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The Golden Spike Still Glitters: The (Re)construction of a Global Chronostratigraphy

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Introduction

Stratigraphy, placing the sequence of events in Earth history into order, is a fundamental part of the geosciences. Traditionally the starting point is a regional stratigraphy, based on lithological, mappable units, correlated by fossils with local, regional and global chronostratigraphical schemes. Chronostratigraphic units were traditionally defined on their fossil content, as essentially unit stratotypes. But, commonly there were no clear boundaries, the lower and upper parts of units being coincident with major faunal changes such as extinction events that delimited given units. There were problems with this approach and during the latter part of the 1900s, geologists moved towards a more rigorous and robust method of defining chronostratigraphic units based on Global Stratotype Sections and Points (GSSPs), anchored by 'Golden Spikes'. As the stratigraphic column reaches completion with the majority of the stages, series and systems defined by GSSPs, the challenge is now to calibrate the geological timescale and refine the correlations of regional and global stratigraphical schemes. Radiometric dating, isotope curves, magnetostratigraphy and orbital-tuning are providing more accurate and precise methods for correlation, and dating the timescale in absolute terms.

The birth of stratigraphy

Pioneer work by the Danish polymath Nicolaus Steno (1638-1686) in northern Italy, during the late 17th Century, established the obvious fact that older rocks are overlain by younger rocks, if the sequence has not been inverted. His law of superposition of strata is fundamental to all stratigraphic studies. In addition, Steno established in experiments that sediments are deposited horizontally and rock units can be traced laterally, often for considerable distances; remarkably simple concepts to us now, but paradigm shifting at the time. This, however, was preceded by the studies of Leonardo da Vinci (1452–1519) who essentially rediscovered geological perspective, some 200 years before Steno, during the Renaissance. In his drawing of the hills of Tuscany, da Vinci portrayed a clear sequence of laterally continuous, horizontal strata displaying the concept of superposition; he also noted fossil shell beds in some of his sketches.

The organization of rocks

About a century after Steno, Giovanni Arduino recognized, again using superposition, three basically different rocks suites in the Italian part of the Alpine belt. A crystalline basement of older rocks, deformed during the Late Palaeozoic Variscan orogeny, was overlain unconformably by mainly Mesozoic limestones deformed later during the Alpine orogeny; these in turn were overlain unconformably by poorly consolidated clastic rocks, mainly conglomerates. These three units constituted his primary, secondary and tertiary systems; the last term is still used by some for the interval of geological time succeeding the Cretaceous. These three divisions were used widely to describe rock successions elsewhere in Europe showing the same patterns, but these three systems were not necessarily the time correlatives of the type succession in the Apennines. But they needed a time frame. The concept of deep time was provided by James Hutton (1726-1797), while nearly a century later, the role of fossils in stratigraphy was established by William Smith in Britain, and Georges Cuvier and Alexandre Brongniart in France together with Albert Oppel in Germany. William Smith (1769–1839), in the course of his work as a canal engineer in England, realized that different rock units were characterized by distinctive groups or assemblages of fossils. In a traverse from Wales to London, Smith encountered successively younger rocks, and he documented the change from the trilobite-dominated assemblages of the Lower Palaeozoic of Wales through Upper Paleozoic sequences with corals and thick Mesozoic successions with ammonites; finally, he reached the molluscan faunas of the Tertiary strata of the London Basin. In France, a little later, the noted anatomist Georges Cuvier (1769-1832) together with Alexandre Brongniart (1770–1849), a leading mollusc expert of the time, ordered and correlated Tertiary strata in the Paris Basin using series of mainly terrestrial vertebrate faunas, occurring in sequences separated by supposed biological catastrophes. Distinctive lithologies and biotic assemblages would now allow the recognition of a sequence of major stratigraphical units, the systems.

The scramble for systems

Geological time was divided up by the efforts of pioneering British, French and German geologists between 1790 and 1840. The divisions were made first for practical reasons – one of the first systems to be named was the Carboniferous ("coal-bearing"), a unit of rock that early industrialists were keen to exploit. The Cretaceous was established based on the widespread distribution of chalk whereas the Triassic in northern Europe could be split into three distinctive megafacies. Many of the others were based on geographic areas where the systems cropped out or in the case of the Lower Palaeozoic, the proximity to the home of some ancient Welsh tribes.

Some systems were established not without some controversy and rancor. During the 1830s, Roderick Murchison (1792–1871) and Adam Sedgwick (1785–1873) collaborated, and then clashed, over the Lower Palaeozoic. Sedgwick named the Cambrian and Murchison named the Silurian, based on sections in Wales. Each claimed the middle ground for his system, so what Murchison called the "Lower Silurian", Sedgwick called "Upper Cambrian". This territorial claim was resolved later by Charles Lapworth (1842–1920), who agreed with neither of them, and named the contentious rock successions the Ordovician in 1879. In fact, the Ordovician is one of the longest and most lithologically diverse of the geological systems but it was only formally accepted by the international community in 1960. By the mid-1800s a chronostratigraphic framework was in place permitting Darwin (1859) to use palaeontological data to illustrate his theory of evolution and John Phillips to explore the history of life on Earth (Phillips, 1860).

A new age in stratigraphy: The concept and implementation of GSSPs

It became clear, as greater precision was required to correlate events and strata globally, that many of the original boundaries of the geological systems were separated from each other by unconformities (Remane, 2003). For the pioneers, unconformities provided a convenient break between systems and, more importantly, it satisfied their view that the major divisions of Earth's history should be divided by global, catastrophic events. Unfortunately, many of these unconformities turned out to be only regional breaks that occurred in Europe, but not elsewhere. The bases of many systems were represented by stratigraphic gaps, obviously, providing a poor basis for the global correlation of systemic boundaries.

A new approach was required and this was provided by the International Commission on Stratigraphy (ICS). All the system boundaries have been reinvestigated by working groups of the ICS, as have many of the series and stage divisions (Cohen et al., 2013). The potential of each base for international correlation must be maximized, and the bases of these systems must be placed within intervals of continuous sedimentation, with diverse and abundant faunas and floras in geographically and politically accessible areas that can be conserved and protected; ideally the sections should have escaped metamorphism and tectonism and have the potential to use non-biological proxies to aid correlation. The base of a chronostratigraphic interval is defined in a unique stratotype section, in a type area using the concept of a "golden spike" or marker point (Hedberg, 1976). All the usual criteria for a workable stratotype section must, of course, be satisfied (Cowie et al., 1986). The golden spike, which represents a point in the rock section and an instant in geological time, is then driven into the section, at least in theory (Holland, 1986). In reality, the spike is usually adjusted to coincide with the first appearance (FAD) of a distinctive, recognizable fossil within a well-documented lineage, though non-biological markers are also important. The ranges of all fossils occurring across the boundary, together with geochemical and other proxies, are documented in detail as aids to correlating within the section and with sections elsewhere. Establishing stratotypes and golden spikes requires international agreement through the various working groups and subcommissions of the ICS, and that can sometimes be time-consuming and hard to achieve. But, when finally ratified by the IUGS, this horizon will then be the Global Stratotype Section and Point (GSSP) for this unit and reported on the regularly-updated ICS timescale chart (Cohen et al., 2018; Figure 1).

Calibrating the geological timescale

Exciting advances in technology are delivering an improved calibration and correlation of strata; both regional and global-scale divisions at high resolutions can be better linked and the rates of biological and geological processes assessed with greater accuracy. Biological data are commonly matched by chemostratigraphy, cyclostratigraphy and magnetostratigraphy together with high precision absolute dates produced by techniques using new generations of mass spectrometers, sometimes with an accuracy of some 10 kyr. Successions can also be orbitally-tuned using Milankovitch cycles based on eccentricity (variation in the shape of the Earth's orbit from nearly circular to elliptical; 100 kyr cycle), obliquity (wobble of the Earth's axis; 41 kyr cycle) and precession (change in direction of the Earth's axis relative to the sun; 23 kyr cycle). Throughout the stratigraphic record, there are many successions of rhythmically alternating sedimentary beds, for example repeated pairs of limestone and calcareous shales that may have been controlled by Milankovitch processes, although not all modulations may have been constant in deep time. These data, biological and non-biological, can be integrated in the definition and description of chronostratigraphic units. The recent establishment of the GSSP for the Chattian Stage (Paleogene System) is an elegant exemplar (Coccioni et al., 2018).

It is now possible to provide such integrated stratigraphies for an entire country. Shen and Rong (2019) have amassed and integrated all available stratigraphic data from China and compiled these from the Ediacaran to Quaternary in a landmark publication. The reconstruction of the geological timescale is only the start.

Key words: Stratigraphy, biostratigraphy, GSSPs, Milankovitch cycles, timescale

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Fig. 1. The International Chronostratigraphic Chart, 2018, version 8 (Cohen et al., 2018).

INTERNATIONAL CHRONOSTRATIGRAPHIC CHART

www.stratigraphy.org — International Commission on Stratigraphy — v 2018/08

IUGS

Eonothem / Eon	Erathem / Era	System / Period	Series / Epoch	Stage / Age	numerical age (Ma)
					present
Phanerozoic	Cenozoic	Quaternary	Holocene	U/L Meghalayan	0.0042
				M Northgrippian	0.0082
				L/E Greenlandian	0.0117
			Pleistocene	*Upper*	0.126
				Middle	0.781
				Calabrian	1.80
				Gelasian	2.58
		Neogene	Pliocene	Piacenzian	3.600
				Zanclean	5.333
			Miocene	Messinian	7.246
				Tortonian	11.63
				Serravallian	13.82
				Langhian	15.97
				Burdigalian	20.44
				Aquitanian	23.03
		Paleogene	Oligocene	Chattian	27.82
				Rupelian	33.9
			Eocene	Priabonian	37.8
				Bartonian	41.2
				Lutetian	47.8
				Ypresian	56.0
			Paleocene	Thanetian	59.2
				Selandian	61.6
				Danian	66.0
	Mesozoic	Cretaceous	Upper	Maastrichtian	72.1 ±0.2
				Campanian	83.6 ±0.2
				Santonian	86.3 ±0.5
				Coniacian	89.8 ±0.3
				Turonian	93.9
				Cenomanian	100.5
			Lower	Albian	~ 113.0
				Aptian	~ 125.0
				Barremian	~ 129.4
				Hauterivian	~ 132.9
				Valanginian	~ 139.8
				Berriasian	~ 145.0

Eonothem / Eon	Erathem / Era	System / Period	Series / Epoch	Stage / Age	numerical age (Ma)
					~ 145.0
Phanerozoic	Mesozoic	Jurassic	Upper	Tithonian	152.1 ±0.9
				Kimmeridgian	157.3 ±1.0
				Oxfordian	163.5 ±1.0
			Middle	Callovian	166.1 ±1.2
				Bathonian	168.3 ±1.3
				Bajocian	170.3 ±1.4
				Aalenian	174.1 ±1.0
			Lower	Toarcian	182.7 ±0.7
				Pliensbachian	190.8 ±1.0
				Sinemurian	199.3 ±0.3
				Hettangian	201.3 ±0.2
		Triassic	Upper	Rhaetian	~ 208.5
				Norian	~ 227
				Carnian	~ 237
			Middle	Ladinian	~ 242
				Anisian	247.2
			Lower	Olenekian	251.2
				Induan	251.902 ±0.024
	Paleozoic	Permian	Lopingian	Changhsingian	254.14 ±0.07
				Wuchiapingian	259.1 ±0.5
			Guadalupian	Capitanian	265.1 ±0.4
				Wordian	268.8 ±0.5
				Roadian	272.95 ±0.11
			Cisuralian	Kungurian	283.5 ±0.6
				Artinskian	290.1 ±0.26
				Sakmarian	293.52 ±0.17
				Asselian	298.9 ±0.15
		Carboniferous – Pennsylvanian	Upper	Gzhelian	303.7 ±0.1
				Kasimovian	307.0 ±0.1
			Middle	Moscovian	315.2 ±0.2
			Lower	Bashkirian	323.2 ±0.4
		Carboniferous – Mississippian	Upper	Serpukhovian	330.9 ±0.2
			Middle	Visean	346.7 ±0.4
			Lower	Tournaisian	358.9 ±0.4

Eonothem / Eon	Erathem / Era	System / Period	Series / Epoch	Stage / Age	numerical age (Ma)
					358.9 ± 0.4
Phanerozoic	Paleozoic	Devonian	Upper	Famennian	372.2 ±1.6
				Frasnian	382.7 ±1.6
			Middle	Givetian	387.7 ±0.8
				Eifelian	393.3 ±1.2
			Lower	Emsian	407.6 ±2.6
				Pragian	410.8 ±2.8
				Lochkovian	419.2 ±3.2
		Silurian	Pridoli		423.0 ±2.3
			Ludlow	Ludfordian	425.6 ±0.9
				Gorstian	427.4 ±0.5
			Wenlock	Homerian	430.5 ±0.7
				Sheinwoodian	433.4 ±0.8
			Llandovery	Telychian	438.5 ±1.1
				Aeronian	440.8 ±1.2
				Rhuddanian	443.8 ±1.5
		Ordovician	Upper	Hirnantian	445.2 ±1.4
				Katian	453.0 ±0.7
				Sandbian	458.4 ±0.9
			Middle	Darriwilian	467.3 ±1.1
				Dapingian	470.0 ±1.4
			Lower	Floian	477.7 ±1.4
				Tremadocian	485.4 ±1.9
		Cambrian	Furongian	*Stage 10*	~ 489.5
				Jiangshanian	~ 494
				Paibian	~ 497
			Miaolingian	Guzhangian	~ 500.5
				Drumian	~ 504.5
				Wuliuan	~ 509
			Series 2	*Stage 4*	~ 514
				Stage 3	~ 521
			Terreneuvian	*Stage 2*	~ 529
				Fortunian	541.0 ±1.0

Eonothem / Eon	Erathem / Era	System / Period	numerical age (Ma)
			541.0 ±1.0
Precambrian – Proterozoic	Neoproterozoic	Ediacaran	~ 635
		Cryogenian	~ 720
		Tonian	1000
	Mesoproterozoic	Stenian	1200
		Ectasian	1400
		Calymmian	1600
	Paleoproterozoic	Statherian	1800
		Orosirian	2050
		Rhyacian	2300
		Siderian	2500
Precambrian – Archean	Neoarchean		2800
	Mesoarchean		3200
	Paleoarchean		3600
	Eoarchean		4000
Precambrian – *Hadean*			~ 4600

Units of all ranks are in the process of being defined by Global Boundary Stratotype Section and Points (GSSP) for their lower boundaries, including those of the Archean and Proterozoic, long defined by Global Standard Stratigraphic Ages (GSSA). Charts and detailed information on ratified GSSPs are available at the website http://www.stratigraphy.org. The URL to this chart is found below.

Numerical ages are subject to revision and do not define units in the Phanerozoic and the Ediacaran; only GSSPs do. For boundaries in the Phanerozoic without ratified GSSPs or without constrained numerical ages, an approximate numerical age (~) is provided.

Ratified Subseries/Subepochs are abbreviated as U/L (Upper/Late), M (Middle) and L/E (Lower/Early). Numerical ages for all systems except Quaternary, upper Paleogene, Cretaceous, Triassic, Permian and Precambrian are taken from 'A Geologic Time Scale 2012' by Gradstein et al. (2012), those for the Quaternary, upper Paleogene, Cretaceous, Triassic, Permian and Precambrian were provided by the relevant ICS subcommissions.

Colouring follows the Commission for the Geological Map of the World (http://www.ccgm.org)

CCGM CGMW

Chart drafted by K.M. Cohen, D.A.T. Harper, P.L. Gibbard, J.-X. Fan

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