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REVIEW

A Geologic Time Scale 2004

Edited by Felix M. Gradstein, James G. Ogg and Alan G. Smith
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There are many elements of science that invoke wonderment: as a professional biostratigrapher whose livelihood is based on the reality of evolution, it is not unusual for me to think about the amazing achievement represented by our understanding of the history of life. Advances such as plate tectonics and particle physics also come to mind. However, one achievement not so widely appreciated is the geological time scale. Born of the great work of people such as Nicolaus Steno (1638-1686; Cutler 2003), James Hutton (1726-1797; Repcheck 2003), William Smith (1769-1839; Winchester 2001) and Arthur Holmes (1890-1965; Lewis 2000), time scales to the middle of the 20th Century became based on a three-way foundation of the rock record, the fossil record, and radiometric dating. The most significant development since then has been the addition of new tools that provide additional help in calibrating our planet's history. These new tools include magnetostratigraphy, cycle stratigraphy, chemostratigraphy and sequence stratigraphy. No sub-discipline has a complete answer ... the art of time-scale construction lies in collaboration.

Several authoritative time scales have appeared over the last 25 years. These include the "*Decade of North American Geology*" or "*DNAG*" time scale (Palmer 1983); the Haq et al. (1988) scale for the Mesozoic and Cenozoic; and, in Canada, the time scale compiled by Andy Okulitch and distributed as a GSC Open File (Okulitch 1999, 2004). Perhaps the most influential was that produced by Brian Harland and colleagues (Harland et al. 1982) and called, *A Geological Time Scale*. Harland et al. (1990) produced a revised version, *A Geological Time Scale 1989*. The volume under review here is the third version of this initiative: *A Geological Time Scale 2004* (GTS 2004; Gradstein et al. 2005). The publisher has been Cambridge University Press for all three editions and there are familiar aspects such as the detailed charts and tables. But this third edition – under the editorial stewardship of Felix Gradstein, James Ogg and Alan Smith (the only lead author/editor involved in all GTS editions so far) – is clearly the most ambitious venture yet; not just an update of previous editions. Moreover, it seems to have the blessing of the International Commission on Stratigraphy, and the schemes presented for parts of the geological column appear to be those supported, for the most part, by the respective working groups of the authoritative International Union of Geological Sciences.

GTS 2004 is arranged in four parts: Introduction (chapters 1-2), Concepts and Methods (chapters 3-8), Geologic Periods (chapters 9-22) and Summary (Chapter 23). Part 2 on concepts and methods is a largely new and welcome innovation in this edition. The chapters/contributions are individually authored, in contrast to the first two editions. And although charts are still a prominent feature, there is much more background text, which expands the book significantly, but in many ways makes it more approachable. In addition to the chapters, there is an interesting Preface that describes the drawn out process of producing the book and hints at the tribulations of making the contributions of 40 scientists conform seamlessly, with no time warps between intervals. One item that I found a little odd in the Preface (p. xv) was the statement that the aim of the new edition was to "... present a balanced overview designed to be educational and useful for advanced university students": surely a current and detailed time scale is more fundamental than that.

In Chapter 1, Felix Gradstein discusses the nature and evolution of time scales, especially in the context of new and evolving methodologies. In apparent contrast to the preface statement, Gradstein (p. 3) acknowledges that, "All earth scientists should understand how the evolving time scales are constructed and calibrated, rather than merely using the numbers in them." Gradstein points out that the calibration of the stratigraphic record to "absolute" or linear time involves: 1) the relative correlation (chronostratigraphy) of the global rock record using internationally agreed stratigraphic divisions (e.g. "Jurassic", "Maastrichtian" "*Harpoceras falciferum* ammonite zone" or "polarity Chron C24r"); 2) the (chronometric) measurement of linear time (through, for example, radiometric dating) or elapsed durations (e.g. through astronomical cyclicity as reflected in sediments); and 3) the means of joining chronostratigraphic and chronometric schemes. The chronostratigraphic scale is an agreed convention based on (actual or potential) defined boundary stratotypes and reference points, whereas the chronometric scale is "a matter for discovery or estimation".

Chapter 2, by Felix Gradstein, James Ogg and Alan Smith, is about linking time and rock. The authors note that the chronostratigraphic scale (i.e. the geological column in more popular parlance) was originally established from a combination of the correlation of regional lithologic units (e.g. the western European Chalk, in part, defining the Cretaceous) and the unique, non-recurring events provided by biological evolution. Classically based on the largely marginal marine and pelagic rock record in Europe, the chronostratigraphic units (systems, stages, etc.) that developed are an incomplete record of geological time. The authors provide a striking demonstration of this in Fig. 2.1, where traditional stratotypes of stages for the Paleocene and Oligocene are shown to represent only about a quarter to a third of the actual time interval represented; the Eocene is only slightly better off. As a result (p. 20) "... a distinction between a hierarchy of material chronostratigraphic units (rock-time) and abstract geochronologic units (Earth time) units was required, and a dual nomenclatural system was codified...." Hence, we can refer to the Maastrichtian Stage of the Cretaceous System of the Mesozoic Erathem in a chronostratigraphic sense or to the Maastrichtian Age of the Cretaceous Period of the Mesozoic Era in a geochronologic sense; similarly, chronostratigraphic units can be subdivided into lower, middle and upper subunits; geochronologic units can be subdivided into early, mid and late subunits. I will return to this matter of terminology later in this review.

In recent decades, under the auspices of the International Commission on Stratigraphy (ICS), the designation of Global Stratotype Sections and Points (GSSPs) has helped (arguably to some) to clarify and stabilize the link between rocks and time. As the authors of Chapter 2 point out, the basal boundary of each chronostratigraphic unit (effectively stages because the base of a system will be the base of its lowest stage) is standardized at a point ("golden spike") in a reference section within an interval exhibiting continuous sedimentation. Careful study and extensive international discussion takes place before each GSSP is ratified, in contrast to the somewhat individual and *ad hoc* process that went into the development of the systems and stages in the 19th and early 20th centuries. Gradstein et al. note that it is over 25 years since the first "golden spike" was "hammered" in place – at the base of the Devonian at a place called, appropriately, Klonk in the Czech Republic. The base of the Devonian (actually the base of the Lochkovian stage) coincides with the first occurrence of the graptolite *Monograptus uniformis* in bed No. 20 of the Klonk section. The authors (p.23) note, however, that "... once the golden spike has been agreed, the discovery ... of *Monograptus uniformis* below the GSSP does not require a re-definition ..., but simply an acknowledgement that the ... level chosen was not ... the lowest occurrence of the ... [species]."

At the time of writing, 46 "golden spikes" had been defined, and updates are reported on the ICP website. Most are biostratigraphically based, but other criteria have been used, such as the iridium spike at the base Cenozoic, the carbon isotope anomaly at the base of the Eocene, and a specific Milankovitch cycle at the base of the Pleistocene.

Returning to the matter of terminology, there seems to me to have been much confusion in recent decades over the application of the terms chronostratigraphy and geochronology themselves, as well as extensive misuse of the related terminologies, e.g. system versus period or lower versus early. Such items are perennial "bones of contention" for manuscript editors and reviewers. By way of a section header, the authors (p. 41) ask "Do GSSP boundary stratotypes simplify stratigraphic classification?" They note that, given GSSPs, the limits of chronostratigraphic units (stages) are (actually or potentially) "fully defined in time." They note that Harland et al. (1990) realized that the GSSP concept leads to a redundancy of separate "time-rock" (meaning chronostratigraphic) terms. The authors (p. 41) cite Harland et al. (1990): "The use of time-rock terms (e.g. Lower Cambrian) predates the standardization of time terms, so it is an understandable perpetuation of an old habit that it is now nevertheless timely to replace. By referring to Early Cambrian rather than Lower Cambrian, the definition (and concept) is more direct. Early Cambrian rocks are any rocks formed in early Cambrian time." Gradstein et al. hint that they are sympathetic with this point of view but had some resistance to it from other authors contributing to the volume. I am inclined to agree with Harland et al. (1990).

Part 2 of the book focuses on concepts and methods. There are chapters on biostratigraphy 3), orbital parameters and cycle stratigraphy 4), geomagnetic polarity 5), radiogenic isotopes 6), strontium isotopes 7), and geomathematics 8). Even though it was identified in Chapter 2 as a cornerstone of time scale building, "stratigraphic reasoning" (i.e. the rock record itself) does not merit a chapter, perhaps because it is considered "old hat" or "understood". However, a short review chapter, in my view, would not have been out of place, and would serve to remind readers how important the fundamentals are still.

One aspect that comes across strongly in this suite of chapters is how the various methodologies are working together to refine the time scale. For example, although magnetic polarity unit boundaries are globally simultaneous, in contrast to some of the other correlation tools, the authors of Chapter 5 (James Ogg and Alan Smith; p. 64) leave no doubt that magnetostratigraphy needs biostratigraphy to corroborate general stratigraphic position. They state, "It is essential to have some biostratigraphic constraints on the polarity zone pattern resolved from any given section in order to propose a non-ambiguous ... correlation to the ... geomagnetic polarity time scale." The oldest (magnetic or polarity) units (chrons) identifiable from the ocean floor are Middle Jurassic. Radiometric dates from drilled seafloor basalts from this age forward allow not only for dating of the magnetic units, but also for dating of biostratigraphic events (Williams et al. 2004). A problem, however, is the current dearth of reliable dates from the Middle Jurassic Oxfordian Stage to the Early Cretaceous Barremian Stage, a span of some 35 million years. Ogg and Smith explain how seafloor spreading rates and, to a lesser extent, cycle stratigraphy have been used to develop a provisional time scale for this interval. Regarding the youngest chrons, the authors note how, initially, potassium-argon radiometric ages were used, but have been superseded by "absolute orbital-cycle ages with very high precision." They further comment (p. 73) that "Cycle stratigraphy will eventually ... assign absolute durations to polarity chrons throughout the Phanerozoic." This statement seems optimistic perhaps given the statement (p. 60) in Chapter 4 on cycle stratigraphy by Linda Hinnov that "... cycle stratigraphy much older than ~20 Ma may never successfully be correlated directly to the orbital cycles, but only indirectly through comparison of average signal characteristics between data and orbital theory."

From Chapter 6 by Mike Villeneuve, it was interesting to discover that generally only results from the U-Pb and $^{40}Ar/^{39}Ar$ methodologies are now considered reliable. Moreover, as Felix Gradstein notes in the book's Introduction, high precision does not always imply accuracy. For example, Villeneuve reports the example of two high-precision studies of the same horizon around the Permian-Triassic boundary: one yielded a date of 251.4 ± 0.3 Ma and the other 253 ± 0.3 Ma. The author uses this example to stress the importance of understanding the geological processes and avoiding samples with, for example, thermal overprinting; in the above example, the second date is inaccurate because of unrecognized Pb loss. Of course, radiometric dating is especially important for the Precambrian, for which most or all of the other methodologies are unavailable.

Chapter 7 by John McArthur and Richard Howarth covers strontium isotope stratigraphy, a methodology based on the observation that the $^{87}Sr/^{86}Sr$ value of Sr, dissolved in the world's oceans, has varied through time. It is disappointing that there are no similar contributions in the volume on isotopes of oxygen and carbon; these are becoming increasingly important in stratigraphy: for example, as mentioned above, a dramatic spike in carbon isotope values is now used to define the Paleocene/Eocene boundary. Part 2 wraps up with a chapter on Geomathematics by Fritz Agterberg, a vital aspect in modern time construction.

Chapters 9 through 22 then work their way through the geological intervals, mainly periods, each written by one to eleven experts. The chapters covering Cambrian to Neogene follow a similar internal structure. However, the Precambrian and Quaternary/Pleistocene have their own special problems and/or character, and so demand special treatment.

There are two chapters on the Precambrian, expressing different philosophical approaches - and it is to the editors' credit that they have included both. The first paper, by Laurence Robb and others, emphasizes the chronometric (not to be confused ... as it sometimes is ... with geochronologic) nature of the Precambrian time scale, although it points out the increasing utility and promise of isotope stratigraphy in that interval. The authors acknowledge that the Neoproterozoic shows promise for a chronostratigraphic scale, but note (p. 129) that "It will be a long time before such developments can be applied to the whole of the Proterozoic, or to the Archaean, and the present chapter should, therefore, be regarded as an interim report on a challenging topic." The chronometric subdivision of the Precambrian, ratified by IUGS in 1990, thus involves the familiar break down into the Archean and Proterozoic eons, further subdivided respectively into Eo-, Paleo-, Meso and Neoarchean eras, and Paleo-, Meso-, and Neoproterozoic eras. Less familiar to most geologists are the periods of the Proterozoic. These are, from oldest to youngest (with age and "typical, but not necessarily diagnostic" features from which the names are derived): Siderian (2500-2300 Ma; banded iron formations), Rhyacean (2300-2050 Ma; injection of layered complexes), Orosirian (2050-1800 Ma; global orogenic period), Stratherian (1800-1600

Ma; stabilization of cratons), Calymmian (1600-1400 Ma; platform covers), Ectasian (1400-1200 Ma; continued expansion of platform covers), Stenian (1200-1000 Ma; narrow belts of metamorphism and deformation), Tonian (1000-850 Ma; apparently an interval of stretching), Cryogenian (850-630 Ma; global glaciation), and the chronostratigraphically defined Ediacaran (630-542 Ma). All of these units except for the Ediacaran are defined chronometrically.

The alternative Precambrian chapter by Wouter Bleeker is one of the most interesting in the book. Bleeker (p. 141) states that "Definition of boundaries [in the Precambrian] in terms of arbitrary, round, absolute ages, although superficially appealing, is ... naïve." The author discusses problems with reliance on radiometric dates, noting that "As new [data] ... become available, rocks that had previously been assigned to the Archean might become Proterozoic or vice versa." He also casts serious doubt on the value of the IUGS-ratified period system for the Proterozoic; his search of the Georef database for "Ectasian" or "Calymmian" yielded zero results; as Bleeker comments, "Precambrian stratigraphers are simply ignoring the formal terminology for ... [periods]." The author recommends retention of the Archean and Proterozoic eons and the 7 eras (Neoproterozoic, etc); but proposes that the boundaries be based on natural events tied to interpretations of rocks. For example, the base of the Archean (Eoarchean) would be defined by the base of the oldest (preserved) supracrustal rocks at about 3850 Ma. The author also proposes an interval between the Archean and Proterozoic termed the "Transition" from about 2600 to 2300 Ma. This interval reflects the diachronous nature of the transition between the granite-greenstone tectonic style of the Archean and the incipient plate-tectonic style of the Proterozoic. In promoting these ideas, Bleeker is following a trend set by earlier Canadian authors (Stockwell 1973; Douglas 1982 and Okulitch 1987); Andy Okulitch (personal communication, 2007) notes that, "since arguments continue about when plate tectonics began, this transition zone is merely a complex portion of Earth history whose timing may be better defined by mafic dyke swarms than orogenic events."

Chapters 11 through 21 cover the periods from Cambrian to Neogene and encompass a wealth of information. As well as detailed tables and figures that present the evidence for the time scale for that interval, each chapter has sections on History and Subdivisions, Stratigraphy, Time Scale, with occasional extra sections where necessary (for example Previous Standard Divisions in the Ordovician). For those not interested in stratigraphic details like the basal conodont zone of the Eifelian, a useful overview for each period (plate tectonics, life, extinctions, climate, environments, stages in global history, and more) can be plucked out without too much sieving. And if you are into the history of the time scale and its units (the Sedgwick-Murchison debate for example), each of these chapters provides an overview.

One of the most striking realizations for me was how few radiometric dates the authors found acceptable in the Phanerozoic: only 11 reliable dates for the entire Cambrian, for example. This means that much of the time scale is controlled by graphic and/or statistical methodology based on biostratigraphic analyses and tied by these relatively few radiometric dates; assumptions about evolutionary or depositional rates play significant roles in these calculations. The comment in Chapter 11 (p. 164) states that, "our estimates of stage durations become correspondingly intuitive and the age of stage boundaries in the Early Cambrian ... should be regarded as highly approximate." The Early Cambrian is an extreme example, but there are many sections through the Phanerozoic where similar, if milder cautions would not be amiss. There is no implied criticism in this observation: this is just the way it is (see Okulitch 2004), although it does underscore the fact that there is still much work to do.

In spite of the problems surrounding radiometric dates, there is no doubt of the value that they bring to understanding our geological past – largely because of them, there can be no serious doubt about the general temporal framework of our planet's evolution. However, it is my impression that the public perception of the way that rocks are dated solely involves people in white lab coats with shiny multi-computer-linked machines: specimens are collected and prepared, buttons are pressed, widgets whir, and, hey presto, a number comes up: eureka – the rock is 197.223 million years old. The corollary is a general impression that palaeontology (with biostratigraphy as one of its main contributions) is nowadays redundant. That this impression is wrong is compellingly brought home in the Devonian chapter, where the late Michael House and Felix Gradstein (p. 215) note that "The detailed and high-resolution conodont-ammonoid zonation ..., with over 35 zones ..., is in stark contrast to the handful of [reliable] radiometric dates employed in Devonian time scale building." An almost identical statement is made in the Carboniferous chapter, this time citing 35-40 zones and 21 radiometric dates.

Ordovician aficionados will be interested, and some probably dismayed, to know that the historical series/epoch terms Arenig, Llanvirn, Llandeilo, Carodoc and Ashgill have been dropped. To an outsider like me, it is a little perplexing to read (p. 169) that, although these terms are formally discarded, "... it is likely that they will continue to be widely used ...": yet they are not included in most of the figures and tables as a regional option. This is even more perplexing when one reads, under the general heading of "Evolutionary Events" (p. 174), that "Two spectacular bursts in diversity took place [in the broad Ordovician context], one in the late Arenig and the other in the late Llanvirnian to early Caradocian ...." One gets the impression of conflict within the Ordovician establishment.

In my own work, I focus on Mesozoic-Cenozoic (especially Jurassic through Paleogene) material, so chapters 18-20 were of special interest. In recent years, there has been an increasing trend in dinoflagellate biostratigraphy to use events (first and last appearances) rather than zones. Based on methods and techniques discussed above, the chronostratigraphic age for each event is established and, either directly or indirectly, the chronometric age is determined. This is a complex process, but any chronometric ages thus determined must be related to a particular time scale. The scale used by many Mesozoic-Cenozoic micropaleontologists in recent years is that by Hardenbol et al. (1998). These authors incorporated a detailed event stratigraphy associated with their time scale. The problem with a changing time scale is that somewhat complicated conversions need to made, and users have to get used to a new set of numbers: it would be very trying to have to do this more often than every 5-10 years.

Like the bottom (Precambrian) part of the time scale, the top part is also highly contentious. And strangely enough there is a similar reason: for both, fossils have not been as prominent in the process of determining units. Unlike the other Phanerozoic intervals, which the GTS treats mainly, if not exclusively, from a marine biochronological context, stratigraphy for the most recent geological past has tended to emphasize climatically controlled continental lithostratigraphy (Van Couvering 2006). At least, the basis for the definition and subdivision of the Quaternary has been the recognition and interpretation of climatically driven glacial and interglacial sedimentary sequences. On the other hand, the Pleistocene and its subdivisions are based on largely fossil and paleomagnetic criteria, while the Holocene base is defined at 10 000 radiocarbon years (about 11 500 real years). The view represented by GTS 2004 is thus, that the Pleistocene-Holocene terminology conceptually fits the top of the GTS, whereas the Tertiary-Quaternary terminology is a quaint throwback, and at odds with current philosophy. Thus, although keeping the term Quaternary as an option, GTS 2004 decoupled it from the Pliocene-Pleistocene-Holocene terminology; the term Tertiary is dropped altogether. This is a new issue: until recently, the base of the Quaternary was assumed to correspond to the base of the Pleistocene. The problem has been made real (rather than semantic) by the designation of a golden spike at the base of the Pleistocene, estimated at 1.806 Ma; those who favour a Quaternary terminology (including it seems most of those working on rocks at the top of the geological column) consider the base of the Quaternary as the onset of oscillating glacial and non-glacial episodes, at about 2.6 Ma, as calibrated loosely by geomagnetics.

To this point, I have carefully avoided naming the authors of Chapter 22 on "The Pleistocene and Holocene Epochs": they are Phil Gibbard and Thijs van Kolfschoten. The chapter and youngest part of GTS 2004 have set off a heated debate: according to Bowen and Gibbard (2007), its publication "... surprised one of its co-authors, who published a swift rebuttal on the omission [sic] of the term Quaternary...." The rebuttal appeared in Gibbard et al. (2005). For an alternate perspective, see Van Couvering (2006).

Despite its problems, this book represents a tremendous achievement: insofar as a compendious book can be, it represents a state of the art of the geological time scale up to 2005. As an active research tool, this type of book is probably becoming superseded by dynamic databases (e.g. the GeoWhen Database: [http://www.stratigraphy.org/geowhen/]). For those interested in gaining a sense of developments since 2004/2005, especially with regard to the seemingly increasing controversial nature of the GSSP approach, Berggren et al. (2006) is worth checking out. Nevertheless, GTS 2004 is a "must" for all institutional libraries that make any claim to cover the natural sciences. At US$70 it is not cheap, but – given its almost 600 pages plus pull-out chart – good value nonetheless, and most geologists will want to at least have ready access to a copy. It is an excellent source of technical and non-technical information, and the bibliography alone makes it a great resource for many projects.

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