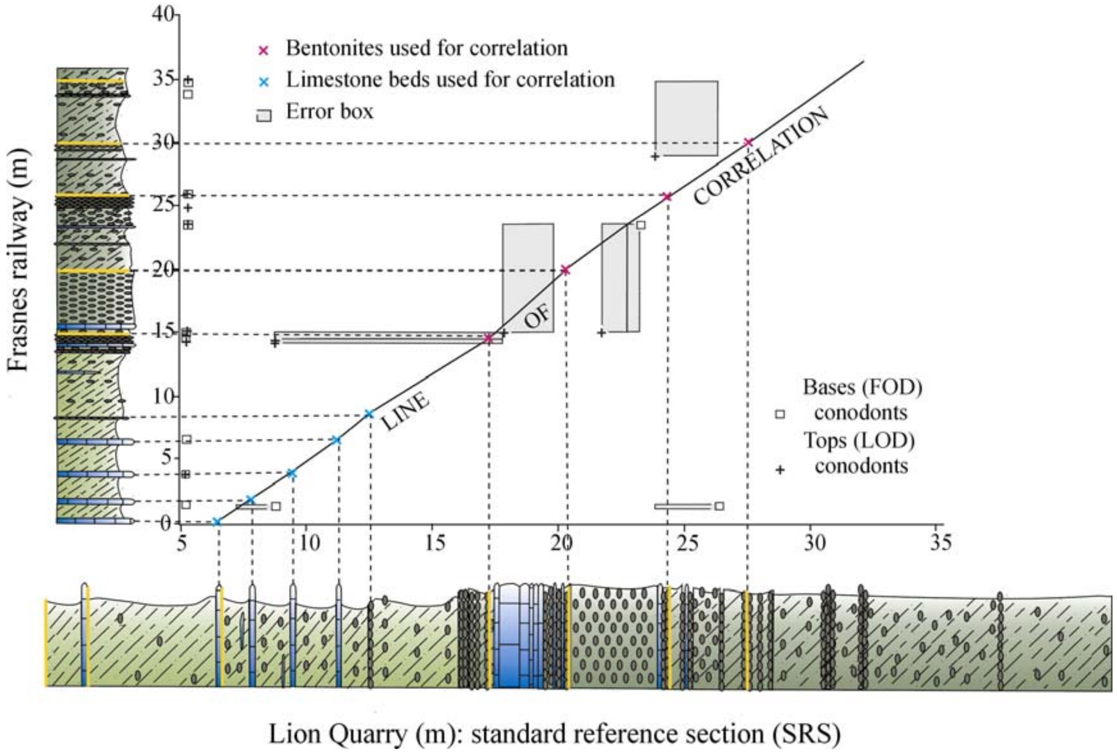
CORRELAZIONI GRAFICHE



Appunti tratti da:

GOUWY S., 2004, The graphic correlation method as a tool for integrated stratigraphy – Application to the uppermost Emsian-lowermost Famennian (Devonian) from the Ardenne area (Belgium – N-France) and correlation with the eastern Anti-Atlas area (Morocco) and the New York area (N-America). Unpublished PhD thesis, Università di Leuven. 214 pp..

Esempio di Applicazione:

GOUWY S. & CORRADINI C., 2006, Graphic correlation of the Sardinian Ockerkalk (Late Silurian): implications on the conodont biostratigraphy. *GFF*, 128, 103-108.

2. The Graphic Correlation Method

2.1 Introduction and history of Graphic Correlation

Graphic Correlation is a method of correlation that can be used instead of the more traditional cross-section correlation. Normally sections are placed parallel to each other (Fig. 2-1) and lines are drawn between correlative points. Graphic correlation places the two sections at right angles as the axes of an x-y plot displaying the best stratigraphic correlation between the sections.

SHAW first published the method in his book ‘Time in Stratigraphy’ in 1964. He found that traditional biostratigraphic zonations were inadequate to answer the stratigraphic problems he faced. In the early years of graphic correlation (1962-1968) the method was further developed and used by only a small group of staff members at the Amoco Oil Company. Several composite standards (Lower-Middle Ordovician, Cretaceous, an early version of the Upper Devonian database) were started. During the following years (1968-1992), the graphic correlation and database building proceeded at Amoco but was endorsed as well as criticized by staff members. In the mean time academic and governmental geologists started using the method and since the ’80 the number of publications on graphic correlation increased rapidly. A much more detailed historical analysis of the method is given by MANN & LANE (1995) and KLAPPER *et al.* (1995). Although some authors (MILLER, 1977; EDWARDS, 1984; MANN & LANE, 1995) published papers to explain the method and the technique was used by a leading oil company for such a long time, it took quite a while before the method started to blossom. Geologists have used and developed graphic correlation in many ways, not only using paleontological data, to resolve particular geological problems, like the integration of graphic correlation into sequence stratigraphy. It has been used with geophysical log data, magnetic polarity data, lithological marker layers (e.g. volcanic ash layers), stable isotope data…. Now more and more geologists are using graphic correlation because it integrates many types of stratigraphic data and provides a higher level of stratigraphic resolution than the traditional biozonations.

The correlation implies a multi-step process in which numerous individual stratigraphic sections are analysed to produce a synthetic composite standard section. At the simplest level discrete stratigraphic sections can be plotted against one another, at a higher level, composite sections can be constructed. At a third level of sophistication, the composite section can be subdivided into composite standard units. From the set of sections, which we want to correlate, a reference section is selected. Typically the thickest, most fossiliferous, and least structurally complex succession is designated to be the standard reference section (SRS). The SRS serves as initial estimate of the global sequence of events and provides the numerical scale for all subsequent comparisons.

2.2 The process of Graphic Correlation

The only requirements for making a graphic correlation plot of two stratigraphic sections are that they must overlap in time and that they must include reliable, recognizable events in common to correlate.

- **Data/ Fossil range charts (Table 2-1)**

  The basic step in the process of graphic correlation is the assembly of the raw data. Data selected for the process should be unique events so that a one-to-one correspondence can be established between the two sections. Data are generally paleontologic, but could also be non-unique or non-paleontologic

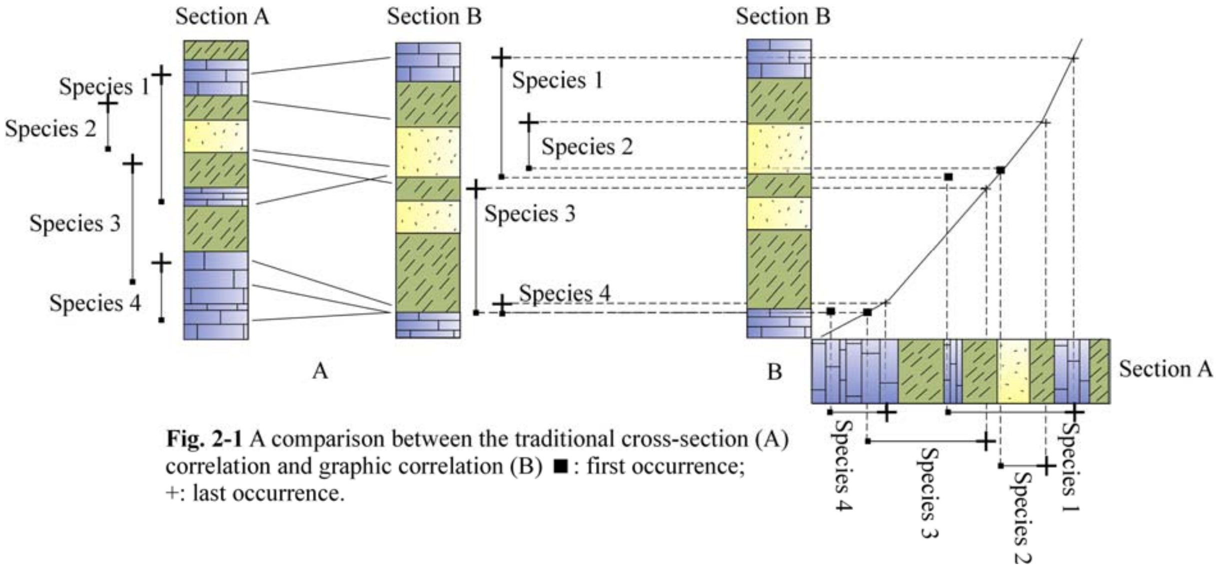


Fig. 2-1 A comparison between the traditional cross-section (A) correlation and graphic correlation (B) ■: first occurrence; +: last occurrence.

but stratigraphic important events such as geophysical log data, magnetic polarity data, lithological marker layers (e.g. volcanic ash layers), stable isotope data, etc.). It should be emphasised that there is an important difference between paleontologic data and most types of lithologic data. In paleontology species occur in an interval of time, but only two points in that time interval can be specified as unique events: the lowest (FOD) and highest (LOD) stratigraphic occurrences of the species. Unfortunately, these events are only exceptionally the evolutionary first and last occurrences of the species. Due to several causes e.g. the sampling density and size, fossil preservation, facies changes, migration of taxa this is seldom the case. The true lowest local occurrence lies whether at or stratigraphically below the observed one and the highest true local occurrence always lies at or stratigraphically above the observed one. So in this case we make an estimate of the location of the event. The goal is to improve the estimate.

Some lithological events such as ‘fingerprinted’ volcanic ash beds (which means that the ash layer has characteristics that makes it distinguishable from other ash layers: zircon typology, rare-earth element ratios, stable isotope ratios, etc.) or bentonites are unique events and can be taken as a time marker. When such unique events are present, the graphic correlation is simplified. Lithologic events that are expected to occur more than once, or at different stratigraphic levels, should not be used. Important is that the data are related to a vertically measured scale.

	FOD (m)	LOD (m)
Species1	1.25	104.06
Species2	23.98	78.50
Species3	0.00	14.76

Table 2-1 Example of a data file.

❑ **Correlation graph (Fig. 2-2)**

The fundamental difference in graphic correlation plots is that the two sections are placed at right angles as the axes of an x-y graph. The oldest parts of each section are placed together in the lower left of the graph so that the plot is oldest in the lower left and youngest in the upper right. The section of interest is generally placed on the y-axis and the standard reference is placed on the x-axis. The section of interest thus remains upright in the orientation in which stratigraphic sections are normally seen. The positions of a given event are identified in each of the two sections and lines are projected from these positions across the graph. The point at which the projected lines meet is plotted to represent that event. What would be a correlation line on a cross-section display is now a correlation point on a graphic correlation plot. Events that are present in the section and not yet in the SRS will plot along the Y-axis. When all the correlation points have been plotted, a line of correlation (LOC) is drawn through them. The estimate of the position of this line and the interpretation is the most important step in the graphic correlation. When fossils are used the lowest and highest occurrences are usually marked with different symbols (lowest= □, highest= +) and different fossil groups can also be marked with different symbols (see Chapter 4 on the Middle Devonian).

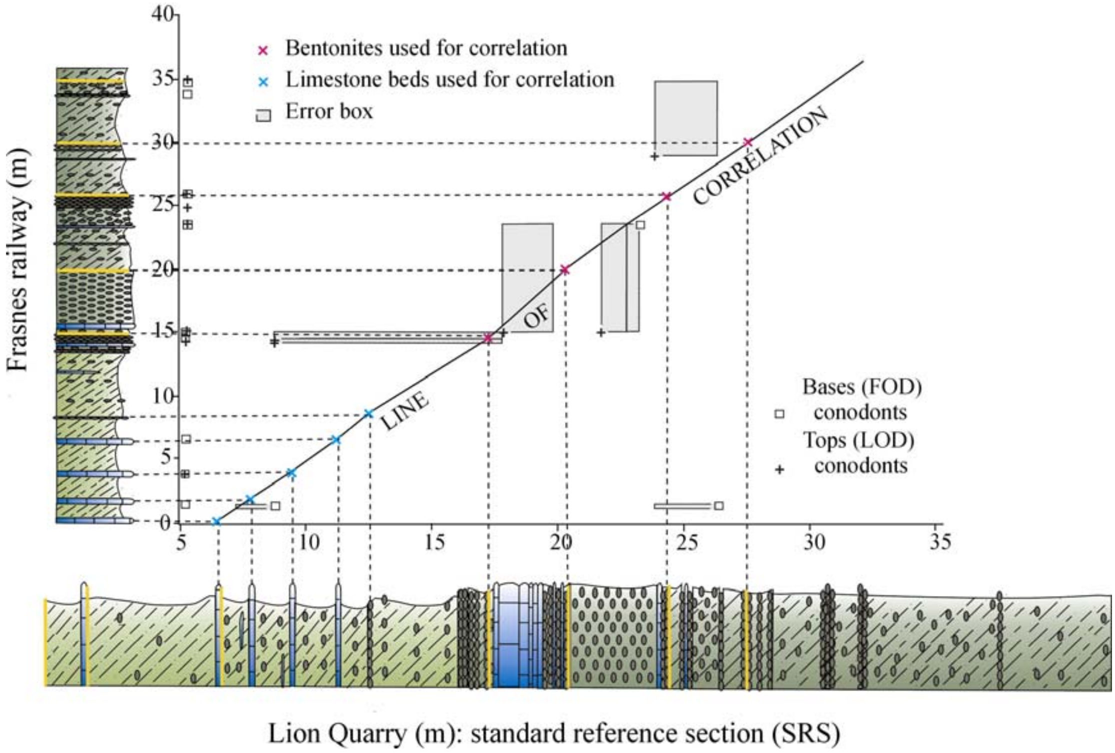


Fig. 2-2 Graphic correlation between two stratigraphic sections based on bentonite layers and biostratigraphic data.

❑ Line of Correlation (LOC)/ Use of error boxes (Fig. 2-2)

The succession of correlation points on an x-y plot should approximate a line. If each correlation point is absolutely correct, the points will fall on an approximately straight or segmented line. This can be the case if the line is based on a sequence of bentonites that are truly unique events (see Chapter 5.2 on Frasnian bentonites). If the correlation points are only estimates of the unique events, which in general is the case with fossil data, then the correlation points will be somewhat scattered around a line. In this case the correlation line has to be estimated from the available data. We take this into account by plotting the range endpoints as boxes in the graph. The areas of the boxes reflect the intervals of uncertainty. The sides of the boxes represent the sample intervals, i.e. the interval between the lowest sample containing a fossil species and the first sample below, which does not contain the species, or the distance between the highest sample containing the species and the first sample above without it. So the real local lowest and highest occurrences and therefore the correlation points lie somewhere in the boxes and the best estimate for the line of correlation would thus be a line that goes through the error boxes. The most common method for estimating the LOC involves the qualitative assessment of LOC geometries according to a principle called ‘splitting tops and bases’ (MILLER, 1977). This means that when we compare a section to the SRS based on biostratigraphic data, all FODs that are synchronous or that occur later than the corresponding positions on the SRS will plot either on or right of the true LOC, while all LODs that are synchronous or that occur earlier than the corresponding positions on the SRS will plot either on or left of the true LOC. Biostratigraphic data that are out of their proper position in the global sequence as represented by the SRS (what means that the ranges of the SRS are not yet the true, maximum ranges), will be identified on the graph as FODs and LODs that plot respectively right and left of the normal trend of the data (‘out of sequence data’ of MILLER, 1977). The common procedure for the geologist is to visually estimate the correlation line, taking into consideration that some data points might have a greater value than others. The line can be straight or can consist of multiple segments with different slopes. In earlier days the mathematical least square method was sometimes used to estimate the correlation line. This is no longer the case because of the nature of the data. With fossil data the correlation points do not fall on a straight line due to a number of factors (preservation, sampling, etc.). The least square method cannot take these factors into account, as is possible by visual estimates.

- **Graphing data with incomplete fossil ranges (Figs. 2-2, 2-3)**

In datasets from outcrops or wells, observed local stratigraphic ranges are often not fully developed. For various reasons (paleoenvironmental conditions, imperfect preservation, sample quality, etc.), the total stratigraphic range bases of some species tend to be somewhat above (younger than) their worldwide FODs and their local stratigraphic range tops tend to be somewhat lower than (older than) their worldwide LODs. By systematically composing all locally observed stratigraphic ranges, the total stratigraphic range or CS range of a given fossil species is derived.

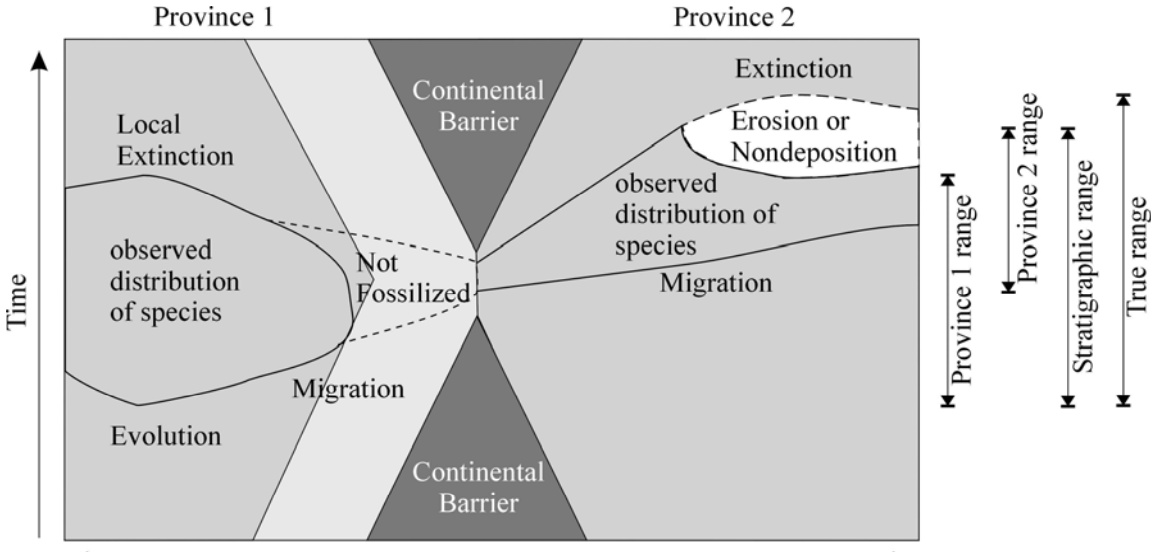


Fig. 2-3 Geographic, stratigraphic and true ranges of hypothetical species. (MANN & LANE, 1995)

Assuming the maturity of the CS range of a given fossil in the database, if the lower part of its range is not developed, its local stratigraphic base will fall to the left of a properly interpreted LOC. Likewise, if it disappeared locally earlier than the time of its worldwide LOD, its local stratigraphic top will plot somewhat to the right of a properly interpreted LOC, which will not be the case for species with immature CS ranges. Using the LOC, the stratigrapher can then transfer graphically or mathematically data present in one section to the other section. This procedure allows the stratigrapher to predict where a fossil should occur in the section, or where a zonal boundary should be located.

- **Reworked fossil tops**

When older sediments are eroded and the products of the erosion are transported and redeposited, fossils typical for the older sediments can become incorporated in the younger deposits. This results in local stratigraphic ranges with tops that plot much higher than would be expected. Since graphic correlation is based on all fossils in a sample it is an excellent means to spot anomalously high, reworked tops, presumed that the composite standard is mature. It depends on the completeness of the chosen reference section whether such tops can be discovered. If the ranges of the composite standard are not yet complete, a top plotting on the left side of the correlation line can just be an indication that the range of that particular species has not yet reached its maximum in the composite standard and has to be extended. So other indications for reworking (sedimentology, preservation state of the different species in the sample…) should be present before one can assume reworked fossils with an immature composite standard.

- **Patterns in the line of correlation (Fig. 2-4)**

Very often multiple LOC geometries that more or less equally satisfy the ‘splitting of tops and bases’ rule can be found. Several criteria can be taken into account when to select one of these. The existence of unique lithostratigraphic units with precise stratigraphic significance (bentonite layers, volcanic ash layers) can provide important additional information concerning the position of the LOC.

The graphic correlation between a section and the mature composite standard can be considered as plotting rock thickness against geological time. In this way an estimate of the relative rates of rock accumulation (related to but not the same as the sedimentation rate) can be made and more important, intervals of non-deposition or erosion can easily be recognised. Some patterns in the line of correlation are more common than others while some are signatures for certain geological provinces (fold or overthrust belts). Fig. 2-4 shows the most common LOC patterns. Correlations A and B show LOCs that suggest normal (not overthrusted) sections, A represents a greater rate of rock accumulation than B. C shown a doglegged LOC representing a normal section with an early phase of rapid rock accumulation followed by a slower phase what means that the rate of rock accumulation changes in time. D is the LOC pattern that occurs when a section is overturned. The upper part of the section is older than the lower part. In E a horizontal terrace offsets two segments. The terrace is due to several events occurring at different horizons in the composite standard, but all occurring at the same level in the other section. This horizontal segment implies a stratigraphic discontinuity. Such a LOC represents a normal, non-overturned section with a certain interval of time not represented by a significant thickness of rock and with similar rates of rock accumulation above and below the missing part. This pattern is attributed to a fault or to an extremely condensed section. If a condensed section is sufficiently thick, it can produce a very gentle slope rather than a horizontal terrace. Graphic correlation allows an estimate of the missing rock by sliding the upper part of the curve upwards parallel to the x-axis until it aligns with the portion below the unconformity. This is where the curve would have been if there had been no missing interval in the Y-axis. If the LOC has a vertical segment, this would mean that an interval of time present in the section is missing in the composite standard (or the reference section), so that another section has to be taken as reference section. LOC F is derived from a section with a repeated interval. This is typical for reverse faulting and is difficult to recognise. The sampling intervals of the correlated section should be very small otherwise the repeated ranges would be seen as the last occurrences of the species instead of a repetition and the horizontal terrace would not be visible. Repeated sections have the effect of stretching the ranges through a longer interval, which would appear to be an interval of rapid deposition. Unique events (e.g. bentonites) can help in a case like this, because they will appear twice.

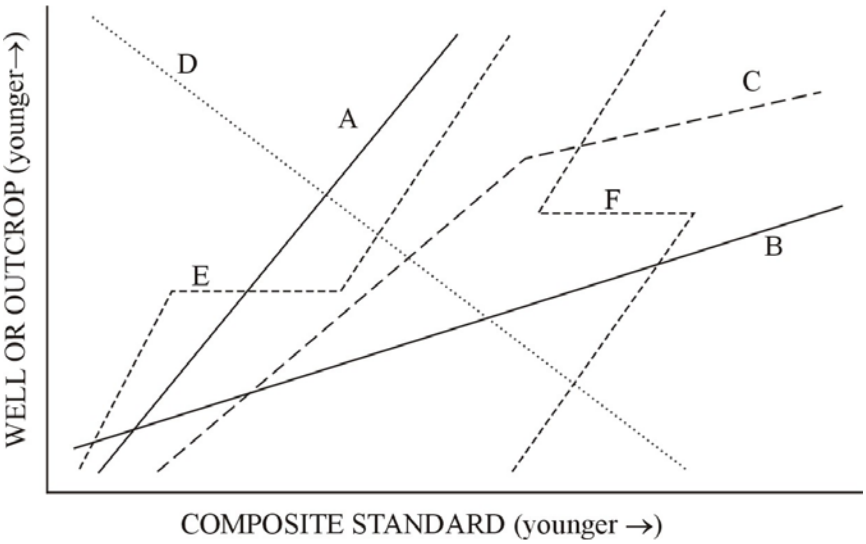


Fig. 2-4 The most common LOC patterns: A. section with high rock accumulation rate, B. section with low rock accumulation rate, C section with decrease in rock accumulation rate, D. overturned section, E. section with unconformity or fault, F. section with reverse fault.

- **Building of the composite standard (CS)**

Why do we use a composite standard? Why not just compare all the sections to a single section? One of the disadvantages of correlating two measured sections against one another is that if the same interval is missing in both sections, no indication will be seen on the graph. There are several other reasons why a single section is not always an ideal comparison standard, some are contributed by nature, like the ecological differences between sections with a large geographic separation, taphonomy (marine benthic organism could have been present in an area but were selectively removed before they were incorporated in the sedimentological record), others are contributed by the geologist taking the samples: sample intervals that are too large so that ranges cannot be accurately delimited, sample preparation can destroy specimens, others can be misidentified. These reasons show that the known distributions of the species in a single section are probably not the maximum ranges. Therefore the positions of the first and last occurrences of the species are probably not the same time horizon in both sections. The solution is to construct a composite standard that contains information from many measured sections.

The composing process is cyclic. At any point in the process of building the CS, data from sections that were already added may be regraphed. Since new species are constantly being added to the database and the ranges of species in the database are constantly being adjusted it is necessary to re-evaluate the data from some of the original sections by comparing them to the more mature CS. The starting reference (Standard Reference Section) should be the best of the available sections (see before), and the first section to be compared with it should be the second best one. This is the best way for starting the construction of the composite standard. A stratigraphic section is compared to the existing composite standard in a graphic correlation plot. The plot is examined to see if the section has more extended ranges (a lower first occurrence or a higher last occurrence) than the composite. If that is the case the species is extended in the composite by projection through the correlation line. Of course caution must be used when extending the stratigraphic range of a species. Points that fall far from the LOC are an indication that something unusual has happened with the species distribution (only with mature CS) and careless application of the correlation method could lead to an overextended range chart that lacks the precision that is needed for being useful. Factors that could cause the far off line position of the points are reworking (see before), misidentification, biogeography, contamination (e.g. downhole), etc. The correlation process is repeated with all the additional stratigraphic sections. This is generally referred to as the first round of graphing. After this round the actual composite standard is much more mature than when it was correlated for the first time with the different sections: new species from the additional sections have been added and some ranges have been extended. So we need to recorrelate the sections with the actual more mature composite standard in a second correlation round. The LOC can now change slightly in some plots because there might be additional correlation points, and that will have an effect on the ranges in the composite standard. Therefore we need to go through several rounds of correlations until the LOCs stabilize, depending on how many sections are used and the magnitude of repositioning of the LOC after each correlation round.

- ☐ **Scaling of the Composite Standard/Composite Standard Units (CSU) (Fig. 2-5)**

In the first step of Graphic Correlation where a section is compared to the SRS, the latter is scaled in meters (at this point it is just a normal section). Once the data of another section are added to the SRS, the building of the CS begins and measurements in meters on the X-axis would cause confusion. At this point in the process the CS becomes a compilation of data from multiple sections in which a certain increment of rock thickness can represent a broad range of time intervals and rock accumulation rates. Since the CS represents a sequence of stratigraphic events it is better to use time as scale. Once a stabilised CS has been built, it can be divided into equal intervals (CSU) that serve as a relative time scale. Generally the original meter scale of the SRS is used as division of the CS. A non-annual scale serves several purposes: it allows bases and tops of species to be expressed numerically; it keeps the tops and bases in their proper relative position as new data are added to the database; it provides stable numerical values for the boundaries of biozones and stages and it permits correlation interpretations to be quantified.

The mature CS database serves as a geochronological scale onto which additional stratigraphic sections can be projected. Based on the events (bases and tops of the ranges of species in the database) the database can be linked to the worldwide scheme of biostratigraphic units (biozonation) and to a chronometric scale in absolute time.

The CSU scale of the CS can be reprojected onto the different sections through the correlation lines. These CSU now allow a high-resolution correlation between the sections; even between sections that did not have enough data in common to correlate them amongst each other in the traditional cross-section plot.

2.3 Displaying the interpretations: chronostratigraphic diagram/stratigraphic nomograph/time-depth plots

The results of the correlation can be displayed in several ways. The graphic correlation plot is a very useful display: it shows the stratigraphic interpretation and the evidence (tops and bases) on which it is based. However, a limitation is that it only shows the correlation between two sections or between a section and the CS. Other displays are needed when we want to visualise the interpretations of multiple sections.

Chronostratigraphic diagrams (Fig. 2-6) demonstrate the isochronic or diachronic nature of the sedimentary deposits that can be related to transgressive-regressive sea-level changes in the basin. In the diagram the vertical axis represents relative time and all horizontal lines are isochronous. The different sections are shown as columns on a bar graph, with hiatuses as blank intervals. This allows a visual comparison from one section to another of intervals of time represented by rock or intervals represented by hiatuses.

A stratigraphic nomograph (Fig. 2-7) is a graphic correlation plot that shows the LOCs of multiple sections superimposed. The X-axis is the relative time scale; the vertical axis is scaled in meters. This display allows comparison of the different rates in rock accumulation and makes it easy to see the stratigraphic alignment of horizontal terraces in the LOCs. The vertical alignment of the terraces implies a genetic relationship between them. On the X-axis a time scale can be used instead of a CS. This creates a time-depth plot that converts depth (thickness of the deposits) into time, relative time if biozonations (Fig. 2-5) are used or absolute time when the scale is linked to radiometric data from literature.

2.4 Worldwide and local composite standard

A worldwide CS is composed of the total chronostratigraphic range of taxa, including the absolute first and last appearances. It should include worldwide reference sections: the most stratigraphic valuable sections (contain the most complete record of time, climates, facies, etc.). The advantage of such a CS is that it can be linked later to absolute time and the increased potential for interregional correlations. The complete and accurate chronostratigraphy of the database allows the location of hiatuses, the testing of eustatic sea-level changes and the understanding of provincialism and migration of species through time all of which have an influence on the interpretation of global tectonics, paleogeography, etc.

The relevance of the worldwide CS can be less important in the case of local basins where due to provincialism and facies control, first appearances are higher and last appearances are lower. These ranges are indicated on the plots by bases and tops that plot far from the correlation line. Locally very important species can have less importance on a worldwide scale. The local composite standard contains the stratigraphic ranges of taxa in a particular basin in order to preserve the regional utility of the local ranges of fossils. The advantage of this type of database is the optimising of the local resolution. The disadvantage however of the reliance on a purely local database is that it might not see local unconformities or hiatuses because they are also present in the local CS. These can only be detected by correlation with the global CS.

The solution is to use the local database for the correlation of new sections of the local basin. The local database can be correlated with local databases of other regions to build up a worldwide CS. This latter correlation will detect basin related hiatuses or unconformities.

2.5 Graphic Correlation compared to the traditional correlation method (Fig. 2-1)

In the conventional stratigraphic correlation method where two sections are placed parallel to each other, considerable emphasis is placed on the ranges of few taxa. Only few taxa are present in both sections and can be used in the correlation. The observed local stratigraphic ranges of many taxa are of no use for the correlation. No correlation information is obtained for the intervals between the correlation points and above and below the highest and lowest correlation point. Only few sections contain all zonal or index taxa and show a consistent order of the taxa; this leads to subjective judgement regarding zonations.

Semi-quantitative or quantitative methods like graphic correlation offer a lot of advantages in stratigraphy:

- Standardization of the fossil record during computer input
- Data sets and results are easier to communicate and rapidly updated with new information
- Integration of all fossil data and physical events increases resolution and practical use
- Method and result are more objective than conventional method
- The possibility to attach error boxes to the events
- More than one solution is provided for the data
- Transgression-regression trends may be visualised
- The methods can handle large and complex data sets

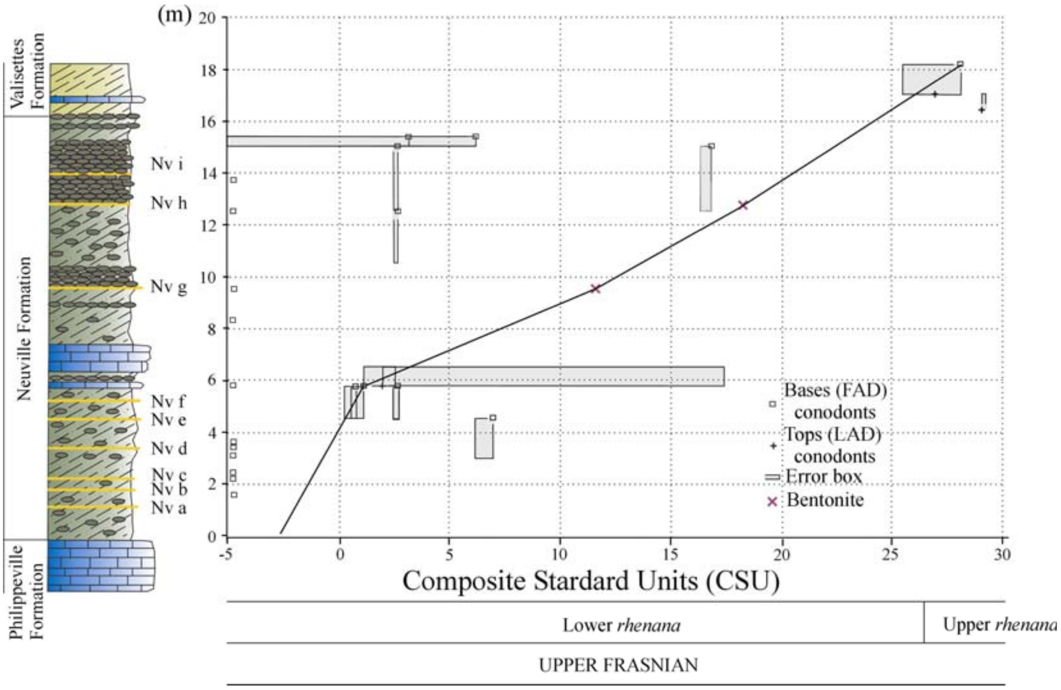


Fig. 2-5 Correlation of a section with the composite standard (CS) and subdivision of the standard into units (CSU).

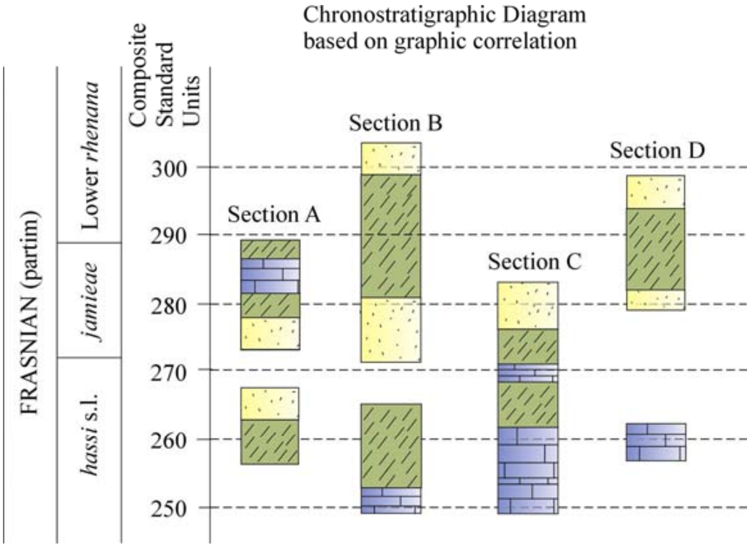
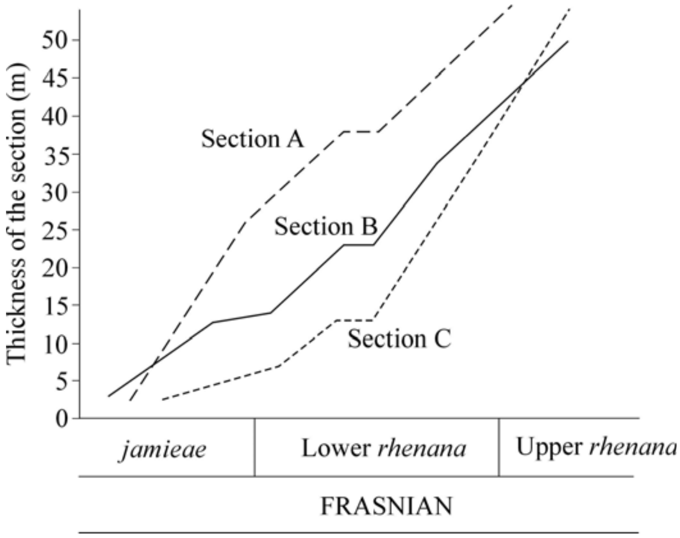


Fig. 2-6 Chronostratigraphic diagram based on graphic correlation.

Fig. 2-7 Stratigraphic nomograph showing the correlation lines of three sections, with alignment of terraces.



Graphic correlation uses all data that are available in the sections. Instead of correlating a section to another section, it is compared to a CS containing data of multiple sections providing a lot more correlation points (higher resolution correlation) than the traditional method. Stratigraphic ranges of taxa only present in one section are added to the CS and can be of use in future correlations with new sections that do contain these taxa. Correlation with the CS also allows estimating the position in a section of biozones' boundaries even if the zone defining taxa are not present in that section. Through the correlation line each point of the section can be correlated and not only the samples containing the taxa used for the correlation.

2.6 Quantitative stratigraphic methods

We should make a distinction between deterministic and probabilistic correlation methods (Fig. 2-8). Deterministic methods are looking for the total or maximum range of taxa. These methods assume that there is a true order of events and that inconsistencies in the relative order of the events from one section to another are due to missing data. Probabilistic methods consider these inconsistencies as random deviations from a most likely or optimum sequence of events and approach the range of a taxon by statistically estimating the most probable or average range, accompanied by an estimate of stratigraphic uncertainty.

The choice of the method will depend on the purpose of the study. The most probable succession of stratigraphic events in a sedimentary basin best predicts the order of events to be expected in a new stratigraphic section. Calculating the true order of events is more comparable to conventional results in range charts.

- **Deterministic methods**

  - *Graphic Correlation* (see above), semi-quantitative non-statistical method.

    This method is the closest to the normal processes of paleontological analysis. The advantage is that the paleontologist stays in control, in touch with the data, disadvantage is that the method is still somewhat subjective and operator dependent.

  - *CONOP* (CONstrained OPtimisation) developed by KEMPLE *et al*. (1995)

    This is an extended version of graphic correlation to many dimensions. This method uses event order and thickness spacing of the events and is suited for large data sets. It automatically fits a multidimensional line of correlation simultaneously to all points in all sections and can generate several composites depending on the run parameters. The relative spacing of the events in the composite is derived from the original event spacing. The analysis proceeds in two steps. In the first, the number of possible solutions is constrained by observed co-existences (the ranges of two taxa that are observed to overlap in a section, must overlap in the solution). In the second step, the stratigraphic ranges of all species in all sections are adjusted to fit the best correlation scheme, which is optimised in a sense that it requires less adjustment than any other scheme. The species with the most consistent range in the sections have the most influence on the solution. Measuring the amount of adjustment permits a quantitative comparison with rival correlation schemes. This method automatically correlates sections and can be used to build a regional event time scale. Advantage is that all sections and data are used at the same time; no starting sections have to be selected and the method is completely objective. The disadvantage is that one looses continuous contact with the data.

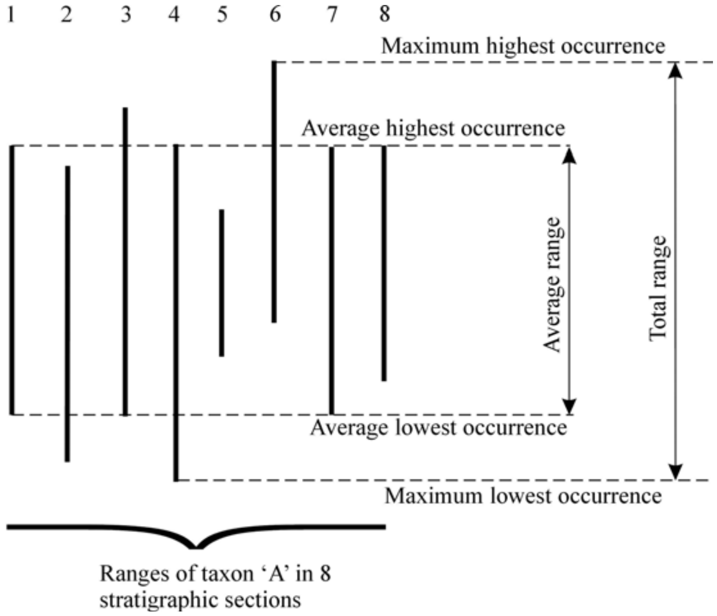


Fig. 2-8 The difference between the average and the total range of a taxon in different sections. Probabilistic methods consider the average stratigraphic range; deterministic methods look for the total range (after COOPER *et al.*, 2000)

❖ *Unitary Association analysis* (GUEX, 1984, 1991) (Fig. 2-9)

The basic idea behind this method is to generate a number of assemblage zones, which are optimal in the sense that they give maximal stratigraphic resolution with a minimum of superpositional contradictions. The data input consists of a presence/absence matrix with samples in horizontal rows and taxa in columns. The method is rather complicated and consists of a number of steps. It assumes that taxa have been present at all levels between the first and last occurrence in a section. Then any samples with a set of taxa that is contained in another sample are discarded. The remaining samples are the residual maximal horizons. Next, all pairs of taxa are inspected for their superpositional relationships: if A occurs below B in one section and above B in another section, they are considered to be co-occurring although they have never been found together. Maximal cliques are groups of co-occurring taxa not contained in any larger group of co-occurring taxa. These are candidates for the unitary association status. Now the superpositional relationship between the maximal cliques is investigated by inspecting the relationships between their constituent taxa and contradictions (some taxa in clique A occur below some taxa in clique B en vice versa) are resolved by "majority vote". At this stage a single chain of superpositional relationships should be obtained between the maximal cliques. The original samples are now correlated using the unitary associations. Big disadvantage of this method is that for samples that lack key taxa, which could differentiate between two or more associations, only a range can be given.

- *No-space graphs* (EDWARDS, 1978)

  In this method it is significant whether one sample occurs before or after another, but the distance between them is of no importance. The relative position of the samples is retained, but the scaling factor is ignored. This method is used to order events, not to access depositional rate changes.

- **Probabilistic methods**
  - *RASC & CASC* (RAnking and SCaling) & (Correlation And Standard error Calculation) method, developed by GRADSTEIN & AGTERBERG (1982); AGTERBERG & GRADSTEIN (1999) (Fig. 2-10).

In this method ranges of all species in all stratigraphic sections to be considered are entered at once in a large data matrix. The program determines a mathematically most-likely sequence of first and last appearances: each event position is an average of all individual positions encountered in the sections. The method of Ranking & Scaling consists of two steps: the first step is to produce a single stratigraphic ordering of events, even if the data contain contradictions (event A above event B in one section and B above A in another). The principle of 'majority vote' is used to accomplish this: counting the number of times each event occurs above, below or together with all others. The second step is estimating the stratigraphic distances between the events, by counting the number of observed superpositional relationships between each pair of events. A low crossover frequency between two events means a long stratigraphic distance. The final distance estimates are presented in dendrogram format; groups of events with short interevent distances form clusters, which can be named and used for zonation. The scaled version of the most-likely sequence of events features time successive clusters in the dendrogram, each of which bundles distinct events. Large interfossil distances between successive clusters reflect breaks in the fossil record due to grouping of extinctions. Such extinctions could reflect sequence boundaries. The method called CASC takes the RASC zonation and calculates the most likely correlation of all events in the zonation over all sections/wells. The event positions have error bars attached and are compared to observed event positions in the sections/wells examined.

This method is good for use with data that have consistent ranges because it assumes a random, symmetrical scatter around a midpoint, called the average event. The use of ranking and scaling is problematic with species with patchy vertical distributions (inconsistent, preservation controlled ranges), which could make that the sequence of events is rarely the same in two sections and that many events could be coeval. It leads to many small interfossil distances and creates uncertainty in rank. The value of this method is that the task of event sequencing is solved first and the spacing of the events is only done after the best event sequence has been found (in graphic correlation these steps are done simultaneously).

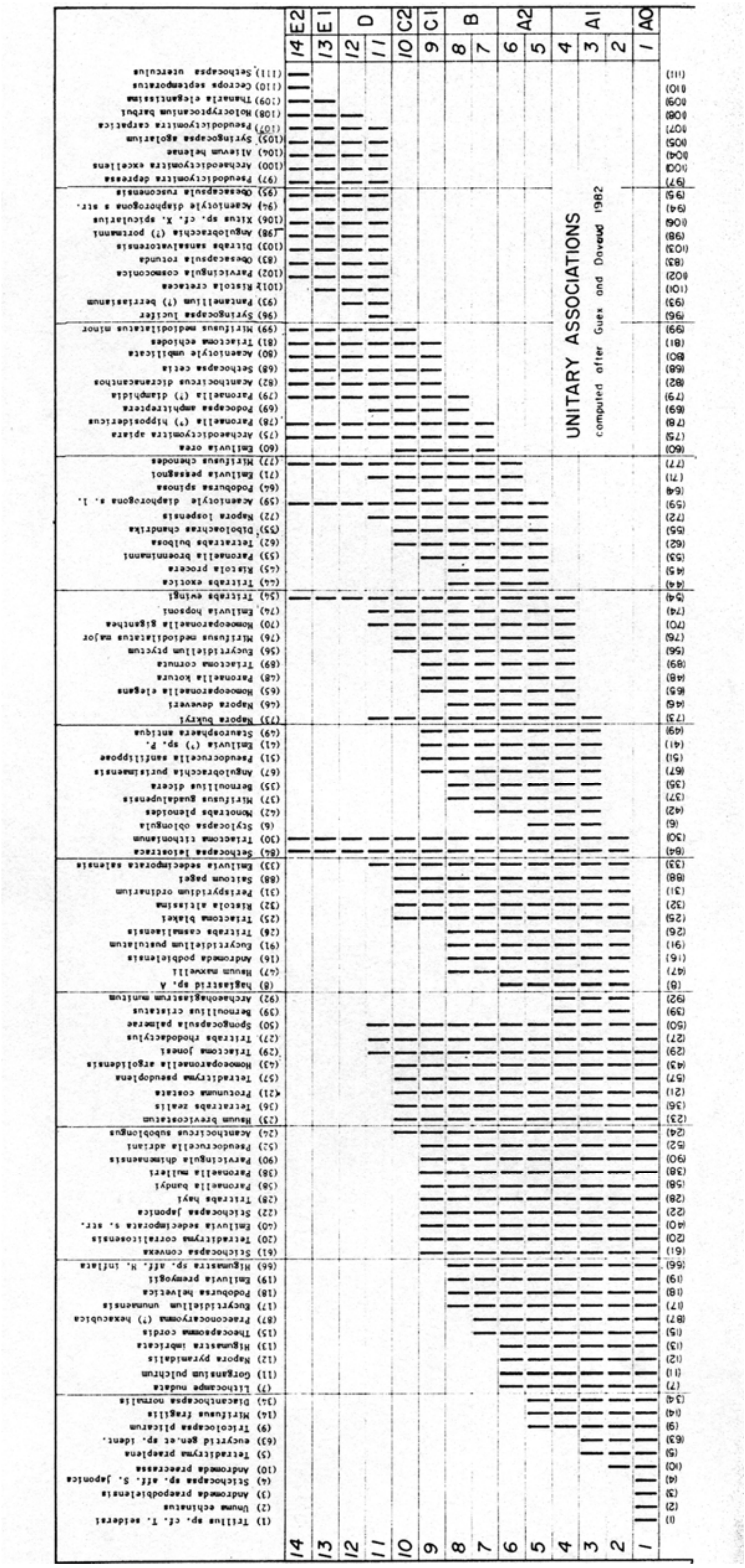


Fig. 2-9 Range chart of Mesozoic radiolarians produced by Unitary Associations. 1-14 are the unitary associations, A0-E2 are the deduced biochronozones (BAUMGARTNER, 1984).

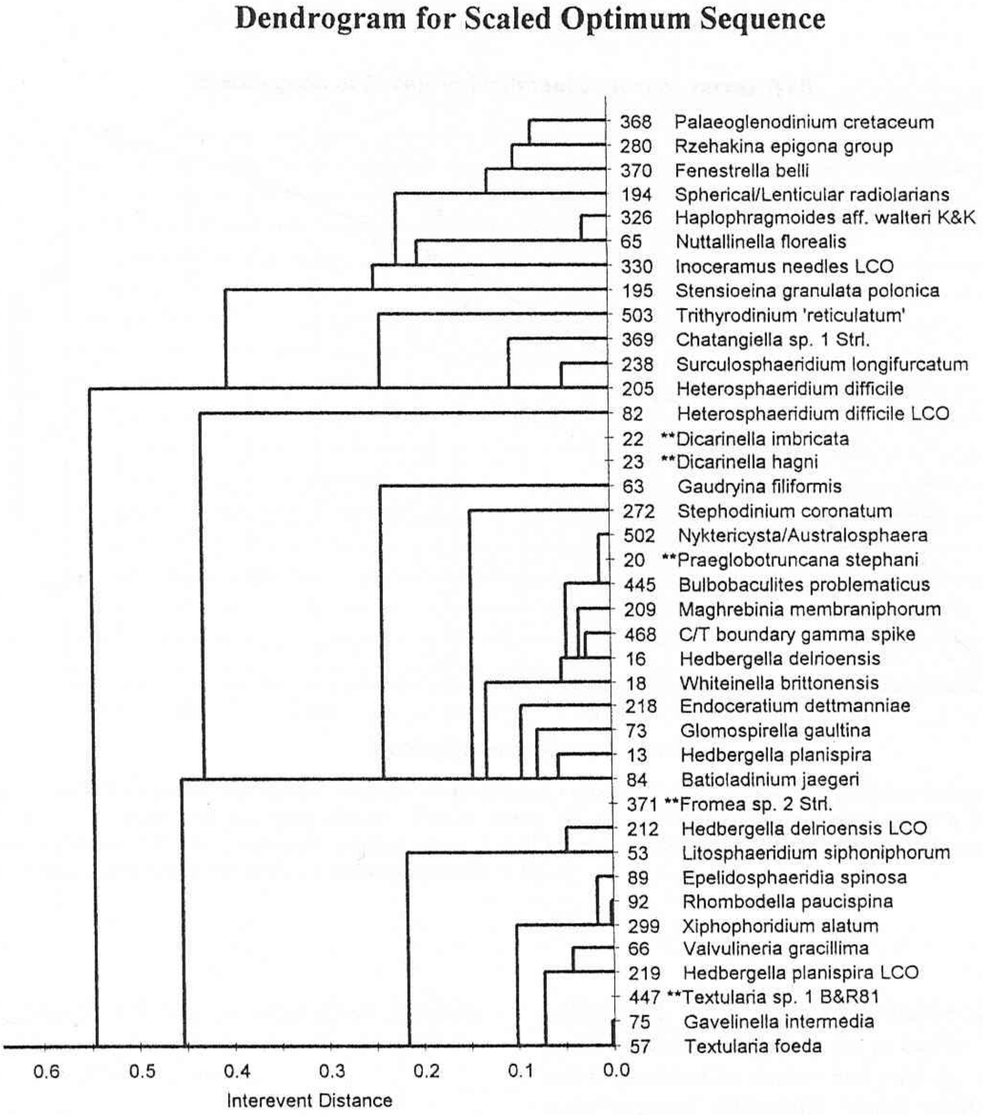


Fig. 2-10 Dendrogram of the scaled optimum sequences obtained by RASC (AGTERBERG & GRADSTEIN, 1999)

In this study, the Graphic Correlation method is preferred because it best approaches the traditional (deterministic) cross-plot correlation method and allows comparison with results in previous studies. The method also allows continuous control of the processing of the data and to intervene in it: correlation points are individually accessed for reworking, misidentifications or other problems; ranges are not extended until the geologist decides to do so and additional information can always be added. KLAPPER (1997) started a Frasnian Composite Standard for the Montagne Noire (France), Western Canada, North America, Europe and Western Australia. BELKA *et al*. (1997) introduced an Eifelian-Lower Givetian Composite Standard for the Eastern Anti-Atlas (Morocco). The Middle Devonian and Frasnian Composite Standards herein established for the Ardenne can be correlated with these composite standards and complete them.

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GFF volume 128 (2006), pp. 103–108. *Article*

Graphic correlation of the Sardinian Ockerkalk (upper Silurian): implications on the conodont biostratigraphy

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Abstract: Eight sections representing the upper Silurian of SE Sardinia have been correlated using Graphic Correlation. New data combined with already published data allow high-resolution correlations between the sections and a subdivision of the upper Silurian of SE Sardinia into 24.7 Composite Standard Units (CSU). The well-known Silius section was chosen as reference section for the studied area. Correlations of the SE Sardinian composite standard with sections outside the studied area (Cellon in the Carnic Alps, Klonk in Bohemia and Mason Porcus in SW Sardinia) show an earlier first occurrence of *Oulodus elegans detortus* in Sardinia; therefore, the use of this taxon as marker for interregional correlations is to be discouraged.

Keywords: Graphic correlation, biostratigraphy, conodonts, Sardinia, upper Silurian.

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Introduction

During the last decade the East Sardinian Ockerkalk has been the subject of an intensive study mainly based on conodonts (Barca et al. 1994, 1995; Corradini & Olivieri 1997; Serpagli et al. 1998; Corradini et al. 1998, 2000, 2001, 2002b). A dozen of sections from the Gerrei tectonic Unit have been investigated and positioned in the Late Silurian time frame. Up till now these sections have always been correlated based on the conodont zonation. The purpose of this study is to obtain a higher resolution correlation between those sections and a very detailed conodont range chart. Therefore conodont data from the eight best-preserved sections (Fig. 1) have been integrated into a graphic correlation project.

Graphic correlation of Silurian sections based on conodonts and graptolites was started by Kleffner (1989, 1995) and updated during the years using sections worldwide. Our study focuses on the southeastern part of Sardinia to construct a very accurate composite standard for that area and compare the results with a few well-known and well-studied Silurian sections outside the studied area.

Geological setting

The Palaeozoic Basement of Sardinia is part of the South European Variscan Chain (Carmignani et al. 1992 and references herein). This is evidenced by the stratigraphic and structural affinities with other Variscan massifs of Southern Europe and by palaeomagnetic data. The Variscan Orogeny affected the whole Sardinian Basement producing various degrees of deformation and metamorphism followed by important and extended post-collisional magmatism. The Sardinian Basement represents a complete section of the south-verging Variscan Chain (Fig. 1). This chain segment has a NW–SE orientation and shows a tectono-metamorphic zonation typical of continental collisional chains (Carmignani et al. 1992).

The regional metamorphism makes it possible to recognize a "nappe" zone between the Metamorphic High Grade Complex in the NE and the autochthonous External Zone in the SW. In that "nappe" zone we can distinguish external nappes (Sarrabus Unit, Gerrei Unit, Arburese Unit) from internal nappes (Nurra Unit, Baronie Unit, Gennargentu Unit). In the External Zone and the External Nappe Zone, the original lithological features and the palaeontologic content have not been destroyed, thanks to only weak tectonic deformations and low-grade metamorphism. The Gerrei tectonic Unit, one of the main units of the External Nappe Zone of Central-Southern Sardinia, bears the most complete Lower Palaeozoic sequences, which were only mildly affected by metamorphism (Corradini et al. 2002a). Here the upper Silurian is represented by the Ockerkalk, a calcareous unit sandwiched between two shaly units (Lower Graptolitic Shales and Upper Graptolitic Shales).

In SW Sardinia, where the Silurian rocks are also quite widespread, the upper Silurian is represented by a different calcareous facies: the "Orthoceras Limestone" of the Fluminimaggiore Formation. The relationship between these areas is still unclear, but they probably represent two terranes joined together by the Variscan orogeny. For a complete discussion on the Silurian of Sardinia, see Ferretti & Serpagli (1996).

The Ockerkalk

The Ockerkalk is an argillaceous limestone with a blue-grey colour, weathering into ochre (wherefrom the name), and a typical irregular flaser texture. It is about 25 m thick. The only macro-

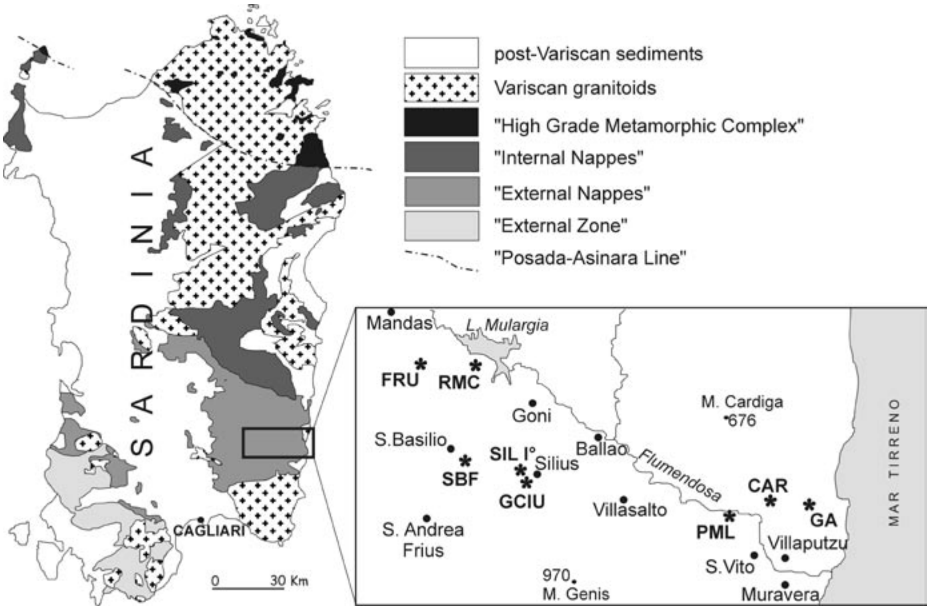

Fig. 1. Simplified structural map of Sardinia (modified from Carmignani et al. 1992) and location of the sections investigated in this study. Section abbreviations: CAR – Punta Carroga; FRU – Monte Fruccas; GA – Genna Arrela; GCIU – Genna Ciuerciu; PML – Ponte Monte Lora; RMC – Riu Murru de Callus; SBF – San Basilio Fenugu; SIL I – Silius I.

fossils visible in the outcrops are crinoid stems, rare cephalopods and loboliths. The lobolith level with bulbous holdfasts of giant pelagic scyphocrinoids, well-known along the Silurian–Devonian boundary of northern Gondwana is found in the upper part of the Ockerkalk. At a microscopic scale ostracods, thin-shelled bivalves, brachiopods, gastropods, trilobite fragments, crinoids, small cephalopods, and sponge spicules are also found. A detailed biostratigraphy of the Ockerkalk is possible because of an abundant conodont fauna: twenty-seven taxa reported from this limestone document eight conodont zones of the Sardinian Silurian Zonation (Corradini & Serpagli 1999) and suggest a lower Ludlow–upper Přídolí age for this unit.

The Graphic Correlation method

The Graphic Correlation method (Shaw 1964) used here to correlate several time-equivalent sections is a technique based on a Cartesian coordinate system. The sections are correlated by plotting them two-by-two on the perpendicular axes of an X–Y graph. The scale on the axes is the thickness of the sections. One of the sections is chosen as the standard reference section to which all other sections of the area will be correlated. This is generally the best sampled, non-tectonised section with the largest and most varied fossil content and also the thickest one containing the youngest and oldest deposits to be studied. Data selected for the process should be unique events so that a one-to-one correspondence can be established between two sections. The data are the first and last occurrences of conodont species. Unfortunately, these events are only exceptionally the evolutionary first and last occurrences of the species. Due to several causes e.g. the sampling density, sample size, fossil preservation, facies changes, migration of taxa this is seldom the case. The true lowest local occurrence lies either at or stratigraphically below the observed one and the highest true local occurrence always lies at or stratigraphically above the observed one. To take this into account, we use errorboxes. They indicate the distance between the sample containing the first occurrence of a species and the first sample right below that does not contain it or the distance between the sample containing the last occurrence of a species and the first sample right above that does not contain the species. The respective real first or last occurrence will presumably lie in the errorbox. So in this case we make an estimate of the location of the event. The goal is to improve the estimate.

Each section is correlated with the standard reference section. The fossil data in common between the two sections plot in the field of the graph [☐: first appearence datum (FAD), +: last appearence datum (LAD)]. The line of correlation representing the point-by-point time-equivalence of the sections is drawn in a way as to cause minimum change of known ranges ("splitting tops and bases"). After each correlation, data from the correlated section are projected onto the standard reference section thus composing a composite section or 'composite standard' for the region. After completing the whole correlation process, this composite standard will contain the maximum ranges of the conodont species for this area.

The scale of the composite standard is subdivided into composite standard units (CSU) based on the original thickness scale of the reference section. These units can be projected onto the different sections through their lines of correlation allowing then a high-resolution correlation amongst the different sections.

This method has the advantage that time-equivalent sections that could not be correlated due to a lack of a mutual fossil content can now be correlated accurately by means of the composite standard. To apply the method, the software program Graphcor 3.0 (Hood 1998) was used.

Conodont data

Conodonts are quite abundant in all the investigated sections throughout the Ockerkalk. For this project we selected eight of these sections, most of which are already well known in literature: Genna Ciuerciu and Silius I (Barca et al. 1995; Serpagli et al. 1998; Corradini et al. 1998, 2002b); Genna Arrela, Monte Fruccas and Ponte Monte Lora (Corradini & Olivieri 1997) and

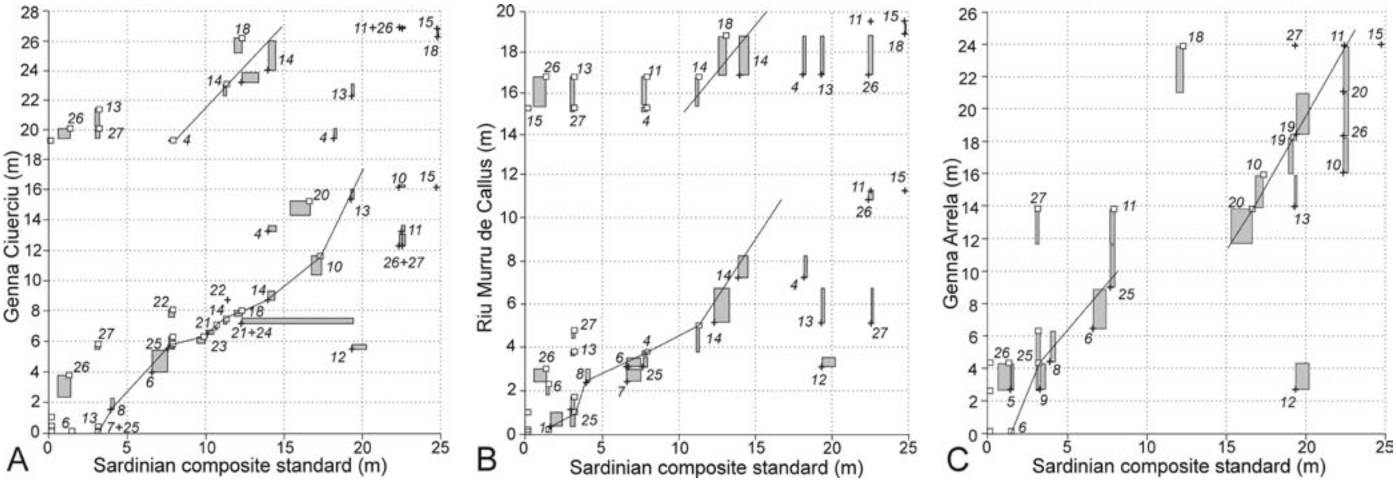

Fig. 2. Correlation graphs of the Sardinian composite standard with **A.** Genna Ciuerciu section. **B.** Riu Murru de Callus section. **C.** Genna Arrela section. See the appendix for the names of the numbered species.

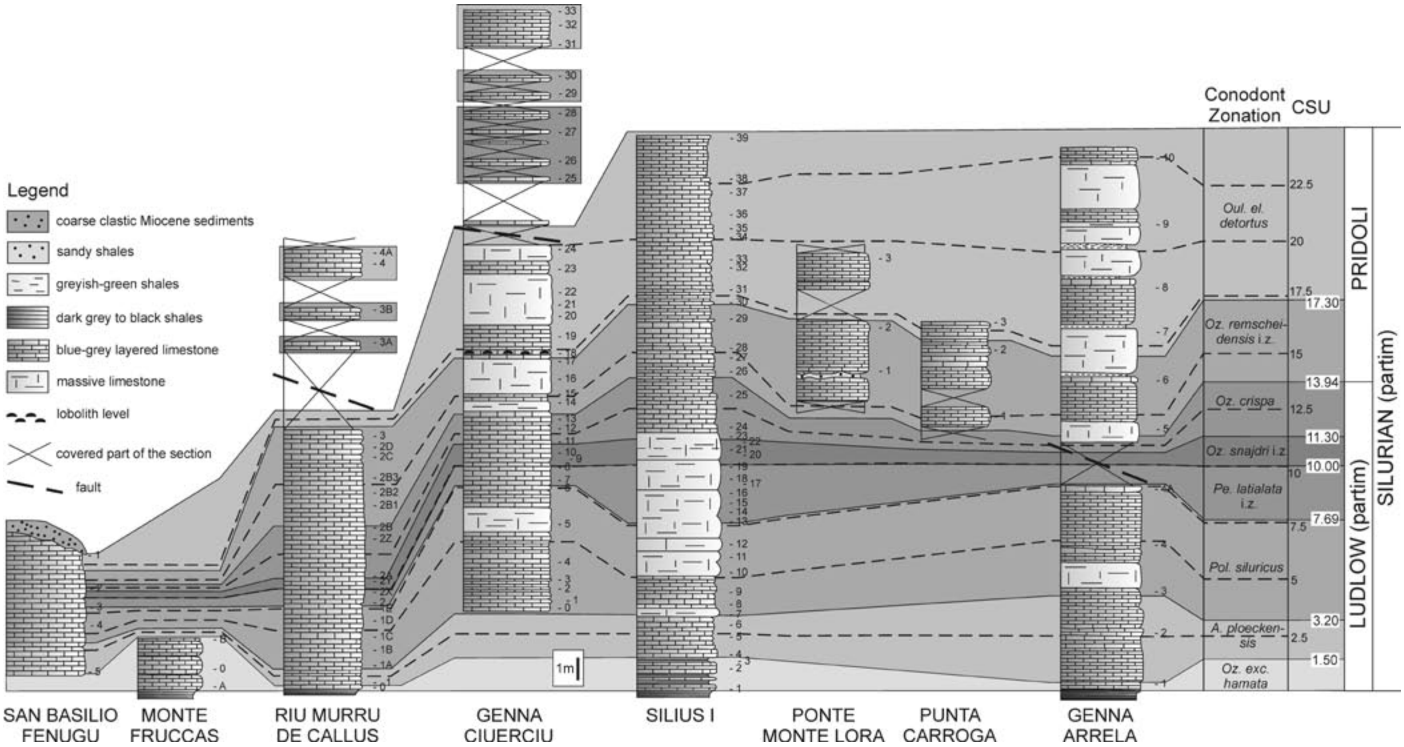

Fig. 3. Correlation of the upper Silurian sections in the Ockerkalk based on graphic correlation. Sample numbers are indicated along the columns. Different shades of grey are used to mark the conodont zones. The thick dashed lines mark every 2.5 CSU. i.z. – interval zone. Please note that in the upper part of the Genna Ciuerciu section and the Riu Murru de Callus section the *Oz. snajdri* interval zone, the *Oz. crispa* Zone and the *Oz. remscheidensis* interval zone are repeated.

the Silurian part of the San Basilio Fenugu section (Corradini et al. 2001). The Rio Murru de Callus and Punta Carroga sections are still unpublished. Conodonts from these sections are also illustrated in taxonomic papers on the genera *Coryssognathus* (Serpagli et al. 1997), *Kockelella* (Serpagli & Corradini 1998, 1999) and *Pseudooneotodus* (Corradini 2001). The databases of these sections have been extended with new samples and the older samples have been re-evaluated.

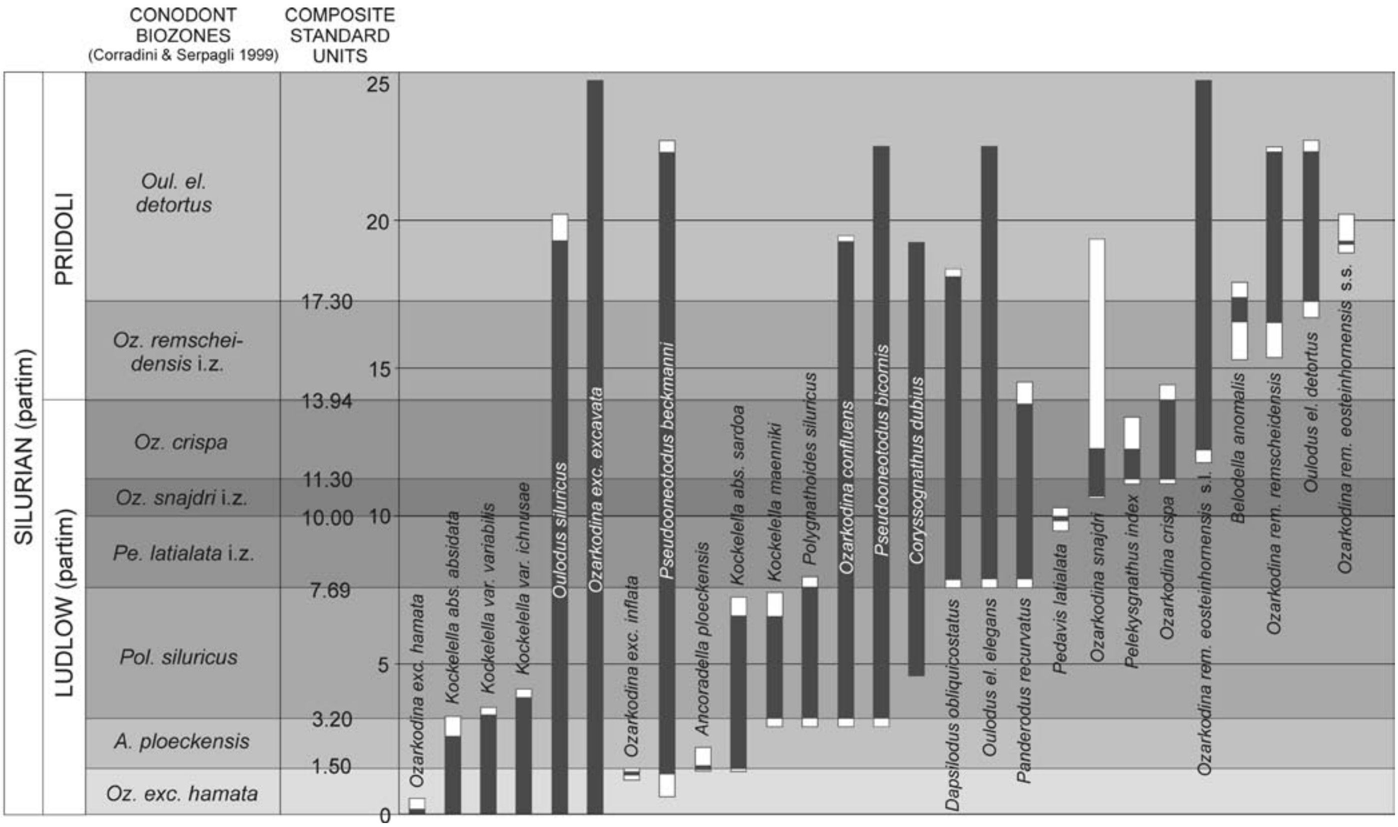

Fig. 4. Conodont range chart in the Sardinian Ockerkalk.

Results

In this graphic correlation project the obvious standard reference section is Silius I. It is by far the best section of the area. The sections were correlated with the reference section in this order: Genna Ciuerciu, Riu Murru de Callus, Genna Arrela, Monte Fruccas, Ponte Monte Lora, San Basilio Fenugu, and Punta Carroga. The lines of correlation stabilised after five correlation rounds. The first three correlation graphs of the fifth round are shown in Fig. 2. Two of them indicate the presence of a fault and a repeated part of the section at the top (Fig. 2A, B), shown by the 'back jump' of the line of correlation. For the Genna Ciuerciu section the tops and bases in the field of the graph can be split quiet well by locating the line of correlation through the FAD of *Oz. confluens*, *Oz. crispa*, *K. maenniki, Pol. siluricus, Oz. snajdri, Pe. latialata*, and *Oul. el. detortus* and the LAD of *Pol. siluricus, Oz. crispa and Oz. confluens*. To cause the smallest as possible disturbance in the species ranges, a multi-segment line of correlation is used. The line is controlled by the FAD and LAD of *Oz. crispa* and the FAD of *D. obliquicostatus* in the repeated part. The Riu Murru de Callus section can be correlated with the reference section by a segmented line of correlation, intersecting the FAD of *A. ploeckensis, Oz. crispa* and *Pol. siluricus* and the LAD of *K. var. ichnusae* and *Oz. crispa*. In the repeated part the line is drawn between the FAD and LAD of *Oz. crispa*. For the Genna Arrela section, the fifth round shows a multi-segment line based on the FAD of *K. abs. sardoa, Oz. rem. remscheidensis* and *Oul. el. detortus* and the FAD and LAD of *Pol. siluricus* and *Oz. rem. eosteinhornensis* s.s. All data from the seven sections are reprojected onto the reference section through their respective lines of correlation to build the regional conodont composite standard.

The composite standard for the Silurian of SE Sardinia allows a subdivision of the upper Silurian Ockerkalk into 24.70 CSUs derived from the thickness measurement of the Silius section. It provides a much higher resolution than the traditionally used conodont zonation (Corradini & Serpagli 1999) that separates this interval into eight biozones. The bases of the conodont zones are situated at 1.50 CSU (*A. ploeckensis*), 3.20 CSU (*Pol. siluricus*) 7.69 CSU (*Pe. latialata* i.z.), 10.00 CSU (*Oz. snajdri* i.z.), 11.30 CSU (*Oz. crispa*), 13.94 CSU (*Oz. remscheidensis* i.z.), and 17.30 CSU (*Oul. el. detortus*). Reprojection of the composite standard units from the composite standard onto each section creates a very detailed correlation between the composite standard and the sections, and between the sections (Fig. 3). This projection also allows the positioning of conodont zone boundaries in section parts almost barren of conodonts. The detailed conodont range chart obtained is reported in Fig. 4 and in the appendix.

Comparison with other areas and discussion

The SE Sardinia Composite Standard has been compared with a few other well known upper Silurian sections: Cellon (Carnic Alps; Walliser 1964), Klonk (Bohemia; Jeppsson 1988), Mason Porcus (SW Sardinia; Olivieri & Serpagli 1990), and with the Silurian Composite Standard (SCS) by Kleffner (pers. com.).

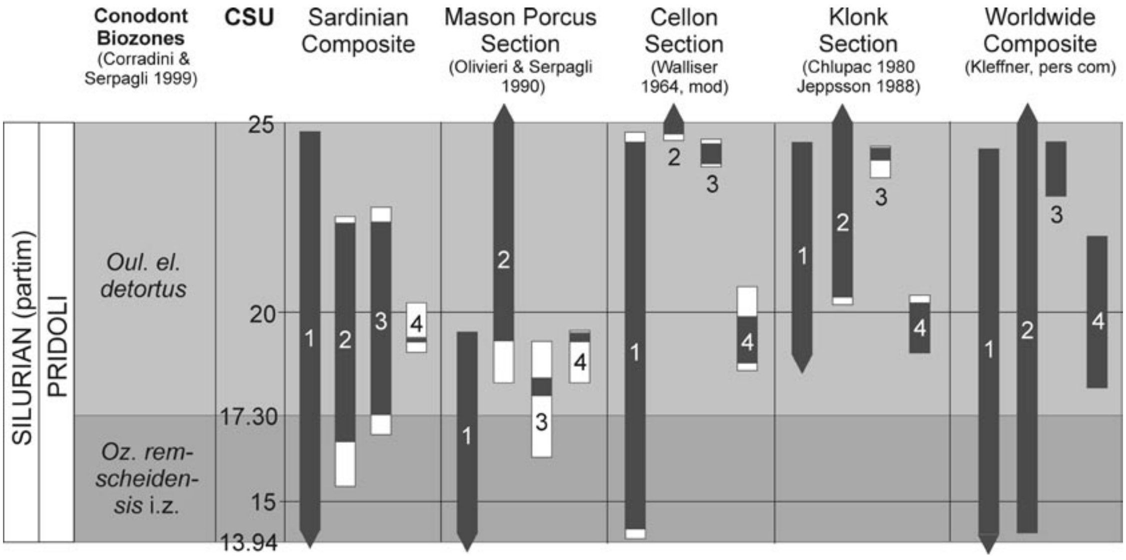

Fig. 5. Comparison of the range of selected Přídolí taxa in the Ockerkalk Composite, in the Silurian Composite Standard and in other sections. Ranges indicated in dark grey, error boxes drawn in white. 1 – *Ozarkodina rem. eosteinhornensis* s.l.; 2 – *Oz. rem. remscheidensis*; 3 – *Oulodus elegans detortus*; 4 – *Ozarkodina rem. eosteinhornensis* s.s.; i.z. – interval zone.

Updated data from Cellon have been obtained thanks to a restudy of Walliser material during a scientific visit by C.C. in Göttingen.

These comparisons demonstrate that most of the conodont taxa have a similar range in Sardinia and the other areas, while a few taxa show remarkable differences. For two of the latter, this fact was already stated in the literature: *Coryssognathus dubius* reaches into the Přídolí (Serpagli et al. 1997) and *Pseudooneotodus bicornis* reaches the top of the Silurian (Corradini 2001) in Sardinia. The third main range variation is recognised here for the first time: *Oulodus elegans detortus* has its FAD in Sardinia well before that in other regions. Figure 5 shows the compared occurrence of the stratigraphically most important conodont taxa for the Přídolí in the Sardinian upper Silurian composite, in the other sections considered and in the SCS. To obtain this figure, we graphically correlated the other sections with the SE Sardinian Standard, in order to have all the data referred to the same scale.

In the studied localities outside Sardinia, *Oul. el. detortus* has a very short range in the latest Přídolí. Beside these localities, this is also the case in the Monte Cocco area (eastern part of the Italian side of the Carnic Alps; Corradini unpubl. data), in other Bohemian sections and in the Spanish Sahara (Jeppsson 1988). In Sardinia the range is definitely different, since it first appears in the middle part of the Přídolí and disappears before the end of the Silurian. However since the conodont abundance in the top Přídolí strata is quite low, it could be possible that in the future the taxa will be found higher up into the Silurian. In SW Sardinia *Oul. el. detortus* occurs only within the lower part of the species range in the Ockerkalk Composite, i.e. well below the occurence of the taxon elsewhere. Therefore, it is evident that *Oul. el. detortus* has an older range in Sardinia than anywhere else. This is also confirmed by the relative position of *Oul. el. detortus* and *Oz. rem. eosteinhornensis* s.s. in the range charts. *Oz. rem. eosteinhornensis* s.s. is considered the morphotype closest to the holotype figured by Walliser (1964, pl. 20, fig. 21), having a node or a small ridge on one side of the platform. *Oz. rem. eosteinhornensis* s.s. has a short range, easily comparable in all considered sections and in the SCS. In Sardinia it falls within the range of *Oul. el. detortus*, while elsewhere it is found well below.

The different range of *Oul. el. detortus* in Sardinia has important implications for the conodont biostratigraphy: in fact, in almost all biostratigraphic schemes the FAD of this taxon marks the base of the youngest Silurian biozone. Among the characteristics of a good marker, the most important fact is that its first occurrence should be synchronous everywhere. Therefore, the use of *Oul. el. detortus* should be discouraged in worldwide correlations but can still be used in local studies to indicate upper Přídolí strata. For interregional correlations it looks to be more appropriate to use *Oz. rem. eosteinhornensis* s.s., even if this taxon has only a short range and does not reach the top of the Silurian.

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Appendix

Conodont ranges in the SE Sardinian Silurian Composite Standard. FAD: first appearance datum, LAD: last appearance datum. ***: errorbox not defined. Errorboxes indicate error caused by the sampling distance.

Conodont species	FAD	(error box)	LAD	(error box)
1. *Ancoradella ploeckensis* Walliser, 1964	1.50	(1.43)	1.61	(2.17)
2. *Belodella anomalis* Cooper, 1974	16.60	(15.30)	17.40	(17.90)
3. *Coryssognathus dubius* (Rhodes, 1953)	3.20	(2.91)	18.79	(***)
4. *Dapsilodus obliquicostatus* (Branson & Mehl, 1933)	7.90	(7.60)	18.12	(18.31)
5. *Kockelella abs. absidata* Barrick & Klapper, 1976	0.00	(***)	2.59	(3.24)
6. *Kockelella abs. sardoa* Serpagli & Corradini, 1998	1.50	(1.40)	6.60	(7.34)
7. *Kockelella maenniki* Serpagli & Corradini, 1998	3.20	(2.90)	6.60	(7.51)
8. *Kockelella var. ichnusae* Serpagli & Corradini, 1998	0.00	(***)	3.90	(4.14)
9. *Kockelella var. variabilis* Walliser, 1957	0.00	(***)	3.28	(3.55)
10. *Oulodus el. detortus* (Walliser, 1964)	17.30	(16.81)	22.30	(22.70)
11. *Oulodus el. elegans* (Walliser, 1964)	7.90	(7.60)	22.47	(***)
12. *Oulodus siluricus* (Branson & Mehl, 1933)	0.00	(***)	19.35	(20.20)
13. *Ozarkodina confluens* (Branson & Mehl, 1933)	3.20	(2.90)	19.27	(19.43)
14. *Ozarkodina crispa* (Walliser, 1964)	11.30	(11.10)	13.94	(14.45)
15. *Ozarkodina exc. excavata* (Branson & Mehl, 1933)	0.00	(***)	24.70	(***)
16. *Ozarkodina exc. hamata* (Walliser, 1964)	0.00	(***)	0.10	(0.48)
17. *Ozarkodina exc. inflata* (Walliser, 1964)	1.30	(1.10)	1.40	(1.50)
18. *Ozarkodina rem. eosteinhornensis* s.l. (Ziegler,1960)	12.30	(11.80)	24.70	(***)
19. *Ozarkodina rem. eosteinhornensis* s.s. (Walliser, 1964)	19.20	(18.90)	19.35	(20.20)
20. *Ozarkodina rem. remscheidensis* (Ziegler, 1960)	16.60	(15.38)	22.30	(22.47)
21. *Ozarkodina snajdri* (Walliser, 1964)	10.69	(10.60)	12.30	(19.35)
22. *Panderodus recurvatus* (Rhodes, 1953)	7.90	(7.60)	13.82	(14.56)
23. *Pedavis latialata* (Walliser, 1964)	9.90	(9.50)	10.00	(10.29)
24. *Pelekysgnathus index* (Klapper & Murphy, 1975	11.30	(11.10)	12.30	(13.35)
25. *Polygnathoides siluricus* Branson & Mehl, 1933	3.20	(2.91)	7.69	(7.94)
26. *Pseudooneotodus beckmanni* (Bischoff & Sanneman, 1957)	1.33	(0.54)	22.30	(22.70)
27. *Pseudooneotodus bicornis* Drygant, 1984	3.20	(2.90)	22.47	(***)