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Palaeoclimatology and Palaeoceanography from Laminated Sediments

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Laminated sediments as palaeo-indicators

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As society at large becomes increasingly concerned with the issues surrounding global climate change, so the pressure on the scientific community to produce models and predictions of climate variability increases. In many respects, however, that branch of science concerned with climate change is in its infancy. While recent meteorological and oceanographic studies have shed light on the processes and mechanisms of atmospheric and oceanic circulation, this has produced only a 'snapshot' perspective of global change, limited by the range of instrumental or historical records. On the other hand, palaeoclimatic and palaeoceanographic studies have been mainly on coarser (millennial) timescales that have a more academic and less immediate appeal. The palaeorecords which have the required temporal (interannual/ decadal) resolution are limited to tree rings, ice cores, coral records and laminated marine or lacustrine sediments. This volume is concerned with the wide-ranging application of lacustrine and marine laminated sediments as palaeo-indicators.

Environments of lamina formation and preservation

The two fundamental requirements for development of a laminated sediment sequence are: (1) variation in input/chemical conditions/biological activity that will result in compositional changes in the sediment; and (2) environmental conditions that will preserve the laminated sediment fabric from bioturbation. Within lakes, strong seasonal signals are dominant while preservation is effected by bottom water/ sediment anoxia resulting from stratification, high salinities or high sedimentation rates. In the marine environment, the dominant control on lamina preservation is reduced oxygen in anoxic silled basins (e.g. California Borderland basins) or marginal seas (e.g. Black Sea), or beneath regions of high primary productivity such as coastal upwelling zones (e.g. the Peru margin). A more recently recognized preservation mechanism applies to deep-sea laminated sediments, where rapid flux of strong diatom mats or giant diatoms overwhelms benthic activity in oxygenated bottom environments.

Approaches and methodology

The essential step prior to using laminated sediments as palaeo-indicators is to examine the sediment composition and micro-fabrics to develop a model for origins of the lamination. The examples given in this volume amply illustrate the range of lamina compositions, from clastic sediment through biological and chemical. The development of such sediments and the dominance of the annual cycle is discussed by **Anderson**, while an earlier review by Anderson & Dean (1988) gives an account of the composition of lacustrine lamina over geological timescales.

Given a thorough knowledge of the lamina components, a knowledge of the atmospheric and water column processes producing the lamina-forming flux is an important prerequisite to developing palaeoclimatic/palaeoceanographic models of lamina formation (**Sancetta**). With cores taken from existing marine basins or lakes the flux events recorded within the laminae may be directly compared with water column observations, meterological records and sediment traps. With ancient examples, appropriate modern analogues must be sought.

To ensure that individual flux events can be observed in samples of laminated sediments, the appropriate sampling and analysis techniques must be deployed. Recently, scanning electron microscope (SEM) methods have been increasingly used to resolve microfabrics and lamina components (**Pike & Kemp**). Such SEM-led approaches now facilitate study of seasonal-scale variability.

Defining varves: lamina origins

In this volume, the word 'varve' is used for the lamina or group of laminae that are interpreted to represent one year's deposition. Depending on the environment, the varve may be a couplet (two laminae, as is the case for the classical Swedish varves), triplet or have a larger number of laminae (see **Anderson; Pike & Kemp**).

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Laminae defined by changes in terrigenous sediment grain size

The classical Swedish varves are clearly defined by a coarse terrigenous lamina (resulting from spring meltwater discharge) alternating with finer sediment (**Anderson**; **Petterson**). Lamination defined by similar changes in grain size of terrigenous sediment is common in marginal marine basins where seasonal climatic forcing produces a distinct coarser sub-lamina (e.g. Santa Barbara Basin; **Bull & Kemp**). Similar differences in grain size, however, may be also produced by a variety of mechanisms of particle sorting in sediment gravity flows or in sediment-bed interaction as well as by periodic changes in the grain size of settling sediment (see review by **O'Brien**). Thus, assessing the origins of lamination in ancient shales may not be straightforward and in some cases, differences in interpretation of lamina origins have arisen (e.g. for Silurian shales: Dimberline *et al.* 1990; Kemp 1991).

Biogenic lamination

Biogenic lamination may form either by episodic flux of plankton with hard parts or by in situ formation of organic structures within the sediment. The dominant record of biogenic flux within laminated sediments is the fall-out from surface-water algal blooms, either the opaline frustules of diatom algae, or the delicate calcite plates of coccolithophorid algae.

Diatom lamination. Diatom laminae are common in both marine and lacustrine sediments in which they record the seasonal productivity cycle, generally the spring bloom. **Pike & Kemp** show that more than one bloom episode may be recorded per year and further show, as do **Bull & Kemp** that multiple bloom episodes may be recorded within any one diatom ooze lamina. Such diatom laminae may also contain different sub-laminae containing a succession of species corresponding to the evolving bloom. Diatom laminae are generally parallel-sided and contain intact, unfragmented frustules and are thus interpreted to be mainly sedimented by rapid deposition as flocculated aggregates without the mediation of zooplankton.

Coccolith lamination. Coccolith laminae occur in settings ranging from Holocene sediments from the Black Sea (Hay 1988) through Oligocene shales and limestones (**Haczewski**) to Jurassic black shales (**O'Brien**). Individual coccolith laminae differ in form from diatom laminae in being more blebby and discontinuous, possibly due to sedimentation as faecal pellets (Pilskaln 1989). In sediments containing both diatoms and coccoliths (e.g. Black Sea), diatoms may form the deposit from the spring bloom while coccoliths are deposited from the Autumn bloom (Hay *et al.* 1990).

Lamination produced by algal or bacterial mats

Lamination produced by cyanobacterial mats in which organic filaments (which may be produced seasonally) alternate with clastic sediment is illustrated by **O'Brien**. Benthic bacterial mats (such as *Beggiotoa* or *Thioploca*) have been inferred to form laminae in the Santa Barbara Basin (see summary in **Schimmelmann & Lange**) although doubt is cast on this mechanism by **Bull & Kemp**.

Chemically induced lamination

Chemically induced lamination may form as water column precipitates which then settle or may develop within the surficial sediment due to early diagenesis. In some redox-sensitive cases, e.g. pyrite in marine environments and siderite in lacustrine environments minerals may form either within the water column or within the sediment.

Water-column precipitation. Many lakes precipitate calcium carbonate in the form of low-magnesium calcite during the summer when photosynthesis decreases dissolved CO_2 and temperatures increase (Kelts & Hsu 1978). In evaporitic basins, an annual cycle of evaporation may lead to alternating layers of halite/sulfate or calcite/anhydrite (Anderson; **Leslie *et al.***).

Early diagenetic lamination. Early diagenetic changes related to variation of redox and the metabolisation of organic matter may influence lamina composition. For example, organic-rich laminae may form a locus of pyrite formation. Annual manganese carbonate laminae in sediments from the Baltic Sea and similar features in ancient black shales may result from seasonal changes in bottom water oxygenation (Huckriede & Meischner 1996).

Laminated sediments as geo-chronometers

Following the pioneering work of De Geer (see **Anderson**; **Petterson**) the development of varve chronologies has been a major research goal. This has led to the development of the Swedish Time Scale covering 13 527 varve years and to calibration of ^{14}C chronologies with varve years (Wohlfarth *et al.* 1995; references in **Petterson**). Where laminae are indistinct, however, or where complete couplets are not deposited every year, lamina-based timescales cannot be erected (e.g. Black Sea; Crusius & Anderson 1992).

Counting varves

Of course, the down side to having a thick laminated sediment sequence capable of use for chronology and generation of time series is that the varves must be counted! Until recently, such counting was exclusively manual. Automated varve counting by digital imaging and subsequent image analysis offers a solution to this. **Zolitschka** presents such analyses but emphasizes that with composite varves and the occurrence of thin varves complications arise that require additional resolution/examination. Ripepe *et al.* (1991) used automated image analysis from acetate peels for studies of cyclicity in Eocene oil shales. Schaaf & Thurow (1994) have developed a rapid method for laminated sediment core image acquisition and analysis but from the ap proach of using bulk or interpolated sedimentation rates rather than identifying separate years.

Non-annual laminae

In most environments of deposition of laminated sediments, the seasonal/annual signal is the strongest influence on sedimentation, as **Anderson** emphasizes. There are, however, other variations in climate/ocean dynamics which have a strong signal, the most prominent of which is the El Niño/Southern Oscillation (ENSO). Sequences that contain laminae interpreted to represent other than annual deposition are rare, but **Hagadorn** presents analysis of the Santa Monica Basin sediments, in which lamina couplets occur with 3–6 year periodicities charactersitic of El Niño. Elsewhere, in Africa, based on records from Lake Turkana, Halfman & Johnson (1988) also suggest an El Niño periodicity for laminae.

Cyclicity recorded in annually laminated sediments

Varved sediments are a readily decipherable repository for records of interannual variability. In lake sediments, periodicites of 11 and 22 years, marking the solar (sunspot) cycles are common and longer period, decadal and century-scale periodicities are also recognized from spectral analysis (Glenn & Kelts 1991). ENSO signals (rare in lake sediments) are relatively common in marine sediments and 50–60 year cycles have also been identified (**Schimmelmann & Lange**; **Bull & Kemp**; **Hagadorn**). Increasing use of image analysis of laminated sediment sequences is producing more material for time series production, however, care is required in assessing the reliability and statistical validity of peaks produced in spectral analysis.

Laminated sediments as event correlators of palaeoseismicity and neotectonics

The chronological schemes derived from laminated sediments may also be applied to precisely date and correlate sedimentary or tectonic events. The reconstruction of geological events hinges on the ability to identify the relative timing of events recorded in the sedimentary record. It is here that the ability to correlate annual laminae over long distances can give precise information on the synchroneity of events. An illustration of this is derived from ancient Oligocene laminated limestones of the Polish Carpathians, allowing **Haczewski** to correlate palaeoseismicity over large distances. Holocene laminated sediments are being increasingly used for accurate dating in studies of neotectonics in tectonically active settings such as convergent plate margins (Brobowsky & Clague, 1990).

Laminated sediments as palaeo-oxygenation indicators

In settings where preservation of lamination may be confidently ascribed to reduced concentrations of dissolved oxygen (not deep-sea diatom ooze – see below), the degree of lamina disruption may be used as a palaeo-oxygenation index. A classification scheme based on lamination and the occurrence of trace-fossils was proposed by Savrda & Bottjer (1986) while a more refined scheme, based on the degree of disruption to laminae, integrated with benthic foraminiferal evidence has been employed in the Santa Barbara Basin by Behl & Kennett (1996).

Significance of deep-sea laminated diatom oozes

An exciting new development is the increasing recognition of the occurrence of laminated sediments composed of diatom mats or giant diatoms in open-ocean, deep-sea environments. Because of the laminated nature of these deposits, and given the existing preconceptions, origins have been ascribed previously to *ad hoc* and implausible occurrences of reduced oxygen conditions e.g. Muller *et al.* (1991). Work on laminated diatom mat deposits of the eastern equatorial Pacific (Kemp & Baldauf 1993) together with new insights into the oceanography of frontal systems (Yoder *et al.* 1994) have led to the development of integrated models for the origins of these enigmatic sediments (**Kemp *et al.***; **Pearce *et al.***). Analogous laminated diatom mat deposits have been described recently from the North Atlantic by Boden & Backman (1996) who ascribe their origins to a similar frontal zone origin to those of the equatorial Pacific.

The lamina-scale periodicities present within these deep-sea laminites are not as straightforward to interpret as those from lacustrine or marginal marine settings where an annually/seasonally-driven terrigenous sediment pulse provides a temporal control. **Kemp *et al.*** ascribe lamina-scale alternations in equatorial Pacific sediments to possible anti-El Niño perioditicies.

Laminated sediments as palaeoproductivity indicators

Biogenic laminae composed of diatoms commonly display thickness variation within individual sequences. Such thickness variation within Santa Barbara Basin sediments is related to variation in upwelling-driven productivity in the basin **Bull & Kemp** and new time series analysis of this reveals 4–7 year periodicities. In laminated sediments of the Cariaco Basin **Hughen *et al.*** (2) also ascribe increased thickness of diatom-rich laminae to increased productivity.

Although variation in diatom lamina thickness (hence biogenic opal content) may be related to variations in primary production in marginal upwelling environments there is substantial evidence that variation in opal content in open-ocean, deep-sea settings may not be straightforwardly related to productivity (Kemp 1995; **Kemp *et al.***).

Onset of laminations: monitoring anthropogenic effects

The recent onset of laminations in many marginal marine and lake environments is a direct record of anthropogenically induced eutrophication. **Petterson** illustrates the increasing incidence of laminae in Swedish Lakes within the last century which are a direct result of anthropogenic activity. In a marine environment, Jonsson *et al.* (1990) document the increasing incidence of laminae in surficial sediment samples from the Baltic since the end of the 1940s. However, care must be taken in oversimplifying such relationships. **Gorsline** summarizes the expansion of the laminated zone within the Santa Monica Basin over the last three hundred years: well before the incidence of significant anthropogenic influence. Such instances underscore the requirement to characterize natural trends in order to identify anthropogenically induced change and to separate local from regional and global-scale changes.

Laminated sediments as correlators of rapid global events

Some of the most intriguing questions in global change research concern the global extent and timing of change. How rapidly are variations in North Atlantic thermohaline circulation transmitted through the global ocean? Do the Dansgaard–Oeschger cycles have a global signature? Recent work from ODP Site 893 in the Santa Barbara Basin (Behl & Kennett 1996) has built on earlier work from the Gulf of California (Keigwin & Jones 1990) to show that changes in North Atlantic circulation (associated with Greenland Ice Core oxygen isotope variations) correlate with variations in preservation of laminae in basin sediments. Behl & Kennett (1996) relate these variations in lamina preservation to changes in the oxygenation of Pacific Intermediate Water controlled by variation in the volume of North Atlantic Deep Water production.

Another recent insight into transmission of high-latitude events has come from comparison of lamina thickness in sediments from the Cariaco Basin (**Hughen *et al.***; Fig. 1) and the Greenland, GRIP ice core $\delta^{18}O$, which show a remarkable similarity in the timing and duration of events and in decadal-scale patterns of variability (Hughen *et al.* 1996).

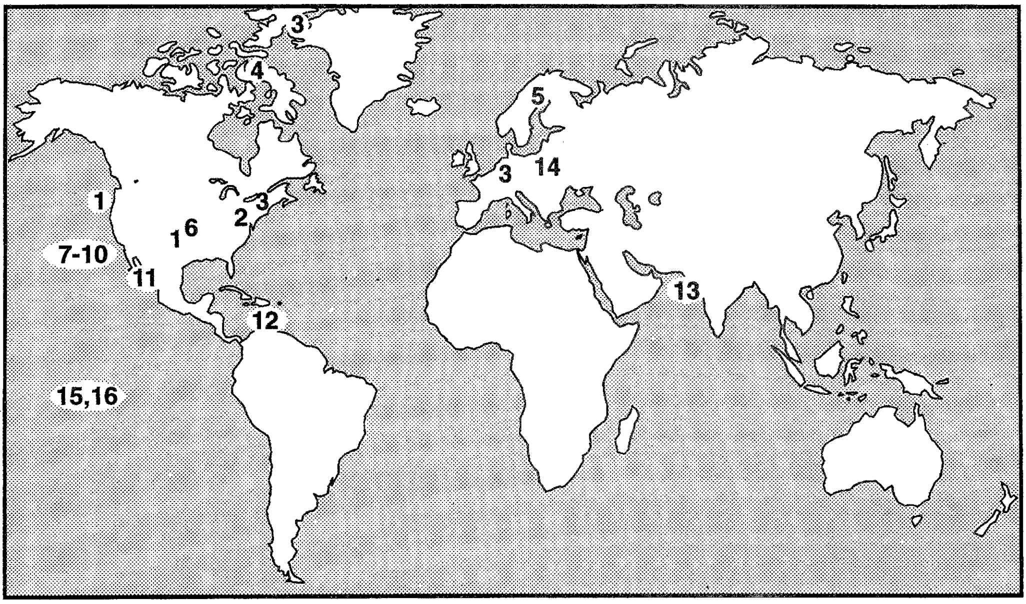

Fig. 1. Location of case studies of laminated sediments: (1) Anderson: evaporite basins, New Mexico & Texas; marine laminae, California Margin. (2) ÓBrien: Devonian shales, New York (& other miscellaneous Mesozoic-Proterozoic examples). (3) Zolitschka, Holzmaar, Germany; Fayetteville Green Lake (New York); Lake C2 (Canada). (4) Hughen *et al.*: tidewater lakes, Baffin Island (Canada). (5) Petterson: Swedish lakes, estuaries and seas. (6) Leslie *et al.*: evaporite basin, New Mexico. (7) Gorsline *et al.*: California Borderland Basins. (8) Hagadorn: Santa Monica Basin, California Borderland. (9) Schimmelmann & Lange: Santa Barbara Basin. (10) Bull & Kemp: Santa Barbara Basin. (11) Pike & Kemp: Gulf of California. (12) Hughen *et al.*: Cariaco Basin, offshore Venezuela. (13) von Rad & von Stackelberg: Northeastern Arabian Sea. (14) Haczewski: Polish Carpathians. (15, 16) Pearce *et al.*, Kemp *et al.*: eastern Equatorial Pacific Ocean.

Future research directions and initiatives

There is increasing focus on the acquisition of high-resolution records of environmental change and laminated sediment targets have featured prominently. One of the most notable developments in the production of highest-resolution data is the recent adoption of individual sites as targets of the Ocean Drilling Program (ODP). The ODP's *Joides Resolution* is the only platform capable of piston coring to greater than 50 m sediment depths. Several recent targets, including ODP Site 893 in the Santa Barbara Basin (200 m sediment to isotope stage 6); ODP Site 1002 in the Cariaco Basin and, most recently, the mini-Leg 169S to Saanich Inlet in British Columbia, have already started to produce fascinating new palaeoclimatic and palaeoceanographic data. The acquisition of increasingly longer, high quality cores from continental lakes (such as Monticchio) has also produced new high resolution records spanning the last glacial cycles and the new continental drilling initiatives promise more. Integration and correlation of multiparameter data-sets from these sites will provide key input to global change research.

This volume

Many of the papers included in this volume were presented at a conference on 'Palaeoclimatology and Palaeoceanography from Laminated Sediments' held at the Geological Society in September 1993. This meeting brought together workers on both marine and lacustrine laminated sediments. It emerged that the two communities were to a large extent quite separate and there had been only limited communication between terrestrial and marine researchers. As the meeting progressed, it became evident that the two communities had much in common yet, at the same time, had developed some quite separate sampling and analytical methods and approaches. The benefits from pooling the expertise from the two communities were readily apparent, both in terms of methodology and from a broader awareness of the combined approach of studying a global array of lacustrine and marine sites in the context of major initiatives such as the PAGES, PEP (Pole–Equator–Pole) transects. In order to initiate an ongoing method for interaction a proposal was submitted to initiate a IUGS/ UNESCO International Geological Correlation Programme. Subsequently IGCP 374 (Palaeoclimatology and Palaeoceanography from Laminated Sediments) has held a series of meetings designed as forums for interaction and to disseminate results of ongoing studies. The papers presented in this volume which cover approaches and methods as well as research results form a contribution to IGCP 374.

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