Palaeoclimatology and Palaeoceanography from Laminated Sediments

Geological Society
Special Publication
No. 116

edited by A. E. S. Kemp

Published by The Geological Society

GEOLOGICAL SOCIETY SPECIAL PUBLICATION NO. 116

Palaeoclimatology and Palaeoceanography from Laminated Sediments

EDITED BY

A. E. S. KEMP
Department of Oceanography
University of Southampton
Southampton Oceanography Centre
UK

IGCP 374

1996

Published by

The Geological Society

London

THE GEOLOGICAL SOCIETY

The Society was founded in 1807 as The Geological Society of London and is the oldest geological society in the world. It received its Royal Charter in 1825 for the purpose of 'investigating the mineral structure of the Earth'. The Society is Britain's national society for geology with a membership of around 8000. It has countrywide coverage and approximately 1000 members reside overseas. The Society is responsible for all aspects of the geological sciences including professional matters. The Society has its own publishing house, which produces the Society's international journals, books and maps, and which acts as the European distributor for publications of the American Association of Petroleum Geologists, SEPM and the Geological Society of America.

Fellowship is open to those holding a recognized honours degree in geology or cognate subject and who have at least two years' relevant postgraduate experience, or who have not less than six years' relevant experience in geology or a cognate subject. A Fellow who has not less than five years' relevant postgraduate experience in the practice of geology may apply for validation and, subject to approval, may be able to use the designatory letters C Geol (Chartered Geologist).

Further information about the Society is available from the Membership Manager, The Geological Society, Burlington House, Piccadilly, London W1V 0JU, UK. The Society is a Registered Charity, No. 210161.

Published by The Geological Society from:
The Geological Society Publishing House
Unit 7, Brassmill Enterprise Centre
Brassmill Lane
Bath BA1 3JN
UK
(*Orders*: Tel. 01225 445046
Fax 01225 442836)

First published 1996

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library.

ISBN 1-897799-67-5
ISSN 0305-8719

Typeset by Aarontype Limited,
Easton, Bristol, UK.

Printed by The Alden Press,
Osney Mead, Oxford, UK.

Distributors
USA
AAPG Bookstore
PO Box 979
Tulsa
OK 74101-0979
USA
(*Orders*: Tel. (918) 584-2555
Fax (918) 560-2652)

Australia
Australian Mineral Foundation
63 Conyngham Street
Glenside
South Australia 5065
Australia
(*Orders*: Tel. (08) 379-0444
Fax (08) 379-4634)

India
Affiliated East-West Press PVT Ltd
G-1/16 Ansari Road
New Delhi 110 002
India
(*Orders:* Tel. (11) 327-9113
Fax (11) 326-0538)

Japan
Kanda Book Trading Co.
Tanikawa Building
3-2 Kanda Surugadai
Chiyoda-Ku
Tokyo 101
Japan
(*Orders*: Tel. (03) 3255-3497
Fax (03) 3255-3495)

Palaeoclimatology and Palaeoceanography from Laminated Sediments

Geological Society Special Publications

Series Editor A. J. FLEET

Laminated sediments as palaeo-indicators

ALAN E. S. KEMP

Department of Oceanography, University of Southampton, Southampton Oceanography Centre, European Way, Southampton SO14 3ZH, UK

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**).

From Kemp, A. E. S. (ed.), 1996, *Palaeoclimatology and Palaeoceanography from Laminated Sediments*, Geological Society Special Publication No. 116, pp. vii–xii.

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).

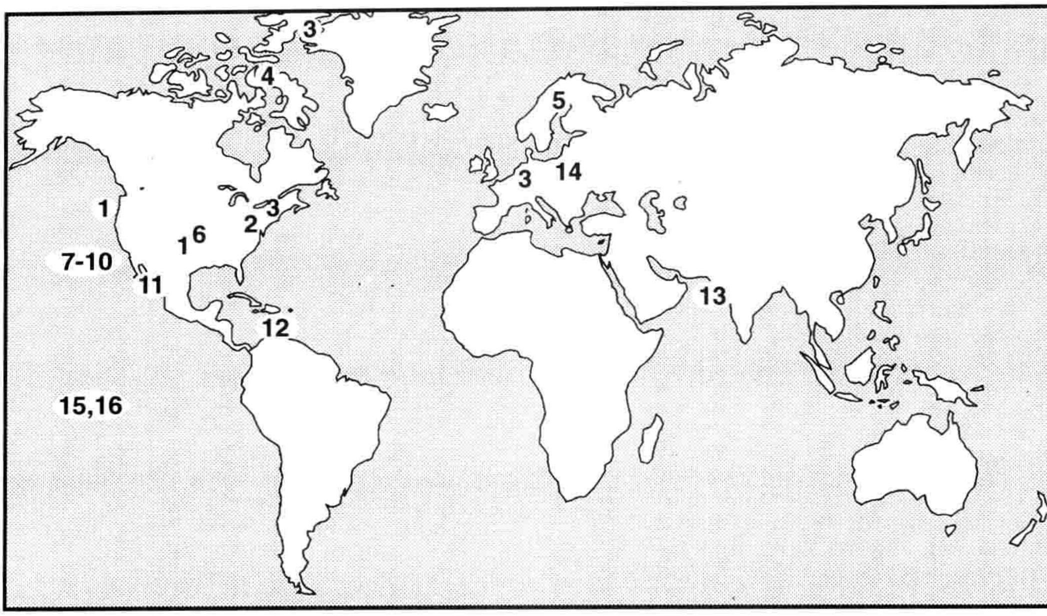

Fig. 1. Location of case studies of laminated sediments: (1) Anderson: evaporite basins, New Mexico & Texas; marine laminae, California Margin. (2) ÓBrien: Devonian shales, New York (& other miscellaneous Mesozoic-Proterozoic examples). (3) Zolitschka, Holzmaar, Germany; Fayetteville Green Lake (New 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.

References

ANDERSON, R. Y. & DEAN, W. E. 1988. Lacustrine varve formation through time. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **62**, 215–235.

BEHL, R. J. & KENNETT, J. P. 1996. Brief interstadial events in the Santa Barbara Basin, NE Pacific, during the past 60 kyr. *Nature*, **379**, 243–246.

BODEN, P. & BACKMAN, J. 1996. A laminated sediment sequence from the northern north Atlantic Ocean and its climatic record. *Geology*, **24**, 507–510.

BROBOWSKY, P. T. & CLAGUE, J. J. 1990. Holocene sediments from Saanich Inlet, British Columbia, and their neotectonic implications. *Current Research, Part E Geological Survey of Canada, Paper* **90-E1**, 251–256.

CRUSIUS, J. & ANDERSON, R. F. 1992. Inconsistencies in accumulation rates of Black Sea sediments inferred from records of laminae and ^{210}Pb. *Palaeoceanography*, **7**, 215–227.

DIMBERLINE, A. J., BELL, A. & WOODCOCK, N. H. 1990. A laminated hemipelagic facies from the Wenlock and Ludlow of the Welsh Basin. *Journal of the Geological Society, London*, **147**, 693–702.

GLENN, C. R. & KELTS, K. 1991. Sedimentary rhythms in lake deposits. *In*: EINSELE, G., RICKEN, W. & SEILACHER, A. (eds) *Cycles and Events in Stratigraphy*. Springer, Berlin, 188–221.

HAY, B. J. 1988. Sediment accumulation in the central eastern Black Sea over the last 5100 years. *Paleoceanography*, **3**, 491–508.

——, HONJO, S., KEMPE, S., ITTEKOT, V. A., DEGENS, E. T., KONUK, T. & IZDAR, E. 1990. Interannual variablity in particle flux in the southwestern Black Sea. *Deep-Sea Research*, **37**, 911–928.

HALFMAN, J. D. & JOHNSON, T. C. 1988. High resolution record of cyclic climatic change during the past 4 ka from Lake Turkana, Kenya. *Geology*, **16**, 496–500.

HUCKRIEDE, H. & MEISCHNER, D. 1996. Origin and environment of manganese-rich sediments within black-shale basins. *Geochimica et Cosmochimica Acta*, **60**, 1399–1413.

HUGHEN, K. A., OVERPECK, J. T., PETERSON, L. C. & TRUMBORE, S. 1996. Rapid climate changes in the tropical Atlantic duting the last deglaciation. *Nature*, **380**, 51–54.

JONSSON, P., CARMAN, P. & WULFF, F. 1990. Laminated sediments in the Baltic – a tool for evaluating nutrient mass balances. *Ambio*, **19**, 152–158.

KEIGWIN, L. D. & JONES, G. A. 1990. Deglacial climatic oscillations in the Gulf of California. *Paleoceanography*, **5**, 1009–1023.

KELTS, K. & HSU, K. J. 1978. Freshwater carbonate sedimentation. *In*: LERMAN, A. (ed.) *Lakes: Chemistry, Geology, Physics*. Springer, Berlin, 295–323.

KEMP, A. E. S. 1991. Silurian pelagic and hemipelagic sedimentation and palaeoceanography. *In*: BASSETT, M. G., LANE, P. D. & EDWARDS, D. (eds) *Special Paper in Palaeontology*, **44**, 261–300.

——1995. Laminated sediments from coastal and open ocean upwelling systems: what variability do they record? *In*: SUMMERHAYES, C. EMEIS, K.-C., ANGEL, M. V., SMITH, R. L. & ZEITZSCHEL, B. (eds) Upwelling in the Ocean: Modern Processes and Ancient Records. *Dahlem Workshop Report* ES18. Wiley, Chichester, 239–257.

—— & BALDAUF, J. G. 1993. Vast Neogene laminated diatom mat deposits from the eastern equatorial Pacific Ocean. *Nature*, **362**, 141–144.

MULLER, D. W., HODELL, D. A. & CIESIELSKI, P. F. 1991. Late Miocene to earliest Pliocene (9.8–4.5 Ma) paleoceanography of the subantarctic southeast Atlantic: stable isotopic, sedimentologic, and microfossil evidence. *In*: CIESIELSKI, P. F., KRISTOFFERSEN, Y. *et al. Proceedings ODP, Sci. Results*, **114**, College Station, TX (Ocean Drilling Program), 459–474.

PILSKALN, C. H. 1991. Biogenic aggregate sedimentation in the Black Sea Basin. *In*: IZDAR, E. & MURRAY, J. W. (eds) *Black Sea Oceanography*. Kluwer, Dordrecht, 293–306.

RIPEPE, M., ROBERTS, L. T. & FISCHER, A. G. 1991. ENSO and sunspot cycles in varved Eocene oil shales from image analysis. *Journal of Sedimentary Petrology*, **61**, 1155–1163.

SAVRDA, C. E. & BOTTJER, D. J. 1986. Trace-fossil model for reconstruction of paleo-oxygenation in bottom waters. *Geology*, **14**, 3–6.

SCHAAF, M. & THUROW, J. 1994. A fast and easy method to derive highest-resolution time-series datasets from drillcores and rock samples. *Sedimentary Geology*, **94**, 1–10.

WOHLFARTH, B., BJÖRK, S. & POSSNERT, G. 1995. The Swedish Time Scale – a potential calibration tool for the radiocarbon time-scale during the late Weichselian. *Radiocarbon*, **37**, 347–359.

YODER, J. A., ACKLESON, S., BARBER, R. T., FLAMANT, P. & BALCH, W. A. 1994. A line in the Sea. *Nature*, **371**, 689–692.

Contents

Seasonal sedimentation: a framework for reconstructing climatic and environmental change

ROGER Y. ANDERSON

Department of Earth and Planetary Sciences, University of New Mexico, Albuquerque, NM 87131, USA

'Of the late glacial sediments the most important is the glaci-marine clay, the ***varvig lera*** *(Hvarfvig lera) ... Already in my first field-work as a geologist, in 1878, I was struck by the regularity of these laminae, much reminding of the annual rings of trees ... The laminae were found to be so regular and so continuous that they could scarcely be due to any less regular period than the annual one ... I also succeeded in finding the first correlation between clay layers at three points, though not very far from one another ... Finally, in 1904, I happened to get a very good correlation between two clay sections 1 km apart from each other, and now I determined to make an earnest attempt to realize my old plan for a clay-chronology.*

I secured the assistance of a number of students from the Universities of Stockholm and Upsalla ... and after some training they all went out on a summer morning in 1905, each of them to his special part of a line about 200 km long ... going as nearly as possible in the direction of the ice recession. The main work was performed in four days.

I now finally have the conclusive proofs for the assumption that the individual 'varves' had a very wide distribution. This, together with their regular structure definitively showed, that they could not be due to any local or accidental cause of smaller importance or less pronounced periodicity than the climatic period of the year.'

Gerard de Geer (1912)

De Geer's intuition about the effects of seasonal climate forcing on sedimentation proved to be correct. His determination to leap-frog varve correlations from one site to another allowed him to recognize the power of the solstice cycle. In the late 1950s and early 1960s, my students and I performed a similar experiment by correlating much thinner, non-glacial laminae across single geological basins (Anderson & Kirkland 1966; Kirkland & Anderson 1970; Anderson *et al.* 1972). We relived the heady excitement of de Geer's discovery of varve correlation by extending his discovery into other environments. Long-distance, millimetre-scale correlations in single basins eventually were extended to around 1000 km in the Black Sea (Hay *et al.* 1991). It was de Geer's insight, the work of Sauramo (1923), of Richter-Bernberg (1960), and some of our own long-distance correlations that demonstrated that the annual cycle of climate forcing was strong enough to regulate the accumulation of sediment over entire basins, over broad geographic areas, and within a wide range of geological settings and environments.

Appreciation of the effects of the solstice cycle on sedimentation was reinforced by results from sediment trapping investigations carried out during the 1970s and 1980s. The design of sediment traps was improved to include time-series sampling (Anderson 1977), which revealed associations of specific sediment types with the seasons. It was found that sediment traps, even when deployed far from land and at great depths in the ocean, revealed a clear pattern of seasonal accumulation of sediment of varying composition. This information, when added to earlier detailed investigations of extant, seasonal organisms and their association with sedimentary laminations (Heim 1909; Nipkov 1927; Welten 1944; Kirkland & Anderson 1969), reduced resistance within the geological community to the idea that certain types of non-glacial laminations were also varves.

Seasonally generated accumulations of sediment were the rule, not the exception. Were it not for bioturbation, virtually the entire sediment pile, even in environments with very high accumulation rates, would bear evidence of seasonality in their laminated structure, as is the case for much of the Precambrian (Anderson *et al.* 1985*b*). Today, as the pendulum swings from skepticism about varves toward belief, a word of caution is in order. Laminations, even in quiet environments, are not necessarily varves and it is not safe to conclude that laminations are varves until one or more important criteria have been met. These criteria include known

From Kemp, A. E. S. (ed.), 1996, *Palaeoclimatology and Palaeoceanography from Laminated Sediments*, Geological Society Special Publication No. 116, pp. 1–15.

seasonal associations of major or minor components, an established chronology, and evidence for lateral continuity. However, when direct or indirect evidence for the annual cycle is not available, it is sometimes possible to conclude, through the cautious use of analogues, that laminations were generated seasonally and have faithfully recorded the annual cycle of climate forcing.

De Geer, in defining varves, recognized their persistence and noted that regularity of expression over time was characteristic of the process. Some non-glacial varve sequences display great regularity over time (Anderson 1982). In my opinion, however, it is not necessary that couplets or groups of seasonal laminations be precisely annual or continuously expressed to be considered varves. The key statement of de Geer is that the layering... 'could not be due to any local or accidental cause of smaller importance... than the climatic period of the year.' Thus, it is the relationship to the annual climate cycle and not regularity or persistence over time that defines the varve concept.

The majority of seasonally generated laminations in lacustrine environments, and especially in marine environments, are not beautifully preserved as regular varves. More commonly, a sequence of laminations is variable in expression, and continuity is interrupted by bioturbation, scour, turbidites, etc. For example, parts of a varve time series may be greatly expanded by the addition of sediment, to a point where the annual cycle of accumulation is not decipherable (Anderson 1992*a*, *b*; 1993). At the other extreme, rates of accumulation may be so slow that annual accumulations are unrecognizable and interannual and decadal changes in composition are mistaken for varves. There are probably many cases where there is but a single dominant seasonal component, leaving little physical evidence for seasonal accumulation. Other examples of less-than-perfect varving, in addition to disturbance by bioturbation, include cases where accumulations are interrupted or truncated by currents and downslope processes.

Limitations imposed on the use of varves by other processes can be seen, not as a deterrent to investigation, but as an important source of information about responses to environmental and climatic change. However, to obtain this information, and to use less-than-perfect laminations to reconstruct environmental and climatic variability, it helps to place the processes that generate seasonal laminations within a framework that facilitates environmental and climatic interpretation.

Seasonal sedimentation

Climatic effects on sedimentation

Joseph Barrell (1908) noted:

> *'It is natural that the influence of climatic change in producing shiftings of the sedimentary facies should be the last kind of action to reach a true appreciation.'*

Now, many years later, and especially after the success of orbital forcing as a mechanism for explaining long-term changes in climate, Barrell's observation seems obvious. But it is not at all obvious that orbital forcing can account for the patterns of stratification found in deposits of clays and marls because the atmosphere, and especially the oceans, are very weakly coupled to the small, net changes in insolation that accompany orbital forcing. However, a sedimentation response within the Milankovitch band is more believable if most sediment is mobilized seasonally because orbital climate forcing works through seasonal changes in insolation. In the varved Permian Castile evaporite, for example, it is probably year by year changes in seasonal rates of accumulation of calcium sulphate that are responsible for the expression of cycles of precession and eccentricity (Anderson 1982, 1984).

An important conclusion drawn from large-scale changes in climate and stratification in the Milankovitch band is that the climate system must be in delicate balance. So delicate, in fact, that other subtle mechanisms of climate forcing probably are responsible for changes in sedimentation and stratification expressed on the time scale of decades to millennia. This conclusion is reinforced by the long, annual climate record from the Castile, which shows that variance within the Milankovitch band is not as strong as for millennial changes (Anderson 1982). The search is now on to find high-resolution climate records in lacustrine and marine environments and to understand climate variability at decadal to millennial timescales. Interpreting such records is aided by recognizing controls on seasonal sedimentation.

Framework for environmental and climatic reconstruction

Because seasonal changes in climate have a central role in regulating sedimentation, one can build a framework for sedimentology that is based on responses to the annual cycle of forcing.

My goal in this article is to present, in very general terms, a paradigm for sedimentology in which the centrepiece is not the environment of deposition. Rather, the focus is temporal, and the theme is the strong coupling that exists between seasonal climate forcing and the sedimentation response, as preserved in different sedimentary environments.

This brief sketch of a framework for seasonal sedimentation relies principally on examples

Table 1. Articles related to seasonal sedimentation published by R. Y. Anderson and co-workers

Category	Topics	Citations
Reviews	Evaporites, Orbital Forcing	Anderson (1984)
	Varve genesis. Meromictic Lakes	Anderson *et al.* (1985)
	Lacustrine Varves	Anderson & Dean (1988)
	Solar Variability in Varves	Anderson (1991)
Varve 'Theory'	Varves, Stratification	Anderson (1964; 1986)
	Marine Varves, ENSO	Anderson *et al.* (1990)
	Seasonal Sedimentation	This paper.
Methods, traps, seasonal processes	Time Series Methods	Anderson & Koopmans (1963; 1969; 1975)
	*	Anderson (1968)
	Sediment Trap Investigations	Anderson (1977)
	*	Dean & Anderson (1974)
	*	Anderson *et al.* (1984; 1985)
	*	Nuhfer & Anderson (1985)
	*	Nuhfer, *et al.* (1993)
Correlation and basin analysis	Varve Correlations	Anderson & Kirkland (1966; 1973)
	Turbidite Correlation	Dean & Anderson (1967)
	Evaporite Laminae	Dean *et al.* (1975)
	Folded Laminations	Kirkland & Anderson (1977)
	Brecciated Laminations	Anderson *et al.* (1978)
	Evaporites, Isotopic Shifts	Magaritz *et al.* (1983)
	Hydrologic Associations	Anderson & Dean (1995)
Palaeoclimatic time series		
Lacustrine	Rita Blanca, TX	Anderson (1969)
	*	Anderson & Kirkland (1969*a*, *b*)
	*	Kirkland & Anderson (1969)
	Elk Lake, MN	Dean *et al.* (1984)
	*	Bradbury *et al.* (1993)
	*	Anderson (1993)
	*	Anderson *et al.* (1993)
	*	Anderson, *et al.* (1993)
	Lake Estancia, NM	Allen & Anderson (1993)
	Florissant, CO	McLeroy & Anderson (1966)
Evaporite	Todilto Formation	Anderson & Kirkland (1960)
	Castile Formation	Anderson *et al.* (1972)
	*	Dean & Anderson (1973; 1978; 1982)
	*	Anderson (1982)
	*	Anderson & Kirkland (1987)
Marine, ENSO	Continental Slope, OMZ	Anderson *et al.* (1987)
	*	Anderson *et al.* (1989)
	*	Anderson *et al.* (1990)
	*	Dean *et al.* (1994)
	Isotopic Shifts	Linsley *et al.* (1990)
	ENSO Variability	Anderson, (1992*b*)
		Anderson *et al.* (1992)
Solar-climate associations	General	Anderson (1961; 1983; 1991)
	ENSO	Anderson (1990)
	Geomagnetic	Anderson (1992; 1993)

developed in a series of papers by myself and co-workers over nearly four decades. For the convenience of the reader I have assembled these investigations in Table 1. Articles in each category are cited chronologically and, along with other citations in the discussion to follow, provide the reader with examples of some of the methods used to reconstruct climate histories from laminated, partly laminated, and non-laminated sediments.

Earlier attempts to formulate a 'theory of sedimentation' based on varves drew on the observation that a varve was a 'microcosm' of stratification on a larger scale (Anderson 1986). That is, changes in sediment composition and geochemical and biological associations found during a single, annual cycle of sedimentation are repeated at all lower frequencies (longer periods), provided there has been no substantial change in the physical-biological system. Although this concept is an elaboration of the truism that the whole is the sum of the parts, it can be very useful when interpreting changes in composition and environmental associations under circumstances when laminations or varves are poorly preserved.

When examining the coupling between sedimentation and climate across the entire band of climate frequencies, I have found it useful to adopt a terminology developed for episodic processes, but less commonly applied in sedimentology.

Domains

Sedimentary processes are naturally separated into two domains according to their episodic behaviour and their resistance to forcing during the annual climate cycle. These domains were recognized as the most appropriate basis for rock classification (Walther 1897; Grabau 1904). Grabau based his genetic classification on agents or processes that produced rocks and he recognized that rocks were generated as the result of either mechanical (exogenetic) agents, or as a result of processes related to solution (endogenetic) agents. These two domains, here called mechanical and bio/chemical, (Fig. 1), can be used to categorize different types of seasonal laminations. Also, the concept is useful for recognizing the climatic implications of various

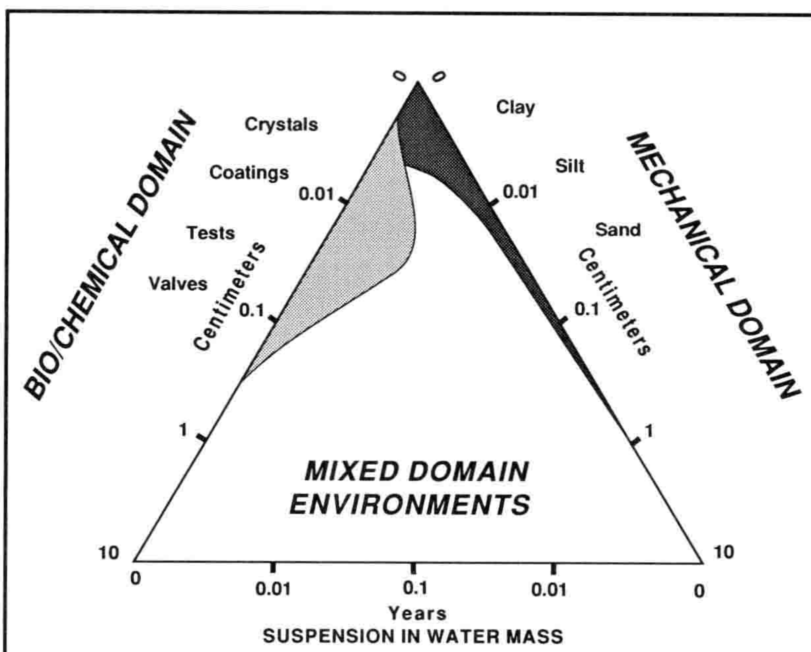

Fig. 1. Domains of episodic sedimentation. Sediment in the mechanical domain is suspended and advected after a forcing (climate) event exceeds a shear threshold. Sediment in the bio/chemical domian is generated in the water mass after a forcing event exceeds a weak chemical or vital threshold and accumulates as a 'sediment rain'. Fine particles generated in both domains remain suspended for long intervals, resulting in sedimentation in a mixed domain.