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# THE NATURAL HISTORY OF SLAPTON LEY NATIONAL NATURE RESERVE

## XXI: THE PALAEOLIMNOLOGY OF THE UPPERMOST SEDIMENTS OF THE LOWER LEY, WITH INTERPRETATIONS BASED ON $^{210}$Pb DATING AND THE HISTORICAL RECORD.

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### ABSTRACT

Lead–210, mineral magnetic, sequential inorganic chemical, chlorophyll 'a', and microfossil analyses of sediment cores from the bed of the Lower Ley, Slapton have been used to study the history and development of the lake, and its catchment, mainly over the last 200 years. According to $^{210}$Pb dating, the uppermost 40 cm of a core from Ireland Bay have accumulated in the period since *ca* 1790 AD. Multiple coring, and inter-core correlation by means of determination of whole-core volume magnetic susceptibility (K), shows that patterns of sedimentation within the Ley are uneven, with accumulation proceeding most quickly at the southern end, but more slowly in the north.

Analyses of mass-specific magnetic susceptibility ($\chi$), SIRM, and SIRM/$\chi$ ratio in the sediments, and in catchment material, indicate that since *ca* 1950, erosion of topsoil, associated with the post-war intensification of agriculture, has resulted in an increase in the rate of sediment accumulation within the Ley. Current sediment influx, based on the rate of dry matter sedimentation, is calculated to be 610 t $a^{-1}$. This is equivalent to a sediment accumulation rate of 9 mm $a^{-1}$, or to an erosion rate from the catchment of 13.4 t $km^{-2}$ $a^{-1}$, although the last figure may be a considerable underestimate, owing to the presence of substantial delta and reedswamp areas at the mouths of the main inflowing streams.

Sequential inorganic geochemical analysis, based on the fractionation protocol devised by Engstrom & Wright (1984), allows the separation of sediment into authigenic (mobile), biogenic (biologically-fixed) and allogenic (minerogenic) components. Along with $^{210}$Pb dating, this procedure then enables trends in both concentration (mg $g^{-1}$ dry mass) and in influx (mg dry mass $cm^{-2}$ $a^{-1}$) of selected elements to be evaluated. According to the results obtained, before 1856, Slapton Ley was a shallow, well-oxygenated lake, into which, beginning in that year, much calcareous material was introduced by a phase of lime-kiln operation, road construction and raising of the lake level. The latter change also led to an episode of mild seasonal deoxygenation of the sediment-water interface (SWI), which lasted from *ca* 1910 until the middle 1970s.

Chemical data then confirms that since *ca* 1948, erosion of detrital material from the catchment has increased, as indicated by the enhanced influx of allogenic forms of potassium, aluminium, and phosphorus. That this was associated with some eutrophication of the Ley is shown by a parallel rise in both concentration and influx of biogenic silica. An increase in influx of *authigenic* phosphorus is indicated by the $^{210}$Pb chronology to be related to the connection, in 1953, of a substantial number of new houses in the village of Slapton to the sewage treatment works located 1 km upstream of the Lower Ley, which had been commissioned in 1934.

A major peak in authigenic nitrogen, 6 cm below the present sediment surface, is then correlated with the severe drought of 1976, when for the first time for many years, the Lower Ley became isolated hydrologically from the Upper Ley, and therefore from *ca* 70% of its inflowing waters. The ecosystem of the Lower Ley may have been triggered by this event into its present hypereutrophicated state.

Diatom analysis of the topmost sediments shows that the earliest evidence for mild eutrophication of the Ley, in the form of a slight increase in frequency of planktonic centric taxa, can in fact be traced back to *ca* 1910, and the impact of a land use change from arable cultivation and the rearing of sheep, to pasture and the keeping of dairy cattle, which took place in the period 1885–1915. Centric diatoms then expand further, however, in *ca* 1960, when the ecosystem of the Ley appears to have responded to a further increase in the amount of sewage effluent received. In the mid–1970s, a major shift in the trophic status of the Ley occurred, when the former clear macrophyte lake with abundant epiphytic diatoms began to be replaced by a turbid, hypereutrophicated system, characterised by centric species, which now began to make up more than 60% of all sedimentary diatoms. This event is also attributed to the effect of the major drought of 1976.

The above events are also recorded in provisional fine resolution pollen assemblage zones which can be related both to the same land use changes in the catchment, and to their effects on the macrophyte flora of the Lower Ley. A decline in the frequency of oak pollen, and an increase in that of the Gramineae, are tentatively correlated with the enclosure of rough grazing and scrub in the upper part of the catchment in the eighteenth century. At this level, *Myriophyllum* replaces *Potamogeton* as the most abundant freshwater macrophyte pollen present.

A further increase in grass pollen is correlated with the land-use change documented for the period 1885–1915, when the amount of pasture expanded at the expense of arable land. Recent changes in the frequencies of aquatic macrophytes and *Urtica* are thought to be associated with eutrophication, and an increase in the amount of phosphorus in the ecosystem of the Ley and its catchment.

In recent years, production in the Ley has oscillated between massive phytoplankton blooms, mainly of *Anabaena flos-aquae* and *Microcystis aeruginosa,* and extensive growth of macrophytes (mostly *Ceratophyllum demersum, Myriophyllum spicatum* and *Elodea canadensis*), and *Cladophora.* As shown by Johnes & O'Sullivan (1989), phosphorus loadings upon the lake are at the level where such a changeover might be expected (Moss, 1983). As well as eutrophication, however, this is also thought to be related to variations in numbers of fish, and to their impact on the grazing of benthic and planktonic algae by zooplankton. In order to return Slapton Ley to its formerly stable, naturally productive state, not only should all sewage phosphorus be removed from the system, but diffuse ('non-point') loads, which come mainly from agriculture, will need to be reduced by *ca* 30%. Even then, some form of biomanipulation of the lake ecosystem, disrupted by eight decades of eutrophication, may be necessary.

## INTRODUCTION

Lakes and their drainage basins have long been recognised as extremely valuable frameworks for the study of environmental change, and of human impact upon the rest of nature (Binford, Deevey & Crisman, 1983; Deevey, 1984; Oldfield 1981, 1983; Oldfield, Battarbee & Dearing, 1985; O'Sullivan, 1979; Smith *et al.,* 1991). The material incorporated in the sediments of a freshwater lake may be *allochthonous* (i.e. originating outside the basin of the lake, usually either in the rocks, soils, or the biota of the catchment, or in the atmosphere over both the catchment and the lake), or *autochthonous* (produced by sources and processes within the lake itself). As it accumulates through time, such sediment continuously records the history not only of the lake itself, but also of its catchment, and of the important interactions which take place between processes on the land and those in water, and of human impact upon these relationships (O'Sullivan, 1979).

Analyses may be based on the physical, chemical, or biological properties of the sediments, or on all three. As pointed out by Moss (1980, p 195), lake sediments contain far more information than we can presently extract. In recent years, the development of increasingly precise chronological methods (Oldfield, 1981; O'Sullivan, 1983) has enabled investigators to study much more recent events, particularly human impact upon contemporary or near-contemporary environments. Similarly, rapid methods of analysis of large numbers of cores, and of correlation between them, based mainly on the magnetic properties of the mineral content of the sediment (Dearing, 1983, 1986, 1991; Thompson & Oldfield, 1986), has, along with the development of more precise chronologies, allowed the calculation of sediment influx, and the quantification of the rate at which many processes in lakes and their catchments operate.

Chemical analysis of freshwater lake sediments was pioneered by Mackereth (1965, 1966). He concentrated on bulk (or total) inorganic elemental determinands, and expressed his results in terms of the relative composition of the material analysed (concentration in mg $g^{-1}$ dry sediment or mg $g^{-1}$ mineral matter). For nearly twenty years, his was the model which all inorganic chemical analyses of lake sediments followed. Engstrom & Wright (1984) then devised a step-wise procedure for isolating the three fractions (authigenic, biogenic and allogenic) of a lake sediment, each of which originates in a different sector of the lake-watershed ecosystem.

The *authigenic* fraction is that fixed by processes such as chemical precipitation and flocculation occurring in the lake water column. Most authigenic material first enters the lake in solution via precipitation, or in stream water, so that it is in fact ultimately *allogenic* in origin. It consists of the most mobile forms of each element present (usually ions), often adsorbed on to colloidal particles of clay, humus and other substances in the form of ligands, and is the fraction most easily leached from the sediment matrix by weak acids, or other, similar reagents.

*Biogenic* material has, in contrast, been passed through the food chains either of the lake itself or, perhaps, of the catchment, and has therefore been fixed by organisms. It is often made up of the partly-decomposed tissues of those organisms and, therefore, mainly records the history of the biota of the lake and its watershed. *Allogenic* material is mainly minerogenic, and consists largely of matter in crystalline form. As such, it is refractory, and much less easily extracted from the sediment. It constitutes, however, a record of events taking place in the catchment, as opposed to the authigenic and biogenic components which, despite their ultimate terrestrial source, refer respectively to changes in lake physics, chemistry and biology.

Engstrom & Wright's method allows a more precise identification of sediment provenance and, therefore, of changing sediment source. When allied with modern techniques for dating near-surface sediments (for example, lead–210 ($^{210}$Pb) or Caesium–137 ($^{137}$Cs) analysis, Oldfield 1981; palaeomagnetism, Thompson 1973; or varve counts, O'Sullivan 1983), it enables the expression of results in terms of sediment influx (mg $cm^{-2}$ $year^{-1}$). This represents a much more powerful means of investigation, from an inorganic chemical perspective, of the recent history of a lake and its catchment.

The investigation described below was designed to increase knowledge regarding the history, over the past two centuries, of the eutrophication of the Lower Ley, Slapton a small, productive, eutrophicated* lake in Southwest England. Slapton Ley is a

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* Throughout this paper, following Moss (1988), and Deevey (1984), the term eutrophication is reserved for the process of enrichment of a lake or other wetland by nutrients originating in its catchment. It is thus regarded as being a separate process both from succession, and from infilling with sediment, neither of which are necessarily accompanied by nutrient enrichment, even though they may, particularly in the case of succession, involve enhanced productivity (O'Sullivan, 1994).

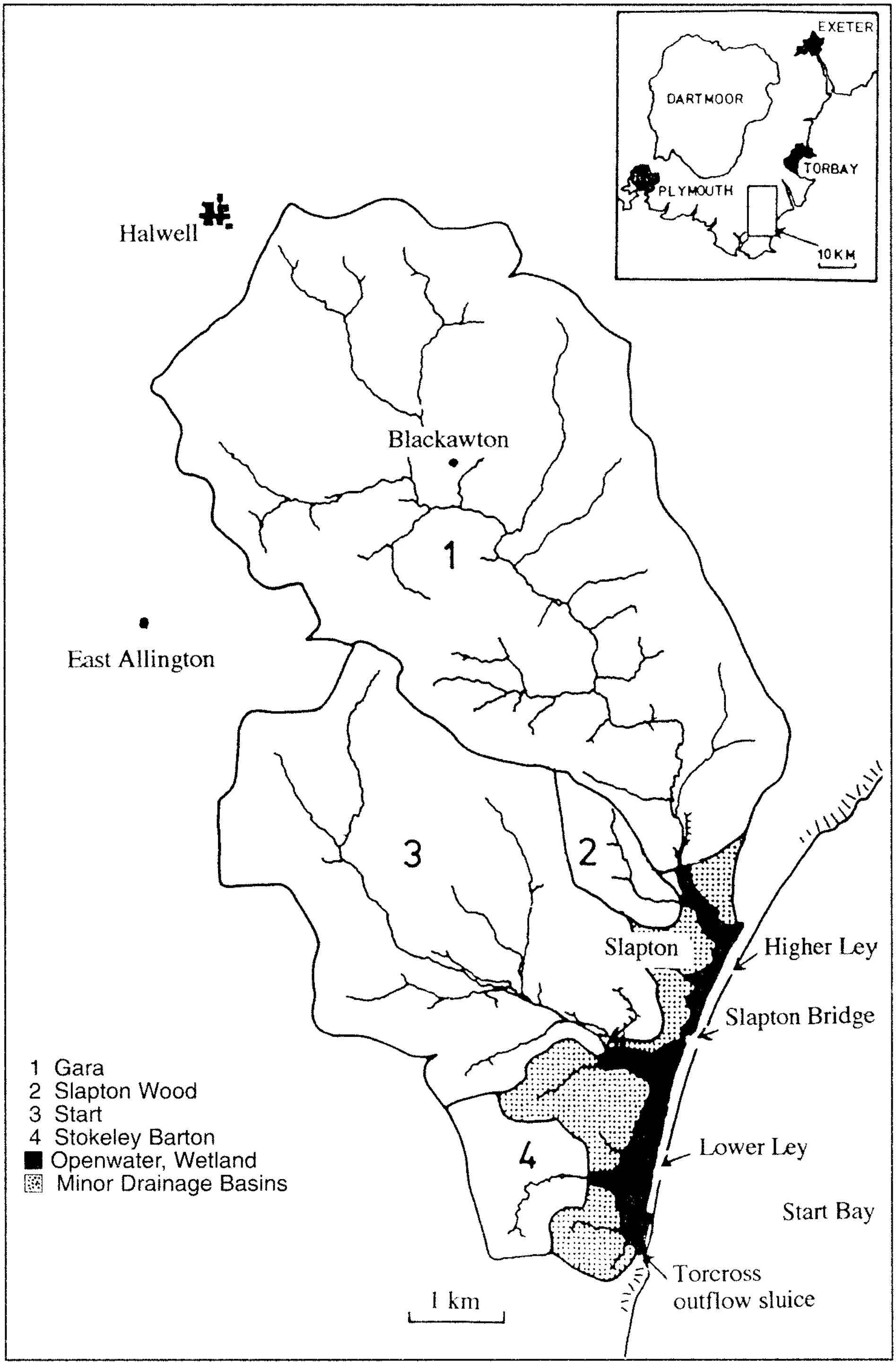

FIG. 1

Slapton Ley and its catchments. Based on Fig. 1 from Van Vlymen (1979)

National Nature Reserve administered by the Field Studies Council. It is also an important part of the economy of the area in which it lies. Concern for its future is reflected in the recent choice of its catchment as one of seven pilot areas for the Water Fringe Option of the Habitat Improvement Scheme by the Ministry of Agriculture (*The Guardian*, London, 16 May 1994; *Western Morning News*, Plymouth, 17 May 1994). Data concerning the history and causes of its eutrophication are, therefore, a key input into policies concerned with the conservation and management of the site.

## SITE DESCRIPTION

Slapton Ley (Fig. 1) is a coastal wetland, located ca 10 km south of Dartmouth, Devon, SW England, formed behind a shingle bar some 6 km in length. The wetland is divided into two basins, the Higher Ley which is mainly reedswamp, and the Lower Ley which is a long, narrow, shallow freshwater lake orientated NNE/SSW, nowhere deeper than 2.8 m, despite its area of 77 ha (Table 1). The Ley is fringed by extensive reedswamps and other habitats making up a Reserve of some 116 ha.

At the northern end of the Ley (Fig. 2) is Ireland Bay, in which the water is *ca* 1.5 - 2 m deep, and from which most of the cores employed in this and earlier studies have been collected. The narrow central 'neck' portion of the Ley is somewhat deeper, but, especially in its northern half, was much damaged by bombardment with live ammunition in 1943, during rehearsals for the Allied invasion of Europe (Morey, 1976). At the southern end, in Stokeley Bay and near Torcross, water depths of less than 1.5 m are common.

The Ley is now a shallow, mainly well-oxygenated, turbulent lake. On many days of the year, Langmuir cells form whose diameter is such that the whole of the water column must be in circulation (author's personal observation). Conversely, in periods of calm weather, oxygen gradients develop at the SWI, and there is some evidence for phosphorus release from the sediments (Bark, 1986; Smith, 1988; Van Vlymen, 1980). For most of the year, however, the surface of the sediments, in which diatoms and the faecal pellets of copepods are abundant, remains well-oxygenated. The Lower Ley is a highly productive lake, inhabited by a macrophyte flora in which *Ceratophyllum demersum, Myriophyllum spicatum* and *Elodea canadensis* are prominent (Wilson, 1991). In some recent years (e.g., 1984, 1994), these, along with filamentous green algae including *Cladophora*, appear to have replaced phytoplankton as the main producer organisms, even in the limnetic zone. However, in most years spring growth of diatoms is followed by a bloom of *Anabaena flos-aquae* in the period June to August and, in September, by one of *Microcystis aeruginosa* (Benson-Evans *et al.*, 1967; Van Vlymen, 1980). During the period 1973–1976, chlorophyll 'a' levels of up to *ca* 600 mg $m^{-2}$ were observed (Van Vlymen, 1980). In 1984, the fish populations of the Ley, mainly the perch, *Perca fluviatilis* L., roach, *Rutilus rutilus* (L.) and rudd, *Scardinius erythrophthalmus* (L.), were severely reduced and have only recently begun to recover (Kennedy, 1991; *Dartmouth Chronicle*, Dartmouth, 24th January, 1992). Numbers of the common eel, *Anguilla anguilla* (L.), do not appear to have been affected.

The catchment of Slapton Ley (Fig. 1) is a deeply dissected plateau (maximum elevation > 200 m), developed over Lower Devonian slates which weather to shallow (0-0.5 m) silty loams (Trudgill, 1983) rich in haematite ($\alpha Fe_2O_3$) but poor in lime. The main inflowing tributaries are the River Gara (catchment area, D = *ca* 27 km$^2$), which

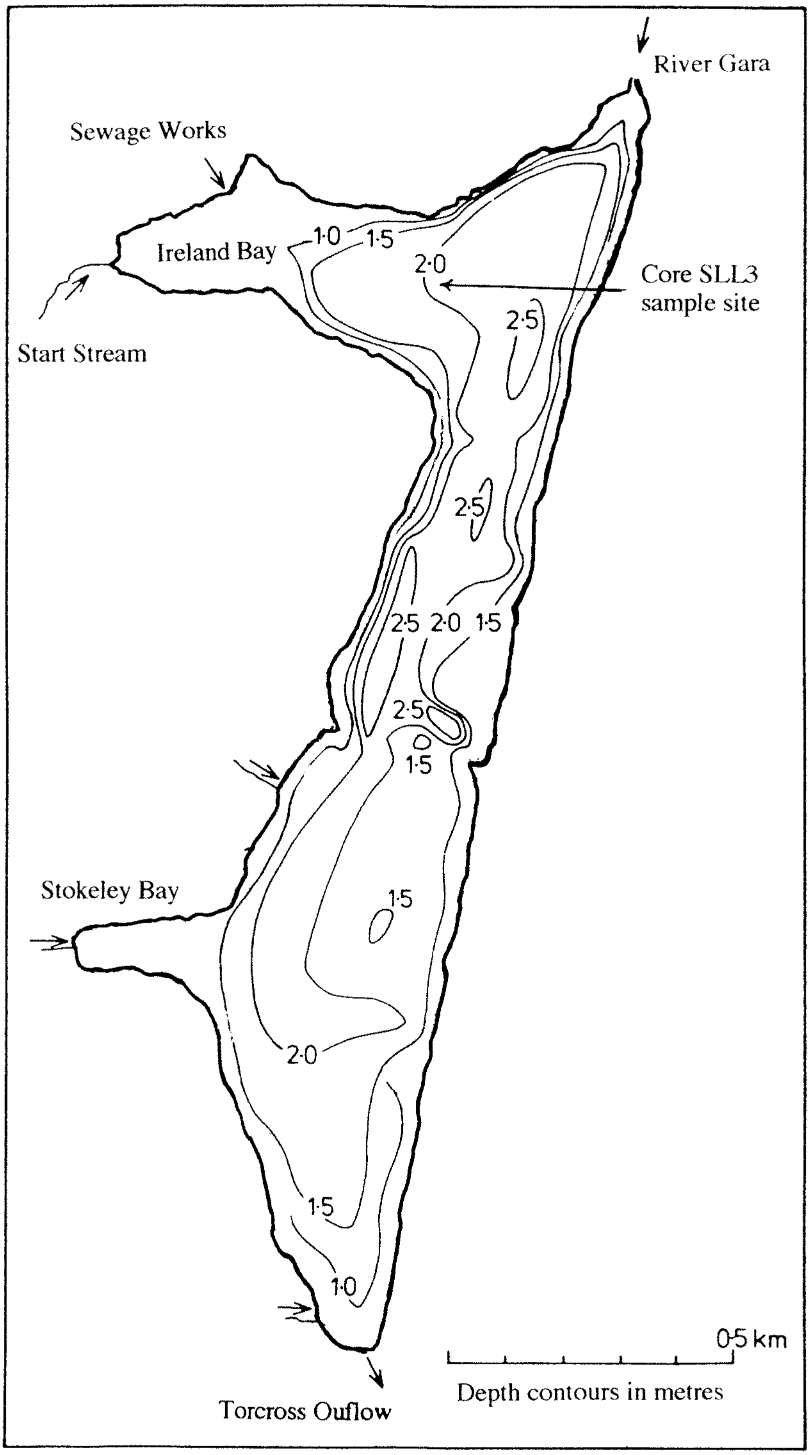

FIG. 2
Bathymetry of Slapton Ley (from Van Vlymen, 1979) and site of core SLL3

TABLE 1. *Morphometric characteristics of the Lower Ley, Slapton (from Van Vlymen, 1980)*

| | |
|---|---|
| Mean depth (z) | 1.55 m |
| Maximum depth ($z_{max}$) | 2.80 m |
| Area (A) | 77 ha |
| Volume (V) | 1.19 x $10^6$ $m^3$ |
| Mean water residence time ($T_w$) | 17.5 days |

enters via the Higher Ley at Slapton Bridge, and the Start Stream (D = *ca* 13 $km^2$) which flows in through Ireland Bay (Fig.1). Other drainage totals *ca* 6 $km^2$. The Ley drains through a culvert at its extreme southern end, at the village of Torcross. This outflow was constructed in 1856, at the same time as the road which runs along the shingle ridge (Stanes, 1983).

The main land use of the catchment of Slapton Ley is agriculture. About 38% of the area consists of permanent grassland, mainly confined to steeper slopes. Improved, temporary grass makes up 32%. Other land-use types include cereal cultivation (16%), arable (3.7%), rough grazing (3.5%), and woodland (4%). Johnes & O'Sullivan (1989) predicted that, in 1985, average annual losses of nitrogen and phosphorus from this catchment into the Ley were 160 tonnes of nitrogen (t N) and 4.8 tonnes of phosphorus (t P), of which *ca* 148 t N and 2.44 t P came from agriculture, and 8 t N and 2.3 t P from sewage. The total external nitrogen load on the Ley may in fact be somewhat higher, and of the order of 260 t $a^{-1}$ (O'Sullivan *et al.*, 1989), but monitored phosphorus levels are close to those predicted. According to Stanes (1983), the parish of Slapton (corresponding to part of the lower reaches of the Gara and Start catchments) was traditionally an area of arable farming, with the growing of oats and barley. Cattle were grazed on temporary pastures, rotated with cereals, and sheep were raised in rough pastures on the higher ground at the edge of the parish. Hay was grown in irrigated meadows along the streams and valley sides.

In the parishes of East Allington and Blackawton (which include the higher parts of the Gara and Start catchments), there was much rough grazing and scrub land ('furze') which, according to Stanes, was not enclosed until the C18th (see also McCoy, 1989). Further studies of more recent changes in land-use (Barrows, 1991) show that, in the late C19th, early C20th, 'traditional' farming was largely replaced by dairying, with a decline in arable land and the numbers of sheep but an increase in the stocking rates of cattle and of the amount of land given over to grass, both permanent and temporary. In the late C19th, external nitrogen and phosphorus loads on the Ley were probably *ca* 40 t N, and 1 t P, $a^{-1}$ (Acott, Barrows & O'Sullivan, in preparation).

After 1945, agriculture intensified and numbers of both cattle and sheep, and the acreage of grassland, continued to rise. Nitrogen loadings upon the Ley probably increased to *ca* 58 t $a^{-1}$ in 1945 and, thence, more rapidly to present values (see above). Phosphorus losses from agricultural land may have fallen slowly throughout this period, from *ca* 4 t $a^{-1}$ in the late C19th to 2-3 t $a^{-1}$ from 1945 onwards.

As mentioned, Slapton Ley is a National Nature Reserve and a conservation site of European importance. It is also a significant factor in the economy of the South Hams district of South Devon, in which it lies, attracting many visitors. In recent years, there has been concern that the Ley is becoming increasingly productive, which is now reflected in the selection of its catchment as one of seven pilot areas for the Water Fringe Option of the Ministry of Agriculture's Habitat Improvement Scheme. Consequently, any information regarding its recent history and the development of its eutrophication is of prime importance. This paper presents a summary of research into the palaeolimnology of Slapton Ley carried out over the past sixteen years.

## PREVIOUS PALAEOECOLOGICAL WORK

The sediments of Slapton Ley have previously been studied by Crabtree & Round (1967) and by Morey (1976). The first analysed a 1.2 m core from Ireland Bay and found that, for most of the period since its formation, the Lower Ley has been a mildly productive lake, in which diatoms of the genus *Fragilaria* have been particularly abundant. That the waters of the Ley were both clear and shallow at this time is shown by the occurrence of many epiphytic, benthic and littoral taxa. Little evidence for prolonged marine incursions was found, but there was some indication of episodes of erosion of catchment material, in the form of layers of both red and grey clay.

Morey (1976) studied the longer-term development of the Ley. He confirmed that it was formed both by onshore and south-to-north movement of beach material (Hails, 1975; Mercer, 1966) and that, below the present freshwater *gyttjas*, are peat and clay layers indicating a succession from estuarine deposits through reedswamp peats to open water. Radiocarbon dates from the uppermost peat showed that the present phase of freshwater sedimentation cannot be older than 1800 years. Comparing the altitude of the Ley bed with a curve of Holocene sea level rise (Clarke, 1970) gives an age of *ca* 1000 years for this most recent freshwater stage.

## METHODS

### *1. Core collection*

All cores were collected using the 1 m 'Mini-Mackereth' sampler designed by Mackereth (1969). The main coring site employed was located as close as can be determined from their description to that used by Crabtree and Round (1967) in Ireland Bay, in the northern part of the Lower Ley (Fig. 2). Here, cores for $^{210}$Pb dating (cores SLT3 and SLL3), whole core and single sample mineral magnetic analyses (SLJW), and chemical (SLL3) and microfossil analysis were collected. The locations of the multiple cores used for studies of patterns of sedimentation in the Ley are shown in Fig. 6 (see below).

### *2. Wet volume/dry mass, bulk density, loss on ignition, carbonate content*

Selected cores were carefully sectioned by gently pressing the full core tube vertically downwards onto a rubber bung supported by a wooden rod, thus forcing the sediment slowly out of the top of the tube, where it was sliced using a template of the same diameter. From each slice, 2 ml of wet sediment were collected and weighed, in order to determine the wet mass of a known volume (V) of sediment (and, hence, bulk density (D)). These samples were then dried at 110°C for 24 hours and reweighed, so that dry mass/water content (DM) could be estimated. They were then ignited in a muffle furnace, first at 550°C, and then at 950°C, for four hours on each occasion, in order to determine respectively (a) loss on ignition (LOI, the reciprocal of ash content), and (b) carbonate content.

### *3. Lead–210 dating*

Non-destructive determination of lead–210 ($^{210}$Pb), radium–226 ($^{226}$Ra), caesium–137 ($^{137}$Cs) (and americium–241; $^{241}$Am) content of core SLL3 was carried out at the Environmental Radiometric Unit, University of Liverpool. Lead–210 is measured by gamma emissions at 46.5 keV, and $^{226}$Ra by 295 keV and 352 keV gamma rays emitted by its daughter isotope $^{214}$Pb. Caesium–137 and $^{241}$Am are determined by means of their emissions at 662 keV and 59.5 keV respectively. Hence, it is possible to obtain $^{210}$Pb, $^{137}$Cs and $^{241}$Am chronologies from the same assay (Appleby *et al.*, 1990). The $^{210}$Pb chronology from core SLL3 was thus moderated against the 1963 peak for $^{137}$Cs. Lead–210 content of core SLT3 was determined at the Scottish Universities Research and Reactor Centre, East Kilbride, Scotland, by Dr A. G. Mackenzie.

### *4. Mineral magnetic analyses*

Whole core volume initial apparent reversible magnetic susceptibility (K) was determined on all cores using a Bartington MS1B susceptibility bridge and loop sensor designed specifically for use with Mackereth cores. Results, which are dimensionless, are therefore expressed in arbitrary units (Figs. 5 and 6). Single sample, mass specific susceptibility ($\chi$) was determined for one sediment core, and for samples of catchment material (Table 2, Fig. 7), using a well-sensor and the same susceptibility bridge as employed in the volume measurements. SIRM, coercivity and 'S' ratio were measured using a MOLSPIN portable spinning magnetometer, samples having been first magnetised or de-magnetised in a MOLSPIN pulse-magnetiser. The geophysical basis of the techniques employed here, and definitions of the variables determined, may be obtained from Thompson & Oldfield (1986).

### *5. Sequential inorganic chemical analyses*

Cores were stored intact at 5°C until subsampling took place. Twenty 1 cm slices were extracted from the top 20 cm of core SLL3, and 2 cm intervals from 20 cm downwards, using the method described under (2), above. The sediment below 40 cm was discarded because the $^{210}$Pb profile for the adjacent core SLT3 (completed earlier) had indicated that below this depth material would be of an age beyond the range of that technique. The core slices were subsampled for the determination of wet volume (V), bulk density (D), dry matter content (DM), loss on ignition (LOI), mineral matter content (MM, reciprocal of LOI), and carbonate content immediately after slicing (after Allen, 1989).

The sequential chemical fractionation procedure used here follows that of Engstrom & Wright (1984) except that analysis began with 1 ml fresh wet material rather than 1 g dry sediment. This makes no difference to the calculations, provided the dry mass/wet volume relationship for the sediment has already been recorded (see above), and renders the calculation of influx (mg $g^{-2}$ $a^{-1}$) somewhat easier. The protocol, which is still in the process of being adopted by palaeolimnologists, and which may therefore not be entirely familiar to workers in other fields, is briefly repeated here for reference.

One g or 1 ml of fresh wet sediment is reacted with 25 ml 30% hydrogen peroxide, in order to destroy organic matter. When oxidation ceases, 5 ml of 0.3 Normal hydrochloric acid are added, and the sample is brought to volume with 50 ml pure water. It is then heated at 90-95°C for 30 minutes, in order to extract carbonates and amorphous oxides. The sample is then passed through a 0.45 µm millipore filter, and the filtrate brought to volume with 1 l pure water.

The residue is washed into 50 ml 0.2 Normal sodium hydroxide solution, and the sample again heated at 90-95°C for 15 minutes, in order to dissolve biogenic silica. It is then filtered again. This second residue is placed in a graphite crucible, with 0.5 g lithium borate, and fused in a muffle furnace for 15 minutes at 950°C. The molten bead is then dissolved in 100 ml 0.5 Normal hydrochloric acid on an ultrasonic mixer, and diluted by a factor of 1:10 for analysis.

The filtrate from each stage of the procedure is used for determinations. The same analytical method is applied to all three sets of filtrates. All elements except potassium, nitrogen and phosphorus were determined by atomic absorption spectrophotometry (AAS) using a Pye-Unicam SP9. Potassium was determined by means of flame emission spectroscopy using the same instrument, and nitrogen and phosphorus by means of autoanalysis, and by the modified methods of Crooke & Simpson (1970) and Murphy & Riley (1962) respectively, using a Chemlab Autoanalyser.

### *6. Chlorophyll 'a'*

Chlorophyll 'a' was determined after the method of Fogg & Belcher (1961), as described by Bengtsson (1979). The pigment was extracted from fresh wet sediment samples with acetone, and its carotenoid derivatives were subsequently isolated in petroleum ether. Concentrations were determined on a Perkin-Elmer 124 double beam spectrophotometer at 664-667nm for chlorophyll derivatives, and 445-450nm for carotenoids. Results are expressed in arbitrary sedimentary chlorophyll units (SCU) $g^{-1}$ dry mass, or influx of SCU in g $m^{-2}$ $a^{-1}$, one unit being equivalent to an absorbence of 0.1 in a 1 ml cell when dissolved in 100 ml of solvent (Vallentyne, 1955).

### *7. Microfossil analyses*

Diatoms were prepared for counting by Moscrop (1987) by cleaning with 30 volume hydrogen peroxide, and mounting in Naphrax (Battarbee, 1986). The number of frustules counted on each slide varied between 285 and 305. Pollen was extracted from a 1m Mackereth core from Ireland Bay by Nicholls (1988) using the methods described in Faegri & Iversen (1974) and in Moore & Webb (1978). Both the results of pollen and diatom analyses are expressed in terms of percentage counts, and so cannot be used to estimate changes in productivity, but only to detect floristic variations related to changes in community structure.

## RESULTS AND INITIAL DISCUSSION

### *1 Sediment stratigraphy*

The majority of cores employed in the investigation exhibited the following stratigraphy:-

| | |
|---|---|
| 0–0.35/0.4 m | Dark brown *gyttja*. |
| 0.35/0.4–0.45/0.6 m | Red brown or paler brown clay-*gyttja* |
| below 0.45/0.6 m | Dark grey clay-*gyttja*. |

In core SLL3, taken in Ireland Bay, however, the stratigraphy was

| | |
|---|---|
| 0–0.12 m | mottled black and pale brown *gyttja* |
| 0.12–0.23 m | pale brown clay-*gyttja* |
| 0.23–0.4 m | mottled black and pale brown *gyttja*,<br>becoming sandier towards the base of the core. |

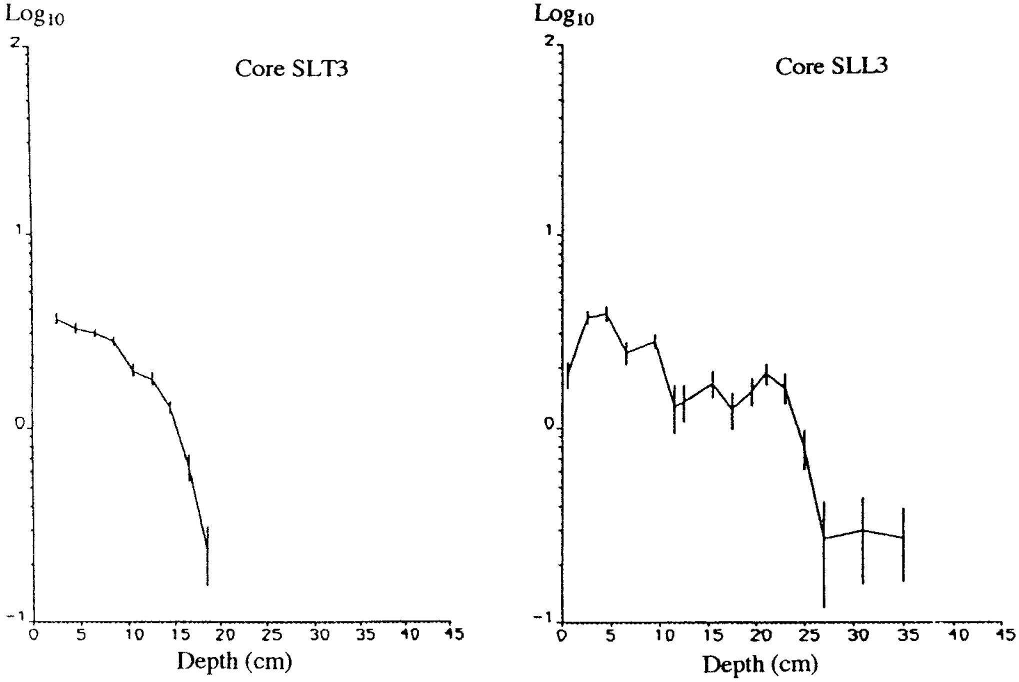

Fig. 3
Unsupported $^{210}$Pb concentration (pCi g$^{-1}$) in cores SLL3 and SLT3 from Slapton Ley.

that some 8 t ha$^{-1}$ of dry matter are deposited annually on the bed of the Ley. This is equivalent to an accumulation rate of 9 mm a$^{-1}$, or an influx of material from the catchment of some 610 t of dry matter a$^{-1}$. The former value gives rather faster average accumulation rates for the bed of the Lower Ley as whole than those obtained from the $^{210}$Pb dated cores (see above). These, however, were collected in Ireland Bay, an area of the lake bed where the isopach map (Fig. 6) shows that the accumulation rate is about half that of much of the lake. An input to the Lower Ley of 601 t dry matter a$^{-1}$ would be equivalent to an erosion rate from its catchment of 13 t km$^{-2}$ a$^{-1}$.That this figure may be, however, a considerable underestimate is shown by direct monitoring of suspended sediment loads in the rivers discharging into the Ley (A. L. Heathwaite, personal communication). These indicate that when allowance is made for the effects of floods, the total annual suspended sediment input into the Ley may be of the order of 1440 t, or the equivalent of an erosion rate of *ca* 30 t km$^{-2}$ a$^{-1}$. That this value may also, in turn, be an underestimate is suggested by studies of accumulation of alluvial sediments in the area around Deer Bridge (Fig. 1) by Owens (1990). Instead, he concludes that the erosion rate for the catchment of Slapton Ley as a whole lies somewhere between 82 and 148 t km$^{-2}$ a$^{-1}$.

Thus, the multiple core studies conducted here indicate fairly accurately the amount of influx of sediment (601 t a$^{-1}$) *to the lake bed.* Direct monitoring (quoted above) similarly records the amount of sediment (1440 t a$^{-1}$) *delivered* to the lake. However, owing to retention 'higher up' within the system, and probably also because

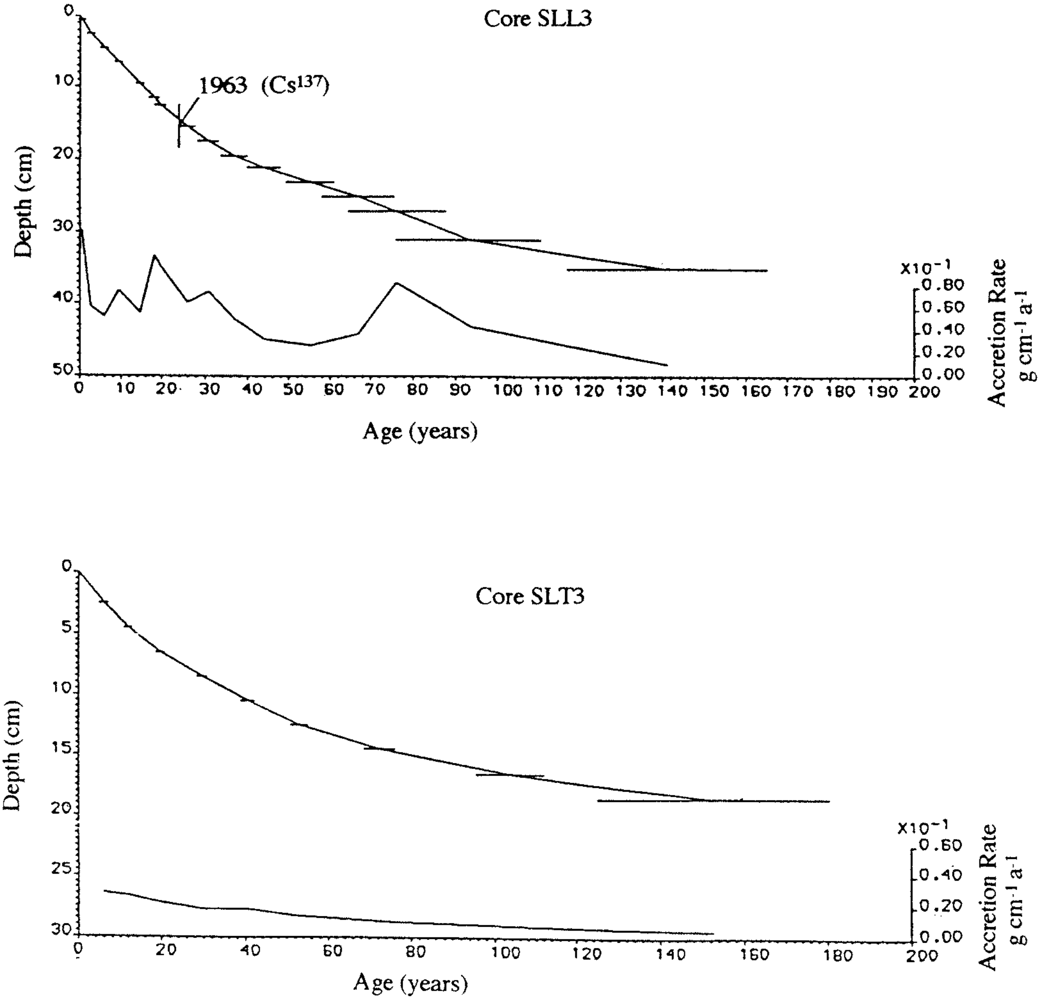

FIG. 4
Age-depth relationships for cores SLL3 and SLT3.

of flushing of fine sediments through the lake in winter (Van Vlymen, 1979; 1980), neither figure provides an accurate estimate of the rate at which material is *eroded* from the catchment. This has been the case with other lake-sediment based studies of catchment erosion (Foster *et al.*, 1985; O'Sullivan *et al.*, 1982), and reflects a need for careful choice of sites at which to conduct such investigations (Dearing, 1991).

### *4. Single sample susceptibility (χ), SIRM and coercivity ('S') of catchment source material, and of lake sediments.*

Table 2 summarises the results of determination of χ, SIRM, SIRM / χ and coercivity

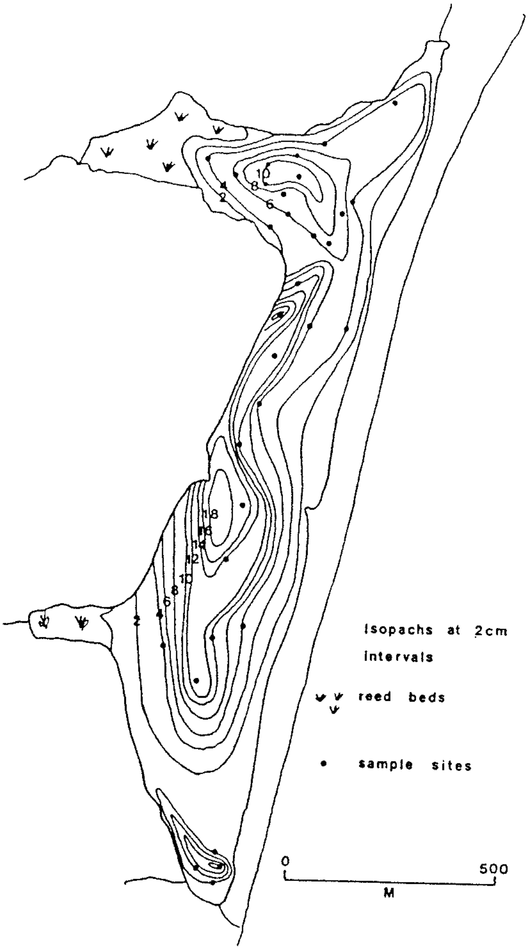

FIG. 5
Isopach map for the Lower Ley, Slapton, showing locations of cores used in estimating sediment thickness.

('S') of bedrock, soil, and fine bedload material from the Slapton catchment, and sediments from the Lower Ley, by Crick (1985) and Ms Janet Wilmshurst. Compared to bedrock, $\chi$ is much greater in the stream bed and soil material, with the latter containing the most enhanced values. Levels of SIRM are also highest in the soil matter, with the bedrock again giving the lowest readings. With respect to coercivity (-IRM / SIRM or 'S'; Oldfield, 1981; Thompson & Oldfield, 1986), bedrock is magnetically the 'hardest', with less than 50% of SIRM being removed at $IRM_{-2000}$. The soil matter exhibits the greatest values of 'S', with up to 60% of SIRM being erased at only $IRM_{-200}$, and 80-95% at $IRM_{-1000}$. This is therefore magnetically the 'softest' of the three types of catchment material examined.

The soils of the Slapton catchment are developed mainly over rocks of the Lower Devonian (Mercer, 1966). These weather to produce the characteristically red soils of South Devon, whose colour is due to the presence of haematite ($\chi Fe_2O_3$), typically a

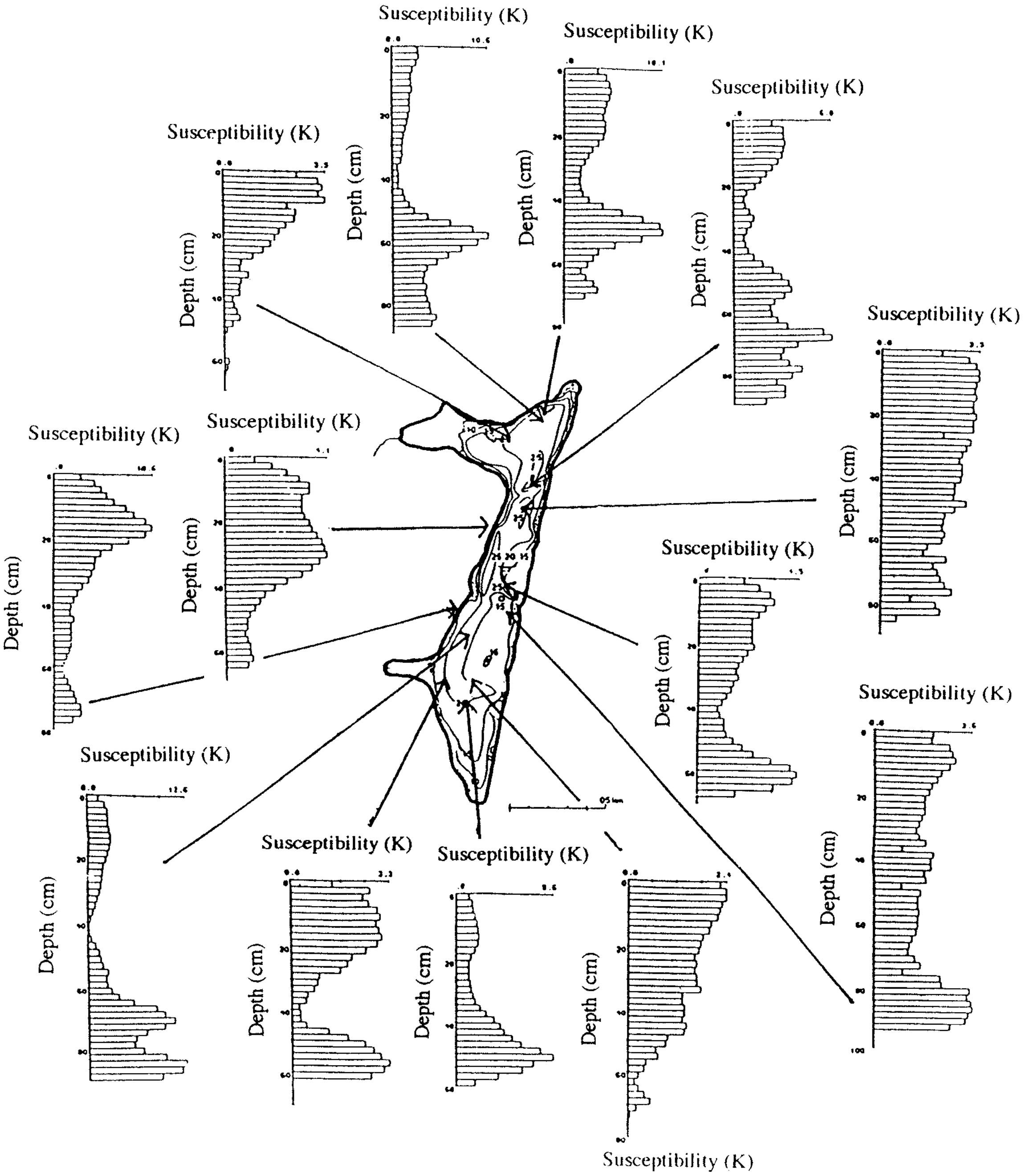

FIG. 6
Whole core susceptibility (K) profiles from Slapton Ley
(analysts T. Mulder, M. Crick & N. Vernon).

TABLE 2. *Characteristic values of $^c$, SIRM, SIRM/$^c$ and 'S' of environmental materials from Slapton Ley and its catchment (after Crick, 1985).*

| | Bedrock | Soil | Stream sediments | Lake sediments |
|---|---|---|---|---|
| $\chi$ (10$^{-2}$ cm$^3$ kg$^{-1}$) | 0.4–1 | 6–30 | 5–20 | 1.25–5 |
| SIRM (Am$^2$ kg$^{-1}$) | 55–270 | 570–1900 | 100–400 | 105–515 |
| SIRM / $^c$ (kAm$^{-1}$) | 65–520 | 38–128 | 80–350 | 80–170 |
| 'S' (IRM$_{-200}$ / SIRM %) | 5–10 | 40–55 | 5–50 | 20–30 |
| 'S' (IRM$_{-1000}$ / SIRM %) | 10–20 | 77–95 | 7–60 | 80–90 |
| 'S' (IRM$_{-2000}$ / SIRM %) | 20–50 | 80–100 | 20–90 | 90–100 |

'hard' magnetic mineral (Thompson & Oldfield, 1986). Nevertheless, these results show that despite their red coloration, being 'softer' magnetically than the underlying bedrock, the soils around Slapton Ley have also become enhanced to a certain extent with other iron minerals, amongst which is probably magnetite ($Fe_3O_4$).

In the lake sediments, values of $\chi$ most closely resemble those of the stream bed material, but levels of SIRM are closest to, or in some cases even exceed, those recorded in the soil matter. Similarly, the coercivity of the lake sediments is similar to that of the soil material, with 20-35% of SIRM removed at IRM$_{-200}$, and 70-90% at IRM$_{-1000}$. Thus the lake sediments, which are of course a mixture, contain material contributed partly by stream bed sources, but with a strong component which originates in the soils of the catchment of the Ley.

Analysis by Crick (1985) of a 1 m core from the deltaic area of Ireland Bay (see Morey, 1976) indicates (Fig. 7) that in the lowermost 50 cm, $\chi$, SIRM, SIRM/$\chi$ and IRM–200 remain fairly constant, or increase only slowly. In the top 25 cm, however, values of $\chi$ rise more rapidly, and peaks in SIRM (and hence troughs in 'hard' –IRM/SIRM) are recorded. A similar study of a core collected further out into Ireland Bay by Ms. Janet Wilmshurst (Fig. 8), records the same trend. $\chi$ and SIRM begin to expand from very low levels at *ca* 30 cm which, by correlation with core SLL3, is dated at *ca* 1900 AD. $\chi_{fd}$ (frequency-dependent susceptibility, Oldfield, 1981), which is associated with very fine magnetic particles formed in topsoil, varies between 5 and 20% of $\chi$ below this level, and then falls to 5–10%. It expands again only in the top few cm of the SIRM/$\chi$ increases from less than 500 kAm$^{-1}$ below 20 cm, to more than 500 kAm$^{-1}$ above that level (dated by $^{210}$Pb at *ca* 1950). Determination of SIRM and the 'S' ratios in both cores suggests that, in general, the haematite component of the sediments increases towards the SWI.

These results therefore indicate that, after *ca* 1910, and again following 1945, increasing amounts of topsoil were eroded into Slapton Ley. The existence of peaks in sediment influx at or around both dates is confirmed by the $^{210}$Pb chronology. Such

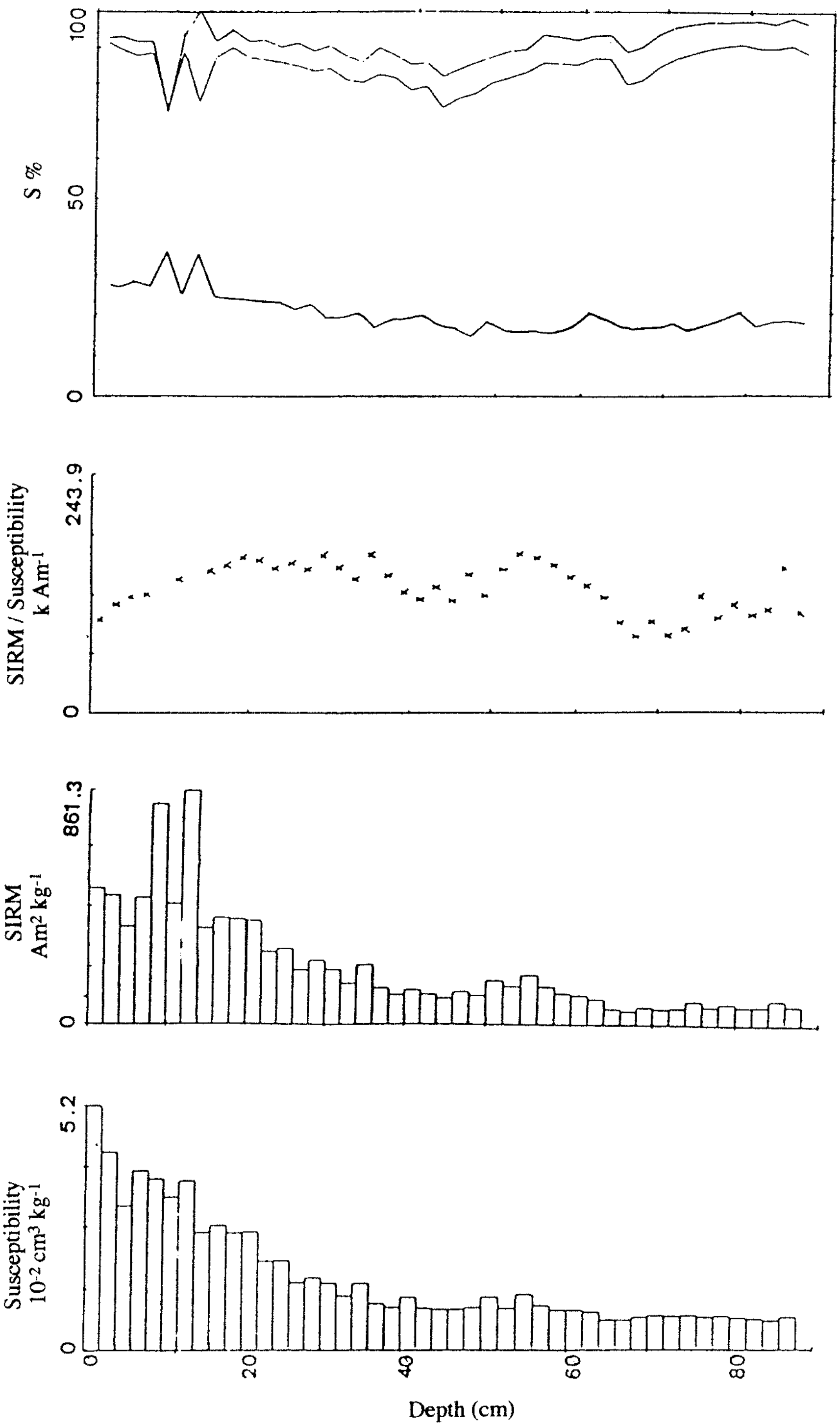

FIG. 7
Mineral magnetic properties of core M1 from Slapton Ley (from Crick, 1985).

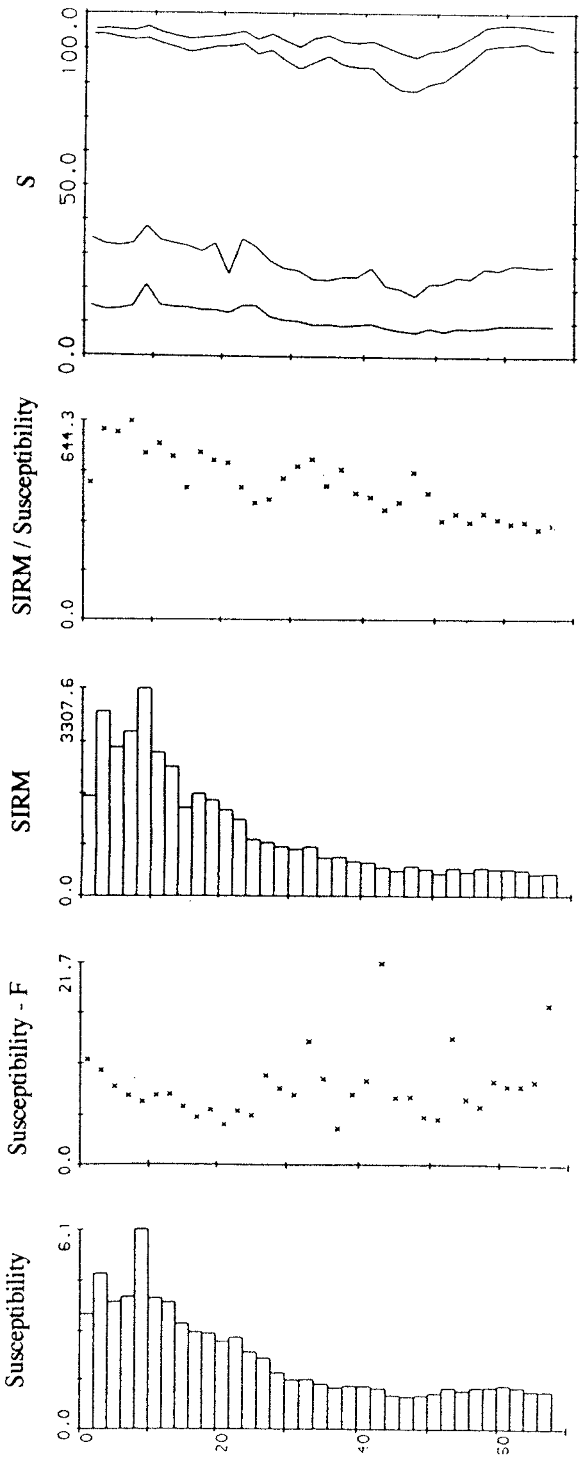

FIG. 8
Mineral magnetic properties of core SLJW from Slapton Ley (analyst J. Wilmshurst).

increases are attributed to changes in land use, and in particular to (a) a switch in production from arable cultivation and sheep rearing, to pasture and dairying which took place in the late C19th, early C20th (Barrows, 1991), and (b) the intensification of agriculture after 1945 (Acott, 1989).

### 5. *Total sediment influx, bulk density, dry matter content, loss on ignition, mineral matter and carbonate content of core SLL3.*

Fig. 9 depicts total sediment influx (I), bulk density (D), dry matter content (DM), ignition loss (LOI), mineral matter (MM), and carbonate content for core SLL3. Also added, is the $^{210}$Pb chronology from the same core. A major change in the physical properties of the sediment takes place in the section 24–28 cm, where D, DM and MM fall, and LOI increases. The change is mirrored in the profile for carbonate content, which exhibits a sharp decrease, and in the stratigraphy (see above).

From the $^{210}$Pb chronology, it may be seen that this change occurred in the period 1906–1926 AD, centred on the year 1910. Peaks in total sediment influx, which apply, of course, to this core only and not to the sediments of the Ley in general, are dated at 1822, 1908, 1968 and 1987 AD. Superimposed upon these is a general upward trend in sediment influx, and of influx of mineral matter.

### 6. *Sequential inorganic chemistry*

The data presented in this section must be considered in terms of both concentration and influx for, as explained by Engstrom & Wright (1984), the two methods of expressing the results give different, but complementary information. In the diagrams (Figs 10–12), the complete curves represent *total* concentration or *total* influx as appropriate, and the light portions, the authigenic fraction. The abundance of the *allogenic* component (the dark portion of the curve) may therefore be assessed visually by subtracting the authigenic component from the total. The only exception to this rule is the curve for silica (Fig. 10), where the paler shaded portion consists of the biogenic rather than the authigenic fraction.

It is not possible to correlate these results at all closely with those obtained by Crabtree & Round (1967), whose study was conducted upon a longer core, and whose samples were positioned at much wider intervals. However, comparison of their curve for sedimentary calcium concentration (Crabtree & Round, 1967, Fig. 2, p 258; Fig. 4, p 260) with our own (Fig. 11a) suggests that core SLL3 probably represents approximately the top 28 cm of Crabtree & Round's core, plus the 12 cm of sediment which had accumulated in the intervening twenty years. This is supported by the $^{210}$Pb chronology, in which 12cm is equivalent to 19 years BP (where P (present) = 1987).

In core SLL3, three elements (potassium, aluminium and silicon, Fig. 10) are located mainly in the allogenic fraction. According Engstrom's model, their contribution to the sediment therefore consists mostly of mineral matter embedded in the crystal lattice, which only passes into solution during the last stage of fractionation. Six others (magnesium, calcium, manganese, iron, nitrogen and phosphorus) are attached mainly to the authigenic component, which means that, whatever their ultimate source, they are delivered *to the sediment* by processes of chemical fixation *within the lake.* Two of these (calcium, manganese, Fig. 11) are almost exclusively authigenic in origin, whereas the others (Fig. 12) possess small allogenic components. Of these, iron, nitrogen and phosphorus follow each other quite closely, whilst the curve for magnesium is similar to that of iron in the top half of the core, but mimics those of

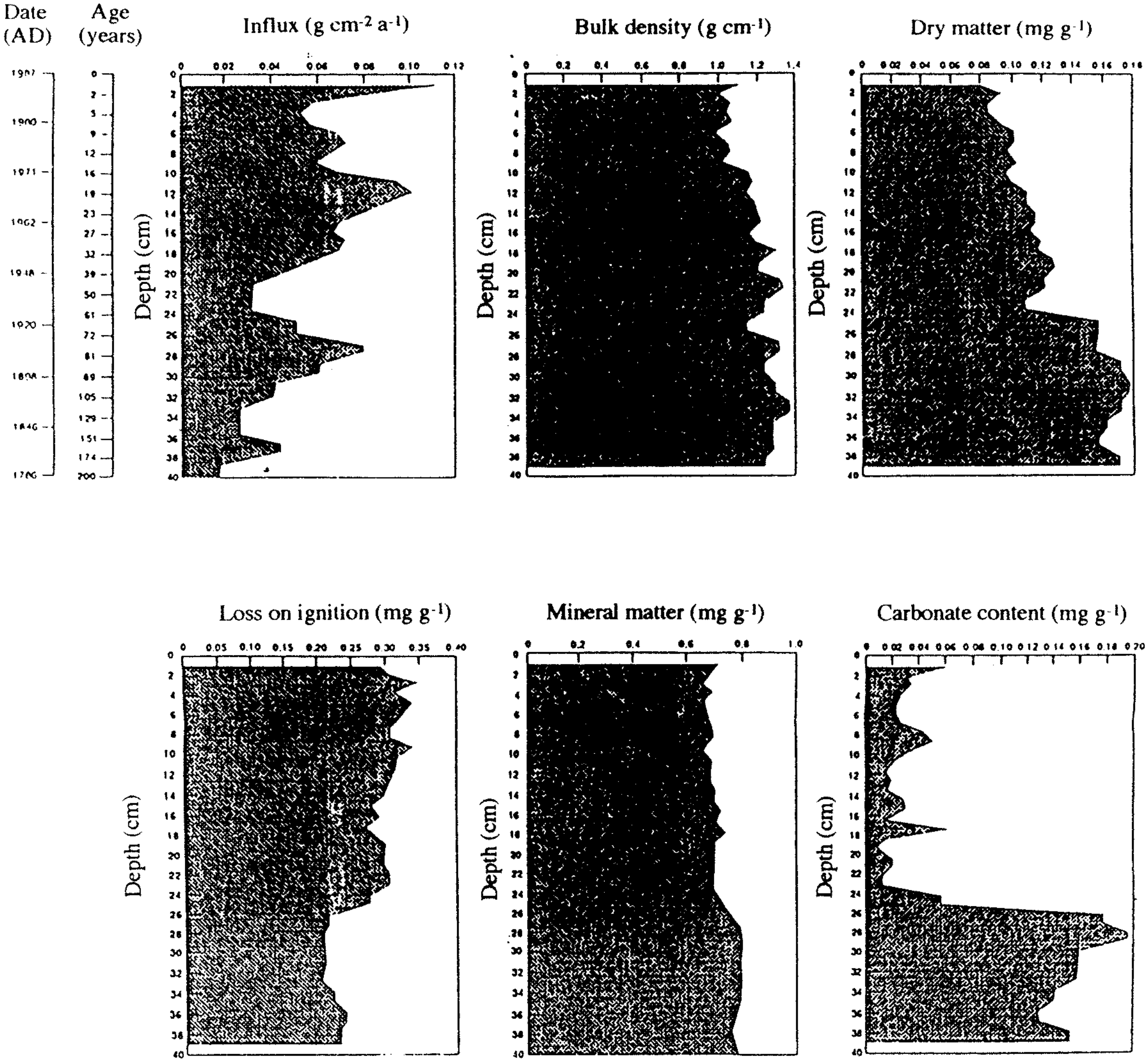

FIG. 9
Chronology, total sediment influx, bulk density, dry matter content, loss on ignition, mineral matter and carbonate content of core SLL3.

calcium and manganese in the lower part (Fig. 11). The profile for carbonate, which closely follows that of calcium, has also been added to Fig. 11. The only element which exhibits a substantial biogenic component is silicon. This is effectively biogenic silica (Schelske *et al.*, 1987), contributed to the sediment by the fallout of diatom frustules, sponge spicules and other silica-secreting organisms.

The results may therefore be described in terms of three categories of determinand, these being (a) the exclusively or mainly 'allogenic' elements (potassium, aluminium, and silicon; Fig. 10), (b) the exclusively 'authigenic' fraction (calcium, manganese, carbonate; Fig. 11), and (c) those which are mainly authigenic in provenance (mag-

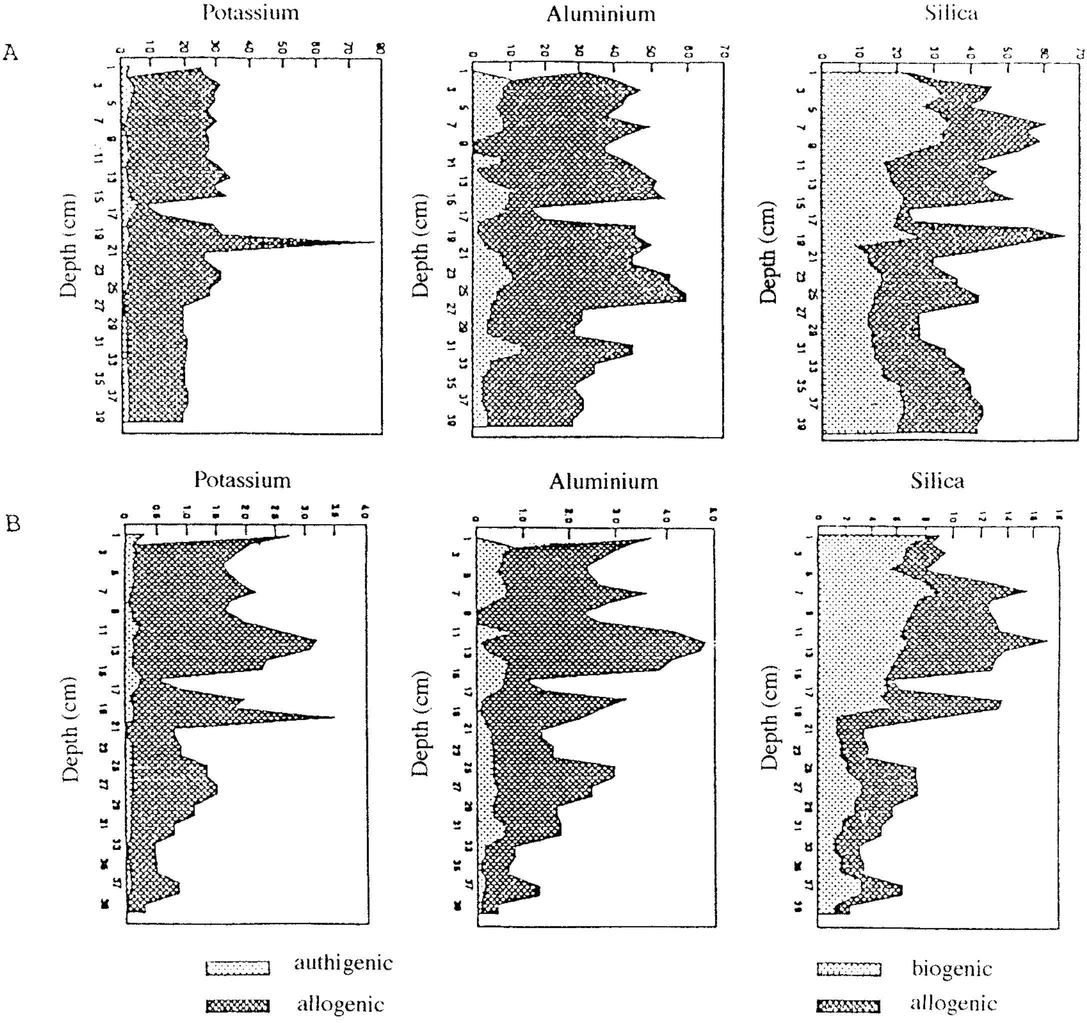

FIG. 10
Concentration (A, mg g-1) and influx (B, mg cm$^{-2}$ a$^{-1}$) of potassium, aluminium and silicon in core SLL3.

nesium, iron, nitrogen and phosphorus, Fig. 12). In terms of concentration, the allogenic component (Fig. 10) remains constant throughout most of the core, with a general increase above *ca* 25 cm, and fluctuating values around 16 cm. Biogenic silica concentration rises markedly above 10 cm. In contrast, the exclusive authigens calcium and manganese (Fig. 11) are abundant in the lower parts of the core (especially between 35 and 26 cm), but fall very low above 24 cm. Values rise again in the top few cm. Magnesium (Fig. 12) is also abundant in the lower sections, reaching a peak in concentration at 32 cm. Above 24 cm, however, its curve follows much more closely those of iron, nitrogen and phosphorus, varying erratically towards the SWI.

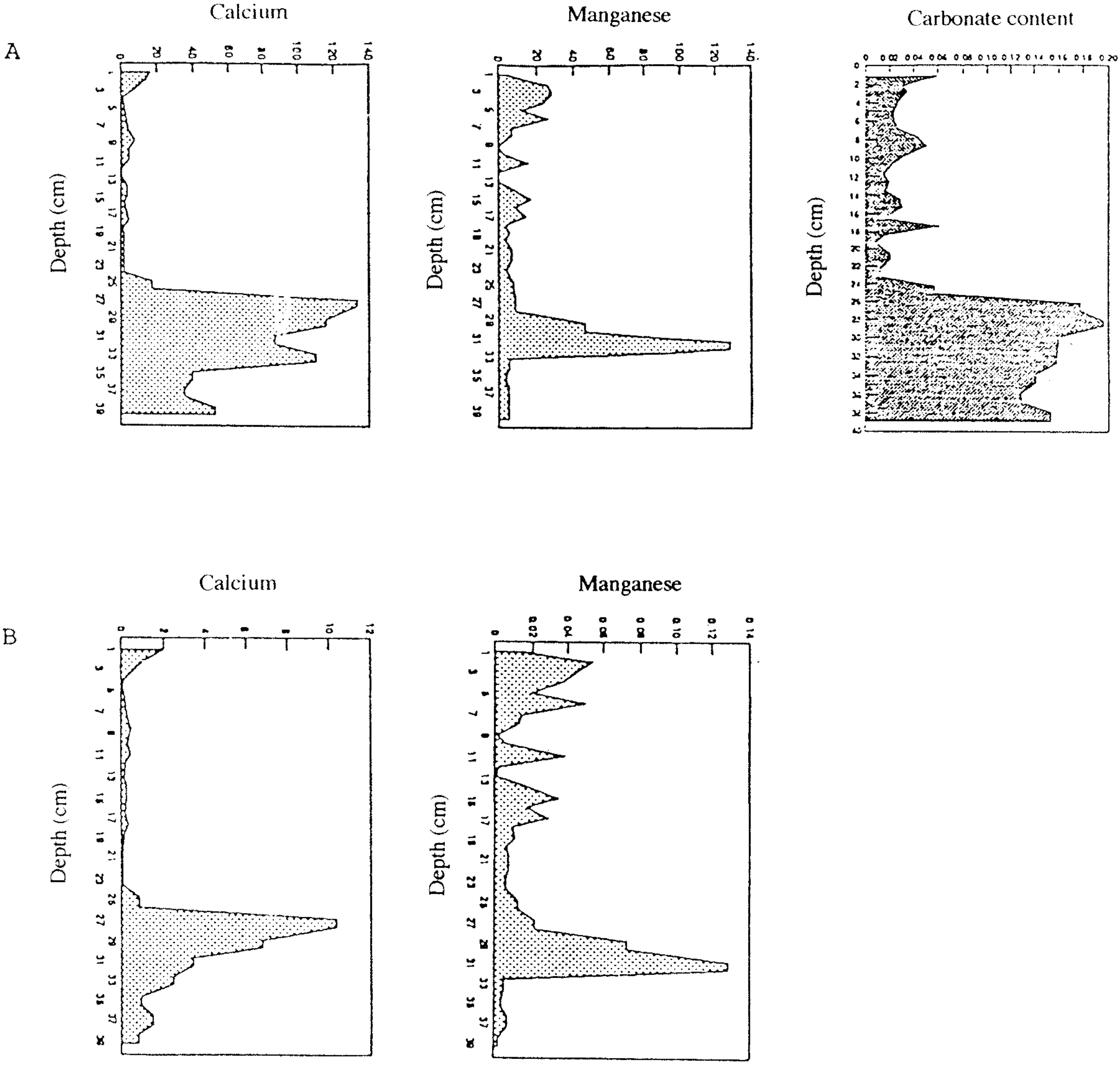

FIG. 11
Concentration (A) and influx (B) of calcium, manganese and carbonate (concentration only) in core SLL3.

Expressing the results in terms of influx appears to clarify most of the above trends. Allogenic influx, mainly potassium, aluminium and silicon (Fig. 10) is very low below 32 cm, reaches a maximum at 26 cm, falls, and then exhibits a general increase above 21 cm. Biogenic silica as a proportion of total silicon (Fig. 10) also increases above 5 cm. The exclusive authigens (calcium and manganese, Fig. 11) reach maxima at 28 and 32 cm respectively, and then fall very low, but recover just below the SWI. The influx profiles of the mainly authigenic determinands (magnesium, iron, nitrogen and phosphorus, Fig. 12) are similar to those for calcium and manganese in their lower parts, but in the top half, they follow much more closely the curves for aluminium, potassium and silicon. Allogenic phosphorus as proportion of total phosphorus (Fig. 12) mimics the curve of influx of biogenic silica as a proportion of total silicon (Fig.10).

In terms of concentration, the profiles for potassium, aluminium and silicon (Fig. 10) exhibit only a slight increase from the base to the top of the core. In the influx data there is, however, a strong upward trend. On a concentration basis, these elements are not correlated with mineral matter, which would have led us to reject Mackereth's hypothesis that they are indicators of erosion. However, their influx exhibits a strong association with mineral matter (see Fig. 9), so that (like Engstrom & Wright, 1984) we can conclude that this may be used to demonstrate that the amount of eroded material reaching Slapton Ley has gradually increased over the past two centuries, at least as far as this part of the lake is concerned. Multiple-core studies of other parts of the Ley (Figs. 5-6) confirm this conclusion for very recent times.

As stated above, the profile for silicon (Fig. 10) records the presence of roughly equal proportions of allogenic and biogenic material, with an increase in influx of *both* components above 21 cm, and especially of the biogenic form just below the SWI. Whereas, in the case of iron (Fig. 12), the proportion of allogenic material sedimented *decreases* towards the sediment water interface (SWI), for phosphorus, the opposite is the case. Above 21 cm, the contribution of allogenic phosphorus to the total increases. The section 28–20 cm in core SLL3 (1906–1948 AD) therefore represents a major change in sediment quality, above and below which the sedimentation regime of this part of the Lower Ley appears to have been very different. Events below this datum are given over mainly to sedimentation of authigenic species, but above it, until very recent times, there is a record of increased allochthonous inputs. Then, just below the SWI, authigenic sedimentation becomes more important again.

The timing of the above events, according to the $^{210}$Pb chronology obtained from this core, is set out in Table 3. Before 1910, sedimentation in the Lower Ley of the elements determined was mainly confined to the authigenic fraction. Peaks in magnesium, manganese and calcium are dated at 1882, 1890 and 1910 respectively. Maxima in authigenic iron, nitrogen and aluminium coincide with the peak in manganese. Above the 1910 level, a general increase in allogenic sedimentation begins. The 'exclusive authigens', calcium and manganese, decline and are replaced in the authigenic fraction by iron, magnesium, nitrogen and phosphorus.

A further major increase in influx of these elements is dated at 1945, at which time influx of the mainly allogenic elements potassium, aluminium and silicon also expands. Above this horizon, allogenic phosphorus, and biogenic silica increase as a proportion of the total influx and concentration of those elements.

The main expansion in *concentration* of biogenic silica is dated to *ca* 1975. A major peak in both authigenic nitrogen concentration and influx coincides with the $^{210}$Pb year 1978. Either side of this peak, *authigenic* phosphorus concentration also expands. The decline in both influx and concentration both of biogenic silica and allogenic silicon, which is seen in the uppermost few cm of the core, began in *ca* 1981. This feature is thought to be related to a switch in production within the algal communities, from diatoms to 'blue-greens' (cyanobacteria).

Again it is possible to attribute several of these observations to the impact of historically documented changes in land use in the catchment of the Ley, especially the switch from arable cultivation and sheep rearing to pasture and dairying which occurred

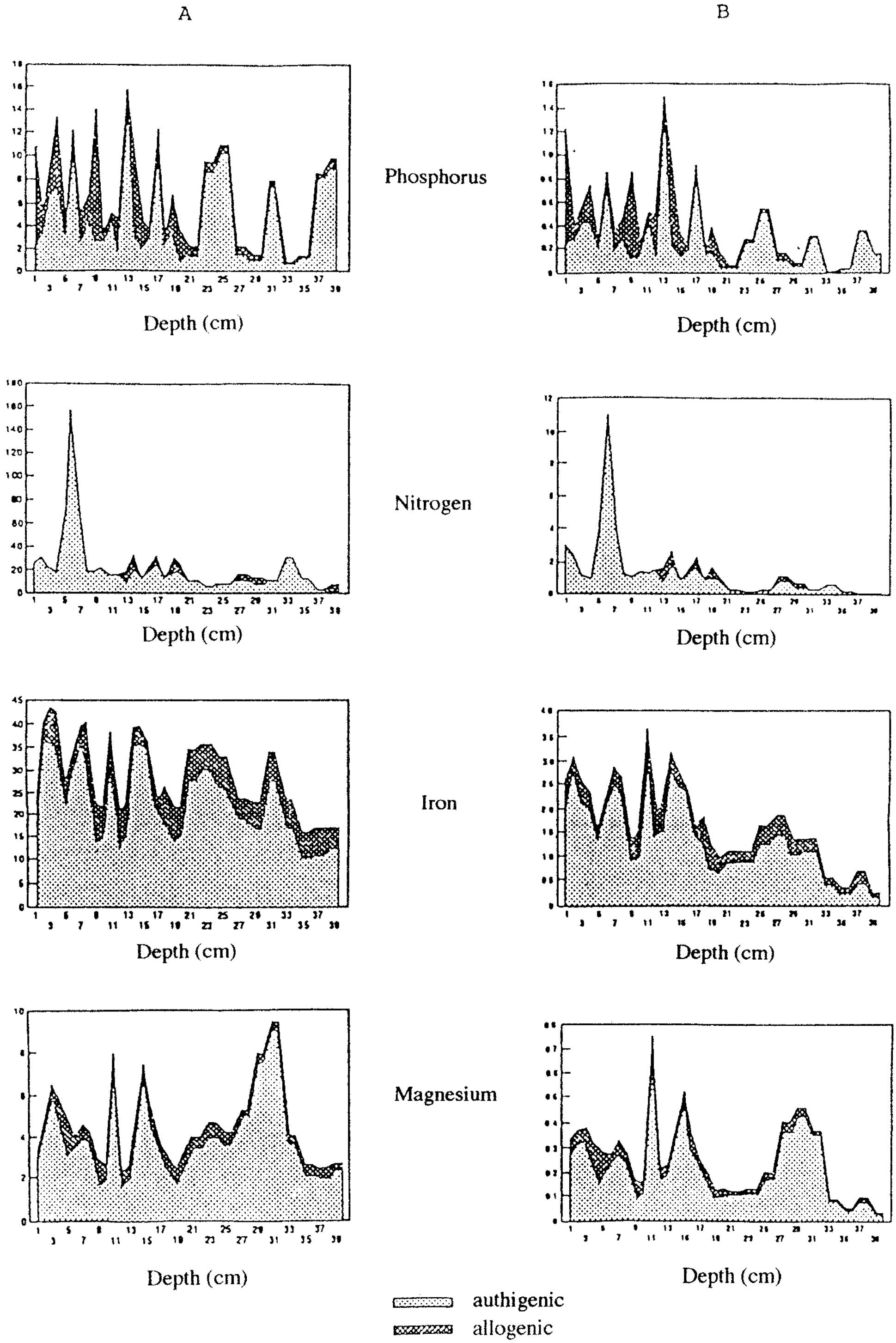

FIG. 12
Concentration (A) and influx (B) of magnesium, iron, nitrogen and phosphorus in core SLL3

TABLE 3. *Chronology of chemical sedimentation in core SLL3 from Slapton Ley, according to $^{210}Pb$ dating.*

| Concentration | Event | Influx | Date |
|---|---|---|---|
| decline in allogenic silicon | | | 1981 |
| <———————— | peak in nitrogen | ————————> | 1978 |
| increased authigenic phosphorus | | increased authigenic iron, nitrogen and phosphorus | 1974 |
| increased biogenic silica | | | 1970 |
| | | increased authigenic iron and magnesium | 1960 |
| | | increased authigenic nitrogen and phosphorus | 1953 |
| | | increased biogenic silica and allochthonous input | 1948 |
| increased allogenic input; peak in calcium | | peak in calcium | 1910 |
| <———————— | peak in authigenic manganese | ————————> | 1890 |
| <———————— | peak in authigenic magnesium | ————————> | 1882 |
| | | allogenic increase | 1870 |

in the two decades either side of 1910 (Barrows, 1991), and the further intensification which took place after 1945 (Acott, 1989). However, in the case of the most recent fluctuations, other influences, especially the influx of sewage phosphorus and nitrogen to the Ley after 1960, and the effect of the 1976 drought in Southern England, must also be considered (see below).

### 7. *Ratio of authigenic iron to manganese*

The ratio of authigenic iron to authigenic manganese in core SLL3 is shown in Fig 13. Whereas, in this core, both concentration and influx of allogenic iron are substantial, sedimentation of manganese is low, and is confined to the authigenic component. Below 34 cm (dated at *ca* 1867), the ratio is *ca* 60. It then falls to a minimum of *ca* 15 at the 30-32cm level which, coincides in the $^{210}Pb$ chronology, with the period 1882–1902. In parallel with total allogenic influx (Fig. 9), and those determinands located mainly in the allogenic fraction (Fig. 10), the ratio then rises (at 24 cm, dated to *ca* 1910) to *ca* 120 (± 60). These values then persist until 8 cm below the MWI, or the mid 1970s. They then fall to *ca* 50 (with the range 40-70) for a few cm, but rise at the SWI to 140.

Mackereth (1965, 1966) used the ratio of iron to manganese in lake sediments to monitor changing redox conditions in the soils of the catchment. He postulated that increased sedimentation of manganese relative to iron was indicative of mild stagnation of terrestrial soil profiles, in that under conditions of progressive acidification and deoxygenation, the former element is more easily mobilised, and conveyed into lake sediments, than the latter. Enhancement of the ratio in favour of iron thus suggests

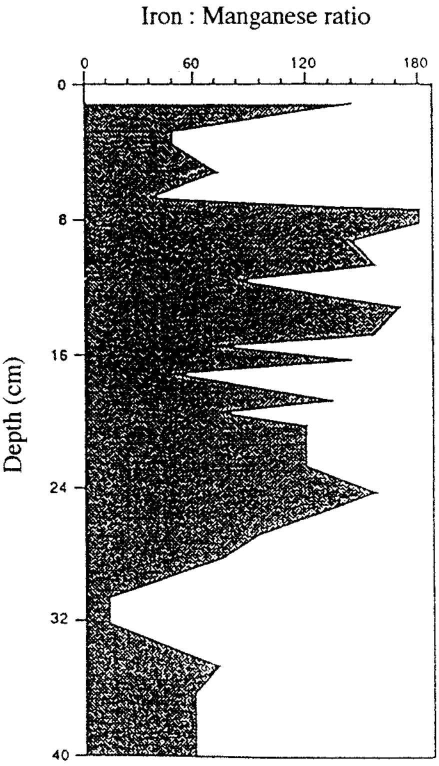

FIG. 13
Authigenic iron to authigenic manganese ratio for core SLL3.

much more advanced mobilisation, and the development of podsols in the catchment of the lake.

Unfortunately, as correctly identified by Mackereth, the ratio of sedimentary iron to manganese is also vulnerable to changes in redox conditions at the SWI. Under a regime of periodic hypolimnetic deoxygenation, manganese previously sedimented will be released preferentially relative to iron, thus affecting the ratio in the opposite direction to that indicative of terrestrial events. Thus, in many productive lakes, it is not possible to relate variations in the iron/manganese ratio *calculated on a total basis*, to processes in the catchment, but only to changing abundance of oxygen in the deeper waters of the lake. The analysis is further complicated by the knowledge that the elements are contributed to the lake not only by mobilisation and removal in solution, but also by physical erosion and transport of soil material in particulate form.

However, by separating the sediments into their respective components, and determining the iron/manganese ratio of each, it is at least possible to distinguish between allogenic iron and manganese produced by erosion, and authigenic iron and manganese which represent chemical precipitation of the elements in the lake itself. It is then necessary to have information regarding changing oxygen availability both in the soils of the catchment, and in the lake itself, in order to interpret changes in the authigenic iron/manganese ratio further.

In the presence of oxygen at the SWI, the iron/manganese ratio of lake sediments composed of material which originates in a catchment supporting free-draining soils normally exceeds 50:1 (Engstrom & Wright, 1984; Crabtree & Round, 1967; Mackereth, 1965, 1966). The soils of the catchment of Slapton Ley do indeed fall into this category (Trudgill, 1983), and there is no historical reason to suppose that this has not been the case for many centuries (Stanes, 1983). It is therefore concluded that in the case of core SLL3, the authigenic iron/manganese ratio refers to conditions of oxygen availability within the Lower Ley itself, rather than in the soils of its catchment. The variations in the ratio recorded in Fig. 13 may therefore be interpreted as follows.

The values found below 34cm in core SLL3 are greater than 50:1, and therefore record the existence before *ca* 1870 of a well-oxygenated lake. The pronounced minimum between 30 and 32 cm is caused by a large influx of authigenic manganese (and also magnesium, calcium and carbonate, Figs 11 and 12) which took place in the period 1870–1910. As explained in an earlier paper (Heathwaite & O'Sullivan, 1991), it is thought that these events are associated with a period of lime-kiln operation at the former village of Slapton Cellars, located behind the shingle ridge, on the shore of the Lower Ley, very close to the present Slapton Bridge (Stanes, 1983; see Fig. 1, this paper). According to Stanes, the kilns were in operation by the late C18th, but it was not until the raising of the level of the Ley that carbonates, washed in from this source, began to be deposited in the sediments in greater amounts. Manganese influx to the sediments also increased in response to elevated calcium load (Engstrom & Wright, 1984).

Above the level dated at *ca* 1910 (27 cm), concentrations and influx of calcium, magnesium, manganese and carbonate fall rapidly. Values of authigenic iron influx and concentration then rise, and the iron:manganese ratio increases to *ca* 120. In accordance with the ideas of Engstrom & Wright (1984), set out above, this increase is interpreted as being due to periodic deoxygenation of the bottom waters of the Lower Ley, resulting from the general rise in its water level caused by the construction of the outflow sluice.

It is not known precisely why, in *ca* 1910, high sedimentation of calcium, magnesium and manganese ceased. Perhaps operation of the lime-kilns was discontinued. However, the coincidence of this event with the horizon which denotes a much more comprehensive change in lake sedimentation, from mainly authigenic to more allogenic, suggests that a more general cause may have to be sought. A strong candidate is the switch from arable cultivation and the rearing of sheep, to dairying and the raising of cattle. This may have given rise to increased allochthonous sedimentation, particularly if conversion of *slopes* from permanent to temporary pasture took place. That an increase in the extent of temporary pasture at this time did indeed occur seems clear (Barrows, 1991), but the *location* of these areas cannot be determined from the data so far inspected.

Either way, the raising of the lake level in 1856 created, for about a century, a water body which was deep enough for the development, in summer, of conditions of oxygen deficiency, in at least some parts. Once operation of the kilns ceased, conditions for reduced deposition of manganese under periodic deoxygenation of the SWI came into operation. Whether this corresponded to a true hypolimnion, or was just temporary stagnation of a few deep parts of the Ley remains an open question.

At 8 cm (*ca* 1975), values of iron/manganese fall sharply back to *ca* 50, suggesting that deoxygenation of the bottom waters of the Ley became less frequent, and that the lake returned to a regime of more complete mixing. As sedimentation proceeded, eventually the Ley once more became too shallow, and hence, too turbulent, for oxygen gradients to form regularly. Finally, the rise in the ratio just below the SWI suggests renewed mobilisation of sedimentary manganese, and the return of periodic deoxygenation, under the influence of recent eutrophication. Alternatively, this may just be an effect produced by periodic deoxygenation of the SWI itself. In total, these variations broadly follow the course of the iron/manganese ratio from the core analysed by Crabtree & Round (1967), where below 10 cm, values of more than 50 are observed. Above that the ratio falls to less than 50.

### *8. Sedimentary chlorophyll 'a'*

Fig. 14 illustrates a profile of sedimentary chlorophyll 'a' in a core from Ireland Bay, along with organic matter determined as ignition loss, and total available phosphorus (TAP) measured by Kjeldahl digestion and autoanalysis (see above), produced by Brookfield (1981). All three determinands increase towards the sediment surface, ignition loss from 70 cm upward, but TAP and chlorophyll 'a' from *ca* 40 cm, and then more sharply just below the SWI. According to the $^{210}$Pb chronology for core SLL3, this latter increase began in the mid 1970s, and coincides with the horizon where influx of authigenic phosphorus and biogenic silica rise, but *concentration* of biogenic silica *falls* (see above). This event is thought to record a switch in the phytoplankton production in the lake, in favour of blue-greens, which took place during the mid-1970s, during which the lake also became more productive.

### *9. Diatom analysis*

In Fig. 15 are shown the results of diatom analysis of the top 40 cm of a 1 m Mackereth core from Ireland Bay by Moscrop (1987). The results are expressed in terms of percentage composition only, so that whilst they may be used to deduce past *qualitative* ecological change in the Lower Ley, they do not record quantitative variations in productivity (Battarbee, 1986). In this investigation, however, influx of biogenic silica may be used to study this aspect of lake history (Engstrom & Wright, 1984; Schelske *et al.*, 1987).

Four diatom* assemblages may be defined as follows:-

| | |
|---|---|
| Zone D | *Cyclostephanus dubius* - *Melosira varians* - *M.* (= *Aulacoseira*) *granulata* - *Asterionella formosa* zone (6-0 cm) |
| Zone C | *Cyclostephanus dubius* - *Melosira varians* - *Cocconeis* spp.- *Gyrosigma acuminatum* - *Fragilaria construens* var. *venter* zone (16-6 cm) |
| Zone B | *Cymbella* spp. - *Cocconeis pediculus* - *C. placentula* - *Gyrosigma acuminatum* - *Fragilaria construens* var. *venter* zone (28–16 cm) |
| Zone A | *Cymbella* - *Cocconeis pediculus* - *C. placentula* - *Fragilaria construens* var. *venter* zone (40–28 cm) |

In Zone A, centric diatoms, represented only by various species of *Melosira* and *Cyclotella*, are relatively scarce. The main taxa present are *Cymbella ventricosa*, *C. cistula*, *Cocconeis pediculus*, *C. placentula*, *Fragilaria intermedia*, *F. construens*, and *F. construens* var. *venter*. In Zone B, these are joined by *Gyrosigma acuminatum* and *G. attenuatum*.

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* Diatom nomenclature follows that of Williams *et al.*, 1988, and the authorities listed therein - for example, Germain, 1981

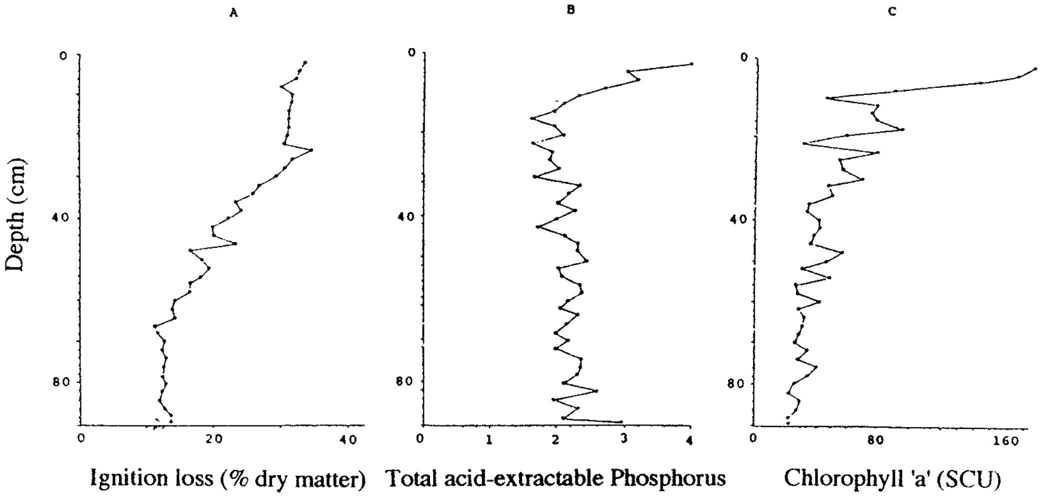

FIG. 14
Ignition loss (% dry matter), total acid extractable phosphorus (mg g$^{-1}$) and chlorophyll 'a' concentration (SCU units) in a core from Slapton Ley (from Brookfield, 1980)

*Fragilaria intermedia* and *F. construens* decline in importance, as do *Cymbella ventricosa* and *C. cistula*, especially towards the top of the zone. Other taxa including *Amphora ovalis* and *Fragilaria brevistriata* are somewhat better represented. Centric diatoms, notably *Cyclostephanus dubius*, increase slightly in importance.

Zone C is characterised by the expansion of centric taxa, most notably *C. dubius*, *Stephanodiscus hantzschii*, and *Melosira varians*. *Cocconeis pediculus* and *C.placentula* decline in abundance, as do *Amphora ovalis* and *Fragilaria brevistriata*. In Zone D, members of the genus *Stephanodiscus* are somewhat less-well represented, but *Cyclostephanus dubius* and *Melosira varians* expand, the former especially so at the SWI, to 35% of the total number of frustules recorded.

Table 4. *Chronology of diatom assemblage zones in the uppermost sediments of Slapton Ley.*

| Zone | Assemblage | Date of zone boundary |
|---|---|---|
| SLD$_{D}$ | *Cyclostephanus dubius, Melosira varians, Melosira granulata, Asterionella formosa* | |
| | | 1978 |
| SLD$_{C}$ | *Cyclostephanus dubius, Melosira varians, Melosira granulata, Cocconeis* spp., *Gyrosigma acuminatum, Fragilaria construens* var. *venter* | |
| | | 1960 |
| SLD$_{B}$ | *Cymbella* sp., *Cocconeis pediculus, Cocconeis placentula, Gyrosigma acuminatum, Fragilaria construens* var. *venter* | |
| | | 1910 |
| SLD$_{A}$ | *Cymbella* spp., *Cocconeis pediculus, Cocconeis placentula, Fragilaria construens* var. *venter* | |

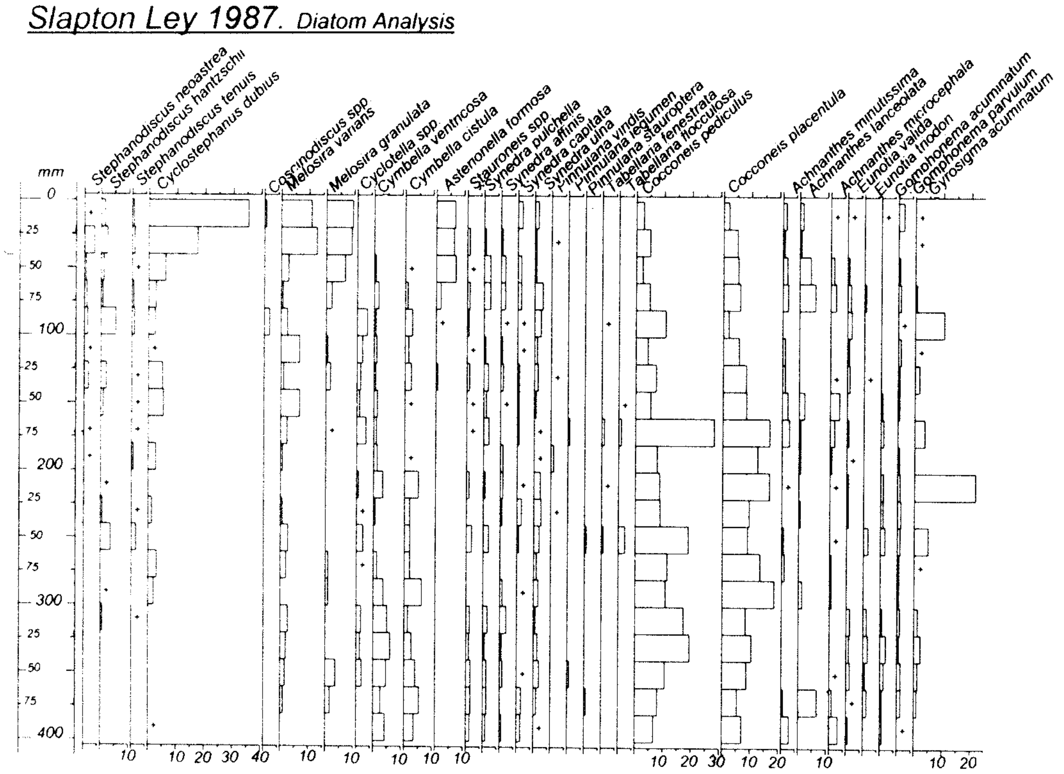

FIG. 15 (Part)
Diatom profile (% of total diatom frustules) of the uppermost sediments of Slapton Ley (from Moscrop, 1987).

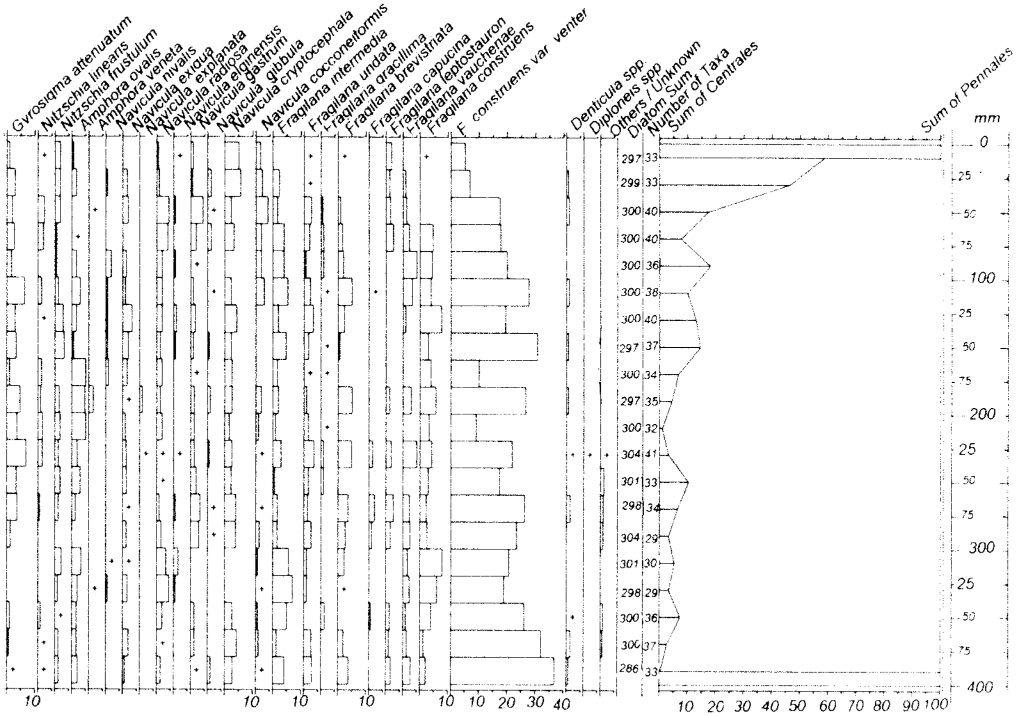

FIG. 15 (Completion)
Diatom profile (% of total diatom frustules) of the uppermost sediments of Slapton Ley (from Moscrop, 1987).

Another centric species, *Melosira granulata* (now called *Aulacoseira granulata*, Williams *et al.*, 1988) also increases in abundance in this zone, as does *Asterionella formosa*. Species of *Cocconeis* and *Gyrosigma* continue to decline, as do many other pennate taxa, including *Fragilaria construens* var. *venter*, and most of the other *Fragilaria* species present. *Acnanthes lanceolata* and *Navicula radiosa* reach maxima at the Zone C/D boundary, and *Navicula cryptocephala* at the very top of the sequence.

Generally, the trend recorded in the diagram is first of a gradual, and then of a rapid replacement of pennate diatoms by centric species, which reach 60% of total diatoms in the topmost sample. The principal pennate taxa involved (*Amphora ovalis, Cocconeis pediculus, C. placentula, Gyrosigma acuminatum, G. attenuatum, Fragilaria brevistriata, F. construens, F. construens* var. *venter, F. intermedia, F. leptostauron, Navicula cryptocephala, N. gastrum* and *N. radiosa*) are mostly epiphytic or benthic forms, whereas the centric diatoms present are mainly planktonic species (Germain, 1981).

Superimposed on this is a parallel tendency towards increasing productivity, with the appearance, in Zone D, of *Melosira (=Aulacoseira) granulata* and *Asterionella formosa,* and the major expansion of *Cyclostephanus dubius. A. formosa* is a further planktonic species, and is associated with eutrophication by agricultural sources. *C. dubius* and members of the genus *Stephanodiscus* are much more closely related to influx of organic phosphorus from sewage effluent or other sources (Battarbee, 1986).

Comparison of these results with those of Crabtree & Round (1967) confirms the conclusion, arrived at on stratigraphic and inorganic chemical grounds, that the base of core SLL3 corresponds to the top parts of their earlier core, plus the 12 cm of sediment deposited since that time. Those authors found that centric diatoms were so scarce that, whilst they did expand to a very limited extent towards the top of the sequence, their numbers were still so small that they did not think it worthwhile separating them into species, genera, or even families.

According to the $^{210}$Pb dates obtained from core SLL3, the chronology of the four diatom zones described by Moscrop is that set out in Table 4. Thus, from this data, and that of Crabtree & Round (1967), it would appear that until about *ca* 1960, the Lower Ley was a shallow, mildly productive lake possessing clear waters and inhabited by numerous benthic, littoral and epiphytic diatom species, with only a few planktonic forms. The main biological response to increased nutrient loading began in that year, accelerating from *ca* 1978 onwards. At the same time there was a second, qualitative change, away from shallow water taxa towards planktonic forms, suggesting displacement of the habitats occupied by the former (the illuminated sediment surface, the bodies of aquatic macrophytes), in favour of open water which may therefore also have become considerably more turbid. That this qualitative change may have been accompanied by a real increase in productivity is suggested by the profile of biogenic silica concentration (Fig. 10), which expands in core SLL3 at the level also dated by $^{210}$Pb to 1978.

However, as pointed out above, eutrophication represents *enrichment* of an ecosystem by nutrients from outside (Moss, 1988). It would therefore be more correct to say that whereas the beginning of the main *response* of the Lower Ley to eutrophication (in the form of a change in the composition of its biota) dates from 1960, the main episode of nutrient *enrichment*, as depicted by the profiles for sedimentary nitrogen and phosphorus, began in the 1940's, and then accelerated from *ca* 1960 onwards. Even then, there is some evidence for an earlier episode of biological

TABLE 5. *Preliminary fine resolution pollen zones from the uppermost sediments of Slapton Ley (after Nicholls, 1988).*

| Zone | Assemblage | Date of proposed zone boundary |
|---|---|---|
| SL$_{\text{PF}}$ | Gramineae, *Rumex, Urtica,* Cyperaceae, *Potamogeton, Typha,* Filicales | |
| | | 1971 |
| SL$_{\text{PE}}$ | *Quercus,* Gramineae, *Rumex, Plantago lanceolata, Ranunculus,* Cyperaceae, *Typha/Sparganium* | |
| | | 1960 |
| SL$_{\text{PD}}$ | Gramineae, *Plantago lanceolata, Ranunculus, Myriophyllum* | |
| | | 1910 |
| SL$_{\text{PC}}$ | Gramineae, *Plantago lanceolata, Ranunculus,* Cyperaceae, *Myriophyllum* | |
| | | *ca* 1790 |
| SL$_{\text{PB}}$ | *Quercus,* Gramineae, Compositae (Liguliflorae), *Ranunculus,* Cyperaceae, *Myriophyllum* | |
| | | unknown |
| SL$_{\text{PA}}$ | *Quercus,* Gramineae, Compositae (Liguliflorae), *Plantago lanceolata,* Cyperaceae, *Potamogeton* | |

response to what may have been mild eutrophication, in the shape of the appearance of *Cyclostephanus dubius* in the sediments deposited after 1910.

### *10. Pollen analysis*

Preliminary results of a fine-resolution pollen analysis of a 60 cm core from Ireland Bay by Nicholls (1988) have also been used to compile this account. No detailed results are presented here, but provisional pollen zones are defined, and their stratigraphic and proposed chronological boundaries are recorded in Table 5. As well as the previously published work of Crabtree & Round (1967), an unpublished pollen diagram from a 2.25 m core, again from Ireland Bay, by Dr Colin Morey, has also been available.

The results of the present study confirm the findings of earlier authors, that for some considerable time, probably beginning before the formation of the current Ley, the area which is now its catchment has been mostly devoid of woodland. The present pattern, of virtually treeless plateaux, separated by valleys which are heavily wooded in their lower courses (Johnes & O'Sullivan, 1989), may well be one which is of some antiquity although, in the parish of Slapton, most of the woods (with the exception of Slapton Wood) appear to have been planted in the early C19th (Stanes, 1983).

The pollen of grasses, as well as that of weeds of cultivation (ruderals) such as *Plantago lanceolata*, are abundant throughout the core, strongly suggesting the continued presence of much agricultural land, especially pasture. At the Zone SL$_{\text{PA}}$/SL$_{\text{PB}}$ boundary, tree pollen, notably that of *Quercus* (oak), declines, and the pollen of Gramineae (grasses) expands. This horizon is beyond the range of the $^{210}$Pb chronology, but lies only some 13 cm below the next zone boundary (Zone SL$_{\text{PB}}$/SL$_{\text{PC}}$), which by correlation with the $^{210}$Pb chronology from core SLL3 is dated to *ca* 1790 AD. At which level, plants of the subfamily Liguliflorae[*] (Compositae) become less abundant. The

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[*] The subfamily Liguliflorae is referred to as the Cichorioideae in the third edition of the *Flora of the British Isles* (Clapham, Tutin & Moore, 1987), roughly equivalent to the Lactucoideae of *The Plant Book* (Mabberley, 1987). It includes some vegetables, chicory, salsify, lettuce, and ruderal weeds cat's-ear, dandelion, hawkbit, sow-thistle, hawkweed etc.

earlier event suggests that a change away from woodland and wasteland, towards an increased amount of cultivated land in the catchment of the Ley, may have taken place some time in the late C17th / early C18th.

Then, at the Zone $SL_{PC}/SL_{PD}$ boundary, dated by $^{210}Pb$ to *ca* 1910, the pollen of Cyperaceae (sedges) declines, perhaps indicating some change towards better drainage of wetland areas. At the horizon dated at 1960 (Zone $SL_{PD}/SL_{PE}$ boundary), the pollen of *Rumex* (docks and sorrels), which is associated by palaeoecologists with arable cultivation, expands. In Zone $SL_{PF}$, the uppermost zone, the assemblage includes much greater abundance of the pollen of *Urtica* (nettles), a genus which has been linked with high levels of soil phosphorus.

Variations in the abundance of aquatic macrophyte pollen record parallel changes. The date of the replacement of *Potamogeton* (pond weeds) by *Myriophyllum* (water milfoil), which defines the Zone $SL_{PA}/SL_{PB}$ boundary at 51 cm, is unknown, as it is again beyond the range of the $^{210}Pb$ chronology. *Myriophyllum* then remains the most abundant aquatic taxon until the Zone $SL_{PD}/SL_{PE}$ boundary, dated by $^{210}Pb$ at 1960. In turn, in the topmost zone ($SL_{PF}$), *Typha / Sparganium* (bull-rush / bur-reed) type is replaced as the most abundant aquatic pollen type by *Potamogeton.*

The changes in the aquatic macrophyte flora are mirrored by variations in the diatom assemblages (see above). In particular, the date of the decline of *Myriophyllum* in the pollen stratigraphy coincides precisely with the main expansion of centric taxa, especially *Cyclostephanus dubius*, which is associated with increased influx of organic phosphorus to lakes.

Correlation of these results with those of Crabtree & Round (1967) is possible only in the broadest terms. The whole of the 60 cm core used here overlaps only with their two topmost samples, in which pollen spectra indicative of a largely treeless landscape are also recorded. Morey (unpublished) found evidence for the existence of a landscape broadly similar to that of the present (in terms of the proportion of woodland) before *ca* 3900 BP. Above this is a layer in which the pollen of ruderals becomes less frequent, but then in sediments lying above an horizon dated at *ca* 1900 BP they become abundant once more. Thus, the events which originally created the mainly treeless landscape of that part of the South Hams draining into Slapton Ley, may well pre-date the arrival of human Iron Age populations, confirming Stanes' idea (1983), that among the earliest farmers in the area were Bronze Age peoples.

By the time of Domesday, open fields for the growing of cereals were established around Slapton and Blackawton villages. These were probably enclosed in the C15th, but arable cultivation continued. Enclosure of the areas of rough grazing and scrubland then present in the higher parts of the catchment in the C18th may well be the vegetation changes recorded at the Zone $SL_{PA}/SL_{PB}$ and $SL_{PB}/SL_{PC}$ boundary, provisionally dated to the late C17th / early C18th, and at *ca* 1790 AD where, respectively, tree pollen, including *Quercus*, and then Compositae Liguliflorae, plants of waste ground, decline, and grass (Gramineae) pollen expands.

The next major land use change to take place in the catchment of the Ley involved the decline of traditional arable cultivation, and its replacement by dairying and the expansion of the amount of pasture present (Barrows, 1991). This took place in the late C19th / early C20th, and is perhaps reflected in the decrease of Cyperaceae pollen at the Zone $SL_{PC}/SL_{PD}$ boundary (and the appearance in the sedimentary record of the diatom *Cyclostephanus dubius*), dated at 1910. After 1945, agriculture in the catchment of Slapton Ley intensified considerably, with further increase in the extent of grassland, a continued decline in arable, and a major expansion in livestock numbers reaching a maximum during the middle 1960s (Acott, 1989).

Changes in the relative abundance of aquatic macrophyte pollen may be compared to the history of those communities in the Ley as reviewed by Wilson (1991). She found that sheltered areas of the lake, such as Ireland and Stokeley Bays (Fig. 1), contain a 'relict' flora in which taxa such as *Myriophyllum*, whose pollen is now less abundant in the sediments, are more prominent. In contrast, in the main parts of the Ley, this community is less well developed, and has been replaced by phytoplankton.

Most (89%) of the macrophyte biomass is now located at the southern end. *Ceratophyllum demersum* (rigid hornwort), which Brookes & Burns (1969) recorded as uncommon, now makes up 73% of the fresh weight macrophyte biomass of the entire Ley.

## SYNTHESIS

The palaeolimnological evidence for the development of the ecosystem of Slapton Ley over the last two centuries may be discussed in terms of a number of time periods which reflect stages in the recent history of the lake and its catchment. Three principal subsets of information may be extracted from the data. These are concerned with:-

- The influence of catchment processes upon the nature and rate of transfer of materials from catchment to lake,
- The impact of water level changes upon the sedimentary record, and upon lake geochemistry, and
- The evidence for eutrophication of the lake by increases in nutrient loadings, both in terms of actual nutrient enrichment, and the biological response to it.

Six main phases of development (Table 6) may be defined:-

### *Phase 1 - before 1790 AD*

Relatively little detailed information is available for this period, as its age exceeds the time beyond which the $^{210}$Pb chronology can be extended. No new diatom or chemical evidence, beside that produced by Crabtree & Round (1967) or by Morey (unpublished), is available. Values of $\chi$, $\chi_{fd}$, SIRM and SIRM/$\chi$ (Figs 7-8) are all low, and 'S' ratios suggest that erosion into the Ley was confined to catchment material more closely resembling stream sediments and bedrock than topsoil.

The results of diatom analyses by Crabtree & Round (1967) show that the condition of the Ley at this time was that of a shallow, clear, mildly productive lake in which saline influences were minimal, and in which abundant freshwater macrophytes supported an extensive epiphytic diatom flora. In this respect, Slapton Ley resembles certain of the Norfolk Broads, many of which were also, at one time, clear, shallow, productive lakes with abundant macrophytes (Moss, 1983).

Two preliminary pollen assemblage zones (Zones SLP$_A$ and SLP$_B$, Table 5) are correlated broadly with this period. They denote the presence of an open landscape with limited woodland (probably confined, as now, to the lower valley bottoms), a considerable amount of pasture, and some arable land, thus again confirming earlier findings (Crabtree & Round, 1967; Morey, unpublished). The transition between the zones is marked by a decline in tree pollen, an expansion of Gramineae, and a reduction in *Potamogeton* in favour of *Myriophyllum*.

TABLE 6. *A Synthesis of the Events in the History and Palaeolimnology of Slapton Ley since about 1790*

| | | |
|---|---|---|
| present | HIGHLY EUTROPHICATED | Ley turbid, centric diatoms abundant, increased influx of biogenic silica and authigenic phosphorus, and in concentration of sedimentary chlorophyll 'a'. Fluctuation of fish, macrophyte and algal populations. |
| 1976 | Severe drought | major peak in authigenic nitrogen, deoxygenation of SWI much less frequent |
| | INCREASING EUTROPHICATION | Ley increasingly productive, cyanobacteria abundant, algal blooms frequent, change in macrophyte flora |
| 1960 | Slapton sewage treatment works (STW) upgraded | increase of centric diatoms, change in macrophyte flora |
| 1953 | Increased load on Slapton STW | increase in biogenic silica and authigenic phosphorus |
| | EUTROPHICATION | shallow, clear, productive lake |
| 1948 | Post-war intensification of agriculture | increase in influx of 'topsoil' iron, allogenic silicon, iron, and phosphorus, and biogenic silica |
| 1934/5 | Slapton and Blackawton STWs commissioned | increase in authigenic phosphorus |
| | MILD EUTROPHICATION | SWI periodically deoxygenated |
| 1910 | Change from sheep and arable to dairying | increase in influx of eroded, allogenic matter, decline in authigenic sedimentation, change in macrophyte flora, appearance of centric diatoms. |
| 1856 | Construction of road and outflow sluice | depth of Ley and water residence time increased, SWI periodically deoxygenated, increased influx of calcium carbonate |
| | SHALLOW, CLEAR, PRODUCTIVE, WELL-OXYGENATED LAKE WITH ABUNDANT MACROPHYTES | |
| 1790 | | |

More detailed analysis is required, but the evidence suggests that a land-use change involving the expansion of the amount of pasture, which may have taken place some time in the late C17th, or early C18th, affected the aquatic macrophyte flora of the Ley. This change appears to have involved little extra erosion from catchment to lake, but may have led to an increase in its external solute loadings. This hypothesis is not testable by reference to core SLL3, as the relevant horizon lies beyond the limit of the $^{210}$Pb chronology. According to Stanes (1983), both lime and clover were in use as fertilisers in the Slapton area by the C17th.

### *Phase 2 - 1790 to 1870*

This is the earliest period for which fine-resolution inorganic chemical and diatom evidence are available. Values of $\chi$, SIRM, and SIRM/$\chi$ remain low, denoting little change in the erosional load from catchment to lake. This is confirmed by the inorganic chemistry of the sediments, where both influx and concentration of all forms of determinand are also low. The diatom assemblage is composed mainly of benthic and littoral taxa, denoting the continued existence of a shallow, clear, mildly productive lake with abundant macrophytes. *Myriophyllum* remains the most abundant aquatic pollen recorded.

### *Phase 3 - 1870 to 1910*

This period is characterised by major peaks in authigenic chemical sedimentation, especially of calcium, manganese, and carbonate (Fig. 11), and magnesium (Fig. 12). As explained above, these events are thought to reflect the response of lake water chemistry to the raising of the level of the Ley in 1856. The road, which now runs from Torcross to Strete along the crest of the shingle ridge (Fig. 1), was opened in that year. At the same time, in order further to ease communications, the outflow from the Lower Ley was confined in a sluice, and a weir, used to control the level of water in summer, was also introduced. These measures raised the general water level in the Ley (Stanes, 1983), increasing its hydraulic residence time, effectively enhancing mean annual lake concentration of all chemical species.

The source of the calcium carbonate was a series of lime kilns sited on the shore of the Ley just below Slapton Bridge (Fig. 1; Stanes, 1983, Fig. 12, p 53). Limestone was transported to the village by sea, and roasted in the kilns, in order to produce lime which was then applied to the adjacent fields. This was a very common practise all over SW England in former times, owing to the acidity of the soils produced by weathering of the local Devonian slates. The kilns in question are shown as being present on a map of 1830 printed in Loudon's *Magazine of Natural History* (reproduced in Stanes, 1983, p. 53), so that they were in active operation well before 1870, but it was not until the raising of the level of the Ley that carbonates, washed in from this source, began to be deposited in the sediments in greater amounts. Furthermore, according to Engstrom & Wright (1984), manganese is one of a number of elements which is scavenged and preferentially sedimented in the presence of high concentrations of carbonate. The pronounced minimum in the authigenic iron:manganese ratio for this core (Fig. 13) is therefore attributed to the above combination of factors.

### *Phase 4 - 1910 to 1960*

Throughout this period, the Lower Ley remained a clear, shallow, mildly productive lake, with species of *Cocconeis, Fragilaria* and *Gyrosigma* abundant. There is some evidence, however, that in terms of nutrient supply, the eutrophication which is today such a prominent feature of the lake, may have begun during this phase.

The horizon dated at 1910 is marked by an increase in SIRM/X, a decline in calcium and manganese concentration and influx, and a general rise in allogenic sedimentation (both influx and concentration). The first and last of these suggest that there was an increase in influx of sediment from outside the lake. The main response of the diatom flora of the lake to this change is shown by the expansion of *Gyrosigma acuminatum* and *G. attenuatum*, via a transition dating from *ca* 1898 to 1915. Both are littoral, benthic species, sensitive to pollution (Germain, 1981). Although the lake may have become slightly more productive at this time, the clarity of the waters denoted by this and previous diatom assemblages persisted for a few decades.

At the same level, however, the centric planktonic diatom *Cyclostephanus dubius*, often associated with eutrophication, first appears in the record. This horizon probably records the very beginnings of eutrophication of the Lower Ley.

Historical studies of land-use changes of the period by Barrows (1991) have shown that between 1885 and 1915, the amount of permanent pasture present in the catchment of Slapton Ley increased sharply (from *ca* 1200 ha to just over 2000 ha), whilst the extent of arable land decreased from *ca* 1800 ha in 1875 to *ca* 1350 ha in 1895. At the same time, the number of sheep declined (from *ca* 9000 in 1895 to *ca* 6000), whereas the cattle population increased from *ca* 1900 to just over 2400.

This was clearly a major land-use change, brought about, as in many other parts of Britain, by the import of cereals from abroad, and the coming of the railway (Hoskins, 1972; Stanes, 1983). As shown by the appearance of *Cyclostephanus dubius*, it was also responsible for the beginning of eutrophication of the Lower Ley. However, it is also the case that clear waters with abundant macrophytes persisted for another 60-70 years before this eutrophication began to make its full impact.

At a level dated at *ca* 1948, there is a substantial increase in influx to the sediment of authigenic nitrogen and phosphorus and, in both concentration and influx, of allogenic (i.e. mineral) phosphorus. Coupled with the evidence for a second rise in influx of magnetically 'harder' mineral matter originating as topsoil (increased $\chi$, SIRM and SIRM/$\chi$), and of allogenic potassium, aluminium and silicon, this suggests that further increased sediment and nutrient loading of the Ley may have been brought about by changes in agriculture, particularly any involving increased ploughing, and thus greater erosion of soils. No qualitative change in the diatom flora accompanies this increase in nutrient loadings, but the expansion of influx to the sediments of biogenic silica shows that it did generate an increase in lake productivity (Schelske *et al.*, 1987).

Further studies of land-use changes by Acott (1989) indicate that, after 1945, considerable intensification of agriculture in the catchment of Slapton Ley took place. The amount of land given over to temporary pasture increased from just under 800 ha in 1945 to *ca* 1700 ha in 1965. Permanent pastures expanded again, from *ca* 1200 ha in 1965 back to 2200 ha in 1985. Similarly, over the same period, cattle numbers increased, from *ca* 2000 to nearly 7000. The sheep population, however, began to rise as well, from a minimum of 3000 in 1945 to *ca* 15,000 in 1965. Much of this intensification was associated with mechanisation (Hoskins, 1972; Stanes, 1983), and with use of 'artificial' fertilisers. Thus the increase in allogenic sedimentation recorded for this time in core SLL3 may well be related to the increased efficiency of ploughing. However, as well as inorganic nitrogen from the new, synthetic fertilisers, intensification of pastoral farming would also have introduced a large amount of organic nitrogen and phosphorus to the system (Johnes & O'Sullivan, 1989).

Current research into nitrogen and phosphorus inputs from the catchment of Slapton Ley (Burt *et al.*, 1990; Heathwaite *et al.*, 1990) has shown that phosphorus adsorbed on to the sediment particles forms a major component of the total external load of that element to the lake. The source of this material is the topsoil of fields in the catchment, especially grassland that is heavily grazed and, to a lesser extent, those areas under arable cultivation. Part of this second phase of eutrophication of the Lower Ley is, therefore, probably attributable, like the initial period, to agricultural intensification, particularly in the period after 1945.

However, the influence of sewage phosphorus cannot be entirely ruled out, as it was in 1953 that the treatment works at Slapton began to receive greater inputs of sewage, following the construction of extra, local authority houses in the village. The capacity of the works was upgraded in the early 1960s, in order to accommodate discharges from a caravan park at the east end of the village (Fig. 1), and also those from the new Slapton Ley Field Centre! Such events would be associated with increases in authigenic nitrogen and phosphorus such as those recorded above 21 cm in core SLL3 (Fig. 11).

*Phase 5 - 1960 to ca 1975*

At an horizon dated by correlation with the $^{210}$Pb profile from core SLL3 at 1960, frequencies of the planktonic centric diatoms *Cyclostephanus dubius, Melosira varians, Aulacoseira granulata* and *Stephanodiscus hantzschii* expand, at the expense of benthic and epiphytic pennate taxa, especially *Cocconeis placentula, C. pediculus* and *Gyrosigma acuminatum.* Members of the genus *Fragilaria,* however, persist or become more frequent. For the first time, centric taxa make up more than 10% of the diatom flora. That the Lower Ley became more productive at this time is also shown by the slow rise of influx of biogenic silica (Schelske *et al.,* 1987), and of authigenic phosphorus concentration.

This level, therefore, marks the onset of more pronounced eutrophication of the Lower Ley. Expansion of these particular species suggests the involvement of phosphorus from sewage rather than from agriculture. Values of $\chi$, SIRM and SIRM/$\chi$ stabilise, and do not expand further, indicating perhaps that in terms of erosion of catchment soils, the post-war intensification of agriculture begun in the late 1940's reached its culmination. No significant increase in numbers of cattle or sheep is recorded after 1965 (Acott, 1989). In the pollen assemblages, this period is characterised by increased frequencies of *Rumex,* perhaps indicating that rather more ploughed land was present at this time than before. Reference to historical data by Acott (1989) indicates an increase in temporary pasture during the 1960s and 1970s.

In terms of the aquatic pollen, *Myriophyllum,* which had been the most abundant type in the three zones below (i.e. for at least the previous two hundred years), declines in importance, and is replaced by *Typha/Sparganium* type. This suggests that the ecological changes recorded in the diatom spectra had also begun to affect the macrophyte flora of the lake more severely, as confirmed by Wilson (1991), who found that, since that time, communities containing *Myriophyllum* have been replaced by those in which *Ceratophyllum demersum* is the main species present.

Further confirmation that the Ley was being eutrophicated during this time (1960–1975) may be obtained from studies of the history of the freshwater fish populations and their parasites (Bregazzi, Burrough & Kennedy, 1982; Kennedy, 1975). During the C19th, the fishery of Slapton Ley was renowned, especially for pike (*Esox lucius* L.), but by the 1970s, it had severely declined. The main fish historically abundant in the lake, the rudd, had been largely replaced by the roach.

However, during the 1970s, this population was itself severely reduced by parasite infestation, and the numbers of rudd recovered. A series of 'roach' or 'rudd' years have followed, depending on the vigour of the parasite population. Numbers of all fish species, except eels, may also have been reduced during the 1980s by deoxygenation of the lake under winter ice (Kennedy, 1991).

Whereas roach are detritus and benthic feeders, rudd are known to live mainly, but not exclusively, on surface invertebrates and plant material (Bregazzi *et al.,* 1982). Replacement during the 1960s of rudd by roach is therefore consistent with the hypothesis that, at the same time, the macrophyte communities of the Ley (the main food habitat of rudd), were both being changed, and diminished in extent, by eutrophication. The effects of parasitism on the roach population has served to complicate and even, at times, to reverse the process of replacement of rudd by roach but, as a whole, the evidence is consistent with the idea of eutrophication of the Ley during this period, especially since roach are known to promote the growth, in lakes, of Cyanobacteria such as *Microcystis aeruginosa* (Ryding & Rast, 1989).

There is no long term monitoring data on the magnitude of the nutrient loadings from the Slapton sewage works, or from that at Blackawton in the north of the Gara catchment (Fig. 1). The former probably contributes between 10 and 25% of the total annual phosphorus load of the Lower Ley (Johnes & O'Sullivan, 1989) and may, since the increase in its effluent load in 1953, have formed a significant proportion of the authigenic phosphorus in the sediment primarily because of its proximity to the Lower Ley rather than to the magnitude of the input.

Using the $^{210}$Pb chronology, in core SLL3 the year 1953 would be found at a depth of 19 cm. Both authigenic phosphorus and biogenic silica influx increase significantly above this level. Acott (1989) has shown how the population of the Slapton catchment has increased from *ca* 1600 persons in 1945, to *ca* 2200 in 1981. Many of these people live in dwellings which are probably not directly connected to the sewers (V. Mercer, M. Michelmore, unpublished), but this permanent population is increased each summer by an unknown number of tourists, and by students at Slapton Ley Field Centre, all of whom must add to the sewage phosphorus loading of the Ley.

Confirmation of such ideas may be obtained from analysis of data on mean annual phosphate concentrations in the Ley determined from the 1970s to the 1990s by Van Vlymen (1980) and by Slapton Ley Field Centre, recently collated by Neal (1994). It is possible to show that, whereas during the 1970s mean annual phosphate concentration was *ca* 50 $\mu$g $l^{-1}$ $a^{-1}$, by the 1980s this had risen to *ca* 77 $\mu$g $l^{-1}$. During the 1990s, however, the value has increased again, to *ca* 111 $\mu$g $l^{-1}$ $a^{-1}$, a significant change in that beyond 100 $\mu$g $l^{-1}$ $a^{-1}$, many shallow freshwater lakes experience a switch from production mainly by macrophytes to a preponderance of phytoplankton (Moss, 1988).

### *Phase 6 - ca 1975 to the present (1987 in the cores)*

This most recent phase is marked by a major expansion of frequencies of planktonic, centric diatoms (to more than 60% of the total diatom sum), especially *Cyclostephanus dubius*, and also, for the first time, *Asterionella formosa*. The latter, of course, is not a centric diatom, but is considered to be associated with eutrophication of lakes by agriculture. In this most recent period, therefore, the diatom evidence suggests that the Lower Ley has been receiving high phosphorus loads both from sewage effluent *and* from agricultural sources.

That this has resulted in advanced eutrophication is shown by the massive replacement of benthic and epiphytic taxa by planktonic species, and the increase in both concentration and influx of authigenic nitrogen and phosphorus. This is also accompanied by a sharp rise in concentration of sedimentary chlorophyll 'a' (Fig. 14). Concentration of biogenic silica also increases, but not influx, an observation which is consistent with the idea that as the Ley has become more eutrophicated, production by planktonic algae has switched away from diatoms to other forms such as blue-greens (Cyanobacteria), a common feature of advanced eutrophication (Moss, 1983; Ryding and Rast, 1989).

In the pollen assemblages, two main further changes are recorded. First, the pollen of *Urtica* becomes much more abundant towards the top of the sediment column. Second, in the aquatic pollen, *Typha/Sparganium* type is replaced by *Potamogeton*. These events suggest respectively (1) that the amount of available phosphorus present in the lake-watershed ecosystem of the Ley as a whole has continued to increase, and (2) that the change in the macrophyte flora of the Lower Ley recorded in the previous phase has continued, in parallel with eutrophication (Wilson, 1991).

The main feature of the nitrogen profile from core SLL3 (Fig. 12) is the large peak of authigenic nitrogen at 6 cm. Here, for example, concentration of this form of the element increases from < 40 mg $g^{-1}$ to *ca* 160 mg $g^{-1}$, and influx from an average of 1–2 mg $cm^{-2}$ $a^{-1}$ to over 11 mg $cm^{-2}$ $a^{-1}$. According to the $^{210}$Pb chronology, this peak coincides with the years 1977–1980. Water quality records for one of the catchments discharging into Slapton Ley (Burt *et al.*, 1988) suggest that, over the period 1970–1985, stream nitrate concentration exhibits a general upward trend (from 5 mg $l^{-1}$ to 7 mg $l^{-1}$) . A major peak in concentration (to 14 mg $l^{-1}$) was observed following the 1976 drought (Doornkamp & Gregory, 1980). It would appear from the present results that this event may have triggered a major shift in the trophic status of the Ley. According to Van Vlymen (1980), during this drought, the Lower Ley was isolated hydrologically from the Higher Ley (the only scientifically recorded instance of such an event), and thus cut off from 70% of its inflowing waters, which are contributed by the River Gara (Fig. 1). The hydraulic residence time of the Ley must therefore have been increased many fold at this time, allowing nutrient levels to rise, and making nutrients available for recycling many more times than usual.

## CURRENT STATUS OF THE LOWER LEY

That the Lower Ley has been eutrophicated by inputs of nutrients from its catchment over the past eight decades thus seems reasonably clear. Analysis of mean annual phosphorus concentrations in its waters indicates that during the 1980s, the lake crossed the threshold between mainly macrophyte and mainly phytoplankton production (100 µg $l^{-1}$ $a^{-1}$) as defined by Moss (1988). Johnes & O'Sullivan (1989) showed that, even allowing for its short hydraulic residence time (Table 1) which flushes many nutrients through the lake before they can take part in growth, the Lower Ley is overloaded with phosphorus, beyond OECD permissible limits (Vollenweider, 1975), by a factor of 3. As sewage and detergent phosphorus constitute about 50% of this total, even if they were removed from the system, it would still be overloaded by a factor of 1.5.

In order to reduce loads further, some attention would need to be paid to agricultural sources. Clearly the economic implications of any proposed solutions would also need to be explored, but O'Sullivan (1992, 1993), and Wilson, Gibson & O'Sullivan (1993), have shown that one possible option is the creation of buffer zones of woodland along the rivers draining into the Ley (Mander, 1985) which, if wide enough (15–20 m), could reduce agricultural phosphorus loads to the point where permitted levels are not exceeded. Recently, this measure has been incorporated in the Water Fringe Option of the MAFF Habitat Improvement Scheme and applied to the catchment of the Ley, which has been adopted as a pilot area for this programme (*The Guardian*, London, 16 May 1994; *Western Morning News*, Plymouth, 17 May 1994).

However, in order to restore Slapton Ley to a stable condition, reductionist measures alone may not be enough (Moss, 1983; Moss, Balls & Irvine, 1985; Ryding &

Rast, 1989). In such shallow eutrophicated lakes, there appears to be an association between Cyanobacteria and substantial populations of fish, especially roach, which has almost certainly developed in Slapton Ley since the 1960s, and which may eventually need to be adjusted by some kind of biomanipulation (Shapiro, Lamarra & Lynch, 1975), if water quality is to be improved. The diminution of the cyanobacterial populations, and the increased growth of macrophytes in the Ley, which took place during the 'low fish' years of the early 1980s are circumstantial indications that such a policy, which is probably necessary, might also meet with some success.

## CONCLUSIONS

The Lower Ley, Slapton, a shallow, eutrophicated lake in SW England, was formed by longshore and onshore movement of marine material behind a shingle barrier *ca* 1000 years ago. Until recently, the Ley possessed a diatom flora composed mainly of epiphytic, benthic and littoral forms. For most of its existence, the Ley has been a naturally productive, clear water lake, with abundant macrophytes.

Pollen diagrams from the sediments of the Ley show that a mainly treeless landscape, with woodland confined to the valley sides and valley bottoms was established well before the arrival of Saxon settlers in area after *ca* 700 AD, and probably in the Late Bronze Age. By the time of Domesday, open fields for arable cultivation had been created close to the village of Slapton. These were enclosed in the C15th, but arable cultivation continued. The last areas of scrub land and heath were enclosed in the late C17th, early C18th.

A major change in the sedimentation regime of the Ley occurred in the period following the construction, in 1856, of a road along the shingle ridge dividing the Ley from the sea, and the raising of the lake level by the building of an outflow sluice. These events resulted in an increase in the lake's hydraulic retention time, and a considerable influx of calcium, manganese, magnesium and carbonate, probably from lime-kilns operating close to the lake shore.

The record of iron and manganese sedimentation suggests that, following the raising of the water level, periodic deoxygenation of bottom waters of the Ley occurred. This took place mainly in the period 1910–1975. In *ca* 1910 , a further major change in the sedimentation regime of the Ley, from mainly authigenic to mainly allogenic material, took place. This is thought to be associated with a major land use change which is documented for the period 1885 to 1915, when the 'traditional' arable cultivation and sheep rearing were replaced by pasture and the raising of dairy cattle. Initial, mild eutrophication of the Ley began at this time, as witnessed by the appearance in the sedimentary record of centric, planktonic diatoms.

After 1945, erosion of catchment material, especially topsoil from arable fields, associated with the post-war intensification of agriculture, resulted in a second expansion in the rate of sediment influx to the Ley. Levels of sedimentary authigenic nitrogen and phosphorus, allogenic phosphorus, and biogenic silica also increase, showing that although no major qualitative change in the diatom flora occurred, further eutrophication, in the form of a rise in nutrient loadings did indeed take place, and that the response of the ecosystem of the Ley was an increase in productivity. In 1960, planktonic diatoms indicative of increasing nutrient status expand further in the sedimentary record. This appears to be related to an increase in the numbers of people served by Slapton sewage treatment works, both in 1953, and again in the early 1960s.

These events appear also to have affected both the aquatic macrophyte flora and the freshwater fish populations of the Ley.

A peak in sedimentary authigenic nitrogen is correlated with the severe drought of 1976. The lake appears to have been triggered by this event to transcend a threshold in its trophic status, and to become the present highly productive system in which phytoplankton is gradually replacing macrophytes.

Slapton Ley thus became eutrophicated in a number of stages, with the first two associated with intensification of agriculture in *ca* 1910, and 1945. The main response of the ecosystem of the Ley to nutrient increase came in the period after 1960, however, with the introduction of increasing sewage phosphorus into the system. This was exacerbated by the drought of 1976, when the Lower Ley became isolated from much of its catchment.

The present highly eutrophicated condition of the Ley is a result of receiving both sewage phosphorus, and nutrients from substantial cattle populations in its catchment. Current sediment influx is calculated at 610 t $a^{-1}$, which is equivalent to a sediment accumulation rate of 9 mm $a^{-1}$. Present phosphorus loadings upon the Ley, of which 25–50% are contributed by sewage and detergents, exceed OECD permitted limits by a factor of three.

Therefore, even if all sewage phosphorus inputs to the system were removed, the lake would remain overloaded unless inputs from agriculture were reduced. This could be achieved by zoning of the catchment, and the creation of buffer strips of woodland. Even then, some kind of manipulation to the ecosystem of the Ley may eventually be necessary, in order to remove the effects of more than eighty years of eutrophication.

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