Cenozoic chronostratigraphic terminology: In defense of formal subseries

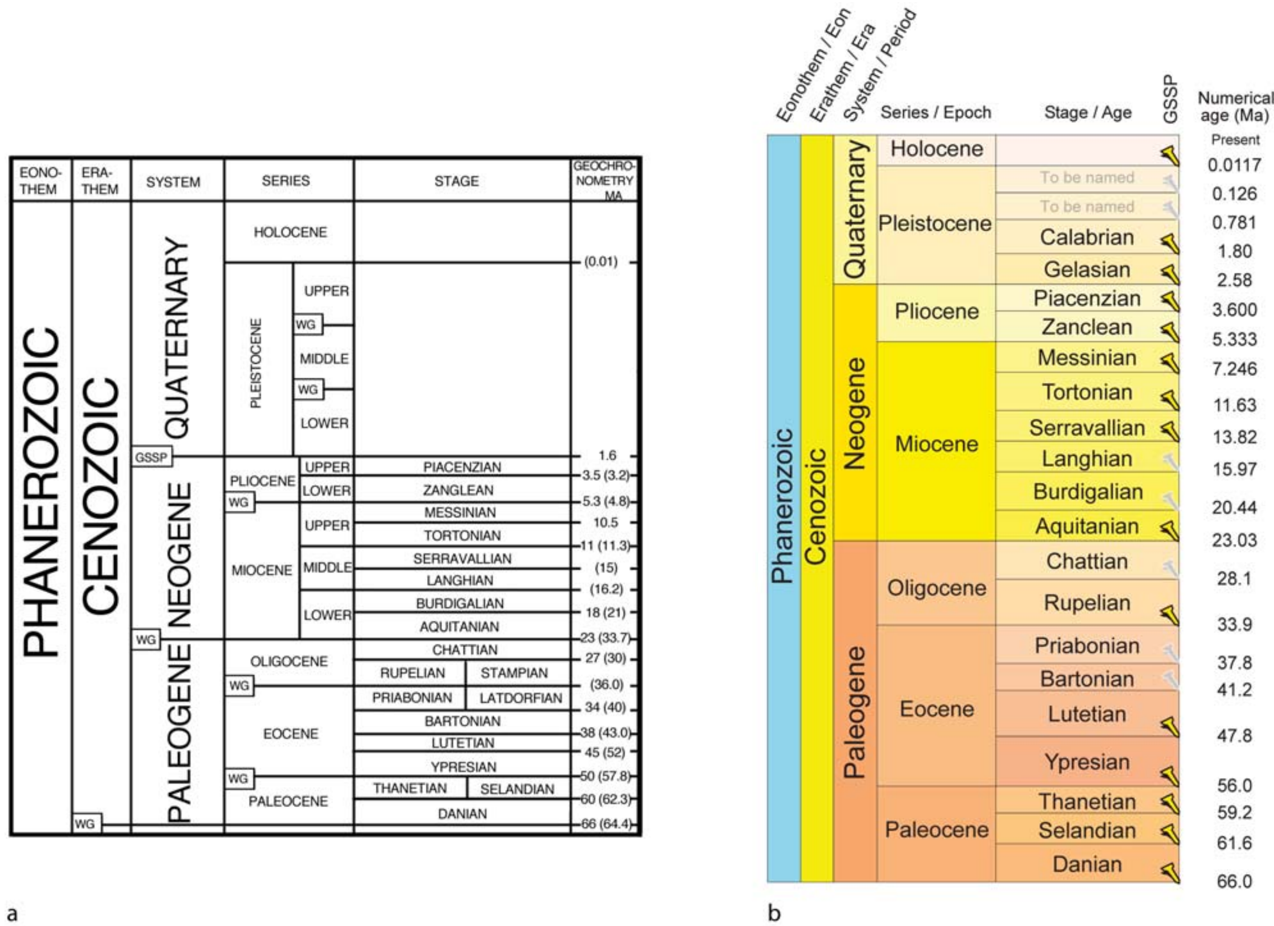
Marie-Pierre Aubry
Department of Earth & Planetary Sciences, Rutgers University, Piscataway, NJ 08854-8066
email: aubry@rci.rutgers.edu

ABSTRACT: Ever since the series and corresponding epochs of the Cenozoic began to be defined over 180 years ago, the Earth science community has recognized bi- and tripartite lower/early, middle, and upper/late divisions of these units. As chronostratigraphy became more precise, these divisions assumed an essential role in the integration of the continuous deep-sea successions where the tools for world-wide correlation were developed, and the historic but disjunct sequences on land in which the stages/ages of the time scale were defined. Rather than being discarded as too vague, the essential value of these subdivisions has been tacitly recognized by describing them in terms of the newly recognized global stages, allowing their boundaries to be identified by the GSSPs (Global Stratotype Section and Point) of the lowest component stage. In this way, and without noticeable controversy, the modern Cenozoic literature treats the lower, middle and upper divisions of its series as elements within the chronostratigraphic hierarchy, i.e., as *de facto* subseries. Their status in the hierarchy has nonetheless been questioned recently by several members of the ICS (International Commission of Stratigraphy) Bureau on the basis that subseries, as such, have not been explicitly defined by ratified GSSPs. Accordingly, this rank has been omitted from versions of the ICC (International Chronostratigraphic Chart), a product of the ICS. Such omission fails to consider that subseries (and by inference subepochs) are valuable in circumstances where individual stages are inappropriate or often not applicable, e.g., in such disciplines as seismic stratigraphy and climatostratigraphy. The status of subseries in the Cenozoic Erathem is presently under discussion, and there exists within the Subcommissions on Paleogene and Neogene Stratigraphy of the ICS the view that such divisions should have informal status (i.e., non IUGS-ratified subseries/subepochs). This would seemingly contradict the primary goal of the ICS, which since 1986 has focused on establishing a functional common language for all who work with geological time, by making the widely used concepts of subseries and subepochs open to misunderstanding. It also begs the question, as to *why should something that consists of GSSP-defined units, and which is in turn a component of higher units in the chronostratigraphic hierarchy, not be considered a formal chronostratigraphic unit in its own right?* The reality is that whether formal or informal, the subseries/subepochs of the Cenozoic will continue to be broadly used. Therefore, the interest of the ICS and the Earth science community is best served by formally recognizing them in the ICC hierarchy. This will clarify the problem of inconsistent capitalization of the terms *lower, early, middle, upper* and *late* where these are in fact part of a formal unit name and not just a modifier for an indefinite interval, and it will satisfy the broad consensus of the profession, as evidenced during a recent open meeting of the ICS during the 2nd International Congress on Stratigraphy in Graz in 2015.

INTRODUCTION

In recent decades the ICS (International Commission on Stratigraphy) has promoted a concerted effort to stabilize the linked stratigraphic and chronological terminology in modern chronostratigraphy and to facilitate effective and accurate communication among its users. At the core of this effort is the formalization of chronostratigraphic subdivisions, in a hierarchical framework based on the fundamental principle of "base defines boundary" in which the definitions of all higher-level units are the lower boundary of their oldest incorporated stage (as promoted by Hedberg 1976; Salvador 1994, Murphy and Salvador 1999). This boundary is itself fixed to a carefully selected, physical stratigraphic horizon, or GSSP (Global Stratotype Section and Point), which is ratified by the IUGS (International Union of Geological Scientists) (Cowie 1986; Cowie et al. 1986; Remane et al. 1996). The ICC (International Chronostratigraphic Chart), which embodies the ICS concept, is understandably made as simple and homogeneous as possible for ease of use by the community at large, while justifiably incorporating elements from prior steps in the process that led to the present chart. This increasing simplicity is apparent, when the current ICC (Cohen et al. 2013 updated, based on Remane 2000) is compared with its antecedent, the GCC (Global Chronostratigraphic Chart) of Cowie and Bassett (1989) (Text-fig. 1a, b). This comparison, however, also reveals the absence in the ICC (Text-fig. 1b) of the previous subdivision of the Cenozoic series/epochs into lower/early, middle, and upper/late parts, according to long usage in disciplines as different as geochronology, geophysics, historical geology, paleontology, evolutionary biology and paleoceanography. In response to comments from the community, the Bureau of the ICS brought the matter forward during its Open Meeting on the occasion of the 2nd International Congress on Stratigraphy in Graz, Austria (July 2015) where formal recognition of these terms received overwhelming support by an attendance of over 100 stratigraphers. The rationale for formalizing these widely and consistently recognized lower/early, middle, and upper/late divisions of the series/epochs of the Cenozoic Erathem, and the re-incorporation of these terms in the ICC hiererachy, is the subject of this paper.

Note: in the following, for the sake of convenience I use "series" and "stage" in place of the more accurate nomenclature "series/epoch" and "stage/age" to mean these chronostratigraphic units in space and time, except where the time term or the expanded form is required by the textual context. By "formal chronostratigraphic unit" I mean chronostratigraphic units that are defined between two IUGS-ratified GSSPs (or in the process of being defined and ratified), and while the term "subseries" has – as yet — no formal meaning, I capitalize this word as well as the positional term in the names of these units.



TEXT-FIGURE 1
Comparison between the first Cenozoic GCC and its current counterpart as ICC.
1a- The five-fold division of the Cenozoic in the 1989 GCC compiled by Cowie and Bassett (1989; see also Cowie et al. 1989). In this scheme, the subseries are included under the single heading of "series". The absence of subseries for the Paleogene System probably reflects the then unresolved decisions of the International Subcommission on Paleogene Stratigraphy with regard to their stage content (see Jenkins and Luterbacher 1992).
1b. The four-fold division of the Cenozoic in the 2015 ICC Chart. Note the omission of the subseries in the latter. (http://www.stratigraphy.org/index.php/ics-chart-timescale; September 29, 2015; reproduced by permission of the ICS). Thus, officially, the invaluable subseries of the Cenozoic are merely treated as casual stratigraphic entities (subseries) since 2000.

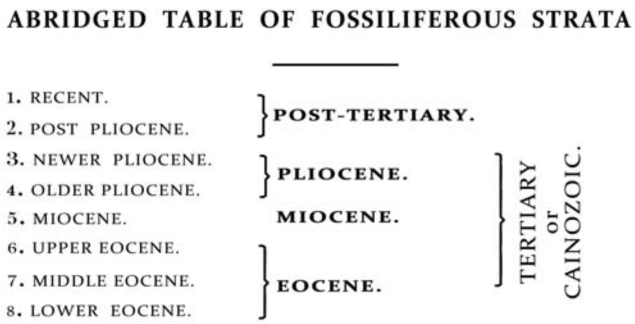
HISTORICAL BACKGROUND

The divisions of the series of the Cenozoic into lower, middle and upper parts originated with Lyell (1833) who wrote "we may still find an appropriate place for all [stratigraphic successions], by forming subdivisions on the same principle as that which has determined us to separate the lower from the upper Pliocene groups", continuing "Thus, for example, we might have three divisions of the Eocene epoch,—the older, middle and newer; and three similar subdivisions, both of the Miocene and Pliocene epochs" (op. cit., p. 57, 58). This simple but pregnant idea led him (1855, 1857a, b) to establish what may be the first comprehensive Cenozoic chronostratigraphic scale, in which he organized and correlated the major lithologic formations then known in his divisions of series (Text-fig. 2), thus prefiguring the future Cenozoic time scale. Although this nascent framework was modified by addition of the Oligocene and Paleocene series, we see in it the basis of the current chronostratigraphic classification of sedimentary rocks, with, for example, the placement of the Bracklesham Beds (Hampshire Basin) and *Calcaire Grossier* (Paris Basin) in a "Middle Eocene" interval and the Bembridge Beds and *Gypse de Montmartre* in an "Upper Eocene". Lyell's contemporaries immediately adopted his system of division incorporated in a three-fold hierarchical classification (Text-fig. 3). Beyrich (1854, 1856) assigned the strata of his new series to Lower, Middle and Upper Oligocene. Mayer-Eymar (Mayer in Gressly 1853; see Zöbelein 1960, Csepreghy-Meznerics 1964 and Szöts 1966) first assigned his Aquitanian Stage to the Lower Miocene Subseries. The bi- and tripartite divisions of series into subseries thus became the chronostratigraphic frame of reference used to classify and correlate successions in disjunct sedimentary basins, to be incorporated without debate in the earliest time scales (Text-fig. 4) and adopted by stratigraphic commissions (e.g., Paleogene Stratigraphic Commission of the Soviet Union 1962, 1963, 1964; cf. Berggren 1971, table 52.19). The boundaries between series and their subseries were the first chronostratigraphic elements to be dated, much before Berggren (1971, 1972) began assigning their best-documented stages as globally correlated components in the time scale, fulfilling Hedberg's vision of a stage-based chronostratigraphy which he developed between 1937 and 1976 (see Aubry et al. 1999 and references therein).

Proposed Modification of the Table of Fossiliferous Strata,

Periods and Groups	British Examples.	Foreign Equivalents and Synonyms.
POST-TERTIARY.		TERRAINS CONTEMPORAINS.
1. **POST-PLIOCENE.**	1. *Recent.*– Peat of British Isles, with human remains. (Princi ples of Geology, ch. 45) Alluvial plans of the Thames, Mersey, and the Rother, with buried ships. p. 120., and Principles, ch. 48. 2. *Post-Pliocene.*– Deposits, with fossil shells of living species, in which no human remains have yet been found Shell-marl of Scotch and Irish Lakes.	1. Marine Strata inclosing Temple of Serapis at Puzzuoli. Principles, ch. 29. 1. Freshawater Strata Inclosing Temple in Cashmere. *Ibid.* 9th ed. p. 762. 2. Volcanic tuff of Ischia and Naples, with living species of marine shells, and as yet without human remains, p. 118. 2. Newer part of t boulder-formation of Sweden, with brackish water shells of species now liying in the Baltic, p. 130.
TERTIARY, PLIOCENE		TERRAINS TERTIAIRES.
2. **NEWER PLIOCENE, or Pleistocene.**	1. *Glacial.*– Drift or boulder-formation, with remains of *Elephas primigenius* and shells, nearly all of the living species. Ochreous gravel of valley of Thames, p. 154. Supp. p. 7. *Glacial deposits* of the Clyde, p. 131.; of North Wales, p. 135. 2. *Preglacial* deposits of Grays, Thurrock, and Ilford (valley of Thames), with *Elephas antiquus*, Falc., and shells, nearly all of recent species, p. 154. *Supp.* p. 4. 4. Norwich Crag, with marine shells (85 per cent. of recent species), p. 155., and *Supp.* p. 4. Cave deposits of Britain, chiefly Newer Pliocene, p. 161.	Terrain quaternaire, diluvium. Terrains tertiaires supérieurs p. 139. 1. Glacial drift of Northern United Sates, p. 140.; and Alpine erratics, p. 149. 3. Limestone aof Girgenti, p. 159. Australian cave-breccias, p. 162.
3. **OLDER PLIOCENE.**	1. Red Crag of Suffolk, pp. 169–171., and *Supp.* p. 2. 2. Coralline Crag of Suffolk, pp. 169–172., and *Supp.* p. 2.	Subapennine strata, p. 174 Hills of Rome, Monte Mario, &c., p. 176. and p. 535. Antwerp and Normandy crag, p. 174. Aralo-Caspian deposits, p. 176.
MIOCENE.		TERRAINS TERTIAIRES MOYENS.
4. **UPPER MIOCENE.**	Wanting in the British Isles.	Faluns of Touraine, p. 176. Bolderberg Strata in Belgium, p. 179. Sansans, near Pyrenees, South of France. Basin of Vienna, p. 180.
5. LOWER MIOCENE.	Hempstead Beds, Isle of Wight, p. 193.	Grès de Fontainebleau, p. 195. Calcaire de la Beauce. *Ibid.* Mayence basin, p. 191. Limburg beds, Belgium, p. 189. “Oligocene” strata of North Germany. Nebraska beds in United States, p. 207.
EOCENE.		TERRAINS TERTIAIRES INFÉRIEURS.
6. **UPPER EOCENE.**	1. Bembridge Beds, Isle of Wight, p. 209. 2. Osborne Series, p. 211. 3. Headon Series. Ibid. 4. Barton Clay, p. 213.	1. Gypseous Series of Montmartre, p. 224. 2 & 3. Calcaire Siliceux, p. 226; or Travertin inférieur. 4. Grès de Beauchamp, or Sables Moyens, p. 227.
7. **MIDDLE EOCENE.**	1. Bagshot and Bracklesham Beds, p. 214. 2. Wanting.	1. Calcaire Grossier of Paris basin, p. 227. 2. Upper Soissonnais, Sands of Cuisse-Lamotte. p. 229. 1 & 2. Nummulitic formation of Europse, Asia, &c., p. 230.
8. **LOWER EOCENE.**	As in the table, p. 106.	

TEXT-FIGURE 2
Lyell's classification of major Cenozoic lithostratigraphic units in a hierarchical framework of series and their divisions (the future subseries; Lyell 1857b, p. 13; see also Berggren 1971, table 52.5, p. 700). In the fifth edition of his Manual of Elementary Geology, Lyell (1855, p. 105-106: Tabular view of the Fossiliferous Strata) used for the first time subdivisions of his series to organize in tabular form the main lithological formations known from Northwestern Europe but also from Italy, North America, Asia, Australia, India and Russia. Lyell revised and expanded considerably this framework of classification and correlations in his supplements to the Fifth Edition (op. cit. 1857a, p. 10: "Proposed Modifications of the Table of Fossiliferous Strata pp. 105–106", and 1857b, p. 13: "Proposed Modifications of the Table of Fossiliferous Strata). In the progressive development of Lyell's ideas regarding classification and stratigraphy that transpires through the successive editions of the Principles of Geology and Manual of Elementary Geology, the 1857 revisions to the fifth edition of the Tabular view of Fossiliferous Strata represent a crucial step by its modernity. For instance, the lithostratigraphic units then assigned to "Periods" 5 to 7 (as shown also in this figure) are those that would play a significant role in the development of the Paleogene time scale from the nineteen seventies to this day.


ABRIDGED TABLE OF FOSSILIFEROUS STRATA

1. RECENT.
2. POST PLIOCENE. } POST-TERTIARY.
3. NEWER PLIOCENE.
4. OLDER PLIOCENE. } PLIOCENE.
5. MIOCENE. MIOCENE.
6. UPPER EOCENE.
7. MIDDLE EOCENE.
8. LOWER EOCENE. } EOCENE.

} TERTIARY or CAINOZOIC.

TEXT-FIGURE 3
Lyell's three-fold hierarchical framework for the classification of sedimentary rocks (reproduced partim from Lyell 1855, p. 109). For the Cenozoic, Lyell conceived the bi- and tripartite divisions of series/epochs as the lowest-ranking units of a three-fold hierarchical framework with series/epochs and erathems/eras above them. This original framework specific of the Cenozoic was further elaborated in the *Tableau Abrégé des Couches Fossilifères* of the French version of the fifth edition of the *Manuel de Géologie élémentaire* (Lyell 1856, p. 175; see Vai 2007, fig. 7). Lyell regrouped his Cainozoic and Mesozoic into the obsolete term Neozoic (not shown).

While concurrent stages were multiplying in the sixties, particularly in Europe, series and their divisions continued to provide the stable chronostratigraphic framework for the development of deep-sea stratigraphy and the stratigraphy of land-based deep-water sections. The deep-sea in particular provided thick, uninterrupted successions through the series of the Cenozoic, and global marine biozonations and high-resolution magnetostratigraphy developed with reference to their informal subseries (e.g., Bolli 1957a-c, 1966; Berggren 1967; McElhinny 1978), with little or no regard for the various stages found in different regional sequences on the continents. Berggren (1971) laid the foundation for the current chronostratigraphic framework by correlating the core European stages to the subseries in the marine literature (Text-fig. 4), an integrative step that was quickly accepted by the scientific community at large. The continuing importance of the subseries concept in the further development of Cenozoic chronostratigraphy may be seen in such instances as 1) the acceptance of the Zanclean Stage in Neogene chronostratigraphy following documentation that its microfossil biozonal content was also that of Lower Pliocene marine successions (see Cita and Gartner 1973), and 2) the demonstration that the Bartonian Stage belonged to the Middle Eocene rather than to the Upper Eocene Subseries, which is represented on-land by the Priabonian Stage (Hardenbol and Berggren 1978). We note in this case that what was changed was the position of a stage with regard to a subseries, and not the other way around. In other words, until recently (1986) *the subseries have been essentially permanent, whereas the position of stages within series have been adjusted to them* (as were lithostratigraphic and biostratigraphic units).

As global stages became fully incorporated in the chronostratigraphic scale following Berggren (1972), Lyell's two-fold hierarchy of series and subseries morphed into a three-fold hierarchy with global stages introduced as the lowest rank. The Neogene and Paleogene Subcommissions in the 1960s to 1980s debated which of these stages should be recognized in the chronostratigraphic chart as well as their position with regard to the subseries — *but not the position of subseries with regard to groups of stages*. For instance, the decision as to which component stages should be used in defining the subseries within the series of the Paleogene was finalized—through a show of hands — during a meeting of the Subcommission on Paleogene Stratigraphy at the 28th International Geological Congress in Washington, D.C., 1989 (Jenkins and Luterbacher 1992).

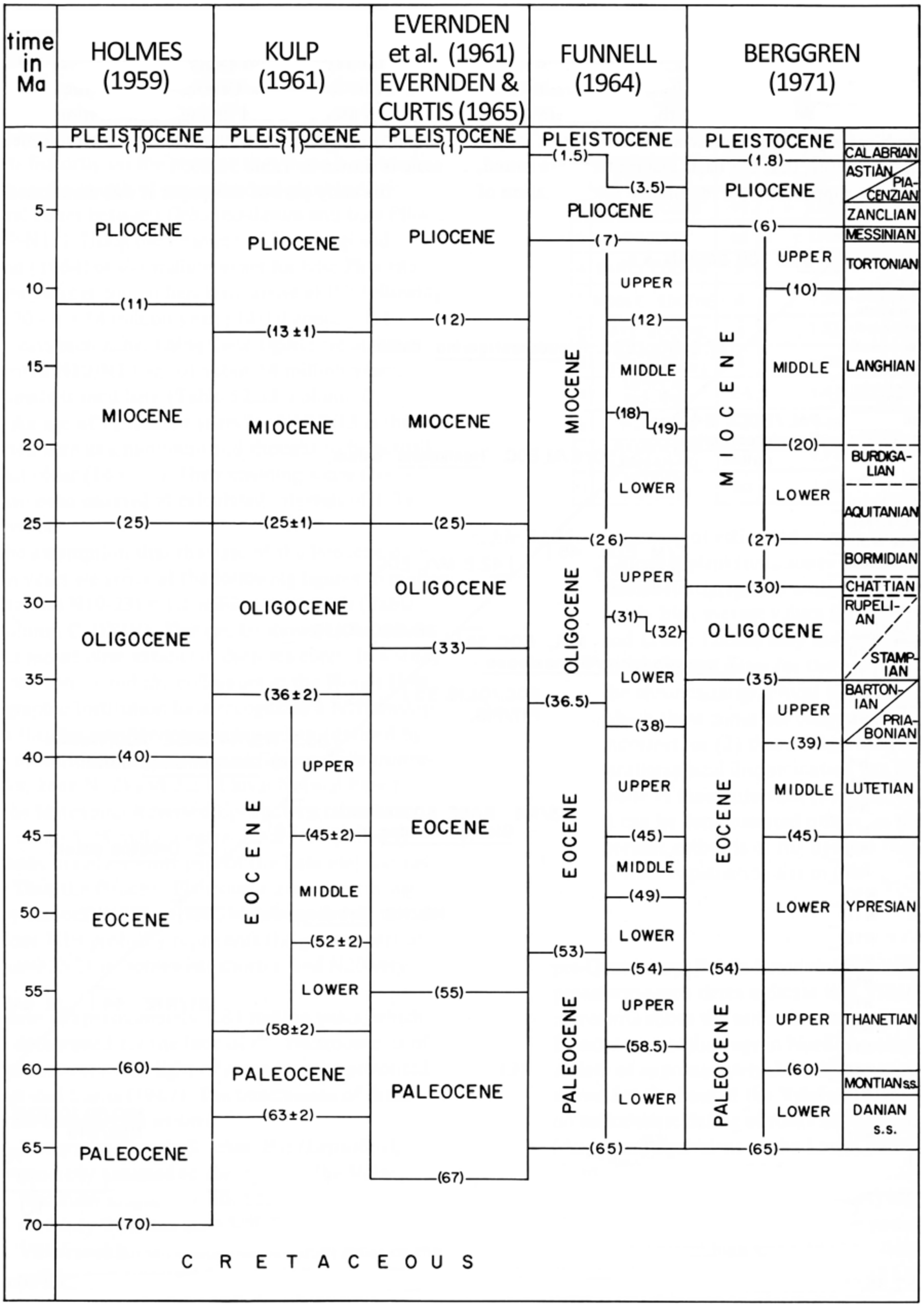
The success of the three-fold chronostratigraphic scale (series, subseries, stages) is seen in its almost unanimous acceptance and ubiquitous use in the earth sciences – for example, in major work such as Kennett and Srinivasan (1983), Bolli et al. (1985), Salvador (1985), Haq et al. (1987), Harland et al. (1990), Bown (ed. 1998), Miller et al. (2005), Catuneanu (2006), Catuneanu et al. (2009). Other major works, such as Pomerol and Premoli-Silva (1986), Olsson et al. (1999), and Pearson et al. (2006) retained only the series and subseries (the latter authors in discussion of biochronology and description of planktonic foraminiferal phylogenies). The fundamental role of the subseries of the Cenozoic extends to newly introduced areas of study such as the GPTS (Geomagnetic Polarity Time Scale), the IMBS (Integrated Magneto-Biochronologic Scale) and the ATS (Astronomic Time Scale) (Berggren et al. 1985a, b, 1995; Cande and Kent 1992; Shackleton et al. 1999; Gradstein et al. 2004, Hilgen et al. 2012 (partim); Pillans and Gibbard 2012; although not in Vandenberghe et al. 2012 and Gradstein et al. 2012; see discussion in Lourens 2008 concerning the ATS). It is also seen in their persistence in recent revisions to planktonic biozonal frameworks (Wade et al. 2011; Backman et al. 2012; Agnini et al. 2014).

SUBSERIES IN CURRENT CENOZOIC CHRONOSTRATIGRAPHY

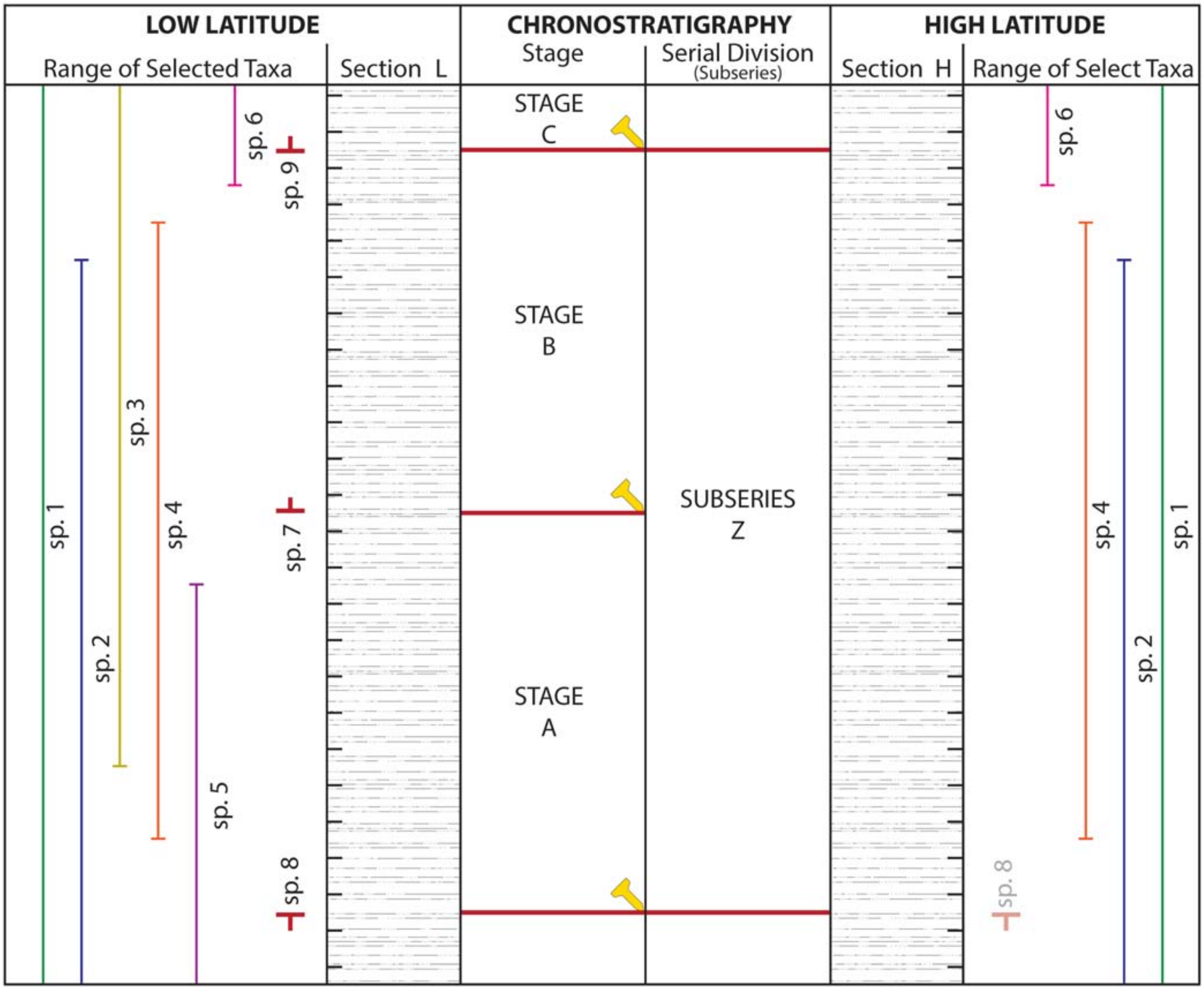
The subseries of the Cenozoic are broadly used today, in academia, classroom and industry. This may indicate a deep-rooted need, or it could be little more than habit and tradition, perhaps with insufficient consideration of recent advances in chronostratigraphy. This then raises the questions of 1) whether these subseries are actually useful, and in what way, and 2) what underlies their success.

Are subseries relevant in current chronostratigraphy? Since the subseries are not just equal halves or thirds of the total time allotted to the series, but instead conform with the stratigraphic logic of the interval, it is not immediately obvious as to why they should still be in wide use when coeval stages are available that correspond to the same intervals. For instance, the subseries of the Oligocene and Paleocene series are set to coincide with, respectively, the two and three component stages over the same stratigraphic intervals (Table 1), while each subseries of the Miocene is composed of two stages, as does the Middle Eocene Subseries.

In fact, the subseries constitute an efficient and practical intermediate rank between stages and series, since it is not always possible — or useful — to work with chronostratigraphic resolution at the stage level. While the means to identify precise chronostratigraphic levels may be readily available under optimal circumstances, this may be difficult or even impossible elsewhere. For instance, the biostratigraphic criteria for characterizing a stage boundary may be absent, or skewed, in areas of differing paleolatitudes or provincial bias (Text-fig. 5). In other instances the data used in an earth-historical discipline may not be amenable to classification according to stages. One example



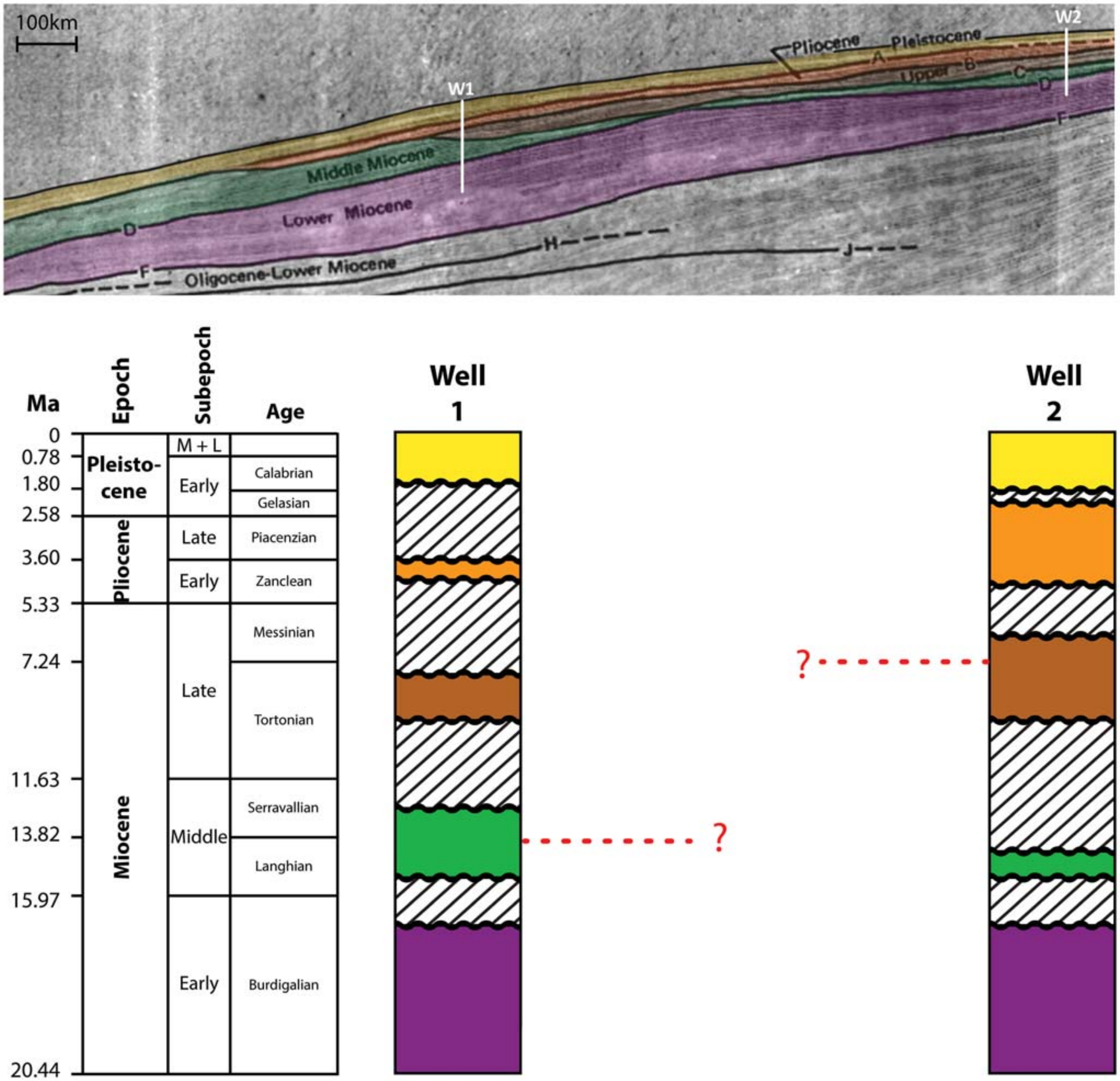
TEXT-FIGURE 4
History of the early time scale/chronostratigraphic chart for the Cenozoic. Note the insertion of the subseries of the Eocene Series by Kulp (1961), the consistent use of subseries for the whole Cenozoic by Funnell (1964), and their estimated ages. Berggren (1971) was first to introduce stages in the time scale. Note reference to concurrent stages (as Astian and Piacenzian) and uncertain location vis à vis subseries (as Burdigalian/Langhian boundary). (Modified from Berggren, 1971, Table 52.37, p. 774.)



TEXT-FIGURE 5
Comparison of chronostratigraphic resolution at low and high latitudes. In this example, the LAD (Last Appearance Datum; species [sp.] 8) and FADs (First Appearance Datum; sp. 7 and sp. 9) of three planktonic calcareous species of high-ranking Taxon M are the primary means of correlation of the GSSPs of Stages A, B and C. These three species are part of fast evolving lineages at low latitude. Hence, Taxon M exhibits high diversity in low latitude areas (e.g., in Section L) where the base of each stage is readily characterized at the same time as its lower and upper parts are easily delineated. In these ideal conditions, the rank of stage efficiently describes the chronostratigraphic succession in Section L. In contrast, due to biogeographic preferences, several species of Taxon M – among which the marker sp. 8, 7 and 9 – do not occur at high latitudes (e.g., in Section H; the expected position of the FAD of the chronostratigraphically significant sp. 8 is shown in light gray). In this circumstance, not only the characterization of the GSSP of Stage B is not possible, but the two Stages A and B cannot be differentiated, even though the range of sp. 4 allows characterization of an interval encompassing most of them, which is also an interval in Subseries Z. A choice thus arises between stating that most of section H belongs to Stage A and B undifferentiated, or that it belongs to Subseries Z. The latter expression is more practical and straightforward, and it constitutes an advantageous positive statement whereas its alternative is imbued with uncertainty. This figure clearly shows, however, that reference to subseries rather than to stage is beneficial only if the boundaries of Subseries Z are exactly aligned with the GSSPs of Stage A and Stage C – that is, if the chronostratigraphic character of Subseries Z is recognized through formal recognition of this rank. Note: To avoid the common problems related to biostratigraphic applications, it is considered that in both sections sampling resolution is high and Taxon M is abundant and well preserved. Note also that the reasoning above applies as well to cases of poor preservation, shallow water depth, and many others cases.

is seismic stratigraphy, in which seismic sequences are seldom identified with the precision of a stage (Text-fig. 6). Likewise, the limits of tectonic events are rarely sufficiently distinct to justify resolution at the stage level (but see Hu et al. 2015).

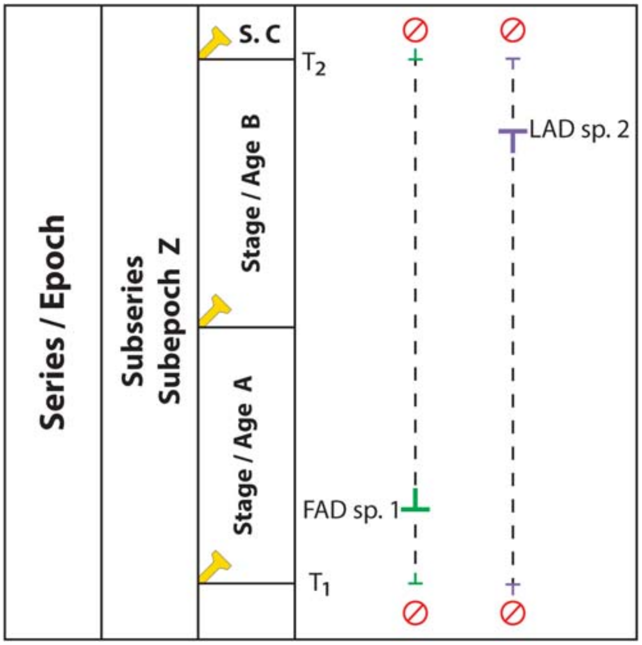
Marine–continental correlations are additional instances in which identification in terms of marine stages is largely irrelevant, because the chronostratigraphic frameworks in these two realms have developed independently. For instance, vertebrate paleontologists rely on units defined in terms of (predominantly) land vertebrate history (i.e., Land Mammal Ages; see Flynn and Swisher 1995; Prothero 1995) with chronostratigraphic resolution comparable to stages. There are also narratives that do not require resolution at the rank of stage, and for which the rank of series is too broad, such as the description of evolutionary trends and discussion of evolutionary processes (Text-fig. 7). The inter-



TEXT-FIGURE 6
Seismic stratigraphy and chronostratigraphy. Subsurface seismic sequences on epicontinental margins (upper panel) correspond to the unconformity-bounded sequences of surface stratigraphy. Dated with carefully located wells, and placed in a temporal framework (lower panel), such sequences have been shown to form the broad packages of allostratigraphy, which are best characterized in terms of subseries. As each hiatus varies along a seismic surface, the completeness of subseries in individual seismic sequence varies as well, with their component stages unevenly represented laterally. Thus, whereas a stage boundary may be easily delineated in a well, it is difficult to delineate its lateral extension. In these circumstances, confident chronostratigraphic assignment of a formal subseries is highly preferable to ambiguous assignment to one stage or another. This theoretical example is based on an allostratigraphic study of the Neogene of the northern Gulf of Mexico (Aubry 1993), and the seismic profile is modeled from Mitchum (1978).

mediate rank of subseries is ideal for such narratives because Lyell's series/epochs were originally biostratigraphic/ biochronologic units in essence (Rudwick 1978; Berggren 1998; see Vai 2007 for a different point of view).

It may also be asked why at this time subseries should be deemed necessary only in the Cenozoic, given the justification above. The answer likely lies in the fact that this rank has been widely used in the dialogues among scientists interested in the Earth history during the Cenozoic. Certainly the names of Paleogene paleoclimatic events described in terms of subseries have brought an aura to them and aroused the interest of the community, not least because this makes their temporal position immediately recognizable to the wider audience. From this perspective it could hardly be desirable to replace such acronyms as EECO for Early Eocene Climatic Optimum, MECO for Mid-

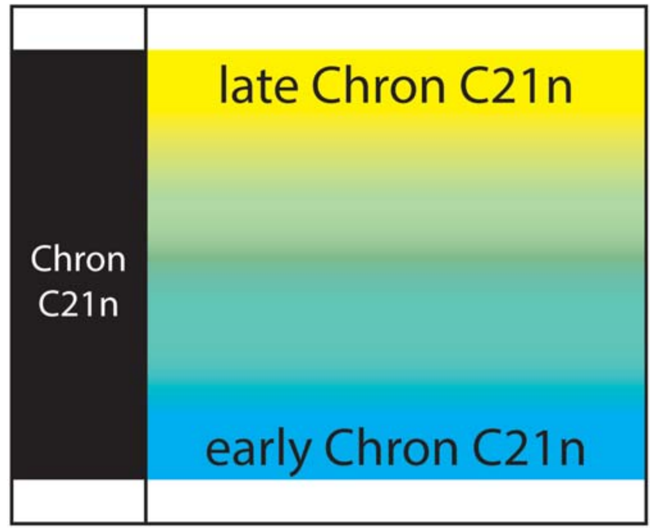


TEXT-FIGURE 7
Example of the use of subseries with regard to the life span of two species (between their respective FAD and LAD). Whereas species diversity in planktonic organisms is very high, the complete ranges of only a handful of them is precisely known. For species whose range is only approximately known, it is *more direct and positive* to state that their FADs/LADs are in a subseries rather than in either of the two consecutive stages in that subseries. For this to be meaningful, however, subseries must be formal, which means/requires that they must be defined by ratified GSSPs. In reference to the example here, it follows from the placement of the FAD of species sp. 1 in Subseries Z that this datum cannot be older than the GSSP that defines the base of Stage A and younger than the GSSP that defines the base of the Stage C (S. C in figure). Of primary importance, then, is the fact that the FAD of sp. 1 is now constrained by the time (T1) of deposition of the older GSSP. The same reasoning applies for the LAD of sp. 2. If subseries are informal, this inference is not guaranteed, and it may be necessary to specify the ages of the boundaries between subseries in every scientific paper, which would be utterly cumbersome. This example brings additional illumination to the significance of the range of species sp. 4 in Section H in text-figure 5.

dle Eocene Climatic Optimum, and the former LPTM for Late Paleocene Thermal Maximum (now PETM, Paleocene/Eocene Thermal Maximum) with the equivalent stage-based terms YCO, BCO and TTM for Ypresian Climatic Optimum, Bartonian Climatic Optimum or Thanetian Thermal Maximum, let alone to refer on the one hand to the PETM, and on the other to the YCO and BCO.

What underlies the sustained success of subseries? The success of subseries may lie in their permanence and simplicity. Their permanence comes from the fact that they were integral parts of series from the beginning (Lyell 1833), as compared to the impermanence of stage names, which have been repeatedly replaced, redefined or abandoned over the years. Their simplicity (lower, middle, upper) embodies the principle of stratigraphic superposition, and complements the names of the series with their prefixes paleo-, eo-, oligo-, mio-, plio-, pleisto- indicating relative position within the Ceno-zoic.

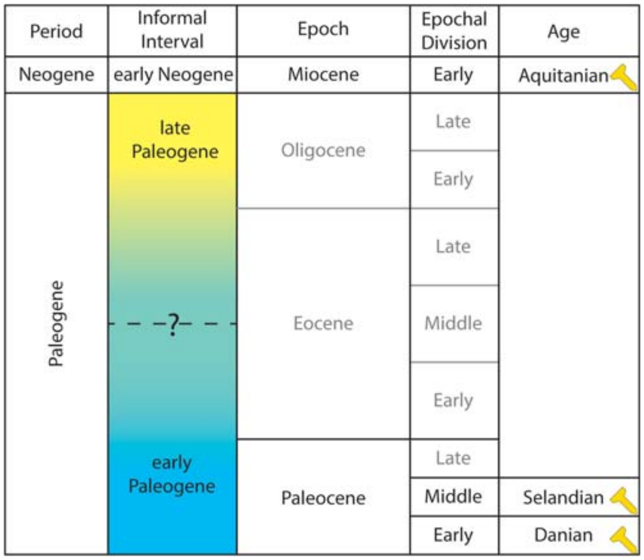
It is always possible to use two (or more) consecutive stages to identify the age of a prolonged stratigraphic interval, but this



TEXT-FIGURE 8
Usages of the qualifiers "early" and "late" in association with non-chronostratigraphic terms: the case of magnetochronology. The expressions "early Chron C5n" or "late Chron C5n" are vague and informal. The use of color helps delineate an arbitrary minimum extent for the early (blue) and late (yellow) Chron C5n.1n, but the progressive change in color shows that the full extent of either interval is fuzzy. The same would be true of expressions such as "late Biochron CNM7" or "early Biochron NP9"

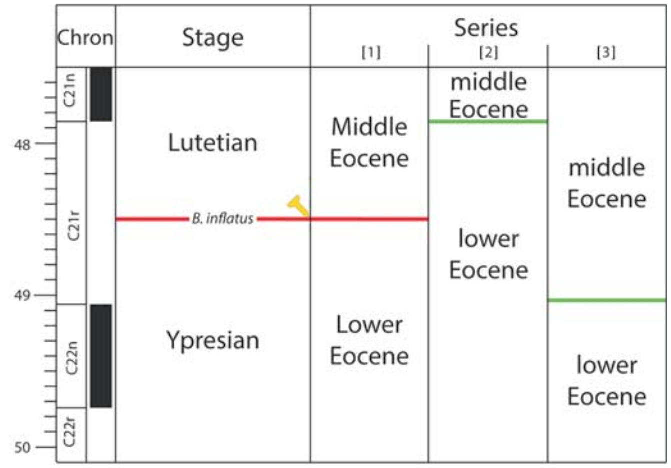
can be cumbersome. Designation of a subseries, on the other hand, conveys immediate, positive information that is indicative of the arrow of time (Gould 1987). For instance, compare "These sections are assigned to the Aquitanian and Burdigalian, and to the Langhian and Serravallian stages, respectively" and "these sections are assigned to Lower and Middle Miocene subseries, respectively". This simplicity is invaluable for those less familiar with the details of the chronostratigraphic hierarchy, whether in related professions or in public education. There can be no question of the relative position of a stage identified with a subseries, even for the novice, but there is no inherent logic in the placement of one stage below or above another simply according to their names, not to mention the difficulty in memorizing such terms as Piacenzian, Selandian, Serravallian, Zanclean or Gelasian. Moreover, whereas assignment of an event or process to two consecutive stages leaves its apportionment open to question, assigning it to the corresponding subseries is simplifying without being less accurate.

Formal versus informal status. Even with this history, and despite the fact that subseries have been consistently recognized in time scales and chronostratigraphic frameworks, not to mention discussion of their boundary ages (Text-fig. 4), their status has not been formally recognized and their usage, because of this, has often been casually inconsistent both between and within given subdisciplines. Prior to 1986, little importance was given to formalization and consensus prevailed (see Aubry et al. 1999). The chronostratigraphic status of subseries was a matter of unspoken agreement whether their positional term ("lower", "early", etc.) was capitalized or not. We see this in the long-standing tradition in deep sea stratigraphy, which, while attributing an unquestioned chronostratigraphic connotation to the subseries, generally uses an uncapitalized positional term. The situation changed with the introduction of formalized, IUGS-ratified definition of GSSPs, but while the prominent role



TEXT-FIGURE 9
Informal temporal expressions. Expressions such as "early Paleogene" and "late Paleogene" are informal and without chronostratigraphic meaning because their boundaries are vague. The beginning of the early Paleogene is defined by the GSSP of the Danian Stage, but its end is vague. Similarly the end of the late Paleogene is defined by the GSSP of the Aquitanian Stage, but its beginning is unspecified. In contrast, the Early Paleocene can only be the interval comprised between the GSSP for the Danian Stage and the GSSP for the Selandian Stage. In other words, placement of the end of the early Paleogene is at the discretion of the user whereas the end of the Early Paleocene (subepoch) is rigidly defined. The Early Paleocene Subseries is a chronostratigraphic unit, the early Paleogene is not. Formalization of subseries would be beneficial in specifying the difference.

of subseries was recognized in the first chronostratigraphic chart of the ICS intended for international use (Text-fig. 1a) their column was not identified as such. The indication on the chart of working groups devoted to the definition of the lower/middle and middle/upper boundaries of the Pleistocene subseries is particularly significant, and in accord with the current activities of the SQS (Subcommission on Quaternary Stratigraphy; see Head and Gibbard 2015). Ten years later, however, the subseries were deleted from the ICC (Remane 2000) without explanation. As a result, standardized usage of subseries currently suffers from confusion about the status of these units, with proper capitalization of their titles left to the arbitrary decision of editors and authors even within the same publication. The formal usage, however, with capitalized positional terms, is used throughout some reference works (see above), as well as in TimeScale Creator (Ogg and Gradstein 2005-2015) and in textbooks for students (e.g., Stanley and Luczaj 2015). Also, the formal capitalization of the full subseries names has been included by the IUGS in the ratification of corresponding GSSPs (Appendix 1). Even with these examples, however, it would seem that universal recognition of the proper orthographic style for these units would be greatly aided by their formal recognition in the ICC. Although the Cenozoic community has continued to use them widely with their intended chronostratigraphic meaning, can and should subseries continue at the same time as informal concepts without recognition by the ICS? More importantly, would not their continued informal use regardless of their strict ties to GSSPs have the undesirable effect of introducing a *double standard in chronostratigraphy*, in which formal and informal chronostratigraphic units could coexist although nested in the same hierarchy and bounded by the same ratified GSSPs?

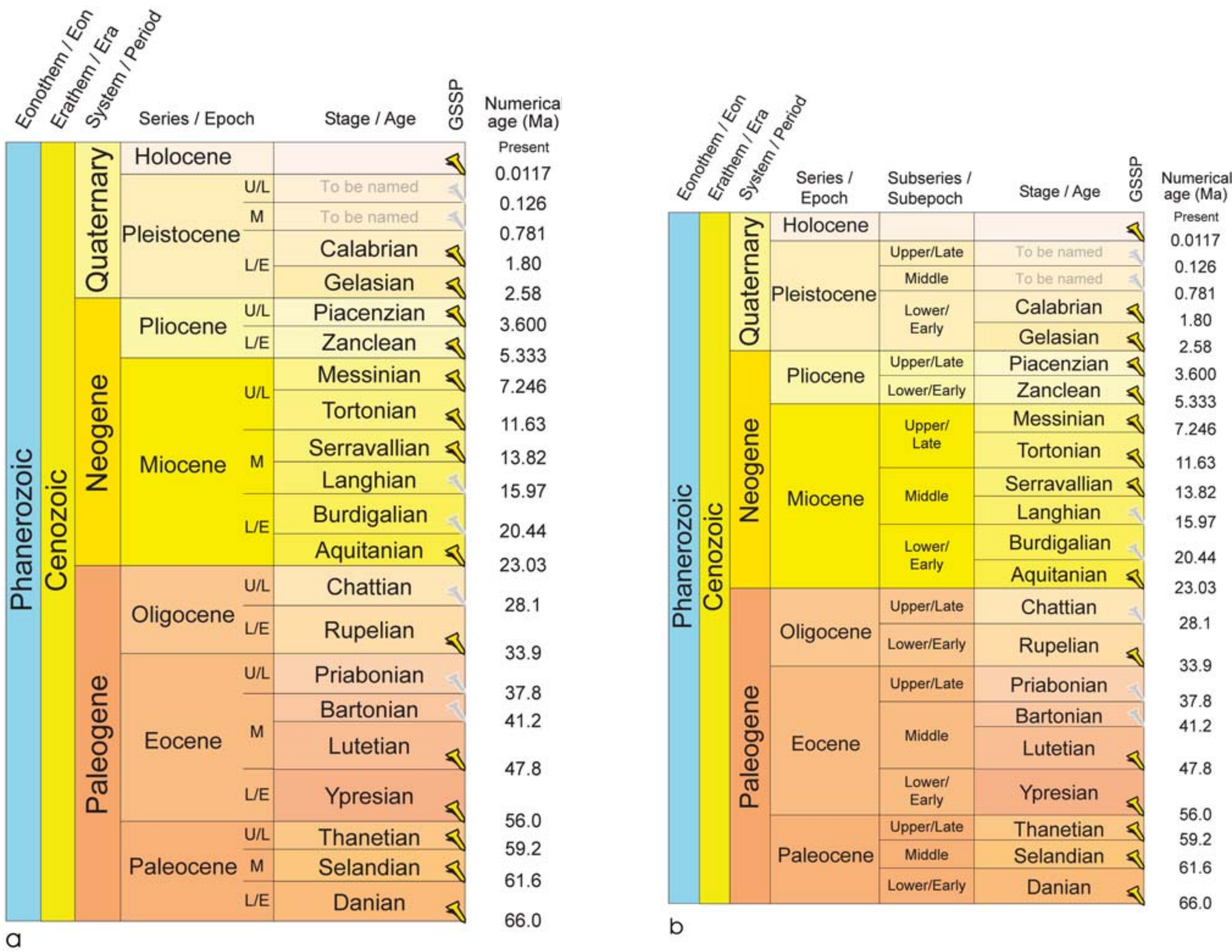


TEXT-FIGURE 10
GSSP of the Lutetian, Gorrondatxe section, Spain (Molina et al. 2011). The GSSP of the Lutetian Stage is a lithostratigraphic horizon in Chron C21r. It is characterized by the lowest occurrence of the coccolithophore *Blackites inflatus*. As the bases of the Lutetian Stage and Middle Eocene Subseries have always been seen to be correlative (see Text-fig. 4), the GSSP at Gorrondatxe simultaneously defines the base of the Middle Eocene Subseries and the base of the Lutetian Stage ([1] in the figure). Although not shown, the GSSP for (the base of) the Priabonian Stage will define as well the base of the Upper Eocene Subseries, so that the Middle Eocene Subseries will be defined between two GSSPs. All earth scientists have tacitly accepted this relationship and the chronostratigraphic use of the subseries cannot be in doubt regardless of whether editorial style has implied formal or informal status. However, official decision to deny subseries an informal status would regrettably relax them from their chronostratigraphic significance, allowing relocation of their boundaries at any author's discretion ([2] and [3] in the figure) causing miscommunication among earth scientists, and in particular stratigraphers. This is because there is no scientific, procedural or otherwise reason for them to remain tied to a GSSP, and recommendation to this effect could not be enforced. The problem is acute for both the middle and upper subseries, less so for the lower subseries, although the latter may be affected as well once chronostratigraphy is destabilized.

PRESERVING THE CHRONOSTRATIGRAPHIC MEANING OF SUBSERIES

As recognized above, the message communicated by subseries is essentially a chronostratigraphic statement concerning intervals, fixed in superpositional or sequential order with an implied measurable duration. If this standardization were not the case, there would be endless miscommunication in the earth sciences because of the inconsistent characterization of boundaries between the subseries. As the current mechanism for this worldwide stability is the ratified GSSPs, the subseries are now tacitly accepted as the interval between two GSSPs. For example, in referring to the Upper Miocene Subseries (whether in upper- or lowercase) we refer, in accord with established use and convention, to a stratigraphic interval between the GSSPs of the Tortonian and Zanclean stages.

The difference between formally defined and informal terminology is crucial for the metrics of the subepochs. The primary use of the ICC is not so much in the definition and naming of



TEXT-FIGURE 11
Models of incorporation of the subseries/subepochs in the ICC. In one model (a) the subseries/subepochs are shown, unlabeled, within the column labeled "Series/Epoch". In the other model (b, preferred and recommended) the subseries/subepochs form an independent, formal rank which is labeled as such.

chronostratigraphic units, as in identifying the equivalent time intervals that are basic to the narrative of earth history. In other words, the ICC provides the framework for a relative temporal information that is sought by every user. It is at this basic temporal level that the formalization of subseries and consistency of stylistic format makes a substantial difference.

There is a trade off to the simplicity of denoting of subseries and the corresponding subepochs by such adjectives as *lower, early, middle, upper* and *late*, as these are not unique to them and are used in earth sciences in other circumstances without formalized meaning. The problem is particularly acute for the subepochs in which such expressions as "late Biochron NP9" and "early Chron C5n" (Text-fig. 8) are examples of informal, imprecisely defined portions of non-chronostratigraphic units. In expressions that are common in the literature such as "late Cenozoic" and "early Paleogene", not to mention "late Neogene" (cf. Berggren and Van Couvering 1974), the teporal meaning of chronostratigraphic units is modified without implying any consistent or fixed value (Text-fig. 9). Likewise, "early Middle Miocene", "early Aquitanian" and "late Tortonian" modify the temporal meaning of these chronostratigraphic terms without reference to a fixed interval.

Since the basic concept of formal chronostratigraphic units is an interval between two fixed points in the stratigraphic record — ideally, ratified GSSPs — the subseries and subepochs fall *de facto* into this category. Given this plain fact, failure to recognize them as a formal part of the ICC and time scale for the Cenozoic opens the possibility that these widely-used terms will introduce diverse, conflicting informal values into the literature, without regard to the GSSP-defined limits of the series/epochs they refer to (Text-fig. 10), with far-reaching consequences. Retention of the status quo, in which the subseries/subepochs retain their chronostratigraphic character while remaining informal, leads to the fundamental question of *whether there can be both formal and informal chronostratigraphic units within a nested chronostratigraphic hierarchy*. With regard to the case discussed here, this is asking: *is it conceivable that series can be formally defined by stage GSSPs, while their component subseries are considered to be informal even though identified by the same IUGS-ratified criteria*?

INCORPORATING THE SUBSERIES OF THE CENOZOIC IN THE INTERNATIONAL CHRONOSTRATIGRAPHIC CHART

Assuming the subseries and subepochs of the Cenozoic series and epochs, respectively, can be recognized as formal chronostratigraphic units, their inclusion in the ICC is not entirely without difficulty.

In serving as a straightforward reference to the chronostratigraphy of Earth's geological record for the past 4.6 Ga, the ICC is intentionally uniform in style and content as far as possible. Nevertheless, exceptions to this format have been needed – for example, the Carboniferous System is uniquely divided into two subsystems to accommodate the well-known Mississippian and Pennsylvanian. Also, while most series are denominated by the terms "lower", "middle" and "upper" (i.e., Upper Cretaceous), those of the Cambrian, Silurian and Permian systems are not, nor those of the Cenozoic as well. It should therefore be acceptable to use positional terms ("lower", etc.), in the names of subdivisions of Cenozoic series.

At least three solutions are available for the inclusion of the subseries of the Cenozoic into the ICC (Text-fig. 1b). The first, which would be minimally invasive but perhaps not the most suitable, would be to simply add a note to the chart explaining that the series/epochs of the Cenozoic Erathem/Era are comprised of formal lower/early, middle and upper/late subseries/subepochs defined by stage GSSPs. This would require an asterisk or another indicator under the heading "Series/Epoch" in the chart. A more explicit presentation of the formal status of these units would be to insert a sub-column for series/epoch in the Cenozoic section, in which the subseries/subepochs would be shown as an unnamed category (Text-fig. 11a).

The main difficulty with the two solutions above is that the subseries would be identified merely as divisions of series. "Division" is not clearly identified as a chronostratigraphic term in any current stratigraphic guide and code (Salvador, ed. 1994, NACSN 2005) although Harland et al. (1990, p. 21) specifies: "A division is defined only by its boundary-stratotype points (GSSP)". A third solution, to alleviate this difficulty, would be to recognize "subseries" as a formal rank in the chronostratigraphic hierarchy of the Cenozoic. While subseries have not been given an independent column in most scientific illustrations, the conceptual ontogeny of the time scale (Text-fig. 4) provides reasons for such a pragmatic iconography, starting with Berggren (1972), who made space for incorporation of the full — and long — names of stages. The implicit intention has been followed in later works such as the 1989 GCC of Cowie and Bassett (1989) (Text-fig. 11a).

The term *subseries* does not commonly appear in the literature, and while it is mentioned only once in the *International Stratigraphic Guide* it is not included in the *North American Stratigraphic Code*. Examples of its use include King and Oakley (1949), Bukry (1973), Steininger et al. (1997), Aubry et al. (1999), Hilgen et al. (2000, 2005), Gibbard and Head (2010), Cita et al. (2012) and Head and Gibbard 2015). The reference to subseries in association with the ratification of specific GSSPs (Appendix 1) reveals an interest or desire in officially formalizing the term. This would be the most efficient means to give the subseries/ subepochs a full and formal place in chronostratigraphy (Text-fig. 11b), and, to judge from the consensus evident at the ICS open meeting in Graz, it would also meet the

TABLE 1
Low-rank Cenozoic chronostratigraphic units for the Cenozoic and duration (D) of the subepochs. There is some redundancy between stages/ages and subseries/subepochs. However, note that redundancy is generally for the shortest series/epochs. Subseries/subepochs are of considerable help for the longer series/epochs.

Series/ Epochs	D (Myr)	Serial/epochal divisions	D (Myr)	Stages/ Ages	D (Myr)
Pleistocene		Late Pleistocene	0.12		
		Middle Pleistocene	0.66		
		Early Pleistocene	1.799	Calabrian	1.019
				Gelasian	0.78
Pliocene	2.75	Late Pliocene	1.02	Piacenzian	1.02
		Early Pliocene	1.73	Zanclean	1.73
Miocene	17.697	Late Miocene	6.397	Messinian	1.913
				Tortonian	4.484
		Middle Miocene	4.34	Serravallian	2.19
				Langhian	2.15
		Early Miocene	7.06	Burdigalian	4.47
				Aquitanian	2.59
Oligocene	10.87	Late Oligocene	5.07	Chattian	5.07
		Early Oligocene	5.8	Rupelian	5.8
Eocene	22.1	Late Eocene	3.9	Priabonian	3.9
		Middle Eocene	10	Bartonian	3.4
				Lutetian	6.6
		Early Eocene	8.2	Ypresian	8.2
Paleocene	10	Late Paleocene	3.2	Thanetian	3.2
		Middle Paleocene	2.4	Selandian	2.4
		Early Paleocene	4.4	Danian	4.4

preference and expectation of a majority of the stratigraphic community.

The SQS has sought/is seeking formal status for subseries, because of the long history of such preferred divisions in stratigraphy of the Pleistocene Series (e.g., King and Oakley 1949; see Head and Gibbard 2015). In this regard, Cita et al. (2012, p. 189) commented "Several potential GSSPs for the Lower/Middle Pleistocene boundary (e.g., Head et al. 2008; Maiorano et al. 2010) are under consideration. While treating the Lower, Middle, and Upper Pleistocene Subseries as formal subdivisions following current practice (e.g., Gibbard et al. 2010), we do note that these terms have yet to be officially sanctioned by the ICS/IUGS." Candidate GSSPs for the Middle Pleistocene Subseries and its corresponding stages are presently under consideration while potential GSSPs for the Upper Pleistocene Subseries and its corresponding stage are being discussed. Additionally, a proposal is under consideration by the SQS to divide the Holocene Series into three subseries and their corresponding stages (Walker et al. 2012). If GSSPs are ratified for the subseries of the Pleistocene and Holocene, then their extension to other Cenozoic Series should be automatic.

THE IMPACT OF THE GSSP ON CHRONOSTRATIGRAPHY

It is important to clarify the (lack of) difference between global stages and higher-ranking chronostratigraphic units. Prior to the development of the GSSP concept, stage stratotypes were the embodiment of specific intervals of time, representing natural stratigraphic entities in regional geological history. In this, they differed from the higher chronostratigraphic units, that were entirely conceptual in nature. The GSSP concept represents a paradigm shift, in that only a specific horizon at a particular location is given the property of embodying time, with the result that the chronostratigraphic scale today is a virtual construct linked to the Earth' s history at these unique physical points, or stratigraphic moments (see Hilgen et al. 2006; Aubry 2007). In this way global stages are no longer represented in the rock as local examples of geological history during a particular interval, but are instead the basic units of measurement in global chronostratigraphy. This explains why a top-down hierarchy in selecting GSSPs has recently been adopted, such that the Eocene/Oligocene boundary could be defined without reference to the Rupelian Stage, and why there is a specific GSSP for the Cretaceous/Paleogene boundary, which also stands for the Maastrichtian/Danian boundary; and a GSSP for the base of the Neogene which is also the base of the Aquitanian Stage. In short, there is no longer a fundamental conceptual difference between stages and any rank above them, including subseries. In this one sees that the chronostratigraphic scale is not meant to be — and has never been — a natural division of earth history, but rather a conventional temporal framework of reference among earth scientists (see McGowran 2005).

CONCLUSION

For all the reasons, scientific and otherwise, discussed above and in Appendix 2, I encourage formal, IUGS-ratified definition of subseries/subepochs of the Cenozoic. The strength of the scientific reasons cannot be doubted. Like Ariadne's thread this concept guides the stratigrapher through more than 180 years of progressive development of the global chronostratigraphic scheme. The subseries have been the fundamental link between the deep-sea successions where stratigraphic means of correlation are often best developed and the non-marine successions in which geochronological calibration of chronostratigraphy is mainly found. These units constitute a practical, efficient and interdisciplinary means of communication among scientists interested in Cenozoic history in academia, industry, and with the public including educators. In other words, it is not only that subseries are divisions that begin and end at GSSPs, just as series, systems and erathems do, but the stronger reason for their recognition as formal elements in chronostratigraphy is that the purpose for which they were introduced has only proven more useful over the years.

From a practical and orderly point of view, the denial of formal status to subseries within the chronostratigraphic hierarchy makes little sense. For one thing, this would make their relationship to global stage GSSPs unclear and irrelevant, to the detriment of accurate communication across the profession. Moreover, encouraging the use of subseries as chronostratigraphic-entities-without-formal-status would introduce an acceptance of inconsistent usage in chronostratigraphy that is opposite to the fundamental goal of the ICS. Indeed, subseries cannot be both informal and chronostratigraphic in character, and the use of adjectives to identify them is not a sufficient reason to disregard their reality. To put it bluntly, *the subseries of the Cenozoic should be used formally or they should not be used at all* — and the latter option is plainly unrealistic, when we consider their pervasive employment.

Official recognition of the formal status of Cenozoic subseries, while ending the current editorial inconsistency, will also help to clarify the differences between strictly defined chronostratigraphic units, such as the subseries/subepochs (e.g., Lower/Early Miocene), and undefined portions of stage/age (e.g., lower/early Serravallian), systems/periods (e.g., lower/early Neogene) and erathem/era (e.g., lower/early Cenozoic) that are not. At the same time as formally ratified subseries should be reincorporated in the ICC this rank should be fully recognized in Cenozoic chronostratigraphy in acknowledgement of its essential contribution to a common language for all disciplines of earth sciences.

ACKNOWLEDGMENTS

The ideas discussed in this manuscript developed three years ago when I approached current ICS president Stanley Finney requesting that formalization of the Cenozoic subseries be considered. They were first presented at the Open Meeting of the Bureau of the ICS at the 2nd International Congress on Stratigraphy in Graz (2015). I acknowledge gratefully the advices and encouragements of many colleagues and in particular W. A. Berggren, S. Finney, M. J. Head, D. V. Kent, B. McGowran, K. G. Miller, W. Piller, and F. Steininger. I thank P. N. Pearson for involving me in pre- and post-Graz discussions, and members of the International Subcommissions on Neogene Stratigraphy (J. Backman, P. Pearson, I. Raffi) and the International Subcommission on Paleogene Stratigraphy (S. Monechi) for e-mail discussion on the matters developed in Appendix 2. I also thank J. Ogg for providing information on the current status of "subseries" in chronostratigraphy. I am grateful to B. McGowran, D. V. Kent and two anonymous reviewers for their thoughtful reviews of the manuscript; to Lucy Edwards for its editing, and Sarah Klingler for the artwork. I am also indebted to Ms Wendy Cawthorne (Geological Society London) for her help in finding the source of the Table reproduced in Berggren 1971 (Text-fig. 2 herein). Finally, I am deeply grateful to John Van Couvering for sustained discussion and his invaluable editing for presenting with clarity the ideas in this paper.

REFERENCES

AGNINI, C., FORNACIARI, E., RAFFI, I., CATANZANI, R., PÄLIKE, H., BACKMAN, J. and RIO, D., 2014. Biozonation and biochronology of Paleogene calcareous nannofossils from low and middle latitudes. *Newsletters on Stratigraphy*, 47: 131–181.

AUBRY, M.–P., 1993. Neogene allostratigraphy and depositional history of the De Soto Canyon area, northern Gulf of Mexico. *Micropaleontology*, 39: 327–366.

———, 2007. Chronostratigraphy beyond the GSSP. *Stratigraphy*, 4: 127–138.

AUBRY, M.–P., BERGGREN, W. A., VAN COUVERING, J. A. and STEININGER, F., 1999. Problems in chronostratigraphy: Stages, series, unit and boundary stratotypes, GSSPs and tarnished golden spikes. In: Gradstein, F. M. and van der Zwaan, B., Eds., *Earth Science Reviews*, 46: 99–148.

BACKMAN, J., RAFFI, I., RIO, D., FORNACIARI., E. and PÄLIKE, H., 2012. Biozonation and biochronology of Miocene through Pleistocene calcareous nannofossils from low and middle latitudes. *Newsletters in Stratigraphy,* 45: 221–244.

BASSETT, M. G., 1985. Towards a common language in stratigraphy. *Episodes*, 8: 87–92.

BERGGREN, W. A., 1967. Late Pliocene–Pleistocene stratigraphy in deep sea cores from the South–central North Atlantic. *Nature*, 216: 253–254.

———, 1971. Tertiary boundaries and correlations. In: Funnell, M. B. and Riedel, W. R., Eds., *The micropalaeontology of oceans,* 693–809. Cambridge: Cambridge University Press.

———, 1972. A Cenozoic time scale; some implications from regional geology and paleobiogeography. *Lethaia*, 5: 195–215.

———, 1998. The Cenozoic Era: Lyellian (chrono)stratigraphy and nomenclatural reform at the millennium. In: Blundell, D. J. and Scott, A. C., Eds., *Lyell: the past is the key to the present,* 111–132. London: The Geological Society. Special Publication 143.

———, 2007. Status of the hierarchical subdivision of higher order marine Cenozoic chronostratigraphic units. *Stratigraphy*, 4: 99–108.

BERGGREN, W. A. and VAN COUVERING, J. A., 1974. *The Late Neogene: Biostratigraphy, geochronology and paleoclimatology of the last 15 million years in marine and continental sequences.* Amsterdam: Elsevier. (Rprinted from *Paleogeography, Paleoclimatology, Paleoecology*, 16: 1–216.

BERGGREN, W. A., KENT, D. V. and FLYNN, J. J., 1985a. Paleogene geochronology and chronostratigraphy. In: Snelling, N. J., Ed., *The chronology of the geological record*, 141–195. London: The Geological Society. Memoir 10.

BERGGREN, W. A., KENT, D. V. and VAN COUVERING, J. A., 1985b. Neogene geochronology and chronostratigraphy. In: Snelling, N. J. (ed.), *The chronology of the geological record,* 211–260. London: The Geological Society. Memoir 10.

BERGGREN, W. A., KENT, D. V., SWISHER, C. C. and AUBRY, M.–P., 1995. A revised Cenozoic geochronology and chronostratigraphy. In: Berggren, W. A., Kent, D. V., Aubry, M.–P., and Hardenbol, J., Eds., *Geochronology, time scales and global stratigraphic correlations,*129–212. Tulsa: Society of Economic Paleontologists and Mineralogists (SEPM). Special Volume 54.

BEYRICH, E., 1854. Über die Stellung der Hessichen Tertiärbildinger. *Berichte von der Verhandlugen der Königliche Preussische Akademie der Wissenschaft zu Berlin*, 1854: 640–666.

———,1856. Über den Zusammenhang der nord-deutschen Tertiärbildungen. *Abhandlungen der Akadamie der Wissenschaft zu Berlin (Physikalische Abhandlungen)*, 1856: 1–20.

BOLLI, H. M., 1957a. The genera *Globigerina* and *Globorotalia* in the Paleocene–lower Eocene Lizard Springs Formation of Trinidad, B.W.I. *United States National Museum Bulletin*, 215, 51–81.

———, 1957b. Planktonic foraminifera from the Oligocene–Miocene Cipero and Lengua Formations of Trinidad, B.W.I. *United States National Museum Bulletin*, 215: 97–123.

———, 1957c. Planktonic foraminifera from the Eocene Navet and San Fernando Formations of Trinidad, B.W.I. *United States National Museum Bulletin*, 215: 155–172.

———, 1966. Zonation of Cretaceous to Pliocene marine sediments based on planktonic foraminifera. *Boletin Informativo, Asociacion Venezolano de Geologia, Minerologia y Petroleo*, 9: 3–32.

BOLLI, H. M., SAUNDERS, J. B. and PERCH–NIELSEN, K., Editors, 1985. *Plankton stratigraphy.* Cambridge: Cambridge University Press, 599 pp.

BOWN, P. R., Editor, 1998. *Calcareous nannofossil biostratigraphy.* London: Kluwer Academic Publishers, 314 pp.

BUKRY, D., 1973. Low–latitude coccolith biostratigraphic zonation. In: Edgar, N. T., Saunders, J. B., et al., *Initial Reports of the Deep Sea Drilling Project, vol. 15*, 685–703. Washington, D. C.: U.S. Government Printing Office.

CANDE, S. C. and KENT, D. V., 1992. A new geomagnetic polarity time scale for the Late Cretaceous and Cenozoic. *Journal of Geophysical Research*, 97(B10): 13917–13951.

CASTRADORI, D., RIO, D., HILGEN, F. J. and LOURENS, L. J., 1998. The global standard stratotype–section and point (GSSP) of the Piacenzian Stage (Middle Pliocene). *Episodes*, 21: 88–93.

CATUNEANU, O., 2006. *Principles of sequence stratigraphy.* Amsterdam: Elsevier, 375 pp.

CATUNEANU, O., ABREU, V., BHATTACHARYA, et al., 2009. Towards the standardization of sequence stratigraphy. *Earth-Sciences Reviews,* 92: 1–33.

CITA, M. B. and GARTNER, S., 1973. Study sul Pliocene e sugli strati di passagio dal Miocene al Pliocene. IV. The stratotype Zanclean foraminiferal and nannofossil biostratigraphy. *Rivista Italiana di Paleontologia e Stratigrafia*, 79, 503–558.

CITA, M. B., GIBBARD, P. L., HEAD, M. J. and The ICS Subcommission on Quaternary Stratigraphy, 2012. Formal ratification of the GSSP for the base of the Calabrian Stage (second stage of the Pleistocene Series, Quaternary System). *Episodes*, 35: 388–397.

COHEN, K. M., FINNEY, S. G., GIBBARD, P. L. and FAN, J. X., 2013. The ICS International Chronostratigraphic Chart. *Episodes*, 36: 199–204.

COWIE, J. W., 1986. Guidelines for boundary stratotypes. *Episodes*, 9: 78–82.

COWIE, J.W. and BASSETT, M.G. (compilers), 1989. 1989 global stratigraphic chart with geochronometric and magnetostratigraphic calibration. *Episodes*, 2, supplement sheet.

COWIE, J. W., ZIEGLER, W. and REMANE, J., 1989. Stratigraphic Commission accelerates progress, 1984 to 1989. *Episodes*, 12: 79–83.

COWIE, J. W., ZIEGLER, W., BOUCOT, A. J., BASSETT, M. G. and REMANE, J., 1986. Guidelines and statutes of the International Commission on Stratigraphie. *Courier Forschungsinstitut Senckenberg*, 83: 1–9.

CSEPREGHY–MEZNERICS, J., 1964. L'évolution de certains Pectinidés Néogènes, la question de "Chattien" et la limite Oligo–Miocène. *Instituto "Lucas Malladas", C.S. I. C., Cursillo y Conferencias*, IX: 33–50.

EVERNDEN, J. F. and CURTIS, G. H., 1961. Present state of potassium–argon dating of Tertiary and Quaternary rocks. Warsaw: Service géologique de Pologne. Travaux du INQUA Congress,Varsava 1961,

EVERNDEN, J. F. and CURTIS, G. H., 1965. The potassium–argon dating of Late Cenozoic rocks in East Africa and Italy. *Current Anthropology*, 6: 343–385 (with comments p. 364–285).

FLYNN, J. J. and SWISHER, C. C. III, 1995. Cenozoic South American Land Mammal Ages: Correlation to global geochronologies. In: Berggren, W. A., Kent, D. V., Aubry, M.–P., and Hardenbol, J., Eds., *Geochronology, time scales and global stratigraphic correlations,* 317–333. Tulsa: Society of Economic Paleontologists and Mineralogists (SEPM). Special Volume 54..

FUNNELL, B. F., 1964. The Tertiary Period. In: Harland, W. B., Smith, A. G., and Wilcock, B., Eds., The Phanerozoic Time Scale – A symposium). *Quarterly Journal of the Geological Society of London*, *Supplement,* 120: 179–191.

GIBBARD, P. L. and HEAD, M. J., 2010. The newly–ratified definition of the Quaternary System/Period and redefinition of the Pleistocene Series/Epoch, and comparison of proposals advanced prior to formal ratification. *Episodes*, 33: 152–158.

GIBBARD, P. L., HEAD, M. J., WALKER, M. J. C. and the Subcommission on Quaternary Stratigraphy, 2010. Formal ratification of the

Quaternary System/Period and the Pleistocene Series/Epoch with a base at 2.58 Ma. *Journal of Quaternary Science*, 25: 96–102.

GOULD, S. J., 1987. *Time's arrow, time's cycle*. Cambridge, MA: Harvard University Press, 222 pp.

GRADSTEIN, F. M., OGG, J. and HILGEN, F. J., 2012. On the geological time scale. *Newsletters on Stratigraphy*, 45: 171–188.

GRADSTEIN, F. M., OGG, J. and SMITH, A., 2004. *A geological time scale 2004.* Cambridge: Cambridge University Press, 589 pp.

GRESSLY, A., 1853. Nouvelles données sur les faunes tertiaires d'Ajoie, avec les determinations de M. Mayer. *Actes de la Societé Helvétique des Sciences naturelles,* 38: 251–261.

HAQ, B. U. and VAN EYSINGA, W. M., 1987. *Geological time table*. Amsterdam: Elsevier (wall chart).

HAQ, B. U., HARDENBOL, J. and VAIL, P. R., 1987. Chronology of fluctuating sea levels since the Triassic. *Science*, 235: 1156–1167.

HARDENBOL, J. and BERGGREN, W. A., 1978. A new Paleogene numerical time scale. In Cohee, G. V., Glaessner, M. F. and Heldberg, H., *Contributions to the geological time scale*, 213–234. Tulsa: American Association of Petroleum Geologists.

HARLAND, W. B., ARMSTRONG, R. L., COX, A. V., CRAIG, L. E., SMITH, A. G. and SMITH, D. G., 1990. *A geological time scale 1989*. Cambridge: Cambridge University Press, 263 pp.

HEAD, M. J. and GIBBARD, P. L., 2015. Formal subdivision of the Quaternary System/Period: Past, present, and future. *Quaternary International.* http://dx.doi.org/10.1016/j.quaint.2015.06.039.

HEAD, M. J., PILLANS, B. and FARQUHAR, S., 2008. The early–middle Pleistocene transition: characterization and proposed guide for the defining boundary. *Episodes*, 31: 255–259.

HEDBERG, H. D., Editor, 1976. *International stratigraphic guide*. New York: John Wiley and Sons, 200 pp.

HILGEN, F. J., 1991a. Astronomical calibration of Gauss to Matuyama sapropels in the Mediterranean and implication for the Geomagnetic Polarity Time Scale. *Earth and Planetary Science Letters*, 104: 226–244.

———, 1991b. Extension of the astronomically calibrated (polarity) time scale to the Miocene/Pliocene boundary. *Earth and Planetary Science Letters*, 107: 349–368.

HILGEN, F. J., ABELS, H. A., BICE, D., IACCARINO, S., KRIJSMAN, W., KUIPER, K., MONTANARI, A., RAFFI, A., TURCO, E. and ZACHARIASSE, W.–J., 2005. The global boundary stratotype section and point (GSSP) of the Tortonian Stage (upper Miocene) at Monte Dei Corvi. *Episodes*, 28: 6–17.

HILGEN, F. J., ABELS, H. A., IACCARINO, S., KRIJGSMAN, W., RAFFI, I., SPROVIERI, R., TURCO, E. and ZACHARIASSE, W. J., 2009. The global stratotype section and point (GSSP) of the Serravallian Stage (middle Miocene). *Episodes*, 32: 152–164.

HILGEN, F., BRINKHIUS, H. and ZACHARIASSE, W.–J., 2006, Unit stratotypes for global stages: The Neogene perspective. *Earth Science Reviews*, 74: 113–125.

HILGEN, F. J., IACCARINO, S., KRIJGSMAN, VILLA, G., LANGEREIS, C. G. and ZACHARIASSE, W.–J., 2000. The global boundary stratotype section and point (GSSP) of the Messinian Stage (uppermost Miocene). *Episodes*, 28: 172–178.

HILGEN, F. J., KRIJGSMAN, W., LANGEREIS, C. G., LOURENS, L., SANTARELLI, A. and ZACHARIASSE, W. J., 1995. Extension of the astronomical (polarity) time scale into the Miocene. *Earth and Planetary Science Letters*, 136: 495–510.

HILGEN, F. J., LOURENS, L. J. and VAN DAM, J. A., 2012. The Neogene period. In: Gradstein, F. M., et al., Eds., *The geological time scale 2012*, 923–978. Cambridge: Cambridge University Press.

HOLMES, A., 1959. A revised geological time scale. *Edinburgh Geological Society Transactions*, 17: 2119–2136.

HU, X., GARZANTI, E., MOORE, T. and RAFFI, I., 2015. Direct stratigraphic dating of India–Asia collision onset at the Selandian (middle Paleocene, 59 ± 1 Ma). *Geology*, 43: 859–862.

JENKYNS, D. J. and LUTERBACHER, H., 1992. Paleogene stages and their boundaries (introductory remarks). *Neues Jahrbuch für Geologie und Paläontologie, Abhandlungen*, 186: 1–5.

KENNETT, J. P. and SRINAVASAN, M. S., 1983. *Neogene planktonic foraminifera.* Stroudsburg, PA: Hutchinson Ross Publishing Company, 265 pp.

KING, W. B. R. and OAKLEY, K. P., 1949. Report of the temporary commission on the Plio–Pleistocene boundary, appointed 16th August 1948. In: Butler, A. J., Ed., *IGC, 18th Session, Great Britain, 1948. Part I. General Proceedings,* 213–228. London: The Geological Society.

KULP, J. L., 1961. Geological time scale. *Science*, 133: 1105–1114.

LOURENS, L. J., 2008. On the Neogene–Quaternary debate. *Episodes*, 31: 239–242.

LYELL, C., 1833. *Principles of geology. Volume 3.* London: John Murray. 398 pp. + 160 pp. appendices [1990 reprint by the University of Chicago Press, with a new introduction by M. J. S. Rudwick].

———, 1855. *A manual of elementary geology. Fifth edition.* London: John Murray, 655 pp.

———, 1856. *Manuel de Géologie élémentaire. Edition 5*. Paris: Langlois et Leclercq, 492 pp.

———, 1857a. *Supplement to the fifth edition of a manual of elementary geology*, 34 pp. London: John Murray.

———, 1857b. *Supplement to the fifth edition of a manual of elementary geology. Second edition, revised,* 40 pp. London: John Murray.

MAIORANO, P., CAPOTONDI, L., CIARANFI, N., GIRONE, A., LIRER, F., MARINO, M., PELOSI, N., PETROSINO, P. and PISCITELLI, A., 2010. Vrica–Crotone and Montalbano Jonico sections: A potential unit-stratotype of the Calabrian Stage. *Episodes*, 33: 218–233.

MAYER (MAYER–EYMAR). K., 1858. Versuch einer synchronistichen Tabelle der Tertiär-Gebilde Europas. *Verhandlungen der Schweizerischen Naturforschenden Gesellschaft*, 1857, 1–32.

MCELHINNY, M. W., 1978. The Magnetic Polarity Time Scale: Prospects and possibilities in magnetostratigraphy. In Cohee, G. V., Glaessner, M. F., and Heldberg, H., *Contributions to the geological time scale,*57–65. Tulsa: American Association of Petroleum Geologists.

MCGOWRAN, B., 2005. *Biostratigraphy.* Cambridge: Cambridge University Press, 459 pp.

MILLER, K. G., KOMINZ, M. A., BROWNING, J. V., WRIGHT, J. D., MOUNTAIN, G. S., KATZ, M. E., SUGARMAN, P. J., CRAMER, B. S., CHRISTIE–BLICK, N. and PEKAR, S. F., 2005. The

Phanerozoic record of global sea level change. *Science*, 310, 1293–1298.

MITCHUM, R. M., JR., 1978. Seismic stratigraphic investigation of West Florida slope, Gulf of Mexico. In: Bouma, A. H., Moore, G. T., and Coelman, J. M., Eds., *Framework, facies, and oil-trapping characteristics of the upper continental margin,* 193–223. Tulsa; American Association of Petroleum Geologists. Studies in Geology, 7.

MOLINA, E., ALEGRET, L., APELLANIZ, E., et al., 2011. The global stratotype section and point (GSSP) for the base of the Lutetian Stage at the Gorrondatxe section, Spain. *Episodes*, 34: 86–108.

MOLINA, E., ALEGRET, L., ARENILLAS, I., ARZ, J. A., GALLALA, N., HARDENBOL, J., SALIS, K. VON, STEURBAUT, E., VANDENBERGHE, N. and ZAGHBIB-TURKI, D., 2006. The global stratotype section and point (GSSP) for the base of the Danian Stage (Paleocene, Paleogene, "Tertiary", Cenozoic) at El Kef, Tunisia – Original definition and revision. *Episodes*, 29: 263–272.

MURPHY, M. A. and SALVADOR, A., 1999. International stratigraphic guide – An abridged version. *Episodes*, 22: 255–272.

NORTH AMERICAN COMMISSION ON STRATIGRAPHIC NOMENCLATURE, 2005. North American Stratigraphic Code. *American Association of Petroleum Geologists Bulletin*, 89: 1547–1591.

OGG, J. and GRADSTEIN, F. M., 2015. *TimeScale Creator (TSCreator).* https://engineering.purdue.edu/Stratigraphy/tscreator/

OLSSON, R. K., HEMLEBEN, C., BERGGREN, W. A. and HUBER, B. T., 1999. *Atlas of Paleocene planktonic foraminifera.* Washington, D. C.: Smithonian Institution. Contributions to Paleobiology, 85, 112 pp.

PARETO, L., 1865. Note sur les subdivisions que l'on pourrait établir dans les terrains tertiaires de l' Apennin septentrional. *Bulletin de la Société géologique de France*, 2: 210–217.

PEARSON, P. N., OLSSON, R. K., HUBER, B. T., HEMLEBEN, C. and BERGGREN, W. A., 2006. *Atlas of Eocene planktonic foraminifera*. Washington, DC: Cushman Foundation. Special Publication 41, 513 pp.

PILLANS, B. and GIBBARD, P., 2012. The Quaternary period. In: Gradstein, F. M., et al., Eds., *The geological time scale 2012*, 979–1032. Cambridge: Cambridge University Press.

POMEROL, Ch. and PREMOLI–SILVA, I., Editors, 1986. *Terminal Eocene events.* Amsterdam: Elsevier. Developments in Palaeontology and Stratigraphy 9, 414 pp.

PREMOLI–SILVA, I. and JENKYNS, D. G., 1993. Decision on the Eocene–Oligocene boundary stratotype. *Episodes*, 16: 379–382.

PROTHERO, D. R., 1995. Geochronology and magnetostratigraphy of Paleogene North American Land Mammal "ages": an update. In: Berggren, W. A., Kent, D. V., Aubry, M.–P., and Hardenbol, J., Eds., *Geochronology, time scales and global stratigraphic correlations,* 305–315. Tulsa: Society of Economic Paleontologists and Mineralogists (SEPM). Special Volume 54.

REMANE, J., 2000. *International stratigraphic chart, with explanatory note*. Rio de Janeiro: 31st International Geological Congress, 2000: p. 16 and chart.

REMANE, J., BASSETT, M. G., COWIE, J. W., GOHRBANDT, K. H., LANE, H. R., MICHELSEN, O. and NAIWEN, W., 1996. Revised guidelines for the establishment of global chronostratigraphic standards by the International Commission on Stratigraphy ICS. *Episodes* 19, 77–81.

RIO, D., SPROVIERI, R., CASTRADORI, D. and DI STEPHANO, E., 1998. The Gelasian Stage (upper Pliocene): A new unit of the global standard chronostratigraphic scale. *Episodes*, 21: 82–87.

RUDWICK, M. J. S., 1978. Charles Lyell's dream of a statistical palaeontology. *Palaeontology*, 21: 225–244.

SALVADOR, A., 1985. Chronostratigraphic and geochronometric scales in COSUNA stratigraphic correlation charts of the United States. *American Association of Petroleum Geologist Bulletin*, 69: 181–189.

———, Editor, 1994. *International Stratigraphic Guide*. Boulder: Geological Society of America, 214 pp.

SCHMITZ, B., PUJALTE, V., MOLINA, E., et al., 2011. The global stratotype sections and points for the bases of the Selandian (middle Paleocene) and Thanetian (upper Paleocene) stages at Zumaia, Spain. *Episodes*, 34: 220–243.

SHACKLETON, N. J. and CROWHURST, S., 1997. Sediment fluxes based on an orbitally tuned time scale 5 Ma to 14 Ma, Site 926. In: Shackleton, N., Curry, W. B., Richter, C., and Bralower, T. J., Eds., *Proceedings of the Ocean Drilling Program, Scientific Results*, *154,* 69–82. College Station, Texas: Ocean Drilling Program.

SHACKLETON, N. J., CROWHURST, S. J., WEEDON, G. and LASKAR, J., 1999. Astrochronomical calibration of Oligocene–Miocene time. *Royal Society London, Philosophical Transactions*, *series A,* 357: 1909–1927.

STANLEY, S. M. and LUCZAJ, J. A., 2015, *Earth system history. Fourth edition*. New York: Freeman and Company, 587 pp.

STEININGER, F., AUBRY, M.–P., BERGGREN W. A., et al., 1997. The global stratotype section and point (GSSP) for the base of the Neogene. *Episodes*, 20: 23–28.

SZÖTS, E., 1966. Stratotype de l' Aquitanian (Mayer–Eymar 1857/1858). *Bulletin de la Société géologique de France*, 7: 743–746.

VAI, G. B., 2007. A history of chronostratigraphy. *Stratigraphy*, 4: 83–97.

VAN COUVERING, J. A., CASTRADORI, D., CITA, M. B., HILGEN, F. J. and RIO, D., 2000. The base of the Zanclean Stage and of the Pliocene Series. *Episodes*, 23: 179–187.

VANDENBERGHE, N., HILGEN, F. J., SPEIJER, R. P., 2012. The Paleogene Period. In: Gradstein, F. M., et al., Eds., *The geological time scale 2012,* 855–921. Cambridge: Cambridge University Press.

WADE. B. S., PEARSON, P. N., BERGGREN, W. A. and PÄLIKE, H., 2011. Review and revision of Cenozoic tropical planktonic foraminiferal biostratigraphy and calibration to the geomagnetic polarity and astronomical time scale. *Earth–Science Reviews*, 104: 111–142.

WALKER, M. J. C., BERKELHAMMER, M., BJORK, S., CWYNAR, L. C., FISHER, D. A., LONG, A. J., LOWE, J. J., NEWNHAM, R. M., RASMUSSEN, S. O. and WEISS, H., 2012. Formal subdivision of the Holocene Series/Epoch: a discussion paper by a Working Group of INTIMATE (Integration of ice–core marine and terrestrial records) and the Subcommission on Quaternary Stratigraphy (International Commission on Stratigraphy). *Journal of Quaternary Science*, 27, 649–659.

ZÖBELEIN, H. K., 1960. Über die chattische und aquitanische Stufe und die Grenze Oligozän/Miozän (Palaeogene/Neogen) in Westeuropa. *Mitteilungeun der Geologische Gesellschaft in Wien*, 1960: 245–265.

APPENDIX 1

References to subseries in summaries of ICS subcommissions and ratifications of the GSSPs of Cenozoic Stages. Quotes are taken verbatim from the descriptions of GSSPs as published in Episodes, although emphasis is mine. In all Paleocene and Neogene instances the names of subseries were printed using an initial uppercase letter, implying intended formal status. If there is any doubt that formalization was intentional, compare the titles of the papers by Hilgen et al. (2000) and Hilgen et al. (2005) in describing the GSSPs for the Messinian and the Tortonian Stages, respectively. These titles are essentially the same, beginning with "The Global Boundary Stratotype Section and Point (GSSP) of the …" but continuing with "Messinian Stage (uppermost Miocene)" in Hilgen et al. (2000, p. 172; emphasis mine) but "Tortonian Stage (Upper Miocene) …" in Hilgen et al. (2005, p. 6; emphasis mine). Upper Miocene refers to a chronostratigraphic interval, uppermost does not.

PALEOCENE SERIES

Lower Paleocene: not mentioned at the time of ratifcation of the Danian Stage (Molina et al. 2006).

Middle Paleocene, **Upper Paleocene**

The use of upper case M in Middle, and U in Upper, at the time of ratification of the GSSPs for the base of the **Selandian Stage** and **Thanetian Stage**, respectively, would indicate recognition of formal use of the terms.

"The global stratotype sections and points for the bases of the Selandian (**M**iddle Paleocene) and Thanetian (**U**pper Paleocene) stages have been defined in …." (Schmitz et al. 2011, cit., p. 220).

EOCENE SERIES

Lower Eocene: not mentioned at the time of ratifcation.

Middle Eocene:

Statements in Jenkins and Luterbacher (1992, p. 3) read:

"The Lutetian […] is the lowermost stage of the **M**iddle Eocene".

"The Bartonian […] is the uppermost stage of the **M**iddle Eocene" .

Lutetian Stage

Statements in Molina et al. (2011, p. 86) read:

"The GSSP for the base of the Lutetian Stage (**e**arly/**m**iddle Eocene boundary) is defined…."

"The Ypresian and Lutetian are the global standard stages of the **l**ower and **m**iddle Eocene (Jenkins and Luterbacher 1992)."

"The Ypresian/Lutetian boundary stratotype has to be defined at a level equivalent with the base of the Lutetian, which is the lowermost standard stage of the **m**iddle Eocene (Jenkins and Lutrbacher 1992)."

Note: "lower" and "middle" are used informally throughout Molina et al. (2011), except on p. 88 which reads: "….previously described from the **M**iddle Eoecene, and first appear in **L**ower Eocene deposits in the study area:. This suggests disagreement among authors as to stylistic preference or editorial intervention.

Bartonian Stage: definition of GSSP in progress.

Upper Eocene:

"The Priabonian is the only stage of the **U**pper Eocene". (Jenkins and Luterbacher (1992, p. 4).

Priabonian Stage: definition of GSSP in progress.

OLIGOCENE SERIES

Lower Oligocene:

The definition of the GSSP for the base of the Eocene (Premoli Silva and Jenkins 1993) was ratified without reference to the base of the Rupelian Stage (selected at 26th Geological Congress, see Jenkins and Luterbacher 1992). (See discussion in Berggren 2007.) Whereas there was no reference to the oldest division of the Oligocene series at the tiem of defintion and ratification, Figure 2 includes the younger division of the Eocene and older division of the Oligocene, and the text reads:

"The Massignano section, which covers the **l**ate Eocene and **e**arly Oligocene …." (op. cit., p. 380).

Upper Oligocene: definition of a GSSP for the Chattian Stage is in progress.

MIOCENE SERIES

Lower Miocene: There was no reference to this division at the time of ratification of the GSSP for the Paleogene/Neogene boundary (Steininger et al. 1997). However these authors refer in the text to upper and **l**ate Oligocene (op. cit. p. 24) as well as to upper and late Eocene, lower, upper, early and late Oligocene, and late Miocene (also p. 24).

Middle Miocene: This division comprises the Langhian and Serravallian.

Hilgen et al. (2009, p. 153) state:

"A proposal was presented — and accepted — at the RCMS congress in Bratislava (1975) to incorporate the Serravalian in the Standard Chronostratigraphic Scale as the second upper subdivision of the Middle Miocene, above the Langhian and below the Tortonian."

Langhian Stage: definition of GSSP in progress.

Serravallian Stage

In defining ths Serravallian Stage, Pareto (1865, in Hilgen et al., 2009, p. 153) wrote:

"I place the lower limit of the third division of the Miocene terrains, which is that of the **U**pper Miocene and which I name the Serravallian Stage …" (Pareto placed the Serravalian in the Upper Miocene).

In describing the ratified GSSP for the base of the Serravalian Stage, Hilgen et al. (2009, p. 152) stated:

"The Global Stratype section and Point (GSSP) for the base of the Serravallian Stage (**M**iddle Miocene) is defined in the Ras il Pellegrin…."

"The aim of this paper is to announce the formal ratification of the Global Stratotype Section and Point (GSSP) for the Serravallian Stage which, together with the preceding Langhian, constitutes the twofold subdivision of the **M**iddle Miocene in the Global Standard Global [*sic*] Chronostratigraphic scale."

"Formal definition of **M**iddle Miocene chronostratigraphic units via their GSSPs is also…"

"One of the major changes in the climate system is termed the **M**iddle Miocene climate transition..."

"The major shift in **M**iddle Miocene marine isotope records…" (op. cit., p. 154)

APPENDIX 1
Continued.

Upper Miocene:

"Together with the Messinian, the Tortonian represents the twofold subdivision of the Upper Miocene Subseries in the Global Chronostratigraphic scale." (Hilgen et al., 2005, p. 6)

Tortonian Stage

In describing the GSSP for the base of the Tortonian Stage, Hilgen et al. (2005, p. 6) stated:

"The GSSP of the Tortonian Stage, which per definition marks the base of the Tortonian and, hence, the boundary between the Serravallian and Tortonian stages of the **M**iddle and **U**pper Miocene subseries, has recently been defined and ratified by the IUGS." (note the use of 'subseries').

"The logical next step is to select and define the GSSP for the next older stage in the Miocene, the Tortonian (Mayer-Eymar, 1858). This step is greatly facilitated by the progress recently made in establishing orbital-tuned integrated stratigraphic frameworks for the Middle/Upper Miocene both in the Mediterranean (Hilgen et al. 1995, 2000b, 2003) and in the open ocean (Shackleton and Crowhurst 1997; Shackleton et al. 1999)."

Messinian Stage: (Hilgen et al. 2000)

In describing the ratified GSSP for the base of the Messinian Stage, Hilgen et al. (2000, p. 172) stated:

"The GSSP of the Messinian Stage, which per definition marks the base of the Messinian and, hence, the boundary between the Tortonian and Messinian Stages of the Upper Miocene Series, has recently been defined and ratified by the IUGS."

"Together with the Tortonian, the Messinian represents the two-fold subdivision of the **U**pper Miocene Subseries in the Global Standard Chronostratigraphic Scale. Controversies concerning the status of the Messinian as global chronostratigraphic unit and the placement of the Miocene/Pliocene boundary have now formally been settled with the official acceptance by the International Commission on Stratigraphy (ICS) and the ratification by the Executice Committee of the International Union of Geological Sciences (IUGS) of both the Zanclean (**L**ower Pliocene) and Messinian GSSPs."

"High quality magnetostratigraphic records from **U**pper Miocene sections on Crete…" (op. cit., p. 173).

PLIOCENE SERIES

Lower Pliocene:

Van Couvering et al. (2000) summarized the chronostratigraphic subdivision of the Pliocene Series (prior to 2008):

"From bottom to top, the Pliocene consists of the **L**ower Pliocene Zanclean Stage, with a boundary-stratotype at Eraclea Minoa and a unit-stratotype at Capo Rossello; the **M**iddle Pliocene Piacenzian Stage, defined at Punta Piccola (Castradori et al. 1998); and the **U**pper Pliocene Gelasian Stage, defined at Monte San Nicola near Gela …" (op. cit., p. 179).

"This composite section [Eraclea Minoa] constitutes the **L**ower and **M**iddle Pliocene part of the stratigraphic reference for the Astronomical Polarity Time Scale or APTS (Hilgen 1991a, b)." (op. cit., p. 181).

Upper Pliocene:

In describing the ratified GSSP for the base of the Piacenzina Stage, Castradori et al. (1998, p. 88) stated:

"The base of the Piacenzian Stage, representing the **L**ower Pliocene-**M**iddle Pliocene boundary has been recently defined and ratified by IUGS."

<u>Note</u>: the Piacenzian Stage is now assigned to the **U**pper Pliocene following the transfer of the (ex **U**pper Piocene) Gelasian Stage to the **L**ower Pleistocene Subseries.

PLEISTOCENE SERIES

The Pleistocene Series is comprised of a ratified Lower Subseries that includes the Gelasian and Calabrian Stages, and proposals for a Middle and Upper Subseries are pending (Head and Gibbard 2015).

Lower Pleistocene:

In describing the ratified GSSP for the base of the Calabrian Stage, Cita et al. (2012, p. 388) stated:

"Indeed, these two stages [Gelasian and Calabrian] together will comprise the **L**ower Pleistocene Subseries (**E**arly Pleistocene Subepoch)."

Gelasian Stage

In reporting on the ratification of the GSSP for the base of the Gelasian, Rio et al. (1998, p. 82) stated:

"*The Gelasian has been formally accepted as third (and uppermost) subdivision of the Pliocene Series, thus representing the Upper Pliocene*."

"This report announces the formal ratification of the Gelasian Stage as the uppermost subdivision of the Pliocene series, which is now subdivided into three stages (**L**ower, **M**iddle and **U**pper)."

Note: Rio et al. (op. cit., p. 82) explained: "Even if numerous stages have been proposed over the years for subdividing the 3.5 Ma [sic] long Pliocene Series (Astian, Piacenzian, Zanclean, Fossanian, etc.), a two-fold subdivision into a Zanclean (**L**ower Pliocene) and Piacenzian (**U**pper Pliocene) Stages became well established in the eighties (e.g., Berggren et al. 1985; Haq and Van Eysinga 1987)" (op. cit., p. 82).

Calabrian Stage

In reporting on the ratification of the GSSP for the base of the Calabrian, Cita et al (2012) stated:

" Ratification of the Calabrian Stage effectively completes the **L**ower Pleistocene Subseries" (op. cit., p. 388).

"Indeed, the Crotone Series, which includes the Vrica section, is without doubt the best-studied **L**ower Pleistocene succession in the world, and has been the subject of a recent synthesis…" (p. 395).

Middle and Upper Pleistocene: in progress.

APPENDIX 2
Summary of an e-mail discussion among members of the Subcommissions on Neogene and Paleogene Stratigraphy and ICS President Stanley Finney, between 14 August 2015 to 21 October 2015, concerning the controversial formalization (IUGS ratification) of the rank of subseries for the Cenozoic. Questions are in italics, followed by my responses.

1- Would it not be simpler to use the informal, but understandable and meaningful terms "lower/early", "middle" and "upper/late"?

If the terms lower/early, middle and upper/late continue to be used informally for Cenozoic subseries, how would one know that these are used with consistent/identical chronostratigraphic meaning since only IUGS-ratified terms are strictly defined under current ICS-IUGS regulations? To serve their full purpose for relative dating and correlation these terms should indeed be defined. To take an example among many similar ones, the base of the (informal) **m**iddle Eocene could be adjusted so as to correspond to the Chron C21n/C21r magnetic reversal rather than to align with the GSSP of the Lutetian Stage as conventionally agreed (see Text-fig. 10 above). Such a move would readily allow for precise marine-continental correlations considering that the primary criterion for correlation of the GSSP of the Lutetian Stage is the HO/LAD (Highest Occurrence/Last Appearance Datum) of the coccolithophore *Blackites inflatus* in mid-Chron C21r. Whereas the interval encompassed by the **M**iddle Eocene would be readily and precisely known as defined between the GSSP of the Lutetian and the GSSP of the Priabonian, the interval encompassed by the **m**iddle Eocene is not automatically tied to those GSSPs. Under the current ICS/IUGS regulations, the subseries of the Cenozoic are not IUGS-ratified: Undefined, their content is not immediately known.

Conclusion: There can be multiple opportunistic definitions of the **m**iddle Eocene subseries but there can be only one, global definition of the **M**iddle Eocene Subseries.

2- There is a long history of widespread convention to consider the sub-series as informal with a lower case letter. Why should this change?

In fact, subseries were previously used both formally and informally. In my view, the fact that informal use was acceptable in the past should be balanced against the benefit of strict chronostratigraphic regulation of such a widely used unit.

The salient point is that with or without formal names (upper-case/lower-case L/l, M/m, and U/u), the subseries of the Cenozoic have always been understood as chronostratigraphic units, and this should be the focus of a decision. The introduction of regulation in chronostratigraphy (Cowie et al. 1986) resulted in subseries thereafter being tacitly composed of formal stages. The logical next step would be to recognize these as formal units in their own right, since they are already identified with the ratified GSSPs of the component stages. If subseries are not formalized, on the other hand, then we must accept the likelihood that they will again be used in various inconsistent ways, without regard for the pragmatic benefit of formalization (see Text-Fig. 10). The basic question, therefore, is whether this informality is in the long-term interest of the scientific community.

Conclusion: the advantage of simplicity through informality must be weighed against the advantage of pragmatic usage of formal subseries and a consistent, uniform language in chronostratigraphy.

3- Is it the case that the subseries are useful in being somehow less precise than the global stages? Could it be the case that formalizing subseries is also formalizing uncertainty?

Two concepts are conflated here. One (a) concerns the precision of boundary recognition. The other (b) concerns the identification of a chronostratigraphic interval (see Text-fig. 5 above).

(a) The precision at the boundary between two formal subseries is the same as the precision at the boundary between two bounding stages, since they are both defined by the same GSSP. If the primary or secondary criteria for correlation of the GSSP are not present in a section, neither the stage boundary nor the subseries boundary can be delineated. This is true as well for series and system boundaries.

(b) With regard to the recognition of a stratigraphic interval, it will likely be easier to identify a larger chronostratigraphic interval than a smaller one in less-than-perfect-circumstances, as when provincialism occurs with differentiated paleobiogeography of planktonic taxa between low and high latitudes, or when the information of interest (i.e., plate movement, paleoenvironmental trend) is not of stage-level scope.

As an example, uppercase **U**pper/**L**ate Miocene would imply that the interval is that between the GSSP of the Tortonian Stage and that of the Zanclean Stage (= 11.63 – 5.33 Ma). Lowercase **u**pper/**l**ate Miocene would yield no guarantee of such a precise timing. A recent example of this is seen in Hu et al. (2015) where the use of lowercase 'm' in "middle Paleocene" in the title does not carry the same precise information with regard to the location of the Selandian Stage in the chronostratigraphic scale as use of the upper case "M" in "Middle Paleocene" would have. The implications of such difference are readily seen in the manner in which data can be trusted, in particular if quantified (e.g., calculation of rates of sedimentation, diversification, etc.).

There is an important advantage in using the name of a (formal) subseries rather than that of two stages when determination at the stage level is uncertain. A statement such as "this interval belongs to the Langhian-Serravallian" contains an uncertainty whereas a statement such as "this interval belongs to the Middle Miocene" is fully affirmative. This alleviates difficulties for disciplines in which stratigraphic uncertainty is not fully understood: a positive statement is more to the stratigrapher's advantage than one that is imbued with doubt.

Conclusions: It can be seen from the above that formalizing subseries will prevent uncertainty as to their extent (ages of boundaries and duration), means of determination and correlation, whereas not formalizing them will in fact be endorsing uncertainty.

4- If stages are universal, global entities, how could there be a limitation to their usefulness? They should be recognizable in all stratigraphies, in all disciplines, and everywhere.

The concept of GSSP implies that, in theory, stages, as well as series, systems and erathems, are applicable worldwide. In fact the global stage is no longer a single body of rock, but an interval that is known only between two horizons (GSSPs), the older horizon that defines the base of that stage, and the younger horizon that defines the base of the next stage. These two horizons must be referenced and, as far as possible, identified in order to characterize a global stage in any section. However in practice it may be difficult to clearly recognize, or realistically apply, a stage boundary, as exemplified in Text-figures 5 and 6.

Conclusions: There is no limit to the usefulness of stages in theory, but there is a practical limit to their applicability.

5- The author uses the names of paleoclimatic events (PETM, MECO, EECO) in terms of subseries, actually subepochs, to underline their broad use and easy meaning. It would seem that this has nothing to do with the discussion. PETM, MECO, EECO are acronyms used to indicate the geological time interval during which the events occurred.

On the contrary, these names have a lot to do with the discussion, and the reason is contained in the question: They are "acronyms used to indicate the geological time interval during which the events occurred." This is what chronostratigraphy and time scales are about, is it not?

Conclusions: Two alternative (unsatisfactory) solutions are to name the paleoclimatic events 1) in reference to stages [T/P, BCO, YCO, respectively), or 2) by their age: the ~56 Ma event for the PETM (however, numerical ages are not yet stable).

6- It is not realistic — and in a way it is ignoring correct procedures — to state that the ratification of subseries in Pleistocene and Holocene will automatically lead to the ratification of subseries in the Cenozoic. There are two problems with this: (a) a single subcommission should not be able to decide an issue that affects the others, for all the others, and (b) why stop at the Cenozoic? ... Just because we have the Mississippian and Pennsylvanian Sub-Systems does not mean they apply to all the other systems.

Our discussion strictly concerns the subseries of the Cenozoic. In fact, formal subdivision of other major units of the time scale are notably inconsistent, and we do not need to follow any one in preference to another in regard to what is desirable and historically justified here.

It would not be very desirable to present a heterogeneous chronostratigraphic scheme for the Cenozoic. I am unclear as to what would be gained by accepting formal subseries for the Quaternary, but not for the Neogene and Paleogene parts of the same System/Era. **L**ower Pleistocene but only **l**ower Miocene? Aside from the inevitable confusion and inconsistent use, it would be difficult to imagine an explanation for this discrepancy.

Conclusions: Chronostratigraphic practices should be homogeneous throughout the Cenozoic to respect the integrity of this era.

7- Would not the formalization of subseries constitute a precedent encouraging the introduction of sub- and super-categories?

The subseries of the Cenozoic are a special case, because of a long history (>180 years) of well-understood and broad use unparalleled in other parts of the chronostratigraphic scale.

Higher level divisions, e.g. subsystem/superseries/subera are already found in other parts of the time scale (i.e., Carboniferous) and have been proposed with regard to the resolution of the Neogene/Quaternary debate, and such special divisions have always been an option, if seldom used. The introduction of formal substages is especially unlikely, since this could not be accomplished without definition of new, internal GSSPs.

Conclusions: No special steps or new rules would be introduced with formalization of Cenozoic subseries, since they are already identified by basal stage GSSPs, and their status in the chronostratigraphic system only requires ratification by the IUGS.

8- Should stages be avoided because their names are difficult to remember? Would not this mean ignoring the history of stratigraphy, and rendering somehow useless the work conducted on the behalf of stages? Should stages be given numbers in order to be easier to remember?

There is no suggestion of abandoning global stages. Their GSSPs are the concrete expression in the rock of specific moments of time to which Earth history is tied, and they serve in defining all chronostratigraphic units of higher ranks. It is important to recognize, however, that there are contexts for which it is more relevant/practical to use subseries as groups of Stages. The acknowledged role of the ICS is to facilitate communication among scientists — to provide the "common language in stratigraphy" sought by Bassett (1985). Every scientist must have at his disposal an array of chronostratigraphic terms to communicate his results.

Conclusion: the concept of Global Stage is an inclusive one: the GSSP of a stage defines the base of all units of higher rank above the stage. The concept of a global stage is thus embedded in the definition of every chronostratigraphic unit above it, including subseries once ratified.

9- Should not the use of stages be encouraged considering the tremendous effort (money and time) that has been spent in defining them?

Because of the nested stage–subseries–series–system–erathem hierarchy, the rewards of the effort expended in defining global stages is multiplied five-fold in the whole hierarchy.

All things considered, a similar situation would consist in discouraging the use of kilometer because of the considerable effort that has been devoted to the definition of the meter.

I do not see any reason to encourage *or* discourage the use of stage, or of any chronostratigraphic unit above it. Narratives relative to Mesozoic and Paleozoic stratigraphy seem to rely primarily on a three-fold chronostratigraphic hierarchy of system, series (Lower–, Middle–, Upper–) and stages. Each rank is comprised of IUGS-ratified units. Narratives on Cenozoic stratigraphy are also best served by a three-fold chronostratigraphic hierarchy but which consists of series, subseries (Upper–, middle–, lower–) and stages. Only series and stages are currently IUGS-ratified, although the informal Cenozoic subseries occupies the same role in Earth history narratives as the Mesozoic and Paleozoic IUGS-ratified series. It may be unfortunate that the names of Cenozoic subseries (and subepochs) on the one hand, and those of Paleozoic and Mesozoic series (and epochs) on the other hand, partly overlap, but this cannot be a major difficulty since the names of Cenozoic series have an etymology fundamentally different from that of the names of Mesozoic and Paleozoic systems, the former being based on biostratigraphic content, the latter (with one exception) on geographic localities.

Conclusion: The role of stage in chronostratigraphy is well acknowledged, but there is no scientific nor political reason to push for its exclusive use, particularly at the expense of the very useful subseries of the Cenozoic.