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A case for formalizing subseries (subepochs) of the Cenozoic Era[(a)]

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Subseries/subepochs (e.g., Lower/Early Eocene, Upper/Late Pleistocene) have yet to be formally defined despite their wide use in the Cenozoic literature. This has led to concerns about the stability of their definition and uncertainty over their status that has led to inconsistencies in capitalization. To address these issues, we propose for the Cenozoic that subseries/subepochs be defined formally by reference to Global Boundary Stratotype Sections and Points and ratified in the same way as for other formal chronostratigraphic units. Formalization of subseries/subepochs for the Cenozoic will respect their deep historical roots, recognise their chronostratigraphic nature, stabilize their definition, ensure consistency in application, embrace their de-facto use as formal terms within the Paleogene, Neogene and especially Quaternary communities, and resolve the question of capitalization: an upper-case initial letter without exception.

The case for Cenozoic subseries/subepochs

Subseries/subepochs (e.g., Lower/Early Eocene, Upper/Late Pleistocene) are not formally recognised by the International Commission on Stratigraphy (ICS) despite their wide use in the Cenozoic literature and sanction by the International Stratigraphic Guide (Hedberg, 1976, p. 72, tab. 2; Salvador, 1994, p. 80, tab. 3). Yet the concept of subdividing series/epochs (hereafter "series") is as old as the series themselves, and dates back to the work of Charles Lyell (1833). Divisions of series predate stages, which became systematically incorporated into the Cenozoic time scale only in the 1970s, with the boundaries of stages adjusted to fit subseries, not the other way around. Aubry (2016) provides a comprehensive history of the subdivision of series for the Cenozoic and their relationship to stages, the broader history of chronostratigraphy having been outlined by Aubry et al. (1999) and Vai (2007).

The ICS-imprinted Global Stratigraphic Chart of 1989 (Cowie and Bassett, 1989) included divisions of series for the Neogene and Quaternary [There was no subdivision of the Paleogene series because the ICS Subcommission on Paleogene Stratigraphy (SPS) was still working on this (Aubry, 2016)]. While significant as an indication of notional acceptance of subseries by ICS, this would not be an explicit approval of subseries, and such divisions have not since appeared on explicitly sanctioned ICS charts. Even so, announcements of global boundary stratotype sections and points (GSSPs) published in the journal *Episodes* frequently contain references to subseries for the Cenozoic, and the positional terms "Lower/Early", "Middle", and "Upper/Late"are applied to all series of the Cenozoic: their use in the literature is pervasive. They are treated as formal terms when the initial letter is in upper-case (e.g., Upper Eocene), or informal when in lower-case (e.g., upper Eocene), but this decision is often imposed by no more than editorial fiat and house style. Cenozoic subseries are used always in reference to a ratified or anticipated GSSP: they are de-facto chronostratigraphic units, as we explain below (point 14). We therefore use upper-case for these terms in the present paper.

The lack of official definition of subseries for the Cenozoic has nonetheless led to: 1) uncertainty about their status (formal or informal) leading to inconsistencies in capitalization, and 2) concern about the stability of their definition. These issues have caused the status of Cenozoic subseries to be discussed within ICS. Two distinct positions have emerged:

[(a)]In order to determine the level of support within the three relevant ICS subcommissions (SPS, SNS, and SQS) for the formalization of subseries in the Cenozoic, a ballot was held among all voting members of these subcommissions. This paper is the position statement for formalization, and was circulated on June 21, 2016, along with the other voting materials. Figure 2 is included here because it had been part of an earlier version, but did not appear in the circulated document. The position statement as circulated included the ICS affiliations of the authors: Martin J. Head, Chair, Subcommission on Quaternary Stratigraphy (SQS); Marie-Pierre Aubry, Voting Member, Subcommission on Neogene Stratigraphy (SNS); Mike Walker, Voting Member, SQS; Kenneth G. Miller, Vice-Chair, SNS; Brian R. Pratt, Chair, Subcommission on Stratigraphic Classification.

1) the continuance of "informal" status with no position taken by ICS, so that individual authors are free to make their own decisions about subseries definitions (the status quo); but with clarification placed on the ICS website to indicate that subseries are to be treated as informal and indicated as such with a lower-case initial letter;

2) our own position in which subseries are treated as defined, ratified and hence *formal* chronostratigraphic units for the Cenozoic.

The first position (status quo) would perpetuate all the problems we are trying to resolve: uncertainty in the application of subseries, instability in their definition, denial of their actual chronostratigraphic status, and continued divergence in the practice of capitalization especially within the Quaternary community.

The second position (this proposal) requires that subseries definitions for the Cenozoic be accomplished in the usual way for formal chronostratigraphic units: a proposal by the relevant subcommission, approval by the voting membership of ICS, and ratification by the Executive Committee (EC) of the International Union of Geological Sciences (IUGS). Ratification is the essential final step, providing oversight and legitimacy to the entire process. A commonly used grouping of stages into subseries is shown (Fig. 1). But there are alternative schemes, and we argue that these subseries must be *formally* defined to ensure their legitimacy and stability. Nonetheless, we recommend that formal subseries do not appear on the International Chronostratigraphic Chart, but instead reside on a more detailed auxiliary chart displayed on the ICS website. This will preserve the simplicity and integrity of the main chart. We make the following additional observations:

1. The historical legitimacy of subseries as chronostratigraphic units is incontestable. The subdivision of series is as old as the series themselves, and dates back to Lyell (1833) with his Older and Newer Pliocene and the anticipated subdivision of his other series, Eocene and Miocene (Lyell, 1833, pp. 57, 58). Lyell (1833, p. 53, 54) used upper-cased initial letters for his Older and Newer Pliocene presumably to stress their formal standing, although he did this somewhat inconsistently as with other terms. However, by 1838 he was using these terms persistently in upper case. In 1855, Lyell published what is probably the first-ever multi-hierarchical chronostratigraphic chart (Lyell, 1855, p. 109, Fig. 2). All terms are set fully in upper case in this chart; but elsewhere in the text he typically upper-cased initial letters of all positional modifiers, including Lower Silurian, Upper Silurian, Lower Cretaceous, Upper Cretaceous, and significantly Lower Eocene, Middle Eocene, Upper Eocene, Lower Miocene, and Upper Miocene. In 1857, Lyell discussed the Middle Miocene with reference to an earlier publication (by V. Raulin), and also Lower, Middle, and Upper Oligocene with respect to the newly introduced "Oligocene" of Beyrich (1854), in all cases using upper-cased initial letters. There can be little doubt that Lyell intended these as formal subdivisions.

The subdivision of series in fact predates stages for the Cenozoic, with for example Mayer (in Gressly, 1853) assigning his Aquitanian Stage to the Lower Miocene. The GSSP concept, inaugurated at the 18th International Geological Congress in 1948, was first applied to the Pliocene–Pleistocene boundary, with the Upper Pliocene and Lower Pleistocene (initial letters capitalized in the original) being specifically mentioned along with the Calabrian (regional) Stage (King and Oakley, 1949). It was not until the 1970s (Berggren, 1971, 1972) that

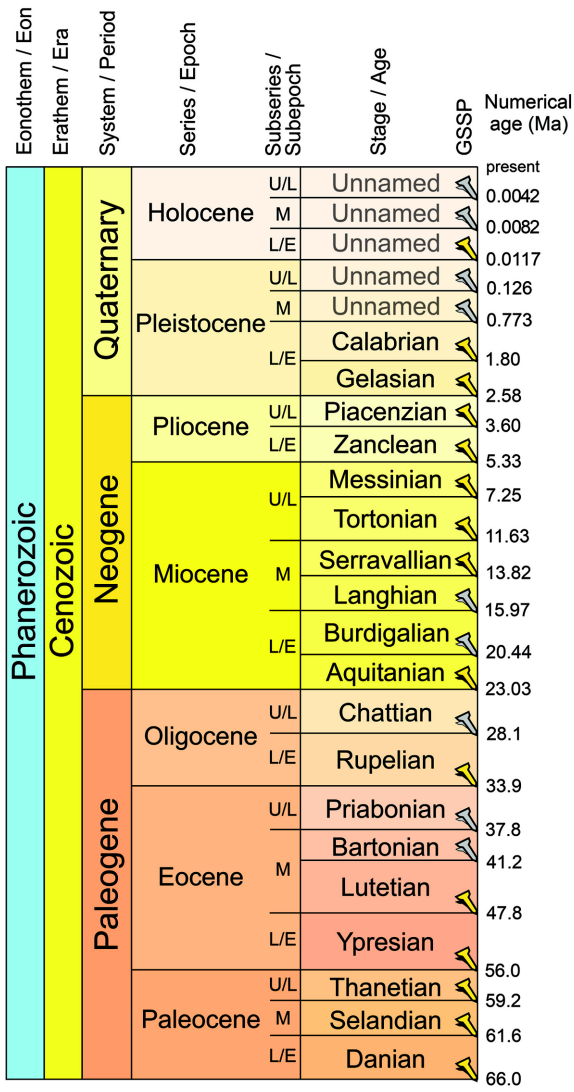

Figure 1: The Cenozoic part of the International Chronostratigraphic Chart (modified from Cohen et al., 2013, v. 2016/04) showing the subseries/subepoch scheme following Luterbacher et al. (2005) for the Paleogene, and Lourens et al. (2005) for the Neogene, except that the Quaternary follows Gibbard et al. (2010) and Head and Gibbard (2015). The tripartite subdivision of the Holocene Series is long established (Walker et al., 2012). Its subdivision into Early, Middle and Late Holocene subepochs and their corresponding ages/stages, at 8.2 and 4.2 ka, has been recommended by the SQS. Abbreviations: L/E = Lower/Early, M = Middle, U/L = Upper/Late, all capitalized to indicate units of formal rank. Golden spikes are ratified GSSPs, grey spikes are pending. For each "unnamed" Quaternary Stage, a geographically based name will be proposed along with its corresponding subseries/subepoch. This figure is for illustrative purposes only: we recommend that subseries divisions do not appear on the International Chronostratigraphic Chart but be placed on a separate detailed auxiliary chart maintained on the ICS website (see point 15).

Cenozoic stages became systematically incorporated into the time scale (Aubry et al., 1999), accomplished by adjusting stages to pre-existing subseries boundaries. Subseries positional names (Lower/Middle/Upper) reflect a fundamental tenet of stratigraphy (the Principle of Superposition) and are intuitive and appropriate. Series subdivisions have always been used in a chronostratigraphic context, regardless

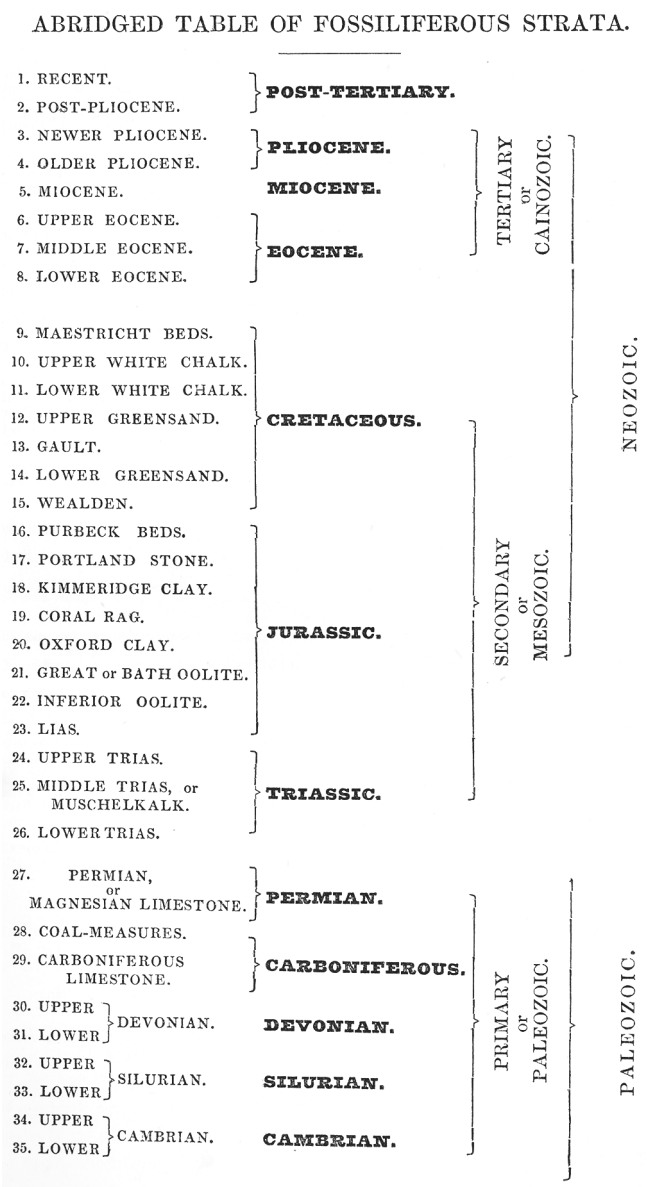

Figure 2: The chronostratigraphic chart of Charles Lyell (1855, p. 109, "Abridged table of fossiliferous strata"), probably the first-ever multi-hierarchical chronostratigraphic chart. Note the hierarchical topology and division of the Pliocene and Eocene series [See also Aubry, 2016, text-fig. 2 for Lyell's later detailed subdivision of series including that of the Miocene].

of whether treated as formal or informal. To define stages formally, but not subseries, runs counter to historical precedent. These themes are elaborated by Aubry (2016; see also Van Couvering et al., 2015), and a detailed history of the extensive use of subseries from the early nineteenth century to the present day is also given by Aubry (2016). To give an arbitrary example of the pervasive usage of subseries, a search for "Lower Miocene" (no case sensitivity) in Google Scholar retrieves 35,000 entries. The long and continuous use of subseries for the Cenozoic supports the formalization of this rank by the ICS.

We acknowledge that positional subseries names, while being intuitive, are not immutable. When the base of the Pleistocene was lowered in 2009 (Gibbard and Head, 2010), it incorporated the Gelasian Stage which then changed from an Upper Pliocene to Lower Pleistocene designation, in turn causing the Middle Pliocene Piacenzian Stage to become Upper Pliocene. The Gelasian is nonetheless now stabilized and a unique case that seems unlikely to be repeated.

2. It has been pointed out that the Integrated Ocean Discovery Program (IODP) and its predecessors, the Ocean Drilling Program (ODP) and the Deep Sea Drilling Project (DSDP), and the United States Geological Survey, have instructed authors not to capitalize the modifiers early/middle/late with respect to subseries because they are not formally defined by the ICS. We see this not so much as evidence for the support of informal subseries, but rather a passive editorial compliance with the status quo. We note that the IODP is only a subset of a wider geoscience community that includes the study of shallow-marine, terrestrial, and lacustrine deposits, and ice-cores. More significant to us are examples (see Aubry, 2016, and point 3 below) where subseries terms *are* capitalized to confer formal meaning even without ICS sanction. We note that subseries are frequently capitalized in several Quaternary (e.g., *Boreas, Journal of Quaternary Science, Quaternary International*) and petroleum geoscience (e.g., *Marine and Petroleum Geology*) journals and other geoscience journals. In the two most recent editions of the Geologic Time Scale, the influential Quaternary chapters (Gibbard and van Kolfschoten, 2005; Pillans and Gibbard, 2012) both use upper-case subseries terms almost exclusively. The equally influential global chronostratigraphic correlation table for the Quaternary (Gibbard and Cohen, 2008, and subsequent updates), including the 2010 version of this table which currently appears on the ICS website, all depict upper-case subseries terms. We contend that even in the absence of formal definition, many authors prefer to use subseries in the formal sense.

3. Subseries are frequently referenced in descriptions of Cenozoic GSSPs in the journal *Episodes*, and are often written with an initial capital letter to indicate formal use. The Middle Paleocene, Upper Paleocene, Middle Eocene, Upper Eocene, Middle Miocene, Upper Miocene, Lower Pliocene, Upper Pliocene, and Lower Pleistocene are all cited in this way (see Aubry, 2016, appendix 1 for details). The Middle Pleistocene and Upper Pleistocene have yet to be proposed, and the Lower, Middle and Upper Holocene are in progress, but these too are intended as formal terms (see point 6, below).

4. The rank of subseries is given support without specific qualification in the *International Stratigraphic Guide* (Hedberg, 1976, p. tab. 2; Salvador, 1994, p. 80, tab. 3), unlike sub- and superstages where "restraint is recommended ... to avoid complicating the nomenclature unnecessarily" (Salvador, 1994, p. 80). The *Guide* does in general recommend restraint in using sub- and super- for new ranks (Salvador, 1994, tab. 1), but this could apply equally to the rank of subsystem/subperiod, which is in fact sanctioned for the Carboniferous System (Metcalfe, 2000). The ICS statutes (www.stratigraphy.org/index.php/ics-statutesofics) make no specific judgment on subseries, simply stating that "formal stratigraphic stage names and units of higher rank" may be ratified by the IUGS.

5. The very fact that subseries have been treated both formally and informally speaks to the need for clear and universally agreed definition. This can only be accomplished by defining subseries explicitly

with ratified GSSP boundaries, rendering them as formal units. By so doing, the perennial issue of whether Lower/Early, Middle, and Upper/Late should be in upper-case will be resolved permanently.

6. The Quaternary has no enduring tradition of international stages: the Gelasian Stage was ratified only in 1996 and the Calabrian Stage in 2011, with no additional stages yet defined. Subseries have therefore long acquired special prominence. The positional terms Lower, Middle and Upper Pleistocene have been used continuously since the 1930s (Head and Gibbard, 2015), are now unambiguously defined, and are treated as formal terms in the Quaternary literature and by the International Union for Quaternary Research (INQUA). More widely employed by the Quaternary community are the equivalent subepochs (Early, Middle, Late). These subseries/subepochs nonetheless require sanction by GSSP and IUGS ratification, and SQS has the following boundary working groups explicitly tasked with this purpose: the Early/Middle Pleistocene Working Group, the Middle/Late Pleistocene Working Group, and the Working Group on the Formal Subdivision of the Holocene. A proposal by the last of these to subdivide the Holocene Series into Lower, Middle and Upper Holocene subseries (Early, Middle, Late subepochs), with corresponding stages, has been recommended with an 81% majority by the SQS. Hence, the formal subdivision of the Quaternary into subseries/subepochs, and their corresponding stages, is well advanced (Head and Gibbard, 2015). Regarding Holocene subdivision, many practitioners (geographers, archaeologists, environmental and climate scientists etc.) are not trained geoscientists. Some may use the stage names we are proposing, but most will use subseries (or rather subepochs) formally for the Holocene regardless of whether we officially recognize them or not (Walker et al., 2012). This is long-established practice, and we have little control over it.

7. Quaternary stratigraphers make use of geochronology universally. They present their data in terms of time and thus naturally use the terms Early, Middle and Late. For example, annual/seasonal layering in ice cores, speleothems, and lacustrine and anoxic marine records, and growth bands in shells and wood, all give absolute ages by direct counting from the present. The base of the Holocene itself is dated in this way (Walker et al., 2009). These records typically show data relative to a time scale in years before present, not core or sediment depth. Geochronometry is used routinely in the study of Quaternary sedimentary successions: radiocarbon dating, lead-210 dating, thermoluminescence dating, and numerous other techniques all give age estimates in years before present (or a proxy for the present). Since the 1960s, astrochronology has extended this approach into deeper Quaternary time (and of course into the Neogene and even Paleogene) by counting rhythmic sedimentary successions and their isotopic signatures, and calibrating them to mathematical solutions for orbital forcing. Data from Pliocene and Pleistocene oceanic successions are typically shown relative to years before present, not core depth. Geochronology is pervasive in Quaternary stratigraphy, whereas traditional stratigraphy is hampered by the extreme climatic gradients that emerged at this time. Subseries/subepoch terminology is accordingly widespread in the Quaternary literature, which is why these terms need to be formally defined.

8. INQUA is a full Scientific Union member of the International Council for Science, together with the IUGS. INQUA has long shared responsibility with ICS for the Quaternary part of the International Geological Time Scale, and was active in its formal definition (Finney, 2010; Gibbard and Head, 2010; Head and Gibbard, 2015). Until 2001, its Commission on Stratigraphy also served as the de-facto SQS but with its officers appointed by INQUA. Although the structure of SQS was brought in line with other ICS subcommissions in 2001, INQUA remains actively involved with its portion of the time scale (Head and Gibbard, 2015). For example, the Working Group on the Formal Subdivision of the Holocene is a joint working group of SQS and the INQUA international focus group INTIMATE (Walker et al., 2012). INQUA's opinion is important. While INQUA embraces the use of international stages for the Quaternary, its position on subseries is clear. *INQUA supports without reservation the case for formal subseries/subepochs for the Quaternary, and indeed already treats this rank as a formal term.*

9. ICS-recognized working groups on the Middle and Upper Pleistocene have been in existence since at least 1989 (Cowie and Bassett, 1989). ICS has already supported formal subseries for the Quaternary. A proposal for a Lower Pleistocene Subseries GSSP in 2008 (Litt et al., 2008) was considered by SQS which voted unanimously in support (18 in favour, 2 not responding), reflecting the need for subseries in the Quaternary. This proposal was then approved by ICS with a majority of 71% (10 in favour, 4 against; Ogg and Bowen, 2008). None of those voting against cited the introduction of subseries as problematic. The IUGS EC declined to ratify this proposal citing eight objections, of which one was that "restraint is recommended in creating new orders of chronostratigraphic units, as sub-erathem, subsystem, sub-series and sub-stage" (Riccardi, 2008), which brings us to the present discussion. Nonetheless, voting within ICS had demonstrated overwhelming support for subseries, at least for the Quaternary. It should be noted that the need for formally defined subseries for the Quaternary was recognized by the ICS Executive as early as 2001 (P.L. Gibbard *in* Ogg and Bowen, 2008), and SQS has made the definition of subseries a focus of its annual science plan consistently since 2003 (see SQS website), with no objection ever having been raised by the ICS Executive. The widely distributed Quaternary correlation chart (Cohen and Gibbard, 2010), e.g., as posted on the ICS website, illustrates the fundamental use of subseries for the Pleistocene. Even the current International Chronostratigraphic Chart (Cohen et al., 2013, version 2016/04) uses the terms "Middle" and "Upper" as placeholders for Pleistocene stage names (yet to be defined), which certainly Quaternarists would consider as referencing the widely used subseries for the Pleistocene.

10. The ICS open meeting at the Second International Congress on Stratigraphy in Graz in July 2015 was held to gauge opinion on the formalization of subseries. Positions for and against the adoption of official subseries for the Cenozoic were expressed from the floor, with the great majority speaking in favor of adoption. While this does not constitute a vote on the matter, it must be concluded that adoption of formal subseries was favored among those attending.

11. It is undeniable that the use of subseries creates redundancy, but this is the price one pays for choice. The Middle Eocene, the entire

Miocene, and the Lower Pleistocene all benefit from the availability of subseries.

12. Stages, not subseries, are the fundamental units of chronostratigraphy. However, concern that stages will decline in use if subseries are formalized is overstated (see also point 15 below). Although subseries are already pervasive in the literature, this has not diminished the use of stages. But whether subseries are given formal sanction (by IUGS-EC ratification, as we propose) or left undefined, practitioners will continue to use the terms they find most useful and appropriate. As demonstrated in Aubry (2016), the only other alternative to the present confusion would be to suppress subseries, but this of course is not an option.

13. Stages and subseries are mostly used to express different levels of chronostratigraphic precision and certainty. For example, deposits of imprecisely known age could be expressed as "Lutetian and/or Bartonian", or more ambiguously as "Lutetian–Bartonian"; but "Middle Eocene" is more efficient and elegant. Likewise, "Middle Eocene cooling" is clearer than "Lutetian–Bartonian cooling" (see Aubry, 2016, for additional examples). Subseries are more frequently used by terrestrial and shallow-marine workers than stages because the stratigraphy is often discontinuous and its dating therefore less precise. However, we contend that stages and subseries are *both* useful, allow necessary flexibility, and warrant full official definition and recognition.

14. A capital initial letter identifies that a chronostratigraphic term is formal and represents a defined interval of time. Subseries are defined by GSSP, and therefore are intrinsically chronostratigraphic and formal in a general sense. The International Stratigraphic Guide (ISG; Salvador, 1994, p. 7, 8) recognises chronostratigraphic units as *formal* units. Moreover, the ISG considers formal stratigraphic terms those that are "properly defined and named according to an established or conventionally agreed scheme of classification", and in such cases capitalization of the initial letter is required (Salvador, 1994, p. 14). According to the North American Stratigraphic Code (North American Commission on Stratigraphic Nomenclature, 2005), *formal* units (indicated by capitalization) are those named in accordance with an established classification scheme. The terms "uppermost Oligocene" or "lower Quaternary" are immediately and correctly recognised as having no strictly defined duration: they are informal. The ISG uses "late Quaternary" to indicate the last 50 to 70 kyr of Earth history (Salvador, 1994, p. 88). To lowercase a subseries term, such as "lower Miocene", wrongly implies that it is not strictly defined. The term "lower Lower Eocene" immediately distinguishes between the first "lower" which has no strictly defined duration, and the second "Lower" which does (Aubry, 2016).

15. We recognise the desirability for the main International Chronostratigraphic Chart (Cohen et al., 2013) to have an uncluttered appearance. Accordingly, we recommend that formal subseries *not* appear on this main chart but feature instead on a more detailed auxiliary chart maintained on the ICS website. Hence the simplicity and aesthetic value of the main chart will not be compromised by the formalization of subseries, as it will continue to display the cardinal ranks exclusively. This also means that stages, which are the fundamental building blocks of chronostratigraphy, will continue to receive the prominence they merit because on the main chart they will not be competing with, or overshadowed by, subseries.

In closing, we advocate defining subseries in the Cenozoic by formal IUGS-EC ratification to stabilize the use of these terms and circumvent a two-tier system of legitimacy for chronostratigraphic units. Formal status will respect the deep historical roots of subseries for the Paleogene and Neogene, and provide legitimacy for a system in universal use within the Quaternary community that already treats subseries/subepochs as formal units. Our proposal respects the primacy of stages as the fundamental building blocks of chronostratigraphy, but acknowledges the chronostratigraphic legitimacy of subseries. Formalization will also provide a final resolution to the capitalization conundrum: upper case without exception for the positional terms Lower/Early, Middle, and Upper/Late throughout the Cenozoic.

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