A short history of the Ordovician System: from overlapping unit stratotypes to global stratotype sections and points

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Abstract: The Ordovician System was introduced by Charles Lapworth as a solution to the overlapping unit stratotypes loosely defined by Adam Sedgwick, for the Cambrian, and Roderick Murchison, for the Silurian. The Ordovician has emerged as one of the longest and most significant of the geological periods. Following an interval of intensive research of all the key regions of the globe, unit stratotypes in the type areas of England and Wales have been replaced by seven global stages and three series based on Global Stratotype Sections and Points (GSSPs), enhancing the definition of these chronostratigraphic units and facilitating global correlation. As a consequence, the biological and geological events during the period can be recognized and the magnitude and significance of biotic originations and extinctions understood with some confidence.

Stratigraphy is one of the oldest of the geological disciplines, dating at least from Leonardo da Vinci's (1452–1519) sketch of a clear sequence of laterally continuous, horizontal strata displaying order in the rocks in the hills of northern Italy. A concept formulated as the Law of Superposition of Strata by the Danish polymath Nicolaus Steno (1638–68) ordered strata within a succession illustrating in his *Prodomus* the depositional history of a basin and the lateral continuity of strata. Giovanni Arduino (1714–95) recognized that strata were ordered on a larger scale; three basically different rocks suites are exposed in the Italian part of the Alpine belt. A crystalline basement of older rocks, overlain unconformably by mainly Mesozoic limestone, slightly deformed, in turn overlain unconformably by poorly consolidated clastic rocks. These three units constituted his primary, secondary and tertiary systems; the last term was retained and formalized for the period of geological time succeeding the Cretaceous.

The role of fossils in stratigraphy can be traced back to the work of William Smith (1769–1839) in Britain and Georges Cuvier (1769–1832) and Alexandre Brongniart (1770–1847) in France. William Smith, in the course of his work as a canal engineer in England, realized that different rocks units were characterized by distinctive groups of fossils. In a traverse from Wales to London, Smith encountered successively younger groups of rocks, and he documented the change from the trilobite-dominated assemblages of the Lower Paleozoic 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 together with Alexandre Brongniart, ordered and correlated Tertiary strata in the Paris Basin using series of mainly terrestrial vertebrate faunas, occurring in sequences separated by supposed biological catastrophes.

Early geologists thought the Earth was very young, but the Scottish scientist James Hutton (1726–97) noted the great cyclic process of mountain uplift, followed by erosion, sediment transport by rivers, deposition in the sea, and then uplift again, and argued that such processes had been going on all through Earth's history. He wrote in his *Theory of the Earth* (1795) that his understanding of geological time indicated 'no vestige of a beginning, – no prospect of an end'. An example of Hutton's evidence is the spectacular unconformity at Siccar Point, Berwickshire, southern Scotland, where near-horizontal Old Red Sandstone (Devonian) strata overlie steeply dipping Silurian greywackes. Beneath the unconformity, Hutton recognized the 'ruins of an earlier world', establishing the immensity of geological time (1795).

Using these tools, geological time was divided up by the efforts of 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

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('coal-bearing') rocks that early industrialists were keen to exploit. The first descriptions were from countries with a well-developed coal industry in the nineteenth century, which are reflected in stage names such as the Visean (Belgium) or Westphalian (Germany). In Britain all three divisions of the Carboniferous were of economic value (the Mountain Limestone, Millstone Grit and the Coal Measures). Many of the original definitions were logically based on the rocks present locally. For example, the Triassic System was originally described from the three-fold series of the Buntsandstein, Muschelkalk and Keuper (von Alberti 1834) in southern Germany. Based mainly on his studies in the Paris Basin, France, d'Orbigny (1802–57) not only introduced stages as subdivisions of strata with unique fossil assemblages, but also established five of the Jurassic and four of the Cretaceous stages still used today. Not surprisingly, many of the Lower Paleozoic stratotypes were thus described first from Great Britain, especially in the Anglo-Welsh Basin, where these rocks are particularly widespread and relatively well exposed.

Yet many of the original definitions of the geological systems were in terms of unit stratotypes, commonly separated from each other by unconformities. Unconformities provided a convenient break between systems; they also satisfied the contemporary view that the major divisions of Earth's history should be divided by global, catastrophic events. Many, however, of these unconformities are only regional breaks. The bases of most systems thus were represented by stratigraphic gaps, providing a poor basis for the global correlation of systemic boundaries. The legacy of this methodology figured large in the initial definition of the Lower Paleozoic systems and their series, not least the Ordovician during its turbulent history. In Britain the Lower Paleozoic rocks were included in the Greywacke Series and this was the subject of a controversy which would last nearly half a century.

The Ordovician System and its British origins

Charles Lapworth's expedient solution to the great and damaging Cambrian–Silurian dispute (Secord 1986) involved the assignment of the overlapping ground that included Sedgwick's upper Cambrian and Murchison's lower Silurian (Sedgwick and Murchison 1835) to an entirely new system, the Ordovician (Lapworth 1879). The human dimension to this dispute and its solution has been described in detail by Davidson (2021), highlighting the contrasting experience, expertise and traits of a priest, a soldier and a school teacher. The bold action of Lapworth, however, challenging the British establishment (its Cambridge professors and directors of the Geological Survey of Britain and Ireland), set the agenda for the next 130 years of Ordovician research, its rocks and its fossils. Most geologists agree that the Ordovician Period was special if not unique (e.g. Jaanusson 1984; Ross 1984; Harper 2011). Thalassocratic (a word rarely used outside Ordovician research) conditions were promoted by the spread of extensive, epicontinental seas, with flat sea beds and relatively restricted land areas. Magmatic and tectonic activity was associated with rapid plate movements and widespread volcanic activity. The emerging island arcs and mountain belts provided sources for clastic sediment, in competition with the carbonate belts associated with most of the epicontinental seas (Jaanusson 1973, 1982). Most significant was the radiation of life (Harper 2006), including a shelly fauna of suspension-feeding brachiopods, bryozoans, cephalopods, corals, crinoids and stromatoporoids, together with predatory cephalopods and mainly deposit-feeding trilobites as well as the nektobenthic conodonts and the pelagic graptolites. Biogeographical differentiation was marked, affecting the plankton, nekton and benthos, and climatic zonation was significant, particularly in the Southern Hemisphere, where the continents were gathered. Ironically it was these very exciting aspects of Ordovician geology that would provide difficulties for both intra and intercontinental correlation within the system. The almost bewildering range of environments and facies, many without modern analogues, and the intense provincialism of Ordovician biotas appeared to be a formidable barrier to any acceptable global chronostratigraphy for the system. Nevertheless, within the last 40 years a massive international effort has involved intense research, lively debate and a degree of compromise. Three global series and seven stages are in place (Bergström *et al.* 2009), providing a well-grounded infrastructure and a framework to address the problems of the origins of modern climate and modern ecosystems deep in the Paleozoic. The Ordovician Period was key.

Starting with a compromise

The Ordovician was born out of controversy, being the centre of a bitter territorial fight between Professor Adam Sedgwick and Sir Roderick Murchison during the mid-nineteenth century (Secord 1986) ranging across the mountains of Wales and the Welsh borderlands (Fig. 1a). Clear difficulties developed when it was clear that Murchison's Shelly Sandstone in the middle part of his Upper Greywacke Series (Silurian) was equivalent to Sedgwick's Bala Limestone in the middle part of his Lower Greywacke Series (Cambrian). There was thus considerable overlap between the two series.

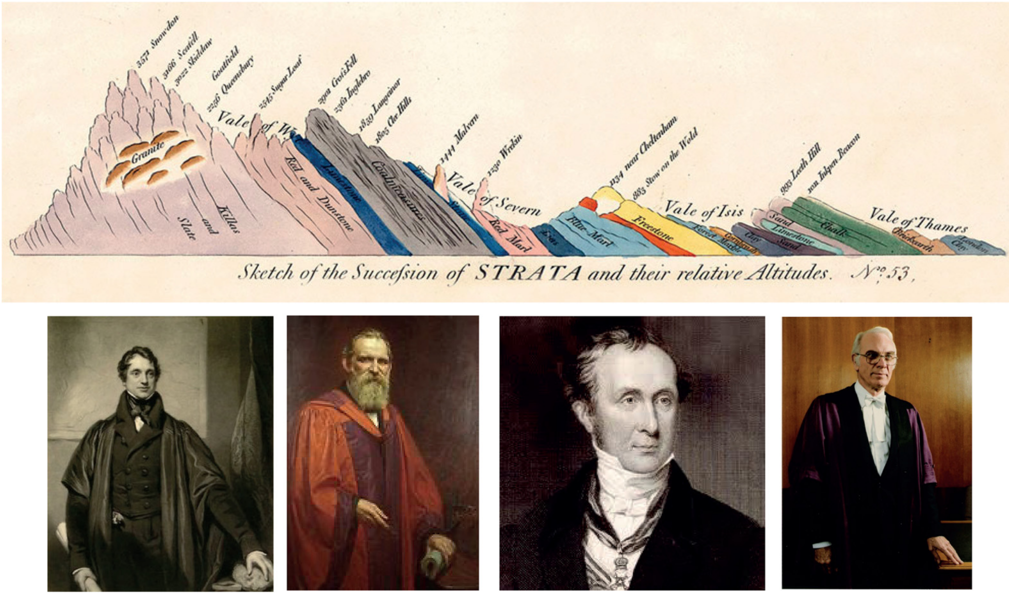

Fig. 1. (**a**) Section through the geology of southern England and Wales, indicating the large area of Wales and Welsh Borderlands poorly studied prior to William Smith's survey (1815). (**b**) From left to right, Professor Adam Sedgwick, Professor Charles Lapworth, Sir Roderick Murchison and Sir Alwyn Williams. Last photo courtesy of the late Lady Joan Williams.

Charles Lapworth provided a compromise, one developed further by UK geologists, led by Alwyn Williams (Fig. 1b). In his seminal paper published in 1879, Lapworth explained his position thus:

> On this arrangement the Lower Palaeozoic Rocks of Britain stand as follows:
>
> (c) SILURIAN SYSTEM: Strata comprehended between the base of the Old Red Sandstone and that of the Lower Llandovery.
>
> (b) ORDOVICIAN SYSTEM: Strata included between the base of the Lower Llandovery formation and that of the Lower Arenig.
>
> (a) CAMBRIAN SYSTEM: Strata included between the base of the Lower Arenig formation and that of the Harlech Grits.
>
> Every geologist will at last be driven to the same conclusion that Nature has distributed our Lower Palaeozoic Rocks in three subequal systems, and that history, circumstance, and geologic convenience, have so arranged matters that the title here for the central system is the only one possible.

In many respects this tripartite division of the Lower Paleozoic was already anticipated in Bohemia by Joachim Barrande in his three faunas (Bassett 1979) and more specifically his Stage D, including Tremadocian–Hirnantian strata (Kríz and Pojeta 1974); the inclusion of the Tremadocian aligned more correctly with the current concept of the Ordovician than Lapworth's original definition (Fig. 2). The tripartite division of Lower Paleozoic strata was clearly recognized in Estonia and adjacent Russia where Ordovician strata, virtually in the sense of Lapworth's system, had been used since the middle of nineteenth century as 'the Lower Silurian Formation' (*Untersilurische Formation* or *Untersilurformation*; Schmidt 1858, 1881). Schmidt (1832–1908) retained the same subdivision even in his final publication (Schmidt 1908), although the term 'Ordovician' had already been defined some 30 years previously in 1879.

Charles Lapworth: the founder

Charles Lapworth L.L.D., FRS, was born at Faringdon, Oxfordshire in 1842 and undertook teacher training in Culham College, Abingdon, graduating in 1864. His first assignment was in Galashiels Episcopal Church School in the heart of the Southern Uplands of Scotland, a fortunate and serendipitous posting. Lapworth's relatively short tenure in the Scottish Borders was to prove of fundamental and lasting value, not only to himself, but to the wider geological community. From his base in the Southern Uplands he set in train a formidable research programme based on detailed mapping, graptolite stratigraphy and taxonomy. From the outset of his

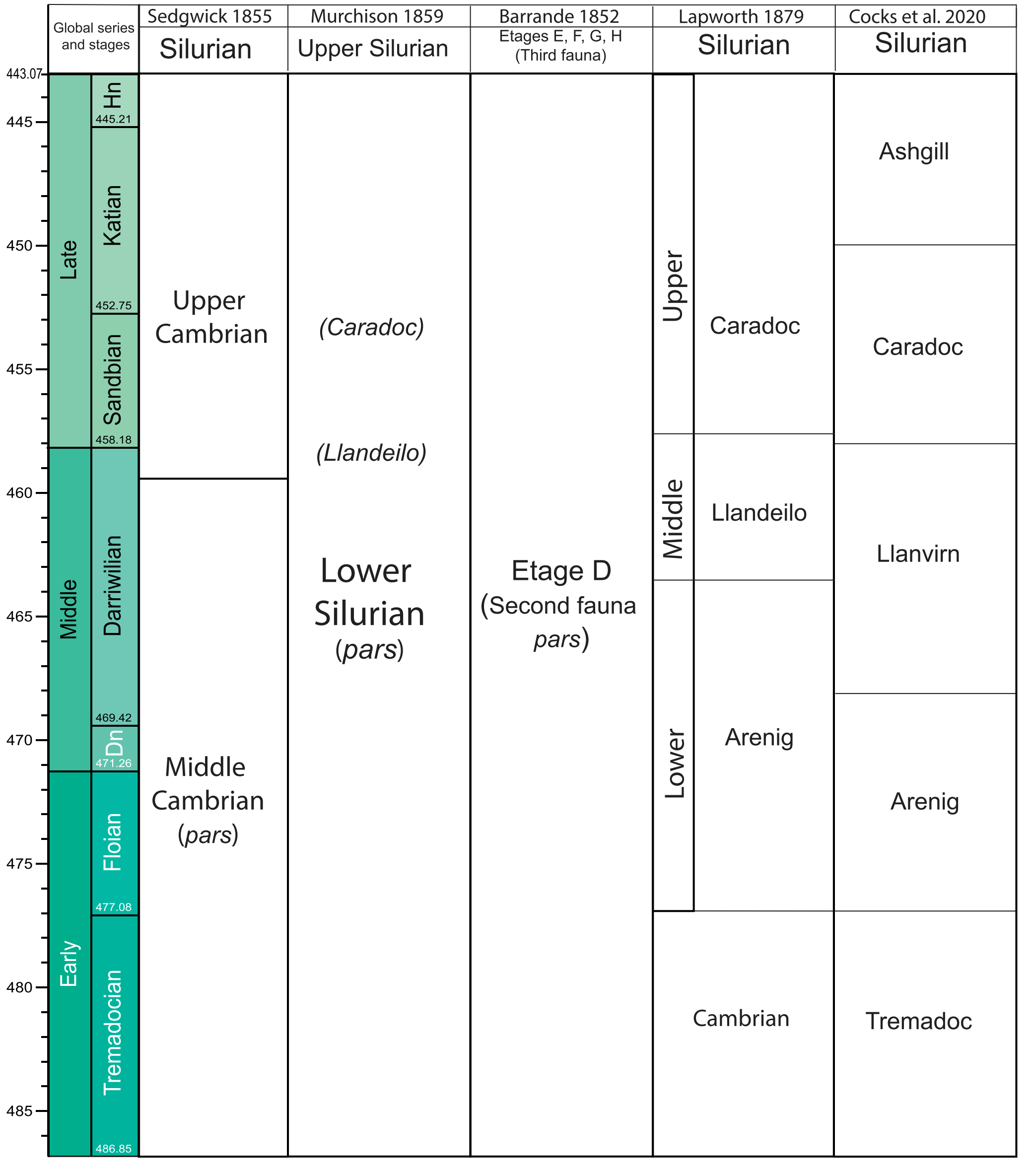

Fig. 2. Chart indicating the equivalences between the stratigraphical schemes of Sedgwick, Murchison and Barrande together with those of the International Commission on Stratigraphy and the Geological Society.

career he drew on advice from the eminent Swedish geologist Gustav Linnarsson (1841–81), who encouraged Lapworth to collect and identify graptolites, bed-by-bed, through his mapped sections. In this way Lapworth could identify a succession of graptolite faunas, essentially Oppel zones (see Balini *et al.* 2017), confirming the similarities between the Scottish and Swedish Lower Paleozoic graptolitic successions.

By 1875 Lapworth had moved to Madras College in St Andrews, Fife. He had already embarked on an exceptionally detailed study of distribution, stratigraphy and graptolite biostratigraphy of the Moffat Series of the Southern Uplands; details of the graptolite faunas were presented at the meeting of the British Advancement of Science in 1876, prior to publication of the substantial and significant account of the Moffat succession (Lapworth 1880). These were deep-water facies, rich in abundant and beautifully preserved graptolites.

Lapworth extended this research to the shelf and slope faunas of the Girvan district of SW Scotland (Lapworth 1882), enhancing the international reputation of the small fishing town on the west coast of Ayrshire. The succession, exposed north and south of the valley, is thick, consisting mainly of conglomerate, sandstone, siltstone and limestone, and was deposited mainly on the shelf and upper slope. He mapped the whole area in great detail, and most of his interpretations have been sustained, although refined and extended. There are, however, graptolite bands within the succession, and Lapworth was able to correlate the Girvan sequence with that of Southern Scotland. This was of considerable significance, indicating a means to correlate between graptolitic and shelly successions, through intermediaries.

Yet although the Ordovician was accepted by colleagues elsewhere in Europe and North America relatively quickly, in Britain this compromise was not without criticism. Here there was a general reluctance to adopt the term Ordovician. There was, however, an enthusiastic acceptance of the tripartite division by one Charles Callaway (1838–1915), a voice independent of the establishment. Callaway had worked on the Lower Paleozoic rocks of Anglesey and Shropshire and offered strong support for the implementation of the Ordovician System on scientific grounds (Callaway 1879). His correspondence in *Geological Magazine* closed with the enduring statement ‘Those of us who are simply workers, and not sectarians, should not have our tools broken by the worshippers of great men’.

Nevertheless, the influence of the Cambridge School was strong and reached far; in deference to Sedgwick’s Cambrian System, the British establishment had no wish to contradict one of their own (Geikie 1897). Leading the blockade was T. McKenny Hughes (1832–1917), who had succeeded Sedgwick to the Woodwardian Professorship.

> A proposal has been made to take all Sedgwick’s Arenig and Bala Beds, and Murchison’s Llandeilo and Caradoc, and constitute, not Upper Cambrian, not Lower Silurian, but Ordovician, with a view to putting an end to controversy! One shell is given to Sedgwick, the other to Murchison, but who gets the oyster?

There is, however, no doubt in most people’s minds who got the oyster. On the other hand, the Geological Survey of Great Britain and Ireland, in the guise of the director Sir Archibald Geikie (1835–1924), supported its former director Sir Roderick Murchison; the language could not be clearer.

> It has been proposed by Professor Lapworth that the strata named by Murchison Lower Silurian and claimed by Sedgwick as Upper Cambrian, should be taken from both and be given a new name, ‘Ordovician.’ By all the laws that regulate scientific priority the strata which were first separated by Murchison and distinguished by their fossils, should retain the name of Lower Silurian which he gave them.

Hughes’s stance had a strong advocate in his former student and eventual successor to the Woodwardian chair. John E. Marr (1857–1933), who was to later establish the ultimate series of the Ordovician System, the Ashgill in NW England, specifically rejected the use of the term Ordovician in 1881; however, Marr also advised of the requirement to present this proposal before the International Commission for the Unification of Geological Nomenclature (a body of the International Geological Congress, IGC), for whatever reason. At the third session of the IGC in Berlin (1885), Marr rejected Lapworth’s proposal. He did, however, note that his own recommendation for the adoption of Sedgwick’s Cambrian did not meet with the approval of many members of the subcommission set up to investigate the matter; no decisions were taken. At the subsequent meeting in London in 1888, discussions continued. Lapworth’s strong encouragement to adopt the Ordovician on the grounds of expediency was now supported by Marr; he indicated that first there was a need to recognize systems on the basis of palaeontological data (all three Lower Paleozoic systems have mutually distinctive faunas) and second the definition of the Ordovician would add to clarity to the definitions of the adjacent Cambrian and Silurian systems. It was a remarkable but valuable *volte face*.

This opinion was not supported by the then Director of the Geological Survey of Britain and Ireland, Sir Archibald Geikie. However, upon his retirement in 1900 the situation was rapidly reversed by his successor, Jethro Teall (1849–1924), with ‘Ordovician’ appearing in his first annual report. Ordovician was subsequently adopted by the Geological Survey of Great Britain and Ireland as a mapping term in 1906, replacing Lower Silurian, nearly 40 years after Lapworth’s proposal.

In the early 1920s, the term Ordovician was also introduced for Estonia by Hendrik Bekker (1891–1925), the first Professor of Geology with Estonian roots in the University of Tartu (Bekker 1921). This was seemingly a direct influence from Britain as Bekker obtained his doctoral degree in London.

The term Ordovician was becoming common currency amongst geologists during the twentieth century but had not yet been ratified by any of the appropriate governing bodies in the science. Ironically neither had the Silurian. The twenty-first session of the International Geological Congress was held in Oslo in 1960 under the chairmanship of

Professor Leif Størmer. The congress proposed the following in a position paper:

(1) Two systems are to be recognized between the Cambrian and Devonian.
(2) The name of the lower system shall be Ordovician
(3) The name of the upper system shall be Silurian.

These proposals were approved by the Commission on Stratigraphy on 22 August 1960, and adopted by the Congress. The reality of the Ordovician System was finally confirmed some 80 years after its conception. Twelve years later, at the twenty-fourth session of the IGC in Montreal, the Commission on Stratigraphy of the International Union of Geological Sciences established a Subcommission on Ordovician Stratigraphy, and Professor Alwyn Williams (UK, 1921–2004) was invited to become the founding chairman and organize the group.

The rise and decline of the British series

The debate surrounding the base of the system is admirably discussed elsewhere (see Whittington and Williams 1964; Williams *et al.* 1972) and is only briefly noted here. Lapworth (1879) in distinguishing the Ordovician System from those below and above, adopted a conceptual approach. It was clear the system extended downwards from the base of the lower Llandovery to the base of the lower Arenig but the boundaries were discussed in general terms and a type section, the entire Arenig-Bala district, cited. The lower boundary of the system was marked by the 'Basal Grit' of Sedgwick's Arenig Group, which rests unconformably on the Tremadoc Amnodd Shales. Unfortunately an error in correlation served to confuse a choice of level for the base of the system. Hicks (1875) described a lower Arenig graptolite fauna from Pembrokeshire which he mistakenly correlated with the upper Tremadoc of North Wales. Thus began a lengthy debate, initiated by an error, regarding the inclusion or otherwise of the Tremadocian within the system. Despite lengthy arguments from both sides, the balance of opinion, particularly advocated by European geologists, was for the inclusion of the Tremadocian in the Ordovician System (Henningsmoen 1973). The base of the Arenig, in its type area, is in any case, represented by a gap and could not serve as a GSSP.

The location of the upper boundary of the system, the base of the Silurian, was less in doubt. In Lapworth's type area, the Cwm yr Aethnen Mudstones, overlying the Foel y Ddinas Mudstones of the Bala Group, formed the lower boundary of the Llandovery. Lapworth had already carefully mapped the boundary section in the graptolitic facies of the Southern Uplands (Lapworth 1880) and his sketch, its interpretation and the excavated trench (in connection with the search for a boundary stratotype) are illustrated here (Fig. 3).

The British series (e.g. Williams *et al.* 1972) have been widely used on the grounds of availability, historical priority and by the 'colonial' geologists who left Europe to map the then remoter parts of the world. Later definitions have been formalized and modified to aid modern international correlation with the British series (Fortey *et al.* 1991, 1995, 2000), and a case can be made for their wider use in the greater Avalonian and Gondwanan regions (Cocks *et al.* 2010). At the same time, the parallel development of regional stratigraphic standards led to some very refined subdivisions in some areas, e.g. the Baltic stages that were also partly introduced for Scandinavia (Männil 1966; Jaanusson 1982).

Yet how would the original series and stage divisions, established mainly in shelly facies in England and Wales, stand scrutiny against a set of new international criteria for the establishment of a truly global chronostratigraphy?

During the first international symposium devoted entirely to the Ordovician, Alwyn Williams delivered a comprehensive keynote address on the rocks and fossils of the period; he supported the modification and refinement of the English and Welsh type sections for the British series as global standards for the system. Yet, ironically, some of the key points advanced in his address (Williams 1976) indicated precisely why the adherence to a single region for a complete Ordovician stratotype would prove difficult if not impossible. He noted (Williams 1976) that any attempt to establish a global correlation chart for the system must take into consideration, firstly, the complex and perplexing distribution of the continents, microcontinents and their sedimentary facies, and secondly, the contrasting biofacies and provincial distribution of its faunas. Williams went further to suggest some key criteria for an Ordovician type section: (1) areas in close proximity; (2) homogeneity of attendant faunas and their use in correlation; and (3) a flexible approach to classification of regional successions. Yet some of the shortcomings of the type sections in the UK were already apparent to some congress participants, not least gaps in the sections, poor exposures and limited correlation value of at least some of the shelly faunas. The role of the British series as internationally accepted unit chronostratigraphic stratotypes was diminishing, and in a new world order where chronostratigraphic units would be defined by basal stratotypes, the series were severely challenged. However, for many areas around the world, for example throughout the vast territory of northern Eurasia, within the former USSR and its influence area, the British series became a part of the regional stratigraphic standard since the middle of twentieth century and are still

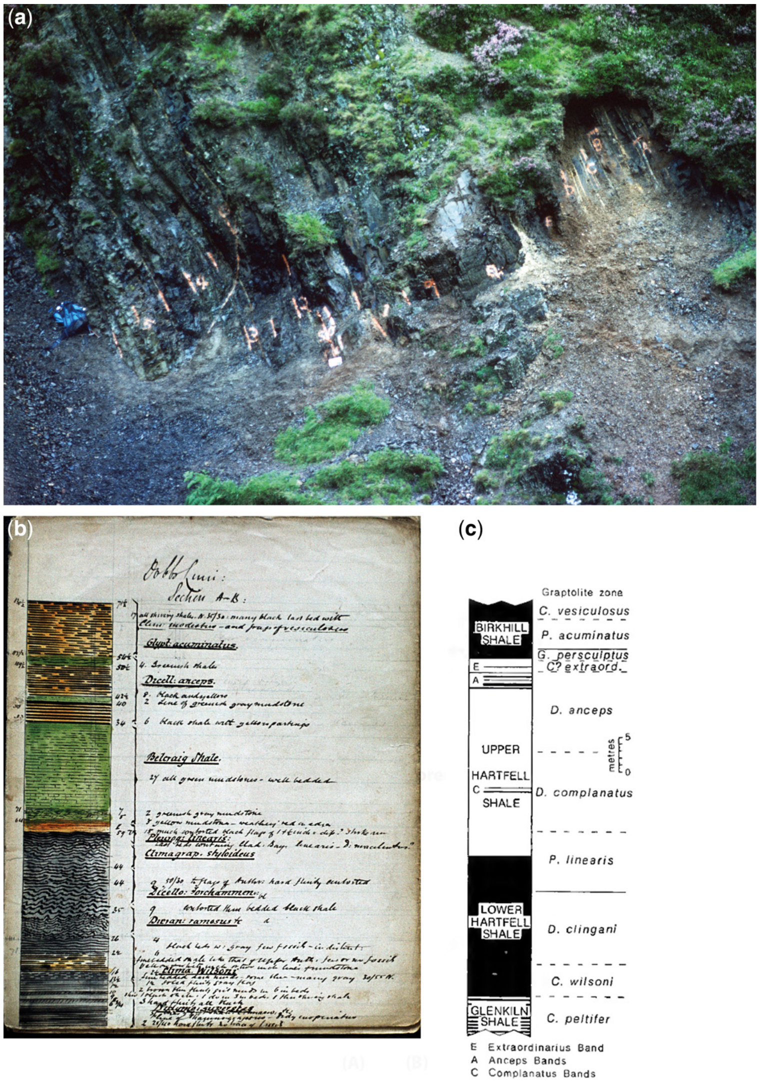

Fig. 3. The Ordovician–Silurian boundary. (**a**) Trench B in the 1980s (photograph courtesy of S. Henry Williams). (**b**) A page from Charles Lapworth's field notebook illustrating the section at Dob's Linn (courtesy of Jon Clatworthy, Director of the Lapworth Museum, Birmingham University). (**c**) Interpretation of Lapworth's section (see Williams 1988).

used in the stratigraphic charts, for example in Russia as the official subdivisions of the standard series, in the position of global stages (*Stratigraphic Code for Russia* 2006; Zhamoida 2015).

Fortey *et al.* (1991, 1995, 2000) attempted to modify the series and focused on attempts to find possible basal stratotypes. In summary, some of the key points emerged from these attempts to modernize the series.

Tremadoc. There are few sections in the UK that adequately display the base of Tremadoc, the best being exposed in the forestry road at Bryn-llin-fawr, near Tremadog. The base of the series is recognized by the first appearance of *Rhabdinopora*.

Arenig. Arennig Fawr mountain is the type area for the Arenig. The series includes three well-defined stages but no continuous sections between the Tremadoc and Arenig have been described.

Llanvirn. The base of the Llanvirn is coincident with the base of the *Didymograptus artus* Biozone; the type section at the Farmstead of Llanvirn is inadequate, the contact with the underlying Arenig is not exposed, and the section is only sporadically fossiliferous. Elsewhere adequate sections are hard to find.

Llandeilo. The type area of this series is composite, extending south from Dynevor Park through the Ffairfâch Railway cutting to the Cennan Valley. The trilobite *Lloydolithus lloydi* has been used to indicate the base of the Llandeilo but sections are poorly exposed and those available indicate that the basal Llandeilo sandstone rests on rhyolite, possibly indicating a gap in the succession.

Caradoc. The base of the Caradoc is marked by the Costonian Stage in the type area; conglomerate and coarse sandstone contain diagnostic large brachiopods and some trilobites. Here there is a marked unconformity at the base of the series in its type area.

Ashgill. The Ashgill is the only series defined outside the Anglo-Welsh area. The base of the series (and the Pusgillian Stage) is well defined in Foggy Gill and can be correlated by the appearance of several brachiopod and trilobite species.

Viewed from a North American perspective (Laurentia displays several extensive, well-exposed basins with complete Ordovician successions), Finney (2005) was scathing in his criticism of the British series. He noted that these were simply local stratigraphic successions with endemic faunas based on unit stratotypes, in geographically separated areas and commonly bounded by unconformities obscured by lateral facies changes; in assessing the boundaries, he noted significant gaps and overlaps between successive series, as originally defined. Moreover, the changes made by Fortey *et al.* (1995, 2000) to modernize the Ordovician in its type area, in Finney's opinion, removed any vestige of historical precedent. Finney continued with a more detailed critique of some of the individual series. This critique was in line with the development of new global stratigraphy for the system based on GSSPs (not unit stratotypes), defined in the most appropriate section to facilitate global correlation.

Most international opinion favoured the adoption of GSSPs rather than unit stratotypes and the British series performed poorly in this respect. It was clear that a global standard was required. A new global standard would facilitate reliable global correlation. It would provide a common language for discussing Ordovician strata, fossils and geologic events. It would be of fundamental importance in advancing research on Ordovician rocks worldwide (Harper *et al.* 2022).

Moving towards a global subdivision of the Ordovician Series

The International Subcommission on Ordovician Stratigraphy was established in 1974, initially with its main focus on the lower and upper boundaries of the system; work on the global series and stage divisions would follow later. The top of the system, defined by the base of the Silurian at Dob's Linn, southern Scotland, was ratified in 1985 (by the International Subcommision on Silurian Stratigraphy); the graptolite zone effecting boundary correlation has since been modified, but the position of the boundary remains unchanged, retaining the importance of the historical investigations by Charles Lapworth. The base of the Ordovician took a little longer to define; it was ratified in 2000, defined at Green Point in western Newfoundland and correlated on the basis of a conodont species. During the early stages of this process, Ross (1984) in a comprehensive and thoughtful review of the system outlined the many distinctive and exciting elements of Ordovician geology; for example, its then length (80 myr), its significant biotas (fishes and land plants), fluctuating climates and sea-level and widespread volcanism (with the opportunity to develop isotopic dating), together with the cosmopolitan distribution of Ordovician strata across every continent, even reaching the summit of Everest (see also Harper *et al.* 2011).

Fundamental, however, to the development of a global chronostratigraphy was the detailed research on as many as possible of the commonly distinctive regional Ordovician sections. The regional correlation charts published by the International Union of Geological Sciences (IUGS) formed a formidable basis for the future discussions of a global stratigraphy. Both Webby (1998) and Finney (2005) have documented in some detail the long and arduous progress towards the functional and pragmatic global chronostratigraphy (Bergström *et al.* 2009), a monument to the work of the previous chairs of the Subcommission and the many dedicated working groups and other interested parties. Despite deliberation on the base of the Ordovician that lasted some 25 years, the Ordovician series and stages were agreed and ratified within 10 years (1997–2007). Each of the bases of the seven stages are defined as a point in time (Table 1), by a hypothetical golden spike, and the point correlated by the first appearance of a key pelagic fossil, a conodont or a graptolite, to permit the maximum possible reach for widespread correlation. All the stratotypes are readily accessible, in deeper water facies and in fossiliferous sections. All seven GSSPs are illustrated in addition to that for the base of the Silurian (Fig. 4h). No stratotype is perfect and each has its own, minor shortcomings.

Table 1. *Key data for the seven Ordovician Global Stratotype Sections and Points (see https://stratigraphy.org/gssps/#ordovician)*

Upper Ordovician Series							
Hirnantian Stage	445.2 ± 1.4	Wangjiawan North section, north of Yichang city, Western Hubei Province, China	30.9841° N 111.4197° E	0.39 m below the base of the Kuanyinchiao Bed	Graptolite FAD *Normalograptus extraordinarius*	Ratified 2006	*Episodes* 2006; **29**, 183–196
Katian Stage	453.0 ± 0.7	Black Knob Ridge Section, Atoka, Oklahoma (USA)	34.4305° N 96.0746° W	4.0 m above the base of the Bigfork Chert	Graptolite FAD *Diplacanthograptus caudatus*	Ratified 2006	*Episodes* 2007; **30**, 258–270
Sandbian Stage	458.4 ± 0.9	Sularp Brook, Fågelsång, Sweden	55.7137° N 13.3255° E	1.4 m below a phosphorite marker bed in the E14b outcrop	Graptolite FAD *Nemagraptus gracilis*	Ratified 2002	*Episodes* 2000; **23**, 102–109
Middle Ordovician Series							
Darriwilian Stage	467.3 ± 1.1	Huangnitang section, Changshan, Zhejiang Province, SE China	28.8539° N 118.4897° E	base of Bed AEP 184	Graptolite FAD *Undulograptus austrodentatus*	Ratified 1987	*Episodes* 1997; **20**, 158–166
Dapingian Stage	470.0 ± 1.4	Huanghuachang Section, NE of Yichang city, Hubei Province, southern China	30.8605° N 110.3740° E	10.57 m above base of the Dawan Formation	Conodont FAD of *Baltoniodus triangularis*	Ratified 2007	*Episodes* 2005; **28**, 105–117; *Episodes* 2009; **32**, 96–113
Lower Ordovician Series							
Floian Stage	477.7 ± 1.4	Diabasbrottet, Hunneberg, Sweden	58.3589° N 12.5024° E	In the lower Tøyen Shale, 2.1 m above the top of the Cambrian	Graptolite FAD *Tetragraptus approximatus*	Ratified 2002	*Episodes* 2004; **27**, 265–272
Tremadocian Stage	485.4 ± 1.9	Green Point Section, western Newfoundland	49.6829° N 57.9653° W	At the 101.8 m level, within Bed 23, in the measured section	Conodont FAD *Iapetognathus fluctivagus*	Ratified 2000	*Episodes* 2001; **24**, 19–28

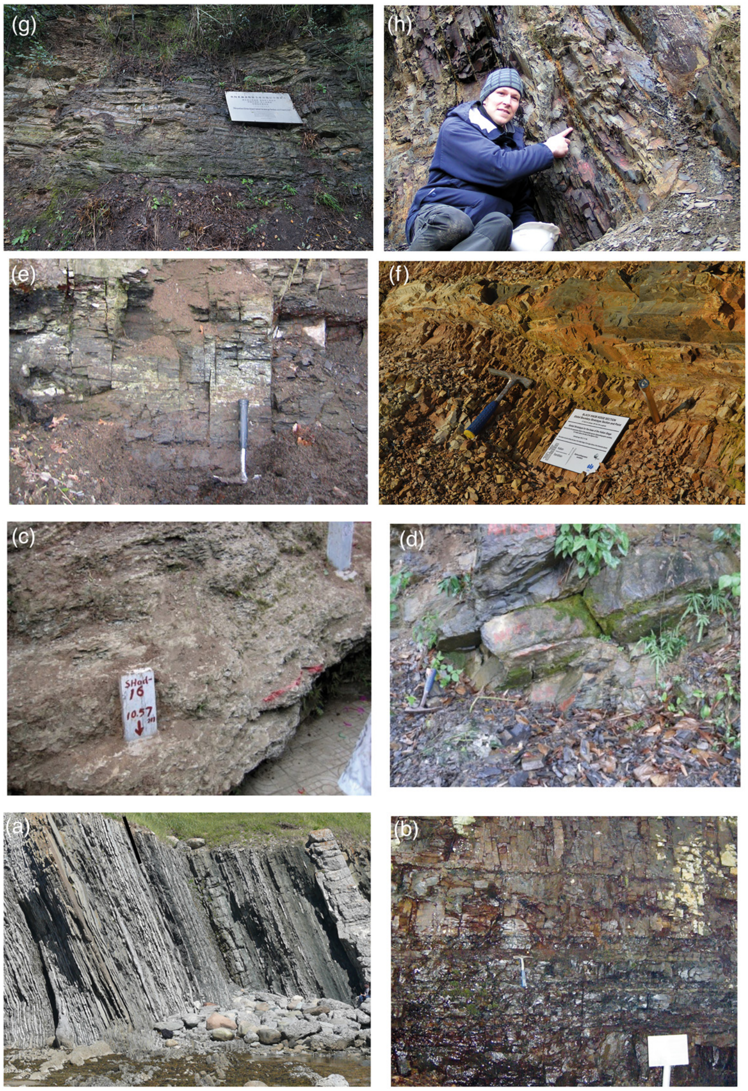

Fig. 4. Global Stratotype Sections and Points (GSSPs) for the global stages of the Ordovician System and the GSSP for the base of the Silurian. See Table 1 for full details. (**a**) The GSSP for the base of the Ordovician System (and the base of the Tremadocian Stage), Green Point Section, western Newfoundland. The boundary is indicated by a thin black line. Note the succession is inverted. Photo courtesy of Svend Stouge. (**b**) The GSSP for the base of the Floian Stage, Diabasbrottet, Hunneberg, Sweden. The boundary is indicated by the Golden Spike. Photo courtesy of Per Ahlberg. (**c**) The GSSP for the base of the Dapingian Stage, Huanghuachang Section, NE of Yichang city, Hubei Province, S. China. The boundary is indicated by the marker. (**d**) The GSSP for the base of the Darriwilian Stage, Huangnitang section, Changshan, Zhejiang Province, SE China. The boundary is at the base of the bed adjacent to the hammer. (**e**) The GSSP for the base of the Sandbian Stage, Sularp Brook, Fågelsång, Sweden. The hammer shaft is standing on the boundary. Photo courtesy of Per Ahlberg. (**f**) The GSSP for the base of the Katian, Black Knob Ridge Section, Atoka, Oklahoma (USA). The boundary is indicated by a Golden Spike. Photo courtesy of Dan Goldman. (**g**) The GSSP for the base of the Hirnantian Stage, Wangjiawan North section, North of Yichang City, Western Hubei Province, China, indicated by the information board. Photo courtesy of Huang Bing. (**h**) The GSSP for the base of the Silurian System (and the base of the Rhuddanian Stage) indicated by a 50 pence coin. Note the succession is inverted.

Regional series becoming global subdivisions

The detailed studies on different regional series, from all around the world, formed the basis for the selection and ratification of all seven Ordovician GSSPs, without significant controversy, that today permit precise correlation between continents. The Silurian Subcommission on Stratigraphy ratified its chronostratigraphic units in a relatively short period (from 1980 to 1984), defining all boundaries by preserving not only the British sections, but also the traditional British names of Series and Stages, with the exception of the uppermost Pridoli Series, selected in the Czech Republic (Holland 1985). In contrast the Ordovician Subcommission took more time, carefully exploring the context of potential sections, and ratified all Global Series and Stages over a period of some 20 years. Following these intensive discussions the first Ordovician GSSP excluding the lower boundary of the system itself, the base of the Darriwilian Stage was ratified in 1987, and the last were ratified in 2006 (the Katian and Hirnantian stages; see Bergström *et al.* 2009).

Whereas the Silurian Subcommission focused essentially on the traditional (stratigraphical index) fossil group, the graptolites from the British Isles, the Ordovician Subcommission selected, about 20 years later, sections from other (palaeo-)continents, and with the GSSPs being based on the first occurrence (first appearance datum, FAD) of either a graptolite or a conodont species, of which the taxonomies were carefully revised, and that would allow intercontinental correlation through their widespread distributions.

The British graptolite biozonation (based on Elles and Wood 1901 and additional volumes) was used for almost the entire twentieth century as the global standard, and the classical British series, as described above, served for most stratigraphers around the world as the standard to which regional series were correlated, although the global Series had not been formally defined. Because of this extensive use, some of the traditional names were selected to serve at the global level (e.g. Tremadocian and Hirnantian, marking the base and the top of the system). However, none of the GSSPs from the Ordovician were selected in the historical type area of the system, Great Britain.

Webby (1998) summarized in detail the evolution of the subdivisions of the Ordovician for all the major palaeocontinents, opposing the different regional versions of bipartite (Webby 1998, fig. 2) and tripartite (Webby 1998, fig. 3) subdivisions. A bipartite subdivision (Lower and Upper Ordovician Series) was advocated mostly in Britain, Australia and China, whereas for most other parts of the world, a tripartite subdivision was introduced, the latter subdivision into three global Series (Lower, Middle and Upper Ordovician) being finally adopted by the Ordovician Subcommission on Stratigraphy.

Based on his incomparable knowledge of the Ordovician successions of Baltoscandia, Jaanusson (1960) was one of the first to point out the importance of the regional series, advocating the adoption of separate sets of regional names for the major palaeobiogeographical provinces of the world, next to the British 'standard'. In that context, Jaanusson (1960) used the regional Baltoscandian series names (Oeland, Virju and Harju series) to define the Lower, Middle and Upper Ordovician in the regional usage of Scandinavia and the Baltic States (see e.g. Meidla *et al.* 2023; Nielsen *et al.* 2023 part 1).

The tripartite subdivision of the Baltoscandian Ordovician (e.g. Jaanusson 1960) also received widespread acceptance in the former Soviet Union. Western and central Russia, belonging to the palaeocontinent of Baltica, have many faunal groups in common with the Baltoscandian sections from Scandinavia and Estonia, with which correlations are much more evident than with the British sections from the microcontinent Avalonia, which occupied during most parts of the Ordovician completely different palaeolatitudinal positions and displays very different faunas (Molyneux *et al.* this volume, in press).

Some of the Avalonian faunas, including graptolites, were also found outside the British Isles, in particular in western Europe. For these reasons, Belgian and German Ordovician successions were usually correlated with the British standard (see e.g. Lefebvre *et al.* this volume, in press). In southern (in particular Spain) and central Europe (e.g. Bohemia) the British series names were used for decades, but regional series, based on palaeontological investigations of the regional faunas from localities at the margin of Gondwana ('North Gondwana' of Webby 1998; but see Servais and Sintubin 2009) have been introduced, such as the Dobrotivian, Berounian, Kralodvorian and Kosovian from Bohemia, and the Oretan from Spain. These regional stages (see e.g. Kraft *et al.* 2023) were also partly used in other countries, including North Africa.

The Ordovician of North America (palaeocontinent Laurentia) was subdivided into three regional series, independently of those from British successions, with the historical subdivision into Canadian (lower), Champlainian (middle) and Cincinnatian (upper Ordovician). A subsequent classification into Ibexian (lower), Whiterockian (middle) and Mohawkian/Cincinnatian (upper) Ordovician series is still in use today. The extensive studies in North America include those from several major outcrop areas, such as the Cincinnatian Arch and the Great Basin areas. These areas served as the basis for the conodont-based North American Composite

Standard, as well as for the definition of the Ibexian and Whiterockian faunas (for more details, see Webby 1998; McLaughlin and Stigall in press).

South America, in contrast, belonged mainly to the palaeocontinent of Gondwana. With detailed studies from Argentina, but also in other areas, a tripartite subdivision of the Ordovician was generally adopted, with a partial correlation to the British standards (see Waisfeld *et al.* 2023).

China plays today an essential role in Ordovician stratigraphy. A detailed summary of the history of Ordovician studies from China is provided by Zhang *et al.* (2018). After a relatively late start to intensive stratigraphical studies, in comparison with the British, Baltoscandian or North American series, the Ordovician successions of China have been investigated in great detail in recent decades, with several Ordovician GGSPs defined in China. The Chinese successions belong to different palaeogeographical settings, including the palaeocontinents South China, North China and Tarim. Different subdivisions have been proposed; for example, a fivefold regional series scheme presented (Ichangian, Yushanian, Zhejiangian, Neichiashanian and Chientangkiangian) during the 1990s now has been modified to better correspond to the Global Stages (three Global Series and six regional stages). As a result of these extensive studies, three of the Ordovician GSSPs have been selected from China (base of the Dapingian, Darriwilian, and Hirnantian) and in addition one Auxiliary Boundary Stratigraphic Section and Point section (ASSP) for the base of the Ordovician System. Furthermore, the name of one Global Stage (Dapingian) derives from a Chinese locality (Daping, Hubei Province).

The Ordovician of Australia was also traditionally divided into three regional series, but several authors proposed a bipartite subdivision (see summary in Webby 1998). The regional Australian stage of the Darriwilian was selected as the name of the Global Stage that corresponds to the upper part of the Middle Ordovician (Mitchell *et al.* 1997).

Global stages and series

Based on the detailed investigations by several working groups, the seven Global Stages of the Ordovician have been defined as indicated below. Two stage names from the classical British series were kept, whereas the other names were selected from other palaeocontinents. The GSSPs were selected as follows: two from North America (Laurentia – bases of the Tremadocian and Katian), two from Baltoscandia (Baltica – bases of the Floian and Sandbian) and three from the Yangtze Platform in China (South China Plate – bases of the Dapingian, Darriwilian and Hirnantian). There has been little dissention (Cope 2007).

Tremadocian. The GSSP for the base of the Ordovician, Lower Ordovician Series and the Tremadocian Stage is designated in the Green Point Section, western Newfoundland, (Fig. 4a) at the 101.8 m level, within Bed 23, in the measured section (Cooper *et al.* 2001); the basal stratotype is marked by the first appearance of the conodont *Iapetognathus fluctivagus.* Doubt has been cast on the identification of the key index taxon; however, it occurs within an evolutionary lineage of species of *Cordylodus* and below the lowest occurrence of *Rhabdinopora* and related graptolites.

Floian. The GSSP for the base of this stage is defined at Diabasbrottet, Hunneberg, Sweden, 2.1 m above the top of the Cambrian in the lower Tøyen Shale (Fig. 4b; Bergström *et al.* 2004); the boundary is marked by the first appearance of the graptolite *Tetragraptus approximatus*.

Dapingian. The GSSP is defined for this stage and the Middle Ordovician Series in the Huanghuachang Section, NE of Yichang city, Hubei Province, South China, 10.57 m above the base of the Dawan Formation (Fig. 4c; Wang *et al.* 2009); the boundary is marked by the first appearance of the conodont *Baltoniodus triangularis*.

Darriwilian. The base of this stage is defined in the Huangnitang section, Changshan, Zhejiang Province, SE China (Fig. 4d; Mitchell *et al.* 1997) at the base of base of Bed AEP 184. The GSSP is marked by the first appearance of the graptolite *Undulograptus austrodentatus*.

Sandbian. The GSSP is defined in the banks of Sularp Brook, Fågelsång, Sweden, 1.4 m below a phosphorite marker bed (Fig. 4e) Bergström *et al.* 2000); it is signalled by the first appearance of the graptolite *Nemagraptus gracilis*. Doubts have been cast on the actual range of *N. gracilis* and while the deep-water facies provide for global correlations across deep-water shelf and upper slope environments, correlation into even the adjacent carbonate shelves of Baltica is difficult. However, the lowest occurrence of *N. gracilis* occurs immediately above the base of the conodont *Pygodus anserinus*, which is widespread in the North Atlantic conodont province.

Katian. The base of the stage is defined in Black Knob Ridge Section, Atoka, Oklahoma, USA, 4.0 m above the base of the Bigfork Chert (Fig. 4f; Goldman *et al.* 2007); the first appearance of the graptolite *Diplacanthograptus caudatus* marks the boundary. This is a long stage covering the upper part of the Caradoc and most of the Ashgill Series.

Hirnantian. The GSSP is defined in the Wangjiawan North section, North of Yichang city, Western Hubei

Province, China, 0.39 m below the base of the Kuanyinchiao Bed (Fig. 4g; Chen *et al.* 2006); the boundary is marked by the appearance of the graptolite *Normalograptus extraordinarius*. The *Hirnantia* brachiopod fauna occurs diachronously across the graptolitic shale succession.

Auxilliary stratotypes

An auxiliary section (Auxiliary Boundary Stratotype Section and Point ASSP) can be formally identified in cases where not all the criteria can be met in one section or a further reference section is needed to improve correlatability: for instance, in a different facies or in a different palaeogeographical context. Two have been identified for the base of the Ordovician System (Fig. 5): Miller *et al.* (2016) have defined an ASSP in the Lawsons Cove section in Utah, USA (Fig. 5a) and Wang *et al.* (2021) in a section in north China see Fig. 5b). Both were ratified by the International Subcommission on Ordovician Stratigraphy. There can, however, only be one GSSP, and the exactitude of correlations between these stratotypes and the GSSP may vary for whatever reason. The concept of auxiliary unit stratotypes has been suggested to partly mitigate these problems (Head *et al.* 2022).

The Ordovician internationally

The Subcommission on Ordovician Stratigraphy

Since its creation five decades ago, the Subcommission on Ordovician Stratigraphy has been one of the most active subcommissions, in particular first defining the currently used subdivisions and stratotypes for the system (see above) and secondly utilizing its chronostratigraphy in framing and resolving global research questions. As explained above, there has been a shift from the traditionally used British series to the currently used global stages, based on GSSPs, described from different parts of the world. The activities of the Subcommission, in particular the official symposia, are a testament to these activities. The First International Symposium on the Ordovician System (first ISOS) was organized (as part of a larger conference with Silurian colleagues) by Claude Babin (1934–2022) in Brest, Brittany, France (Babin 1971). It was followed by the second and third meetings in Great Britain (1974; proceedings published by Bassett 1976) and the USA (1977). Bruton (1984) published the proceedings of the IV International Symposium held in Norway in 1982. The fifth meeting was organized in St. Johns, Newfoundland, Canada, in 1988 (Barnes and Williams 1991). The proceedings of the next (sixth) symposium in Sydney, Australia, were published by Webby and Laurie (1992). Subsequent meetings were organized in Las Vegas (seventh ISOS, Cooper *et al.* 1995), Prague (eighth ISOS, Kraft and Fatka 1999), San Juan, Argentina (ninth ISOS, Albanesi *et al.* 2003), Nanjing, China (tenth ISOS, 2007, Li *et al.* 2007), Alcala de Henares, Spain (eleventh ISOS, Gutiérrez-Marco *et al.* 2011), Harrisonburg, Virginia, USA, (twelfth ISOS 2015, Leslie *et al.* 2015) and the last meeting was organized in Novosibirsk, Russia (thirteenth ISOS, 2019, Obut *et al.* 2019). The very strong international network of Ordovician researchers and their research is also documented in the Newsletter *Ordovician News* that is published annually since 1983, with the current issue, no. 39 published in 2022.

International Geoscience Programmes

A number of International Geoscience Programmes (formerly known as International Geological Correlation Programmes, IGCPs) have also been dedicated to the Ordovician. These IGCPs were organized in close relationship with the Ordovician Subcommission. The IGCP no. 410 (1997–2002) was dedicated to the 'Great Ordovician Biodiversification Event' (Webby *et al.* 2004*a*), whereas the subsequent IGCP no. 503 focused on 'Ordovician Palaeogeography and Palaeoclimate' between 2004 and 2009 (Harper *et al.* 2011). IGCP no. 653 (2016–21) analysed the 'Onset of the Great Ordovician Biodiversification Event', whereas the current project (IGCP no. 735, 2021–25), 'Rocks and Rise of Ordovician Life', continues to fill gaps in our knowledge of the Early Paleozoic biodiversification.

Consequences

The dividends of establishing a workable set of international series and stages, together with a range of more precise chronostratigraphic divisions, has proved immense and of immediate consequence. In addition, the global series and stages are now correlated with main regional chronostratigraphies (Bergström *et al.* 2009; Fig. 6). More accurate, precise and reproducible global studies were now feasible, capitalized by three IGCP projects (410, 503 and 653), closely tied to the work of the Subcommission. Estimates of changing global diversity were now a reality (Webby *et al.* 2004*b*) and a more global approach was possible for the two main events during the period, the Great Ordovician Biodiversification and the End Ordovician Extinction. In addition to the many recent publications on the Ordovician (listed in issues of Ordovician News) a range of thematic issues and volumes have been recently

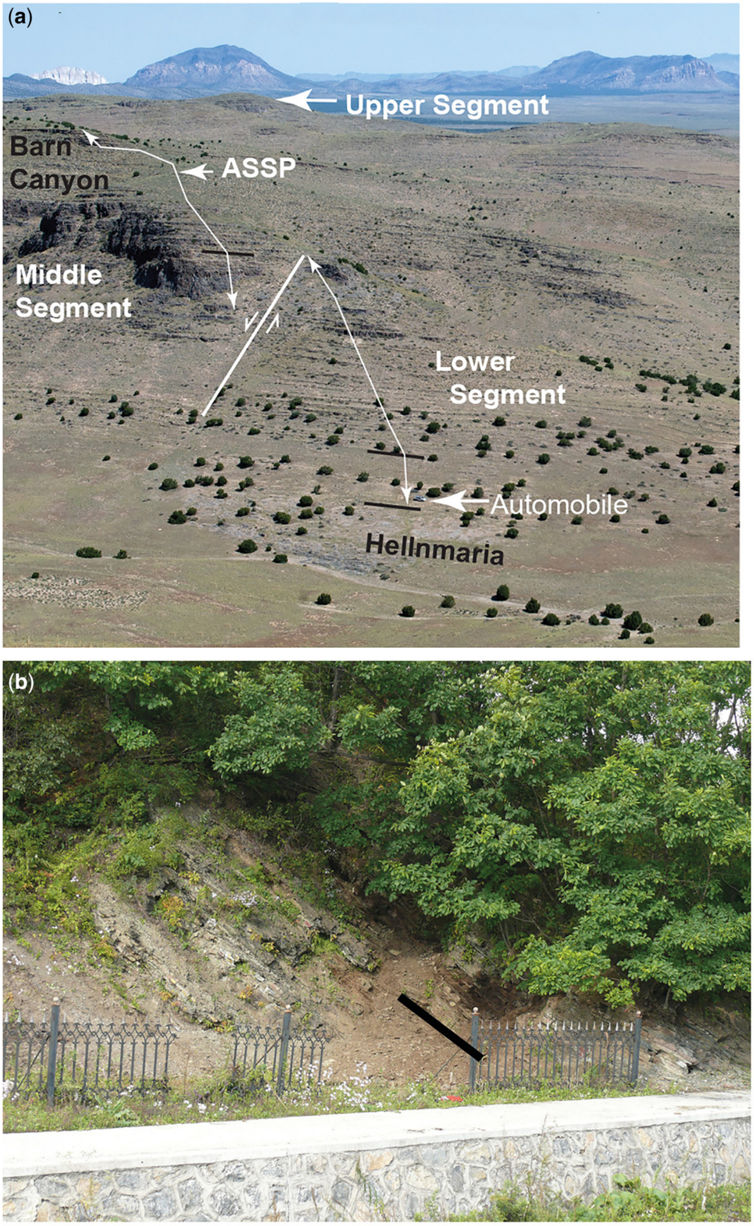

Fig. 5. Auxilliary Stratotype Sections and Points (ASSPs) for the base of the Ordovician System. (**a**) The ASSP for the base of the Ordovician System (and the base of the Tremadocian Stage) in Lawson Cove, Utah, USA (Miller *et al.* 2016). Photo courtesy of James Miller. (**b**) The ASSP for the base of the Ordovician System (and the base of the Tremadocian Stage) in the Xiaoyangqiao section, Dayangcha, North China (Wang *et al.* 2021). Photo courtesy of Svend Stouge.

published: Early Paleozoic palaeogeography and palaeoclimate (Munnecke and Servais 2007); Ordovician biogeography and biodiversity change (Owen 2008); Ordovician palaeoecology (Servais and Owen 2010); Ordovician and Silurian sea-water chemistry, sea-level and climate (Munnecke *et al.* 2010), Ordovician Earth System (Finney and Berry 2010), Early Paleozoic palaeobiogeography (Harper and Servais 2013), making use of BugPlates software, the context of the Great Ordovician

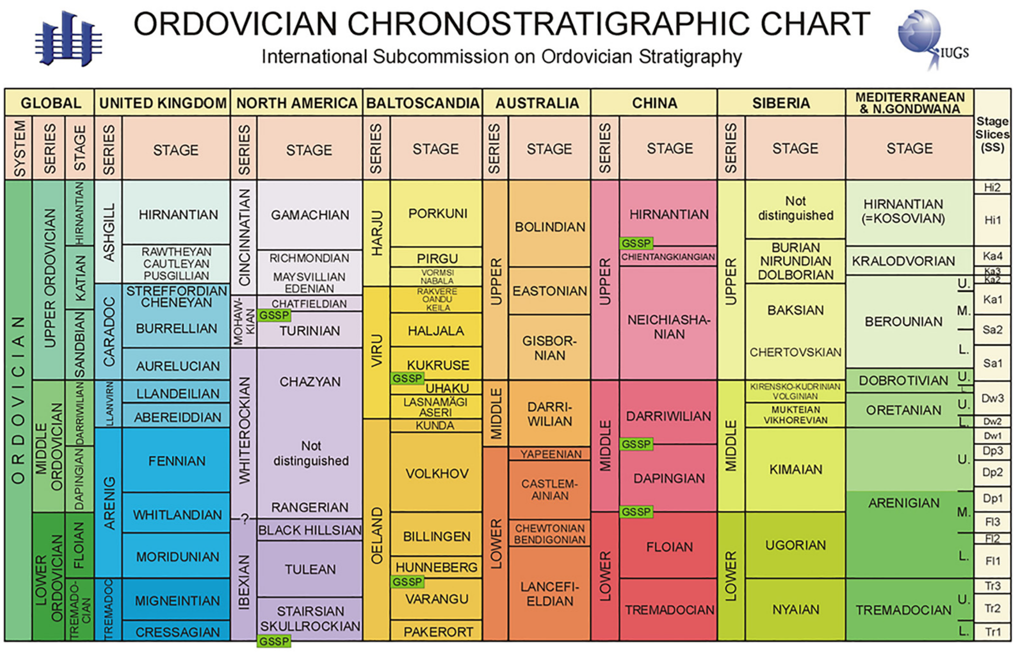

Fig. 6. Chart showing proposed correlation between the new global series and stages and regional chronostratigraphic units recognized in major outcrop areas of Ordovician rocks. Also shown are the stratigraphic positions of the stage slices (SS). The Siberian and Mediterranean/N. Gondwanan columns were compiled by Andrei Dronov and Juan Carlos Gutiérrez-Marco, respectively. The Global Boundary Stratotype Section and Point (GSSP) boxes in the North American column refer to the base of the Ordovician System and the base of the Katian Stage, respectively; those in the Baltoscandian column to the bases of the Floian and Sandbian stages, respectively; and those in the Chinese column to the bases of the Dapingian, Darriwilian, and Hirnantian stages, respectively. © International Commission on Stratigraphy.

Biodiversification Event (Harper and Servais 2018), the onset of the GOBE (Zhang *et al.* 2019) and a perspective on the GOBE (Stigall *et al.* 2020). These many studies have sharpened our focus on the importance of climatic and environmental change for the evolution of Early Paleozoic biotas while also identifying the need for the continued careful sampling of regional sections against a well-constrained biostratigraphy across a wide range of palaeolatitudes, correlated with regional chronostratigraphies. Many new geochemical proxies are now available to match our more refined biotic data, and cyclostratigraphy is providing the promise of orbitally tuning of many Ordovician successions.

In spite of advances in the global stratigraphy of the Ordovician System, not only local/regional stages but also regional series and subseries are still commonly referred to in many publications, in parallel with the internationally accepted subdivision of the Ordovician. With further refinements of the international stratigraphic standard and improved interregional correlations, such units may lose their practical value and only reflect the history of regional correlation standards.

Essential to our understanding of Early Paleozoic earth systems is the continued search for links and relationships between environments, ecosystems and evolution within a precise global chronostratigraphical framework; this we have now.

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Author contributions **DATH**: conceptualization (lead), investigation (lead), validation (equal), writing – original draft (lead), writing – review & editing (equal); **TM**: conceptualization (supporting), investigation (supporting), validation (supporting), writing – review & editing (supporting); **TS**: conceptualization (supporting), investigation (supporting), validation (equal), writing – original draft (supporting), writing – review & editing (equal).

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Data availability Data sharing is not applicable to this article as no new datasets were generated or analysed during the current study.

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