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Cutting Time in slices☆

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ABSTRACT

During the 18th and 19th centuries, the conquest of deep time emerged as a pivotal achievement when geologists recognized that the age of rocks far exceeded earlier age estimates and exhibited a systematic order of deposition. Geological processes were reframed within an immense temporal framework, prompting efforts to identify and correlate strata worldwide using field-observable discontinuities and lithological traits. As Earth's antiquity became accepted, it also became clear that rock layers preserved records of countless biological and geological events. Biological markers—fossils—offered the most reliable data, but stratigraphers debated whether abrupt changes (catastrophism) or gradual processes (uniformitarianism) should define time slices. They refined biozonation by evaluating species' first and last appearances, ranges, abundance, and geographic distributions. Despite sophisticated biostratigraphic schemes, such subdivisions lacked numerical precision. Only with the discovery of radioactivity and development of radioisotopic dating could geologists assign numerical ages to strata, transforming the geological time scale from a relative framework into one anchored by numerical dates. This breakthrough established a rigid time grid, populated by formally defined periods, epochs, and ages, and with dates geologists could establish the rates of biological and geological processes. Later techniques introduced chemical signatures, magnetic reversal records, and orbital cyclicity as new correlation tools. Today, stratigraphers integrate these diverse markers while continually subdividing intervals to enhance the precision, exactness, and reliability of the Phanerozoic timescale. This multifaceted approach promises even more accurate correlations. By dividing time into thinner intervals and uniting various stratigraphical disciplines, geologists are moving towards a global and finely resolved chronostratigraphic framework.

Our aim is to synthesize the principal developments that have shaped the conceptualization of geological time, with the purpose of establishing a rigorous foundation for future advances in the subdivision and quantification of temporal intervals.

> *"Alice: How long is forever? White Rabbit: Sometimes, just one second."*
> Lewis Carroll, Alice in Wonderland.

1. The idea of Time

The idea of interrogating time is certainly not original. There is a long list of authors who have discussed the concept of time. Among the myriad of published papers (see, among others, Albritton Jr., 1980; Gould, 1987; Rudwick, 2005, 2014), the book by Holland (1988) remains a landmark publication. In a series of chapters, he explores the various concepts of time, from art to cosmology and even to philosophy and religion. This multifaceted approach, however, is not surprising, as Holland simply applied the original holistic concept of "science" that had persisted for centuries. From the Latin "*scientia*" (= knowledge), science reflects the unitarian concept of knowledge derived from classical antiquity to the Middle Ages, which then persisted until the 19th century, according to which any distinction between the various disciplines was a key part of natural philosophy, considered the perfect science (Battaglia, 1961–2002, 2004, 2009). It was only later, in the Modern Period, that science was split into many separate fields.

The human idea of time is dictated by observable life cycles. Sunrise

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Fig. 1. A hillside with an outcrop of stratified rock (Leonardo da Vinci, ca. 1510–1513). Royal Collection of the United Kingdom.

and sunset represent the most immediate biological clock, annual rhythms are recorded in incremental growth of animals and trees, and a life span is the extreme unit we can use to estimate time. When we deal with longer time frames, such as deep time, we are inevitably lost as we feel unable to measure it by any human scale. As eloquently expressed by Gould (1987, p. 3):

> "*Deep time is so alien that we can really only comprehend it as metaphor.*"

The way we perceive the passage of time varies from person to person, conditioned and delimited by the subjective nature of personal experience. In addition, and surprisingly, we are trained to conform to the perception of time. Before 18 months, children can appreciate just a simple sequence of actions. Memory of ordering of events gradually improves with age, so that annual patterns of events can be fully understood and accepted in six-years old children. This is reflected as well in the language of children, with verbs that begin at that age to be used also in the past and future tenses. Only beginning at eight years, is it possible to be conscious of historical time (Holland, 1988). Accordingly, history text-books for our children are strictly based on their ability to fully understand the proper idea of time.

There is a fundamental difference in the scales of memory and history. As individuals, we tend to remember our parents, perhaps our grandparents, but rarely those who came before. Our memories are shaped by personal experiences and the stories passed down to us, events from our own childhood or those recounted by our parents. World War II still lives in the memories of many older people, while the recollections of World War I are gradually fading. The Napoleonic Wars have long since become the domain of historians. Ancient civilizations like those of Rome and Greece endure through their architectural remains and written records. And beyond all of these lies a vastly different scale: geological time, whose events, spanning millions of years, are almost impossible to grasp within the limits of a human lifespan.

2. The witnesses of Time

2.1. From Time to Times

The discovery of a past before historical time arrived with the recognition of fossils as witnesses of ancient life on the Earth. Times past, in other words, were frozen inside rocks.

Leonardo da Vinci (1452–1519), among others, clearly understood that the marine shells that he found high in the Italian mountains were remains of marine animals which once lived there. He had received an instruction characterized by pervasive interaction and mutual contamination between Mathematics, Art, Music, Engineering and Natural Sciences (Ferretti et al., 2020). Consequently, Leonardo's geological perspective surfaces in his drawings and paintings (Fig. 1), with a realistic representation of layers and stratifications, and his writings outline, perhaps in an embryonic way, all the fundamentals of stratigraphy (Vai, 2007; Ferretti et al., 2020).

During the Renaissance, the Biblical account of Genesis was widely accepted as truth. It was commonly believed that all species of plants and animals existing on Earth had remained unchanged since their divine Creation. Fossilized shells found in mountainous regions were interpreted as evidence of the Great Flood, thought to be the remains of creatures drowned during this universal Deluge (far from being exclusive to European or Christian narratives, the motif of a Great Flood is a recurring element in the mythologies and historical traditions of numerous ancient cultures: similar flood accounts are found in Chinese, Mesopotamian, Indian, and Mesoamerican traditions). Any unusual natural events, such as earthquakes or meteor showers, were seen as catastrophic disruptions to Nature's usual order, acts of divine punishment inflicted by God (De Lorenzo, 1920). Leonardo challenged the idea of the Great Flood using a variety of arguments, including a straightforward physical observation: if such a flood had truly been universal, it would have covered the entire surface of a spherical Earth with water at a consistent altitude. This would result in a perfectly level surface, leaving no gradient for the water to flow downward, an inconsistency that undermines the plausibility of the Deluge. He also added that such an event would leave behind a single, uniform fossil layer. Instead, the existence of fossils embedded in multiple, superimposed strata indicates that their deposition occurred at different times, successively, rather than as the result of a single catastrophic event. Furthermore, Leonardo described how rivers have carved through and separated the great Alpine formations, a fact evident in the alignment of stratified rock layers: from the mountain peaks down to the riverbanks, the strata on one side of the river match those on the opposite side. He explained that the layered rock beds, referred to as "*pietre faldate*", were formed by

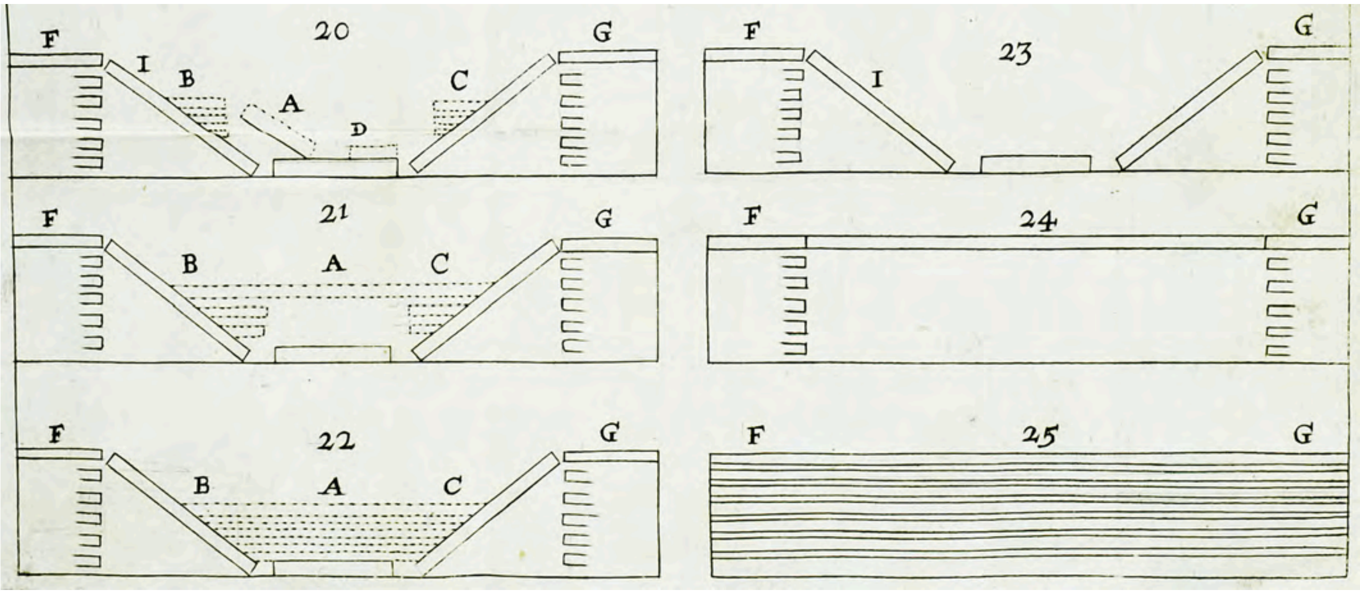


Fig. 2. The six transformations of Tuscany, with State 25 representing the earliest phase and State 20 denoting the most recent (Steno, 1669). Courtesy of The Linda Hall Library of Science, Engineering and Technology.

successive deposits of various types of mud, each laid down by different flooding events. The varying thicknesses of these layers, he noted, reflect the intensity of the floods, some more severe, others more minor. Furthermore, Leonardo pointed out that marine mud still contained fossilized snails, preserved together with the sediment in which they were buried when alive (Ferretti et al., 2020).

The rocks had therefore revealed a succession of events in the history of the Earth, documenting diverse and distinct ages, instead of simply being the result of one instant of creation, occurring in a single time. Fossils and minerals were the primary constituents within layers, recording many separate episodes. It became therefore imperative to organize the deposition of geological strata in a coherent manner.

2.2. *The order of Time*

Niels Stensen (1638–1686), known in Latin as Nicolaus Steno, is universally celebrated for having introduced a set of geometric principles that laid the foundation for ordering sedimentary rock layers chronologically (Morello, 2003, 2006). The Danish polymath had a medical degree and was a brilliant anatomist, contributing to studies of the muscular system and brain and providing critical revisions of the anatomical models proposed by Galen and Descartes (Bek-Thomsen, 2013). He later was deeply involved in scientific problems, specifically those concerning the shaping of the Earth, driven by a theological motivation to uncover evidence of divine design in the natural world. Steno travelled extensively throughout Europe during his lifetime with the patronage of Grand Duke Ferdinando II, but his most significant contribution to the history of stratigraphy was made in Florence, the same city of Leonardo, where Steno had the opportunity to study rock formations shaped by fluvial erosion in the surrounding region. These observations led him to formulate the four fundamental principles of stratigraphy (Steno, 1669), with “strata” being the Latin term for sedimentary layers or beds: original horizontality, lateral continuity, superposition and cross cutting relationships. Sedimentary layers are originally deposited in a horizontal or nearly horizontal position (Principle of original horizontality). Layers of sediment initially extend laterally in all directions until they thin out or encounter a physical barrier (Principle of lateral continuity). In an undeformed sequence of sedimentary rocks, the oldest layers are at the bottom, and the layers become progressively younger towards the top (Principle of superposition). Any geological feature (like a fault or intrusion) that cuts across a sequence of rocks must be younger than the rocks it disrupts (Principle of cross cutting relationships). These principles laid the groundwork for modern stratigraphy and geological time interpretation. He also stated (Steno, 1667):

> “*At what time there was formed any Bed, the matter incumbent on it was all fluid, and by consequence, when the lowest Bed was laid, none of the upper Beds was extant.*”

Steno summarized the geological evolution of Tuscany and the relationship between strata with the support of six well-known simplified but extremely effective geological sections from the Arno River valley (Fig. 2), where he illustrated the evolution of a sequence with age increasing from State 20 to State 25 (Steno, 1669). Owing to his religious background, Steno sought to demonstrate that there was no fundamental conflict between empirical observations of the natural world and the accounts presented in the Bible. The central question concerned how biblical descriptions could be interpreted in light of empirical observations made in the natural world (Bek-Thomsen, 2013). Steno proposed that during the time of Genesis, the Earth was entirely submerged under water, allowing sediments to accumulate and form horizontal strata through natural depositional processes (State 25). As the waters receded and eventually disappeared, the sedimentary strata remained in place, while voids and cavities formed beneath them by the action of fire, running water and escaping gases (State 24). As these subsurface cavities caused the overlying strata to collapse, the resulting deformation gave rise to mountains and valleys, with the uppermost layers remaining preserved at the top of the newly formed valleys (State 23). Subsequently, the Universal Deluge once again submerged the Earth, leading to the deposition of new sedimentary layers within the previously formed valleys (State 22). As the waters receded, the earlier process repeated: cavities developed beneath the now-exposed upper strata, causing structural collapse. This sequence of events contributed to the formation of hills within the mountainous valleys (States 21 and 20) (Bek-Thomsen, 2013). However, these six successive facies changes in the geological history of Tuscany should not be read as a strict religious dictate, but could be possibly revisited in a modern geological perspective as evidence of transgressions (States 25 and 22), and regressions (States 23 and 20) (Vai, 2021).

The notable convergence between Steno’s and Leonardo da Vinci’s interpretations of stratigraphical processes, despite being separated by over 150 years, likely reflects both the abundance and accessibility of

Fig. 3. A, Cliffs of folded and faulted lower Llandovery rocks on the approach to Siccar Point, Berwickshire. The cliffs are about 70 m high. B, A view of the unconformity from the sea, the exposure first apparent to James Hutton together with James Hall and John Playfair on their boat trip in 1788. The path leading down to site is in the background. C, Classic on-land view of the unconformity, steeply inclined lower Llandovery marine strata overlain with an angular discordance by Upper Devonian terrestrial strata. Metre stick for scale. Photos courtesy of David A.T. Harper.

well-exposed geological outcrops in Tuscany, and Florence's unique intellectual environment. Under the patronage of the Medici family, the city emerged as a major hub of Renaissance thought, where scientific inquiry, artistic innovation, and humanistic scholarship were actively supported and integrated with figures such as Galileo Galilei, whom they appointed as court mathematician and philosopher. In addition, the family established institutions like the Accademia del Cimento (1657), one of the first scientific societies in Europe and in the World dedicated to empirical science.

This environment fostered a unique culture of experimental observation and interdisciplinary exchange, which likely influenced both Leonardo's and Steno's geological insights and contributions.

2.3. *The pioneers of Time*

New ideas and groundbreaking theories seldom emerge instantaneously. Their acceptance can, in nearly all cases, be traced to germinal ideas embedded within earlier frameworks.

Thomas Burnet (?1635–1715) proposed in his "*Telluris Theoria Sacra, or Sacred Theory of the Earth*" (first part published in 1681 in Latin, the second in 1689 in English) a scientific approach to explain the formation of the Earth. The work aimed to reconcile the biblical account of Creation with the scientific theories of its time. Burnet (1681–1689) proposed that the Earth was originally hollow, containing subterranean waters that erupted during the Great Flood, thereby forming the oceans and shaping the mountains. According to Burnet the Earth had been modifying from a past (including Creation, Eden, and the Flood) towards a future, marked by a final conflagration and the emergence of new heavens and a new Earth.

William Whiston (1667–1752), better known as Assistant and later successor of Isaac Newton in Cambridge, published "*A New Theory of the Earth*" (Whiston, 1696). He attributed the origin of the Earth and its successive modifications, including the Universal Deluge, to the action of comets. In his interpretation, the Earth was already in existence before the Creation, and God acted as a sort of director, adapting the Earth as a habitable planet to mankind. Such ideas were extremely dangerous, particularly because Whiston acknowledged the existence of a past preceding what had traditionally been considered the point of origin of the Universe. Furthermore, the biblical stories of Creation, the Flood, and the final destruction could be understood scientifically as accounts based on real historical events. In 1710 Whiston was dismissed from his professorial post and subsequently expelled from the university due to the heterodox nature of his religious convictions.

2.4. The conquest of Time

The discovery that there was a past before history gradually gave rise to what Holland (1988, p. 53) defined a "*growing sense of geological time*". And it was James Hutton (1726–1797), a Scottish doctor who never practiced medicine but instead devoted much of his life to innovative farming and industrial methods, who discovered the dimension of time. He was a key participant in the Scottish Age of Enlightenment, and understood that geological processes acting today, though often imperceptible on human timescales, yet significant cumulatively, operate by the same mechanisms and at comparable rates as those in Earth's past. This concept, later named "uniformitarianism" (see below), was a monumental achievement, displacing the catastrophic theories and extraordinary events, such as the Great Flood, long invoked to explain anomalies in Earth's natural processes. In his "*Theory of the Earth*" (Hutton, 1788), he writes what is probably the most famous citation on the duration of time:

> "*Here are three distinct successive periods of existence, and each of these is, in our measurement of time, a thing of indefinite duration.... The result, therefore, of this physical inquiry is, that we find no vestige of a beginning, no prospect of an end.*"

Applying this framework to stratigraphical sequences led to the perception that the formation of exposed rock layers necessitates great expanses of time and rocks could be much older than previously supposed (Fig. 3). In this way, geological processes could be understood within the vastness of time. Despite Hutton's brilliant insight, it was not until the work of Charles Lyell (1797–1875), summarized in the well-known words "*the present is the key to the past*", that the concept gained widespread acceptance within the scientific community.

Two essential points nevertheless deserve attention. The common attribution of the term "uniformitarianism" to either Charles Lyell or his predecessor James Hutton is misleading, as the term was actually coined by William Whewell (1832) and was neither used nor referenced by Lyell himself (Romano, 2015). Whewell identified uniformitarianism as a core principle underpinning Lyell's theoretical framework, particularly the idea that natural processes operate at consistent rates and intensities over time. This stood in direct opposition to the notion that Earth's major structural changes occurred during brief, violent episodes, a view central to catastrophism. According to Whewell, these contrasting perspectives effectively split geologists into two camps: "the Uniformitarians and the Catastrophists" (Whewell, 1832, p. 126), establishing a foundational dichotomy that continues to shape geological discourse to this day (Romano, 2015). Nevertheless, this apparent dichotomy should be approached with caution. According to Gould (1987, p. 113):

> "*In textbook cardboard, Georges Cuvier is Lyell's catastrophist enemy. He accepts the biblical chronology (or at least an earth of very short duration); he advocates the total extirpation of life (and its subsequent miraculous recreation) at each catastrophe; he works, probably consciously, for the church against science. What a vulgar misinterpretation! Cuvier, perhaps the finest intellect in nineteenth-century science, was a child of the French Enlightenment who viewed dogmatic theology as anathema in science. He was a great empiricist who believed in the literal interpretation of geological phenomena… His earth, though subject to intermittent paroxysm, was as ancient as Lyell's. He argued that many faunal changes following catastrophes represented migrations of preexisting biotas from distant areas. The real debate between Lyell and Cuvier, or of uniformity and catastrophism, was a grand scientific argument of substance-and its main subject was time's arrow and time's cycle.*"

Finally, fully aware of the associated risks, Lyell never attempted to give an indication of the vastness of geological time; he had deliberately resisted the temptation to give a numeric value to geological time, just as he had avoided the term "infinite" (Burchfield, 1974).

2.5. From rocks to Time

In his multifaceted contributions to science, Georges-Louis Leclerc, Comte de Buffon (1707–1788), proposed in the first edition of his "*Histoire Naturelle*" (Leclerc and Comte de Buffon, 1749–1789) that the planets were formed from molten matter ejected by the sun, whose heat inevitably diminished over time. It was during this fluid state that the planets assumed their circular shapes.

This idea bordered on blasphemy in two significant ways, each striking at the heart of prevailing theological and cosmological beliefs of the time. First, Buffon's theory effectively removed the divine hand from the act of Creation. By suggesting that the planets originated by a purely physical and mechanical process, he challenged the notion of a purposeful, supernatural genesis. In this view, the universe was not the result of a deliberate act by a Creator, but rather the outcome of natural forces governed by physical laws. This mechanistic explanation undermined centuries of religious doctrine that placed God at the center of cosmic creation. Second, Buffon proposed that the Earth's formation was not instantaneous but occurred over an extended period, and that the Earth might be older than previously thought. This contradicted the biblical account in Genesis, which described the Creation of the world as a series of divine acts completed within six days (Roberts, 2024).

Buffon went even further. His model implied a slow, gradual evolution of planetary bodies, shaped by cooling, solidification, and natural transformation, including also their death. Similarly, he envisioned a continuous chain of living creatures, a sort of *continuum*, whose defining essence lays in reproduction, the capacity of one generation to give rise to the next (Roberts, 2024). In this view, individuals were not linked spatially, but temporally, forming a lineage that unfolded through time rather than existing side by side. The great actor of this transformation was time itself (Hoquet, 2010). As he wrote in the sixth volume of his "*Histoire naturelle*":

> "*… le grand ouvrier de la Nature est le Temps: comme il marche toujours d'un pas égal, uniforme & réglé, il ne fait rien par sauts: mais par degrés, par nuances, par succession, il fait tout; & ces changemens, d'abord imperceptibles, deviennent peu à peu sensibles, & se marquent enfin par des resultats auxquels on ne peut se méprendre (= The great worker of Nature is Time: as it always moves with an equal, uniform, and regulated pace, it does nothing by leaps; but by degrees, by nuances, by succession, it does everything. And these changes, at first imperceptible, gradually*

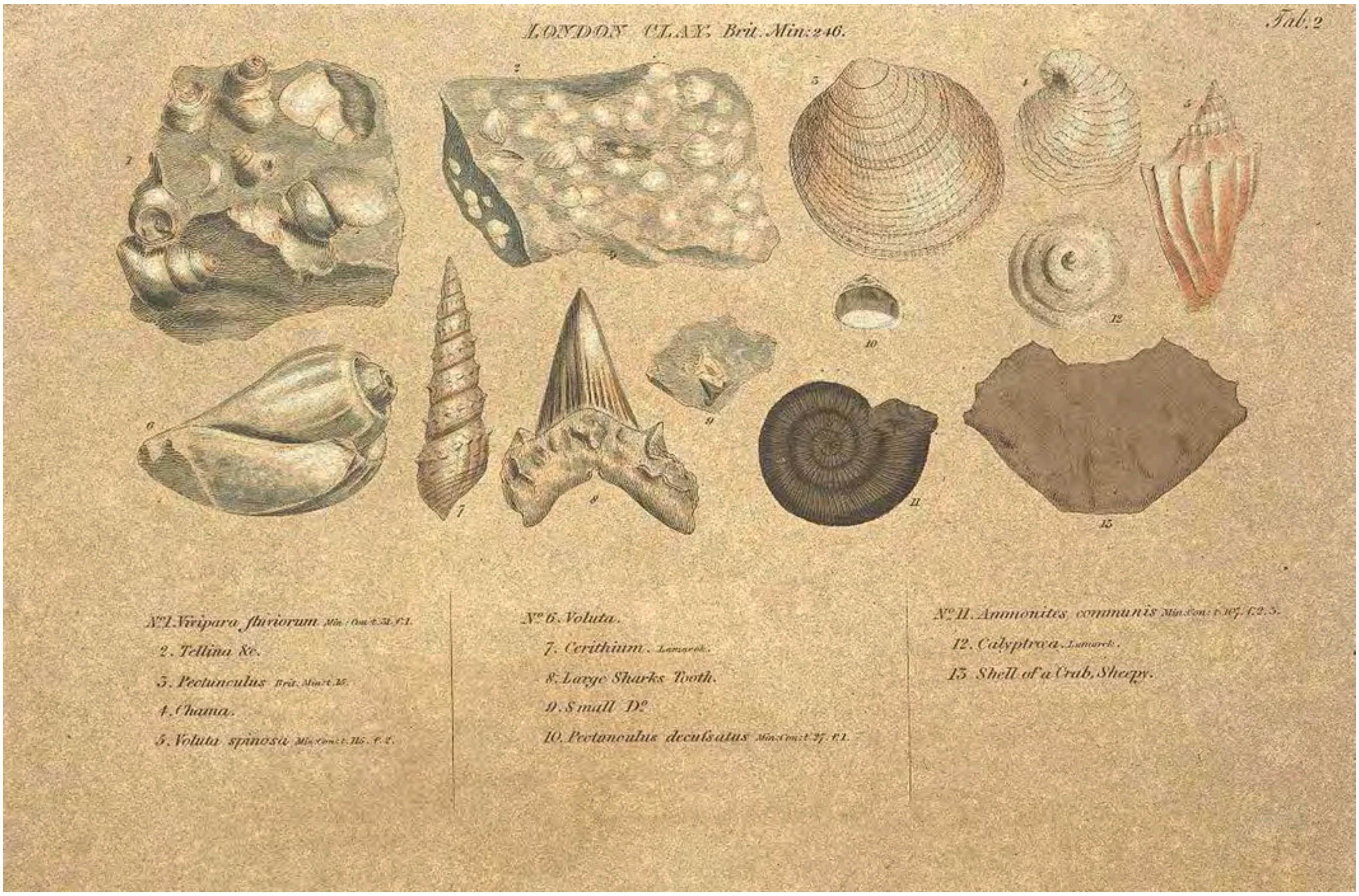


Fig. 4. Commencing in 1816, Smith worked on his main paper "*Strata Identified by Organized Fossils*", a type of manual for recognizing England's sedimentary horizons by their fossil assemblages. This work included colour-coded plates, each tinted to match the stratum's tone, with detailed illustrations of the marker fossils found in those layers. Examples shown are from the Eocene London Clay.

become noticeable, and finally are marked by results that cannot be mistaken)" (Buffon, 1756, vol. 6, p. 60).

We were finally ready to move from rocks to time, with the inclusion of life.

3. The main players in Time

3.1. Fossils in Time

Steno's principles long provided stratigraphy's theoretical foundation, but its first practical applications did not appear until the mid–18th century, when Lehmann (1756) and Füchsel (1761, 1773) documented sedimentary successions in Thuringia and Saxony. Füchsel introduced the Latin term strata, which entered English geological usage through Hutton's "*Theory of the Earth*" (Hutton, 1788), Smith's "*Strata Identified by Organized Fossils*" (Smith, 1816–1819), Lyell's three-volumes "*Principles of Geology*" (Lyell, 1830–1833), and Phillips's "*Treatise on Geology*" (Phillips, 1837–1839) (Ferretti et al., 2020).

However, a satisfactory system for classifying strata, essential for reconstructing the sequence of events, was still needed, and this could only be achieved through the use of fossils (see also Harper, 2024).

William "Strata" Smith (1769–1839) directly applied "organized fossils" to recognize strata, order them within a succession and correlate them across regions. According to Torrens (2001), Smith was more a man of action rather than a theoretical scientist. Starting with canal surveys in the 1790s and early 1800s, during the initial phases of the Industrial Revolution, he noted that each sedimentary layer yielded a

Fig. 5. View of the chalk escarpment of the South Downs. Taken from the Devil's Dike, looking towards the west and south-west (Lyell, 1830–1833).

distinctive fossil assemblage, allowing him to distinguish beds even when their rock type looked similar. Smith's extensive fossil collection, much of which survives in the Natural History Museum in London, is a tribute to his capture of specimens while surveying canals for the transport of raw material, including coal and metallic ores, and finished products such as steel (Torrens, 2001). In 1815, he published the first geological map covering England, Wales, and parts of Scotland, colour-coding 27 stratigraphical units based on their characteristic fossils. Smith (1816–1819) later introduced formal guidelines for using index fossils, such as ammonoids, bivalves, gastropods, sharks' teeth and even plants (Fig. 4), to correlate layers regionally and reconstruct the chronological order of geological events. Smith's pioneering work demonstrated that fossil content, rather than lithology alone, provided a reliable, reproducible framework for arranging strata and interpreting Earth's history.

3.2. The evolution of Time

The idea of evolution was quickly advancing. Not only geological processes were wrestling with time: Darwin finally introduced the dimension of time also in biological processes. However, time was more an embarrassment than an aid to his theory. Darwin himself was deeply concerned about the lack of available time to explain necessary modifications to generate new species and regarded this issue as one of the major criticisms of his model (Burchfield, 1974). He was impressed with the slow rate of erosion of the land and the great thickness of sedimentary formations. Using only this parameter, he had developed one of the examples mentioned by Lyell in his "*Principles of Geology*" and attempted to calculate the amount of time needed to erode the Weald in the South of England (Fig. 5), arriving at a value of 306,662,400 years in the first edition of the "*On the Origin of Species*" (Darwin, 1859). Subsequently, in the second edition published only one month after the first, Darwin proposed a moderate rephrasing and completely removed any indication of a numerical estimation of geological time in the third edition published in April 1861.

However, that estimate triggered a strong critique, both by geologists and non-geologists. John Phillips, Professor of Geology at Oxford and President of the Geological Society, by comparing the action of a similar river in the tropics like that driving the erosion of the Weald, calculated that 1.3 million years or even less could have been a more reasonable time frame (Phillips, 1860).

Whatever the approach, the Earth was necessarily becoming older than previously supposed, but what was the precise age of the Earth? The date for Creation (October 23rd, 4004 BC) as calculated by Archbishop James Ussher (1650), reading the Bible as a sequence of events, could no longer be accepted.

3.3. The brevity of Time

As often happens, major debates spark lively discussions that split people into two conflicting camps. The Cambrian-Silurian Dispute in 19th Century Geology, perhaps the most famous geological dispute of the time, brought Adam Sedgwick (1785–1873) and Roderick Impey Murchison (1792–1871) into direct conflict, and was only resolved posthumously when Charles Lapworth (1842–1920) introduced the Ordovician System in 1879 as a solution to the impasse (Thackray, 1976; Harper et al., 2023). Even the attempt to measure the age of the Earth resulted in an animated discussion between geologists on one side, that were using biological evolution, sedimentation rates and recurrence of volcanic eruptions as geochronometric markers, and physicists on the other hand by means of physical parameters, primarily the slow cooling down of the Planet from a primordial molten Earth as previously indicated by Leibnitz (1646–1716). Following experiments by Buffon who was measuring the time taken for cannonballs to cool down, it was William Thomson (1824–1907), later Lord Kelvin, who polarized opinion (Poirier, 2017). His first estimation of the age of the Earth of 98 million years was more cautiously bracketed in a range of 20–400 million years (Thomson, 1863). However, this and his subsequent publications mostly opposed the idea of uniformitarianism, as constant geological processes contradicted thermodynamic laws, but consequently indicated the need to shorten Earth's estimated age. According to Kelvin (Thomson, 1868, p. 1):

"*a very earnest effort was made by geologists, at the end of last century, to bring geology within the region of physical science … The necessity for* more time *to account for geological phenomena than was the generally supposed to be necessary, became apparent* (p. 24) ... *I shall conclude by simply referring to calculations regarding the quantity of heat at present conducted out from the interior of the earth … the present rate of increase of underground temperature could not last for twenty or thirty thousand million years, without there being dissipated out of the earth as much heat as would be given off by a quantity of ordinary surface rock equal to 100 times the earth's mass, cooling from 100° cent. to 0° … the present condition implies either a heating of the surface, within the last 20,000 years of as much as 100 degrees, Fahr., or a greater heating all over the surface at some time farther back than 20,000 years. Now, are geologists prepared to admit that at some time within the last 20,000 years there has been all over the earth so high a temperature as that? I presume not; no geologist—*no modern *geologist—would for a moment admit the hypothesis that the present state of underground heat is due to a heating of the surface at so late a period as 20,000 years ago. If that is not admitted we are driven to a greater heat at some time more than 20,000 years ago. A greater heating all over the surface than 100 degrees, Fahr., would kill nearly all existing plants and animals, I may safely say. Are modern geologists prepared to say that all life was killed off the earth 50,000, 100,000, or 200,000 years ago? For the uniformity theory, the farther back the time of high surface temperature is put the better; but the farther back the time of the heating, the hotter it must have been …* (p. 25) *And when finally we consider underground temperature we find ourselves driven to the conclusion in every way, that the existing state of things on the earth, lie on the earth, all geological history showing continuity of life, must be limited within some such period of past time as one hundred million years.*"

The physician Peter Guthrie Tait (1831–1901) reinforced Kelvin's conclusions (Tait, 1869), arguing that geological methods alone were entirely insufficient to solve the problem. He asserted that Kelvin's only possible error was in granting geology every benefit of the doubt, and claimed that examining the data more rigorously would drive the age estimate down to at most 10 or 15 million years (Burchfield, 1974, 1998).

The strong personality of Kelvin, supported by numerical arguments, resulted that in less than ten years, Lyell's notion of boundless time had shrunk to the finite limits calculated by Kelvin's approach (Burchfield, 1974). As had happened with Sedgwick and Murchison, the impasse was ended by a third party, specifically Arthur Holmes's revelation of radioactivity at the beginning of the 20th century. The discovery of radioactivity by Henri Becquerel (1852–1908) and the successive application of X-rays in detecting new elements by Wilhelm Conrad Röntgen (1845–1923), Marie Skłodowska-Curie (1867–1934) and Pierre Curie (1859–1906) opened up an entirely new field of research. Rutherford and Soddy (1902a, 1902b) had revealed that radioactive decay transformed a radium atom into radon, releasing contemporaneously a helium atom. That process, according to the ongoing studies run by Curie and Laborde (1903), was associated with release of energy in the form of heat. That was a turning point, demonstrating that at the same time the Earth was cooling, its internal radioactive elements produced enough heat to extend that cooling far beyond geologists' and physicists' estimates, and geological time assumed an entirely new dimension (Lewis, 2001).

The following discovery that every radioactive element decays at a constant, measurable rate, opened the door to the use of radioactivity in measuring time, and the first tentative radioisotopic dating of a fergusonite mineral obtained an age of 40 Ma (Rutherford, 1905). Holmes (1890–1965) perfected the uranium–lead dating method, producing a 370 Ma age for Devonian rocks, later supplemented by an age of 340 Ma

Fig. 6. Cross-section of the Val d'Agno (Agno Valley) exposing the succession of strata on both sides of the Agno valley, 35 km north of Verona, drawn by G. Arduino in 1758. In modern terminology the strata shown by Arduino are as follows (Gibbard, 2019): A, Palaeozoic crystalline schists; B-G, Permian sediments; H, Limestone and dolomite; I, Middle Triassic Ladinian dolomitic limestone; K, Middle Triassic Ladinian dacitic lavas; L, strongly deformed Norian-Liassic Jurassic sediments; M, Cretaceous clastic limestone; N, P and R, volcanic basalts, tuffs, etc.; O, lower and middle Eocene bioclastic sediments and Q, Priabonian (upper Eocene-Oligocene) calcareous clays.

for the Carboniferous and an age of 430 Ma for the Silurian or Ordovician (Holmes, 1911). Holmes (1933, 1944, 1947, 1960) continued to refine the estimated age of the Earth, an endeavor intrinsically associated with the advancement of isotope methodologies, ultimately earning him the title "*The Father of Geological Timescales*" suggested by Nier in 1960 (Lewis, 2001).

Prior to the development of radioisotopic dating techniques, the chronological placement within the geological timescale relied exclusively on the stratigraphical relationships to fossiliferous sedimentary units. For the first time, the geological timescale could now be quantitatively anchored using absolute ages derived from radioisotopic analyses of minerals within the rocks themselves, providing a robust temporal framework that was independent of biostratigraphic constraints and stratigraphical ambiguities. The oldest age recorded in Holmes' rock suite was 1,640 million years, still distant from the measurement we propose today, but extending the known boundaries of geological time further than ever before (Lewis, 2001).

4. Cutting Time in slices

Such a huge expanse of time had to be framed by a scale. Inevitably, attention moved now to the criteria by which successions of strata could be identified and correlated throughout the world.

4.1. Orders in Time

The most immediate criterion was to stress the major discontinuities directly observable in the field by lithological evidence. Giovanni Arduino (1714–1795), an Italian mining engineer and field geologist, had already proposed this approach in the 18th century, going beyond the two-fold division scheme of previous authors, with the identification of four basic units called "*ordini*" based only on lithology and without using palaeontological indicators (Vaccari, 2006; Gibbard, 2019). In 1759 he first set out his ideas in two letters to Antonio Vallisneri the Younger (1708–1777), Professor of Natural Sciences at the University of Padua, which were published in Venice in 1760 (Arduino, 1760) and subsequently refined (Arduino, 1774). After completing his 1758–1759 fieldwork in the valleys north of Vicenza, ranging from the Po Valley into the Apuane Alps (Fig. 6), integrated by observations from the Tuscan-Emilian Apennines and the Metalliferous Hills in Tuscany, Arduino introduced his general scheme of stratigraphical divisions including different rock types, which formed three kinds of mountains and one kind of plain, in a regular chronological order: "Primary" (underlain by "Primitive" or "Primeval" schist considered to be the oldest rock type), "Secondary," and "Tertiary". The fourth and younger "Quarto ordine" included only alluvial deposits. Arduino viewed his "four-order divisions" as four massive units of superimposed strata ("*quattro grandissimi strati*"), each internally subdivided into numerous minor strata ("*strati minori*") (Vaccari, 2006, 2008). These stratigraphical units were deposited successively, each reflecting distinct depositional environments within a geochronological framework. Each order was hypothesized to be bounded by a major revolution in Earth-system processes. For the first time, deposits of the Quaternary were identified and delineated as a discrete succession (Gibbard, 2019).

Although not explicitly incorporated into his lithological classifications, palaeontological evidence is nonetheless present within Arduino's writings (Arduino, "*Letter to Antonio Vallisneri junior*", 7 July 1760 in Vaccari, 2008, p. 56):

"*But I have other no less marvellous things in my Collection; that is, different degrees of perfection in the said species of aquatic, petrified animals—*'*Animali impietriti*' in the original Italian text—*rougher and more imperfect in the lower strata of the mountains, which I have distinguished as secondary in my Letters … and more perfect in the upper strata from one layer to the next, according to the order of their successive formation, so that in the last strata, that is, in those that form the mountains and tertiary hills, we see these species as perfect and in every way similar to those that can be seen in the same sea*".

4.2. Events in Time

While Earth was becoming older and older, it was evident that rocks were populated by a myriad of events, which were the most reliable for arranging sequences of strata in order. While William Smith was conducting stratigraphical investigations in England (see above), France played a pivotal role in the reciprocal flow of cultural and intellectual exchange that defined the development of Western Europe with leading figures like Jean-Baptiste de Lamarck (1744–1829) and Georges Cuvier (1769–1832) (Servais et al., 2012). Lamarck, who introduced the term "fossil" in the sense commonly accepted today, was not only a pioneer of "transformism" but also the founder of invertebrate palaeontology. His scientific career benefited from the patronage of Georges Buffon. In his "*Système des animaux sans vertèbres*" (Lamarck, 1801), Lamarck established a systematic classification of numerous fossil invertebrates. This work was followed by his "*Mémoires sur les fossiles des environs de Paris*" (Lamarck, 1802), a series of publications that further advanced the field. Through these contributions, Lamarck emerged as one of the earliest scientists to engage in biostratigraphy and palaeoclimatology, laying foundational principles for both disciplines.

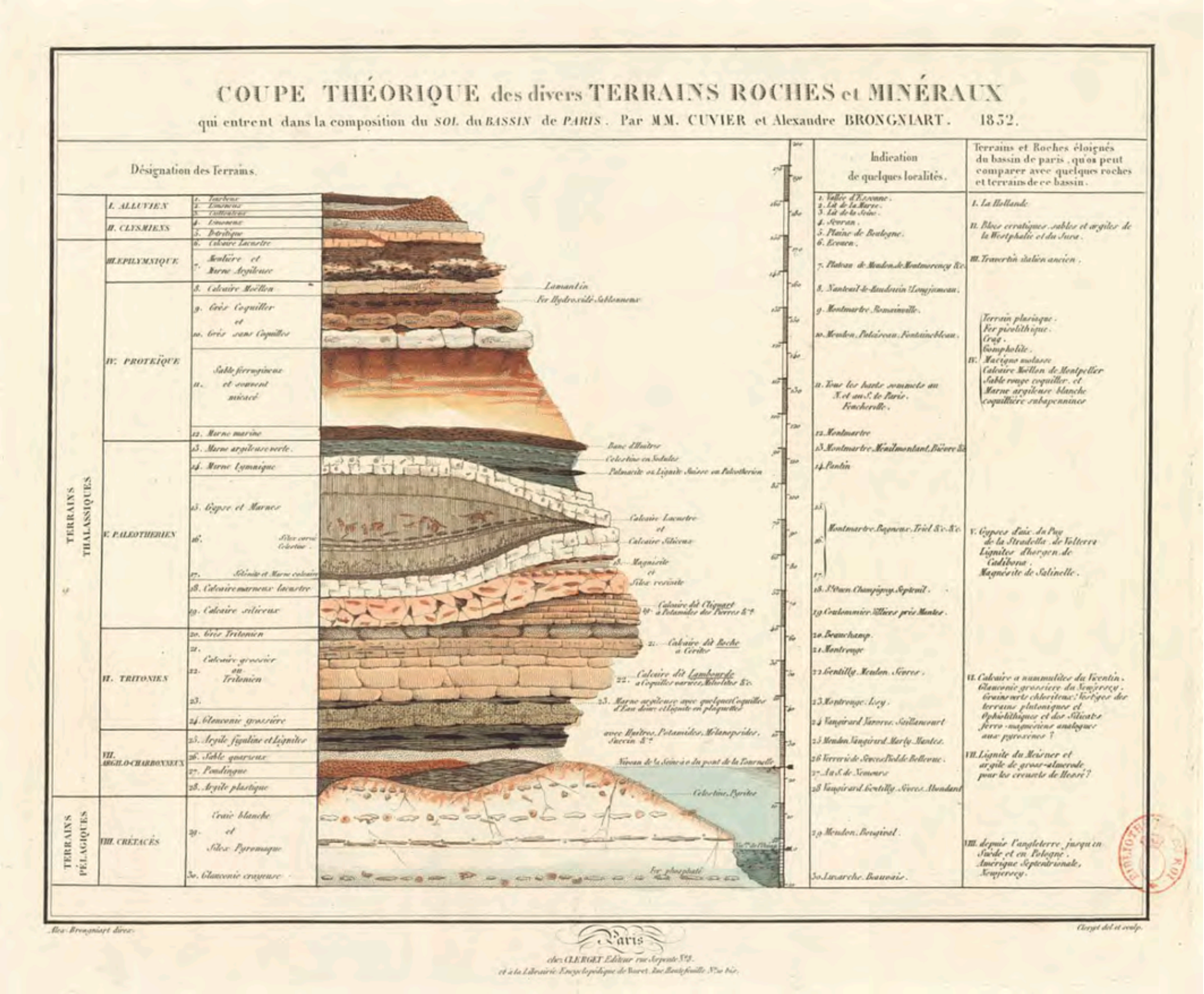


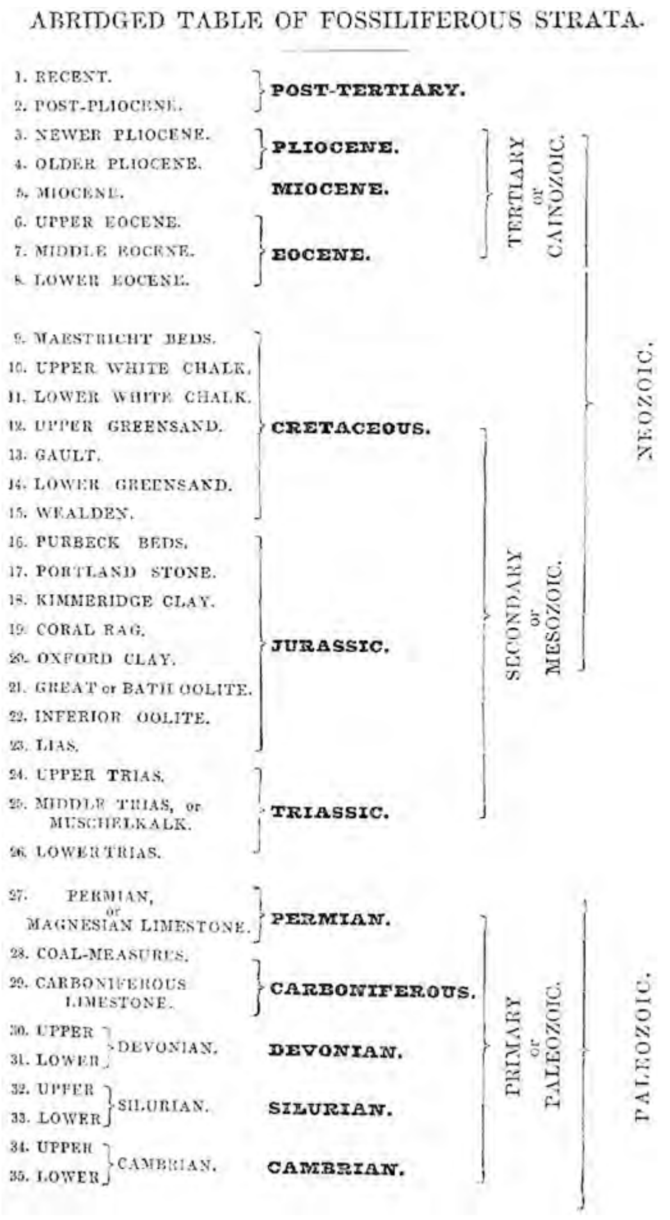
Fig. 7. Georges Cuvier and Alexandre Brongniart (1832) illustrated the Paris region with several carefully measured traverse sections illustrating the succession of "terrains" there exposed. On the two right columns the indications of the localities referred to in the section with numbers and a list of similar units in other areas (in France and outside, e.g., Holland and Italy). Source gallica.bnf.fr, Bibliothèque nationale de France.

Cuvier, in collaboration with Alexandre Brongniart (1770–1847), was active in delineating the stratigraphical succession of the Paris Basin, particularly the Cenozoic formations (Fig. 7). A contemporary of Cuvier, Napoleon Bonaparte held his compatriot's multifaceted intellect in such high esteem that, by 1800, he had incorporated him into his inner circle, entrusting him with responsibilities that spanned both personal counsel and matters of state (Soloviev, 2010). As a pioneer of comparative anatomy, Cuvier applied rigorous morphological analysis to fossil vertebrates, enabling him to reconstruct extinct organisms with remarkable accuracy. His method was grounded in the principle of the "correlation of parts," which speculated that the structure of one anatomical feature could predict the form and function of others. This approach allowed him to identify and classify fossil species with a level of precision previously unachievable. At the same time, he demonstrated that certain fossil forms lacked any resemblance to any living species, arguing convincingly that these organisms had vanished from the Earth and that extinction was a real and natural process (Laurent, 2000).

> "*Let us ask ourselves why we find so many remains of unknown animals, while we find almost none that can be said to belong to the species we know, and we will see how likely it is that they belonged to beings from a world prior to ours, beings destroyed by some revolution of this globe; beings whose exist today have filled the place, to see themselves perhaps one day also destroyed and replaced by others*" (Cuvier, 1799, p. 21).

Further supported by the extensive collections and institutional resources of the Muséum National d'Histoire Naturelle in Paris, Cuvier observed pronounced shifts in both fossil assemblages and lithological characteristics throughout the stratigraphical succession (Rudwick, 1996). Interpreting these discontinuities as abrupt and widespread, he formulated the concept of catastrophic events shaping Earth's geological history. Catastrophic events were both frequent and sudden rather than gradual, the most recent of which transpired within the final five to six thousand years of Earth's history (Barsanti, 1979; Servais et al., 2012). This vision stood in contrast to the emerging uniformitarian view which would later be rigorously formulated and advocated by Charles Lyell. Curiously, Brogniart (1829), possibly influenced by the emerging evolutionary theory of Lamarck, asserted that catastrophes might have resulted in the destruction of many species, but they might also have resulted in the modification and even transformation of surviving species (Barsanti, 2005; Servais et al., 2021).

Henri-Marie Ducrotay de Blainville (1777–1850), a student of both



ABRIDGED TABLE OF FOSSILIFEROUS STRATA.

1. RECENT.	POST-TERTIARY.			
2. POST-PLIOCENE.				
3. NEWER PLIOCENE.	PLIOCENE.	TERTIARY or CAINOZOIC.	NEOZOIC.	
4. OLDER PLIOCENE.				
5. MIOCENE.	MIOCENE.			
6. UPPER EOCENE.	EOCENE.			
7. MIDDLE EOCENE.				
8. LOWER EOCENE.				
9. MAESTRICHT BEDS.	CRETACEOUS.	SECONDARY or MESOZOIC.		
10. UPPER WHITE CHALK.				
11. LOWER WHITE CHALK.				
12. UPPER GREENSAND.				
13. GAULT.				
14. LOWER GREENSAND.				
15. WEALDEN.				
16. PURBECK BEDS.	JURASSIC.			
17. PORTLAND STONE.				
18. KIMMERIDGE CLAY.				
19. CORAL RAG.				
20. OXFORD CLAY.				
21. GREAT or BATH OOLITE.				
22. INFERIOR OOLITE.				
23. LIAS.				
24. UPPER TRIAS.	TRIASSIC.			
25. MIDDLE TRIAS, or MUSCHELKALK.				
26. LOWER TRIAS.				
27. PERMIAN, or MAGNESIAN LIMESTONE.	PERMIAN.	PRIMARY or PALEOZOIC.	PALEOZOIC.	
28. COAL-MEASURES.	CARBONIFEROUS.			
29. CARBONIFEROUS LIMESTONE.				
30. UPPER DEVONIAN.	DEVONIAN.			
31. LOWER DEVONIAN.				
32. UPPER SILURIAN.	SILURIAN.			
33. LOWER SILURIAN.				
34. UPPER CAMBRIAN.	CAMBRIAN.			
35. LOWER CAMBRIAN.				

Fig. 8. The chronostratigraphic chart of Charles Lyell (1855), claimed as the first formally structured, multi-level chronostratigraphic chart in the history of geological classification.

Cuvier and Lamarck, succeeded Cuvier in the chair at the Paris Museum in 1832, ironically becoming one of his fiercest scientific rivals. It was Blainville who, in 1822, coined the term "*paléontologie*" to define the emerging scientific discipline devoted to the study of fossil organisms (Servais et al., 2012).

4.3. *The naming of Time*

As geological investigations expanded throughout the 19th and early 20th centuries, the need for greater precision became increasingly evident. Arduino's terms Primary and Secondary were later replaced by Palaeozoic (Sedgwick, 1838) and Mesozoic (Phillips, 1840) as major, fossil-based divisions of the scale. A reason for replacing primary with Palaeozoic was to distinguish the oldest fossiliferous from the underlying "azoic" crystalline rocks. The primary divisions of the geological column were further systematically refined through the delineation of increasingly detailed subordinate units, reflecting enhanced stratigraphical resolution and a more sophisticated understanding of temporal continuity and palaeoenvironmental variability within the rock record. In the latter half of the 19th century, stratigraphical classification increasingly prioritized biological and geological criteria, with a particular focus on facilitating global correlation. Emphasis was placed on identifying major palaeontological discontinuities, regional unconformities, and orogenic events, which served as reliable markers for delineating chronostratigraphic boundaries. This approach tended to reinforce the definition of the boundaries themselves rather than the internal content of individual time intervals. As a result, stratigraphical sequences became more readily usable on a global scale. Within this evolving stratigraphical scheme, Charles Lyell (1855) introduced a structured, hierarchical chronostratigraphic scheme based on the principle of fossil succession, offering a coherent temporal framework for organizing Earth's geological history (Fig. 8).

4.4. *The splitting of Time*

More or less at the same time, the concept of the biozone emerged. Albert Oppel (1831–1865) was the first to apply time-zones not only for subdividing vertical successions of beds, as d'Orbigny had done, but also for correlating those layers across long, horizontal distances. Oppel (1856–1858) introduced a Jurassic timescale comprising eight stages ("*Etagen*") and 33 ammonoid-based zones, offering finer subdivisions than d'Orbigny's (1842) framework of ten stages and 25 zones. Although he did not create the term "zone," his more detailed scheme enabled geologists to pinpoint relative ages with meter-scale precision in outcrop and correlate those horizons hundreds of kilometers apart (Oppel, 1866), shaping the standard chronostratigraphic scale for nearly a century (Balini et al., 2017).

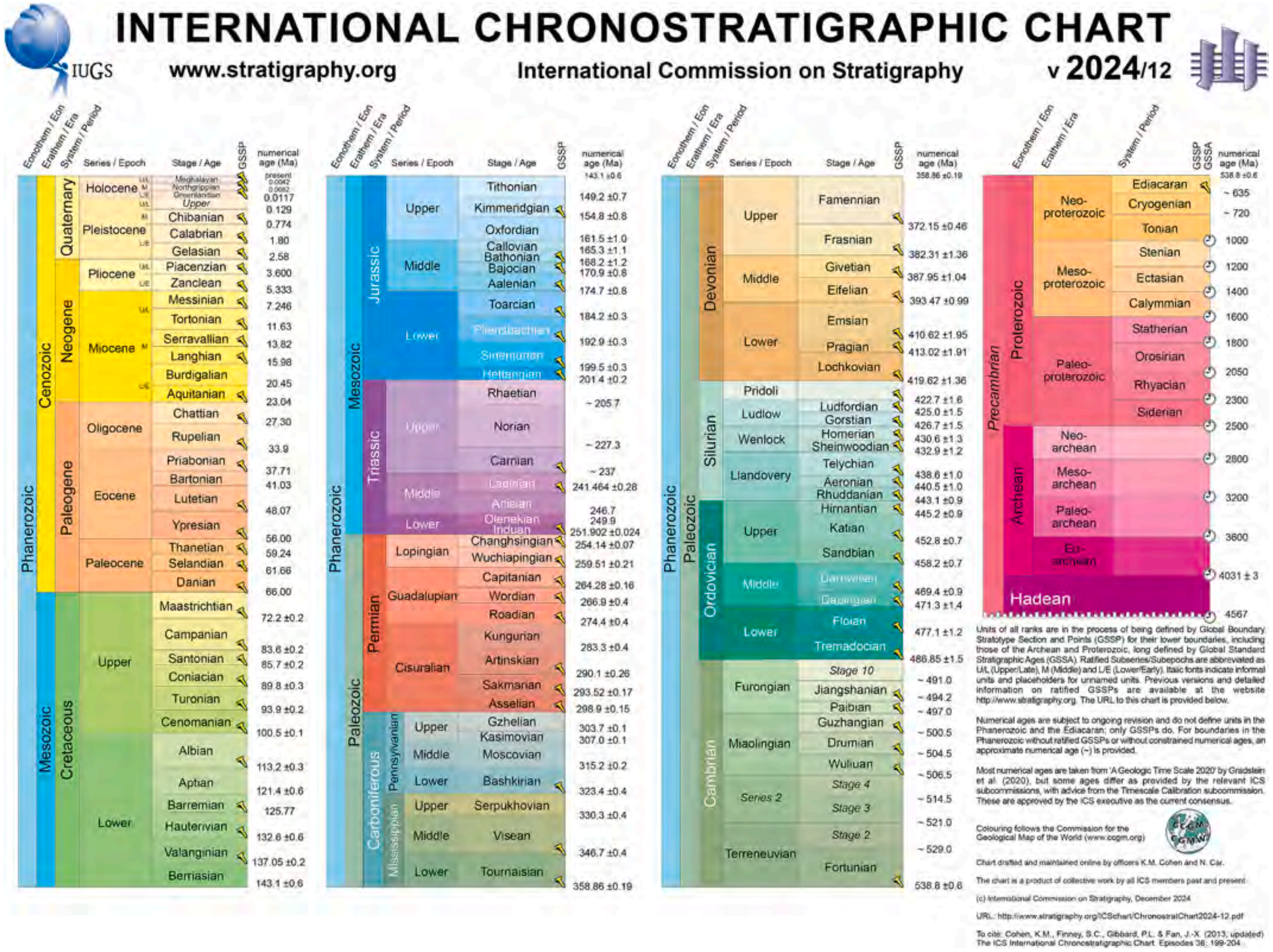
Building on this approach, researchers evaluated which combination of fossil evidence (e.g., first and last appearances, stratigraphical range, abundance and geographic distribution) most precisely delineated discrete time slices. Even the most advanced biozonation models, however, proved insufficient for exact chronological subdivision, prompting the adoption of more robust stratigraphical markers.

Although traditionally fossil events (First Appearance Datum: FAD and Last Appearance Datum: LAD) were used to correlate Global Boundary Stratotype Sections and Points (GSSPs), with advancing technology other nonbiological proxies (e.g., magnetostratigraphy, allostratigraphy, cyclostratigraphy, chemical stratigraphy, and sequence stratigraphy) are becoming important, adding accuracy and precision to correlations. These proxies, together with orbital tuning and radioisotope dating, are expanding the toolkit available to cut geological time. Given that each of these methods may present limitations in the future, this reinforces the importance of integrating multiple disciplines to ensure a reliable and resilient temporal framework.

The Valanginian/Hauterivian transition was calibrated by Hennig et al. (1999) integrating carbon isotope stratigraphy and standard ammonite stratigraphy (further refined with nannofossil- and magnetostratigraphy). Their final words (Hennig et al., 1999, p. 95) may now be read with hindsight, two decades later, as a premonition:

> "*Based on our study of the Valanginian-Hauterivian transition we conclude that C-isotope stratigraphy will provide extremely useful information for stratigraphy which will result in a significant improvement of the stratigraphic timescale.*"

Moreover, it has become increasingly evident that sedimentation is not a continuous or perpetual process; rather, deposition is characterized by interruptions and gaps, occasionally punctuated by episodes of sediment accumulation (Ager, 1981).



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). Ratified Subseries/Subepochs are abbreviated as U/L (Upper/Late), M (Middle) and L/E (Lower/Early). Italic fonts indicate informal units and placeholders for unnamed units. Previous versions and detailed information on ratified GSSPs are available at the website http://www.stratigraphy.org. The URL to this chart is provided below.

Numerical ages are subject to ongoing 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.

Most numerical ages are taken from 'A Geologic Time Scale 2020' by Gradstein et al. (2020), but some ages differ as provided by the relevant ICS subcommissions, with advice from the Timescale Calibration subcommission. These are approved by the ICS executive as the current consensus.

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

Chart drafted and maintained online by officers K.M. Cohen and N. Car.

The chart is a product of collective work by all ICS members past and present.

(c) International Commission on Stratigraphy, December 2024

URL: http://www.stratigraphy.org/ICSchart/ChronostratChart2024-12.pdf

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Fig. 9. The International Chronostratigraphic Chart displays the hierarchical ordering of Eonothems, Erathems, Systems, Series, and Stages, alongside the calibrated numerical ages of their boundaries. Small yellow pins adjacent to most stage names signify that a GSSP has been formally ratified for that Stage's lower boundary. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

5. The Time Lords

5.1. *The International Geological Congress (IGC)*

The emergence of an unprecedented volume of novel empirical data arising from different fields, not only related to palaeontology but for the first time integrating new disciplines, evidenced the need of a common language in international communication. That objective became feasible with the birth of several International Commissions and the organization of international meetings. The first International Geological Congress (IGC) was held in Paris in 1878 in the Trocadero Palace and was attended by 310 members from 23 countries. The most pressing objective was to standardize classification frameworks, nomenclature, and geological symbols. Two International Commissions were nominated, one charged respectively with looking into the standardization of geological symbols, and the other, the regularization of geological nomenclature (Ellenberger, 1978). The binomial classification of chronostratigraphic and chronologic units was formally established during the 2nd IGC held in Bologna in 1881 (Vai, 2004). From then on, for about 150 years, the International Geological Congresses have offered geologists an organized platform to convene regularly in a spirit of active and mutual cooperation. These meetings directly led to the establishment of numerous International Commissions and working groups.

5.2. *The International Commission on Stratigraphy (ICS)*

At the 19th IGC held in Algiers (1952) the International Commission on Stratigraphy (ICS), chaired by Raymond C. Moore, was formally introduced, replacing the former Commission for the Stratigraphic Lexicon (Vai, 2007). The ICS is the largest and oldest constituent scientific body of the International Union of Geological Sciences (IUGS). Its primary objective is to establish a unified hierarchy of globally standardized chronostratigraphic units, with each boundary formally defined by a ratified GSSP (Cohen et al., 2025). This boundary–stratotype methodology yields units whose limits are precisely delineated, leaving neither overlaps nor gaps between successive intervals. These are expressed in the International Chronostratigraphic Chart (Fig. 9), that established a hierarchical framework of chronostratigraphic units (Systems, Series, and Stages) and corresponding geochronological divisions (Periods, Epochs, and Ages), that Lucas (2018, p. 2) defines the "taxonomy of time". By assigning calibrated numerical ages to each boundary, the Chart acts as the International Geological Timescale (Cohen et al., 2013, 2025), which integrates a chronostratigraphic framework, classifying the global subdivisions of the geological time-rock record, with a geochronometric scale that estimates their durations (Witteveen, 2024). The Chart undergoes multiple updates to integrate refined numerical ages or further modifications. The ICS Executive Committee oversees coordination and ratification

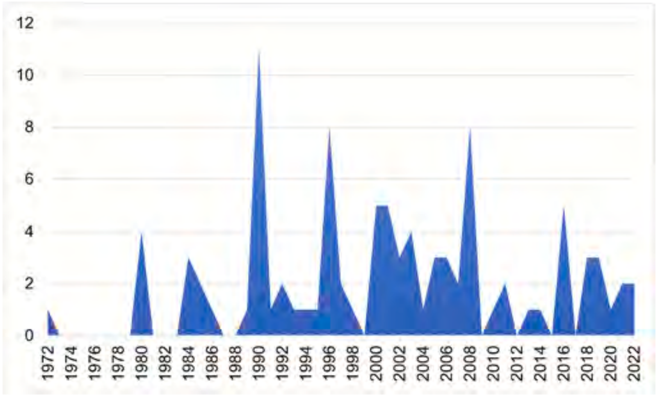

Fig. 10. Number of ratifications of GSSPs between 1972 and 2022 (based on https://timescalefoundation.org/gssp/index.php?parentid=all).

processes of seventeen Subcommissions, fifteen focusing on a specific interval of geological time, and two on stratigraphical classification and timescale calibration. Subcommissions draft proposals for new boundaries, review GSSP candidates, and publish working guides on stratigraphical topics.

5.3. Global Boundary Stratotype Sections and Points (GSSPs)

Since 1961, the International Commission on Stratigraphy has required that all chronostratigraphic boundaries be defined by GSSPs (Fig. 10). GSSPs pinpoint the exact horizons where rock-layer boundaries coincide with divisions of geological time, so where time-rock and rock overlaps:

> "*Only at the strictly geometrical point of the Golden Spike can time-rock and rock be known to coincide in space; that is only at this point can the boundary between two global standard stratigraphical divisions be known to coincide with a boundary in time*" (Holland, 1988, p. 85).

In the Chronostratigraphic Chart, each approved GSSP is marked by a small golden-spike icon at the base of the division it defines. Clock icons similarly denote the status of each Global Standard Stratigraphic Age (GSSA) (Fig. 9).

GSSPs are commonly defined by a primary signal, usually a biostratigraphic datum, reinforced by secondary signals such as chemostratigraphy, magnetostratigraphy, radioisotopic data, and other stratigraphical markers, a process that had lasted with modifications for over 50 years (e.g., Harper, 2019). The primary GSSP signal must be correlatable across a broad region and backed by secondary proxies that enable correlation where the primary datum is absent (Harper et al., 2022). Stratotypes must be accessible to all who are interested in their study, regardless of political or other circumstances, and there should be reasonable assurance of their long-term preservation. According to Ager (1981, p. 77), a GSSP should favour uninterrupted stratigraphical continuity, minimize any hiatuses, and ideally be situated:

> "*… in a section where sedimentation seems to have been nearly as continuous as is ever possible, where there are no marked lithological changes and where there are unbroken records of several different groups of fossils.*"

5.4. The Anthropocene

Although its mandate may seem purely theoretical, the ICS's recent involvement in the proposal to officially formalize the Anthropocene underscores its vitality and contemporary relevance. Stoppani's late-19th-century neologism "Anthropozoic," proposed to compare humanity with a novel telluric force, had inspired the term "Anthropocene." For the sake of accuracy, in the original three volumes of his "C*orso di Geologia*", written in Italian, Stoppani (1871–1873) employs randomly the terms "Anthropozoic period", "Anthropozoic era" and "Anthropozoic epochs." More importantly, his idea of humanity as a "telluric force" is grounded in a biblical framework (Stoppani was a Catholic priest), drawing on Genesis, where man is depicted as divinely ordained to exercise dominion over the Earth.

The current focus on global heating has brought into sharp focus the appropriateness or otherwise of the definition of an Anthropocene Epoch to emphasize the effects of anthropogenic interventions on the planet and its ecosystems. Few Earth scientists would deny that anthropogenic processes are contributing to global heating and an accelerated rate of extinction. The term Anthropocene, however, is well embedded in the economic, political and social sciences and researchers communicate within this frame not least through the journal "Anthropocene". In most cases, however, the definition is broad and flexible. It is accepted like human cultures, that the Anthropocene is diachronous and on a global scale its impact is variable, geographically.

The Nobel prize-winning chemist Paul Krutzen whose inspirational work on the ozone layer earned international acclaim, sought to more clearly identify the origin and impact of the Anthropocene. He highlighted the Industrial Revolution as the starting point. He stated "*This epoch may be defined to have started about two centuries ago, coinciding with James Watt's design of the steam engine in 1784*" (Krutzen, 2006, p. 13). This invention kick-started the Industrial Revolution in Northern Europe and more specifically in Great Britain. The "dark satanic mills" of Britain were initially localized although gradually industrial processes spread as did their pollutants. There have been strong arguments to suggest the process of human-induced climate change started much earlier with Neolithic farming practices and the later colonization of the Caribbean and elsewhere in the New World (Goffe, 2025).

During the International Geological Congress in Cape Town (2016) a group of Quaternary scientists were invited by the ICS to establish a working group to assess the viability of the Anthropocene as a chronostratigraphic unit above the Holocene. Over time the group expanded, as other scientists from other disciplines were added, and contracted as the ICS demanded that only earth scientists should be involved in discussions. The group generated a huge opus of exciting science and much media attention, not always positive. The Anthropocene was thus on the map to the benefit of science and our understanding of the effects of anthropogenic processes. The long-awaited report of the group was delivered in late 2023. The recommendation was to define the base of the Crawfordian Stage (and Anthropocene Series) in a lake bed in northern Canada. The Crawfordian Stage would thus be defined by a GSSP in the lake core of dark rhythmic muds, coincident with the start of the Great Acceleration (Head et al., 2021) and correlated by the products from nuclear tests, principally ^{239}Pu. This level too is coincident with a calendar date of 1952. The substantial proposal, which included a range of auxiliary sections, was rejected by the Subcommission on Quaternary Stratigraphy. The Subcommission considered that its proximity in time, or recency (it has a historical record) and the diachronous nature of human impacts ranging from the Neolithic, speak to the unsuitability of a chronostratigraphic definition. Rather, the looser definition as an extended event may be more appropriate (Gibbard et al., 2021).

It is beyond the scope of this review paper to discuss the vast literature now available on the Anthropocene, nevertheless Zalasiecwicz et al. (2019) remains a key entry point for the debates that later unfolded on the pages of the IUGS journal Episodes.

The IUGS succinctly captured the decision as follows:

> "*It is with the delegated authority of the IUGS President and Secretary General and on behalf of the International Commission on Stratigraphy (ICS) that the vote by the ICS Subcommission on Quaternary Stratigraphy (SQS) to reject the proposal for an Anthropocene Epoch as a formal unit of the Geologic Time Scale is approved. The voting members of SQS have*

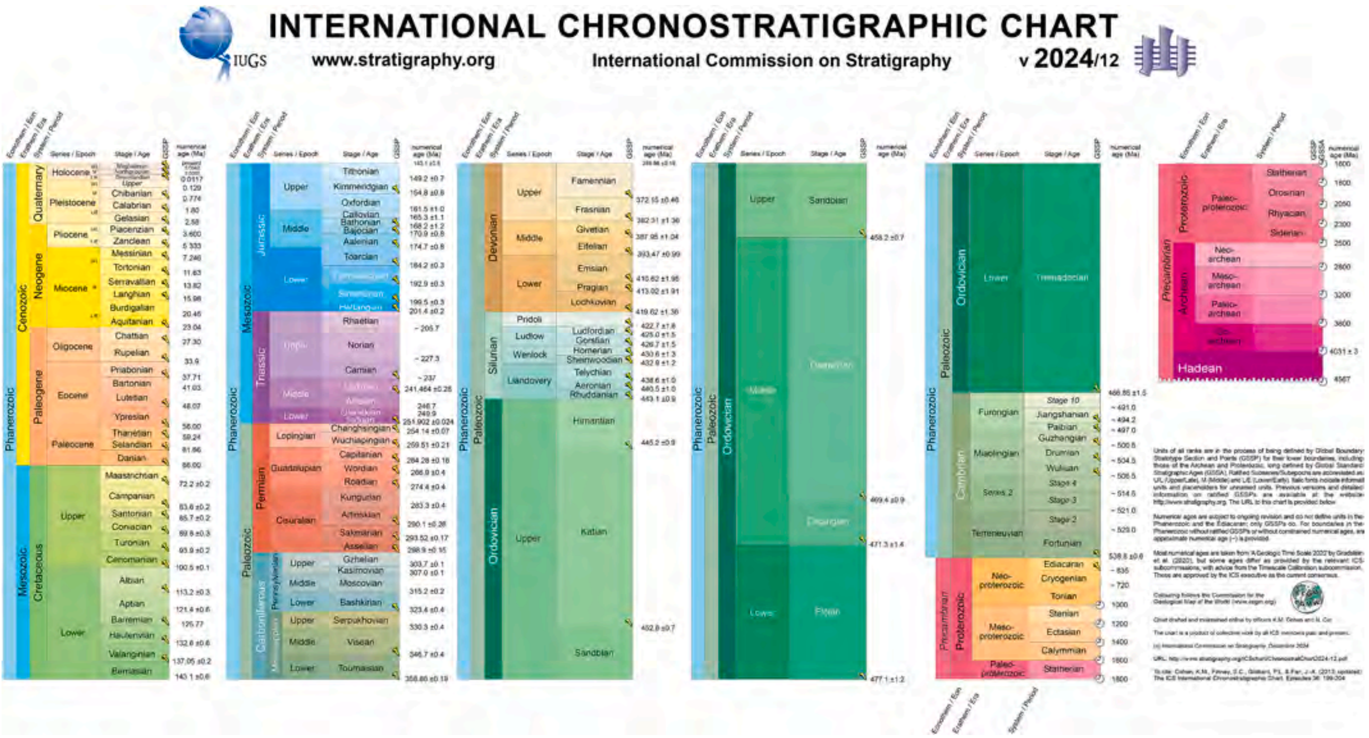

Fig. 11. "Decompression" of the International Chronostratigraphic Chart (2024/12) with the Ordovician redrawn exactly at the same scale as the Quaternary.

extensive experience and wide expertise in Quaternary stratigraphy and chronology. Their vote was approved by the ICS executive, and that approval was overwhelmingly supported by the chairs of the ICS subcommissions. Despite its rejection as a formal unit of the Geologic Time Scale, the Anthropocene will nevertheless continue to be used not only by Earth and environmental scientists, but also by social scientists, politicians and economists, as well as by the public at large. It will remain an invaluable descriptor of human impact on the Earth system." IUGS webpage, ww.stratigraphy.com (downloaded 5th November 2025).

6. The relativity of Time

On July 11, 2022, NASA's James Webb Space Telescope unveiled the deepest, sharpest infrared images of the distant universe ever captured. The image captured galaxy cluster SMACS 0723 as it existed 4.6 billion years ago, revealing a multitude of galaxies both in front of and behind the cluster. By acting as a gravitational lens, the cluster's immense mass magnifies even more distant galaxies, some dating to when the universe was under a billion years old. The surprising level of maturity seen in these early galaxies has prompted some to speculate that they might have formed before the Big Bang, a hypothesis that challenges the foundations of standard cosmological theory. If this finding is confirmed, we would be compelled to extend our conception of time even further into the past. And move further back, once again, to the starting point of time.

There is another relativity in time. In the ICS Chart, chronostratigraphic units are not plotted on a uniform scale, as the time intervals appear increasingly dilated moving towards the Holocene. We often overlook this, possibly because we are too focused on events closer to our species' emergence, and continue splitting obsessively nearby time into thinner and thinner chronostratigraphic units. We conducted a graphical experiment for own satisfaction. As three of us work on the Ordovician, we "decompressed" the chart rescaling the Ordovician to match the duration of the Quaternary, arriving at the version shown in Fig. 11. Applying this rescaling to every geological period, effectively "unzipping" the time of older eras, would yield a vastly larger chart.

7. The future of Time

For an intricate series of reasons, we feel more confident in an unlimited past than in an extended future. Toni Morrison, Nobel Prize in Literature in 1993, affirmed in her monumental Jefferson Lecture, the U. S. federal government's highest honour for achievement in the humanities, that (Morrison, 1996, p. 1):

> *Time, it seems, has no future… It certainly seems not to have a future that equals the length … of its past. Infinity is now, apparently, the domain of the past… The course of time seems to be narrowing to a vanishing point beyond which humanity neither exists nor wants to… it is the past that has been getting longer and longer."*

Making the past longer and longer was made possible, as demonstrated above, through a series of steps that clearly reveal an ongoing reconfiguration of time, both in its quantitative measurement and in our approach to it. The long list of scientists mentioned herein arises from a lively debate resulting from a vibrant exchange of opinions aiming to uncover new knowledge. Most of them share the common background of having proposed innovative ideas at the wrong time, often contrasting with or even opposed by their contemporaries in the scientific community. Just for that reason, the greatest mistake one can make now is to regard current knowledge as the final destination. Rather, it is imperative to persistently question, refine, and correct our understanding in the pursuit of deeper insight, looking for new ideas from often ignored or unnoticed scientists. Only in this way we will be able to seriously contribute to any advance in science. For example, what are the inaccuracies or limitations within the actual Chronostratigraphic Chart?

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The authors confirm that all data necessary for supporting the scientific findings of this paper have been provided.

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