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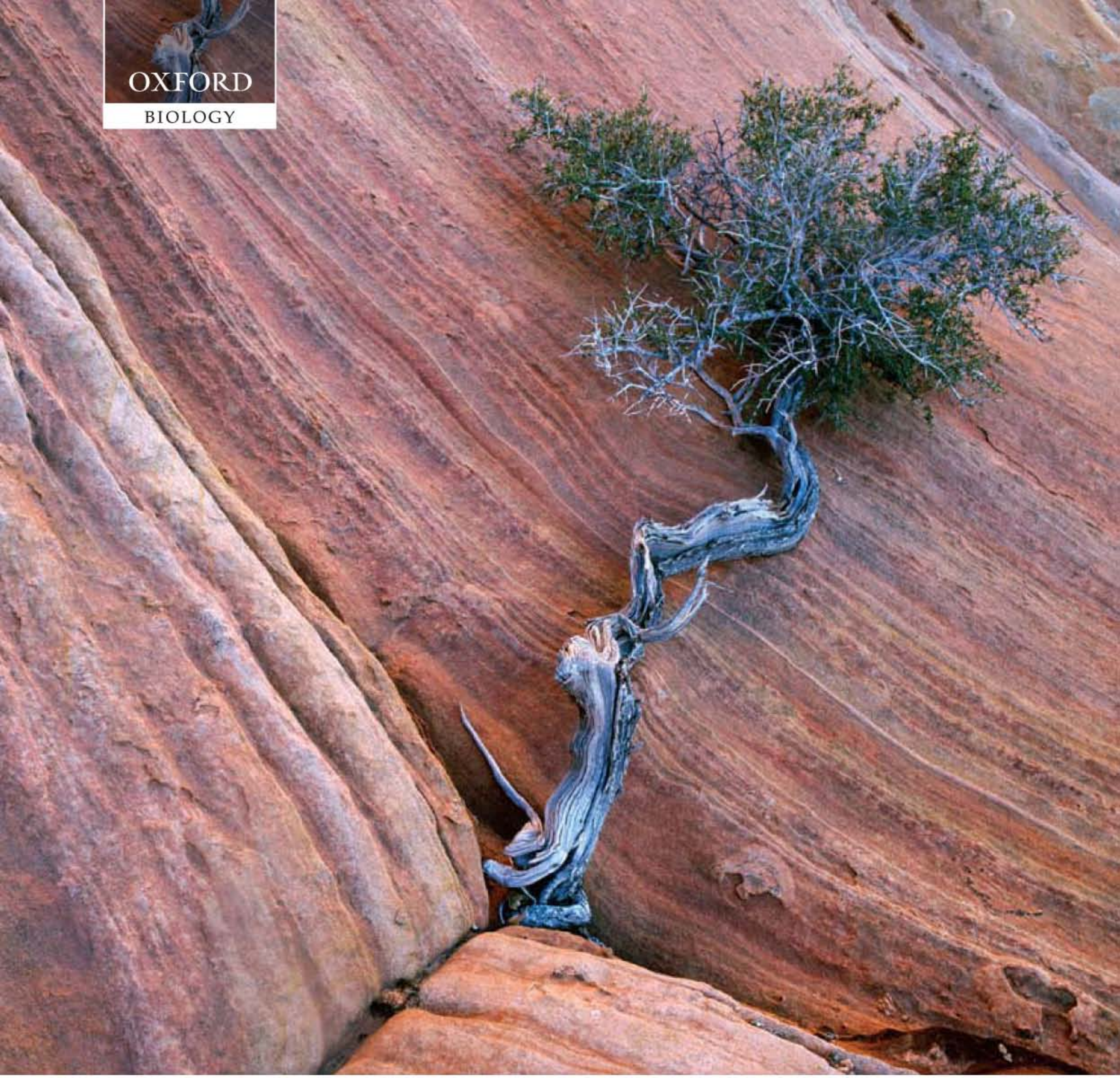

the TIMETREE of LIFE

edited by S. BLAIR HEDGES and SUDHIR KUMAR
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The geologic time scale

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Abstract

Construction and assembly of the Geologic Time Scale involves: (a) constructing a relative (chronostratigraphic) standard scale for key periods in the Earth's rock record; (b) identifying high-resolution linear age dates to calibrate this relative scale in linear time; (c) astronomically tuning intervals with cyclic sediments or stable isotope sequences which have sufficient fossil or geomagnetic ties to be merged in the standard scale, and increase its resolution; (d) interpolating for those relative time intervals where direct linear age information is insufficient; and (e) estimating error bars on the age of boundaries and on unit durations.

Time is an indispensable tool for all of us. The time kept by innumerable watches and a great variety of clocks regulates our everyday life, while the familiar calendar governs our weekly, monthly, and yearly doings. These 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. The atomic second is defined as the duration of 9.192.631.770 periods of the radiation corresponding to the transition between two hyperfine levels of the ground state of the Cesium 133 atom. This value was established to agree as closely as possible with the ephemeris second based on the Earth's motion. The advantage of having the atomic second as the unit of time in the International System of Units is the relative ease, in theory, for anyone to build and calibrate an atomic clock with a precision of 1 part per 10^{11} (or better). In practice, clocks are calibrated against broadcast time signals, with frequency oscillations in Hertz being the "pendulum" of the atomic time-keeping device.

The tick of the second paces the quick heart beat, and traditionally was the 60th part of the 60th part of the 24th part of the 24-h day, with the minute and the hour being convenient multiples to organize our daily life and productivity. 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 from the present to the future. Events along its path mark the arrow of time, and the arrow is graded either in relative "natural" units, or in units of duration—the standard second and its multiples, like hours and years, and millions of years.

Geologic time and the sediment record

A majority of geologists consider time as a vector pointing from the distant past to the present. Instead of "distant past," the term "deep time" has been coined in the vernacular. What is exactly the concept of geologic time, what are its natural units, how are they defined, and how do we use these units properly? A good understanding of geologic time is vital for every scientist who deals with events in the Earth sediment and rock record, or with the genetic record of evolution in living organisms, especially those who strive to understand past processes and determine rates of change. This understanding takes place in a framework called Earth Geological History, a super calendar of local and global events. The challenge to this understanding is reading, organizing, and sorting the Earth's stone calendar pages. In the process, we often have to reconstruct the content of missing pages. Correlation of the rock record between regions is a vital part of the reconstruction process.

One of the earliest reconstructions is by Nicolas Steno (1631–1687) who made careful and original stratigraphic observations. Based on these observations, Steno concluded that the Earth's strata contain the superimposed records of a chronological sequence of events that can be correlated worldwide. Geological correlation formally is expressed in terms of five consecutive operations (each is followed by one or more examples):

(a) Rock units, like formations or well log intervals = lithostratigraphic correlation
Kimmeridge Clay Formation of England

F. M. Gradstein and J. G. Ogg. The geologic time scale. Pp. 26–34 in *The Timetree of Life*, S. B. Hedges and S. Kumar, Eds. (Oxford University Press, 2009).

(b) Fossil units, like zones = biostratigraphic correlation
Turrilina alsatica benthic foraminifer zone
(c) Relative time units = geochronologic ("Earth time") correlations
Jurassic Period, Eocene Epoch, Oxfordian Age, polarity chron C29r
(d) Rocks deposited during these time units = chronostratigraphic (time–rock) correlation
Jurassic System, Eocene Series, Oxfordian Stage, polarity zone C29r
(e) Linear time units or ages = geochronologic correlation
150 million years ago (Ma), 10,000 years ago (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 the understanding of Earth history elsewhere. The rules of hierarchy in geological correlation, from rocks and fossils to relative and linear time, are carefully laid down in the International Stratigraphic Guide. An abbreviated copy of this "rule book" with further references may be found on the Web site of the International Commission on Stratigraphy (ICS) under www.stratigraphy.org.

Before we deal with linear geological time, a few words are necessary about the common geological calendar built from relative age units. This chronostratigraphic scheme is not unlike a historical calendar in which societal periods, for example, the Minoan Period, the reign of Louis XIV, the American Civil War, are used as building blocks, devoid of a linear scale. Archeological relics deposited during these intervals (e.g., the Palace of Minos on Crete, Versailles or spent cannon balls at Gettysburg, respectively) comprise the associated physical and chronostratigraphic record. A chronostratigraphic scale is assembled from rock sequences stacked and segmented in relative units based on their unique fossil and physical content. When unique local fossil and physical records are matched with those of other rock sequences across the globe—in a process known as stratigraphic correlation—a relative scale can be assembled that, when calibrated to stage type sections, becomes a chronostratigraphic scale. The standard chronostratigraphic scale, in downloadable graphics format, is available from the ICS Web site. This time scale is made of successive stages in the rock record, like Cenomanian, Turonian, Coniacian, and so on, 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. This is the concept of defining stage units with type sections, commonly referred to as stratotype sections. The principles and building blocks of this chronostratigraphy were slowly established during centuries of study in many discontinuous and incomplete outcrop sections. Inevitably, lateral changes in lithology between regions and lack of agreement on criteria, particularly in which fossils were characteristics of a relative unit of rock, have always resulted in a considerable amount of confusion and disagreement on stage nomenclature and stage use. Almost invariably classical stage stratotypes turned out to only represent part of stages. Hence, a suite of global subdivisions with precise correlation horizons was required.

Global stratotype section and point

Now, relatively rapid progress is being made with definition of Global Stratotype Sections and Points (GSSPs) to fix the lower boundary of all geologic stages, using discrete fossil and physical events that correlate well in the rock record. For the ladder of chronostratigraphy, this GSSP concept switches the emphasis from marking the spaces between steps (stage stratotypes) to fixing the rungs (boundaries of stages).

Each progressive pair of GSSPs in the rock record also precisely defines the associated subdivision of geologic time. It is now 25 years ago that a "golden spike" struck the first GSSP. This event of historic proportions for the geologic time scale involved the boundary between the Silurian and Devonian Periods, or rather the lower limit of the Devonian, at a locality called Klonk in Czechoslovakia.

The problem of the Silurian–Devonian boundary and its consensus settlement in the Klonk section hinged on a century-old debate known as the "Hercynian Question" that touched many outstanding geoscientists of the nineteenth century. The issue came to the forefront after 1877, when Kaiser stated that the youngest stages (étages) of Barrande's "Silurian System" in Bohemia correspond to the Devonian System in the Harz Mountains of Germany and other regions. Kaiser's findings contrasted with the conventional nineteenth century wisdom that graptolite fossils became extinct at the end of the Silurian. Eventually, it became clear that so-called Silurian graptolites in some sections occur together with so-called Devonian fossils in other sections, leading to the modern consensus that graptolites are not limited to Silurian strata.

A bronze plaque in the Klonk outcrop shows the exact position of the modern Silurian–Devonian Boundary, which is taken at the base of the Lochkovian Stage, the lowest stage in the Devonian. The base of the Lochkovian Stage is defined by the first occurrence of the Devonian graptolite *Monograptus uniformis* in bed #20 of the Klonk Section, northeast of the village of Suchomasty. The lower Lochkovian index trilobites with representatives of the *Warburgella rugulosa* group occur in the next younger limestone bed #21 of that section.

The concept of the GSSP has gained acceptance among those stratigraphers who consider it a pragmatic and practical solution to the common problem that conventional stage type sections inevitably leave gaps, or lead to overlap between successive stages. The boundary stratotype very much relies on the notion that it is possible to arrive at accuracy in correlation through the use of events, like a geomagnetic reversal, a global change in a stable isotope value, or the evolutionary appearance of one or more prominent and widespread fossil taxa. Thus, the limits of a stage can now be defined with multiple event criteria that to the best of our current knowledge are synchronous over the world. Delimiting successive stages in a clear and practical manner enhances their value as standard units in chronostratigraphy and ultimately in geochronology. Without standardized units neither the (relative) stratigraphic scale nor the (linear) time scale can exist.

At present over 55 GSSPs have been defined (Fig. 1; see www.stratigraphy.org for details), but there are more stages in the Phanerozoic Eon in need of base definition. Fortunately, a majority of those now have target definitions, and are awaiting consensus on the best outcrop or borehole section to place a "golden spike." Thus, with the definitions in place, we can proceed to scale the "deep time" stage units linearly.

This brings us to Geochronology, referring to the geochronologic calendar of Earth events called the Geologic Time Scale. While the chronostratigraphic scale is a convention to be agreed upon rather than discovered, calibration of the scale in seconds and (mega-) years is a matter for discovery and estimation rather than agreement. Like human time, linear geological time is expressed in units of standard duration—the second and hence (thousands or millions of) years.

Building a geological time scale

The ideal time scale is built from accurate radiometric ages, taken precisely at stage boundaries throughout the stratigraphic column in the Phanerozoic Eon. For more detailed resolution, the exact number of orbitally tuned sedimentary cycles is counted within each stage, such that calibrations and correlation may be achieved within

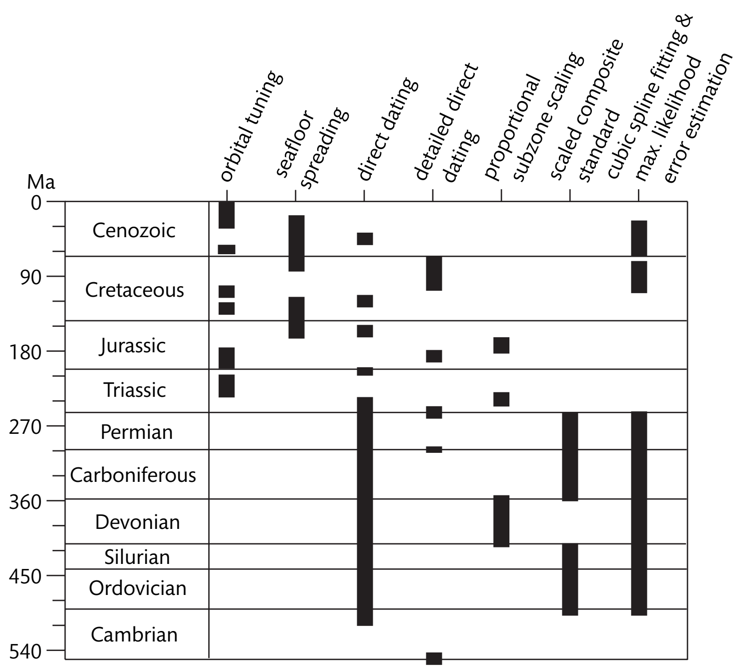

Fig. 1 Methods used to construct Geologic Time Scale 2004 (GTS2004) (*1*).

> 20 thousand years for the last 540 million years or so.... If this sounds too good to be true, let it rest. Back to reality.

Geologic reality is schematically illustrated in Fig. 1, providing a quick overview of the actual methodology applied to construct Geologic Time Scale 2004 (GTS2004) (*1*), the most recent standard time scale. Before the Cambrian, the first period of the Phanerozoic Era, the geologic time scale is less sophisticated, and based only on sparse radiometric dates. The steps involved in Phanerozoic time scale construction may be summarized as follows:

(a) Construct a relative (chronostratigraphic) standard scale for the key periods in the Earth's rock record
(b) Identify high-resolution linear age dates to calibrate this relative scale in linear time
(c) Astronomically tune (see later) intervals with cyclic sediments or stable isotope sequences which have sufficient fossil or geomagnetic correlation ties to be merged in the standard scale, and increase its resolution
(d) Interpolate for those relative time intervals where direct linear age information is insufficient
(e) Estimate error bars on the age of boundaries and on unit durations.

The first step, integrating multiple types of stratigraphic information to construct the standard chronostratigraphic scale, is the most time consuming; it summarizes and synthesizes centuries of detailed geological research and tries to understand all relative correlations and calibration to the standard.

The second and third steps, identifying which radiometric and cycle-stratigraphic studies to use as the primary constraints for assigning linear ages, are the ones that have much evolved. Historically, Phanerozoic time scale building went from an exercise with very few and relatively inaccurate radiometric dates, as available to the pioneer of the geologic time scale Arthur Holmes, to one with many dates with greatly varying analytical precision, as in the mid-1980s. Next, time scale studies started to appear of selected intervals, like Paleogene, Late Cretaceous, or Ordovician, that selected a small suite of radiometric dates with high analytical precision and relatively precise stratigraphic position.

At the same time, a high-resolution Neogene time scale started to take shape, using orbital tuning of long sequences of sedimentary and/or oxygen isotope cycles in the Mediterranean region and in Atlantic and Pacific pelagic sediments. The present trend for the pre-Neogene is to incorporate radiometric dates that have very small analytical and stratigraphic uncertainties, and pass the most stringent tests.

The fourth step, interpolating the stratigraphic and radiometric information, has much evolved. An early method already constructed the basic two-way graph, used until now. It plotted the cumulative sum of maximum global thickness of strata per stratigraphic unit along the vertical axis and selected radiometric dates from volcanic tuffs and other suitable layers along the horizontal linear axis. This best fit line method interpolated ages to the stages, but is a far cry from methods used today that scale stages along the vertical axis with composite standards of fossil zones. In the mid-1990s, Frits Agterberg and Felix Gradstein started to apply mathematical/statistical error analysis to the time scale ages, which, for the first time, allowed them to assign fairly realistic error bars to ages of Mesozoic stage boundaries, a trend that persists today for the whole of Phanerozoic below the Neogene.

The following is a simplified introduction to the modern building tools depicted in Fig. 1.

Music of the spheres

Let us start with a brief outline of the principle of the sedimentary cycles approach to time scale building, as is now standard for the last 23 Ma (Neogene), and provides superior resolution and precision. Gravitational interactions of the Earth with the Sun, Moon, and other planets cause systematic changes in the Earth's orbital and rotational system. These interactions give rise to cyclic oscillations in the eccentricity of the Earth'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 vs. warmer and wetter vs. 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 sites.

Counting of this 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, produced a very detailed

Neogene cycle pattern. 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 by earth scientists at Utrecht and Cambridge Universities such as Luc Lourens, Frits Hilgen, and Nick Shackleton led to unprecedented accuracy and resolution for the last 23 million years (*2*). In New Zealand, Tim Naish and colleagues have calibrated the upper Neogene record to the standard Neogene time scale. Using the high-resolution land-based cycle, isotope and magnetic record in the Wanganui Basin, these authors thereby transferred precise absolute ages to local shallow marine sediments and demonstrated the link between sequence and cycle stratigraphy.

Efforts are underway to extend the continuous astrochronologic scale back into Oligocene and Eocene by applying a combination of cycle stratigraphy, improved astronomical projections, oxygen isotope stratigraphy, and magnetostratigraphy to the deep sea record.

A special application of orbitally tuned cyclic sediment sequences is to "rubber-band" stratigraphically floating units, like parts of Paleocene, Albian, and parts of Lower Jurassic, skilfully executed by specialists like Ursula Rohl, Tim Herbert, and Graham Weedon. A quantitative estimation of the duration of all cycles within a stratigraphic unit allows estimates of their duration.

Decay of atoms

For rocks older than Neogene, the derivation of a numerical time scale depends on the availability of suitable radiometric ages. Radiometric dating 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 then be calculated by means of the isotopic decay constant. Depending on the half-life of the element, several radiometric clocks are available; $^{40}Ar/^{39}Ar$ and the family of U/Pb isotopes are the most common suites nowadays applied to the Phanerozoic, because of analytical precision and utility with tuffaceous beds in marine or non-marine sequences. 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 $^{40}K/^{40}Ar$ clock in glauconite. Another problem is that glauconite also contains an abundance of tiny flakes that allow diffusion of Ar at low temperatures. The result is that glauconite dates may be too young. Because of such problems which may be difficult to detect, modern geologic time scales avoid 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. Astrochronologic and interlaboratory recalibration of the $^{40}Ar/^{39}Ar$ monitor standard indicates that many of the $^{40}Ar/^{39}Ar$ ages used in previous Phanerozoic time scales are too young by about 0.5% to 1.0%. For example, the 65.0 Ma age, assigned 10 years ago to the top Cretaceous, is now 65.5 Ma.

Radiometric dating techniques with less than 1% analytical error are providing suites of high-precision U/Pb and Ar/Ar dates for the Paleozoic and Mesozoic. Surprisingly, perhaps, there are only seven direct age dates on period or stage boundaries (Fig. 1), with a majority of the 200+ radiometric age dates used for GTS2004 "floating" at some level within a stage.

The integration of this level of chronometric precision with high-resolution biostratigraphy, magnetostratigraphy, or cyclic scales is a major challenge to time scale studies. Even the most detailed biostratigraphic scheme probably has no biozonal units of less than 0.5–1.0 million year (my) 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 my. 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 toward the latter, despite the fact that both may have equal litho-, bio-, and chronostratigraphic precision.

Nevertheless, the combination of precise stratigraphic definitions through GSSPs and accurate radiometric dates near these levels is paving the way for a substantial increase in the precision and accuracy of the Geologic Time Scale. The bases of Paleozoic, Mesozoic, and Cenozoic Eras are bracketed by analytically precise ages at their GSSP or primary correlation markers—542.0 ± 1.0 Ma, 251.0 ± 0.4 Ma, and 65.5 ± 0.3 Ma respectively—and there are direct age dates for the base Carboniferous, base Permian, base Jurassic, base Aptian, base Cenomanian, and the base Oligocene. Most other period or stage boundaries lack direct age control. Therefore, the third step, linear interpolation, also plays a key role for the time scale.

Interpolation and statistics

Despite the progress in standardization and dating, parts of the Mesozoic and Paleozoic Eras have sparse radiometric records (see Fig. 2). Ideally, each of the 90+ stage boundaries that comprise the Paleozoic, Mesozoic, and Cenozoic Eras of the Phanerozoic Eon should coincide with an accurate radiometric date from volcanic ash. However, this coincidence is rare in the geological record. The combined number of fossil events and magnetic reversals far exceeds the total number of radiometrically datable horizons in the Phanerozoic. Therefore, a framework of bio-, magneto-, and chronostratigraphy provides the principal fabric for stretching of the relative time scale between dated tiepoints on the loom of linear time. For such stretching, interpolation methods that are employed are both geological and statistical in nature.

Earlier, we mentioned the outdated method of plotting the cumulative global thickness of periods against selected linear age dates. Among the modern geological scaling methods, an assumption of relative constancy of seafloor spreading over limited periods of time is a common tool for interpolating the Latest Cretaceous through Paleogene relative scale. Magnetic polarity chrons, the units of magnetochronology, can be recognized both on the ocean floor as magnetic anomalies measured in kilometers from the mid-ocean spreading center, and in marine sediments as polarity zones that contain biostratigraphic events and can be linked to linear time. Knowing the linear 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.

A second geological method involves building a zonal composite to scale stages. Several outstanding examples are documented in GTS2004 built by a large international team of scientists under the direction of Felix Gradstein and James Ogg. For this scale, Roger Cooper and colleagues have built a very detailed composite standard of graptolite zones from 200+ sections in oceanic and slope environment basins for the uppermost Cambrian, Ordovician, and Silurian intervals. With zone thickness taken as directly proportional to zone duration, the detailed composite sequence was scaled using selected, high-precision age dates. For the Carboniferous through Permian, a composite standard of conodont, fusulinid, and ammonoid events from many classical sections can now be calibrated to a combination of U/Pb and $^{40}Ar/^{39}Ar$ dates. A composite standard of conodont zones was used for early Triassic. This procedure directly scales all stage boundaries and biostratigraphic horizons.

The two-way graph of linear age vs. scaled stages requires a best fitting method, and that is where statistics comes into play, with cubic spline fitting and maximum likelihood interpolation most suitable. On the time scale chart (late 2008 edition; Fig. 3), a majority of Phanerozoic stage boundaries for the first time show error bars; an exception is the Neogene Period where analytical errors are negligible. The error bars reflect both radiometric and stratigraphic uncertainty; in addition, error bars were calculated on stage duration. Uncertainty in the duration of the age units is less than the error in age of their boundaries.

TS-Creator©

Now, Adam Lugowski, Ogg, and Gradstein are producing an electronic version of the Geologic Time Scale with the international standard bio-magneto-sequence time scale charts. There are charts for Paleozoic, Mesozoic, and Cenozoic Eras and for each period. This JAVA language package, called TS-Creator©, can be freely downloaded from the ICS website (www.stratigraphy.org).

It contains tables of Cambrian through Holocene stratigraphic events calibrated to GTS2004 ages. There are nearly 15,000 biostratigraphic, sea-level, and magnetic zones and levels, plus a suite of geochemical curves. Documentation of zonal definitions, relative age assignments, and how these events were recalibrated to GTS2004 was also compiled. This included updating cross correlations and enhancing detail for selected stratigraphic methods using trilobites, conodonts, graptolites, ammonoids, fusulinids, chitinozoans, megaspores,

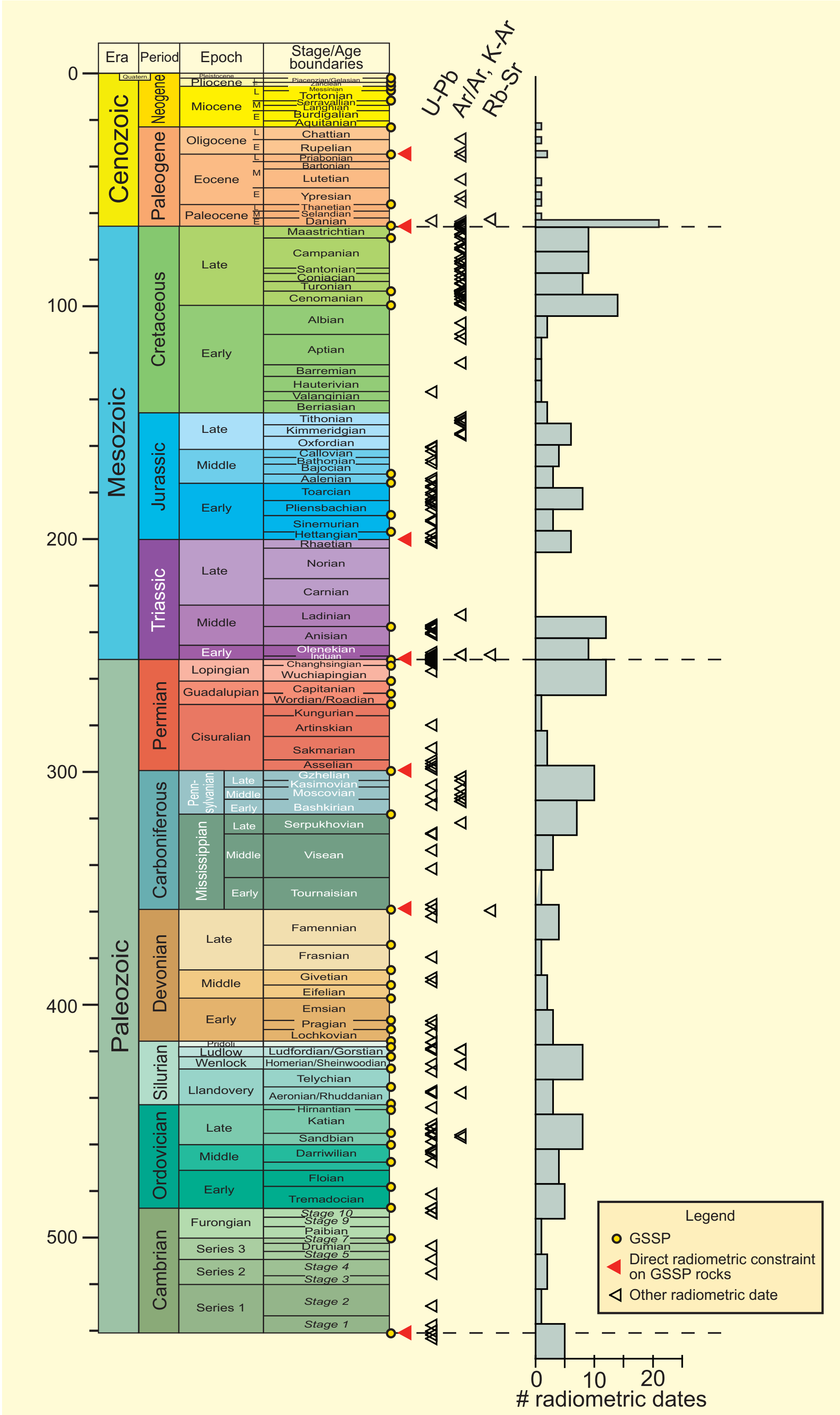

Fig. 2 Geologic Time Scale 2004 showing which stage and period boundaries have a Global Boundary Stratotype Section and Point (GSSP), which ones are dated directly and which other age dates were used. Intervals with sparse or no dates required interpolation.

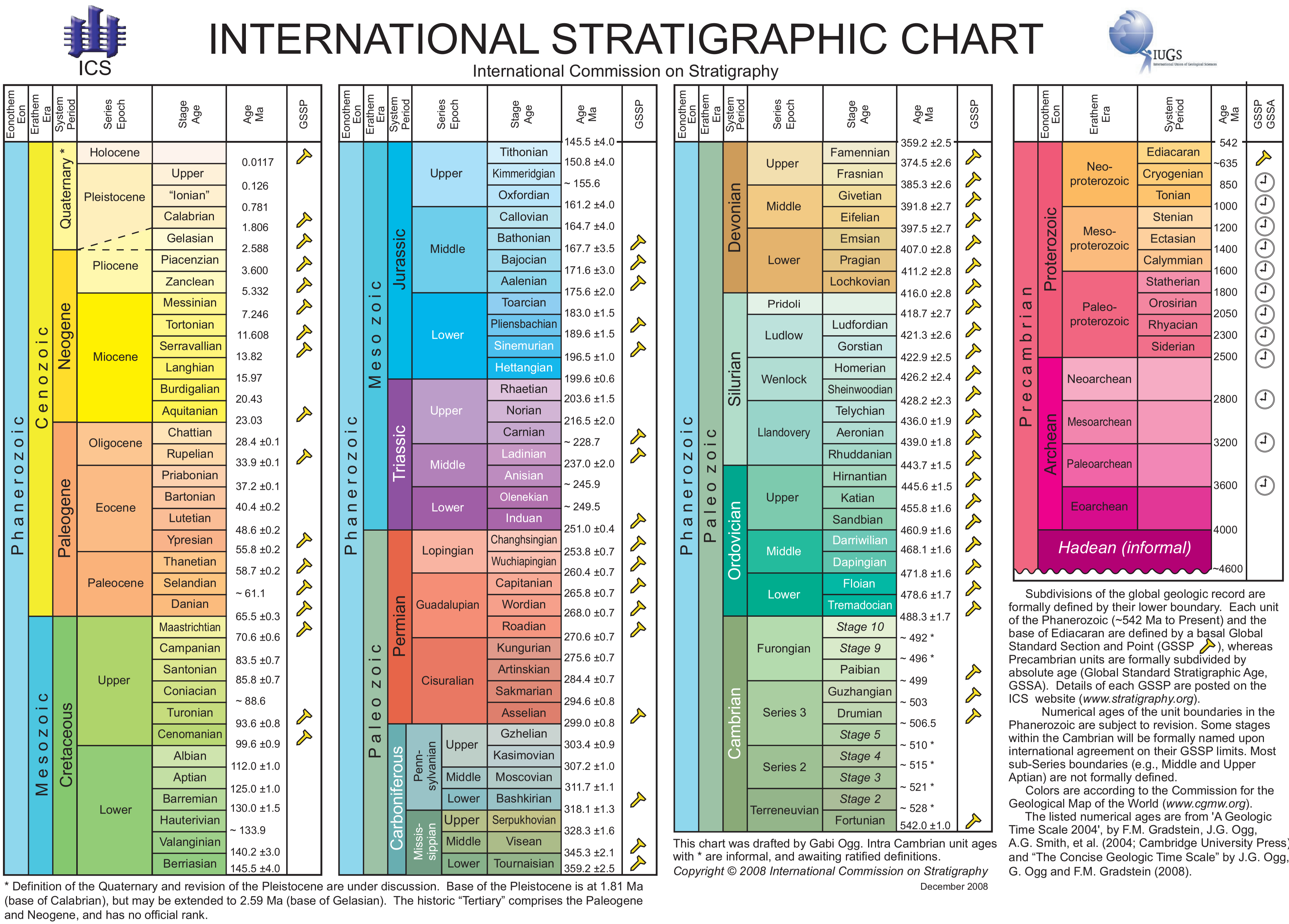

Fig. 3 The International Stratigraphic Chart summarizes the set of chronostratigraphic units (geologic stages, periods) and their computed ages, which are the main framework for Geologic Time Scale 2004. Uncertainties on ages are expressed as two-sigma (95% confidence). This version incorporates changes made by the International Commission up to December, 2008.

nannofossils, foraminifers, dinoflagellates, radiolarians, diatoms, strontium isotope, and C-org curves.

Numerical ages are calculated within the database using the calibrations; therefore, all ages can be automatically recomputed when control ages are improved in future time scales. Regional scales of selected areas (e.g., Russia, China, North America, and New Zealand) are also included.

TS-Creator© automatically takes the reference database, gets instructions from the user on the stratigraphic interval and stratigraphic information to be displayed, and then generates both on-screen and scalable-vector graphic (SVG) renditions that directly input into drafting programs. Next, the user can click on a value, zone, or boundary in the charts on the computer screen, and a window opens with an explanation of the calibration, definition, and interpolated age. This "hot-linked" chart suite is currently a back-looking reference to information in the source tables, but in the future will also provide links to other tables and text from the GTS2004 book, images of stage-boundary outcrops and fossil taxa, and the additional enhancements anticipated during the major update for "Geologic Time Scale 2010."

Additional information on geologic time

The goal of this brief synopsis was to introduce the basic concepts involved in the construction of the geologic time scale. Further details can be found elsewhere (*1–18*).

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