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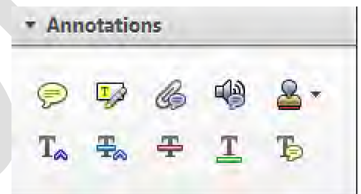


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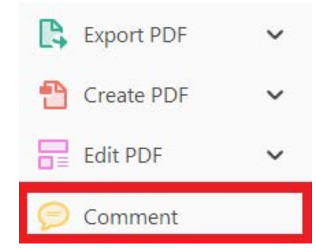


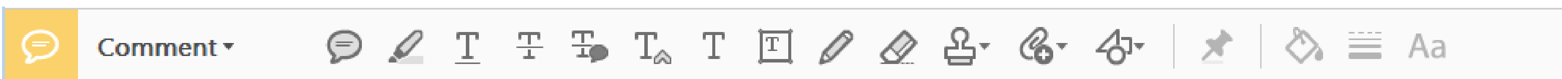


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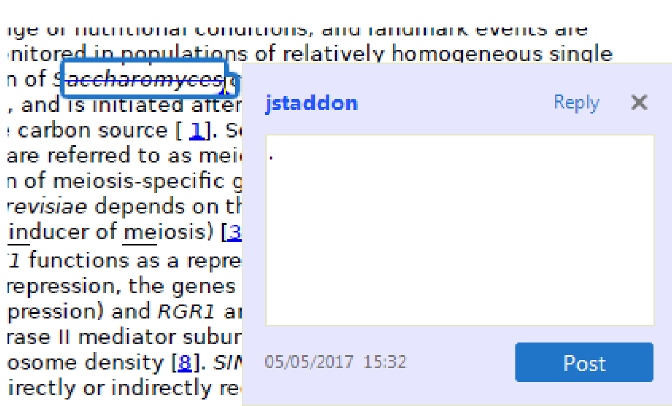


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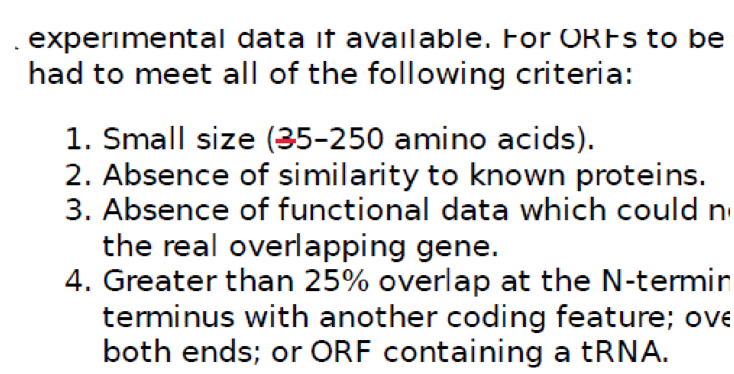


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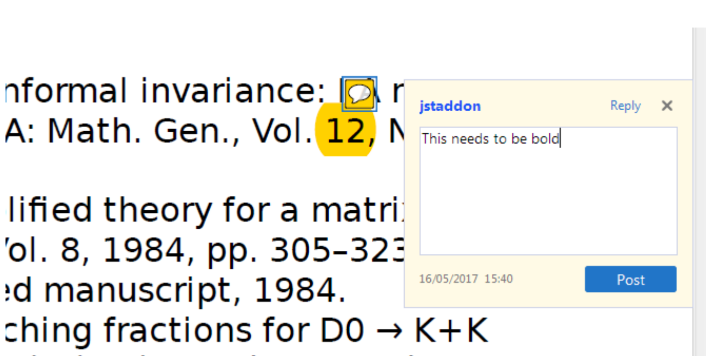


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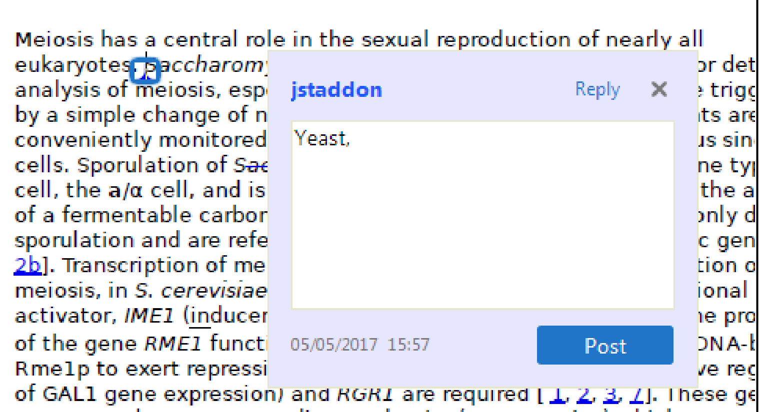

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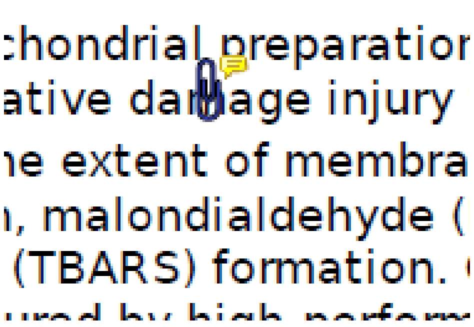


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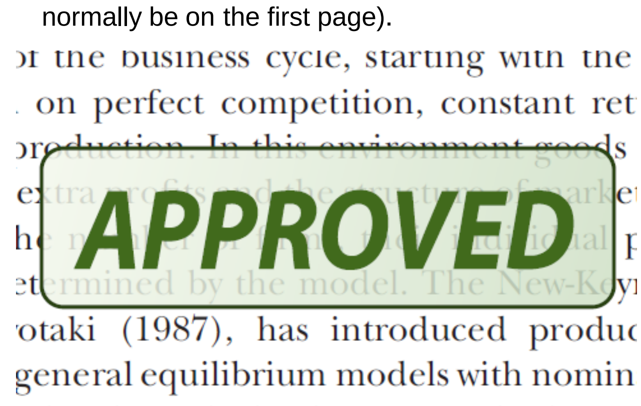


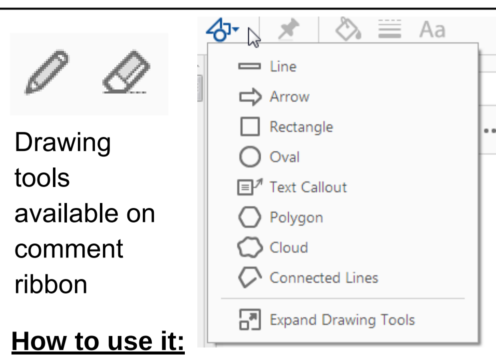


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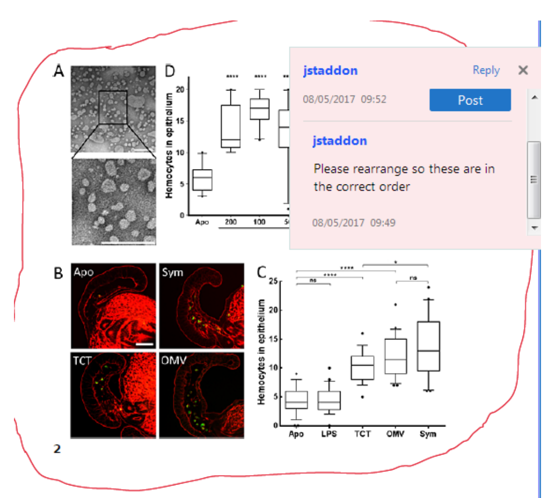


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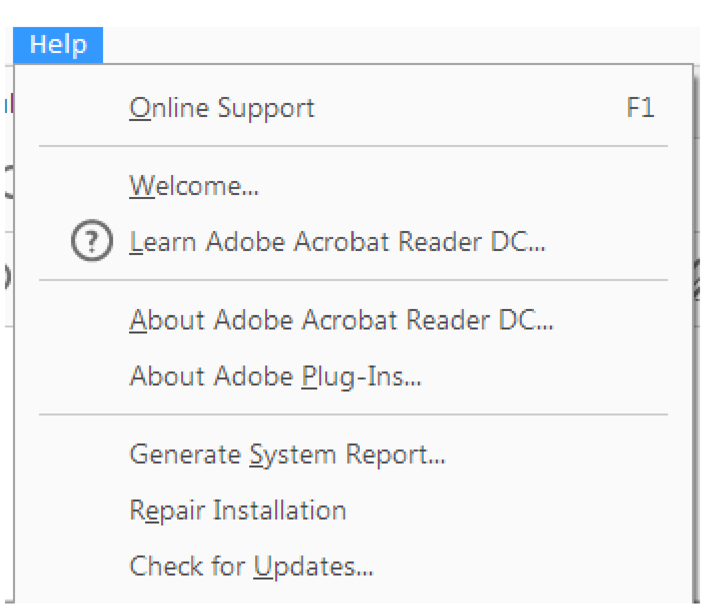

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# The contribution of fossils to chronostratigraphy, 150 years after Albert Oppel

MARCO BALINI, ANNALISA FERRETTI, STAN FINNEY AND SIMONETTA MONECHI

LETHAIA

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The 150th anniversary of the death of Albert Oppel (1831–65) provided the opportunity to celebrate this outstanding stratigrapher with a Thematic Issue dedicated to the importance of fossils for dating and correlating of sedimentary rocks. In this issue, we analyse Oppel's significant contribution to modern chronostratigraphy, before exploring the Phanerozoic through all its major fossil groups, to verify if fossils are still able to make a significant contribution to chronostratigraphy. The extraordinary merit of Oppel's work has been the demonstration that fossils can be used to sub-divide sedimentary sequences into zones, which in turn might be organized in higher chronostratigraphical units. The zone for Oppel is characterized by the distinctive fossil content, and his view strongly influenced the development of the standard chronostratigraphical scale for about one century, until the introduction, in the 1950s, of the log-based range chart as the common practice to study the fossil record of sedimentary successions. This approach forced the stratigraphers to shift the focus from the fossil content of the zones to their boundaries. This new view allowed for the introduction of new kind of zones with precisely defined boundaries based on bioevents and to the decline of the Oppel Zone. This turning point in the history of chronostratigraphy was fuelled by the International Commission on Stratigraphy programme of definition of the units of the International Chronostratigraphical Chart based on the boundary stratotype and point (GSSP) concept, which started in 1973. ☐ *Biostratigraphy, chronostratigraphy, fossils, global stratotype section and point, Oppel, phanerozoic, time, zone.*

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The 2nd International Symposium on Stratigraphy, STRATI 2015, held in Graz in July 2015 provided the opportunity to celebrate the 150th anniversary of the death of one of the most prominent scientists in the history of geology, Albert Oppel (1831–65), a specialist on Jurassic ammonoids who is widely considered as the father of modern bio- and chronostratigraphy. Surprisingly, despite the rich and varied programme of international symposia and workshops running at that time and devoted to different aspects of palaeontology and sedimentary geology, this important anniversary went apparently unnoticed and no special events were scheduled. At the end of 2014, we decided therefore to submit to the Organizing Committee of STRATI 2015 a proposal for a special session devoted to Oppel and to a discussion of the importance of fossils for dating and correlation of sedimentary rocks. The session was accepted and the publication of selected papers resulting from it was welcomed and encouraged by the editors of *Lethaia*. The invited contributions were deliberately wide-ranging in order to bring together apparently unrelated lines to assess the significance of diverse fossil groups through a long time span and to explore their potential for high-resolution stratigraphy and their modern contribution to chronostratigraphy. Our invitation was accepted by many specialists working on different fossil groups, representing the entire Phanerozoic stratigraphical record. The Oppel session was the most successful of the Graz Symposium both in terms of contributions and public attendance. It attracted 25 participants from 14 countries of all continents. Several speakers accepted our further invitation to contribute to this Thematic Issue. In the following sections, we briefly offer a starting point focusing on the extraordinary profile of Albert Oppel and present later the general framework of the Oppel Thematic Issue.

## Life and achievements of the 'Mozart of the Jurassic'

Born on 19 December 1831 in Hohenheim, Germany, the young Albert (Fig. 1) studied at Tübingen

*Fig. 1.* Portrait of Albert Oppel (1831–65).

University from 1851 to 53. At that time Friedrich August von Quenstedt, a specialist on Jurassic ammonoids, was in charge of teaching palaeontology. Albert Oppel earned his PhD in 1853 with a thesis *Ueber den mittleren Lias Schwabens*. From 1854 to 55 he visited numerous Jurassic localities in France, England, Switzerland and Germany, where he collected many fossils directly in the outcrops and he also studied museum collections. The results of these investigations were published in the outstanding monograph *Die Juraformation Englands, Frankreichs und des südwestlichen Deutschlands* (1856–58), in which he revealed a new method of using fossils for sub-dividing and grouping beds into zones and for their accurate time correlation over long (for that time) distances. He provided a Jurassic scale consisting of eight stages (‘Etagen’) and 33 zones (Fig. 2), mostly based on ammonoids. This scale was more finely sub-divided than the one published previously by d’Orbigny (1842), in which the Jurassic was sub-divided into ten stages and 25 zones. After the publication of this monograph, in 1858 Oppel moved to Munich, where he obtained habilitation as Professor. After a short stay in Gottingen (1859), he returned to Munich (1860) where he was appointed (1861) full professor in Palaeontology and curator of the Palaeontological collections at the *Bayerische Staatssammlung*. His reputation was rapidly increasing and he was invited to join the Bavarian Academy of Science in Munich, as well as other prestigious scientific societies. His bright and rapidly rising career was compared to that of Wolfgang A. Mozart (1756–91) by Callomon (1995), but it was tragically cut short at the age of 34 when he died of typhoid fever in Munich on 22 December 1865.

## Oppel’s revolutionary innovations to stratigraphy, in the middle of 19th century

Whereas the life of Oppel is relatively well known (e.g. Gümbel 1887; Mayr 1999; Schweigert 2005, 2008), his conceptual and philosophical approach to stratigraphy was somehow more difficult to decipher, probably also because of his early unexpected death. Several scientists have attempted to understand Oppel’s theoretical approach from his papers, and their analyses developed in two main directions. The first direction was focused on the analysis of Oppel’s contribution specifically to Jurassic stratigraphy. In particular, Arkell (1933, 1956a,b) was probably the most accurate analyst of Oppel’s scientific production, together with his student John Callomon (see Callomon 1995). The second direction was purely theoretical and consisted of the analysis of Oppel’s concept of the ‘zone’ in the framework of the development of the new branch of biostratigraphy (Dollo 1904 *fide* Diener 1925, p. 1; Dollo 1910, p. 384). In this regard, the most significant contributors were Diener (1918, 1919, 1925), Kleinpell (1938), Schindewolf (1950), Teichert (1958), Hancock (1977) and MacLeod (2005).

To better introduce the contributions and significance of this Thematic Issue, we try here to do something that has not yet been done, namely to emphasize Oppel’s innovations and his broad influence on biostratigraphy, from a historical perspective.

The fame of Oppel is related not only to his impressive monograph on the Jurassic, but also to the fact that in that contribution, published in his mid-20s, he introduced many innovations. They are listed and discussed one by one below, in an attempt to highlight their crucial importance and innovation within the context of mid-19th-century science.

### *The ‘zone’*

Oppel did not coin the term zone, an idiom that was already in use at that time (e.g. d’Orbigny 1842).

| Formationsabtheilungen. | Etagen *oder Zonengruppen.* | Zonen *(Lager oder Stufen, d. h. paläontol. bestimmbare Schichtencomplexe).* | Conybeare & Phillips. 1822. *England.* | Dufrénoy & Élie de Beaumont. 1848. *Frankreich.* |
|---|---|---|---|---|
| Oberer Jura oder Malm. | *Kimmeridgegruppe.* | Zone der Trigonia gibbosa. | Upper Division of Oolites. | Ét. supér. du système oolithique. |
| | | Zone der Pterocera Oceani. | | |
| | | Zone d. Astarte supracorallina. | | |
| | ? { | Zone der Diceras arietina. | { ? | Étage moyen du système oolithique. |
| | *Oxfordgruppe.* | Zone des Cidaris florigemma. | Middle Division of Oolites. | |
| | | Low.calc.grit & Scyphienkalke. | | |
| | | Zone des Amm. biarmatus. | | |
| | *Kellowaygruppe.* | Zone des Amm. athleta. | | |
| | | Zone des Amm. anceps. | | |
| | | Zone des Amm. macrocephalus. | | |
| Mittlerer Jura oder Dogger. | *Bathgruppe.* | Zone der Terebr. lagenalis. | Lower Division of Oolites. | Étage inférieur du système oolithique. |
| | | Zone der Terebr. digona. | | |
| | *Bayeuxgruppe.* | Zone des Amm. Parkinsoni. | | |
| | | Zone d. Amm. Humphriesianus. | | |
| | | Zone des Amm. Sauzei. | | |
| | | Zone des Amm. Murchisonae. | | |
| | | Zone der Trigonia navis. | | |
| | | Zone des Amm. torulosus. | | |
| Unterer Jura oder Lias. | *Thouarsgruppe.* | Zone des Amm. jurensis. | Lias. | |
| | | Zone der Posidon. Bronni. | | |
| | *Pliensbachgruppe.* (Liasien d'Orb.) | Zone des Amm. spinatus. | | |
| | | Obere Z. d. A. margaritatus. | | |
| | | Untere Z. d. A. margaritatus. | | |
| | | Zone des Amm. Davöi. | | |
| | | Zone des Amm. ibex. | | |
| | | Zone des Amm. Jamesoni. | | |
| | *Semurgruppe.* | Zone des Amm. raricostatus. | | Calcaire à Gryphées arquées ou Lias. |
| | | Zone des Amm. oxynotus. | | |
| | | Zone des Amm. obtusus. | | |
| | | Zone des Pentacr. tuberculatus. | | |
| | | Zone des Amm. Bucklandi. | | |
| | | Zone des Amm. angulatus. | | |
| | | Zone des Amm. planorbis. | | |

*Fig. 2.* Oppel's ~~chronostratigraphic~~ scale of the Jurassic, published at the end of 'Die Juraformation Englands, Frankreichs und des südwestlichen Deutschlands' (~~1858~~). The Jurassic (=Jura) is divided into eight stages (=Étagen) and 31 zones (=Zonen), one of them divided into two parts. The zones were mostly named after ammonoids (21 zones), but some of them were indexed by species from other groups such as bivalves (five zones), brachiopods (two zones), echinoderms (two zones) and gastropods (one zone). The middle portion of the 'Oxfordgruppe' was left without zonal assignment even though its fossil content was described in the text (Oppel ~~1858~~, pp. 673–689).

However, Oppel applied for the first time a way to use zones not only to sub-divide successions of beds (vertical stratigraphy) as previously done by d'Orbigny, but also to compare them over long distances (horizontal stratigraphy).

Oppel never defined what he meant by Zone, neither in his 1856–58 monograph nor in the following publications (e.g. 1862–63, 1863–65, 1866). He established a new way of recognizing and using zones in practice, not only as theoretical units. For Oppel, a Zone was a group of beds ('Schichten') defined by a list of characteristic species ('wichtigsten' or 'leitenden Arten'), including the one that is selected as the index of the Zone. A Zone may include also other species present in underlying or overlying zones. To identify a specific Zone in a new locality, it is enough to recognize one of its typical species, not necessarily the index. Because the lists of characteristic species of his zones are quite long (sometimes including even tens of taxa), the potential for correlations of this type of zone was formidable.

### *The importance of the accuracy of sampling*

Oppel learnt the importance of accurate sampling from Quenstedt. Based on precise (for that time) fieldwork, Oppel was able to distinguish species that are limited to a specific Zone, and species that can be found also in the underlying and overlying beds, thus encompassing two or more zones. He recognized that the former type of species is extremely valuable in Stratigraphy, and can be used to recognize zones, while the latter type does not have any special importance. This innovation was again highly important because by examining several hundred species throughout the entire Jurassic System, he was able to identify the marker species from the mass of available taxa. Today, we would refer to the two types of taxa as short-ranging and long-ranging, but Oppel never used this terminology.

### *Power of resolution*

Oppel was not the first stratigrapher to propose a sub-division of the Jurassic, but his chronostratigraphical scale, consisting of 33 zones, was founded on a wealth of information and it was ready to be used by anybody interested in dating or correlating Jurassic rocks. This was not always the case with the previous scales proposed for the Jurassic, such as that by von Buch (1839) and the already mentioned scale by d'Orbigny (1842).

Von Buch, who is included in the 'hall of fame' of the history of stratigraphy for the definition of the 'guide fossil' ('Leit-Muscheln'; von Buch 1839, p. 13, 16, 27), was the first to propose a threefold sub-division of the Jurassic. However, he did not provide any further sub-division as his 102 guide fossils were simply referred to the Lower, Middle or Upper divisions of the Jurassic (respectively 37, 31 and 34 taxa).

d'Orbigny (1842, 1852) defined the concept of stage by sub-dividing the Jurassic into ten units (1842), named after significant localities. This scale was further sub-divided into 25 zones (1842, 1852). However, the true power of resolution of his scale was 1/10 of the duration of the Jurassic, not 1/25, because he only provided a detailed list of taxa for the ten stages (1842, 1850, 1852), but he never showed the faunal composition of the proposed zones. This means that his zones were only theoretical units, nearly impossible to identify from the practical point of view due to the lack of supporting information.

### *Zone and facies*

Oppel demonstrated the possibility of recognizing the same zone in different facies, over distances of several hundreds of kilometres, by comparing the fossil assemblages. His discussions and comparison of faunal lists *vs.* facies (=formations) were already very detailed in *Die Juraformation* (1856–58), but they were best developed in his last monograph on the *Über die Zone des* Ammonites transversarius, published posthumously in 1866 (Fig. 3). However, the possibility of laterally tracing zones within different facies was limited, as Oppel pointed out many times in his monographs that this tracing depends on the lateral distribution of characteristic taxa. These considerations might sound really obvious today, in the 21st century, however, in the mid 19th century the fossil-based correlations of Oppel were revolutionary.

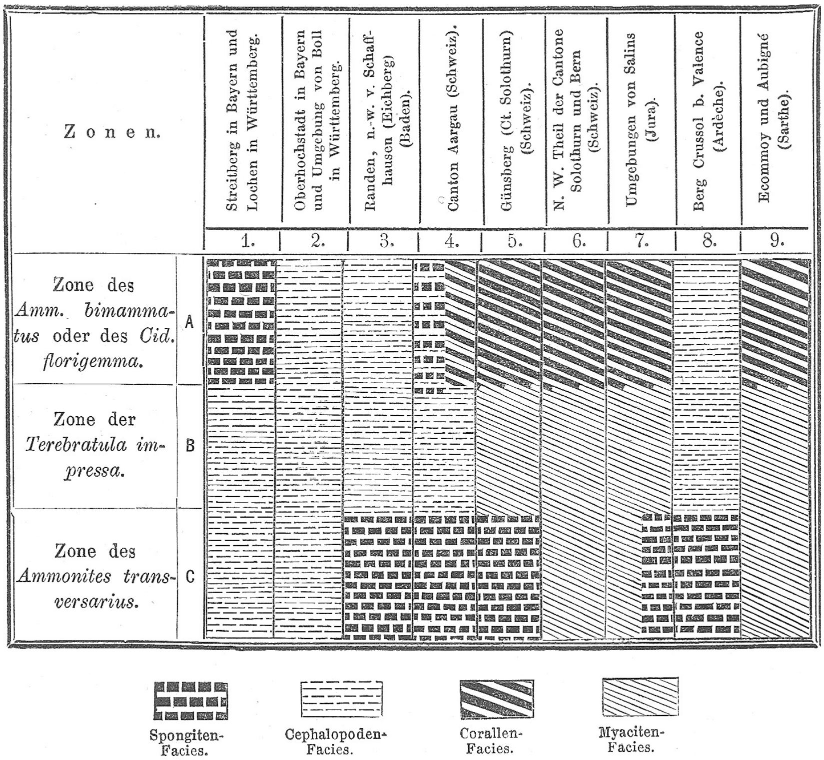
The first half of the 19th century was strongly influenced by Smith (1816), who had realized the practical utility of using fossil assemblages in support of the vertical sub-division of sedimentary successions based on lithology (*Strata Identified by Organized Fossils*, 1816) and defined a correlation procedure in which the lithology and fossil content together were used to recognize lateral continuity of the beds.

### *Biozone or chronozone?*

Both terms were coined much later, but there are no doubts that for Oppel the zone was strictly related to faunas. He in fact never mentioned the concept of time in his descriptions of zones. In this respect, and taking also into account the lateral distribution of a zone, strictly depending on the range of its characteristic species, this type of zone should be a biozone, in our present day knowledge. The idea of time, however, was implicit in the lateral tracing of the zones, that is in correlation. This is clearly stated by Oppel in the Preface (1856–58, p. 3), where he wrote that the components (=beds) of the same age in different profiles (=sections) are characterized by the same species.

## Oppel's influence

The zonation and correlation introduced by Oppel with *Die Juraformation* had an enormous impact on




39 *Fig. 3.* The correlation of Oppel's Tranversarius Zone across Germany (columns 1–3), Switzerland (columns 4–5) and France (columns 7–9) (Oppel 1866). This stratigraphical chart was revolutionary at that time because it demonstrated the greater potential of the correlations based on fossils in contrast to that of the correlations based on facies. Palaeontological evidence in support of this chart was listed and discussed by Oppel in his text.



a very wide scientific community. Specialists working on the Jurassic were directly pushed to use the zones described by Oppel. His influence also spread quickly to the development of the chronostratigraphy of other systems such as the Ordovician and Silurian (Lapworth 1879–1880; 5 Fig. 4) and the Triassic (Mojsisovics 1879, 1882). However, the subdivision of many systems was not as advanced as that of the Jurassic, for the simple reason that the Jurassic had been established much earlier (von Humboldt 1799) than the other systems (see summary provided by Callomon 1995) and its scale was improved ~~twice~~ before Oppel (von Buch 1839; 6 d'Orbigny~~, 1848~~). The effect of Oppel's work on these newly born systems was like the discovery of gold in a remote territory and many palaeontologists and geologists started a 'zone rush' to emulate Oppel. The knowledge of the sedimentary successions of these systems was not as good as that of the Jurassic, thus progress was not always easy. Stratigraphers were so much involved in identifying zones that sometimes they grouped together fossils from outcrops with fossils from debris, thus introducing imprecisions or errors both in the definition of zones and in their correlations (e.g. for the Triassic see Tozer 1984; Balini *et al.* 2010).

The use of Oppel's method was promoted by his students, some of whom became professors and moved to other universities in Germany and Austria. Among them, we can mention Ernst W. Benecke (1838–1917) who moved to the University of Strasbourg, Melchior Neumayr (1845–90) who became a professor at the University of Vienna, Georg J.C.U. Schloenbach (1841–70) who was first at the Geological Survey of Austria and later moved to Prague, and Wilhelm H. Waagen (1841–1900) who moved to India, then to the University of Vienna.

## The evolution of the concept of zone

The zone as conceived by Oppel, was the only type of zone used in stratigraphy for several decades – even if some Jurassic palaeontologists suggested new ways to improve the accuracy of the available scales. One of the most important contributors was Sydney Savory Buckman (1860–1929) another specialist on Jurassic ammonoids, who might be considered one of the fathers of biochronology (e.g. Callomon 1995, 2002). Buckman provided some new ideas and concepts, such has the hemerae (1893), as well as the distinction between faunizone and biozone (1902).

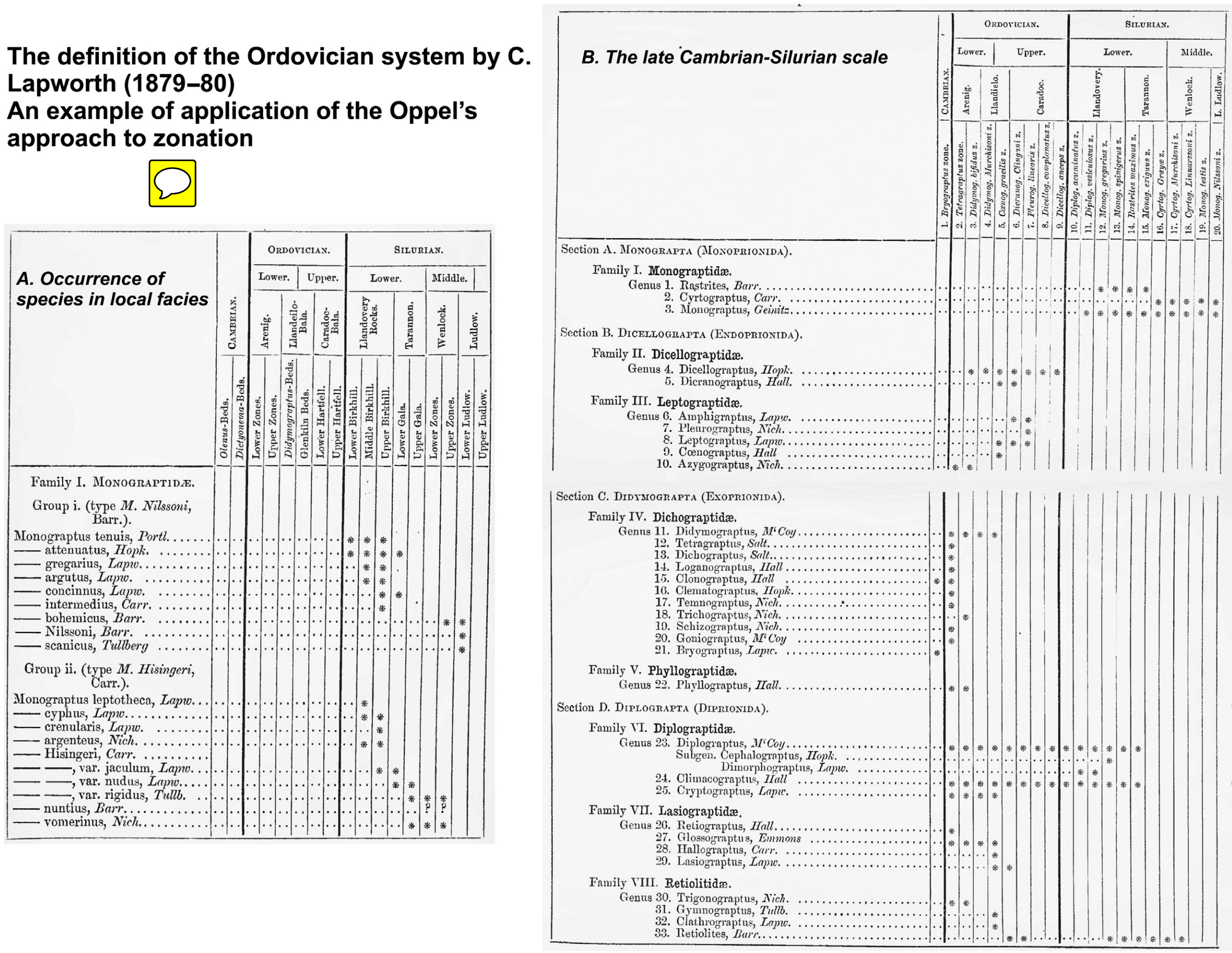



*Fig. 4.* One example of the influence of Oppel methods on the development of the 19th-century chronostratigraphy. The two sketches are from Charles Lapworth's historical paper on Rhabdopora (1878–80), in which the Ordovician System was officially introduced to solve the long-lasting controversy between Sir Roderick Impey Murchison and Adam Sedgwick on the Cambrian and Silurian systems. A, in this proto-range chart (Lapworth 1879–1880; table 10-*pars*), the occurrence of index graptolite species is plotted against lithological units. B, this figure (Lapworth 1879–1880, table 11) shows the distribution of ~~the~~ graptolite genera within the uppermost Cambrian-Silurian ~~chronostratigraphic~~ scale. This scale is based on 20 new zones, described in the text (pp. 196–202). For each zone, Lapworth reported the 'characteristic' species or genera or the unique combination of taxa. In all respects, this zonation perfectly matches Oppel's concept of zone: a rock unit based on its fossil content. As a consequence all of the chronostratigraphical units based on (Oppel) zones were defined on the fossil content, eventually combined with lithological boundaries.

Hemerae were conceived as chronological units based on the acme of one or more species (1893) representing the sub-divisions of ages (1902), thus they are not directly related to zones. A faunizone was intended by Buckman (1902, p. 557) as 'belt of strata, each of which is characterized by an assemblage of organic remains', thus in practice, this concept was very close to the Oppel zone. A biozone was proposed (p. 556) 'to signify the range of organisms in time as indicated by their entombment in the strata'.

Overall, the work of Buckman on the sub-division of the Jurassic was outstanding, but surprisingly, the impact of his new concepts was not that significant especially outside the community of Jurassic ammonoid specialists (see Sylvester-Bradley 1979; Page this issue; for a detailed analysis). His terminology was not adopted, and his definition of biozone was exactly equivalent to the definition of biochron provided by Williams, 1 year before (Williams 1901), then the latter had priority and was accepted in literature.

The most important innovation in biostratigraphy after Oppel was the introduction, between the 1930s and 1950s, of log-based range charts as the standard approach for studying the stratigraphical distribution of fossils. The merit for this innovation goes to the planktonic foraminiferan specialists Glaessner and Subbotina (e.g. Glaessner 1937; Subbotina 1947, 1950), who were working in the Caucasus, and to Cushman who was working in Trinidad (for a summary of his contribution see Todd 1950 and Henbest 1952). This new approach requires accurate sampling and emphasizes the relative position of the species with the precise identification of their first and last occurrences (FOs and LOs). These bioevents might be used to group and compare sedimentary layers, in addition to the traditional approach of studying their faunal content.

Previously, the range chart approach was followed by very few specialists, and not as a general rule. The general attitude of stratigraphers had been in fact to summarize data in tables where the taxa were plotted against the zones (Fig. 4). Oppel himself was quite accurate in showing rather detailed stratigraphical sections (mostly for the Lower Jurassic) with the synthetic faunal content of the fossil-bearing beds, but he never plotted the species on the logs, one-by-one and bed-by-bed.

The wide variety of options provided by the log-based range chart approach lead to an increase in the number of kind of zones that can be recognized by means of fossils and at the same time demonstrated the limitations of the Oppel Zone.

The American Commission on Stratigraphical Nomenclature (ACSN) included in 1957 in its fifth report two kinds of biozones: assemblage zone and range zone. This number was already enlarged in 1961, when the first edition of the *North American Stratigraphical Code* (ACSN, 1961) listed three kinds of biozones, namely the assemblage zone, the range zone and the concurrent range zone. This sub-division was confirmed in 1970 (ACSN, 1961). The chronozone was formally separated from the biozone only in the first edition of the *International Stratigraphic Guide* (Hedberg 1976), which also included a complete review of seven kinds of biozones, including the Oppel Zone. The review of the Oppel Zone by Hedberg (pp. 57–58) represents the best modern analysis of this Zone, but at the same time it is the prelude to its formal suppression from the list of the valid zones announced in the second edition of the *International Stratigraphic Guide* (Salvador 1996, p. 63).

## *No more Oppel Zones?*

The Oppel Zone is no longer accepted as valid, because it does not conform to the high standards of objective and univocal identification in the stratigraphical sections that are required in stratigraphy since the late 20th century.

Hedberg (1976) was very clear in listing the problems of Oppel zones, more than a century after their introduction. He stated (p. 58) that 'The Oppel Zone may be defined as a zone characterized by an association or aggregation of selected taxons of restricted and largely concurrent range, chosen as indicative of approximate contemporaneity. Not all of the taxons [sic!] considered diagnostic need to be present at any one place for the zone to be legitimately identified.' However, the Oppel Zone 'is a more subjective, more loosely defined, and more easily applied biozone than the concurrent – range zone'. The main problems are in the definition of its boundaries: 'The Oppel Zone is difficult to define empirically because judgement may vary as to how many and which of the selected diagnostic taxons need be present to identify the zone', and 'Boundaries of adjacent Oppel zones must often be placed within transition intervals, and different workers might well choose different positions'.

To best show the limitations of the Oppel Zone, Hedberg produced a figure (1976; fig. 8; see Fig. 5 herein) but did not explain, in the text or the caption, two crucial points, namely that: 1, the Oppel zones were never originally defined on log-based range charts, and their authors did not specify the positions of the FOs and LOs of the characteristic species; and 2, the figure shows the range chart of the taxa characteristic of two Oppel zones after their log-based bed-by-bed re-sampling, not from their original definition (Fig. 6). 8

This lack of explanations in support of Hedberg's Figure 8, together with mistakes on the understand- 9
ing of the historical framework of Oppel and Hedberg's contributions, led to a line of thinking (e.g. Berry 1977; McGowran 1986, 2005; Scott 2013) that considers the Oppel Zone as traditionally based on assemblages but also on boundaries (Berry 1977, p. 324; Fig. 1; McGowran 1986; 2006; Scott 2013, 10
p. 266) and the Hedberg's review as a true formalization of a zone that is not consistent with the concept of the other biozones as well as with chronozones (Scott 2013). The latter author (2013; p. 269) even came to the wrong conclusion that the equivocal status of Hedberg's Oppel Zone was the reason for the rejection of this zone by Salvador (1996).

## *Revision of Oppel zones*

The suppression of Oppel zones by Salvador (1996) was not a top-down decision made by the International Subcommission on Stratigraphical Classification (ISSC). It was based on more than 20 years of experience of field stratigraphers working on Oppel zones, on many fossil groups and many intervals of the Phanerozoic. The only realistic solution to the severe limitations of Oppel zones is to replace them by, or sub-divide them into more valid zones, in order to define accurately and univocally their limits and fossil content. This is not an easy task for many reasons (taxonomic issues, difficulty in sampling

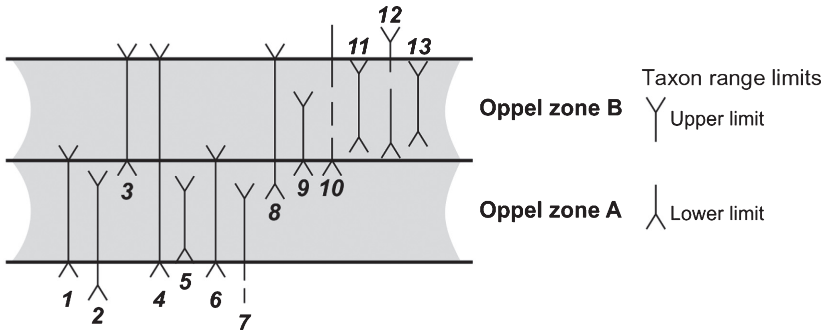



*Fig. 5.* Oppel zones according to Hedberg (1976) (redrawn from his fig. 8; numbers 1–13 for taxa added here). This figure shows the typical problematic situation that results from re-investigating Oppel zones by a log-based bed-by-bed sampling approach (see text for additional explanations and also Mönnig this issue). Bed-by-bed sampling of sections where Oppel zones are known to occur, inevitably reveals that the FOs and LOs of the characteristic species (‘wichtigsten’ and ‘leitenden Arten’ *sensu* Oppel 1856–58) are not coeval, and that the range of these species overlaps only in part. The drawing of the boundaries of the Oppel zones results highly subjective on range charts, as their position depends on which taxa are selected for this purpose. The cautious solution suggested by Hedberg (1976) was to mark the separation of adjacent Oppel zones within transitional intervals. Any other search for precise boundaries inevitably leads to a focus on bioevents, and this would transform the Oppel zones into interval zones. However, even in this case, the interpretation of the boundaries of these zones is not unequivocal. For example, in this figure, there are three options for the lower boundary of Oppel Zone A (FO of taxon 1, 2 or 5) and three options for the upper boundary of Oppel Zone B (LO of taxa 3, 4 and 8; LO of taxa 11 and 13; LO of taxon 12).

Colour online, B&W in print

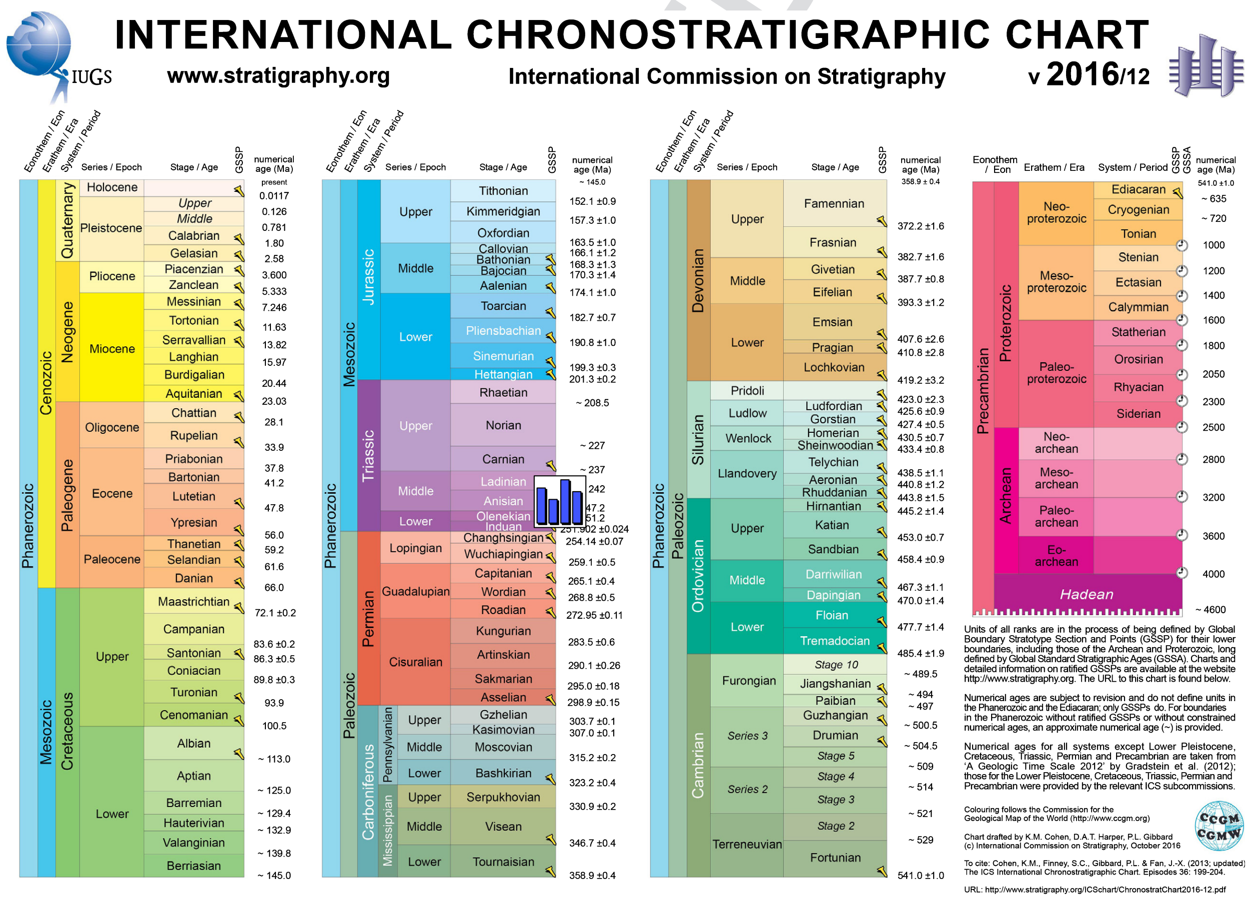



*Fig. 6.* The latest version of the International Commission on Stratigraphy Chronostratigraphic Chart (2016/12: http://www.stratigraphy.org/index.php/ics-chart-timescale; see Cohen *et al.* 2013, updated 2016).

classic localities, discrete fossil record, etc.) and has engaged many palaeontologists and biostratigraphers over the past 40 years, and the work is not yet over.

If the fate of the obsolete Oppel zones is to be replaced by other types of zones, the huge amount of literature that was published between the middle of

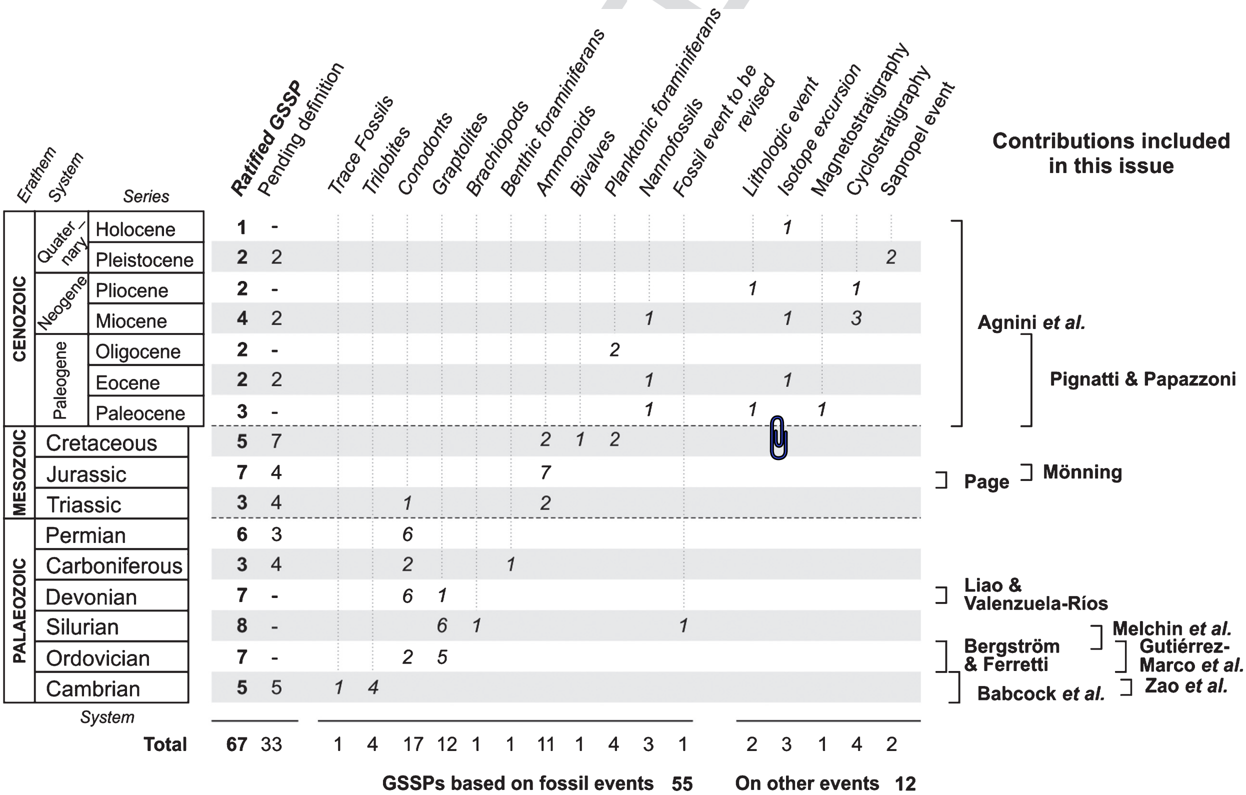
19th to middle of 20th century in the framework of Oppel zonations, consisting of hundreds of monographs on fossil invertebrates and several thousands of species, is still valid. Moreover, Oppel zones represent a fundamental part of the stratigraphical literature, consisting probably of hundreds of papers published between 1858 and 1970s. To understand and to use this huge amount of knowledge, it is crucial that the present and the future generations of stratigraphers have clear in mind the conceptual framework and the historical background behind Oppel zonation.

## Fossils and chronostratigraphy in the 21st century

Since the 1970s, stratigraphical investigations have been enriched by the addition of several new tools, usually first tested on DSDP, ODP and IODP coring projects. Magnetostratigraphy, cyclostratigraphy, chemostratigraphy, sequence stratigraphy and radioisotopic dating have been notably improved and they now perfectly integrate the traditional fossil tools. In this integrated and multidisciplinary framework, what is the role of fossils for high-resolution dating and correlations of sedimentary rocks in the 21st century? Addressing this issue is obviously complex, and the problem might be approached from different point of views. Here we present a top-down view, that is synthetic and objective but that at the same time provides an incomplete answer to the main question. Then we introduce a bottom-up view, which is documented by the papers of the contributors to Session S 01 of STRATI 2015, who have accepted our invitation to submit manuscripts for this Thematic Issue.

### *GSSPs based on fossils*

A measure of the continuing importance of fossils to 21st Century chronostratigraphical correlation is the number of Phanerozoic units defined by them in the *International Chronostratigraphic Chart* (Fig. 7)



| Erathem | System | Series | Ratified GSSP | Pending definition | Trace Fossils | Trilobites | Conodonts | Graptolites | Brachiopods | Benthic foraminiferans | Ammonoids | Bivalves | Planktonic foraminiferans | Nannofossils | Fossil event to be revised | Lithologic event | Isotope excursion | Magnetostratigraphy | Cyclostratigraphy | Sapropel event |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| CENOZOIC | Quaternary | Holocene | 1 | - | | | | | | | | | | | | | 1 | | | |
| CENOZOIC | Quaternary | Pleistocene | 2 | 2 | | | | | | | | | | | | | | | | 2 |
| CENOZOIC | Neogene | Pliocene | 2 | - | | | | | | | | | | | | 1 | | | 1 | |
| CENOZOIC | Neogene | Miocene | 4 | 2 | | | | | | | | | | 1 | | | 1 | | 3 | |
| CENOZOIC | Paleogene | Oligocene | 2 | - | | | | | | | | | 2 | | | | | | | |
| CENOZOIC | Paleogene | Eocene | 2 | 2 | | | | | | | | | | 1 | | | 1 | | | |
| CENOZOIC | Paleogene | Paleocene | 3 | - | | | | | | | | | | 1 | | 1 | | 1 | | |
| MESOZOIC | Cretaceous | | 5 | 7 | | | | | | | 2 | 1 | 2 | | | | | | | |
| MESOZOIC | Jurassic | | 7 | 4 | | | | | | | 7 | | | | | | | | | |
| MESOZOIC | Triassic | | 3 | 4 | | | 1 | | | | 2 | | | | | | | | | |
| PALAEOZOIC | Permian | | 6 | 3 | | | 6 | | | | | | | | | | | | | |
| PALAEOZOIC | Carboniferous | | 3 | 4 | | | 2 | | | 1 | | | | | | | | | | |
| PALAEOZOIC | Devonian | | 7 | - | | | 6 | 1 | | | | | | | | | | | | |
| PALAEOZOIC | Silurian | | 8 | - | | | | 6 | 1 | | | | | | 1 | | | | | |
| PALAEOZOIC | Ordovician | | 7 | - | | | 2 | 5 | | | | | | | | | | | | |
| PALAEOZOIC | Cambrian | | 5 | 5 | 1 | 4 | | | | | | | | | | | | | | |
| | System | Total | 67 | 33 | 1 | 4 | 17 | 12 | 1 | 1 | 11 | 1 | 4 | 3 | 1 | 2 | 3 | 1 | 4 | 2 |

GSSPs based on fossil events 55 On other events 12



*Fig. 7.* Summary of primary events of the GSSPs of the stages of the Phanerozoic included in the ICS CC 2016/12 (Fig. 6). The right part of this figure shows also the intervals that are discussed by the contributors to this volume. The definitions of the stages of the Cenozoic, on average, are supported by many more additional marker events from different tools than those currently available for the Palaeozoic and Mesozoic. It should be noted that focusing only on the primary event may offer a partial view of these GSSPs. For instance, the base of the Paleocene Series and of the Paleogene System is technically drawn at the base of the 'boundary clay' in the El Kef section, Tunisia (Molina *et al.* 2006). The lithologic change co-occurs with evidence of a meteorite impact (iridium anomaly, Ni-rich spinel in crystals) and the mass-extinction of planktic foraminiferans and nannofossils. These lines of evidence are more important for the correlation than the mere lithologic event.

produced by the International Commission on Stratigraphy.

The *International Chronostratigraphic Chart* with its numerical calibration is the official Time Scale of the IUGS. Every chronostratigraphical unit included in this chart, from stage level upward, must be defined by the selection of an appropriate Global Boundary Stratotype Section and Point (GSSP; Hedberg 1976; Salvador 1996; Remane *et al.* 1996; Walsh *et al.* 2004). A GSSP is defined by a primary event, accompanied by as many additional events (proxies) as possible. The procedure for the selection of the GSSPs is very complex and time-consuming, because most of the units of the chronostratigraphical chart were introduced long time ago, based on the knowledge then available but no longer up-to-date or sufficiently precisely defined. For this reason, the selection of the GSSP usually implies a review of the original definition in the light of the new knowledge. This is usually done through the re-examination of the best sections, new samplings for facies characterization and for fossils, as well as for as many 'new' tools as possible. Biostratigraphical investigations often have to face complex taxonomic issues that might require the taxonomic revision of the most significant fossil groups.

Most of the activities of the Working Groups (WG) of the sub-commissions of the ICS actually consist in the search for and comparison of candidate events, in term of their isochroneity and correlatability over long distances. The event that best fulfils the two requirements is selected as a primary marker, while the other candidate events become the additional markers. There is no restriction on the number of additional marker events necessary to support the primary marker, in order to leave maximum freedom and flexibility to the WGs. This results in a wide range of solutions, with GSSPs supported by 2–3 or up to 6–7 additional markers.

In order to provide a uniform picture of the state of the art of the contribution of fossils to the definition of the *ICS Chronostratigraphic Chart of the Phanerozoic*, we have limited our examination to the primary marker events. The counting of additional events would have provided non-homogeneous data. The primary events of the GSSPs of the stages of Phanerozoic thus far ratified are shown in Figure 7. Of 67 ratified GSSPs, 55 (82%) are based on fossil events, and 12 (18%) are based on other events, such as ~~lithologic~~ changes, stable isotope excursions, magnetostratigraphy, cyclostratigraphy, sapropels. It is worth noting that the 12 GSSPs that are not based on fossils all belong to the Cenozoic, in which they represent the 75% of the ratified GSSPs. Most of these GSSPs cannot be correlated, however, without biostratigraphy which is used as the first step in recognizing the boundary interval in other sections. All the stages and higher chronostratigraphical units of the Palaeozoic and Mesozoic thus far ratified are based on fossil events. In term of fossil groups, conodonts are the most often used group, as they provide primary events for 17 GSSPs, followed in decreasing order by graptolites (12 GSSPs), ammonoids (11 GSSPs) and by trilobites (4 GSSPs).

### *Fossils and chronostratigraphy behind the GSSPs*

Statistics on the GSSP can only provide a partial picture of the usefulness of fossils in modern chronostratigraphy. Our idea, since the submission to the Organizing Committee of STRATI 2015 of the proposal for a session, was to involve as many specialists as possible from very different time intervals and working on diverse fossil groups. Our call for contributions had no restrictions: papers related to modern definition of zones; history of bio- and chronostratigraphy; history of zones; fossil-based chronozones in the Geological Time Scale; theory and practice in modern definition of zones; time calibration of bioevents; evolution, evolutionary rates and power of resolution of the most important fossil tools; fossils and long distance correlations were all solicited and welcome. As with many topics, sometimes examining the data available from another perspective can produce a new solution to a much-debated dilemma.

## Papers in this issue

A first group of papers of the Thematic Issue focuses on the heritage of Albert Oppel in modern ~~S~~tratigraphy. Page revisits Oppel's contribution to the sub-division of the Jurassic in the framework of a comprehensive review of the history of the chronostratigraphy of this system. Ammonoid zones ('Standard Zone' *sensu* Arkell ~~1993~~), which provided 11 support for the best-refined sub-division of the Jurassic for nearly one century after Oppel, are now sub-divided into biohorizons (*sensu* Page 1995; see also Page this ~~volume~~). This kind of subzonal unit is defined as the smallest consecutive division of a sedimentary succession that can be recognized on the basis of a single index-species or assemblage within a maximum development of a stratigraphical interval. Biohorizons allow for high-resolution sub-divisions and correlations that are required by the 21st-century chronostratigraphy.

Mönnig (this issue) discusses the evolution and significance of Oppel's 'Macrocephalusbett' as a chronostratigraphical unit in the Middle Jurassic, and the resolution of the lower Callovian with ammonites, which has enabled the definition of eight subzones and 20 biohorizons. This contribution is an excellent example of the difficulties of finding a univocal definition of an Oppel Zone. Pignatti & Papazzoni (this issue) review the history and magnitude of the Oppel Zone, comparing the Jurassic zonal ammonite biostratigraphy with the current biostratigraphy of Palaeogene–Miocene larger foraminiferans, the Shallow Benthic Zones (SBZ), where Oppelian (e.g. nummulitids, alveolinids) and non-Oppelian (e.g. based on orthophragmines, lepidocyclinids, miogypsinids) biozones are in use and a novel integrated research programme is envisaged.

Further contributions review the significance of specific fossil groups in specific parts of the stratigraphic column.

Babcock *et al.* (this issue) review the global use of trilobites in biostratigraphical and chronostratigraphical studies that have led to the development of the global series and stage nomenclature for the Cambrian System. Of the two series and five stages now ratified, apart from the Terreneuvian Series/Fortunian Stage base defined on a trace fossil, each of the other defined stage bases is identifiable primarily by the first appearance of a cosmopolitan agnostoid species. Specific intervals of the Cambrian are analysed in a more regional perspective, in particular Zhao *et al.* (this issuea,b) focus on the boundary between Series 2/Series 3 in South China by the succession of three trilobite zones.

A new global series and stage classification of the Ordovician and mainly based on graptolites and conodonts has been recently summarized (Bergström *et al.* 2009). Bergström & Ferretti (this issue) revisit the biostratigraphical sub-division of the Ordovician by means of conodonts and propose a comparison between conodont zone classifications over the entire System in six regions (Baltoscandia, North America, Siberia, North China, South China and Argentina). The great importance of conodonts in Ordovician biostratigraphy is shown by the fact that they are used for the definition of two of the seven global stages, and seven of the 20 stage slices, now recognized within this System. Gutiérrez-Marco *et al.* (this issue) focus on the Ordovician of the Bohemo-Iberian (Mediterranean) area, located at that time at high latitudes and where the dominance of shallow-water taxa (trilobites, brachiopods, molluscs and echinoderms) coupled with the scarcity of graptolites and conodonts has so far hindered the use of the formal global chronostratigraphy. By updating an impressive quantity of available palaeontological data, the regional correlation scheme in use in Southern Gondwana is related to the global Ordovician chronostratigraphy.

Melchin *et al.* (this issue) apply the relatively newly developed method of quantitative stratigraphical correlation of Horizon Annealing to the study of the GSSPs at and adjacent to the Ordovician/Silurian boundary. By this method, graptolite occurrence data have been analysed from 27 sections from four plates spanning the uppermost Ordovician to the lowermost Silurian, including the GSSP in China of the Hirnantian Stage and the GSSP of the base of the Rhuddanian Stage (base of the Llandovery Series and of the Silurian System) in Scotland. The resulting average temporal resolution of 319 kyr is comparable to that achieved by current radioisotopic dating methods and is approaching the range of that needed to test hypotheses of orbitally driven cyclicity.

Conodonts proved to be fundamental also in the Devonian for the threefold sub-division of the Givetian into the Lower, Middle and Upper Givetian sub-stages. Liao & Valenzuela-Ríos (this issue) revise this historical sub-division which was accomplished by the conceptual evolution from a stage based on almost a unique Zone to one with ten zones, mostly based on pelagic conodont taxa. An alternative biostratigraphical sub-division for the Lower and Middle Givetian based on shallow-water faunas is discussed and correlated with the standard one.

Agnini *et al.* (this issue) explore the role of calcareous nannofossils in chronostratigraphy during the Cenozoic. After an explosive evolution of related research starting from the 1950s, mostly due to the availability of deep-sea sediment cores from ocean drilling projects, this group is achieving an increasingly prominent role in biostratigraphy and correlations.

As a whole, the contributions presented in this Oppel Thematic Issue are puzzle frames, perfectly integrated with each other, that explore different time-windows of the Phanerozoic, from the Cambrian to the Holocene (Fig. 7, right part) by the use of all major marine index fossil groups (conodonts, graptolites, trilobites, ammonoids, calcareous nannofossils and benthic foraminiferans), sometimes overlapping diverse organisms in the investigation of the same time-frame. Time-stratigraphical resolution is quite variable in the assorted methodologies here described, from a single Biozone to an entire System. For many papers, this study has represented an occasion to go through decades of available bio- and chronostratigraphical data. These papers stand as a fundamental and objective evaluation of the actual significance of many fossil groups in modern Stratigraphy. At the same time, and for the same reason, they represent as well an exciting starting point for a real high-resolution integrated approach. Each of the articles that follow is, in other words, a clear signal and firm documentation that fossils still contribute to chronostratigraphy, 150 after the death of Albert Oppel.

*Acknowledgements.* – We thank in particular Werner Piller and the co-organizers of the STRATI 2015 Meeting in Graz for accepting our proposal to explore this 'old-style' topic within such a broad forum. Thanks are also due to Kevin Page for his memorable keynote talk. We thank Peter Doyle, Dave Harper, Alan Owen and Brooks Britt for having supported our idea and for believing in us even more than we did. Special acknowledgements are due to all Symposium participants and to the authors of the individual research papers for having accepted our challenge, for their hard work and for their efforts in submitting their contributions. We are especially grateful to all the scientists who have reviewed the papers in this volume for their generosity both of their time and expertise. The manuscript has been improved by suggestions from Kevin Page, Johannes Pignatti and Isabella Premoli Silva, as well as by the accurate readings of Alan Owen and an anonymous reviewer. A special thanks finally to Massimo Barbieri for creating the Oppel web page; to Cabri photo, Frank Kovalchek, Chris Martino, Diego Pinetti, psyberartist, Rene Rivers, Michael Seljos and www.fossilmuseum.net for sharing their photographs (session flyer and web page); and to the full Lethaia staff for the editorial help in bringing this project to reality.

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