PALAEOLIMNOLOGY: AN INTRODUCTION

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Summary

Lake sediments provide a unique record of environmental changes. Chemical and biological methods, laboratory techniques, dating, the most investigated proxy-records and their application to monitoring and plankton dynamics programs are presented and discussed. The importance of biological remains analysis in palaeolimnology is emphasized. Particular prominence is given to fossil pigments (chlorophyll derivatives and carotenoids) as a proxy for past phototrophic communities and primary production, and as biomarkers of environmental change. The nature of proxy data and associated techniques have been discussed and proven to be a useful way of improving our understanding of human-climate ecosystem interactions. The final section focuses on advances in palaeolimnology and future directions.

"The present would be full of all possible futures, if the past had not already projected a pattern upon it." *André Gide (Paris, 22 november 1869 - Paris, 19 february 1951) Nobel Prize in 1947*

1. Introduction

History does not merely mean re-reading the past: it provides us with much more. It tells us where we have come from and where we might go. It reminds us of our successes and our failures. The past encourages us to go on, but it also warns us about what might happen in the future.

This is especially true of environmental studies. Without long-term data, for instance, we cannot show how far an ecosystem has deteriorated (or recovered), we cannot establish realistic mitigation measures or determine the disturbance level which has had a negative effect on the environment; nor will it be possible to understand the trajectories of change.

Over the years a number of accounts have been published of palaeolimnological studies from all over the world, and the data has already been reviewed on a number of occasions.

Sporadic records exist from the early 1950s, but the bulk of our information comes from the years since the 1980s. In this chapter the author cannot avoid referring to some of the existing reviews, but an attempt was made to interpret the literature in terms of new data and present the new ideas and future challenges in this fascinating field of environmental research. A bibliography and a references list are provided, with the intention of guiding the reader through the vast amount of palaeolimnological literature available.

1.1. A Necessary Premise

The main general concepts underlying palaeolimnological and palaeoecological research originated between the 18th and 19th centuries, when James Hutton, a Scotsman who later became famous as one of the fathers of modern geology, and an Italian, Arduino, put forward what was for the time the revolutionary idea (subsequently taken up by another great geologist, Charles Lyell) that “the present is the key to the past”, and that the geological characteristics of the Earth must be the result of processes which were still going on, working over long time periods. This theory, known as *uniformitarianism*, can be regarded as the basic principle behind all geology, and also the branch of geology which goes under the name of palaeoecology, or in the case of lakes, of palaeolimnology.

1.2. What is Palaeolimnology?

The science of palaeolimnology covers an area where limnology, the branch of ecology studying lakes, meets palaeontology, the study of fossils. This means that palaeolimnology is the study of lakes as they were in past periods, from the most recent (Holocene) to those very remote from the present (Middle Pleistocene or even farther back). The discipline studies the origin and the geomorphological history of lake basins and the response of their biocenoses (plant and animal communities) to the variations in e.g. trophic state, climate, water levels, and dissolved substances which have occurred over time.

Palaeolimnology does not confine itself to the study of a lake, but also takes in its watershed. Through the stratigraphic study of sediment cores, it discovers phenomena linked to local situations clearly limited in time, and phenomena of global relevance such as the great climate changes associated with the various phases of glaciation and the more recent global warming (palaeoclimatology).

Palaeolimnology, in its modern sense, is typically multidisciplinary, in so far as a number of different disciplines contribute to it. For example, anyone studying climates through the different periods of geological time, or a researcher intending to reconstruct the palaeoenvironment, will use the tools and methods of geochemistry and sedimentology, as well as those of micropalaeontology.

Thus, compared with limnology, the composite science studying lakes, palaeolimnology involves the further dimension of geological time.

1.3. The Need for Certain Assumptions

Understanding the present involves and understanding of what came before, and at the same time understanding the past requires a profound insight into the processes that are going on at the moment, and which presumably went on in the same way in the past.

The assumptions underlying palaeolimnology, and palaeoecology in general, are essentially two, as in geology. They are (1) that the ecological laws have remained essentially the same through the various geological periods, and (2) that the ecology of fossil organisms can be deduced on the basis of the ecology of equivalent or similar species living today.

Thus, the past, present and future are inextricably linked together. Since we cannot observe directly the changes that occurred in the past, we must infer them from the observable results of these changes in modern times.

1.4. Focus on the Past

The main aim of palaeolimnological studies is to reconstruct the state of a lake from several standpoints (physical, chemical and biological) from a period which may be quite far back in the past, down to the present day. In other words, what we want to know is, for example, whether a lake has always hosted the same flora and fauna, whether its trophic conditions or its water level have changed through time, and so on.

The Earth’s ecosystems have not stayed unchanged over the years, on the contrary they have often experienced profound changes, and in some cases parts of lakes have become separate from the main body, giving rise to other lakes. This happened, for example, with a bay of Lake Maggiore (Northern Italy), which in historic times became Lake Mergozzo. Many lakes have sunk, becoming bogs, others have become smaller, in area or in depth, while still others have disappeared, after occupying volcanic craters, hollows and valleys.

We also know that the Earth’s climate has undergone profound changes throughout the geological periods, and in our period, the Quaternary, in particular. During this time the transition from glacial to warm periods has had a direct or indirect influence on the landscape, and in the most recent period on the daily life of human beings. Since they first began to have a social structure and occupy certain territories permanently, giving rise to the first civilizations, human beings have altered their ecosystem, both terrestrial and aquatic, often in radical ways.

1.5. Some Stimulating Challenges

The above brief observations lead to the conclusion that one of the greatest challenges for palaeolimnologists is to interpret correctly the impact that the climate (for example) has had on a lake and its surrounding area, and to distinguish and quantify the two effects, the natural and the human-induced, which have occurred in the last 6,000 years, corresponding to the active presence of man.

Even though they use the same methods, palaeolimnologists have to come to terms with two major research activities, each with quite separate aims and objectives. One involves reconstructing the events of the past which occurred due to natural phenomena such as the climate changes so widely discussed today, the other investigates the changes resulting from human activities (industry and agriculture). The most classic example in this connection is perhaps provided by studies on the phenomenon of the eutrophication of water bodies.

The other major activity that palaeolimnologists are required to perform is using existing knowledge to describe and quantify the beginning, the extent and the impact of natural phenomena or human disturbance on lake environments, both in recent and historical times.

Palaeolimnological information is therefore important because it includes (1) information on the environmental conditions preceding an event, and therefore the relative evolution in time of the parameter under analysis (e.g. an algal nutrient or fossil remains), and (2) the nature and the extent of natural variability (not affected by human activities), including rare and infrequent events.

1.6. Techniques for Assessing Past Environmental Change

How do we acquire past limnological information?

Historical data can be acquired in five ways:

1. direct measurements on the environment: these are very rare and often not readily comparable, because of the different measurement methods used. Moreover, these data rarely go back more than 50-60 years from the present.
2. using simulation models: these are sometimes inaccurate, because the data inserted are inadequate, or because important mechanisms are not taken into account by the model.
3. Comparison with other similar reference environments, for which we have historical information.
4. Consulting old texts and documents.
5. Palaeolimnological analyses.

Of these, the palaeolimnological/palaeoceanographic approach is indubitably one of the most complete, and is often the only way to get information on the prehistoric period.

In tackling some environmental problems, the palaeolimnologist has to answer major limnological questions such as: what were the pre-disturbance conditions? What is the range of natural variability? Have conditions changed? How? How much? How fast? When? Why? Can evidence of human activity be detected? How much improvement can be expected? Where lake sediments are available, reconstruction of past ecological conditions may shed light on these questions, since the sediments preserve not only a record of ecological change in the form of biological remains, but also a partial record of mineral input from the drainage basin of the lake.

1.7. Natural Archives: A Window Open on the Past

These premises provide a general framework for the topic, and help us make a concrete analysis of the problems which have developed in palaeolimnology, along with the research methods used and how the results are to be interpreted. It is hoped that the examples given here show the usefulness of the palaeolimnological approach in monitoring programs, and especially the great potential offered by these studies in tackling and resolving some of the current, and often worrying, environmental problems which are perceived as critical by public opinion.

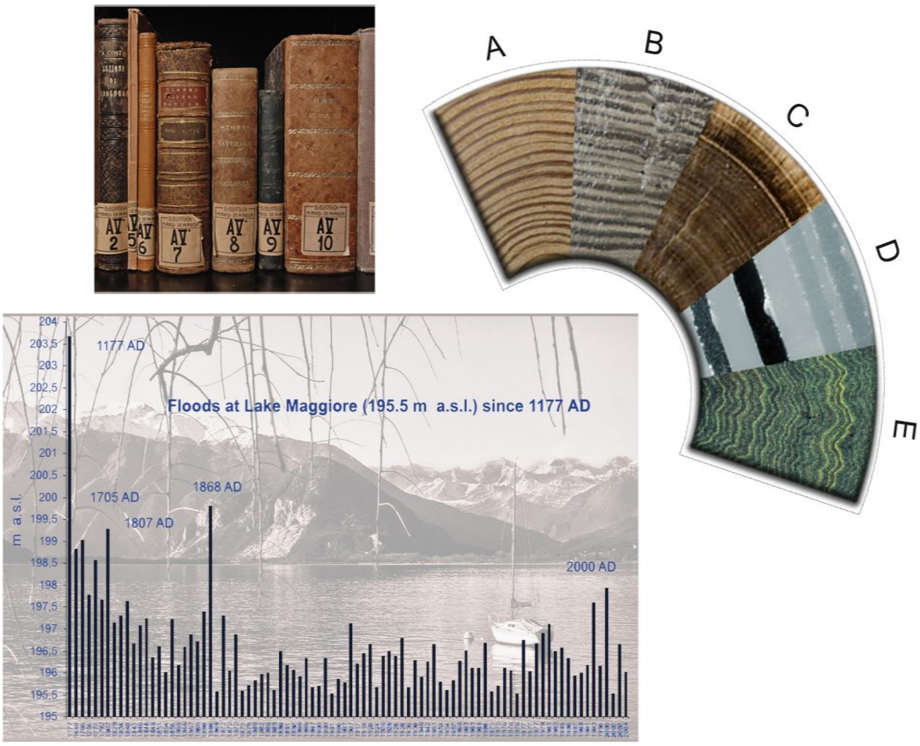

Figure 1. The Earth has several natural “archives” or historical records: the best studied of these are shown here. A: tree rings; B: lake/ocean sediments; C: stalactites (speleothems); D: ice; E: corals. Historical records such as documents, articles, chronicles, etc. and long-term data are additional sources, or techniques for, assessing environmental changes. The record of extreme floods events in Lago Maggiore (N. Italy) since 1177 AD are also inserted as an example of available long-term data.

The Earth has many natural “archives” or records: glaciers, speleothems (typically formed in limestone or dolostone solutional caves), bogs, tree rings, sea and lake

sediments (Figure 1); by studying these we can reconstruct the history of a region, gathering information on the climate changes and human impact which occurred at times before the first measurements were made in the field.
Natural and human-induced events from historic times can be reconstructed merely by reading old documents, chronicles and books which have come down to the present.

This is a major body of information, and over time palaeolimnologists have learned to interpret and de-code a whole series of “proxy records”, thanks to links between what is found in natural archives and historical information on the one hand, and current scientific knowledge on the other.

2. Sediments and Their Importance

2.1. Formation and Structure of Lacustrine Natural Sediment.

Lake sediments are one of the most complete and detailed natural archives, documenting – often in greater detail than ocean sediments – the temporal evolution of the chemical, physical and biological characteristics of a lake, the surrounding territory and the climate of the region.

The annual rate of deposition of sediment is known as the “accumulation rate” or “sedimentation rate” and are expressed in gram m^{-2} or cm of sediment per year. Though there are many exceptions (e.g. the Adriatic Sea), marine sediments have a much lower sedimentation rate; nevertheless, a long history can be reconstructed from this material, maybe starting from millions of years ago, but obviously poor in detail.

In many cases there are problems of resolution and temporal classification of the data, or problems with the dating of the material, with the result that parameters such as the duration and rate of the changes must remain approximate. The ensuing scientific interpretation might be compared to an old magnetic tape, forgotten in some dusty cellar, damaged by time, and on which you can hear clearly only a few passages among the crackles and hisses.

We will now take a closer look at sediments and the substances they are made up of.

Sediments contain material which is the result of the chemical, physical and biological processes which have taken place in the water mass and its watershed as long as the lake has existed. They are home to vast, diversified benthic and microbial communities, and are the site of complex interactions with the overlying water.

A large variety of different kinds of materials and substances arrive in the lake from the watershed and the atmosphere, some of them important for plant and animal life, of which they determine the abundance and diversity, others of more exclusively geochemical interest. All of these substances originating outside the lake (of allochthonous origin), along with those produced in the lake (of autochthonous origin), contribute to the formation of sediment which gradually, season after season, accumulates on the bottom. Sediment includes both an organic and an inorganic component, the latter usually of fine grain size.

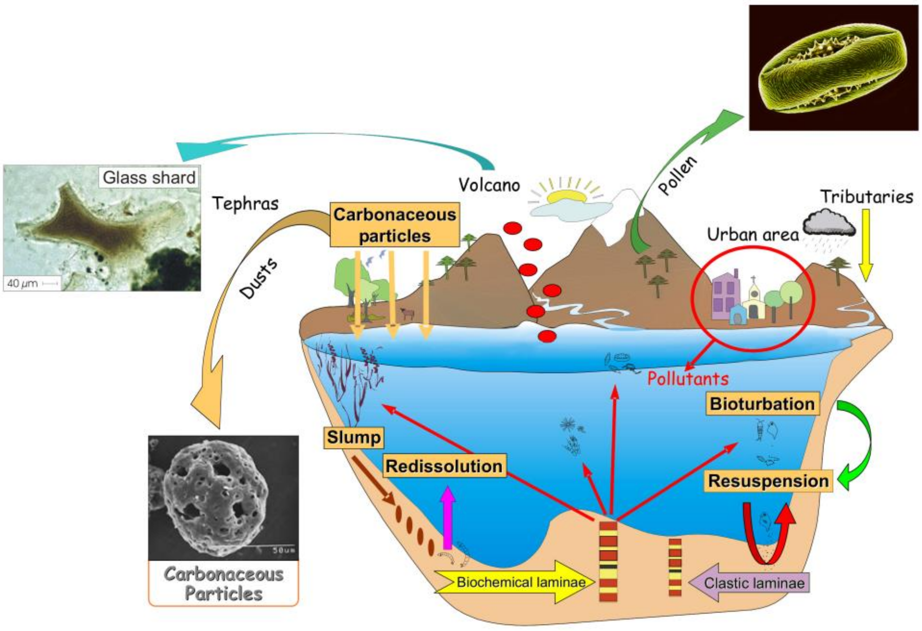

Figure 2. Sediment sources, distribution mechanisms, sedimentation processes and resulting sediment types: schematic drawing showing the main factors contributing to the formation of lake sediments. Allochthonous materials include: dusts, soil particles, pollen grains, rivers-and urban-derived discharges; atmospheric transport compounds (e.g. contaminants) and volcanic ash (tephra). Autochthonous materials are: vegetal and animal remains. For processes such as bioturbation, sediment resuspension, redissolution of chemicals and slump formation see the text. Schematic composition of the biochemical and clastic laminations are also shown (redrawn from Sturm and Lotter, 1995).

The foregoing description may be illustrated to better effect in a schematic drawing like that shown in Figure 2, which shows the main factors contributing to the formation of lake sediments. Organic substances include a percentage of sedimentary plants, largely represented by algal and bacteria photosynthetic pigments (chlorophylls and carotenoids) of algal and macrophyte origin (from aquatic plants), and by the debris from the land and the littoral zone. Along with the remains of dead animals, these plant substances make up the overall pool of organic sediments. The inorganic percentage includes mineral particles washed into the lake from the surrounding territory, or which have been convoyed by the tributaries or surface runoff, particles transported by the wind, inorganic ions dissolved in the inflowing water and coming from atmospheric precipitation. In-lake processes can also produce minerals such as carbonates from intense photosynthetic activity.

Deep subalpine lakes located in longitudinal valleys with a sediment source mainly derived from rivers and thus of predominantly allochthonous in origin, and with a strong thermal stratification, show a sediment structure rich in graded clastic layers deposited after flooding (see below), and centimeter-thick faintly graded dark-grey layers (turbidites) originating from turbidity currents. These can be triggered by the turbid melt water entering the lakes each spring.

If the activity of benthic organisms (insect larvae, oligochaetes, etc.) is limited or absent – which happens when the sediments are poorly oxygenated for long periods, if there is a minimum of mechanical disturbance from underwater currents, and if the formation of gyttja, (i.e. dark sediment very rich in organic matter) has not yet proceeded so far that the stratification can be destroyed by the formation of gas bubbles (methane), correctly-sampled sediment viewed in the laboratory may display a laminar structure with clearly distinct and variously colored laminae. This means they can form different layers, each very regular, with different colors, usually deriving from the alternation of light- and dark-colored layers, which are called varves (Figure 3). Each varve encapsulates data on the events of a single year, from events occurring exclusively within the lake, such as changes in trophic state, to the larger-scale events of climate change. Depending on the type of lake, whether in low-lying territory and eutrophic, or in a mountain environment, influenced by a glacier, two types of varve can be identified: *biochemical*, rich in biological remains preserved in anoxic conditions, and *clastic*, typical of pro-glacial oligotrophic lakes and environments impacted by major loads of allochthonous minerals (Figure 2). Varves can be compared to tree rings: like them, varves can be counted and thus used for dating the sediment layer with a high degree of accuracy.

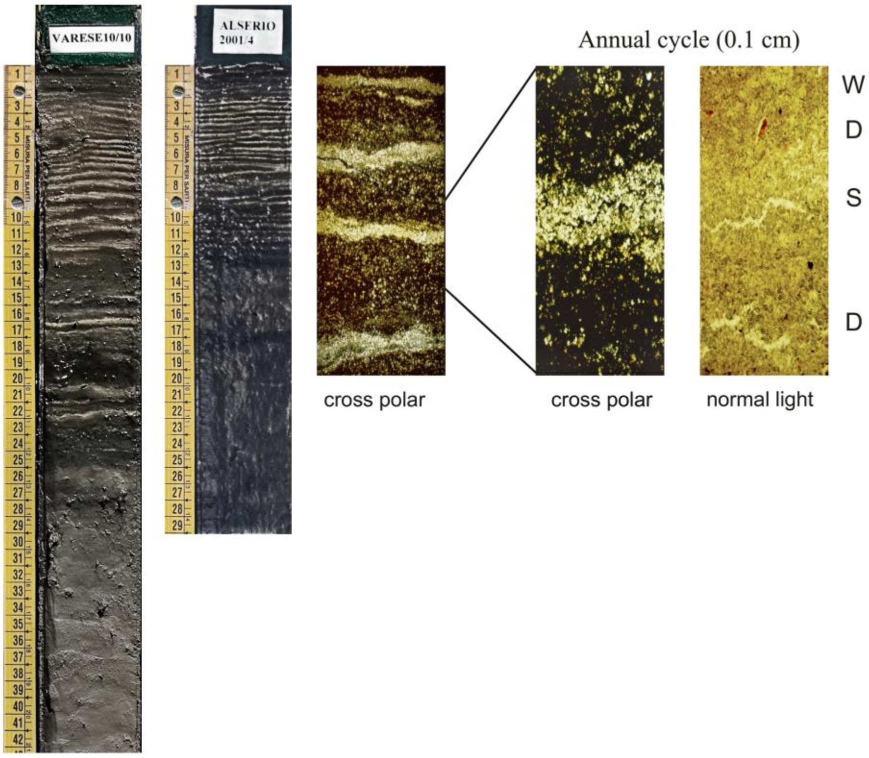

Figure 3. Annually banded sediments from two sub-alpine Italian lakes (Alserio and Varese). The varves are distinct in the upper part of the sequence (probably due to strong eutrophication and changing physical conditions), becoming more indistinct and thinner with depth. A thin layer micrography of varves from the sediments of a volcanic lake (Albano) is also shown W: winter (detrital material); D: autumn and spring (diatom frustules); S: summer (authigenic and diatom frustules). (Photograph ETH Zentrum, Zürich).

To verify and quantify bioturbation, an index (the Bioturbation Index) is used following the scheme proposed by Behl and Kennett (1996). A value of 1 on the index represents distinct, continuous lamination; 2, diffuse, discontinuous or irregular lamination; 3, bioturbated sediments with few patches of diffuse lamination; and 4, completely bioturbated sediments. The quality of the lamination is further evaluated using radiographs of sub-samples at selected depth intervals along the sediment core.

In conclusion, many are the processes involved in the sediment records, natural and anthropogenic, some of these discussed above. A few additional processes are: origin and fate of sedimentation particles (e.g., POC, particulate organic carbon); release rates of contaminants and nutrients; incorporation of toxic substances by benthic organisms that then enter the food chain (bioaccumulation); decomposition of organic matter, and so on. Thus, in order to interpret properly the sedimentary records we first have to understand the processes of sediment formation.

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Biographical Sketch

Piero Guilizzoni is a Senior Scientist at CNR-ISE (National Research Council - Institute of Ecosystem study), Verbania Pallanza, formerly the "Istituto Italiano di Idrobiologia".
He has been involved in palaeolimnological research since 1978 when, together with M.S. Adams (Univ. of Wisconsin, Madison), he made a first attempt to construct a calibration data set to infer primary production from the concentration of algal pigments in lake sediment.
An Honorary Fellow in Botany (July-November 1975; July-December 1981) at the Department of Botany, Institute for Environmental Studies, University of Wisconsin - Madison, WI, USA, he has coordinated or participated in many European projects, some of them listed here. Since 2007 he has headed the Working Group on POPs and trace metals in the Lago Maggiore ecosystem (International Commission for the Protection of Italian Swiss Waters). In 2008 he was appointed Associate Editor of the ‘Journal of Paleolimnology’. In 2000 he was selected as a member of POLARNET, a National Research Council Organisation for Italian Polar research activity in Antarctica and the Svalbards. Since 1997 has been an invited speakers of the European Lake Drilling Project (ESF-ELDP), European Science Foundation. He has participated in six other EU Projects (Air pollution effects on terrestrial and aquatic ecosystems; aquatic food chain biomanipulation and its effects on water quality, ALPE and ALPE 2, MOLAR and EMERGE, on alpine lakes, acidification, anthropogenic and climate impacts). Leader of a work package in the European Project PALICLAS, Palaeoenvironmental Analysis of Italian Crater Lakes and Adriatic Sediments (Contract N. EV5V-CT93-0267) (1994-1996). Head of the Italian side of a Bilateral Project between Italy and Argentina (CNR-CONICET, 2004-2006; 2005-2007) on the Palaeoenvironment and palaeoclimate of Italian and Argentinean lakes. Leader for Italy of a work package in the funded European Project EUROLIMPACS (“Reference conditions and restoration strategies”). Head of a CNR-ISE Research Group entitled: “Use of palaeolimnological techniques as a tool for palaeoclimate evolution”. Member of expert evaluators panel for "Global Change, Climate and Biodiversity", a Key action under the Energy, Environment and Sustainable Development Programme. Member of the CNR-ISE Institute Committee. In 2010, 2006 and 2004 he taught courses at the University of Milan on “Alpine lakes”. Member of the Lecturers’ Committee of the Doctoral Thesis on Ecology, University of Parma.
After more than thirty years, he still enjoys sailing on all kinds of lakes to take new cores, and he likes to sample mountain lakes in August, when all his younger colleagues are on holiday. Piero Guilizzoni’s main interests are algal fossil pigments, and in general all biological remains and geochemistry, but he laments the amount of time he has to spend writing papers, research applications and reports, which elicits much understanding and agreement from colleagues who share this experience. He has worked on lakes in Italy, Switzerland, France, UK, Vermont, high mountain regions (Alps, Himalayas), and remote regions (Arctic, Patagonia, Pampas, Antarctica, Tibet, Finnish Lapland, and Siberia).
He is author or co-author of 248 scientific publications (105 in international journals; one on the Encyclopedia of Environmental Microbiology; 49 in Italian journals; 6 Chapters in books; 88 technical reports) on the following topics:
Studies on the metabolism and primary production of aquatic plants;
Distribution of photosynthetic pigments in sediments;
Effects of heavy metals on aquatic plant metabolism;
Thin layer chromatography of algal and bacterial pigments;
Eutrophication control by biomanipulation;
Palaeolimnology of alpine, sub-alpine and volcanic lakes in Italy, Switzerland, remote areas (e.g. Himalayas, Patagonia, Svalbard, Tibet).