Varves are laminated sediments formed annually in aquatic environments by seasonal climatic changes. Each varve is made of two thin, alternating light and dark sedimentary laminae representing one year of deposition (Figure 1). The coupling of varve sedimentation with seasonality makes varved sequences useful as high-resolution archives of climate. The geologist de Geer first defined varves in the late 1800s from glacial sediments in Sweden. He and his students surveyed Swedish glacial lakes and found that sediment thickness patterns correlated between adjacent lakes. From the regularity, continuity, and broad distribution of the laminated sediments, he concluded that their deposition was driven by a widespread, regular, and strong forcing mechanism, i.e. annual climate.

Varve Formation

Varves form in depositional basins characterized by seasonal variation in sediment composition and low-oxygen bottom waters. Changes in sediment flux result in laminae of alternating composition, while low-oxygen waters prevent burrowing animals from mixing the sediment and obliterating the laminated structure. The two necessary conditions required for the formation of varves are found in both fresh water and salt water environments. In glacial lakes, for example, meltwater carries fine sand, clay, and silt into the lake along the glacier margin during spring and early summer (Figure 2). Finer particles are kept suspended in the water column during summer by wind-driven currents, whereas coarser, heavier sediment falls to the lake floor. As ice melts, nutrients are released into the lake, resulting in diatom blooms during the productive spring season. The coarser particles and the diatom frustules form a distinct light layer in spring and early summer. During summer, runoff from rain and melting ice continues to transport silt and clay into the lake. In winter, the lake freezes, terminating terrigenous input, wind mixing, and diatom growth. Without wind mixing, the fine clay material falls out of suspension, is deposited, and forms a dark sedimentary layer. In high-latitude lakes, anoxic bottom waters are maintained by strong thermal gradients that persist when the lakes are not covered by ice. In lakes formed by drowned fiords (tidewater lakes) the seasonally deposited laminae are preserved because sills between the lake and open ocean retain salt water at the lake bottom that is covered by fresh water. The resulting density gradient generates a strong pycnocline that prevents deep mixing. High input of organic matter to the lake bottom reduces the oxygen content enough to prohibit animals from living and burrowing in the sediments.

Marine varves exist in temperate environments such as fiords, marginal seas, silled basins, and other areas of the continental shelf and slope where sediment input is seasonal. Bottom waters are anoxic because of strong density gradients that prevent vertical mixing (fiords and marginal seas) or because of the oxygen minimum zone impinging on the ocean floor (silled basins, continental shelf and slope) (Figure 3). In regions of extraordinarily high biological production, diatom mats or very large diatoms can preserve laminae even in the presence of oxygenated bottom waters. Dark layers of marine varves are typically deposited by runoff of terrigenous material during the rainy season. Aeolian deposits may occasionally be the source of lithogenic laminae, such as in varves deposited off Baja California, Mexico. Light layers are biogenic-rich sediments formed by siliceous diatoms and/or calcareous coccolithophorids, or cyanobacterial mats deposited during the productive spring and summer seasons.

Varve Chronology

Varves are sampled using methods that preserve the sediment fabric and recover the sediment–water...
interface. That surface boundary provides the baseline for isotopic and visual dating of the laminae, and is therefore necessary for development of a varve chronology. Both box cores and freeze-cores retrieve sediments with the sediment–water interface intact. Once the sediment is collected, the varves can be impregnated with epoxy and cut into thin sections for analysis. When analyses require separating varves from one another for study of microfossils or chemical tracers, the sediment can be X-radiographed then sliced into discrete varves.

Varves can be dated by visual counting and by isotopic methods. X-radiography of sediment cores greatly enhances varve boundaries and facilitates varve counting. Accurate counts are complicated by turbidites, i.e., sediment layers that represent an abrupt event rather than a whole season. Turbidites can be identified on X-radiographs by their intermediate color and frequently homogeneous texture. The age of varves is also estimated by measuring concentrations of an unstable lead isotope, $^{210}\text{Pb}$. Knowing the $^{210}\text{Pb}$ radioactive decay rate and naturally occurring concentration at the core surface, one can measure the $^{210}\text{Pb}$ downcore concentration, and use that to infer sedimentation rate and varve chronology. If the laminated sediments are truly varves, the age profile based on isotopic dating should match ages determined by visual counting. The rapid decay of $^{210}\text{Pb}$ limits its use to the past century or so.

False varves can result from an out-of-sequence deposition of material. For example, a major storm that produces significant runoff or an underwater earthquake that generates a turbidity current during the productive season will deposit a dark sublaminar within a light lamina. Conversely, an upwelling event during winter that leads to a phytoplankton bloom
will generate a layer of biogenic (light) material within a dark lamina. False varves can be identified by their microscopic composition and internal structure in thin sections, by mismatches between varve counts and geochemical dates ($^{210}$Pb) of the sediment, and by cross-comparison among multiple core samples taken from the same locality.

Paleovarves are lithified, alternating light–dark laminae that suggest cyclic processes in geological time. Lithified varves can be used to estimate climate variability driven by temperature, precipitation, and upwelling using modern analogs and by statistical analysis of light and dark layer components. Lamina thickness and composition reflect the intensity and duration of the driving force just as in modern varves.

**Paleoclimate Reconstruction**

Knowledge of regional climatology and sedimentation processes is needed to use varves for paleoclimate reconstruction. For instance, the thickness of lithogenic laminae in glacial lake varves can reflect precipitation amount or runoff, as dark layers may thicken with higher rainfall or with warmer temperatures that accelerate glacial melting. Deglaciation, shore displacement, and climate change influence seasonal changes in meltwater discharge that affect mineral composition and thickness of varves formed in fresh water lakes as glaciers retreat. Thick biogenic layers suggest highly productive periods of enhanced nutrient input, which in marine varves can be associated with increased wind stress and upwelling. Microfossil assemblages preserved in the sediment, as well as geochemical and mineralogical composition of the varves, are sensitive indicators of past ecosystem production, water mass circulation, and climate. Terrestrial particles, especially pollen, are also stored in the sedimentary column, and have been used to estimate vegetation changes, shifts in land use, aridity, and wind patterns over time.
Developing Climate Proxies

Climate proxies from varves have been developed using direct and indirect approaches. Sediment traps provide a direct measurement of deposition flux for lithogenic and biogenic components under specific climate conditions. Sediment trap collections along the west coast of North America indicate that sediment flux during the rainy, stormy season is dominated by lithogenic material carried into the basin by river runoff, winds blowing across adjacent deserts, or resuspension of shelf material by internal waves. As the productive season progresses, a succession of phytoplankton assemblages comprise the light biogenic laminae of varves. Knowledge of these assemblages is useful for interpreting sedimentary records. A phytoplankton sequence interrupted by a lithogenic layer could suggest an unusual storm event during the normal productive season. And a lithogenic lamina laced with a thin biogenic layer of a single assemblage may be interpreted as a mixing event during an otherwise nonproductive season.

An indirect approach is to compare time-series derived from varved sediments to those of instrumental climate records. Climatic histories can be constructed from laminated sediments after calibration/verification with instrumental observations. For example, statistical relationships between microplankton species and sea surface temperature records illustrate which species occur during warm or cold periods. The abundance of these temperature-sensitive species can then be used as a proxy record of climate to extend temperature series into pre-instrumental time. Another indirect method of climate reconstruction is time-series analysis of varve parameters. Relationships between biogenic and lithogenic components can be in phase or out of phase at different frequencies. Based on knowledge of local, regional, and global processes, these relationships may indicate climate variability on annual to millennial scales.

Examples

Scandinavian Lakes

The climate of northern Sweden and Finland leads to the deposition of varves in many lakes. The snowmelt period is short, typically limited to the month of May, and meltwater runoff deposits a lithogenic layer. The biogenic layer is produced from approximately June to September. This can be capped by a second lithogenic layer if there is enough rain during the fall. A fine-grained lithogenic layer is deposited in winter when lakes are ice-covered and the water column is stable. Pollen preserved in varves has been used to reconstruct vegetation histories and varve thickness has been used as a paleotemperature proxy.

Cariaco Basin, Venezuela

Sediments from the Cariaco Basin off the Venezuela coast exhibit fine laminae in X-ray radiographs that have been confirmed as varves by $^{210}$Pb dating. Varves deposited during the Younger Dryas (about 10–11 thousand years ago) have thicker laminae. Increased thickness of lithogenic laminae points to higher terrigenous input either because of increased precipitation or because of changes in sea level and river locations. The thicker light laminae indicate higher biological productivity, which can result from greater upwelling forced by intensified Trade Winds, and/or from upwelling of waters with higher nutrient content.

Glacial Lake Hitchcock, North-eastern USA

A 4000-year varve record from Glacial Lake Hitchcock spanning 17 500 to 13 500 years ago reflects glacial retreat, but also contains a temperature signal related to El Niño. Varve thickness during the late Pleistocene varied strongly in the 3–5-year bands, revealing a teleconnection between the tropical Pacific and North America.

Guaymas Basin, Gulf of California

Thin section analysis of varved sediments from Guaymas Basin reveals a pattern of deposition with three phases per varve that relate to different climate conditions. The dark layer is a clay and silt lamina with a minor component of diatom resting spores and frustules. This is overlaid by a biogenic lamina with a diverse diatom assemblage and little lithogenic material. The third layer is comprised almost entirely of a single diatom species, which changes depending on climatic conditions at time of deposition. The first, lithogenic layer reflects aeolian deposits from the Baja California peninsula and Sonora Desert in late summer and fall when convective thunderstorms, hurricanes, and tropical storms are most common. The lithogenic laminae may also represent shelf particles resuspended by tropical storms and hurricanes that enter the gulf. In early winter, north-westerly winds develop and cause wind-mixing and upwelling. Diatoms respond to the nutrient input with blooms of the diverse assemblage present at the time, and are deposited in the second, biogenic layer. The overlying monospecific diatom layer is typically comprised of Chaetoceros spp. resting spores deposited at the end of the strongest upwelling period in spring.
Marginal Seas

Isostatic uplift of marginal seas, such as the Baltic Sea in the late Quaternary, cuts the seas off from open ocean input. The saline water that remained in the basin after uplift was dense enough to prevent overturning of the water. As sea level rose following deglaciation, two-way circulation periodically occurred between the Baltic Sea and North Atlantic Ocean. Therefore, bottom waters were oxygenated and seasonal deposition was not preserved in varves because of bioturbation. However, varves were deposited during the Quaternary when effects of isostatic uplift outweighed those of sea level rise. Today, the balance between isostatic uplift and sea level rise has resulted in primarily brackish conditions in the Black Sea. Varves are currently forming in the deeper parts of the basin.

Laminated sediments from another marginal sea, the Black Sea, provide a record of sea level change. Approximately 23 000 years ago the Black Sea contained fresh water and was isolated from the Mediterranean Sea. As sea level started to rise approximately 9000 years ago, sea water spilled into the basin, filling the bottom of the basin with dense saline water under a cap of fresh water. Wind-driven vertical mixing could not overcome the resulting density gradient. Eventually, the bottom waters became anoxic and varves formed. These conditions persisted until about 3000 years ago when sea level was high enough to maintain open circulation between the Black and Mediterranean Seas.

North-east Arabian Sea

Laminated sediments from the North-east Arabian Sea along the India–Pakistan continental slope extend through the past several thousand years. Ages assigned by counting the laminae are consistent with radiocarbon dates, suggesting the presence of varves. Primary production in the Arabian Sea is strongly driven by the atmospheric monsoonal circulation and is recorded by the calcareous microfossils preserved in the sediment. The dark layers of the varves reflect aeolian deposits from the Baluchistan and Thar deserts in the north and north-east.

Saanich Inlet, British Columbia

Saanich Inlet on the west coast of British Columbia receives runoff from rain between November and March, depositing a lamina of terrigenous material. The light biogenic layer consists of diatoms. Sediment trap observations show that a sequence of diatom assemblages is deposited from spring through early fall. The first assemblages represent the spring bloom, followed by an assemblage indicative of moderate summer production, and finishing with an assemblage deposited after a small fall bloom. This same sequence of assemblages has been found in the light layers of deeper varves, suggesting stability of the climate system over time.

Santa Barbara Basin, California

The Santa Barbara Basin in the Continental Borderland off southern California has contained varves throughout most of the Holocene. Variation in sediment accumulation rate relates to precipitation. Analysis of varve parameters over the past 1000 years has revealed that a major change in precipitation around AD 1600 altered sediment flux into the Basin, leading to thicker varves with increased organic carbon content. Variability in biological production and oceanic circulation has been reconstructed from diatom and fish scale time-series developed from the varves. Geochemical proxies for sea surface temperature have been constructed from alkenones preserved in the sediment and stable isotopes extracted from calcareous microfossils (foraminifera). Paleotemperatures, upwelling and strength of circulation in the California Current System have also been reconstructed using radiolarian and foraminifera assemblages. Changes in proxy temperature records suggest that circulation in Santa Barbara Basin responds to El Niño events, as well as Little Ice Age, Medieval, Dansgaard–Oeschger, and glacial–interglacial events. Over the Holocene, intermittent bioturbation of sediment indicates oxygenation episodes associated with greater ventilation of intermediate waters during glaciation.

See also

Biogeochemical Cycles: Heavy Metals (0018); Sulfur Cycle (015). Climate Variability: Decadal to Centennial Variability (0107). Paleoclimatology: Ice Cores (0304).

Further Reading