# TIME AND STRATIGRAPHIC CORRELATION

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**Introduction**

It is impossible to discuss time in geology without making reference to the law of superposition. The fact that sediments consist of layers which are piled on top of each other, forms the basis of all stratigraphy. If a sediment body (lithosome) is considered as a three dimensional object with the co-ordinates $x$, $y$, and $z$, then the famous law by Hutton permits a translation of the co-ordinate $z$ into a time co-ordinate $t$. If this translation is possible, most of the problems of stratigraphy can be solved. The basis of the superposition law is the sedimentation process, which may be represented by a simple random walk model. Sedimentation increases in irregular steps (for example the arrival of particles) and at irregular time intervals. The cumulative thickness of the sediment therefore performs a random walk in space and time. The expected endpoint of this process will tend towards a normal distribution which is quite independent of the distributions of the step sizes and time intervals (central limit theorem). The cumulative thickness curve, where the thickness $h$ depends on the number of steps or time, will be a more or less straight line as long as a sedimentation process continues unchanged. This will be illustrated by a number of examples.

**Geological time**

The random walk model permits the expression of $z$ as a function of $t$ to which a random variable $e$ is added

$$z = f(t) + e.$$

For the construction of geological time scales, it is clearly important to evaluate this equation in units of actual time. For this, we have several possibilities. On a rough scale, one can use radiometric time scales to arrive at an average sedimentation rate and estimate the time intervals. In such cases, there is always a likelihood that the sequence contains erosional intervals which are not recorded in the stratigraphic column. This incompleteness leads to different sedimentation rates being derived from sections of different lengths (Sadler 1981; Tipper 1983). The completeness is the degree to which a stratigraphic record is filled with recognisable events (Schwarzacher 1998). The shortest time interval between events is called resolution and both properties are measured in time units, whereby completeness is the percentage of time units which can be recognised in a given length of section.

**Sedimentary cycles**

Sedimentary cycles sometimes provide a method of evaluating the relationship between thickness and time in greater detail. For a cyclostratigraphic method to be successful, the cause and duration of a sedimentary cycle has to be known. This leads to a dilemma because sedimentary cycles can only be identified if it is possible to show that they represent equal or nearly equal time intervals, but this in turn can only be done by searching for equal thickness intervals in the section. Since we know that any recording of time events by sedimentation involves some errors, spatial non-periodicity in the sediment can either represent deviations from the periodicity of the cycle generating process, or variations in the sedimentation rates. The difficulty can be overcome if the cause of the cyclicity can be identified, for example, if it can be demonstrated from the spectrum of the cycles that one is dealing with Milankovitch type cycles.

**Milankovitch cycles**

It is not possible to give a definite recipe for recognising Milankovitch cycles, but the following procedure is fairly standard. Initially, one assumes a constant sedimentation rate which is estimated either from bio- or magnetostratigraphic data. Based on this, one can examine the spectral composition of the record and tune the section in such a way that the most prominent cycle is represented by a constant thickness. Alternatively, one can tune the section directly to some actual Milankovitch determined target curve. Milankovitch cycles are of particular importance in the establishment of absolute time scales, which are obtained by correlating stratigraphic data to calculated orbital variations, or to their climatic effects within definite time intervals. Absolute time is obtained by establishing a completely continuous series which runs from the present to the past. Such calculations are limited by the chaotic elements within the solar system and it is impossible to extend the calculation beyond 35 MA to 50 MA (Laskar 1999). Within the more recent past, it is possible to bridge gaps in a continuous series by making use of the low frequency variations of orbital changes. These give the astronomical target curve a characteristic shape which can be used for matching the stratigraphic data. In this way, a Mediterranean chronology reaching the Miocene was established (Hilgen et al. 1997) and an approximate chronology was established which extends back to the Oligocene (Shackleton et al. 1999). Although chaos in the solar system limits the accurate calculations of past orbital elements, there is good evidence that Milankovitch cycles have been effective at least back to the Pre Cambrian. Cycles in the range of 10 ka to 2000 ka therefore provide an extremely important framework for many stratigraphical and general geological problems. Shorter cycles such as varves and cycles in solar activity with periods of 1 year to several hundred years, are particularly important in the study of the most recent past.

**Stratigraphic correlation**

No basin analysis can proceed without correlating individually established sections, or to put it differently, without finding in the originally mentioned three dimensional sediment, the appropriate time planes which connect events of identical age. Stratigraphic correlation is defined as the process of finding time equivalent stratigraphic units in different localities. In quantitative approaches, the accuracy of stratigraphic correlation can be measured by the time range within which synchronism can be established. Correlation in stratigraphy and its measurement is not the same as correlation in statistics which describes the similarity (relation) between two variables. The difference is easily seen when statistical correlation is applied to a strictly cyclic section. Because of the periodic nature of the section, there will be many positions of high correlation but there is only one valid stratigraphic correlation. To avoid confusion, it is useful to speak of matching procedures rather than correlation, when numerical methods for comparing different sections are used. The step from matching to stratigraphic correlation can be difficult. The problem is relatively simple when one is dealing with a series containing unique or at least rare events, for example, the first appearance of a taxa in biostratigraphy or the positions of magnetic reversals. The biostratigraphic aspects of quantitative correlation have been treated in detail by Agterberg (1990) and the accuracy of such correlations ultimately depends on how extensively a stratigraphic section is sampled. A difficulty which is common to any correlation problem, is that most recorded events studied in stratigraphy have not only a position in the time component but also in space; even the effect of a meteorite impact takes time to spread and will migrate. In basin analysis, it is frequently the migration of environmental conditions leading to facies migration, which is the main interest. When biostratigraphic events are absent or too widely spaced for a detailed correlation, matching procedures can be used to compare lithological and other physical properties, task that can be accomplished manually or with the assistance of computers. In general, results from biostratigraphic correlation and lithostratigraphic correlation are different as lateral variations in physical properties do not necessarily follow taxonomic changes.

**Automated correlation**

There are almost as many computer correlation methods as individuals publishing on the subject. The search for correlations operates on pairs of sequences of measurements (logs), $\lambda$, typically along vertical cores or wells. For easy reference, the well to the left of a display can be termed "reference well" and the one to the right, "matching well." We used the program "Correlator" for our work (Olea 1994), which uses a pair of logs per well generically called shale log and correlation log. Given any depth $z_i$ in the reference well, "Correlator" automatically selects as the correlating elevation the level $z_{k_{best}}$ in the matching well that maximizes the weighted correlation coefficient. If the logs are sampled at regular intervals, the weighted correlation coefficient $\omega_{1,2,3,4}(i,k;n)$ is defined as the product of the normalized shale similarity coefficient $\alpha_{1,3}(i,k;n)$ for the shale logs and the Pearsonian correlation coefficient $r_{2,4}(i,k;n)$ for the correlation logs:

$$\omega_{1,2,3,4}(i,k;n) = \alpha_{1,3}(i,k;n) r_{2,4}(i,k;n)$$

$$\alpha_{1,3}(i,k;n) = 1 - \frac{1}{2n+1} \sum_{j=1-n}^{i+n} \left| \frac{\lambda_1(j) - \lambda_{\min 1}}{\lambda_{\max 1} - \lambda_{\min 1}} - \frac{\lambda_3(j+k) - \lambda_{\min 3}}{\lambda_{\max 3} - \lambda_{\min 3}} \right|$$

$$r_{2,4}(i,k;n) = \frac{\mathrm{cov}_{2,4}(i,k;n)}{s_2(i;n)\, s_4(k;n)}$$

The normalized shale similarity, the covariance $cov_{2,4}(i,k;n)$, and the standard deviations $s_2(i;n)$ and $s_4(k;n)$, are calculated over correlation intervals of $2n+1$ readings each. The correlation coefficient is sensitive to the matching of the signatures of the correlation logs and the other coefficient is sensitive to the discrepancy in the relative proportions of shale as given by the shale logs. The maximization of the weighted correlation coefficient comprises an additional parameter, the interval $k_{min} \leq k \leq k_{max}$ of search for the best match. The automatic maximization of the weighted correlation coefficient always yields one largest value $\omega_{1,2,3,4_{max}}(i,k_{best};n)$ for every elevation $z_i$ in the reference well. However, not all correlations are saved. In a first step, the system discards all weak correlations below a threshold. In a final stage an expert system checks for global consistency and interactively suggests to the user the discarding of crossing or inconsistent correlations. By combining the correlations obtained from several pairs of wells, "Correlator" is capable to display cross-sections showing top and bottoms of lithostratigraphic units, correlations present in all wells for the same lithostratigraphic level, and cross-sections showing the spatial variation in the amount of shale. By solving the three-point problem—determining the dip and azimuth of every plane defined by lithostratigraphically equivalent points in three wells located in the vertices of a triangle, preferably close to equilateral—the program is also able to generate dips representing the regional inclination of the strata. Such dip plots are extremely useful for detecting faults and unconformities and summarizing the geological evolution of any portion of a basin through geologic time.

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