Graham Weedon

Time Series Analysis and Cyclostratigraphy

Examining Stratigraphic Records of Environmental Cycles

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Examining stratigraphic records of environmental cycles

Increasingly environmental scientists, palaeoceanographers and geologists are collecting quantitative records of environmental changes from sediments, ice cores, cave calcite, corals and trees. These records reveal climatic cycles lasting between one year and hundreds-of-thousands of years, and tidal cycles lasting from half a day to one and a half thousand years. The study of such records is known as cyclostratigraphy and the records themselves, time series. This book uses straightforward explanations of time-series analysis based on numerous original diagrams rather than formal mathematical derivations and equations.

All the main methods used in cyclostratigraphy are covered, including spectral analysis, cross-spectral analysis, filtering, complex demodulation, wavelet analysis and singular spectrum analysis. The problems of distortions of environmental signals during stratigraphic encoding are considered in detail, as are the practical problems of time-series analysis. Finally, there is a summary of the state of research into various types of tidal and climatic cycles and their cyclostratigraphic records. Extensive referencing allows ready access to the literature and the appendix provides a list of sources of computer algorithms.

This book provides the ideal reference for all those using time-series analysis to study the nature and history of sedimentary, climatic and tidal cycles. It is suitable for senior undergraduate and graduate courses in environmental science, palaeoceanography and geology.

Graham Weedon is Senior Lecturer in Geology at the University of Luton. His current research involves studying records of annual cycles in cave calcite, El Niño/Southern Oscillation (ENSO) cycles in varved sediment and Milankovitch cycles in ancient deep-sea sediments.

He received a D.Phil from Oxford University in 1987, and has participated in Ocean Drilling Program cruises, off Oman (1987), Brazil (1994) and New Zealand (1998). In 1999 he co-convened a Royal Society Meeting entitled 'Astronomical (Milankovitch) Calibration of the Geological Time Scale'.

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For Alexis and ‘Felix-man’.

Contents

Preface

This book is designed to introduce the main methods used in the examination of quantitative records of ancient environmental changes. Such records are obtained from sources as diverse as the composition of sedimentary rocks, the varying percentages of microfossils and the thicknesses of growth bands in corals. These data sets, or time series, describe environmental changes lasting from half a day to millions of years. The emphasis of the book is on explaining concepts, procedures and problems *not* the details of the mathematics. I have avoided equations and derivations and have instead tried to employ simple diagrams in the explanations. This is because palaeoceanographers, environmental scientists, palaeoclimatologists, sedimentologists and palaeontologists sometimes find it easier to grasp new ideas graphically, rather than through formal mathematical treatments. There are, of course, many texts devoted to mathematical explanations, but this book attempts to explain time-series analysis to non-mathematicians in an accessible form.

Examination of ancient examples of varves and sedimentary cycles linked to orbital-climatic forcing (Milankovitch cycles, explained in Chapter 6) using time-series analysis began in the early 1960s. My own work spans Silurian to Recent cyclic sediments and includes the study of cores from three oceans with an emphasis on orbital-climatic (Milankovitch) forcing (Ocean Drilling Program Legs 117, 154 and 181). However, over the last few years the fastest growth in the use of time-series analysis has been amongst environmental scientists studying short period cyclicity related to phenomena such as El Niño and the Southern Oscillation and millennial-scale cycles and sedimentologists interested in stratigraphic records of tidal cycles. So despite my own perspectives, which have undoubtedly influenced the makeup of the book, I have tried to provide a treatment that is useful to all those interested in time series obtained from a stratigraphic context.

Throughout the book, in addition to demonstrations using artificial time series, I have used an example of a real cyclostratigraphic data set, obtained from British Lower Jurassic strata, to illustrate the major principles. Although this example is not ideal for every situation it does help to understand the procedures described as applied to real data. In several places I have made reference to issues concerned with the processing of sound and electronic digital signals in order to exemplify time series issues from everyday life. I have assumed that the reader is familiar with the concepts of standard deviation, correlation coefficients, moving averages, the normal and chi-squared distributions and covariance (e.g. Williams, 1984; Davis, 1986).

The subject of time-series analysis is full of jargon, so the first use of an important term is placed in **bold** along with the most common synonyms to allow easier reference to other publications. All the computations for the book illustrations used a modest PC running programs based on modifications of the published FORTRAN algorithms listed in the Appendix. Due to their central role, and at the risk of repeating the text, the figures have captions that allow them to almost ‘stand alone’. To produce a consistent format all the figures are original and virtually all were created using the package *Microcal* Origin 6.

The intention has been to provide a text that will appeal to many disciplines while recognizing that some material may not appear directly relevant. This book is necessarily only an introduction, but if it helps to encourage new researchers into the field it will have served its purpose.

Graham P. Weedon
February 2002

Acknowledgements

This book took five years to write, but it has been great fun. A wide range of literature and mathematical techniques needed to be reviewed and associated computer algorithms assessed, and much of relevance was published during writing (one-third of the references cited date from 1997 or later). Fortunately many people have helped me both during and at the end of the writing.

I had useful discussions with, and suggestions from, Steve Clemens, Ian Hall, Tim Herbert, Linda Hinnov, Paul Olsen, Walther Schwarzacher and Nick Shackleton. Heiko Pälike helped with the wavelet spectrum in Fig. 4.19 and Paul Cole (the '2 m scale' in the photograph on the front cover) helped me with EPS formats for Figs. 1.8, 1.9 and 6.1. Additionally, Shaun Hines processed Fig. 1.9 electronically and Harvey Alison sorted out various difficulties with Origin files. Data for figures were generously supplied by Ben Walsworth-Bell (Fig. 2.5), Al Archer (Fig. 6.17) and Jerry McManus (Fig. 6.23). Thanks to Cambridge University Library and the Cambridge Department of Earth Sciences Library for allowing me access.

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Chapter 1

Introduction

1.1 Cyclostratigraphic data

Increasingly, quantitative records of environmental change covering intervals of between half a day to millions of years are being sought by palaeoceanographers, environmental scientists, palaeoclimatologists, sedimentologists and palaeontologists. The 'media' from which these records are obtained range from sediments and sedimentary rocks to living organisms and fossils showing growth bands (especially trees, corals and molluscs), ice cores and cave calcite. This book is concerned with explaining the quantitative methods that can be employed to derive useful information from these records. Much of the discussion is concerned with explaining the problems and limitations of the procedures and with exploring some of the difficulties with interpretation. Most frequently environmental records are obtained from sedimentary sections making up the stratigraphic record and, using a rather broad definition, all the 'media' described above are 'stratigraphic'. The nature of cycles in environmental signals and in stratigraphic records are explored later. However, for now cycles can be thought of as essentially periodic, or regular, oscillations in some variable. The study of stratigraphic records of environmental cycles has been called cyclostratigraphy (Fischer *et al.*, 1990).

By regarding stratigraphic records of environmental change as signals, it is clear that the methods and interpretations reached during analysis must allow for the imperfections inherent in all recording procedures. In cyclostratigraphic data the environmental signal, which is 'encoded' during sedimentation, is often corrupted to some extent by interruptions caused by processes that are not part of the normal depositional system. Such processes, for sediments, include non-deposition, erosion, seafloor dissolution or event-bed deposition and they make the later recognition of the normal environmental signal more difficult. Yet the interruptions convey information themselves, and in some cases they result from the extremes of the normal environmental variations. For example, Dunbar *et al.* (1994), in their study of corals, pointed out that growth band thickness was related to sea surface temperature. However, episodes of unusually high sea surface temperatures cause growth band generation to stop completely for several years, thus interrupting the proxy temperature record.

As well as interruptions, the recording processes can introduce distortions that need to be taken into account. For example, accumulation rate variations and diagenesis frequently modify the final shapes of cyclostratigraphic data sets. In a similar manner to the interruptions, the distorting processes often depend on the nature of the environment. Hence, cyclostratigraphic data contain information about normal environmental variability, abnormal environmental variations and the processes that produce the records themselves. In other words, the stratigraphic information that is observed can be regarded as the product of many superimposed environmental and sedimentological, or metabolic, processes.

The methods described in this book are primarily concerned with detecting and describing regular cyclic environmental processes. Hence, the data are treated as though they consist of regular cycles plus irregular oscillations. The irregular components result from both normal and abnormal environmental conditions as well as the effects of sedimentation and diagenesis (or equivalent processes in skeletal growth, etc.). As explained below, there are sound geological reasons for using mathematics to search for regular cycles. Regular components of cyclostratigraphic data are often studied more easily than the irregular components. If methods could be developed to distinguish the various types and origins of the irregular components, much of value could be uncovered. Quantitative studies of the interruption and distortion processes will undoubtedly be useful for understanding ancient environmental and diagenetic mechanisms, but such investigations are relatively rare (e.g. Sadler, 1981; Ricken, 1986; Ricken and Eder, 1991; Ricken, 1993).

The idea that stratigraphic data consist of regular components – the signal, plus irregular components or noise – is based on a linear view of the processes involved. In reality non-linear processes abound in environmental systems (e.g. Le Treut and Ghil, 1983; Imbrie *et al.*, 1993a; Smith, 1994). In non-linear systems, the output does not vary in direct proportion to the input. There are many aspects of cyclostratigraphic data that cannot be easily investigated using the standard linear methods of analysis described in this book. From the perspective of non-linear dynamical systems, part of the irregular components can be considered to be as much a part of the environmental signal as the regular components (Stewart, 1990; Kantz and Schreiber, 1997). Some non-linear methods are described very briefly within Chapter 4 and some non-linear issues in signal distortion are considered in Chapter 5. Despite the view that non-linear approaches might explain more of the data than the linear methods, the latter are currently best understood mathematically and are the most frequently used.

A good demonstration of the success of the standard linear approach to cyclostratigraphic data concerns the time scale developed using late Neogene deep-sea sediments.

Hilgen (Hilgen and Langereis, 1989; Hilgen, 1991) and Shackleton *et al.* (1990) independently derived orbital cycle chronologies based on matching sedimentary cycles and oxygen isotope curves to the calculated history of insolation changes (Section 6.9). The results were at odds with the widely accepted radiometric ages that had been obtained using potassium-argon dating. Subsequently, improved radiometric dating and studies of sea-floor spreading rates confirmed the validity and utility of the so-called astronomical time scale approach (Wilson, 1993; Shackleton *et al.*, 1995a, 1999a). Consequently, a recent geochronometric scale for part of the Neogene has been based directly on orbital-cycle chronology rather than the traditional data derived from radiometrically calibrated rates of sea-floor spreading (Berggren *et al.*, 1995). In this case the standard, linear methods of time-series analysis have yielded results of fundamental importance to many other areas of the Earth Sciences.

1.2 Past studies of cyclic sediments

Examination of cyclic sediments intensified in the 1960s as modern depositional environments were better understood and conceptual models became more sophisticated. Historically sedimentologists were looking for explanations for cyclic stratigraphic sequences that did not simply require **random** (i.e. unconnected, meaning uncorrelated or 'independent') events. Perhaps if the underlying controls could be uncovered, more could be learnt about the environment of deposition. Cycle-generating processes were described as autocyclic if they originated inside the basin of deposition. Alternatively, allocyclic processes originated outside the basin (Beerbower, 1964). Coal measure cyclothems were a particular target for investigation since they had a wide range of interbedded lithologies, and resulted from a range of suspected autocyclic and allocyclic mechanisms. The definition of a cyclothem (Wanless and Weller, 1932) soon became contentious once the variety of lithological successions and inferred origins was appreciated (Duff *et al.*, 1967; Riegel, 1991). Simpler cyclic sections involving two alternating lithologies, often described as rhythmic, were often mentioned in reviews of cyclic sedimentation but, aside from sequences that were inferred to contain varves, they were little studied (e.g. Anderson and Koopmans, 1963; Schwarzacher, 1964).

In many early investigations, pattern recognition was centred on the analysis of the observed sequences of lithologies. This made sedimentological sense as the predictions of qualitative models could be compared with the observations. Of course no reasonably long stratigraphic section actually corresponded exactly to the pattern predicted by the models. Unfortunately, since it was easy to imagine situations where the expected or 'ideal cycle' (Pearn, 1964) was not encoded in the sedimentary rocks, it proved impossible to falsify the models. Duff and Walton (1962) argued that sedimentary cycles can be recognized as having a particular order of lithologies that frequently occur in a particular sequence. They called the most frequently occurring sequence a modal cycle. However, their definition of cyclicity was criticized as being so vague that it could include sequences that are indistinguishable from the result of random fluctuations – which would also exhibit modal cycles (Schwarzacher, 1975).

Markov chain analysis was used to test sequences for the presence of a **Markov property** or the dependence of successive observations (lithologies or numbers) on previous observations. This captured some of the concept of a ‘pattern’ in a cyclic sequence since it implied a certain preferred order to the observed lithologies. However, stratigraphic data as structured for Markov analysis apparently always have preferred lithological transitions, and thus never correspond to a truly independent random sequence (Schwarzacher, 1975). This is because environmental systems include a degree of ‘inertia’. Even instantaneous changes in the ‘boundary conditions’ (e.g. sea level, rainfall, etc.) do not cause instantaneous changes in the environment. For example, it can be as much as a few years before the release, over a few weeks or months, of a large volume of sulphate aerosols into the atmosphere by a volcanic eruption causes a drop in global atmospheric temperatures (Stuiver *et al.*, 1995). Therefore, the ubiquitous detection of a Markov property in cyclic sections merely indicated that there is a degree of ‘smoothness’ in the transitions between successive observations. Since virtually all physical systems exhibit inertia, the detection of a Markov property proved to be of little use for characterizing sedimentary cyclicity. Nevertheless, Markov analysis is useful when, for example, the particular order of lithologies helps in the description of sedimentological processes (e.g. Wilkinson *et al.*, 1997).

Schwarzacher’s (1975) book represented a landmark in the examination of sedimentary cyclicity. Instead of just examining the transitions between lithologies at bed boundaries in Markov chain analysis, he reasoned that the thickness of successive beds provided information of fundamental importance in the assessment of sedimentary cycles. This meant that the stratigraphic data should be collected as **time series**. Time series include any sequence of measurements or observations collected in a particular order. Usually the measurements are made at constant intervals of some scale of measurement such as cumulative rock thickness, geographic distance, time, growth band number, etc. Some authors have referred to data collected relative to a depth or thickness scale as ‘depth series’, but time series is actually the correct mathematical term for historical reasons (Schwarzacher, 1975; Priestley, 1981; Schwarzacher, 1993). The variable that is recorded need not be restricted to lithology of course, and this significantly widens the scope of potential investigations of sedimentary cyclicity. The quantitative techniques used for the study of such data are described as methods of **time-series analysis**.

Schwarzacher argued that to be meaningful the term ‘sedimentary cycles’ must refer to oscillations having perfectly or nearly perfectly constant **wavelength**. Only if the wavelength can be measured in time does one refer to the cycle’s **period**. However, whether a time or thickness scale is being used, oscillations of constant wavelength are described by mathematicians as **periodic**, and those of nearly constant wavelength as **quasi-periodic**. Periodic or quasi-periodic cyclostratigraphic sections have repetitions of a particular observation (such as a particular rock type) at essentially constant stratigraphic intervals. To many mathematicians stratigraphic sections that do not