Geologic Time Scale 2004 – why, how, and where next!

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A Geologic Time Scale (GTS2004) is presented that integrates currently available stratigraphic and geochronologic information. The construction of Geologic Time Scale 2004 (GTS2004) incorporated different techniques depending on the data available within each interval. Construction involved a large number of specialists, including contributions by past and present subcommissions officers of the International Commission on Stratigraphy (ICS), geochemists working with radiogenic and stable isotopes, stratigraphers using diverse tools from traditional fossils to astronomical cycles to database programming, and geomathematicians. Anticipated advances during the next four years include formalization of all Phanerozoic stage boundaries, orbital tuning extended into the Cretaceous, standardization of radiometric dating methods and resolving poorly dated intervals, detailed integrated stratigraphy for all periods, and on-line stratigraphic databases and tools. The geochronological science community and the International Commission on Stratigraphy are focusing on these issues. The next version of the Geologic Time Scale is planned for 2008, concurrent with the planned completion of boundary-stratotype (GSSP) definitions for all international stages. □ *Cenozoic, chronostratigraphy, Mesozoic, Palaeozoic, timescale.*

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The geologic time scale is the framework for deciphering the history of the Earth and has three components:

(1) The international chronostratigraphic divisions and their correlation in the global rock record.
(2) The means of measuring absolute (linear) time or elapsed durations from the rock record; *and*
(3) The methods of effectively joining the two scales.

Continual improvements in data coverage, methodology and standardization of chronostratigraphic units imply that no geologic time scale can be final. Since the publication of *Geologic Time Scale 1989* (GTS1989) by Harland and his team, many developments have taken place:

(1) Stratigraphic standardization through the work of the International Commission on Stratigraphy (ICS) has greatly refined the international chronostratigraphic scale. In some cases, such as for the Ordovician and Permian periods, traditional European- or Asian-based stages have been replaced with new subdivisions that allow global correlation.
(2) New or enhanced methods of extracting high-precision age assignments with realistic uncertainties from the rock record. Numerous high-resolution radiometric dates have been generated that has led to improved age assignments of key geologic stage boundaries and other global correlation horizons. At the same time, the records of global geochemical variations, Milankovitch climate cycles, and magnetic reversals have become important calibration tools.
(3) Statistical techniques of interpolating ages and associated uncertainties to stratigraphic events have evolved to meet the challenge of more accurate age dates and more precise zonal assignments. Fossil event databases with multiple stratigraphic sections through the globe can be integrated into high-resolution composite standards for internal scaling of geologic stages.

The Geologic Time Scale in 2004 (GTS2004), as documented in detail in Gradstein *et al.* (2004), is the successor to GTS1989 (Harland *et al.* 1990), which in turn was preceded by GTS1982 (Harland *et al.* 1982). GTS2004 also replaces the International Stratigraphic Chart of the International Commission on Stratigraphy (ICS) issued four years ago (Remane 2000).

There are several reasons why this new geologic time scale of 2004 was required, including:

- Nearly 50 of 90+ Phanerozoic stage boundaries are now defined, versus <15 in 1990.

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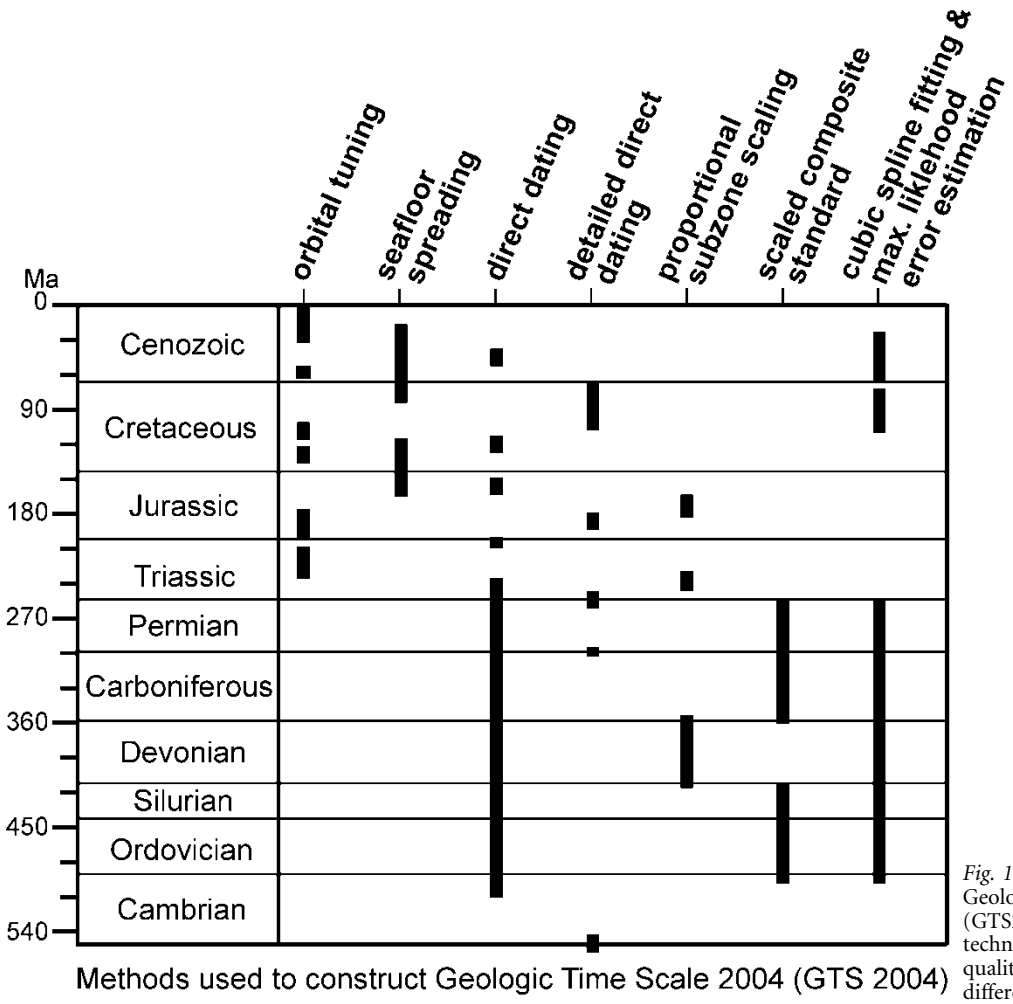

Fig. 1. Methods used to construct Geologic Time Scale 2004 (GTS2004) integrate different techniques depending on the quality of data available within different intervals.

- Stable international stage subdivisions rendered invalid about 15% of the 'stage' names of 1990.
- Last 23 million years (Neogene) is orbitally tuned with 40 kyr accuracy.
- High-resolution cycle scaling now exists in portions of the Paleocene, lower Cretaceous, lower Jurassic, and upper Triassic.
- Superior stratigraphic integration in Mesozoic has merged direct dating, seafloor spreading (M-sequence), zonal scaling and orbital tuning.
- Superior stratigraphic scaling of Palaeozoic was achieved using high-resolution composite zonal standards.
- A 'natural' geologic Precambrian time scale has been proposed to replace the current artificial scale.
- More accurate and precise age dating has provided over 200 Ar/Ar and U/Pb dates with external (systematic) error analysis, of which only a few of these were available to GTS89
- Improved mathematical/statistical techniques can combine biostratigraphic zones, polarity chrons, geologic stages and absolute ages to calculate the time scale, with estimates of uncertainty on stage boundaries and durations.

A listing is provided at the end of this document of outstanding issues that, once resolved, will pave the way for an updated version of the standard Geologic Time Scale, scheduled for the year 2008.

The following brief overview of GTS2004 was partially excerpted from a comprehensive review (Gradstein *et al.* in press).

Construction of geologic time scale 2004

The compilation of GTS2004 involved a large number of specialists, listed above, including contributions by past and present chairs of different subcommissions of ICS, geochemists working with radiogenic and stable isotopes, stratigraphers using diverse tools from

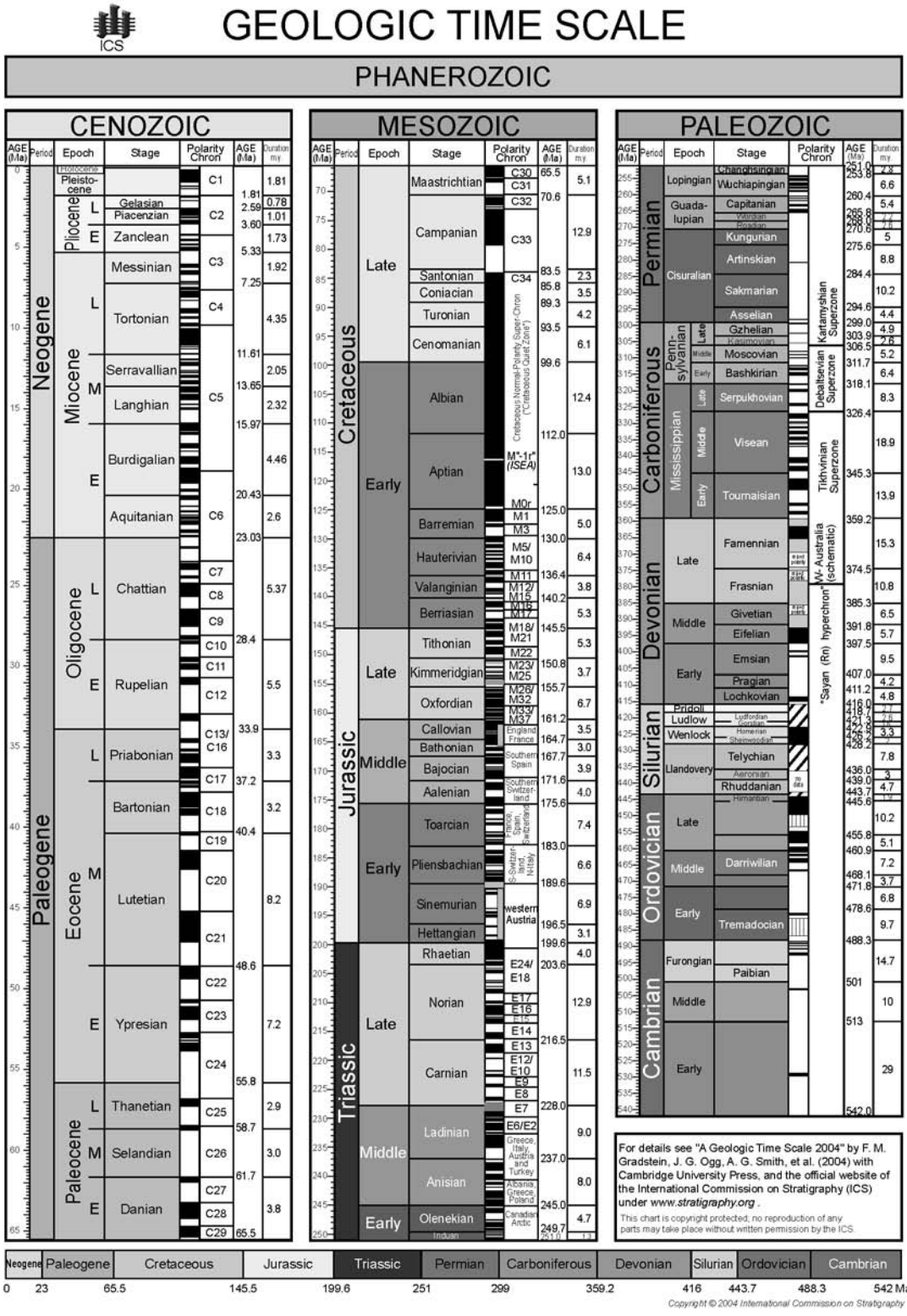

Fig. 2. The set of chronostratigraphic units (stages, periods, etc.) and their computed ages, which constitute the main framework of Geologic Time Scale 2004.
This chart has also been produced as a loose insert and is attached to the inside back cover.

traditional fossils to astronomical cycles to database programming, and geomathematicians.

The methods used to construct Geologic Time Scale 2004 (GTS2004) integrate different techniques depending on the quality of data available within different intervals (Fig. 1). The set of chronostratigraphic units (geologic stages, periods) and their computed ages that constitute the main framework for the Geologic Time Scale 2004 are summarized in the International Stratigraphic Chart (Fig. 2). Uncertainties on ages are expressed at 2-sigma (95% confidence). A companion paper by James Ogg (2004, this issue) summarizes the present stage of stratigraphic standardization for the entire geologic column. ICS is making steady progress with further standardization.

The main steps involved in the GTS2004 time scale construction were:

- Step 1. Construct an updated global chronostratigraphic scale for the Earth's rock record (see *www.stratigraphy.org* website reproduced as Table 2 (*in* Ogg 2004, this issue).
- Step 2. Identify key linear-age calibration levels for the chronostratigraphic scale using radiometric age dates, and/or apply astronomical tuning to cyclic sediment or stable isotope sequences which had biostratigraphic or magnetostratigraphic correlations.
- Step 3. Interpolate the combined chronostratigraphic and chronometric scale where direct information is insufficient.
- Step 4. Calculate or estimate error bars on the combined chronostratigraphic and chronometric information to obtain a geologic time scale with estimates of uncertainty on boundaries and on unit durations.
- Step 5. Peer review the geologic time scale through ICS.

The first step, integrating multiple types of stratigraphic information in order to construct the chronostratigraphic scale, is the most time-consuming. This relative geologic time scale summarizes and synthesizes centuries of detailed geological research. The second step, identifying which radiometric and cycle-stratigraphic studies would be used as the primary constraints for assigning linear ages, is the one that is evolved most rapidly during the past decade. Historically, Phanerozoic time scale building went from an exercise with very few and relatively inaccurate radiometric dates, as used by Holmes (1947, 1960), to one with many dates with greatly varying analytical precision (like GTS89, or to some extent Gradstein *et al.* 1994). Next came studies on relatively short stratigraphic intervals that selected a few radiometric dates with high internal analytical precision (e.g. Obradovich 1993; Cande & Kent 1992, 1995; Cooper 1999) or measured time relative to present using astronomical cycles (e.g. Shackleton *et al.* 1999; Hilgen *et al.* 1995, 2000). This later philosophy is adhered to in this scale.

In addition to selecting radiometric ages based upon their stratigraphic control and analytical precision, we also applied the following criteria or corrections:

(1) Stratigraphically constrained radiometric ages with the U-Pb method on zircons were accepted from the isotope dilution mass spectrometry (TIMS) method, but generally not from the high-resolution ion microprobe (HR-SIMS, also known as 'SHRIMP') that uses the Sri Lanka (SL)13 standard. An exception is the Carboniferous Period, where there is a dearth of TIMS dates, and more uncertainty.
(2) ^{40}Ar-^{39}Ar radiometric ages were re-computed to be in accord with the revised ages for laboratory monitor standards: 523.1 ± 4.6 Ma for MMhb-1 (Montana hornblende), 28.34 ± 0.28 Ma for TCR (Taylor Creek sanidine) and 28.02 ± 0.28 Ma for FCT (Fish Canyon sanidine). Systematic ('external') errors and uncertainties in decay constants are partially incorporated. No glauconite dates are used.

The bases of the Palaeozoic, Mesozoic and Cenozoic eras are bracketed by analytically precise ages at their GSSP (Global Standard Section and Point) or primary correlation markers – 542 ± 1.0 Ma, 251.0 ± 0.4 Ma, and 65.5 ± 0.3 Ma – and there are direct age-dates on base-Carboniferous, base-Permian, base-Jurassic, and base-Oligocene; but most other period or stage boundaries prior to the Neogene lack direct age control. Therefore, the third step, interpolation, plays a key role for most of GTS2004. A set of detailed and high-resolution interpolation processes incorporated several techniques, depending upon the available information:

(1) A composite standard of graptolite zones spanning the uppermost Cambrian, Ordovician and Silurian interval was derived from 200+ sections in oceanic and slope environment basins using the constrained optimization method. With zone thickness taken as directly proportional to zone duration, the detailed composite sequence was scaled using selected, high precision zircon and sanidine age dates. For the Carboniferous through Permian a composite standard of conodont,

fusulinid, and ammonoids events from many classical sections was calibrated to a combination of U-Pb and ^{40}Ar-^{39}Ar dates with assigned external error estimates. A composite standard of conodont zones was used for Early Triassic. This procedure directly scaled all stage boundaries and biostratigraphic horizons.

(2) Detailed direct ages for Upper Cretaceous ammonite zones of the Western Interior of the USA were obtained by a cubic spline fit of the zonal events and 25 ^{40}Ar-^{39}Ar dates. The base-Turonian age is directly bracketed by this ^{40}Ar-^{39}Ar set, and ages of other stage boundaries and stratigraphic events are estimated using calibrations to this primary scale.

(3) Seafloor spreading interpolations were done on a composite marine magnetic lineation pattern for the Late Jurassic through Early Cretaceous in the Western Pacific and for the late Cretaceous through early Neogene in the South Atlantic Oceans. Ages of biostratigraphic events were assigned according to their calibration to these magnetic polarity time scales.

(4) Astronomical tuning of cyclic sediments was used for Neogene and Upper Triassic, and for portions of the Lower and Middle Jurassic, middle part of Cretaceous, and Paleocene. The Neogene astronomical scale is directly tied to the Present; the older astronomical scale provides absolute-duration constraints on polarity chrons, biostratigraphic zones and entire stages.

(5) Proportional scaling relative to component biozones or subzones. In intervals where none of the above information under Items 1 through 4 was available, it was necessary to return to the methodology employed by previous geologic time scales. This procedure was necessary in portions of the Middle Triassic, and Middle Jurassic. Devonian stages were scaled from approximate equal duration of a set of high-resolution subzones of ammonoids and conodonts, fitted to an array of high-precision dates. These intervals should be the future focus for both acquiring more radiometric ages and performing quantitative integrated stratigraphy.

The geomathematics employed for data sets (Items 1, 2, 3 and 5) constructed for the Ordovician–Silurian, Devonian, Carboniferous–Permian, Late Cretaceous, and Palaeogene involved cubic spline curve fitting to relate the observed ages to their stratigraphic position. During this process, the ages were weighted according to their variances based on the lengths of their error bars. A chi-square test was used for identifying and reducing the weights of relatively few outliers with error bars that are much narrower than could be expected on the basis of most ages in the data set.

Stratigraphic uncertainty was incorporated in the weights assigned to the observed ages during the spline-curve fitting. In the final stage of analysis, Ripley's algorithm for Maximum Likelihood fitting of a Functional Relationship (MLFR) was used for error estimation, resulting in 2-sigma (95% confidence) error bars for the computed chronostratigraphic boundary ages and stage durations. These uncertainties are discussed and displayed on the time scale charts as part of Gradstein *et al.* (2004) and the summary chart on the ICS website (*www.stratigraphy.org*). The uncertainties on older stage boundaries generally increase owing to potential systematic errors in the different radiometric 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.

In Mesozoic intervals that were scaled using the seafloor spreading model or proportionally scaled using palaeontological subzones, the assigned uncertainties are conservative estimates based on variability observed when applying different assumptions (see discussions in the Triassic, Jurassic and Cretaceous chapters of GTS2004). 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.

'Quaternary' is traditionally considered to be the interval of oscillating climatic extremes (glacial and interglacial episodes) that was initiated at about 2.5 Ma, therefore encompasses the Holocene, Pleistocene, and uppermost Pliocene. It is not a formal chronostratigraphic unit, but a composite 'Epoch' (see under GSSP's at www.stratigraphy.org) from Gelasian to Recent.

GTS quo vadis?

The changing philosophy in time scale building has made it more important to undertake high-resolution geochronologic study of critical stratigraphic boundaries, and extend the astronomical tuning into progressively older sediments. The Palaeogene and parts of Cretaceous are prime candidates for a high-resolution orbital time scale, although chaos theory appears to limit the ultimate resolution achieved in the Neogene. Good examples of high-resolution geochronologic studies are Bowring *et al.* (1989) for basal-Triassic radiometric age, Amthor *et al.* (2003)

for basal-Cambrian radiometric age and Hilgen *et al.* (2000) for Messinian orbital scaling. The philosophy is that obtaining high-precision age dating at a precisely defined stratigraphic boundary avoids stratigraphic bias and its associated uncertainty in rock and in time.

In this respect, it is of vital importance to geochronology that ICS not only completes the definition of all Phanerozoic stage boundaries, but also actively considers standardization of subdivisions within the longer stages. Examples of long stages (spanning more than 10 myr) that lack international standardization of internal divisions are the Campanian, Albian, Aptian, Norian, Carnian, Sakmarian, Visean, Tournaisian, Famennian and Tremadocian stages. Among long periods the Cambrian stand out as rather undivided; it presents a formidable challenge to stratigraphers with its long interval of limited biostratigraphic resolution and high continental partitioning. Despite the challenges, ICS is optimistic that the consensus process to define and subdivide all stages and periods should be completed in a timely manner. Regional and philosophical arguments between stratigraphers should be actively resolved to reach consensus conclusions focusing on the global correlation implications. Stratigraphic standardization precedes linear time calibration.

Future challenges to time scale building are presented in detail in Gradstein *et al.* (2004) and may be summarized as follows:

(1) Achieve formal definition of all Phanerozoic stage boundaries, and formal interior subdivisions of long stages.
(2) Directly link polarity chrons and cycles for the 13–23 Ma orbitally tuned scale.
(3) Orbitally tune the Palaeogene time scale, 23–65.5 Ma, and extend tuning 'down' into the Cretaceous.
(4) Achieve a consensus Ar/Ar monitor age (? 28.24 ± 0.01 Ma from orbital tuning).
(5) Achieve consensus values for decay constants in the K-Ar isotope family.
(6) Achieve full error propagation on all published, high-resolution ages; create listings in a master file.
(7) Resolve the seemingly intractable zircon controversies across Devonian/Carboniferous, Permian/Triassic, and Anisian/Ladinian boundaries, either through more sampling or re-evaluation of different laboratory techniques.
(8) Undertake detailed age dating of several comparatively 'neglected' intervals, including Upper Jurassic – Lower Cretaceous (M-sequence spreading and 'tuned' stages), base Carboniferous (Kellwasser extinction event; glaciation), and within Albian, Aptian, Norian, Carnian, Visean, and intra Permian.
(9) Achieve detailed composite standard zonal schemes for Upper Palaeozoic and Lower Mesozoic.

We note with satisfaction that the geochronological science community and ICS are actively focusing on these challenging stratigraphic and geochronologic issues. A new version of the present time scale may be in place at the time of the 33rd International Geological Congress in 2008, concurrent with consensus on boundary stratotypes (GSSPs) for all international stages.

Note: This article summarizes key features of *Geologic Time Scale 2004* ($\sim$ 500 pages, Cambridge University Press). The Geologic Time Scale Project under auspices of the International Commission on Stratigraphy is a joint undertaking of F. M. Gradstein, J. G. Ogg, A. G. Smith, F. P. Agterberg, W. Bleeker, R. A. Cooper, V. Davydov, P. Gibbard, L. A. Hinnov, M. R. House (†), L. J. Lourens, H-P. Luterbacher, J. McArthur, M. J. Melchin, L. J. Robb, J. Shergold, M. Villeneuve, B. R. Wardlaw, J. Ali, H. Brinkhuis, F. J. Hilgen, J. Hooker, R. J. Howarth, A. H. Knoll, J. Laskar, S. Monechi, J. Powell, K. A. Plumb, I. Raffi, U. Röhl, A. Sanfilippo, B. Schmitz, N. J. Shackleton, G. A. Shields, H. Strauss, J. Van Dam, J. Veizer, Th. van Kolfschoten and D. Wilson.

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