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Palaeolimnological study of the history of Loe Pool. Helston, and its catchment

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Palaeolimnological study of the history of Loe Pool, Helston, and its catchment.

by

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Abstract

The study traces the history and development of Loe Pool, a 50 hectare freshwater coastal lake near Helston, Cornwall, using a wide variety of palaeolimnological and associated research techniques. The principle upon which such research is based is that there is an intimate relationship between the history of a catchment and the lake into which it drains. In addition, the history of the shingle bar which now isolates Loe Pool from the sea is explored, as this has also had a significant bearing on the lake's physical and ecological development.

The study uses a combination of lines of evidence to interpret the development of the lake-catchment system. Palaeolimnological techniques employed include the examination of the physical nature of the lake sediments themselves, and chemical and biological analyses, in particular for sub-fossil diatoms. These are used to establish both a chronology of sediment deposition, and also a detailed history of the principal ecological changes experienced by the Pool. In addition, a considerable amount of historical documentary and cartographic material is incorporated in the study, in order to provide corroborative evidence of the major events that have taken place in the history of the lake and catchment.

The results highlight the main influences on the lake, and in particular, those of the last two hundred years. Marine incursions dominated the lake's history up until the late 19th century, when both natural overspill of lake water and the customary practise by local residents of 'breaching the bar' ceased. Tin mining within the catchment has also had a major impact on the lake and has given rise to several periods of very rapid sediment accumulation, the most significant of which took place in the 1920's and 1930's. Following the cessation, in 1939, of all mining activity within the catchment, the discharge of treated sewage effluent, which had begun in 1930, became the dominant influence upon the lake's ecology.

It is hoped that such an historical background will allow a more sympathetic management of the lake in future years.

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Not least go thanks to my wife, Frances, who put up with a random filing system of infinite piles of paper in almost every room of the house for more years than she cares to remember.

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H_1: An Alternative Hypothesis

(Particularly favoured by the author of the present study.)

"When the winter winds sweep over the hills around, and ruffle at such times the almost leaden stillness of Dosmary Pool; when the misty rain dims the landscape, or the sound of the tempest almost stuns the ear, the Cornish cry, "Tregagle is roaring, hark!". The nurses from one end of the county to the other continually exclaim, in order to silence their crying children, "Be quiet; thou art roaring like Tregagle". The only explanation the people give of this personage's business and identity, consists in their stating that Tregagle is a giant, condemned, not "to toil in fire" at such seasons, but in water, and "to teem" out Dosmary Pool with a limpet shell; he is consequently said to be roaring with anger at the hopelessness of his task, even sometimes when midnight wraps this inhospitable spot. Often the devil chases him round the borders of the fearful pool, until, fairly out-running the evil one, Tregagle reaches Roche Rock, and, thrusting his head in the chapel window, finds a respite from his tormentor. Having once upon a time a vast load of sand upon his back, and being pursued by Satan, he dropped it between Loe Pool and the sea, near Helston, and thus formed the large sand bar existing there."

From: Syrus Redding's "Illustrated Itinerary of the County of Cornwall", 1842.

Chapter 1

Introduction and literature review

1.1 Introduction

The last fifty years have seen an increasing interest in the ecology of freshwater lakes, and particular concern has been expressed over the degree to which cultural factors may influence the development of such systems.

Many such studies have been conducted in parts of North America and Fennoscandia where lakes are both numerous, as well as ecologically and economically important. In the United Kingdom however, freshwater lakes are comparatively few and are particularly scarce in the southern lowland zone.

Loe Pool is one of only two large, natural, freshwater lakes in the south-west of England. It is a coastal lake, separated from the sea by a shingle barrier, but is entirely freshwater (Lacey, unpublished data). In recent years it has been increasingly evident that the Pool is undergoing nutrient enrichment, resulting in nuisance blooms of Cyanobacteria (blue-green algae), formed mainly by _Microcystis aeruginosa_ (Coard _et al_., 1983). Loe Pool is of high recreational and amenity value as well as being of considerable ecological importance, a fact which is underlined by its status as a Site of Special Scientific Interest (S.S.S.I.). The lake is now owned by the National Trust, who, amongst others, have expressed concern (letter to P.E. O'Sullivan from John Carslake, 09.12.77), over the frequent and obtrusive occurrence in summer months of algal blooms.

This concern, together with a general interest in the historical development of the area, have prompted a number of studies on the lake, including the present one.

1.2 Aims

The aims and objectives of the study reflect this concern, and are outlined below:

1) To investigate the history of the lake and if feasible, to date its isolation from the sea.

2) To trace the subsequent ecological development of the lake and to compare past conditions with its present ecological and trophic status.

3) To identify the major physical and cultural influences on the lake and catchment.

4) To date any significant ecological changes resulting therefrom.

It is hoped that this report will also provide a background for future management of the site. The techniques which may be applied to achieve these objectives are many and varied, but the principles which underlie them are now well established.

1.3 Background to palaeolimnological study

Any palaeolimnological investigation aims to provide an empirical basis for the reconstruction of past lacustrine environments and communities. This evidence may be aquired through the analysis of accumulated lake sediments in combination with related documentary material. The use of lake sediments themselves is founded on the premise that a lake receives material, both organic and inorganic, from its catchment. This, combined with the organic remains of a lake's own productivity, and a small atmospheric input, comprise the resultant sediments. A diagrammatic representation of the inputs and outputs to such a system is depicted in Fig. 1.1. Accumulating over time, these deposits represent a chronological record of the development of what Oldfield (1977) terms the 'lake-watershed ecosystem'. Interpretation of the various allochthonous and autochthonous components of the sediments can thus reveal much information on the changes which have taken place throughout the period of their deposition.

Early studies, particularly that of Deevey (1942), laid the basis for the development of palaeolimnology. His work on sediment cores from Linsley Pond, Connecticut, was the first to demonstrate the evolution of a lake from a state of oligotrophy to one of eutrophy, a process which he termed 'eutrophication'. Subsequent studies however led to the realization that trophic status could change in any direction through time, depending on a large number of environmental influences. Deevey adopted the word 'biostratonomy' to describe the structured information held within the sediment column, and from which his interpretation of the lake's history was made.

The scope of palaeolimnological study has since expanded, as outlined by Frey (1974) and Oldfield (1977). Symposia such as that held at Joensuu, Finland (Meriläinen *et al*. 1983) reflect both the worldwide interest in the field and the applicability of such studies to such current problems as those of eutrophication and acid rain.

From the work by Deevey (1942), palaeolimnology has broadened into a multidisciplinary field, encompassing and integrating many separate subject areas. However, work on lake sediments can be very loosely divided into analyses using biological, chemical, physical and chronological techniques. The backgrounds and recent developments in these four areas are now discussed.

1.4 Palaeolimnological techniques

1.4.1 Biological analyses

Although a wide variety of microfossils can been used in palaeolimnological investigations, including pollen, cladoceran and chironomid remains and a number of algae, biological analyses of lake sediments have largely revolved around the interpretation of diatom remains, based on the work of such as Kolbe (1927), Hustedt (1937-39) and Cholnoky (1968). Diatoms have been used as indicators of historical and contemporary pH, salinity and trophic status. Nygaard (1956) and to a greater extent Merilälnen (1967), refined Hustedt's ideas in order to facilitate the use of diatoms in the calculation of an index from which changes in pH could be observed. This principle has since been used by many authors in studying pH changes in lakes over time (e.g. Nygaard 1956; Digerfeldt 1972; Renberg & Hellberg 1982; Flower & Battarbee 1983).

In a similar manner, the degree of palaeosalinity may be inferred from the diatom flora. The Halobian system of Kolbe (1927, 1932) has been used to this end by such as Florin (1946), where tracing the isolation of freshwater lakes from a marine environment.

Of wider interest has been the use of diatoms to assess productivity. Many systems of trophic classification have been devised (e.g. Jorgensen 1948; Nygaard 1949; Stockner

1971, 1972). However their widespread application has frequently been questioned. Battarbee (1979) suggests that the only direct technique for quantifying productivity changes is the calculation of annual influx of diatoms to the sediment. This has a number of advantages over other methods, the most important of which is that it is divorced from floristic changes. Estimates of productivity can therefore be obtained during periods when the floristic content of the sediment shows little or no variation. Such advances in technique coupled with more precise methods of obtaining absolute diatom data (Battarbee 1973, 1983) have contributed significantly to recent palaeolimnological research.

Although diatoms are by far the most widely used microfossils in the study of limnological change, other remains are also commonly studied. Deevey (1942), Goulden (1964) and Frey (1976, 1979) have used cladoceran mouthparts, preserved within the sediments, to indicate variation in lake ecology. Sponge spicules have been employed in a similar manner (e.g. Jewell 1942; Racek 1966, 1970; Harrison <u>et al</u>. 1979; Hall & Herrman 1980) but they have limited value as the sponges in general display less stringent water quality tolerances.

The remains of many species of Chrysophyte are also present in lake sediments. Siliceous chrysophycean cysts have often been recorded (e.g. Nygaard 1956; Hutchinson <u>et al</u>. 1970; Kaczmarska 1976), but their use in palaeolimnology is limited by the paucity of information relating cysts to parent species (c.f. Nygaard 1956). Of greater potential are the siliceous scales and bristles originating from species of Mallomonas, Synura and other chrysophytes. Their remains can be identified with greater taxonomic precision than cysts, and have been shown to occur seasonally in certain laminated sediments (Battarbee 1983). In the present study, diatoms are the primary microfossil used, but some information has been gained from chrysophyte remains and sponge spicules.

1.4.2 Chemical analyses

The early biological analyses of lake sediments were paralleled by equally detailed examinations of their chemical composition (e.g. Hutchinson & Wollack 1940). The work of Mackereth (1966) was particularly important in the development of this aspect of palaeolimnology. He saw lake sediments as a series of soils washed into the lake from its catchment, combined with a percentage of material of autogenic origin. He not only interpreted individual elemental analyses, but also introduced the idea that ratios of certain pairs of elements could give further information. The ratio of , for instance, Fe to Mn could reflect redox conditions at the sediment water interface. Unfortunately for the palaeolimnologist, the ratio may also be governed by redox conditions in the soils of the catchment. Many of Mackereth's ideas were, however, confirmed after further research by Mortimer (1969). Bengtsson (1979) suggested a series of extraction techniques for routine palaeolimnological analysis, and these methods determine the organically bound and acid soluble amounts of various elements. More recently, Engstrom and Wright (1984) have developed selective dissolution techniques which, unlike those of Bengtsson (1979), can discriminate between allochthonous and autochthonous components of the sediment. As these latter techniques had not been published prior to the work conducted on the sediments from Loe Pool, Bengtsson's procedures were adopted in this study.

Numerous elements are commonly extracted from lake sediments. A number are particularly useful, either alone or in combination, in the interpretation of the depositional history of the sediments and the history of the lake itself. Many authors have employed such techniques (e.g. Shapiro _et al_. 1971; Tolonen 1972; Digerfeldt _et al_. 1975; Renberg 1976), frequently in combination with biological analyses of the sediment. The main areas of information to be gained from some of the key elements are outlined below. The results of the analyses conducted on the Loe Pool sediments are detailed in Chapter 6.

1.4.2.1 Nitrogen and phosphorus

Nitrogen and phosphorus within lake sediments can originate from both point and diffuse sources in the catchment. The two sources which have come to the fore in recent decades have been sewage and waste water discharge from human settlements, and the nutrient-rich runoff resulting from the agricultural use of artificial fertilisers (Sawyer 1947; Hasler 1947).

Nitrogen exists within lake sediments almost entirely as ammonium nitrogen or as organically bound nitrogen. These forms originate from both allochthonous and autochthonous sources. The nitrogen content of the sediment is thus dependent on both the quality and quantity of the allochthonous materials entering the lake, and the rate of production, decomposition and sedimentation of autochthonous materials within the lake itself (Keeney, 1973).

Phosphorus is the element which most commonly acts as a growth limiting nutrient in lacustrine primary productivity (Vollenweider 1968, Smith 1979). This, together with the propensity for sediment to act as a sink for phosphorus, has meant that numerous studies have attempted to use the levels of sedimentary phosphorus to reconstruct palaeo-productivity. Bengtsson (1979) states that the excessive use of fertilizers, detergents and the disposal of various industrial and domestic wastes can increase the concentrations of sedimentary phosphorus by up to one order of magnitude. However, despite numerous studies, there are still reservations concerning the use of phosphorus as a palaeoindicator (Sayers <u>et al</u>. 1973). Some of these problems have also been discussed by Mortimer (1969).

Despite these reservations, numerous studies which include analysis for the phosphorus content of recent sediments from culturally eutrophicated lakes, have been published (e.g. Shapiro <u>et al</u>. 1971, Digerfeldt 1972, Williams <u>et al</u>. 1976, Bengtsson & Persson 1978, Bradbury 1978, Pennington 1978).

These studies associate a rise in sedimentary phosphorus with increased eutrophy. Other authors (e.g. Brugham 1978, Brugham & Speziale 1983) obtained less clearcut results. In addition, the ratio of N/P has been used by Digerfeldt et al. (1975) to show changes in nutrient status.

The pathways by which phosphorus reaches final deposition are numerous and complex. These are covered in detail by Engstrom & Wright (1984). The most common pathway for autochthonous phosphorus takes place via the biological uptake of dissolved inorganic phosphorus to be followed by deposition as particulate organic phosphorus. Iron can also be important in precipitation through sorption of phosphorus by iron oxides and by precipitation as iron phosphates. Thus, inferences that can be made from sedimentary phosphorus can be confused and may not only be linked to increased cultural inputs but to iron and manganese precipitation and sedimentation as well.

1.4.2.2 Sodium, potassium, magnesium and calcium

The alkali and alkaline earth elements are the major constituents of the common silicate minerals. Their influx into the lake system is therefore very largely from catchment soils and and rocks. Mackereth (1966) concluded that sedimentary Na, K and Mg thus directly reflect the intensity of weathering and erosion within the catchment. However, he also recognised that variation in the rate of deposition of other sedimentary components, particularly organic matter, would alter sedimentary composition independently of the rate of mineral erosion. Where rock or soils are artificially disturbed, as occurs during certain agricultural activity, or where large quantities of artificially 'eroded' material are made available to erosional processes, as in the case of mining, the levels of these elements entering the lake system might reasonably be expected to be higher than normal. A number of studies have found evidence of accelerated erosion as implied by the chemical profiles of lake sediments. Farming activity is suggested for such rises in Prastssjön in Sweden (Renberg 1976) and Lovojärvi in Finland (Huttunen & Tolonen 1977), although the time scales and rates of sedimentation are considerably different from those which relate to the Loe Pool sediments.

In the lake system, Na, K and Mg tend to be sorbed onto suspended particles whereas Ca has a very strong affinity for organic ligands. There tends therefore to be a strong correlation between the calcium content and the organic content of lake sediments as has been observed by Mackereth (1966), Tolonen (1972) and Brugham (1978).

The ratio of Na:K has been suggested as a measure of palaeo-salinity. Ericsson (1973) however, found no relationship between the extractable Na and K content of the sediment and former salinity levels. Similarly inconclusive results were produced by Kjensmo (1968) and Tolonen (1972), and in general, the evidence for palaeosalinity from these two elements is very difficult to interpret.

1.4.2.3 Metals

A number of metals may be usefully extracted from lake sediments. Those suggested by Bengtsson (1979) include iron, manganese and copper, which can be used to indicate palaeo-redox conditions, and zinc, chromium and lead, which can be used as indicators of pollution.

Of all these metals, iron and manganese are perhaps of greatest importance to the palaeolimnologist (Engstrom & Wright 1984), and their ratio can reflect redox conditions and erosional transport in both the catchment and the lake. Iron and manganese are both relatively insoluble in their oxidised states, but mainly soluble when reduced. Therefore, when catchment soils are reduced, the transport of these two elements will be greater. The same effect can, however, result from increased erosion within the catchment. As manganese is relatively more soluble than iron, changes in redox conditions may be reflected in the ratio of Fe:Mn. This phenomenon was first applied to the interpretation of both catchment soil and lake history by Mackereth (1966). The difficulties in interpretation of such analyses are more fully discussed by Engstrom & Wright (1984). Indications of sediment redox conditions can also be obtained from the quotient of Cu:Zn (Hallberg 1972).

1.4.2.4 Organic compounds

Plant pigments and their derivatives were first isolated from lake sediments in the 1950's by Vallentyne (1954, 1955, 1956), Anderson and Gundersen (1955), Vallentyne & Swabey (1955) and Vallentyne & Craston (1957). They have since been used in numerous palaeo-limnological investigations (e.g. Renberg 1976, Huttunen & Tolonen 1977, Tolonen 1978), and the range of pigments and their derivatives which can be identified from freshwater sediments is now extensive (Brown 1969).

The plant pigments themselves may be derived from vegetation entering the lake or from phytoplankton or other aquatic plants from within the lake itself. Brown (1969) suggests that their role in palaeolimnology is primarily twofold. They can yield an estimate of past phytoplankton abundance as a whole, and, if separated into specific compounds, can give these data for taxa which can be distinguished by their particular pigment content. In particular, specific carotenoids have been used to establish the presence and absence of blue-green algae (Vallentyne 1956; Zullig 1961; Griffiths _et al_. 1969), and to indicate palaeoproductivity (Sanger & Gorham 1972) and trophic conditions (Vallentyne 1960). Similarly, Züllig (1981) used carotenoids to detect changing phytoplankton productivity, while Fogg and Belcher (1961) and Belcher and Fogg (1964) employed chlorophyll derivative to carotenoid ratios to examine the relative contributions of autochthonous and allochthonous material to lake sediments. The ratio between these two groups has been been used to reflect the changes in the relative contributions of allochthonous and autochthonous organic matter (Gorham & Sanger 1975) and changing oxygen conditions at the S.W.I. (Sanger & Crowl 1979). These analyses can, however, be difficult to interpret, as levels of pigments and their derivatives may depend more on their degree of preservation rather than the original quantities deposited (Tolonen 1978).

The field of organic geochemistry is expanding rapidly and is no longer restricted to fossil plant pigments (Eglington 1975; Mackenzie <u>et al</u>. 1982, Cranwell 1984). Whilst in this study analyses have been limited to the detection of chlorophyll derivitives and carotenoids, a much more detailed examination of the organic chemistry of the sediments of Loe Pool has been undertaken by Pickering (Ph.D. thesis, Plymouth Polytechnic, 1987).

1.4.3 Physical analyses

Apart from the calculation of dry weight and loss on ignition from fresh sediment samples, a number of physical parameters and characteristics have been of use.

Particle size of the material shows considerable variation and can be related to changing depositional regimes, fluvial processes and source material. When combined with other data, such as the percentage of autochthonous material present, further inferences are possible as to rates of deposition of the sediment.

Colour changes are of major importance in core correlation and in the identification of repetitive sequences of sediment which may represent annual units of deposition. Of particular use in the sediments from Loe Pool have been prominent marker horizons of haematite-rich clays which have greatly facilitated core correlation. Little of this kind of analysis has previously been carried out in a palaeolimnological context, but it is appropriate where there have been considerable changes in sediment depositional history, as in the case of Loe Pool.

1.4.4 Establishment of a chronology

The dating of sediments is one of the most interdisciplinary aspects of palaeolimnology, incorporating both biological, physical and chemical analyses, and often calling upon documentary sources for corroboration. Without accurate dating of sediments, the calculation of annual influx (e.g. of diatoms) is impossible, and in the absence of good chronological fixes, estimates of past lake productivity cannot be made. Various approaches and methods have been developed.

1.4.4.1 Palaeomagnetic dating

Estimates of sediment age can be based on the continuous, if limited changes in the Earth's geomagnetic field. This 'secular variation' (McElhinney 1973) consists of changes in both the horizontal and the vertical components, as well as in intensity, of the field. Mackereth (1971) first revealed the record of these variations in a core from Lake Windermere, and his work has since been confirmed for other lakes in Europe by Thompson (e.g. 1973, 1975). The method of detection is quick and non destructive (Molyneux 1971), and standard reference curves (Thompson & Turner 1979) permit comparison between dated and undated sediment sequences. These techniques were applied to sediment cores from Loe Pool, but were found to be of limited value as the sediments are too young.

1.4.4.2 Radioisotope dating

A number of isotopes have been shown to be suitable for the dating of lake sediments. The use of 14-C is inappropriate to studies such as this, where material younger than 200-300 years is being examined. The Suess effect, dilution of 14-C by material derived from cultural sources such as fossil fuel combustion, is amongst the problems inherent in using this technique on such young material (Pennington _et al_. 1976). In Loe Pool however, the inclusion of old carbon, derived from soils within the catchment, would probably have been a more serious source of error and the technique was not attempted.

1.4.4.3 210-Pb

More appropriate to the dating of recent sediments is a technique employing the isotope 210-Pb. This is a natural decay product, forming part of the of the 238-U decay series, and has a half-life of 22.26 years. It reaches the sediments via two pathways. 'Unsupported' 210-Pb (Appleby & Oldfield 1978) is derived from atmospheric sources, washed out by precipitation and from the catchment. The 'supported' component is derived from 226-Ra, its precursor in the decay series, which is itself also present in the sediment. This 226-Ra originates from eroded catchment material (Koide _et al_. 1973). The method of analysis used by Pennington _et al_. (1976) and Robbins & Edgington (1975) assumed a constant initial concentration of unsupported 210-Pb. An alternative approach was adopted by Appleby & Oldfield (1978) and Oldfield _et al_. (1978). This latter method assumes instead a constant rate of supply of unsupported 210-Pb to the sediment and has been shown to be more applicable in cases where sediment accumulation rates have accelerated over time. The problems encountered in the use of 210-Pb dating on the sediments from Loe Pool are discussed in Chapter 4.

1.4.4.4 137-Cs

Where dating of very recent sediments is required, the application of a method based on the presence of the isotope 137-Cs may be appropriate. Caesium-137 is a by product of atomic fission and as such is not a naturally occuring isotope. Its main origin in the environment has been from the detonation of atomic weapons.

Deposition of detectable levels of 137-Cs in lake sediments began in 1954, and peaked in 1963 (Pennington et al. 1973). Following the signing of the Test Ban Treaty in 1963, environmental levels of 137-Cs fell. Consequently, in the Northern Hemisphere, 1963 represents the year of maximum deposition of the isotope. Work by Richie et al. (1973) and Pennington et al. (1973) has revealed the presence of 137-Cs in the topmost sediments of a number of North American and European lakes. This dating technique has been applied with some success to near-surface sediments from Loe Pool.

1.4.4.5 Dating by annual laminations

A dating technique with, potentially, far greater resolution and accuracy is that utilising the distinct seasonal structures characteristic of annually laminated sediments.

In order to clarify the terminology used in this and later chapters, it must be stated that the term 'annual lamination' is here considered synonymous with the word 'varve'. Both are used to describe the sediment deposited in the course of one year, whether consisting of a single layer or a series of two or more laminae or layers (Renberg 1978, 1981a).

Sediments with annual laminations are by no means a recent discovery, but were described for a number of lakes (e.g.

Nipkow 1920; Whittaker 1922; Welten 1944) in the early part of this century. Developments in palaeolimnological techniques, particularly those relating to sediment retrieval, have since revealed the ubiquity of these deposits.

Seasonal climatic variations in the temperate zone cause an annual variation in the supply of allochthonous and autochthonous material to lake sediments (Renberg 1982). This seasonality provides the potential for varve formation but a number of factors determine whether this potential is fulfilled. The major precondition is that, once deposited, the sediment should remain undisturbed. Bioturbation, excessive water movement and/or the formation of gas bubbles can all disrupt the preservation of varved sediments (Renberg 1981a). Ludlam (1976) concluded however that for the lakes that he had studied, laminated sediments could be formed wherever (a) a mechanism for their formation existed, (b) the rate of sediment accumulation was high enough relative to the rate of disturbance, and (c) the proper sampling technique was used.

The character and mode of formation of annually laminated sediments thus varies considerably from site to site. Some laminations are calcareous in origin, others are ferrogenic (O'Sullivan 1983), produced by changes in the solubility of iron at the sediment water interface. Yet more are termed biogenic, where biostratigraphic changes are the primary variations recorded. Clastic varves (Sturm 1979), form where variation in the influx of allochthonous minerogenic material is the dominant process. The sediments of Loe Pool are largely clastic in origin (Simola et al. 1981), but bio- and ferrogenic components are also present.

A comprehensive review of the formation and range of annually laminated sediments has been compiled by O'Sullivan (1983), who outlines the diversity of circumstances under which seasonality of environmental conditions may be reflected in the structure of lake sediments.

Investigation of the fine structure of the Loe Pool sediments has been aided by the development of cryo-sampling techniques, in which sediments are frozen in situ, and solid sediment samples subsequently retrieved. This method was first used by Shapiro (1958) and has more recently been developed by Swain (1973), Saarnisto (1975), Huttunen & Meriläinen (1978), and Renberg (1981b). Although undisturbed samples can also be taken using conventional coring equipment, freezer or 'crust-freeze' samplers (Renberg 1981b), are of particular use when retrieval of the unconsolidated uppermost sediments is necessary, as in this investigation.

Subsequent methods of examination of the samples have also been refined, and are discussed at length in a later chapter. However, most relevant to this study has been the work of Simola (1977), who developed a method of examining freeze-dried material from frozen sediments, attached to adhesive tape and mounted on microscope slides. This technique has been used to examine the fine structure of sediments with particular reference to diatoms and other sediment microfossils (e.g. Simola 1977, 1979, 1981; K. Tolonen 1980).

The method is capable of establishing whether laminae which appear to be annual are indeed varves, and its application has been of great value in this study in detecting annual sequences of sediment. Once annual units of deposition can be defined, dating by varve counting is then possible. As a chronological method, this is now widely employed and has been used in several studies to calibrate other dating techniques (e.g. Battarbee & Digerfeldt 1976; M. Tolonen 1978; K. Tolonen 1980; K. Tolonen & Jaakola 1983).

1.5 Historical Records

Where available, documentary material may add important background or substantive evidence to a palaeolimnological study. On the finest scale, individual, documented events such as the building of a barn and a road on the shore of the small lake Lovojärvi, S. Finland (Simola 1979), were matched to their resultant clay layers within the lake sediment. Comparable instances have been recorded in Lake Washington (Edmondson _et al_. 1956), and in Frain's Lake, Michigan (Davis 1976). On a larger scale, historical records of land use may help to explain changes in rates of deposition or erosion (e.g. Swain 1973; Digerfeldt _et al_. 1975; Cwynar 1978).

In this study considerable emphasis has been placed on historical material. The documentary sources examined have provided an invaluable framework around which the palaeolimnological work has been placed.

Chapter 2

Loe Pool and its catchment

2.1 Physical setting

The Loe Pool catchment (Fig. 2.1) lies between the Land's End and Lizard peninsulas in south-west Cornwall. Its total area is 55km^2 (see Table 2.1 for a summary of the lake and catchment statistics). Loe Pool, (N.G.R. SW648250, Lat. 50°4'W, Long. 5°17'W), the lake impounded by Loe Bar, lies at about 4m O.D., at the southernmost extent of the catchment (Plates 2.1 and 2.1).

2.2 Geology

The surface geology of the catchment is illustrated in Fig. 2.2 and is quantified in Table 2.2.

The northern part is dominated by the outcrop of the Carnmenellis granite which is an igneous intrusion dating from Permo-Carboniferous times. It is thought to be contemporary with the Dartmoor granite, dated at 275 million years B.P. (Barton 1964), and a string of granite bosses stretching from the Isles of Scilly to Dartmoor. The Carnmenellis granite is ringed by an area of contact

Table 2.1

Loe Pool - Lake and catchment data

Catchment area	54.55km^2
Lake surface area	55.6ha (0.556km^2)
Lake:catchment area ratio	0.0102:1
Altitude of lake surface	4.0m O.D.
Maximum depth	10.0m
Mean depth	4.0m
Lake volume	3.04 x 10^{6}m^3
Mean hydraulic residence time	57 days
Main contributing stream	River Cober
Mean discharge (gauged at Helston)	1.01m^{3}sec^{-1}
Mean annual rainfall:	
At R.N.A.S. Culdrose (82m O.D.)	942mm
At Wendron (140m O.D.)	1149mm
Population of Helston	10,000 approx.
Population of catchment	13,000 approx.

Loe Pool catchment

Surface geology by area and percentage area

	km^2	% area
Total catchment area	54.55	100.00
Granite	31.45	57.65
Killas	23.10	42.35

	km^2	% area
Granite area comprises:		
(Fine grained granite)	(1.05)	(1.92)
(Alluvium)	(3.13)	(5.74)
(Polcrebo gravel)	(0.25)	(0.46)
Killas area comprises:		
(Mylor beds)	(18.20)	(33.36)
(Gramscatho beds)	(4.90)	(8.98)
and includes:		
(Alluvium)	(1.88)	(3.45)
(Loe Pool)	(0.56)	(1.01)

metamorphism, about 1.5km wide, which is a zone of considerable fissurization and mineralization. The resulting metalliferous deposits have been extensively exploited over many centuries. These activities have significantly affected the sediment yield of the catchment during periods of mining, a record of which is now contained within the sediments of Loe Pool.

The aureole gradually merges into the country rock, a Devonian clay-slate known locally as killas, into which the granite was intruded. The slates are of Middle Devonian age and most belong to the Mylor series, comprising a mixture of slates and siltstones. To the east of Loe Bar the very similar Gramscatho beds also outcrop with the occasional inclusion of limestones and spilitic lavas (Dewey 1969). Both beds can be seen to be intensely folded and are shot with numerous quartz veins. The local geology is more fully discussed by Barton (1964) and Dewey (1975).

2.3 Quaternary geology

Clear evidence for the impact of the Quaternary in South-West England is confined to the late Pleistocene and the Holocene (Kidson 1977). It is generally accepted that the most southerly limits of the Pleistocene glaciations in this area approximate to the present day north coasts of Devon and Cornwall. Fluctuating sea levels during the Pleistocene have left evidence of a number of marine erosion platforms, the most noticeable of which is at 131m O.D. (Kidson 1977). This is best preserved locally on the Lizard peninsula immediately to the south-east of Loe Pool. Further raised beaches have been identified around the south Cornish coast at 4.5m (James 1968) and at 10.8m (James 1975). An example of the latter can be seen at Gunwalloe Fishing Cove, some 2km to the east of Loe Bar. The full Pleistocene stratigraphy was detailed by James (1975) and is given in Table 2.3. The area which now forms the Loe Pool catchment is thought only to have experienced periglacial conditions. As evidence of this, head deposits of up to 4m depth are visible on both sides of the Bar, capping the low cliffs. These soliflucted deposits consist largely of local slates and quartz and are very angular in nature.

At the end of each Pleistocene glacial, large quantities of coarse material from the granite and aureole were deposited as alluvium. Considerable depths of these gravels which contain significant quantities of tin, overlie bedrock in the Cober Valley. Much of the earliest exploitation of the mineral wealth of the region was through stream tinning of these deposits.

Overlying this alluvial material can be found peat deposits and tree remains. Rogers (1865) examined the alluvial strata of the Lower Cober Valley to a depth of around 10m when a shaft of Wheal Cober (Fig. 2.3) was sunk about 1km south of Helston. Little detail is given in his report, save that the strata included one peat layer at a depth of 8.5m (approx. 1m O.D.) containing "leaves of different trees, hazel nuts and

Table 2.3

Stratigraphy of the Pleistocene deposits at

Gunwalloe Fishing Cove

From: James (1975)

Deposit	Comments	Suggested dating
Head	1.0-4.0m in depth	Devensisn
Upper sand layer	1.0-4.0m in depth The two sand layers combined can be in excess of 10m.	Early Devensian
Lower sand layer	A coarse lens marks the upper limit of the lower sand layer which is approx 6.0m in depth.	Ipswichian
Raised Beach	Mean thickness 2.0m	Ipswichian
Raised shore platform	Notch at 10.8m	Early Ipswichian

trunks of trees, of which one, an oak, measured 30 inches [0.76m] in diameter.", (p.354). This organic deposit lay directly above tin-ground.

Similar observations were made by Patterson (1865), who found three such layers in the Fowey Valley. Rogers (1818) reported finding the stumps of oaks and willows embedded in a 'vegetable mould' about 3.0m below the surface of the sand in Porthleven Basin. Submerged forests are also fairly common in the area with examples at Falmouth Bay and Maenporth on the eastern side of the Lizard peninsula (Rogers 1832) and in the north-eastern part of Mount's Bay (Carne 1818).

Higher in the catchment, the alluvium of Porkellis and Medlyn Moors reaches similar depths (circa 10m). Early tinners had a substantial thickness of overburden of sands, silts, gravels and peats to remove before encountering the stanniferous gravels of the old river channels.

The ice melt at the end of the last glacial resulted in a rise in mean sea level (Hawkins & Kellaway 1971) culminating in the present day limit which lies at about 4m to 5m below that of the last interglacial. The most recent transgression flooded the Pleistocene valleys and deposited marine clays above the earlier alluvium. Loe Bar, the shingle bank which now dams the drowned estuary of the River Cober, clearly developed following this rise in sea level. For a period of time however, the valley was probably a tidal estuary.

2.4 Composition and formation of Loe Bar

The composition and geomorphological development of Loe Bar can be compared with that of other similar features around the British coastline. Little et al. (1973) have studied the development of the Swanpool, a smaller lake near Falmouth, also retained by a shingle bar, which is composed of material of local origin with a small proportion of non-local flints. In comparison, Loe Bar is composed largely of non-local, rounded flints and chert pebbles. Slapton Sands and the beaches of Chesil, Porlock and Newgate are also similar in form and origin. All consist of a shingle ribbon spread over a stable substrate and containing a large percentage of non-local material (Morey 1976). Slapton bay ,shingle never contains more than 30 percent local material (Mercer 1966). King (1972) suggests that large quantities of material can be deposited across the mouths of estuaries only where the amount of water draining seawards is very small, or where the barrier is very permeable. The latter was probably the case in the early stages of the development of Loe Bar.

The origin of the beach material of which Loe Bar is a part, has been the subject of some debate. The entire coast of Mount's Bay from Marazion to Mullion posesses similar material. The presence of unusually large quantities of flints on this part of the coast was remarked on by Borlase (1758) who dismissed earlier suggestions that they might have originated from ships' ballast. He cited a similar deposit lying slightly inland at Ludgvan as circumstantial proof. Toy

(1936) skirts the point by stating that the material of Loe Bar originates from Prah Sands to the west, resulting from easterly transport by tidal action. Reid (1904) examined material from the beach at Gunwalloe Fishing Cove, some 2km to the east of Loe Bar. A summary of the geological composition of the shingle is given in Table 2.4. He compares the flints from this site to those found in the Eocene gravels of Devon and Dorset, finding particular similarity with flints from Haldon, to the west of Exeter. He concludes that the Gunwalloe material could have originated from an Eocene outlier off the coast in Mount's Bay. Reid dismisses a suggestion by Woodward (in Reid 1904) that the material might be some form of glacial deposit.

James (1975) has described a sequence of Pleistocene deposits in the low cliffs at Gunwalloe Fishing Cove (N.G.R. SW654224). A summary of the stratigraphy together with a suggested dating is shown in Table 2.4. The raised beach component, lying on top of the raised shore platform, consists of 70 percent slate, 25 percent quartz, and 5 percent flint. Personal examination of this deposit confirms the absence of a large percentage of flints, and that which is present is fairly angular. It has been suggested by Hill (1984) that this indicates that the present type of well rounded flint and chert dominated beach material was unavailable as a source of supply when the raised beach at Gunwalloe Fishing Cove was formed. He further suggests that present beach material was derived via one or more cycles of fluvial activity from a source, now completely eroded, during

The composition of shingle at Gunwalloe Fishing Cove

From: Reid (1904)

"The shingle, which was being extensively carted away for gravel, was so perfectly rounded, and in appearance was so unlike anything that I had expected to find in Cornwall, that I examined it closely, taking away samples to give to the Museum of Practical Geology, Jermyn Street. The coarser beach provided to consist of largely (about 70 per cent by weight) of Chalk-flint and Greensand-chert, only 30 per cent being Palaeozoic at the spot where it was examined. A large quantity of the fine shingle yeilded:-

	%
Chalk-flint	86.0
Greensand-chert	2.0
Quartz	9.0
Grit	2.5
Serpentine	0.5
	100.0

the late Pleistocene or early Holocene. Its immediate source locally was very probably as Reid (1904) suggested, an outlier of flints in Mount's Bay.

If this is the case, then the formation of Loe Bar could have resulted from a combination of the movement of shingle back and forth along the coast of Mount's Bay, and a slow movement inland up the coastal slope in pace with a progressively rising sea level, a process assisted by sporadic but significant inland movement of material by storms.

The importance of longshore drift, predominantly from north-west to south-east, is supported by the fact that from Porthleven to Gunwalloe, an increase in the percentage of the larger flint component of the shingle occurs (c.f. Slapton Sands, Morey 1976). During south-westerly storms, large quantities of material are often removed from Porthleven beach to reveal the underlying bedrock. A subsequent build-up of shingle occurs south-eastward towards Gunwalloe. This is usually quickly replaced by the next strong south-easterly winds which cause movement of shingle in the opposite direction. The dominant direction of movement is however from north-west to south-east (Toy 1934), concurrent with the prevailing south-westerly winds.

Sudden and massive movements of shingle on the Bar are not unknown, and events which have resulted in this, such as the 'tidal wave' of January 1924 (Toy 1936), have been well recorded. This event threw vast quantities of sand and shingle on to and over the bar, considerably altering its shape. Similar instances were recorded in the previous century by Edmonds (1846, 1865) and Rogers (1868). The storms of February 1979 produced equally dramatic changes (personal observation).

The date of final closure of the Cober estuary by the bar, and thus the transition from estuarine to freshwater/brackish conditions, is uncertain. Once established across the mouth of the Cober, the bar continued to develop and change in form. As Morey (1976) suggests, such features, once they have reached a stable width and height, may attain some sort of equilibrium, being of sufficient size to resist storm action. Loe Bar appears to be reaching such a point. Today, it is seldom, except in the most severe of storms, that seawater overwashes the barrier.

A Cornwall River Authority report (C.R.A. 1967) gives the maximum height of the bar as +9.14m O.D. (Newlyn), i.e. some 3.0m above High Water Spring Tides (H.W.S.T.). The width of the bar from the sea at mean low tide level to the lake is given as in excess of 183m. This contrasts with the data of Foliot-Stokes (1909) who gave the width of the bar as greater than 137m at its maximum extent, and highlights the growth that has occured over the last few decades.

2.5 Lake morphometry

At average lake level (circa 4.0m O.D.), the present area of open water which constitutes Loe Pool is 55.0 ha. The surface area of the lake has changed considerably over the last 200 years, and figures from a number of sources dating from the 18th century onwards are given in Table 2.5 and Fig. 2.4. The latter shows the decrease in lake area to be about 10ha in a period of about 110 years with an acceleration in the loss of open water occuring in the past 40 years.

The isobath map of the lake (Fig. 2.5), is based on a bathymetric survey by the Cornwall River Authority (C.R.A. 1967), carried out in connection with a proposal to use Loe Pool as a source of water for domestic supply. Contours were compiled from soundings taken from a boat, with water level being referred to O.D. at regular intervals during the survey period (G.E. Bull, South West Water Authority, pers. comm.). Additional soundings taken during this investigation confirm these findings. Using the C.R.A. survey, the volume of the lake has been calculated as 2,343,600m^3, with a surface area of 63.0ha, and a mean depth of 3.72m.

Owing to progressive sedimentation and colonization by vegetation, particularly in the area of the inflow of the River Cober, the lake has since been reduced in surface area. From the 1973 Ordnance Survey 1:2,500 maps, it is possible to estimate the surface area as 57.0ha. The present figure is around 55.6ha.

Loe Pool surface area from cartographic and documentary sources, 1771-1980

Date	Area (ha)	Area (acres)	Data source
1771	66.0	163	Hitchins & Drew (1824) "..at its lowest extent.." p.510
1836	70.3	174	Gunwalloe tythe map (measured by planimetry)
1874	66.0	163	Johns (1874) (Area probably derived from Hitchins & Drew (1824))
1907	63.6	157	Ordnance Survey 25" to the mile SW62NW
1906-8	66.7		Ordnance Survey 1:2500 (measured by planimetry)
1934	60.7	150	Toy (1934)
1945	61.6		Cornwall County Surveyor, map of Loe Pool (measured by planimetry)
1967	60.3		Cornwall River Authority survey (measured by planimetry)
1973	57.0		Ordnance Survey 1:2500 (measured by planimetry)
1980	55.6		This study

2.6 Lake hydrodynamics

The lake is fed by one main river, the Cober, which drains 73 percent of the total catchment. According to Rendel (1837) the River Cober supplies 93 percent of the water entering the lake. He estimated the average flow of the Cober to be 2300ft^3/min (1.085 cumecs). This figure can be compared with 1.013 cumecs, the mean flow calculated from S.W.W.A. data for the period 1969-1980, (monitoring station at N.G.R. SW654273).

In addition to this main input, two large streams, Penrose and Carminowe, drain the majority of the remainder of the catchment (Fig. 2.6). Their contribution has not been monitored.

Lake volume varies seasonally by a considerable amount owing to a rise and fall in the lake water level. However this occurs to a lesser extent now than in the past, when the lake level fluctuated to an even greater degree. Hind (1907) and Harper (1910) both reported rises of over 3.0m after heavy rainfall. Lake level fluctuation has depended primarily on the flow restrictions imposed by the discharge pathway from the Pool. Prior to the 1880's, discharge was effected by means of natural seepage through the shingle barrier. As the Bar further developed, natural seepage would have probably decreased, owing to the greater thickness of the bar.

In the early 19th century Rendel (1837) estimated the seaward movement of water through the bar to be of the order of 198,000m^3 day^{-1}. The build-up of shingle and the clogging effect of mine wastes, discussed in a later chapter, have since been sufficient to stem this flow. In more recent times the Cornwall River Authority report (C.R.A. 1967) recorded no significant movement of water through the bar in either direction. This finding is upheld by the results of water sample analyses conducted by Lacey (unpublished data).

From the early 1900's, flooding of the valley up to Helston became more and more frequent, and eventually,in the late 19th century, a long neglected mine adit at its south-west corner was re-opened to accommodate the drainage from the lake. This route still functions but suffers blockage by shingle following severe storms. There have been recent efforts by the South West Water Authority (work commenced in 1986) to renovate and improve the inlet to this adit.

Using data from the South West Water Authority on the flow of the River Cober from 1969-79 and the calculated volume of the lake, it can be shown that the mean residence time for water in the lake is 57 days, although in winter this can be reduced to between seven and fifteen days.

The seasonality of flow into the lake is partly a reflection of seasonal rainfall variation. Precipitation is currently monitored at two points within the catchment, at Wendron (N.G.R. SW677307) and at the Royal Naval Air Station (R.N.A.S.) Culdrose (N.G.R. SW669264). A number of other raingauges have operated in the catchment at various times in the past century. These locations and periods of data availability are given in Fig. 2.7 and Table 2.6.

These data record the maritime nature of the climate of west Cornwall, with its prevailing south-westerly winds. Mean daily rainfall for Culdrose and Wendron is given in Figs. 2.8 and 2.9, and mean monthly figures are shown in Table 2.7.

It has been suggested that seasonality of climate has a considerable influence on the pattern of sedimentation within Loe Pool. It leads, at least in part, to variation in sediment supply to the Pool and thus the formation of annual laminations (Simola _et al_. 1981).

2.8 Human influence

The lake is an integral part of the catchment system and as such is heavily influenced by nutrient and sediment loading from catchment sources. Changes in demography, land use and human activity have thus significantly affected the lake-watershed system, particularly in the last century.

2.8.1 Population and settlement

The population statistics available for the area are given in Table 2.8 and Fig. 2.10. The present population of the catchment can be estimated at around 15,000. The two largest

Table 2.6

Loe Pool catchment

Raingauge locations and dates of operation

All data supplied by the Meteorological Office, Bracknell. The records available comprise daily rainfall figures for the years given below.

Gauge	N.G.R.	Hydrometric Number	Dates of Operation
Wendron	SW677307	379919	1947-
Sithney, Council School	SW637303	379920	1926-1945
RNAS Culdrose Met. Office	SW669264	379934	1952-
Wendron, Nine Maidens	SW676370	380675	1930-1950
Sithney, Tregathenan	SW655307	380790	1943-1954
Helston	SW659275	380806	1842-1874
Porkellis Moor	SW691326	380673	1977-1978

Table 2.7

Mean monthly climatological data

R.N.A.S. Culdrose (N.G.R. SW669264) Altitude 82m

Temperature (°C) 1961-1970

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
5.9	5.5	6.5	8.5	10.7	13.7	14.9	15.1	14.0	11.9	8.3	6.5

Sunshine (Hours per day) 1961-1970

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1.82	2.64	4.04	5.53	6.87	7.50	6.68	5.95	4.94	3.40	2.37	1.82

Rainfall (mm) 1961-1970

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
107	79	73	54	64	49	61	72	78	87	108	111

Wendron (N.G.R. SW677307) Altitude 140m

Rainfall (mm) 1961-1970

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
132	94	90	65	78	61	74	88	96	105	132	134

Table 2.8

Population data for Helston, 1694-1973

Year	Population	Area (acres)	Area (ha)	Source
1694	1348	130	53	Redding (1842)
1801	2248	130	53	Redding (1842)
1811	2297	130	53	Redding (1842)
1821	2671	130	53	Redding (1842)
1831	3293	130	53	Buckle & Chapman (1831)
1841	3584	130	53	Helston Town Council
1851	3355	130	53	Helston Town Council
1861	3843	291*	89	Symons (1884)
1871	3797	291	89	Symons (1884)
1881	4090	291	89	Symons (1884)
1891	3198	309*	125	Helston Town Council
1901	3088	309	125	Helston Town Council
1911	2937	309	125	Helston Town Council
1921	2616	309	125	Helston Town Council
1931	2548	309	125	Helston Town Council
1951	5545	4014**	1624	Helston Town Council
1961	7086	4014	1624	Helston Town Council
1971	9978	4014	1624	Helston Town Council
1873	10681	4014	1624	Helston Town Council

* The alterations in area were due to minor boundary changes and changes in boundary definitions. The areas given between 1801 and 1931 refer to Helston Municipal Borough.

** Between 1931 and 1951, the Municipal Borough was enlarged to include Helston Rural District, hence the further increase in area.

settlements are the town of Helston and the Royal Naval Air Station Culdrose.

Helston lies on the eastern side of the Cober Valley, about 1km north of Loe Pool (Plate 2.3). The population is currently approaching 12,000 (Kerrier District Council) although the annual influx of tourists in summer months significantly increases this figure. The town itself has a long history, chronicled in detail by Toy (1936).

R.N.A.S. Culdrose is situated at the head of Carminowe Stream (Fig. 2.11). The base has expanded in a number of stages since it was first commissioned (as H.M.S. Seahawk) in 1947. The number of personnel stationed at the base varies from around 2,000 to 2,500, although exact figures are unavailable for reasons of security.

The remainder of the catchment's population comprises numerous small and scattered settlements.

2.8.2 Sewage Treatment

Helston sewage treatment works (S.T.W.) was built in 1930 on a site (N.G.R. SW654269) below the town in the Loe Valley (Plate 2.4). It discharges into the River Cober just to the south of the works, and thus has an influence on the nutrient supply to Loe Pool. R.N.A.S. Culdrose has two treatment works. From one, effluent discharges into Carminowe Stream and thence into the lake. From the other, it passes directly into the sea. The more outlying houses in the catchment utilise septic tanks.

Information on the treatment of sewage from the Helston district prior to the 1930's is scarce. Before 1875, most of the houses in the catchment used ash pits and earth closets, with no direct discharge to the river system (Lacey 1979). The 'night soil' or waste from the town earth closets was regularly removed by the Borough Council and deposited on a refuse tip. Following the 1875 Public Health Act, Helston Borough Council introduced a sewerage system consisting of one main sewer which carried the sewage from 40 households into the River Cober (Lacey 1979). By 1897 these had been joined by a further 50 households. This however accounted for only 25-30 percent of the total sewerage from the Borough, as the connected households were largely business establishments (Case for the Opinion of Council, 1909). From 1930 onwards, the sewered population was rapidly increased by further sewer construction.

2.9 Land Use and Soils

No land use or soil survey currently exists for the catchment area, although a land use survey is being undertaken by O'Sullivan. Over 40 percent of the catchment is moorland with thin soils derived from the underlying granite. The slates in the south of the catchment have given rise to brown acidic soils.

The Cober catchment is largely given over to agriculture, with permanent grazing on the higher parts and mixed farming, largely arable and dairying, on lower ground. Closer to the lake much of the land is devoted to market gardening. There is very little woodland in the catchment other than around 46ha surrounding the Loe itself. Some patches of woodland exist on the alluvial infill of the Cober Valley between Porkellis Moor and the lake. These areas have been so heavily worked and re-worked for tin that most are now of little agricultural use, and have been classified as acid heathland, grassland and scrub (Johnson & Holliday 1978).

2.10 Lake Ecology

Although the Bar and an area of carr at the head of the lake have been designated a Site of Special Scientific Interest (S.S.S.I.) by the Nature Conservancy Council (E. Tonkin, N.C.C., pers. comm.), the lake itself has no such recognition. The Loe and its immediate surroundings are of considerable ecological interest, comprising a wide variety of habitat types. The lake itself and the wetland area of the Loe Valley are a valuable haven for breeding and migratory birds, particularly wildfowl (Penhallurick 1969).

Turk & Turk (1976) have surveyed the Pool and Bar from a botanical viewpoint and have also described the Loe Pool as having a rich invertebrate fauna. Of some interest to palaeolimnological investigations is the occurance of the freshwater sponge <u>Spongilla fluviatalis</u>, present in large numbers on and under the stones of the waters edge around the Bar. The siliceous spicules of the organism can be found preserved in the lake sediments and have some limited application in estimating past ecological conditions within the lake.

Until very recently, there has been only very limited work on the ecology of the lake. Vallentin (1903) published a study of zooplankton populations of the Pool carried out between 1899 and 1901. In 1970 and 1972, in response to a number of instances of algal blooms and fish deaths, the South West Water Authority investigated the biological status of the lake. Plankton samples taken then showed that "clean water algae" were restricted to the Carminowe inlet, with "polluted water algae" dominant in the Cober inlet, early in the year. _Microcystis_ cf. _M. aeruginosa_ dominated the blooms which developed in early summer, and became prevalent by mid-summer. It was concluded that the cause of these blooms was organic matter entering the lake via the River Cober.

Present studies by Diver (unpublished data) show that the lake currently supports a diverse phytoplankton flora which is dominated by diatoms in the spring, Chlorophyceae (green algae) in summer, and Cyanobacteria in late August and September. The latter gave rise to blooms in 1981 and 1982. Composition and productivity (Chlorophyll-a production) of the phytoplankton flora reflects the high nutrient loading received by the lake, and would suggest a fairly high eutrophic status.

2.11 Lake nutrient chemistry

Lowland water bodies, typified by Loe Pool, are considered to be under increasing ecological pressure (Osborne 1973). Hutchinson (1973) suggests that higher population densities and more intensive agricultural land use of lowland areas are increasing the risk of nutrient enrichment in lowland catchments. Cultural eutrophication, the anthropogenic enrichment of lakes by nutrients, is a common occurence in lowland lakes. As mentioned above, Loe Pool has, in recent years, shown evidence of such a process through the annual occurence of phytoplankton blooms. As Vollenweider (1968) states, this can impair not only water quality but also the aesthetic and recreational value of lakes. The elements phosphorus and nitrogen are the most important influences on the process of eutrophication. In this connection, sewage and waste water discharge from human settlements, together with artificial fertilisers carried by runoff from agricultural land have been seen as the most significant cultural sources of these two elements (Sawyer 1944, Hasler 1947).

The mean concentrations of nitrogen and phosphorus, together with other common chemical parameters which reflect the comtemporary status of Loe Pool are given in Table 2.10.

Studies by Lacey (unpublished data) have included the measurement of annual N and P loadings to the lake via the River Cober. Preliminary results for the year October 1980 to September 1981 reveal exceptionally high levels of both elements, Table 2.9. Such levels are attributable to the discharges from the sewage treatment works at Helston and place Loe Pool well into the category of a eutrophic lake. It has been suggested by Ryding & Forsberg (1980) however, that such gross annual loadings can be misleading and that an adjusted value, the "hydrologically relevant load", or H.R.L., is a more appropriate measure. As a general principle, Ryding & Forsberg (1980) suggest that for shallow lakes, the gross annual loading of phosphorus can be cut by 50% to give the H.R.L.

The sewage treatment works have only been in operation since 1930, (see section 2.8.2) and so it would seem likely that this process of eutrophication has been enhanced as effluent discharge has increased with a growing population since that time.

As a consequence of both natural infill of the lake through sediment accumulation and changes in the physical pathway by which water drains from the lake, the bathymetry and mean depth of water in the lake have changed considerably over the past two centuries. This has influenced the way in which the lake chemistry changes seasonally and in the degree to which the lake statffies during certain periods of the year. The mean depth of only 4.0m and maximum depth of around 10.0m means that stratification of the water body occurs much less frequently than must have been the case in the past. However, stratification does still occasionally occur during favourable weather conditions, and evidence of such an

Table 2.9

Annual loadings of nitrogen and phosphorus from flow concentration data Oct 1980 - Sept 1981 for the River Cober From: Lacey (unpublished data)

Sampling point	Phosphorus (Tonnes year^{-1})	Nitrogen (tonnes year^{-1})
Above Helston sewage treatment works	3.54	143.5
Below Helston sewage treatment works	16.65	615.7
Inlet of River Cober to Loe Pool	14.29	370.0

Table 2.10

Loe Pool, contemporary lake chemistry.

(Mean figures from data collected between 1977-1981)

pH	7.1
Conductivity	261µmhos
Si	2.7mg/l
Cl	41.1mg/l
T.O.N.	5.0mg/l
PO_4	0.13mg/l
Chlorophyll a	>500µg/l - August 1980 (Coard *et al* 1983)

Figures for temperature and oxygen concentration range are unavailable, but the annual variation in these two variables between July 1980 and August 1981 can be seen in Figs 2.12 & 2.13 (Lacey, unpublished data).

occurence is illustrated in Figs. 2.12 and 2.13. These present data collected from the deepest part of the lake during a parallel study by Lacey (unpublished data) and cover the period July 1980 to August 1981. There is a clear indication of thermal stratification and of anoxia at the sediment surface during August 1981. Such phenomena are generally restricted to the deepest area of the lake.

Chapter 3

Historical background

3.1 12th Century - mid 18th Century

The earliest reference thought to mention Loe Pool is in an Assize Roll (A.D.1302) from the reign of Edward I. A translation from the latin in Toy (1936) reads:

> "Concerning serjeantries, they say that William de Treville holds one Cornish acre of land in Degibna and Eglosderry, which is worth twenty shillings a year, by the seargentry of supplying a boat and nets for fishing in the lake whenever the lord comes to Helston ..." (p 470-471)

The latin word lacus is translated as lake, but it should be noted that some ambiguity is possible with this term. "St. John's Lake" for instance, is the name given to an arm of the Tamar estuary in east Cornwall.

In the same assize roll it is recorded that the burgesses of Helston exercised jurisdiction over the ships anchored at Gweek (NGR SW707268) about 5km east of Helston at the head of the estuary known as the Helford River. No mention is made of ships at Helston, or of a link with the sea.

A number of authors refer to a harbour at Helston (Maton 1794-96; Defoe 1724; Pococke 1750), but both earlier and contemporary sources suggest otherwise.

Referring to Helston, John Leland (Smith 1907) describes it as "Haylston (Hailstoun) alias Hellas" which Gilbert (1817) interprets as "the town seated near the salt water river". If this is correct, it is more likely to refer to the considerable degree of marine influence on freshwater, and not on a true estuarine situation.

In the Itinerary of 1535-1543, Leland refers to Loe Pool in the two sections on Cornwall. These have been edited together by Chope (1918) to give a continuous narrative:

> "A Ryver runnyng under the same vestigia of the Castel yssueth toward the South Se, (and) stopped ther with South Est Wyndes casting up sandes, maketh a poole called Loo of an Arow shot yn Breede and a ii Myle yn cumpas yn the Somer. In the Wynter, by reason of fluddes floweng to Haylston Town, wherby the Mylles nere Heylston beying stopped, they be constrayned to cut the Sandye Banke betwyxt the Mowth of the Poole and the Se, wherby the water may have Yssue, and the Myles grynd: by the which Gut so opened the Se floweth and ebbeth yn to the Poole, wherby Se Fysch

> enteryng with a Sowth Est Wynde ys clos yn the Poole, the Gut beyng agayn choked and fylled with sand, and so after taken with Trowtes and Eles drawen yu the same Poole. Ons yn 3. or 4. Yeres, what by the wait of the fresch Water and Rage of the Se, it brekith out, and then the fresch and salt Water metyng makith a wonderful Noise; but sone after the mouth is barrid again with Sande. At other Tymes the superfluite of the Water of Lo Poole drewith out through the sandy Barre into the Se. If this Barre might always be kept open, it would be a goodly Haven up to Hailestoun." (p30-31)

This is by far the most authoritative historical account of the lake before 1800. It confirms the presence of a substantial shingle bar impounding a freshwater lake. It also reveals that a sufficient rise in water level could cause spontaneous breaching of the bar. This took place when winter inflow sufficiently exceeded the natural rate of percolation through the shingle, resulting in an increase in lake volume.

The town mills, still standing but now a residential property (N.G.R. SW65392764), were periodically stopped by the backlog of water during winter. As Leland recounted, the bar was then cut artificially, before a natural breakage could occur.

This practise is well recorded (e.g. Borlase 1758; Lysons & Lysons 1814) and involved the custom of the granting of permission by the owner of Penrose House upon receipt of a leather purse containing three half-pence. A number of these are still held by the present occupier of the house (Plate 3.1). Each purse is dated and represents one bar-cutting.

When this became necessary, men were employed to cut a trench from the lake toward the sea until the flow of water was sufficient for it to cut its own channel. The net effect was the same as a natural breakage and the resulting gap in the bar allowed the sea to enter freely. The channel remained open until naturally infilled by shingle movement or storms. The conditions in the lake were thus more like those of an estuary for a period of several weeks or even months at a time, judging by 19th century accounts (see below).

Contemporary with Leland is a chart in the British Library (Cotton MS Augustus I i 35) dating from 1536 (Plates 3.2 & 3.3). This clearly shows a barrier across the mouth of the lake and refers to the lake as "Looe".

Carew (1602) refers to the lake and bar as follows:

> "....the river Loe, whose passage to the sea is thwarted by a sand bank, which forceth the same to quurt back a great way and so to make a pool of some miles in compass.... The foreremembered bank serveth as a bridge to deliver wayfarers with a compendious passage to the other side, howbeit sometimes with more haste than good speed, for now and then it is so pressed on the inside with the

> increasing rivers weight, and a portion of the utter sand so washed down by the waves that at a sudden outbreaketh the upper part of the pool and away goeth a great deal of the sand, water and fish, which instant, if it take any passenger tardy, shrewdly endangereth him to flit for company and some have so miscarried." (p 227-228)

Norden visited Cornwall in 1584, although he did not publish the account of his tour until 1650. He writes (Norden 1650) of the lake as a "Verrie large water" (p 34), blocked from the sea by "a banck of sande, through which it maketh a kynde of issue." (p 34)

However, in company with all small scale maps of the area dating from the 17th and 18th centuries, his accompanying map of Cornwall displays no bar across the mouth of the pool. The lake is, however, named on many maps, e.g. "The Looe Pole" in Morden's map of Cornwall (1700) and "loo-Pool" in a county map by Bowen (c. 1756). More typical is Saxton's map of Cornwall (1576) which shows no bar, but only "loo flu", even though it accompanies Carew's text (1602) describing the lake.

The rather fragile equilibrium between sea, bar and lake is portrayed in numerous references. Cox (1700) describes how:

> "[the sea] by the Violence of the Waves and Wind, will break thro' the Bank, which when it happens it

> fills the Neighbourhood with an affrighting Noise."
> (p 310)

The prevention of the mill working both at Helston and at the smaller mills at Carminowe and St.John's, together with the problem of flooding in the lower parts of Helston, were obviously economically undesirable as well as inconvenient. The only solution available to the population of Helston was to release the flood water by cutting the bar. By the middle of the 18th century, this custom must have been well established.

The salinity of the lake is first mentioned by Martin (1756-62):

> "Loo Pool ... parted from the Sea by a wide and strong Beach of Sand and Pebble, through which the water and the Sea and Lake are supposed to communicate by Percolation, for the Waters which run into the lake have no visible Discharge, and the Waters of the Lake are salt, which cannot be accounted for, by the Sea overflowing the Beach now and then." (p 15-16)

The Loe would undoubtedly have remained saline for a period of time between the "healing" of the cut in the bar and the complete flushing of the lake. The length of this period is entirely dependent on the degree of rainfall, which governs the winter flushing rate, estimated by the author in this study as between seven and fifteen days.

With the purchase of the Penrose Estate by the Rogers family in 1770, Hugh Rogers commissioned a survey of Penrose and the lake from J. Blackamore (Plate 3.4). This is the first large scale map of the lake and bar, and is dated 1771. As such it is a valuable source of information.

On the map, at the narrowest part of the bar, appear the words "the Looe Pool broke here in 1770", and the lines of the breakage are faintly indicated (Plate 3.5). Calculated from the scale of the map, the gap measures about 75m in width. Frequent breakages would have dictated the shape of the bar, with the narrowest and thus the weakest section being the site for both natural and artificial channels. It is probable that with the regular removal of thousands of tonnes of shingle, the channel section rarely built up to the level of the remainder of the bar before the next breach took place. Hence, even up to the late 1900's the bar maintained a characteristically indented profile on its inner side, (Figs. 3.1 to 3.4).

The regular removal of such large quantities of shingle must also have retarded the natural growth of the bar. This growth was also hindered, to a smaller extent, by the slow loss of shingle on the seaward side, caused by movement of lake water through the bar. Rendel (1837) calculated this to be $7,000,000ft^{3}day^{-1}$ ($198,000m^{3}day^{-1}$), (c.f. Slapton Ley, Van Vlymen 1979). Jason Rendel was an accomplished civil engineer and considerable reliability can be placed on his calculations.

3.2 19th Century

The 19th century provides a wealth of information on lake morphometry and changing ecology.

Hitchins and Drew (1824) give a graphic account of the aftermath of a breaking of the bar which is of particular importance to the palaeolimnologist.

> "The water thus discharged leaves the bed of the lake exposed to view ... The returning tide enters the chasm, and ebbs and flows through the emptied excavation: till collecting sand and pebbles choke the aperture and the waters begin again to collect within. A strong south-west wind soon enables the sea to effect this..." (p 512)

The scouring of the sediment by tides may well have disrupted uniform sediment accumulation and resulted in substantial discontinuities in the sediment column in some parts of the lake.

A report on the feasibility of converting the Loe into a harbour, commissioned by the Rev. Canon Rogers from Jason Rendel is of particular interest, (Rendel 1837). The report includes details of borings made on the bar and of one on

Weath Green, now the site of the Coronation Lake immediately below the town of Helston, Plate 2.4. He also estimated the rates of inflow and outflow, and provided a useful bathymetry of the main body of the lake. His plan of the complete lake is given in Figs. 3.5 & 3.6. His proposals were, however, considered too expensive at £118,523 and were taken no further.

The manuscripts of two brothers, George and Richard Cunnack, both lifelong residents of Helston, provide considerable information. Those of George Cunnack were written in 1898 and of Richard Cunnack in 1885. They state that the adit which now drains the pool from the south-west corner of the lake was excavated through the bedrock underlying that side of the bar in order to limit the height to which the lake water could rise. This prevented inundation of the mining operations at Wheal Pool, a mine situated close to Lower Nansloe in the Loe Valley (N.G.R. SW65292629, remains of smelting house).

The date of the construction of the adit is unclear, but as the mine was in operation between 1785-96 (Jenkin 1962) the adit is most probably contemporary with this first period of working at Wheal Pool. The entrance to the drainage adit was difficult to keep open and as Richard Cunnack wrote:

> "This was a famous piece of work, but the sand was found to be liable to close up the mouth in stormy weather, so that great attention was necessary to

keep it clear."

With the mine working suspended in 1800, the adit was not maintained. It remained blocked until about 1850 (Cunnack 1885), from which time it operated sporadically when tin streaming works were underway in the Loe Valley. One such instance was recorded in the Penrose Estate Books, when "Liberty to re-open the adit at Loe Bar" was granted on 27th April 1857 (Toy 1936).

During periods of blockage the Loe continued to flood Helston. George Cunnack's diaries record the dates on which he noted that the bar broke or was broken. The occasions on which he recorded such events are given in Table 3.1, together with dates from other sources between 1849 and 1874. Cunnack's entries include the words "broke", "[was] broken" and "went of". It is not always clear whether the bar was broken naturally or deliberately. Toy (1936) believed that the natural outbreaks ceased somewhere between 1600 and 1800, although Cunnack's diaries place suspicion on this suggestion. From Table 3.1 it can be seen that in the twenty six years between 1848 and 1874 there were a minimum of 14 recorded occasions on which the bar broke or was cut, giving an average figure of about once every two years. This is probably an underestimate.

Few of the leather purses which were presented to the "lord of the manor" (of Penrose) are still in existence, and the inscriptions on those which do remain are often illegible.

Table 3.1

Documented records of the breaking of Loe Bar, 1849-74

The absence of any record a particular year does not exclude the possibility that such an event in fact occurred.

Year	Date of record	Source
1849	8th Feb 1849	Cunnack (1885)
-		
1850		
-		
1851		
-		
1852	2nd Feb 1852	Cunnack (1885)
-	27th Nov 1852	Cunnack (1885)
1853		
-		
1854		
-		
1855		
-		
1856	12th Dec 1856	Cunnack (1885)
-		
1857	27th Apr 1857	Toy (1836)
-		
1858		
-		
1859		
-		
1860		
-		
1861		
-		
1862		
-		
1863		
-		
1864		
-		
1865	11th Feb 1865	Cunnack (1885)
-	29th Nov 1865	Cunnack (1885)
1866	Winter 1865/6	Toy (1936)
-		
1867	7th Jan 1867	West Briton, 11th Jan 1867
-	Winter 1867/8	Rogers (1868)
1868	18th Dec 1868	Cunnack (1885)
-		
1869		
-		
1870	25th Feb 1870	Cunnack (1885) records the bar as being "open"
-		
1871	13th Nov 1871	Cunnack (1885) and on a purse held at Penrose House
-		
1872	25th Jan 1872	Cunnack (1885)
-	22nd Feb 1872	Date on purse at Penrose House
1973		
-		
1974	25th Feb 1874	Date on purse at Penrose House

Three purses, still held at Penrose House, can be dated and these instances are included in Table 3.1, and the purses are shown in Plate 3.1.

Johns (1874) states that "It is rarely necessary to break the bar twice in one year, sometimes not even once", (p 167). Referring also to the bar cutting, Rogers (1934) notes that "it sometimes had to be done several times in a year", (p 4). The average was probably between once every one and two years, depending on the amount of rainfall and the ferocity of storms during the winter months.

Subsequent to Cunnack's diaries there is no written evidence of dates of bar breakage. The last known occurence of this custom was thus in February 1874, and not in the winter of 1867-68 as stated by Toy (1936).

When the bar was cut in 1865, the event was recorded in a photograph (Plate 3.6) now held in Helston Museum. As estimated from the height of the man and horse at the edge of the channel, the gap must have exceeded 80m in width, and shows the lake in open communication with the sea.

A number of 19th century authors add to the description of the bar breakage already mentioned. For example, Johns (1874) writes:

> "In a very few hours after the torrent (through the channel) has reached its height, a great part of

> the bed of the lake may be traversed on foot: the eastern creek called Carminowe alone remains a large body of water and a river of considerable depth still flows out through the channel." (p 167)

At low tide the Cober must also have cut into the exposed lake bed, further disrupting the sediment stratigraphy where the channel was cut. He further comments on residual salinity:

> "Sometimes the mouth of the channel is not closed again for many days, during which the tide ebbs and flows into the lake. But if a storm comes from the west or south-west, the breach in the bar is soon repaired and not infrequently enough salt water is shut in to impart a brackish flavour to a part of the lake for several months after." (p 167)

Cunnack (1898) tells of how the lake level could rise very rapidly, and not only through high flow in the River Cober:

> "...water used to accumulate in the Loe principally through the sea running over the bar during gales from the south-west, flooding the Lower Road and stopping the town mills."

Johns (1874) comments further on this:

> "In the winter months, too, the sea, during a storm

> from the south-west, makes a breach over the Bar, so that it is not unusual to find seaweed and the broken corks of nets lying on the edge of the lake a long way up. If a large quantity of sea water is thrown in, the necessity of cutting the bar is accelerated. While the channel remains open, herrings, flounders, and shrimps find their way into the lake and are shut in: a marine plant, also, _Ruppia maritima_, flourishes in Carminowe Creek." (p 167)

Although this plant was also reported in the lake by Page (1906), according to Turk and Turk (1976), both _Ruppia maritima_ and _R. spiralis_ have now disappeared.

The problems of flooding and the periodic necessity to cut the bar continued well into the latter half of the 19th century. Mining activity in the Loe Valley also continued on and off between 1850 and 1882, with the adit being cleared when appropriate. After that date the owners of Penrose kept the adit clear (Cunnack 1898). Around 1899, Capt. John Rogers enlarged and improved the adit and adit mouth and a plan showing a series of new vent shafts is held in the Penrose Estate Office (Plate 3.7). Subsequently , the flow of water from the lake kept the adit free from blockage.

The permanent functioning of the adit had a number of significant effects on the lake and bar system. Apart from a few well recorded occasions upon which the adit was choked, the annual fluctuation in lake level was reduced, with a subsequent decrease in the frequency of flooding in Helston. Cunnack (1898) recalls that the lake was generally 6 feet (1.83m) deeper in the 1830's than in the 1890's.

The custom of cutting the bar was discontinued by the late 1800's and so the regular removal of a percentage of the bar material also ceased. This allowed the bar to continue its natural growth and movement onshore. Toy (1934) speaks of a "gradual, though not slow" change in bar shape from 1850 to 1923. This is confirmed by examination of the available maps, in particular the O.S. 1:2500 series (Figs. 3.1 to 3.4).

The build-up of the bar through shingle accumulation together with the "filter clogging" effect caused by the large quantities of mining waste being trapped out of suspension as it percolated through the bar, must have reduced the amount of water lost through the bar itself. (The degree of pollution caused by mine waste is discussed further in the latter part of this chapter.) As as result, a higher percentage of the lake overflow was conducted through the adit.

A consequence of bar growth, both in width and height, was that the marine influence on the lake became considerably less. Storm overwash was reduced, and with the cessation of bar breaking, Loe Pool was no longer invaded regularly by the sea. The lake thus probably became continuously fresh rather than brackish, with a subsequent stabilization of the lake ecosystem.

In September 1967, the Cornwall River Authority (1967) reported that:

> "Samples of water taken by the Pollution Prevention Department of the Loe Pool indicate that there is at present no intrusion of sea water through the Bar to the Pool. It also appears that there is at present no appreciable leakage of freshwater through the Bar to the sea....." (p 2)

In addition to the gradual growth of the shingle bar, other significant events have helped the build-up of material. In January 1924, the configuration of the bar was completely altered by what was described in the Coastguard's 'log' as a "tidal wave" (Toy 1934). Although during the same month there were heavy storms, this single event was neither preceded by, nor followed by, bad weather (ibid). The single wave did substantial damage to neighbouring Porthleven and vast quantities of shingle were thrown onto and over the bar. A number of photographs (Plates 3.8 to 3.10) illustrate the subsequent flooding, as the entrance to the adit which drains the lake was completely buried. Similar phenomena have been recorded in the past (Rogers 1868, Edmonds 1865). The most likely explanation for these unusual movements of the sea is the occurence of storm surges in the English Channel which may have played an important part in the development of the bar.

The 'West Briton' newspaper (Monday 14th January 1924, p.3, col.5) reported on the flooding caused by the adit blockage, and "it was decided to engage twelve men from the Labour Exchange to assist 17 engaged by Capt. Rogers in clearing the obstruction", (Plates 3.11 & 3.12).

Although the bar continued gradually to grow, helped occasionally by severe storms, recent growth has been relatively undramatic, and the bar is probably reaching an equilibrium.

One recent event which did contribute to the growth of the bar occured in February 1979. Following severe storms, the South West Water Authority were forced to cut a channel through the bar (Plates 3.13 to 3.15) to relieve the flooding of the lower parts of Helson. The adit had again been completely buried by shingle overwash. The bar being so much more substantial than in the 19th century, mechanical excavators, in contrast to the traditional gang of men with shovels, were employed . The channel did not enlarge sufficiently to drain the pool, as in the past, but merely lowered the lake level, allowing the adit to be cleared safely. The potential level of water was, however, much greater than in the past, the crest of the bar being significantly higher. Had not the adit been cleared, spontaneous breaching of the bar would not have occured until a very much higher level had been reached, and flooding would have been much more severe than in the past. The channel which was cut through the bar gave an opportunity to photograph the vertical structure of the bar, Plate 3.16. Bands of coarse shingle included in the general matrix of the bar most probably resulted from storm events which tend to be the major constructional process in such coastal features (King 1972). This layered structure would tend to support the idea of a progressive build up of the bar structure through storm action.

In November/December of 1984, the South West Water Authority again had cause to excavate a channel through the bar to alleviate the risk of flooding after a further blockage of the adit. Mechanical excavators were used to cut the bar and the lake was drained to below its normal level. Natural 'healing' of this channel took a number of weeks. One outcome of this excavation was that it revealed considerable amounts of red clay within the structure of the inner side of the bar itself (Plates 3.17 & 3.18). This would tend to support the idea that such material, originating from mining activities within the catchment, was in part responsible for the reduction in natural drainage of the lake water through the bar. Again, the cut allowed an appreciation of the complex bar stratigraphy (Plate 3.19).

In the Summer of 1985, the old adit entrance, through which the lake drains, was altered in an attempt to maintain a constant lake level. To this end, a new sluice was constructed and the adit mouth modified to prevent blockage by shingle during future storms.

3.3 History of the Loe Valley

Since 1900, a number of changes have taken place in the stretch of the valley of the River Cober between Helston and the Loe. These have been due largely to alterations in the course of the Cober and deposition of alluvial material at the mouth of the river.

Prior to the turn of the century, the river followed a natural and sinuous course between Helston and the lake (Fig. 3.7). The valley floor was frequently flooded, and although marshy, was not as heavily vegetated with willow and oak scrub as at present.

Postcards from the early 20th century (Plates 3.20 & 3.21) show the mouth of the River Cober and the extent of open water, which corresponds with the position of the lake shoreline on the 1906 O.S. 1:2500 maps, Fig. 3.7. An oblique aerial photograph thought to date from the 1920's, Plate 3.22, also shows this area. The extent of valley infill would appear to have remained largely unchanged from the 1771 estate survey to the early part of this century. In contrast to this period of relative stability, the period 1906 to the present saw a rapid increase in alluvial deposition and a reduction in lake area of about 14.4 percent. This can be attributed largely to mining activities with catchment, which are further discussed in section 3.4.

In 1946, a plan was issued by the Cornwall County Surveyor, detailing extensive alterations to the course of the River Cober through the Loe Valley, and designed to reduce the flooding which commonly occured at peak flow (Plate 3.23). This involved a straightening of the river's many meanders and a widening of the channel to increase peak flow capacity. In 1946-47, the work was implemented and this canalisation considerably shortened the channel length. It is this course which the river currently follows.

The northern part of the valley, adjacent to the B3304 Helston to Porthleven road has been the site of refuse dispoal for many decades, raising the natural level of the valley floor by 2 or 3 metres. From 1910 to 1946 the area beneath the public swimming baths (NGR SW654269) (demolished circa 1981) was the town's refuse disposal site. More recently the area on the opposite side of the river has served the same function. This part of the valley also received the material from a major road cutting excavated in 1968-69 which now carries a section of the A394 Helston to Penzance road, just to the west of the town. These activities may all have increased the sediment load of the Cober to a greater or lesser degree.

The vegetation cover in the lower parts of the valley has increased markedly since the 1940's. Scrub willow (_Salix sp._), oak (_Quercus sp._) and alder (_Alnus glutinosa_) have developed, together with extensive beds of _Phragmites australis_ and _Typha latifolia_. These enhance sediment trapping and valley infill. The northern part of the lake is now very shallow and colonisation by macrophytes is proceeding fairly rapidly.

The various stages of valley infill, compiled from sources dating from 1771 to 1973, are outlined in Figs. 3.7 to 3.8.

The extent of the present area of open water has also been estimated and included in Fig. 3.8.

3.4 Mining history

Although metalliferous mining has taken place within the catchment of Loe Pool for many centuries, it was only in the 19th and 20th centuries that it had a major effect on sediment supply to the lake system.

Over 30 mines are known to have been in operation within the catchment boundary in the last 150 years, almost all of which were primarily concerned with the retrieval of tin. In most cases, knowledge of their dates of operation is scarce, and the quantitative information on yields of ore are even rarer. Fig. 3.9 shows the periods of operation of all the known mines of the catcment. The two most active phases of mining were 1845-1880 and 1908-1938.

The 19th century mining boom involved a very large number of mines, of which all but a handful were relatively small ventures. Two of the major mines were Wendron Consols (NGR SW688318) and Porkellis United, later known as Basset &

Grylls and the Jantar mine (NGR SW692331). In 1861 Wendron Consols employed 368 people (Jenkin 1962) and in 1864 Porkellis United, 419. Many of the smaller mines had a workforce of less than 50. Their locations are shown in Fig. 3.10. Mines such as Wheal Ann, Trumpet, Trumpet East and Franchise lie just outside the catchment boundary, but have been included because they employed the stamps at Coverack Bridges (NGR SW668303) to process their ores.

The River Cober and its tributaries were an integral part of the mining industry, supplying power to the stamps and other machinery, and a ready supply of water to separate the waste from the ore. These rivers also acted as a convenient carrier for the disposal of mine wastes. This additional suspended load significantly increased the allochthonous sediment input to the lake, which acted as the final 'settling pond' for the mines of the catchment.

A prospectus for the re-working of some of the tin deposits in the area of Loe Pool was put forward by John Warburton, Somerset Herald in the College of Arms, shortly after 1720 (Jenkin 1962). His project included the dredging of the Loe for tin and includes a map of the lake, Plate 3.24, which probably predates the 1771 estate map described in section 3.1. The prospectus states that:

> "Immense quantities [of tin] are lodged in its [Loe Pool's] bottom and continually washed into it, as is visible from those that are occasionally thrown

> out on the sea sands when the Loe Floods break over the Bar into the Ocean, ...Thirty Thousand sacks of tin have been sometimes spewed out at one of these breakings". (Document held by Reginald Rogers & Son., Solicitors, 17 Coinagehall Street, Helston.)

To recover this tin Warburton proposed to employ a "new Invented Engine". Plate 3.25 shows the machine with the caption "The Engine fishing for Tin". No further reference to the project has been found, so although the principle of re-working alluvial tin was sound, the proposal probably never came to fruition.

A number of authors have commented on the iron rich wastes which emanated from the mine workings during the 19th century. Rogers (1857), referring to the River Cober, states that it "is not fit to drink, because it collects a great deal of tin from the mine, and is not very clean." (p 31). Of the Loe, he remarks that "the water is clearest by the Bar and in Carminowe Creek, but it has everywhere a reddish tint, which rather spoils its beauty." (p 31). Sometimes the bar was broken to release the mine wastes from the Loe, and as Johns (1874) reports, "the sea for twenty or thirty miles is tinged of an ochreous hue." (p 166-7).

Collier (1899) says of the river that it was :

> "....foul with mining water. There was no fishing

> in the Cober, but when it reached the Loe it seemed to deposit its refuse. It would have been a lovely river without the mines. There were only one or two streams near Helleston unpolluted by the mines...." (p 120-1)

The degree of pollution carried by the Cober was thus considerable, and only subsided with the decline in mining activity in the latter part of the 19th century. One of the smaller mines which may have contributed sediment on a more local scale was Wheal Pool, in production between 1850 and 1865. It was situated close to the lake in the Loe Valley at NGR SW653265, and the sett included a large part of the Loe and the adjacent "mud lands", with prospecting rights over both sides of the valley (Jenkin 1962). Flooding of the works was a constant hazard and operations ceased altogether after about 1860.

A period of comparative inactivity followed the fall in tin prices in the early 1880's (Figs. 3.11 & 3.12 and Tables 3.2 & 3.3). The industry only picked up again after the turn of the century when both Basset & Grylls mine and Boswin Mine resumed working in 1907.

The majority of the production in this period came from Basset & Grylls, then operating as Porkellis Mine. This venture continued on and off until its closure in 1939, the final periods of production being between 1928-29 (as Jantar Mine) and 1934-38. Fouling of the river was of such a degree that between May and November of 1928, Capt. J. J. Rogers of Penrose brought an action against H.W.H. Syndicate Ltd., the owners of Jantar, in respect of the pollution of the Cober and Loe Pool. The action was subsequently "settled on terms", (documents held by Penrose Estate Office).

The input of silt and sand, however, continued. At a meeting of Helston Town Council on 2nd April 1930 the matter was aired. In a report of the proceedings (West Briton, 3rd April 1930, p.9, col.6), it was stated that:

> "sand and silt.... was being permitted to enter the river from mine workings in Wendron Parish", and that "more frequent flooding in the future was inevitable unless some action was taken to clear the bed and course of the river and to prevent the mining companies from sending down such quantities of sand".

At the same meeting, Alderman H. Toy stated that the mining companies "had undertaken to put into operation certain mechanical devices with the object of preventing the major portion of the sand and silt from entering the river", (ibid).

The problem did not lessen and operations carried on, largely from two main lodes at Porkellis Mine, known as 'Wheal Cock' and 'Old Mens' or 'Red Lode'. The latter was particularly iron-rich and the waste from it resulted in the deposition within the lake of large quantities of haematite-rich clay and e ? silt. This period of deposition is clearly discernable in the sediment column, (see Chapter 5). Porkellis Mine ceased active operation in 1938 and the company was liquidated in 1941. This was the last large scale mine to operate in the catchment.

Closure of the mine, although governed by the fall in the price of tin prior to the Second World War, may also have been influenced by the Rogers family. They owned many of the mining rights in the Wendron and Porkellis area, and had objected for many years to the levels of pollution in the Loe. The family is said to have bought up the remaining mining rights to prevent further mining from taking place (J.P. Rogers, pers.comm.).

An ore processing works at Lowertown (N.G.R. SW658291) is known to have been active in the 1930's, working slimes from the South Crofty mine near Camborne. The period of working is unknown although some activity may have continued until as late as the end of World War II (Justin Brooke, pers. comm.).

The inefficiency of 19th century operations meant that workable quantities of tin, originating from the mines of Porkellis Moor and Medlyn Moor, were redeposited lower in the catchment. These deposits were reworked by a number of ventures. One in particular was established in 1911 to exploit the rich alluvial deposits of the Loe Valley. Known as the Helston Valley Tin Company Ltd., it built a processing works near Castle Wary on the eastern side of the valley. The remains of the settling tanks and buddles can still be found (N.G.R. SW653266) and can clearly be seen in the aerial photograph of the valley, thought to date from the 1920's, Plate 3.22. A narrow guage railway was constructed to transport the alluvium to the works. The venture was operative between 1911 and 1914. Much of the waste must have been directed back into the Cober and the lake itself.

The rich deposits of alluvial tin in the Loe Valley have also attracted the attention of contemporary mining interests. In 1980, Billiton Minerals conducted preliminary sampling to evaluate the feasibility of dredging the swamp area at the head of the Loe. To date, no further action has ensued.

The mining has been one of the principal factors affecting sediment deposition rates within the lake. It is unlikely that the mining activity in the catchment prior to the 19th century would have been on a scale which might have significantly increased the natural allochthonous sediment supply. With advances in mining technology and the financial inducement provided by a rise in tin prices in the mid-19th century, tin extraction flourished. Operations were then on a scale sufficient to enhance the sediment supply to the lake system and thus the rate of sediment accumulation. Mining operations were renewed and substantially increased in scale in the 1920's and 1930's, resulting in an artifically high rate of sediment deposition (O'Sullivan _et. al_. 1982).

With the possible exception of Lowertown Stream Works, all active mining, and hence the accompanying pollution, ceased in 1938 or 1939 with the closure of Porkellis Tin Mine.

Chapter 4

Field and laboratory methods

4.1 Field methods

4.1.1 Location of cores

Loe Pool is an unusual shape, being compared to a "buckes horne" by Norden (1650). As such there is no obvious site for sediment sampling. Furthermore there are a number of problems which prohibit coring in certain parts of the lake and which restrict the range of suitable localities for sediment sampling.

For example, the deepest point is close to the shingle bar and early sampling of bottom material here showed a high proportion of shingle. On the other hand, cores taken at the northern end of the lake contain high proportions of allochthonous material. More important, present water depth in this area is between 1-4m, so that resuspension of material from the sediment surface by turbulence probably generalises the sediment record, and appears to prohibit the formation of laminations. Bioturbation is also more prevalent in these shallow waters.

The majority of the cores taken during the investigation were therefore confined to the central, narrow section of the lake, with the main site, Station A, lying adjacent to the southernmost pair of small promentories on the western shore, and equidistant from either side. This site is located south of the prominent 'step' in the lake bed (Fig. 4.1) and therefore lies beneath approximately 7.0m of water. Subsequent coring in a variety of other sites confirmed that this location yields a well laminated and fairly representative sediment column.

4.1.2 Coring devices

4.1.2.1 3m Mackereth corer

In this investigation, a range of coring and sediment sampling devices were employed. The main core for chemical and diatom analysis, core LP3M3, was taken at Station A, using a 3m Mackereth corer, a half sized version of that described by Mackereth (1958). A number of other cores for comparative and magnetic purposes were also taken using this device. Samples from this corer were contained in 5cm I.D. black polypropylene tubing, and were sealed top and bottom on site using rubber bungs and P.V.C. insulating tape to reduce moisture loss. Considerable disturbance of the mud-water interface occured , both during the coring operation and in the subsequent transportation of the samples, horizontally, to the laboratory.

4.1.2.2 1m Mackereth corer

For retrieval of a large number of samples of the uppermost sediments, including the sediment-water interface (SWI), a 1m Mackereth mini-corer (Mackereth, 1969) was used. Transparent Perspex tubes enabled quick measurement of the major stratigraphic units of the top 80-100cm of the sediment column. Considerable smearing of material down the inside of the tube occured, but colour differences between the major units were still clearly visible, Plate 4.1. Cores which were to be returned to the laboratory were again sealed and stacked vertically in a rack to minimise disturbance of the SWI. Disturbance of the upper 5-10cm often occured whilst sampling, owing to the very liquid nature of the most recent sediment.

4.1.2.3 "Russian" borer

At two locations, a "Russian borer" (Jowsey 1966) was employed to take consecutive 50 x 2cm semi-cylindrical samples of the sediment column down to and below 3m depth, Plate 4.2. The difficulties of obtaining consecutive samples from depths greater than 3m below the sediment surface, and in more than 6m of water, were considerable. To minimise flexing of the string of rods and to enable relocation of the sampling hole, the borer was delivered down a 6m length of 15cm diameter PVC pipe. The pipe was anchored to the sediment at its base and was kept upright by a bouyant flotation collar. It proved to be physically impossible to retrieve samples from a depth greater than 5m into the sediment column using this method.

4.1.2.4 "Freezer" samples

To recover undisturbed samples of the upper sediments, and in particular, the very easily disrupted surface material, both cylindrical and box-type freezer samplers were used. Initial experiments with this technique involved the use of cylindrical metal tubes of various dimensions, Plate 4.3, similar to those described by Swain (1973) and Saarnisto (1975). These were filled with solid CO_2 and dropped vertically into the sediment on the end of a rope.

This type of sampler takes a 1-3cm thick cylinder of sediment. The general shape of the sample, which results from the progressive sublimation of the CO_2 from the top of the tube downwards, can be seen in Plate 4.4. The base of the sample is thus thicker than the top. This can, to some extent, be evened out by insulating the upper section of a longer tube with layers of 2mm thick polystyrene wall insulation material.

The cylindrical sampler does, however, cause some distortion of the sediment upon freezing. This problem can largely be avoided by the use of the box sampler, designed by Huttunen & Meriläinen (1978). This has a rectangular cross section and is chisel shaped in profile (Fig. 4.2). The shape is designed to disturb the sediment on the rear of the sampler whilst cutting cleanly into the sediment on the front. Insulation within the sampler means that the majority of sediment sample is collected by the front face.

The device used in Loe Pool was made of sheet steel which was galvanised after fabrication to prevent corrosion. The front face was regularly coated with polytetraflouroethane (PTFE), to reduce friction and ease removal of the sample from the box.

Granular or pelleted CO_2 was used as a refrigerant. This is both easier to use than the block form and enables a more even cooling of the sampler face.

Adding a liquid such as acetone, which has a low freezing point, to the CO_2 in the sampler, helps the process of heat transfer and can regulate the speed of sample freezing. The greater the volume of acetone added, the faster the freezing process.

The box sampler was also allowed to freefall into the sediment. The depth of penetration depends on sediment consistency, sampler weight and the depth of water through which the sampler is permitted to fall. Once in position, a period of about ten minutes is sufficient to freeze a crust of sediment 2-3cm in thickness onto the face.

Once the sampler is retrieved, any residual CO_2 is removed from the inside of the box and lake water introduced to warm cutting cleanly into the sediment on the front. Insulation within the sampler means that the majority of sediment sample is collected by the front face.

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Once the sampler is retrieved, any residual CO_2 is removed from the inside of the box and lake water introduced to warm the thin layer of ice between sampler and sediment. The sheet of frozen sediment can then be removed in one piece. This form of sampling provides remarkably undisturbed sediments, and even preserves the delicate structures within the very sloppy surface gyttja.

Frozen samples, of whatever type, were returned to the laboratory deep-freeze in a large insulated box packed with CO_2.

All sampling devices were operated from an inflatable boat, which was prone to drifting in all but the calmest of weather. Sampling sites were located by compass bearing. Considerable inaccuracy can occur with this method and positions were accurate to within a circle of approximately 20m diameter of the actual site.

4.2 Laboratory methods

4.2.1 Core storage and preparation

4.2.1.1 Mackereth cores

The 3m Mackereth cores were stored frozen. Core tubes were initially slit up the full length of both sides using a portable circular saw and jig. Each cut left a thin sliver of plastic which held the two halves of the tube together and which could finally be cut with a knife. The tubes were also cut into two 1.5m lengths, the division being made at 45 degrees to provide some overlap between material in the two halves. The sediment was then frozen horizontally in a large domestic chest freezer, the logitudinal cuts in each tube allowing for lateral expansion and minimising longitudinal expansion and distortion. Once frozen the cores were sealed with insulating tape and plastic sheeting to prevent water loss, and stored at -20 degrees Celsius. The slow freezing technique did result in the formation of large ice crystals, although the structure of the sediment remained visible.

Subsampling of these cores was performed whilst still frozen. One half of the tube wall was removed and successive 10cm half-cylindrical sections cut, using a hot wire (18 S.W.G. resistance wire), heated by a rheostat supplying approximately 3.25 volts D.C. at 10 amps. As the wire was moved down the core, guided by the lower half of the core tube, a thin sheet of rigid plastic was inserted to separate the upper and lower halves of the sediment. Each segment was then placed in a container, sealed to prevent evaporation, allowed to thaw and then weighed.

For chemical and diatom analysis, subsamples from each well mixed 10cm segment of core were used. This was to prevent the variation which might have resulted from point sampling, and was especially important given the highly laminated character of the sediment. Bulk density and wet/dry weight were determined as soon as possible after thawing.

The other half of each 1.5m core section was kept frozen and the exposed face carefully cleaned using a hair-dryer and Skarsten-type paint scraper. Material was successively thawed and removed to reveal a clean face for photography. This then allowed counting and measurement of lamina and provided a permanent record of each core.

4.2.1.2 "Freezer" samples

The samples collected using a box-type freezer sampler and the "icy-finger" cylindrical samplers were also wrapped in aluminium foil over "cling-wrap" plastic and stored in a freezer at -20°C.

Initial work on the flat samples provided by the box sampler involved the preparation of a 'clean' face for photography and subsampling. Most samples were heavily smeared on withdrawal from the lake bed and so generally about 1cm thickness of material had to be removed in order to reveal undisturbed sediment. This operation was again performed using a hair-dryer and paint scraper. The process is fairly lengthy and cores had to be returned to the freezer periodically in order to prevent total defrosting. Final scraping was performed from side to side to minimise contamination by material from one layer to another. The prepared surface was then photographed.

A similar preparation technique was used for the cylindrical frozen sediment samples. A tangential section of material was removed from each core in order to reveal undisturbed sediment. These samples were, however, only used for preliminary sediment investigation and lamination counting, and not for diatom counting.

The flat sample used for Cs-137 analysis was initially cut in half longitudinally, one half was used for dating, the other for reference purposes. Subsectioning for dating was performed once the sediment had been allowed to defrost sufficiently for it to be cut with a knife, but before the material lost its structure. Subsamples were then weighed, dried and reweighed prior to the dating procedure.

4.2.1.3 Russian borer samples

In an attempt to prevent the growth of large ice crystals, these were frozen using liquid nitrogen. Sections of 50cm length were lowered into a bath of liquid nitrogen using a wire mesh cradle to support the samples horizontally. Formation of large ice crystals was avoided, but the sediment became considerably distorted owing to the rapid freezing of the material in immediate contact with the coolant. A hard crust was formed, followed by the freezing and expansion of the centre of the sample. Subsequent preparation of a tangential section allowed for the preparation of adhesive tape peels, following the same cleaning procedure as before and using the least distorted areas of the sample.

4.2.2 Methods of physical and chemical analysis

A number of analyses were performed on a 3m Mackereth core, LP3M3, taken from the site shown in Fig. 4.1. The methodology for chemical analysis follows the guidelines given by Bengtsson (1979). Sampling has already been described in section 4.2.1.1. The core was cut into twenty eight 10cm sections, each being well mixed before subsampling to ensure representitivness from each sample. A $5cm^3$ subsample was removed using a modified plastic syringe. Each subsample was placed in a pre-weighed and pre-ignited porcelain crucible and the following analysés performed.

4.2.2.1 Density (D)

Wet density was calculated from the weight and volume of the subsample. Density is expressed as g/cm^3.

4.2.2.2 Dry weight (D.W.)

The fresh sediment was dried at 105°C for 24 hours. Dry weight is expressed as mg/g fresh weight (F.W.) and $mg/cm^2/yr$.

4.2.2.3 Loss on ignition (I.L.)

The dried samples were transferred to a muffle furnace and ignited at 550°C for 4 hours. Ignition loss is expressed as mg/g D.W. and $mg/cm^2/yr$.

Loss on ignition can be used as an estimate of organic matter (e.g. Shapiro et al. 1971; Likens & Davis 1975; Bengtsson & Persson 1978; Tolonen 1978). Allen et al. (1974) have shown that for non-calcareous samples, there is an acceptable correlation between organic carbon and loss on ignition. Bengtsson (1979) states that organic carbon is usually 40-60 percent of loss on ignition. However, any given conversion factor may not be consistently applicable even within a single sediment profile owing to changes in material type. Methods of estimating organic carbon such as that suggested by Jansson & Valdmaa (1962) were not used in this case and so ignition loss has been adopted as an approximation to organic carbon. No attempt has been made to adjust these figures to more strongly reflect organic carbon content.

4.2.2.4 Kjeldhal nitrogen (Kj-N)

Determination of nitrogen using the Kjeldhal method measures both organic and ammonium nitrogen and thus represents the total nitrogen present in the sediment (Digerfeldt 1972). The Kjeldhal digestion converts organic nitrogen into ammonia and was performed in a Tecator digestion unit, using concentrated sulphuric acid and a selenium catalyst. The method follows that outlined by Avery & Bascomb (1982) which is based on the procedures of Ma & Zuazaga (1942). Nitrogen was subsequently determined using a 'Hoskins' apparatus (Hoskins 1944). Results are expressed as mg/g D.W. and as mg/cm^2/yr.

4.2.2.5 Sedimentary plant pigments

Chlorophylls and carotenoids, together with their degradation products are the simplest plant pigments to isolate. The method used for their extraction was that suggested by Bengtsson (1979) which in turn is based on the procedures of Fogg & Belcher (1961).

Chlorophyll derivatives are extracted using a 9:1 acetone:water mix. Carotenoids are subsequently isolated in petroleum ether. A Perkin-Elmer 124 double beam spectrophotometer was used to detect the level of pigments at the 664-667nm peak for chlorophyll derivatives and the 445-450nm peak for carotenoids. Pigment concentrations were then expressed as spectrophotometric units (P.U.) per gram of organic matter, one unit being equivalent to an absorbance of 0.1 in a 1cm cell when dissolved in 100ml of solvent, as outlined by Vallentyne (1955). The results are also expressed as units/cm^2/yr.

4.2.2.6 Phosphorus and metals

The samples used for the determination of density, dry weight and loss on ignition were subsequently used to prepare stock solutions for the analysis of phosphorus and a number of other elements. The method enployed here determines the organically bound and acid soluble amounts of various elements.

The method of acid extraction given by Bengtsson (1979) was followed. Concentrated nitric and hydrochloric acids (aqua regia) are used to extract the elements, resulting in a stock solution which can be employed with a number of different analytical techniques.

For two elements, tin (Sn) and copper (Cu), the results of x-ray fluorescence analyses are given. These determinations were supplied by Cousen (1981) who used subsamples from core LP3M3.

Total phosphorus was determined using the molybdenum blue method developed by Murphy & Riley (1962). A blue phosphomolybdate compound is developed in aqueous solution. The concentration of this is then determined colorimetrically at 882nm, for which a Technicon Auto-Analyser II was used. Results are expressed as mg/g D.W. and as mg/cm^{2}/yr.

The following elements were also determined from the stock solutions:

Na, K, Mn, Ca
Fe, Cu, Zn
Pb, Al, Cr

Na and K were determined using a Corning 400 flame photometer. The remainder of the elements were measured using an Instrumentation Laboratories Model 151 atomic absorbtion spectrophotometer.. These results are expressed as mg/g D.W.

and in $mg/cm^2/yr$.

4.2.3 Particle size analysis

Particle size analyses were performed on each of the 10cm sections of core LP3M3. Owing to the diverse nature of the material which constitutes the upper 3m of the sediment column, it was thought that such information might help in the interpretation of the chemical results and in the correlation between historical information, particularly on mining, and the type of sediment produced as a result. The location of the coring site and the very nature of the material tends to place a restriction on the upper particle size which is found in core LP3M3. By virtue of Stokes' Law, the largest size of minerogenic particle within the sediment was in the order of 0.063-0.125mm, very fine sand. The procedures adopted to analyse the material for particle size had therefore to be applicable to this range of material down to the clay fraction.

The weight of sample used varied between 5g and 15g depending on the amount of material remaining from each of the original 10cm sections of the core after all the other analyses had been performed. The lack of sufficient material combined with the possibility that some mixing may have occured before sampling of the uppermost four samples of the core, resulted in the use of part of a frozen core for these uppermost samples. The frozen core (BFS21) originated from the same site as core LP3M3, Fig. 4.1. This substitution ensured that the particle size results would accurately reflect the nature of the material which comprises the most recent sediments up to the S.W.I. Taking note of the position of the boundary between samples 4 and 5 from core LP3M3, material from the substitute frozen core was divided into 4 samples of equal depth, the base of the 4th sample corresponding to the same position, stratigraphically, as that of sample 4 from LP3M3. Initially, subsamples from each section of the core were dried and weighed. The material was then treated with 30 percent hydrogen peroxide for about 2 hours at 95°C in a water bath. This was generally sufficient to oxidise all the organic material. The samples were centrifuged and washed, dried at 105°C, then cooled and reweighed as a cross-check against the previous results of loss on ignition. Each subsample was then rewetted and washed through 0.125mm and 0.63mm aperture sieves. The silt and clay fraction (<0.063mm) was collected and dried. A subsample of known weight of this fraction was then used for the subsequent pipette analysis.

The procedure for the particle size analysis of the <0.063mm fraction was based on that outlined under Test 7(C) of BS1377 (B.S.I. 1975). To each subsample was added 50ml of Calgon, (50.0g sodium hexametaphosphate, 5.7g sodium carbonate in 1000ml water), to disperse the material, aided by the use of a mechanical stirrer. The total suspension was then placed into a suitable glass tube and made up to 500ml. The suspension is thoroughly mixed and then allowed to settle at a constant temperature (in this case 23°C). At predetermined intervals, subsamples of the suspension are taken from a depth of 10cm from the surface. These are then dried and weighed. The timing of the sampling is dependent on temperature, and can be calculated using Stokes' Law. Details of the sample timing for different temperatures are given by Tanner & Jackson (1947). The relevant sampling times at 23°C and their associated particle size fractions are given in Table 4.1.

The weight of sediment in each subsample was calculated and combined with the sieve data to produce the percentage of each size fraction in each sample. These results are given in Table 6.3 and are represented graphically in Fig. 6.8 and Figs. 6.9 to 6.37.

4.3 Diatom analysis

4.3.1 Adhesive tape peels.

In order to analyse for subfossil diatom and other algal remains from the lake sediments on a continuous and not a bulked subsample basis, adhesive tape peels were taken based on the method given by Simola (1977). This allows for the counting of microfossils at very close intervals (e.g. 200µm) through a sequence of sediments, without disturbing the composition or the fine structure of the material.

Peels were taken from a number of cores in order to examine, in great detail, the diatom flora from different sections of the sediment column. The most suitable type of core to use is

Table 4.1

Andreasen pipette sampling times and size fractions

Sampling times at 23°C and at 100mm depth

Size fraction (microns)	Time after start (hh:mm:ss)
<50.0	00:00:37
<20.0	00:04:28
<9.8	00:18:37
<5.6	01:10:00
<2.0	07:26:00

the in situ frozen sample but both 3m Mackereth and 'Russian' borer cores were also used once they had been frozen in the laboratory. This type of analysis was important in the establishment of a chronology and in the interpretation of the laminations present within the sediment column.

Cores were prepared by cleaning the face of frozen sample using a paint scraper and hair dryer. Once a clean flat face had been exposed, the sample was placed back in a domestic freezer at about -20°C to freeze dry. With the sample exposed to the air within the freezer, it took about 1-2 weeks for the surface of the material to dry. At this point, adhesive tape was pressed gently but firmly onto the surface of the sample and then carefully removed. The choice of adhesive tape is important. The type of tape sold as 'invisible' or 'magic' tape (e.g. Scotch 810 Magic Tape) is very uniform in thickness, has a very fine grained ahesive backing and is less obtrusive under the microscope than normal 'Sellotape'.

This process of taking a peel was usually repeated from the same area of the sample in order to ensure a surface which was free of material which might have been smeared during the initial cleaning procedure. The final peel was used for diatom counting. Careful note was made of the previous position of the peel in relation to the core stratigraphy so that diatom results could be related to known stratigraphic features. This was particularly important when considering the black and brown pairs of laminations in the lower half of core LP3M3.

The peels were then cut into 40mm lengths and each was mounted on a microscope slide with the adhesive and sediment side up, under a 20mm x 50mm glass coverslip. The mountant normally used was Naphrax (R.I. 1.74). Care had to be taken that the adhesive tape was not heated too fiercely or distortion and shrinkage could occur. After mounting, the length of the adhesive strip was measured to check for shrinkage.

Diatom counts were then made from consecutive 200µm fields of view down the length of the peel. The number of valves of each species observed in each field of view was noted and the most frequent species were then displayed graphically. A number of FORTRAN programs were written to generate the fairly complex diatom diagrams which display this ese data. An added advantage of using computer graphics is the flexibility of layout which this type of presentation facilitates. The diatom results are discussed in Chapter 7.

4.3.2 Relative and absolute diatom analysis

The techniques established for the preparation of sediment samples for relative and absolute diatom analysis are well discussed in the literature and are comprehensively summarised by Battarbee (1979).

4.3.2.1 Sample preparation

Preparation of samples for both absolute and relative counting was undertaken from one core, LP3M3, material from which was also used for the chemical and physical analyses detailed above.

The core had been divided into twenty eight 10cm sections, and each section was thoroughly homogenised to provide representative subsamples from each section. For diatom analysis, a modified plastic syringe was used to take a 1cm^3 subsample from each section. These were placed into preweighed 10ml glass beakers, weighed and dried at 105°C. The dry weight was recorded as a check against the basic physical data gathered previously from this core. Each subsample was then transferred to a 50ml plastic centrifuge tube and treated with approximately 20ml of cold 30 percent hydrogen peroxide. The samples were warmed until all the organic matter had been oxidised, indicated by a cessation of bubbling. No further treatment was deemed necessary and the residues were thoroughly washed and centrifuged using filtered, deionised water. Each sample was then transferred quantitatively to a 100ml volumetric flask.

Both absolute and relative data were obtained from the same samples, the technique adopted being that described by Battarbee (1973) and Battarbee & McCallan (1974). This procedure involves the use of an evaporation tray which provides an evenly distributed and quantifiable subsample of the diatom suspension on a number of coverslips. The statistical precision of the method is fully discussed by Battarbee & McCallan (1974).

In this case a slightly modified design of dish was used. The dishes were made of perspex, with a well of 110mm diameter and 10mm depth. Four evenly spaced coverslip wells of 22mm diameter and 0.17mm depth were inset into the floor of the tray. In addition, a 1.8mm hole was drilled through the base of the dish at the centre of each coverslip well. The purpose of these holes was to facilitate the removal of the coverslips from each well after evaporation had taken place. This was accomplished using a needle or similar tool, inserted from below. During operation the holes were blocked using a small quantity of silicone, or similar, grease. This served both to prevent the suspension from draining from the dish and also acted as a means of anchoring the coverslips in their wells, as otherwise the introduction of the diatom suspension into the dish can lift the coverslips from their correct locations.

If a large quantity (e.g. 50ml) of water is to be evaporated from the dish, the process can be considerably speeded up by the removal of excess water once the suspended material has settled. This can either be done, as suggested by Battarbee (1979), by pipetting off about 15ml of the supernatant liquid, or by incorporating a raised drainage hole, as was adopted in this case, in the centre of the dish.

A 3mm hole was drilled vertically through the centre of the dish, and a 50cm length of plastic tubing (3mm O.D., 1mm I.D) was glued in place using an epoxy adhesive. The top of the tube protruded approximately 0.5mm above the floor of the tray. After settling had taken place from the suspension, the excess water was allowed to drain under the influence of gravity from the dish. The process was initiated by using a syringe and needle to gently suck water into the tube. It was found that the water would then drip out slowly, without disturbance to the settled sediment. The suspension was checked for diatom remains.

In this analysis, a 5ml subsample of the 100ml suspension was pipetted into a 250ml volumetric flask and made up to volume. This was thoroughly mixed and whilst using a magnetic stirrer to maintain the material in suspension, a 50ml subsample was pipetted off and transferred to the evaporation dish. This dilution resulted in 1 percent of the original material being evaporated in the dish. The addition of a small amount of detergent to the dish assisted in reducing surface tension during evaporation. Each coverslip was then mounted in Naphrax.

4.3.2.2 Diatom counting

Generally, a mimimum of one complete traverse across the centre of each of four coverslips was performed for each level of the core. In some instances more traverses were required, particularly where exceptionally high sedimentation rates had diluted the total diatom influx. Generally, between 300 and 500 valves were counted from each level.

Counting was performed using a Zeiss microscope with x10 eyepieces and an oil immersion objective lens. Routine counting and photography was done using phase contrast. Microphotography was performed using a Zeiss MC-63 camera and control unit.

4.3.3 Electron microscopy

To assist in the identification of difficult diatom species, both transmission electron microscopy (T.E.M.) and scanning electron microscopy (S.E.M.) were used.

Preparation for T.E.M. involved the evaporation of a suspension of sediment on to coated copper grids appropriate to the machine in use. The transmission microscope used was a Philips EM300.

Preparation of samples for examination under the S.E.M. was similar. A suspension of material was evaporated onto brass or aluminium stubs, with the addition that these were then sputter coated with about 15 angstroms of gold. Two types of S.E.M. were used, a Jeol JSM35C and a Jeol T20.

4.3.4 Diatom identification and ecology

Identification was accomplished with reference to a number of different floras, the most frequently consulted being Cleve-Euler (1951-55), Patrick & Reimer (1966), Hustedt (1930) and Van der Werff & Huls (1958-66). A full list of the taxa found in the Loe Pool sediments is given in Appendix 1. Particular taxonomic problems were solved by reference to a number of more specific papers, fully discussed in Chapter 7. The ecological preferences, particularly in relation to pH, were derived largely from the same texts, with addition reference to works such as those of Lowe (1974). A synthesis of such information is given in Appendix 2.

4.3.5 TWINSPAN analysis of diatom peel counts

The numerical classification used was a two-way indicator species analysis (TWINSPAN) developed by Hill (1979). Analyses were run on the PR1ME computer system at Plymouth Polytechnic using versions of the programs adapted by Kent (1980). TWINSPAN is now generally recognised to be as good, if not better than, most other methods for numerical classification and provides a very efficient means of summarising variation in species sample data sets (Kershaw & Looney 1985). The analysis splits the samples into progressively more and more homologous groups, first into two, then four, then eight and so on. Individual samples resemble most closely those within the same group. In this analysis, either four or eight groups were used to define groups of counts made using the adhesive tape peel method. Thus counts which show similar diatom flora are grouped together. In this way it was hoped to distinguish, objectively, variations either in seasonal diatom deposition, or in the overall changes in the diatom flora over a number of years.

Chapter 5

Chronology and sediment stratigraphy

5.1 Location of cores

During the period of study, a large number of cores were taken from Loe Pool for a number of different analyses. The sites from which each core to which reference is made here was retrieved, are shown in Fig. 4.1. For the main chemical analyses and for magnetic and some radio-isotope studies, two types of piston corer were used, both based on the designs of Mackereth (1958, 1969). The resultant cores are referred to with the prefix of either LP3M for those taken using the 3m version, or LP1M for those from the 1m mini-corer. The fine stratigraphy, diatom work and 137-Cs analyses were performed on frozen samples (not 'cores' as such) taken using either an 'icy finger' sampler, denoted by the letters IF, or a box-type freezer sampler, prefixed by the letters BFS. Sequences of 50cm samples taken using the "Russian" type of peat borer (Jowsey, 1966), are prefixed by the letters RB.

5.2 General stratigraphy

Many sediment samples have been taken from the lake and all exhibit a common and distinct zonation of sediment types. A generalised stratigraphy can be outlined which reflects the overall structure of the sediments from Loe Pool.

Zone A:

Approx. 0-30cm depth. Unconsolidated, brown, intermittently laminated, highly bioturbed sediment.

Zone B:

Approx. 30-140cm depth. Finely laminated sediments with limited bioturbation. Colour varies enormously from pink to greys, browns and black. Well compacted and apart from the upper and lower bounding haematite-rich layers, very low in clay content.

Zone C:

Deeper than approx. 140cm. Fairly regularly laminated black and brown or black and grey sequences of sediments. Well compacted with no bioturbation.

The sediments are laminated to some degree throughout the sediment column. To facilitate cross correlation of cores and to establish exact points through the sequences of laminations, the most prominent individual or groups of laminations have been numbered. Each one to be thus labelled is prefixed with the letter of the zone within which it lies, followed by its identifying number. Numbers increase with depth, but the numeration is not directly related to actual depth. The numbering of the laminae is by necessity fairly generalised, as the majority of the laminations can be subdivided into numerous microlaminae. This reflects not only the complexity of the sediment structure, but also the quality of the material retrieved using the in situ freezing devices. These are capable of preserving even the finest of structures.

5.3 Establishment of a chronology

Initial investigations were directed toward a preliminary dating of the sediments, in order to establish the rate of sediment deposition within Loe Pool. Without this, the time scale over which any ecological changes had taken place could not be gauged.

5.3.1 Initial palaeomagnetic analyses

A 3m Mackereth core (LP3M1) taken in 1978 was analysed by Dr. Roy Thompson at Edinburgh University for the horizontal component of natural remnant magnetisation. The results were inconclusive, with the declination drifting slowly towards the west with increasing depth. There was no sign of the expected westerly maximum which, according to the standard reference curves (Thompson & Turner 1979), occured in 1820.

This suggested that the upper 3m of sediment postdated 1820, and implied a relatively high rate of sedimentation. No further palaeomagnetic dating was performed, although analysis of magnetic susceptibility was performed on a number of cores. The results of these analyses proved useful in the initial correlation of cores.

5.3.2 Core correlation

Cores LP3M2 and LP1M2 were used for this purpose, and the susceptibility results are shown in Fig. 5.1 & 5.2. The strong peaks of susceptibility correspond to the very prominent bands of pink clays which are also visible in a further 3m Mackereth core, LP3M3, shown in Plate 5.1. These layers were used as markers to correlate cores before a more detailed stratigraphy was constructed. In all the 1m Mackereth cores taken from the lake, the upper of these pink bands was clearly visible through the perspex core tubes, Plate 4.1.

5.3.3 Initial chronology from historical data

Concurrent research into past events within the catchment, in particular those occuring close to the lake, revealed a number of events which might have significantly affected the supply of sediment to the lake in recent years and resulted in the deposition of the uppermost pink clay bands. As we had little idea at this stage of the date of deposition of this band of sediment, emphasis was placed on events within the past two or three decades.

Two possible events were identified. The first was the canalisation of the River Cober in 1946-1947. This involved the straightening of the original sinuous course of the river already described in Chapter 2. It would have involved the disturbance of considerable quantities of sediment in this section of the river's course and might have increased the sedimentation rate within the lake to a figure over and above the 'normal' rate of deposition.

The second possibility was the construction of a road cutting (N.G.R. SW653277) some 2km north of the lake. This formed part of a programme of improvements to the A394 Helston to Penzance road just to the west of Helston. All the material removed from the deep cutting was dumped on an area of the valley floor to the south of Zachary's Bridge (N.G.R. SW652268), next to the River Cober. The work took place between 1968 and 1969. A very large quantity of material was deposited and may have provided an additional influx of sediment to the River Cober.

It was thought initially that one of these two events might have resulted in the appearence of the thick band of sediment below the upper brown gyttja which obviously had a much higher mineral content than the sediments above.

5.3.4 137-Cs analysis

Two of the earliest frozen cores retrieved in late 1979 from the Pool using a box-type freezer sampler (Huttunen & Meriläinen 1978), revealed the true complexity and degree of preservation of laminations present in the brown gyttja. Core FBS7 (Plate 5.2) contained the upper 42cm of sediment and included the sediment water interface (SWI). Core FBS9 (Plate 5.3) recovered sediments from a depth of 20cm to 72cm. The two cores, taken very close together, were correlated using the uppermost extent of the red clay band and smaller black laminae within the clay.

From these it was evident that what had previously been thought to be an amorphous brown gyttja actually contained black and brown laminations. The laminae were somewhat unclear and were in places mixed by bioturbation. However, laminations were visible and so a tentative division of the cores was made into what appeared, visually, pairs of black and brown laminations. These were assumed to be annual in nature. This resulted in the chronology outlined in Figs. 5.3 and 5.4, which relate directly to Plates 5.2 and 5.3. It was decided to use these two cores for 137-Cs analysis and to test the hypothesis that one of the events already described had resulted in the deposition of the clay band occuring at about 35-40cm depth. The visual dating in Figs. 5.3 and 5.4 suggest that the road cutting would have occured at about the right time, although the canalisation was more likely to have resulted in the type of sediment which comprised the clay band.

If the visual chronology based on the counting of pairs of laminations was correct, then the 137-Cs peak associated with the maximum deposition of the isotope in 1963, should be found at a depth of about 43.0cm to 52.0cm. If incorrect, some sort of chronology would at least be obtained.

The two frozen cores were divided vertically into two halves, one for radioisotope dating and the other to be retained for basic physical analyses. The half destined for dating was then divided into sections, the subdivisions being as in Figs. 5.3 and 5.4. Each hypothetically annual segment was then dried at 105°C.

Analysis was limited to 25 samples, and it was decided to include the deepest subsample ("1955/1956", 39.5-42.0cm) in preference to the uppermost ("1979", 0.0-6.5cm). In retrospect this was an unwise decision.

The samples were taken to A.E.R.E. Harwell, where the analyses were performed by Dr. R.S. Cambray. In the event, two additional samples were analysed, making 27 in total, and included three (Nos. 14, 15 and 16) which represented the overlap of Core FBS9 over FBS7.

The results of these analyses are shown in Table 5.1 and Fig. 5.5, and clearly show the misjudgement of the initial subdivision. The peak of 137-Cs in fact occurs at a depth of

Table 5.1

Cs-137 results obtained by Dr. R. S. Cambray, A.E.R.E, Harwell, from cores FBS7 and FBS9. Figures are expressed as pCi/section. Each section consisted of approximately 5g of dried sediment.

Sample No.	Estimated date	Cs-137	
		Core FBS7	Core FBS9
1	"1978-79"	24.0	
2	"1977-78"	32.5	
3	"1976-77"	13.8	
4	"1975-76"	8.9	
5	"1974-75"	<3	
6	"1973-74"	<3	
7	"1972-73"	<3	
8	"1971-72"	<3	
9	"1970-71"	~5	
10	"1969-70"	<3	
11	"1968-69"	<3	
12	"1967-68"	~5	
13	"1966-67"	<3	
14	"1968-69"		<3
15	"1967-68"		<3
16	"1966-67"		<3
17	"1965-66"		<3
18	"1964-65"		<3
19	"1963-64"		<3
20	"1962-63"		~5
21	"1961-62"		<3
22	"1960-61"		~6
23	"1959-60"		~5
24	"1958-59"		<3
25	"1957-58"		~5
26	"1956-57"		<3
27	"1955-56"		<3

"There is no significant Cs-137 below the "75-76" section. Anything from 5pCi or less is too near the limit of detection to be relied upon. Only the top 4 sections contain significant Cs-137." (R.S. Cambray, letter to P.E.O'S dated 12.10.79) between 12.0 and 15.5cm. The 137-Cs results for this upper section of the core are more exactly plotted in Fig. 5.6. In both of these diagrams, the levels of Cs-137 below that labelled "1975-76" are not significant, being too close to the detection limits to be relied upon (letter from R.S. Cambray, A.E.R.E, Harwell, 12.10.79).

The resultant division of sediment chronology negated the original supposition that deposition had been occuring at a mean rate of about 3.0cm/yr (72.0cm between 1979 and 1955, 24 years). If the peak of 137-Cs deposition occured at about 14.0cm, then sedimentation would be closer to 0.8cm/yr. It follows that the pink clay band would date from the late 1930's or early 1940's.

Research into the history of mining in the area had at the same time revealed that the last mine to operate within the catchment had ceased production in 1938/39. The mine in question was the Porkellis Tin Mine (previously known as Basset & Grylls and then Jantar), and one of the lodes to be worked in this final period of mining was Old Mens' Lode or Red Lode as it was also known (Jenkin 1978). This was a lode where the tin was in a haematite-rich matrix, the waste from which had frequently been known to discolour the River Cober. No reference has been found to indicate any alternative source for this type of material.

Both the 137-Cs and historical evidence thus eventually pointed toward the origins and period of deposition of the thick pink band of sediment, and the topmost occurence of this band was therefore taken to represent material deposited in 1938, or at the latest 1939.

The chronology of the upper sediments was thus established with some degree of certainty. The variability of the lower sediments, however, suggested that the rates of deposition calculated for the brown gyttja would not necessarily be applicable to either the irregularly laminated sediments between the two major pink clay bands (Zone B), nor the more regularly structured sediments below that (Zone C). Efforts to date these sediments were thus directed towards a more detailed appraisal of the laminations themselves, and the significance of the complex patterns of laminae found throughout Zones B and C. Combining this with all available historical information was the only appropriate approach to the problem of chronology.

5.3 Detailed sediment stratigraphy

5.3.1 Zone A

Some of the first cores taken from Loe Pool were retrieved using a 1m Mackereth mini-corer. This equipment employs 1m-long clear perspex sample tubes which allow for some visual assessment of the material contained within. Always clearly visible were the pink clay bands from about 40cm depth. The structure of the upper brown gyttja was never visible and only a hint of any laminated structure was given by some mottling in the colour of this material upon extrusion. With the introduction of the box freezer sampler however, the true nature of the uppermost sediments was revealed.

As can be seen in Plate 5.4 (Core FBS3), Plate 5.2 (Core FBS7) and Plate 5.5 (Core FBS12), the uppermost gyttja is far from structureless. The apparently uniform brown sediments retreived by using the Mackereth mini-corer proved, when sampled <u>in situ</u>, to be well structured and to contain bands of darker sediment. These are discussed at greater length in Chapter 6.

In the large number of frozen samples taken from various parts of the lake, the structure was not always found to be preserved. Preservation appeared to be dependent on the degree of disturbance of the structure by bioturbation. Plate 5.4 (Core FBS3) clearly shows the mixing effect associated with bioturbation and the laminae are only apparent between the patches of bioturbed sediment.

However, it is evident that over large areas of the lake bed, any laminae which may form initially are eventually completely destroyed by zoobenthic activity. In only a small percentage of the frozen samples to include the sediment water interface were the structures still present to any degree. Evidence of bioturbation was never completely absent and because of this and the often hazy gradation between light and dark laminations, correlation of cores using these bands was never reliable.

The mechanisms which may have led to the formation of this banding in Zone A and the information gained from diatom analysis are discussed fully in the following chapter.

5.3.2 Zone B

As with Zone A, the nature and complexity of the laminations were not fully appreciated until in situ frozen material was recovered. Two 3m Mackereth cores, LP3M3 (Plate 5.1) and LP3M4 (Plate 5.6), taken early in the project, had been prepared as described in section 4.2.1.1 by freezing in the laboratory before sub-sampling or photography. These two cores showed, for the first time, the structure of Zone B and the upper 1.5m of Zone C. The freezing process, however, caused the formation of large ice crystals within the sediments, masking some of the finer detail, particularly in Zone B. The major laminae were nevertheless visible and using Zone B, cross-correlation was possible between the two cores.

Zone B is bounded at the top by a finely structured band of black sediment (B001), above a series of pink clay bands best preserved by an 'icy-finger' core, IF2, Plate 5.7, and in sample FBS9, Plate 5.3. In core LM3M3, Plate 5.1, these appear as three pink bands at a depth of 38.7cm to 41.1cm, 42.4cm to 45.3cm and 48.2cm to 52.5cm respectively. In Core IF2 the upper of the pink bands (B002/B003) is heavily bioturbed, but the middle band is very well preserved and includes three distinct black laminae (B006, B008 and B010) visible in almost all of the other frozen samples taken.

Below this series of laminations is a complex sequence of slightly coarser brown sediments interspersed with a number of distinctive black layers. These can be easily cross-correlated with similar sequences in other cores, including LP3M3 and LP3M4. The thickness of these brown sequences varies considerably from core to core but, as might be expected, it increases greatly with proximity to the mouth of the River Cober.

There appears to be a gradient of bioturbation activity from the bottom of Zone B up into Zone A. At the base of Zone B there are a few laminations which contain evidence of zoobenthic activity. In core IF6, Plate 5.9, the burrows can be seen as small specs of black in some of the lighter bands such as B087, B049, B038 and particularly in B034. Core FBS14 (Plate 5.8) also shows this very clearly in layer B034. Above layer B036, the nature of the bioturbation changes. The bioturbation is of a greater magnitude with much larger burrows visible, particularly in the layers above B027 in core FBS9 (Plate 5.3). The burrows take the form of a central core of mixed sediment some 5-6mm in diameter surrounded by a 'corona' of largely unmixed sediment of approximately 13-14mm diameter. The 'corona' differs only by a slight variation in colour from the surrounding sediment. This may be a result of chemical rather than physical alteration. The frequency of these burrows increases rapidly until by layer B005, bioturbation begins to mask the original structure of the sediment to a very large degree.

Estimates of the rate of sedimentation in Zone B proved to be very difficult, with no regular sequences of sediments to suggest seasonality of deposition. However, between B033 and B048 (e.g. Plate 5.8, Core FBS14), layers were of such a regular and undisturbed appearance as to suggest very rapid deposition. A slowing down of the rate from B033 upward might explain the recurrence of bioturbation seen in layer B034 where it would appear that material from B033 has been incorporated in the burrows present in the lower layer.

No satisfactory estimate of the rate of deposition was available until diatom analysis by Simola (unpublished data) suggested the existence of seven annual sequences of diatoms from layer B003, (Core FBS14, Plate 5.8), through to layer B080 which can be seen in Core IF6, Plate 5.9. This gives a mean deposition rate of 10cm/yr for this section of the sediment column. The author's own interpretation of this sequence of sediments, taking into account both the diatom analyses performed by Simola and contemporary reports of the mining activities within the catchment would however suggest a total of 11 years, 1928-1938 inclusive for this part of Zone B. The lower pink clay bands from B088 to B071 would then represent the years 1928 and 1929 when Jantar mine was operational. Above this is a section of very high deposition which would be contemporary with newspaper reports of very high sediment loads in the River Cober in 1930 (West Briton, 3rd April 1930, p.9, col.6). If so, then the last period of production of Basset & Grylls mine in 1938 prior to closure in 1939 would have produced the upper pink clay bands bounded at their upper limit by layer B003.

Layers B088 to B086 may also represent the end product of a period of high sediment load over which Captain J.P. Rogers, the then owner of Loe Pool, brought legal action against the owners of Jantar mine. This followed heavy pollution of the lake by mine wastes. The use of diatom analyses in the dating of this zone are more fully discussed in the following chapter.

Working on the hypothesis that the top of Zone B is the boundary between 1938 and 1939 and the base of this section is the boundary between 1927 and 1928, then the rate of deposition over 11 years for 106cm (in core LP3M3) averages 9.6cm/yr. This figure is obviously a mean rate and varies considerably within the zone.

5.3.3 Zone C

This zone differs markedly from the two above, being composed almost entirely of sequences of alternating black and grey or pinkish grey laminae. The couplets are frequently fragmented by thin bands of contrasting sediments.

In core LP3M3, Plate 5.1, this zone can be seen below 143cm depth. From 143cm to 220cm, the black/pinkish grey laminae dominate, whilst below 220cm the layers are more frequently black and varying shades of grey in a less ordered sequence.

Correlation with core LP3M4 is relatively simple in the upper sections of Zone c but below about 200cm in core LP3M3, cross correlation becomes impossible by visual means owing to the increasing complexity and intricacy of the laminae.

It should be noted that the laminae of Zone C, as depicted in Plates 5.1 and 5.6 of cores LP3M3 and LP3M4 are no longer in their original reduced state. When fresh, the laminae are very much darker in colour and in places can appear almost uniformly black. Exposure to the air oxidises the surface very quickly, resulting in the colours represented in Plates 5.1 and 5.6. This is also true of all the deeper frozen samples.

Few of the 'icy finger' or box sampler devices penetrated below about 1.0 to 1.5m depth where Zone C can normally be found and so samples frozen _in situ_ from the required depth were rarely retrieved. Core IF6 does include the top of Zone C and shows (Plate 5.9) the complexity of micro-laminations contained within the major bands, which are themselves distinguished by relatively abrupt changes in colour.

Bioturbation is no longer evident at this depth and the laminations are very well preserved. Some clarity of sediment structure was lost in core LP3M3, owing to the formation of ice crystals during the process of freezing in the laboratory. The compensation is that the sediment, in its solid form, is much easier to clean, photograph and handle than in the unfrozen state.

With no recourse, for the reasons already discussed, to radioisotope or magnetic dating methods lamination counts were used to date the material instead. This is based on the premise that pairs of black/grey or pinkish grey laminae represent annual units of sediment deposition. The basis for this assumption is discussed at length in the following chapter. This analysis undoubtedly suffered from a degree of subjectivity as the annual sequences are not always clearcut but it was the only appropriate dating technique.

By counting what may now be referred to as varves in Zone C of core LP3M3, a period of some 53 years appears to be represented by 137cm of sediment. This yields a mean figure of 2.6cm/yr (c.f. O'Sullivan <u>et al</u>. 1984) as the rate of sediment deposition. Applying this to the previous estimates of chronology for Zones A and B, at a depth of 2.8m in Zone C the sediment would appear to date from 1875.

These figures are a refinement of the the findings published by Simola <u>et al</u>., (1981), resulting from a more structured appraisal of the historical data.

5.4 Technical problems

Two serious storage freezer breakdowns occurred during the period of study. These resulted in the loss of a large number of frozen cores. The most vulnerable aspect of the storage of frozen sediment samples is the danger of melting and all the cores to which mention has been made in this chapter were lost as a result of these breakdowns. Once melted, the sediment samples are irretrievable. Fortunately, a number of cores had undergone the initial preparation and photography before this occurence. However, no physical analyses (e.g. loss on ignition) were performed on cores FBS7 and FBS9 between subsampling for 137-Cs analysis and their subsequent loss.

Cores LP3M3 and LP3M4 were also deformed to such an extent by melting that they were of no use for further analyses, although core LP3M3 had already been subsampled for chemical, diatom and particle size analyses.

Chapter 6

Physical and chemical results

6.1 Introduction

The data presented in this chapter are largely the result of work on one core, LP3M3, Plate 5.1, taken at the location shown in Fig. 4.1. This particular core was selected because it was the most representative of all the deeper cores taken from the lake and appeared to cover the maximum period of deposition of any of the 3m cores. The results of diatom analyses carried out on the same core are given in Chapter 7.

In line with the terminology adopted in the previous chapter, the uppermost 3m of the sediment column have been subdivided into three distinct zones, A to C. In core LP3M3, when subdivision for all the analyses was into 10cm sections, Zone A comprises samples 1-4 (0-40cm) with transition to Zone B occuring at the base of sample 4. Zone B continues down from sample 5 to sample 14 (50-140cm) with the lowermost boundary of Zone B included in sample 15 (140-150cm). Zone C thus constitutes the majority of samples, from number 15 down to sample 28 (i.e. 140-280cm).

As can be seen in Plate 5.1, the material which comprises

Zone A has slumped in the core tube. This has resulted from the semi-liquid nature of the most recent sediments and horizontal transportation from the sampling site. This has undoubtedly led to inaccuracy, as some mixing of the sediment will have occurred prior to subsampling.

Where applicable, results of the physical and chemical analyses have been expressed not only on the basis of concentration, in units per gram of dry sediment, Figs. 6.1 to 6.4, but also in terms of influx, expressed as units per cm^2 per year, Figs. 6.5 to 6.7.

Such a division in the presentation of results forms the basis for a distinction between the quality and the quantity of material being examined.

Essentially, results expressed in terms of concentration are a reflection of relative amounts of material present. They express the proportion that each element or compound contributes to the overall composition of the dry sediment. Variation in the level of one component influences the concentration profiles of all others (Engstrom & Wright (1984). Such covariation can lead to problems in interpretation. In addition, concentration values give no insight into the quantities of sediment being deposited and make no reference to changing rates of sedimentation.

In contrast, once the basic data is expressed with respect to time, it can be interpreted in terms of influx or the quantity of material being deposited per unit area over a given period of time. However, as Engstrom & Wright (1984) note, accumulation calculations are highly dependent on reliable dating and even small errors in the precision of a chronology may produce quite large changes in influx values.

This dichotomy in the representation of data can lead to apparent contradictions between the two sets of results. An example is the variation shown in the results from Zone B, core LP3M3, (Figs. 6.1-6.7). The dry weight concentrations of some elements (e.g. K and Fe) decline, whereas the corresponding influx values show a considerable increase.

Interpretation of results can depict quite different changes taking place in the lake and catchment. The concentration or dry weight results record changes in the relative composition of the sediment. These events can reflect variation in the source of material entering the system. Changes in the influx or absolute amounts of the various components of the sediment represent variations in the intensity of the processes which supply materials to the system. They are an indication of the overall quantities of materials being transported or synthesised, and deposited, within the system. Such expression can therefore shed light on processes such as eutrophication (Battarbee 1979), where the rate of nutrient cycling may be increasing, or erosion, where rates of removal and transport of suspended sediment may vary. In this context, mining, which has had such a significant impact on the Loe Pool catchment as a whole, may essentially be seen as an acceleration of the natural processes of transfer of material from catchment to lake, and may be very specific to localised areas within the catchment. As a consequence, it can result in major changes, both to the rate of supply of material to the sediments and to the relative composition of those sediments.

At this juncture, two points relating to the subsequent interpretation of influx results from Loe Pool should be noted. The first is the representativness of results from a single core. Although a large number of cores have been retrieved from the lake, analysis of chemical influx has been limited to a single one. Comparison of data from multiple cores might have enhanced the reliance that could be placed on such results, but this practise is a recent innovation and is not without its problems. As Engstrom & Wright (1984) point out, sediment accumulation, within any lake, proceeds in a shifting and complex manner. Changes in sedimentation rate vary both spatially and temporally, and the average influx of materials to the lake cannot be accurately reconstructed even from several coring sites. Secondly, the calculation of influx depends largely on an accurate chronology of the sediments. The range of deposition rates associated with the material which comprises core LP3M3 means that small changes to the chronology of some sections can lead to considerable variations in the resultant influx levels, which in turn would lead to changes in interpretation.

The dating outlined in the previous chapter was applied to core LP3M3 and the period of deposition covered by every 10cm section was derived from the combination of dating techniques adopted. Many factors were considered in the development of this chronology, including the interpretation, by the author, of a continuous diatom count performed by Simola (unpublished data) on a section of the sediment column between the upper and lower pink clay bands of cores FBS14 and IF6. The resultant rates of deposition in years per 10cm section of sediment are given in Table 6.1.

In the calculation of influx results for core LP3M3, compensation has been made for the disturbance of the uppermost sediment (see Plate 5.1). Although this section was originally sampled by division into four 10cm lengths, comparison with later, frozen samples from the same locality indicate that there is about 25cm of material above the top of the upper pink clay, used to delimit Zone B. The depth occupied by these four samples was therefore scaled down proportionately in order to more accurately assess the true rate of influx.

6.1.1 Density and water content (see Fig. 6.1)

Any inaccuracy in the measurement of these variables, particularly in Zone A, will affect the conversion of all results into influx figures. With only four 10cm subsamples representing Zone A, trends may be difficult to assess. The water content of these subsamples from Zone A do not record

Core LP3M3: chronology adopted for each 10cm subsample

Segment	Depth (cm)	Years
1	0-10	1970-79
2	10-20	1960-70
3	20-30	1951-60
4	30-40	1938-51
5	40-50	1936-38
6	50-60	1934-36
7	60-70	1932-34
8	70-80	1931-32
9	80-90	1930-31
10	90-100	1930
11	100-110	1929-30
12	110-120	1929
13	120-130	1928-29
14	130-140	1928
15	140-150	1925-28
16	150-160	1921-25
17	160-170	1917-21
18	170-180	1913-17
19	180-190	1909-13
20	190-200	1905-09
21	200-210	1901-05
22	210-220	1898-1901
23	220-230	1894-98
24	230-240	1890-94
25	240-250	1886-90
26	250-260	1882-86
27	260-270	1878-82
28	270-280	1875-78

any increase towards the surface as might be expected, a fact which reinforces the belief that some mixing has occurred.

The density of sediments from Zone A lies between 1.1 and 1.2, as compared with the maximum of 1.7 in Zone B. In Zone C, the density is fairly consistent, averaging around 1.36. Water content shows a similar pattern, with Zone A, the most recent and least compacted sediment, possessing a value of between 80 and 87 percent. This falls to a minimum of 37.6 percent in Zone B, and ranges between 52 and 60 percent in Zone C.

The low density and high water content of Zone A is a reflection of the unconsolidated nature of the material, which differs markedly in character from the sediments below. In Zone B, the high rate of deposition and the dramatic change in sediment type result in a very dense and compact material. The pre-1928 sediments of Zone C are comparatively consistent in nature and so both density and water content vary only slightly.

6.1.2 Minerogenic material (Fig. 6.5)

In some lakes, sedimentary mineral matter may be both allochthonous and autochthonous in its origin. In Loe Pool, however, the overwhelming proportion of minerogenic material in the sediment originates from the catchment (Pickering, Ph.D. thesis, Plymouth Polytechnic, 1987), carried in as suspended sediment by the River Cober and the other contributory streams. This is true even of Zone A. As such, Loe Pool sediments constitute a record of the changes in the rate of transfer of material from catchment to the lake. Some of the materials deposited may originate from reworked or eroded material from the shore, but this is likely to be only a very small percentage of the total. In Loe Pool, the only autochthonous mineral component results from deposition of diatom frustules and a few other siliceous remains from other organisms. No attempt was made in the study to quantify this autochthonous component.

The results show a fairly constant influx of between 1.3 and 2.0g/cm^2/yr in Zone C. In Zone B there is an increase to a maximum of 26.3g/cm^2/yr, and a subsequent fall above 90cm depth to a much lower figure of around 0.1g/cm^2/yr in Zone A. The substantial change associated with Zone B is due to a high influx of allochthonous material. This increase in the influx of some elements has the the effect of diluting the relative composition of other allochthonous species as well as the autochthonous component of the sediment. Changes in the natural rates of removal and transport of catchment materials are insufficient to explain these differences and the supply of copious quantities of mine wastes must constitute the major source of additional suspended sediment.

6.1.3 Loss on ignition (Figs. 6.1 & 6.5)

As already discussed in Section 4.2.2.3, ignition loss (I.L.) can, with reservations, be equated with the organic content of the sediments. Such matter can be both allochthonous or autochthonous in origin.

In terms of both influx and dry weight concentration, the levels of material lost on ignition remain relatively constant throughout Zone C. In Zone B there is a fall in the levels of I.L. (Fig. 6.1), i.e. the concentration of organic material declines. There is, however, an increase in the <u>influx</u> of organic material in this zone (Fig. 6.5). Toward the top of Zone B, influx of organic material decreases sharply, reaching a fairly constant, but much lower value in Zone A. The dry weight concentration of organic matter, represented by I.L., increases in Zone A to levels above those found in Zone C. Of the three zones, Zone A contains the highest proportion of organic material, and Zone B the lowest. It is difficult to separate the allochthonous and autochthonous organic contributions to the sediment, but it would seem likely, particularly in light of the diatom results discussed in Chapter 7, that the rise in influx of organic material in Zone B is due largely to an increase in the allochthonous component, and not through any change in lake productivity.

6.1.4 Kjeldhal nitrogen (Figs. 6.1 & 6.5)

The dry weight values of nitrogen (Fig 6.1) are strongly correlated with loss on ignition (correlation coefficient (r) of 0.7853, Table 6.2), and nitrogen influx (Fig 6.5) also follows the general trend of minerogenic influx, with the exception of some higher values in the upper half of Zone B. When expressed in terms of sediment dry weight (Fig. 6.1), it can be seen that nitrogen represents a higher proportion of total sediment weight in Zone A than in Zone C, with the lowest values found in Zone B. <u>Influx</u> of nitrogen would appear to have been <u>higher</u> prior to the 1920's than in the last few decades, but Zone B displays by far the largest figures.

6.1.5 Ignition loss : Nitrogen ratio (see Fig. 6.1)

The sediments of Zones B and C very largely possess a C/N ratio of less than 10, but the ratio rises considerably .in Zone A.

6.1.6 Phosphorus (Figs. 6.1 & 6.5)

In terms of <u>dry weight</u> (Fig. 6.1), phosphorus levels remain fairly constant in Zone C, rise gradually in Zone B and peak at considerably higher values in Zone A.

The <u>influx</u> of phosphorus (Fig. 6.5) remains fairly steady from 1875 to 1928 (Zone C). It rises markedly in Zone B and but in Zone A it falls back to levels below those in either Zones C or B.

Phosphorus <u>influx</u> thus falls towards the sediment surface, but at present, phosphorus constitutes a higher <u>proportion</u> of the sediment being deposited.

6.1.7 Nitrogen : Phosphorus ratio (see Fig. 6.1)

A number of workers have used the ratio of N : P as an indicator of nutrient status (e.g. Digerfeldt 1975, Bengtsson & Persson 1978). A lowering of the ratio indicates increased trophic status. Results from these sediments (Fig. 6.1) show that the ratio fluctuates throughout the core and other than a decrease in Zone B, no overall trend can be distinguished.

6.1.8 Sedimentary plant pigments (Figs. 6.2 & 6.5)

In this analysis, chlorophyll derivatives and total carotenoids were extracted separately and levels of these pigments in Loe Pool vary considerably.

Chlorophyll derivatives, expressed as pigment units (P.U.) per gram organic matter (Fig. 6.2), show no obvious trend. In Zone C, the highest values occur at the base of the core. A decline to a general level of around 5.0 P.U. in Zone B, is followed by an increase to a maximum of about 18.0 in Zone A.

Influx results for chlorophyll derivatives (Fig. 6.5) are more variable, with the lowest values of between 1 and 2 P.U. cm^{-2} yr^{-1}. There is an increase in Zone B with values varying considerably and with no discernible change in pattern in Zone A.

Carotenoids show a very similar pattern in both dry weight (Fig. 6.2) and influx terms (Fig. 6.5).

6.1.9 Chlorophyll : Carotenoid ratio (Fig. 6.2)

This ratio been been used to indicate changes in the relative contributions of allochthonous and autochthonous organic matter and changing oxygen conditions at the mud water interface (see Section 1.4.2.4). The results from Core LP3M3 show no particular pattern except for a slight increase in the ratio in Zone B.

6.1.10 Phosphorus : Chlorophyll ratio (Fig. 6.2)

From a minimum at the base of Zone C, the ratio increases to a level of around 0.4 for the rest of this zone. In Zone B the ratio rises to a maximum of 1.1 between 100 and 90cm, with a second but smaller peak in Zone A.

6.1.11 Sodium, potassium, magnesium, calcium (Figs.6.3 & 6.6)

In relative terms, sodium, potassium and magnesium all show a similar pattern (Fig. 6.3). There is a gradual decline in values from the base of Zone C, with a sharp decrease in Zone B where the minimum values are to be found. In the results for sodium and magnesium, there is then a rise to levels below those found in Zone C, towards the surface. For potassium there is a peak at the top of Zone B, followed by a reduction in values in Zone A. There is a much clearer trend in the results for calcium, with an overall decline from the base of the core to the sediment surface.

Influx results (Fig. 6.6) are very similar for all four elements. Levels for Zone C are relatively uniform, but there is generally a four-fold increase in Zone B. The influx of all of these elements then tails off at the top of Zone B to settle at steadier, but much lower values, in Zone A.

6.1.12 Sodium : Potassium ratio (Fig. 6.3)

There is a distinct trend in the Na/K results from this core. The ratio declines slowly from the base of the core to the middle of Zone B, after which it rises with proximity to the sediment surface.

6.1.13 Iron and manganese (Figs. 6.3 & 6.6)

The results for these two elements, expressed in terms of dry weight of sediment differ markedly (Fig. 6.3). Iron is more variable, decreasing from an early maximum at the base of Zone C to a lower but relatively steady level in the upper part of this zone and the lower part of Zone B. Between 110 and 60cm the values reach their minimum, but increase again in Zone A.

Manganese shows a more regular pattern, displaying a fairly steady increase from the base of the core to the top of Zone B. In Zone A there is considerable variation but an overall decrease in manganese levels

The influx values are again dominated by the very high sediment deposition rates of Zone B (Fig. 6.6). In Zones A and C, the levels of both elements are relatively uniform with the lowest figures in Zone A. However, the two elements do show slightly different patterns in Zone B. Iron influx increases rapidly at the base of Zone B and then tails off above 90cm. Manganese reaches a maximum between 100 and 80cm, somewhat later than iron.

6.1.14 Iron : Manganese ratio (Fig. 6.3)

This ratio has been suggested as an indicator of redox conditions (see Section 1.4.2.3), and there is certainly a trend in the results from this core. The ratio declines from just above the base of the core to a minimum at the top of Zone B. There is then a slight increase to a fairly steady level in Zone A.

6.1.15 Metals (Figs. 6.4 & 6.7)

In terms of the relative concentration of the various metals extracted, some trends are apparent (Fig. 6.4).

Results for copper are given for both the acid extraction and x-ray fluorescence techniques. The two sets of results correlate closely (r = 0.5506, Table 6.2), although it must be noted that the two methods of measurement are quite dissimilar and results differ by an order of magnitude.

Expressed in terms of dry weight (Fig. 6.4), copper shows a

Figures represent Spearman's Rank Correlation Coefficients. Those without brackets are significant at the 99% confidence limit; those within brackets are significant at the 95% confidence limit. Where no value is given, the correlation was not significant.

	WD	DW	PW	IL	NN	PP	CH	CT	NA	KK	CA	MG	FE	MN	CU	CX	ZN	SX	PB	AL	CR
NA																					
WD																					
DW	0.9792																				
PW	-0.9825	-0.9989																			
IL	-0.7888	-0.7768	0.7885																		
NN	-0.9304	-0.9189	0.9217	0.7853																	
PP	(-0.4160)	(-0.4277)	(0.4310)		(0.3814)																
CH		-0.6546	0.6640	0.4746	0.6814	0.5027															
CT	-0.6789	-0.7799	0.7316	0.6112	0.7745		0.7471														
NA	-0.7827	-0.6207	0.6206	0.6128	0.6667		(0.3552)	-0.9295													
KK	-0.6382	-0.4592	0.4559	(0.3315)	(0.3503)			-0.5116	0.4701												
CA	-0.4767					-0.6718	-0.9989		(0.3683)												
MG	(-0.4033)	(-0.3310)	(0.3346)	0.4792	(0.4087)	(-0.4259)	0.7885	0.7471	0.6774	(0.4194)	0.7220										
FE	-0.5818	-0.5534	0.5577	(0.3239)	0.5977		-0.9295	-0.4768		(0.3328)		(0.3622)									
MN						0.8100	-0.5166	(0.3552)			-0.7673	-0.5787									
CU						0.5065		0.9792			(-0.4022)	(-0.4221)		0.7274							
CX						(0.3639)	0.7471	-0.9989				(-0.3255)		(0.3908)	0.5506						
ZN						0.5725					-0.4948	(-0.4396)		0.7542	0.7449	0.5391					
SX	0.7657	0.7312	-0.7274	-0.6093	-0.6863	(-0.3292)	(0.3552)	-0.7006	(-0.3913)	(-0.3339)			(-0.3541)	(-0.3393)							
PB																					
AL				(0.4005)		-0.6308	0.9792		0.4745	0.6825	0.5654	0.7910		-0.5687			(-0.3746)		(0.4368)		
CR	-0.7827	-0.7799	0.7316	0.6112	0.7745		-0.9989					(0.3786)	0.6841					-0.7006			

WD	Wet Density	CT	Carotenoids	CU	Copper
DW	Dry Weight	NA	Sodium	CX	Copper (XRF)
PW	Percentage Water	KK	Potassium	ZN	Zinc
IL	Ignition Loss	CA	Calcium	SX	Tin (XRF)
NN	Kjeldjal Nitrogen	MG	Magnesium	PB	Lead
PP	Phosphorus	FE	Iron	AL	Aluminium
CH	Chlorophyll Derivatives	MN	Manganese	CR	Chromium

Table 6.2 Spearman's Rank Correlation Matrix

Chemical analysis results, core LP3M3

decline from the base of the core to the middle of Zone C, rising to a fairly constant level in the upper portion of Zone C and into Zone B. Maximum values occur on the boundary between Zones B and A. The results for zinc correlate very strongly with those of copper (r = 0.7449, Table 6.2), but the ratio between the two elements shows no trend (Fig. 6.4).

Analysis for tin was limited to the x-ray fluorescence technique (see Section 4.2.2.6) owing to the difficulties of extracting this element using the methods employed for the others. From these results (Fig.6.4), a fairly constant level is maintained throughout Zones C and B with the exception of very high values between 210 and 190cm. Tin values decline from the upper part of Zone B into a minimum in Zone A.

A similar anomaly occurs in the relative results for lead (Fig. 6.4). Throughout all three zones, lead levels remain fairly uniformly low, with the exception of a slight rise between 260 and 230cm and a major peak between 60 and 50cm.

Aluminium and chromium results, expressed in terms of dry weight, show similar patterns, with both remaining fairly steady throughout Zone C and declining to a minimum in the centre of Zone B. The values for both elements then increase to previous levels at the top of Zone B. In Zone A, however, aluminium decreases in concentration whereas chromium continues to increase to a maximum towards the sediment surface.

Fig. 6.7 displays the influx results for five of the metals. The patterns of influx are very similar, dominated by the considerable increase in sediment deposition in Zone B and tend to mask the more subtle changes apparent in the corresponding dry weight values in Fig. 6.4.

6.2 Particle size analysis

The results of particle size analysis are displayed in Figs. 6.8 and Figs. 6.9 to 6.37 and are detailed in Table 6.3.

Between the base of the core and 140cm (Zone C), the pattern of particle size is relatively constant, with only one or two samples, notably numbers 18 and 23, showing a slight rise in the fine sand fraction.

Sample 14, at the base of Zone B, is almost unique in possessing only a very small proportion (10%) of material greater than 20 microns. The sample consists almost entirely of fine silts and clays. Between 130 and 80cms (samples 13 to 9), the proportion of coarser material, particularly the coarse silts, increases markedly. Sample 9 is almost devoid of clays and fine silts. Between 80 and 40cm (samples 8 to 5) there is a trend towards finer sediments. Samples 5 and 4 represent the top of Zone B. Sample 4 is very similar in character to sample 14, being predominantly fine silts and clays. Both samples 14 and 4 are associated with the pink clay bands deposited in 1928 and 1938.

Table 6.3

Core LP3M3 particle size analysis results

Fraction sizes in microns:
A: <2.00
B: 2.0-5.6
C: 5.6-9.8
D: 9.8-20.0
E: 20.0-50.0
F: 50.0-63.0
G: 63.0-125.0

Fraction %

Sample	A	B	C	D	E	F	G
1	26.42	15.98	13.56	25.71	10.17	7.22	0.94
2	26.54	16.52	16.48	18.96	15.45	5.69	0.36
3	24.63	17.34	17.43	20.95	14.34	5.07	0.24
4	27.13	27.30	22.71	15.66	5.84	1.15	0.21
5	35.07	26.84	12.63	7.31	4.24	11.51	2.40
6	32.01	23.60	15.53	9.57	7.23	7.57	4.49
7	27.37	26.55	18.60	10.32	5.49	7.62	4.05
8	16.75	20.23	19.38	18.38	18.45	5.19	1.62
9	2.82	2.90	12.63	18.27	37.14	16.72	9.52
10	8.14	9.29	12.14	19.86	41.00	5.70	3.87
11	15.64	17.41	19.67	20.96	16.04	6.32	3.96
12	20.08	19.78	18.70	18.01	11.04	9.10	3.29
13	16.82	18.34	20.71	20.31	13.17	6.73	3.92
14	42.38	32.01	15.62	6.27	3.06	0.66	0.00
15	37.76	20.05	14.34	15.36	9.48	0.58	2.43
16	45.03	20.44	14.82	11.42	6.62	0.08	1.59
17	40.77	19.63	14.66	15.12	8.84	0.17	0.81
18	30.86	14.37	13.88	17.72	17.47	0.33	5.37
19	39.07	17.85	17.07	15.74	8.61	0.79	0.87
20	45.02	19.43	15.85	10.22	8.48	0.84	0.16
21	33.01	20.28	15.45	17.31	5.74	7.80	0.41
22	35.29	18.18	14.99	15.72	13.04	1.74	1.04
23	37.82	12.99	8.15	10.18	17.07	12.92	0.87
24	34.78	16.13	14.18	15.20	12.66	4.80	2.25
25	41.67	21.31	13.63	11.82	7.07	3.94	0.56
26	39.86	19.03	15.60	12.17	9.09	2.76	1.49
27	41.07	20.31	13.07	10.69	7.95	4.93	1.98
28	37.62	20.25	15.57	13.69	8.11	3.82	0.94
Means for all samples	30.77	19.08	15.61	15.10	12.25	5.06	2.13
Means for Zone A	26.18	19.29	17.55	20.32	11.45	4.78	.44
Means for Zone B	21.71	19.70	16.56	14.93	15.69	7.71	3.71
Means for Zone C	38.55	18.59	14.38	13.74	10.02	3.25	1.48

Zone A, which includes part of sample 4, differs in character from Zone C. However, there are similarities, in terms of particle size, to samples 13 to 11 in Zone B, although numbers 3 to 1 lack the fine sand fraction.

Chapter 7

Results of microfossil analyses

7.1 Introduction

One of the aims of this research programme was to examine the ecological development of Loe Pool. The use of sedimentary microfossils has long been an important technique in such investigations and a variety of such analyses were performed on a number of sediment cores and samples from the lake. Diatoms are the microfossils which can yield a large amount of environmental information but other remains, encountered whilst counting diatoms, have also been included where appropriate. These include the cysts and scales of some Chrysophyceaen species, the spicules of some freshwater sponges (Porifera) and in Zone A, the remains of some green algae such as species of Pediastrum, Scenedesmus and Staurastrum.

The analyses associated with these microfossils fall principally into two categories. First, there are those in which the results are expressed in relative terms. These show the changes in the composition of a particular microfossil assemblage through time. Second, there are absolute analyses which not only clarify changes in the composition of a community but also determine the total quantity of microfossils per unit volume of sediment concentration. When these data are combined with information on rates of sediment deposition, an estimate of the annual influx of mmicrofossils to the sediment can be arrived at. This can then be related to lake productivity (Battarbee 1979).

In this investigation, both types of analysis were employed. Core LP3M3 was used to study both relative and absolute microfossil numbers, in order to detail the ecological development of the Pool over the past century. The same twenty eight 10cm subdivisions of core LP3M3 were used for diatom analysis as were employed for the physical and chemical analyses detailed in the previous chapter. However, the part of this core in the region of the sediment water interface was to some extent disturbed upon retrieval. Consequently, a more detailed diatom analysis of this section was performed on a frozen sediment sample, BFS10, which included an undisturbed sediment water interface. The adhesive tape peel method, the results of which more clearly demonstrate the changes in diatom flora over the past fifty years, was employed in this case.

The dating of the sediment column in such cores as LP3M3 relies heavily on the assumption that certain laminated sequences, particularly those in Zone C, are of an annual nature. Diatom counts, again using the adhesive tape method, from a from a section of Zone C in core LP3M3, and a deeper section from core RB2, obtained using a 'Russian' borer, demonstrate the validity of this assumption and provide clearer information on both annual changes in diatom populations and the overall variation in the diatom flora over time.

The adhesive tape method of diatom analysis falls half way between the conventional classifications of 'relative' and 'absolute' counts. It might best be described as semi-quantitative in that it measures the total numbers of diatoms in consecutive but discreet fields of view down the length of an adhesive tape peel. It can never be truly quantitative in that the amount of sediment adhering to the tape is never even throughout its length. However, the advantages offered by this much finer level of stratigraphic detail make it a valuable analytical technique.

In this chapter, the results of microfossil counts from each of the sediment sequences analysed, will be detailed in turn. In addition, the results of TWINSPAN analysis, introduced in Chapter 4, and applied to all the adhesive tape counts, are described in the latter part of the chapter.

7.2 Core LP3M3

7.2.1 Relative diatom analysis

The results of a relative diatom analysis of core LP3M3 are shown in Fig. 7.1. Owing to a loss of data during the study, only figures relating to the upper 14 core divisions out of the original 28 can be presented.

As mentioned in section 6.1, a certain amount of slumping and subsequent mixing of the surface sediments occurred upon retrieval, affecting the uppermost three 10cm subsamples. The results of the diatom analyses from these samples almost certainly reflect this disturbance, although substantial differences in diatom counts still appear.

A second point to note is that with a better knowledge of the sediment chronology at the time of subsampling, smaller subdivisions might have been preferable, in order to increase the resolution of the diatom analyses.

Given these limitations, a number of major changes in the diatom flora preserved within the sediments can be observed from these subsamples.

The results presented here cover Zones A and B. From the base of Zone B at a depth of 140cm, the most noticeable change in the diatom taxa involves <u>Synedra rumpens</u>. This is the dominant taxon in Zone B. Its frequency is around 30-40% in most of Zone B, with a decline between 80 and 100cm depth. Above 40cm, however, its frequency declines. A similar pattern is shown by <u>Surirella ovata</u> although the decline in the percentage of this taxon is more marked and above 30cm it is all but absent. <u>Tabellaria flocculosa</u> and <u>Nitzschia palaea</u> display a greater frequency in Zone B than Zone A, and <u>Synedra acus</u>, evident in Zone B, is absent above 40cm.

In contrast to the pattern exhibited by the above, taxa such as Thalassiosira pseudonana show a steady increase from 50cm up to the surface. Asterionella formosa displays a similar pattern with a sharp increase in relative abundance above 40cm. Cyclotella meneghiniana, present in very low frequencies in Zone B attains a maximum between 20 and 30cm in Zone A, then declines towards the surface. Melosira granulata var. angustissima presents a slightly different pattern, being absent below 70cm and showing a maximum between 40 and 30cm before levelling off at around 10% between 30cm and the surface. Melosira varians echoes this pattern, but at a lower relative frequency.

There are several taxa which show little significant change throughout Zones A and B. These include Chaetoceras muelleri, Fragilaria pinnata and Fragilaria vaucheriae.

Overall, the pattern which emerges is of a subfossil diatom flora dominated in Zone B primarily by a single taxon, Synedra rumpens. As the relative importance of this species declines, it is replaced in Zone A by four main planktonic taxa, Thalassiosira pseudonana, Asterionella formosa, Melosira granulata var. angustissima, and to a lesser extent Cyclotella meneghiniana. A number of other taxa show similar trends but with much lower frequencies.

7.2.2 Absolute diatom analysis

The results of the absolute diatom analysis of core LP3M3 are shown in Fig. 7.2 and display the same raw data as above but expressed in terms of the numbers of diatom valves deposited per square cm per year.

The qualitative species changes are obviously identical to those of the relative analysis but when the data is converted to illustrate annual influx, a different pattern emerges.

The main trends can be seen in the total number of diatom valves being deposited cm^{-2} $year^{-1}$. There appears to be an increase from around 1.8×10^7 valves cm^{-2} $year^{-1}$ at the base of Zone B to a maximum of around 6.2×10^7 valves cm^{-2} $year^{-1}$ between 70 and 50cm depth. This rise in Zone B is due mainly to the very large numbers of <u>Synedra rumpens</u> deposited in this part of the sediment. The total then declines markedly in Zone A.

In Zone B, the general trend is one of maximum deposition of frustules in the upper part of the zone. This pattern is exhibited by taxa such as <u>Cyclotella meneghiniana</u>, <u>Synedra pulchella</u>, <u>Chaetoceras muelleri</u> and <u>Fragilaria vaucheriae</u>. <u>Synedra rumpens</u> displays a fairly even depositional pattern, with the exception of a considerable increase between 80 and 60cm. <u>Surirella ovata</u> is evident in considerable numbers in this region of the core, showing a general increase with depth, and together with <u>Synedra rumpens</u>, assumes dominance in Zone B.

The general trend shown by the main planktonic taxa in Zone A, (*Thalassiosira pseudonana*, *Asterionella* and *Melosira granulata* var. *angustissima*) is an increase from the base of the zone toward the sediment surface, indicating that production of these diatoms may have increased since 1937 (40cm depth). *Melosira granulata* var. *angistissima* only appears above 80cm (1929) and *Melosira varians* only above 60cm (1932). The vast majority of the other taxa present in Zone A show a decline towards the surface.

7.2.3 Estimation of past pH conditions

Much has been written concerning the interpretation of past pH conditions using the preferences of each diatom taxon. The classic work upon which many present day interpretations are based and which outlines the pH system used, is that of Hustedt (1937-39). A number of authors have built upon this system, notably Nygaard (1956), who developed an index α for pH estimation. This was used and further refined by such authors as Meriläinen (1967), Digerfeldt (1972), and Renberg (1976). In this study the formula used to calculate pH is that of Renberg & Hellberg (1982) who improved Nygaard's index α with the development of index B, where:

$$\text{index B} = (\%ind+5x\%acf+40x\%acb)/(\%ind+3.5x\%alkf+108x\%alkb)$$

pH can then be derived using the formula:

$$pH = 6.4 - 0.85 \log \text{index B}$$

The results are given in Fig. 7.3 and Table 7.1.

pH classifications for each of the taxa encountered in the Loe Pool sediments, together with further ecological preferences are tabulated in Appendix B.

The pH derived from the diatom flora in the basal sediments is around 6.5. This falls slowly to a minimum of 6.00 in the sample from 90-80cm depth. There is then a rise to around 6.75 at a depth of 60cm. In Zone A, the pH value indicated is above 7.0, varying to a maximum of 7.22 between 30 and 20cm, and 7.13 at the sediment surface.

7.3 Sample FBS10

This material was taken from a flat frozen sample which displayed very similar stratigraphy to core FBS12 but with a slightly thinner layer of upper brown gyttja (Zone A) above the uppermost pink clay. The sample itself was lost prior to photography after one of the freezer breakdowns.

The count is from an adhesive tape peel and comprises all diatoms in consecutive 500µm fields of view from the sediment water interface down to a depth of 26.0cm, terminating in layer B015 (c.f. Plate 5.8, Sample FBS14).

pH estimates from diatom analysis of Core LP3M3 using the formula for Index B detailed by Renberg & Hellberg (1982)

Segment	Depth (cm)	pHB
1	0-10	7.13
2	10-20	7.19
3	20-30	7.22
4	30-40	7.06
5	40-50	6.71
6	50-60	6.74
7	60-70	6.76
8	70-80	6.56
9	80-90	6.00
10	90-100	6.33
11	100-110	6.49
12	110-120	6.48
13	120-130	6.56
14	130-140	6.51

Zone A, the uppermost gyttja, which may have posessed some structure upon inital deposition, is now considerably bioturbed in both this sample, and in the vast majority of samples retrieved. Differentiation of any seasonal structure is only occasionally possible in the most recently deposited material (Simola _et al_. 1981). However, in this zone, variations in microfossil populations are evident, as bioturbation appears to operate on a limited depth of material at any one time. This means that some 'blurring' of the stratigraphy occurs but the entire zone is never fully mixed. The microfossil evidence is thus less detailed than that from some of the deeper sediments, but the adhesive tape peel counts do reveal a much clearer picture of change than traditional subsampling and preparation techniques.

The results of the diatom analysis of sample BF810 are shown in Fig. 7.5, and are expressed as valves per field of view. The majority of diatom taxa counted were planktonic, although a number of epiphytic species were also present.

In Zone A there are a number of notable changes. Between about 16.0cm and 5.0cm depth, the total diatom count remains relatively constant. Between 5.0cm and 1.0cm there is a marked rise, followed by a fall towards the sediment surface. This fall is probably due to lack of compaction of the surface sediment where the water content is very high. The sudden rise in diatom numbers is due to the appearance of _Melosira granulata_ var. _angustissima_. Below 6.0cm this taxon was not observed. This is the most recent and most noticeable change in the fossil diatom flora of the Pool. Another abrupt change appears to occur at the base of Zone A at a depth of about 20.0cm where one taxon, *Asterionella formosa*, not present in deeper sediments, makes its first appearance. Above 14.5cm this taxon dominates the flora until it declines at about 4.0cm depth. Above this, *Melosira granulata* var. *angustissima* assumes dominance.

Three other planktonic taxa in Zone A which are present in very small numbers in deeper sediments, increase in abundance. These are *Thalassiosira pseudonana*, *Cyclotella meneghiniana* and to a lesser extent, *Melosira varians*. *Cyclotella meneghiniana* appears above 20.0cm but *Thalassiosira pseudonana* is not recorded until above 13.0cm, following the major rise in *Asterionella formosa*. *Melosira varians* is certainly present in deeper sediments but is absent in much of Zone B. It reappears at about 20.0cm in layer B008 and is also present in small numbers at the sediment surface.

The most noticeable decline towards the sediment surface is that of *Synedra rumpens*, which is one of the most numerous of all species prior to 1940. A strong peak occurs in layer B010 at around 22.0cm depth but above that level the species is very infrequent, making its last appearance in this sample at about 11.0cm.

The remains of some green algae are quite prominent in Zone A. In the case of *Pediastum boryanum* and *Scenedesmus* sp., these appear at a depth of 20.0cm and above, with Staurastrum sp. evident above 10.4cm. As cells from these species were found at greater depths, albeit in very small numbers, it is probable that their sharp increase in abundance above 20.0cm and 10.4cm respectively, is due to a genuine increase in their presence, rather than through natural decay of the remains within the sediment.

Of the other microfossils counted, the sponge spicules displayed no apparent trend of deposition either on an annual basis or in their overall occurrence in the sediment over time. The numbers of Chrysophyte cysts on the other hand displayed some kind of pattern, tending to occur in marked peaks such as that in the middle of layer B010.

The microfossil stratigraphy of sample FBS10 is closely allied to the sediment stratigraphy. The upper and lower bands of pink clay, comprising layers B007-B009 and B011-B012 show a distinct paucity of microfossils, especially layer B011 which is completely devoid of remains. This is certainly linked to the very high rates of deposition of these layers and can be contrasted with what may be the darker summer layers of B010 and B013 beneath each clay band, where the rate of deposition must have been much smaller.

The zonation of the sediment column into Zones A and B on stratigraphic grounds as described in Chapter 6 is paralleled by the distinct change in the algal microfossil flora which occurs at and above about 16.0cm depth. Below this, in Zone

B, the flora is dominated by Synedra rumpens, whereas Zone A exhibits a more diverse flora which above about 5.0cm itself changes from one characterised by the occurrence of Asterionella formosa to one dominated by Melosira granulata var. angustissima.

In both zones a number of other planktonic species persist throughout although in comparatively low numbers. These include Synedra pulchella, S. acus, S. ulna and a number of epiphytic diatoms such as Cocconeis placentula and Surirella capronii.

7.4 Core LP3M3 (161-173cm)

Simola et al. (1981) described the microfossil sequence of a 12.0cm section of core LP3M3 from 173-185cm depth (wrongly labelled '194-206cm' in that paper), which was prepared using the adhesive tape peel method. Fig. 7.4 shows the 12.0cm sequence directly above this, from 161-173cm, derived using the same technique. Both sequences exhibit a variation in the diatom flora, which is mirrored also in the colouration of the sediments. These characteristics, which are interpreted as seasonal features have been the basis of the dating of Zone C, of which this section is fairly typical.

The darker bands of sediment are associated with increases in the two most abundant taxa, which in this region of the sediment column are Surirella ovata and Synedra rumpens. The occurrence of these is sometimes associated with Chaetoceros muelleri, but this species is much less frequent. In both this section and that reported by Simola et al. (1981), these species exhibit some seasonal succession. The sequence has been divided into four units (l, m, n and o) within which peaks of diatom depositiion have occurred. The most prominent maxima are those exhibited by Synedra rumpens. In units l, m and n the peaks in Synedra rumpens are associated with those in the numbers of Cysta microcarpa (sensu Nygaard 1956) contained largely within the darker layers. These cysts are thought to be deposited in the autumn. The layers between these peaks, which contain fewer diatoms, are thought to represent winter months and are associated with the grey-brown clays (Simola et al. 1981). Unit o, which straddles the two 12.0cm sequences, displays sediments characteristic of winter deposition between 171.4cm and 172.8cm and the Synedra rumpens summer peak between 172.8cm and 174.0cm. In total, the combined 24.0cm of sediment contains nine annual sequences.

The overall diatom flora of this section is very different from that found in the sediments of Zone A. The diversity of species is considerably reduced but exhibits a strong seasonal influence.

7.5 Core RB2

This 10cm section is part of a 'Russian' borer sample which was retrieved from Carminowe Creek, the south-easterly arm of the lake, fed largely by Carminowe Stream (Fig. 2.6). Each of the 50.0cm sections of the core were frozen in the laboratory using liquid nitrogen and then stored frozen, This allowed cleaning and freeze-drying of the flat face of each unit. The core could then be treated as any other frozen sample and adhesive tape peels for microfossil analysis could be taken. This was performed on a relatively undisturbed part of the deepest 50.0cm section.

This sample was analysed for microfossils as it represents the deepest sediments retrieved from Loe Pool during this study. No further analysis was performed on these samples as the cores were considerably distorted following the breakdown of the storage freezer.

The material showed similar stratigraphic characteristics to Zone C of core LP3M3 but came from a depth of 460.0-470.0cm. Any comparison of the stratigraphy of cores RB2 with that of core LP3M3 is difficult owing to their different source locations within the lake, although Zones A and B are discernible in the upper part of the core sequence. Tracing the exact correlation of Zone C between the two cores is, however, almost impossible. In addition, discontinuities between the 50.0cm sections of the 'Russian' core mean that an uninterrupted sequence of sediments was not obtained.

Dating of this material is at best, therefore, somewhat tentative, but applying the rate of deposition of Zone C of core LP3M3, (2.6cm per annum), as an estimate, the 10.0cm section would date from the early 19th century. As rates of deposition obviously vary according to location within the lake, it is emphasised that this is a very approximate dating. The sample is valuable, however, in that it reveals something of the diatom flora which existed prior to that represented by the samples from core LP3M3, discussed in section 7.4 above.

The flora observed differs markedly from any other portion of the sediment stratigraphy. Two planktonic species, Cyclotella meneghiniana and Melosira juergensii, dominate. Tabellaria flocculosa and Diatoma elongatum, also largely planktonic, are present in smaller numbers. In the case of both Cyclotella meneghiniana and Melosira juergensii there would appear to be a similar cyclicity of deposition as occurred with species such as Synedra rumpens in Zone C, and again, some seasonality of deposition may be inferred. From a simple visual interpretation of the plotted data, four annual cycles or part cycles are evident within the 10.0cm section.

The seasonal succession would appear to be initiated in early spring by Melosira juergensii. This is followed by Tabellaria flocculosa, the species common to late summer/autumn, Cyclotella meneghiniana follows these two species, and coincides with an increase in the number of chrysophyte cysts. Using this sequence, the four cycles or part cycles are indicated in Fig. 7.6 as a, b, c and d.

The occurrences of the three marine or estuarine species Paralia sulcata, (referred to in older keys as Melosira sulcata), Gomphonema acuminatum var. coronata and Epithemia turgida, tend to cluster around the appearance of Melosira juergensii, indicating that these species may well have arrived through seawater overwashing the bar during winter or spring storms. The proximity of the coring site to the bar makes this all the more likely.

These species, together with the more dominant taxa, reflect a very different lacustrine environment to anything indicated by the floras preserved within other parts of the sediment stratigraphy.

Included in the counts were the siliceous spicules of a freshwater sponge, probably Spongilla lacustris, although reliable identification of species from their spicular remains can be difficult. Turk & Turk (1976) have, however, identified freshwater sponges as being common around the shores of the lake. A distinction is made between gemmoscleres, microscleres and megascleres, although these are simply subdivisions of the general term 'spicule'. Although each may serve a particular function within the sponge, there is unlikely to be any distinction between the deposition of the different types on a seasonal basis.

The chrysophyte cysts included in the diagram have not been identified to species but are included as their presence in lake sediments has been associated with deposition in the autumn.

7.6 Floral associations derived using TWINSPAN

7.6.1 Introduction

The use of TWINSPAN to divide samples into groups displaying similar floral associations has not been applied to this type of adhesive tape peel microfossil count before. It was hoped that some objective distinction could be drawn between the seasonal variations in diatom occurrence which are subjectively apparent in the results of counts from the samples detailed above. Similarly, it was hoped to distinguish major changes in the microfossil stratigraphy over time, particularly in the counts made on the most recent sediments. The results of these analyses are shown at the far right of each of the counts displayed in Figs. 7.4, 7.5 and 7.6, and are discussed individually below. It should also be noted that the group divisions identified by TWINSPAN are only valid for each individual section of sediment analysed, and that there may be no similarity between the diatoms placed in, for instance, Group 001 from one sample and those placed in Group 001 from another.

Each individual count, comprising the microfossils recorded within one field of view, is compared for similarity with every other. They are then subdivided by TWINSPAN into groups of counts showing greatest overall similarity of species content. The analysis provides up to 6 levels of subdivision, or 64 groups. In practice 3 levels of subdivision (8 groups) were found to be more than adequate in providing a distinction between associations of species characteristic of particular levels within the sediment stratigraphy. In some instances, 2 levels (4 groups) were found to be sufficient.

7.6.2 TWINSPAN analysis of Sample FBS10

Of all the samples analysed using TWINSPAN, this core produced the clearest divisions, illustrating the changes that took place in the diatom flora as a whole over the period 1936-1980. The results of the analysis are represented in diagrammatic form at the far right of Fig. 7.5.

Group 000 comprises a group of counts which are dominated by one characteristic taxon, Melosira granulata var. angustissima. Other species are present, but much less consistently.

Group 001 is distinguished by two indicator species, Cyclotella meneghiniana and Navicula cryptocephala. Also commonly occurring in association with these species are Thalassiosira pseudonana, Asterionella formosa and Synedra pulchella.

Group 010 consists of a group of counts with a more diverse selection of taxa. However, the indicator species for this group are Thalassiosira pseudonana, Synedra pulchella, Cyclotella meneghiniana and Synedra rumpens in combination.

Group 011 is characterised by the indicator Synedra ulna and Surirella capronii.

Groups 100 to 111 are less useful in defining specific groups of taxa, although group 101 does pinpoint the larger occurrences of Synedra rumpens.

This type of analysis groups the counts into those with combinations of species in common. It may completely ignore the more obvious dominant species but use consistent associations of species instead. As such it can add an additional dimension to the normal visual interpretation of such diagrams, highlighting groupings which might otherwise be difficult to discern.

The TWINSPAN analysis of this core does show a progression of diatom associations with the clearest trend being from those characterised by the species typical of group 011 in the lower half of the section, through groups 010 and 001 in the central portion, to group 000 at the surface. Clearly some ecological change has prompted a change in the flora from that of the late 1930's to that of the past decade.

7.6.3 TWINSPAN analysis of Core LP3M3 sample (161-173cm)

The results of the TWINSPAN analysis of this sample are displayed on the far right of Fig. 7.4.

Zone C of core LP3M3 is characterised by a relative paucity of diatom species, with the flora overwhelmingly dominated by Synedra rumpens and Surirella ovata. Although both Chaetoceras muelleri and the microfossils identified as Cysta microcarpa are also present, they occur only sporadically and, apart from one marked peak in the numbers of the latter in very small numbers.

With this low diversity of species, TWINSPAN was found to be less helpful at distinguishing seasonal changes than simple visual inspection of the plotted data. With 2 levels of subdivision giving four groups of counts, only group 10 was of use in the distinction of the major occurrences of Synedra rumpens. Varying the cut levels used by TWINSPAN might improve the distinction between groups.

7.6.4 TWINSPAN analysis of Sample RB2

The results of the TWINSPAN analysis of this sample are shown on the far right of Fig. 7.6.

This deeper part of the sediment stratigraphy has a far greater diversity of diatom species than Zone C in core LP3M3, with chrysophyte cysts and sponge spicules also present in some numbers.

The results are complex to interpret but could be used to apply a different interpretation on the number of annual cycles than is suggested in section 7.5 above.

Using group 11, with indicator species Melosira jurgénsii and Tabellaria flocculosa as characteristic of spring deposition, there would appear to be only two major depositional zones of this type. The other groups, however, do not reflect the dominant species associated with summer or autumn deposition and so such an interpretation is less discriminating than the interpretation based on seasonal sequences of dominant species which TWINSPAN is unable to discern.

7.7 Summary

The information derived from diatom and other microfossil analysis presents evidence of a number of phases of changing ecological status. Each of the sequences of sediment analysed differs markedly in the diatom floras which have been preserved within them, suggesting that a number of different environmental influences have governed the lake's ecology over time. This evidence is interpreted, together with both the physical, chemical and historical information already outlined, in the following chapter.

Chapter 8

Discussion

8.1 Introduction

The history of Loe Pool would appear to be one dominated for many centuries by the natural interaction of fluvial and coastal processes, followed by a period of some two hundred years which have seen ever increasing human pressure on the lake and catchment system. Through this combination of influences has evolved a lake with a unique and complex history. This study has aimed to elucidate both the nature and the degree of these influences on the lake, so that comparison can be made between the present system and its status in the past. A number of different but frequently corroborative lines of research have been pursued in order to obtain an insight into the environmental history and geomorphic development of the Loe Pool system. When considered in combination, a fairly detailed history of the lake's evolution can be assembled.

This discussion will review the development of the lake chronologically, working from the earliest evidence of its formation and evolution, to its condition at the present day.

A summary diagram covering the period 1800 to the present is given in Fig. 8.1. A separate copy is supplied inside the back cover of Volume 2.

8.2 Post-Glacial development

Work on the Quaternary history of the South-West peninsula and on eustatic changes during this period can suggest the way in which Loe Bar and the lake impounded by it have evolved over the past 12,000 years. The source material for the bar would appear to have been largely derived from deposits laid down on what is now the bed of Mount's Bay. This was moved 'landward' to form our present coastal deposits in line with a rising sea level which followed the last (Devensian) glaciation. Other analogous features, such as the Swan Pool near Falmouth in Cornwall and Slapton Ley to the south of Dartmouth in Devon, have similar and contemporary origins. The material which constitutes both Loe Bar itself and the entire beach between Porthleven to beyond Gunwalloe Fishing Cove is comprised of a very high proportion of flints. Mixed in with these is a smaller proportion of shingle of local origin.

It would therefore seem probable that the bar, and thus the impoundment of the river Cober behind it, had started to develop into a recognisable feature as the Holocene rise in sea levels began to stabilise around 6,000 years B.P. At any one time, the levels of discharge of the River Cober would have determined whether the feature was a spit or a complete bar. Although the fine tuning of eustatic changes is still a matter of considerable debate, sea level curves (e.g. Fairbridge 1961, Shepard 1963, Jelgersma 1966) generally show a reduction in the rate of sea level rise from an initial rate of 1m/100 years to 2 or 3cm/100 years between 7,000 and 5,000 years B.P. This reduction would have allowed the development of a fairly stable shingle feature at the mouth of the Cober. The balance between shingle deposition and river discharge would again be all important in determining the nature of that feature. Estimates of past climatic conditions, and more specifically of precipitation, are tentative at best. If the climate at this time was significantly colder than at present, then some enhancement of seasonality of discharge might be expected. This being the case, a regular spring thaw might have involved the annual clearance of a discharge channel through any shingle barrier. It would only be at a point when precipitation and temperature levels approach those of the present that the feature might have attained any level of stability or permanence.

Clearly, without recourse to a very detailed examination of Quaternary deposits in the Loe Valley, such hypotheses must remain untested.

8.3 Pre-19th Century development.

Evidence for the existence of a bar and lake prior to the 16th Century is very scarce, with the only reference thought to mention the Loe dating from 1302 (Toy 1936).

The earliest date at which the presence of a bar, and by implication, the presence of a predominantly freshwater lake behind it, can be established with any degree of certainty is in the beginning of the 16th century. Two very different but contemporary sources, the <u>Itinerary</u> of John Leland (1535-1543) and the chart of the coast of the Southwest peninsula (British Library, Cotton MS Augustus I i 35) (Plates 3.2 & 3.3), clearly record the existence of a lake and bar.

Sources from the 16th and early 17th centuries, detailed in section 3.1, give an insight into the nature, stability and degree of permanence of the bar. In summary, they indicate the presence of a predominantly freshwater lake, but with seasonal and spontaneous outbreaks of lake water. These undoubtedly resulted from the fact that there was no natural overflow or outflow channel from the lake, and at each occurrence removed large quantities of shingle from the bar. With the exception of evaporation, loss of lake water was entirely by percolation through the bar material. When winter discharge from the catchment was in excess of the percolation rate through the shingle, overflow occurred and the natural drainage channel thus produced carried large quantities of shingle back out to sea.

The ecological stability of such a system must have been negligible. Two competing influences were operating. The first was the hydrological effect of the catchment feeding the lake. With the bar as a complete entity, the lake would have been dominated by the throughflow of freshwater from the catchment. Percolation through the bar would have been maintained in a seaward direction, although some sort of saline wedge may have ingressed landward at some depth (c.f. Slapton Ley, Van Vlymen 1979). The second influence was when this freshwater environment was periodically disrupted by the breaching of the shingle bar. Such was the degree of energy expended when a breach took place that the lake could remain in communication with the sea for a period of up to several months until the natural processes of longshore drift or the deposition of shingle by storm action closed the passage of communication. During this period, however, a considerable saline influence would have been imposed on an otherwise freshwater environment.

The legacy of these saline incursions would have been the persistence of a degree of salinity within the lake for a considerable time. The period of saline retention would have been governed by the flushing rate of the lake itself. In addition to these major saline incursions, there would also have been the more frequent but less influential instances of storm overwash of seawater into the lake. The bar was undoubtedly of lesser proportions than at the present (c.f. Figs. 3.1-3.4), and so overwash by waves was probably a far more common occurrence. This would also have 'topped up' the salt concentration, however small, of the lake water. Under these combined circumstances it would seem unlikely that the early lake was ever truly freshwater, but was more likely to have been, to a greater or lesser degree, brackish in nature.

The physical structure and shape of the bar was also influenced by bar breaching. The natural build-up of shingle by wave action, and particularly by storm action, might have resulted in an altogether more substantial barrier had it not been for the regular removal of material during breaching. Leland (1535-43) refers to the fact that an increase in lake water level resulted in the flooding of the lower parts of Helston. The residents affected, as a matter of custom, were allowed to cut the bar to release the flood waters. Carew (1602) also makes reference to the natural or spontaneous discharge of flood water through the bar. It is clear that either of these methods relieved the problem of flooding in the short term, although the very fact that the bar breaching had become a local custom indicates that flooding of this nature was a regular occurrence.

The degree of natural growth of the bar was therefore curtailed by this regular removal of shingle. As a result the bar remained relatively narrow and weak in its central portion as is illustrated by Figs. 3.1 & 3.2. This also facilitated the custom of cutting the bar manually. Storm and wave build-up of shingle can rarely have exceeded the quantities of material removed during a breach and so the bar remained far smaller in profile than is the case today.

It is also interesting to note that as early as the 17th and 18th centuries, through a comparatively minor custom, albeit assisting an established natural process, this specific human impact had major repercussions on the physical and ecological environment of Loe Pool. The frequency of bar breaching was undoubtedly increased by the intervention of the local population. In most other ways, the human presence in the catchment had little impact on the lake system. Mining, up until the 19th century, was on a minor scale, although the scale of the mineral resources of the area had been long appreciated. Stream tinning was fairly common and may have artificially increased sediment yield from the catchment, but it is difficult to assess by what degree. No artificial fertilisers were applied to the land and sewage disposal was by local burial with no direct input to the lake.

The end of the 18th century also saw the first steps taken to regulate the lake level artificially. This occurred indirectly as a result of the excavation of Wheal Pool, a mine shaft dug into the Loe Valley on the edge of the lake. Jenkin (1962) suggests that this was first in operation between 1785 and 1786. The adit which now drains the lake is thought to be contemporary with this, as its purpose was to prevent inundation of the shaft by any rise in lake level. As mine workings were suspended in 1800, however, the adit was not maintained and was soon blocked with shingle allowing winter discharge again to pond back and affect the lower parts of Helston.

8.4 The period 1800-1874

The most significant events from 1800 onward are summarised in Fig 8.1.

Documentary evidence from this period is much more abundant and detailed, as is the availability of cartographic material. The deepest sediments retrieved during this investigation are also thought to date from the first quarter of the 19th century, and therefore to augment the available information on lake ecology.

The general picture of a lake periodically inundated by the sea continues to hold true for most of the 19th century. Contemporary accounts (e.g. Lysons & Lysons 1814, Hitchins & Drew 1824) confirm that bar breaching, both natural and artificial, continued at that time. The frequency of this occurrence can only be estimated from the available records, but from the information gathered during this investigation, for the period 1849-74, a minimum of once every two years is certain. The sources of this information, largely Cunnack (1885), Toy (1936) and dates from the purses customarily given to the lord of the manor of Penrose, are certainly not a complete record. Many of the purses, which are dated (see Plate 3.1), have been lost and many that do still survive (in the possession of Lt. Cdr. J.P. Rogers, Penrose House) are now illegible. The manuscript notes of Cunnack (1885) lack any records for several of the years between 1849 and 1874. Evidence from both Johns (1874) and Rogers (1934) suggest that breaching commonly occurred annually, and in some years, several times during the year.

The result can only have been the continued disturbance of the lake environment by marine incursion. Plate 3.6, which shows the breach which took place in 1865, illustrates the extent to which this inundation could occur. The current lake surface lies at about 3.8m O.D., and so with a tidal range of around 4.8m at Loe Bar (data from Penzance, Wilson & Wilson 1968), the water level within the lake could well have fallen by some 6.2m at low spring tide. This would have exposed a significant area of the lake bed, a phenomenon which was noted by Hitchins & Drew (1824). Periodic exposure would have had an impact on both the flora and fauna of the lake margins. At the other extreme, the regular flooding of the Loe Valley below Helston would have influenced the environment of the valley floor.

Examination of the diatom flora from the sediments which are estimated to have been deposited in the first quarter of the 19th century (Core RB02, 460-470cm depth, Fig. 7.7), (using the salinity classification of Van der Werff & Hulls, 1958-66), shows that a mixture of marine, brackish and freshwater taxa was preserved within the sediment at this time.

<u>Parelia sulcata</u> is a true marine planktonic diatom which occurs sporadically, but in considerable numbers, throughout this section of core. It would seem improbable that such numbers of valves could be the result of spray. If this were so, then it would be likely that the species would continue to be represented in the flora throughout the sediment

column. This does not appear to be the case.

Diploneis interrupta, which appears in small numbers at this depth, is a brackish water species, as is by far the most numerous diatom, Melosira jurgensii. In this part of the sediment stratigraphy the latter appears to be associated with winter or spring deposition, the period when bar breaching was most frequent. Its presence in the flora suggests that in the winter months the lake did indeed possess a degree of salinity. During periods when the lake was open to the sea, the deposition of sediment was probably reduced by the combined effect of tidal scour and a lowering of the overall water level. The fact that these brackish water species, in particular M. jurgensii, are found throughout this section of sediment, would indicate that they were deposited from the lake plankton when the bar was closed and normal lacustrine sediment deposition was taking place rather than being directly resultant from the marine incursions themselves.

Cyclotella meneghiniana and Diatoma elongatum are both brackish/freshwater species, which tolerate less saline conditions than the taxa mentioned above. C. meneghiniana in particular shows seasonality of deposition, but appears after Melosira jurgensii in the annual sequences. The brackish influence of a marine incursion would presumably diminish with the subsequent flushing of the lake system by freshwater from the catchment, and this is suggested by the fact that M. jurgensii is replaced as the dominant species by C.

meneghiniana. Variations in the consistency of numbers of *M. jurgensii* may be explained by the reduction of marine influence in some years, for instance if breaching did not occur at all in a particular year. *C. meneghiniana* however displays a more consistent pattern, falling to very low numbers only in the winter months.

The remainder of the diatom taxa which occur in any significant numbers, *Tabellaria fenestata*, *Synedra acus*, *Synedra ulna*, *Gomphonema acuminatum* var. *coronata* and *Epithemia turgida* are all classified as freshwater/brackish, with only one taxon, *T. flocculosa* being considered as truly freshwater in habitat.

The diatom record from sediments deposited in the early part of the 19th century therefore also reflects significant marine influence on the lake environment. This ties in with the general impression created by the literature of the time, of a rather unstable system, prone to extreme fluctuations of lake water level and lake salinity.

The shape of the bar itself also reflects the instability of the system. Figs. 3.1 and 3.2, taken from a number of sources, show it in plan view. That dated 1837 is taken from Rendel's design for a harbour at Helston. As Rendel was a noted civil engineer, his cartography is likely to be as accurate as any from that time. He shows the characteristic indentation of the inner central portion of the bar. This narrowest region was the area to be regularly removed by natural breaching, and was obviously the easiest section through which to dig a channel to release flood water artifically. The map dated 1838 shows some variation from this shape, but the Tithe map of Sithney Parish from 1844 is consistent in terms of bar form with that of Rendel.

There is a noticeble change in the profile detailed by the 1867 Ordnance Survey 1:2500 map of the area. The narrowest portion has shifted westwards and a distinct channel feeding the entrance to the drainage adit in the south-west corner of the lake is apparent . It is known that mining activity in the Loe Valley between Helston and the lake itself continued on and off between 1850 and 1882 (Cunnack 1898), and so it is likely that the adit was cleared from time to time when required by the mine workings. This would explain the appearance of the adit channel on the 1867 O.S. map. The fact that it quickly became blocked again when not in use is certain, as Cunnack (1885) and the other sources detailed in Table 3.1 give dates for bar breaching between 1865 and 1874.

A number of significant changes to affect both the lake and bar occurred within the catchment in the second half of the 19th century.

Metalliferous mining had expanded since the turn of the century and output of metallic tin from Cornwall grew steadily during the early 1800's (Fig. 3.11), to reach a peak between 1860 and 1880 with production declining thereafter until 1900 (Fig. 3.12). Mining within the Loe Pool catchment followed this general trend, with some of the larger mines, notably Wendron Consols and Porkellis United, employing a considerable labour force in the 1860's and 1870's. Numerous smaller mines also sprang up during this boom period in Cornish mining.

The River Cober offered a convenient route for the disposal of mine wastes, and much of this material, in the form of fine sediments, was deposited in both the Loe Valley and in the lake itself. Rogers (1857) commented on the pollution of the River Cober and on the reddish tint which pervaded all parts of the Pool. Such was the inefficiency of many of the extraction procedures at that time that the tin which was re-deposited in the Loe Valley in the 19th century below Helston was re-worked commercially in the early part of the 20th.

These mine wastes therefore represented an additional allochthonous sediment source for the lake. It may be difficult to assess the degree to which these increased the rate of sediment deposition within the Pool. Most of the larger particles would have settled out quickly with a decrease in the velocity of the River Cober in the Loe Valley or upon contact with the lake itself. They would certainly have contributed to the infill of the northern limits of Loe Pool.

The bar is also known to have been cut during this period specifically to release the polluted waters of the lake, and so a proportion of the finer material in suspension at the time would have been removed on those occasions. Johns (1874) reported that such occasions resulted in the sea off Loe Bar being tainted with an ochreous hue for twenty or thirty miles offshore. Despite these attempts to reduce the effects of this mine waste pollution, some material would inevitably have been incorporated into the sediment column.

8.5 The period 1875-1927 (Sediment Zone C)

This period is singled out as it represents 53 years within which a number of very important changes in the Loe Pool system occured. It is also represented in Core LP3M3 by a sequence of characteristically laminated sediments designated in the overall stratigraphy as Zone C.

Perhaps the most significant change occurred at the beginning. After 1874 there is no record of the bar having been breached either naturally or deliberately. This was to change substantially the development of the bar and lake system.

The reasons for cessation in bar breaching can only be guessed at, but it may well have been through economic necessity, with active mining taking place in the Loe Valley, that from this date onward the adit was kept clear. As a consequence, the hazard of flooding in Helston was reduced. Cunnack (1898) reports that after 1882 the owners of the Penrose estate (of which Loe Pool was a part) kept the adit clear. Around 1899, Capt. John Rogers of Penrose had it enlarged and improved so that subsequent blockage by shingle occurred only very rarely.

Improved maintenance of the drainage channel was indeed timely. The natural percolation of lake water through the bar must have been reduced by the 'filter clogging' effect of the mine wastes passing through the shingle. The red sediments which were so characteristic of mining activity are still evident within the matrix of the bar. The constant and increasing pollution of the Loe throughout the 19th century would certainly have reduced the natural drainage of the lake by this means. Some support for this idea comes from the frequency of recorded instances of bar breaching, which seem to show an increase in the late 1860's and early 1870's although it is difficult to assess this objectively without comparative information from the earlier part of the century. Such an increase (if it exists) might also have been the stimulus for the more consistent maintenance of the drainage adit in the latter part of the century.

The cessation of breaching of Loe Bar had repercussions for both the structure of the bar and the ecology of the lake itself. The regular removal of shingle which occurred whenever the bar was broken no longer took place. Instead there was a net gain of material through wave and storm action. As a result, the bar gradually increased both in height and in width. The change in area can be seen by a comparison of the 1867 and the 1906-8 O.S. 1:2500 maps (Figs.

3.2 and 3.3). As the dimensions of the bar gradually increased, the frequency of wave overwash must correspondingly have decreased.

This factor in the reduction in marine influence was minimal in comparison with the fact that from 1874 onwards, the lake was no longer regularly open to the sea. For what was probably the first time in its history, the Pool became predominantly fresh throughout the year. This change alone would have produced a significant alteration in the overall lake ecology, and in the nature of the lake sediments.

LP3013

The base of this core appears to be contemporary with the start of this new period of stability. As can be seen from Plate 5.1, the material which comprises sediment Zone C and which makes up the lower half of this core, consists of a series of laminated sediments which have been shown to exhibit seasonal variation in subfossil diatom content (Simola <u>et al</u>. 1981). The sediments themselves are composed very largely of silts (on average 60%) and clays (40%) (Fig. 6.8). There is seasonal variation in both particle size and in sediment colour. Generally, the darker laminations or groups of laminations represent summer deposition, whilst the lighter and generally wider laminations constitute winter. This has been shown by adhesive tape peel analyses of the continuous diatom stratigraphy from two sections of this core, both during this investigation, and also by Simola <u>et al</u>. (1981). These clearly demonstrate the seasonality of diatom deposition in Zone C and have identified annual sequences of sediment. Such properties have also been used to develop a general model for the dating of this portion of the sediment.

This study has employed the seasonal variation in diatom deposition within the lake to differentiate between the bands of darker (black) and the lighter (grey) bands of sediment. The former are considered to represent summer deposition and the latter the winter (Simola et al., 1981). Additional research on the chemistry of individual laminae in this zone by Pickering (Ph.D. thesis, Plymouth Polytechnic, 1987) supports the hypothesis. Both chlorophyll c and the phaeopigments were found to reach higher concentrations in the black laminations than the grey. Pickering interprets this as being consistent with an increase in aquatic productivity and grazing by zooplankton in the summer.

He also found the C:N ratio to be lower in summer sediments (which is consistent with a greater algal input), and higher in the winter, when terrestrial plant material is a more common source of organic matter. Finally, Pickering notes that perylene, the major polycyclic aromatic hydrocarbon found in many aquatic sediments, is, overall, found in higher concentrations in the black laminations than the grey. He states that perylene has been shown to display higher concentrations in sediments where the overlying waters are both productive and anoxic.

Pickering (above) has also shown that the black laminations are so coloured by the presence of metallic sulphides. He suggests that these were formed under reducing conditions at the sediment/water interface during periods of anoxia in the summer months. During the latter part of the 19th century, lake level was also more stable than before, owing to cessation of bar breaching and more consistent management of the drainage adit. At the same time, the mean depth of water in the lake during the latter part of the 19th century was greater (ca. 7m) than today (4m), if only because of the smaller thickness of sediment then present. Both factors would suggest that at this time, anoxia of bottom waters in summer was a more frequent occurrence. In turn, this gives us a possible mechanism for the deposition of sulphide-rich summer sediment, and grey, oxidised clays in winter.

The information available on the diatom flora for this zone records the existence of a high influx of diatom frustules, from predominantly one or two taxa, to the sediment. These diatoms, <u>Synedra rumpens</u> and <u>Surirella ovata</u>, are classified by Van der Werff & Hulls (1959-66) as being indicators of eutrophic conditions. Their dominance of the diatom flora and their maximum occurrence within the black, summer, laminae supports the hypothesis that the lake at this time was both productive and therefore more prone to anoxia during the summer months. This combination of circumstances, incluing the influence of mining with its associated high allochthonous sediment input, particularly during winter months, has provided a series of annually laminated sediments which have enabled the dating of this portion of the stratigraphy.

Zone C in Core LP3M3 is estimated to span the period from 1875 at the base of the core to 1927 at a depth of 144cm, representing 53 years in total. This records the recovery of the lake from regular marine incursions and a steady increase in the influence of mining activity.

A reduction in marine influence is reflected in the sediment chemistry. Figs. 6.3 and 6.6 show that both the percentage sodium, and the sodium influx decline slowly from the base to the top of Zone C. This would indicate that the relative and absolute amounts of sodium being deposited were declining. In Fig. 6.3 the sodium:potassium ratio exhibits a corresponding decline. There is little within the results of the chemical analyses of Zone C to demonstrate the influence of mining, with the exception of some variation in lead influx at a depth of 230-260cm. The major boom in mining during the 1860's and 1870's was almost over at this time. Mining activity within the catchment declined markedly between the late 1870's and its major resurgence in the late 1920's. The physical structure and composition of the sediments deposited during the last quarter of the 19th century display little evidence of such mining activity.

One exception to this conclusion is the notable rise in the amount of tin incorporated in the sediments between 190 and 210cm depth (Fig. 6.4). These two 10cm sections cover the period of operation of the Helston Valley Tin Company Ltd., which commenced in 1911. The company transported alluvium from the valley floor between Helston and the lake, via a narrow gauge railway, to its processing works at Casle Wary on the eastern side of the Loe Valley. Tin was then extracted from the alluvium, much of which had been deposited from earlier deep mining activity higher up in the catchment, and the final waste returned to the River Cober. Such an operation so close to the lake inevitably had a greater impact on the lake sediments than many of its predecessors which were in operation at a much greater distance.

The Helston Valley Tin Company is thought to have ceased operations around 1914 with the outbreak of war, but processing may have continued for a period after this (J. Brooke, pers. comm.). The colouration of the sediments laid down during this period also reflects the reworking of these deposits. The characteristic pink colouration is apparent at this depth, suggesting an increased rate of deposition of haematite rich sediment (Plate 5.1).

The diatom flora from the section of core LP3M3 from 171cm to 183cm depth (Fig. 7.4) also reflects the general influence of mining activity within the catchment. This had replaced marine incursions as the dominant influence on lake ecology. When compared with the taxa seen in the deeper sediments, the diatom flora here is markedly lower in diversity, with only two dominant taxa, Synedra rumpens and Surirella ovata. No other species, with the possible exception of Chaetoceras muelleri appear in significant numbers.

Such a paucity of taxa may be accounted for by the influence of high turbidity. Synedra rumpens may be planktonic or periphytic in habit (Van der Werff and Hulls 1959-66), and its presence here may indicate an ability to withstand both low light availability and any increase in the concentration of heavy metals which might have been increased by the inflow of mine wastes. Surirella ovata would appear to have similar tolerances. Certainly Synedra rumpens is the only taxon to display periodically high concentrations of valves within this portion of the sediment. These would seem to represent the remains of seasonal blooms. Both of these dominant species lie at the freshwater end of the salinity spectrum (Van der Werff and Hulls 1959-66) and so it can be assumed that the lake environment was certainly no longer under the same degree of marine influence as had been the case prior to 1874.

The dating of this section of sediment may shed light on the occurrence of Chetoceras muelleri which is classified by Van der Werff and Hulls (1959-66) as a brackish water species. In the 12cm sequence of sediments examined here, four annual or part annual cycles of sedimentation can be recognised (Fig. 7.4). Using the overall chronology of the sediments of core LP3M3 presented in Chapter 5, the uppermost annual unit (1) dates from 1924. Severe storms during January 1924 were known to have thrown large quantities of shingle over the bar, blocking the adit and causing flooding to occur at Helston (Plates 3.8-3.10). Such storms would have introduced some seawater to the lake and this additional salinity may have favoured the growth of C. muelleri. It is only present in relatively small numbers, in this one unit, and is all but absent in the rest of the upper sediments. In the sequence analysed by Simola et al. (1981), which is directly below the one currently being discussed, C. muelleri again only occurs in units s and t, which represent 1916 and 1917. No information is available on the occurrence of storms for these years and so the hypothesis must remain fairly tentative. A brief but sharp rise in the sodium influx at this time (170-180cm depth, Fig. 6.6) is, however, consistent with the idea of renewed marine influence.

The period from 1875 to 1927 is therefore one of stabilisation. The dominance of regular marine incursions, which had been the norm for several centuries, now ceased. The lake became a predominantly freshwater environment with corresponding changes in the diatom flora. The influence of mining is also evident but owing to the general decline in activity during this period, the industry had comparatively little impact.

8.6 The period 1928-1938 (Sediment Zone B)

This eleven year period is the most significant in terms of the catchment's mining influence. It marked a major resurgence of mining in the area. Although not the only one active during this period, the mine known originally as Basset & Grylls, was of considerable importance. It resumed working in 1928 under the name of Jantar, only to cease once more in 1929. Its last period of working, this time under the name of Porkellis Mine, was between 1934 and 1938. The company was liquidated in 1941. The technology associated with mining at this time was much in advance of that employed in the last century, and so output was far greater. The result was that the levels of mine waste were correspondingly higher, and reached such magnitude that the pollution became the subject of considerable public concern.

It has already been detailed in Chapter 5 that both legal action and pressure from the local council had been directed at the owners of Jantar. The practical consequences of the use of the Cober to receive mine wastes were that the river became choked with large quantities of silt and sand, much of which also entered Loe Pool. Despite promises by the mine owners to install additional machinery to reduce the problem, it would appear that this pollution continued for some considerable time. In the second of the two periods of operation, production was from two main lodes, known as 'Wheal Cock', and 'Old Mens' or 'Red Lode'. The latter was so named because of the haematite-rich nature of the ore.

Not only did the quantity of sediment increase, but considerable changes in the nature of the sediment itself occurred. Figs. 6.8, and 6.13 to 6.22 show the changes in particle size which resulted. Between 140 and 130cm depth, the mean particle size increases to include a higher proportion of sand and coarse silts, with very little clay.

In the central portion of Zone B the opposite is true, with a much higher proportion of fine silts and clays, particularly between 80 and 90cm. Above this the sediments revert to being similar to those of Zone C. These changes illustrate the very different nature of the materials being brought down from the mine workings by the River Cober.

Core LP3M3 was retrieved from around the centre of the lake (Fig. 4.1) and so may not truly represent the overall change in sediment character. Much of the larger particle size fractions were probably deposited at the head of the lake causing considerable infill. A comparison of the Ordnance Survey 1:2500 map of 1906-8 and that made by the Cornwall River Authority, which accompanies a report on the straightening of the River Cober (C.R.A. 1946), shows a considerable reduction in the area of open water at the head of the lake between these two dates (Figs. 3.7 and 3.8).

The extent of the infill is supported by evidence from the lake sediments. The period is recorded in a number of cores retrieved during this investigation and appears as a quite unique sequence of sediments. These can be seen in samples LP3M3 (Plate 5.1), LP3M4 (Plate 5.6), IF2 (Plate 5.7) and FBS9 (Plate 5.3) and have been designated as Zone B. As presented in Chapter 5, the mean sedimentation rate for this zone (from Core LP3M3) has been calculated as 9.6cm/yr. This is very high, even in comparison with the mean rate of 2.6cm/yr for Zone C. However, newspaper reports such as that from the West Briton (3rd April 1930) tend to support the fact that the River Cober was carrying enormous quantities of sediment into the lake at this time.

An additional event of significance which occurred in 1930 was the construction of the Helston sewage treatment works. Prior to this date, the waste from the sewered population of Helston had been discharged untreated into the River Cober. After the commissioning of the treatment works, the effluent from Helston, with a population in 1931 of some 2500 people, was given primary and secondary treatment at the works before it was discharged into the River Cober. The treated effluent nevertheless represented a new source of readily available nitrogen and phosphorus for the lake ecosystem.

Chemical influx and concentrations for Zone B of Core LP3M3 record considerable change as a consequence of the increase in sediment loading. In relative terms, many of the elements show a decrease in concentration in Zone B. This can be explained as a consequence of dilution by quartz and silicates produced by mining activity, and can be seen for elements such as sodium, potassium, magnesium and iron (Fig. 6.3) as well as for aluminium and chromium (Fig. 6.4). When these figures are adjusted to represent influx (in units $cm^{-2}yr^{-1}$), the influence of such a high rate of sediment deposition becomes evident. The pattern generally reflects the substantial rise in the total amounts of material being supplied to the lake via the River Cober during this period. In contrast to the increases exhibited by those elements mentioned above, whose origins are largely allochthonous, compounds such as the chlorophyll derivatives and carotenoids, which may be mainly autochthonous, show a decreased influx during this period.

Mackereth (1966) attributes the relative increases in lake sediments of elements such as sodium, potassium, and magnesium to changes in erosion rates within the catchment. In the case of Loe Pool, natural erosion has been substantially and artificially enhanced by the supply of mine wastes. These will certainly produce sediments with different characteristics to those which originate from the normal processes of erosion within the catchment. Mine wastes will not generally have been subjected to the same period of weathering as soils, and so the quantities of extractable cations and metals may differ from those associated with naturally eroded materials. For instance, according to Ochsenbein et al. (1983) magnesium is related to erosion rather than leaching, and is positively correlated with aluminium which is also associated with erosion. The results obtained from this core also show magnesium and aluminium to be very strongly correlated (r = 0.791, Table 6.2).

In general, the levels of metals within the sediments of Zone B must be closely allied to the amount of mining activity within the catchment. Yim (1981), investigating the fluvial sediments which originated in part from tailings from tin mines in Cornwall, found evidence of the presence of tin, copper, zinc, iron, manganese, arsenic and tungsten. The last two elements were not determined in this investigation, but the high levels of the other five are characteristic of this type of mine waste.

Phosphorus (Fig. 6.5) follows the pattern of mineral matter influx very closely. Mackereth (1966) states that co-precipitation with both iron and manganese is one of the pathways via which phosphorus enters the sediment. Much of the ore that originated from the mines in the catchment was rich in haematite and other iron minerals and so iron as an element is a major sediment constituent. The increased availability of phosphorus after 1930 as a result of sewage treatment may also have been reflected in the amounts being incorporated into the sediment. Lacey (1979) suggests that prior to 1930, the levels of phosphorus within the sediment are attributable to inorganic phosphorus from catchment erosion, whereas after this date, a much higher proportion is from organic sources.

Levels of nitrogen influx in Zone B are some 100-200% higher than in Zone C. The method used in the analysis of this element measures both organic and ammonium nitrogen, and thus gives the total concentration present in the sediment (Digerfeldt 1972). This originates from both allochthonous and autochthonous sources, and indeed, in this analysis, the levels of nitrogen are strongly correlated with the levels of organic matter, (as estimated by measurement of ignition loss, $r = 0.785$, Table 6.2). This may reflect changes in the annual influx of the element into the lake, but it is as likely to be a function of the speed of incorporation of organic material into the sediment. At times of lower rates of sediment accumulation, nitrogen compounds spend longer at the sediment-water interface and so become degraded and perhaps more easily re-released into the water, rather than incorporated in the sediments. The results for ignition loss, a surrogate for organic carbon, may be explained in the same way. Under conditions of fast deposition, organic materials have little time in which to become degraded before burial by further sediment. The uniform composition of some of the sediments in Zone B supports the idea of the extraordinary rates of deposition that have been calculated in this study.

Variations in sedimentary chlorophyll derivatives and carotenoids might at first appear to contradict the above findings. However, if a distinction is drawn between total organic material and and that which is merely autochthonous in origin, in particular the remains of phytoplankton, then lake productivity, as implied by these plant pigments, might reasonably be expected to decrease during periods of very high sediment influx. Decreased light availability as a result of high turbidity would limit photosynthetic potential, and as is indicated by the paucity of taxa found in some sections of these sediments, the diatom flora was certainly affected by these conditions. Much of the organic matter incorporated into the sediment during this period must therefore be of allochthonous origin, and again is a function of the quantities of material being carried by the River Cober at this time.

The phosphorus:chlorophyll ratio (Fig. 6.2) increases during Zone B, and also reflects the changes discussed above. The diatom record for Zone B (Figs.7.1 and 7.2) from core LP3M3 shows many similarities with that observed from the section of Zone C. The dominant taxa are still Synedra rumpens and Surirella ovata. In terms of influx (Fig. 7.2), their contribution to the sediment is an order of magnitude greater than that of any of the other species present. Synedra acus is the only other taxon to approach these levels. The sampling procedure, which used subsamples from homogenised 10cm sections of the core, is unable to distinguish the very fine detail of changes in diatom flora recorded within these sediments and only an overall impression of the flora can be given. Simola et al. (1981) have shown that within Zone B, the diatom remains are concentrated in distinct bands, usually the black laminae, and are very poorly represented in many of the rapidly deposited sections. Nevertheless, in most of Zone B, the overall number of diatom valves which are preserved within the sediment is very high. Considering the rather hostile environment prevailing within the lake between 1928 and 1938, this would appear to contradict some of the observations on productivity discussed above. An explanation may lie both in the relative abundance of available silica at this time, a consequence of the very high sediment influx to the lake, and in the percentage of diatom remains which were actually preserved within the sediments once deposited.

The first of these points would mean that silica was never a limiting factor in the production of diatoms. The results of phosphorus and nitrogen influx indicate that both of these elements were readily available. Diatom productivity would therefore appear to have been limited only by factors such as light availability or heavy metal pollution. With such an abundance of silica within the system, diatom valves which were incorporated within the sediment were probably not subject to dissolution and were most likely quickly buried by further rapid sediment accumulation. Evidence of bioturbation in this zone is also relatively low, although the burrows of some benthic fauna are visible in certain layers. Ingestion of diatoms by faunal predation can cause a reduction in the proportion of whole or identifiable remains, further reducing the numbers counted (Battarbee 1979), but this would appear to be insignificant here, except perhaps in the uppermost layers of Zone B. The percentage of total diatom production which was preserved within the sediment column must therefore have been high in comparison with periods when the sediment deposition rate was lower and bioturbation more significant.

The appearance of benthic faunal burrows in layer B034 (Plates 5.5, 5.8 and 5.9) appears to be the first record of this type of disturbance of the Loe Pool sediments. Above layer B034, and particularly evident in many of the upper parts of Zone B in core FBS09 (Plate 5.3), both the size of burrows and their frequency increase. This may simply be the result of progressive shallowing of the lake through the accumulation of sediments or it may be the first indirect evidence of lake nutrient enrichment. An additional possibility may be a change in redox conditions as a result of these and other factors. The iron:manganese ratio (Fig. 6.3) would certainly appear to decline in Zone B, indicating, according to authors such as Hutchinson (1957) and Mackereth (1966), that the lake environment had become less reducing. Engstrom and Wright (1984) however, believe that the interpretation of the Fe:Mn ratio is fraught with problems. In circumstances such as these, such comments are particularly salient.

Within just over a decade, humans would appear to have made a major impact on the lake system through industrial activity in the catchment. Metalliferous mining during this period delivered very large and unprecedented quantities of material to the lake and appears to have affected both the physical, chemical and biotic composition of the lake sediments. An additional effect seems to have been the loss of a fairly large area of open water at the head of the lake owing to sediment deposition at the mouth of the River Cober. Of no less importance is the fact that lake volume must also have decreased with the deposition of such volumes of material. This would in itself have reduced residence time and increased nutrient loadings. Owing to the shallowing of the water, wind-induced mixing would have increased with a subsequent reduction in the frequency of seasonal anoxia at the sediment surface. All of these effects would have had an impact on the chemical exchanges at the sediment water interface and on the biological productivity of the lake as a whole. The overwhelming influence of mining may also have masked evidence of the early impact of sewage effluent on the lake sediments.

8.7 The period 1939-1980 (Zone A)

This forty-two year period, represented by Zone A in the Loe Pool sediment column, also saw many changes in the lake and catchment system.

Active mining ceased in 1939, with a subsequent effect on sediment loading. In 1946-47 the Cornwall River Authority implemented their plan to reduce the risk of flooding in the Loe Valley by straightening or 'canalising' the River Cober below Helston (Plate 3.23). The work in fact did little to ameliorate the problems of a winter rise in lake level, and inundation of the Loe Valley to a greater or lesser degree was still common. This rise in lake level on a seasonal basis also meant that much of the River Cober's sediment load was at times deposited over a large area of the southern end of the Loe Valley. Rapid colonisation by vegetation of these relatively recent areas of sediment infill also increased sediment trapping in the area. This in turn promoted further vegetation growth. Between about 1910 and 1980, about 17% of the lake's area of open water was lost in this way. The process of vegetation succession has resulted in the growth of scrub woodland over much of the southern end of the Loe Valley and the development of extensive beds of _Phragmites australis_ and other lake marginal species around the northern fringes of the Loe itself.

In the last 40 years, the sewered population served by the Helson Sewage Treatment works increased from around 2,500 in the 1930's to approximately 10,000 in 1980. To accommodate this expanding population the works was enlarged on two occasions but even now cannot deal with peak flow caused by storm runoff. This, together with the sewage treatment works which serves R.N.A.S Culdrose and which discharges into the lake via Carminowe Stream, has sharply increased the input of phosphorus and nitrogen entering the system. In addition to these point sources, diffuse sources of nitrates and phosphates derived from agricultural fertilisers have also become more prominent in the last half century. In this, the most recent period in the lake's history, nutrient enrichment has become the dominant influence on the ecology of Loe Pool. Again, an examination of a number of aspects of the lake sediments support this view.

With the cessation of active mining in 1939, the degree of allochthonous sediment influx decreased sharply from the levels experienced in Zone B, creating an abrupt change in the sediment type. Zone A is distinguished by a uniformity of colour and, in most cases, structure.

The main problems associated with any detailed analysis of the sediments of Zone A is bioturbation. These uppermost sediments, particularly in the shallower areas of the lake, are heavily bioturbed and such mixing of the sediment masks the kind of fine stratigraphic detail available in Zones B and C.

Some samples retrieved during this investigation had escaped the worst effects of bioturbation and allowed examination of the relatively undisturbed structure of the sediments. This was clearest in those such as FBS07 (Fig. 5.2) where some laminations are visible. These were initially thought to be varves but the results of Cs-137 analysis dismissed this hypothesis. Far fewer "varves" than the number of years indicated by the dating technique were counted.

Even in FBS07, one of the clearest and least disturbed samples retrieved from Zone A, there is some bioturbation. This could have destroyed much finer laminations which formed upon initial deposition. Simola et al. (1981) showed that the sediments closest to the mud-water interface display annual sequences of diatoms, but this property dissipates with depth, perhaps indicating that bioturbation, and in shallower waters, turbulence created by winds, quickly disturbs the original structure. The conditions which would favour the formation of such varves certainly exist. There is sufficient seasonality of discharge and sediment supply and also of diatom and other algal production to produce rhythmic changes in sediment composition.

The degree to which bioturbation can disrupt the sediment structure can be seen in a number of samples where laminations are clearly cut through by faunal burrows and mixing. Samples FBS03 and FBS12 (Plates 5.4 and 5.5) illustrate this well. Many other samples of these uppermost sediments retrieved from Loe Pool during this study were so heavily bioturbed as to be of little analytical use. That used for Cs-137 analysis (FBS07), and that employed for detailed diatom analysis (FBS10), were similar but somewhat unusual in their degree of structural multiformity.

No detailed chemical analysis of Zone A was performed. The somewhat coarse analysis using 10cm homogenised sections of core LP3M3 was really insufficient to distinguish any fine detail in the levels of, particularly, nitrogen and phosphorus. These results shed little light on the eutrophication of Loe Pool. The additional problem of mixing of the uppermost three or four sections of this core after retrieval from the lake add to the problems of interpretation of chemical results. The only generalised results for Zone A are that the alkaline earth elements and metals decline in terms of influx when compared with both Zones B and C. This might be expected and can be explained by the substantial reduction in the rate of sediment deposition. This is illustrated by the levels of mineral matter influx (Fig. 6.5). Even phosphorus and nitrogen show little sign of reflecting the growing inputs to the system during this period. It is possible that some of the uppermost sediments were lost during the process of sampling for this core. The most recent unconsolidated materials are also the most likely to have contained higher concentrations of these elements. Work by Lacey (1979) using 1m Mackereth cores from Loe Pool and 1cm subdivisions for chemical analysis have shown significant rises in both nitrogen and phosphorus in the most recent sediments. Both this and the diatom results discussed below suggest that the 3m core could well have lost material from the surface.

The most detailed evidence for ecological change since the late 1930's was obtained by the diatom analysis of sample FBS10. A continuous count of diatoms was made, using the adhesive tape peel technique, from the sediment water interface to a depth of 26cm, incorporating the whole of Zone A and the upper portion of Zone B from layer B001 to B013. The changes which are evident certainly illustrate that ecological shifts have occurred over the past half century.

At the base of the section, sediments from the year 1937 (layers B013 to B005) contain a rather mixed flora comprising a fairly large number of unidentifiable diatom fragments but also a certain amount of Nitzschia and Synedra, including Synedra rumpens. Layers B009-B005 probably represent the winter of 1937-38 followed by a bloom of Synedra rumpens evident within layer B004. After this, Cyclotella meneghiniana appears, together with the remains of some green algae of the genera Pediastrum and Scenedesmus. Above this there is little trace of seasonality and the bands of very high sedimentation no longer appear.

Zone A subsequently displays a very different diatom flora. At the base of Zone A diatom numbers are very low. It would have taken the lake some time to have recovered from the effects of such heavy inputs of mine waste. Clearly conditions in the early 1940's no longer favoured Synedra rumpens as there is no evidence of the very large numbers of the taxon which occurred in Zone B. It persists in very small numbers for a period but vanishes above about 12cm depth. A more limited supply of silica may not have been tolerated.

Around the mid 1940's, at a depth of 15cm, Cyclotella meneghiniana reappears, followed by Asterionella formosa and Thalassiosira pseudonana at depths of 14.5cm and 12.8cm respectively. These give the first indications of eutrophy. A number of taxa such as Cyclotella meneghiniana are to be found in both slightly saline environments and in eutrophic freshwaters. Likewise, Thalassiosira pseudonana has only been reported as a marine or estuarine species (Hasle & Heimdal 1970) but here seems to have adapted to an increasingly eutrophic freshwater environment. Asterionella formosa is classified by a number of authors (e.g. Hustedt 1957, Simonsen 1962, Van der Werff & Hulls 1958-66) as a eutrophic diatom. Appearing from the base of Zone A but in smaller numbers and less consistently is Melosira varians. Again this is a species which is classified as both freshwater/brackish and an indicator of eutrophic conditions (Van der Werff & Hulls 1958-66).

Above about 14cm the remains of Pediastrum sp. reappear, followed Scenedesmus and Staurastrum. Their presence in the sediments also indicated a degree of eutrophy.

The most striking change in the diatom flora is the sudden appearance at about 6cm depth of Melosira granulata var.

angustissima. This again is a eutrophic species and it attains dominance at the expense of both *Cyclotella meneghiniana* and *Asterionella formosa*. *Thalassiosira pseudonana* maintains its values. Although diatom numbers appear to decrease at the sediment surface, this is a function of a lack of compaction.

TWINSPAN analysis of this sample (Fig. 7.5) shows a number of distinct associations of taxa which are more complex in nature than this immediate visual interpretation. It tends to give equal weighting to the less numerous taxa and as such is a less subjective technique for discerning changes in floral associations.

The picture which emerges from all these sources of evidence is one of a lake system suddenly relieved of the influx of the mine wastes which had, in one way or another, significantly influenced both the lake ecology and lake chemistry for many decades. The nature of these sediments and in particular the quantities which entered the lake from the catchment had altered the character of both the lake biota and the lake volume, the latter by virtue of the total depth of material added to the sediment column (c.f. O'Sullivan *et al*. 1982). After 1939 this influx had all but ceased and the lake was able to adjust to a different set of conditions.

Up until this point in the sediment column, the material is highly structured, not only with annual sequences of sediments, but also, in places, with numerous sub-annual laminations of considerable complexity. In Zone A, post-1939, both the colour and the structure of the sediments change. Laminations all but cease~~s~~ to be present except in a small minority of samples. Even in these few cores, the structures which are apparent, such as those preserved in core FBS7, Plate 5.2, are much less distinct than in deeper sediments and do not appear to be annual in nature. The general absence of laminations in Zone A may not be due to a cessation of lamination formation, but is probably due to a lack of preservation. As has already been mentioned, bioturbation is very evident in these sediments and considerable sediment mixing is the result. Laminations, again as a result of seasonal variation in sediment supply, still form, but are largely destroyed by the action of benthic organisms. The sudden reappearance of benthic activity in the sediment column is further evidence of the change in lake conditions which resulted from an overall shallowing of the lake and a period of increasing nutrient influx.

Although all mining had ceased after 1939, the influence of human settlement continued, and the next major influence on the lake system had already had some impact. Sewage effluent discharge entering the lake via the River Cober progressively increased in quantity as the population of Helston grew. In addition, commissioning of the Royal Naval Air Station at Culdrose, with a population in excess of 2,000, brought the total sewered population to some 12,000 people. The effluent from this population enters the lake and the effect has been the progressive cultural eutrophication of Loe Pool. This is not only reflected in the subfossil diatom record. In recent years, blooms of blue-green algae, largely *Microcystis* cf. *aeruginosa* regularly occur in the late summer (Coard *et al*. 1983) reducing the available oxygen and killing large numbers of fish.

The differences in sediment colouration in Zone A are likely to result from periodic, but much less frequent, instances of anoxia in summer. Rather than being a normal annual occurrence, as would appear to be the case particularly in Zone C, stratification and anoxia would only occur under very favourable, warm, calm conditions. The resultant black metallic sulphides are discernible in some cores but have been largely dispersed in most of the sediments through bioturbation. The fact that laminations of some sort are still being formed has been established by Simola *et al*. (1981), who found evidence of laminations displaying seasonal diatom deposition close to the sediment-water interface. The same seasonal influences on sediment formation that were acting on the lake system during the formation of the sediments of Zones C and B are still in operation now , but the physical, chemical and biological conditions have changed such that preservation of sediment structure is now rare.

The Pool, particularly in the past twenty years, has also changed in both ownership and function. From 1771 to 1976, it was part of the Penrose Estate owned and managed by the Rogers family. In 1976 Lt. Cdr. J.P. Rogers gave the area of the Penrose estate surrounding the Pool to the National

Trust. The family retained occupation of Penrose House and an active interest in the management of the lake. Under private ownership Loe Pool was used simply for fishing, with very limited public access. Stipulations made by the Rogers family upon transfer of ownership to the National Trust were that this level of use should not be significantly increased, with the exception of public access to the footpaths around the lake. To this day, the only recreational activity allowed on the lake is fishing, and this has been severely affected by recent pollution. The grounds and footpaths around the lake now support a much increased recreational useage and so objections to the seasonal blooms of algae which regularly result in a rotting and noxious scum of decaying algae around the lake, are growing. The only long-term solution to the problem is further treatment of the sewage to remove phosphorus (Wankowski 1979), or the cessation of sewage effluent discharge into the lake.

The last 40 years has also seen the growth in both height and width of Loe Bar. Following the instigation of regular maintenance of the drainage adit in the late 19th century and the last true breaching of the bar in 1874, a net gain in material began. The process of wave and storm build up continued into the present century (Figs. 3.3 and 3.4) and the bar has now attained some degree of equilibrium. Further addition of shingle only occurs during the most severe of storms. Such events have taken place in the last decade and the adit has again been blocked for short periods. The bar is now of such dimensions that cutting a channel by hand to release the flood water is not only impractical but impossible. Following the storms of January 1979 and November 1984 the Water Authority resorted to mechanical excavators to achieve this objective. Whether they presented Lt. Cdr Rogers with a purse containing the customary three halfpence for permission to cut the bar is not known. At the time of writing, a new adit entrance is nearing completion with the aim of easing the flow of water from the lake and allowing improved control of the lake water level. The alterations have been conducted with the cooperation of the Camborne School of Mines.

What is clear is that the lake has never been allowed to attain any sort of natural equilibrium as a truly freshwater lake. Human influence has been such that there has never been a period of stability within the system. Even prior to the 18th century, before human influence was of any real significance, the system was very dynamic, being affected by the conflict between a considerable marine input and the freshwater influence of the River Cober.

8.8 General comments

8.8.1 Loe Pool as a site for study

Loe Pool would appear to be unique in its combination of physical setting and history. Human influence has had an extraordinary inpact on the lake system. Although there are similar coastal freshwater lakes in the British Isles, e.g.

Slapton Ley near Dartmouth in Devon, none show the same degree of human influence, although their general physical development must have been similar. Even this must be governed by the relative influences of the sea and the lake's catchment. A study of the development of Loe Pool has therefore limited general applicability, but is important as a background for the future management of the lake. Some of the processes studied here can be applied to other lacustrine systems.

Some other British lakes have been found to contain varved sediments. These include Rostherne Mere (Haworth 1980), Diss Mere (Peglar _et al_. 1984), Loch Lomond (Dickson _et al_. 1978), Swanpool in Cornwall, Braydon Pond in Wiltshire (O'Sullivan unpublished), and a number of other Shropshire-Cheshire meres (O'Sullivan 1985). Few other varved or laminated lake sediments have been found or studied in Britain, and of the above, the sediments of Swanpool alone bear any overall resemblance to those of Loe Pool. The sediments observed in this investigation differ from any others published to date, and the varves have been classified as clastic/ferrogenic by O'Sullivan (1983). However, many of the sedimentary structures to be found in Loe Pool could well be formed in any similar lake influenced by the same seasonality of climate and sediment input. The techniques used to investigate these resultant sediment structures could also be usefully applied, and indeed are now being applied, to other British lakes.

None of the above lakes has been subject to the same combination of influences as Loe Pool. In particular, the influence of mining activity has resulted in very high sedimentation rates. Urswick Tarn (Oldfield & Statham 1963) was affected by mine wastes and contains a haematite layer close to the top of the sediment column, but sediment accumulation was not of the same order as in Loe Pool. In the Loe, rates have been shown to exceed 10cm per year. There are very few published instances of higher deposition rates in lakes. Normack & Dickinson (1976) found rates of 1.1m per year in a mine waste tailing deposit in Lake Superior. Hay & Waters (1985) discovered sedimentation rates of 0.57-1.29m per year in a coastal marine environment at Rupert Inlet, British Columbia, where diatoms were also used to establish a chronology for sediment accumulation.

There have been many published examples of small lakes which have varved sediments and which have also been influenced by the influx of sewage effluent. Lovojärvi (Saarnisto et al. 1977, Simola 1977) is an example, but sedimentation rates are very low and although the sediments show seasonality of diatom deposition, the varve structures are not comparable.

Loe Pool's history is unique. The same combination of marine and complex cultural influences would be hard to find elsewhere. As such it allows a rare insight into the response of such a system to these influences, some of which have been outlined in this study. Further studies of the fine structure of the lake sediments have been undertaken (Pickering, Ph.D.

thesis, Plymouth Polytechnic, 1987) and these enlarge upon certain aspects of the lake's development.

8.8.2 Techniques

Conventional dating methods such as many of the radio-isotope techniques and more recent magnetic analyses were found to be inappropriate to these sediments. As a result a combination of Cs-137 dating, varve counting and the discernment of annual sequences of sediments by diatom analysis were used. These were combined with all available documentary and cartographic material to assemble a sediment chronology. With such a variation in sediment types and rates of sedimentation, such a dating is bound to include inaccuracies and errors. However the mutual reinforcement of several lines of evidence has resulted in a chronology which makes sense. There is, as ever, room for refinement. Accurate dating is essential if the results of both chemical and diatom influx calculations are to be reliable.

The rate of deposition within Loe Pool was such that even with a 3m Mackereth corer, sediments containing little more than a century of deposition could be retrieved. This limited the period over which sedimentary analysis could contribute to an understanding of the lake's development. Although 'Russian' borers were also used, the degree of difficulty in maintaining position and sampling up to 5m of sediment in 6m of water was considerable. The subsequent freezing of both these samples and the 3m Mackereth cores highlighted other problems. Unless frozen quickly and in situ, the sediments are disturbed by ice crystal formation during the freezing process, which itself was aimed at allowing freeze-drying and subsequent adhesive tape peels to be taken. All types of frozen sediment samples have to be kept frozen, and the failure of storage facilities such as chest-freezers can result in the catastrophic loss of material through melting.

The use of a combination of in situ freezing of sediment samples and the subsequent adhesive tape peels for diatom analysis can give much more detailed information on diatom changes than is possible using more conventional coring devices and subsampling techniques. Owing to the very minimum of disturbance to the sediment column during sampling, very much finer detail of stratigraphy is discernable. The technique is particularly applicable to the collection and examination of unconsolidated near surface sediments. Without the employment of this technique, much of the dating of the stratigraphy of the Pool sediments would have remained impossible.

It is clear from the relatively coarse nature of the rest of the diatom, and the chemical, analyses, that the information that can be drawn from them is fairly limited. Since the methods of chemical analysis that were adopted here were published by Bengtsson (1979), more sophisticated techniques for the chemical analysis of lake sediments have been put forward by Engstrom and Wright (1984). These now allow much more information to be gained from the sediment chemistry, although the number of instances where these techniques have been applied is, as yet, limited. The techniques adopted in this investigation however, do allow comparison with many other published studies.

The microfossils observed during analysis of the lake sediments also have varied applicability and use. Of greatest importance are the diatoms, details of whose taxonomy and environmental preferences are available from a wide variety of sources. A number of other microfossils were also counted alongside the diatoms. Sponge spicules have received considerable attention in recent years as indicators of lacustrine conditions. In Loe Pool they showed no seasonal pattern of deposition or distinct changes with presumed variation in water chemistry. The cysts of various Chrysopyte taxa were also noted and these played some role in the identification of seasonal changes within the sediments. They have been associated with autumnal sediment deposition by authors such as Battarbee (1983).

The further analysis of the continuous diatom counts by indicator species analysis (TWINSPAN) proved useful in only one of the samples. In sample FBS10, clear changes were observed in the results of the analysis although these were harder to interpret than the simple interpretation of the diatom diagrams. It did however provide a more objective illustration of floral change. In most of the other cases where TWINSPAN was applied, the analysis was unable to provide a clearer picture of seasonal changes in diatom deposition. The use of such analyses of TWINSPAN requires both caution and careful interpretation of results.

Chapter 9

Summary

From the evidence which has been collected and collated during this investigation, a detailed picture of the development of the Loe Pool system has, for the first time, been compiled.

No one line of investigation can provide sufficient information to assemble a complete picture. However, a multidisciplinary approach, such as has been adopted here, has provided a wider perspective on the development of this particular lake and catchment system.

Loe Pool is undoubtedly unique. Superficial similarities with other lowland freshwater lakes, such as Slapton Ley or Swanpool, are outweighed by the extraordinary combination of natural and cultural influences which have operated on the catchment, the shingle bar and the lake itself over the past 6000 years, and in particular, over the past four or five centuries.

It has been possible to fulfill the aims of the investigation detailed in Section 1.2, with the exception of dating the timing of isolation of the lake from the sea. The major physical and cultural influences on the lake have been identified and a chronology has been established which is linked to the most significant ecological changes that have happened to the system.

In summary, therefore, the most important influences on the lake system have been those of climatic change, the sea, human management of the system, the metalliferous mining industry, and the influx of sewage effluent.

The first of these, climatic change, governed the long term development of the lake-watershed system as a whole. Overdeepening of the Cober Valley during periods of lower sea level laid the geomorphic foundation for the development of the lake itself. The rise in sea level known as the Holocene transgression provided a mechanism for the onshore movement of shingle which constitutes a high proportion of the present shoreline material around Mount's Bay. Variation in climatic regimes also governed the volume of runoff discharged from the Loe Pool catchment area. The balance between this and the constructive processes of coastal shingle movement in turn controlled the development of a spit or bar feature across the mouth of the River Cober. Depending on the nature of this equilibrium, the area now occupied by Loe Pool may at times have been either an estuary, freshwater, or a freshwater lake with considerable brackish-water influence.

A slowing of the rate of sea level rise after around 6000 years B.P. provided the system with a degree of relative stability, allowing any bar feature which may have begun to form, the chance to establish. Any equilibrium, however, could easily have been upset by changes in discharge from the catchment, resulting from climatic change. Present day conditions are such that the coastal depositional processes outweigh the ability of catchment discharge to remove shingle, and so the bar has developed into a substantial feature.

The most significant long-term ecological influence on the lake itself has been the sea, and it was only in the latter part of the last century that its impact diminished. Prior to 1875, the Pool was regularly open to the sea both through spontaneous natural outbreaks of lake water, and the customary breaching of the bar by local residents, to reduce flooding in the lower parts of Helston. The subsequent changes in lake salinity sometimes lasted for many months, imparting a brackish influence on the ecosystem of the Pool.

The cessation of bar breaching, which followed the adoption of a more consistent management of the drainage adit, allowed the bar to accumulate material without the regular loss of shingle which was normally associated with each breach. The marine influence diminished as a consequence, and the Pool became entirely freshwater with an associated change in the lake biota.

The metalliferous mining industry, which had been active to a greater or lesser degree throughout the previous two centuries, reached its most intensive period in the 1920's and 1930's. During this period, the lake was dominated by the industry's wastes, with the rates of sediment deposition within the lake rising to very high values. The influence of these wastes on lake turbidity and on water chemistry is reflected in the diatom flora preserved within the sediments.

Climate, lake morphometry and mining have been responsible for the formation of the quite unique laminations deposited between 1875 and 1938 (Zones C and B). Seasonal variation in rainfall, and thus streamflow, provided the basis for a differentiation between winter and summer deposition. In the 19th century, with the mean depth of the lake was some 3m greater than today, anoxia at the sediment-water interface in the summer months was more frequent. These conditions promoted the formation of black metallic sulphides which resulted in a distinct seasonal change in sediment colour, in contrast to the grey, oxidised, winter sediments. This distinction between winter and summer sediment character is further confirmed by the seasonality of diatom deposition which is evident within the annual sequences. Having established that these black (summer) and grey (winter) sediments represent varves, it was then possible to use the property of seasonal diatom deposition to provide a chronology for the sediments of Zone B (1928-38), during which time huge quantities of mine wastes radically altered the regular sedimentation patterns of previous years. The unusual nature of the sediments precluded the use of any other conventional dating techniques.

When, in 1939, all active mining ceased, a further cultural influence assumed a growing dominance over the lake ecosystem. The influx of sewage effluent from the treatment works at Helston increased in quantity from the early 1930's when the plant became operational. This point source of abundant phosphorus and nitrogen increased in line with a rising population and was joined in 1947 by the discharge from the treatment works which serves R.N.A.S. Culdrose. Again, the lake sediments record changes in water chemistry and algal flora, and results indicate a growing level of cultural eutrophy over a period of fifty years. This evidence, combined with the fact that the Pool now has an increasing problem of algal blooms, illustrates the extent to which human influence has attained dominance over its ecology.

The sediments of Zone A, from 1939 to the present, appear initially to be quite different from the deeper deposits. Their source material lacks the artificial supplement of mine wastes, present to a greater or lesser degree throughout Zones C and B. Deposition rates consequently diminished, but the seasonality of sedimentation was still present. Fewer instances of anoxia led to greater uniformity of colour and a diminution in the deposition of black sediments. The overall shallowing of the lake together with an increased nutrient input from treated sewage effluent encouraged a newly active benthic fauna. This in turn promoted mixing and bioturbation of the sediments with a subsequent loss of structural preservation. Seasonal differences in sediment supply mean that laminations still form upon deposition but can quite rapidly become homogenised.

The lake sysem has therefore rarely been allowed to attain stability for any period of time. The influences of marine incursion, mine wastes, and more latterly, cultural eutrophication, have meant that the system has remained in a state of dynamism, reacting and adapting to changing inputs and pressures. To provide the preconditions for a more ecolologically stable and long term future for Loe Pool would require an effective management policy which could deal with these current cultural pressures by, for instance, reducing the phosphorus load which enters the lake. Unfortunately, "economic" restraints may prevent such action, with the inevitable result that the lake will continue to decline in ecological value and aesthetic appeal under the persistent pressure of chemical pollution.

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