Applications of quantitative biostratigraphy in chronostratigraphy and time scale construction

József Pálfy
Research Group for Paleontology, Hungarian Academy of Sciences–Hungarian Natural History Museum, POB 137, Budapest, H-1431 Hungary
email: palfy@nhmus.hu

ABSTRACT: Quantitative biostratigraphy finds useful applications in chronostratigraphy and time scale calibration. Fixing the Global Stratotype Section and Point (GSSP) is made more objective if correlation potential of alternative boundary levels is compared using the Unitary Association (UA) method. The base of the Ladinian (Middle Triassic) GSSP is a case in which not the regionally most easily correlatable ammonoid datum was selected. Radio-isotopic dates are often obtained outside the province where the primary standard biozonation is established, introducing a correlation uncertainty into time scale calibration. In the Early Jurassic, an uncertainty of approximately one standard ammonoid substage is demonstrated using the UA method, if using a North American U-Pb date requires correlation with the northwest European zonation. The resolution of the time scale was significantly improved for the Ordovician and Silurian by employing constrained optimization to construct a global sequence of graptolite bioevents. Interpolation between the available U-Pb dates is possible by scaling using the assumption of near-constant sedimentation rate in pelagic facies. Future uses of quantitative biostratigraphy may include exploitation of large paleontologic databases (e.g. the Paleobiology Database) and contribution to the generation of dynamic, interactive geologic time scales.

INTRODUCTION

Biostratigraphy can best harness the full potential of vast amount of spatial and temporal distribution data of fossil organisms by using quantitative, computer-assisted techniques. Following notable forerunners such as the graphic correlation method (Shaw 1964), modern quantitative stratigraphy developed spectacularly during the 1980s, in response to the increasing availability of computers (e.g. Gradstein et al. 1985). The personal computer revolution, in full swing by the 1990's, provided adequate computing power to every user to run sophisticated algorithms on large amount of raw stratigraphic data. Yet a mental barrier of traditionalist biostratigraphers proved more powerful than vanishing limitations of computing resources and prevented many practitioners from embracing quantitative stratigraphic methods. Gradually gaining popularity, however, a wide range of quantitative stratigraphic methods is now available.

As Phanerozoic chronostratigraphic units are primarily based on biostratigraphic definition, successful quantitative approaches to biostratigraphy are useful for modern chronostratigraphy. I will focus on those applications that offer the best potential for chronostratigraphic use. Methods from the family of deterministic techniques, including the Unitary Association (UA) (Guex 1991) and Constrained Optimization (CONOP) methods (Kemple et al. 1995), have proved their strength beyond the most common use of solving correlation problems. Herein I present three case studies to demonstrate the relevance of computer-assisted biostratigraphic methods for chronostratigraphic and time scale issues. The first one suggests a way to impartially assess the correlation potential of boundary horizons considered in a GSSP selection process. The second one attempts to quantify the biochronologic correlation uncertainty for time scale calibration. The third one provides a method for interpolation of time scale between calibration points. Finally, I outline some of the possibilities where quantitative biostratigraphy can lead to further improvements of the geologic time scale.

Assessing the correlation potential of boundary horizons

A major ongoing activity of the International Commission on Stratigraphy is the typological standardization of the chronostratigraphic scale by selection of GSSPs (Global Stratotype Section and Point). In some cases the votes that decide the GSSP selection are hotly contested, especially if more than one boundary level is considered by the stratigraphic community. Quantitative stratigraphic methods can bring an element of objectivity in debates that are sometimes contaminated by non-scientific aspects. The recently settled Anisian–Ladinian boundary (Middle Triassic) (Brack et al. 2005) provides an example to demonstrate the potential utility of quantitative stratigraphy in assessing boundary issues.

A consensus had existed that the base of the Ladinian should be defined on the basis of ammonoids in a western Tethyan section. However, no less than five possible levels were suggested and three formal proposals were put forward, for the base of the Reitzi Zone (Vörös et al. 2003), the Avisianum Subzone (Mietto et al. 2003) and the Curionii Zone (Brack et al. 2003), respectively. In the period leading up to the votes, Pálfy and Vörös (1998) used the UA method to provide an unbiased evaluation of boundary proposals. The UA method is well-suited for assessing both the magnitude of biotic turnover at and the correlatability of the various horizons under consideration. The ammonoid distribution of the 14 best documented stratigraphic sections from two key areas of the western Tethys (Southern Alps, Italy and the Balaton Highland, Hungary) was analysed. For the present review I updated the stratigraphic database with new information published in the past 10 years (Mietto et al. 2003, Vörös et al. 2003, Brack et al. 2005, Manfrin et al. 2005). From all localities, published ranges of 60 taxa that occur in multiple sections were processed using the BioGraph software (Savary and Guex 1991) and its implementation in the PAST software package (Hammer et al. 2001).

In the broad Anisian–Ladinian boundary interval 22 UA (i.e. elementary biostratigraphic units) were distinguished (Fig. 1) which can be readily grouped to conform with conventional biostratigraphic terminology. The most pronounced faunal change occurs at the base of the Avisianum Subzone (UA 11), which is characterized by the highest number of incoming taxa. On the basis of their faunal content, the Reitzi Zone and its Reitzi and Avisianum subzones offer robust correlation between the Southern Alps and the Balaton Highland. The Avisianum Subzone has the highest diversity within the studied interval and is easily correlatable between most sections. On the other hand, the UA 20–22 corresponding to the Curionii Zone are characterized by significantly fewer taxa, several of which are restricted to few sections and only one region.

However, the underlying UA 19 that corresponds to the *Chieseiceras chiesense* horizon is well reproducible in both regions. Eventually, the base of the Ladinian was defined at the base of the Curionii Zone (i.e. UA 20 in this scheme), a choice not fully supported by the quantitative biostratigraphic analysis presented here.

It was argued that the the marker event of the GSSP, the FAD (First Appearance Datum) of *Eoprotrachyceras* permits Tethyan to Panthalassan correlation. A lack of common taxa hinders global correlation at the species level, therefore our study necessarily remains restricted to the western Tethyan ammonoid record. Insights from the next case study, however, suggest caution as FADs of Jurassic ammonoid genera are often proven diachronous in different ocean basins.

Quantifying biochronologic correlation error

A notoriously difficult, hence commonly ignored problem of time scale construction is the error estimation of biostratigraphic correlation. A striking inbalance exists between the rigorously calculated errors of radioisotopic ages and the biostratigraphic correlation charts that typically show no indication of any error or uncertainty. A Toarcian (Early Jurassic) example is presented to illustrate how the UA method can be employed for assessment of biostratigraphic error of ammonoid-based correlation for time scales. The Jurassic standard chronostratigraphy is founded on well-established northwest European ammonoid biostratigraphy. Because this region lacks radio-isotopically dateable units, the majority of time scale calibration points is obtained from volcanic island arc terranes of western North America (Pálfy et al. 2000). An example is a biostratigraphically tightly constrained U-Pb age (Pálfy et al. 1997) from the most highly resolved ammonoid-bearing North American Toarcian stratigraphic section at Yakoun River in the Queen Charlotte Islands (Jakobs 1997). Several North American Toarcian regional ammonoid zones are defined in this section (Jakobs et al. 1994), including the Crassicosta Zone from which the isotopically dated sample was collected. Traditionally, the Crassicosta Zone is correlated with the standard Variabilis Zone except for its lowermost part (Jakobs et al. 1994). However, it is recognized that paleobiogeographic differences and complex space–time distribution pattern of certain taxa confounds correlation and FAD/LAD (First/Last Appearance Datum) sequences may be significantly different in different faunal realms and provinces. For intercontinental correlation, the advantage of the UA method over conventional expert-based biostratigraphy lies in that it seeks out maximum ranges, does not discriminate regarding the correlation value of different taxa, and is able to process a large number of sections and taxon occurrences.

To correlate between North American and northwest European ammonoid successions, a global biostratigraphic correlation web was built by selecting 16 of the most complete and representative sections of four provinces, including South America and the Tethys. Processing occurrence data of 103 ammonoid taxa produced a framework of 40 UA, treated as elementary biostratigraphic units (Pálfy et al. 1997, fig. 5).The environs of Thouars in France is traditionally regarded as the type region of Toarcian biostratigraphy. The standard Variabilis Zone and under- and overlying units are particularly well-documented from the section at Anse Saint-Nicolas by Gabilly (1976). The UA-based correlation between Yakoun River and Anse Saint-Nicolas is therefore regarded to best approximate the correlation to the primary standard. At Yakoun River, the isotopically dated level falls within the interval of UA 22 to 25 (Pálfy et al. 1997, fig. 6). The characteristic events of these UAs, the FAD of *Denckmannia, Haugia variabilis,* and *Brodeia primaria* are used to define at Anse Saint-Nicolas the standard Variabilis and Illustris subzones of Variabilis Zone. Thus it is concluded that the uncertainty in correlating the isotopically dated North American level with the primary standard is ±1 subzone.

The probabilistic ranking and scaling method (RASC) can more readily calculate the correlation uncertainty using its sister method, the CASC (correlation and standard error calculation) (Gradstein and Agterberg 1998) but they are inferior to deterministic approaches beyond the regional or basin-wide scale. For intercontinental or global correlation, deterministic methods that seek maximum ranges are recommended and a case-by-case assessment of uncertainty is necessary.

Interpolation of boundary ages between tie-points in time scale

Calibration points such as the U-Pb dated level and its biostratigraphic constraints discussed above form the backbone of the geological time scale. A further step remains necessary in constructing time scales: the interpolation and scaling between the available sparse calibration points. It is imperative to abandon the simplistic notion of equal duration of biochronologic units (either ages, chrons, or subchrons) used in earlier time scales (e.g. Harland et al. 1990). For the Ordovician and Silurian part of the most recent geological time scale (Gradstein et al. 2004), Sadler and Cooper (2004) employed the CONOP method to build a global composite graptolite biochronology. CONOP differs from the UA method in that it seeks to determine the sequence of events (FADs and LADs) rather than the sequence of successive faunal assemblages. The method may be regarded as a multidimensional implementation of graphic correlation. A world-wide dataset of more than 230 measured sections with

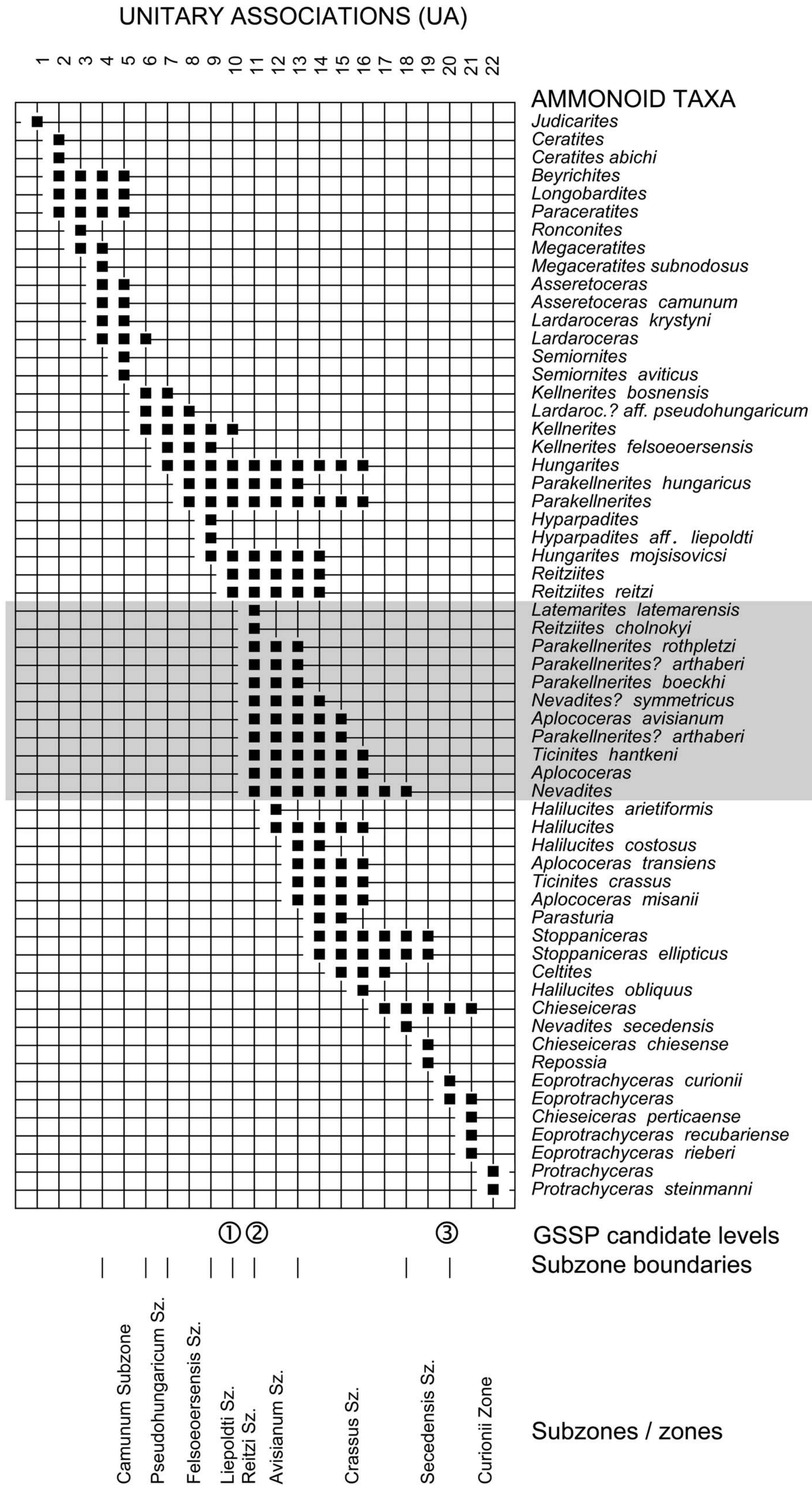

FIGURE 1
Ranges of 60 ammonoid taxa in the Anisian–Ladinian boundary interval of the Southern Alps and Balaton Highland, in the framework of 22 Unitary Associations determined using the BioGraph software. Numbers 1 to 3 along the zonal/subzonal scheme mark the three proposed GSSP levels. Note that option 2 (base of Avisianum subzone) shows the largest faunal turnover (shading denotes incoming taxa at this level) and best correlation potential but option 3 was eventually selected to define the boundary. Modified after Pálfy and Vörös (1998).

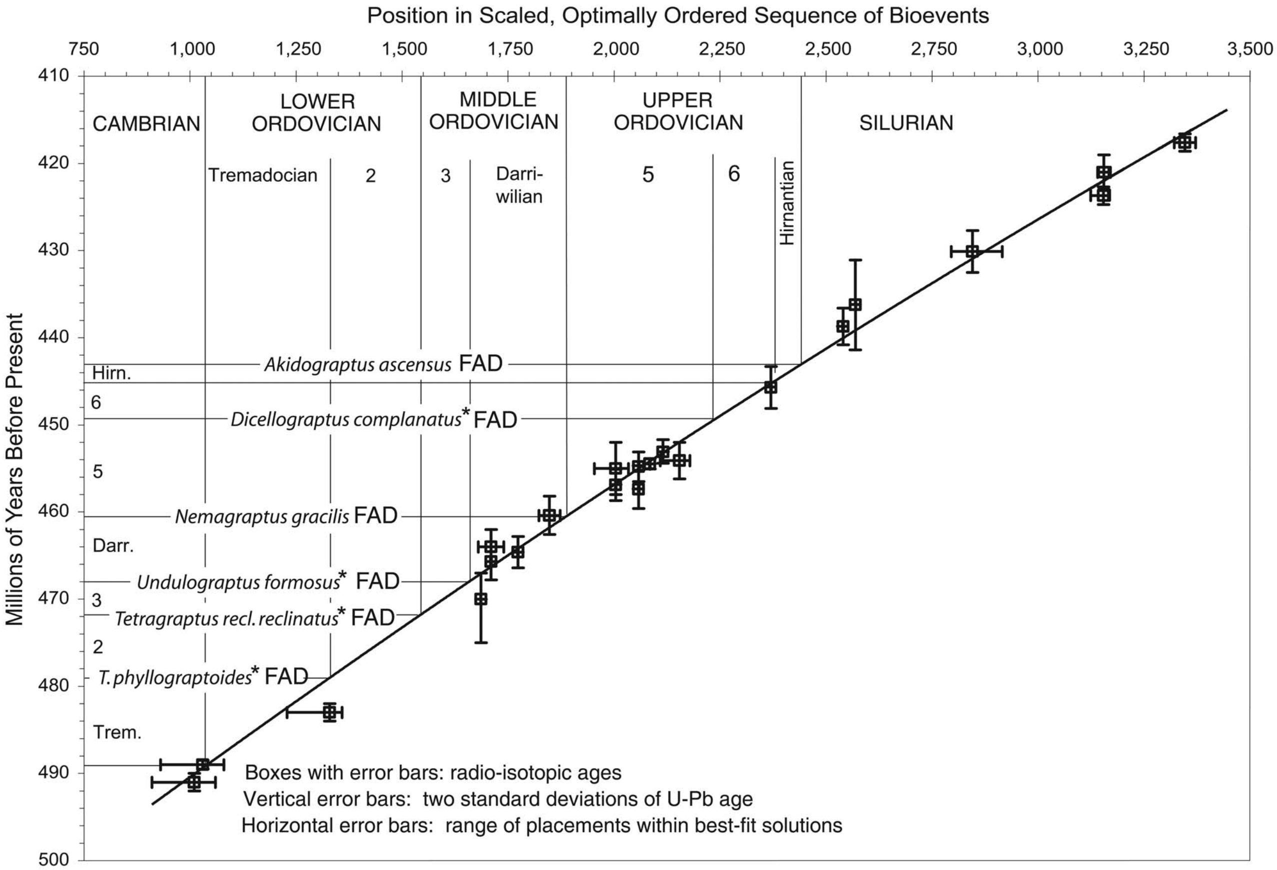

FIGURE 2
The Ordovician numeric time scale, calibrated using radio-isotopic dates and a sequence of graptolite bioevents as determined by the CONOP algorithm. Note that scaling of the sequence on horizontal axis uses relative time deduced from stratigraphic thickness and projection to the time (vertical) axis employs a regression line fitted through the radio-isotopic dates. Modified after Sadler and Cooper (2004) and Cooper and Sadler (2004).

occurrences of some 1400 species was built and processed using CONOP9 software to derive a global composite sequence of graptolite bioevents (Sadler et al. 2004). Graptolites as pelagic organisms occur mostly in deep-water shaly facies for which it is geologically reasonable to assume near-constant sedimentation rates locally over various time spans. Thus local stratigraphic thicknesses separating successive events can be averaged and used to scale the composite sequence. There are now 20 radio-isotopic dates available from the Ordovician and Silurian. Placing them in the framework of composite graptolite bioevents allows interpolation of intervening biochronological boundaries by linear or spline fitting. This can be fine-tuned using interpolation derived from the relative time scale of bioevents derived from sediment thickness distribution. The resulting high-resolution time scale (Sadler and Cooper 2004, Cooper and Sadler 2004) is reproduced here in Figure 2.

Concluding remarks

Quantitative biostratigraphy shall play an increasing role in refining chronostratigraphy and the geological time scale. The pending selection of the as yet undecided stage boundary GSSPs may benefit from the unbiased evaluation of correlation potential of alternative primary marker events through the UA method.

The accuracy and reliability of the geological time scale can be enhanced if the biochronological correlation error is fully assessed in its construction. Computer-assisted methods (UA, CONOP, and RASC/CASC) are amenable to quantify the uncertainty which cannot be neglected in long-distance correlation involving different continents or ancient ocean basins.

Until a much larger set of biostratigraphically constrained radio-isotopic dates will be available, interpolation remains an important step in time scale calibration. High-resolution global composite sequences of pelagic organisms preserved in facies with near-constant sedimentation rates shall help fine-tune the pre-Middle Jurassic time scale, for which sea-floor magnetic anomalies cannot be used and reliable astronomical calibration is not yet achievable.

Increasingly large and comprehensive databases such as the Paleobiology Database are suitable for systematic entering and "mining" biostratigraphic data for use in chronostratigraphy and time scale calibration. Such collaborative, international efforts may provide the most effective use of biostratigraphic data accumulated over centuries of paleontological research. As discussed at the 2006 Penrose Conference on Chronostratigraphy, the geological time scale is evolving towards a dynamic model that accommodates newly acquired data. The emerging platforms shall include quantitative biostratigraphic methods for efficient and flexible handling of paleontologic data of chronologic significance.

ACKNOWLEDGMENTS

The organizers and participants of the Penrose Conference at Seggau, Austria are thanked for a stimulating meeting and thoughtful feedback on my presentation that formed the basis of this paper. Comments by P. Ozsvárt and A. Vörös helped improve the manuscript. B. McGowran is thanked for his patience, encouragement, and editorial help. The research was supported by a grant from the Hungarian Scientific Research Fund (OTKA T042802).

REFERENCES

BRACK, P., RIEBER, H., NICORA, A. and MUNDIL, R., 2005. The Global Boundary Stratotype Section and Point (GSSP) of the Ladinian Stage (Middle Triassic) at Bagolino (Southern Alps, Northern Italy) and its implications for the Triassic time scale. *Episodes,* 28(4): 233-244.

BRACK, P., RIEBER, H. and NICORA, A., 2003. The Global Stratigraphic Section and Point (GSSP) of the base of the Ladinian Stage (Middle Triassic). A proposal for the GSSP at the base of the Curionii Zone in the Bagolino section (Southern Alps, Northern Italy). *Albertiana,* 28: 13-25.

COOPER, R.A. and SADLER, P. M., 2004. The Ordovician Period. In: Gradstein, F.M., Ogg, J.G. and Smith, A.B., Eds., *A Geologic Time Scale 2004.* Cambridge: Cambridge University Press, 165-187.

GABILLY, J., 1976. *Le Toarcien a Thouars et dans le centre-ouest de la France.* Les Stratotypes français, 3. Paris, Centre Nationale de la Recherche Scientifique, 217 pp.

GRADSTEIN, F.M. and AGTERBERG, F.P., 1998. Uncertainty in stratigraphic correlation. In: Gradstein, F.M., Sandvik, K.O. and Milton, N.J., Eds., *Sequence stratigraphy, concepts and applications*, 9-29, Norwegian Petroleum Society Special Publication 8.

GRADSTEIN, F.M., AGTERBERG, F.P., BROWER, J.C. and SCHWARZACHER, W., 1985. *Quantitative Stratigraphy.* Paris: Reidel and UNESCO, 598 pp.

GRADSTEIN, F. M., OGG, J. G. and SMITH, A. G., 2004. *A Geologic Time Scale 2004.* Cambridge: Cambridge University Press, 589 pp.

GUEX, J., 1991. *Biochronological correlations.* Berlin: Springer-Verlag, 252pp.

HAMMER, O., HARPER, D.A.T. and RYAN, P.D., 2001. PAST: Paleontological Statistics software package for education and data analysis. *Palaeontologia Electronica, 4(1):* 9 pp. (http://palaeo-electronica.org/2001_1/past/issue1_01.htm).

HARLAND, W.B., ARMSTRONG, R.L., COX, A.V., CRAIG, L.E., SMITH, A.G. and SMITH, D.G., 1990. *A Geologic Time Scale 1989.* Cambridge: Cambridge University Press, 263 pp.

JAKOBS, G.K., 1997. Toarcian (Early Jurassic) ammonoids from western North America. *Geological Survey of Canada Bulletin,* 428: 137pp.

JAKOBS, G.K., SMITH, P.L. and TIPPER, H.W., 1994. An ammonite zonation for the Toarcian (Lower Jurassic) of the North American Cordillera. *Canadian Journal of Earth Sciences,* 3 1(6): 919-942.

KEMPLE, W.G., SADLER, P.M. and STRAUSS, D.J., 1995. Extending graphic correlation to many dimensions: stratigraphic correlation as constrained optimization. In: Mann, K.O. and Lane, H.R., Eds., *Graphic Correlation*, 65-82. Society for Sedimentary Geology Special Publication 53.

MANFRIN, S., MIETTO, P. and PRETO, N., 2005. Ammonoid biostratigraphy of the Middle Triassic Latemar platform (Dolomites, Italy) and its correlation with Nevada and Canada. *Geobios,* 38(4): 477-504.

MIETTO, P., MANFRIN, S., PRETO, N., GIANOLLA, P., KRYSTYN, L. and ROGHI, G., 2003. Proposal of the Global Stratigraphic Section and Point (GSSP) for the base of the Ladinian Stage (Middle Triassic). GSSP at the base of the Avisianum Subzone (FAD of *Aplococeras avisianum)* in the Bagolino section (Southern Alps, NE Italy). *Albertiana,* 28: 26-34.

PÁLFY, J. and VÖRÖS, A., 1998. Quantitative ammonoid biochronological assessment of the Anisian-Ladinian (Middle Triassic) stage boundary proposals. *Albertiana,* 21: 19-26.

PÁLFY, J., PARRISH, R.R. and SMITH, P.L., 1997. A U–Pb age from the Toarcian (Lower Jurassic) and its use for time scale calibration through error analysis of biochronologic dating. *Earth and Planetary Science Letters,* 146(3-4): 659-675.

PÁLFY, J., SMITH, P.L. and MORTENSEN, J.K., 2000. A U-Pb and $^{40}Ar/^{39}Ar$ time scale for the Jurassic. *Canadian Journal of Earth Sciences,* 37(6): 923-944.

SADLER, P.M. and COOPER, R.A., 2004. Calibration of the Ordovician timescale. In: Webby, B.D., Droser, M.L. and Paris, F., Eds., *The Great Ordovician Biodiversification Event.* New York: Columbia University Pr ess, 48-51.

SADLER, P.M., KEMPLE, W.G. and KOOSER, M.A., 2004. CONOP9 programs for solving the stratigraphic correlation and seriation problems as constrained optimizitaion. In: Harries, P.J., Ed., *Approaches in High-Resolution Stratigraphic Paleontology.* Dordrecht: Kluwer, 461-465.

SAVARY, J. and GUEX, J., 1991. BioGraph: un nouveau programme de construction des corrélations biochronologiques basées sur les associations unitaires. *Bulletin de Géologie, Lausanne,* 313: 317-340.

SHAW, A.B., 1964. *Time in stratigraphy.* New York: McGraw-Hill, 365 pp.

VÖRÖS, A., BUDAI, T., HAAS, J., KOVÁCS, S., KOZUR, H. and PÁLFY, J., 2003. GSSP (Global Boundary Stratotype Section and Point) proposal for the base of Ladinian (Triassic). A proposal for the GSSP at the base of the Reitzi Zone (sensu stricto) at Bed 105 in the Felsörs section, Balaton Highland, Hungary. *Albertiana,* 28: 35-47.