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The ICS international chronostratigraphic chart this decade

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The International Commission on Stratigraphy (ICS) has been producing and updating its International Chronostratigraphic Chart for several decades. The chart communicates higher-order divisions of geological time and actual knowledge on the numerical ages of their boundaries. Distributed via the ICS website www.stratigraphy.org the chart promotes use in graphic, tabulated and further digital forms in multiple languages. This paper is a status update, eleven years since the last such publication, covering activities between 2012 and 2024. Chart updates during the past decade have echoed the ICS's primary objective of precisely defining a global standard set of time-correlative units (Systems, Series, Stages) for stratigraphic successions worldwide. These units are, in turn, the basis for the Periods, Epochs, and Ages of the Geological Time Scale. Their standardization is fundamental for expressing geological knowledge, in application and education, outreach and continuing research. The chart offers a framework through which regional-scale higher-resolution divisions can be linked, equated and collated. Likewise it offers a framework for digital representation of the Geological Time Scale. Maintenance and distribution of chart versions on the web has been a manual endeavour, a process that ICS is upgrading to serve an increasingly digital world.

Introduction

The ICS Chart communicates the hierarchy of chronostratigaphical units (e.g., Systems, Series, and Stages) on which geochronological units (e.g., Periods, Epochs and Ages) are based (Fig. 1). With the addition of calibrated numerical ages for unit boundaries, it serves as the International Geological Timescale. As an infographic, the chart caters to a range of users: geologists who are relatively new to a particular time-stratigraphic interval and seek to place named divisions in their correct order and hierarchical structure, professionals that need to look up the latest specific estimates of numerical ages, earth science students at all levels, and the general public interested in the long history of the Earth (Cohen *et al.*, 2013). For the International Commission on Stratigraphy (ICS: www.stratigraphy.org) within the International Union of Geological Sciences (IUGS), the chart is also important for communicating the progress in formalising a single set of global chronostratigraphic units defined by specific boundaries (e.g., Finney, 2013), and for communicating standards of colour coding the divisions for use on geological maps and sections, which uses the scheme established by the Commission for the Geological Map of the World (CGMW: www.ccgm.org). Furthermore, the Commission on the Management and Application of Geoscience Information (CGI: cgi-iugs.org) uses the units and formally defined boundaries as international standards. They have, for example, been included in the library of GeoSciML, an application for globally accessing standards-based geoscience data and information.

The ICS' chronostratigraphical definition of boundaries for recognition as international geostandards, makes use of GSSPs (Global Boundary Stratotype Section and Points) and GSSAs (Global Standard Stratigraphic Ages), that may be supported by further auxiliary sections (SABSs: Standard Auxiliary Boundary Stratotypes). When GSSPs and/or GSSAs are defined or updated, the ICS chart updates. Between mid-2013 (Cohen *et al.*, 2013) and mid-2023 (i.e., a decade), twenty chart updates have been released as web publications, and released following IUGS ratifications of ICS commission, subcommission and working group discussion and voting outcomes since the Brisbane 2012 International Geological Congress (three 4-year ICS-commission terms). Year and month of these releases make up the chart version number. The 2024/12 chart is the first chart released of the 2024-2028 ICS commission term, starting from the Busan 2024 International Geological Congress. The ICS website (www.stratigraphy.org) hosts the most current chart, keeps a change log, together with an archive of previous charts. The aim of this paper is to summarize and contextualize the updates to the International Chronostratigraphic Chart, and through that progress of the ICS and subcommissions and working groups in defining precise global rock-time units through GSSPs and GSSAs, allowing to calibrate the numerical ages and facilitating international geological communication. As such it is a status update on the ICS chart, 11 years after Cohen et al. (2013) last did so. The paper declares the administrative procedures along which the chart and related tabulated materials are maintained by ICS officers, importantly with increased attention to digital data representation. Lastly, the paper connects chart updating and GSSP definition progress to outreach, via the ICS website and via activities at sites holding the GSSPs, for which ICS encourages the placement of markers, educational exhibits, and even 'golden spikes' in well-attended dedication ceremonies.

Graphic Stability Over 20 Versions

This paper includes the most recently updated version of the ICS Chart (2024/12; Fig. 1). Traditionally, the main ICS chart is that in landscape format with the time divisions using four columns. Three columns present the Phanerozoic (Cenozoic, Mesozoic, and Paleozoic), showing four systems in each column. At the lowest level these display 36 + 34 + 32 stages. A fourth, shorter column shows the Precambrian, divided to system level with at its base, the Hadean. This splitting over 3+1 columns, breaking the Mesozoic and Paleozoic over two columns, was continued from the ICS chart design of the decade before (e.g., Ogg et al., 2008). Redesign in 2012 (Cohen *et al.*, 2013) made more visual that the division of geological time is irregular, the historically emerged definitions (including step-wise revisions) governed by stratigraphical successions. The way the chart does so, is to accommodate graphically the relatively longer stages as thicker cell intervals in each of its four columns, while giving relatively shorter duration stages a minimal height. The Phanerozoic columns span 143, 216 and 180 Myr respectively, but have equal heights in the chart. Within these columns, each stage is given a fixed minimum proportion of the column height (e.g., 2%) and the remaining height (e.g., 100–(34 × 2) = 32%) is then distributed proportionally over the subset of stage cells that in a linear plot would also have covered more than 2%. Placement of numerical ages further makes clear that the chronostratigraphical units are not of equal temporal duration. In these two ways - cell height variation and numeric ticks - it makes clear that the divisions of the geological time scale are not linear and irregular, which is believed to help students, educators and regular users. The ICS website also offers regularised interactive versions of the chart, as well as experimental digital definitions of its hierarchical geological time division scheme for automised use (see below).

The 2012 redesign was well received. Minor modifications to graphics and text placement have been part of chart maintenance in the years since, with 20 updated chart releases since 2013. Duration changes owing to updated numerical ages (see next sections) of Cretaceous stages and the introduction of the tripartite Holocene in the first

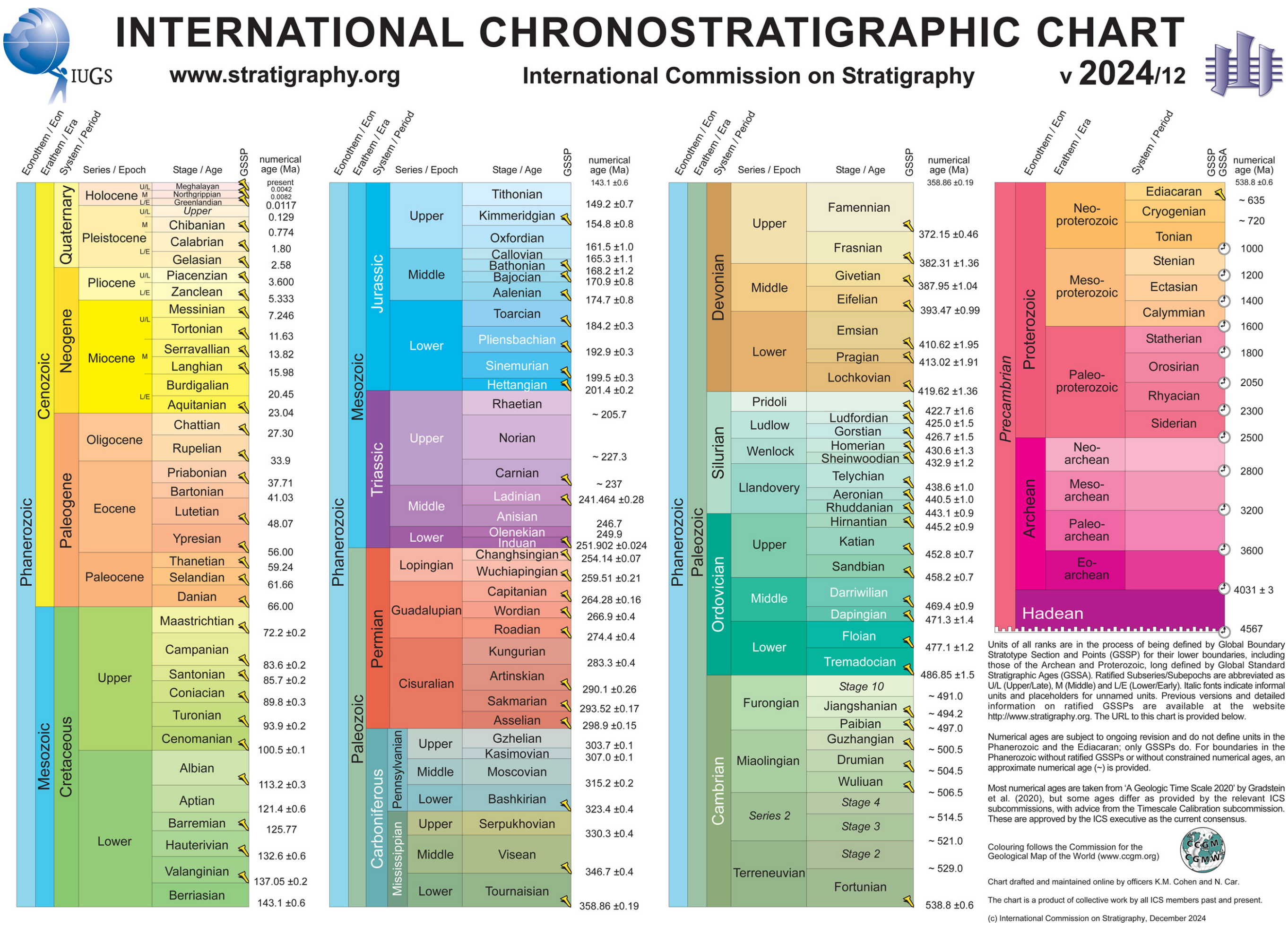

Figure 1. Actual version of the ICS International Chronostratigraphic Chart (v 2024/12). https://stratigraphy.org/ICSchart/ChronostratChart2024-12.pdf

column, and to the Cryogenian in the last column, have been accommodated by adjusting respective cell heights in these columns subtly, but overall graphic changes over ten years have been minimal. Introduction of formalised units of intermediate subseries rank in the Quaternary and Neogene (see below) did not require inserting extra cells.

Ratification of GSSPs and GSSAs as the outcome of ICS producers (see next sections), has been followed by adding the golden spike symbol on the chart and approving and releasing the new chart version within days to weeks. Changes to numerical ages not associated to GSSP/GSSA ratifications and other textual and graphic changes were saved and combined with releases right after GSSP/GSSA ratifications, so as to not release a new version too often. All changes were logged, and this changelog was made available on the website, updated with each chart release. Table 1A gives a summary of changes, divided by chart column, based on this change log. Table 1B provides the same summary divided over Cenozoic, Mesozoic and Paleozoic.

Progress of GSSP Definitions

The chronostratigraphical chart prominently features the status of formal boundary definitions using 'golden spike' and 'clock' icons for GSSPs and GSSAs respectively. A key task within ICS (see Finney, 2013 and Cohen et al. 2013 for rationale and history) is to have units of all ranks each defined by GSSPs for their lower boundaries, also in the Proterozoic and potentially beyond. The GSSP concept was created to allow for stratigraphical correlation around the globe, i.e., alignment of well-researched sections from multiple localities. In turn that allows to combine global boundary-bracketing chronometric evidence for many sections, and revision of a numerical age associated to a long instated GSSP can thus be regarded as its success. It is also possible that long-established GSSPs turn out to be unsuccessful/unsuitable and require replacement.

GSSPs define a point in the rock record (Remane et al., 1996; Finney, 2013; Harper, 2019; Harper et al., 2022), at hitherto deemed most-suitable, intensively researched locations, preferably in the marine sedimentary record (exception possible for very youngest and very oldest parts of the chart). That boundary-stratotype approach results in units with precisely defined boundaries and with no overlaps, nor gaps between successive units. In the Chart, stage GSSPs function as anchors to the beginning of these units in the rock record, and through it for aligned bases of higher hierarchy units. Numerical age is *not* part of a GSSP definition, although abundant chronometric work is usually carried out on the same stratotype section, above and below the point.

In the ICS, the part geological-scientific, part geological-administrative unit and boundary definition process is undertaken by subcommissions and working groups, and guided by step-wise proposal formulation, discussion and voting procedures (Box 1). Revisions to definitions of chronostratigraphical time units as outcomes of this procedure occur infrequently. The 2024/12 chart (Fig. 1) features 81 GSSPs for 102 Phanerozoic stages, of which 17 were ratified in the last twelve years (Table 1). This tallies as 1-3 GSSPs ratified annually. If one wants to see the number of golden spikes (GSSPs) on successive charts as a progress bar, from 2013 to 2024 this moved from 69% to 84%, with relative catch up in the Cenozoic and Cretaceous (left chart column) and relative stalling in the older Phanerozoic (middle chart columns).

Table 1. Summary of changes in ICS International Chronostratigraphic Chart 2013-2024

A) Breakdown by chart column (3 × 4 systems)

	Chart column 1 143 Myr	Chart column 2 216 Myr	Chart column 3 180 Myr	Chart column 4 4,028 Myr
	Phanerozoic 1st four systems: Quaternary down to Cretaceous	Phanerozoic 2nd four systems: Jurassic down to Carboniferous	Phanerozoic 3rd four systems: Devonian down to Cambrian	'Precambrian': Proterozoic, Archean, Hadean
Defining rank	Stages	Stages	Stages	Systems
# divisions	36 (two added)	34 (no change)	32 (no change)	15 (no change)
New GSSP/GSSA ratifications	+13 (36%)	+3 (9%)	+1 (3%)	-1*
GSSP/GSSA redefinitions	0	1	2	2
GSSP/GSSA total	31 (86%)	22 (65%)	28 (88%)	14 (93%)
Age revisions 2013 to 2023/09	17	30	1	3
Age revisions 2024/12	12	8	24	0

B) Alternative breakdown (4 × 3 systems) for Phanerozoic chart columns

	Cenozoic 66 Myr	Mesozoic 186 Myr	Paleozoic P-C-D 167 Myr	Paleozoic S-O-C 120 Myr
	Phanerozoic 1st three systems	Phanerozoic 2nd three systems	Phanerozoic 3rd three systems	Phanerozoic last three systems
Defining rank	Stages	Stages	Stages	Stages
# divisions	26	30	23	25
New GSSP/GSSA ratifications	+7 (26%) 4 newly named	+8 (27%)	+1 (4%)	+1 (4%) 1 newly named
GSSP/GSSA redefinitions	0	0	1	2
GSSP/GSSA total	21 (81%)	22 (67%)	18 (78%)	22 (88%)
Age revisions 2013 to 2023/09	12	19	16	1
Age revisions 2024/12	7	7	12	18

An online index table (stratigraphy.org/gssps) for each GSSP lists the status (defined; considered), location, main characteristics of the boundary level and correlation events as well as a key reference. In the chart and index table, boundaries defined by GSSPs have numerical ages associated to it. For boundaries lacking formal definition status or constraining numerical ages, still an approximate numerical age is provided (indicated with ~ symbol). This online index table also lists ICS-ratified SABSs: Standard Auxiliary Boundary Stratotypes (Head et al., 2023) that were formalised in the ICS stratigraphical framework in the last years. These reference sites support GSSPs, and are defined using similar proposal formulation, discussion and voting procedures as the GSSPs.

The chart and online table extend into the Proterozoic, where the Ediacaran has a GSSP-defined base and where for the Cryogenian a former GSSA has been dropped (since Chart 2015/01), and then to the Archean and Hadean Eonothems/Eons, of which the base GSSAs have recently been updated (since Charts 2023/09, resp. 2022/10). For the GSSA indicated boundaries in this fourth column the numerical age is the definition.

In most cases definition and ratification of GSSPs applies to existing named units on the chart. Examples from the last few years are that for the Campanian (Gale et al., 2023), Coniacian (Walaszczyk et al., 2022), Barremian (Company et al., 2024) and Valanginian (per 2024/12) in the Cretaceous System. Occasionally, a new subdivision of geological units in the chart is proposed. For example, the past decade has seen the formalisation of Subseries/Subepochs (Head et al., 2017; Aubry et al., 2022a), used in the Quaternary and Neogene (Walker et al., 2018; Aubry et al., 2022b). In the case of the Holocene Series, subseries introduction was associated with newly introduced stages and GSSPs (Walker et al., 2018).

When GSSPs are introduced for formerly unnamed stages, the definition also involves naming the stage. In the past decade this happened three times, affecting five stages: Megalayan, Northgrippian, Greenlandian (the tripartite Holocene stages; Walker et al. 2018); Chibanian (the Middle Pleistocene stage; Suganuma et al., 2021), the Wuliuan Stage and Miaolingian Series (Cambrian; formerly *Stage 5* and *Series 3*; Zhao et al., 2019). With these introductions, one stage in the Quaternary (the Upper Pleistocene stage), one in the Silurian (the Pridoli Series equivalent; candidate to be defined as two stages; Manda et al., 2023), and four stages and a series in the Cambrian (provisional *Stages 2*, *3*, *4* and *10*; *Stages 3-4* equating to *Series 2*) remain unnamed.

Occasionally, GSSP relocations are proposed. One reason for this is loss of access to the original location. The example of the past decade is that of the Wuchiapingian Stage, Lopingian Series, Permian (Shen et al., 2024). The previous GSSP location (ratified 2004) was permanently flooded owing to hydroelectric power-dam construction; the local stratigraphy was traced upwards and a replacement GSSP location defined at a nearby accessible locality (ratified 2023). Two other GSSP relocations over greater distance (ratified 2024), affect Silurian stages originally defined in 1984. The Telychian GSSP is relocated from Wales, U.K. to Seville Province, Spain and the Aeronian GSSP from Wales, U.K. to central Bohemia, Czech Republic.

Occasionally, GSSA definitions are dropped awaiting redefinition and/or replacement by a GSSP. The example of the past decade is that of the Cryogenian System in the Proterozoic (Shields-Zhou et al., 2016). Its GSSA of 850 Ma (ratified 1991/1992) was dropped and replaced by an interim numerical age of ~720 Ma (since 2015/01), awaiting formulation of a Cryogenian GSSP proposal. Occasionally, GSSA definitions are revised, with two examples in the past decade affecting the lowest two division of the chart (see next section).

Rarely, GSSP/GSSA definitions for entirely new units are proposed, the approval of which would mean hierarchical positions and relationships reconsidered. Between 2013 and 2024, this has been the case for the Anthropocene series and associated stage bearing a GSSP (Waters et al., 2023), the voting for approval by the subcommission in early 2024 produced a negative result.

TEXT BOX 1:

ICS' workflow and protocol for chronostratigraphic boundary-definition proposals

Candidate GSSPs [and likewise GSSAs] are evaluated by the ICS and its constituent subcommissions and working groups based on a long list of criteria (Hedberg, 1976; Cowie et al., 1986; Salvador, 1994; Remane et al., 1996; Harper et al., 2022). The most important of these is that the boundary at the candidate stratotype is defined at the level in rock coincident with 'a single stratigraphic signal within an interval of multiple, varied stratigraphic signals', that should allow for reliable, high-resolution correlation across the greatest possible palaeogeographical range of palaeo-environmental settings (Finney, 2013).

Identification and field investigations of candidate stratotype sections and boundary intervals, and drafting of proposals, are carried out by subcommissions of ICS (stratigraphy.org/subcommissions) and usually by smaller boundary-working groups. One or more candidate GSSP proposals [and/or GSSA proposals] may be considered for approval by the voting members (*ca.* 20; voting member tenured for a maximum of 12 years) of a subcommission, and a single proposal that receives a supermajority vote (>60% of the voting membership) is considered approved. One consequence of this approach is that disagreement can arise, because type sections that are favoured for historical reasons may be abandoned, previously established boundary levels may be changed, and in some instances historical units (and their names) are replaced by new and different ones (retiring old names).

Once *accepted by* a subcommission, a proposal is then forwarded to the ICS for consideration and *approval*. The ICS voting members are the executive officers of ICS and the chairs of the 17 ICS subcommissions, each of whom has a single vote. They evaluate and discuss each proposal, then vote. If the proposal is approved by supermajority votes, the proposal is forwarded to the IUGS Executive Committee. Once it is also approved by majority within the IUGS Executive Committee, the proposal is *formally ratified* and recognised as an international geostandard. The ICS executive updates the International Chronostratigraphic Chart and the GSSP table on www.stratigraphy.org (typically within days). A manuscript documenting the ratified GSSP proposal is submitted for publication, generally in the IUGS's journal *Episodes* (episodes.org). At the GSSP stratotype locality, a physical marker should be placed, that may be officially launched in a public dedication ceremony (typically 1-3 year after ratification). A proposal to change a newly established unit and/or GSSP cannot be made within the first 10 years after its ratification, a clause to ensure the stability of the global chronostratigraphic framework.

GSSP Dedication Ceremonies and Their Outreach

Dedication ceremonies at the actual GSSP locality, are essential for their establishment and visibility. Where practical the GSSP is marked physically in the rock by a 'golden spike' (although in practice it is an alloy, usually bronze) and revealed to a public in a ceremony involving the organisations (local, governmental, environmental) that ensure the quality and accessibility of the sites, with invited media attention. Having the GSSP physically installed, and making this publicly known, provides important outreach opportunities, besides being an opportunity to conclude many years of research and thank working groups and subcommissions for their tireless efforts. The ceremonies are led by the many scientists involved, but senior administrative and government officials, including the relevant mayors, host the occasion, and local residents are invited; commonly some 100 attend the ceremonies and reception. Short lectures on the significance of the spike precede the driving in and securing of the spike in the rock, unveiling of information panels, and further celebration. Local media

Figure 2. Photographic impressions from dedication ceremonies. Top row: Chibanian GSSP (Chiba, Japan) physical 'golden spike' reveal and installation (May 21, 2022; from report by MJ Head, M Okada, Y Suganuma, Subcommission on Quaternary Stratigraphy website). Second row: Campanian GSSP (July 26, 2023; Gubbio, Italy), information panel, physical 'golden spike' and symposium. Third row: Coniacian GSSP (September 19, 2023, Salzgitter-Salder, Germany) information panel, physical installation, ICS attendance group photo. Bottom row: Albian GSSP (June 29, 2024, La Charce, France): physical spike and info plaque at mirador (from reports by MR Petrizzo, Subcommission on Cretaceous Stratigraphy website; bottom row by DAT Harper).

attention is also frequent for these ceremonies, in turn stimulating further outreach.

The relevant subcommissions, the ICS and IUGS promote the sites internationally, not least on the International Chronostratigraphic Chart and summaries on the ICS web pages. The ownership of the GSSP is left very much in the hands of the local community and in many places forms the basis for a themed geological park, a magnet for school and university groups together with tourists. Several of the GSSP sites are located in UNESCO Global Geoparks (UGGPs; unesco.org/en/iggp/geoparks). Examples are those for the Paleocene Thanetian and Selandian stages in The Basque Coast UGGP, the Jurassic Aalenian Stage in Molina and Alto Tajo UGGP, and the recently relocated Silurian Telychian Stage in the Sierra Morena de Sevilla UGGP in Spain (Gutiérrez-Marco et al., 2024); the Jurassic Toarcian Stage in Oeste UGGP in Portugal; the Jurassic Bathonian Stage in the Haute Provence UGGP in France; and the Cambrian Paibian and Guzhangian stages at Xiangi UGGP, China. There is a double stimulus for this: (i) organisations aspiring to UNESCO Global Geopark status put established GSSP sites forward as one of the assets of their park underlying the scientific understanding and global importance of the park's geology, (ii) having sites within geoparks implies that a properly equipped regional organization is in place to safeguard quality and accessibility of sections and organise public information, and thus is an asset to a GSSP proposal (Finney & Hilario, 2018).

Three sites, those for the bases of the Changhsingian and Iduan stages (the latter also marks the base of the Triassic System and Mesozoic Erathem) at Meishan, South China, the bases of the Selandian and Thanetian stages, Zumaia, Spain and the base of the Meghalayan Stage, Mawmluh Cave, India are featured in the First 100 IUGS Geological Heritage Sites (iugs-geoheritage.org). Two more GSSP sites and a SABS site have been proposed as part of the second 100 (IUGS, 2024). These are the aforementioned Toarcian (Peniche, Portugal) and Paibian (Xiangxi, China) GSSPs, and the Middle Pleistocene SABS (Marino et al., 2024) at Montalbano-Ideale (Italy).

The majority of GSSPs are located within Western Europe reflecting historical factors but also the better knowledge, and in some cases accessibility, of these sections and the location of most active stratigraphers. There are much smaller clusters in China and North America but relatively few in the global south. Updates to the GSSP-anchored global chronostratigraphical framework – not only new GSSPs but also the revision and relocation of GSSPs established in the 20th century (see above) – provides opportunities to add stratotypes from the global south to the framework. The ICS website includes a map showing the locations of GSSPs around the world.

With the intervention of the Covid restrictions, such ceremonies were relatively few for some years. In the last four years there have been seven formal dedication ceremonies (Fig. 2). For the Quaternary Chibanian Stage (Middle Pleistocene Subseries) in Chiba Prefecture, Japan; for the Paleogene Chattian Stage in Monte Cagnero, Italy; for several Cretaceous stages: for the Campanian in Gubbio, Italy; for the Coniacian in Salzgitter-Salder, Germany, for the Albian and Hauterivian stages in Drôme, France; for the Jurassic Hettangian Stage (and the base of the Jurassic System) in Innsbruck, Austria. Additionally a SABS for the base of the Tremadocian Stage (and the base of Ordovician System) was dedicated in style at the section in Xioayangqiao, Northeast China.

Updates to Numerical Ages

The chronostratigraphical units of the ICS Chart serve as the fundamental, material basis on which the geochronological units of the Geological Timescale are based. The numerical ages shown for the boundaries between successive units are determined by using a range of geochronological techniques, including stable and unstable isotopes, palaeomagneto-chronology, and astronomical tuning of sedimentary cycles. Sometimes numerical ages have been determined from specific levels within boundary intervals at stratotype sections, but the majority have been determined from distantly separated stratigraphical sequences. They have been correlated to stratotype sections with varying degrees of confidence and resolution. Many numerical ages for boundaries are interpolated between widely-spaced geological levels for which numerical ages were originally obtained (Gradstein et al., 2004; 2012; 2020). The GTS volumes up to 2012 were closely associated with ICS when the two lead editors served as Chair and Secretary-General of ICS (2000-2008). However, because continued updates to the publications were created independently of ICS, and lacked formal ICS oversight on content, since 2012 the ICS Chart is maintained, produced and disseminated independently of GTS volumes, using the ICS website and the section 'Communication of IUGS Geological Standards' of *Episodes*. This has meant that numerical ages displayed on successive chart versions, for some systems began to deviate from the numerical ages considered in e.g., GTS2020 (Gradstein et al., 2020). The ICS chart between 2013 and 2024 has displayed those numerical ages that the subcommissions have put forward. The chairs of the Quaternary, Paleogene, Cretaceous, Jurassic, Triassic, Permian, Cambrian, Cryogenian and Pre-Cryogenian subcommissions have filed such numerical age updates in the past. This has included synchronisation with GTS2020, as the chart changelog has documented. The ICS subcommission of Timescale Calibration established in 2020 may call to change this procedure in the coming decade. Indeed, the 2024/12 chart replaced GTS2012 with GTS2020 as the reference for most of its numerical ages, with their input and with period specific subcommission consultations.

Continued acquisition of new numerical ages from field and laboratory work and the development of high-precision numerical dating and self-consistent age-calibration techniques continue to increase the refinement of the time scale. During the last century, as the geological sciences matured, the ages of individual boundaries changed significantly with generally increasing global coverage of observations, since the 1990s or so they appear to become more firmly established: numerical geological ages appear to gain precision, and their shifts with revisions may best be characterised as nudges (small shifts). Rephrased and repeated from the 2013 paper: the ICS regards this principally *due* to continued data gathering and technological growth in the Earth Sciences in general, and principally *aided* by the formal stratigraphic procedures (notably that of the concept of GSSPs) and international collaborations, curated and advocated by the ICS. Some numerical ages are already highly constrained, whilst others will remain less certain, perhaps perpetually. This is also reason to continue to have ICS chart boundaries in the Phanerozoic defined by GSSPs. Nevertheless, full convergence will probably never be reached and it is to be expected that as techniques improve, almost all the ages will be subject to further calibration revisions.

Between 2013 and 2023, 47 numerical age revisions were implemented in the Phanerozoic columns of the chart (Table 1). Eleven of these changes were associated to the ratification of a GSSP, 37 times it was for other reasons, such as to re-synchronise with the new timescale calibrations (e.g., 2013: 12× calibrations by subcommissions; 2022: 13× Jurassic and Cretaceous calibrations in GTS2020; 2014-2017: 7× recalibrations Permian stage boundaries; 2019-2020 2× Middle and Upper Pleistocene stages; 2022: 1× base Cambrian recalibration), or to more correctly reflect numerical accuracy (2014: 2× Lower Pleistocene ages one decimal dropped). Four more instances of change (kept out of the Table 1 totals) were to correct typing mistakes and from inheriting the review version rather than the final copy of GTS2012 as the chart starting point (implemented 2014/10). Particularly large age shifts were: the base Fortunian (base Cambrian) 2.2 Myr younger from ~541 Ma to 538.8 ± 0.2 Ma (cf. Linnemann et al., 2019); base Toarcian (in Lower Jurassic) 1.5 Myr older from 182.7 ± 0.7 to 184.2 ± 0.3 Ma; base Tithonian (in Upper Jurassic) 2.9 Myr younger from 152.1 ± 0.9 Ma to 149.2 ± 0.7 Ma; base Kimmeridgian (in Upper Jurassic) 2.5 Myr younger from 157.3 ± 1.0 Ma to 154.8 ± 0.8 Ma (cf. Hesselbo et al., 2020); base Barremian (base Cretaceous) 3.6 Ma younger from ~129.4 Ma to ~125.77 Ma (GSSP definition; Company et al., 2024).

At the release of the 2023/09 chart, 60 (51%) of the 117 numerical ages were those of GTS2012. Cross-comparison of that chart's numerical ages with those in GTS2020 (series of chapters in Gradstein et al., 2020) was carried out in 2023-2024. This gives further insight into progressive numerical age convergence (the dating becoming increasingly constrained) and divergence (owing to choices of mathematical methods, besides chronostratigraphical preferences and uncertainties) in international geological timescale construction. For the 102 Phanerozoic stages, nine numerical ages deviated more than 1 Ma between GTS2020 and ICS2023/09, and twenty five more differed between 0.1 and 1 Ma. The 2024/12 chart release (Fig. 1) has been used to update from GTS2012 to GTS2020 as a main reference, adopting many but not all GTS2020 ages: 87 (74%) of the 117 numerical ages on the chart are those from GTS2020, while 30 Phanerozoic stages and two Precambrian systems GSSAs (see below) deviate, for various reasons. For the Cretaceous, the series of GSSPs ratified in 2020-2024 makes that for several of its stages numerical ages deviate. For the lower Permian and upper Carboniferous (Schmitz and Davydov, 2012), and for the base Carboniferous and Devonian (Harrigan et al., 2022), numerical age modelling alternative to that in GTS2020 was adopted.

In the Proterozoic, GSSPs with associated numerical ages are only considered for the uppermost systems (Ediacaran GSSP defined, Cryogenian GSSP in preparation) and otherwise the timescale division builds on GSSAs. The set of GSSAs since the 1990s (Plumb, 1991, 1992) have carried interim rounded ages. Three age revisions occurred in this column (Table 1). One was associated with the aforementioned Cryogenian GSSP revision. Two new numerical age definitions by the Pre-Cryogenian subcommission mark the other two, new ratified GSSAs for the bases of the Hadean and Archean Eonothems/Eons.

For the Hadean, chronometric data obtained from primitive meteorites, representative of the time of formation of the planet and solar system, put the numerical age at 4567 Ma (Halla et al., 2024), defining a GSSA, replacing the interim age of ~4600 Ma and formalising the Hadean Eonothem/Eon status (since 2022/10). For the Archean and its lowermost Eoarchean Erathem/Era, oldest direct chronometric evidence of continental growth and preservation obtained from the Acasta Gneiss Complex Formation in Canada put the numerical age to 4031 ± 3 Ma, redefining the GSSA (since 2023/09) and replacing the former interim age of 4000 Ma.

Overall, Table 1 summarizes that since 2012 a total of 51 numerical age updates occurred (31 to 56 stages of Cenozoic and Mesozoic; 17 to the 48 stages of the Paleozoic; 3 to the 15 systems of the Precambrian), accumulating to a point that about half (51%) of the ages on the chart still resembled GTS2012. Resyncing with GTS2020 (see above) as the main reference involved 44 further numerical age updates (Table 1 and online chart changelog). The 2024/12 chart numerical age updates were all in the Phanerozoic. They affected 25% (14/56) of the Cenozoic and Mesozoic stages and 63% (30/48) of the Paleozoic stages. In 25 of the 44 cases the shift in numerical age to younger or older side was less than 0.5 Ma. Particularly noticeable numerical age changes between ICS chart 2023/09 (and GTS2012) and ICS chart 2024/12 (and GTS2020) are those for base Cretaceous (from 145 Ma to 143.1 Ma; Gale et al., 2020) and base Ordovician (from 485.4 to 486.9 Ma; Goldman et al., 2020).

ICS Website: Outlet and Archive

Since 2013 (Cohen et al., 2013), documentation of archived and present ICS decisions (e.g., GSSP proposals and later revisions, summaries of deliberations and discussions, ballots, tabulations of votes, and letters of approval) have been distributed using the ICS website as much as possible. This has replaced documentary archives of ICS decisions held in both paper and digital formats by the ICS Chair and Secretary-General, for reasons of transparency and transferability. The ICS website is intended to function as the primary archive in future.

The ICS chart and the table of GSSPs have a prominent function on the website (see below) and are what draws most users and visits. The website also provides transparent information on executive, commission, subcommission and working-group activities and memberships, and their workflows, statutes and guidelines (exemplified in Box 1).

Chart Distribution: Present and Future

The ICS website functions as the ICS' primary distribution point for its versioned International Chronostratigraphic Chart, lists and status updates of geological units, their GSSPs and numerical ages. As such they function as an international reference point, with as main landing pages: stratigraphy.org/chart (chart variants; actual and archived) and stratigraphy.org/gssps (GSSP table; map).

The distribution includes the English edition (Fig. 1) and translated versions of the chart, which have steadily accumulated over the last decade. The parent version of any translation of the chart is the English edition (Fig. 1) with its version number. By 2024, the ICS Chart has been translated into French, German, Russian, Chinese, Japanese, Korean, Spanish (Castilian), American Spanish, Catalan, Basque, Portuguese, Brazilian Portuguese, Norwegian, Dutch (Belgium), Dutch (Netherlands), Turkish, Hungarian, Finnish, Czech, Slovak and Lithuanian. These charts are of identical format to the original ICS Chart and carry the logos of both the ICS and IUGS. Translation affects unit names, headings and brief explanatory text. Translated charts carry brief additional information from the national groups that produced the translation, together with their logos, as appropriate and permitted. The version numbering of a translation mirrors that of the English version used as the source. These translations communicate standardised official spellings for the chronostratigraphical units in the target language. The ICS website updates past translations to new functioning versions.

The ICS holds copyright of its charts as distributed through its website. The ICS has not yet moved to a Creative Commons license variant. Over the last decade, the ICS upheld a policy of allowing reproduction of the ICS chart in unmodified form, upon receipt of written authorisation from the ICS Chair. Placing the IUGS and ICS logos on an altered chart design is not permitted. One should explicitly reference the version used (year/month; e.g., 2024/12). The descriptive text on the chart includes brief guidance to this. One can cite the chart documenting paper (i.e., this paper) and mention the actual version used in addition. One can also cite the www.stratigraphy.org specific URL of the latest version, found on each chart.

For authors of textbooks and conference promotion, the ICS holds alternative chart designs – which include space for a sponsor logotype(s). These include a two-sided, double-column version that can be laminated to provide a field-reference card, and a three-column version that fits a square-format mouse mat. On occasion, the ICS grants sponsor logotype placement when hard copies of the chart are reproduced for circulations at meetings and other gatherings of geoscientists. The digital version available for download on the web does not include any commercial logotype. The PDF-versions distributed on the web can be privately reproduced at a range of scales. They contain vector graphics only and produce well both as a large poster or as pocket-sized reference cards.

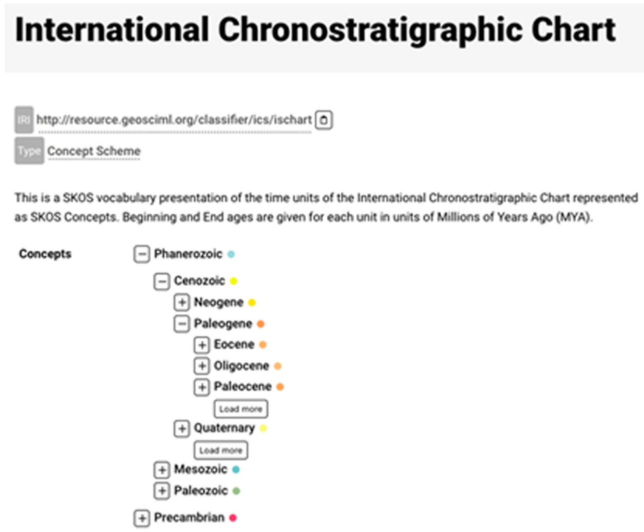

Figure 3. A human-readable form of the Semantic Web version of the chart generated automatically from the data in a standard display tool, showing time elements with their standard colours. The elements can be expanded for their individual details. Note that chronostratigraphic sorting requires custom display tools. This data version of the chart is currently put to machine-to-machine use by the Geological Survey of Western Australia within their internal geoscience Knowledge Graph – enterprise database. Its source is online at https://vocabulary.gswa.kurrawong. ai/v/vocab/ics:ischart.

A machine-readable, data form of the actual chart is now also available (Fig. 3); it is being implemented to serve content creation on the website, and is available for download. The machine-readable form of the chart is formulated as a taxonomy of its elements according to Seman-

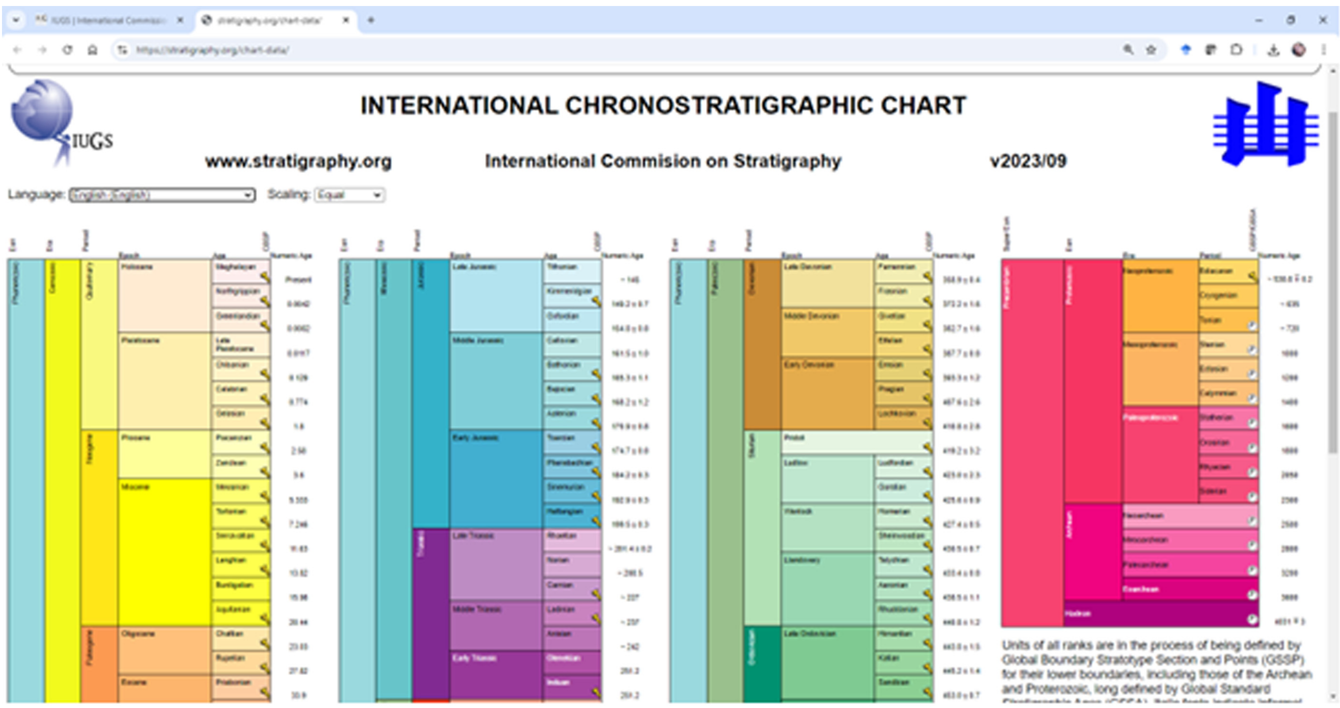

Figure 4. Browser-rendered interactive graphic chart, based on ICS chart-as-data (see text). Screenshot from https://stratigraphy.org/chart-data/[01/12/2024]. Note options to redisplay in other language. Note options to rescale to preference.

tic Web principles (Berners-Lee et al., 2001). This follows many recent initiatives in international geology to make data available in this way, for example the Deep Time Digital Earth initiative (Hou et al., 2024).

Work is currently underway to generate all the current English and other language versions of the chart in digital document (PDF) format from the machine-readable data form. Once this is completed, the machine-readable data form will be extended with GSSP details, which will enable auto-generation of the GSSP table as well as allow for sophisticated queries. A previous experimental data form of the chart (online at http://resource.geosciml.org/classifier/ics/ischart/) has piloted this. The data version of the chart will be available for direct machine-to-machine use via standard Linked Data Application Programming Interfaces (APIs). It is currently in direct use as per Figure 4.

The main goals of the move to use the data form of the chart are (i) to reduce the manual effort in chart creation, and the chance of error, and (ii) to provide a foundational geoscience "Knowledge Graph" to the international community to save chart users from having to convert the current chart information into machine-readable data themselves. Full operational implementation, putting the data form centrally in digital ICS chart and timescale maintenance workflows, is foreseen in 2025.

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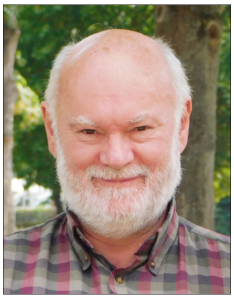

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