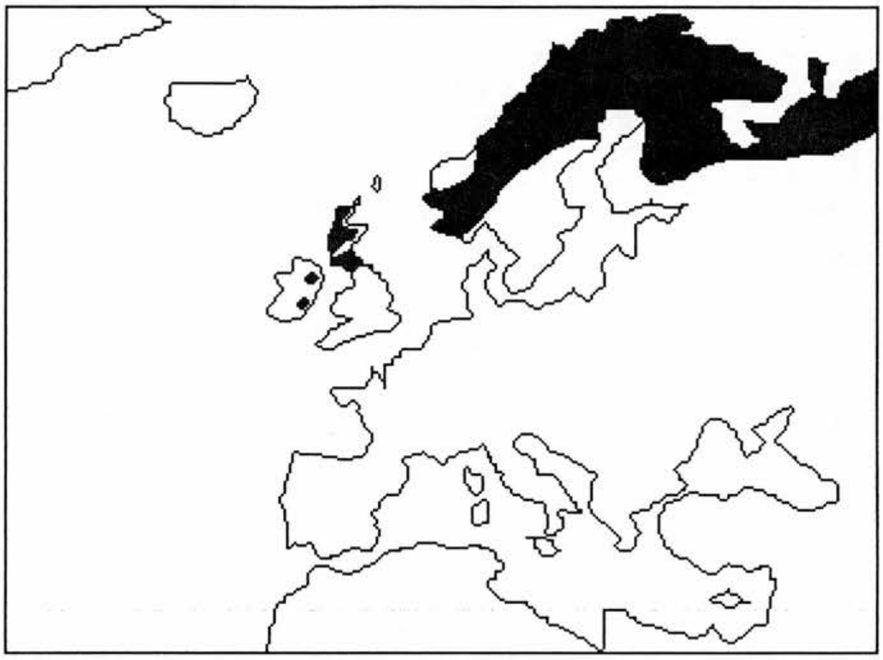
Platambus maculatus (L.)

A eurytopic species, commonly found in Britain. This species lives in submerged vegetation along the edges and in the shallows of streams and rivers and also well-aerated lakes. However, it is most commonly found in shallow streams (Balfour-Brown, 1950).

Agabus arcticus Payk.

As the name suggests this is a boreomontane species found in cold boggy pools usually in association with *Potamonectes griseostriatus* and *Helophorus lapponicus* . On the continent of Europe it is found north of Latitude 60 °N, although on the western Atlantic seaboard it is found further south. It occurs throughout Scotland and in isolated communities in northern England and Ireland (Balfour-Brown, 1950).

Figure 2.9. The modern geographical distribution of *Agabus arcticus* Payk. (after Holdhaus & Lindroth, 1935).



A. serricornis Payk.

This species is no longer found in Britain. It occurs in Fennoscandia, northern Russia and Siberia. Its typical habitat is in stationary, plant-rich water (Strand, 1944).

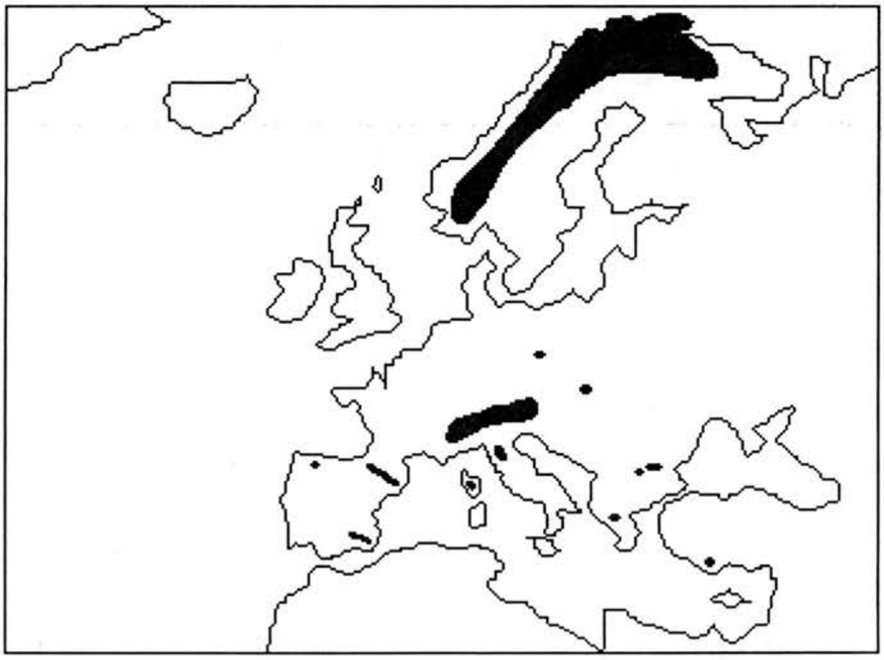
Hydraena gracilis Germ.

A species that inhabits moss, under stones and on branches/twigs etc. in fast flowing rivers and streams. It is widely distributed in Denmark and Fennoscandia, in the rest of northern and central Europe is is most common in mountainous areas (Hansen, 1987).

Helophorus glacialis Villa.

A boreomontane species that is widespread in northern and central Fennoscandia. Further south than this, its distribution is limited to mountains ; it does not occur in Britain at present (Fig. 2.10). The species lives in stagnant water, apparently confined to very cold water at the edge of snow patches (where the water temperature is always close to 0 °C. Its usual habitat is small, shallow pools of melted snow with a stony/clayey bottom and rich in moss (Hansen, 1987).

Figure 2.10. The modern geographical distribution of *Helophorus glacialis* Villa. (after Holdhaus and Lindroth, 1939).



H. lapponicus Thomps.

The distribution of this species is also boreomontane. It is widespread in north and central Fennoscandia but it is not found in Denmark or Britain. In the east it ranges from Fennoscandia through the USSR. There are isolated communities in the

Cantabrian mountains of northern Spain and the Caucasus. It lives in stagnant fresh water, preferring shallow, sparsely vegetated, acidic pools surrounded by *Polytrichium* (Hansen, 1987).

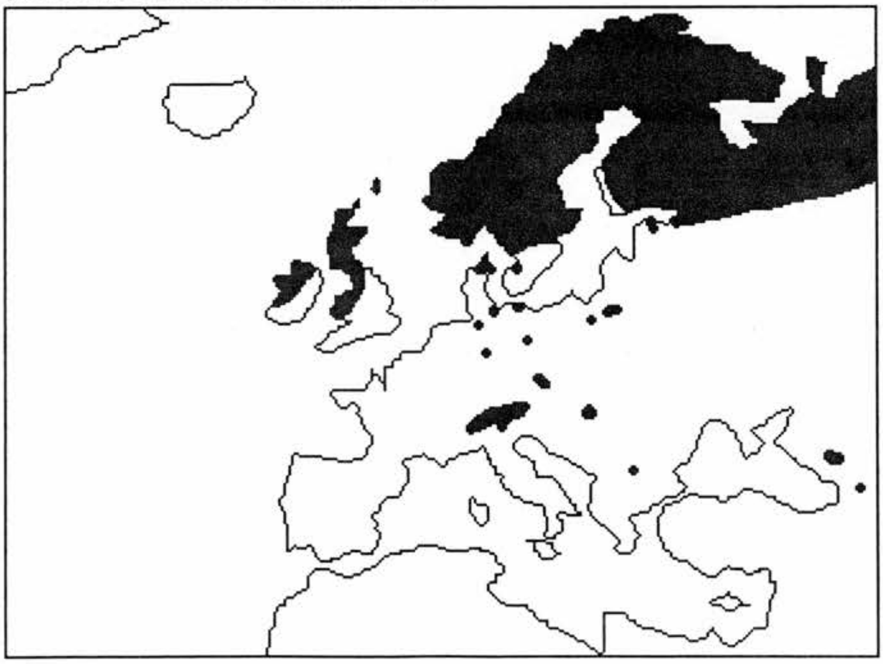
Olophrum boreale (Payk.)

A boreomontane species from Arctic Russia, not found in the British Isles. In common with other Staphylinids it preys on soil arthropods in moss and leaf litter.

Euchnecosum brachypterum (Grav.)

A species with a boreomontane distribution which extends south to include the northern parts of the British Isles. Found under leaf litter and moss. It is almost impossible to differentiate from E. norvegicum and it is likely that both species are present here.

Figure 2.11. The modern geographical distribution of *Euchnecosum brachypterum* (Grav.) (after Holdhaus and Lindroth, 1935).



Acidota quadrata Zett.

A northern Staphylinid species which does not occur in the British Isles.

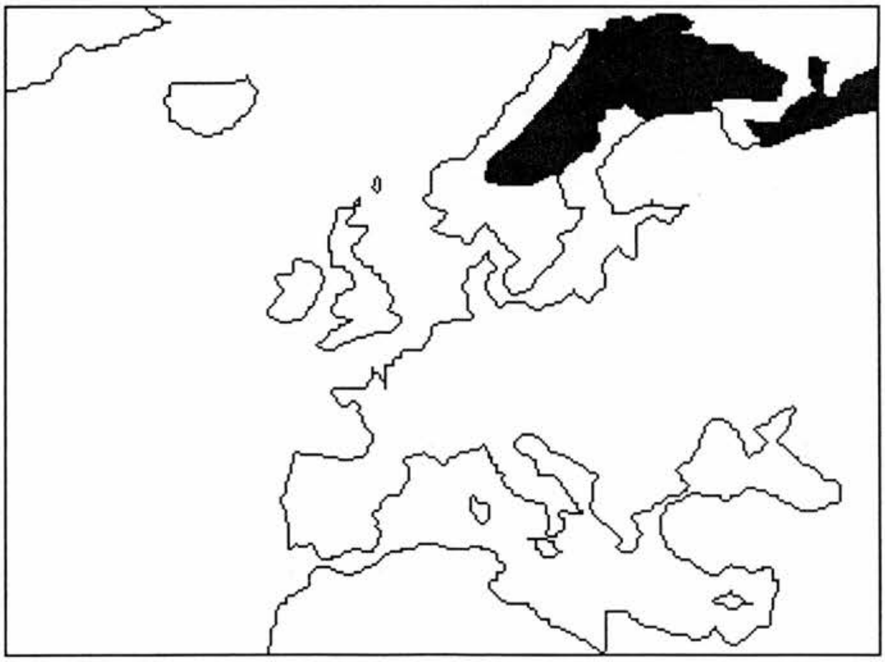
Geodromicus nigrita (Müll)

The distribution of this species is local and uncommon in northern Britain. Its usual habitat is wet moss.

Boreaphilus henningianus Sahlb.

A non-British species (fig. 2.12.) that preys on soil arthropods under leaf litter and moss and also grassy marshes.

Figure 2.12. The modern geographical distribution of *Boreaphilus henningianus* Sahlb. (after Coope and Brophy, 1972).



Hypnoidus riparius (F.)

This species inhabitats river banks and naturally damp places, particularly along the coast. In Britain it is common from the English midlands northwards, but much less so in the southern counties of England.

H. rivularius (Gyll.)

The distribution of this species is widespread in northern Fennoscandia and occurs with decreasing abundance into southern Sweden, it does not occur in Britain. There is an isolated occurrence in the mountains of Germany.

Elmis aenea (Müll.)

Although this species is the only British representative of its genus it has a fairly widespread distribution. Its habitat is running water and moss.

Limnius volckmari (Panz.)

A stenotopic species that is found in running water under stones or in moss (Koch, 1989).

Oedemera lurida (Marsh.)

A eurytopic species widely spread in Britain and Ireland, although with a local distribution. It lives in dry places on flowers and in grass. It feeds on pollen (Koch, 1989).

Aphodius prodromus (Brahm.)

This species, commonly found in England, Wales and Scotland, is found in various kinds of dung and decomposing vegetable matter.

Donacia cinerea Hbst.

This species lives, for the most part, on *Typha*, *Phragmites*, *Sparganium* and *Carex* (Freude *et al.*, 1983).

Melasoma collaris (L.)

Occurs in northern and central Europe, but not in the British Isles. It is usually found in association with *Salix*.

Galeruca tenaceti (L.)

A local species, though it is eurytopic and widely distributed in Britain. It is polyphagous and found in grassy places where it is dry and sandy.

Bruchidus debilis (Gyll.)/*unicolor* (Ol.)

These are essentially southern species from the temperate regions of western Europe whose distribution extends as far north as southern England. They are found in association with plants of the Papilionaceae family and are phytophagous, living off the seeds of various legumes e.g *Lotus corniculatus*. If this is the case then their restriction to southern areas cannot be attributed to the lack of availability of host plants in northern Europe. However, Freude *et al.* (1983) state that these species feed on *Onobrychis* which is restricted to southern and central Europe.

Litodactylus leucogaster (Marsh.)

A widespread species, though its distribution is local. It is phytophagous and lives on aquatic plants, usually Myriophyllum.

Ceutorhynchidius errisimi (F.)

One of the most common species in Britain. Its distribution is confined to Cruciferae (Freude et al., v11 1983).

Rhynchaenus foliorum (Müll.)

This species is widely distributed throughout Europe, and is found in association with *Salix*.

Rhamphus pulicarius (Hbst.)

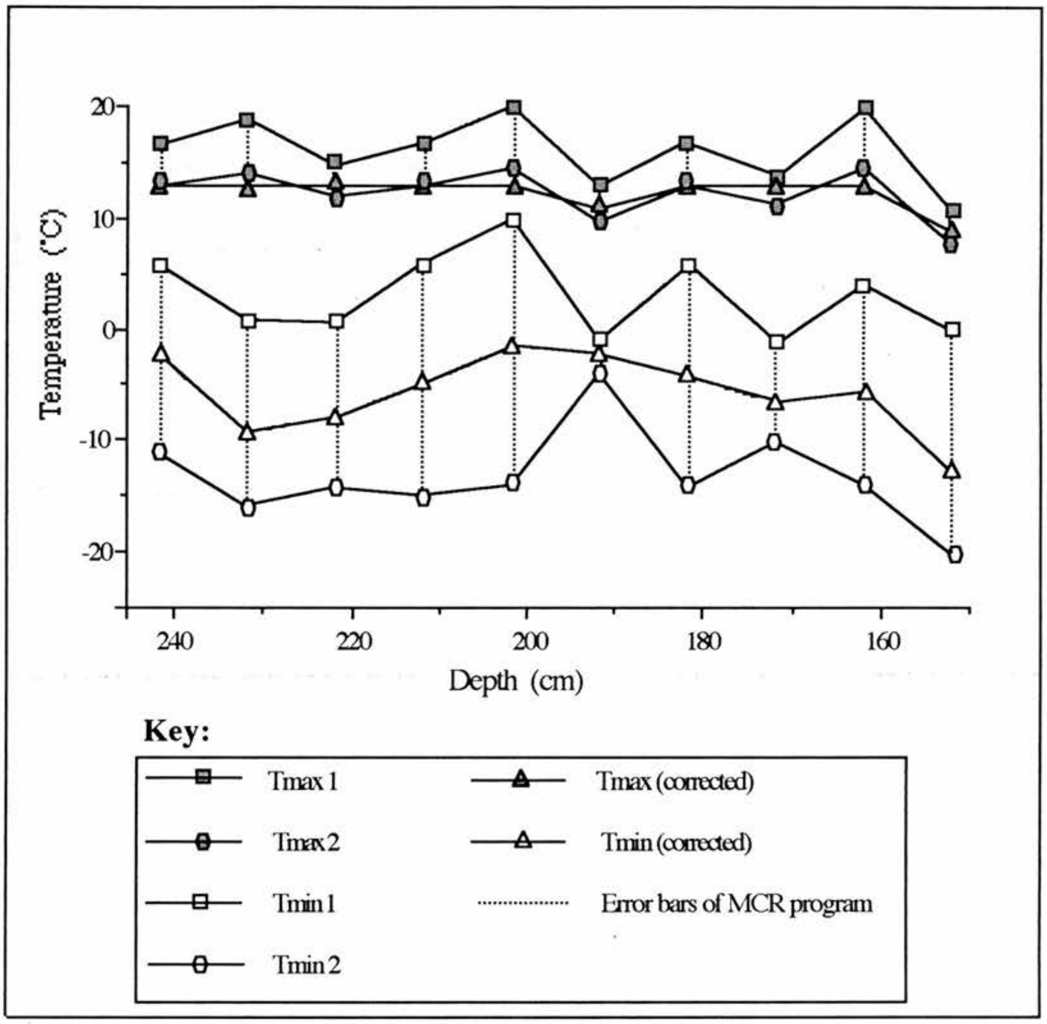
A common species that is found on the foliage of sallow, willow, birch and cherry trees.

2.4.5. Mutual Climatic Range results

The results obtained from the fossil Coleoptera recovered from Logie are limited by the nature of the fossil assemblage. For reasons already discussed the assemblage is somewhat fragmentary and thus the inferences that can be drawn about certain aspects of the Lateglacial palaeoenvironment are similarly limited. It was possible to use the Mutual Climatic Range Reconstruction Programme (MCRRP) to obtain a reconstruction of the thermal climate of Fife during the Lateglacial period. This process is outlined in chapter 1.2.9 and a detailed account of the method is given by Atkinson *et al.* (1986).

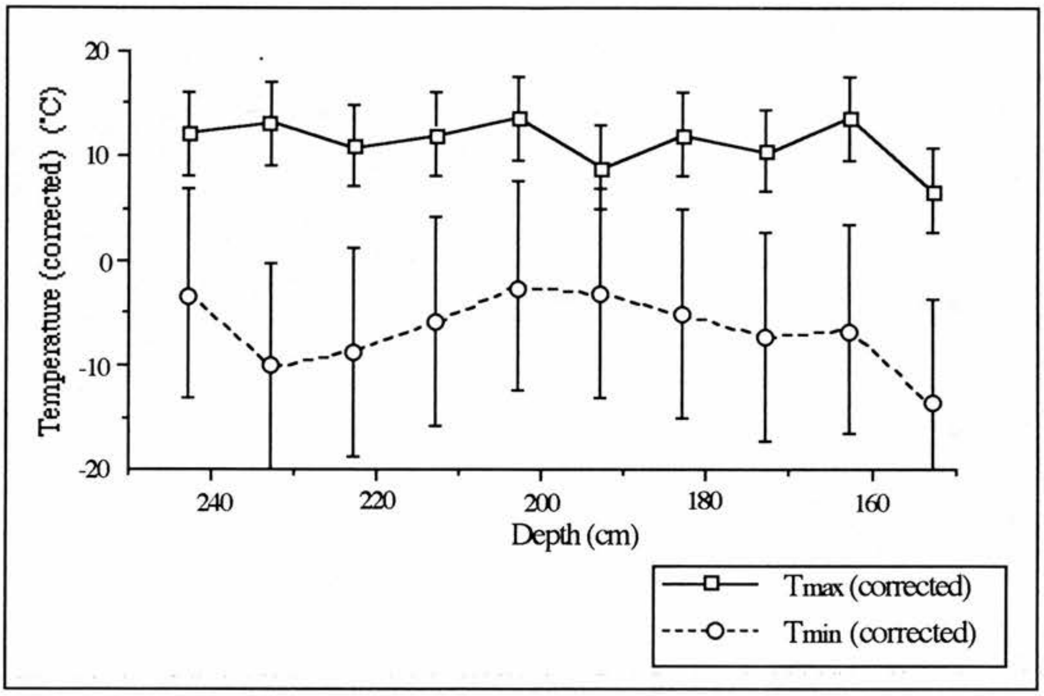
Figure 2.13. illustrates the values given for the thermal climate of Logie when the details of the fauna recovered from Logie were processed by the MCRRP at Birmingham University. The values for $t_{max}1$ and $t_{max}2$ represent the two extremes of the values calculated by the computer for the average temperature of the warmest month of the year (mean July temperature). Similarly the values $t_{min}1$ and $t_{min}2$ represent the coldest month of the year. The values given for t_{max} and t_{min}(corrected) are the "most probable" temperatures derived from the correction equation quoted in section 1.2.9. and Atkinson *et al.* (1987). These corrected temperatures are themselves only accurate to ± 2 °C for t_{max} and ±5 °C for t_{min}. This variation in error is the result of beetle species being more sensitive to summer temperatures than winter because the majority of their active life occurs during the summer months. The errors of the corrected values are shown in figure 2.14.

Figure 2.13. Mutual Climatic Range results.



Coleoptera were only recovered from the core Logie 1. Financial constraints meant that a second set of bulk samples could not be recovered. A Russian core was taken to provide pollen samples into the Flandrian, however it is not feasible to take enough sediment for an adequate palaeoentomological study using even multiple Russian cores. Thus the highest point for which Coleoptera data are available is a depth of 146 cm; this corresponds to a part of the Loch Lomond stadial period.

Figure 2.14. Corrected palaeotemperature values for Logie with error bars.



2.4.6 Interpretation of Coleopteran palaeoclimatic data.

The sequence of sediments sampled at Logie unfortunately did not include the thermal maximum that occurred at the beginning of the Lateglacial Interstadial and the beginning of the Flandrian Interglacial. Thus the palaeotemperature curve from Logie is relatively flat. The climate of the later part of the Lateglacial interstadial (represented by the sediment between the depths 245 and 160 cm) appears to be relatively stable and cool. The average temperature of the warmest month (t_{max}) appears to be somewhere in the region of 12 °C. The temperature of the coldest month (t_{min}) is harder to estimate, however the graph in figure 2.14. shows that the most likely palaeotemperature throughout this period was less than 0 °C.

At depths less than 160 cm there is a marked, if relatively small scale climatic change. The summer temperature seems to fall to between 8 and 10 °C with the winter temperatures showing a slightly larger drop, indicating more continental conditions during the Loch Lomond Stadial. This cooling continues to the top of the sampled section (the core "Logie 1") despite a clear change in the lithology of the sediments from pink clay to greenish silts.

The Coleoptera from Logie appear to represent deposits from the later part of the Lateglacial interstadial and the early part of the Loch Lomond Stadial. The palaeoclimatic reconstruction by mutual climatic range shows a cool, relatively stable thermal climate during the Lateglacial interstadial with one or two minor oscillations. The average temperature drops at the top of the sampled sequence, indicating at least the start of the Loch Lomond Stadial. During both climatic phases there are species present which today inhabit more mountainous terrain and more northerly latitudes than north eastern Fife.

2.4.7. Interpretation of the local environment.

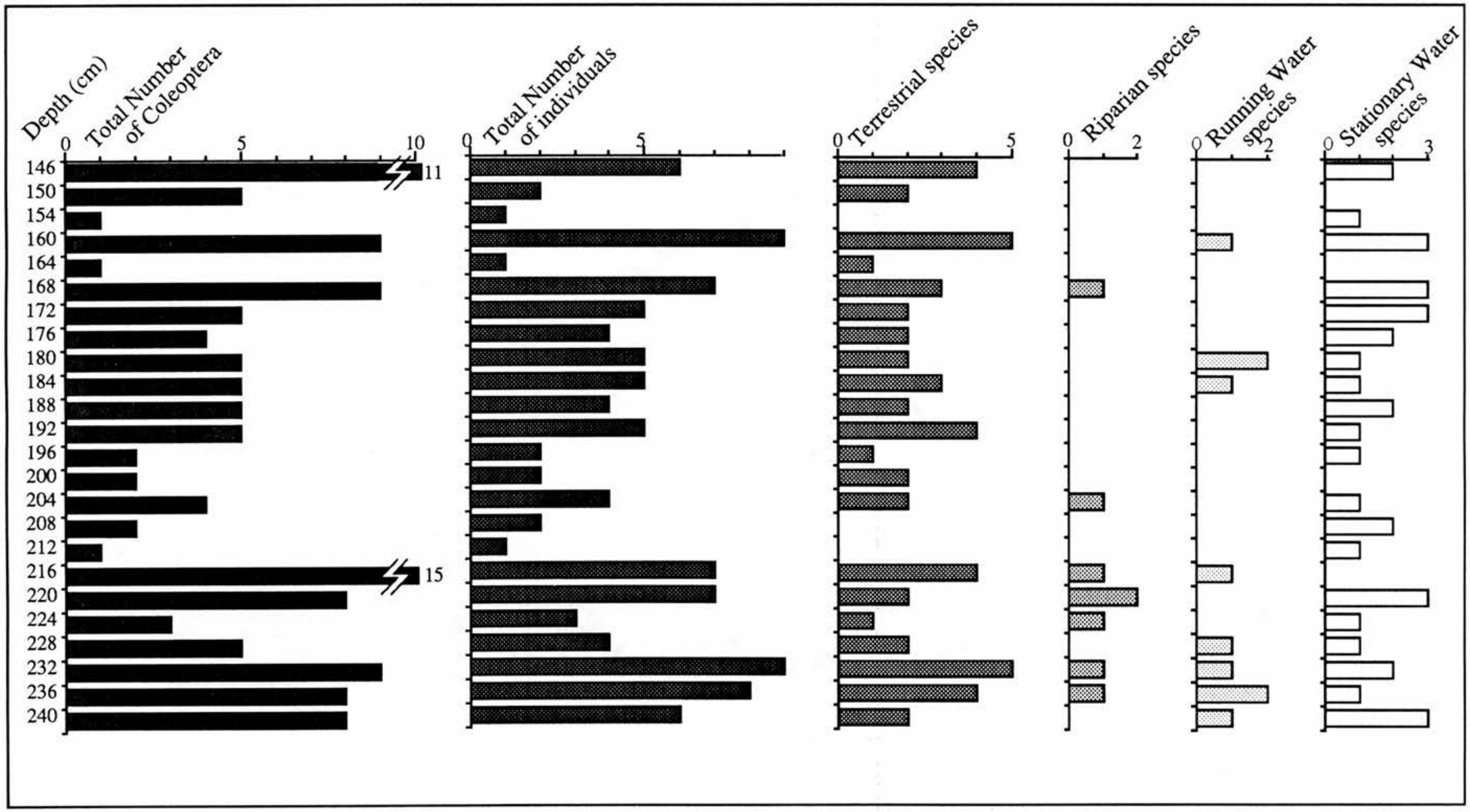
The diagram (figure 2.15.) gives a basic summary of the habitats of the various species of Coleoptera found at Logie. This diagram provides an insight into the palaeoecology of the Lateglacial stratigraphy at Logie, but only the individuals that could be identified to species level are included because their habitats can be defined with greater precision than fossils identified to generic level only. No quantative statements can be made from the results shown in figure 2.15. What can be seen, however, is the occurrence throughout the period studied of species which lived outside the lake basin, i.e. terrestrial, bank and running water species.

The Lateglacial Interstadial fauna from Logie is interesting for the occurrence of several obligate boreo-montane specieswhich no longer live in the British Isles. An example of such a species is *Helophorus glacialis* Villa. which inhabits snow meltwater pools in Fennoscandia and the mountains of central Europe (figure 2.10.). This species is commonly found during the Loch Lomond Stadial period in Britain, but at Logie it occurs during the Interstadial too. Other species in this group also lived in the area around Logie during the Lateglacial Interstadial. *Helophorus lapponicus* Thomps., *Olophrum boreale* (Payk.) and *Boreaphilus henningianus* Sahlb. are all examples of obligate northern species occurring during the Lateglacial Interstadial.

The presence of large mammals is suggested by the occurrence at various levels of the Interstadial of the Scarab beetles *Aphodius* sp. most of which fed upon dung and the species *A. prodromus* (Brahm.) is an obligate dung species.

Figure 2.15 Coleoptera Ecology Diagram

N.B.
The figures are an absolute minimum number of species per level
Only individuals identified to species level are included in this diagram



The Lateglacial fauna of Logie also includes phytophagous beetles. Species were found that fed on plants growing in the lake and others that fed on the plants surrounding the lake. *Donacia cinerea* feeds on *Typha, Phragmites, Sparganium* and *Carex* ; whereas *Litodactylus leucogaster* lives usually on *Myriophyllum* . Terrestrial plant eaters include several species which are found in association with *Salix*; these include *Melasoma collaris* , *Rhychaenus foliorum* , and *Rhamphus pulicarius* . *Bruchidus debilis* /*unicolor* feeds on the seeds of various Papilionaceae. These phytophagous species confirm the <u>local</u> presence of a number of plant taxa recorded in the pollen spectra at Logie.

The Loch Lomond Stadial period is notable for the predominance of boreo-montane species. The same species are found at various levels in the Lateglacial Interstadial, but during the stadial they are more abundant (particularly *Olophrum boreale*, *Euchnecosum brachypterum* and *E. norvegicum*). This combination of such species indicates a climate much colder than is presently the case in northern Fife. *Agabus arcticus* is a species that inhabits cold, stationary water and *Helophorus glacialis* is a characteristic snow patch species found in the Loch Lomond Stadial, sometimes in large numbers.

2.5 POLLEN ANALYSIS

2.5.1. Introduction

Pollen data from Logie were obtained from analysis of two cores ("Logie 1" and "Logie 2"). Samples from both of these cores were counted at intervals of 4 cm (chapters 2.2.3 & 2.2.4.). It is apparent from the pollen spectra that these cores represent a time period stretching from the Lateglacial interstadial to the start of the Flandrian interglacial. Three hundred grains of land pollen were counted at each level and both percentage and absolute diagrams were produced for each core. These diagrams were zoned subjectively into local pollen assemblage zones. The stratigraphy and the pollen zones were correlated using the sharp change in lithology at the base of the Loch Lomond stadial as a marker horizon (figures 2.5. and 2.6.). Thus the percentage and absolute pollen diagrams presented below (figures 2.16. and 2.17.) are composites from the two cores. These diagrams thus represent virtually the full Lateglacial sequence found at Logie.

Figure 2.16. Pollen Percentage Diagram

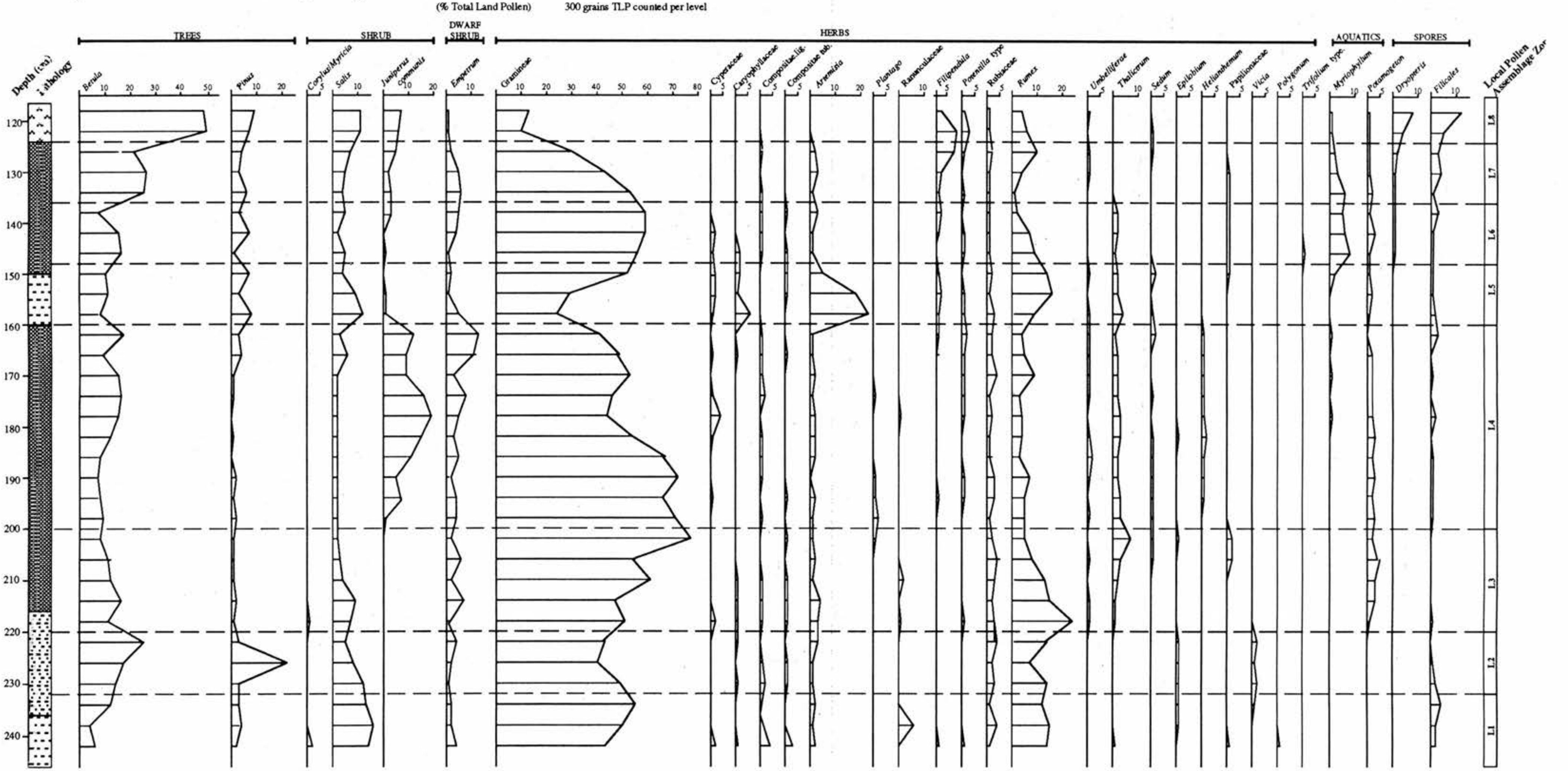


Figure 2.17. Summary Pollen percentage diagram

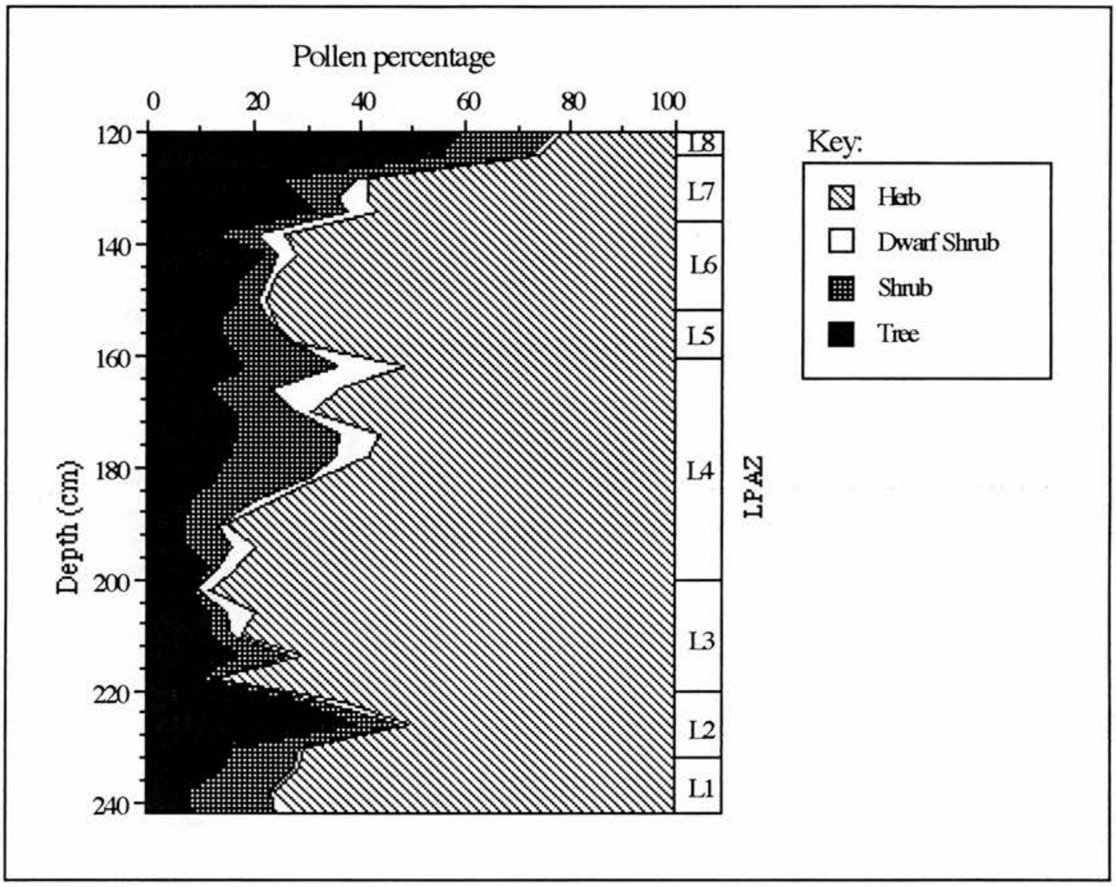
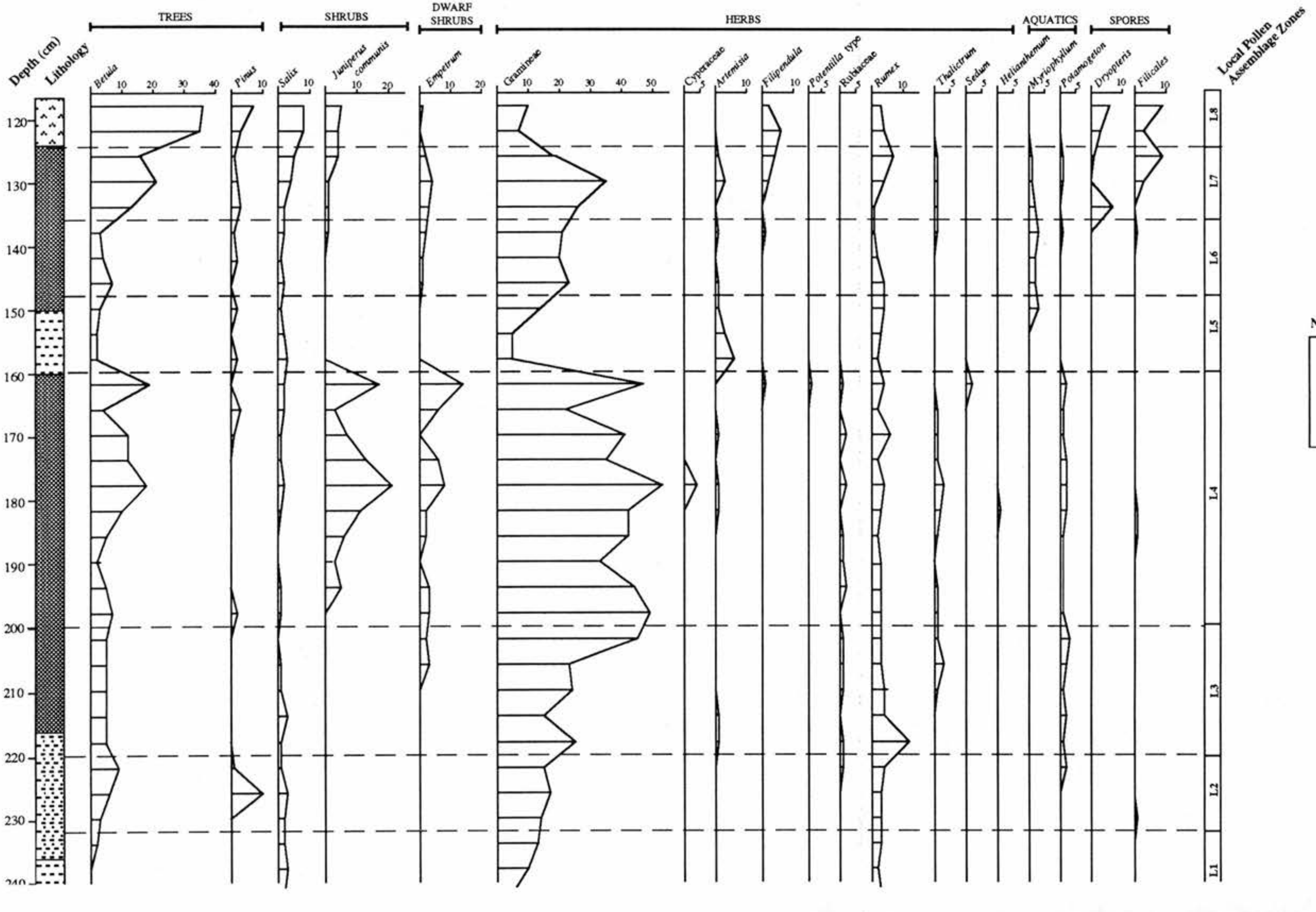


Figure 2.18. Absolute Pollen Diagram



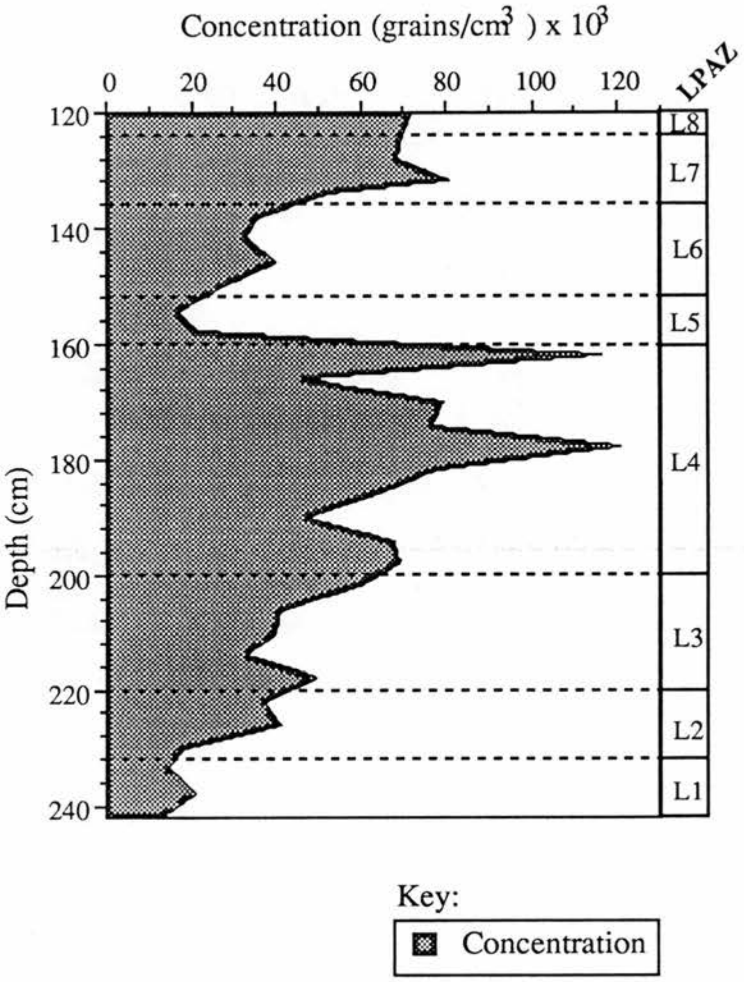
Notes:

300 grains of Total Land Pollen counted per level..

All figures are x10^3 grains of Land Pollen per taxon per cm^3.

Only occurrences > 1000 grains cm^{-3} are plotted.

Figure 2.19. Pollen Concentration Diagram



2.5.2. Local Pollen Assemblage Zones

The pollen zones described below were divided subjectively on the basis of variations in the occurrence of the various taxa of land pollen as represented on the pollen percentage diagrams from both cores. The diagrams from the two cores were only amalgamated after zonation.

All pollen data below a depth of 160 cm (pollen zones L1 to L4) are derived from samples taken from "Logie 1". Pollen spectra from above 160 cm (pollen zones L5 to L8) are from "Logie 2".

A summary of the features of the local pollen assemblage zones is given in figure 2.20.below.

2.5.2.1 L1.

The youngest of the pollen zones identified from Logie is dominated largely by herb taxa. Gramineae forms about 40 % of the assemblage in this zone. Other taxa, including *Salix* and *Rumex* are represented to a lesser degree, each forming 10 % of the assemblage.

The pollen concentration in this zone is very low, not rising above 20,000 grains per cm^{-3} throughout the zone. This is reflected in the absolute pollen diagram where only the three major taxa occur in sufficient numbers to be plotted.

Figure 2.20. Summary of local pollen assemblage zones from Logie

LPAZ	Depth (cm)	Major Zone Characteristics (values are % TLP)	Pollen Concentrations ($x10^3$ grains cm^{-3})	Remarks (Values are % TLP)	Age
L8	120 -126	*Betula* (≈50)	High (70)	High tree and shrub values, very low herb.	Flandrian Interglacial
L7	126 - 136	Gramineae (55-30), *Betula* (≈25)	High (up to 80)	Decreasing Gramineae towards the top of this zone.	Loch Lomond Stadial
L6	136 - 148	Gramineae (>50)	Generally low (30-40)	High herb values, particularly Gramineae.	
L5	148 - 160	*Artemisia* (>20), *Rumex* (>10), *Salix* (>10)	Very low (20)	High herb values but low (25-30) Gramineae values.	
L4	160 - 200	Gramineae (40-70), *Juniperus* (10-20)	Fluctuates markedly from moderate to very high (50-120)	Decreasing trend of Gramineae to the top of this zone. Major occurrence of *Juniperus*.	Lateglacial Interstadial
L3	200 - 220	Gramineae (50-75), *Rumex* (<25)	Moderate to low (40-60)	Very high herb values. *Rumex* declines and Gramineae increases towards the top.	
L2	220 - 232	Gramineae (>40), *Betula* (20-30)	Low to very low (40-20)	Unusual peak of *Pinus*.	
L1	232 - 242	Gramineae (>40)	Very low (<20)		

2.5.2.2 L2

The pollen assemblage zone again has Gramineae as its most abundant taxon, making up about 40 % of the assemblage, although the percentage is generally slightly lower than the older zone immediately below. *Betula* rises through the zone from 15 % at a depth of 230 cm to 27 % at 222 cm. *Rumex* and *Salix* also feature with less than 15 and about 10 % respectively. The most noticeable feature of this pollen assemblage zone is the sudden peak of *Pinus* (rising from 3 % to over 20 % an then falling back to 3 %) at a depth of 226 cm. This feature also shows clearly on the absolute diagram showing a concentration of *Pinus* of approximately 10,000 grains cm^{-3} (Further discussion of this feature can be found in chapter 2.6.2.)

The pollen concentration increases towards the top of this zone from less than 20,000 to about 40,000 grains cm^{-3}.

2.5.2.3 L3

Pollen assemblage zone L3 shows an increasing trend of Gramineae towards its top. As the percentage of Gramineae pollen increases from 50 up to a maximum of 80, the percentage of *Rumex* decreases from over 20 to 5. The other taxa that contribute small but significant amounts of pollen to the assemblage are *Betula*, and to a lesser extent, *Salix* and *Empetrum*..

The concentration of pollen, after an initial fall, increases throughout this zone, reaching 60,000 grains cm^{-3} by a depth of 200 cm.

2.5.2.4 L4

This zone, representing 40 cm of the section studied, has several distinctive features. Gramineae is again the taxon forming the greatest percentage of the assemblage. From a high point of over 70 % towards the base of the zone, this tends to reduce through the zone to 40 % at the top. The zone is most noticeably marked by the major occurrence of *Juniperus communis*. This taxon reaches a peak of almost 20 % of the assemblage. Other taxa represented include *Betula* which varies between 10 and 15 % throughout the zone and *Empetrum* which reaches a maximum of 10 % at the top. The percentage of herb pollen decreases towards the top of this zone, largely as a result of the increase in the occurrence of shrub taxa such as *Juniperus*..

The concentration fluctuates wildly varying from about 50,000 grains cm^{-3} to over 110,000 grains cm^{-3} twice within the limits of the zone.

2.5.2.5 L5

Pollen assemblage zone L5 represents only 12 cm of section, however it shows major changes in its fossil pollen content from the preceding pollen assemblage zones.The percentage of Gramineae pollen dips sharply to less than 30 % at the base of the zone, but increases to more than 50 % by the top. There is a noticeable increase in other herb taxa, namely *Artemisia* and *Rumex*. which reach values of 20 and 15 % respectively. There is also a corresponding small peak of *Salix*, which achieves a maximum of 12 % of the assemblage at the base of the zone.

The concentration is very low throughout the zone. It drops dramatically from nearly 120,000 grains cm^{-3} at the top of zone L4 to 20,000 grains cm^{-3} at the base of Zone L5.This low concentration is reflected on the absolute pollen diagram as the peaks of *Salix* and *Rumex* pollen are smoothed out and the peak in *Artemisia* is muted.

2.5.2.6 L6

This zone is characterised by an increase in Gramineae from zone L5. Gramineae makes up about 60 % of the assemblage in this zone. *Rumex* declines from about 10 to 2 %. *Betula* increases slightly from L5 to constitute about 15 % of the assemblage.

The concentration is higher than in L5, but it is still low (less than 40,000 grains cm^{-3}.

2.5.2.7 L7

The pollen assemblage zone L7 is marked by a sharp decrease in the percentage of Gramineae pollen. This drops from 55 % at the base of the zone to 30 % at the top. *Betula* forms a greater percentage, approximately 25 % of the assemblage, in this zone compared with L6.

The pollen concentration is generally high, reaching a maximum of 80,000 grains cm^{-3}.

2.5.2.8 L8

The youngest of the pollen assemblage zones studied at Logie shows a marked change from those preceding it. The summary pollen percentage diagram (figure 2.17.) shows a sharp increase in the percentage of tree and shrub pollen, at the expense of herb taxa. This is the result of a decline in the percentage of Gramineae pollen, which falls from a low of 30 % in L7 to around 10% in this zone. *Betula* shows an increase from L7, rising to 50 % to dominate the pollen assemblage in this zone. *Salix* also increases, albeit on a smaller scale, to reach a value of 10 % in L8.

The pollen concentration in this zone is just greater than 70,000 grains cm^{-3}.

2.5.3 Vegetation History

The vegetation history of the cores recovered from Logie span a period spanning the latter part of the Lateglacial Interstadial, the whole of the Loch Lomond Stadial and the earliest part of the Flandrian Interglacial. The division of the stratigraphy into these chronozones has been attempted using pollen and beetle content and, to a lesser extent, the lithology of the sediments.

The vegetation history of the different chronozones is described separately below.

2.5.3.1 Lateglacial Interstadial.

The sediments deposited during the Lateglacial Interstadial are represented at Logie by the pollen assemblage zones L1, L2, L3 and L4. The basal sediments of the core recovered from Logie yield high percentages of herb pollen, largely Gramineae. This pattern is retained for most of the zones L1, L2 and L3 along with a small, but significant, occurrence of shrub (*Salix* , which is insect pollinated, shows a decreasing trend from zone L1 to L3) pollen. These zones are divided largely because of an unususal peak of *Pinus* pollen (rising from 2% to over 20% and falling back to 2% within 4 cm). Intermediate levels were counted briefly and no significant amounts of *Pinus* pollen were found. The brevity of this occurrence of *Pinus* suggests that it was not a local vegetation event that caused this peak. This peak is considered in more detail in the discussion (Chapter 2.7.2.).

Zone L4 shows decreasing herb values and a rise of dwarf shrub (*Empetrum*) and shrub pollen, *Juniperus* in particular.

The vegetation history of the area around Logie is broadly similar to that seen in other sites from Fife and central Scotland, e.g. Criech Castle (Cundill & Whittington, 1983) and Black Loch (Whittington *et al.*, 1990). It is difficult to make a good comparison between sites on account of the absence of radiocarbon dates from Logie. However, the general pattern is of open grassland (as represented by such taxa as Gramineae, *Salix* and *Rumex*) earlier in the Interstadial gradually giving way to a *Juniperus* and *Empetrum* heathland. The climatic implications of such changes in vegetation are that the Lateglacial Interstadial in north-east Fife was a cool period. The environment around Logie appears to have been fairly stable at this time. The increase in *Juniperus* towards the end of the interstadial may not be the result of a climatic amelioration, although it does indicate a maintenance of favourable conditions. The occurrence of heath vegetation may be the result of continued stable environmental conditions, allowing soils to mature.

There is no evidence from the pollen spectra from Logie of an "Older Dryas" climatic revertance. Whether the sediments recovered are not old enough to show such an event, or the sampling interval is too coarse to pick it up, or if it exists at all, is impossible to say. Even sites nearby show conflicting results. At Criech Castle there is only evidence of one interstadial (Cundill & Whittington, 1983), possibly due to a sampling interval that was too coarse. However, Pickletillem (Whittington & Edwards, 1991) shows clear indications of an Older Dryas Stadial and recent, unpublished, work at Lundin Tower in Fife supports this theory (Whittington, 1992; pers.comm.)

2.5.3.2 Loch Lomond Stadial

The onset of the Loch Lomond Stadial is marked by an obvious change in lithology, a sharp drop in pollen concentration and a marked change in the pollen spectra. Sediments of this age are represented by the pollen assemblage zones: L5, L6 and L7.

The summary pollen percentage diagram shows an increase in the percentage of herb taxa, largely at the expense of shrub and dwarf shrub pollen. However the composition of the herb component of the assemblage differs greatly from that seen in the Lateglacial Interstadial. The percentage of Gramineae is relatively very low and there is a corresponding increase in the values of *Artemisia* and *Rumex*, the increase in Artemisia is a true increase as it is reflected in the pollen concentration diagram (figure 2.18.). The *Juniperus* pollen that defines zone L4 is absent in L5. These characteristics imply that the vegetation at this time was that of Tundra, with open, disturbed ground and unstable climatic conditions. Disturbed soil conditions at this time are indicated by the presence of *Artemisia* and *Rumex* , commonly found during the Loch Lomond Stadial in Scotland (Sissons, 1979). The amount of *Rumex* present during the stadial is much more than suggested by their pollen percentage values as *Rumex* 's pollen productivity is only 10% that of Gramineae (Markgraf, 1980).

The pollen spectra changes that occur through the 3 pollen assemblage zones that represent the Loch Lomond Stadial at Logie suggest a climatic amelioration towards the end of the stadial period. The vegetation appears to pass from a Tundra type in zone L5, through grassland with increased Gramineae, to heathland with the rise of more thermophilous taxa such as *Betula* , although the climatic tolerances depend on the species of *Betula*.

2.5.3.3 Flandrian Interglacial

Only a small part of the earliest Flandrian was included in this study, with two pollen levels counted to constitute zone L8. Despite the brief coverage another major vegetation change is apparent. There is a large increase in *Betula* , with a sharp drop in Gramineae values. Small increases in the amounts of *Pinus*, *Salix* and *Juniperus* can also be seen. This large occurrence of *Betula* suggests the presence of a Birch dominated woodland, typical of the early Flandrian. The climatic inferences of a marked increase in thermophilous taxa, such as *Betula* dominating the assemblage are clear. A major climatic warming occurred at the beginning of zone L8, possibly a continuation of an amelioration that started during the Loch Lomond Stadial. The presence of such tree pollen (nearly 60% of the assemblage) would also indicate stable soil conditions.

2.6. CHEMICAL ANALYSIS

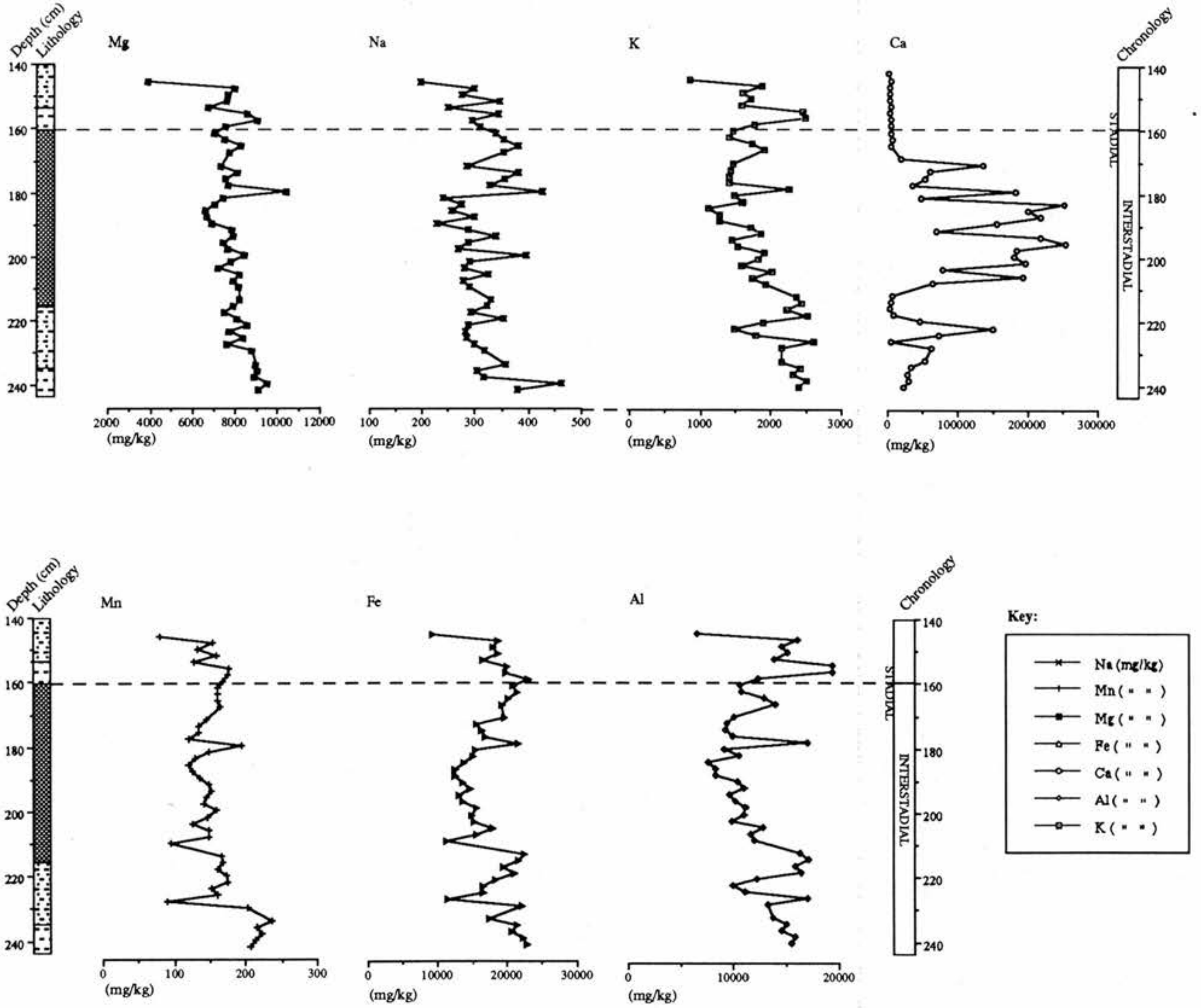
The results obtained from the chemical analysis of sediments from the core "Logie 1" (figure 2.21.) give no clear palaeoclimatic picture. The only elements to show marked reaction to the onset of the Loch Lomond Stadial are aluminium and potassium which rise to a level generally higher than that during the Lateglacial Interstadial. This is probably the result of increased erosion experienced during the Loch Lomond Stadial which led to an increase in the amount of clay minerals entering the lake.

There are trends that can be identified from the graph in figure 2.21. The metals manganese, iron and aluminium appear to be in phase. However, the number of factors that control the concentration of these elements in lake sediments (chapter 1.4.3.) is considerable and such that it is impossible to state categorically the causes of the changes that result in the varied concentrations recorded from Logie.

The alkaline earth elements (magnesium, sodium, potassium and calcium) are thought to be indicators of weathering and erosion intensity within the lake catchment (Mackereth, 1966). However, the sediments recovered from Logie do not reflect this view to any great extent. Calcium can be discounted as the results are heavily distorted by the presence of Characeae during the Lateglacial Interstadial. Of the remaining three alkaline earth elements only potassium has significantly higher concentrations during the Loch Lomond Stadial.

The similarity between the trends of the various metals suggests that the analysis of inorganic elements does record some environmental change. However, as the factors that control the concentration of such elements cannot be determined with any accuracy it is impossible to make any conclusive deduction from the results of these analyses. Much more work needs to be done on post-depositonal processes if this technique is to yield more useful palaeoenvironmental data.

Figure 2.21. Chemical Analysis results from Logie



2.7. DISCUSSION

2.7.1. Methodology

The method used to obtain the main samples for the investigation was an experimental procedure, developed by Dr. J. Jarvis of St. Andrews University. This procedure is described previously in some detail (chapter 2.2.2). The method of sampling was chosen largely by the nature of the deposits to be studied, principally the fact that the sequence of interest was not exposed. Other constraints of safety,time, and money dictated the course of action that was taken. There were several advantages of removing the sediment in a large plastic tube rather than dividing the sediment at the site. The core was divided in a 'clean' laboratory, thus minimising the chance of pollen contamination. The core was also divided slowly and carefully over a period of two days, not something which could have been achieved at the site as time was limited by the availability of the excavator to one day and the fact that in digging the hole the gravel under the Lateglacial sediments (a confined aquifer) was pierced. There were disadvantages to the technique that became apparent as the investigation progressed. The principal problem was that the samples were limited in size to the diameter of the tube (40 cm). This was thought to be sufficient to provide enough material for pollen and chemical analysis and leave enough sediment for entomological work. However the sediment proved to contain few beetles, resulting in a sparse fossil assemblage, which is discussed below.

The techniques used in this investigation can be improved upon. It is obvious from this, and previous studies, that outcropping sites are far superior for fossil Coleopteran work, as well as associated methods of investigation such as C^{14} dating (Walker & Harkness, 1990). If, as in this case, such an exposed site is not available excavation can work. However, it is very important to determine beforehand the nature and the age of the sediments by a brief preliminary study using pollen analysis of a Russian core.

2.7.2. Interpretation

The results obtained from the work on Logie were slightly disappointing. The original aim of the investigation was to attempt a palaeoclimatic reconstruction of the Lateglacial period using several different forms of climatic proxy data and to compare and contrast the palaeoclimatic results derived from the different methods of reconstruction. However, due to an initial error in the sampling which is discussed above, only sediments from the latter part of the Lateglacial interstadial and the early part of the Loch Lomond stadial were recovered in sufficient quantity for multidisciplinary study. Thus the early part of the Lateglacial period, where apparently conflicting results from entomological analysis and pollen analysis occur, is not found in the core "Logie 1" nor is the early Flandrian sequence in which similar discrepacies have been noticed.

Another major absentee from this study is a chronological framework for the climatic changes inferred. The limited timescale of this investigation has precluded the use of C^{14} dating However, the deposits found at Logie may be unsuitable for such traditional methods of C^{14} dating. The occurrence of Characeae during the Lateglacial interstadial and *Drepanaocladus* during the Loch Lomond stadial may well have invalidated any C^{14} dates obtained due to hard water error or biological fractionation. A possible alternative is the relatively new technique of Accelerator Mass Spectrometer (AMS) C^{14} dating which requires a smaller amount of material for analysis than the more conventional gas counting method. Thus a a clearly defined fraction of the sediment can be dated, reducing the chance of errors being incorporated into the date obtained. However, this method too is subject to long waiting lists for few resources. As a result the only way of dating the events indicated by the fossils at Logie is by inference from previous work on other sites.

The results obtained from the pollen and beetle analysis are what could be expected from a Lateglacial site in eastern Scotland. The pollen spectra indicated that the vegetation of the area around the site was largely that of open grassland early in the Lateglacial interstadial, changing to a Juniper/Empetrum heath later in that period. The start of the Loch Lomond Stadial was marked by a change of vegetation to broken ground taxa such as *Rumex* and *Artemisia* ; this was followed by open grassland towards the end of the stadial period. The beginning of the Flandrian Interglacial saw the development of birch forests with the climatic amelioration. The palaeotemperatures indicated by the beetle fossils show a cool, temperate Lateglacial interstadial leading into a cold stadial period. It is interesting to note that the thermal climate reconstruction of the Lateglacial of central Scotland estimated by Coope (1977a) (figure 1.6.) coincides well with the climatic reconstruction from Logie.

The pollen assemblage at the depth 226 cm. in pollen assemblage zone L2 shows an unusual and anomalous peak in the amount of *Pinus* pollen counted. This taxon accounted for 23 % of the assemblage at that level, corresponding to a concentration of about 9,500 grains cm^{-3}. This is similar to a feature found in another Lateglacial site at Criech Castle, also in northern Fife (Cundill and Whittington, 1983). It is impossible to offer any definite explanation of this phenomenon The fact that this feature occurs in more than one site in this area would suggest that the *Pinus* pollen was wind-transported. However, it does not occur at any other Lateglacial site in Fife indicating that such a peak is the result of a local event. Thus the explanations offered by Cundill and Whittington (1983) cannot be improved upon, although as the subsequent investigations of Lateglacial sites in Fife (at Black Loch, Lundin and Pickletillem) have found no evidence of such a feature it is probable that the increase in *Pinus* is the result of local contamination by older pollen.

A direct comparison of the two sets of results obtained from this study is not easily achieved. The beetle fauna, although sufficient to reconstruct the thermal climate of the Lateglacial, does not display enough continuity to make many definitive statements about the general palaeoenvironment. This is a fault of this particular study, and not of the technique of Coleoptera analysis. However the results that have been obtained from this investigation are essentially measuring two different parameters that respond in different ways to the same changes in climate. Such a comparison highlights the advantages and disadvantages of the two methods. Pollen analysis is a simpler technique to employ, particularly in sampling size and number of sites thus made available. However, a combination of taxonomic imprecision (i.e. few species can be determined) and the nature of plant distribution means that the factors which control that distribution are difficult to quantify. The controlling factors of Coleopteran distribution can be established when individuals are identified to species level. It is vital for any palaeoenvironmental reconstruction, using biological proxy data, to be able to quantify those factors which determine the distribution of a particular taxon as the basis of any such reconstruction is the change in species or assemblage distribution with time.

The climatic interpretations from the two methods show a degree of agreement in that both approaches show a cool Lateglacial climate, deteriorating with the onset of the Loch Lomond Stadial. However, the periods of abrupt climatic change at the start of the Lateglacial Interstadial and the Flandrian Interglacial which have been the subject of much debate are not contained within the core "Logie 1". However, as pollen analysis and palaeoentomology produce different results (vegetation history and thermal climate respectively) any comparison must be, by nature, subjective.

It would be incorrect to label one technique of reconstruction as the "better" as both methods have their own particular strength. Palaeoentomology, as the climatic and environmental controls can be established, can provide a quantitative estimate of the thermal climate and a detailed picture of the local environment. However,the requirement for bulk samples limits the sites that can be studied. Pollen analysis does provide an effective means of reconstructing the vegetation history of an area though, as yet, climatic interpretations are difficult to quantify

2.7.3. Further Work

The scope for further work on the Quaternary sediments at Logie is limited. There are too few beetles contained within the sediment for a further study of the entomological history of the area to be worthwhile without greatly enlarging the sample size. The vegetation history of the site has been fairly comprehensively studied, the Lateglacial in this investigation and the Flandrian pollen by Anderson (1985).

Pollen analysis continues to be much used in the study of Quaternary environmental history in Scotland. The debate will continue as to the presence (and if so of its nature), or absence, of an "Older Dryas" climatic revertance, and interest in the technique of reconstructing vegetation history from pollen analysis will remain as long as there are problems to be solved.

There is a great deal of potential for further entomological study of Lateglacial environmental history in Scotland; of the four papers published on the Quaternary entomology of Scotland (Merritt *et al.*, 1990; Bishop & Coope, 1977, Coope, 1968 and 1962) only one of these, Bishop and Coope (1977) is a systematic investigation of a Lateglacial sequence. There is no published work on the entomology of sites from earlier in the Quaternary. There are problems finding such sites in Scotland as this area suffered more from glaciation than did England. However, Lateglacial sites for further study do exist. They have mostly been studied for their pollen content and almost none have been investigated palaeoentomologically. Entomological investigations of such sites would further increase our understanding of the dynamics of climatic change in the British Isles and northern Europe.

2.8. CONCLUSIONS

1. The method used to recover sediment from Logie proved to be a satisfactory means of taking samples from an unexposed site. However, the errors made in this investigation highlight the need to identify, by pollen analysis for example, the exact section to be sampled.

2. The sediments in the subsidiary basin at Logie represent deposits from the Lateglacial Interstadial and the Loch Lomond Stadial periods of the Late devensian and also deposits from the early part of the Flandrian Interglacial. Pollen data was collected for all this period, Coleoptera were only obtained from part of the Interstadial and Stadial periods.

3. The thermal climate of the latter part of the Lateglacial Interstadial in northern Fife, obtained by Coleopteran analysis was a relatively stable 12 - 13 °C for the warmest month. This dropped to about 8 °C with the onset of the Loch Lomond Stadial.

4. The vegetation history of the area around Logie during the Lateglacial Interstadial was an open grassland developing into a Juniper/Empetrum heath. The beginning of the Loch Lomond Stadial was marked by vegetation, such as *Artemisia*, typical of broken and disturbed ground. This passed through an open grassland stage until the climatic amelioration at the start of the Flandrian Interglacial which is marked by the development of *Betula* woodland.

5. The lithological changes observed in the Lateglacial sequence at Logie coincide with the pollen and Coleopteran stratigraphy recorded from the sediments.

6. The basic stratigraphic division of the sequence into three climatostratigraphic periods (an interstadial, stadial and interglacial) is the same, where two sets of data are available. There is no evidence for a climatic oscillation during the Lateglacial interstadial.

7. The thermal climate of the Lateglacial of central Scotland, as indicated by the Coleoptera found at Logie, has proved to be very similar to that predicted by Coope (1977a)

8. There are changes in the vegetation during the Loch Lomond Interstadial that, if the Coleopteran evidence is accepted as an indicator of thermal climate, are not the result of a climatic change. These changes are thought to be the result of soil maturation during the relatively stable climate of the Lateglacial Interstadial.

9. A comparison of the two methods shows the two sets of data to be reasonably complementary for the time period represented by sediments from "Logie 1"

SECTION 3

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SECTION 4

APPENDIX

APPENDIX I

FAUNAL LIST - Coleoptera (in taxonomic order after Lucht, 1987)

CARABIDAE

Leistus rufescens (F.)
Notiophilus sp.
Bembidion bipunctatum (L.)
Amara lunicollis Schdte.

HALIPLIDAE

Haliplus obliquus F. type
Haliplus sp.

DYTISCIDAE

Hydroporus palustris (L.)
Hydroporus sp.
Potamonectes griseostriatus (Geer.) †
P. elegans (Panz.)
Platambus maculatus (L.)
Agabus arcticus Payk. †
A. serricornis Payk. *
Agabus sp.
Ilybius sp.
Rhantus sp.
Colymbetes sp.

HYDRAENIDAE

Hydraena gracilis Germ.
Octhebius sp.
Limnebius truncatellus Thunb.
Limnebius sp.
Helophorus glacialis Villa. *†
H. lapponicus Thomps. *†
Helophorus sp.

HYDROPHILIDAE

Cercyon marinus Thoms.
C. tristis (Ill.)

SILPHIDAE

Silpha sp.

CATOPIDAE

Choleva sp.

LIODIDAE

Hydnobius sp.
Liodes sp.

STAPHYLINIDAE

Megarthrus depressus (Payk.)
Eusphalerum minutum (F.)
Omalium sp.
Deliphrum tectum (Payk.) (†?)
Olophrum fuscum (Grav.)
O. assimile (Payk.) (†?)
O. boreale (Payk.) *†
Euchnecosum brachypterum (Grav.)
E. cf. *norvegicum* Munst. *
Acidota crenata (F.)
A. quadrata Zett. *†
Lesteva longelytrata (Goeze.)
Lesteva sp.
Geodromicus nigrita (Müll)
Boreaphilus henningianus Sahlb. *†
Trogophloeus sp.
Platystethus nodifrons Mannh.
Bledius sp.
Stenus sp.
Xantholinus sp.
Quedius sp.
Mycetoporus sp.
Tachyporus sp.
Tachinus marginellus (F.)

T. corticinus Grav.
T. elongatus Gyll.
Tachinus sp.
Boletobiinae gen. et sp. indet.
Aleocharinae gen. et sp. indet.
Staphylinidae gen. et sp. indet.

CANTHARIDAE
Rhagonycha limbata Thoms.

ELATERIDAE
Hypnoidus riparius (F.)
H. rivularis (Gyll.) *
Elateridae gen. et sp. indet.

HELODIDAE
Helodidae gen. et sp. indet.

DRYOPIDAE
Elmis aenea (Müll.)
Limnius volckmari (Panz.)

BYRRHIDAE
Byrrhus sp.
Simplocaria semistriata (F.)

LATHRIIDAE
Corticaria sp.

COCCINELLIDAE
Scymnus sp.

OEDIMERIDAE
Oedemera lurida (Marsh.)

SCARABAEIDAE
Aphodius prodomus (Brahm.)
Aphodius sp.

CHRYSOMELIDAE

Donacia cinerea Hbst.
Galeruca tenaceti (L.)
Melasoma collaris (L.) *

BRUCHIDAE

Bruchidus debilis (Gyll.)/*unicolor* (Ol.)

CURCULIONIDAE

Apion sp.
Otiorhynchus sp. *
Polydrusus sp.
Litodactylus leucogaster (Marsh.)
Ceutorhynchidius errisimi (F.)
Rhynchaenus foliorum (Müll.)
Rhamphus pulicarius (Hbst.)

Notes:

(* - species whose present distribution is exclusively outside the Britsh Isles)
(† - species whose present distribution is predominantly boreo-montane)

APPENDIX II - Coleoptera from Logie

Depth (cm)	146	150	154	158	160	164	168	172	176	180	184	188	192	196	200	204	208	212	216	220	224	228	232	236	240
CARABIDAE																									
Leistus rufescens (F.)								1																	
Notiophilus sp.																				1					
Bembidion bipunctatum (L.)																									1
Amara lunicollis Schdte.										1															
HALIPLIDAE																									
Haliplus obliquus F. type					1		1		1	1	1	1					1						1		2
Haliplus sp.								1			1				1									1	
DYTISCIDAE																									
Hydroporus palustris (L.)							1										1			1					
Hydroporus sp.												1		1											
Potamonectes griseostriatus (Geer.) †					1				1																
P. elegans (Panz.)								1					1	1		1		1		1				1	
Platambus maculatus (L.)										1	1								1					1	1
Agabus articus Payk.		1																							1
A. serricornis Payk. *																							1		
Agabus sp.																							1	1	
Ilybius sp.	1																			1			1	1	
Rhantus sp.											1														
Colymbetes sp.			1																						
HYDRAENIDAE																									
Hydraena gracilis Germ.					1																		1		
Octhebius sp.																						1			1
Limnebius truncatellus Thunb.								1												1					2
Limnebius sp.															1						1				
Helophorus glacialis Villa. *†	1											1									1				
H. lapponicus Thomps. *†					1		1	1																	
Helophorus sp.									1	1		1					1	1	1		1				
HYDROPHILIDAE																									
Cercyon marinus Thoms.							1																		
C. tristis (Ill.)																			1		1				
SILPHIDAE																									
Silpha sp.								1																	
CATOPIDAE																									
Choleva sp.								1																	
LIODIDAE																									
Hydnobius sp.					1		1			1			1				1								
Liodes sp.								1																	
STAPHYLINIDAE																									
Megarthrus depressus (Payk.)											1														
Eusphalerum minutum (F.)					1				1																
Omalium sp.							1	1		1	1		1	1				1	1						
Deliphrum tectum (Payk.)											1														
Olophrum fuscum (Grav.)																			1						
O. assimile (Payk.) (†?)								1					1												
O. boreale (Payk.) *†	2	3			1														1						
Euchnecosum brachypterum (Grav.)	2																							1	
E. cf. norvegicum Munst. *	4	2				1	2				1	2							9	2					
Acidota crenata (F.)					1														1						
A. quadrata Zett. *†							1																		
Lesteva longelytrata (Goeze.)													1												
Lesteva sp.											1												1	1	
Geodromicus nigrita (Müll.)																							1	1	
Boreaphilus henningianus Sahlb. *†							2						1												
Trogophloeus sp.																						1			
Platystethus nodifrons Mannh.																								1	
Bledius sp.		1																							
Stenus sp.					2						1														
Xantholinus sp.																1								1	1
Quedius sp.												1					1		1						
Mycetoporus sp.																									1
Tachyporus sp.															1		1								1
Tachinus marginellus (F.)												1													
T. corticinus Grav.															1						1	2	1		
T. elongatu C/ll.													1		1				1						
Tachinus sp.							1	1			1	1		1	2			1	1		1	1			
Boletobiinae gen. et sp. indet.					1	1	1				1	2			1				1			1			
Aleocharinae gen. et sp. indet.	9	8	1	1	3	4	11	1	3	2	3	12	4	5	2	1	2	1	4	1	2	4	1	1	1
Staphylinidae gen. et sp. indet.																									1

CANTHARIDAE																									
Rhagonycha limbata Thoms.					1																				
ELATERIDAE																				1					
Hypnoidus riparius (F.)																									
H. rivularis (Gyll.)																							1		
Elateridae gen. et sp. indet.																						1			
HELODIDAE																									
Helodidae gen. et sp. indet.				1	1					1															
DRYOPIDAE																									
Elmis aenea (Müll.)																						1			
Limnius volckmari (Panz.)										1														1	
BYRRHIDAE																									
Byrrhus sp.																				1					
Simplocaria semistriata (F.)																1				1				1	
LATHRIDIIDAE																									
Corticaria sp.					1										1										
COCCINELLIDAE																									
Scymnus sp.					1										1		1	1	1	1					
OEDIMERIDAE																									
Oedemera lurida (Marsh.)																1									
SCARABAEIDAE																									
Aphodius prodomus (Brahm.)																								1	
Aphodius sp.							1	1						1								1	1	1	1
CHRYSOMELIDAE																									
Donacia cinerea Hbst.																						1			
Galeruca tenaceti (L.)					1					1						1									
Melasoma collaris (L.) *	1																								
BRUCHIDAE																									
Bruchidus debilis (Gyll.)/unicolor (Ol.)																						1	1		1
CURCULIONIDAE																									
Apion sp.																1	1			1	1	1	1	2	3
Otiorhynchus sp. *							1											1							
Polydrusus sp.																					1		1		
Litodactylus leucogaster (Marsh.)	1																								
Ceutorhynchidius errisimi (F.)																							1		
Rhynchaenus foliorum (Müll)					1				1																
Rhamphus pulicarius (Hbst.)														1									1		

Depth (cm)	Nº of Species	Tmax1	Tmax2	Tmin1	Tmin2	Tmax (median)	Tmin (median)	Tmax (corrected)	Tmin (corrected)
146-160	4	10	8	-1	-21	9	-11	6.6908	-13.672
160-166	5	19	12	3	-15	15.5	-6	13.634	-6.592
166-176	8	13	12	-2	-11	12.5	-6.5	10.4786	-7.3
176-186	5	16	12	5	-15	14	-5	12.035	-5.176
186-196	8	12	10	-2	-5	11	-3.5	8.8796	-3.052
196-206	5	19	12	9	-15	15.5	-3	13.634	-2.344
206-216	3	16	12	5	-16	14	-5.5	12.0066	-5.884
216-226	7	14	12	0	-15	13	-7.5	10.9974	-8.716
226-236	5	18	12	0	-17	15	-8.5	13.101	-10.132
236-245	8	16	12	5	-12	14	-3.5	12.0776	-3.052

APPENDIX III - Mutual Climatic Range data

Depth (cm)	Total Nº of Coleoptera	Total Nº of Taxa	Terrestrial Coleoptera	Riparian Coleoptera	Running Water Coleoptera	Stationary Water Coleoptera
146	11	6	4			2
150	5	2	2			
154	1	1				1
158						
160	9	9	5		1	3
164	1	1	1			
168	9	7	3	1		3
172	5	5	2			3
176	4	4	2			2
180	5	5	2		2	1
184	5	5	3		1	1
188	5	4	2			2
192	5	5	4			1
196	2	2	1			1
200	2	2	2			
204	4	4	2	1		1
208	2	2				2
212	1	1				1
216	15	7	4	1	1	
220	8	7	2	2		3
224	3	3	1	1		1
228	5	4	2		1	1
232	9	9	5	1	1	2
236	8	8	4	1	2	1
240	8	6	2		1	3

APPENDIX IV - Coleopteran Ecology Data

APPENDIX V - Pollen Data

Depth (cm)	Concentration (grains/cubic cm)	Tree pollen (%)	Shrub pollen (%)	Dwarf Shrub pollen (%)	Herb pollen (%)
120	72330	59	18	1.3	21.6
124	69990	55.6	17.6	0.3	26.3
128	68520	26	13.3	2.3	58.3
132	80370	29.3	7	5.3	58.3
134	52080	31	6.6	6	56.3
138	36150	12	8.6	5.3	74
142	33060	22.6	2	3.6	71.6
146	40170	17.3	5.6	1.6	75.3
150	27000	17	4	1.6	77.3
154	17220	13.6	10	1	75.3
158	21630	15	12.3	0.6	72
162	116250	18.6	17	12.6	51.8
166	46500	11	12.6	12.6	63.8
170	79380	16.6	11	3	69.4
174	76590	17	19.3	7.6	56.1
178	120570	15.6	20	6.3	58.1
182	77490	13	17	2.3	67.7
186	63810	8	12	3.6	76.4
190	47160	7.3	6.6	0.6	85.5
194	67800	7.3	9	4	79.7
198	69270	11.6	2	3.6	82.8
202	59730	9	0.6	2	88.4
206	41460	12.3	2.6	5.6	79.5
210	39930	12.3	3.6	2	82.1
214	33060	17.3	9.6	2.3	70.8
218	49320	10	2.6	0.3	87.1
222	37200	28.3	4.3	4.6	62.8
226	40950	39.3	8	2	50.7
230	18300	16.6	12	1.3	70.1
234	14700	14.6	13	1	71.4
238	20790	7.6	15.6	0.6	76.2
242	12790	9	15.6	3.6	71.6

APPENDIX VI - Chemical Analysis Results

Depth (cm)	Mn (mg/kg)	Fe (mg/kg)	K (mg/kg)	Mg (mg/kg)	Na (mg/kg)	Al (mg/kg)	Ca (mg/kg)
146	79.96	9407.01	844.56	3926.33	197.66	6522.91	2255.17
148	153.03	18729.55	1867.18	8036.57	298.36	16073.15	4898.94
150	132.25	17973.36	1598.48	7735.49	275.93	14529.02	4110.37
152	159.09	18685.77	1719.37	7677.87	345.85	15148.22	3428.85
154	127.36	16577.11	1582.09	6746.27	248.76	13860.70	2865.67
156	176.01	20009.83	2448.38	8613.57	344.15	19419.86	4680.43
158	175.16	19767.65	2493.30	9088.47	294.91	19401.25	4146.56
160	167.66	23053.89	1756.49	7604.79	309.38	12285.43	6057.88
162	160.87	20921.92	1467.54	7036.69	338.66	10649.11	5409.22
164	160.43	21407.48	1407.48	7509.84	354.33	10807.09	6082.68
166	161.13	20087.89	1728.52	8320.31	380.86	12949.22	6914.06
168	164.87	19156.04	1903.83	7801.77	353.29	14013.74	5760.55
172	145.24	19568.20	1472.03	7330.72	284.59	10107.95	18959.76
174	134.93	15550.24	1425.84	8124.40	382.78	9291.87	135023.92
176	134.79	16382.56	1407.33	7591.67	356.79	9187.31	59861.25
178	119.40	16915.42	1402.99	7711.44	328.36	9910.45	54119.40
180	194.68	21547.96	2260.21	10474.83	427.35	17046.53	36068.38
182	147.85	15404.60	1478.52	7452.55	239.76	9140.86	182717.28
184	127.95	15137.80	1614.17	7066.93	275.59	10492.13	48375.98
186	120.67	13808.11	1107.81	6627.10	257.17	7576.66	251236.40
188	124.52	12606.18	1274.13	6718.15	299.23	8262.55	199903.48
190	136.50	12532.15	1275.96	6963.40	227.50	8328.39	217804.15
192	149.06	13603.16	1717.67	7877.59	286.28	10355.38	155281.34
194	152.43	14815.53	1844.66	7951.46	339.81	11058.25	69786.41
196	145.54	13188.12	1455.45	7495.05	287.13	9544.55	218217.82
198	141.15	13588.47	1540.76	7743.54	268.39	10228.63	253677.93
200	158.10	15681.82	1907.11	8478.26	395.26	11136.36	184387.35
202	147.14	14985.48	1819.94	7812.20	290.42	10948.69	180445.31
204	124.63	15194.42	1595.21	7258.23	279.16	9780.66	195712.86
206	148.08	17917.08	2013.82	8262.59	325.77	12764.07	79358.34
208	147.38	15717.11	1721.07	7922.85	276.95	11543.03	193372.90
210	94.53	11233.83	1927.93	8171.17	288.29	11927.93	65162.16
214	166.00	22540.00	2360.00	8260.00	330.00	16350.00	7410.00
216	166.83	21560.98	2429.27	7960.98	321.95	17160.98	4790.24
218	161.17	19396.80	2224.32	7549.48	292.18	15824.69	3817.15
220	172.38	21106.76	2526.93	8129.29	352.60	16503.43	8158.67
222	174.46	18282.37	1888.49	8588.13	287.77	12185.25	46735.61
224	152.34	16464.84	1484.38	7753.91	283.20	9931.64	149804.69
226	160.63	16513.22	1782.57	8403.53	284.04	11106.76	74025.47
228	89.84	11494.14	2614.31	7673.96	298.21	17007.95	5089.46
230	203.78	22007.95	2158.88	8831.78	317.76	13214.95	62242.99
234	235.60	17382.20	2155.32	8996.51	357.77	13743.46	54450.26
236	215.13	21326.13	2416.50	9106.09	304.52	15049.12	34715.13
238	222.33	20667.94	2309.16	8988.55	314.89	14522.90	27958.02
240	213.37	22232.06	2497.54	9537.86	462.14	15909.54	30599.80
242	206.60	22822.50	2395.73	9156.16	378.27	15489.82	23637.25

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