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LACUSTRINE SEDIMENTATION

The lake is a system, that is, a bounded entity possessing a set of unique, interconnected elements, especially of process and response, that can be recognised as such regardless of how they are dealt with by scientific enquiry (Strahler, 1980). Further, the lake is an open system; processes beyond the boundaries relate to those within the system to produce mass and energy exchange across the boundaries. For a lake in equilibrium with its environment, the components of these exchanges lead, over the long term, to a zero-sum result; what goes in must come out. While that is generally true of energy and of water, sediment flux is normally not balanced because input and storage much exceed loss from the system.

Sedimentary processes and deposits in lakes are determined by the physical, chemical and biological environment of the lake and of its watershed and airshed. The processes and products of this environment are controlled in complex interactions among climate, hydrology, biology, geomorphology, geology, and, increasingly, human actions. Figure L1 sets out a conceptual framework that associates these factors and indicates qualitatively the way in which the sedimentology of the lake is controlled.

Limnologic processes affecting sedimentation

The processes in a lake are driven by the energy of the lacustrine system. The most important input of energy is through solar heating as part of the radiation balance which reaches an average of about 200 W/m^2 in summer in mid latitudes. The major ways in which heat energy is lost from the lake are by sensible heat transfer and evaporation. Solar heating is particularly effective because the mean albedo (reflectivity) of the water surface is less than 10 per cent, one of the lowest of any natural surface. Solar radiation penetrates water up to several tens of metres before being absorbed and heating the upper part of the lake, thus reducing the density of the water and leading to a tripartite structure of the water column: an upper epilimnion separated from a colder, higher density hypolimnion by a zone of thermal change, the metalimnion. In mid-latitude lakes the isolation of these zones breaks down twice each year in spring and autumn as water in the epilimnion warms or cools, respectively, through the temperature of the hypolimnion. This semi-annual overturn and mixing of the lake water, referred to as *dimixis*, is important in mass (including sediment) and energy transfer throughout the lake. In high latitudes and tropical to subtropics regions heating or cooling to the near-bottom temperature occurs only in summer or winter, respectively, giving rise to one period of overturn, or *monomixis*. In lakes less than about 2 m to 10 m deep depending on fetch (Gorham and Boyce, 1989) wind-generated forces frequently overcome thermal stabilization of the water column, leading to repeated or near continuous overturn of the lake water referred to as *polymixis*.

Mass exchange of water (the water balance) is important to sedimentary processes because normally a significant amount of sediment is delivered to lakes by rivers. The annual pattern of precipitation is especially important, leading to flushes of water and its sediment load in seasonal events, for example related to snowmelt in the mid to high latitudes or monsoons in the sub-tropics, and to irregular, catastrophic, major storm events. Where evaporation from the lake exceeds precipitation and runoff into the lake, outflow does not occur and dissolved salts accumulate in the lake water. This commonly leads to a persistent structure based on lower density (fresher) water near the surface, and high-density, in some lakes hypersaline, water at depth which does not permit overturn and is referred to as *meromixis*. In extremely arid environments the entire lake may be hypersaline. Salts may also be present in lakes lifted from the sea by tectonic processes. A review of the water and energy balances of lakes is provided by Lerman *et al.* (1995).

The components of the water balance determine the *residence time* of water in the lake which is an important factor influencing sedimentary processes. This is the time that water spends in the lake on average between when it enters the lake as runoff or precipitation and when it leaves the lake as outflow or through evaporation. It is a function of the relative volume of the lake with respect to the volume of input, and can

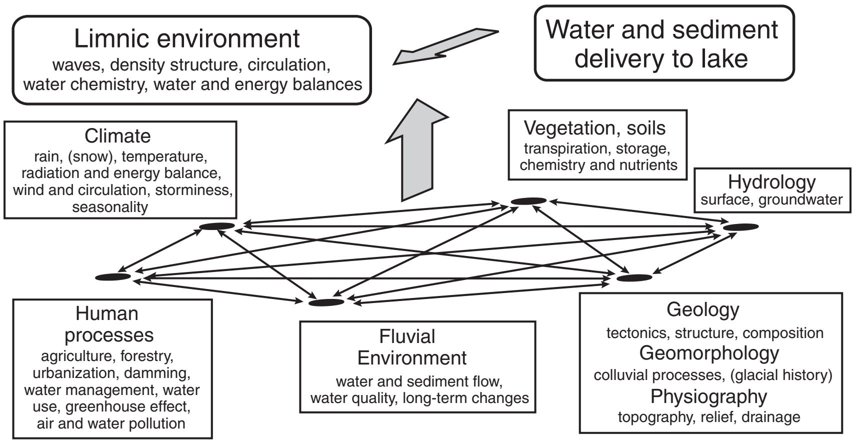

Figure L1 Conceptual model of the relation between the characteristics of the drainage basin and the nature of lacustrine sedimentation.

vary from a few days to many centuries, the latter for large lakes with small drainage basins. The longer the residence time, the more likely that a given sediment particle will have time to settle to the lake floor rather than being swept from the lake. Thus, depending on the formation of precipitates, most of the sediment in solution passes from the lake, while greater amounts of progressively coarser-grained clastic and biogenic sediment are trapped. As a general rule, lakes having residence time of 0.1 years trap 80 per cent to 95 per cent of the sediment input, while those with residences times of 1 year or more trap 95 per cent or more (Brune, 1953).

Of the many other processes that occur in lakes, the action of waves generated by wind is the most important to the sedimentology of the lake, even though as a source of energy to the lake as a whole waves represent a relatively minor component. The size and energy of waves is governed by the velocity and duration of the wind, and the effective fetch (the distance the wind blows across open water, accounting for the irregularities of the shores: Håkanson and Jansson, 1983). There are a number of graphical and numerical methods by which calculations of wave size may be made (e.g., Sinclair and Smith, 1972). Because of the role of waves in shaping coastal environments, wave energy plays a very important role in the sedimentology of the entire water body. Fundamental is the concept of *wave base*, the water depth to which waves erode sediments on the lake floor. This depth is about one quarter of the length (crest to crest distance) of the wave in deep water (Sly, 1978), and so is a function of wind velocity and fetch (Figure L2). In large lakes having an effective fetch of 100 km or more, wave base may reach 40 m in the largest storms. Fine-grained sediments are winnowed from deposits on the lake floor above wave base, and are transported to deeper water for redeposition. In addition, waves generate circulation of the lake water, moving mass and energy through the lake and affecting sedimentary processes.

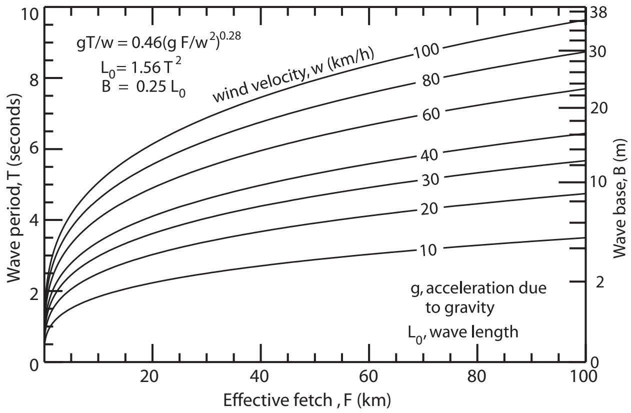

Figure L2 Relation of effective fetch to wave period according to Sinclair and Smith (1972), and wave base. Results correspond with observations of sediment erosion on the lake floor (Håkanson and Jansson, 1983).

Types of lacustrine sediment

Classifications of lacustrine sediments include those based on their place of origin, the processes of their transportation and deposition, their location in the lake, and their composition (Håkanson and Jansson, 1983). Sediments which are transported from the watershed or the airshed to the lake, and are deposited in the lake with little physical or chemical alteration are referred to as *allochthonous*. Those that originate within the lake itself are referred to as *autochthonous*. Most commonly these are created as a result of precipitation of salts dissolved in the lake water or from the remains of aquatic plants and animals. At least some of the components of autochthonous sediments come from outside the lake (as the dissolved or nutrient loads of incoming streams, for example), but the form in which they are deposited is very much altered from the form in which the constituents arrived at the lake.

Primary deposits are those which have undergone only minor changes since they were deposited, while *secondary* or *reworked* deposits have been significantly altered since deposition. Gravitational processes, erosion by waves and currents, and bioturbation are the principal ways in which sediments are reworked and redistributed in the lake. The distinction between primary and secondary deposits becomes important, for example, where ancient sediments are eroded from the lake floor and redeposited elsewhere along with sediments newly arrived in the lake, mixing an ancient paleoenvironmental signal (that might be interpreted from the physical, chemical or biological nature of the sediment) with the signal from the modern environment.

Classification based on the composition of the sediment, divides deposits into *lithogenic*, *biogenic*, and *hydrogenic* sediments. Lithogenic sediments are the clastic detrital products of the physical and chemical weathering of rock or unconsolidated sediment. These sediments may be further classified on the basis of mineral composition, grain size (from boulders to clay size), sedimentary structures and stratigraphy, colour, magnetic characteristics, and so on. Biogenic sediment is the remains of aquatic organisms with normally lesser amounts of allochthonous organic material. It includes detritus dominated by carbon-based molecules, including those in association with calcium (as calcite and aragonite), phosphorous (as phosphate), and silica. This black organic ooze referred to as *gyttja* dominates many mid-latitude lakes. Hydrogenic sediment results from precipitation from solution of salts in the lake water or the interstitial water of previously deposited sediments. Included in this class are the *evaporites* (*q.v.*) of saline lakes and the *marl* deposits of hard-water lakes.

A geochemical classification considers the presence of oxygen in the sedimentary environment. *Oxic* sediments are those in which there is oxygen in sufficient quantity (more than about 10^{-6} moles per litre) to determine processes dominated by oxidization. *Anoxic* sediments where oxygen is insufficient to allow oxidation are divided into *sulfidic* and *non-sulfidic*, depending on the presence of dissolved sulphide. Non-sulfidic environments are divided again into *post-oxic*, where oxygen removal has occurred without sulphate reduction and *methanic* where sulphate reduction and methane gas formation have occurred. These environments commonly change as the redox boundary migrates upward as sediment accumulates, and so remains just below the sediment surface. Oxic deposition is followed by post-oxic, sulfidic and methanic. Deposition of iron and manganese in the sediments or as nodules at the surface is closely associated with this chemistry.

Lacustrine sedimentary processes

Figure L3 shows a generalized, conceptual model of sedimentation in a lake. Not included are components that are unimportant in many lakes (such as the action of seasonal ice cover). Three sources of sediment to lakes are indicated in Figure L3. Fluvial sediment, including coarse-grained bed-load and fine-grained suspended load (wash load), is the most important source of sediment for most lakes. Fine-grained airborne sediment (dust), including mineral and organic material of natural and human origin is important in many lakes, especially where pollutants such as the sulphur and nitrogen compounds that create acid precipitation, and phosphorous in various forms, for example, are delivered in significant quantity. Autochthonous sediments are commonly created from the dissolved load (especially calcium carbonate and similar minerals) in inflowing streams and groundwater, as well as from biological activity, especially photosynthesis.

A delta commonly forms at the mouths of rivers bearing large clastic loads. Flow decelerates in hydraulic backwater, allowing bed-load deposition in a wedge of foreset beds created near the subaqueous angle of repose by quasi-continuous avalanching, overlain by topset beds deposited in response to changing fluvial gradient as the delta advances. Variations occur in lakes having fluctuating water levels and where alluvial fans extend from land to water. Finer-grained material in suspension is transported into the lake in a decelerating jet to be deposited distally from suspension as bottomset beds. Deltas are absent or poorly developed at many river mouths where clastic sediment input is low or where vigorous waves and currents redistribute sediment as quickly as it is delivered.

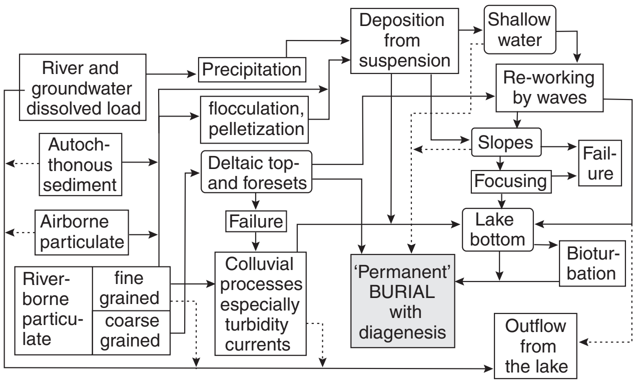

Figure L3 Generalized components of the lacustrine sedimentary environment. This model does not consider coastal processes and sediments.

Fine-grained sediment in suspension settles to the lake floor through calm water according to Stokes Law:

$$v = (\rho_s - \rho_w)g\, d^2/\eta$$

Where ρ is the density of the sediment ($_s$) and water ($_w$), g is the acceleration due to gravity, d is the particle diameter, and η is the dynamic viscosity of the water. Accordingly, a 10 μm diameter particle requires about one to two weeks to settle 100 m, while a 1 μm particle requires several years. An analysis that includes sand size particles where viscous resistance is small in comparison to the weight of the particle (i.e., beyond the range of Stokes Law) and the effect of particle shape is presented by Dietrich (1982). Actual rates of transfer to the lake floor is greater than settling predicted by these models for two principal reasons. First, flocculation even in fresh water increases the effective particle diameter especially of clay minerals such as kaolinite and illite and settling time is reduced by an order of magnitude or more (Droppo *et al.*, 1997). Complimenting this is the incorporation of fine-grained sediments into fecal pellets produced by zooplankton. Second, general circulation carries parcels of water and suspended sediment to depth, although the presence of thermal or chemical stratification prevents mass transport throughout depth, except during overturn.

Colluvial (gravitationally driven) processes commonly redistribute sediment from shallow to deeper basins in a lake. Slides move large quantities of sediment along a well-defined glide plane with little internal deformation, so the deposit remains as a coherent mass retaining clearly recognisable sedimentary characteristics of the original deposit. In slumps the sediment is deformed but the final deposit is recognisable as a single event (Figure L4). In *gravity flows*, which are significant where deposition of clastic sediment predominates, the sediment is completely reworked during transport (see

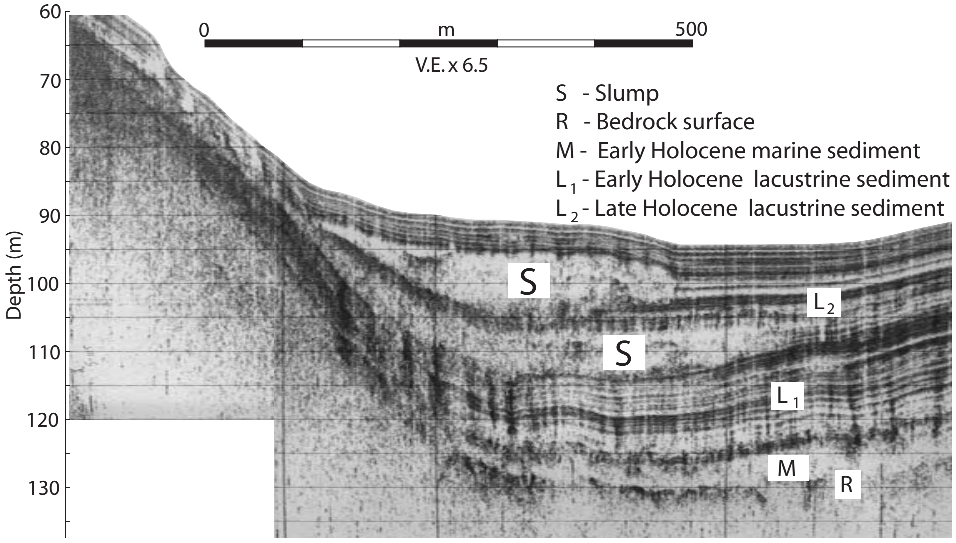

Figure L4 3.5 kHz subbottom acoustic profile from Stave Lake, British Columbia, Canada showing marine sediments deposited over bedrock immediately following deglaciation, then lacustrine sediments deposited and focused to the lake basin, including by slumping, through the Holocene.

Gravity Driven Mass Flows). Middleton and Hampton (1976) distinguish *fluidized flow* in which the sediment is supported by escaping pore water, *grain flow* where particles are supported by grain-to-grain interaction, *debris flow* as a slurry where coarse particles are supported by the matrix of fine particles, and *turbidity currents* where sediment is supported by turbulent flow. Turbidity currents are generated directly from inflowing streams or as a result of colluvial processes on the lake floor; in either case, the current is driven down slope by its greater density due to suspended particulate matter. Behaving as a river under the water of the lake (considering the buoyant effect of the ambient water and the interfacial shear stress with the flow—Middleton, 1966), turbidity currents intermittently distribute relatively coarse-grained sediment widely over the floors of some lakes, even creating leveed channels in a few cases.

An important consequence of the reworking of sediments by waves from the coast to the depth of wave base, and by rapid, episodic, and slow, continuous colluvial processes throughout the lake is that sediment is focused to the deepest basins of the lake (Figure L4). The result is that rates of accumulation vary significantly throughout lakes (Blais and Kalff, 1995). This must be assessed when deciding the location of point samples (cores) used to reconstruct depositional rates and sedimentary history of a lake.

Sediments deposited in deep water are normally subject only to reworking by bioturbation and to diagenesis as they are sequentially buried. Diagenesis refers to the changes that the sediment undergoes after it has been deposited on the lake floor, normally as it is buried in the sediment column (Berner, 1980). The common forms of diagenesis occurring in lacustrine sediment include: (1) compaction and dewatering caused by loading with associated increase of shear strength of the sediment; (2) diffusion or mass transport in pore water of dissolved salts, including metals through the sediment; (3) dissolution or precipitation of, for example of marl (calcium carbonate); and (4) decomposition of organic material in aerobic or anaerobic bacteria. Thus, after the sediment is buried in the lake floor, it may change significantly, and assessment of environmental change from the characteristics of the sediment must take into account these possible changes. For example, a pollutant that migrates upward from older to more recently deposited sediment as compaction and dewatering occur may appear to indicate more recent contamination of the aquatic system than has actually occurred.

Lacustrine sediment as paleoenvironmental proxy

Figure L1 indicates a strong, if complex relation between terrestrial systems and the nature of sedimentation in lakes. If these pathways are understood, the sedimentary record has potential to provide a wealth of knowledge about the lake and its contributing region, both in the present and throughout the history of the lake. Facilitating this are the characteristics of limnic processes and lacustrine sediments:

1. Lacustrine sediments are normally deposited quasi-continuously without subsequent erosion and only minor diagenesis, so according to the Law of Superposition, a long, uninterrupted, decipherable record from present to the beginning of the lake can be assessed.
2. Most of the sediment entering the lake is trapped there so that whatever has occurred in the lake or its basin is registered in the sedimentary record.
3. Commonly, the finest grained sediments are deposited in the lake, while gravel and even sand are left in the rivers and deltas, and on the land. It is this fine organic and inorganic material that is most diagnostic of the environment of the watershed and airshed contributing to the lake.
4. Sediments deposited in a lake represent the entire drainage basin and so integrate and smooth catastrophic events. Thus, while a major storm or localized soil erosion event

may be represented in the lacustrine record, they do not overwhelm a sedimentary sequence as may occur in the terrestrial record.
5. Commonly, annual cycles (varves, *q.v.*) are preserved in lacustrine sediments. These are powerful as dating tools and in high-resolution paleoenvironmental assessment.

There is an extensive and rapidly growing literature interpreting changes in climate, hydrology, geomorphology, and human actions on scales from intra-annual to hundreds of thousands of years. Proxies include the physical characteristics of clastic sediments (Lamoureux, 1999), the chemistry of precipitates (Last and Slezak, 1988) and biologic material including diatoms (Stoermer and Smol, 1999) and pollen.

Investigating the lacustrine sedimentary record

The nature of sediment in a lake is commonly investigated at two scales. First, at a synoptic scale, acoustic techniques provide remotely sensed imagery of the entire lacustrine sedimentary package (Figure L4). Even conventional high frequency (50 kHz and above) echo sounding penetrates soft, organic sediments such as gyttja but lower frequency (commonly centered on 3.5 kHz) provides penetration of tens of meters into most types of lacustrine sediment. In a few cases, low frequency seismic surveys have provided very deep penetration through extremely thick lacustrine sequences. From these records the distribution and thickness of sediment in the lake is mapped, sedimentary processes and rates of accumulation are inferred, and changes in sedimentary processes and deposits through time are documented.

Second, samples of the sediment are recovered for detailed analyses. Many samplers have been devised, each designed to particular needs. Dredges, including trawls and samplers with closing jaws, recover surfical material. Samplers having a chamber to retain sediment include box corers, gravity and piston corers, and side-opening samplers. Adhering samplers cause sediment to accumulate on their outer surfaces, normally by freezing due to a mixture of dry ice and alcohol inside the sampler. All are designed to recover material from the surface or near-surface of the sediment to depth of up to tens of meters with as little disturbance as practicable. Unlike oceanographic surveys where a large ship with heavy equipment is normally available, a major concern in sampler design and deployment in many lake studies is light weight, portability and ease of deployment from small vessels, or where conditions permit, from an ice cover. Details of lacustrine sedimentary analyses are documented in a number of sources including Håkanson and Jansson (1983).

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Cross-references

Climatic Control of Sedimentation
Coring Methods, Cores
Deformation of Sediments
Diagenesis
Deltas and Estuaries
Flocculation
Geophysical Properties of Sediments
Grain Settling
Gravity-Driven Mass Flows
Iron-Manganese Nodules
Palaeolimnology (in the Encyclopedia of Earth System Science.)
Sediment Fluxes and Rates of Sedimentation
Sediment Transport by Waves
Slide and Slump Structures
Varves