

Sedimentary cycles and stratigraphy

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ABSTRACT: Sedimentary cycles are repeated sequences in a stratigraphic section. This paper uses "stratigraphic cycles" to describe observed sequences of sediments in sections and "process cycle" to describe processes that generated the cycles. Repetition of cycles is never completely identical and statistical methods of time series analysis are used to describe cyclicity. The study of process cycles requires the knowledge of a time scale and therefore relies heavily on the interpretation of the sedimentary record.

INTRODUCTION

Sedimentary cycles are traditionally defined as short sequences that are regularly repeated (Duff et al. 1967). Consider a section that contains only three lithologies, for example A, B, and C; then ABC is a cycle if it is followed by A. Indeed, any recurrence of A will define a cycle. However, the important feature of cyclic sections is that similar cycles are repeated. Thus the sequence ABCA is a cycle but it becomes more interesting if it is repeated in a section as: ABCABCABCA ... The regularity of repetition suggests a special mechanism that produced such sections. It is obvious that a precise repetition of sequences cannot be expected and the questions arise as to how much latitude of variation should be allowed and how often a cycle has to be repeated before the section can be described as cyclic. Cycles therefore are not precisely defined and without a more detailed description of the repetition pattern the cycle concept remains ambiguous.

The word "cycle" refers not only to repeated sequences of rocks, but also to the processes that generated it. In the following, cycles that are directly derived from the section will be called the "stratigraphic cycles" and the processes of cycle formation will be called the (environmental) "process cycle". The stratigraphic cycle is determined by the order of the different sediments and their positions, which are typically given in units of length, usually as distances from the base of a section. The environmental process cycle consists of a sequence of events within some time scale.

STRATIGRAPHIC CYCLES

The record of stratigraphic sections contains two basic elements, an observation (that may be a rock type, a fossil content, or any other property of the sediment), and its position. The position is either given as a measured distance from a fixed point in a section, or given relatively in sequential order. However, it is doubtful whether sequential observations without any scale, are useful. Some scale must be at least implied by the specification of the data, for example, rock types or units like beds.

Stratigraphic data consist of observations that are sequentially ordered and therefore can be treated as a time series. The methods of time-series analysis are particularly well suited to clarifying stratigraphic cyclicity, as they can deal with data that either resulted from random processes (stochastic processes) or

at least, have been randomly disturbed. To visualize such a stochastic model of stratigraphic sections, one assumes that each consecutive observation is associated with a probability. The probability determines the event of a particular observation being made and the stratigraphic data are therefore the realization of the process. The word event is invariably used for the realization of a random process in probability theory and in statistics. The events in event stratification of Seilacher (1982), refer to episodic or rare events in what the authors call "cyclic" sections and there is therefore no conflict of terminology.

The stochastic model gives a very realistic representation of stratigraphic sections and their fluctuations and cycles that are not rigidly repeated, can be described. Using such models one can show that there are four different patterns of repetition in sedimentary sections (Schwarzacher 1969).

A) Sediment changes that are completely at random and distributed as one would expect in data that have been perfectly shuffled and it is therefore impossible to predict any successive step.

B) Successive steps are not independent and a limited prediction is possible. However, predictability decreases exponentially. No distinct groups of steps are obvious.

C) Repetitions come in groups but the groups may not be all identical and precisely repeated.

D) Repetitions are in perfect order and correspond to the mathematical definition of periodicity.

Clearly, cases C and D correspond to the concept of sedimentary cycles. Because the definition of cycles relies very much on the position of the observation, any method to describe them must involve the correlation structure of the series. Analyses based on simple statistics like average cycle thickness or standard deviations, are not sufficient. The method most commonly used is power spectral analysis (e.g. Weedon 2003). In this analysis one calculates the variance that each frequency of the oscillations contributes to the series.

The four types of repetition give the following spectra.

A) Independent random sequences produce a flat spectrum that is constant over the whole frequency range. Such spectra are known as white noise spectra.

B) Correlated random processes produce relatively smooth spectra and frequently rise towards the lower frequencies, indicating so-called red noise.

C) Sections containing one or more preferred frequencies, have distinct maxima at such frequencies.

D) Periodic sequences have sharp, spike-shaped maxima at the precise frequencies of the period.

The two extremes of A and D, randomness and perfect order, are never found in actual stratigraphic sections. Complete randomness would imply that there is no correlation between successive steps, but since changing environments control the sedimentation, transitions follow a logical pattern that generates specific sediment associations. Perfect cyclicity on the other hand, is just as unlikely as complete randomness, and there are many reasons why perfectly predictable sections never occur. Repetition type D clearly corresponds accurately to the definition of sedimentary cycles as given in the introduction but as indicated, D is not a realistic model.

Sequences with repetition patterns B and C, are frequently observed in stratigraphic sections. If one allows for the repeated groups not being completely identical, then spectra of type C can be objectively identified as cyclic.

ENVIRONMENTAL PROCESS CYCLES

The environment is a dynamic system that develops in both space and time. Process cycles describe the formation of sediments, resulting from movements and forces in this environment. To understand the formation of cycles one needs the dimension of time.

Most bedded sediments provide good evidence for regular repetitions and the analysis of such sections indicate one or more frequency maxima of recurring lithologies. However, if the stratigraphic position of the observed lithology is replaced by the actual time of its formation very different results could be obtained. The repetition pattern of the time history can again range from completely random to near periodic cyclicity. For example the time history of successive turbidites may be quite unpredictable but the history of varve formation approaches mathematical periodicity. The two processes are quite different and they can only be distinguished if the time history is known.

Systems that produce regularly but not necessarily periodically recurring states, are known as oscillating. Oscillations produce spectra with distinct frequency maxima and they are therefore equivalent to the geological definition of cycles.

Most real systems incorporate friction and persistent cycles can only be maintained by adding energy. If the energy supply remains in phase with the cycles, the system is self-oscillating (self cycling) and it can produce periodic and quasi-periodic cycles from a constant source of energy. The latter are cycles, the frequency of which is constant over considerable intervals of time. Practical examples of self-oscillating systems in daily life are clocks, steam engines or internal combustion engines. Self-oscillating systems are potentially unstable, and some instability can lead to chaotic behavior. Self-oscillating, as used in the theory of oscillators, should not be confused with "autocyclicity", which will be discussed later.

The sedimentary environment is a very complex system, in which different components such as climate, tectonism and de-

velopments in the biosphere, can give rise to many interactions and feedback processes that are potential oscillators. Therefore, there are many possible systems that could lead to cyclic sedimentation with periods representing hours to millions of years. However, apart from celestial mechanics, we know relatively little about systems that can generate oscillations with periods of thousands to millions of years. This is because the time spans involved are considerably longer than any available records of direct observation. Therefore, any explanation of such cycles must be based on hypotheses and theories. Climatologists have formulated theories that were originally developed to explain the repeated occurrence of ice ages involving oscillations caused by feedback between general temperature, land ice masses, and the albedo of the earth. Similar slow oscillations can also arise from the interaction of sea-ice cover and heat loss of the oceans.

Some cycles may result directly from sedimentation processes. Ginsburg (1971) suggested that an advancing tidal flat could cover the area of sediment production and that sedimentation would cease, until further subsidence takes place. Burgess and Wright (2003) considered a model in which a series of islands or shoals regulated the sediment flux, leading to a sequence that recorded alternating shallow and deeper water sedimentation. Ginsburg's model was never elaborated and does not explain oscillating behaviour. In theory, the Burgess and Wright model is capable of oscillation, but the authors assumed that it is driven by random sediment supply and it is consequently, not a self-oscillating system.

A large number of environmental cycles are connected with the daily, monthly, annual, or considerably slower orbital variations of the earth that are determined by celestial mechanics. The theory of such astronomic cycles is relatively well known and their frequencies are relatively constant. Most astronomical cycles are quasi-periodic, meaning that their frequencies are constant over considerable intervals of time, and they are therefore well-suited as stratigraphic time markers. Environmental processes are often more easily understood, if they are thought of as consisting of several subsystems that are causally related to each other. Different subsystems may be responsible for different properties of the environment, or they may interact to produce a specific cycle. For example, solar radiation may be an important component of an environment, but this reacts with the atmosphere and hydrosphere to determine the climate, which in turn, has an effect on some biological activity that could be responsible for cyclic sedimentation. Because different systems interfere with each other, and because random elements can be introduced at various stages, many environmental cycles will have the nature of random (stochastic) processes. The resulting power spectra could be quite complex and a wide variety of frequencies can be generated in this way.

THE DOMAIN OF PROCESS CYCLES AND AUTOCYCLOCITY

The physical boundaries of an environment depend very much on how it is defined by the geologist. It can be a sedimentary basin, or some part of it like a tidal flat, or a carbonate platform. The physical area of a cycle generating system, defines its domain (Schwarzacher 2000). Domains can be quite limited or they can be world-wide; they can even, as in the case of astronomical cycles, include the solar system. Knowing the scale of the domain would clearly help to identify the mechanism of cycle formation. Unfortunately, the distribution of stratigraphic cycles that can be correlated, does not necessarily coincide with

the limits of domains. Domains, like the limits of environments that provide the evidence of a studied cycle, are often ill defined and arbitrary. In many cases, the domain can be identified, only if the origin of the cycles is also known.

A cycle is called an induced cycle if its domain is larger than the extent of a cycle-producing environment (for example a particular basin). A cycle is called an autonomous cycle if its domain is contained within the environment limits (Brinkman 1932). Beerbower (1961) developed a very similar classification and called the autonomous cycles “autocycles” and the induced cycles “allocycles”. Beerbower’s terminology is more commonly used, although it postdates Brinkman’s terminology. Clearly, unless the domain and the extent of environments are specified or known, the terms autocycle and allocycle should not be applied.

The word autocycle seems to suggest that such cycles are self-generated. However, autocyclicality or allocyclicality do not generate cycles. It is the oscillating systems that have to be understood to explain the origin of cycles. A cycle’s origin is not explained, as has been frequently done, by simply calling it autocyclic.

THE SPACE-TIME RELATIONSHIP

Connecting the process cycle to the grouping of rock types, involves the difficult and often unknown relationship between stratigraphic position and time. The interpretation of sediments, in terms of physical processes therefore, is largely determined by how well, accumulated sediments can be translated into time. This depends mainly on three properties: resolution, completeness, and continuity of sedimentation. The resolution of a sediment section is the shortest time between two recognizable events. The completeness is the degree with which the stratigraphic record is filled by such events and the continuity is determined by the consistency with which events of a given resolution occur.

Every sedimentary sequence contains intervals that, at a given scale, can be regarded as being instantaneous and such intervals have at this scale, no time or stratigraphic significance. Rare event deposits of Seilacher (1982) are typical examples of such intervals, as they can only be used as instant time markers and cannot measure time at the scale they recorded. Clearly, rarity depends on the length of time under consideration. Conversely, intervals of non-deposition (hiatuses) do not contribute recognizable time. Only intervals that are long enough to have a meaningful average rate of sedimentation provide stratigraphic divisions that can be used for stratigraphic dating and correlation.

The time-space relationship plays a very important role in connecting stratigraphic cyclicity with process cyclicity. If accumulation rates were constant throughout a section, then cycles of equal thickness would represent equal time intervals. However, we know that sedimentation is frequently interrupted and rarely remains constant. Unequal thickness cycles therefore, do not necessarily indicate unequal time cycles, but equal thickness cycles are very probably the result of equal time cycles. This rule was first given by Sander (1936) and it implies that time cyclicity can be deduced from the stratigraphic section but non-cyclicity of time cannot be proved from the sedimentary record.

All arguments concerning cyclicity have to be combined with detailed sedimentological examinations and two basic questions have to be decided. Are lithological boundaries primary sediment surfaces? Has sedimentation been steady and continuous?

CYCLOSTRATIGRAPHY

The second report of the Cyclostratigraphy Working Group recommended that the term “sedimentary cycle” be restricted to repetitive changes in the stratigraphic record that have, or are inferred to have, time significance (Hilgen et al, 2003). It would indeed be peculiar if cycles used in stratigraphy were not time related. In practice, only astronomical cycles with periods from days to millions of years, millions of years, are used in cyclostratigraphy.

The study of cyclic sedimentation has led to the development of an astronomical time-scale that extends from the present to the Miocene (Gradstein et al. 2004). It is based on the calculated changes of solar radiation due to variations in the earth’s orbit. Orbital cycles have been recognized as far back as the Cambrian, but time scales derived from such cycles are not tied to the present. As floating time scales, they can only be used for relative dating or for stratigraphic correlation. The challenge is to recognize sedimentary sections that can be used to expand and refine the astronomical time scale.

For orbital cycles to be recorded and to be recognized, a number of conditions are necessary. To interpret time as accumulated sediment thickness, it is important that the continuity of sedimentation is commensurate with the scale of the cycles. Obviously, the sediment must be capable of recording the cyclic variables of the environment through one or more of its properties, bio-content, or composition. Needless to say, the sedimentation has to be sensitive to the astronomic variation that will be responsible for variable solar radiation. Support for the assumption that observed cycles are indeed of astronomic origin, can be obtained by at least approximate radio-isotopic dating and by observing the expected ratios of frequencies.

CONCLUSIONS AND SUMMARY

The definition of sedimentary cycles as representing repeated groups like A,B,C,A,B,C... leads to a problem. Repetitions of stratigraphic events are never exact and some variability has to be allowed for. However, if variation of cycles is considered possible, then every sedimentary sequence could ultimately be regarded as cyclic and the term loses its meaning. The change from complete randomness to perfect order of periodicity is continuous and without any natural boundaries. Spectral analysis can indicate maxima in the recurrence pattern, but it is the investigator who has to decide their significance.

A better understanding of cycles is gained by considering the processes that produce cycles. Repetition of similar sediments can either be due to unpredictable random events, or due to events that are correlated in time. The latter is the case for most natural processes. A repetition of process cycles is generated by feedback of interacting events at different moments of time, in the development of the process. Recurring states in dynamic systems due to feedback are known as oscillations. “Repetitions created by oscillating systems”, could well serve as a definition of sedimentary cycles, as it covers what most geologists mean by the term cycle, even if they do not express it explicitly. Obviously, in order to recognize oscillations or cycles and to differentiate them from random fluctuations, the time history of the cycle formation has to be known. Therefore, recognizing

cyclicity always depends on geological and sedimentological judgement, and cannot be deduced exclusively from quantitative analysis.

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