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# On The Geologic Time Scale

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With 6 figures and 1 table

**Abstract.** This report summarizes the international divisions and ages in the Geologic Time Scale, published in 2012 (GTS2012). Since 2004, when GTS2004 was detailed, major developments have taken place that directly bear and have considerable impact on the intricate science of geologic time scaling. Precambrian now has a detailed proposal for chronostratigraphic subdivision instead of an outdated and abstract chronometric one. Of 100 chronostratigraphic units in the Phanerozoic 63 now have formal definitions, but stable chronostratigraphy in part of upper Paleozoic, Triassic and Middle Jurassic/Lower Cretaceous is still wanting.

Detailed age calibration now exist between radiometric methods and orbital tuning, making $^{40}$Ar-$^{39}$Ar dates 0.64 % older and more accurate. In general, numeric uncertainty in the time scale, although complex and not entirely amenable to objective analysis, is improved and reduced. Bases of Paleozoic, Mesozoic and Cenozoic are bracketed by analytically precise ages, respectively 541 ± 0.63, 252.16 ± 0.5, and 65.95 ± 0.05 Ma. High-resolution, direct age-dates now exist for base-Carboniferous, base-Permian, base-Jurassic, base-Cenomanian and base-Eocene. Relative to GTS2004, 26 of 100 time scale boundaries have changed age, of which 14 have changed more than 4 Ma, and 4 (in Middle to Late Triassic) between 6 and 12 Ma. There is much higher stratigraphic resolution in Late Carboniferous, Jurassic, Cretaceous and Paleogene, and improved integration with stable isotopes stratigraphy. Cenozoic and Cretaceous have a refined magneto-biochronology. The spectacular outcrop sections for the Rosello Composite in Sicily, Italy and at Zumaia, Basque Province, Spain encompass the Global Boundary Stratotype Sections and Points for two Pliocene and two Paleocene stages. Since the cycle record indicates, to the best of our knowledge that the stages sediment fill is stratigraphically complete, these sections also may fulfill the important role of stage unit stratotypes for three of these stages, Piacenzian, Zanclean and Danian.

**Key words.** Geologic Time Scale, Precambrian, Stratotype, Standard chronostratigraphy

## Geologic Time Scale 2012 publication

Arthur Holmes, the Father of the Geologic Time Scale once wrote (Holmes 1965, p. 148): “*To place all the scattered pages of earth history in their proper chronological order is by no means an easy task*”. Ordering these scattered and torn pages requires a detailed and accurate time scale. This will greatly facilitate our understanding of the physical, chemical and biological processes since Earth appeared and solidified.

Calibration to linear time of the succession of events recorded in the rocks on Earth has three components:

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(1) the standard stratigraphic divisions and their correlation in the global rock record, (2) the means of measuring linear time or elapsed durations from the rock record, and (3) the methods of effectively joining the two scales, the stratigraphic one and the linear one.

In the last decade, there have been major developments in stratigraphic division and measuring linear time that directly bear and have considerable impact on the World Geologic Time Scale 2012. GTS2012 details and explains the historical background, principal methodology, current chronostratigraphy and new geochronologic results in a systematic manner in 32 chapters, authored and co-authored by a team of over 65 scientists (chapter collaborators not listed), as follows:

Introduction, F. M. Gradstein
Chronostratigraphy, linking time and rock, F. M. Gradstein and J. G. Ogg
Biochronology, F. M. Gradstein
Cyclostratigraphy and astrochronology, L. A. Hinnov and F. J. Hilgen
The geomagnetic polarity time scale, J. G. Ogg
Radiogenic isotopes geochronology, M. Schmitz
Strontium isotope stratigraphy, J. M. Mcarthur, R. J. Howarth and G. Shields
Osmium isotope stratigraphy, B. Peucker-Ehrenbrink and G. Ravizza
Sulfur isotope stratigraphy, A. Paytan and E. T. Gray
Oxygen isotope stratigraphy, E. Grossman
Carbon isotope stratigraphy, M. Saltzman and E. Thomas
A brief history of plants on Earth, S. R. Gradstein and H. Kerp
Sequence chronostratigraphy, M. Simmons
Statistical procedures, F. P. Agterberg, O. Hammer and F. M. Gradstein
The Planetary time scale, K. Tanaka and B. Hartmann
The Precambrian: the Archean and Proterozoic Eons, M. Van Kranendonk et al.
The Cryogenian Period, G. A. Shields, A. C. Hill and B. A. Macgabhann
The Ediacaran Period, G. Narbonne, S. Xiao and G. A. Shields
The Cambrian Period, S. Peng, L. Babcock and R. A. Cooper
The Ordovician Period, R. A. Cooper and P. M. Sadler
The Silurian Period, M. J. Melchin, P. M. Sadler and B. D. Cramer
The Devonian Period, T. Becker, F. M. Gradstein and O. Hammer
The Carboniferous Period, V. Davydov, D. Korn and M. Schmitz
The Permian Period, Ch. Henderson, V. Davydov and B. Wardlaw
The Triassic Period, J. G. Ogg
The Jurassic Period, J. G. Ogg and L. Hinnov
The Cretaceous Period, J. G. Ogg and L. Hinnov
The Paleogene Period, N. Vandenberghe, F. J. Hilgen and R. Speijer
The Neogene Period, F. J. Hilgen, L. Lourens and J. Van Dam
The Quaternary Period, B. Pillans and P. Gibbard
The Prehistoric Human Time Scale, J. A. Catt and M. A. Maslin
The Anthropocene, J. Zalasiewicz, P. Crutzen and W. Steffen

Appendix 1 – Colour coding of Standard Stratigraphic Units
Appendix 2 – M. Schmitz, GTS2012 Radiometric Ages
Appendix 3 – E. Anthonissen and J. G. Ogg, Cretaceous and Cenozoic Microfossil Biochronology.

To ensure continuity between geologic periods and undertake error analysis, the linear age scale using 265 carefully recalibrated radiometric dates was constructed by F. Gradstein, O. Hammer, J. Ogg and M. Schmitz, in close consultation with individual chapter authors.

## Precambrian

Precambrian is at the dawn of a geologically meaningful stratigraphic scale. Several features of the current international stratigraphic chart relating to the Precambrian timescale have raised concern within the geological community, primary among which is the chronometric scheme used for Eon, Era and System/Period boundaries that are based purely on round-number chronometric divisions and ignore geology and stratigraphy (Plumb and James 1986; Fig. 1). The current chronometric scheme for Precambrian time in Figure 1 was partly chosen because of a relative paucity of potential biological-geological criteria. Round number divisions of the scheme has worked reasonably well because there was relatively little precise geochronological information available at the time of compilation more than 30 years ago to disprove these broad divisions. The existing chronometric scheme is now unsatisfactory because there has been a veritable explosion of new geoscience information on the geodynamic evolution of Precambrian terrains and on the geobiological evolution of the planet. In addition, there are now thousands of precise U-Pb zircon age dates and many detailed isotopic studies of Precambrian stratigraphic sections. The new data has revealed that many of the current divisions are either misplaced in terms of global geodynamic events, impractical in terms of global correlation, or meaningless in terms of significant lithostratigraphic, biological, and biochemical changes across much of the globe.

As outlined in great detail by Van Kranendonk and collaborators in GTS2012 (Van Kranendonk 2012) Precambrian Earth evolved in a distinct series of over 20 linked events (Fig. 2), each of which arose directly as a result of antecedent events, and thus they accord well with Gould's (1994) historical principles of directionality and contingency. Each event has global significance. This allows for the very real possibility of a fully revised Precambrian timescale, founded on the linked geological development of the planet and evolution of the biosphere, and based on the extant rock record, with real boundaries marked by Global Boundary Stratotype Sections and Points (GSSP's; see next text section for fundamental details of the concept). Nine events may qualify for such, with the base Ediacaran Period already formalized with a GSSP, and the upper level of the Precambrian formalized with the GSSP for the base Cambrian Period (Fig. 2).

Three Precambrian eons can be identified, relating to: 1) the early development of the planet (Hadean Eon: 4567–4030 Ma); 2) a major period of crust formation and establishment of a biosphere, characterized by a highly reducing atmosphere (Archean Eon: 4030–2420 Ma); and 3) a period marked by the progressive rise in atmospheric oxygen, supercontinent cyclicity, and the evolution of more complex (eukaryotic) life (Proterozoic Eon: 2420–541 Ma).

Each of these eons may be subdivided into a number of eras and periods that reflect lower-order changes in the geological record (Fig. 2).

- 4567 Ma: start of Hadean Eon/Chaotian Era; start of the solar system, formation of Earth; chronometric boundary, on Ca-Al-rich refractory inclusions in meteorites
- 4404 Ma: end of Chaotian Era/start Jack Hillsian (Jacobian) Era; end of major accretion and Moon-forming giant impact, and first appearance of crustal material; chronometric boundary, on oldest detrital

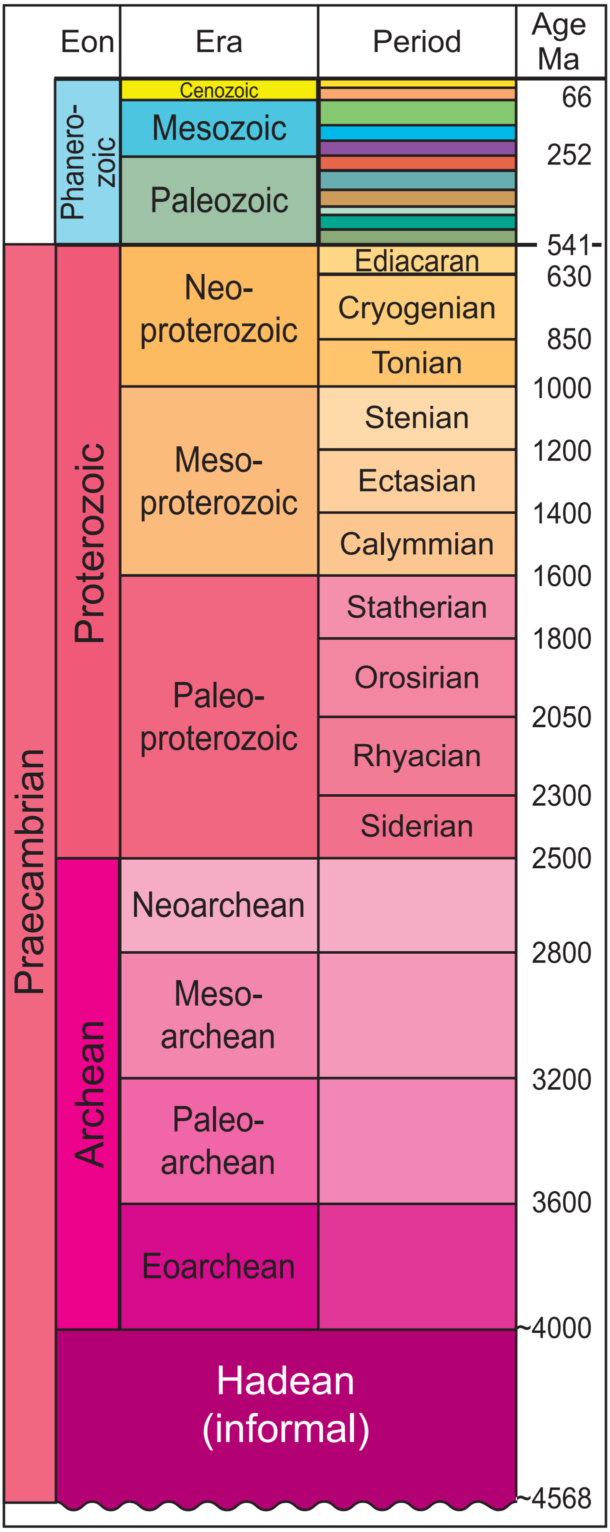


**Fig. 1.** The Precambrian chronometric scheme used for Eon, Era and System/Period boundaries is based purely on round-number chronometric divisions and ignores geology and stratigraphy.

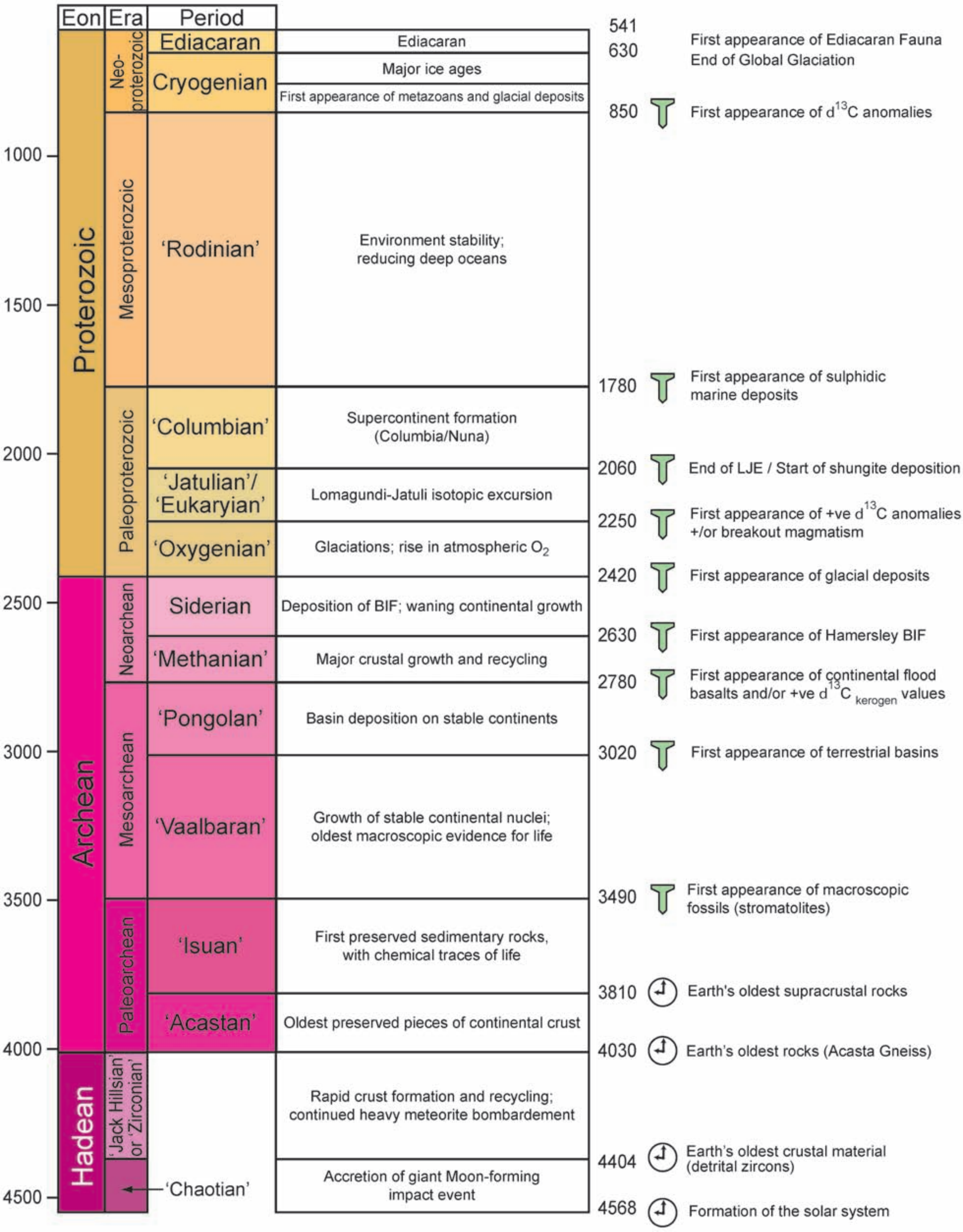


**Fig. 2.** Proposed scheme for a fully revised Precambrian timescale: clock symbols = chronometric boundaries; green spikes = boundaries where possible GSSPs are recognised; yellow spike = formally recognised GSSP (for details see Van Kranendonk, 2012).

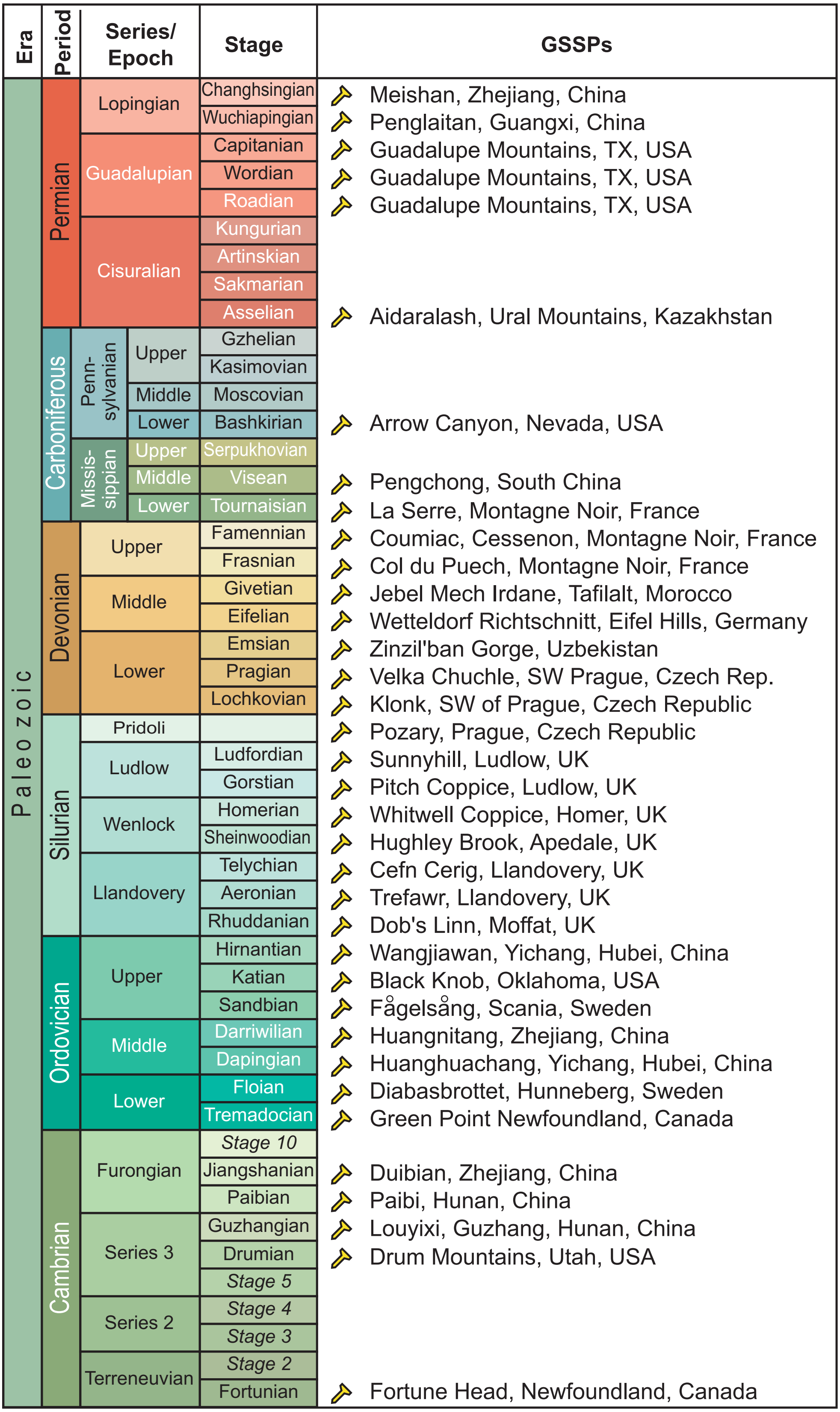
zircon from Jack Hills greenstone belt (Yilgarn Craton, Australia)
- 4030 Ma: end Hadean Eon (Jack Hillsian (Jacobian) Era)/start Archean Eon (Paleoarchean Era, Acastan Period); start of the stratigraphic record; chronometric boundary at world's oldest rock in the Acasta Gneiss (Slave Craton, Canada)
- ~3810 Ma: end Acastan Period/start Isuan Period; first appearance of supracrustal rocks; chronometric boundary in the Isua supracrustal belt (North Atlantic Craton, western Greenland)
- 3490 Ma: end Paleoarchean Era (end Isuan Period)/start Mesoarchean Era (Vaalbaran Period); well-preserved crustal lithosphere with macroscopic evidence of fossil life; GSSP at base of stromatolitic Dresser Formation (Warrawoona Group, Pilbara Supergroup, Australia)
- ~3020 Ma: end Vaalbaran Period/start Pongolan Period; first appearance of stable continental basins, containing evidence of microbial life in terrestrial environments; GSSP just above the base of the De Grey Supergroup (Pilbara Craton, Australia)
- ~2780 Ma: end Mesoarchean Era (Pongolan Period)/start Neoarchean Era (Methanian Period); onset of global volcanism associated with late Archean superevent and of highly negative $\delta^{13}C_{kerogen}$ values; GSSP at base of Mount Roe Basalt (Fortescue Group, Mount Bruce Supergroup, Australia)
- ~2630 Ma: end Methanian Period/start Siderian Period; first appearance of global BIFs; GSSP at base of Marra Mamba Iron Formation (Hamersley Group, Mount Bruce Supergroup, Australia)
- ~2420 Ma: end Archean Eon (Neoarchean Era, Siderian Period)/start Proterozoic Eon (Paleoproterozoic Era, Oxygenian Period); first appearance of glacial deposits, rise in atmospheric oxygen, and disappearance of BIFs; GSSP at base of Kazput Formation (Turee Creek Group, Mount Bruce Supergroup, Australia)
- ~2250 Ma: end Oxygenian Period/start Jatulian (or Eukaryian) Period; end of glaciations and first appearance of cap carbonates with high $\delta^{13}C$ values (start of Lomagundi-Jatuli isotopic excursion), and of oxidised paleosols and redbeds; GSSP at base of Lorrain Formation (Cobalt Group, Huronian Supergroup, Canada)
- 2060 Ma: end Jatulian (or Eukaryian) Period/start Columbian Period; end of Lomagundi-Jatuli isotopic excursion and first appearance of widespread global volcanism and iron-formations: GSSP at conformable base of Rooiberg Group (Bushveld Magmatic Province, Kaapvaal Craton, South Africa), or at base of the Kuetsjärvi Volcanic Formation (Pechenga greenstone belt, Fennoscandia)
- ~1780 Ma: end Paleoproterozoic Era (Columbian Period)/start Mesoproterozoic Era; first appearance of sulphidic reducing oceanic deposits, first acritarchs, and successions with giant sulphide ore deposits; GSSP unassigned
- ~850 Ma: end Mesoproterozoic Era/start Neoproterozoic Era (Cryogenian Period); onset of $\delta^{13}C$ anomalies? GSSP unassigned
- ~630 Ma: end Cryogenian Period/start Ediacaran Period; GSSP at conformable contact at base of cap carbonate overlying Marinoan Glaciation
- 542 Ma: end Proterozoic Eon (Neoproterozoic Era, Ediacaran Period)/start Phanerozoic Eon (Paleozoic Era, Cambrian Period).

The suggested changes proposed herein, include four chronometric and ten chronostratigraphic (GSSP) boundaries as listed above. These boundaries are intended as a guide for future discussions and refinements of the Precambrian timescale. The boundaries will need to be approved by the members of the Precambrian subcommission and formally accepted before they can be made useful in detailed mapping and further study by the geological community at large. The goal over the next few years is to develop proposals for the major eons and their boundaries and then work down through the era and period boundaries, to decide on the best sections for GSSPs and the most suitable names to use.

A separate question is how best to group Precambrian events into Periods, Eras and Eons, a question dealt with in detail in GTS2012. The Subcommission of Precambrian Stratigraphy of ICS is actively engaged with these stratigraphic challenge and formalities.

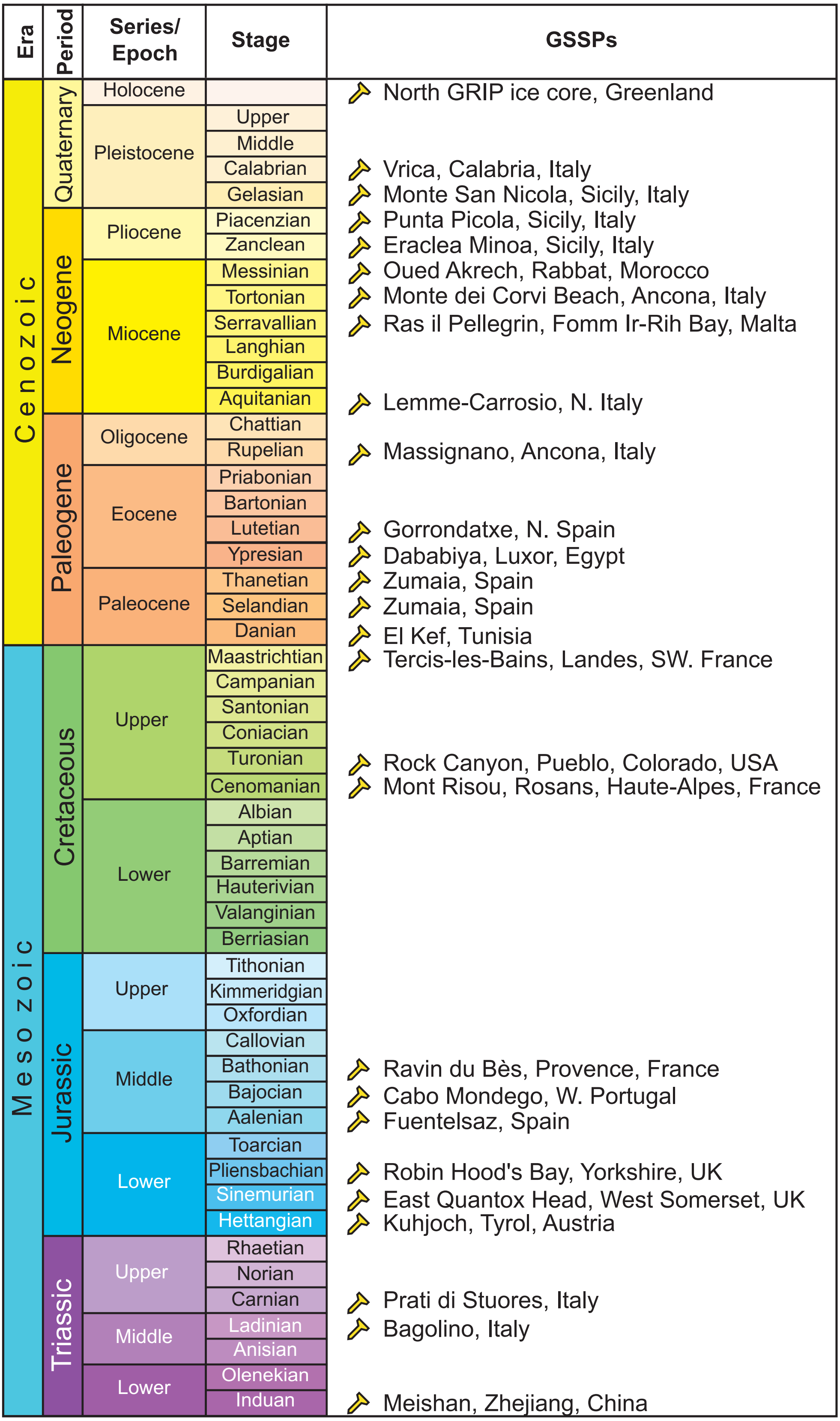
## Global stratotype sections and points

It is not long ago that stratigraphy was spending time in dealing with type sections of stages, and correlation of stage units in terms of zones, and not fossil events. Traditionally, stages would be characterized by a historical type section that contained a body of sediment, since long considered typical for the stage in question. Ideally, the type section also would contain fossil zones allowing correlation of the body of the stage unit



| Era | Period | Series/ Epoch | | Stage | GSSPs |
|---|---|---|---|---|---|
| Paleozoic | Permian | Lopingian | | Changhsingian | Meishan, Zhejiang, China |
| | | | | Wuchiapingian | Penglaitan, Guangxi, China |
| | | Guadalupian | | Capitanian | Guadalupe Mountains, TX, USA |
| | | | | Wordian | Guadalupe Mountains, TX, USA |
| | | | | Roadian | Guadalupe Mountains, TX, USA |
| | | Cisuralian | | Kungurian | |
| | | | | Artinskian | |
| | | | | Sakmarian | |
| | | | | Asselian | Aidaralash, Ural Mountains, Kazakhstan |
| | Carboniferous | Pennsylvanian | Upper | Gzhelian | |
| | | | | Kasimovian | |
| | | | Middle | Moscovian | |
| | | | Lower | Bashkirian | Arrow Canyon, Nevada, USA |
| | | Mississippian | Upper | Serpukhovian | |
| | | | Middle | Visean | Pengchong, South China |
| | | | Lower | Tournaisian | La Serre, Montagne Noir, France |
| | Devonian | Upper | | Famennian | Coumiac, Cessenon, Montagne Noir, France |
| | | | | Frasnian | Col du Puech, Montagne Noir, France |
| | | Middle | | Givetian | Jebel Mech Irdane, Tafilalt, Morocco |
| | | | | Eifelian | Wetteldorf Richtschnitt, Eifel Hills, Germany |
| | | Lower | | Emsian | Zinzil'ban Gorge, Uzbekistan |
| | | | | Pragian | Velka Chuchle, SW Prague, Czech Rep. |
| | | | | Lochkovian | Klonk, SW of Prague, Czech Republic |
| | Silurian | Pridoli | | | Pozary, Prague, Czech Republic |
| | | Ludlow | | Ludfordian | Sunnyhill, Ludlow, UK |
| | | | | Gorstian | Pitch Coppice, Ludlow, UK |
| | | Wenlock | | Homerian | Whitwell Coppice, Homer, UK |
| | | | | Sheinwoodian | Hughley Brook, Apedale, UK |
| | | Llandovery | | Telychian | Cefn Cerig, Llandovery, UK |
| | | | | Aeronian | Trefawr, Llandovery, UK |
| | | | | Rhuddanian | Dob's Linn, Moffat, UK |
| | Ordovician | Upper | | Hirnantian | Wangjiawan, Yichang, Hubei, China |
| | | | | Katian | Black Knob, Oklahoma, USA |
| | | | | Sandbian | Fågelsång, Scania, Sweden |
| | | Middle | | Darriwilian | Huangnitang, Zhejiang, China |
| | | | | Dapingian | Huanghuachang, Yichang, Hubei, China |
| | | Lower | | Floian | Diabasbrottet, Hunneberg, Sweden |
| | | | | Tremadocian | Green Point Newfoundland, Canada |
| | Cambrian | Furongian | | *Stage 10* | |
| | | | | Jiangshanian | Duibian, Zhejiang, China |
| | | | | Paibian | Paibi, Hunan, China |
| | | Series 3 | | Guzhangian | Louyixi, Guzhang, Hunan, China |
| | | | | Drumian | Drum Mountains, Utah, USA |
| | | | | *Stage 5* | |
| | | Series 2 | | *Stage 4* | |
| | | | | *Stage 3* | |
| | | Terreneuvian | | *Stage 2* | |
| | | | | Fortunian | Fortune Head, Newfoundland, Canada |

**Fig. 3.** Distribution of ratified Global Boundary Stratotype Sections and Points (GSSPs) in the Paleozoic, Mesozoic and Cenozoic Eras (see also www.stratigraphy.org or https://engineering.purdue.edu/Stratigraphy/).



| Era | Period | Series/ Epoch | Stage | GSSPs |
|---|---|---|---|---|
| Cenozoic | Quaternary | Holocene | | North GRIP ice core, Greenland |
| | | Pleistocene | Upper | |
| | | | Middle | |
| | | | Calabrian | Vrica, Calabria, Italy |
| | | | Gelasian | Monte San Nicola, Sicily, Italy |
| | Neogene | Pliocene | Piacenzian | Punta Picola, Sicily, Italy |
| | | | Zanclean | Eraclea Minoa, Sicily, Italy |
| | | Miocene | Messinian | Oued Akrech, Rabbat, Morocco |
| | | | Tortonian | Monte dei Corvi Beach, Ancona, Italy |
| | | | Serravallian | Ras il Pellegrin, Fomm Ir-Rih Bay, Malta |
| | | | Langhian | |
| | | | Burdigalian | |
| | | | Aquitanian | Lemme-Carrosio, N. Italy |
| | Paleogene | Oligocene | Chattian | |
| | | | Rupelian | Massignano, Ancona, Italy |
| | | Eocene | Priabonian | |
| | | | Bartonian | |
| | | | Lutetian | Gorrondatxe, N. Spain |
| | | | Ypresian | Dababiya, Luxor, Egypt |
| | | Paleocene | Thanetian | Zumaia, Spain |
| | | | Selandian | Zumaia, Spain |
| | | | Danian | El Kef, Tunisia |
| Mesozoic | Cretaceous | Upper | Maastrichtian | Tercis-les-Bains, Landes, SW. France |
| | | | Campanian | |
| | | | Santonian | |
| | | | Coniacian | |
| | | | Turonian | Rock Canyon, Pueblo, Colorado, USA |
| | | | Cenomanian | Mont Risou, Rosans, Haute-Alpes, France |
| | | Lower | Albian | |
| | | | Aptian | |
| | | | Barremian | |
| | | | Hauterivian | |
| | | | Valanginian | |
| | | | Berriasian | |
| | Jurassic | Upper | Tithonian | |
| | | | Kimmeridgian | |
| | | | Oxfordian | |
| | | Middle | Callovian | |
| | | | Bathonian | Ravin du Bès, Provence, France |
| | | | Bajocian | Cabo Mondego, W. Portugal |
| | | | Aalenian | Fuentelsaz, Spain |
| | | Lower | Toarcian | |
| | | | Pliensbachian | Robin Hood's Bay, Yorkshire, UK |
| | | | Sinemurian | East Quantox Head, West Somerset, UK |
| | | | Hettangian | Kuhjoch, Tyrol, Austria |
| | Triassic | Upper | Rhaetian | |
| | | | Norian | |
| | | | Carnian | Prati di Stuores, Italy |
| | | Middle | Ladinian | Bagolino, Italy |
| | | | Anisian | |
| | | Lower | Olenekian | |
| | | | Induan | Meishan, Zhejiang, China |

sedimentary strata outside the type area. Boundaries between stages would be interpolated, using suitable biostratigraphic criteria, rarely if ever found in the stratotype section. Stage boundaries traditionally had no type sections. It is readily understood that the absence of stage boundary definition in type sections may lead to uncertainty in stage correlation.

Hollis Hedberg, a major champion stratigraphic standardization once wrote (1976, p. 35): "In my opinion, the first and most urgent task in connection with our present international geochronology scale is to achieve a better definition of its units and horizons so that each will have standard fixed-time significance and the same time significance for all geologists everywhere. Most of the named international chronostratigraphic (geochronology) units still lack precise globally accepted definitions and consequently their limits are controversial and variably interpreted by different workers. This is a serious and wholly unnecessary impediment to progress in global stratigraphy. What we need is simply a single permanently fixed and globally accepted standard definition for each named unit or horizon, and this is where the concept of stratotype standards (particularly boundary stratotypes and other horizon stratotypes) provides a satisfactory answer". It is this and other stratigraphic deliberations that have led to the current concept and active and deliberate application of the Global Boundary Stratotype Section and Point (GSSP) to global chronostratigraphic standardization.

The second edition of the International Stratgraphic Guide defines the Global Boundary Stratotype Section and Point (GSSP) as follows: The selected type or standard for the definition and recognition of a stratigraphic boundary between two named standard global chronostratigraphic units, designated as a unique and specific point in a specific sequence of rock strata in a unique and specific location; identified in published form and marked in the section (Salvador 1994, p. 120).

Now, stratigraphic standardization through the work of the International Commission on Stratigraphy (ICS) is steadily refining the international chronostratigraphic scale. Of the 100 stage or series units in the Phanerozoic Eonothem 63 now have ratified boundary definitions, using the Global Stratotype Section and Point (GSSP) concept (Fig. 3), versus 60 in 2008, fewer than 45 in 2004 and just over 30 in the year 2000. Details on the new and existing stage boundary definitions are presented in Gradstein and Ogg (2012), at https://engineering.purdue.edu/Stratigraphy/, and at www.nhm2.uio.no/stratlex. The former internet site has a link to 'TimeScale Creator', a free JAVA program package that enables users to explore and create charts of any portion of the geologic time scale from an extensive suite of global and regional events in Earth History. The internal database suite encompasses over 25,000 paleontological, geomagnetic, sea-level, stable isotope, and other events. All ages in Time Scale Creator are currently standardized to Geologic Time Scale 2012, but may be retro-scaled in Geologic Time Scale 2004 or 2008, if so desired.

In many cases, traditional European-based Late Proterozoic and Phanerozoic stratigraphic unit's stages have now been replaced with new subdivisions that allow global correlation. The Cryogenian and Ediacaran Periods are 'filling up' with stratigraphic information, and the latter is now a ratified Period. New stages have been introduced in Cambrian and Ordovician that allow global correlations, in contrast to British, American, Chinese, Russian or Australian regional stages. Long ratified stage definitions in Silurian and Devonian are undergoing long overdue revision to better reflect the actually observed fossil and rock record. The Jurassic, for a long time the only period in the Phanerozoic without a formal definition for base and top, now has a formal base in the Kuhjoch section in Austria. The boundary is thought to correspond closely to End-Triassic mass extinctions coincident with a negative carbon-isotope excursion, linked to widespread volcanism (see Ogg and Hinnov 2012).

Only base Cretaceous is still undefined, although realistic and practical solutions exist if one considers other zonal events than regional and unpractical ammonites, and also place emphasis on the high-resolution geomagnetic record that transcends facies boundaries (Ogg and Hinnov 2012). Curiously, the largest chronostratigraphic knowledge gap in the Phanerozoic pertains to Callovian through Albian where no GSSP's have yet been defined (Fig. 3).

All Paleocene (Danian, Selandian, Thanetian), two Eocene (Ypresian, Lutetian) and one Oligocene (Rupelian) stage are now defined in the Cenozoic, and all but two Neogene stages (Langhian and Burdigalian) have been defined and ratified. The Pleistocene is formally divided in three units, and Holocene has a new and formal definition. Quaternary, after 150 years of confusion, now has a formal definition also, although it remains to be seen how practical that definition is for marine geosciences. Tertiary, bracketing Paleogene and Neogene, still remains an informal unit, albeit frequently and widely used in popular stratigraphic literature and in oil industry jargon and its publications. Here, ICS has a task to not only serve its academic followers with formalizing chronostratigraphy, but also professionals.

## Stage unit stratotypes

The branch of stratigraphy called chronostratigraphy has as its fundamental building block the time-rock unit. A stage is a time-rock unit, not just a time unit, and not just a rock unit. Unfortunately, the boundary stratotype concept of the previous section in this study only outlines and defines boundaries of units, and not the content of the unit. In a chronologic sense it provides the abstract duration of units, but not its content. It defines an abstraction in time, and not a tangible unit in rock. Hence, it can be argued that each stage should go back to its roots and both have boundary stratotypes for its boundaries and a unit stratotype. And to take it one step further: Would chronostratigraphy not be served best if suitable sedimentary sections could be identified on Earth that harbor both the complete body of rock and the upper and lower boundaries of stages in one and the same section.

Now, recent developments in integrated high-resolution stratigraphy and astronomical tuning of continuous deep marine successions combine potential unit stratotypes and boundary stratotypes for global stages as basic building blocks of the Global Chronostratigraphic Scale (GCS). Within the framework of an integrated high-resolution stratigraphy, the age-calibration of the youngest Neogene part of this time scale is now based entirely on astronomical tuning, resulting in a time scale with an unprecedented accuracy, resolution and stability (Hilgen et al. 2006). This progress in integrated high-resolution stratigraphy in combination with astronomical tuning of cyclic sedimentary successions thus invalidates arguments against unit stratotypes. At the same time, due to the geochronologic quality of the tuned cycle units, it elegantly combines chronostratigraphy with geochronoloy. It argues in favour of a reconsideration of the unit stratotype concept, and, as a consequence, a strengthening of the dual classification of chronostratigraphy (time-rock) and geochronology (time).

For the late Neogene, Global Stratotype Section and Point (GSSP) sections may also serve as unit stratotypes, covering the interval from the base of a stage up to the level that – time-stratigraphically – correlates with the base of the next younger stage in a continuous and well-tuned deep marine succession (Hilgen et al. 2006).

The Rossello Composite Section (RCS, Sicily, Italy; see Fig. 4) is a prime example of the modified unit stratotype approach of classical chronostratigraphy, defining the complete sedimentary record of stages and their stage boundaries. The RCS shows the orbital tuning of the basic precession-controlled sedimentary cycles and the resulting astronomical time scale with accurate and precise astronomical ages for sedimentary cycles, calcareous plankton events and magnetic reversal boundaries. The GSSP's of the Pliocene Zanclean and Piacenzian Stages are formally defined in the RCS while the level that time-stratigraphically correlates with the Gelasian GSSP is found in the topmost part of the section. The well tuned RCS lies at the base of the Early – Middle Pliocene part of the Neogene Time Scale and the Global Standard Chronostratigraphic Scale and as such could serve as unit stratotype for both the Zanclean and Piacenzian Stage (Langereis and Hilgen 1991, Hilgen 1991, Lourens et al. 1996). Similarly, the Monte dei Corvi section may serve as unit stratotype for the Tortonian Stage (Hüsing et al. 2009).

Now, the Zumaia section along the Basque coast of northwestern Spain has the potential to become the Danian unit stratotype (Fig. 5). The Danian GSSP is defined in the El Kef section in Tunisia, but the time correlative level marked by the K/Pg boundary can easily be identified at Zumaia. The Selandian GSSP is defined at the top part of the "Danian" limestones in the Zumaia section itself. The sedimentary cycle pattern is tuned to the eccentricity time series of astronomical solutions La2004 (Laskar et al. 2004) and R7 (Varadi et al. 2003), following Kuiper et al. (2008), who used the astronomically calibrated age of 28.201 ± 0.046 Ma for the FCs dating standard to recalculate single crystal $^{40}Ar/^{39}Ar$ sanidine ages of ash layers intercalated directly above the K/Pg boundary in North America to constrain the tuning to the 405-kyr eccentricity cycle. Tuning to ~ 100-kyr eccentricity is unreliable due to uncertainties in the astronomical solution. 405-kyr eccentricity cycles are numbered back from the Recent and, once the tuning is confirmed, may serve to define and label correlative 405-kyr limestone-marl cycles as – Milankovitch – chronozones (see also Dinares-Turrel et al. 2003, Hilgen et al. 2006, 2010). The finely tuned and finely numbered Late Neogene deep marine oxygen isotope record is the Milankowitch chronozone set 'par excellence' for global, deep marine sedimentary correlation (see below). Ex-

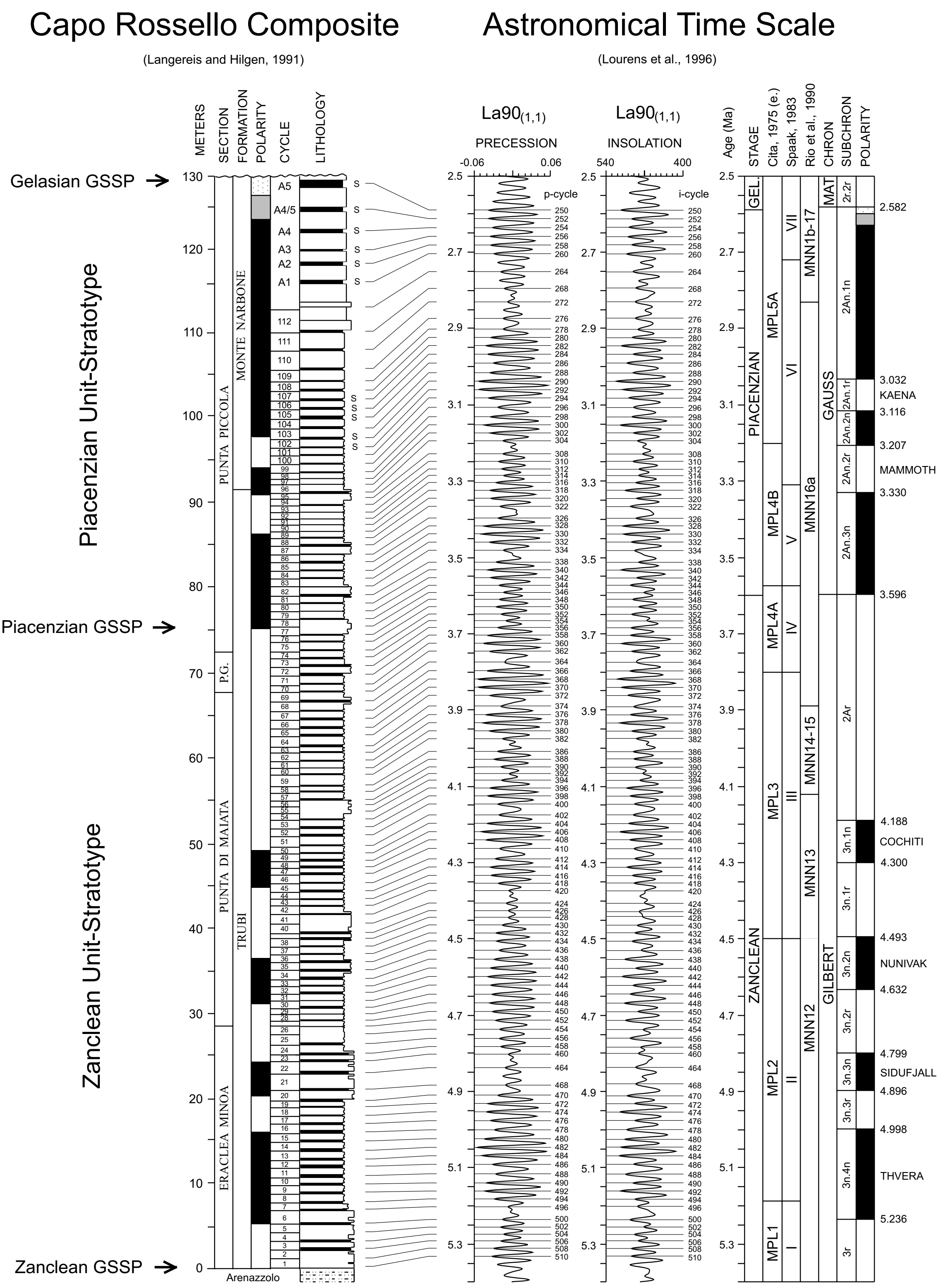


**Fig. 4.** The Rossello Composite Section (RCS, Sicily, Italy) is a prime example of the modified unit stratotype approach showing the orbital tuning of the basic precession-controlled sedimentary cycles and the resulting astronomical time scale with accurate and precise astronomical ages for sedimentary cycles, calcareous plankton events and magnetic reversal boundaries. The Zanclean and Piacenzian GSSPs are formally defined in the RCS while the level that time-stratigraphically correlates with the Gelasian GSSP is found in the topmost part of the section. The well tuned RCS lies at the base of the Early–Middle Pliocene part of the Neogene Time Scale and the Global Standard Chronostratigraphic Scale and as such could serve as unit stratotype for both the Zanclean and Piacenzian Stage.

tending this high-resolution chronozone set back in ‘deep time’ to the Paleogene is now around the corner.

The added value of such sections as the RCS and Zumaia as unit stratotype lies in the integrated high-resolution stratigraphy and astronomical tuning. Such sections provide excellent age control with an unprecedented resolution, precision and accuracy within the entire stage. As such they form the backbone of the new integrated late Neogene time scale and provide the basis for reconstructing Earth’s history. Application of such accurate high-resolution time scales already led to a much better understanding of the Messinian salinity crisis in the Mediterranean (e.g., Krijgsman et al. 1999) and of the potential influence of very long period orbital forcing on climate (e.g., Lourens et al. 2005) and species turnover in small mammals (Van Dam et al. 2006).

In this way a stage is also defined by its content and not only by its boundaries. Extending this concept to older time intervals requires that well-tuned, continuous deep marine sections are employed, thus necessitating the employment of multiple deep sea drilling sites for defining (remaining) stages and stage boundaries in at least the Cenozoic and Cretaceous, and possibly the entire Mesozoic. Evidently, the construction of the Geological Time Scale should be based on the most appropriate sections available while, where possible, taking the historical concept of global stages into account.

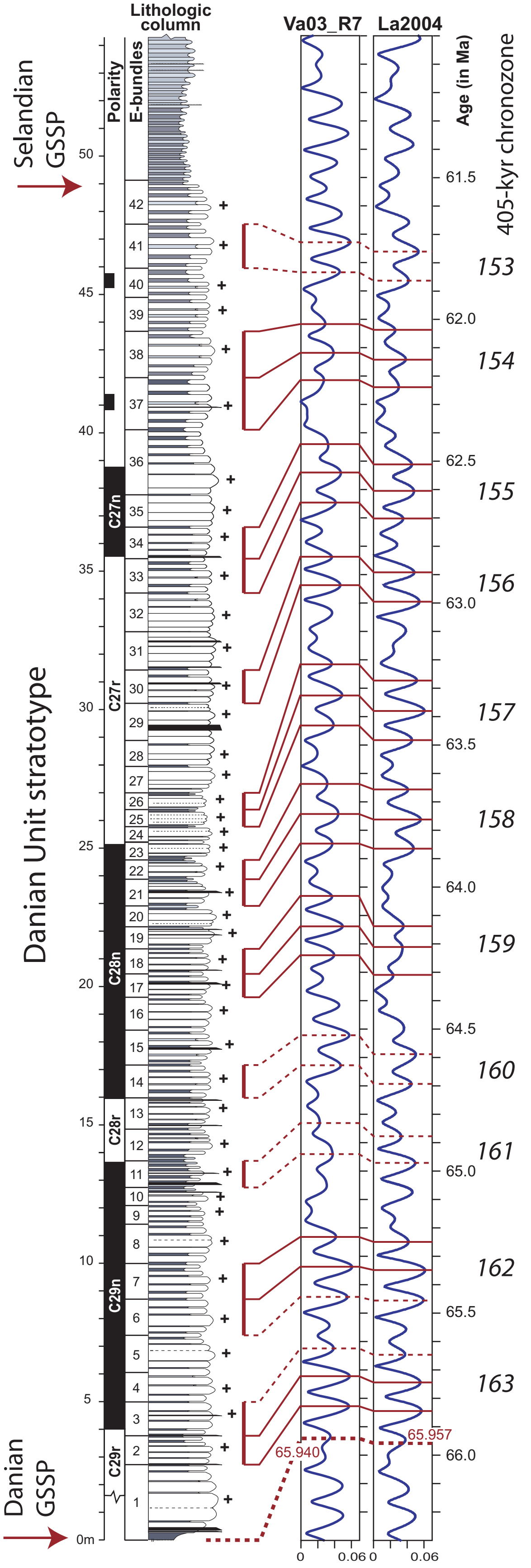


**Fig. 5.** The Zumaia section as potential Danian unit stratotype. The Danian GSSP is defined in the El Kef section in Tunesia, but the time correlative level marked by the K/Pg boundary can easily be identified at Zumaia. The Selandian GSSP is defined at the top part of the “Danian” limestones in the Zumaia section itself. The sedimentary cycle pattern is tuned to the eccentricity time series of astronomical solutions La2004 (Laskar et al. 2004) and R7 (Varadi et al. 2003). The 405-kyr eccentricity cycles are numbered back from the Recent and, once the tuning is confirmed, may serve to define and label correlative 405-kyr limestone-marl cycles as – Milankovitch – chronozones.

## Ages

New or enhanced methods of extracting linear time from the rock record have enabled age assignments with a precision of 0.1 % or better, leading to improved age assignments of key geologic stage boundaries, and intra-stage levels. A good protocol now exists to assign uncertainty to age dates (Schmitz 2012), and intercalibrate the two principal radiogenic isotope techniques using potassium-argon and uranium-lead isotopes. Improved analytical procedures for obtaining uranium-lead ages from single zircons have shifted published ages for some stratigraphic levels to older ages by more than 1 myr (for example at the Permian/Triassic boundary). Similarly, an astronomically assigned age for the neutron irradiation monitor for the $^{40}$Ar-$^{39}$Ar dating method makes earlier reported ages older by 0.64 %. Also, the rhenium-osmium ($^{187}$Re-$^{187}$Os) shale geochronometer has a role to play for organic-rich strata with limited or no potential for ash bed dating with the uranium-led isotopes. For example, Selby (2007) obtained an age of 154.1 ± 2.2 Ma on the base Kimmeridgian in the Flodigarry section on Isle of Skye, NW Scotland. Details on the improved radiogenic isotope methods are in Schmitz (2012).

A welcome practice is that, instead of micro- and macrofossil events, also global geochemical excursions are becoming defining criteria for chronostratigraphic boundaries, like the Corg positive anomaly at the Paleocene/Eocene boundary. Carbon isotope excursions are close proxies for base Cambrian, base Triassic and base Jurassic. The famous iridium anomaly is at the Cretaceous/Paleogene boundary. More GSSP's should use global geochemical events.

Paleozoic chronostratigraphy and geochronology (541–252 Ma) are becoming stable. A majority of stages have ratified boundaries (Fig. 3a). As outlined in detail in GTS2012, improved scaling of stages is feasible with composite standard techniques on fossil zones, as a means of estimating relative zone durations (Cooper and Sadler 2012). It would be desirable to have a second and independent means of scaling stages as a check on potential stratigraphic distortion of zonal composites that ultimately depend on a non-linear evolutionary process. Integration of a refined 100 and 400 kyr sedimentary cycle sequences with a truly high-resolution U/Pb age scale for the Pennsylvanian is a major step towards the global Carboniferous GTS. Although tuning to ~ 100-kyr eccentricity is unreliable due to uncertainties in the astronomical solution back into deep time, it is feasible to recognize ~ 100-kyr eccentricity cycles between high resolution radiometric anchor points. In this case, the high density sequential and high resolution radiometric dating provides an independent means of scaling stages that also have been scaled with composite standard technique (Davydov et al. 2012). Visean with 17 myr duration is the longest stage in the Paleozoic Era.

Several stages in the Mesozoic Era (252–66 Ma) still lack formal boundary definition, but have consensus boundary markers. Lack of the latter and of sufficient radiometric for the Carnian, Norian and Rhaetian Stages in the Triassic make these 3 long stages less certain. The Triassic-Jurassic boundary is well dated at 201.3 ± 0.2 Ma. Earliest Triassic Induan, with 1.5 myr duration is the shortest Mesozoic stage.

The Earth eccentricity component is very stable and extends orbital tuning from the Cenozoic well into the Mesozoic GTS. Jurassic and Cretaceous now have long orbitally tuned segments that confirm the GTS2004 scale built using seafloor spreading. Recalculation of $^{40}$Ar/$^{39}$Ar ages at the Cretaceous–Paleogene boundary yields an age estimate of 65.95 ± 0.0.5 Ma, instead of 65.5 ± 0.3 Ma in GTS2004; the new age rounds off to 66 Ma.

Milankovitch-type orbital climate cyclicity has tuned the Neogene geologic time scale (Hilgen et al. 2012) and for the first time the classical seafloor spreading and magnetochron method to construct the Paleogene time scale has now been matched with the orbitally tuned scale (VandenBerghe et al. 2012). Hence, magneto- and biochronology are refined and stage boundary ages strengthened for the Paleogene also.

A completely astronomical-tuned GTS (AGTS) for the Cenozoic is within reach, showing unprecedented accuracy, precision and resolution. Burdigalian and Langhian in the Miocene, and Chattian, Bartonian and Priabonian Stages in the Paleogene still require formal definition.

## Error bars

Uncertainty in time scales derives from several factors, listed here in decreasing order of difficulty to quantify and often also in magnitude: Uncertainty in bio-magneto and other event stratigraphic correlation, uncertainty in relative scaling of stages, uncertainty in linking radiometric ages dates to precise stage boundary levels, uncertainty in radiometric age dates itself and uncertainty in orbital tuning.

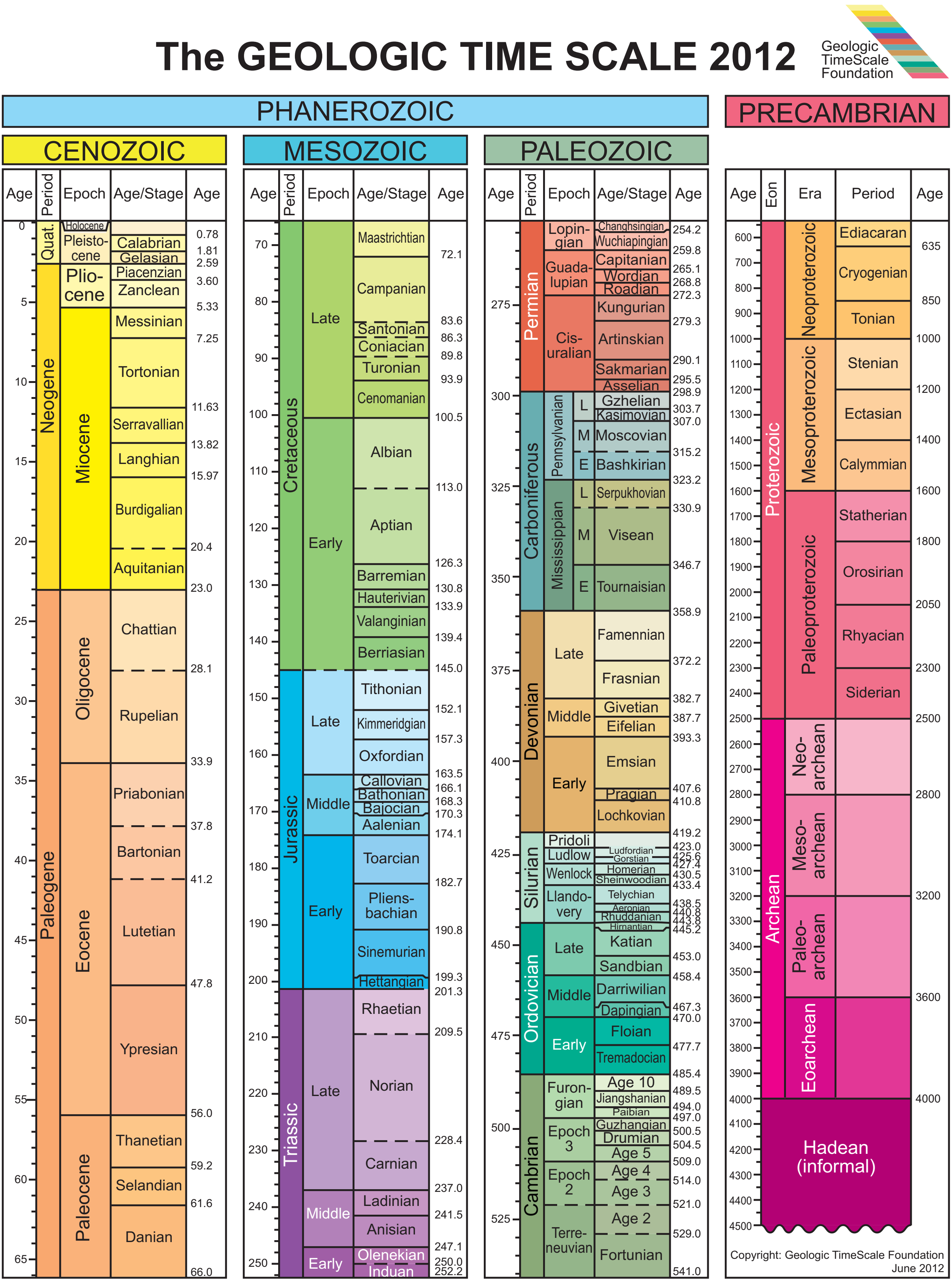

The GEOLOGIC TIME SCALE 2012

**Fig. 6.** The new Geologic Time Scale (GTS2012) with standard chronostratigraphy and ages.

Table 1 Changes in age between GTS2004 and GTS2012. Stages or series that changed by 2 Ma or more in GTS2012 are shown in bold, with Bashkirian, Artinskian, Carnian, Norian and Rhaetian changing numerically most in age. Where the 95% uncertainty estimate of a GTS2012 stage age exceeds the actual numerical age change, such is marked in bold also in this table.

| | Age/Stage | GTS2004 | GTS2012 | Change in Ma | GTS2012 uncertainty in Ma (95%) |
|---|---|---|---|---|---|
| Quaternary | TOP | 0 | 0 (2000) | | |
| | Holocene | 0.0115 | 0.0118 | 0.0003 | |
| | Tarantian | | 0.126 | | |
| | Ionian | | 0.781 | | |
| | Calabrian | 1.81 | 1.806 | −0.004 | |
| | Gelasian | 2.59 | 2.588 | −0.002 | |
| Neogene | Piacenzian | | 3.600 | 0 | |
| | Zanclean | | 5.333 | 0 | |
| | Messinian | | 7.246 | 0 | |
| | Tortonian | 11.61 | 11.63 | 0.02 | |
| | Serravallian | 13.65 | 13.82 | 0.17 | |
| | Langhian | | 15.97 | 0 | |
| | Burdigalian | | 20.44 | 0 | |
| | Aquitanian | | 23.03 | 0 | |
| Paleogene | Chattian | 28.4 | 28.1 | −0.3 | |
| | Rupelian | | 33.9 | 0 | |
| | Priabonian | 37.2 | 37.8 | 0.6 | *0.5* |
| | Bartonian | 40.4 | 41.2 | 0.8 | *0.5* |
| | Lutetian | 48.6 | 47.8 | −0.8 | *0.2* |
| | Ypresian | 55.8 | 56.0 | 0.2 | |
| | Thanetian | 58.7 | 59.2 | 0.5 | |
| | Selandian | 61.7 | 61.6 | −0.1 | |
| | Danian | 65.5 | 66.0 | 0.5 | |
| Cretaceous | Maastrichtian | 70.6 | 72.1 | 1.5 | *0.2* |
| | Campanian | 83.5 | 83.6 | 0.1 | ***0.2*** |
| | Santonian | 85.8 | 86.3 | 0.5 | *0.5* |
| | Coniacian | 89.3 | 89.8 | 0.5 | *0.3* |
| | Turonian | 93.5 | 93.9 | 0.4 | *0.2* |
| | Cenomanian | 99.6 | 100.5 | 0.9 | *0.4* |
| | Albian | 112 | 113.0 | 1 | *0.4* |
| | Aptian | 125 | 126.3 | 1.3 | *0.4* |
| | Barremian | 130 | 130.8 | 0.8 | *0.5* |
| | Hauterivian | 136.4 | **133.9** | −2.5 | *0.6* |
| | Valanginian | 140.2 | 139.4 | −0.8 | *0.7* |
| | Berriasian | 145.5 | 145.0 | −0.5 | ***0.8*** |
| Jurassic | Tithonian | 150.8 | 152.1 | 1.3 | *0.9* |
| | Kimmeridgian | 155.7 | 157.3 | 1.6 | *1.0* |
| | Oxfordian | 161.2 | **163.5** | 2.3 | *1.1* |
| | Callovian | 164.7 | 166.1 | 1.4 | *1.2* |
| | Bathonian | 167.7 | 168.3 | 0.6 | ***1.3*** |
| | Bajocian | 171.6 | 170.3 | −1.3 | ***1.4*** |
| | Aalenian | 175.6 | 174.1 | −1.5 | *1.0* |
| | Toarcian | 183 | 182.7 | −0.3 | ***0.7*** |
| | Pliensbachian | 189.6 | 190.8 | 1.2 | *1.0* |
| | Sinemurian | 196.5 | **199.3** | 2.8 | *0.3* |
| | Hettangian | 199.6 | 201.3 | 1.7 | *0.2* |
| Triassic | Rhaetian | 203.6 | **209.5** | 5.9 | *~1* |
| | Norian | 216.5 | **228.4** | 11.9 | *~2* |
| | Carnian | 228 | **237.0** | 9 | *~1* |
| | Ladinian | 237 | **241.5** | 4.5 | *~1.0* |
| | Anisian | 245 | **247.1** | 2.1 | *~0.2* |
| | Olenekian | 249.7 | 250.0 | 0.3 | ***0.5*** |

Table 1 Continued.

| | Age/Stage | GTS2004 | GTS2012 | Change in Ma | GTS2012 uncertainty in Ma (95%) |
|---|---|---|---|---|---|
| Permian | Changhsingian | 253.8 | 254.2 | 0.4 | *0.3* |
| | Wuchiapingian | 260.4 | 259.8 | –0.6 | *0.3* |
| | Capitanian | 265.8 | 265.1 | –0.7 | *0.4* |
| | Wordian | 268 | 268.8 | 0.8 | *0.5* |
| | Roadian | 270.6 | 272.3 | 1.7 | *0.5* |
| | Kungurian | 275.6 | **279.3** | 3.7 | *0.6* |
| | Artinskian | 284.4 | **290.1** | 5.7 | *0.2* |
| | Sakmarian | 294.6 | 295.5 | 0.9 | *0.4* |
| | Asselian | 299 | 298.9 | –0.1 | ***0.2*** |
| Carboniferous | Gzhelian | 303.9 | 303.7 | –0.2 | *0.1* |
| | Kasimovian | 306.5 | 307.0 | 0.5 | *0.2* |
| | Moscovian | 311.7 | **315.2** | 3.5 | *0.2* |
| | Bashkirian | 318.1 | **323.2** | 5.1 | *0.4* |
| | Serpukhovian | 326.4 | **330.9** | 4.5 | *0.4* |
| | Visean | 345.3 | 346.7 | 1.4 | *0.4* |
| | Tournaisian | 359.2 | 358.9 | –0.3 | ***0.4*** |
| Devonian | Famennian | 374.5 | **372.2** | –2.3 | *1.6* |
| | Frasnian | 385.3 | **382.7** | –2.6 | *1.0* |
| | Givetian | 391.8 | **387.7** | –4.1 | *0.8* |
| | Eifelian | 397.5 | **393.3** | –4.2 | *1.2* |
| | Emsian | 407 | 407.6 | 0.6 | ***2.6*** |
| | Pragian | 411.2 | 410.8 | –0.4 | ***2.8*** |
| | Lochkovian | 416 | **419.2** | 3.2 | *3.2* |
| Silurian | Pridoli | 418.7 | **423.0** | 4.3 | *2.3* |
| | Ludfordian | 421.3 | **425.6** | 4.3 | *0.9* |
| | Gorstian | 422.9 | **427.4** | 4.5 | *0.5* |
| | Homerian | 426.2 | **430.5** | 4.3 | *0.7* |
| | Sheinwoodian | 428.2 | **433.4** | 5.2 | *0.8* |
| | Telychian | 436 | **438.5** | 2.5 | *1.1* |
| | Aeronian | 439 | 440.8 | 1.8 | *1.2* |
| | Rhuddanian | 443.7 | 443.8 | 0.1 | ***1.5*** |
| Ordovician | Hirnantian | 445.6 | 445.2 | –0.4 | ***1.4*** |
| | Katian | 455.8 | **453.0** | –2.8 | *0.7* |
| | Sandbian | 460.9 | **458.4** | –2.5 | *0.9* |
| | Darriwilian | 468.1 | 467.3 | –0.4 | ***1.1*** |
| | Dapingian | 471.8 | 470.0 | –1.8 | *1.4* |
| | Floian | 478.6 | 477.7 | –0.9 | ***1.4*** |
| | Tremadocian | 488.3 | **485.4** | –2.9 | *1.9* |
| Cambrian | Age 10 | *NA* | 489.5 | | *~2.0* |
| | *Jiangshanian* | *NA* | 494 | | *~2.0* |
| | Paibian | 501 | **497** | 4 | *~2.0* |
| | Guzhangian | *NA* | 500.5 | | *~2.0* |
| | Drumian | *NA* | 504.5 | | *~2.0* |
| | Age 5 | '513' | 509 | ~4 | *1.0* |
| | Age 4 | *NA* | 514 | | *~2.0* |
| | Age 3 | *NA* | 521 | | *~2.0* |
| | Age 2 | *NA* | 529 | | *~2.0* |
| | Fortunian | 542 | 541 | –1 | *1.0* |
| Ediacaran | Series 1 | | 635 | | |

Although radiometric ages can be more precise than zonal or fossil event assignments, the uneven spacing and fluctuating accuracy and precision of both radiometric ages and zonal composite scales demands special statistical and mathematical techniques to calculate the geologic time scale; this is outlined in GTS2012 by Agterberg et al. (2012).

The assignment of error bars to ages of stage boundaries, first advocated by Gradstein et al. (1994), attempts to combine the most up-to-date estimate of uncertainty in radiogenic isotope dating and in stratigraphic scaling into one number. Although stratigraphic reasoning to arrive at uncertainties has a role to play, geosciences are no less than physics and chemistry when it comes to assigning realistic error bars to its vital numbers. Error estimates on GTS2012 stratigraphic boundaries are tabulated in Table 1.

In GTS2004, error bars on stage boundary age estimate and stage durations were estimated using a Maximum Likelihood fitting of a Functional Relationship (MLFR) regression of the rectified spline. This spline fit interpolates high-resolution radiometric ages with scaled stages. GTS2012 uses a more direct approach, detailed and executed by Oyvind Hammer with his program PAST (http://nhm2.uio.no/norlex/past) for the Ordovician, Silurian, Carboniferous, Permian, Cretaceous and Paleogene Periods in GTS2012 (see Agterberg et al. 2102). Given our spline fitting procedure and the inaccuracy of the estimates of radiometric dates and stratigraphic positions, we may ask how much an interpolated zonal boundary date would have varied if we carried out the dating's, spline fitting and interpolation repeatedly. This is simulated by a Monte Carlo procedure, picking random stratigraphic positions and dates with distributions as given (normal or rectangular) and then running the spline fitting anew with cross-validation. This is repeated say 10,000 times, producing a histogram of interpolated values from which a 95% confidence interval can be derived. The procedure is computer intensive; for each of the 10,000 Monte Carlo replicates, a number of splines must be computed in the cross-validation procedure. The uncertainties on older stage boundaries systematically increase owing to potential systematic errors in the different radiogenic isotope methods, rather than to the analytical precision of the laboratory measurements. In this connection we mention that biostratigraphic error is fossil event and fossil zone dependent, rather than age dependent.

Ages and durations of Neogene stages derived from orbital tuning are considered to be accurate to within a precession cycle (~20 kyr) assuming that all cycles are correctly identified, and that the theoretical astronomical-tuning for progressively older deposits is precise. Paleogene dating combines orbital tuning, radiometric and C-sequence splining; hence stage ages uncertainty is larger and varies between 0.2 and 0.5 myr.

## GTS2012

Figure 6 is the new and global Geologic Time Scale, created in 2012 (GTS2012) and Table 1 lists the modified ages of stage boundaries in GTS2012 relative to 'A Geologic Time Scale 2004' (GTS2004). No ages shown for stages in the GTS2004 column means there is no change in age in GTS2012, with '*NA*' in the Cambrian reflecting absence of those stages when GTS2004 was conceived. Fifteen Phanerozoic stages got formally defined since 2004, about half with new definitions. A majority of age changes in GTS2012 involves a combination of improved radiometric methodology, higher resolution interpolation methods, and better correlations between key sections. Stages or series that changed by 2 Ma or more in GTS2012 are shown in red, with Bashkirian, Artinskian, Carnian, Norian and Rhaetian changing numerically most in age. The latter three stages also were problematic in GTS2004, due to lack of age dates and uncertainty in correlations. Interestingly, Silurian stages all become (much) older and Ordovician stages younger than in GTS2004. Where the 95% uncertainty estimate of a GTS2012 stage age exceeds the actual numerical age change, such is marked in red also.

## Conclusion

Continual improvements in data coverage, methodology, and standardization of chronostratigraphic units imply that no geologic time scale can be final. The new Geologic Time Scale 2012 provides detailed insight in the most up-to-date geologic time scale, and is the successor to Geologic Time Scale 2004 (GTS2004 by Gradstein et al. 2004), and GTS1989 (Harland et al. 1990). Despite detailed and widespread documentation of new time scales it is no surprise, as Ruban (2011) points out, that subjective deviations from the standard time scale in geologic text books are not uncommon. Authors may prefer different geologic time scales because of deficiencies in distribution of standards among the international geological community, changes in the standards themselves, or problems with applying standard stratigraphy to regional geology.

This points to the obvious that authoritative communication of updates to the standard time scale must be at a deliberate and slow pace to be effective. Minor and quick updates need to be avoided. Having a new and formal definition for a stage does not mean that the standard time scale should be updated. Firstly, redefinition of stages and correlations take many years to take effect in the scientific domain, and secondly acceptance of a new age without updating existing correlation schemes leads to correlation errors. Particularly in the mineral and petroleum industry the introduction of a new time scale demands extensive investments in internal standardization and communication, and is not a trivial undertaking. The only thing that is gained by the publication and introduction of minimal geologic time scale changes is resentment by the user, not eager to re-calibrate data for 'minor' reasons.

**Acknowledgements.** Geologic Time Scale 2012 would not have been possible without the tremendous cooperation received from many colleagues and scientific organizations over many years of research and compilation. It is with thanks and pleasure that we here repeat the *Dedication* of the fourth edition of the *Geologic Time Scale* (Gradstein, Ogg et al. 2012) to the many scientists in the *CHRONOS Project, Geological Time Scale Next* (GTSNext), the *Earth Time Projects* and the *International Commission of Stratigraphy* (ICS). These programs and others champion and strongly support the compilation, standardization, enhancement, numerical age-dating and international public distribution of our progressive unraveling of Earth's fascinating history. Werner Piller is thanked for his valuable review comments that improved the manuscript.

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