3 • Biostratigraphy: time scales from graphic and quantitative methods

F. M. GRADSTEIN, R. A. COOPER, AND P. M. SADLER

Semi-quantitative and quantitative biostratigraphy methods are assisting with scaling of stages, as exemplified in the Ordovician–Silurian and Carboniferous–Permian segments of GTS2004. This chapter focuses on some theory and practical considerations.

3.1 INTRODUCTION

The larger part of the Phanerozoic time scale in this book relies on a construction where stages are first scaled "geologically" with biostratigraphic compositing techniques, and than stretched in linear time using key radiometric dates. The advent of versatile and "clever" semi-quantitative and quantitative biostratigraphy methods is assisting with this geological scaling. The methods also add a new dimension to the construction of local or standard biochronologies, and its time scale derivatives.

In particular, three methods, each with their own PC-based programs, merit attention when it comes to scaling biostratigraphic data for standard or regional time scales:

- graphic correlation,
- constrained optimization
- ranking and scaling.

Each of these three methods aims at a particular segment of time scale building and its application, using complex and/or large microfossil data files. Constrained optimization is directly utilized in building the early Paleozoic segment of GTS2004, and graphic correlation plays a key role in building the biostratigraphic composite for the late Paleozoic. Ranking and scaling has been used in construction of local biochronologies. In this chapter more general examples will be given of the approaches; a summary of the numerical and graphic methods is presented in Table 3.1.

A Geologic Time Scale 2004, eds. Felix M. Gradstein, James G. Ogg, and Alan G. Smith. Published by Cambridge University Press.

3.2 GRAPHIC CORRELATION

Rates of sediment accumulation have been used to derive time scales. The simplest methods average fossil zone thickness in several sections and assume that thickness is directly proportional to duration (e.g. Carter *et al.*, 1980). However, because zone boundaries are defined by the stratigraphic ranges of one, or a few species, only a very small subset of the total biostratigraphic information is used in the exercise. Worse is that sedimentation rarely is constant (linear) through time, making the assumption tenuous.

Graphic correlation (Shaw, 1964; Edwards, 1984; Mann and Lane, 1995; Gradstein, 1996; see also Table 3.1) is a method that makes better use of the biostratigraphic information in sections, and is thus used for time scale construction. Graphic correlation proceeds by the pair-wise correlation of all sections to build up a composite stratigraphic section. With each successive round of correlation, biostratigraphic range-end events missing from the composite are interpolated into it via a "line of correlation" (LOC). At the same time, the stratigraphic ranges of taxa are extended to accommodate the highest range-tops and lowest range-bases recorded in any of the sections used in the analysis. This procedure is based on the assumption that, because of incomplete sampling, non-preservation, unsuitable facies, and other reasons, local sections will underestimate the true stratigraphic range of species. Isotopic dates, and other physical events can also be interpolated (Prell *et al.*, 1986). The composite section thus becomes a hypothetical section that contains all stratigraphic correlation events, and in which local taxon ranges are extended to approximate their true range in time, as recorded among all the sections.

When the composite section is based on a relatively large number of individual stratigraphic sections, it has been regarded as a good approximation of a relative time scale itself (Sweet, 1984, 1988, 1995; Kleffner, 1989; Fordham, 1992). These workers have used conodont-bearing carbonate sections to build graphic correlation time scales for the Ordovician and Silurian. It is assumed that variations in sediment accumulation rate are evened out in the composite, during the process of

Table 3.1 *Summary of graphic and numerical methods in biostratigraphy, used to assist with construction of geologic time scales*

Graphic correlation	Constrained optimization	Ranking and scaling
Programs GRAPHCOR, STRATCOR	Program CONOP	Programs RASC and CASC
Deterministic method – graphic correlation in bivariate plots. Program STRATCOR can also simulate probabilistic solutions	Mostly a deterministic method, but can also simulate probabilistic solutions. Constrained optimization with simulated annealing and penalty score.	Probabilistic method – ranking, scaling normality testing, and most likely correlation of events; error analysis
Uses event order and thickness spacing; works best with data sets having both first and last occurrences of taxa	Uses event order, event cross-over, and thickness spacing; data sets best have both first and last occurrences of taxa	Uses event order, and scores of cross-over from well to well for all event pairs in the ranked optimum sequence
Best suited for small data sets; can also operate on larger data sets	Processes medium to large data sets	Processes large data sets fast; has data input and multi-well data bookkeeper
An initial standard section is selected, after which section after section is composited in the relative standard to arrive at a final standard composite	Treats all sections and events simultaneously (operates a bit like multidimensional graphic correlation)	Treats all sections and events simultaneously
Line of correlation (LOC) fitting in section-by-section plots; technique can be partially automated	Multidimensional LOC; automated fitting; can generate several different composites depending on run options	Automated execution; generates several scaled optimum sequences per data set depending on run parameters, and tests to omit "bad" sections or "bad" events
Attempts to find maximum stratigraphic range of taxa among the sections	Attempts to find maximum or most common stratigraphic ranges of taxa	Finds average stratigraphic position of first and/or last occurrence events
Builds a composite of events by interpolation of missing events in successive section-by-section plots, via the LOC	Uses simulated annealing to find either the "best" or a good multidimensional LOC and composite sequence of events	Uses scores of event order relationships to find their most likely order, which represents the stratigraphic order found on average among the sections
Relative spacing of events is a composite of original event spacing in meters in the sections	Relative spacing of events in the composite is derived from original event spacing in meters or sample levels	Relative spacing of events in the scaled optimum sequence derives from *z*-transformation of cross-over frequencies
No automatic correlation of sections; composite standard can be converted in time scale	***Correlates sections automatically; zonal composite can be converted to time scale***	***Optimum sequence can be scaled to linear time; automated correlation of sections using isochrones***
No error analysis; sensitive to geological reworking and other "stratigraphic noise," and sensitive to order in which sections are composited during analysis	Numerous numerical tests and graphical analysis of stratigraphic results; finds best break points for assemblage zones	Three tests of stratigraphic normality of sections and events; calculates standard deviation of each event as a function of its stratigraphic scatter in wells
Interactive operation under DOS; graphic displays of scattergrams and best-fit lines	Batch operation under Windows®; color graphics display shows progress of run	Button operated under Windows®, fast batch runs; color graphics of output and options for interactive graphics editing

LOC fitting and extension of stratigraphic ranges. The composite units by which the composite section is scaled are assumed to be of approximately equal duration (Sweet, 1988), and therefore are time units of unspecified duration ("standard time units"). Finally, the relative scale can be calibrated with radioisotopic dates that are tied to the biostratigraphic scale. The assumptions, and some of the problems with this method, are summarized by Smith (1993).

In a variation on the method, Cooper (1992) used graphic correlation of long-ranging, deep-water, Ordovician graptolite-bearing shale sections to test for uniformity (steadiness) of depositional rate. A regional composite for Scandinavia was plotted against a composite for Newfoundland and gave a reasonable approximation to a rectilinear fit. The same two sections were then plotted against an exceptionally long-ranging section for western Canada, with the same result, and were taken to indicate that sediment accumulation rates in the three regions were approximately constant with time. The thickness scale for the Scandinavian composite (the most fossiliferous one) was then taken as a reasonable proxy for a relative time scale. This scale was then adjusted as necessary to fit the relatively sparse isotopic dates (Cooper, 1992) to give a calibration of Early Ordovician graptolite zones and stages.

For GTS2004, graphic correlation was applied for the Carboniferous and Permian time scale segment (Section 15.3.3), involving about 40 Carboniferous and 20 Permian sections, using all available fossil groups.

3.3 CONSTRAINED OPTIMIZATION

A major disadvantage of the graphic correlation method is the limited number of sections and taxa that can be used in the analysis, for practical reasons. Another disadvantage is the requirement for one of the sections to be adopted as the starting "standard section," the stratigraphic thickness measurements of which become the composite units in the composite section. Third, assumptions about relative accumulation rates may bias the sequence of events in the composite. These problems are avoided by automating correlation procedure as a constrained optimization (CONOP software, Kemple *et al.*, 1995; Sadler, 1999).

Like graphic correlation, several of the options in CONOP seek the maximum stratigraphic ranges of taxa as represented in the sections and build a composite (Sadler and Cooper, 2004). Unlike graphic correlation, the method readily enables a large number of sections and species to be used and processes all taxa and all sections simultaneously. Thus, it resembles a multidimensional graphical correlation in the sense that it considers all the local stratigraphic sections. It differs, however, in treating all sections simultaneously. A closer analogy exists between CONOP and algorithms that search for the most parsimonious cladogram.

Over 230 measured stratigraphic sections in graptolite-bearing deep-water shales from around the world and containing 1400 species were compiled in a data set. The Ordovician part alone includes 119 sections, containing 669 taxa with ranges wholly or partly in the Ordovician. The total data set was used to derive a global composite section for the Ordovician and Silurian (discussed in more detail in Chapter 12). Since graptolite specimens are rarely, if ever, found reworked, such "stratigraphic noise" is readily avoided.

The impressive graptolite composite was built in two steps. In the first step, the order of events was established by minimizing misfit between the composite and each of the individual sections in turn. The method operates heuristically, searching and discovering, in what can be a very large number of operations, which composite is best. Misfit was gauged by the net distance that range-ends had to be extended among all sections, as measured by the number of correlative biostratigraphic event levels, rather than stratigraphic thickness (as in graphic correlation). The composite is only an ordinal sequence of events. The spacing is undetermined and, unlike graphic correlation, assumptions about accumulation rate do not influence the sequence.

In the second step, the spacing of every pair of adjacent events in the composite was determined from the average of the rescaled spacing of events in the sections. The observed ranges in the individual sections were first extended to match the composite sequence. The thickness of each section was rescaled according to the number of events that it spanned in the composite sequence. The scaling of the composite is therefore derived from all of the sections, rather than from an initial "standard section" as in graphic correlation, and it is the ratio of the thicknesses between events that is used, not the absolute thickness. The influence of aberrant sections, incomplete preservation, and non-uniform depositional rates is thus minimized. Graptolite zone boundaries and stage boundaries were then located in the composite, producing a relative time scale for the Ordovician and Silurian.

Twenty-two U–Pb zircon dates that were reliably tied to the graptolite sequence and included in the compositing process were plotted against the relative time scale, and the resulting near-rectilinear fit demonstrates the reliability of the method (Fig. 3.1). These dates were then used to calibrate the relative scale, which was adjusted accordingly.

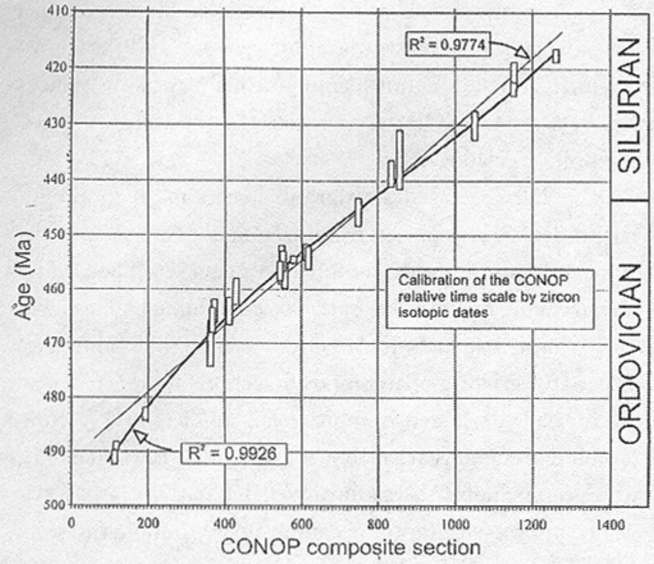

Figure 3.1 Calibration of the CONOP relative time scale in composite units by zircon isotopic dates in the Ordovician and Silurian (Sadler and Cooper, 2003, 2004). The extent to which the best fit is linear is the extent to which the CONOP relative biostratigraphic scale is linear.

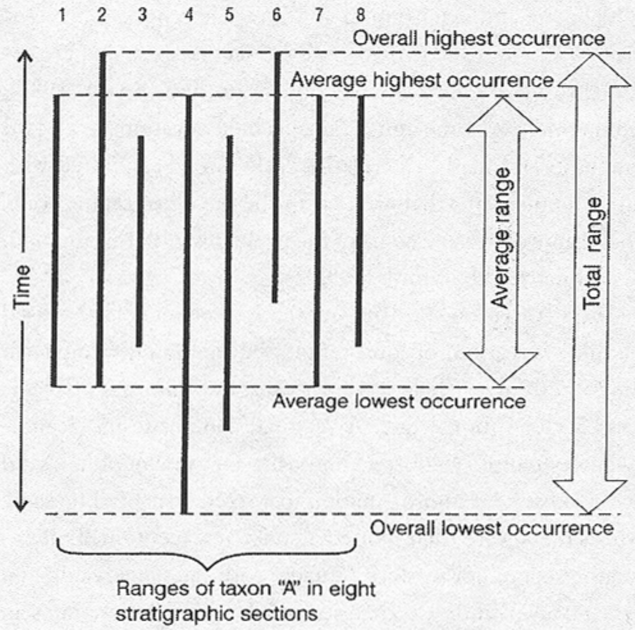

Figure 3.2 Theoretical illustration of the difference between average and maximum ranges of a species (taxon A) in eight stratigraphic sections. Probabilistic methods seek the average stratigraphic range, deterministic methods seek the total range (after Cooper *et al.*, 2001).

The result is a finely calibrated time scale. The method is applicable to any part of the time scale with suitable pelagic fossil groups, and is most suitable where isotopic dates are scarce. It provides a method for estimating the age of biostratigraphic and chronostratigraphic boundaries and events that lie stratigraphically between radiometric calibration points. Its underlying assumptions, methodology, and limitations are outlined by Sadler and Cooper (2004b). These authors demonstrate the method on the Ordovician and Silurian time scale.

In Chapters 12 and 13, the linear scaling of the CONOP graptolite composite is further refined through the use of mathematical and statistical techniques, incorporating error analysis.

3.4 RANKING AND SCALING

Both the graphic correlation and some options in the CONOP methods belong in the category of deterministic stratigraphy methods, and contrast with probabilistic methods. Deterministic methods seek the total or maximum stratigraphic range of taxa, whereas probabilistic methods estimate the most probable or average range (Fig. 3.2), to be accompanied by an estimate of stratigraphic uncertainty. Deterministic methods assume that inconsistencies in the stratigraphic range of a taxon from section to section or well to well are due to missing data. On the other hand, probabilistic methods assume that the inconsistencies are the result of random deviations from a most commonly occurring or average stratigraphic range. Or, to say it in terms of youngest occurrence events of taxa (or "tops" in exploration micropaleontology jargon): deterministic methods assume that there is a true order of events, and that inconsistencies in the relative order of tops from well to well are due to missing data. Probabilistic methods on the other hand consider such inconsistencies to be the result of random deviations from a most likely or optimum sequence of tops.

The most probable order of stratigraphic events in a sedimentary basin, with an estimate of uncertainty in event position, best predicts what order of events to expect in a new well or section. Calculation of the "true" order on the other hand would be most comparable to conventional, subjective results in range charts.

The principal method of probabilistic biostratigraphy, operating completely different from CONOP, is called RASC (Agterberg and Gradstein, 1999; Gradstein *et al.*, 1999). RASC is an acronym for *ra*nking and *sc*aling of biostratigraphic events; its sister method CASC stands for *c*orrelation *a*nd *s*tandard error *c*alculation. Data sets may vary from a few (e.g. 4) to many (25 or many more) wells or outcrop sections, and thousands of records, depending on requirement. For error analysis to have meaning, more wells are better than few.

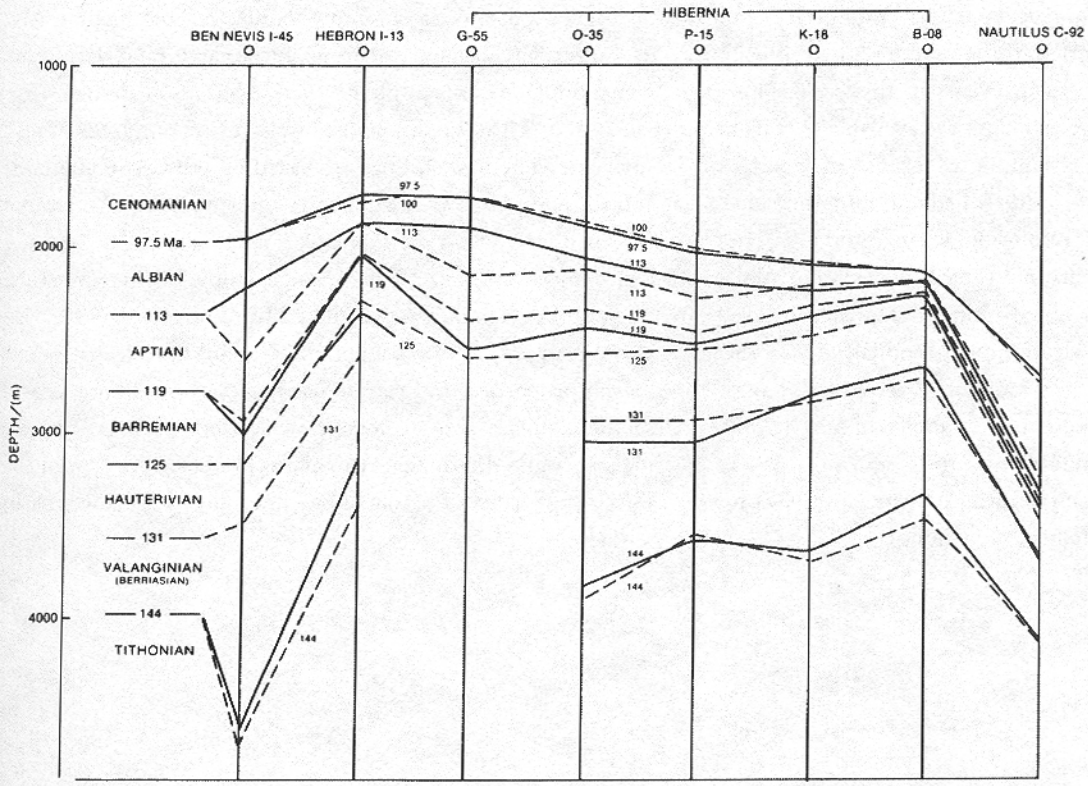

Figure 3.3 By using CASC interpolation, RASC biochronology ischrons can be correlated through the wells, as shown for the subjective (solid line) and most likely (dashed) depths of Cretaceous isochrons in northern Grand Banks wells (after Williamson, 1987). The automation of this process makes the method suitable for subsurface contouring using computer workstations.

Unlike graphic correlation, the RASC method considers the stratigraphic order of all (pairs of) fossil events in all wells simultaneously. It scores all order relationships of all event pairs in a matrix, and, using various modifications of trinomial set theory, calculates the most likely order of events. In this optimum sequence, each event position is an average of all individual positions encountered in the wells. Standard deviations of the event positions in the most likely (optimum) sequence are proportional to the amount of their stratigraphic scatter in all wells or outcrop sections.

Scaling of the optimum sequence in relative time is a function of the frequency with which events in each pair in the optimum sequence cross over their relative positions (observed records) from well to well; the more often two events cross over from well to well, the smaller their inter-fossil distance. Using a statistical model for the frequencies of cross-overs, these estimates are converted to z values of the normal distribution. Final distance estimates are expressed in dendrogram format, where tightness of clustering is a measure of nearness of events along a stratigraphic scale. The scaled version of the optimum sequence features time successive clusters, each of which bundles distinctive events. Individual bundles of events are assigned zonal status. The process of zone assignment in the scaled optimum sequence is subjective, as guided by the stratigraphic experience of the users. Large inter-fossil distances between successive dendrogram clusters agree with zonal boundaries, reflecting breaks in the fossil record due to average grouping of event extinctions. Such extinctions occur for a variety of reasons, and may reflect sequence boundaries. From a practical point of view, it suffices to say that taxa in a zone, on average, top close together in relative time.

The CASC method and program takes the RASC zonation, and calculates the most likely correlation of all events in the zonation over all wells. Interpolated event positions have error bars attached, and are compared to observed event positions in the wells examined. Since 1982, RASC and CASC have has wide stratigraphic application to a variety of microfossils, including dinoflagellate cysts, pollen/spores, diatoms, radiolarians, benthic and planktonic foraminifera, and also physical log markers inserted in zonations. A majority of applications involve well data sets from industry and from scientific ocean drilling. Published literature on the method and its uses is extensive.

Since the RASC optimum sequence has a numerical and linear scale, it may be converted to a time scale. A prerequisite is that, for an appropriate set of events in this scaled optimum sequence, absolute age estimates are available (e.g. from planktonic foraminiferal or nannofossil events in standard zonations). The more events in the scaled optimum sequence, the better the stratigraphic resolution, shrinking the gap between unevenly spaced events in estimated linear time. Next, the conversion of the RASC scaled optimum sequence to a local biochronology enables the stratigrapher familiar with CASC to trace isochrons in the same way as zones are traced. Examples of such exercises are presented in Gradstein *et al.* (1985), in Agterberg and Gradstein (1988) for the Cenozoic, offshore Labrador and Newfoundland, and in Williamson (1987) for the Jurassic–Cretaceous, offshore Newfoundland.

Figure 3.3 shows a close fit of subjective and likely traces of Lower Cretaceous isochrons in some Grand Banks of Newfoundland wells applying the CASC methodology on a most likely RASC zonation in 13 wells, using hundreds of fossil events. The dashed lines are based on the CASC method, and the solid lines are a subjective interpretation. An advantage of the CASC-type interpolation is that it can be used for isochron cross-sections at, for example, 1 myr intervals. Such cross-sections as constructed by Williamson (1987; see also Agterberg, 1990 and Fig. 9.22 therein) have realistic geological properties, and can be used to convert seismic cross-sections quickly into geologic time sections such as Wheeler diagrams, and thus to detect an hiatus in wells. This type of application enhances the role of biochronology in regional basin studies.