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REFLECTIONS ON THE GEOLOGICAL TIME SCALE

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Abstract. Stratigraphic and geomathematical interpolation methods are needed to achieve the Phanerozoic Geological Time Scale. Currently, only the 31 successive stage boundaries within the Mesozoic part have estimates of uncertainty attached to the ages. Constraints on the current Phanerozoic scale are both of a stratigraphic and geochronologic nature, as outlined for several stage boundaries in the Paleozoic and Mesozoic. Agreement, not only on the stratigraphic definition of stages, but also on employment of time scale methods will enhance the consensus character of the geologic time scale and stability in earth science applications.

Keywords: Stratigraphic philosophy, Geological Time scale, Geochronology, Radiometrics, Orbital Time scale, Phanerozoic, Cambrian, Triassic, Seafloor spreading.

INTRODUCTION

Since the publication of time scales in the eighties (e.g., Haq et al., 1988; Harland et al., 1990), a considerable amount of new age dates and more detailed magneto- and biostratigraphy have led to a more precise and more accurate Phanerozoic geochronology. In this study we summarize the 'state of the art', and reflect on activities in progress to arrive at a more detailed time scale.

STRATIGRAPHIC PHILOSOPHY

Human Time

Time is an indispensable tool for all of us. The time kept by innumerable watches and clocks organizes our every day life, while the familiar calendar governs our weekly, monthly and yearly doings that eventually condense into the historical record of the events over centuries. The standard unit of modern time keeping is the second, defined by a precise number of vibrations of the cesium atomic clock. Some sophisticated house clocks keep standard time by calibrating themselves continuously to the extremely low frequency signals coming out of time-keeping radio stations.

The tick of the second paces the quick heart beat, but neither the minute nor the hour is based on natural phenomena. The day carries the record of light and dark, the month the regularly returning shapes of the moon, and the year the cycle of the seasons and the apparent path of the sun. All is clear, and we have grown up with the notion that time is a vector, pointing to the future. Events shape and mark the arrow of time along its path.

Geologic Time and the Rock Record

What is less clear is the concepts of geological time -- what its units are based on, and how to use these units properly. A good understanding of geological time is vital to every scientist that strives to understand geological processes and determine rates of change. This understanding takes place in the framework called Earth Geological History, the super calendar of local and global events since Earth was born. The challenge to this understanding is reading, organizing and sorting the calendar pages in stone, and, last but not least, reconstructing its missing pages. Correlation is a vital part of the reconstruction process.

Geological correlation traditionally is expressed in terms of five progressive systems:

- Rock units, like formations or well log intervals = lithostratigraphic correlation: *Kimmeridge Clay Formation* of England;
- Fossil units, like zones = biostratigraphic correlation: *Turrilina alsatica* benthic foraminifer zone;
- Relative time units = geochronologic ('Earth time') correlations: *Jurassic Period, Eocene Epoch, Oxfordian Age, polarity chron C29r*;
- Rocks deposited during these time units = chronostratigraphic (time - rock) correlation: *Jurassic System, Eocene Series, Oxfordian Stage, polarity zone C29r*.
- Linear time units or ages = geochronologic correlation: *150 Ma, 10 ka*.

Without correlation to a global reference scale, successions of strata or events in time derived in one area, are unique and contribute nothing to understand Eearth history elsewhere.

Before we deal with linear geological time, a few words about the common geological calendar built from relative age units. This calendar called chronostratigraphic calendar is not unlike a historical calendar in which civilization periods, such as the Minoan Period, Reign of Louis XIV or American Civil War, are used as building blocks, devoid of a linear scale. Archeological relicts deposited during these intervals, such as the Palace of Minos on Crete, Versailles or spent cannon balls at Gettysburg, comprise the associated physical chronostratigraphic record.

Standardizing Geologic Time Subdivisions

Geochronology and associated chronostratigraphy are entirely relative and have led to the commonly used scale of geological systems and stages shown on the enclosed time scale (Figure 1) with their equivalent geochronologic periods and ages. The standard chronostratigraphic scheme is made up of successive stages in the rock record, like Cenomanian, Turonian, then Coniacian etc., within the Cretaceous system. Originally, each stage unit was a well-defined body of rocks at a specific location of an assigned and agreed upon relative age span, younger than typical rocks of the underlying stage and older than the typical rocks of the next higher stage. The principles and building blocks of

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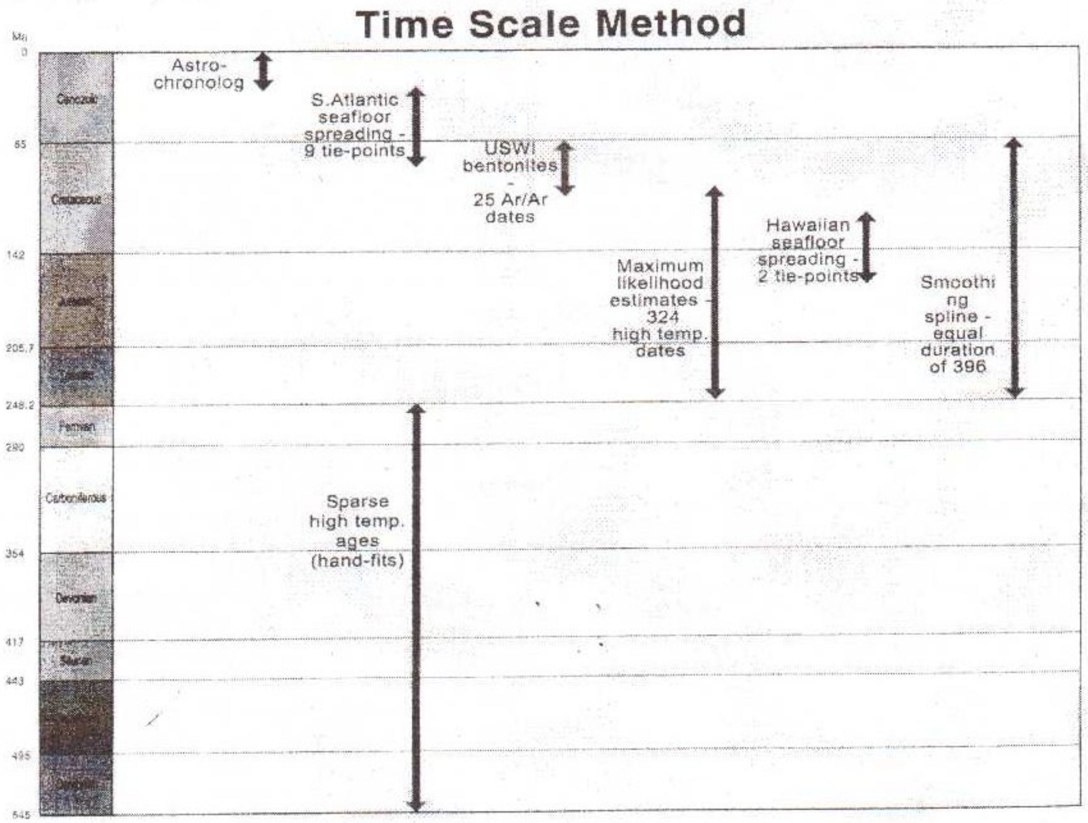

Figure 1 - Methods to achieve the geologic time scale in figure 2.

this chronostratigraphy were slowly established during a century of study in many discontinuous and incomplete outcrop sections. Inevitably, lateral changes in lithology between regions and lack of agreement on criteria, particularly which fossils were characteristic of which relative unit of rock, have always resulted in a considerable amount of confusion and disagreement on stage nomenclature and stage use. A suite of global subdivisions with precise correlation horizons were required. Now, relatively rapid progress is being made with definition of GSSP's (Global Boundary Stratotype Sections and Points) to fix the lower boundary of all Phanerozoic stages. For the ladder of chronostratigraphy, this GSSP concept switches the emphasis to fixing the rungs (boundaries of stages) rather than marking the spaces between steps (stage stratotypes. Each progressive pair of GSSPs in the rock record also precisely defines the associated geochronologic subdivision of geologic time. Hence, philosophical arguments are being heard to cut out chronostratigraphy, and deal only with lithostratigraphic ,and geochronologic and chronologic units. Essentially, the argument is that dual systems of precisely defined subdivisions of geological time and of parallel similarly defined subdivisions of the time-rock record are redundant. Or, even more radical, why not replace the hundreds of melodious, but confusing, "ian" subdivisions (Gelasian, Sinemurian, Spathian, Emsian, etc.) with simple "real" ages — who needs the "Victorian Age" when one has a "Nineteenth Century"?

This brings us to correlationcorrelations in linear time units, called geochronologic correlation, with reference to the geochronologic calendar of Eearth events called Geological Time Scale.

BUILDING A LINEAR GEOLOGICAL TIME SCALE

There are two basic measuring tools to build the linear geological time scale -radiometric dates in millions of years, and tuned sedimentary cycles in thousands of years. Several sophisticated geological or geomathematical interpolation tools assist to calibrate the geological record where data are scarce or insufficient, and to calculate error bars. Figure 1 provides a summary of current time scale methods. It is beyond the scope of this brief review to reiterate methodological details, many of which have been addressed in studies cited. The outline in figure 1 is meant as a simple and quick overview of common methods employed in furnishing a geologic time scale. It is our philosophy that a better understanding of methods and constraints in establishing the scale will enhance consensus, to the benefit of consistent applications in earth sciences.

Music of the Spheres

Let us start with a brief outline of the principle in the sedimentary cycles approach to time scale building. Gravitational interactions of the Earth with the Sun, Moon and other planets cause systematic changes in the orbital and rotational system of our planet. These interactions give rise to cyclic oscillations in the eccentricity of the Eearth's orbit, and in the tilt and precession of the Earth's axis, with mean dominant periods of 100,000, 41,000 and 21,000 years respectively. The associated cyclic variations in annual and seasonal solar radiation onto different latitudes alter long-term climate in colder versus warmer and, wetter versus dryer periods that lead to easily recognizable sedimentary cycles, such as regular interbeds of limy and shaly facies. Massive outcrops of hundreds or thousands of such cycles are observed in numerous geological basins, for example around the Mediterranean, and in sediment cores from ocean drilling wells.

Counting of these centimeter- to meter- thick cycles in great detail over land outcrops and in ocean drilling wells, combined with the additional correlation aids provided by magnetostratigraphy, oxygen isotope stratigraphy and biostratigraphy, is producing a very detailed cycle scaling for the Neogene (youngest period on the enclosed figure). The critical step is the direct linkage of each cycle to the theoretical computed astronomical scale of the 21,000, 41,000 and 100,000 year paleoclimatic cycles. This astronomical tuning of the geological cycle record from the Mediterranean and Atlantic has led to unprecedented accuracy and resolution for the last 11 million years (e.g., Hilgen et al., 1997a). In turn, T. Naish and colleagues have now calibrated the upper Neogene record of New Zealand to late Neogene astrochronologic time scalescale by means of the high-resolution land-based cycle, isotope and magnetic record in the Wanganui Basin, New Zealand (Carter and Naish, 1999), thereby transferring precise absolute ages to local beds. Efforts are underway to extend the continuous astrochronologic scale back into Oligocene by applying a combination of cycle stratigraphy, astronomical projections, oxygen isotope stratigraphy and magnetostratigraphy to the deep sea record (Shackleton et al., 1999).

Decay of Atoms

For rocks older than Neogene, the derivation of a numerical time scale depends on the availability of suitable radiometric ages. Radiometric datings generally involves measuring the ratio of the original element in a mineral, like sanidine feldspar or zircon, to its isotopic daughter products. The age of a mineral may be then calculated by means of the isotopic decay constant. Depending on the half life of the element, several radiometric clocks are available; ^{87}Rb to ^{87}Sr, ^{40}K to ^{40}Ar and U to Pb are the most common suites applied to the Phanerozoic.

Radiometric dating of sedimentary rocks follows several geological strategies:

a. Dating of igneous intrusions within sediments records the time of primary cooling, when the igneous rocks were emplaced and had cooled sufficiently (to a few hundreds of degrees centigrade) to set the radiometric decay clock in action. Because of uncertainty in the relation of the intrusion to the host sediment, such dates may be of limited stratigraphic use.

b. Dating of volcanic flows and tuffs as part of the stratified sedimentary succession.

c. Dating of authigenic sedimentary minerals, mainly involving glauconite, found widespread in many marine sediments. Mild heating or overburden pressure after burial may lead to loss of argon, the daughter product measured in the ^{40}K to ^{40}Ar clock in glauconite. The result is that glauconite dates may be too young. Because of such problems, which may be difficult to detect, the present consensus geological time scale avoids dates based on glauconite.

Calibration of the decay constants or measurement standards can be enhanced by intercalibration to other radiometric methods, or by dating rocks of a known age, for example a volcanic ash within an astronomically tuned succession (Renne et al., 1994; Hilgen et al., 1997b). Astrochronologic and interlaboratory recalibration of the ^{40}Ar/^{39}Ar Ar/Ar monitor standard indicates that many of the ^{40}Ar/^{39}Ar ages used in the published Phanerozoic geological time scales are too young by about 0.5 to 1.0 %. For example, the 65.0 Ma age that was assigned to the K/T mass extinction that terminated the Cretaceous should be approximately 65.5 Ma.

Interpolation and Statistics

A major problem in time scale construction is the lack of suitable dates for parts of the Mesozoic and Paleozoic geological record. Ideally, each of the approximately 95 stage boundaries that comprise the Paleozoic, Mesozoic and Cenozoic eras of the Phanerozoic would coincide with an accurate radiometric date from volcanic ashes deposited at each of the boundaries. However, this coincidence is extremely rare in the geological record. The combined number of fossil events and magnetic reversals far exceeds the total number of datable horizons in the Phanerozoic. Therefore, a framework of bio-, magneto- and chronostratigraphy provides the principal fabric for constrained stretching the relative geological time scale between dated tiepoints on the loom of linear time.

For such stretching, interpolation methods are employed that are either statistical or geological in nature. Among the geological scaling methods, an assumption of relative constancy of seafloor spreading over limited periods of time is a common tool for interpolating parts of the Cretaceous and for the Paleogene relative time scale. Magnetic polarity chrons, the units of magnetochronology, can be recognized both on the ocean floor as magnetic anomalies measured in kilometers from the spreading center, and in marine sediments as polarity zones that contain biostratigraphic events and assemblages. Knowing the age of a few ocean crust magnetic anomalies (earth magnetic reversals or magnetochrons), allows interpolation of the ages of the intervening magnetic pattern, which in turn can be correlated to the fossil record and geological stage boundaries.

The subduction of pre-Late Jurassic oceanic crust precludes such an interpolation approach for older Mesozoic and the Paleozoic strata. In addition, radiometric dates are more sparse for the older part of the Phanerozoic, and new precise radiometric dates have amplified significance for placing stages into the linear time scale. Therefore, in contrast to the relatively well-dated, spreading-constrained and astronomical-tuned Cretaceous through Neogene scales, the older Phanerozoic is experiencing the most changes and updates as we progressively establish the modern geological time scale.

Lastly, a few words about uncertainty. On the enclosed consensus time scale, that forms the basis for an extensive suite of chronostratigraphic and sequence stratigraphy compilations for Europe (Hardenbol et al., 1998; Graciansky et al., 1998), the 31 Mesozoic age boundaries now show error bars. The error bars reflect both radiometric and also stratigraphic uncertainty, and were derived from mathematical and statistical calculations and interpolations. One challenge, other than periodic updating of the consensus time scale (roughly every 7 - 10 years), is to increase insight in the uncertainty of the age for successive stage boundaries. Outfitting stratigraphic reasoning with a measure of uncertainty is desirable. The uncertainty in the duration of the age units is much less than the error in age of their boundaries, but a quantitative estimate of this uncertainty awaits determination.

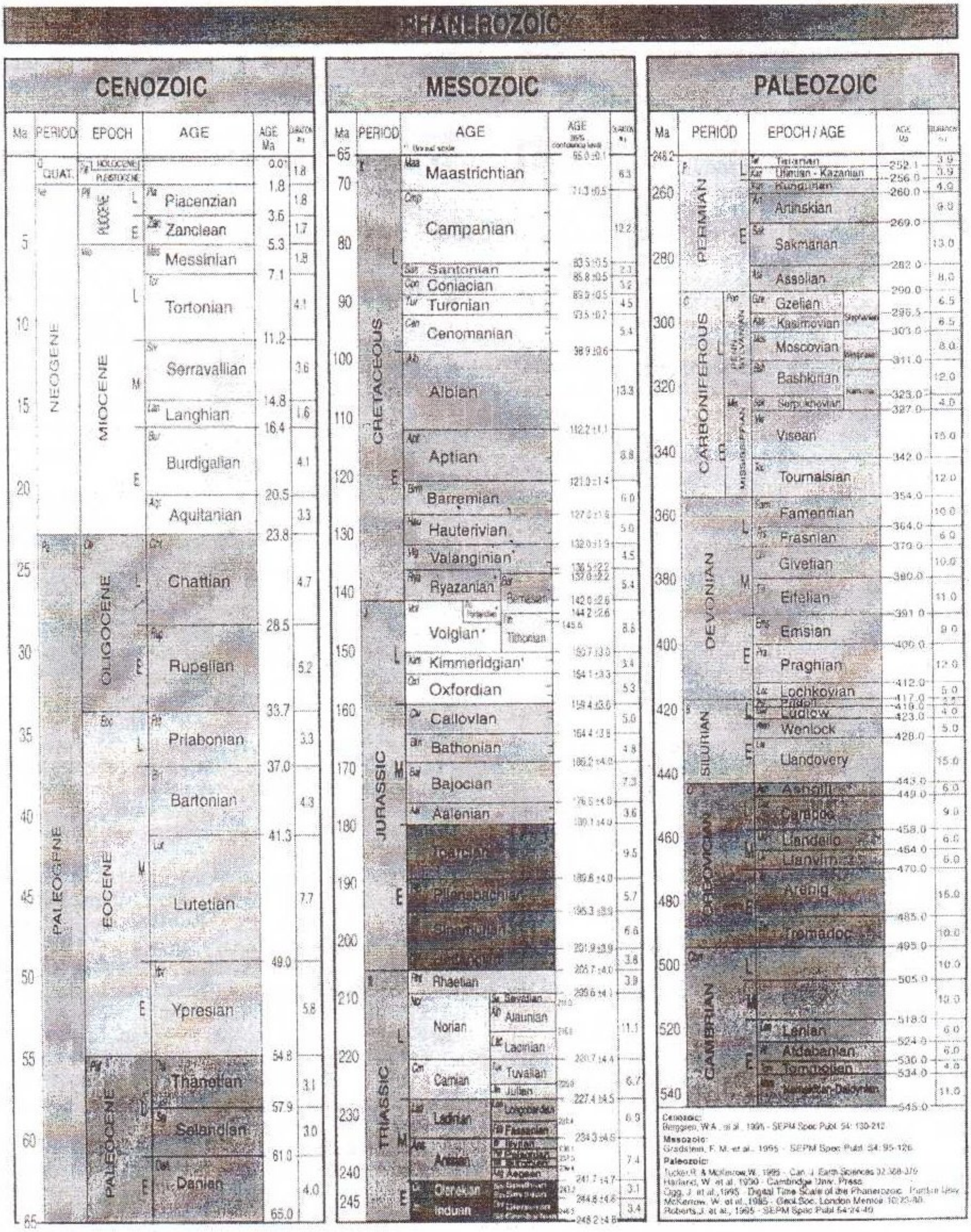

Figure 2 - Geological Time Scale for the Phanerozoic, that forms the basis for an extensive suite of chrono- and sequence-stratigraphic charts for Europe (slightly modified after Gradstein and Ogg, 1996).

CHALLENGES AND REVISIONS

Radiometric dating techniques with less than 1% analytical error are providing suites of high-precision U/Pb and Ar/Ar dates for the Mesozoic (e.g., Mundil et al., 1996; Obradovich, 1993). The integration of this level of chronometric precision with high-resolution biostratigraphy, magnetostratigraphy or Milankovich cyclicity is a major challenge to time scale studies and interpolation mathematics. Even the most detailed Mesozoic biostratigraphic scheme probably has no biozonal units of less than 0.5- 1.0 myr duration, not to speak of the actual precision in dating a particular 'stratigraphic piercing' point, for which an U/Pb age estimate would be available with an analytical uncertainty of 0.1 to 0.5 myr. Similarly, combination of analytically less precise K/Ar dates with much more precise Ar/Ar or U/Pb dates in statistical interpolations creates a strong bias towards the latter, despite the fact that both may have equal litho-, bio-, and chrono-stratigraphic precision.

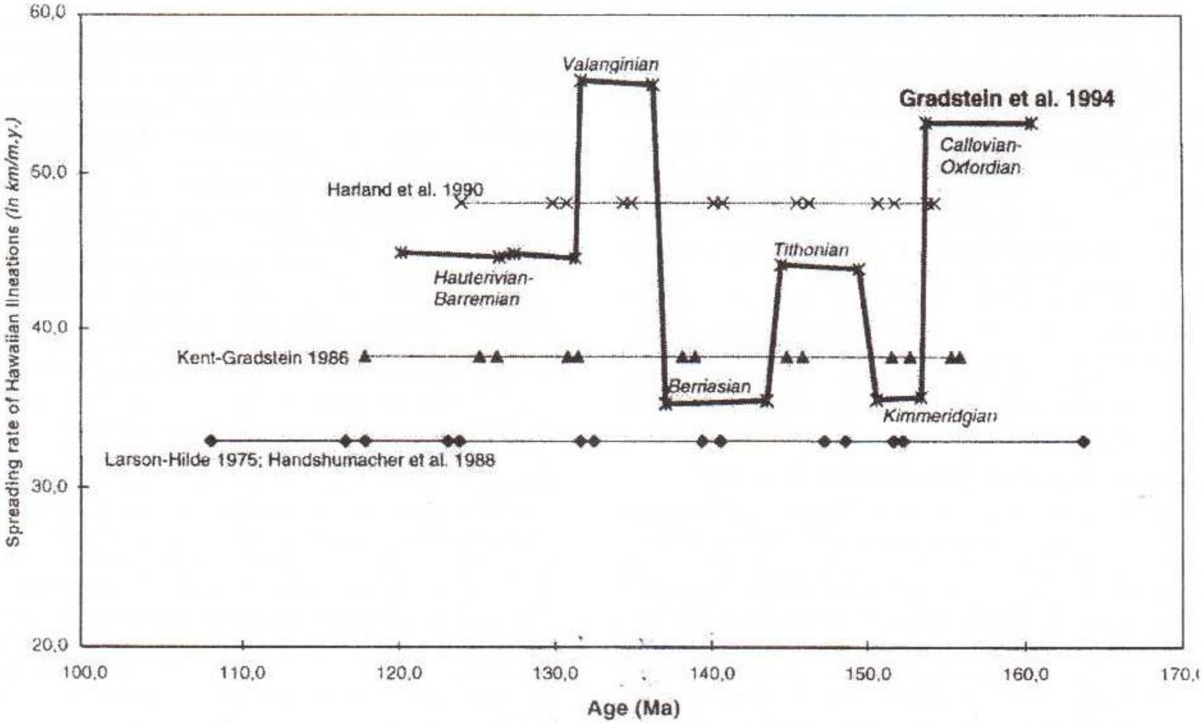

Figure 3 - Late Jurassic through Early Cretaceous Pacific spreading rates implied by different time scales

Below, we will present examples of the resulting complexities in stratigraphic reasoning and mathematical interpolations, using examples of developments in the Phanerozoic stratigraphy and geochronology during the past five years.

Terminal Proterozoic Period

The 'Working Group on the Terminal Proterozoic Period' chaired by A. Knoll (Harvard, Mass., USA) is erecting a relatively detailed bio- and isotope stratigraphy framework and geochronology for this 50+ myrm. period below the Cambrian using new data from Australia and Namibia. A GSSP (Global Boundary Stratotype Section and Point) for the base of the Terminal Proterozoic is considered in a cap carbonate above Varanger tillites in southern Australia. From correlation to tuffs with U/Pb dates on zircons in Namibia, this level may be approximately 570 Ma (Grotzinger et al., 1996).

Arguments are now emerging for a slight upwards revision of the basal age of the Cambrian, the period immediately overlying the Terminal Proterozoic (Grotzinger et al., 1996; Brasier et al., 1994, 1996). The GSSPG for the base of the Cambrian in Newfoundland, marked by the appearance of a trace fossil assemblage bearing *Phycodes-pedum*, can be correlated with strata in N. Siberia, assigned a Nemakit - Daldynian age. Volcanic breccia, slightly below *Phycodes-pedum* have yielded a U/Pb age of 543.6 ± 0.24. In Namibia, this trace fossil assemblage appears near the base of the Nomtsas Formation, above the Spitskopf - Nomtsas erosional unconformity that includes the Precambrian – Cambrian boundary. The boundary is bracketed by U/Pb ages in ashes of 539.4 ± 1 Ma and 543.3 ± 1 Ma. Hence the base of Cambrian may be at, or slightly above, 543 Ma.

Ordovician

The Subcommission on Ordovician Stratigraphy, in a major stratigraphic 'clean-up', has proposed six new subdivisions for this major period (R. Cooper, pers. comm., 1999). Only one of the new subdivisions (Dariwillian) has been named and defined with a GSSP to date. A second stage (Tremadoc) may be formally named and defined soon.

A GSSP for the Cambrian-Ordovician boundary has been formally proposed at Green Point, W. Newfoundland, based on the first appearance of the conodont *Iapetognathus fluctivagus*, and is probably not older than 490 Ma (Cooper and Nowlan, 1999).

Calibration of the standard graptolite and conodont zonations to a set of U/Pb ages on zircons, bypassing the stages altogether, is yielding a new Ordovician time scale between 490 and 442.8 Ma (Cooper, 1999). Therefore, the Ordovician is a period for which a standard zonation, standard definitions of stage boundaries, and a quantitative time scale may be in place before stratotypes for subdivisions and stages are finalized. It can be argued that although stage names are considered a prerequisite in a time scale, the historical stage stratotypes are principally of value only for regional correlations.

Permian

The Subcommission of Permian Stratigraphy is refining a proposal for Permian stage and series classification, which incorporates new insights from China, Kazakhstan, Russia and North America (summarized by Jin Yugan in Subcommission's newsletter "Permophiles", number 28, June 1996). The 'early' Permian Cisuralian seriess incorporates the Asselian, Sakmarian, Artinskian and Kungurian stages. The 'middle' Permian Guadalupian seriess consists of the Roadian, Wordian and Capitanian stages, whereas the youngest Permian Logingian series incorporates the Wuchiapingian and Changhsingian stages.

In the same newsletter issue, A. Klets et al. quote new U/Pb (SHRIMP) dates from tuffs in the lower Permian of Russia and eastern Australia. Although it is not clear how the dates fit into the revised stage classification, the Sakmarian through Kungurian stages might be 5-10 myr older than assigned in previous time scales, pending stratigraphic and mathematical analysis of calibrations, dates and uncertainties.

In the confusion around uppermost Permian stratigraphy, the Illawarra geomagnetic reversal will provide an important global correlation horizon from Australia to the Tatarian of Russia, to China, and to other Permian regions (Menning, 1995, and pers. comm. 1996).

Age and Cause of Permian–Triassic Boundary

The radiometric age of the Paleozoic / Mesozoic erathem boundary has been used as testing ground for fine-tuning dating methods against each other, and among laboratories. In a rare fortuitous coincidence, a candidate GSSP at Meishan in S. China has minor tuffs virtually at the Permian–Triassic boundary (as marked by the first occurrence of a conodont, although placing the 'boundary' at this global correlation horizon, which occurs significantly later than the main global mass extinction level is controversial). A contributing cause of the Permian–Triassic mass extinction may be the rapid extrusion of the Siberian flood basalts. These basalts have published ^{40}Ar/^{39}Ar age very near 250 Ma, (249.3 ± 1.6 Ma; Renne et al., 1995), which converts to about 253 Ma under the revised ^{40}Ar/^{39}Ar monitor standard (R. Mundil, pers. comm., 1999). The Permian–Triassic boundary in China has been dated as 251.4 ± 0.3 Ma by U/Pb (Bowring et al., 1998), which was within the broad 251.2 ± 3.4 Ma from the SHRIMP method of U/Pb (Claoué-Long et al., 1991). However, new zircon standard for SHRIMP yielded a revised age of 252.6 ± 1.2 Ma for this bed, and U/Pb HF-cleaned zircons from this "boundary clay" yield ages that bracket the Permian–Triassic boundary as 253.2 ± 0.7 Ma (R. Mundil, pers. comm., 1999). Due to inter-laboratory differences in techniques and standards, this bewildering array of high-precision ages has not converged to yield a sequential relationship between the timing of the main Siberian flood basalt pulse, the end-Permian mass extinction, and the first occurrence of the proposed conodont "boundary marker".

Middle Triassic Dating and Tuning

An important anchor point in the Triassic is dating of the Anisian/Ladinian boundary in the Grenzbitumen horizon in Switzerland, which contains tuff layers in the basal part of the lowermost Ladinian *Nevadites* (tethyan ammonite) zone (Brack and Rieber, 1994). The homogenous and waterclear, high-sanidine feldspars (type G) in the tuff have a mean K/Ar age of 233 ± 4.5 (2s), and an ^{40}Ar/^{39}Ar plateau age from stepwise heating of approximately 232 ± 4.5 Ma (2s) (Hellmann in Odin et al., 1982, item 196; which revised Hellmann and Lippolt, 1981). When combined with other radiometric age constraints, these ages were critical in interpolating the Early/Middle Triassic boundary at 234.3 ± 4.6 Ma (2s) (Gradstein et al., 1994, 1995).

However, Brack et al. (1995) reported much older single-grain zircon U/Pb age dates from tuffaceous layers associated with the Anisian/Ladinian boundary interval in sections near Bagolino in northern Italy (see also Mundil et al., 1996). This region is a proposed candidate for the GSSP of the base of the Ladinian stage, although disagreements on the precise level have not yet been resolved. A suite of seven zircons from a thin crystal tuff in the lower part of the *Secedensis* [*Nevadites*] ammonite zone yielded a weighted Pb/U mean age of 241.0 ± 0.5 Ma. This bed can be traced to equivalent tuffs in the Grenzbitumen horizon at Monte San Giorgio in southern Switzerland (Brack and Rieber, 1994), which had yielded the ^{40}Ar/^{39}Ar age of 232 ± 4.5 Ma (2s). Brack et al. (1995) report that preliminary zircon ages from this same Grenzbitumen horizon are consistent with their U/Pb age from Bagolino, and they consider that the regional burial and maturation history favors the zircon ages to be stratigraphically reliable.

Other comparisons of ^{40}Ar/^{39}Ar ages in sanidines with U/Pb ages from zircons at the same levels suggest that the U/Pb method generally yields systematically older ages, which may indicate that the decay constants used for either the K/Ar or U/Pb system requires revision when attempting this level of high-precision (R. Mundil, pers. comm., 1999). If this offset is supported by further dual-system dates, then it may be necessary to selectively recalibrate the entire radiometric age dataset, similar to the systematic revisions that were required in the early 1980's, when the current suite of decay constants were standardized (e.g., Harland et al., 1982; Odin et al., 1982).

The new U/Pb radiometric dates for this boundary interval, and the overlying middle Ladinian tuffs (238.8 ± 0.4 Ma in the middle of *Gredleri* ammonite zone; 237.7 ± 0.5 Ma in the middle of *Archelaus* ammonite zone) and other levels ages (Brack et al., 1995) for overlying middle Ladinian tuffs (238.8 ± 0.4 Ma in the middle of *Gredleri* Zone; 237.7 ± 0.5 Ma in the middle of *Archelaus* Zone) have been preliminary tested in the geological time scale. Their incorporation in the maxi-mum-likelihood database (Gradstein et al., 1995), and new spline computations imply a longer time span for the Ladinian Stage (8.3 instead of 6.9 myr in Gradstein et al., 1995), and a greatly reduced extent of the Anisian Stage (3.1 instead of 7.4 myr). However, Brack et al. (1995) recommend placement of the *Nevadites* ammonite zone into the underlying Anisian Stage, rather than its traditional placement in the Ladinian, which would result in a longer Anisian, and a stratigraphically slightly younger Ladinian / Anisian boundary.

It is curious to note that the potential changes in duration of the two successive stages greatly reduce the duration of Anisian ammonite zones over Ladinian ones. An unresolved issue is that the 600 Latemar carbonate platform cycles in the Middle Triassic of the southern Alps, which had been statistically interpreted as Milankovitch orbital - climate oscillations (e.g. Goldhammer et al., 1990), now appear to be formed during a shorter period of time than previously assumed, which casts doubt on the validity of recognition of orbital cycle frequencies in the geologic record (Brack et al., 1996). In turn, both the validity of the zircon U/Pb dates and the stratigraphic correlation of the dated horizons into these platform carbonates are questioned (Hardie and Hinnov, 1997; L. Hinnov, pers. comm., 1999).

Spreading Rates of Late Jurassic and Early Cretaceous

The Oxfordian through earliest Aptian magnetic anomaly record of the east Pacific Ocean coupled with magneto-biostratigraphic correlations provides a powerful means for relative scaling of the associated stages (Larson & Hilde, 1975; Kent & Gradstein, 1986;

Haq et al., 1988; Gradstein et al., 1994, 1995). In the absence of more reasonable constraints, constancy of seafloor spreading was generally utilized to interpolate Late Jurassic through Early Cretaceous ages. The ages for stage boundaries derived from a constant spreading rate assumption must be reconciled with the radiometric database, and associated maximum likelihood age estimates. The Mesozoic time scale of figure 2 combines the seafloor spreading scaling assumption with independent maximum likelihood estimation for the ages of the Oxfordian through Barremian stage boundaries. In the final time scale, limited weight was given to interpolated ages from constant seafloor spreading. Figure 3 illustrates Late Jurassic through Early Cretaceous Pacific spreading rates implied by the different time scales. The incorporation of maximum-likelihood statistics (Gradstein et al., 1994) yields a Valanginian spreading rate that is significantly more rapid than during the preceeding and following stages. This Valanginian pulse of rapid spreading is suggestive of first-order correlation to observed global onlap in the Valanginian following major regression (Haq et al., 1988; Graciansky et al., 1998). More detailed studies may resolve a similar first order 'causal coincidence' among projected trends in Late Jurassic spreading rates and major offlap/onlap cycles, and provide a chronological scale to deduce global geological processes.

In conclusion, the Geological Time Scale is the linear calendar for expressing Earth Geological History. It keeps geologists on the globe on time, wherever they are, whether offshore on an hydrocarbon exploration platform, or in a university classroom. While the fabric of litho-, bio-, magneto-, and chronostratigraphy allows linkage of geological observations into a non-linear geochronology framework, the calibration of that framework to the linear geological scale allows us to examine rates of global change.

SUMMARY OF PRESENT STATUS AND FUTURE DIRECTIONS

Since the publication of time scales in the eighties (Haq et al., 1988; Harland et al., 1990) a considerable amount of new age dates and more detailed magneto- and biostratigraphy have become available, leading to a more precise and more accurate Phanerozoic geochronology.

The Paleogene time scale is primarily calibrated from biostratigraphic correlations to magnetic polarity chrons, which in turn are scaled according to marine magnetic anomaly profiles from the South Atlantic seafloor, pinned to a selected set of 9 Ar/Ar radiometric ages (Cande and Kent, 1992, 1995; Berggren et al., 1995). Interpolation, using constancy of seafloor spreading between radiometrically constrained profile segments, assigns ages to magnetic polarity chrons, which, in turn calibrate zonal events and stage boundaries. The combination of magnetochronology and astrochronology presently refines the Neogene time scale in a continuous and linear manner for the last 11 myr (Hilgen et al., 1997a).

In contrast, the Mesozoic time scale lacks a unifying interpolation concept, because marine magnetic anomaly profiles only extend back to the Callovian stage, and much of the middle Cretaceous Period lacks a magnetic anomaly signature. In addition, the radiometric data set has inadequate precision to constrain the age assignments of most stage boundaries. Therefore, whereas portions of the Mesozoic time scale can now be exactly determined by a combination of precise radiometric ages, many published in the last six years on biostratigraphically constrained sections (e.g, Obradovich, 1993), the majority of the stage boundaries have been assigned ages through geological and mathematical interpolation methods. Mathematical interpolation makes it possible to estimate confidence limits on the age of stage boundaries (Agterberg, 1994). Hence, the Mesozoic time scale (Gradstein et al., 1995) is one of the first geochronologies to incorporate error bars on all (31) Mesozoic stage boundaries.

Since the chronostratigraphic and geochronologic compilation for the Paleozoic in Harland et al. (1990), several studies have been published that use relatively precise isotope dates to improve Paleozoic chronology below the Carboniferous (Tucker and McKerrow, 1995; Roberts et al., 1995). Nevertheless, there remains a general paucity of relatively precise and stratigraphically meaningful age dates in the Paleozoic. This, together with problems in inter-regional stage assignments that hamper standard zonations for parts of the Paleozoic (R. Cooper, pers. comm., 1998) makes the Paleozoic time scale more uncertain.

We have incorporated the Cenozoic, Mesozoic and Paleozoic age assignments in a geologic time scale chart (Gradstein and Ogg, 1996). The Cenozoic scale is after Berggren et al. (1995) and Hilgen (1991), and the Mesozoic one after Gradstein et al. (1995). The Paleozoic time scale is constructed from Harland et al. (1990), with the pre-Carboniferous updated by more precise isotopic ages for stage boundaries by Roberts et al. (1995) and Tucker and McKerrow (1995). A magnetochronology for the Phanerozoic has been published by Ogg (1995). This Mesozoic-Cenozoic time scale forms the chronostratigraphic basis for the sequence stratigraphy of European Basins (Graciansky et al., 1998). The next version of an integrated geological time scale is under preparation under the auspices of the International Stratigraphic Commission (a "Geological Time Scale 2001" project), and it is inevitable that further fine-tunings will occupy stratigraphers of the next generation.

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REFERENCES

Agterberg, F.P., 1994. Estimation of the Mesozoic Geological Time Scale. *Mathematical Geology*, 26 (7), 857- 876.

Berggren, W.A., Kent, D.V., Swisher, C.C., III., Aubry, M-P., 1995. A revised Cenozoic geochronology and chronostratigraphy. In: Berggren, W.A., Kent, D.V., Hardenbol, J. (eds.) *Geochronology, Time Scales and Global Stratigraphic Correlations: A Unified Temporal Framework for a Historical Geology, SEPM Special Volume*, 54, 129-212.

Cande, S.C., Kent, D.V., 1992. A new geomagnetic polarity time scale for the Late Cretaceous and Cenozoic. *Journal of Geophysical Research*, 97, 13917-13951.

Cande, S.C., Kent, D.V., 1995. Revised calibration of the geomagnetic polarity timescale for the Late Cretaceous and Cenozoic. *Journal of Geophysical Research*, 100, 6093-6095.

Bowring, S.A., Erwin, D.H., Jin, Y.G., Martin, M.W., Davidek, K., Wang, W., 1998. U/Pb zircon geochronology and tempo of the end-Permian mass extinction. *Science* 280, 1039-1045.

Brack, P. Rieber, H., 1994. The Anisian/Ladinian boundary: Retrospective and new constraints. *Albertiana* 13, p. 15 - 36.

Brack, P., Rieber, H., Mundil, R., 1995. The Anisian/Ladinian boundary interval at Bagolino (S. Alps, Italy): 1. Summary and new results on ammonoid horizons and radiometric age dating. *Albertiana* 15: 45-56.

Brack, P., Mundil, R., Oberli, F., Meier, M., Rieber, H., 1996. Biostratigraphic and radiometric age data question the Milankovitch characteristics of the Latemar cycles (S. Alps, Italy). *Geology* 24, p. 371-375.

Brasier, M.D., Cowie, J.W., Taylor, M., 1994. Decision on the Precambrian-Cambrian boundary stratotype. *Episodes* 17, p. 3-8.

Brasier, M.D., 1996. U/Pb dates for the base of the terminal Proterozoic and Cambrian. *Episodes* 19, no's 3 & 4.

Cooper, R.A., 1999. The Ordovician time scale – calibration of graptolite and conodont zones. *Acta Universitatis Carolinae – Geological* 43 (1/2), 4p.

Cooper, R.A., Nowlan, G.S., 1999. Proposed Global Stratotype Section and Point for base of the Ordovician System. *Ordovician News* 16.

Carter, R.M., Naish, T.R., eds. (1999). The high-resolution, chronostratigraphic and sequence stratigraphic record of the Plio-Pleistocene, Wanganui Basin, New Zealand. *Institute of Geological and Nuclear Sciences, folio ser.* 2.

Fowell, S.J., Olsen, P.E., 1993. Time calibration of Triassic/Jurassic microfloral turnover, eastern North America. *Tectonophysics* 222, 361-369.

Goldhammer, R.K., Dunn, P.A., Hardie, L.A., 1990. Depositional cycles, composite sea-level changes, cycle stacking patterns and the hierarchy of stratigraphic forcing: examples from the Alpine Triassic platform carbonates. *Geological Society of America Bulletin* 102: 535-562.

Gradstein, F. M., Agterberg, F. P., Ogg, J. G., Hardenbol, J., van Veen, P., Thierry, J., Huang, Z., 1995. A Triassic, Jurassic, and Cretaceous time scale. *SEPM Special Publication* 54, 95 - 126.

Gradstein, F.M. Ogg, J.G., 1996. A Phanerozoic time scale. *Episodes* 19 (2), 3-5 + fig.

Graciansky, P., Hardenbol, J., JacquinJa, T., Vail, P. (eds.eds), 1998. *Mesozoic and Cenozoic Sequence Stratigraphy of European Basins. SEPM Special Publication* 60, 786 pp + appendix.

Grotzinger, J.P., Bowring, S.A., Saylor, B.Z., Kaufman, A.J., 1996. Calibrating the terminal Proterozoic time scale. *30th Intern. Geol. Congress*, Beijing, *Abstract volume* 2, 47.

Handschumacher, D.W., Sager, W.W., Hilde, T.W.C., Bracey, D.R., 1988. Pre-Cretaceous evolution of the Pacific plate and extension of the geomagnetic polarity reversal time scale with implications for the origin of the Jurassic "Quiet Zone". *Tectonophysics* 155, 365-380.

Haq, B.U., Hardenbol, J., Vail, P.R., 1988. Mesozoic and Cenozoic chronostratigraphy and cycles of sea-level change. In: *Sea-level Changes-An integrated approach, SEPM Special Publ.* 42, 71-108.

Hardenbol, J., Thierry, J., Farley, M.B., Jacquin, T., de Graciansky, P.C., Vail, P.R., 1998. Mesozoic and Cenozoic sequence chronostratigraphic framework of European basins (chart series). In: Graciansky, P., Hardenbol, J., Jacquin, T., Vail, P. (eds.) *Mesozoic and Cenozoic Sequence Stratigraphy of European Basins. SEPM Special Publication* 60.

Hardie, L.A., Hinnov, L.A., 1997. Biostratigraphic and radiometric data question the Milankovitch characteristics of the Latemar cycles-comment. *Geology* 25, 470-471.

Harland, W. B., Cox, A. V., Lewellyn, P. G., Pickton, C. A. G., Smith, A. G., Walters, R., 1982. *A Geologic Time Scale. Cambridge University Press*, 131 p.

Harland, W. B., Armstrong, R. L., Cox, A. V., Craig, L. E., Smith, A. G., Smith, D. G., 1990. *A Geologic Time Scale 1989. Cambridge University Press*, 265 pp.

Hellmann, K.N. Lippolt, H.J., 1981. Calibration of the Middle Triassic time scale by conventional K-Ar and Ar-Ar dating of alkali feldspars, *Journal of. Geophysics.*, 50, 73-86.

Hilgen, F.J., 1991. Extension of the astronomically calibrated (polarity) time scale to the Miocene/Pliocene boundary. *Earth and Planetary Science Letters* 107, 349-368.

Hilgen, F.J., Krijgsman, W., Langereis, C.G. Lourens, L.J., 1997a. Breakthrough Made in Dating of the Geological Record. *Eos* (Transactions of the American Geophysical Union), 78 , no. (28), pages 285 and 288-289.

Hilgen, F.J., Krijgsman, W., Wijbrans, J.R., 1997b. Direct comparison of astronomical and ^{40}Ar/^{39}Ar ages of ash beds: Potential implications for the age of mineral dating standards. *Geophysical Research Letters*, 24, 2043-2046

Kent, D.V. Gradstein, F.M., 1986. A Jurassic to Recent Chronology. In: *The Geology of North America, Volume M, The Western North Atlantic Region*, P.R. Vogt B.E. Tucholke (eds.), *Geological Society of America*, Boulder, CO: 45 – 50.

Larson, R.L. Hilde, T.W.C., 1975. A revised time scale of magnetic reversals for the Early Cretaceous and Late Jurassic, *Journal of Geophysical. Researchs.* 80, 2586-2594.

Menning, M., 1995. A numerical time scale for the Permian and Triassic Periods: An integrated analysis. In, Scholle, P. Pery, T., Ulmer-Scholle, D., (eds.eds): *The Permian of northern Pangea 1, Springer Verlag*, Berlin, 77-97.

Mundil, R., Brack, P., Meier, M., Rieber, H., Oberli, F., 1996. High-resolution U-Pb dating of middle Triassic volcaniclastics: Time-scale calibration and verification of tuning parameters for carbonate sedimentation. *Earth and Planetary Science Letters* 141, 137-151.

Obradovich, J.D., 1993. A Cretaceous time scale. In: Evolution of the Western Interior Basin, W.G.E. Caldwell (ed.), *Geological Association of Canada Special Paper* 39, 379-396.

Odin, G.S., (ed.), 1982. Numerical Dating in Stratigraphy 1, 2. J. Wiley & Sons, Chichester, U.K.

Ogg, J. G., 1995. Magnetic polarity time scale of the Phanerozoic. *In* Ahrens, T. (, ed.), *Global Earth Physics: A Handbook of Physical Constants*; *AGU Reference Shelf* 1, American Geophysical Union, Washington, , 240-270.

Palmer, A.R., 1983. Decade of North American Geology (DNAG). Geological Time Scale. *Geology* 2, 503 – 504.

Renne, P.R., Zichao, Z., Richards, M., Black, M., Basu, A., 1995. Synchroneity and causal relations between Permian-Triassic boundary crises and Siberian flood volcanism. *Science* 269, 1413-1416.

Renne, P.R., 1995. Excess ^{40}Ar in biotite and hornblende from the Noril'sk 1 intrusion, Siberia: implications for the age of the Siberian Traps. *Earth and Planetary Science Letters* 131, 165-176.

Renne, P.R., Deino, A.L., Walther, R.C., Thurrin, B.D., Swisher, C.C., Becker, T.A., Curtis, G.H., Sharp, W.D. Jaouni, A.R., 1994. Intercalibration of astronomical and radio-isotopic time. *Geology* 22, 783 (1994).

Roberts, J., Claoue-Long, J., Jones, P.J., 1995. Australian Early Carboniferous Time. *SEPM Special Publication* 54, 24 - 40.

Shackleton, N.J., Crowhurst, S.J., Weedon, G.P., Laskar, J., 1999. Astronomical calibration of Oligocene-Miocene time. *Philosophical Transactions of the Royal Society of London, Series A (Mathematical, Physical and Engineering Sciences)*, 357: 1907-1929.

Tucker, R.D., McKerrow, W.S., 1995. Early Paleozoic chronology: A review in light of new U- Pb zircon ages from Newfoundland and Britain. *Canadian Journal of Earth Science* 32, 368 - 379.