Stratigraphy into the 21st century

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ABSTRACT: 19th and 20th century stratigraphy often concerned itself primarily with classification and nomenclature, during what can be termed the heroic and codex ages of stratigraphy. In contrast, 21st century stratigraphy will fall within the post-modern age. In possession of agreed classification schemes, future stratigraphers will concentrate on (i) the reconstruction of earth environments and processes (including evolution) through time, (ii) the eficient location and recovery of useful earth resources, and (iii) the study of those geological hazards that can be understood within a stratigraphic context.

The first objective - reconstructing environments through time - requires the use of a conceptual framework similar to the one that we term the geological time scale (GTS). The 21st century GTS will be based on GSSP designations at the base of all geological Periods and, ultimately, Ages, i.e. it will comprise an internationally agreed chronologic hierarchy. Recognition of local chronologic schemes (as distinct from biostratigraphies based on Oppelzones) will thereafter serve no useful purpose and local "Ages" will become redundant. Globally, recognition of a separate but completely parallel chronostratigraphic classification will also serve no useful purpose, and this hierarchy too will be abandoned. Correlation of events into the GTS will be undertaken using a wide variety of methods, including numeric dating, fossil occurrence, physical and chemical properties, tephrochronology and astrochronologic retrodictions. Biostratigraphy, though remaining a vital tool, especially for Phanerozoic strata, will carry no necessary correlation primacy.

Meeting the second and third objectives - locating and recovering earth resources, and studying hazards - requires first and foremost the creation of detailed geological maps and stratigraphic columns. The lithostratigraphic hierarchy of Bed-Member-Formation-Group-Supergroup is an efficient and mostly objective classification whereby useful maps and columns are created. Because geological mapping is concerned with local stratigraphic detail and complexity, it cannot, like chronology, be organized within a global nomenclature. Over different large areas, different major, genetically-related packages of sediments correspond to the form ation, filling and sometimes destruction of sedimentary basins - as driven by regional tectonic events, and as influenced by regional climatic and oceanographic histories. At the supra-Group or supra-Supergroup level, major sediment assemblages of this type are separated by regional unconformities, as recognized by the creation of a category of Unconformity-bounded Units (UBU) in the 1994 2nd edition of the *International Stratigraphic Guide.* Whether or not UBU are continued with as a formal unit of classification, the strong need will persist for the type of regional, unconformity-bounded units that have successively been termed Sequence and Synthem, for use as the highest level within the lithostratigraphic hierarchy.

INTRODUCTION

Stratigraphy is a venerable science with roots deep within European history. Its *nascent* phase, during the Italian renaissance, was marked especially by Leonardo's recognition that marine fossil shells represented the remains of animals that formerly lived on ancient seabeds, and Steno's elucidation of the time significance of stratification.

> "If the deluge had had to carry shells three or four hundred miles from the sea, it would have carried the various kinds mixed and heaped up together; yet we see at such distances oysters all together, and conchs and cuttle-fish, and all the other shells which live gregariously, all found together in death, while the solitary shells are found apart from one another, just as we may see them any day on the sea shore". (Leonardo da Vinci, Leicester Codex, folio 9 verso).

For the *heroic* age of stratigraphy, the scene shifted to post-Enlightenment western Europe. There, in late 18th century Scotland, James Hutton generalized Leonardo's earlier insights by applying them to igneous rocks and geological observation in general. Then, in early 19th century England, William Smith laid the foundations of geological mapping and biostratigraphy, work that led to the recognition and naming of the Periods of the geological time scale by stratigraphic pioneers such as Sedgwick, Lapworth and Murchison. Meanwhile, Charles Lyell wove the gold thread of uniformitarian interpretation into geological study in his book *Principles of Geology,* thereby allowing the previous 400 years of insight to be summarized by the pithy aphorism - "the present is the key to the past".

> "In examining things present, we have data from which to reason with regard to what has been; and, from what has actually been, we have data for concluding with regard to that which is to happen thereafter". (Hutton, *Theory of the Earth* 1795).

The development of the geological time scale, and all preceding geological studies, largely had their basis in observational field evidence. By the late 19th century, with the increasing specialization of different branches of geology and the widespread adoption of the petrographic microscope, the need arose for a more systematic approach to the naming and classification of different types of strata, which led into the *codex* age of stratigraphy.

The demand for more organized codifications of sedimentary rocks was reflected in the distinction drawn at the 2nd International Geological Conference at Bologna (1881) between those terms to be used for past geological time periods (Era, Period, Epoch and Age) and the distinct hierarchy of terms that were then concerned with the naming of rock bodies (Group, System, Series, Stage). Pivotal events over succeeding decades that followed the recognition of this distinction included: the introduction into classification of Formation, Member and Bed as main members of the lithologic hierarchy of terms (United States Code, 1933); the assertion by Hedberg (1937) that four basic types of unit were necessary for clear stratigraphic classification – time, time-stratigraphic (time-rock), lithologic and biostratigraphic; the adoption of Hedbergian schema in many national stratigraphic codes, followed by its full flowering in the first edition of the International Stratigraphic Guide (Hedberg 1976) – which recognized geochronologic, chronostratigraphic, lithostratigraphic and biostratigraphic hierarchies as the four elemental skeletons of stratigraphic classification; and, finally, the introduction of Global Stratotype and Section Points (GSSP) as a means of defining the Geological Time Scale in a manner that avoids both gaps and overlaps (George et al. 1969; Remane et al. 1996; Walsh et al. 2004).

Two developments during the late 20th century changed geology and stratigraphy for ever, and led to the *post-modern* phase of our science. First, the delineation of plate tectonic theory delivered to stratigraphers, as to other geologists, the means by which they could understand and interpret sedimentary basins in their full dynamic context (e.g. Mitchell and Reading 1969). Second, the introduction of digital computers, and rapid increases in their processing power, had its initial impact mainly in the field of seismic profiling, by delivering basin-wide and –deep visualizations of sedimentary strata in three-dimensional complexity, spawning awhile the powerful approach of sequence stratigraphic analysis (e.g. Payton 1977).

Beyond seismic imaging, the development of powerful graphic and cartographic software and related developments in printing technology have provided the means for the rapid production and revision of maps, sections and three-dimensional geological reconstructions of sometimes breathtaking beauty and scientific power. With the parallel development of database software, the dream of storing and retrieving images alongside structured text has become reality. Stratigraphy, and especially paleontology, has moved from the dusty world of library and museum storage into the flickering light of modern electronic display panels. There has been a revolution - which continues - in the ways in which maps are prepared and printed *(vale* Rottring pens), library resources facilitated *(vale* serried racks of books), taxonomic and stratigraphic monographs prepared *(vale* card indexes and, soon, printed monographs), fossils prepared and reconstructed (welcome CAT scanners), and paleoenvironmental reconstructions developed (welcome "Walking with Dinosaurs").

It is not that the hammer and field notebook have become redundant - indeed, careful field observation remains as important as it ever has been - but rather that they have now been supplemented. For today's stratigraphers, as for virtually all scientists, the possession of a personal computer linked to the internet is now a pivotal research tool, second in importance only to the field and laboratory observations that generate the data that is to be studied and manipulated.

Armed, then, with a mature classification system and powerful analytical computing tools, how will the stratigrapher of the 21st century spend her time?

WHERE NEXT?

Stratigraphy is not an end in itself, but rather a means to several intellectual and societal ends. First and foremost, stratigraphy provides the time frame and descriptive background against which all geology is undertaken, including particularly the description of fossil organisms with an eye to pragmatic correlation, the deciphering of evolutionary patterns, and the reconstruction of earth's ancient environments. Second, advanced stratigraphic techniques underpin the discovery and exploitation of sedimentary mineral resources, including the important energy resources of coal, oil and gas, and uranium. And third, stratigraphy has a part to play in the understanding of dangerous natural hazards such as tsunami, volcanic eruptions, earthquakes and climate change.

Long ago, on a distant planet called Mid-20th Century Science, the public purse provided for heuristic as well as practical studies in stratigraphy and related sciences. Today, taxpayers are said to demand specified, and preferably practical, results in return for the expenditure of public monies on science. The question that has to be faced, therefore, is "why should 21st century taxpayers continue to pay stratigraphers to indulge their hobby?" And the most applicable answer that will be listened to is "because something useful will result".

Twenty-first century stratigraphy will, then, like all other science, have to fashion itself to conform to criteria of usefulness - both scientific and political. At the same time, the discipline will need to remain true to its historic scientific roots, of which the most important is the application of a strong principle of priority of nomenclature to preserve the value of older observations and literature; for as Arkell (1933) pointed out

> "Once we deviate from the original meanings of the terms and abandon the principle of priority, we lose our hold on the only life-line that can save us from the slough of conflicting opinions."

After 200 years of discussion, two editions of the International Stratigraphic Guide and with the forthcoming completion of definition of GSSP at all Period boundaries, the stratigraphic community is well prepared to contribute to dealing with mankind's needs and problems, though fiascos such as the recent squabbling over the Tertiary/Quaternary nomenclatural issue need to be avoided. Reclassifications such as this should not be imposed by international bodies, but arrived at by consensus within the appropriate user groups. Stratigraphic classification needs to add value, not subtract it.

Impediments which today remain to ready and consistent communication of stratigraphic information include (i) differences in approach, and sometimes nomenclature, between different national or regional geological communities (not discussed in this paper); and (ii) a number of minor inconsistencies in stratigraphic usage that need to be tidied up. The remainder of this paper will discuss several of the ways in which our current classification scheme needs improvement

Distinguishing definition from correlation: the primacy of the Geological Time Scale

The modern GSSP technique of defining the named intervals of the geological time scale by their bases only is generally attributed to George et al. (1967; cf. Hughes et al. 1967). However, the idea has longer historical roots and goes back at least as far as the early 20th century, when J. Allen Thomson (1916) (who, incidentally, was New Zealand's first Rhodes Scholar) wrote:

> "There are two objects to be aimed at in framing a classification of the younger rocks of New Zealand, and it is important to distinguish them. The first is to set up a standard of reference by which rocks from different parts of the country may be correlated with one another; the second is to correlate the various

> divisions of the classification thus established with their equivalents in classifications of other parts of the world, and particularly in the accepted time-scale based on the rocks of Europe".

Thomson's writings in turn influenced Allan (1933), Campbell (1955, 1959) and Campbell and McKellar (1956), who introduced the first de facto application of the GSSP principle in a series of papers that contained definitions of local New Zealand Triassic stages. A typical definition, for the Late Triassic Warepan Stage, reads:

> The Warepan Stage is here defined as those beds laid down at the type locality after the appearance of *Monotis richmondiana* Zittel and before the appearance of an Otapirian fauna (including *Spiriferina* (*Rastelligera*) *dimedea* Trechmann).

These New Zealand authors all insisted on separating the concept of the *definition* of a stage, by nominating its base in a type locality, from the logically separate act of *correlation* - which allows recognition of the top of the stage in the same type locality by utilizing all dating techniques, including fossil ranges, to identify there the level that corresponds to the base of the next succeeding stage in its own, generally separate, type locality. This logical distinction is pivotal for clear thinking, and though the point is now often taken to be self-evident it bears restating often.

The writings of Thomson and Allan long predated the equally classic but much more influential paper by American stratigraphers Schenck and Muller (1941). In introducing the concept of time-rock stratigraphy, Schenck and Muller contributed more or less directly to the Hedbergian orthodoxy of parallel schemes of geochronologic and chronostratigraphic classification, as blessed in the first edition of the International Stratigraphic Guide (Hedberg 1976). Meanwhile, on the other side of the Pacific the Thomson-Allan philosophy had led to the first effective use of the GSSP principle that was later to be adopted by the ISSC for international application.

Now, with the publication of the paper by Zalasiewicz et al. (2004), the wheel has turned almost full circle. The unnecessary redundancy and complexity of maintaining Hedberg's scheme of parallel chronologic and chronostratigraphic units is again under attack, as it was over 30 years ago by stratigraphers such as Bell (1959), Scott (1965), Allan (1966), Gage (1966) and Sylvester-Bradley (1967), as reviewed by Carter (1974). In recommending the primacy of chronologic units, earlier authors have made the following comments about the ISSC dual system (using the Age/Stage example for the purposes of discussion):

Both Ages (the time span) and Stages (the strata deposited during the equivalent time span) rest ultimately on the same GSSP definition; the distinction between the Age and the Stage is largely if not entirely semantic, and introduces unnecessary complexity into stratigraphic classification; the distinction between Age and Stage is also subtle to a degree that is confusing both to new students and experienced professional geologists alike, and such that technically incorrect usage is a regular occurrence in even the most august science journals (e.g. referring to a geologic event as happening in the Upper Jurassic);

The term Stage is applicable only to stratified rocks, and not, for example, to an intruded granite; but in describing the geological history, statements are made about both the strata and the granite in terms of the respective Ages in which they formed, because the Age is the basic unit for communication about events through time; and

The classic time Periods of the standard Geological Time Scale (into which Ages are concatenated) are not only conceptually basic, but also have clear priority of usage, and have not encompassed confusing lithostratigraphic or biostratigraphic aspects in the recent past.

No useful purpose is being served by maintenance of the time-rock hierarchy in parallel with the time periods defined by GSSP. As Williams (1894, p.148) wrote long ago:

> "There is a geological time-scale, and however we subdivide it, or however we mark or distinguish the divisions from one another, as a scale it is one and continuous, the parts or divisions of the scale come up to each other and are in regular succession, but they cannot, from the nature of the scale itself, overlap or duplicate each other."

This fine ambition has now been attained by the introduction of the GSSP technique of defining the time scale; recognizing a parallel chronostratigraphic hierarchy of terms adds only pedantic complexity. Even Hedberg, the person perhaps most responsible for the formalisation of the modern ISSC dual system, agreed that the reason for the dualism was historical usage and not logic. After discussing the matter and pointing out that either set of terms could be discarded without loss (Hedberg 1973, p. 179), Hedberg concluded

> "However, we have inherited the two sets of terms, one chronostratigraphic and the other geochronologic, and they are already in common use so it seems simpler to go on using both rather than trying to suppress one. Certainly the two sets of terms do no harm."

Regrettably, the last sentence has proved very wrong, because several generations of western geology students have since been confused by the dualism issue during their training, and many of them still contribute to the daily misuse of time and time-rock terminology that permeates the geological profession. For example, in discussing this very issue Walsh et al. (2004) cite as an example of correct usage "Upper Cretaceous rocks" rather than "Late Cretaceous rocks", thus appearing to completely miss the point that units of the chronostratigraphic hierarchy are nouns not adjectives; the Upper Cretaceous being a concrete rock entity, if you wish to refer to the age such a rock package then of course "Late Cretaceous rocks" is entirely the proper usage and "Upper Cretaceous rocks" is a tautology. If such scholastically well-versed and experienced stratigraphers as Walsh, Gradstein and Ogg can't get the pedantic distinction right between time and time-rock categories, then pity help the rest of us.

Despite some views that - admitting the redundancy inherent in two parallel hierarchies - it is the geochronologic hierarchy that should be discontinued (e.g. Jeletzky 1956; Wheeler 1959), and other views that support Hedberg's policy of allowing the dualism to stand (e.g. Walsh 2005), I agree with Zalasiewicz et al. (2004) and many earlier critics who wish to accord primacy to the geochronologic (time) hierarchy and discard the chronostratigraphic (time-rock) one.

Recommendation 1: The formal chronostratigraphic category (Erathem, System, Series, Stage) should be removed from the next edition of the ISSC Guide, and the use of chronostratigraphic units phased out.

The value of oppelzones: relationship to classical biostratigraphic stages

There is an intricate historic relationship between, and a voluminous literature about, differing usages of biostratigraphic zones and stages. In European classical tradition, the stage generally represented a grouping of stratigraphic biozones, i.e. was a practical working stratigraphic unit. But after Schenck and Muller (1941), and with the publication of the first edition of the ISSC Guide (Hedberg 1976) , the Age/Stage came to be defined as a strict time unit by reference to a type section, and was only incidentally related to any constituent biozones. Perhaps appreciating that their restricted definition of stage was usurping a valuable working tool of the biostratigrapher, the authors of the Guide went to considerable lengths to provide a variety of types of biozone, including introduction of the new category of oppelzone.

The term oppelzone was possibly first used formally by Arkell (1933) who, based on Oppel's earlier example, defined an oppelzone as "a bed or group of beds, identified by paleontological criteria (by a fossil or an assemblage of fossils)". Later, with the introduction of rigidly defined concurrent range zones in the ISSC Guide (Hedberg 1976), it was realized that these units became increasingly impractical as the number of taxa used in their definition increased. Oppelzones were therefore introduced to approximate to concurrent range zones, but with the flexibility of being "more subjective, more loosely defined, and more easily applied" so that they corresponded with "a widespread practice in stratigraphic zonation" (Hedberg 1976, p.58). In other words, oppelzones *sensu* ISSC approximated to the traditional biostratigraphic "stages" as used by Albert Oppel 1831-65, and many later workers, including Arkell.

The Guide's formal definition of oppelzones read:

> 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"; and importantly, "Not all of the taxons considered diagnostic need be present in any one place for the zone to be legitimately identified.

As so defined, ISSC oppelzones are closely similar to the independent suggestion of Fleming (1953, p. 101-102) that a single fossiliferous bed or interval could be used in order to fix the concept of a biostratigraphic stage as then used in New Zealand biostratigraphy. Fleming drew an analogy with the holotype concept in biology, whereby the holotype defines but does not fix the boundaries of a species. Similarly, a type fossiliferous bed could define but not fix the boundaries for a stage. With this historical antecedent, and given Hedberg's intentions, it is not surprising that as soon as oppelzones were established it was argued that they were equivalent to, and should replace, the local New Zealand biostratigaphic stages of the day (Carter 1970; 1974). Equally unsurprising, given the deep conservatism of stratigraphers, is that biostratigraphic stage usage continued in New Zealand in defiance of the then new ISSC definition of stages as strictly chronostratigraphic units, and the provision of the oppelzone category for precisely such local biostratigraphic units as the New Zealand stages. Only much later - and ironically after local stage systems could be argued to be redundant anyway (see text, later) – did New Zealand usage move towards the strict chronostratigraphic definition of stages, using Local Section and Stratotype Points (LSSP) for their demarcation (e.g. Morgans et al. 1999; Cooper 2004).

On the introduction of oppelzones by the ISSC, Sloss (1977, p. 645) commented:

> "the admission of Oppel-zones to the lexicon implies acceptance of a degree of reasoned and competent subjectivity in the definition of biostratigraphic zones. Identification of a concurrent-range zone, sensu stricto, requires the presence of all the taxons named in the original definition of the zone, a condition seldom met, and commonly breached in practice. Oppel-zones need not be confined to identical presence/absence tallies of diagnostic taxons and are thus a kind of non-recurring assemblage zone of demonstrable chronostratigraphic significance."

Other stratigraphers also found oppelzones to be a useful biostratigraphic category, and they were widely adopted for biostratigraphic correlation schemes within Paleozoic (Ordovician, Rasmussen 2000; Devonian, Streel et al. 1987; Permo-Carboniferous, Melynk and Maddocks 1988; Permian, Foster and Waterhouse 1988), Mesozoic (Triassic; Retallack 1995; Jurassic, Davies 1983; Cretaceous, Helby et al. 1987) and Cenozoic (Popova et al. 2002; McGowran 1986; Matsuoka et al. 1987) strata.

Surprisingly, the oppelzone category was omitted from the second edition of the ISSC Stratigraphic Guide (Salvador 1994), where they were dismissed with the following comment:

> "The Oppel zone ... has previously been considered as a type of assemblage zone or as a multi-taxon concurrent-range zone. However, neither Oppel nor subsequent biostratigraphers have precisely defined the biozones used by Oppel, which, in any case, do not appear to correspond consistently to any one kind of biozone (op. cit., p. 63)."

This puzzling comment manages to turn the very reason that the oppelzone is a useful category - its flexibility and deliberate lack of precisely defined boundaries – into the reason for its discontinuation! To paraphrase Gage (1972, p.496) when he was criticizing an analogous ex cathedra change in the New Zealand stage scheme:

> "… fortunately, we do not have to work within a system demanding acceptance by all of oficially sanctioned definitions and terminologies, (individual stratigraphers are) … quite free to discontinue the use of (oppelzones) for given reasons, but I am questioning whether (ISSC) or anyone else is entitled to declare them out of existence."

Recommendation 2: The oppelzone category is in active use, corresponds closely to the units that comprise regional stratigraphic stages (Carter 1974), and should be restored in the next edition of the ISSC Guide.

The Synthem as top dog in the lithostratigraphic hierarchy

A clear distinction between the terminology needed for geological mapping and stratigraphic description – what we now call lithostratigraphy – and that of the Geological Time Scale was clearly established by the last decades of the 19th century (e.g. Williams 1894). Though its codification has been successively improved, lithostratigraphy has remained relatively uncontroversial ever since, especially by comparison with the protracted disputes that have dogged biostratigraphy and its relationship with chronostratigraphy, including the vexed multiple usages of the term "stage". For pioneer geologists in many countries, it was however self-evident that the major "chunks" of stratigraphy that characterized particular continents were not necessarily equivalent in age-span with each other, nor with the sediment packages that formed the basis for classic European stratigraphy. As Fleming (1970, p. 126) remarked at the opening of his William Smith Lecture:

> "If the pioneers of stratigraphical geology had worked in New Zealand instead of in Western Europe, the stratigraphic column would have been divided at different levels from the world standard divisions. The Palaeozoic, including at first the Pre-Cambrian as an obscure older part, would end after the

> Lower Devonian, and the Silurian would not have been recognized until some local Murchison had crossed to Australia. The middle period of earth history would extend from Permian to Jurassic, and the 'Tertiary' would begin with the Cretaceous."

North American geologists have a long history of recognizing and naming these large regional sediment packages, which they first described as dynasties or terranes. For example, Williams (1893, p. 284, 290) referred to the Green Mountain, Appalachian, Rocky Mountain and Glacial terranes as the main unconformity-bounded Phanerozoic sediment packages of North America. Each such unit was said to represent

> periods of continuity of deposition for the regions in which they were formed, separated from one another by grand revolutions interrupting the regularity of deposition, disturbed by faulting, folding and sometimes metamorphosing the older strata upon which the following strata rest unconformably and form the beginnings of a new system.

50 years later, after much further mapping, research and discussion, these regional units had transmuted into the unconformity-bounded Sauk, Tippecanoe, Kaskaskia, Absaroka, Zuni and Tejas sediment packages, which were classified as craton-wide sequences by Sloss et al. (1949) and Sloss (1963). On other continents, some local stratigraphers also recognized regional sediment packages, for example the Tuhua, Rangitata and Kaikoura Sequences in New Zealand (Carter et al. 1974), and the Karroo Sequence in South Africa. Others (Suggate, quoted in Nathan et al. 1986, p. 3) preferred to continue to coin unfelicitous terms like "Cretaceous-Cenozoic Project" in description of regional sequences (in this case, the Kaikoura Sequence) that overlapped two major international time-scale periods, in so doing harking back over 100 years to the equally unsatisfactory Cretaceo-Tertiary usage of pioneer geologists such as Hector (1886).

In the late 1970s, the use of the term sequence for large, regional stratigraphic units was abruptly usurped by the parallel deployment of the term in the new discipline of sequence stratigraphy (e.g. Payton 1977). Developed within the petroleum industry from analyses of seismic reflection profiles, sequence stratigraphy was based upon the recognition of much smaller scale, intra-basinal, unconformity-bounded units that were believed to have been deposited under control of a changing sea-level. Therefore, when the new category of unconformity-bounded units (UBUs) was introduced into the second edition of the ISSC Guide (Salvador 1984, Chapter 6), the term synthem rather than sequence was used for craton-wide UBUs (ibid, Fig. 4).

In addition to sequence stratigraphy and the ISSC formal category of UBUs, unconformity-bounded stratigraphic units became the focus of special attention in the late 20th century because of the introduction of allostratigraphic units (allogroup, alloformation and allomember) within the North American Stratigraphic Code (1983).

The application of both allostratigraphy and sequence stratigraphy requires a strong element of genetic interpretation. Indeed, this is one of the strengths of those particular systems. At the same time, the lithostratigraphic hierarchy remains a vital means of objective description, grouping and mapping of sedimentary rocks. With the usurping of the term sequence by the nouveau petroleum sequence stratigraphers, followed by the ISSC in turn gazumping the term synthem in order to establish a new UBU category, the lithostratigraphic hierarchy currently still lacks a high-level term for the craton-wide grouping of major packages of unconformably-bounded strata. Astonishingly, a nomenclatural need that was identified, and first satisfied, over 100 years ago, today remains unfulfilled.

The solution is simple.

Recommendation 3: Irrespective of the status of allostratigraphy or UBUs in future editions of the ISSC Guide, the term synthem, in the sense depicted on Fig. 4 of Salvador (1994), should be moved into the lithostratigraphic section of the guide. There, it will comprise the top level of the lithostratigraphic hierarchy, i.e. a grouping of Supergroups and/or Groups.

The future of local biostratigraphic "time" scales

Local biostratigraphic stage systems had their origin in the late 19th century, as it became apparent that William Smith's dictum that the relative age of strata could be determined from their fossil content was valid beyond western Europe, but that different faunal assemblages occurred from place to place. As Thomson (1916, p.28) noted, the need for local biostratigraphic schemes

> "is imposed by the differentiation of the world's fauna into geographical provinces, a differentiation that has been, on the whole, accentuated as the present day is approached."

Most such schemes were used as a pragmatic means of "dating", or more strictly correlating, strata within a particular geographic area. The units within such schemes, usually termed stages, are conceptually similar to Oppel's earlier use of stages. As discussed earlier, with the publication of the first edition of the ISSC Guide (Hedberg 1976), a new category of oppelzone was introduced that corresponded precisely to most local stage schemes.

The first leg of the Deep Sea Drilling Program was undertaken in 1968. Over the next three decades, a quantum improvement occurred in the resolution of biostratigraphic correlation within Cenozoic sediments. The recovery of thick, continuous successions of biopelagic and hemipelagic strata from throughout the world's oceans led to a great increase in knowledge of the taxonomy and stratigraphy of important microfossil groups. These discoveries were combined with the development of new dating techniques that included magnetostratigraphy, tephrochronology, isotope stratigraphy, numeric dating and astrochronometric tuning. By the turn of the 20th century extremely refined schemes of subdivision of the Neogene were available (e.g. Lourens et al. 1996), and it was feasible to recognize the classic stages of the European Cenozoic time scale throughout the world.

Given these developments, the publication of the first edition of the Guide produced a perhaps surprising result. The term oppelzone was adopted by some paleontologists to provide correlation schemes for particular taxa or age periods (see references cited earlier), but, despite recommendations such as those of Carter (1974), Cenozoic stratigraphers showed no inclination to rebadge their local biostratigraphic schemes correctly as oppelzones; rather, they continued using local "stages", as if nothing had changed. Where changes in attitude did occur, they were towards the stricter definition of local biostratigraphies as rigorous LSSP-delineated local time scale schemes (Morgans et al. 1999; Cooper 2004) that were redundant at birth. As Walsh et al. (2004, p. 205) have commented:

> "certain usages of 'stage' are improper, because they can only lead to a confusion of fundamentally different categories," adding that "biostratigraphic units in the strict sense should never be called stages because such units are not and cannot possibly be chronostratigraphic units."

To the degree that local stage schemes are currently used as time-scales, they will in future be supplanted by use of the relevant GSSP-term. To the degree that local stage schemes summarise regional biostratigraphies, and remain useful, they should be maintained as biostratigraphic schemes. The term oppelzone, having been introduced for precisely this purpose, it will need to be reinstated by the IPCC.

Recommendation 4: With the GSSP-delineation of all the major intervals of the standard Phanerozoic time scale, local "time scales" will become redundant. Local scales should be discontinued, because stratigraphic communication is enhanced by the use of a single rather than many standards. Where local biostratigraphies continue to provide valuable information for accurate local correlation, they should be expressed as oppelzone rather than stage schemes.

CONCLUSIONS

Stratigraphy is a handmaiden rather than a knight. She plays a vital enabling role for all geological studies by providing the time framework and the rock taxonomy for describing the materials of the earth's crust, and for reconstructing events and environments through time. Modern stratigraphic studies are also contributing to the discovery of earth resources, the reduction of geological hazards, the understanding of organic evolution, the delineation of earth's natural climatic and environmental history, and the study of other planetary bodies.

During the 21st century, stratigraphers will continue to provide both the time skeleton and the environmental flesh for imaginative reconstructions of the history of planet earth. Stratigraphers will also remain deeply involved in the search for earth resources, especially sedimentary-based energy resources such as coal, petroleum and uranium, and will help to provide high resolution histories of the occurrence of earthquakes, tsunami, volcanic eruptions and floods.

Stratigraphy should add value by providing concise and clear nomenclatural schemes, not subtract value by interminable arguments over arcane stratigraphic trivia, or by introducing unnecessary complexity of classification. The 1st and 2nd editions of the ISSC Stratigraphic Guide have laid a firm foundation for future stratigraphic studies. To improve the signal to noise ratio of the Guide even more, four alterations are suggested for inclusion in the next edition. They are:

1) The **chronostratigraphic category** (Erathem, System, Series, Stage) should be removed from the Guide, and the use of chronostratigraphic units phased out.

2) The **oppelzone category** is in active use in regional biostratigraphies, and should therefore be restored to the Guide.

3) Irrespective of the status of allostratigraphy or unconformity-bounded-units in future editions of the Guide, the term **synthem** should be moved into the lithostratigraphic section to comprise the top level of the hierarchy, i.e. a grouping of Supergroups and/or Groups.

4) With the completion of GSSP-delineation of the geological time scale, local "time scales" should be discontinued, because stratigraphic communication is enhanced by the use of a single rather than many standards. Where local biostratigraphies continue to provide valuable information for accurate local correlation, they should be expressed as **oppelzone** rather than stage schemes.

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