History, philosophy, and application of the Global Stratotype Section and Point (GSSP)

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The history, philosophy, and application of the concept of the Global Stratotype Section and Point (GSSP) are reviewed. Geochronologic units defined by GSSPs serve as practical classificatory pigeonholes for the subdivision of geologic time. Accordingly, the main factor involved in the definition of GSSPs must be global correlatability. Early opposition to the GSSP concept centered around the desire for a traditional biochronologic time scale defined conceptually in terms of palaeobiological events, but such time scales are inherently unstable and thus unsuitable for the use of all geoscientists. The GSSP concept is also generally incompatible with the desire for 'natural' geochronologic boundaries. GSSPs have been defined mainly on the basis of biostratigraphic guiding criteria, but magnetic polarity reversals and chemostratigraphic and cyclostratigraphic horizons are now playing an important role. Most primary guiding criteria used to place a 'golden spike' will eventually become problematical in some way, so GSSPs should be defined so as to be correlatable by as many different lines of age-significant information as possible. The 'Global Standard Stratigraphic Age' (better renamed 'Standard Global Numerical Age') is a numerical analogue of the golden spike. Numerical definitions are currently appropriate for the formal subdivision of the Precambrian, and perhaps also for the Pleistocene/Holocene boundary. Recent suggestions to abandon chronostratigraphic terms (system, series, stage) in favor of geochronologic terms (period, epoch, age) are logically defensible, but could perpetuate the continuing confusion between various stratigraphic categories. □ *Boundary stratotype, chronostratigraphy, geochronologic unit, geologic time scale, golden spike, GSSP.*

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For most of the nineteenth century and the first two-thirds of the twentieth century, the standard geologic time units of the Phanerozoic Eon (periods, epochs, and ages) were generally conceptualized in three different ways. First, some of these time units were viewed as the spans of time subtended by the original type sections (unit stratotypes) of the corresponding systems, series, and stages (e.g. Dunbar & Rodgers 1957, pp. 290–293; Vai 2001; Zalasiewicz *et al.* 2004). More often, the periods, epochs, and ages were loosely-defined as the times of existence of the faunas and floras whose fossils were contained in the type sequences of the systems, series, and stages and their biostratigraphic correlatives in other areas (Berry 1987, chapter six). In both cases, however, the original systems, series, and stages were generally what we would now call lithostratigraphic and/or unconformity-bounded units (e.g. Carboniferous System; Wenlock Series; Thanetian Stage; American Commission on Stratigraphic Nomenclature [ACSN] 1965; Berry 1987), and not time-stratigraphic units in the modern sense. Under this general approach of conceiving time units, gaps and overlaps were inevitably created between successive units, because the original type sections or rock bodies as a whole were necessarily located in different geographic areas (Ager 1973, p. 70), and it was virtually impossible that the spans of time that they subtended (or the times of existence of their contained faunas) should be perfectly contiguous.

In order to eliminate these gaps and overlaps, the periods, epochs, and ages gradually became viewed as contiguous spans of time divorced from any particular section, and conceptually defined by palaeobiological events abstracted from biostratigraphic zones (Schenck & Muller 1941; Teichert 1958; Donovan 1966; Hancock 1977). These so-called 'standard' biochronologic units were defined using the most appropriate pelagic marine fossils available in any given part of the time scale (e.g. graptolites for the

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Ordovician; ammonites for the Jurassic, etc.). However, in the absence of any authoritative international body, fruitless debates about whether this graptolite or that conodont or that cephalopod (etc.) event should define a given period, epoch, or age boundary were inevitable (Ager 1973, p. 67). In addition, boundaries defined by palaeobiological events are inherently unstable owing to taxonomic changes and new fossil discoveries, and often difficult to correlate globally owing to faunal provinciality. As a result, the names of the supposedly 'standard' periods, epochs, and ages were used in significantly different ways by geologists in different parts of the world.

In a series of papers, H. D. Hedberg (1976, and references therein) argued that the situation described above was scientifically indefensible, and proposed to the International Geological Congress in 1952 that the International Subcommission on Stratigraphic Terminology be established, with the goal that "the upper and lower limits of all time-stratigraphic units should be specifically defined, both geographically and as regards position in the rock succession, in some type section or type area, in order to provide a standard control for the unit" (Hedberg 1954, p. 220). Gradually, and over much initial opposition, Hedberg's views were accepted and his vision evolved into the concept of the Global Stratotype Section and Point or GSSP (Cowie *et al.* 1986), in which two marker points ('golden spikes') in two boundary stratotype sections are used to define a span of geologic time (e.g. the Silurian Period). The corresponding chronostratigraphic unit (Silurian System) is thus now conceptualized as the set of all existing strata on Earth that were formed during that span of time (Harland 1978, p. 23; Hedberg 1978, p. 36; Harland *et al.* 1990, p. 3). As stated by Hedberg (1976, p. 83) "Stratotypes of the lower and upper boundaries of a chronostratigraphic unit best define its time span, which is its diagnostic character" (see also Salvador 1994, p. 88).

The status of GSSPs used in defining the standard global geologic time scale are summarized by Ogg (2004, this issue), and key features of the comprehensive Geologic Time Scale 2004, developed under the auspices of the International Commission on Stratigraphy (ICS), are discussed by Gradstein & Ogg (2004, this issue). The purpose of this paper is to explore the history, philosophy, and practical application of the GSSP concept. In addition to the formal documents of the ISSC (Hedberg 1976; Salvador 1994) and the ICS (Cowie *et al.* 1986; Remane *et al.* 1996), several pertinent essays have been written on this subject by McLaren (1977), Harland (1978, 1992), Hedberg (1978), Holland (1986, 1998), Odin (1997a, b), Odin *et al.* (1997), Aubry *et al.* (1999, 2000a, b), Vai (2001), Remane (2000a, 2003), Walsh (2001, 2003, 2004), Gradstein *et al.* (2003) and Zalasiewicz *et al.* (2004), so an attempt will be made to discuss issues not already covered in detail in those articles.

Hedberg and the International Subcommission on Stratigraphic Terminology

Many workers have contributed to the present status of the GSSP concept, but there can be little doubt that the efforts of Hollis D. Hedberg were primarily responsible for the eventual acceptance of stratotype-based, permanent, internationally-accepted definitions for the standard global geochronologic/chronostratigraphic units of the Phanerozoic time scale. Nevertheless, Hedberg had predecessors, and Harland (1978, p. 22) and Vai (2001) noted that embryonic concepts of the GSSP can be found in some early stratigraphic discussions. Some fairly modern general views on defining a standard global time scale were discussed in the textbook of Grabau (1924, pp. 1100–1101):

"What, then, are the criteria which must guide us in the selection of our typical section? First and foremost, the section must show continuous deposition. No sharp break either lithic or faunal should occur between the members, but all should be transitional. The character and origin of the strata composing the section must be carefully considered, since all rocks are not of equal value as indices of continuous deposition… Thus marine formations alone will serve for the erection of a standard scale, all formations of a continental type, whether of fresh water or of atmo-, anemo-, or pyroclastic origin, must be ruled out of the standard scale."

The emphasis placed by Grabau on conformable marine sections anticipates the modern GSSP concept, although the exact method of boundary defintion was not made clear in that work. In contrast, some of the discussions on the Plio-Pleistocene boundary held at the International Geological Congress in 1948 were quite explicit. King (1950, p. 5) stated:

"If it were possible to agree upon a type-locality where the boundary between the Pleistocene and the Pliocene can be seen, then future work could be tied to that 'bench-mark.' It is to be admitted that the exact bedding-plane which is chosen for the dividing line would be an arbitrary one."

King's (1950) concept is plainly identical to what would later be called the boundary stratotype, marker point, or golden spike, and is consistent with the views expressed in a contemporaneous article by Hedberg (1948).

Hedberg's original proposal for the establishment of an international commission on stratigraphic nomenclature that would help to bring about such rigorous definitions for all of the standard global geochronologic/chronostratigraphic boundaries was made at the very end of his paper given at the 19th International Geological Congress held at Algiers in 1952 (Hedberg 1954, p. 230):

"In view of the complex nature of stratigraphic nomenclature, the existing differences and inconsistencies in usage, and the resulting confusion in the international exchange of geological observations and ideas, it is here recommended that the 19th International Geological Congress take steps toward the creation of an International Commission to establish principles and harmonize practice in stratigraphic nomenclature and terminology."

The International Subcommission on Stratigraphic Terminology (ISST) of the International Geological Congress was duly formed in 1952. In 1965, the ISST became the International Subcommission on Stratigraphic Classification (ISSC) of the International Commission on Stratigraphy (ICS), both under the aegis of the International Union of Geological Sciences (IUGS). Hedberg was the President of the ISST/ISSC from 1952 to 1977, and was primarily responsible for the distribution to the stratigraphic community of many lengthy Circulars and their contained questionairres (see Hedberg 1976, p. 102). After consideration of the responses to the first ten Circulars, the ISST presented its preliminary 'Statement of Principles of Stratigraphic Classification and Terminology' at the 21st International Geological Congress in 1960 (ISST 1961). In this document, the emphasis on the definition of geochronologic/chronostratigraphic units was still being placed on the notion of a *unit stratotype* (body stratotype of Harland 1978), i.e., a physically superposed section in which both the base and the top of a system, series, or stage were to be defined. For example, the ISSC (1961, pp. 25–26) stated:

"The specific interval of geologic time which the rocks of any series represent is defined by the time-scope of a type sequence of strata for that series.... The basis for definition of a series should be a specifically designated and delimited type or reference sequence of strata.... The specific interval of geologic time which the rocks of any system represent is defined by the type sequence of strata for that system.... The basis for definition of a system should be a specifically designated and delimited type or reference sequence of strata."

This emphasis on the unit stratotype concept was consistent with long-standing practice in Europe, but the use of successive unit stratotypes to define contiguous, non-overlapping spans of time was impossible, as numerous stratigraphers pointed out (e.g. Carter 1970, p. 352; Ager 1973, p. 70).

Boundary stratotypes, golden spikes, and GSSPs

After the publication of the initial 'Statement of Principles of Stratigraphic Classification and Terminology' (ISSC 1961), it was soon realized that: (1) few if any continuous sequences existed on Earth that could serve as unit stratotypes to define chronostratigraphic units of the magnitude of a series or system (or even most stages); and (2), that even if such sequences could be found, their establishment in different geographic areas would inevitably result in the creation of unresolvable gaps and overlaps between successive chronostratigraphic units. To solve these problems, the concept of the boundary stratotype was discussed by R. von Gaertner, H. D. Hedberg, J. D. Lawson, J. Stöcklin, and others in ISST Circulars 14 and 15, and later published in an article jointly coauthored by the ISST and the ACSN (1965, p. 1696):

"Consequently, the best ultimate standard of reference for the boundary of a System appears to be a designated horizon in a specific type section of continuously deposited strata. From this type section (stratotype) the boundary may be extended around the world, by means of palaeontology or any other useful supplementary methods of time correlation, to achieve as nearly as possible the ideal of an isochronous boundary, while at the same time maintaining a fixed and immutable standard of reference in the stratotype."

Contemporaneously, however, the British Mesozoic Committee was also pondering this problem, and recommended that 'the base of each stage should be regarded as fixed for all time (preferably by reference to a specified point in a type section). This would still allow for future adjustments, if needed, for example, to accommodate newly recognized strata, at the top of each stage [Ager 1963, p. 1046]. These 'specified points' were equivalent to the boundary stratotypes of the ISST and ACSN (1965), and would soon be informally referred to by many workers as 'golden spikes'. Holland (1986; 1998) assumed that this term was taken from the ceremonial golden spikes used to mark the completion of important railway lines in North America. Sylvester-Bradley (1967, p. 53), however, hinted at a different origin:

"The concept of marker points is not, of course, a British invention. I became acquainted with it in 1961 during a session of the International Field Institute in Britain, held under the auspices of the American Geological institute. I was leading a party of American geologists over the classic localities of the Jurassic System in England. Dr. W. C. Bell, a member of the American Stratigraphic Commission, had brought with him a 'golden pick'. At each type locality, the pick was driven into the section at the base of the formation, and a photograph of it and the type section was taken. Now, many British stratigraphers feel that marker points should be physically inserted in type sections as permanent records, only to be altered by decision of an International Commission."

Much has been written on the disagreement between the British school and Hedberg on the significance of the 'base defines boundary principle' (Ager 1973; George *et al.* 1967; Hedberg 1968, 1977; Aubry *et al.* 1999, pp. 105–106; Walsh 2004), but the problem is mainly semantic. Hedberg (1968, p. 196) seemed not to realize that when George *et al.* (1967) recommended defining only the base of each standard global geochronologic/chronostratigraphic unit, they simply meant that in the selected stratotype section, only the base (and not the base *and* the top) of a given unit would be defined. This is just another way of saying that the standard global units would be defined by boundary stratotypes and not by successive unit stratotypes. As such, the end/top of each standard global geochronologic/chronostratigraphic unit would naturally be defined by the beginning/base of the next succeeding unit, a point with which Hedberg (1968, p. 196) fully agreed.

Nevertheless, one substantive disagreement did exist between Hedberg and the British school on this subject, and that involved Hedberg's (1977, p. 230) view that "If the type boundary was unwittingly placed at an unconformity, then it could not have been a valid chronostratigraphic boundary and should be corrected". This statement underscores Hedberg's emphasis on the *correlatability* of boundary stratotypes (Walsh 2004). The British stratigraphers, in contrast, would have been content in such a case to let the original definition stand, and to stipulate that for the purpose of defining a moment in time (e.g. the Silurian/Devonian *Period* boundary), the golden spike was hammered into the base of the upper bounding surface of the unconformity, rather than into the top of the lower bounding surface of the unconformity. This 'base defines boundary principle' has since been incorporated into the Guidelines of the ICS (Cowie *et al.* 1986; Remane *et al.* 1996) and the second edition of the International Stratigraphic Guide (Salvador 1994, p. 90), and is no longer contentious.

It should be noted that a very different concept of the 'base defines boundary principle' also exists, with some of its more prominent advocates being Odin (1997b) and Aubry *et al.* (1999, 2000a,b). These workers contend that the beginning/base of any Standard Global Age/Stage taking its name from a historical European 'stage' (usually, a synthem or depositional sequence) must be defined so as to correspond to the base of the unit stratotype of that historical 'stage'. While such a view may be perfectly appropriate in those cases where excellent correlation criteria are present at the relevant horizon, the universal application of this philosophy would be impractical (Walsh 2004).

Hedberg's (1976, p. 24; fig. 2) definition of a boundary stratotype referred to the boundary level or boundary point itself, rather than to the stratigraphic section in which that boundary point was located. Traditionally, however, a 'stratotype' referred to a thickness of strata, and some workers understandably preferred to use the term 'boundary stratotype' for the specific section in which the boundary point was located (e.g. Zhamoida 1984, p. 10). This usage was eventually adopted in Salvador (1994, p. 26). In addition, a boundary stratotype as defined in Hedberg (1976) is a general concept applicable to the definitions of lithostratigraphic, unconformity-bounded, magnetostratigraphic, and other local and regional stratigraphic units (Salvador 1994). However, the standard global geochronologic/chronostratigraphic units differ from such local units in two major ways. First, the requirements for the definitions of their boundaries are much more strict than the requirements for local stratigraphic units, and second, boundary definitions of the standard global geochronologic/chronostratigraphic units are intended to be permanent (Hedberg 1978; Murphy 1994). A new term was clearly needed to denote the unique nature of the formal boundaries of the standard global geochronologic/chronostratigraphic units, and it was supplied by Cowie *et al.* (1986): 'Global Stratotype Section and Point', or GSSP. This self-defining phrase has been widely accepted (Salvador 1994, p. 90), and under it, the colloquial 'golden spike' is often still used to denote the 'Point.'

Nature and purpose of GSSPs

Despite widespread agreement on their necessity, there remains some disagreement about what GSSPs really *are*. Hedberg (1961, p. 510) stated:

"If we fix the basis of a system, or a series, or a stage, as a designated section (or sections) of rock strata, then we all have a common standard of reference which in its type can mean only one specific interval in the time scale to any of us regardless of our ever-changing interpretation of history. This is not a freezing of what we measure, as some have claimed (Bell 1959), but a freezing of the units by which we measure. And I think this constancy is what we want in any standard of measurement."

Similarly, Remane *et al.* (1996) suggested that 'A GSSP cannot be compared to the holotype of Zoological Nomenclature; it corresponds rather to a standard of measure in physics (Harland 1992)'. This view is correct in that holotypes in biological taxonomy merely establish the priority of a name and do not define the boundaries or meaning of anything (Bell 1959), whereas GSSPs in stratigraphy, by fixing the boundaries of a named geochronologic/ chronostratigraphic unit, automatically serve to define the *meaning* of that name. Nevertheless, Aubry & Berggren (2000, p. 109) pointed out that the analogy between chronostratigraphic units and units of measure was not quite valid:

"In our opinion, a chronostratigraphic unit cannot be compared to units of measure in physics as hinted by Harland (1992; see also Remane *et al.* 1996). A stage cannot compare to a meter. It represents a certain interval of time, but that measure is always certain with regard to strata and uncertain with regard to duration; it is *not a measure of time* [italics in original]."

Although we would quibble with the view that any stage is 'certain with regard to strata,' we would reformulate the statement of Aubry & Berggren (2000) and agree that the actual duration of any Standard Global Age defined by two GSSPs is uncertain, and as such is not comparable to, for example, the standard second in physics. Rather, the Standard Global Geochronologic Units (including the 'geochronometric' units used for the Precambrian time scale; e.g. North American Commission on Stratigraphic Nomenclature [NACSN] 1983, p. 872) are more profitably regarded as classificatory pigeonholes, analogous to the arbitrarily-defined grain-size pigeonholes used for classifying clastic sediments, and the arbitrarily-defined compositional pigeonholes used for classifying plutonic rocks (Walsh 2001). These standard pigeonholes of the geologic time scale provide a stable, theory-neutral framework for expressing similarity in age, 'regardless of our ever-changing interpretation of history'.

If it is accepted that the standard global geochronologic/chronostratigraphic units are basically practical, classificatory pigeonholes, then all else being equal, those pigeonholes should be defined so as to allow as many objects of classification (rocks) as possible to be thrown into them, because that is what pigeonholes are for. In regard to selecting GSSPs, this will generally require that the main emphasis be placed on global correlatability (Remane *et al.* 1996; Remane 2000a; Walsh 2004; Gradstein *et al.* 2003).

Stages of evolution

Although the need for a single set of standard global periods/systems and epochs/series was widely accepted for most of the twentieth century, the extension of such a scheme to the age/stage level was much more controversial. The term 'Standard Global Stage' was first introduced by the ISSC (1970: p.25) in its 'Preliminary Report on Stratotypes', and was subsequently formalized in Hedberg (1976). The concept at first met with considerable opposition, best exemplified by the exchange between Van Couvering (1977) and Hedberg (1977). Some of the difficulties are attributable to the many lingering connotations of 'stage', which historically has been one of the most ambiguous terms in stratigraphy. This term has been restricted to chronostratigraphic entities in recent stratigraphic codes and guides (Hedberg 1976; NACSN 1983; Salvador 1994), and this usage, though still not universal, has gained overall acceptance. Thus, we emphasize that certain usages of 'stage' are improper, because they can only lead to a confusion of fundamentally different categories (Walsh 2004).

Ager (1984, p. 97) stated: "On the continent of Europe, from France to the Soviet Union, there is a fixation with the stratotype, which is the absolute criterion for a stage". Although there are many different kinds of 'stratotypes', a *unit* stratotype is just a very local stratigraphic section whose designated base and top are used to define stratigraphic boundaries (Salvador 1994, pp. 26–27). As implied by Ager (1984), there was a historical tendency among European workers in particular to regard the unit stratotype itself as 'the stage' (rather than the stage being the set of all strata formed during the span of time subtended by that unit stratotype), and this can

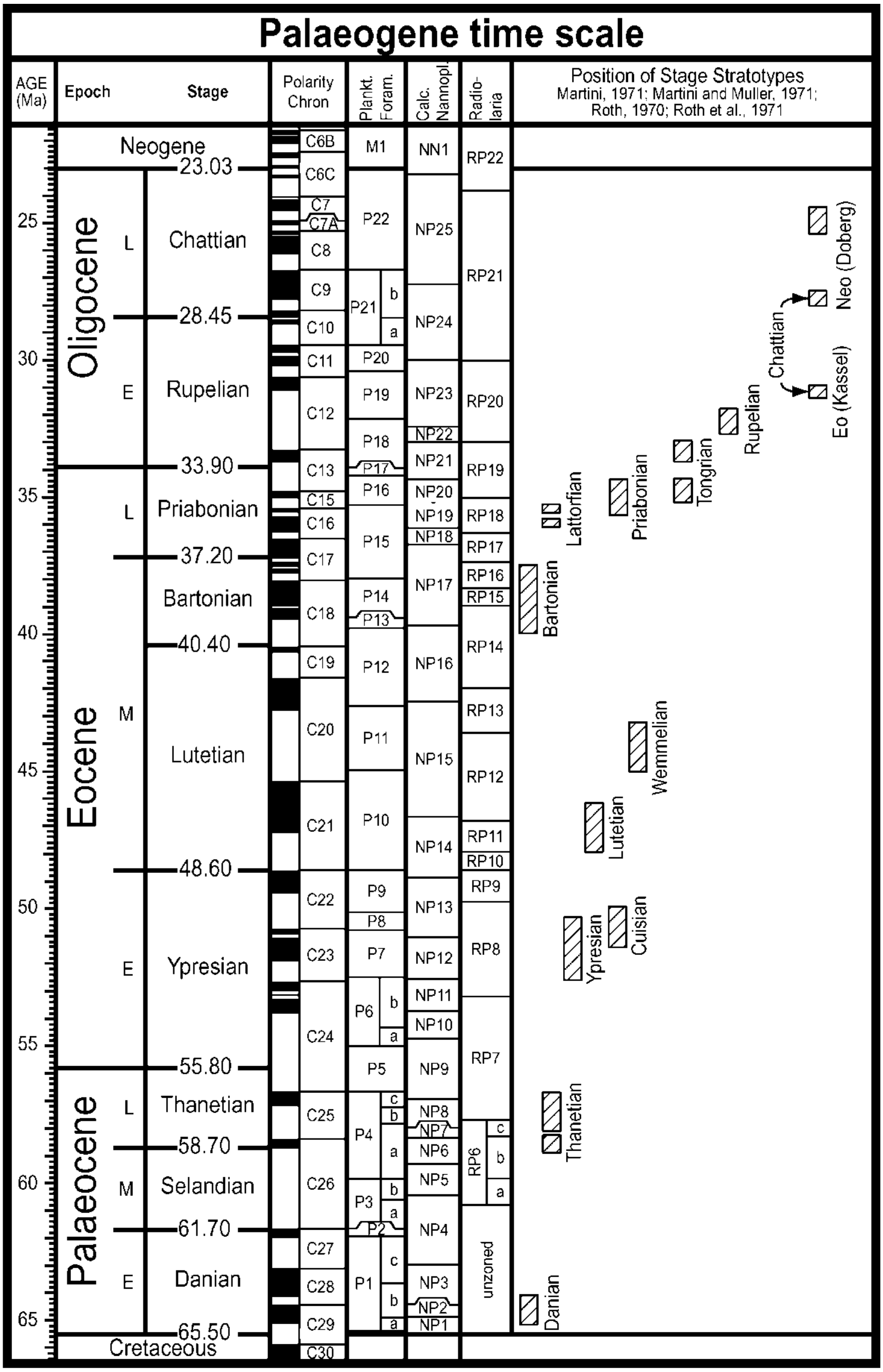

Fig. 1. Age spans of historical stratotypes of some Palaeogene stages. The left columns include the microfossil zones and polarity chrons that span the complete Palaeogene according to coring of marine sediments. The historical stratotypes span less than half of Palaeogene time; some are simply facies equivalents rather than chronostratigraphically distinct units. Only a few of these competing stage concepts were preserved in the nomenclature of the present Palaeogene geologic time scale. Standard Global Stages for the Palaeogene are defined at boundary stratotypes at which the basal boundary of the stage is positioned relative to primary and secondary biostratigraphic, geochemical or magnetic polarity events for global correlation. Modified from Hardenbol & Berggren (1978).

lead to the semantic misunderstandings discussed by Walsh (2001, 2003, 2004).

Perhaps the most common traditional usage of 'stage' was for an abstract assemblage of 'biostratigraphic' zones. Such usage was prevalent in stratigraphic palaeontologists trained in the methods of the great palaeontologist Albert Oppel, and is exemplified by the 'German school' (discussed below), and the remarks of workers such as Donovan (1966), Hancock (1977), Kleinpell (1979), and Ludvigsen & Westrop (1985a, b). While some *biochronologic* and *biochronostratigraphic* units can logically be assigned the rank terms age and stage (Walsh 2001), biostratigraphic units in the strict sense should never be called stages, because such units are not and cannot possibly be chronostratigraphic units (Hedberg 1976; Johnson 1981; Salvador 1994).

Another common European usage of 'stage' was for the concept of either a provincial unconformity-bounded unit, or for a 'natural' depositional sequence of sedimentation resulting from a single marine transgression and regression. These related usages have their roots in the classic works of influential stratigraphers like D'Orbigny and Gignoux (e.g. Monty 1968; Aubry *et al.* 1999). While both are important concepts, it is now improper to use the term 'stage' for them, and they are best referred to as unconformity-bounded units (Salvador 1994), allostratigraphic units (NACSN 1983) or depositional sequences (e.g. Van Wagoner *et al.* 1988).

The differences between the concepts of unit stratotype, synthem, depositional sequence, and standard global stage have been illustrated by diagrams in Hardenbol & Berggren (1978, fig. 3) and Walsh (2004, figs 1–2), and the separation of these concepts by the use of distinct terms is necessary for precise communication (Fig. 1).

Opposition to the GSSP concept

Despite their apparent disagreements over priority and the exact meaning of the boundary stratotype/marker point/golden spike concept, the Hedberg school and the British school were in agreement on the most important issue – that the boundaries of the standard global periods/systems, epochs/series, and ages/stages should be permanently defined in stratotype sections. However, many stratigraphers were opposed to this precept. Their views took various forms and originated in various places, and a look at the reasons for their opposition may be instructive.

Members of the 'German school' preferred to define the standard global units conceptually, in traditional biochronological terms, and saw no need for golden spikes or boundary stratotypes of any kind (Schindewolf 1970; Weidmann 1970; Erben 1972; O.H. Walliser *in* McLaren 1977, p. 12). Some British and American stratigraphers held a similar view (Teichert 1958; Donovan 1966; Hancock 1977; Kleinpell 1979). This was a legitimate philosophical position, and is especially appropriate for the numerous provincial ages/stages defined for major fossil groups, which are intended to have flexible boundaries subject to modification with new data (Walsh 2001). However, the shortcomings of this approach for defining the standard global geochronologic/chronostratigraphic units were effectively explained by Hedberg (1973, 1976), McLaren (1977), Harland (1978) and Cowie *et al.* (1986), and mainly involve the point that precisely because such boundaries are inherently subjective and unstable, they are unsuitable for the definition of a standard global time scale, which by definition must serve all geoscientists and not just the experts working on a particular taxonomic group.

The GSSP concept also had many detractors in America, among the most prominent being those of the 'Berkeley school' (see Berggren 2000), which included leading West Coast Cenozoic stratigraphers like R. M. Kleinpell and D. W. Weaver. The most striking views of the Berkeley school were that the Cenozoic epochs should be left alone as the ill-defined units that we inherited from Lyell, that all age correlations should be made by means of provincial biochronologic ages/stages, and that a Standard Global Age/Stage was a contradiction in terms (Weaver 1969; Philips 1972; Kleinpell 1979). These views are criticizable on some of the same grounds as those of the German school.

Golden spikes vs. golden events

Many criticisms of the GSSP concept were based on a preference for what might be called the 'golden event' rather than the golden spike. A golden spike serves to operationally define a given boundary, requires the choice of a specific stratigraphic section before it can be hammered in, and once driven in, is intended to be permanent. For example, the existing Silurian/Devonian boundary is defined by a golden spike hammered into the level corresponding to the lowest known occurrence (as of 1972) of a fossil of the graptolite *Monograptus uniformis* in a specific section at Klonk, Czech Republic (McLaren 1977). The golden spike would not be moved if a new fossil of *M. uniformis* were to be found lower in this section (Cowie *et al.* 1986; Remane 2003; Gradstein *et al.* 2003). In contrast, the boundaries of an 'event-chronologic unit' would be defined conceptually in terms of inferred geohistorical events, and so would not require golden spikes.

Thus, the analogous golden event definition of the Silurian/Devonian boundary would simply be the evolution of *M. uniformis*, wherever and whenever in the world that event actually took place (cf. O. H. Walliser *in* McLaren 1977). A golden event definition involving a particular magnetic polarity reversal would refer to the magnetic field reversal itself (as inferred from a specified ocean floor magnetic anomaly) and not a magnetozone boundary in a specific stratigraphic section that we interpret to record that specific magnetic field reversal (Richmond 1996). Golden event definitions would be amenable to some modification as our knowledge increased. Also, most of these events would be more or less 'fuzzy,' such as the onset of major glaciations, the evolution of biological species, and reversals of the Earth's magnetic field (which reportedly occur over about 5000 years; Opdyke *et al.* 1973; Clement *et al.* 1982). Other golden events would be instantaneous, however, such as the impact of the large meteorite that could be used to conceptually define the Cretaceous/Palaeogene boundary.

The use of golden events rather than golden spikes to define standard global geochronologic/chronostratigraphic boundaries is appealing in many ways, but again has the important drawback of potential instability (McLaren 1977). For example, if the evolution of *Monograptus uniformis* were used to define the Silurian/Devonian boundary, but this taxon was subsequently found in the Wenlock, or was determined to be a junior synonym of some other species with a very different age range, then other stratigraphers would no doubt start lobbying for the use of their own favorite event to be used in defining the 'new' Silurian/Devonian boundary, and we would find ourselves back in the days of having interminable, scientifically pointless debates about boundary definition (cf. Holland *et al.* 2003).

The problem of 'naturalness' in chronostratigraphy

There has been much discussion in the literature on the desirability of defining the standard global geochronologic boundaries to correspond as closely as possible to objective, 'natural' phases in the overall history of the Earth. This subject is related to the distinction between golden spikes and golden events discussed above. In particular, the insistence on natural boundaries has always been a primary contention of the 'Russian school' of stratigraphy (Ovechkin *et al.* 1961; Meyen 1976; Interdepartmental Stratigraphic Committee of the USSR, 1979), which generally regarded the GSSP concept with suspicion.

The Russian view concerning natural boundaries was diplomatically discussed by Hedberg (1961), and although appealing in concept, is fraught with difficulties (Ager 1973; 1984). Şengör (2001) is instructive here, as is the essay 'On the Sources of Knowledge and of Ignorance' in Popper (1989). These deal with the seductive notion that 'the truth is manifest.' In geology, however, the truth is usually *not* manifest. That is, what are obviously the most 'natural' breaks to stratigrapher A just might not seem to be the most 'natural' breaks to palaeontologist B, and tectonic geologist C would likely disagree with both A and B. Furthermore, if the truth is manifest, then it cannot be contradicted by any new evidence. But *all* human theories about the nature and significance of past geologic events are potentially modifiable with new evidence. As such, the perceived 'naturalness' of any particular temporal boundary is dependent upon the evidence available to humans at any given time, whereas a GSSP is intended to be permanent, and thus immune to future changes in the status of its perceived naturalness.

A second point about natural boundaries is that because innumerable natural events occurred in geohistory, an unnecessarily large number of standard global ages/stages and subages/substages of relatively short duration based on these events can be proposed. This tendency for oversplitting has been a problem in defining some of the subdivisions of the standard global geologic time scale, and has been discussed by Chlupác *et al.* (1981), Menning *et al.* (2001) and Walsh (2001). Such oversplitting may be motivated by the view that if an arbitrary, relatively broad standard global geochronologic framework is defined by GSSPs, then the importance of numerous natural geohistorical events will be obscured. However, this would be a misapprehension, for the same reason that it would be incorrect to claim that the definition of a framework of arbitrarily-located lines of longitude would somehow cause us to ignore important natural geographic features of the Earth.

An important semantic error has also clouded the debate about natural boundaries. 'Natural' and 'unnatural' are 'either-or' terms, that is, contradictories (like legal and illegal, or seen and unseen). In the context of geology, for example, a rock body or geohistorical event is either natural (existing or occurring in nature independently of its conception in the mind of a human being), or it is not. As such, it makes little sense to say that there are 'degrees' of naturalness in chronostratigraphy. For example, consider two hypothetical palaeobiological events. Event 1 is the evolution of a rare terrestrial mammal species that lived only in a small provincial area of North America. Event 2 is the evolution of a pelagic marine species whose abundant fossils are known in many sections around the world. Was the evolution of the pelagic marine species a more 'natural' event than the evolution of the terrestrial mammal species? Obviously not. And yet, because a geochronologic boundary defined using the pelagic marine taxon as the guiding criterion would be much more correlatable for human purposes than a boundary defined using the terrestrial mammal taxon, we would tend to call the former a 'more natural' boundary. However, this conclusion is incorrect, for the same reason that it would be incorrect to say that committing a murder is 'more illegal' than stealing a wallet. Both of these acts are just plain *illegal* (although obviously we could say that one act is more reprehensible than the other). Similarly, numerous natural events occurred in geohistory, but some are more *correlatable* than others, and it is those events that we must focus on when defining the Standard Global Geochronologic/Chronostratigraphic Units.

A final point about naturalness in chronostratigraphy is that even if we used two natural events to conceptually define a geochronologic unit (say, the Silurian Period), the resulting chronostratigraphic unit (Silurian System) would not in any way be natural, because such a unit is necessarily a *class* (Walsh 2001, 2004). For example, as currently defined by the golden spikes in Scotland and the Czech Republic (Bassett 1985; McLaren 1977), the Silurian System is a set of rocks that 'exists' only in the minds of human beings as an abstraction, and so cannot in itself be a natural stratigraphic entity. In short, we would be well-advised to stop using the term 'natural' in the context of chronostratigraphy.

GSSPs in practice

The first GSSP defining a Standard Global Geochronologic/Chronostratigraphic boundary was established at Klonk in the Czech Republic, and defined the boundary between the Silurian and Devonian Periods/Systems (McLaren 1977). This boundary decision was applauded by Hedberg (1973) at the time and provided a good example of the need for compromise and the general procedure to be used. Thirty years later, the value of the Silurian/Devonian GSSP was affirmed by Chlupác & Vacek (2003). Much additional progress has been made in completing the formal definition of the Phanerozoic time scale, as documented by Cowie *et al.* (1989), Vai (2001), Remane (2003), and Gradstein *et al.* (2003, 2004). As stated by Holland (1998, p. 387) 'It is surprising how quickly things settle down and use of the standardized divisions, perhaps once unpopular with some, become uniformly used'.

Some of the different criteria that have been used to define GSSPs are worth noting. The vast majority of GSSPs have been based on a biostratigraphic guiding criterion, i.e. the lowest or highest known occurrence of a fossil of a single specified pelagic marine taxon in the boundary stratotype (such occurrences presumably corresponding closely to the actual time of evolution or extinction of those taxa). These defined levels are generally bracketed by other biostratigraphic data involving several other taxonomic groups, aiding correlation in sections where the primary guiding criterion may be rare, absent, or poorly preserved (McLaren 1977; Murphy 1977).

A few GSSPs have been defined using palaeomagnetic reversal horizons as the primary guiding criterion, with supplementary biostratigraphic data above and below the reversal aiding in correlation. One example is the Palaeogene/Neogene = Oligocene/Miocene boundary GSSP, which was placed at an apparent magnetozone boundary in the Lemme-Carrosio section of Italy interpreted to represent the C6Cn.2r/C6Cn.2n polarity-chronologic boundary (Steininger *et al.* 1997). Other GSSPs that may soon be defined using palaeomagnetic reversals as the primary guiding criterion include the Danian/Selandian and Selandian/Thanetian Age/Stage boundaries in the Paleocene (Gradstein *et al.* 2004), and the Early Pleistocene/Middle Pleistocene Subepoch/Subseries boundary (Richmond 1996). Although appropriate in many cases, the use of polarity reversal horizons as the primary guiding criterion for a GSSP can also be problematical, owing to the binary nature of the signal, our resulting ability to 'correlate' any conceivable apparent magnetostratigraphic pattern to the geomagnetic polarity time scale, and the possible misidentification of the polarity chron that a given alleged or real magnetozone is supposed to represent (Odin *et al.* 1997, p. 600; Shackleton *et al.* 2000). These problems are especially relevant for those parts of the time scale that have had a complex magnetic polarity history (such as the Neogene), with reversals commonly occurring only 100,000 to 200,000 years apart (Cande & Kent 1992).

Unconformities have long been rejected as suitable horizons for placing golden spikes (Hedberg 1976, p. 84; Cowie *et al.* 1986, p. 7; Salvador 1994, p. 90), because such placements would restrict our ability to precisely correlate those golden spikes to the evidence available on just one side of them (Walsh 2004). However, Van Couvering *et al.* (2000) placed the golden spike for the Miocene/Pliocene GSSP at the unconformity between the nonmarine Arenazzollo Formation and the overlying marine Trubi Formation, reflecting the historical concept of the base of the Zanclean Stage in the Mediterranean region. Such an unorthodox placement of the golden spike was thought to be justified in this case by the exceptional astrochronological correlatability of the Trubi Formation. Unconformable horizons might also be used with caution in other situations. For example, GSSPs for the Precambrian are difficult to come by, and it is conceivable that the best available boundary stratotype for defining a particular subdivision of Precambrian time might involve placing the golden spike at a minor disconformity, if the choice of such a boundary still offered better correlation potential than all other available sections.

Chemostratigraphic criteria are now playing an important role in the definition of GSSPs, and in some cases offer the potential for accurate global correlation in both marine and nonmarine facies. The Cretaceous/Palaeogene GSSP was formally defined at El Kef, Tunisia, using the famous iridium anomaly (Alvarez *et al.* 1980) as the primary guiding criterion (e.g. Keller *et al.* 1995). The chemostratigraphic approach is also exemplified by the remarkable negative carbon isotope excursion (CIE) documented by Kennett & Stott (1991), Koch *et al.* (1992, 1995), Stott *et al.* (1996), and other workers, and recently accepted as the guiding criterion for the Paleocene/Eocene boundary (Gradstein *et al.* 2004). The CIE corresponds closely to global faunal changes in mammals (Lucas 1998; Hooker 1998), benthic foraminifera (Thomas 1998), and dinoflagellates (Crouch *et al.* 2001), and so should be readily correlatable throughout the world. The marine oxygen isotope stages (e.g. Shackleton & Opdyke 1973), so fundamental to our understanding of Plio-Pleistocene geohistory, are another example of chemostratigraphic phenomena likely to play a key role in the subdivision of the time scale, in particular for the formal definition of the Middle Pleistocene/Late Pleistocene Subepoch/Subseries boundary (Gradstein *et al.* 2004).

Finally, an innovative approach to GSSP definition was demonstrated by Odin (2001) and Odin & Lamaurelle (2001), who drove the golden spike for the Campanian/Maastrichtian Age/Stage boundary into the midst of a 'bundle' of twelve different biostratigraphic occurrences of various taxa in a marine section in France, but without designating any one of these biostratigraphic occurrences as the primary guiding criterion for the boundary. This approach has merit, as it de-emphasizes the importance of any one correlation criterion, and underscores the fact that once they are defined, golden spikes are intended to serve as stable, theory-neutral levels for correlation.

'Tardy' GSSPs

Vai (2001), Remane (2003) and Gradstein *et al.* (2003) have commented on the apparent hesitancy of some of the Subcommissions of the ICS to formally propose GSSPs for subdividing their assigned period/system. Complete hierarchical subdivision of some of the Phanerozoic periods/systems into Standard Global Epochs/Series and Ages/Stages is indeed difficult (especially the Cambrian; Geyer & Shergold 2000) and in these cases the issue cannot be forced. All members of each of the Subcommissions are conscientious workers who take their task seriously, and their hesitancy may in part be due to their fear of saddling the geologic community with a relatively 'poor' GSSP, should such a GSSP be defined on the basis of premature information. This attitude is scientifically healthy and understandable, and is not in itself a problem. What might be a problem, however, is the tendency to think that we must find a perfect, untarnishable primary guiding crierion before we can propose a GSSP (Vai 2001). It is important to realize that with few exceptions, as temporal resolution increases and new data emerge, we should expect that *any* primary guiding criterion used to place a GSSP will eventually be shown to be somewhat diachronous or problematical in some way. This underscores the fact that the boundary level in any specific GSSP should be placed at a horizon correlatable not just by the primary guiding criterion, but by as many lines of independent age-significant information as possible, such as other fossil groups, radiometrically-dated horizons, chemostratigraphic horizons, magnetic polarity reversal horizons, etc. (Hedberg 1976, p. 80; Cowie *et al.* 1986, p. 7; Odin 1997b, p. 6). That way, if and when the primary guiding criterion is shown to be problematical, the golden spike will still be readily correlatable on the basis of data already observed in the GSSP and closely associated sections.

Standard global chrons/chronozones: logical necessity or impractical oversplitting?

Cowie *et al.* (1986, p. 5) stated: 'ICS still has a great deal of work to get through in the rest of this century and beyond and it will expedite matters if a plethora of lower status candidates are not submitted until the main GSSPs down to stage level are decided'. The next century has arrived, however, and so it must again be asked: Should Standard Global Ages/Stages be further subdivided into golden spike-defined, Standard Global Chrons/Chronozones? This question was first answered in the affirmative by George *et al.* (1967, p. 83), who stated:

"A Standard Chronozone is defined by reference to marker points in type-sections. In future Chrons Standard/Chronozones should be named, as far as possible, after geographical localities (e.g. Casterbridge Standard Chronozone) but in practice many of them will retain fossil names in their titles."

Holland (1986, p. 13) suggested that subdivision of the Standard Global Ages/Stages into golden spike-defined chrons/chronozones would eventually be necessary throughout the time scale (see Walsh 2001). Similarly, Cowie (1987, p. 101), in an official comment on behalf of the ICS appended to the paper of Klapper *et al.* (1987), stated that 'The GSSP at the base of the Frasnian Stage (described above) automatically defines, in line with ICS procedure (Cowie *et al.* 1986 p. 8), the top of the middle Devonian Series, also the top of the Giventian Stage *as well as the top of the lowermost* asymmetricus *Zone* [italics added]'. In contrast, in a reply to Sandberg *et al.* (1988), Klapper (1988, p. 182) stated: 'To make my position clear on the function of boundary stratotypes, I do not agree with the comment of Cowie… that the fixing of the GSSP also defines the base of the Lower *asymmetricus* Zone, because I do not think that zones by their very nature should be tied to boundary stratotypes'.

We tend to agree with Klapper (1988). While the formal definition of standard global subages and substages may be appropriate for some parts of the time scale, 'standard zones' were traditionally *biochrons/biochronozones* (Arkell 1956, pp. 5–6), because they were defined conceptually by palaeobiological events, and were never intended to be defined by golden spikes (Odin 1997a). These biochronologic units are reasonably named after fossil taxa. But if it is ever decided that we really need golden spike-defined Standard Global Chrons/Chronozones of less than subage/substage rank, then these would have to be given geographic names (as originally recommended by George *et al.* 1967) so as not to be confused with the biochrons on which almost all of them would be based. This step would result in the coining of literally hundreds of virtually unmemorizable new geographic names for these minute formal subdivisions of the time scale, a dubious result indeed.

In the majority of cases, the only way that we would be able to tell if a given stratum was assignable to a given golden spike-defined Standard Global Chronozone would be by the presence therein of fossils of the taxa that defined/characterized the corresponding biochron. Clearly, however, this would make a golden spike definition of the Standard Global Chron/Chronozone redundant. In addition, should our concept of the original biochron require modification as a result of new data (a frequent occurrence at the limits of temporal resolution), then we would no longer be able to meaningfully correlate the boundaries of the permanently-defined Standard Global Chron/Chronozone, which would still be based on the now-obsolete concept of the original biochron (Hedberg 1976, p. 70). It is our view that if temporal resolutions finer than a given Standard Global Age/Stage or Subage/Substage need to be discussed, they can be expressed in numerical terms, in local biochronological terms, in 'standard' biochronological terms, or in polarity-chronologic terms, without the need for golden spike-defined chrons/chronozones of such relatively short duration (Walsh 2001, 2004).

Numerical definitions of geochronologic boundaries

Subdivision of Precambrian time

Owing to the lack of a finely-resolved biostratigraphic record for most of the Precambrian, many workers have advocated subdivisions whose boundaries are defined by semi-arbitrarily-chosen numerical ages (e.g Trendall 1966; James 1981; Plumb & James 1986). In order to accommodate such definitions, the category 'Geochronometric Unit' was adopted by the NACSN (1983), but a similar category was used neither by Hedberg (1976), Cowie *et al.* (1986), Salvador (1994), nor Remane *et al.* (1996). Nevertheless, a specific scheme of numerically-defined Precambrian subdivisions was formally approved by the Subcommission on Precambrian Stratigraphy, ratified by the ICS and IUGS in 1989, and subsequently published (Plumb 1991; Remane 2000b). Accordingly, in the revised guidelines of the ICS, Remane *et al.* (1996) formalized the concept of the 'Global Standard Stratigraphic Age' (GSSA), which is an abstract numerical analogue of the golden spike. This phrase contains a misnomer, however, because if a temporal boundary is defined in purely numerical terms, it just cannot be a *stratigraphic* age. The concept is valid, but might be renamed 'Global Standard *Numerical* Age,' or better yet, 'Standard Global Numerical Age,' in order to be consistent with the phrase 'Standard Global Geochronologic/Chronostratigraphic Units' (Hedberg 1976; Salvador 1994).

In contrast to those advocating numerical subdivision of the Precambrian, Crook (1966, 1989), Hedberg (1974, 1976), Cloud (1987) and Salvador (1994) argued that just as in the Phanerozoic, Precambrian subdivisions should be defined using boundary stratotypes. Although the Subcommission on Precambrian Stratigraphy has been dissolved after completing its work, a new ICS 'Subcommission on a Natural

Time Scale for the Precambrian' has recently been formed, and is dedicated to finding natural events upon which subdivision of the Precambrian using GSSPs could be based (Gradstein *et al.* 2003; Bleeker 2004). Their task is daunting, however. Even though numerous geological events of global magnitude certainly occurred during the Precambrian, their confident recognition in various sections as the same event may be difficult. For example, if there were no biostratigraphic record in the Paleocene/Eocene, then the very distinctive negative Carbon Isotope Excursion used as the guiding criterion for the Paleocene/Eocene boundary (Gradstein *et al.* 2004) would never have been recognized as representing the same event in various sections around the world, because we would never have known where to look for it in each local section. If the average age resolution for any randomly selected Precambrian sedimentary section is on the order of 100,000,000–200,000,000 years or more, then several different (e.g. carbon isotope) events could have occurred during this span of time during the Precambrian, and not only would we not be able to tell them apart if they were found in various sections around the world, but we would be at a loss as to exactly where to sample for these chemostratigraphic signals in each section. These problems will be difficult to overcome when attempting to define any pre-Ediacaran GSSPs in the near future.

Nevertheless, some of the problems noted by Bleeker (2004) with the numerical scheme of the IUGS are real, and may in part be attributed to a lack of consideration of some of the practical aspects of defining pigeonholes. The purpose of a pigeonhole is again to classify as many objects as possible. In a hierarchical system, this goal is best achieved when each major pigeonhole is subdivided into two equal parts, and these subdivisions are in turn subdivided into two equal parts, and so on. History and tradition permitting, such a scheme allows for the classification of the most objects, because at any given level in the hierarchy, each pigeonhole contains only one internal boundary. As such, when we are trying to assign objects in a given pigeonhole to subdivisions of that pigeonhole, uncertainty in assignment will occur only for those objects whose attributes would cause them to be classified at or near the boundary between the two internal pigeonholes. In contrast, if we divided a given pigeonhole into three or four subdivisions, then that pigeonhole will contain two or three internal boundaries, thus leaving that many more objects unassignable to a particular subdivision (cf. Walsh 2004, p. 136, regarding the formal subdivision of the Pliocene Epoch into three rather than two standard global ages/stages).

The above principle is clearly illustrated by the finer divisions of the Precambrian time scale ratified by the IUGS (Remane 2000b). For example, the Palaeoproterozoic Era (2500 to 1600 Ma) is subdivided into four named periods of about 200 million years duration each. The Mesoproterozoic Era (1600 to 1000 Ma) is subdivided into three named periods of 200 million years each, and the Neoproterozoic Era (1000 to 542 Ma) is subdivided into three periods, one of 150 million years duration, one of 250 million years duration, and the youngest (Ediacaran) of about 58 million years duration. The pre-Ediacaran period names have been little-used according to Bleeker (2004, this issue), perhaps in part because their durations are close to the average temporal resolution for sedimentary rocks in this part of the time scale. In view of the above, a more practical scheme might have been to subdivide each of the Palaeoproterozoic, Mesoproterozoic, and Neoproterozoic Eras into two Suberas of roughly equal duration (e.g. Early and Late Palaeoproterozoic), and defer recognition of the periods until use of the more inclusive suberas was well-established. Such a scheme could of course still be adopted if thought to be useful.

The Pleistocene/Holocene boundary

Hedberg (1976) and Salvador (1994) urged that the standard global geochronologic/chronostratigraphic units of the Quaternary be defined no differently from those in the rest of the Phanerozoic. This view is reasonable for most of the Quaternary (Italian Commission on Stratigraphy 2002), but there are serious difficulties involved in finding a suitable marine GSSP for the Pleistocene/Holocene boundary (Mörner 1976; Hyvärinen 1976; Gibbard & West 2000). One of these difficulties is similar to the main problem involved in the use of GSSPs for the subdivision of Precambrian time. However, the main problem in defining the Pleistocene/Holocene boundary is not caused by the lack of fossils in general, but rather by the comparative lack of global, relatively synchronous unidirectional marine biotic changes during this interval. In addition, very few easily accessible latest Pleistocene and Holocene marine successions exist, owing to the rise in global sea-level at the end of the last ice age, and the general inability of tectonic forces to uplift these successions quickly enough for them to be observed in terrestrial outcrops.

Alternatively, a Pleistocene/Holocene GSSP might be located in a continental lacustrine sequence containing annually-laminated, pollen-bearing sediments (Litt *et al.* 2001), or even in a Greenland ice core containing a detailed isotopic record (Björck *et al.* 1998). Another possibility, in common informal use for more than 30 years (Hageman 1969), would be to fix the Pleistocene/Holocene boundary at exactly 10,000 radiocarbon years (about 11,500 years BP). Or, given problems with radiocarbon dating (Björck *et al.* 1998), the boundary might be fixed at, say, exactly 11,500 years BP, without specific reference to the radiocarbon system (cf. Hopkins 1975). Such a definition would seem to allow the classification of the greatest number of rocks of this age around the world by all available methods (Mangerud *et al.* 1974, p. 114), so the designation of a numerical age for the formal Pleistocene/Holocene boundary may be appropriate (Gradstein *et al.* 2003).

Is a dual nomenclature necessary?

The dual nomenclature of geochronologic terms (eras, periods, epochs, and ages) and chronostratigraphic terms (erathems, systems, series, and stages) has been deeply embedded in the language of stratigraphy for more than a century (e.g. Renevier 1901). Recently, however, proposals have been made by several British stratigraphers to simplify this nomenclature by abandoning the chronostratigraphic terms (Ager 1984; Hughes 1989, p. 82; Harland *et al.* 1990, p. 21; Zalasiewicz *et al.* 2004). In order to provide context for these proposals, we must first back up a bit. There have been three competing models on the nature of the logical relationship between time and time-rock units. The traditional 'rock-time' model (see Harland 1978) dominated stratigraphy for most of its history, but was clearly based on an equivocation between the modern concept of a 'chronostratigraphic unit' and the traditional concept of a 'unit stratotype,' as demonstrated by Harland (1978, 1992) and Walsh (2001, 2003, 2004).

Another common belief among stratigraphers was that neither a geochronologic unit nor a chronostratigraphic unit can exist in isolation, but that both must exist for either to be valid. This view might be termed the 'yin and yang' model of geochronology/chronostratigraphy, and although it has been in existence for many decades, it necessarily involves a circularity (Walsh 2001, 2003). Thus, Gage (1966, p. 405) noted that 'The definition of whichever unit, 'time' or 'time-rock', that we are concerned with at the moment appears to involve the other one, a logically dubious situation'. This tendency was displayed in the influential paper of Schenck & Muller (1941, p. 1423), who stated:

"The terms in column II of table 1 are the stratal terms *delimited by time*. This time-stratigraphic category comprises material stratigraphic units *consisting of sediments deposited during a given time interval*… these rock terms are *defined by time*; hence, they are referred to as time-rock or time-stratigraphic units [italics added]."

Unfortunately, this clear explanation of the logical priority of the time unit over the time-rock unit was immediately vitiated by Schenck & Muller (1941, p. 1424), who claimed that 'One cannot define time terms without the corresponding time-stratigraphic terms'. But, of course one can. One can logically define the span of time between 1600 and 1000 Ma, or the span of time between the evolution of the trilobites and the extinction of the fusilinids, or the span of time between a golden spike in Scotland and another golden spike in the Czech Republic, or the span of time between the beginning and ending of the Matuyama Reversed Polarity Chron, without ever thinking of the exact sets of all strata on Earth that were deposited during these spans of time.

Only the 'time-rock' model of Harland (1978) is logically consistent with a chronostratigraphic unit as actually conceptualized and defined by Hedberg (1976), Salvador (1994), and Remane *et al.* (1996). Thus, given that the definition of any geochronologic unit (e.g. the Silurian Period) by GSSPs must occur before the exact material content of the corresponding chronostratigraphic unit (Silurian System) can even be conceptualized (Harland 1978, 1992; Walsh 2001, 2003, 2004), the abandonment of chronostratigraphic terms is logically permissible. The only question is, would the resulting simplification of stratigraphic language be genuine, or in fact an oversimplification, obscuring important concepts that ought to be kept separate?

Given that the dual nomenclature was formalized in Hedberg (1976), his own views on this issue are noteworthy. Hedberg (1973, p. 179) stated:

"Comment: There is no need to have one set of terms for the rock strata formed during certain time intervals and another set of terms for the time intervals themselves, e.g., Devonian System and Devonian Period." "Response: Agreed. We could get along with only the stratigraphic term or with only the time term, and use 'time' or 'rocks' for the other. Thus we could say Devonian System and Devonian time, Albian Stage and Albian time; or conversely, Devonian Period and Devonian rocks, Albian Age and Albian rocks. 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."

Thus, although Hedberg believed that the dual nomenclature was not *logically* necessary, it was nevertheless 'simpler' to retain it than to try to 'simplify' it.

The main issue that we would raise concerning the proposal of Zalasiewicz *et al.* (2004) is that a clear distinction must be made between commonly confused but conceptually very different stratigraphic categories such as 'chronostratigraphic unit,' 'biostratigraphic unit,' 'unconformity-bounded unit,' and 'depositional sequence' (Walsh 2004). Owing in part to the historical use of the term 'stage' for all of these concepts, the distinctions between them are still unclear in the minds of many workers and it is probable that the abandonment of chronostratigraphic terms would serve to perpetuate this confusion. In addition, the proposed use of 'stage' for the temporal concept of an 'age' (Harland *et al.* 1990; Zalasiewicz *et al.* 2004) would seem to be an unnecessary departure from the long-established use of the former term for material stratigraphic categories.

Despite these reservations, some of the points made by Zalasiewicz *et al.* (2004) are valid in our view. These include the awkwardness involved in applying chronostratigraphic concepts to non-stratified rocks (Walsh 2001, p. 707), and the annoying editorial bookkeeping required in making sure that we use the 'correct' form in a given context (e.g. '*Upper* Cretaceous rocks' rather than '*Late* Cretaceous rocks'). Further discussion of this topic is not possible here, but the arguments of Zalasiewicz *et al.* (2004) deserve careful consideration. Their recommendations will be tested when they and other workers start to publish papers without using chronostratigraphic terms. Will such usage be unproblematical, or will it lead to unforeseen difficulties in communication? We look forward to the evolution of their proposal.

Concerns and challenges

For advocates of the GSSP concept, the intended permanency of GSSPs may well be their most important attribute, clearly distinguishing the Standard Global Geochronologic/Chronostratigraphic Units from all other categories of stratigraphic units (Hedberg 1978; Murphy 1994). For skeptics, however, this intended permanency may be viewed as being scientifically unrealistic. It must be admitted that the history of science is littered with classifications that, while useful in their day, eventually became irrelevant and were therefore abandoned. Will the same fate befall geochronologic classification based on GSSPs? Only time will tell. Certainly, the normative decisions of one generation of geologists cannot eternally bind future generations of geologists, and new and unforeseen developments in stratigraphy could conceivably render our current classification of geologic time obsolete (cf. McLaren 1977, p. 29). In the absence of any such general paradigm shift, however, we would echo the concerns of numerous workers regarding recent proposals for the redefinitions of various formally established boundaries (e.g. Vai 1997; Aubry *et al.* 1998; Walsh 2001; Italian Commission on Stratigraphy 2002; Holland *et al.* 2003). In our view, no convincing case has yet been made for the redefinition of any standard global geochronologic/chronostratigraphic boundary that has already been formally established by a GSSP.

The development of cyclostratigraphy/astrochronology (e.g. Shackleton *et al.* 1999a; Gradstein *et al.* 2004) is of great importance to stratigraphy and the refinement of the geologic time scale, but in some ways represents a challenge to the GSSP concept. Should existing GSSPs be subject to relocation in sections that consist of cyclic sediments amenable to astrochronologic correlation? The temptation to propose such relocations may be considerable for some relatively 'poor' GSSPs. However, it must be emphasized that all means of correlation are potentially fallible, because all such methods depend on assumptions that, no matter how reasonable and productive at present, may be overturned or modified in the future with additional evidence. We would thus be skeptical of the need to relocate any existing GSSPs to astrochronologically-correlatable sections. Indeed, Shackleton *et al.* (1999b, 2000) and Raffi (1999) demonstrated that although the Oligocene/Miocene GSSP of Steininger *et al.* (1997) was far from perfect, it could still be accurately correlated by the evidence obtained from other Oligocene/Miocene boundary sections containing cyclostratigraphic and biostratigraphic data. Thus, cyclostratigraphic/astrochronologic methods increase the options for placing GSSPs and the means for more accurately correlating them once they are established. From this standpoint, we agree with the suggestion of Carter *et al.* (1999, p. 1867) that cyclostratigraphic/astrochronologic considerations should be added to the list of criteria recommended by the ISSC and ICS for GSSP definition.

Conclusions

For most of the past 150 years, the boundaries of the so-called 'standard' geochronologic/chronostratigraphic units were defined by different workers around the world in various different ways, and this lack of standardization hampered our ability to meaningfully correlate rocks and geohistorical events on a global scale. Although many workers have contributed to the present status of the GSSP concept, it was Hollis D. Hedberg who was primarily responsible for the eventual acceptance of internationally-approved, stratotype-based, permanently-defined boundaries for the standard global geochronologic/chronostratigraphic units.

Modern geochronologic units defined by GSSPs are subdivisions of the standard global geologic time scale. They are analogous neither to holotypes in biology nor to standards of measure in physics, but rather serve as practical classificatory pigeonholes, analogous to the grain-size pigeonholes used for classifying clastic sediments, and compositional pigeonholes used for classifying plutonic rocks. As such, the main factor involved in the definition of standard global geochronologic boundaries must be global correlatability.

Early opposition to the GSSP concept centered around the desire for a traditional biochronologic time scale defined conceptually in terms of palaeobiological events, but such time scales are inherently unstable, and therefore unsuitable for the use of all geoscientists. Geochronologic boundaries conceptually defined by palaeobiological or other geohistorical events (the 'golden event' rather than the golden spike approach) are appealing in many ways, but most such definitions would be potentially unstable, and most of them would also be 'fuzzy' to varying degrees. The GSSP concept is generally incompatible with the desire for 'natural' geochronologic boundaries, a notion that involves several theoretical and practical problems. These include the fact that in geology, our opinions about what are and are not natural events in Earth history must be free to evolve with new data; the fact that innumerable equally 'natural' events occurred in geohistory, and that consideration of all of them would lead to an unnecessarily large number of standard global ages/stages and subages/substages of relatively short duration; the fact that the notion of a 'natural' boundary has often been erroneously equated with a *correlatable* boundary; and the fact that because all chronostratigraphic units are classes (sets of rock formed during a given, human-defined geochronologic unit), no chronostratigraphic unit can itself be a 'natural' stratigraphic entity.

Modern GSSPs have been defined mainly on the basis of biostratigraphic guiding criteria, but magnetic polarity reversals and chemostratigraphic horizons are also playing an important role. Cyclostratigraphic/astrochronologic data also increase the options for placing GSSPs and our ability to correlate them, and should be added to the list of desirable criteria used in GSSP selection. With few exceptions, however, it should be expected that any primary guiding criterion used to place a 'golden spike' will eventually become problematical in some way. As such, GSSPs should be defined so as to be correlatable by as many different lines of age-significant information as possible. Subdivision of standard global ages/stages into golden spike-defined chrons/chronozones based on traditional biochrons/biochronozones would appear to unnecessary. The 'Global Standard Stratigraphic Age' (better renamed 'Standard Global Numerical Age') is a numerical analogue of the golden spike, and is appropriate for the formal subdivision of the Precambrian, and perhaps also for the definition of the Pleistocene/Holocene boundary.

The recent proposal of Zalasiewicz *et al.* (2004) to abandon chronostratigraphic terms (system, series, stage) in favor of geochronologic terms (period, epoch, age) is logically defensible, because geochronologic units necessarily define the material content of their corresponding chronostratigraphic units, and so are logically prior to the latter. However, the abandonment of chronostratigraphic terms could perpetuate the continuing confusion between the categories of chronostratigraphic unit, biostratigraphic unit, unconformity-bounded unit, and depositional sequence, all of which have been termed 'stage' at one time or another.

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