

Chronostratigraphy and geochronology: A proposed realignment

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ABSTRACT

We propose a realignment of the terms *geochronology* and *chronostratigraphy* that brings them broadly into line with current use, while simultaneously resolving the debate over whether the Geological Time Scale should have a “single” or “dual” hierarchy of units: Both parallel sets of units are retained, although there remains the option to adopt either a single (i.e., geochronological) or a dual hierarchy in particular studies, as considered appropriate. Thus, geochronology expresses the timing or age of events (depositional, diagenetic, biotic, climatic, tectonic, magmatic) in Earth’s history (e.g., Hirnantian glaciation, Famennian-Frasnian mass extinction). Geochronology can also qualify rock bodies, stratified or unstratified, with respect to the time interval(s) in which they formed (e.g., Early Ordovician Ixex Group). In addition, geochronology refers to all methods of numerical dating. Chronostratigraphy would include all methods (e.g., biostratigraphy, magnetostratigraphy, chemostratigraphy, cyclostratigraphy, sequence stratigraphy) for (1) establishing the relative time relationships of stratigraphic successions regionally and worldwide; and (2) formally naming bodies of stratified rock that were deposited contemporaneously with units formally defined at their base, ideally by a GSSP (Global Boundary Stratotype Section and Point = “golden spike”) that represents a specific point in time. Geochronologic units may be defined and applied generally by either GSSPs or—as currently in most of the Precambrian—by Global Standard Stratigraphic Ages (GSSAs). Geochronologic units would continue as the *time* units eons/eras/periods/epochs/ages, and chronostratigraphic units as the *time-rock* units eonothems/erathems/systems/series/stages. Both

hierarchies would remain available for use, as recommended by a formal vote of the International Commission on Stratigraphy in 2010. Geological context helps determine the appropriate usage of the component units.

INTRODUCTION

Geology is the natural science in which time plays a central role. The passage of that time and its events (small and large) and intervals (short and long) are recorded in Earth’s rocks, particularly in stratigraphic successions and by the various lithologic, paleontologic, magnetic, and chemical signals within them. Study of these rocks has yielded the 4.6-billion-year history of Earth—study that is ongoing and is now being extended to other planets. Stratigraphy is the means of analyzing and ordering these phenomena, with chronostratigraphy and geochronology dealing explicitly with the relations of rock and time.

The primary means by which geological time information is conveyed is by the use of the Geological Time Scale (GTS = International Chronostratigraphic Chart [ICC] of the International Commission on Stratigraphy [ICS]) and its units. The most familiar of these units are the geological periods of geochronology, *sensu stricto*, or, more simply, of time (e.g., Jurassic, Cambrian) and the corresponding systems of chronostratigraphy, *sensu stricto*, or time-rock on which they are based. Historically, the systems were built from, or subdivided into, series and stages; the periods, epochs, and ages were then used to refer to the intervals of time in which the strata encompassed were deposited. Thus, conceptually, there has been a “dual and parallel hierarchy” of chronostratigraphic (time-rock) units used to designate rock bodies that formed contemporaneously and geochronologic (or time) units used to designate intervals in which they formed¹ or during which other events occurred (e.g., evolution, extinction, deformation, transgression). Many of these units were originally set up as (and remain fundamentally) relative time-rock units. These are typically of the last half billion years (the Phanerozoic Eon), where there are good fossil assemblages (i.e., biostratigraphy) that remain key to their definition, recognition, and correlation. Wherever feasible, additional tools, such as magnetostratigraphy, chemostratigraphy, sequence stratigraphy, cyclostratigraphy, and radiometric dating are employed (e.g., Strasser et al., 2006; Weissert et al., 2008; Langereis et al., 2010; Catuneanu et al., 2011; Gradstein et al., 2012). Most of the Precambrian units of the GTS, which largely lack useful fossil assemblages, remain defined by Global Standard Stratigraphic

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¹By “formed” we mean when the main fabric of the rock was constructed; in sedimentary rocks, this is taken as when the sedimentary particles were deposited; in igneous rocks, this typically means intrusion or crystallization (although these processes may not be precisely synchronous). The “timing of formation” of any individual metamorphic rock is often more problematic, because such a rock commonly includes components that crystallized at different times along a pressure-temperature-time path.

Ages (GSSAs); the Archean–Proterozoic boundary, for instance, is set at 2500 Ma. However, the Ediacaran System/Period was defined by a GSSP in 2004 (Knoll et al., 2006), and the Ediacaran and Cryogenian subcommissions are considering a GSSP for the Cryogenian and subdivision of the Ediacaran by GSSPs. Furthermore, the ICS Subcommittee on Precambrian Stratigraphy is initiating efforts to define GSSPs for subdividing the Archean and Proterozoic by their rock record (e.g., Bleeker, 2004) rather than by arbitrarily chosen numerical ages. These projects will result in a Precambrian time scale that likely will be very different from that presently used.

At the other end of the geologic time scale, the recognition of long oceanic successions with effectively complete Milankovitch signatures has led to the revival of the unit-stratotype concept (Hilgen et al., 2006). Neogene stages (Zanclean and Piacenzian) with upper and lower boundaries defined by GSSPs in the same section have within them all significant biostratigraphic and magnetostratigraphic signals for the time encompassed and numerical ages that are integrated and precisely dated at high resolution through astronomical tuning. The Holocene, until recently defined only numerically, has been redefined with a GSSP in a Greenland ice core (Walker et al., 2009), and this epoch in turn leads to the present. Here geologic events are observed, recorded, and dated as they occur using human time (year, month, day, hour). Superposition in deposits analyzed at such high time resolution may commonly be compromised, for example, by the blurring effects of bioturbation (cf. Zalasiewicz et al., 2007), and this complicates the application of chronostratigraphy in such instances.

Early versions of the GTS were created, and functioned effectively, in the days before radiometric dating (e.g., Jukes-Brown, 1902). Today, considerable effort is expended to calibrate the GTS with numerical ages. Nevertheless, it remains more common to convey geological time information in terms of GTS units rather than by numbers of years. This is partly because of the familiarity and convenience of the units (to geologists at least) and partly because it is usually easier and more useful to establish relative correlations than to establish the numerical ages of rock phenomena. More importantly, however, the rocks formed during a time unit often encompass (and record) distinctive, time-constrained global environments (e.g., the Hirnantian Stage). They provide a convenient and practical method of reference to the events and time intervals they represent, just as with human history, when terms are used for a distinctive time interval (e.g., Renaissance) and its human products (e.g., art, architecture, literature, banking). Even informal terms, such as Caledonian and Grenvillian, are widely used in the same way in geology. For circumstances in which global units are difficult to apply, regional ones have been established (see Gradstein et al., 2004, 2012).

While traditionally chronostratigraphic units consist of rocks, whereas geochronologic units are spans of time, there has been debate over the necessity of retaining a dual and parallel time scale with the same formal names. This leads to terms such as “Jurassic” having two meanings, one an “intangible” unit of time and the other a physical unit of rock (which also means that the geochronologic term “age” may be confused with the word “age” used more generally). Some (e.g., Zalasiewicz et al., 2004a, 2004b, 2007; Gong et al., 2004; Odin et al., 2004; Carter, 2007; Jensen, 2004) have argued for unification of the geochronologic and

chronostratigraphic hierarchies, while others (e.g., Heckert and Lucas, 2004; Bassett et al., 2004; Narkiewicz, 2004; Walsh, 2004; Aubry, 2007; Hilgen et al., 2006) have argued for retention of the long-established dual hierarchy.

This debate represents subtle but distinct perspectives on the stratigraphic record. The issue was discussed extensively at the GSA Penrose Conference “Chronostratigraphy: Beyond the GSSP” held in Graz, Austria, in June 2006 and at a workshop of the International Commission on Stratigraphy in Prague, Czech Republic, in June 2010. In a formal ballot following the workshop, the ICS voting members recommended overwhelmingly (15 yes, 2 no, 0 abstain) to maintain the dual usage. Furthermore, the terms “geochronology” and “chronostratigraphy” have acquired a variety of wider meanings. Next, we consider the definition and application of these terms and of their units, discuss their proper usage, and provide examples and explanations of good practice.

CHRONOSTRATIGRAPHY AND GEOCHRONOLOGY: PREVIOUS DEFINITIONS

According to the latest versions of the International Stratigraphic Guide (Salvador, 1994; Murphy and Salvador, 1999), these two terms are defined as

Chronostratigraphy—“The element of stratigraphy that deals with the relative time relations and ages of rock bodies.”

Geochronology—“The science of dating and determining the time sequence of events in the history of the Earth.”

In this approach, chronostratigraphy deals explicitly with relative time relations of bodies of rock, typically stratified rocks, while geochronology rather more ambiguously suggests numerical dating to determine “absolute” ages (and indeed most specialists in radiometric dating consider themselves to be “geochronologists”). There is also a focus in this definition of chronostratigraphy on the rock bodies—for example, on tangible physical evidence, or material—and in the definition of geochronology on the temporal history derived from that evidence.

Today, certainly, the clear separation that used to exist between relative and absolute dating methods is now considerably blurred by methods such as astrochronology, which simultaneously provide *both* numerical and relative dates, once calibrated by biostratigraphy, at all levels within a stratigraphic succession. Thus, it seems timely to reexamine these terms and their conceptual value.

PROPOSED REALIGNMENT

One might consider here whether stratigraphy should be restricted to stratified rocks (as in the first edition of the International Stratigraphic Guide [Hedberg, 1976]) or be extended to cover *all* rocks (as in the second edition, in which the change in philosophy was introduced with little explanation or discussion [Salvador, 1994]). Nowadays, there is value in a term that refers to all rock-related time relations, not least because of the increasing interdisciplinary nature of the Earth sciences. Yet, there also remain considerable differences between the fundamental geological properties of stratified and non-stratified rocks, and hence of the means of their study and classification. For example, biostratigraphy and astrochronology are only possible in sedimentary strata, where superpositional relationships are present. Furthermore, the time of formation of plutonic and metamorphic rocks is determined with numerical dating, whereas, before the wide application of

radiometric dating, it was determined by cross-cutting relations with stratified rocks. This suggests a means of sharpening the distinction between the two terms, as follows:

Chronostratigraphy, consistent with its general use today, is *the establishing of time relations in stratified rocks*. The term is generally restricted to deposition-related processes in which the superpositional properties are present, and hence the detailed historical record is accessible. Chronostratigraphy is the application of disciplines such as biostratigraphy, magnetostratigraphy, chemostratigraphy, cyclostratigraphy, sequence stratigraphy, and numerical dating to stratigraphic successions in order to interpret temporal correlations. Furthermore, it involves the development of formally named and defined chronostratigraphic units and hierarchies, which comprise the ICS as well as regional chronostratigraphic classifications. On Earth, chronostratigraphy effectively starts in the Archean, ca. 3.8 Ma, when a stratal record begins.

Geochronology denotes *time relations in all rocks*, specifically *when they formed*, whether stratified or non-stratified. It also denotes the time of processes in which rocks not only formed but also were eroded (unconformities) and deformed (structural and cross-cutting relationships). It is used to denote the timing of events throughout all of Earth's history that are interpreted from the rock record (e.g., climatic, biotic, tectonic, and oceanographic). The geochronologic units for much of the Ediacaran to Quaternary are the intervals in time during which corresponding chronostratigraphic bodies of strata were deposited. Thus, the boundaries of chronostratigraphic units defined by GSSPs, chosen for their potential for precise global correlation, mark the beginnings and ends of the respective geochronologic units. Furthermore, geochronology is commonly used to denote the practice of radiometric dating (the term "geochronometry" is available to separately denote the process of numerical dating, though it has not been widely adopted). Thus, geochronology can be expressed in numerical ages and durations, though the dating of geologic events and intervals is most often expressed in terms of the geochronologic units.

The succession of global geochronologic units, equivalent to the units of the ICC, comprise the GTS, and these are calibrated by numerical ages. In some instances, ash layers associated with GSSP sections have provided high-precision ages for boundary levels (e.g., Brack et al., 2005, for the Ladinian Stage of the Triassic). Astronomical tuning of complete, continuous Neogene and Quaternary sections that include GSSPs provides very precise ages for boundaries as well as for enclosed stratal packets within the sections, but these may be subject to revision with alternative tunings and/or new astronomical solutions. Most GSSPs lack such ash layers and need be calibrated with numerical ages (themselves subject to revision and refinement) from elsewhere. For these reasons, boundaries of the chronostratigraphic units are not defined by numerical ages; instead, they are defined by GSSPs chosen within intervals with stratigraphic signals that offer the most reliable and most widespread time correlation. The age of a GSSP is estimated using mainly a radioisotopic age determination in its stratigraphic vicinity. In contrast, the Archean and Proterozoic were first defined as, and subdivided into, geochronologic units defined by numerical ages chosen as large round numbers (3600 Ma, 2500 Ma, 1200 Ma) rather than to reflect accurately the Precambrian rock record and the global events it records. Now, though, the ICS Subcommittee on Precambrian Stratigraphy has

embarked on a program of defining new chronostratigraphic units and corresponding geochronologic units in the Precambrian stratigraphic record, to be defined by GSSPs for which numerical ages will then be calculated.

Accordingly, a *formal chronostratigraphic unit* is the *material stratal (time-rock) body* interpreted to have been deposited contemporaneously and with lower and upper boundaries defined by GSSPs that afford the most reliable stratigraphic signals for their temporal correlation. A *formal geochronologic unit* is the continuous time interval between the deposition of the lowest and highest strata within the unit. In the case of non-stratified rocks, the rock body is referenced in terms of the time it formed (e.g., Early Cretaceous El Capitan Granite). This does not mean that the rock is part of a time unit, for rock and time are separate and distinct phenomena: It simply conveys that a dominant event in the granite's formation (crystallization of the component minerals) took place during a particular time unit, as deduced, for instance, from radiometric ages. The boundaries of the time unit in this example, the Early Cretaceous Epoch (and simultaneously of the equivalent Lower Cretaceous Series), are established using chronostratigraphic methods at GSSP sections and numerically calibrated, for example, by radiometric dating of volcanic ash layers within fossiliferous, correlatable successions.

Thus, detailed analysis and correlation of the stratal record establishes both the chronostratigraphic framework and the equivalent and parallel geochronologic units, while, as noted earlier, for much of the Precambrian, geochronologic units are currently defined by GSSAs.

Chronostratigraphy (time-rock)	Geochronology (time)
Eonothem (e.g., Phanerozoic)	Eon (e.g., Phanerozoic)
Erathem (e.g., Mesozoic)	Era (e.g., Mesozoic)
System (e.g., Cretaceous)	Period (e.g., Cretaceous)
Series (e.g., Upper Cretaceous)	Epoch (e.g., Late Cretaceous)
Stage (e.g., Cenomanian)	Age (e.g., Cenomanian)

Series for several systems have been formally named with the adjectives Lower, Middle, and Upper added to the system name; the respective epochs have been formally named with the adjectives Early, Middle (Mid in the UK), and Late added to the period name. For some systems/periods (e.g., Cambrian, Silurian, Permian, Paleogene, Neogene, and Quaternary), the series/epochs are given formal names without adjectives added to the system/period name. If used informally for any chronostratigraphic or geochronologic unit, the adjectives (lower, middle, upper, early middle, late) are not capitalized. We omit, for the time being, formal subdivisions of stages/ages (i.e., chronozones/chrons). This is a complex question beyond the scope of this paper. Such small-scale units now dominate the chronostratigraphy of younger strata (e.g., the numbered oxygen isotope stages of the Quaternary calibrated by astrochronology—but see Cita and Pillans, 2010), but the necessity or means of formally defining them as higher-order chronostratigraphic units remains unresolved.

That aside, the schema outlined here reflects the current standard meaning and use in practice of these units, both chronostratigraphic and geochronological, although the emphasis has been modified to be more clearly expressed in terms of the fundamental stratified/non-stratified divide. Strata and the stratigraphic signals they contain can be assigned to chronostratigraphic units, which can be mapped, studied, and sampled. However, they (or more precisely the events that shaped them) can also be referred

to geochronologic units that identify them by the time during which they formed. Thus, the Ibex Group can form part of the Lower Ordovician Series and can also be referred to the Early Ordovician Epoch (the phrase “Early Ordovician Ibex Group” means that these strata were deposited during the Early Ordovician Epoch, and not, we emphasize, that they form *part* of that epoch). Then, the history of events interpreted from the study of all rocks, whether stratified or non-stratified, and the relationships between them, would be made in terms of the geochronologic hierarchy (e.g., trilobite species evolving or an orogeny occurring during the Early Ordovician Epoch).

THE DISTINCTION BETWEEN TIME AND TIME-ROCK UNITS

A distinction may be made between a geological time unit and the stratal successions assigned to it—most obviously between geochronologic (time) and chronostratigraphic (time-rock) units, say between the Cenomanian Age and the Cenomanian Stage of the Late/Upper Cretaceous (Fig. 1). Thus, the beginning and base, respectively, of these units are fixed by the GSSP at the type section, while the end/top are fixed by the GSSP of the overlying Turonian Age/Stage, which usually is at another location, far removed, often on a different continent than that of the base/beginning. At any one place, the sedimentary record of the Cenomanian Age is almost invariably incomplete because hiatuses at some level or scale will be present, and there may be more significant non-sequences or unconformities at the base or top or within the succession. Furthermore, many GSSPs are within short stratigraphic sections representing a very small part of the global stratigraphic succession of the unit. In addition, elsewhere in the world and far away from these typically geographically separated GSSPs, the recognition of the Cenomanian Stage depends on the uncertainty in correlation. In practice today, correlation is normally by paleontologic means, because fossil evolution essentially possesses a unidirectional trajectory, but it usually involves uncertainty of a substantial fraction of a million years. Thus, there is an incompleteness omnipresent in the recording of Cenomanian time by deposited

sediment at any place and an imprecision in identifying Cenomanian events in rock. However, the span of geological time encompassed by the Cenomanian Age remains identical everywhere on Earth, by definition. This distinction holds true whether one classifies the strata in chronostratigraphic terms (i.e., Cenomanian Stage, employing the dual hierarchy) or as a geochronologic unit (strata deposited during the Cenomanian, or simply Cenomanian strata). Regardless, recognition of temporal gaps in the Cenomanian stratigraphic record is generally only possible through chrono-correlation.

SUGGESTIONS FOR BEST USAGE

We offer the following suggestions for consistent and effective usage of chronostratigraphic and geochronologic units in geological writing. A simple method is to use a chronostratigraphic unit when referring to stratified rocks and a geochronologic unit when referring to time and to phenomena associated with non-stratified rocks. This presents no problem when most units are used as adjectives (e.g., Hirnantian glaciation, Hirnantian strata in the Vinini Creek section) or in a sentence in which the proper name but not its rank is used (e.g., occurred in the Hirnantian, ranges upward from the base of the Hirnantian). More troublesome units are those with superpositional or time modifiers as part of a formal name or when used informally. Lower and Upper (e.g., Lower Ordovician, Upper Cretaceous) and lower and upper (e.g., lower Paleozoic, lower Silurian) should be used when referring to rocks and positions within stratigraphic successions (e.g., the Lower Ordovician of North America primarily consists of carbonate strata; the isotope excursion is recorded in samples from the Lower Ordovician of Scandinavia; the magnetic-polarity reversal occurs in the lower part of the Upper Ordovician series or lower part of the Hirnantian Stage). Early and Late and early and late are used when referring to time of events and processes (e.g., “the Middle [or Mid in UK English] to Late Ordovician Taconic orogeny”; “this species evolved in the Early Cretaceous”; “the isotope excursions in the early

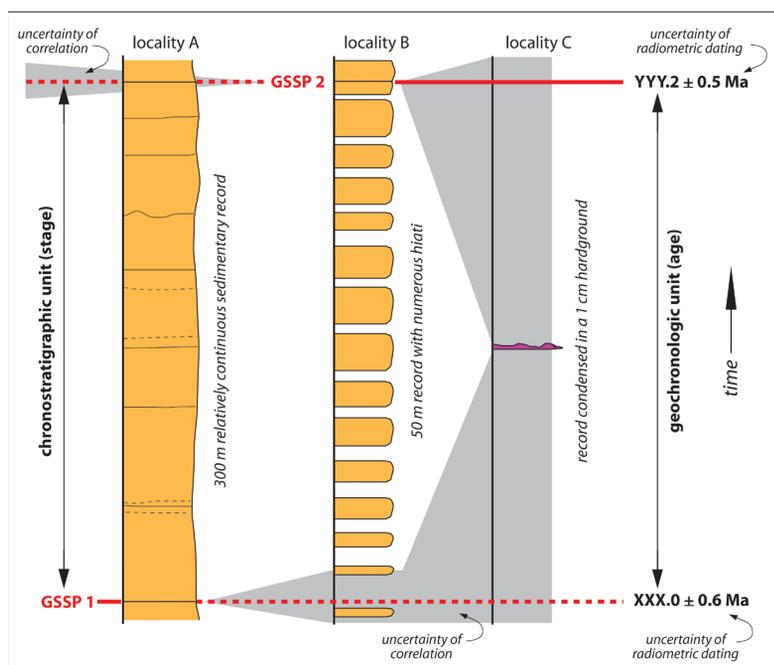


Figure 1. Diagram illustrating the relation of time and rock. Locality A shows a near-continuous succession that includes a GSSP near the base. Locality B shows a succession with sporadic gaps that includes the GSSP of the succeeding time unit near the top. Each of the GSSPs is precisely located at its type section, but there is uncertainty (shown as the gray shading) in locating each away from its respective type section. Locality C shows a highly condensed deposit that is poorly stratigraphically constrained, although best placed within the stage (and thus probably deposited within the age) defined by GSSPs 1 and 2. Radiometric dates provide numerical age estimates for the two GSSPs and hence of the time interval that they define. If taken from immediately adjacent to their respective GSSPs, then the uncertainty relates essentially to the levels of analytical precision obtained; if taken from elsewhere, then uncertainty in correlation/interpolation to the GSSPs is added to the analytical uncertainty.

Neogene”). However, rocks can also be referred to by the time at which they formed (e.g., the Early Ordovician Windfall Formation), but superposition and time terms should not be mixed in the same modifier group, sentence, or paragraph (thus “early Calabrian Stage,” “lower Eocene Epoch,” and “early Upper Ordovician strata” are incorrect). If one is concerned about the proper unit rank term to use or if one is not comfortable using age as the equivalent geochronologic unit for stage, then one can either not use the rank term or use “rock” or “time” instead (e.g., the species evolved in the Hirnantian or during Hirnantian time; the fossil occurrences in the Hirnantian or low in the Hirnantian succession). Although meaning is often clear from context, appropriate usage of chronostratigraphic and geochronologic units can help, for instance, express succinctly the distinction between data and observations and interpretations (e.g., “the successive, closely spaced lowest occurrences of species of *Normalograptus* in the lowest Hirnantian Stage worldwide succeeding the abundant and diverse assemblages of diplograptid-dicellograptid-orthograptid species in the upper Katian Stage reflects a major faunal turnover associated with the Hirnantian glaciation that began in the latest Katian”).

CONCLUSIONS

The scheme outlined in this paper seems a reasonable way to retain the two widely used terms chronostratigraphy and geochronology in both an informal and a formal (classificatory) sense, establishing a clear and practical difference between them more or less in line with current practice and also in line with their etymology. Both parallel sets of units are retained, though there remains the option to adopt either a single (i.e., geochronologic) or a dual hierarchy in particular studies, as considered appropriate. Within the framework proposed here, this question may be allowed to be effectively determined, ultimately, by future majority usage. Nevertheless, clarity and precision of stratigraphic expression seem currently achievable, within the guidelines we suggest.

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