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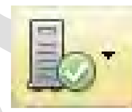
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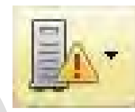
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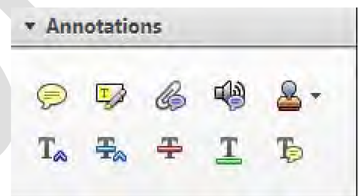

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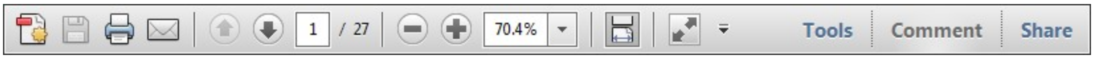

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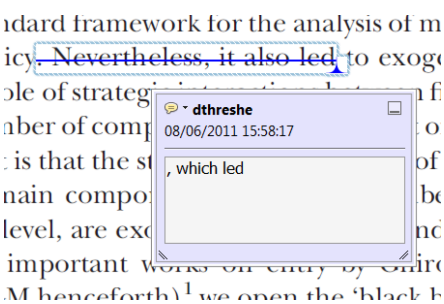

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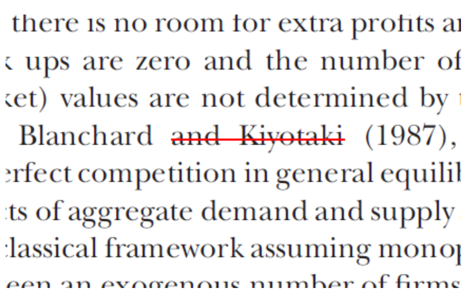

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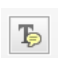

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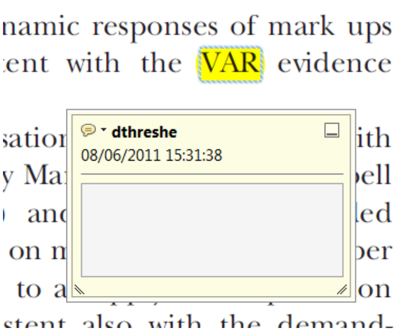

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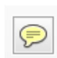

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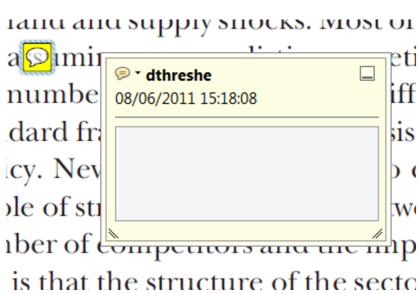

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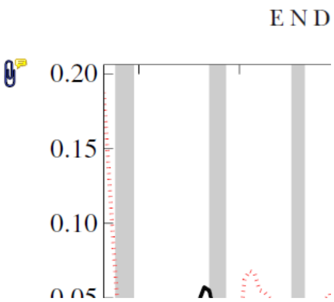

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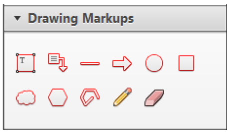

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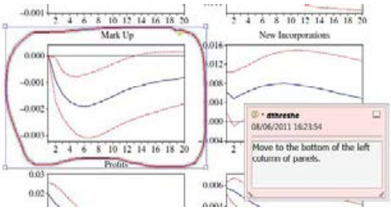

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Oppelzones and their heritage in current larger foraminiferal biostratigraphy

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The Oppelzone remains a controversial topic in stratigraphy, despite the attempts to systematize biozonal units in the *International Stratigraphic Guide* (ISG). In the first edition of the ISG, the Oppelzone was regarded as a particular kind of biozone, although with boundaries were recognized as 'difficult to define empirically'. This is probably the main reason why the Oppelzone was removed from the second edition of the ISG. Here, we review briefly the history and significance of the Oppelzone, starting from Jurassic zonal biostratigraphy as introduced by Oppel himself, and based mainly on ammonites, to its present usage, distinguishing the multiple meanings of the unit – biostratigraphical, chronostratigraphical, or even as a time interval. We review the Oppelzone as integral part of the current biostratigraphy of Palaeogene–Miocene larger foraminifera (the Shallow Benthic Zones, SBZ). Here, different species concepts in individual systematic groups result either in Oppelian (e.g. nummulitids, alveolinids) or non-Oppelian (e.g. lepidocyclinids, miogypsinids and in part orthophragmines) biozones. In addition, various regional larger foraminiferal zonations have been established. These different kinds of biozones are subsumed under the biochronostratigrapic SBZ system in a similar way as regional ammonite zonations are integrated in the standard ammonite zonation. To overcome issues of fuzzy-defined boundaries, a novel research programme is needed to (1) establish the most suitable markers for biozonal boundaries; (2) enhance correlation with different systematic groups (especially planktonic foraminifera and calcareous nannofossils) and with other stratigraphical tools (magnetostratigraphy, radiometric dating, isotopic stratigraphy, etc.); and (3) extend morphometric criteria wherever possible to recognize the markers themselves. ☐ *Biostratigraphy, chronostratigraphy, larger foraminifera, Oppelzone, Palaeogene.* 3

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Contrary to common opinion – as set forth in international stratigraphical guides and national codes – Oppelian zones, whether biostratigraphical or chronostratigraphical, are still currently employed in the stratigraphical use of important fossil groups, such as Mesozoic ammonites and Cenozoic larger foraminifera. The primary aim of this article was to discuss the different interpretations that have been put forward on the subject of Oppelzones, highlighting similarities and differences in these two groups. After addressing this issue, we review the current state of larger foraminiferal biozonation and biochronology and discuss future perspectives.

The dual nature of Oppelzones

Albert Oppel (1831–1865) is remembered as one of the founders of the discipline of biostratigraphy or zonal stratigraphy, as applied in his *Juraformation* (1856–1858) (Hancock 1977). A comprehensive review of his outstanding scientific work is given in Balini *et al.* (2017). Yet, Oppel's zonal concept, 4 interpreted and named in different ways, such as 'Oppel's zone' (Arkell 1956), 'Oppel zone' (e.g. Salvador 1994), 'Oppel-zone' (Hedberg 1976), 'Oppelian Zone' (Callomon 1994), 'Oppelzone' or 'oppelzone' (e.g. Carter 2007), 'Oppel fossizone' (Walsh 1998) and 'Oppel biochron' (Walsh 1998), has given rise to radically different interpretations.

These different interpretations arise from a basic dichotomy, that is whether Oppel's zone (hereafter: Oppelzone) should be considered as a particular kind of biozone (Hedberg 1976), or as a particular kind of chronostratigraphical (biochronological) unit (e.g. Arkell 1956; Callomon 1994, 1995; Fig. 1). Arkell (1956, p. 5) even hinted at a third interpretation, namely that an Oppelzone could be a time interval, although this inference is not discussed further here, because, as stated earlier by the same author, 'before 1893 (. . .) we find no attempt to formulate any strictly chronological ideas, or to

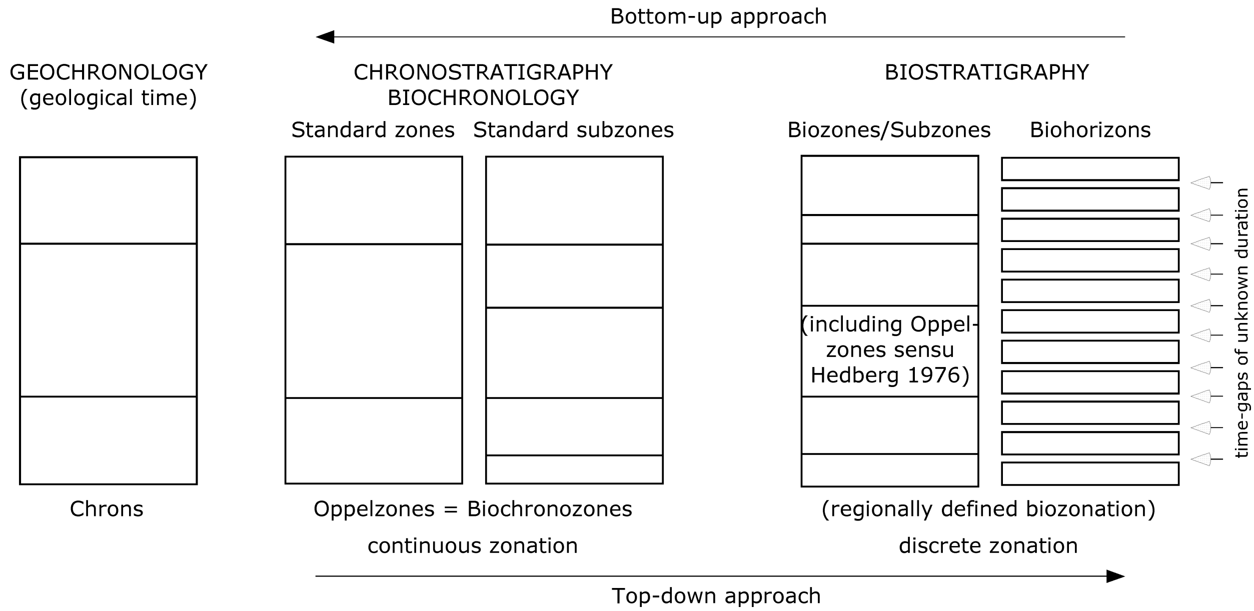

Fig. 1. Bottom-up or top-down approaches to Oppelzones in ammonite biostratigraphy.

construct a time-scale independent of strata (...). No vocabulary for any such conceptions existed' (Arkell 1933, p. 19).

In the same work, Arkell (1933, p. 17) defined the Oppelzone as a biozonal unit, that is as 'a bed or group of beds, identified by palaeontological criteria (by a fossil or an assemblage of fossils)'. This definition is very broad, because it accommodates most kinds of biozones, as presently understood; also, it suggests that an Oppelzone may be characterized either by a single taxon, or by an assemblage of taxa, albeit there is little doubt that in Arkell's (1933) interpretation emphasis is on an assemblage. Finally, Arkell (1933) emphasized that Oppelzones should be considered as biostratigraphical and not chronostratigraphical units, although later he espoused a different view (Arkell 1956).

The concept of Oppelzone as a particular biostratigraphical unit was further circumscribed by Hedberg (1976, p. 58) in the first edition of the *International Stratigraphic Guide* (ISG). Hedberg considered the Oppelzone as one of the main categories of range biozones, that is 'a zone characterized by an association or aggregation of selected taxons [sic] of restricted and largely concurrent range, chosen as indicative of approximate contemporaneity. Not all of the taxons considered diagnostic need be present at any one place for the zone to be legitimately identified. The lower part of the zone is commonly marked largely by first appearance and its upper part by last appearance of certain taxons. The body of the zone is marked largely by concurrences of the diagnostic taxons.' He also recognized its peculiar subjective character, inasmuch an Oppelzone 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' (Hedberg 1976, p. 58).

Considered as biostratigraphical units, Oppelzones possess several distinctive features (Sigal 1984; Pignatti 1998). They are (1) part of an ideal succession of superposed key faunas, representing an ideal reference; (2) a zonation based upon Oppelzones is a discrete zonation, that is, adjacent biozones are separated by intervals of unspecified length; (3) not formally defined by their base, being discrete, non-overlapping concurrent-range zones defined upon the loose co-occurrence of an assemblage of taxa; and (4) they may include correlative vicariant taxa present in other regions, where the index taxa of the original key faunas are absent. Basically, all shallow-water fossil zonations are discrete and Oppelian in essence, because of the fossil record along continental margins, where sea level change and depositional patterns produce a discontinuous record, thus preventing the recognition of reliable first and last occurrences.

In the second edition of the ISG (Salvador 1994) and its abridged version (Murphy & Salvador 1999), the Oppelzone was discarded because it was considered 'not (...) to correspond consistently to any one kind of biozone' (p. 63), or not even mentioned. Similarly, both the North American Stratigraphic Code (2005) and the Stratigraphic Code of Russia (Zhamoida 2006) do not mention the Oppelzone among biostratigraphical units (which they treat summarily), although it would appear to fit within their concept of assemblage biozone. There are only few national codes or guides in which the Oppelzone is mentioned as one of the kinds of biozones, for example in Norway (Nystuen 1989), where it is synonymized with concurrent-range zone. The explicit use of Oppelzones as biostratigraphical units, as employed in Mesozoic ammonite stratigraphy and in Cenozoic larger foraminiferal zonation, is uncommon in other taxonomic groups. Exceptions include occasional examples in spores (Streel *et al.* 1987), radiolarians (Guex *et al.* 2015) and conodonts (Paull 1983); among vertebrates, the Land Mammal 'Ages' are conceptually Oppelzones, as explicitly stated by Walsh (1998). There are several reasons why the use of Oppelzones is so rare. (1) Their boundaries are undefined; as they are defined by their characteristic assemblages and not by their lower and upper limits, they are intrinsically more subjective and less appealing than continuous zonations especially in high-resolution biostratigraphy. (2) The distinction between assemblage zones, concurrent-range zones and Oppelzones has been often considered tenuous (Johnson 1979) or non-existent. Often, the Oppelzone has been considered as subcategory of the assemblage zone or the term assemblage zone has been used in its place, a circumstance which we consider rather unfortunate in the light of the clear definition of this kind of zone in Hedberg (1976). (3) Their recognition is rarely provided for in recent stratigraphical codes and guides, upon which most biostratigraphers rely, and this may actually have inhibited their use. (4) Oppelzones are used in groups that are taxonomically diverse, with many genera and species (ammonites) or species-rank taxa (larger foraminifera).

In recent years, however, there have been some advocates for the reintroduction of Oppelzones as biostratigraphic units (Pignatti 1998; Walsh 1998, 2000; McGowran 2005; Carter 2007), or as biochrons (Walsh 1998).

As to the alternative view, that is the Oppelzone as a chronostratigraphical unit, in our opinion, it is necessary to refer to the use of the term zone in Oppel's (1856–1858) work. Although there, and in his other works (for a summary, see Schweigert 2005), there is no detailed definition of what he intended as a zone, from his use of the concept it seems clear to us that it conforms to the modern definition of chronostratigraphical zone, representing rocks deposited during an interval of time. The Oppelian rationale requires an ideal profile, that is superposed key localities forming an ideal succession ('Nachdem ich die Reihenfolge der einzelnen Horizonte zusammengestellt und somit das ideale Profil gefertigt hatte. . .'; Oppel 1856, p. 4), and key assemblages (characterized by 'the constant and exclusive occurrence of certain species', including long-distance vicariant taxa), representing a scale of discrete, non-overlapping time intervals. Another point stressed by Oppel, in analogy with many later biostratigraphers, is the necessity of precise species circumscription for zonal stratigraphy: 'Je schärfer die Species getrennt ist, desto genauer können auch die Schichten eingetheilt werden.' (p. 3, Vorrede). He also stated that a zone includes only species that do not occur in any other zone ('Jeder der einzelnen Zonen sind immer diejenigen Arten beigeschrieben, welche sie besonders charakterisieren und noch in keiner anderen Schichte gefunden wurden.' p. 15).

Shortly before the publication of Oppel's monograph, the Jurassic stages were systematized by d'Orbigny (1850), although, contrary to common belief, the majority of the eleven currently accepted stages were not introduced by him, that is the Pliensbachian and Tithonian (introduced by Oppel himself in 1856), Hettangian, Aalenian, Bathonian, Oxfordian and Kimmeridgian (see Ogg & Hinnov 2012). Not surprisingly, these stages share a common feature: most of them are intimately linked to ammonites.

Oppel's approach was a top-down approach, starting from the construction of an 'ideal profile', an ideal succession of 33 key faunal assemblages for the Jurassic, each representing a zone (Oppel 1858, 5 p. 822–823, Table 63). In naming his zones, among index fossils ammonites prevailed, but one-third was based on other taxa, such as brachiopods, bivalves, gastropods, crinoids and echinoids. In this famous table (reproduced in Arkell 1933, table 3), zones are characterized as 'Lager oder Stufen, d. h. *paläontol. bestimmbare Schichtencomplexe*' ('layers or stages, i.e., palaeontologically determinable complexes of strata'; our translation and emphasis). However, in the same table stages (*Etagen*) are defined as synonymous with 'groups of zones' (*Zonengruppen*), thus leading many stratigraphers to the interpretation that his zones are chronostratigraphical units.

Walsh (1998) provided a complex theoretical clarification of the two distinct meanings of Oppelzones, biostratigraphical ('Oppel fossizone') and biochronological ('Oppel biochron'), and within the units, he, respectively, termed 'assemblage interval fossizones' and 'assemblage interval biochrons'. In order to avoid needless proliferation of names, later Walsh (2000) retracted the term 'fossizone', reverting to its much more used synonym 'biozone', or simply 'zone'. Within each kind of unit, he distinguished three subcategories: disjunctive zone, minimal overlap zone and strict overlap zone. In our opinion, however, the precise recognition of these different subcategories introduced by Walsh (1998) in biostratigraphy and biochronology, although theoretically sound, appears hardly feasible in practice.

Ammonoids and larger foraminifera: a parallel history of biozonation

Shifting the perspective from theory to practice, it seems appropriate to examine briefly how ammonitologists and foraminiferologists have dealt with this issue. Our aim here is not a comprehensive review of the history of biozonation in Jurassic ammonites and Palaeogene–Neogene larger foraminifera. Instead, we wish to summarize the rationale of the present approaches to biozonation in these groups, pointing out similarities and differences, and keeping the historical development in these two fields to a minimum, as the vast literature on Jurassic ammonite biozonation cannot be dealt with in detail here. In Western European Jurassic ammonoid stratigraphy (e.g. Callomon 1994, 1995; Corna *et al.* 1997), the term Oppelzone – as distinct from Hedberg's (1976) biostratigraphic Oppel-zone – has been generally regarded to coincide with chronozone and standard zone (Meister 2010). Similarly, in Russia, at least since Stepanov (1958) introduced this concept, Oppelzones were generally accepted as chronostratigraphical units (Gladenkov 2010).

The Oppelian ammonite chronostratigraphy represents a primary standard, necessary for hierarchical consistency, directly tied with the definition of Jurassic-Cretaceous stages and their GSSPs, in spite of the uncertainties in correlation among regional (domain, realm) ammonite zonations. As chronostratigraphical units, these ammonite Oppelzones (chronozones and standard zones): (1) are formally defined at their base; (2) reflect a continuous zonation; and (3) are related hierarchically: chronozone or (standard) zone, subchronozone or (standard) subzone, and 'zonule' (sensu Hedberg 1976). In each major faunal realm or province (boreal, subboreal, sub-Mediterranean, Mediterranean, etc.), the Jurassic is currently subdivided into 70–80 standard zones and 160–170 subzones (Ogg & Hinnov 2012).

In contrast to ammonite chronostratigraphy, ammonite biostratigraphy (Kennedy & Cobban 1977) is based on biohorizons (also called simply 'horizons'; Page 1995), which are the least inclusive and fundamental unit in a hierarchy of biozones (Page 2003; Meister 2010; Rogov *et al.* 2012). Biohorizons are biozones that correspond to a bed or a series of beds, characterized by one or more taxa, within which no further subdivision can be made, at least on a local basis (Gabilly 1976). Individual biohorizons are generally confined to one to few palaeogeographical regions.

The number of ammonite biohorizons largely exceeds that of corresponding zones and subzones. For example, in the Jurassic of France about 68 zones, 160 subzones and 292 biohorizons are distinguished in Cariou & Hantzpergue (1997). Assuming a duration of the Jurassic of 56.3 myr as in the GTS2012 (Ogg & Hinnov 2012), in the French Jurassic, the average time span of a zone would correspond to ca. 828 kyr, of a subzone 352 kyr and of a biohorizon 193 kyr. However, such an inference of average duration is misleading for biohorizons, by definition. At a local or regional scale, a biohorizon, however defined, is a discrete unit, separated by hiatuses of unknown duration from other adjacent biohorizons and a scale of biohorizons consequently represents a discrete zonation. Degrees of increasing inclusiveness characterize, respectively, the biohorizon, the faunal horizon and the standard horizon; at regional scale, in addition the concept of 'biosubzone' (or simply 'biozone') has been used (Meister 2010). In contrast to ammonite standard zones (chronozones, Oppelzones), these biozones may conform to any different zonal criteria, such as total range zone, acme-zone, partial range zone, assemblage zone, phylozone, interval zone, including the Oppelzone sensu Hedberg (1976). The recognition of biohorizons, that is of clearly distinct, superposed fossil assemblages, is like building up a ladder step by step. Regardless of the empty spaces between one and the successive step, it covers entirely the vertical space between its base and its top. To provide a clarification of these concepts, a diagrammatic model is set out in Figure 1.

Although the temporal acuity obtained through ammonites is unparalleled by any other fossil group used in Jurassic biostratigraphy, a cautionary note is appropriate (Zeiss 2003). First, long-range biohorizon correlation is not straightforward, because each major palaeogeographical unit has its own parallel zonation or zonations of biohorizons; often, additional elements (e.g. magnetostratigraphy, microfossils) are needed to achieve correlation. Second, the index-species of some horizons may be rare (Dommergues *et al.* 1997), thus hampering their recognizability. An example is *Beaniceras luridum* (Simpson) in NW Europe, the index-species of the Luridum horizon (Dean *et al.* 1961), Luridum Subzone, within the Ibex Zone (Pliensbachian), a zone established by Oppel (1856).

As chronostratigraphical units, Oppelzones may be considered as an historical necessity, because they represent an embryo of a time-scale. As stated by Callomon (1994, p. 22), ‘conceptually, (. . .) Oppel’s Zones were mer[e]ly thinner slices of the standard geological column’.

It is now interesting to compare the history and rationale of biozonation in ammonoids with that in larger foraminifera (also known as larger benthic foraminifera). When Oppel’s *Juraformation* appeared, a rudimentary zonation for Eocene-Oligocene nummulitids already existed (d’Archiac 1850; d’Archiac & Haime 1853). Later, a number of authors, such as de la Harpe, Boussac, Prever, and H. and R. Douvillé, proposed various regional scales based on larger foraminifera that today have mainly historical interest. These zonations focused mainly on the Eocene and Oligocene of France, Switzerland, Italy and other circum-Mediterranean countries; they were more top-down (i.e. reflecting the ideal vertical sequence of stages, formations and fossiliferous key localities) than bottom-up (i.e. established through the detailed analysis of fossiliferous successions). Generally, in these scales larger foraminifera, along with macrofossils, were used as *Leitfossilien* (index fossils) for particular stratigraphical intervals (mostly at stage or substage level), through the superposition of key species from different regions, rather than as zonal markers in a modern sense. In addition, some of these early attempts were affected in part by the non-recognition of reworking.

Not surprisingly, in larger foraminifera the turning point from coarse to fine-scaled zonation coincided with conspicuous advances on two distinct fronts. As to the first front, the systematics and phylogeny of the taxa used in biozonation needed to be adequate; as in other fossil groups, zonation lagged behind major systematic advances. Systematics in larger foraminifera basically follows two different approaches (typological vs. biometrical) (Pignatti 1998).

In the typological approach (Hottinger 2013), species are defined and identified by reference to a type, a specimen that is a term of comparison in respect to other types (ideally, two at a time), each presenting distinctive characters. Emphasis is not on the biometrical characterization of populations, but on their comparison with other coeval taxa, or stratigraphically superposed phylogenetically related taxa. As visual comparison is deemed particularly important, illustration of taxa is standardized and profuse (Hottinger 1960; Schaub 1981). For biozonal assignment, usually the whole assemblage of co-occurring taxa is taken into account. Multiple coeval biozones are established on distinctive successive species from parallel, well-known lineages (Schaub 1981) of different genera (*Alveolina*, *Nummulites*, *Assilina*), originating from stratigraphically superposed key localities, and correlated to each other (Hottinger *et al.* 1964). The ensuing zonation is discrete (Guex *et al.* 2015) and Oppelian in Hedberg’s (1976) meaning.

In the biometrical approach (Drooger 1993; Less & Ó. Kovács 2009), species and subspecies, considered as lineages formed of semi-statistical populations, are defined as morphometrical units. Lineages 6
showing a morphometrical continuum are subdivided into arbitrary segments, representing chrono (sub)species; the ensuing biozonations are either phylozones (lineage-zones sensu Hedberg 1976) or mixed, with phylozones and interval zones (e.g. Drooger & Laagland 1986; Laagland 1990; Drooger 1993), or phylozones, interval zones and Oppelzones sensu Hedberg (1976) (e.g. Less 1998) when in addition to morphometric boundaries, first or last occurrences of genera or species are used as data to produce a continuous zonation (Guex *et al.* 2015).

These separate biozonation approaches reflect thus different: (1) species concepts and identification methods (typological vs. biometrical; Pignatti 1998), resulting in different kinds of biozones (mainly, Oppelzones sensu Hedberg and phylozones); (2) palaeoecological constraints: all groups of larger foraminifera are ecologically restricted taxa (Hottinger 1997), hence the necessity to establish multiple biozonations for a same biogeographical region (Fig. 2); 7
and (3) stratigraphical ranges of individual single-taxon biozonations, that is the vertical range of each taxonomic group used for biozonal stratigraphy (Fig. 2).

Two important analogies between the discrete and continuous larger foraminiferal zonations need to be pointed out. First, none of the single-taxon zonations employs abundance criteria, such as acme (Hedberg 1976), LCO (last common occurrence), for the definition of zonal boundaries. Second, both the typological and the biometrical methods have deal with the issue of populations that are transitional between two subsequent taxa or morphometric subdivisions of a lineage, for which the typological approach uses terms such as ‘transitional form’ or ‘aff.’ (Schaub 1981), whereas the biometrical approach employs the term *exemplum intercentrale* (Drooger 1993).

As to the second front, it was necessary to achieve sufficient sampling detail along representative fossiliferous successions and to construct range charts that could be compared from different depositional facies and regions. In the course of the 20th century, in contrast to planktonic microfossil studies, which were largely dependent from ocean drilling projects, larger foraminiferal zonations were strongly linked

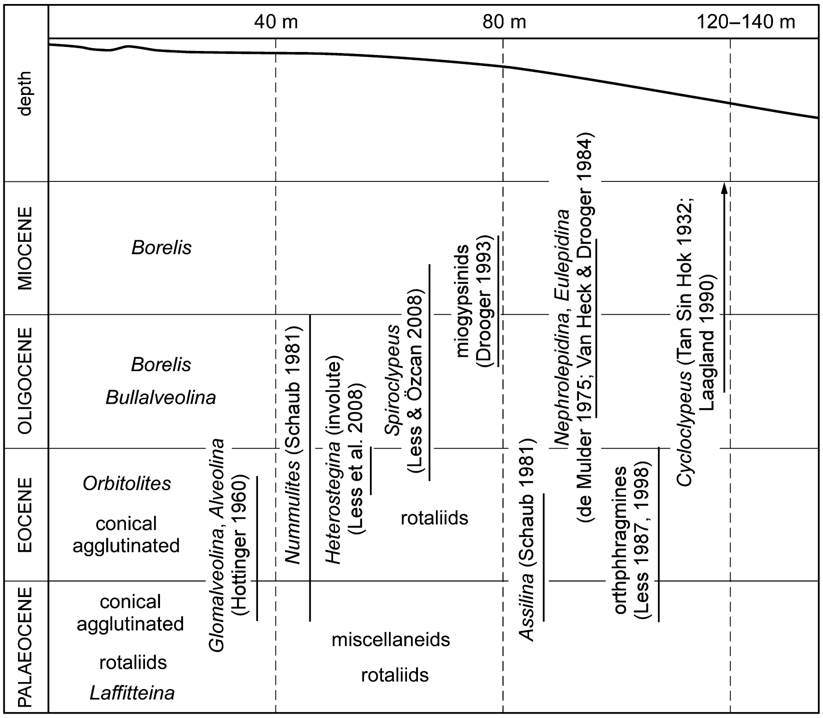

Fig. 2. Inferred distribution along the depth gradient of selected groups of Palaeocene–Miocene larger foraminifera on which single-taxon biozonations have been established; depth ranges of taxa are simplified after Hottinger (1997) and may actually overlap.

with the unprecedented expansion of field geology and, at least regionally, oil industry (e.g. in the Middle East and SE Asia).

Thus, at the end of the 1920s, a distinct larger foraminiferal biozonation, the ‘Letter Classification’ (also known as ‘Letter Stages’), was first proposed by van der Vlerk & Umbgrove (1927) for the East Indian Tertiary (now mainly Indonesia). It was based on assemblage biozones of genera and species of larger foraminifera and recognized in the Palaeogene–Neogene six main zones, labelled ‘a’ through ‘f’ (e.g. Tertiary ‘a’ or ‘Ta’). These biozones were practical tools of Tertiary stratigraphy in SE Asia, a replacement for the apparently ‘unreliable and unwieldly European epochs’ and stages (Lunt 2013). The SE Asian Letter ‘stages’ had no type sections; much later, Adams (1970) attempted to give the Letter Stages a more objective stratigraphical basis, redefining the ranges of their markers, introducing subdivisions (such as Ta1, Ta2) and extending it from Iran to the Western Pacific and Australia. Later, this zonation was further extended, for example to the Philippines and Japan, refined and correlated with planktonic foraminiferal zones (BouDagher-Fadel & Banner 1999; BouDagher-Fadel 2002, 2008).

In the same region, soon both van der Vlerk (e.g. 1955; and references therein) and especially Hok (1932) were pioneers in the biometric investigation of larger foraminiferal lineages for systematic and biostratigraphical purposes. Using *Cycloclypeus*, Hok (1932, p. 127) first proposed 12 biometry-based lineage zones (i.e. phylozones) from the Oligocene to the Plio-Pleistocene, and introduced the term ‘nepionic aurora’ or simply ‘aurora’ for the chronologic interval corresponding to a chrono(sub)species. Since the 1950s, this line of investigation has been successfully developed – especially by the ‘Utrecht School’ – in radial foraminifera (e.g. De Mulder 1975; Drooger & Laagland 1986; Drooger 1993), orthophragmines (Less 1987) and nummulitids (*Cycloclypeus*: Laagland 1990; *Heterostegina*: Less *et al.* 2008; *Spiroclypeus*: Less & Özcan 2008). In these groups, zonations are mainly either phylozones (lineage zones) or a combination of phylozones based on biometrically defined chrono(sub)species and interval zones (Fig. 3). The orthophragmine zonation (Less 1987, 1998; Less *et al.* 2007) is a special case, in which Oppel-zones and phylozones are combined. The biometrical definition of chrono (sub)species as arbitrarily but objectively defined segments of lineages produces a continuous zonation (Guex *et al.* 2015).

More or less at the same time when the ‘Utrecht School’ started, the breakthrough for establishing an Eocene nummulitid zonation was Schaub’s (1951) monograph on *Nummulites* and *Assilina* from flysch formations of Switzerland, a meticulous bottom-up study unravelling the main lineages through typological methods. Through Hottinger's (1960) study of alveolinids, an integrated parallel scale of nummulitid and alveolinid biozones for the circum-Mediterranean area was established, first presented in 1962 at the Colloquium on the Palaeogene in Bordeaux (Hottinger *et al.* 1964). This zonation and unparalleled systematic results (Schaub 1981) represent a seminal contribution of the 'Basle school' in larger foraminifera (Hottinger 2013). These biozones based on nummulitids and alveolinids followed the Oppelian criteria of superposed key localities, key assemblages and vicariant taxa and thus represented a discrete biozonation. The faunal succession and the association of its elements permitted parallel correlation of biozones based on ecologically different groups (e.g. alveolinids, *Nummulites* and *Assilina*). In addition, species circumscription was typological. Given that Oppelzones are intrinsically prone to correlation, their correlation with biozonations established on different taxonomic groups started quite early; for example, nummulitid biozones were correlated with the calcareous nannoplankton (Kapellos & Schaub 1973) and planktonic foraminiferal zones (e.g. von Hillebrandt 1975). 8

Since Serra-Kiel *et al.* (1998), this classical paradigm has been superseded for the Palaeocene and Eocene by twenty SBZ (or SB) biochronozones, at least in part correlated to magnetostratigraphy, mainly based on the Pyrenean domain. At the same time, Cahuzac & Poignant (1997) extended this scale to the Oligocene and Miocene (SB 21-SB 26), mainly basing on Western France. The SB zonation combines the biostratigraphic zonations based on alveolinids (Hottinger 1960), *Nummulites* and *Assilina* (Schaub 1981), orthophragmines (Less 1987, 1998), *Heterostegina*, lepidocyclinids, *Cycloclypeus* and miogypsinids (Drooger 1993), and other taxonomic groups. This zonation remains largely Oppelian, even if it contains the non-Oppelian lepidocyclinid

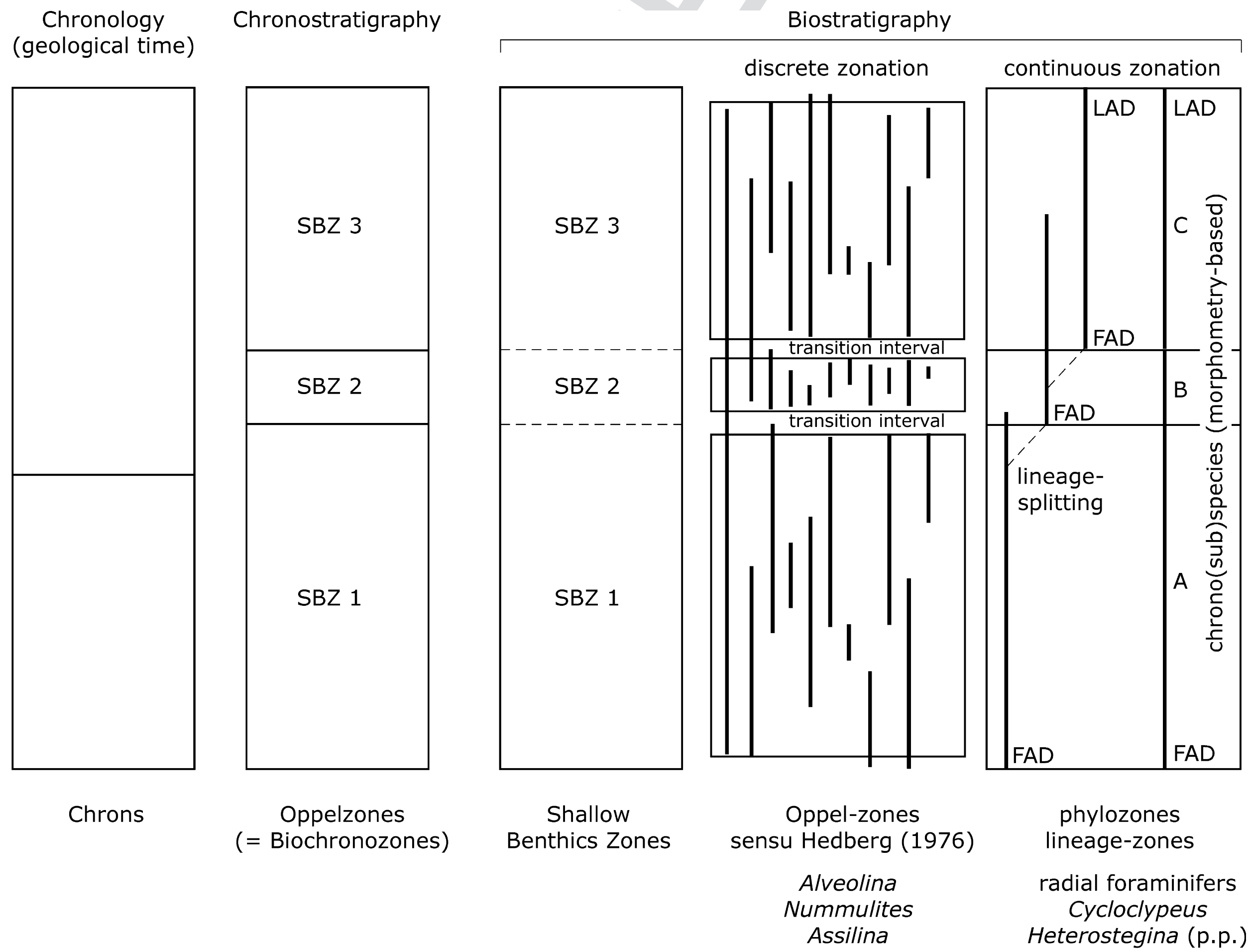

Fig. 3. The Shallow Benthic Zonation (Cahuzac & Poignant 1997; Serra-Kiel *et al.* 1998) in larger foraminiferal biostratigraphy: from Oppel-zones sensu Hedberg (1976) and phylozones to Oppelzones (biochronozones).

and miogypsinid zones and the partly Oppelian orthophragmine zones, because it uses extensively the vicariance of different groups, laterally substituting each other and more or less coeval. Moreover, the SB zonation is linked both to calcareous plankton and nannofossil scales and to the magnetostratigraphical chrons as given in Berggren *et al.* (1995), adding a significant information useful for worldwide correlation and achieving the status of a 'standard' zonation, as shown by its the inclusion in the new edition of the Geological Time Scale (Hilgen *et al.* 2012; Vandenberghe *et al.* 2012).

Conversely, whereas larger foraminifera were conspicuously present in the former stratotypes of Palaeogene stages, they are now usually lacking in the type sections the GSSPs, established on deep-water deposits. The main exception is the Lutetian GSSP in Gorrondatxe (Molina *et al.* 2011) for which the SB zones were recognized already in the preliminary studies (Payros *et al.* 2007, 2009).

In the last decades, several regional larger foraminiferal zonations were established, for example for Oman (Racey 1994, 1995), the Indian Himalayas (Mathur *et al.* 2009) and Tibet (BouDagher-Fadel *et al.* 2015). In contrast, although the systematics and biometry of various groups of radial foraminifera from the Americas and the Caribbean have been investigated in detail (Drooger 1993; BouDagher-Fadel & Price 2010a,b), no 'standard' larger foraminiferal zonation is yet available. An attempt (based on unreferenced data) that did not gain general acceptance is that developed for the Mexican oil industry (Butterlin 1981), that uses five biozones subdivided into thirteen sub-biozones (loosely defined assemblage, total and partial range biozones) for the Palaeocene–middle Miocene. A larger foraminiferal zonation for the Palaeogene of Jamaica and the Caribbean area is that by Robinson & Wright (1993).

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As discussed above, Oppelzones were listed by Hedberg (1976) in the first edition of the ISG. Even if the definition reported seems to be different from the original concept of zone by Oppel, there are some issues deserving further discussion.

First, in Hedberg's (1976) definition of an Oppel-Zone, vicariance is not explicitly mentioned, although he specifies that 'not all of the taxons considered diagnostic need be present at any one place' and 'supplementary use of biostratigraphical criteria other than range-concurrence that are thought to be useful in demonstrating time-equivalence' is allowed. Through this omission, one of the main advantages of the Oppelzones is lost, namely the possibility to use them, through additional taxa, in different palaeoenvironmental settings with the same biochronological significance. In the current SB zonation, which remains essentially Oppelian, we can use the same biozone along the palaeobathymetric gradient.

Second, there are strong analogies between the 9
Oppelzone and the Assemblage zone as defined in Hedberg (1976). The main difference is that the former implies 'an association or aggregation of *selected* taxons [. . .] chosen as indicative of approximate contemporaneity', whereas the latter is defined as 'a body of strata whose content [. . .] constitutes a *natural* assemblage' (italics as in the original). In both cases, the boundaries are fuzzy: '[t]he total range of any constituent taxon may extend beyond the boundaries of the assemblage-zone' and '[b]ecause of the complexity and indefiniteness of Oppel-zone criteria, boundary positions are to a considerable extent subject to worker's judgement'.

In the subsequent second edition of the ISG by Salvador (1994), and in the later abridged version (Murphy & Salvador 1999), the Oppelzone has been deleted and the definition of the assemblage zone is 'a stratum or body of strata characterized by a distinctive assemblage or association of three or more fossil taxa that, taken together, distinguishes it in biostratigraphic character from adjacent strata' (Salvador 1994). A similar concept is presented in the most recent North American Commission on Stratigraphic Nomenclature (2005). The inherent fuzzy definition of the boundaries of the Oppelzone is maintained in the assemblage zone representing at the same time a weakness (because of subjectivity in determining them) and a main advantage (because of their flexibility in being applied to different palaeoenvironmental settings).

Scott (2013) claims that the definition of Oppelzone in Hedberg (1976) is ambiguous, suggesting that this 'equivocal status' could be the reason for its removal in the revised ISG by Salvador (1994). Anyway, the problem remains for the assemblage zone, which seems to be some new name for the same Oppelian conception.

Conclusions

An advantage of Oppelzones is that they help addressing zonal recognition and correlation difficulties arising from two constraints: (1) *palaeoenvironmental constraint*: by integrating biozonations based on different taxa according the depth gradient. The genera and lineages used for establishing biozonations are linked and depend on specific conditions along the depth gradient; and (2) *palaeobiogeographic constraint:* using vicariant taxa, there is no need that a given taxon must be present in all places. Because of (1), Oppelzones allow also the establishment of local zonations and their integration, just as in Jurassic ammonites.

On the other hand, the unparalleled biostratigraphic potential of ammonites resides in the huge number of their basic units, the biohorizons. Their numbers cannot be achieved in larger foraminifera. However, there is latitude for exploring further subdivisions of biozonal units in larger foraminifera, such as using: (1) subtle variations in morphology, as characterized through biometrical studies, or (2) prominent variations in abundance of selected taxa linked to variations in the physical environment, producing at regional to global scale, such as those linked to major eustatic events or strong changes in sea surface temperature fluctuations (PETM, MECO, etc.).

As discussed above, both in Jurassic ammonite and Cenozoic larger foraminiferal stratigraphy, Oppelzones have been used as biostratigraphical and chronostratigraphical tools. In the Shallow Benthic Zonation (Cahuzac & Poignant 1997; Serra-Kiel *et al.* 1998; BouDagher-Fadel *et al.* 2010c), the parallel single-taxon biozonations were merged to build a scale that attempts to be a 'standard' system of biochronozones. In contrast to other micro-fossil zonations, these biochronozones are mostly neither linked to biostratigraphic events such as FOs and HOs and their correlative FADs and LADs, nor to abundance criteria: with a few exceptions, they rely on the concurrent occurrence of several taxa of independent lineages. Intrinsically thus, the recognition of the boundaries between zones is somewhat subjective. Therefore, correlating larger foraminiferal biozones with other biozonal scales, magnetostratigraphy, isotope stratigraphy, etc., to achieve a complete and reliable system of biochronozones needs at least some additional criteria reducing subjectivity, that have indeed been implemented over the years (Papazzoni *et al.* 2017).

Firstly, since the 1960s, when the foundations of a stable system of parallel single-taxon zonations were established, there has been a conspicuous refinement of systematics in many additional larger foraminiferal groups, such as the rotaliids, the conical agglutinated and the porcelaneous forms. These taxa and their bio-events may be used as further biostratigraphical constraints.

Secondly, in the last decades, several previously understudied intervals, such as the Palaeocene, and geographical areas (Asia, Central America and the Caribbean) have yielded an amount of new systematic and distributional data, providing many additional potential biostratigraphical markers. Whereas at species level the vertical ranges of these taxa are still incompletely known, the elements which have the highest potential of becoming useful standard markers are those linked to first and last occurrence of genera. There is not only a potential for more accurate correlation, but also for zonal identification, as the recognition of genera is rather straightforward in larger foraminifera because of their complex shells: genera are distinguished by qualitative characters, species by quantitative characters.

Thirdly, starting with the seminal study by Hok (1932), who first used biometrical methods to investigate evolutionary change through time within lineages of *Cycloclypeus* and suggest a biozonation based on successive morphometrical populations, since the 1980s there are several useful zonal scales based on morphometric criteria that still need to be tested more extensively, but may provide additional objective biostratigraphic data for large-scale correlation. In addition, biometrical methods may provide the means for further refinement of the SB zonation: using successive Bartonian–Priabonian chronosubspecies of *Heterostegina*, Less *et al.* (2008) proposed to subdivide SBZ 18 into three subzones and SBZ 19 into two. We maintain that the main reason for this insufficient knowledge is the lack of interest for biometrical methods in biostratigraphy among many palaeontologists (Dzik 1994), also because the involved splitting, sectioning and measuring work is considered as time-consuming.

Finally, we suggest that the Shallow Benthic Zonation and the regional larger foraminiferal zonations established in different palaeobiogeographical domains (Mediterranean Neotethys, Oman–Iran, Indian Himalaya, Tibet, SE Asia) should be conceived as, respectively, corresponding to the (Oppelian) ammonite chronozones (standard zones) and the regional (domain, realm) ammonite zonations. Different kinds of biozones (Oppel zones sensu Hedberg, phylozones, mixed zonations) are subsumed under the biochronostratigrapic SBZ system in a similar way as regional ammonite zonations are integrated in the standard ammonite zonation. Correlation of the SB zonation with global events is not straightforward. In some cases, however, as for the Palaeocene/Eocene boundary, which is defined by an isotopic shift of C and O, the global signal is detectable in shallow-water settings, too, allowing direct correlation (Scheibner & Speijer 2009; Zhang *et al.* 2013). Among the more recent attempts of direct correlation of the SBZ with calcareous plankton, nannofossils and magnetostratigraphy, there are works from Spain (e.g. Rodríguez-Pintó *et al.* 2012; 10 Costa *et al.* 2013) and Italy (Papazzoni *et al.* 2014).

In conclusion, the Achilles' heel of Oppelian zonations hinges on a paradox. In both Jurassic ammonites and Tertiary larger foraminifera, a striking feature is that their fossil record and many biostratigraphical units based upon them (biohorizons, Oppelzones) are discontinuous, and thus, the resulting biozonations are discrete (Guex *et al.* 2015). However, in both groups, 'standard' (bio)chronostratigraphical scales are, by definition, continuous. The solution of this apparent paradox hinges on the analytical methods used to correlate biostratigraphical and chronostratigraphical units. To achieve correlation, (bio)chronostratigraphical units should be based on as few as possible markers, and not assemblages of taxa, as in biostratigraphical Oppelzones. This implies that, in contrast to Serra-Kiel *et al.* (1998), the number of taxa used to define the SB biochronozones should be reduced to single taxa and their correlative data. Conversely, Oppelian larger foraminiferal biozones should maintain their polytaxic definition, to permit recognition in sediments from different environments and regions; both single-taxon and regional zonations should coexist with these Oppelzones. Thus, a novel research programme is needed to (1) establish the most suitable markers for biozonal boundaries; (2) enhance correlation with different systematic groups (especially planktonic foraminifera and calcareous nannofossils) and with other stratigraphical tools (magnetostratigraphy, radiometric dating, isotopic stratigraphy, etc.); and (3) extend morphometric criteria wherever possible to recognize the markers themselves.

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