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DATING OF LAKE AND LOESS SEDIMENTS

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ABSTRACT. Lake and loess sediments represent archives that record important information about the local, regional and global climate conditions in the past. Lake sediments consist of autochthonous particles formed by biogeochemical processes within the lake and allochthonous particles brought into the lake from the catchment area. After deposition, the stratigraphy of the sediment can be altered by chemical, physical and biological processes. Under favored conditions, the sediment shows individual annual layers (varves), which can be used to date the sediment. Other dating methods are based on radioactive decay (^{14}C, ^{210}Pb) or on time markers such as tephra layers, deposits of natural catastrophes, *e.g.*, floods, or radioactivity, *e.g.*, emissions from a nuclear power plant.

Loess is a windblown deposit of fine dust originating from deserts and mountain areas. During the last 2.5 Ma, dust transported over several thousand kilometers formed plateaus up to 200 m thick. During warm and humid conditions, loess deposits are transformed by biochemical processes into soil. Until now, the main dating techniques applied to loess have been magnetostratigraphy (magnetic reversals), matching the ^{10}Be concentration with the $\delta^{18}O$ deep-sea record, radiocarbon (^{14}C) dating (for the last 40 ka) and thermoluminescence (TL) dating (for the last 100–200 ka).

INTRODUCTION

Terrestrial archives such as sediments and loess contain important information on local, regional and global environmental conditions of the past. They offer a unique opportunity to study the dynamics of the environmental system spanning a period from 10 ka (lakes) up to 1 Ma (loess). Understanding the properties and natural variability of the environmental system is fundamental to estimating the importance of global changes caused by humans. Two main difficulties in using natural archives to reconstruct the history of the environment are to read the information and to establish a precise and reliable time scale. We discuss here two types of archives, lake sediments and loess, in some detail; our intent is not to provide a complete overview of the field, but rather to show the potential contribution of lake and loess sediments to global change study.

LAKE SEDIMENTS

Lake sediments are formed by a variety of biogeochemical and physical processes (Kelts and Hsu 1978). The amounts of autochthonous or allochthonous particles formed by these processes reflect different environmental conditions within a lake, *e.g.*, algal blooms, chemical precipitation, or its catchment area, *e.g.*, erosion, floods, formation of vegetation, respectively. These sediments often show seasonal variations, leading to the deposition of regularly laminated couplets (varves), which represent the duration of a year (Sturm 1979).

Autochthonous biogeochemical processes during the course of a year in lakes without prominent river input are responsible for the formation of suspended particles, which are deposited and subsequently recorded in the composition of an individual varve couplet (Lotter *et al.* 1992). Such biogeochemical varves are distinctly different from physical varves, which are formed in tributary-controlled lakes with high allochthonous particle-loading, reflecting annual meltwater cycles.

After deposition, the main processes that may alter the sedimentary record are:

- Turbidity currents induced by earthquakes or internal waves, which transport large amounts of sediment from unstable slopes to flat parts of a deep lake

- Physical resuspension by currents along the water/sediment interface, which pick up fine particles to redeposit them in different parts of the lake basin
- Chemical remobilization of ions during changing redox conditions
- Bioturbation by activity of benthic fauna may mix the upper centimeters of the sediment.

Figure 1 summarizes the different processes involved in the formation and alteration of sediments.

Environmental Information

From a conceptual point of view, every process governing the input of particles into a lake or the formation of particles within a lake is dependent in complex ways on the climate, the local vegetation and the physical, chemical and biological conditions of the lake. A complete analysis of the chemistry, mineralogy, biology and paleomagnetics of the sediments is usually not feasible, but information that can be extracted includes:

- Regional and global climate—information is provided mainly by stable isotopes ($\delta^{18}O$) and pollen analysis
- Natural catastrophes—frequency and magnitude of extreme events, such as floods, earthquakes and volcanic eruptions
- Atmospheric fallout—natural and artificial radionuclides and other species removed from the atmosphere are built into the sediments
- Human influence on the catchment area—activities such as deforestation, eutrophication, agriculture, and pollution by xenobiotic organic substances and heavy metals.

Lake Sediments As an Archive

An advantage of studying lake sediments is that they are widespread and relatively accessible. They record a variety of natural processes of the past, reflecting changes of environmental conditions, such as climate, hydrology, biology and human activity. Although they contain global information, the dominant signal is determined by local and regional properties of the catchment area. Accumulation rates of lake sediments are typically on the order of 0.1–1.0 cm yr^{-1}. Easily accessible sediment cores cover a time range up to the Late Glacial (15 ka BP). A core with a length of 50–100 m may cover an entire glacial and interglacial period (>100 ka BP).

Dating

The value of an archive is strongly dependent on how datable it is. The establishment of a continuous time scale can be seriously hampered by disturbances in the sedimentary record, caused by slumps, bioturbation and chemical remobilization. Several methods can be used to establish a time scale. The most precise dating is based on counting of annual laminae (varves). Other dating methods are based on the radioactive decay of ^{210}Pb ($t_{1/2}$ = 22.3 yr) (von Gunten and Moser 1993) and ^{14}C ($t_{1/2}$ = 5730 yr) (Hajdas *et al.* 1993). Absolute time markers, such as ^{137}Cs horizons at 1963 (caused by nuclear weapons testing) and 1986 (caused by the Chernobyl accident), volcanic ash layers (Laacher tephra) or historically recorded events, such as rock falls or earthquakes, can also be used for absolute dating. Records can be synchronized by matching these time markers and by correlating records of magnetic susceptibility, pollen/diatom stratigraphy and geochemical parameters, such as $\delta^{18}O$, $\delta^{13}C$, nutrients and metals.

Loess

Loess is a terrestrial windblown silt deposit consisting chiefly of quartz, feldspar, mica, clay minerals and carbonate grains in varying proportions. Loess originates in desert or mountain areas, where

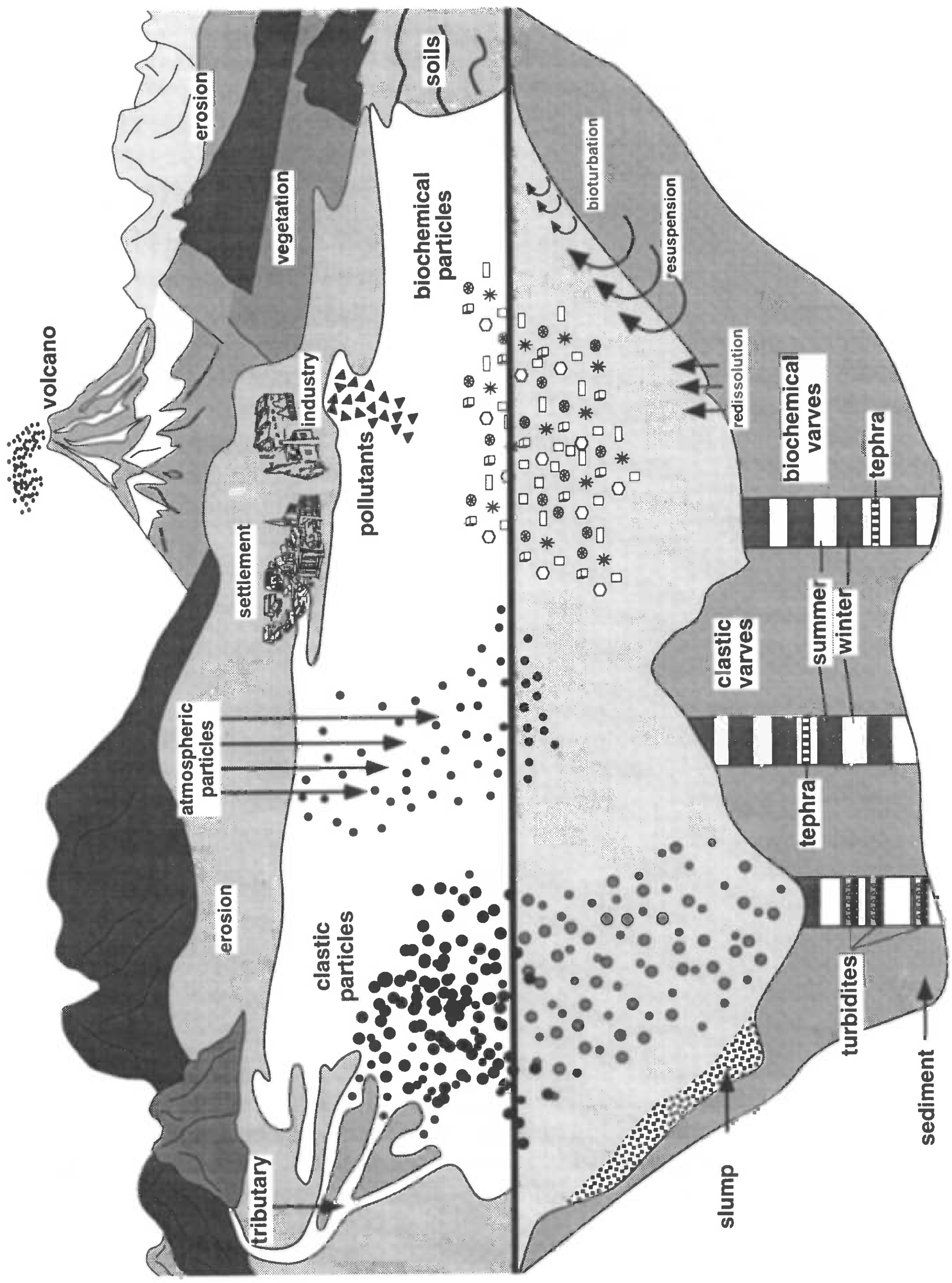

Fig. 1. Overview of the processes forming and altering sediments in lakes (after Sturm and Lotter 1995)

it is formed by such processes as weathering and glacial grinding. The dust is picked up by strong winds, and can reach the stratosphere, where it is transported over several thousand kilometers. *Ca.* 10% of the continents are covered with loess of different thicknesses. The largest loess areas are found in China, with thicknesses up to 200 m, covering a period of 2.5 Ma. The grain-size distribution peaks between 20 and 40 μ. Larger, heavy particles are removed quickly from the atmosphere.

After deposition, the loess is subject to internal changes depending on the climate conditions. During cold and dry periods, the accumulation rate is high, probably due to strong winds and relatively large source regions. Some reworking occurs through raindrop impact, surface wash and soil creep. These are only weak processes. During warm and wet periods, however, the primary loess is seriously modified by weathering, soil formation and diagenesis. Growing vegetation slowly transforms loess into soil, as indicated by change in color, smaller grain sizes and dissolution of $CaCO_3$. Typical accumulation rates for loess deposits are centimeters per thousand years.

Loess represents an archive that is well-suited for studying glacial and interglacial periods, and for deriving information on wind speed and aridity/humidity. For resolution and time span, it is a comparable archive to deep-sea sediments, but far simpler and less expensive to collect (Liu 1985).

Loess Dating

Stratigraphic Methods

Magnetostratigraphy was one of the first methods to show that loess profiles cover several million years (Heller and Liu 1982). Magnetic reversals are very clearly recorded in loess profiles, their ages determined by the K-Ar or Ar-Ar methods on magma of volcanic eruptions. The disadvantage of magnetostratigraphic dating is the limited number of reversals, the youngest of which (B–M) is already 770 ka old. As reversals cannot be distinguished from each other, a complete analysis of the whole record is needed to identify them reliably.

The sequence of loess and paleosol layers can be correlated with glacial and interglacial periods, represented by dated $\delta^{18}O$ variations in deep-sea sediments. Dating by matching two records is a relatively imprecise technique and can easily lead to mismatches between glacial periods and loess layers. However, in combination with magnetostratigraphy, it may be useful, especially for the period 0–770 ka.

Two methods have been used to improve dating between glacial-interglacial transitions, and which can also relate to $\delta^{18}O$ deep-sea records. The first is based on the assumption of a constant atmospheric fallout of magnetic susceptibility. Changes of susceptibility in loess are explained by a varying dilution effect, which is proportional to the accumulation rate (Kukla *et al.* 1988). ^{10}Be measurements on the same samples, however, have shown that, during warm and humid periods, a significant part of the susceptibility is due to *in-situ* diagenetic processes. The concept of a constant fallout is therefore not valid (Beer *et al.* 1993).

A similar concept can be used for ^{10}Be; its flux onto a loess plateau can be attributed to two main sources. The first is the local ^{10}Be fallout caused by cosmic-ray-induced spallation reactions in the atmosphere. The second source is the dust forming the plateau. Because the dust originates from the desert, where it has been exposed to atmospheric fallout for a long time, it contains high concentrations of ^{10}Be. Therefore, the total ^{10}Be flux onto the loess plateau is different for different climate regimes, and leads to increased concentrations during calm climate periods with low accumulation rates. A comparison of ^{10}Be concentration with the $\delta^{18}O$ record shows good agreement, allowing synchronization of the two records (Shen *et al.* 1992). Figure 2 provides a comparison of the ^{10}Be concentration record from Xifeng, China (Beer *et al.* 1993) with the SPECMAP $\delta^{18}O$ deep-sea record.

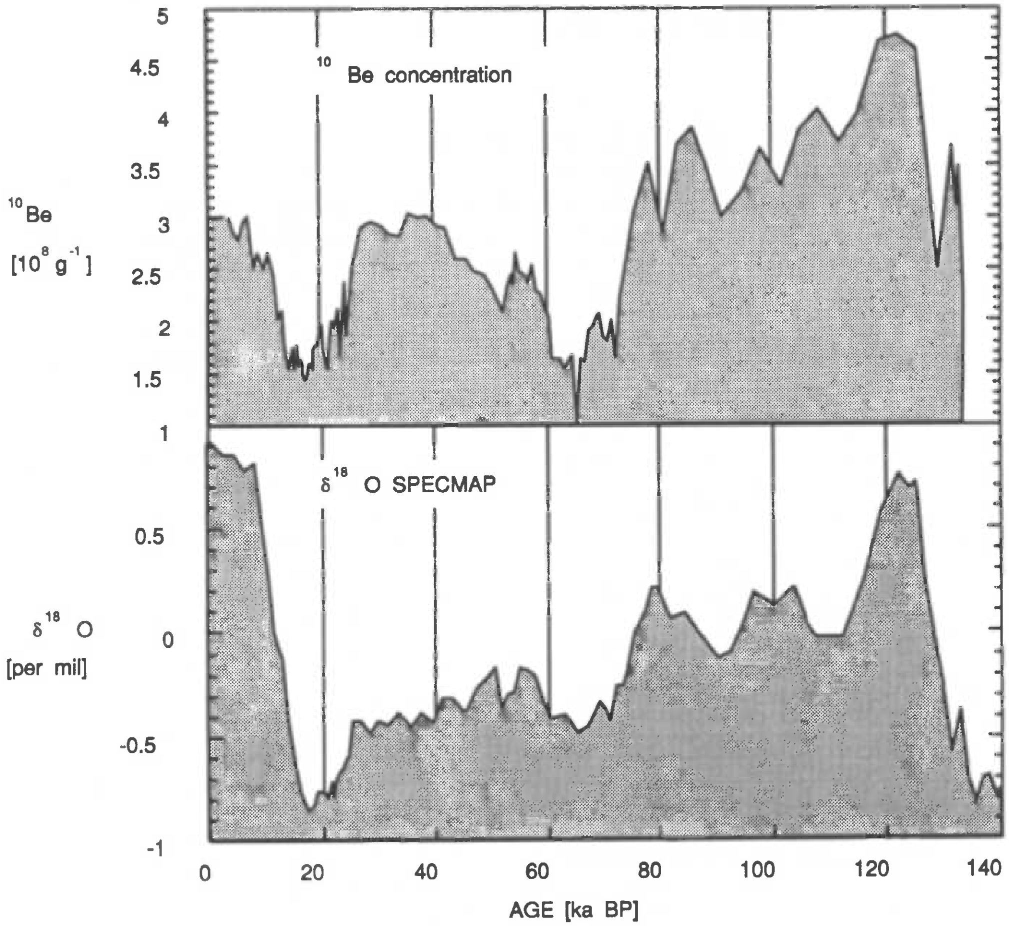

Fig. 2. Dating of the ^{10}Be concentration record of a loess profile from Xifeng, China by matching it to the SPECMAP $\delta^{18}O$ deep-sea record

Radioactive Decay

The most important dating method based on radioactive decay is ^{14}C dating. However, due to the relatively short half-life of 5730 yr, it is applicable only to the last *ca.* 40 ka. ^{14}C dating also requires well-defined carbon material of organic origin to guarantee that it reflects the atmospheric $^{14}C/^{12}C$ ratio. Only material that has never exchanged with other carbon (*e.g.*, $CaCO_3$) present in the loess should be used. Finally, one must be aware that ^{14}C ages have to be calibrated, and at present, the necessary calibration curve covers only the last 13 ka. Older ages may show a 1–2 ka uncertainty, due to changes of the atmospheric $^{14}C/^{12}C$ ratio.

Thermoluminescence (TL) dating has also been applied to loess from the last 100–200 ka. This method is based on several assumptions. During transport, dust is exposed to sunlight, which removes the signal and, therefore, resets the clock. After deposition, the loess is radiated by cosmic rays and the primordial radioactive isotopes of U, Th and K and their daughters. The accumulated dose is assumed to be proportional to the exposure time, and the TL signal released by heating the sample proportionally to the dose. Because these assumptions may not always be fulfilled, not all of the published data are consistent (Wintle 1990).

CONCLUSION

Analyses of lake and loess sediments combined with information revealed from ice and deep-sea sediments provide a rather complete picture of the many complex, interactive, non-linear processes occurring in the past. Studies such as these are important for improving our models and for making realistic predictions about the future development of the environmental system.

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