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The use of laminated lake sediments in the estimation and calibration of erosion rates

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ABSTRACT Recent advances in analytical techniques applied to lake sediments have given rise to much information of interest to geologists and geomorphologists. In particular, the laminated sediments known as clastic varves, which are composed mainly of allochthonous material, afford an excellent opportunity for the study of erosion rates. The clastic varves of Loe Pool, a coastal lagoon in Cornwall, have been used to study erosion rates in the basin of the River Cober in the period from c.1860 to the present. Multiple coring of the most recent sediments was used to calculate volume, mass and influx of dry matter and ash to the Pool during periods of intensive mining, and the subsequent post-mining period. Erosion rates were found to be c.174 t $km^{-2}year^{-1}$ in the late nineteenth century, between 360 and 420 t $km^{-2}year^{-1}$ during the early twentieth century, and c.12 t $km^{-2}year^{-1}$ at present.

INTRODUCTION

A number of recent reviews (e.g. Oldfield, 1977; O'Sullivan, 1979; Wise, 1980) have stressed the value of lake sediments as a potential source of information for the study of the ontogeny of drainage basins. By applying appropriate techniques, it is possible to obtain information from lake sediments of great interest to geologists and geomorphologists who study processes in a drainage basin framework. For example, Davis (1976) used the ash content of pre- and post-settlement sediments in a lake in southern Michigan, USA, to calculate inorganic sediment influx, and to estimate erosion rates in its basin over the last 150-200 years.

Advances in the methodology of analysis of lake sediments for such magnetic properties as susceptibility (Oldfield *et al.*, 1978; Thompson *et al.*, 1980) have, however, greatly increased the ability of paleolimnologists to produce such information, and the rapidity with which such results are obtained. Thus Bloemendahl *et al.* (1979) calculated sediment influx into a small lake in North Wales, UK, and Dearing (1981) has estimated sedimentation and erosion rates over the last 250 years in a lake drainage basin in southern Sweden.

Here we present a preliminary analysis of sedimentation and erosion rates in the lake-drainage basin system of Loe Pool, Cornwall, UK, which is based on a further property of lake sediments, that of annual lamination.

LAMINATIONS IN LAKE SEDIMENTS

Laminated sediments have long been known to occur in the large lakes of Central Europe (Nipkow, 1927). However, in the last 10 years it has become apparent that they are also formed in many smaller lakes. Basically, two main forms of laminations, or varves, have been found (Renberg & Segerström, 1981). The first are often formed in small relatively deep lakes (Zr *sensu* Hutchinson (1957) > 250), where permanent or semi-permanent stratification exists, and are composed mainly of autochthonous material. The second, also known as "clastic varves" (Sturm, 1979) are mainly allochthonous in composition, and clearly represent a potential source of considerable information about the recent history of the catchment of a lake. This lamination is the type found in Loe Pool, a coastal lagoon in south west England (Simola *et al.*, 1981).

LOE POOL AND ITS DRAINAGE BASIN

Loe Pool (Fig.1) is a eutrophic freshwater lagoon (latitude 50°4'N, longitude 5°17'W) at c.4 m OD, 1 km south of Helston, Cornwall, UK (GR SW 648250). The Pool, which has an area of 44 ha, and a mean depth of 4 m, was formed, probably in medieval times, by the damming of the estuary of the River Cober by a shingle bar. This gives the

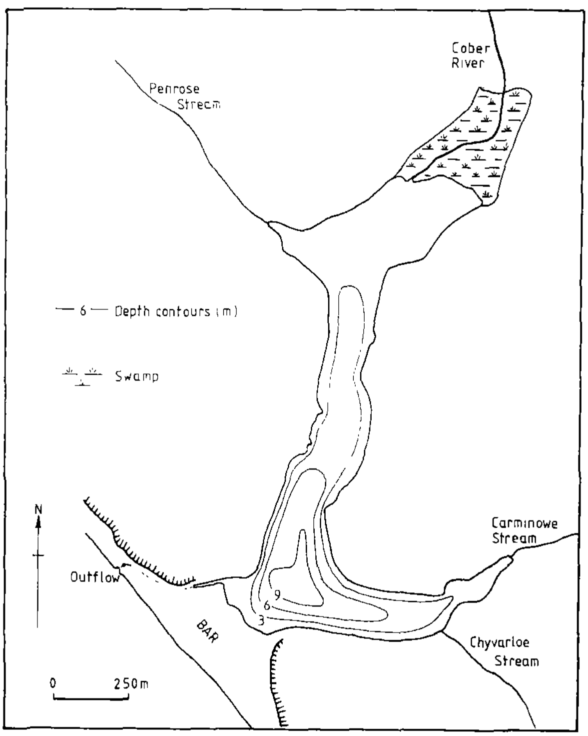

FIG.1 Loe Pool showing main physiographic features mentioned in the text, and depth contours.

site a characteristic morphometry, which in turn affects patterns of sedimentation.

The northern end of the Pool, near the inlet of the River Cober, is relatively shallow (1-3 m depth). Here sedimentation appears to be proceeding at a rapid rate, with considerable alluvial infilling of the valley between Helston and the Pool since 1900 (Coard, unpublished data). The narrow central area of the Pool (or "neck") consists of a steep-sided former channel, 3 m deep at the northern end, shelving towards the sea to about 7 m. At the south end of the lake, close to the shingle bar, is a deeper basin (max. depth 10 m), which may in the past have been excavated by incursions of the sea (Toy, 1934; Coard, unpublished).

The drainage basin of Loe Pool, which is mostly farmland, occupies c.50 km^2. Approximately 90% of the water entering the Pool arrives via the River Cober, which flows in at the northern end. The three other main tributaries are the Penrose stream, which enters from the northwest, and the Carminowe and Chyvarloe streams, which discharge into the bay in the southeastern corner of the lake known as Carminowe Creek.

Most of the catchment of Loe Pool is pasture, devoted to the raising of cattle and the production of milk. At the northern end is an area of moorland, underlain by the Carnmenellis granite. Closer to Helston and the sea, are a few farms where market gardening is carried out, but ploughed land forms less than 10% of the total farmland in the catchment.

In the nineteenth century and early twentieth century, the drainage basin of Loe Pool was the scene of considerable mining activity, principally for tin (Hamilton-Jenkin, 1978). Shaft mining reached a peak in the 1880's, and again in the 1920's and 1930's (Coard, 1981), when newspaper accounts describe the Pool as being heavily polluted and discoloured by mine wastes, especially haematite. Consequently, in 1938, mining operations were closed down, and none have taken place since (Coard, unpublished).

THE SEDIMENTS OF LOE POOL

Detailed descriptions of the stratigraphy of the recent sediments of Loe Pool are given by Coard (1981) and Simola *et al.* (1981). Four basic lithological units exist, the uppermost of which is a dark brown clay-*gyttja*, which may be up to 50 cm thick, and which, immediately below the sediment surface, regularly exhibits 5-7 dark brown and black laminations. Below c.10 cm, however, varves are usually absent, and it seems that during the 1960's, the bottom sediments of the Pool were heavily bioturbed. The effects of this are not, however, entirely general, as occasional sections which are laminated throughout are recovered.

Below the brown clay-*gyttja* is a layer of pink clay, whose distinctive colouration is due to the presence of haematite (Fe_2O_3). We correlate this layer with the late 1930's, the last recorded period of mining in the catchment. Below this in turn is a massive layer of grey clay, also formed from mining waste. The lowest unit widely recorded so far is a regularly-laminated grey/black clay, in which the average thickness of laminations is 3 cm $year^{-1}$.

Incorporated with it are further, less massive, haematite layers.

Data on the physical properties of these respective layers, and the time span they each represent, are shown in Table 1. A chronology of recent sedimentation in Loe Pool was assembled using the "adhesive tape" method of Simola (1977), where thin sections of frozen sediment are examined for the presence of annual cycles of deposition, especially of algal remains, principally diatoms. The uppermost clay-*gyttja* has been deposited in the period since 1938, the year in which mining operations in the catchment ceased. The uppermost pink clay layer then dates from the years 1937-1938, as it incorporates only two annual cycles of sedimentation (Coard, 1981). The massive grey clay represents the years 1930-1936, and the laminated clay 1929 back to about 1860. It should be stressed, however, that this reflects only the limit of the coring devices so far used, and that deeper laminated sediments exist.

TABLE 1 Principal lithostratigraphic units of the recent sediments of Loe Pool, and their physical properties

Unit	*Dry matter (%) content*	*Ash content (% dry matter)*	*Density*	*Lamination number/time span (years)*
Brown clay-gyttja	*20*	*83*	*1.08*	*43*
Pink clay	*33*	*93*	*1.15*	*2*
Grey clay	*51*	*96*	*1.51*	*7*
Laminated black/grey clay	*43*	*92*	*1.37*	*c.3 cm* $year^{-1}$ *(thickness unknown)*

Confirmation of this chronology for the uppermost sediments was obtained by analysis of their ^{137}Cs content. The well documented peak of fallout ^{137}Cs, demonstrated by Pennington *et al.* (1973) to date from 1963 in the northern hemisphere, lies within the brown clay-*gyttja*, approximately halfway between the present sediment-water interface and the top of the pink haematite-clay.

EXPERIMENTAL DESIGN AND METHODS

The main application of studies of laminated lake sediments has been the development of very precise chronologies for the study of the ontogeny of lake-drainage basin ecosystems. Using laminated sediments, it is often possible to speak in terms of the precise year, season, or even day when an event in the catchment of a lake is recorded in its sediments (*cf.* Simola & Tolonen, 1981).

Laminated sediments, especially when coupled with prominent marker horizons, also afford an excellent opportunity for inter-core correlation. Multiple coring of a lake basin in which such sediments are found therefore allows the assessment of annual rates of bulk sediment accumulation, which in turn leads on to calculation of annual rates of erosion into the lake for the period over which laminations have been formed. In this sense, annual laminations are at least as good a research tool as the magnetic parameters employed by Oldfield and his fellow workers (*cf.* Oldfield *et al.*, 1978), and in so far as they directly give rise to annual figures, they may have a significant advantage.

In Fig.2 are shown the locations of the multiple cores of Loe Pool sediments, which were obtained using a standard "Mini-Mackereth" corer (Mackereth, 1969). This method, though usually less satisfactory for laminated sediments than freezer-samplers (Huttunen & Meriläinen, 1978; Saarnisto, 1975; Swain, 1973), is more rapid, and in the case of sediments with prominent markers and spectacular colour changes, reasonably accurate. Care must be taken, however, to avoid errors introduced by smearing of the outer surface of the core against the inner surface of the core-tube. The presence of distinct, well-reserved laminations on the surface of our cores suggests however that smearing effects were not of major importance.

The location of each core was determined by reference to shoreline topography and by taking bearings. The thickness of the brown clay-*gyttja*, the pink clay, the grey clay and where present the black laminated clay were determined by simple measurement in the field.

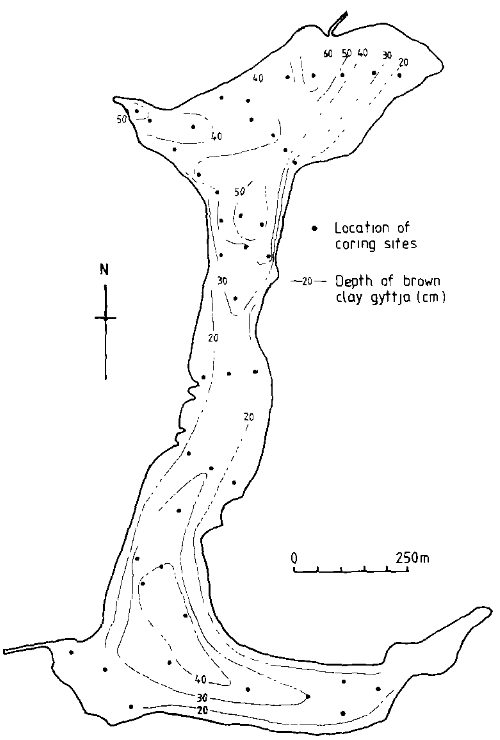

FIG.2 Loe Pool showing location of coring sites, and depth contours for brown clay-gyttja.

RESULTS

The results of the exercise are shown in Figs 2 and 3. Fig.3 depicts a section from north to south along the Pool, obtained by averaging. data from groups of cores from individual transects.

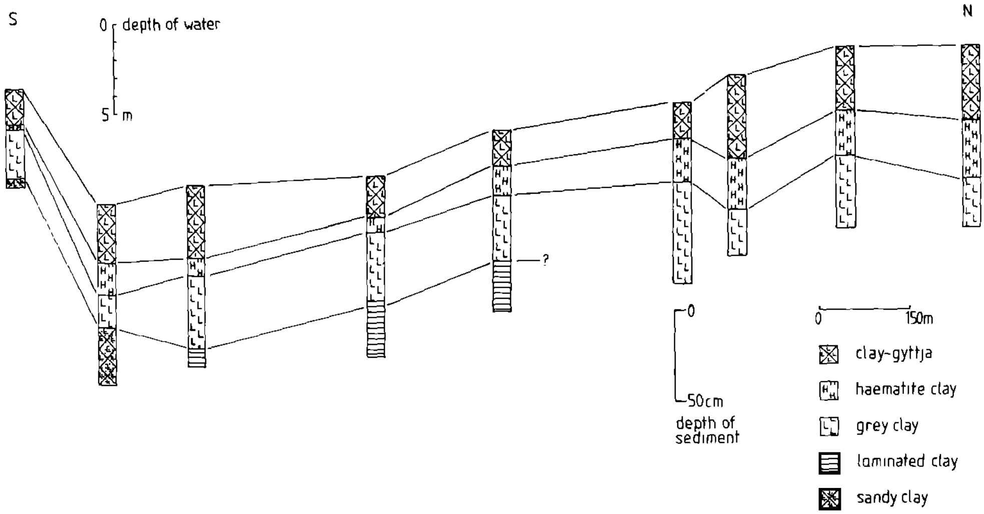

FIG.3 Generalized north-south section of recent sediments of Loe Pool.

The brown clay-*gyttja* is mainly between 35 and 45 cm thick in the northern shallow part of the Pool, but in the narrow "neck" area it declines in thickness to about 20-25 cm. In the deep southern basin, however, its depth increases again to between 30 and 40 cm.

The pink clay exhibits rather more straightforward patterns, in that it thins out from 25-30 cm in the northern part of the lake to only 8-10 cm in the deep part of the "neck". At the very deepest point of the Pool, its thickness is 18 cm however.

The contact between the grey clay and the underlying black/grey laminated clay was not always present in the cores (i.e. the combined thickness of the three uppermost units often exceeded 90-100 cm). We therefore present no data here on the overall thickness of the grey clay. As stated earlier, the total depth of black/grey laminated sediment in Loe Pool is, as yet, unmeasured.

Fig.2 presents an analysis of spatial variation in sediment thickness within the Pool. This confirms the north-south trend of sedimentation demonstrated by Fig.3. A "tongue" of sedimentation proceeding from the mouth of the River Cober into the "neck" is shown, with some increased accumulation also in the deepest part of the lake. Another feature not previously mentioned is, however, the very fast sedimentation rate of the brown clay-*gyttja* in Penrose bay (> 1 m of sediment in 40 years or > 2.5 cm year^{-1}), and the "tongue" of sedimentation also found there. Thus the distribution of recent sediment in Loe Pool seems to reflect stream input, with the River Cober contributing much of the material, but with tributary streams being responsible for the filling up of the bays.

The main exception to this pattern is that in the deep basin near the bar, sedimentation rates are almost as great as in the northern shallow part of the Pool, especially with respect to the clay-*gyttja*. It is possible that some "sediment-focussing" (Davis, 1973) into this deepest part of the lake is occurring, but as yet we have no data on this.

Calculation of sediment influx

Table 2 shows the mean thickness, volume, mass and accumulation rate of the four main units in the recent sediments of Loe Pool. These values can be calculated using the data presented in Table 1 plus figures for mean thickness, and the area of the Pool. It is important to note here that whereas the present area is 44 ha, in 1908 the area was c.54 ha (Coard, unpublished). For the pink and grey clays we have therefore used a figure of 50 ha, and for the black/grey clay, 54 ha. The results shown that the present rate of dry matter accumulation in Loe Pool is 779 t $year^{-1}$ (or 17 t $ha^{-1}year^{-1}$). Similarly, the annual accumulation rate of ash is 644 t $year^{-1}$ (or 14 t $ha^{-1}year^{-1}$). By some standards, these are large figures for accumulation rates in a freshwater lake. For example, Simola & Uimonen-Simola (1981) have found that the rate of accumulation of inorganic matter (dry weight - weight of carbon x 2) in Pääjärvi, in southern Finland, is 4900 t $year^{-1}$, or 3.6 t $ha^{-1}year^{-1}$. The catchment of this lake is 60% forested (Ruuhijärvi, 1974). Davis (1976) however, reported influxes of c.20 t $ha^{-1}year^{-1}$ in the eutrophic Frains Lake in southern Michigan, USA, whose drainage basin is made up of house-lots, meadows and cornfields, so that we do not consider our figures to be gross overestimates. Indeed, the present annual sediment accumulation rate of Loe Pool (c.1 cm $year^{-1}$) as calculated by Simola *et al.* (1981) is much greater than the rates normally measured in freshwater lakes, which are generally expressed in $mm^{-1}year^{-1}$ (Simola, 1981). Instead we feel that the relatively rapid accumulation rate of Loe Pool is attributable to its highly eutrophic status (Coard *et al.*, 1981; Lacey *et al.*, 1982), and particularly to the very small size of the Pool in relation to its drainage area (D/A ratio *sensu* Hutchinson (1957) = 114).

If present rates of influx into Loe Pool are large, then sedimentation rates during the 1920's and 1930's, the time of deposition of the pink and the grey clay, were even more so. For the pink clay, the dry mass and ash accumulation rates are respectively 19 427 t $year^{-1}$ and 18 067 t $year^{-1}$ (or c.388 and 361 t $ha^{-1}year^{-1}$). For the grey clay, estimates are more difficult because of scarcity of data, but rates of the order of 21 895 t $year^{-1}$ (437 t $ha^{-1}year^{-1}$) for dry matter and 21 063 t $year^{-1}$ (421 t $ha^{-1}year^{-1}$) for ash seem likely on the basis of the thickness of this layer in the 3 m Mackereth core analysed by Coard and Simola (Simola *et al.*, 1981).

On first inspection these rates seem again to be rather high, yet newspaper accounts from the 1920's describe the Pool as being completely discoloured by mining wastes. Indeed, mining ceased in the catchment in 1938 not for economic reasons but as a result of

TABLE 2 Thickness, volume, mass and accumulation rates of principal lithostratigraphic units in Loe Pool sediments

Unit	Mean thickness (cm)	Thickness year^{-1} (cm)	Volume (m^3)	Wet mass (t)	Dry mass (t)	Dry mass accumulation rate (t year^{-1})	Ash content (t)	Ash accumulation rate (t year^{-1})
Brown clay-gyttja	35	0.81	153 780	166 082	33 499	779	27 704	644
Pink clay	20	10.16	101 550	116 783	38 854	19 427	36 134	18 067
Grey clay (50 ha)	40	5.71	200 000	302 000	153 265	21 895	147 441	21 063
Laminated clay	unknown	3	16 200 (year^{-1})	22 194 (year^{-1})	-	9 490	-	8 731

litigation (Coard, unpublished data). There may therefore be some grounds for supposing that very considerable rates of sedimentation indeed took place during that period. Also between 1908 and 1945, an area of approximately 10 ha at the north end of the Pool was completely filled in by mining wastes, to what depth we do not know. For the black/grey laminated clay, only an estimate of annual influx is available, and this again is based mainly on observation of a single 3 m Mackereth core. Here, laminations of c.3 cm thickness $year^{-1}$, suggest a dry mass accumulation rate of 9490 t $year^{-1}$ (175 t $ha^{-1}year^{-1}$). For ash the figure is 8731 t $year^{-1}$ (161 t $ha^{-1}year^{-1}$). These rates are also calculated from sediments deposited during a period of active mining.

Erosion losses in the Loe Pool/Cober drainage basin

Davis (1976) used ash content of lake sediment as an indicator of inorganic matter erosion from its basin. If the ash influx figures for Loe Pool are used to calculate erosion rates for the 50 km^2 basin, the figures shown in Table 3 are obtained. These suggest that the current loss of inorganic material from the drainage basin of Loe Pool is exactly 12 t $km^{-2}year^{-1}$, which is at the bottom of the range of losses for natural-agricultural basins suggested by Wolman (1967). However, it must be remembered that what is being measured here is not the suspended sediment load of the River Cober, but sedimentation in Loe Pool, a relatively shallow lake, with a very short hydraulic residence time (Coard *et al.*, 1981). Thus, some of the sediment brought into the Pool by the Cober may in fact be flushed right through, particularly in the period December-February. It may also, to a certain extent, be trapped by the alluvial area at the northern end of the lake.

TABLE 3 Estimated erosion rates in Loe Pool drainage basin 1860-1981

Period	*Rate (t $km^{-2}year^{-1}$)*	*Main or dominant catchment activity*
1938-1981	*12*	*Agriculture*
1937-1938	*361*	*Intensive mining and agriculture*
1930-1936	*421*	*Intensive mining and agriculture*
1860-1920	*174*	*Mining and agriculture*

Erosion rates during former mining periods were, of course, much greater. For the period 1930-1938, the most recent phase of active mining, the average erosion rate was c.360 t $km^{-2}year^{-1}$. For the late nineteenth century, the estimated rate recorded by the laminated clay is c.175 t $km^{-2}year^{-1}$.

These rates are well below the ranges of sediment losses from urban construction sites described by Burton *et al.* (1977), Walling (1974), Walling & Gregory (1970), and Wolman & Schick (1967). However, it should be remembered that the sources of much of the material involved constituted a very small total of the catchment area, and in some cases may almost have been point sources (e.g. mine waste heaps, tin washing plants etc.). Erosion rates in certain parts of the Loe Pool catchment may, in certain periods of the past, have therefore been very great indeed.

CONCLUSIONS

Multiple coring and prominent marker horizons have been used to calculate sediment influx to Loe Pool during three periods of the recent past. A chronology based on the presence of annual laminations has then been used to calculate mean annual influx, and mean erosion rates for each period. Such methods are in theory applicable in any lake where sediments possessing prominent marker horizons are found, but the presence of annual laminations provides a much more precise chronology than is normally available. In this paper, only mean erosion rates were calculated. A more comprehensive analysis, producing erosion rates for each year of deposition is however theoretically possible.

The frequency with which laminated sediments have been discovered since the development of appropriate sampling devices suggests that they are much more common than previously supposed, and that the methods outlined in this paper could eventually become applicable on a reasonably widespread basis.

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